MATHEMATICAL MODELING OF A 500 W_e POWER MODULE COMPOSED BY A PEM FUEL CELL COMBINED WITH A DC-DC ENHANCED POTENTIAL OUTPUT CONVERTER

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ABSTRACT

This work presents the development of a mathematical modeling of a 500 We PEMFC fuel cell stack (MCC500) system combined with a dc-dc enhanced potential output converter. The MCC500 was developed at IPEN (Nuclear and Energy Research Institute) and the company Electrocell, using only Brazilian technology. Mathematical developments and modeling have been performed, relying on experimental data collected at IPEN laboratory. The first step was to prepare an electrical system (pre-design) for the proposed model, which included the MCC500 parameters, like: membrane ohmic resistance, activation resistance, electric double layer capacitance, open circuit potential, as well as DC-DC converter parameters, like: inductor and transistor switching frequency. Using the obtained parameters and a linear differential equation system with some mathematical manipulations, an electrical system model was determined. Simulations experiments demonstrated that the system was very stable. This toll contribution showed to be very important to generate useful potential for practical purposes, increasing the overall system electrical efficiency.

Keywords: Fuel Cell and Hydrogen. Fuel Cells system Model. Energy Efficiency. Mathematical modeling.

1. INTRODUCTION

Electricity, as well as all other energy forms, has played a strategic role at the population life quality indicators, increasing every day in importance (Adam, 1991).

Despite its huge social and economic relevance all activities related to energy exploration, distribution and use cause environmental impacts, while the substances that can release into the atmosphere, the water sources and the soil, endangering the health and survival any terrestrial ecosystem.

The various energy systems steps, such as the extractive activities, conversion, distribution and use are closely related to each other and with all mankind development.

There is a growing need to find solutions to the chain negative effects of production processes, distribution and use of energy, with goals to minimize the social, environmental and economic injuries (Szwarc, 2007).

These facts attest that it is extremely necessary to detail further systems studies, like developments based on fuel cells power modules and other renewable and environmentally sustainable technologies (Schoots *et al*, 2010).

2. OBJECTIVES

The two main objectives of this work are:

1. Development of a mathematical modeling for a system including a PEM fuel cell stack (MCC500) combined to a dc-dc enhanced potential output.
2. Perform simulations using the mathematical model in order to enable the dc-dc converter to raise the potential bus and keep it constant, through the computer simulation on Matlab7® (Mathworks, 2007).

3. STATE OF THE ART

3.1 The PEM Fuel Cell Stack - MCC500

The fuel cell is an electrochemical power converter (Wendt *et al*, 2002). At a PEM fuel cell type, two half-cell reactions occur simultaneously, with an oxidation reaction (losing electrons) at the anode and a reduction reaction (gaining electrons) at the cathode.

These two reactions account for the oxidation-reduction reactions at the device, resulting in water formation, due to fed gaseous hydrogen and oxygen combination, releasing thermal and electrical energy, this one flowing to an external circuit (Kinoshita, 2001).

At the anode, the hydrogen molecules come into contact to the platinum catalyst sites (adsorption) on the gas diffusion electrode surface. The hydrogen molecules break their bonds at the platinum surface to form weak links H-Pt. Each hydrogen atom loses its electron to an external circuit, connected to a load, to meet the oxygen ions at the cathode. In turn, the hydrogen ions associated with water (H_3O^+) passes through the proton exchange membrane, reaching the cathode (Linardi, 2010).

At the cathode, the oxygen molecules come into contact with the platinum catalyst on the gas diffusion electrode surface. The Oxygen molecules adsorb at the platinum electrode surface, where the oxygen-oxygen bond (O-O) is weakened, and creating conditions for the reduction reaction to occur. Each oxygen atom then combines with two electrons and two hydrogen ions to form a water molecule. The platinum catalyst at the cathode gas diffusion electrode is now free to weaken the oxygen new molecules bonds (Spinacé, 2003).

Practical system design requires higher power output than available in a single cell, accordingly, several cells in series association is necessary, named stack, as shown on figure 1, to reach this requirement.

