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Proceeding Paper

Characterization of PEM Fuel Cell in the Context of Smart Microgrids Involving Renewable Energies †

David Calderón, Francisco Javier Folgado *, Isaías González and Antonio José Calderón

Department of Electrical Engineering, Electronics and Automation, Universidad de Extremadura, Avenida de Elvas, s/n, 06006 Badajoz, Spain; dcalderoh@alumnos.unex.es (D.C.); igonzp@unex.es (I.G.); ajcalde@unex.es (A.J.C.)

* Correspondence: ffolgar@unex.es

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Abstract: Fuel Cells (FCs) constitute an enabling technology for the integration of renewable energies and for the deployment of the next generation of power grids, the so-called Smart Grids/Microgrids. These devices perform the process of converting hydrogen into electricity without pollutant emissions. Characteristic curves, mainly polarization curves, are a paramount resource to study the performance of FCs and to determine accurate models that fit their behaviour. This paper presents the characterization of a commercial Polymer Electrolyte Membrane (PEM) FC consisting of 24 cells in series, with a nominal output of 500 W, used to supply electricity in a Smart Microgrid involving renewable energies and hydrogen. The process evolution takes place under different laboratory conditions, so voltage, current and hydrogen flow are measured and plotted to build the polarization curves. The equipment and components involved in the operation of the FC are described, as well as their technical features. Namely, a metal-hydride bottle is used to store the hydrogen that feeds the FC, an electronic programmable load establishes different charge conditions, and a precision multimeter collects the measurements provided by a set of sensors physically coupled to the FC. The characterization conducted in this research is envisioned to be used to build a digital twin of the FC. The developed experimentation and achieved results are described. The obtained results show a proper matching between the experimental data and the curves reported in literature and in the FC datasheet.

Keywords: Fuel Cell; hydrogen; Smart Microgrids; polarization curve; sensors; renewable energies

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1. Introduction

Hydrogen is an energy carrier expected to solve the long-term energy storage issue for power grids based on renewable energy sources [1]. Even, the term “Hydrogen economy” has been gaining strength in recent years [2]. In this context, the so-called Smart Grids are intelligent power networks with enhanced capabilities in terms of performance and stability due to the massive introduction of sensing, automation and monitoring technologies [3]. Small-scale Smart Grids are known as Smart Microgrids which can be connected to the main distributed grid or operate in stand-alone model. Smart Grids and Smart Microgrids integrating renewable energies can reduce the greenhouse gases and help to meet the incessantly rising energy demand [4].

Decentralized generation and consumption are features of these modern grids, so a number of energy conversion equipment is required. For instance, electrolysers can be used to generate hydrogen from local renewable energy sources, whereas Fuel Cells (FCs) can be applied to produce electricity from stored hydrogen in an environmental-friendly system. In fact, FCs receive important research efforts, from constructive aspects [5] to monitoring systems [6] passing through modelling of their behaviour. In this latter regard, existing literature reports a large amount of papers about different models of FCs, including theoretical and empirical models, centred on the whole FC whilst others are focused on different FC components (electrodes, membrane, etc.) [7].

In particular, the polarization curve is a useful tool to analyse the behaviour of Polymer Electrolyte Membrane (PEM) FCs [8–10]. Some examples are devoted to study aged PEM FCs [8], long-term operation [9] or diagnostics methods [10].

In an on-going R&D project, a Smart Microgrid hybridizing photovoltaic generation and hydrogen is being deployed. The goal of this project is to develop digital models of the actors of such microgrid to replicate their behaviours, performances and interactions. This paper presents the characterization of a PEM FC used to supply electricity in the aforementioned Smart Microgrid. The characterization conducted in this research is envisioned to be used to build a digital replica of the FC.

The structure of the rest of the paper is as follows. Section 2 deals with mathematical modelling of FCs. Materials and methods are described in the third section. Section 4 reports the experimental setup and results. Finally, the main conclusions of the research are addressed.

2. Mathematical Modelling of FC

A PEM FC is an electrochemical device that produces electricity from hydrogen and oxygen. Besides the energy released as electricity, water and heat are also generated [11]. Figure 1 illustrates this process.

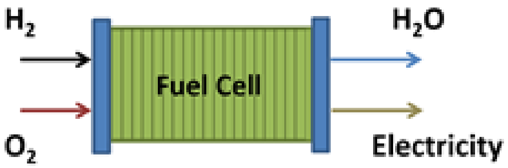


Figure 1. Scheme of the FC system.

