Open Control Architecture for the Characterization and Control of the PEM Fuel Cell

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***Abstract*— Proton exchange membrane (PEM) fuel cells, are an efficient and clean source of electrical energy. The analysis of its operation requires experimental work, which allows measuring, modeling and optimizing PEM fuel cells electrical behavior under different operating conditions. Therefore, having an experimentation platform that allows to easily carry out its study and control is essential. This research presents the design and development of an open instrumental system that allows measuring, controlling and determining the operating parameters of a PEM fuel cell. As results, the polarization curves, voltage-current, obtained by the system itself in different experimental conditions are shown. These curves are a very useful tool to evaluate the electrical behavior of the PEM battery.**

Keywords—PEM fuel cell, Experimental System, Control Engineering.

I. INTRODUCTION

PEM fuel cells, are emerging as one of the chemical energy transformation devices with more chances of success in the near future, due to its easy transport, clean energy, high performance (73 - 90% for low intensities), lack of moving parts and operating temperature close to the environment [1]

Their operating conditions, and their advantages and disadvantages compared to other types of batteries can be found in [2], [3] shows a detailed description and modeling of a fuel cell. The conceptual simplicity of these devices contrasts with the complexity of the factors that affect their operation, so that their study requires the development and optimization of an equipment that allows the adequate measurement and control of the variables involved.

This instrumentation is usually grouped into equipment called experimentation stations or test benches, distributed by several companies, such as Hydrogenics [4] or Electrochem [5]. Most of these offers, for the adjustment of operating conditions; independent control manuals or closed control programs and different test protocols from those established by the equipment manufacturer.

The instrumentation must allow the measurement and control of variables such as:

- Operating temperature of the PEM fuel cell.
- Flow and pressure of feed fluids.
- Humidification conditions in the PEM fuel cell.
- Humidity and temperature of feed gases.
- Chemical energy transformed directly into electrical energy and heat [6].

Therefore, it is necessary to provide the equipment with sensors and actuators that allow the measurement and control of these variables, with the corresponding electronic data acquisition and signal conditioning, their processing and subsequently the decision-making control.

The automation of experimental procedures involves the management of these devices through proper programming. This requires experimentation capable of handling the wide spectrum of variables of diverse nature involved in the different processes: electrochemical, transport of mass, fluid-dynamic, thermal, electrical, among others.

The tests are susceptible to pre-programming conditions, these can be repetitive and / or take a long time, so automated equipment is essential.

II. PEM FUEL CELL PROCESSES

The global PEM fuel cell control system is composed of the following subsystems.

- Central Processor.
- Gas System.
- Cooling System.
- Electronic load.

Fig 1. shows an illustrative scheme of integration of the different basic subsystems, physically differentiated and linked together.

A. Central Processor.

Its mission is to perform the task of: data capture and treatment, perception algorithms, battery status control (degree of membrane wetting and energy efficiency) and user interface, for definition of parameters and setpoints that are sent to *the low-level local processors* where the modules of data acquisition and control of the state variables reside: flow, pressure, temperature and humidity in the gas supply; temperature and speed of the pump in the thermal management of the battery (high average powers); and voltage, current and electrical resistance in the variable electric charge.

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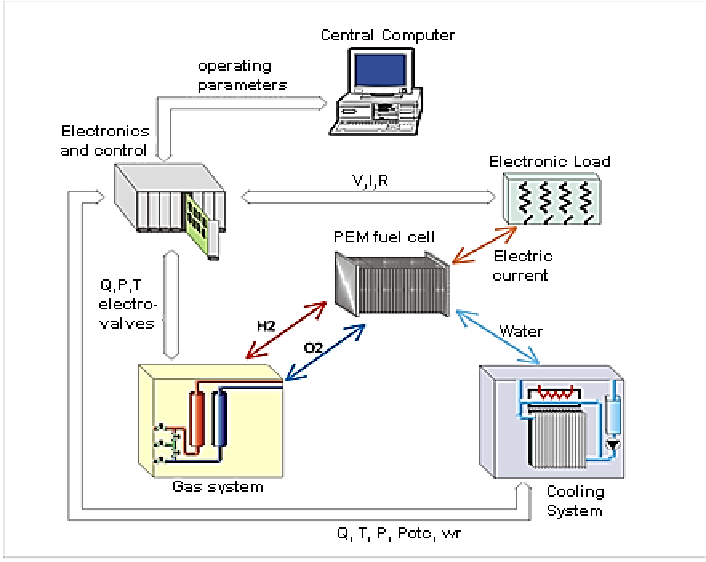

