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MatLab/Simulink as design tool of PEM Fuel Cells as electrical generation systems

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Abstract

Design of electrical power generation systems based on fuel cells demands for an electrical model for these ones. In fact, designing engineering systems is based on accurate simulation tools that require accurate models of components and subsystems. MatLab/Simulink shows a general approach and it is very common tool for designing electrical control systems. To design electrical generation systems based on hydrogen using the MatLab/Simulink as design tool demands for accurate electrical models of the fuel cells. The behaviour of PEM fuel cells is dependent on so many parameters; so obtaining an accurate model of a PEM fuel cell, including dynamical behaviour, becomes essential to design electrical power generation based on fuel cells.

For that purpose, a mathematical model of a PEM fuel cell system developed in MatLab/Simulink is demonstrated. However, the difficulty emerges in the lack of manufacturer data about the exact values of the parameters needed for modelling it. The analytical formulation of the fuel cell behaviour is based on a set of equations demanding knowledge on several parameters whose values are dependent on cell operation as well as on operating temperature. The method adopted in order to determine the optimum set of parameters is the Simulated Annealing (SA) optimization algorithm, which proves to be well adapted to satisfy the goal of a fast convergence to establish the right values for the cell parameters. The good agreement between the simulation and the experimental results shows that the proposed model provides an accurate representation of the static and dynamic behaviour for the PEM fuel cell. As the model is already established, the paper shows that the designing of electrical generation systems based on fuel cells can be easily performed in MatLab/Simulink environment. The results carried out in designing a DC/DC converter appropriate to take control and optimization of operation point of a Fuel Cell show that the model is appropriate to be applied in designing electrical generation systems. The simulation results are compared with real data got from commercial systems.

Introduction

Fuel cells are promising power generation systems for next future. Together with appropriate power static converters, they can be used in stationary and mobile applications, depending on the type of fuel cell. The fuel cells stacks depend on many parameters; so obtaining an accurate model, integrating its dynamical behavior, becomes essential when developing electrical power systems based on fuel cells. Many models have been reported in the literature to describe the physical phenomena that occur inside the cells, in particular in PEM fuel cells [1-9]. These models are usually based on analytical formulations of the involved electrochemical processes, which reflect the physical and chemical phenomena occurring in the cell. Two classes of models are founded in the literature, 1) mechanistic models, describing the heat, mass transfer and electrochemical phenomena inside the fuel cell [10-13], and 2) empirical or semi-empirical models, to analyze the effect of different input parameters on the voltage–current characteristics of the fuel cell, without examining in detail the physical phenomena involved in the cell operation [1, 2, 8, 14-16].

The models are very important because they can provide detailed data that are frequently unavailable from experiments within an operating fuel cell stack. However, the difficulty appears in the lack of manufacturer data about the exact values of the parameters needed for a right model. The analytical formulation of the fuel cell behavior is based on a set of equations demanding knowledge on several parameters whose values are dependent on cell operation as well as on operating temperature.

There are some studies in the literature [17-21] that use the optimization of PEM fuel cell models, but they are focusing exclusively in the performance of the stack in terms of operating conditions (temperature, pressure, concentration of reagents, among others). The most popular methods of optimization are Genetic Algorithms (GA)[22], Simulated Annealing (SA) [23, 24], Tabu Search and Stochastic Programming methods. The method adopted in this study to determine the optimum set of parameters of the fuel cell is the Simulated Annealing. It proves to be very efficient in an optimal determination of cell parameters.

Furthermore, the power electronic converters and their integration in the production energy based on fuel cells, allow clearly at establishing an appropriate characterization of the load presented to the cell.

Several types of power static converters are founded in the literature [25-32]. These converters require a minimum of losses, a minimum of harmonic distortion both in the input and output sides of the converter, and ensure optimum operating points of the cell [27, 33-39]. In this context, the soft-switching converters are analyzed by researchers [33, 36-42], which present significant advantages compared to the linear ones.

