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Design and Development of a Real-time Characterization System for Energy Conversion Devices

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Abstract: *In this communication it is presented an electronic system for acquiring data from experimental energy conversion devices such as solar cells and fuel cells for micro-electronic applications. The electronic system consists of a software installed in a personal computer and an electronic circuit coupled to a four-wire terminal where the electrical variables like voltage and current can be measured from experimental cells. The software contains a feedback control system for allowing the maximum power transfer from the energy conversion device to the electrical load. It is possible to record and plot the obtained data in real time for a dynamic analysis of the experimental devices at transient or stable state conditions. It is a portable and low-cost device useful for educational and research purposes.*

Keywords: Data acquisition system, energy conversion device, I-V curve tracer, E-I curve tracer

1. INTRODUCTION

It is very important to use an accurate equipment to perform measurements of electrical signals obtained from energy conversion systems or devices [1-4]. Voltage and current are significant signals that define the characteristic curve (I-V plot) of any solar cell or fuel cell. Temperature, flow rate and concentration of the fuel are important parameters that could control the performance of fuel cells. On the other hand, the temperature and irradiance are determining parameters that control the performance of solar cells. It is crucial that the electronic system for measuring the electrical variables could consider the acquisition of voltage, current as well as the parameters that control the electrical power of the energy conversion device. It is necessary for the plotting of electrical variables and for the calculation of other characteristics like the electric power, the cell efficiency, fill factor of the solar cell etc. For the characterization of solar cells, it is important to consider the electrical current as defined in equation (1) [5].

$$I = I_L - I_s\left(e^{\frac{V+IR_s}{\frac{nKT}{q}}} - 1\right) - \frac{V+IR_s}{R_{sh}} \tag{1}$$

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The electrical characterization of fuel cell is derived from the Nernst equation shown in equation (2), where the electromotive force is related to the chemical potential formed by redox reactions inside the fuel cell [6].

$$E = E^0 - \frac{RT}{nF} lnQ \tag{2}$$

The physical principle for characterizing solar cells or fuel cells is based on the application of a variable electrical load in parallel to the energy conversion device and a voltage-current pair appears due to power generation (figure 1).

It is very common to find in technical reports related to the characterization of solar cells, the use of variable resistances adjustable manually by the users [7]. The data acquisition is recorded point to point at non-constant time interval and as a consequence, it is not possible to plot the electrical response in real time or calculate kinetic parameters from the experiments [8].

Capacitors or microcontrollers are used to modify electronically the electrical load for characterizing solar cells or fuel cells [9]. Nowadays it is common the use of high sensitivity multimeters with GPIB interface for transferring data to computers during the characterization of photovoltaic modules or solar cells. This method implies the use of an external power supply coupled to a dual

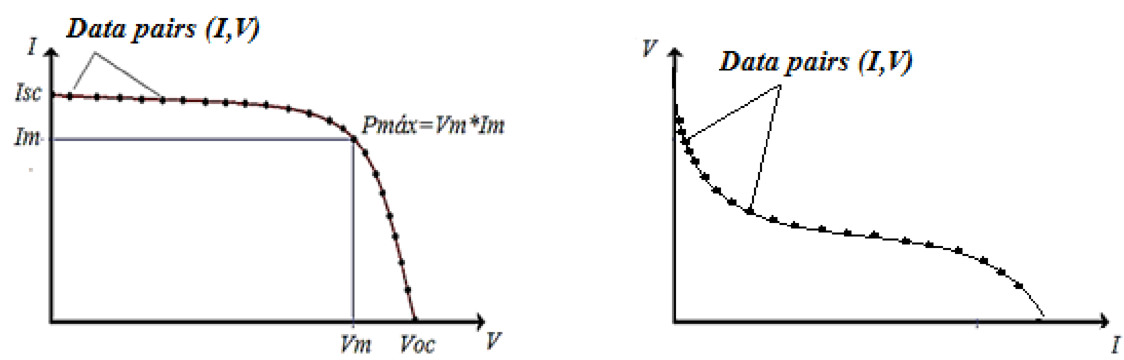

Figure 1. Typical I-V curves for energy converters a) photovoltaic cell, b) fuel cell