Fig. 1. Structure of integration subsystems that make up the system for the integrated control of the PEM stack.

B. Gas system

The main function of this subsystem is to supply the PEM fuel cell with the gases involved in the electrochemical reaction at the working conditions: temperature, humidity, pressure and flow. Gas pressure control in saturation conditions at temperatures above room temperature, makes it difficult to use needle pressure regulating valves due to condensation phenomena. This difficulty is increased in higher power systems due to the use of higher flows.

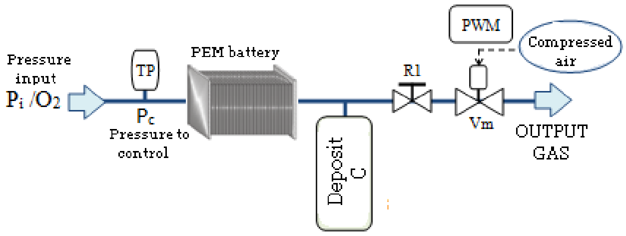

Fig. 2. Pressure regulation system by PWM online.

An innovative solution to this problem is the use of a diaphragm valve with pneumatic actuation and PWM (Pulse Width Modulation) control. This valve is located at the output of the PEM fuel cell, and produces small pressure fluctuations due to PWM actuators, the integration of an accumulator (reservoir) at the output of the cell allows to eliminate these fluctuations, as shown in Fig. 2.

An electrical model has been determined for each state of the diaphragm valve, applying concepts of capacitance and resistance in pressurized gas systems [6]. The transfer function that defines the pressure regulation system in its two operating states of the diaphragm valve is represented in Eq. (1.0)

$$Pc(s) = \frac{1}{RCs}\left[Pi - Pc\left(1 + k\frac{R}{R1}\right)\right] \qquad (1.0)$$

Where: Pi is the inlet pressure in the oxidizing gas supply line; R y R1 are the resistance to gas flow, and; the term k represents the operating state of the valve controlled with PWM taking only two values: open and closed.

C. Cooling System.

In many cases, low power PEM fuel cells (less than 200W) do not dissipate enough power needed to heat themselves. In order to increase their temperature since initial to operation state, it is necessary to use heating mats or resistors, bonded on the fuel cell terminals. These heating mats provide the necessary heat to the battery by PWM applied to a solid-state relay. The power and size of the mats depends on the battery itself, especially of the active area and the material used in the bipolar plates. The heating system coupled to the PEM fuel cell and managed by the temperature regulation subsystem is shown in Fig. 3.

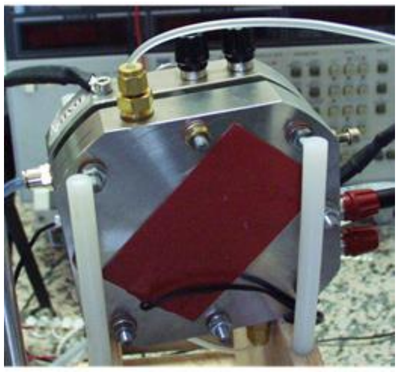

Fig. 3. Heating mat used to raise the temperature of the PEM stack of low power.