It is also important to take in accounting the changes that occur in the performance of fuel cells, due to the ripple caused by power electronics switches, fast load variations and conditioning of starting operation of the cell.

The paper suggests a converter topology, which meets the above requirements. It makes the system model suitable to be applied in the generation of electrical power based on fuel cells and therefore on hydrogen.

1. Theoretical Basis

Electrochemical equivalent model: The electrochemical equivalent circuit shown in Figure 1 can be used for the analysis of the behavior of a PEM fuel cell. This mathematical model is described by a set of equations and corresponding parameters, which are essential for the analysis of the performance of the PEM [4, 5, 9, 44].

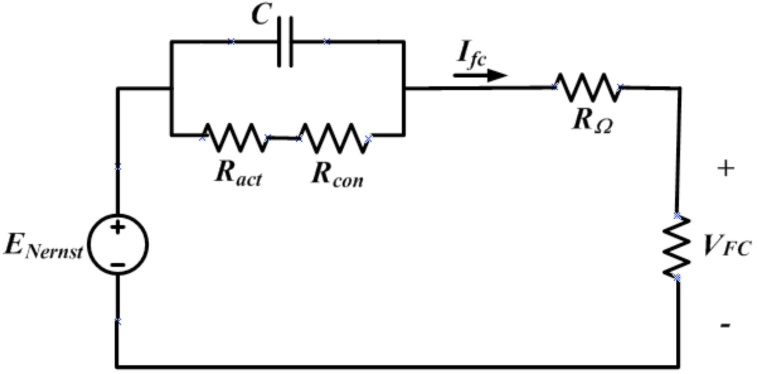

Figure1 – A simplified model of the PEM for only one cell.

This model can be described as follows: The output voltage of a single cell can be calculated by the following expression, according to the Nernst's equation and Ohm's law:

$$V_{FC} = E_{Nernst} - V_{act} - V_{Ohmic} - V_{con} \qquad (1)$$

Where: E_{Nernst} is the thermodynamic potential of the cell in open circuit, which represents its reversible voltage. It is defined by:

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3} \times (T - 298.15) + 4.31 \times 10^{-5} \times T \times \left[\ln(P_{H2}) + \frac{1}{2}\ln(P_{O2}) \right] \qquad (2)$$

P_{H2} and P_{O2} are the partial pressures (atm) of hydrogen and oxygen, respectively. T is the cell temperature in Kelvin. Vact is the voltage drop due to the activation of the anode and cathode (also known as activation over-potential);

$$V_{act} = -[\xi 1 + \xi 2 \times T + \xi 3 \times T \times \ln(CO_2) \qquad (3)$$

With CO2 the concentration of oxygen in the catalytic interface of the cathode (mol.cm-3) and the parametric coefficients for each cell model are represent by ξ1,2,3,4 and ψ.

$$C_{O_2} = \frac{P_{O2}}{5.08 \times 10^6 \times e^{-\left(\frac{498}{T}\right)}} \qquad (4)$$

Vohmic is the ohmic voltage drop (also known as ohmic over-potential), a measure of the ohmic voltage drop resulting from the resistances of the conduction of protons through the solid electrolyte and the electrons through its path;

$$V_{ohmic} = i_{FC}(R_M + R_C) \qquad (5)$$

RM is the equivalent membrane resistance to proton conduction and RC is the equivalent contact resistance to electron conduction.

$$R_M = \frac{\rho_M \times \lambda}{A} \quad (6)$$

Vcon represents the voltage drop resulting from the reduction in concentration of the reactants gases or, alternatively, from the transport of mass of oxygen and hydrogen (also known as concentration over potential).

$$V_{con} = -B \times \ln\left(1 - \frac{J}{J_{\max}}\right) \quad (7)$$

Since a stack is as set of n cells connected in series, the output voltage Vs can be calculated by:

$$V_s = n \times V_{FC} \quad (8)$$

Wherefore, based on the equations above, the parameters of the model that characterizes the system are; A- Area of the membrane (cm^2), λ -Thickness of the membrane (cm), R_C -Equivalent contact resistance (Ω), C –Equivalent capacitor (F), ξ's -Model coefficients, ψ -Empirical parameter and Jmax - Maximum current density (A/cm2) and the input variables are; partial hydrogen pressure P_{H2} (atm) partial oxigen pressure P_{O2}(atm), temperature T(K).