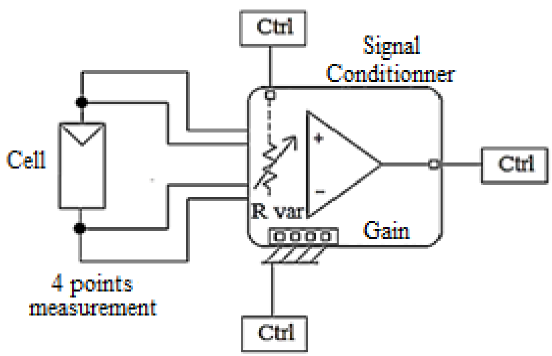

Figure 2. Schematic representation of the control system

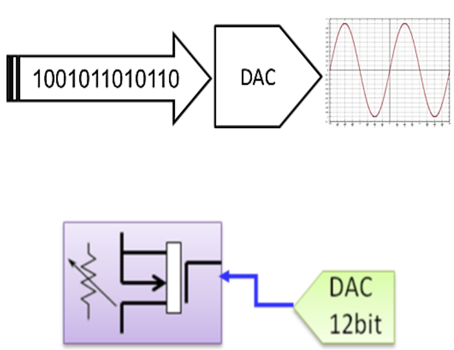

Figure 3. The DAC used for data acquisition of electrical signals from the load

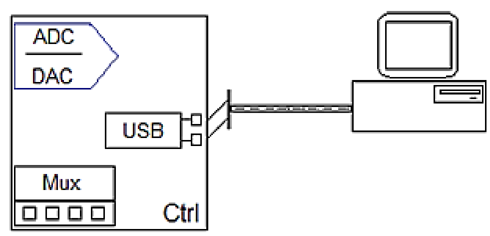

Figure 4. Components of the control circuit and its interfacing to PC

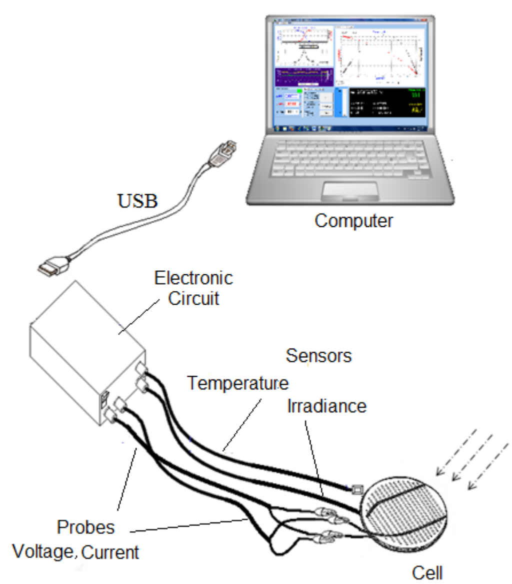

Figure 5. The prototype of the electronic system for acquiring data from the energy conversion devices

oscilloscope for the visualization of the electrical signals [10,11]. The cost of this complex system for acquiring experimental data from the characterization of solar cells can reach a few thousands of USD.

The I-V characteristic plot of a solar cell or fuel cell requires the measurement of the open circuit voltage (Voc), short circuit current (Isc) and the I-V points at the ohmic interval. The I-V points are function of the maximum power transfer [12]. The maximum voltage (Vm) and maximum current (Im) are calculated from the experimental data and the maximum electrical power (Pm) is also calculated according to equation (3).