D. Electronic load.

A point not adequately addressed is that of the link in real time between the conditioning variables of fluids in the supply of the stack, and the parameters that determine its electrical behavior before a variable external electrical load

A point not properly resolved is that of real-time coupling between the conditioning variables of the fluids in the battery supply, and the parameters that determine their electrical behavior before a variable external electrical load. For this reason, a variable electric charge has been incorporated into the control system for the automatic calculation of polarization curves (Voltage-Intensity ratio under certain conditions) and the management of the water balance in the cell. This entails a lower cost of time and guarantees the switching times are always the same, to compare different membrane-electrode assemblies (MEAs), end plates and other components of the PEM fuel cell.

The design of an electric charging system varies significantly depending on the energy to dissipate and the load values to be applied. In fact, the non-linear power delivery of this electric generator requires the load design be developed from the typical response modeling of a PEM cell consisting of two sections.

The first section corresponds to a moderate voltage drop, a section in which the PEM stack has a stable ohmic drop operation, represented by Eq. (1.1).

$$R_1 = m_1 + V_{max} / I \ ; \ (Imin<I<Ip) \qquad (1.1)$$

$$\text{Where: } m_1 = (V_p - V_{max}) / I_p$$

The second section represents a strong voltage drop due to mass transport defect, with an electrical resistance represented by Eq. (1.2).

$$R_2 = m_2 + (V_p/I)(1+ I_p/(I_{max} - I_p)) \ ; \ (I_p<I<I_{max}) \qquad (1.2)$$

$$\text{Where: } m_2 = -V_p/(I_{max} - I_p)$$

The selection of the numeric values are calculated in each section of the polarization curve will depend on the importance and volume of information obtained from the data. A possible solution for low powers is the switched load, the switched sequence of resistances allows to obtain the Voltage-Intensity polarization curve of the PEM fuel cell in all its dynamic range and with the necessary number of points to have a complete information as possible.

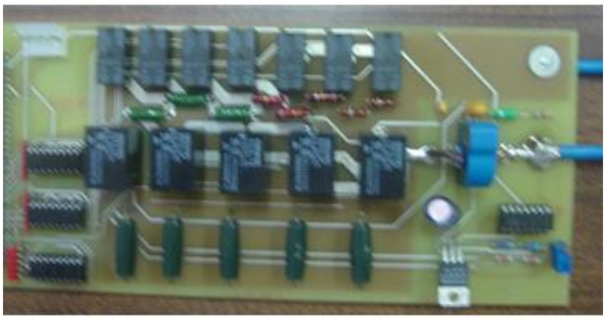

Fig. 4. Power stage of the electric charge.

The electric charge module incorporated into the integral control of the PEM fuel cell is composed of a control and a power stage, the components of these stages: relays, integrated circuits, hall effect current sensor, power resistors and connection cables with the bipolar plates of the cell, are shown in Fig.4.

III. OPEN ARCHITECTURE OF CONTROL

A. *Communication and information management.*

The need to create a robust network of intercommunicated microprocessors to perform control and supervision tasks requires the creation of efficient protocols for information and communications management. The master node is considered a communications manager between the microprocessor network (slave nodes) and the central computer. In fact, the communication protocol, seen from the central computer, is divided into two fundamental cycles: reading and writing.

In the *writing cycle,* the central computer sends the messages, parameters and setpoints addressed to the slave nodes through the gateway to the master node. The master node, the host computer and the slave nodes recognize the number of parameters corresponding to each process to be controlled. The master node sends information to the slaves in a data frame with a previously defined format. The data frame carries a message header, in which is the address of the slave node, the type of action that can be write or read and then the reference data sequentially is shown in Fig. 5.

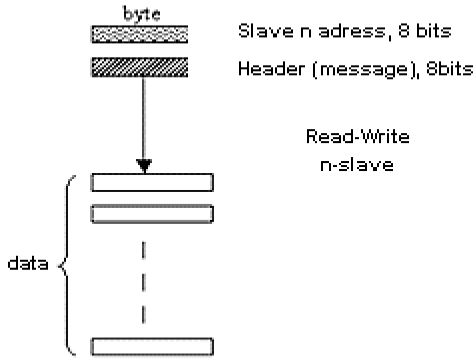

Fig. 5. Data frame: write – read..