The amount of energy produced in the electrochemical process that takes place in a fuel cell can be calculated from changes in Gibbs free energy, that is, the difference between Gibbs free energy of products and reactants. Gibbs free energy represents the energy available for external work and depends on the temperatures and pressures of the reactants. If the electrochemical processes that take place in the cell were reversible, all Gibbs free energy could be converted into electrical energy. Thus, the "reversible" voltage of a PEM cell would be expressed as:

$$E = -\frac{\Delta g_f}{2F} = -\frac{\Delta g_f^0}{2F} + \frac{RT_{fc}}{2F} ln\left[\frac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}}\right] \quad (1)$$

where g_f is the Gibbs free energy, R is the universal constant for ideal gases, P_{H2} is the hydrogen partial pressure, P_{O2} is the oxygen partial pressure, P_{H2O} the water vapour partial pressure, and Δgof the change in the process gf at a standard working pressure (1 bar), which in turn changes with the temperature of the FC (T_{fc}).

The expression (1) is the so-called Nernst voltage of a PEM FC. Applying standard thermodynamic relationships with respect to entropy changes, Equation (1) can be written as:

$$E = 1.229 - 0.85 * 10^{-3}\left(T_{fc} - 298\right) + 4.3 * 10^{-3} T_{fc}\left[\ln\left(P_{H_2}\right) + \frac{1}{2}\ln\left(P_{O_2}\right)\right] \quad (2)$$

The model expressed in Equation (2) aims to reflect the theoretical performance of a generic FC. Additionally, the cell voltage varies with electric load conditions. This is due to electric losses, which can be classified as activation (V_{act}), ohmic (V_{ohm}) and concentration or diffusion losses (V_{conc}) [11]. Therefore, taking into account all the losses, the cell voltage can be written as:

$$V_{fc} = E - V_{act} - V_{ohm} - V_{conc} \tag{3}$$

Substituting the terms associated with the stated losses, the output voltage of the FC can be written as:

$$V_{fc} = E - \frac{RT}{2\alpha F}\ln\left(\frac{i}{i_0}\right) - (R_0 - R_1\lambda_m)i - me^{(n*i)} + b * ln\left(\frac{P_{O_2}}{a}\right) \tag{3}$$

where α, i_0, R_0, R_1, m, n, b and a are empirical parameters that take into account the different polarization effects and are adjusted for a specific FC stack.

Several scientific works are focused on obtaining an extended model for different stack types. In a practical case, the parameters included in each model must be adjusted to fit the semi-empirical model to the real behaviour of the stack [12]. Therefore, before adjusting these parameters of the model to our particular case, it is convenient to verify that the behaviour of the FC under study corresponds to what the manufacturer provides in its datasheet.

3. Materials and Methods

In this section, the involved devices are described, e.g., the FC and the instrumentation equipment. Their most relevant features are given as well as their physical aspect.

3.1. H-500 FC Stack

The FC that used for the development of this work is the H-500 model of the manufacturer Horizon [13]. Figure 2 depicts the aspect of this model of the FC. The main features of this device are summarized in Table 1. In addition, a control unit is required to manage the operation of the FC.

Figure 2. H-500 FC stack.

Table 1. FC main features.

Type of fuel cell	PEM
Number of cells	24
Performance	14.4V @35A
Rated power	500W
Max stack temperature	65 °C
H2 Pressure	0.45–0.55 bar
H2 purity	≧99.995% dry H2
Flow rate at max output	6.5 L/min

3.2. Flow Meter Bronkhorst

To measure the hydrogen flow consumed by the FC, a flow meter of the manufacturer Bronkhorst [14] is mounted. This sensor is shown in Figure 3. The most relevant characteristics of this device are listed in Table 2.

Figure 3. Flow meter Bronkhorst.

Table 2. Flow meter characteristics.

Pressure	6 bar
Power supply	24 V DC (15 – 24 V DC)
Temperature	20 °C
Flow	5000 mln/min

3.3. Current and Voltage Sensors

In order to sense the electrical magnitudes of the FC, two sensors are devoted to measure the voltage and the current supplied. Namely, a voltage divider based on a precision potentiometer is used to measure the voltage output. On the other, a current sensor based on the Hall effect is chosen. In particular, the model LA 25-NP of the company LEM is used [15]. Table 3 contains the signal ranges managed by this sensor.

Table 3. Current sensor signal ranges.

Current range	±25 A
Power supply	±15 V DC
Temperature	−40 to 85 °C
Output current range	±25 mA

3.4. Hydrogen Storage

To enable the operation of the FC, a hydrogen storage means is necessary. In the present case, this issue has been solved through a metal-hydride bottle model HBond-1500L of the manufacturer Labtech [16]. It has a charging pressure of 15 bar and a storage capacity 1500 N liters. The appearance of this storage bottle is shown in Figure 4.

Figure 4. Metal-hydride bottle.

3.5. Ancillary Components

A set of ancillary components are required to complete the experimental arrangement. Namely, electro-valves, pressure sensors, pressure regulator, as well as power supplies for electronics. Furthermore, a programmable load and a precision multimeter have been employed for the polarization process.