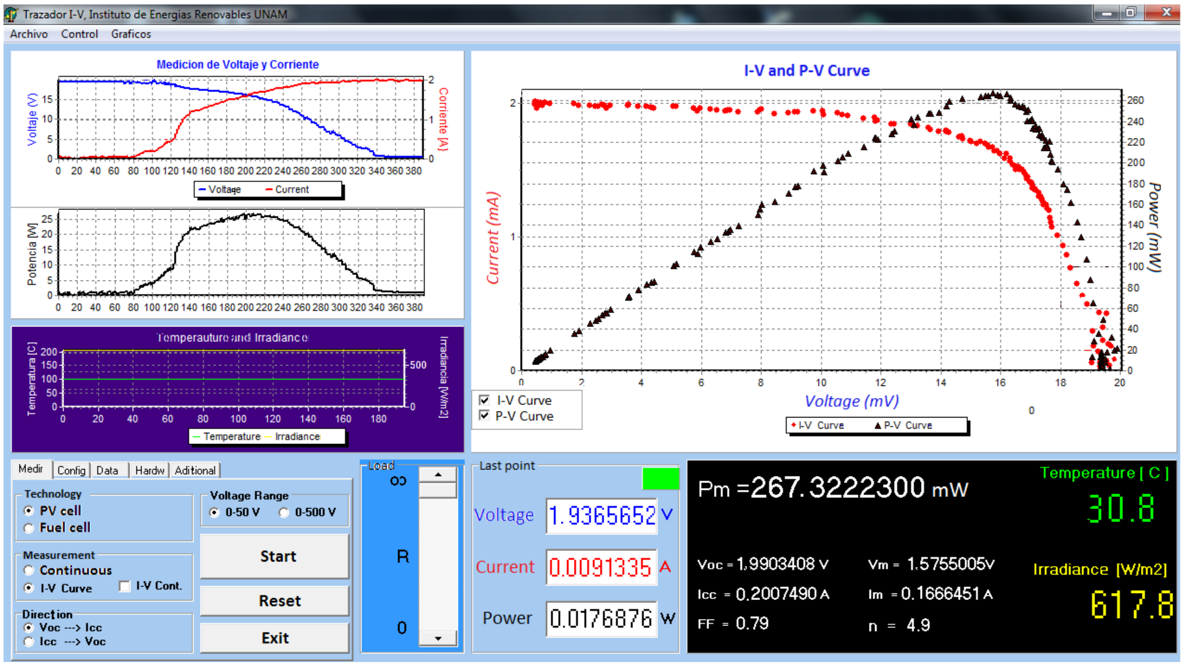

Figure 6. Components of the control circuit and its interfacing to PC

$$P_{máx} = V_m * I_m \tag{3}$$

In this work it is presented an electronic system for characterizing electrically low-power solar cells and fuel cells. The data acquisition system controls the electrical load for assuring the maximum power transfer and obtaining an ohmic response from the experimental cells.

2. DESIGN OF THE ELECTRONIC SYSTEM

The electronic system is shown schematically in figure 2. It consists of a control software and a hardware or interface for offering the maximum power transfer through the electrical load for accurate measurement of the electrical parameters like current, voltage, electrical power of solar cells and fuel cells. It is also possible to calculate the cell efficiency in each case. The hardware involves an algorithm formed by two components: (i) a linear electrical circuit containing the resistive load for the connection to the cell for measuring electrical signals, the electronic arrays for the communication and signal processing from/to the microcontroller and (ii) a logic interface coupled to the computer through a USB standard for the data acquisition. MOSFET and a four-wire method were used for minimizing lead resistance that could affect the measurement and recording of experimental data as voltage, current, temperature and irradiance [13]. They can be saved as files in the electronic system for a complete visualization of the variables and calculations in electrical energy conversion systems.

The electronic system consists of a signal/noise ratio logic filter to sense and record very small signals coming from the activation process when it is starting the characterization of the experimental cells. This is the reason to use a four-wire connection for minimizing power drops by impedance mismatch during acquiring information from the cells, two terminals for current and two for voltage measurements [11]. The electrical terminals are connected to a 12 bit digital to analog converter DAC for the proper conversion of the analogic signals [14] (figure 3).

It was used a USB port as communication channel to synchronize the signals obtained from the experimental cell with the database enabled by the control software (figure 4).

The software contains the subroutines for processing the information related to the voltage and current of the cell as well as the electronic adjustment of the load. The subroutines are focused in a sensitivity analysis of the activation, ohmic and diffusion processes occurring at the experimental cells. It is possible to select the type of energy conversion device or technology that is being characterized, solar cell or fuel cell (figure 5). It is also possible to measure and record the I-V characteristic response of the experimental cells [14].

The control software has the capability to carry out different types of data acquisition from the experiment i.e., mathematical and statistical analysis of recorded data (analysis of variance). It is possible to apply experimental conditions to obtain forward or backward bias sweep that is very useful for the characterization of novel solar and fuel cells, where Voc and Isc can be measured at specified conditions [15,16].