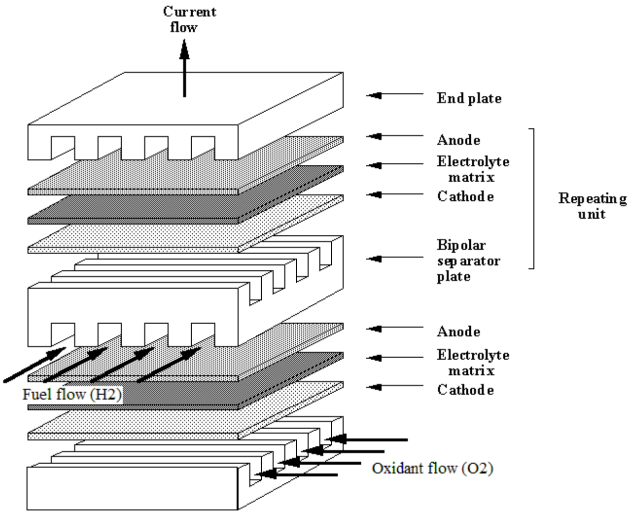

Figure 1: Schematic PEM fuel cell stack (adapted from Kinoshita, 2001).

3.2 The MCC500 developed at IPEN

The called MCC500 system is a stack composed by 20 single fuels cells in a series association. The produced electrodes could have from 25 cm^2 to 144 cm^2 geometrical area, depending on several fuel cell technologies developed at IPEN. In this work 20 electrodes of 144 cm^2 area were, fabricated by the IPEN-Screen Printing Method (Bonifácio, 2011) to be applied to the MCC500 system.

The IPEN-Alcohol Reducing Process was used to produce the Pt/C nano structured electrocatalysts in the gas diffusion electrodes (anode and cathode) (Spinacé, 2003).

For the bipolar plates design, a computational simulation of fluid dynamics on gas flow channels was used (Cunha, 2009).

In this way, a pre-commercial 500 W_e PEMFC power module was developed, as support for the distributed electricity generation industry, using only Brazilian technology. The Brazilian company ELECTROCEL, also contributed to the stack design, on bipolar plate production; sealing, cooling systems and cells assembly.

Previous MCC500 tests showed stable operation achieving the output power of 500 W_e (77.7 A, current at 6.43 V). The device also showed to be able to produce a maximum power of 574 W_e. For heat recovery studies, it was estimated that the thermal power output developed by MCC500 was 652 W_t, at 500 W_e nominal power. The total stack materials cost was estimated to be around US$ 4,500.00 (Cunha, 2009).

3.3 DC-DC Enhanced Potential Output Converter

The DC-DC converter is able to receive the electrical potentials produced (generated) at MCC500 and make it available on relatively stable potential for the load use, and thereby improve the conversion efficiency, especially when demand is high and the potential generated are small, as shown on Figure 2.

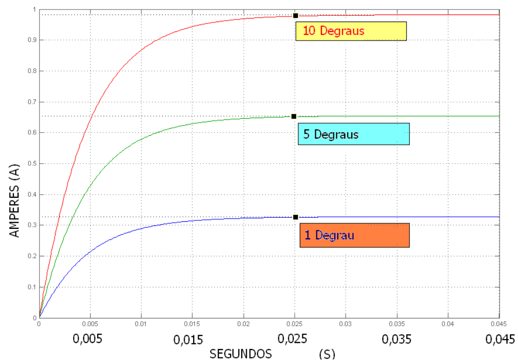

Figure 2: The performance Simulation of the MCC500 with dc-dc converter model to control on the load bar potential, author.

4 METHODOLOGY

4.1 Stability analysis

In the development of stability analysis study, two forms of Nyquist Methods were used. The simulation using Matlab7® computational program proved to be very effective in determining system behavior and in allowing the evaluation of either the output potential elevation or the computational disturbance stability. The system showed to be very stable both by the characteristic equation Root Locus Analysis and by the Nyquist Mapping Theorem (Jonckheere *et al.*, 2002).

4.2 The mathematical model development of the DC-DC enhanced potential output converter (dc-dc converter)

The dc-dc converter mathematical modelling began with a preliminary design of an electrical system, requiring additional steps, as follows:

1. Elaboration of the required polarization curve from current and potential measurements on the MCC500 stack, as shown by Figure 3.
2. Determination of the stood up parameters: inductance of the DC-DC converter inductor (L); the MCC500 electric double layer capacitance (C); the MCC500 membrane ohmic resistance (R_1); the MCC500 resistance activation (R_2), open circuit potential (E), as shown by Figure 4.
3. Combination of the parameters using some mathematical manipulations and the linear differential equations system, combined with mathematical calculations and module parameters (SR-12, Avista Labs). These data permit the electrical system lifting and support the parameterized circuit diagram form for the model presented, as shown by Figure 4.