4. Experimental Setup and Results

The aforementioned equipment has been assembled in a laboratory to perform a set of experiments and measurements. Figure 5 portrays the appearance of the system.

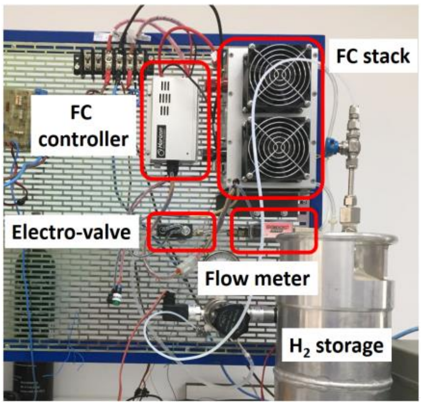
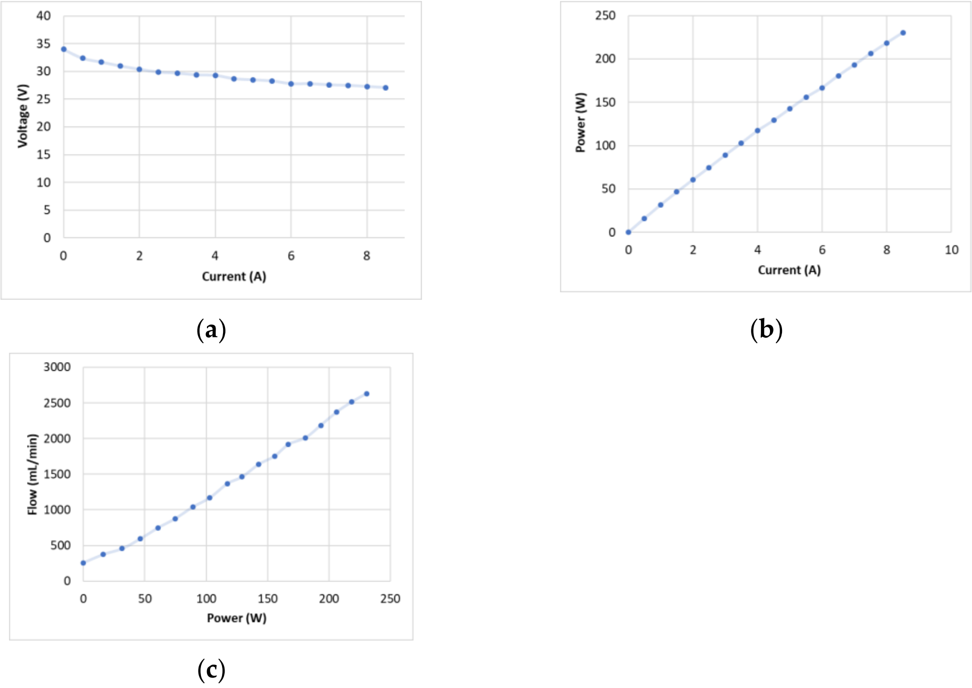


Figure 5. Experimental setup.

The manufacturer of the fuel cell provides a series of theoretical polarization curves on its data sheet. As previously said, the aim of this work is to experimentally obtain the operating curves of the FC. The final purpose consists on obtaining a mathematical model of such a system. The adjustment of the coefficients (parameters) of the chosen model will be done with the set of data obtained for characterizing the FC.

Firstly, the polarization curve corresponding to the relationship between the voltage and the current produced by the FC is given in Figure 6a. Regarding the power generated by the FC with respect to the delivered current, Figure 6b shows the experimental data. Figure 6c depicts the curve obtained for the relationship between the hydrogen fed to the FC and the generated power.



(**a**) (**b**)

(**c**)

Figure 6. FC polarization curves. (**a**) Curve V-I. (**b**) Curve P-I. (**c**) Curve Flow-P.

The trend of the curves corresponds with those reported both in the datasheet and in FC-related literature. Hence, the behaviour of the FC is adequate.

A noteworthy remark is that the curves provided by the manufacturer are illustrative for all the cells of the same model and for determined operating conditions. We have developed the described tests taking into the particular FC and the conditions of pressure and temperature during such tests. These conditions are required for the further adjustment of the parameters of the mathematical model.

5. Conclusions

This paper has presented the experimental characterization of a PEM FC as necessary stage before its usage within a Smart Microgrid which integrates renewable energies and hydrogen. The equipment used for characterizing the FC has been described and the achieved results have been expounded. The obtained results show a proper matching between the experimental data and the curves reported in literature and in the datasheet.

Future works deal with the adjustment of the parameters in the mathematical model of the FC. Additionally, the integration of such FC in the Smart Microgrid will also be carried out. Indeed, further characterizations will be performed aiming at detecting degradations of the stack.

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