The control software was designed to maintain the operation of the energy conversion device at the maximum power point for a period of time. The software can be executed to do repeatedly the data acquisition of I-V characteristic according to a programmed sequence. In all cases, it is then necessary to adjust the electrical load to characterize the devices simulating the real operation conditions of those energy converters in experimental applications.

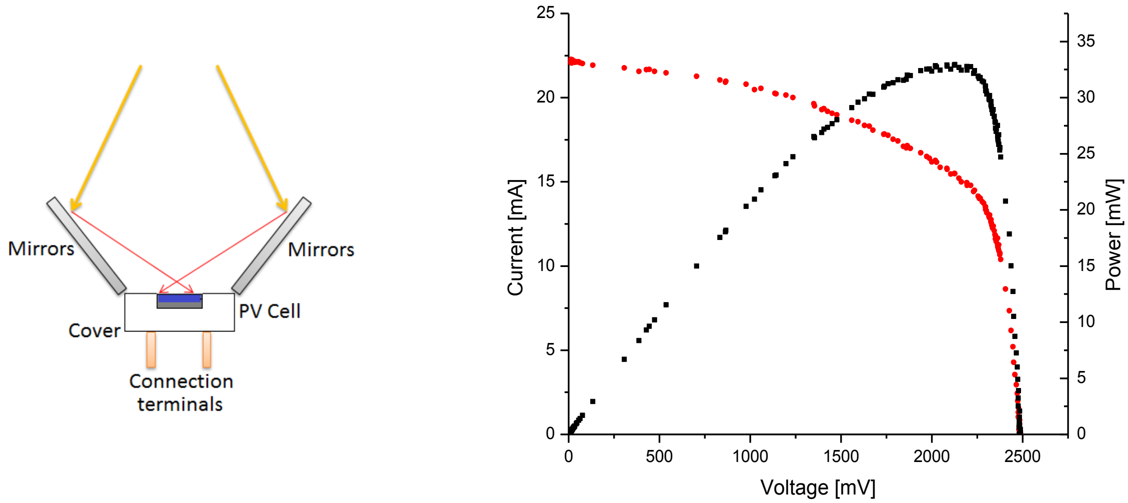

Figure 7. The I-V curve of a PV concentrator cell with mirrors

The data acquisition of each experiment can be paused and resumed at any moment with the possibility of saving data acquired until the interruption moment for further analysis. It is also possible to adjust manually the electrical load if the experiment needs it for some special characterization.

Experimental and calculated values with interesting information like Voc, Isc, Vm, Im, fill factor, maximum power point, current density, efficiency, temperature and irradiance are plotted in intuitive windows (figure 6). The visualization interface can display in real time the electrochemical variables measured in the experiment, e.g., (a) potential vs current plot, (b) power vs current calculations, (c) temperature and irradiance performance plots and (d) sequenced experiments plotted at maximum power point.

The data are available in excel or ascii formats, specially it is used the CSV standard as the easiest mode to share the experimental data with some visualization software. The data files still contain notes of experiment details (date, time of starting and stopping of experiments). The files are saved in selected paths given by the users when the experiments are finished.

The data obtained for the electronic prototype during the characterization of solar cells were compared with the acquired data from a commercial system installed for the same purpose (Keithley 230 Programmable Voltage Source). The results obtained in both systems were completely similar with a difference that the electronic system can be considered as low-cost and high performance modular system very useful for educational purposes.

3. RESULTS

Three different energy conversion devices where characterized in order to show the performance of the electronic system: a commercial concentrator photovoltaic cell, a commercial hydrogen/oxygen fuel cell and a novel micro-direct alcohol fuel cell. The novel alcohol fuel cell is under patent application.

A. Commercial Concentrator Photovoltaic Cell

A 1 cm^2 concentrator photovoltaic cell supported on aluminium case with 4 mirrors of 3 cm^2 was characterized electrically by the electronic system (figure 7). The irradiance applied from a solar simulator was 910 Wm-2 at 21 ºC. The electrical results are shown in Table 1.

The sensibility of the electronic data acquisition system was proved by making small changes to the experimental conditions, in this case, the irradiance was slightly increased ca. 3% with respect to the previous experiment. The temperature was controlled at 24 ºC during the entire experiment.