In the *reading cycle,* the master asks each slave for the messages and variables to be monitored through the data frame, causing an interruption in its execution process. All the information stored in the data memory of the master node is sent in a single frame to the central computer.

B. *Distributes control based on microcontrollers*

The automatic management and control of the status and disturbance variables of the PEM fuel cell is carried out in a network of microcontrollers (T-PIC slave nodes) that communicates through a gateway (T-PIC master node) with the central computer. The master node manages the bi-directional transmission of data between the network of slave nodes through the I2C communication protocol and the central computer through the USB communication protocol.

The T-PIC slave nodes independently control the assigned process, sending the variables to be monitored and the alarm status messages to the central computer, and receiving the value of the setpoints that affect the process. Thus, for the hydrogen / fuel supply system of the battery, the T-PIC slave-H2 node is responsible for managing the transducers and actuators corresponding to this gas supply line, in the same way, the T-PIC node does slave-O2 for the oxidant line; the slave node T-PIC loads for the variation of electric charge. The slave node network has a distributed control and is presented in Fig. 6.

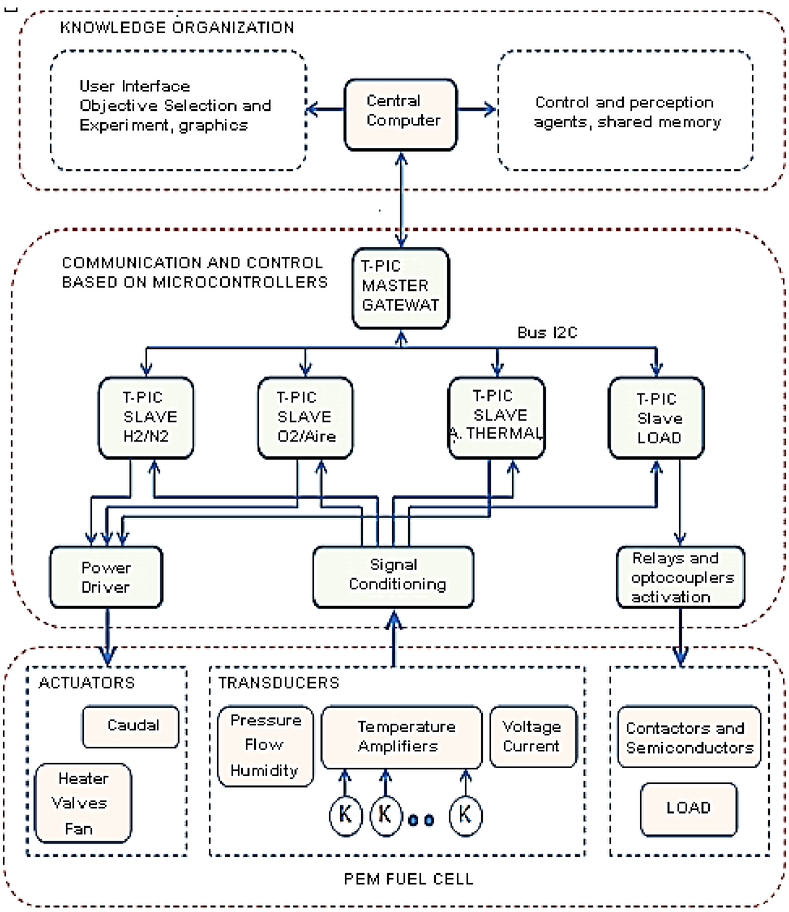

Fig. 6. Distributed network of nodes for monitoring and control of the PEM stack.