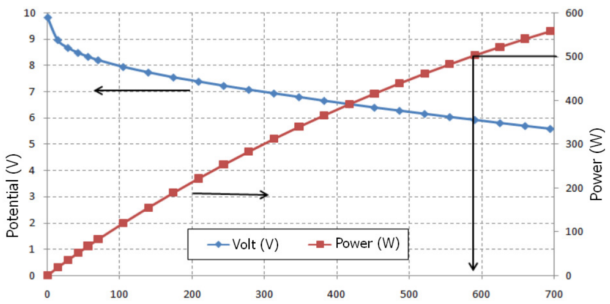

Figure 3: MCC500 Polarization and power curves, (adapted from Cunha, 2009).

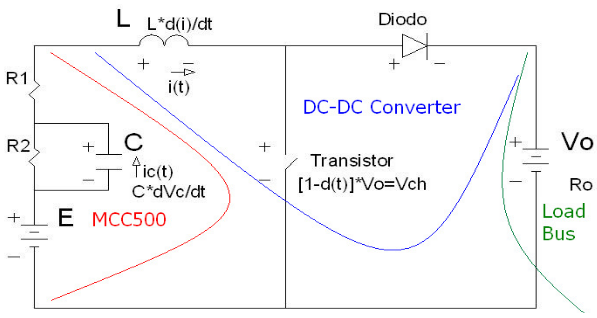

Figure 4: Schema of the electrical model for the MCC500 with dc-dc converter, parameterized to control the load bus potential.

4.3 Simulation of the converter potential to increase capacity and keep it constant

This step was started by defining to apply the steps and pulses number. Then the program routine was development, as well as the assisted simulations on Matlab7® were carried out, culminating with the graphics generation.

5 RESULTS AND DISCUSSION

5.1 Control of the electrical mathematical model

The electrical model is based on the inductor current coming from the PEMFC type, MCC500 fuel cell module, as shown by figure 4.

The six system equations on the time domain (t) and one equation on the complex domain frequency (s) are provided, and results were as obtained as described on the following steps:

The equation 1 is added to the duty cycle by transistor step or impulse to the controller;

$$d(t) = D + \Delta d(t) \qquad (1)$$

Equation 2 shows algebraically the change that occurs on the inductor current by step or impulse on the controller;

$$i(t) = I + \Delta i(t) \qquad (2)$$

Equation 3 shows the potential differences (PD) sum along the closed path, including R_2;

$$E - V_o + d(t)V_o = \frac{Ldi(t)}{dt} + R_1\, i(t) + R_2 \cdot \left[i(t) - i_c(t)\right] \qquad (3)$$

Equation 4 shows the PD algebraic sum along the closed path, including C;

$$E - V_o + d(t)V_o = \frac{Ldi(t)}{dt} + R_1\, i(t) + v_c(t) \qquad (4)$$

Equation 5 shows the MCC500 current on the electric double layer capacitance, due to the potential variation by to the variation in time.

$$i_c(t) = Cdv_c(t)\ /dt \tag{5}$$

Equation 6 was obtained by equation 4 derivation.

$$\frac{d[d(t)]\ .\ V_o}{dt} = \frac{Ld^2\ i(t)}{dt} + \frac{R_1\ di(t)}{dt} + \frac{dv_c(t)}{dt} \tag{6}$$

The system composed by equations 1 to 5 is designed to support the Kirchhoff potentials law (the around potential on closed path sum is always equal to zero), as described as by Nahvi and Edminister, (2011). Equation 6 was obtained from Granville, (1998). By eliminating on the DC terms on time domain (s) for the Laplace transformation application as described as by Nahvi Edminister, (2011), and at the time domain transforming (t) on the complex frequency domain (s). Grouped together on power 's' terms, provides the transfer function, as shown in equation 7.

$$G(s) = \frac{\Delta i(s)}{\Delta d(s)} = \frac{s\,.\,R_2\,.\,V_0\,.\,C + V_0}{s^2\,.\,R_2\,.\,L\,.\,C + s\,.\,(L + R_2\,.\,R_1\,.\,C) + (R_1 + R_2)} \tag{7}$$

Using this methodology, a transfer function was obtained coupling experimental data obtained from the power module and some mathematical transformation. The final result is shown in equation 8.

$$G(s) = \frac{\Delta i(s)}{\Delta d(s)} = \frac{s.0.0107 + 14.4}{s^2.169.6.10^{-9} + s.239.1.10^{-6} + 0.0110} \tag{8}$$

The control simulation results exerted by the dc-dc converter on load bar, through the simulation of the equation 8 can be observed by figure 2.

6 CONCLUSIONS

The contribution given by the present developed model showed to be very important to generated useful potential for practical purposes, increasing the overall electrical efficiency, using the MCC500 system, built using only Brazilian technology.

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