The mirrors help to increase the cell efficiency by partial concentration of the solar irradiance on the cell surface. It is then possible to calculate the efficiency of the solar cell as a superposition of the irradiance angle from the mirrors in addition to the global irradiance from the sun.

B. Commercial Concentrator Lens based Photovoltaic Cell

There were measured photovoltaic parameters of a photovoltaic cell coupled to concentrator lens under controlled experimental conditions such as an irradiance of 940Wm^{-2} at 24°C. The obtained results are shown in table 2.

The sensibility of the electronic data acquisition system was proved by making small changes to the experimental conditions, in this case, the irradiance was slightly increased ca. 3% with respect to the previous experiment. The temperature was controlled at 24 ºC during the entire experiment. The results of the experi-

Table 1. Results obtained with mirror based concentrator

$P_{máx}$:	32.94mW	η:	33%
V_{oc}:	2.49V	I_{sc}:	22.2mA
V_m:	2.127V	I_m:	15.4mA
A_{cell}:	1cm2	F.F.:	0.85

Table 2. Results obtained from lens based concentrator

$P_{máx}$	76.2mW	η	24%
V_{oc}	2.75V	I_{sc}	32.6mA
V_m	2.43V	I_m	31.4mA
A_{cell}	1cm^2	F.F.	0.88

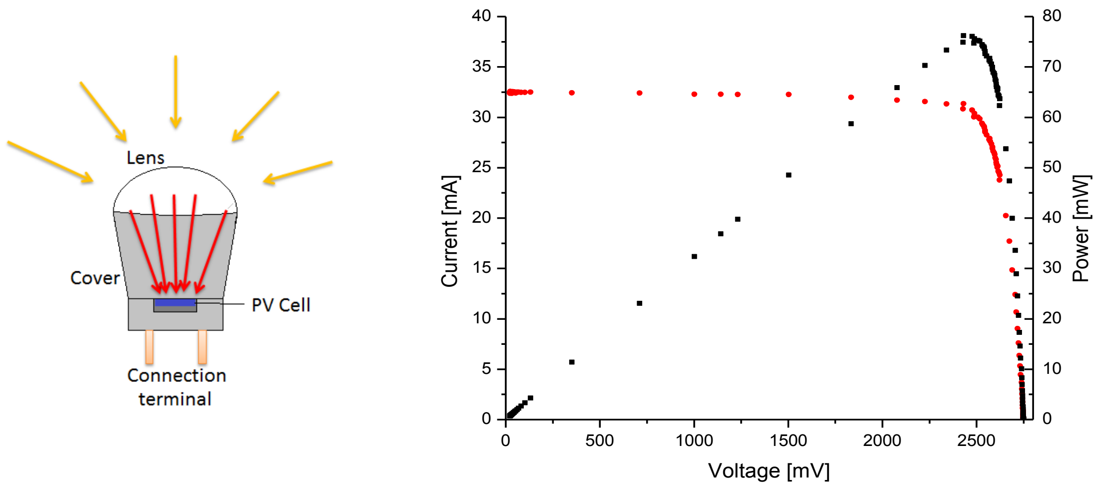

Figure 8. I-V curve of a photovoltaic cell with concentrator lens

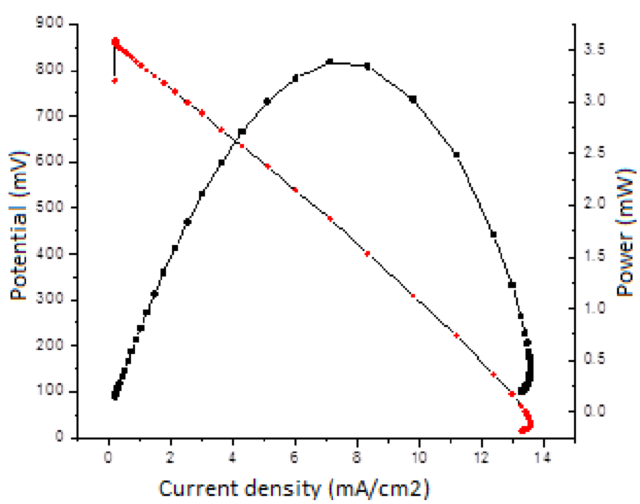

Figure 9. The E-I curve of the PEM fuel cell

ments were reproduced three times obtaining not more than 0.1% variation at each acquired point (figure 8).