C. Local processor (T-PIC)

In order to obtain versatility and robustness in low-level communication and control processes, a local general-purpose processor (T-PIC) has been developed for both the acquisition and treatment of sensor signals, and for communication and control of variables in each assigned process, Fig. 7.

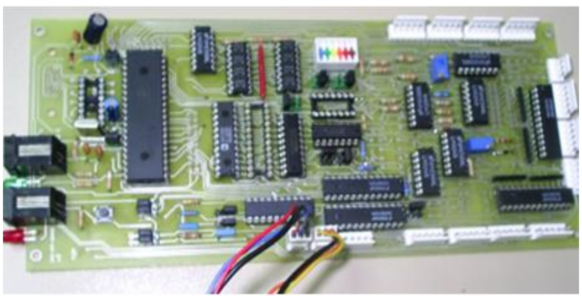

Fig. 7. General purpose T-PIC local processor (slave / master node).

The local processor has a wide variety of analog and digital inputs and outputs, as well as communication protocols to operate as a slave in control tasks or as a master in communication tasks, thereby facilitating the incorporation of new tasks, variables or parameters to control.

IV. Results

The initial conditions set for the status variables of the PEM fuel cell and electric charge steps can be configured in the parameter configuration window, incorporated in the software application developed as an interface and incorporated in the integral control of the PEM fuel cell, shown in Fig. 8. In this window, the Variable Load scenario has been selected, with 10 points of sequential load changes on curve VI, that is, on the value of the short-circuit current, Icc.

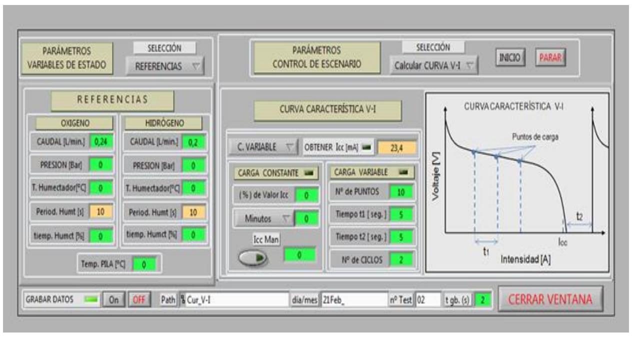

Fig. 8. Experiment configuration window.

Fig. 9 shows the different V-I polarization curves obtained from a small-power PEM fuel cell under the operating conditions defined in the configuration window and with variations in electric charge.

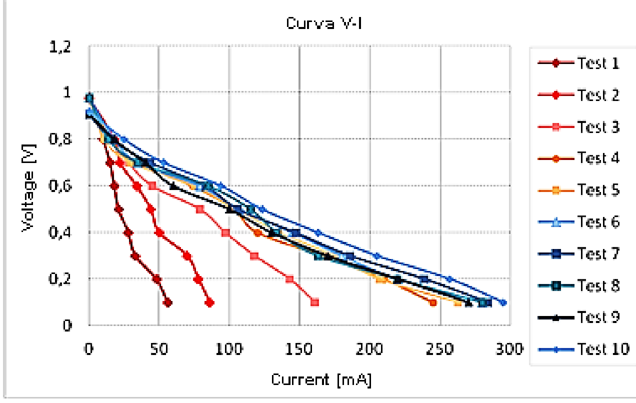

Fig. 9. Polarization curves obtained from a PEM fuel cell.

The system allows not only to obtain the current-voltage polarization curves of a PEM fuel cell, but also a wide variety of experiments such as, the application of load steps for the study of transients and durability protocols of components of a PEM cell, which requires automatic and unattended processes.

This system based on a network of distributed nodes that facilitate the characterization and control of the PEM fuel cell has been developed as a flexible system with the possibility of rapid reconfiguration. Unlike most commercial systems, it has an open structure, both in the control programs and on the cards, which allows new modes of operation, new variables to be controlled and, including optimization algorithms and pattern recognition.

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VI. REFERENCES

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