A small change in radiation power produces a significant change in power response of this kind of solar cell. The electrical power increases from 32.94 mW to 76.2 mW. This result is possible due to the high sensibility of the electronic system to acquire low signals of electrical parameters.

It is possible to calculate the efficiency of concentrated solar cells at controlled temperature. In this case, the fill factor and efficiency of the cell show values higher than conventional solar cells. The control of the cooler cover is crucial for this kind of experiments because it is necessary to maintain the cell at stable temperature. The electronic system used for characterizing concentrated solar cells considered an adequate feedback for avoiding the addition of error or noise signals. It was obtained by a selected hardware and logic software included in the data acquisition system.

C. Commercial Hydrogen/Oxygen Fuel Cell

A commercial proton exchange membrane fuel cell (PEM-FC) of 1.0 cm^2 apparent area with Pt mesh on carbon as anode and cathode was characterized electrically by flowing 8.0 cm^3 of hydrogen and 10.0 cm^3 of oxygen at the anode and cathode respectively. The experiment was carried out at 25 ºC.

In figure 9 it is shown the electrical response of the fuel cell at the experimental conditions. In table 3 it is shown the results obtained from the experiment.

It is clearly observed that the electronic system has the capability of leading the electrical response of the fuel cell through the maximum power transfer by maintaining the performance of the fuel cell at a large ohmic range, it is from 0.1 to 13 mAcm^{-2} until to reach the mass transport control (ca. 13.5 mAcm^{-2}).

D. Novel Direct Ethanol Fuel Cell

An experimental alkaline direct ethanol fuel of 1.0 cm^2 apparent area, still under preliminary trials and patent application was characterized electrically by using the electronic data acquisition system. Alcohol fuel cells have the characteristics of producing high current at low voltage (at about 500 mV) and at room temperature. This performance could be interesting for sensors and actuators in micro-electronic applications. Figure 10 shows the potential vs current density plot (E-I) of the experimental direct alcohol fuel cell at 24ºC with 1 µL of ethanol.

The potential-current density plot shows the experimental response of the fuel cell following the ohmic performance in the range from 0.5 to 0.85 mAcm^{-2}. Table 4 shows the electrical characteristics of this novel fuel cell. The experiments were performed at 24 ºC.

Figure 11 shows the feasibility of performing an analysis in real time of the instant current and voltage going through the electrical load. It is an adequate tool for further calculation of electro-kinetic parameters and identification of mechanistic processes at the ener-

Table 3. Commercial hydrogen fuel cell.

Pmáx:	3.4mW	A_{cell}:	5 cm^2
V_{oc}:	865mV	I_{sc}:	13.5 mA
V_m:	477mV	I_m:	7.01 mA

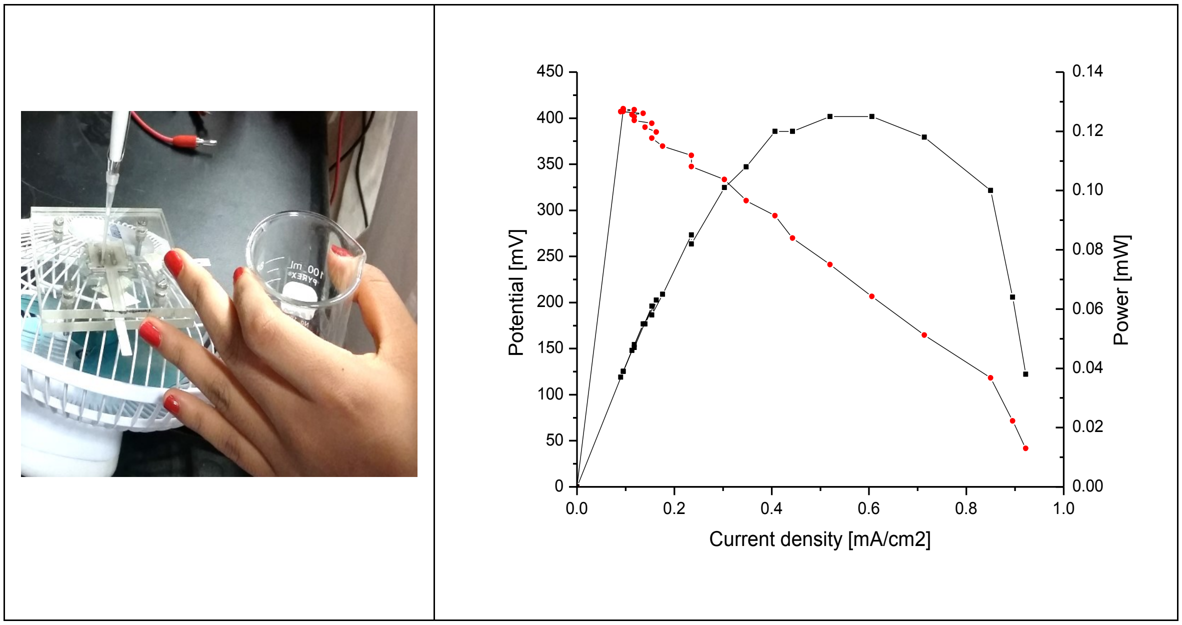

Figure 10. The E-I curve of the experimental direct ethanol fuel cell

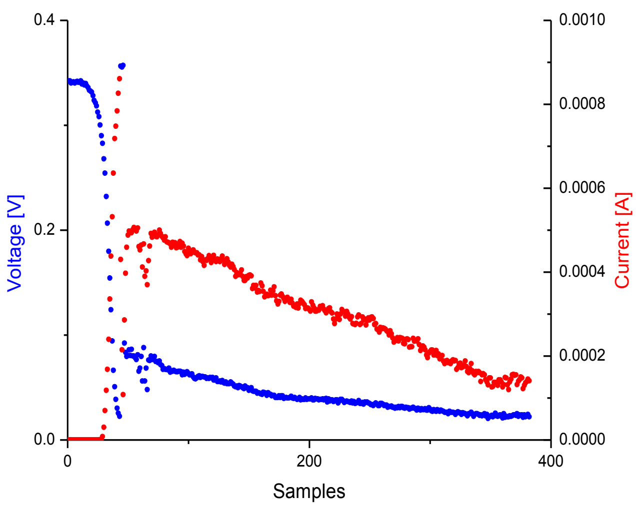

Figure 11. The variation of voltage and current during measurement

gy conversion devices. As in the case of the solar cell characterization, the electronic data acquisition system had the capability of adjusting the electrical load by control feedback for transferring the maximum power from the fuel cell.

The definition of the plots can be adjusted by selecting the number of points associated to the delayed time for every experiment. The electrical features for the performance of the electronic system for acquiring and plotting experimental data from solar cells and fuel cells are shown in table 5.

Table 4. Results obtained from the direct ethanol fuel cell

Pmáx:	0.13mW	A_{cell}:	1.0cm^2
V_{oc}:	410mV	I_{sc}:	0.92mA
V_m:	241mV	I_m:	0.52mA

The minimum current detectable as signal is 95 µA. It means that with this electronic system it is possible to acquire data information of transient and/or stable state conditions from micro-devices at extreme conditions of over-potential or over-current to evaluate the safety performance, especially of fuel cells.

4. CONCLUSIONS

The use of the electronic system showed the feasibility of obtaining electrical variables from experimental energy conversion devices, such as solar cells and micro-fuel cells. The system also has the capability of acquiring very low current signals during the electrical characterization of novel direct ethanol fuel cells for microelectronic applications. It is possible to plot voltage vs current characteristics as well as calculated parameters like the electric power supplied by the solar cell and fuel cells. The logic design used for developing the electronic system assures the ability to acquire and record electrical values of experimental devices at transient and stable state conditions, it means that it is possible to perform the I-

Table 5. Features of the electronic measurement system

Power consumption	0.47	W
Voltage Range	0-5	V
Voltage Resolution	4.88	mV
Current range	0-500	mA
Current Resolution	95	µA
Voltage Sensibility	0.125	V/V
Current Sensibility	50	mA/V
Frecuency	470	Hz
Temperature range	0-90	°C
Irradiance range	>1000	W/m2

V characterization from Voc to Isc at the maximum power transfer of the devices.

5. ACKNOWLEDGMENTS

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