Once identified the set of equations and parameters of the model, which is based on analytical formulations of the electrochemical process, and because there is a lack of manufacturer data about the exact values of the parameters needed for a right model, a second step is to get these values. The method used is Simulated Annealing (SA).

2. PEM model in MatLab/Simulink

As the model already established by the analogue equivalent circuit and the exact parameters achieved by the SA, the design can be easily performed in MatLab environment. The input – output created system comprehends two subsystems, whose scheme can be shown in Figure 3. The subsystems modeled through equations (1) to (9) and through (10) to (12) simulate the fuel cell static and dynamic behavior respectively. The output signals of static behavior are inputs of the subsystem describing the dynamic behavior according to analytical formulation.

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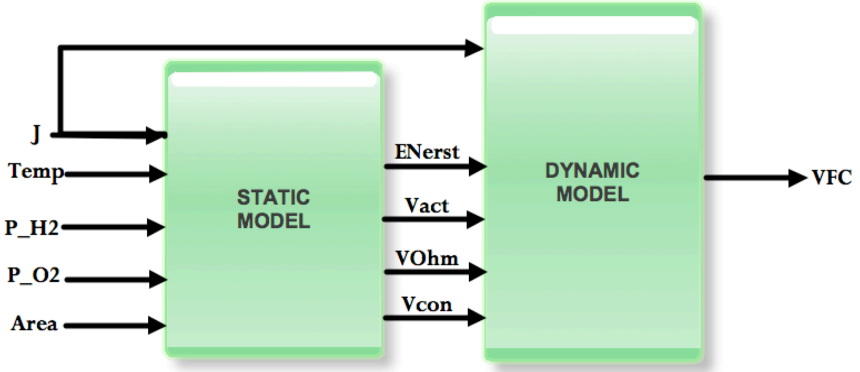

Figure 2– Fuel cell subsystem models implemented in MatLab/Simulink.

The implementation of the fuel cell as a source of voltage controlled by current is represented in Figure 3.

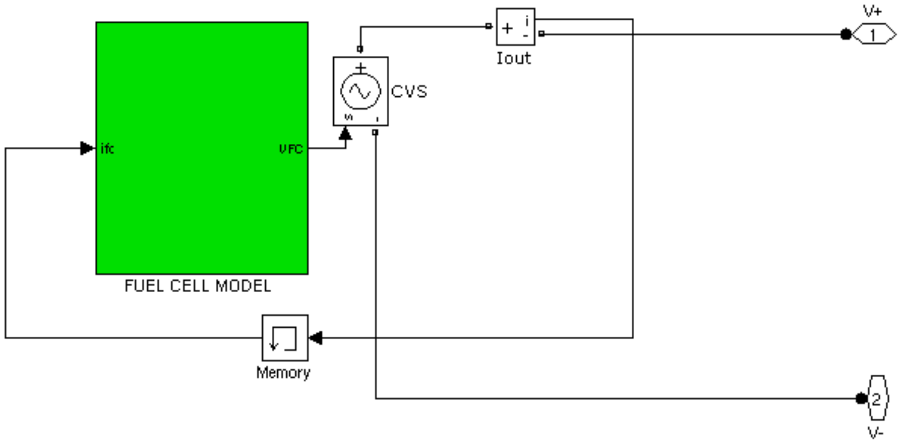

Figure 3 - Fuel cell model as a voltage source controlled in current.

2. Power electronic converter in MatLab/Simulink

In the conversion stage, an appropriate power electronics converter is necessary to take control of the operation point of the fuel cell, the generated power, in fact. Several types of converters in cascade can be designed and applied to the fuel cell systems [27, 28]. Two cascade topologies are commonly used: DC/DC together with DC/AC and DC/AC interfacing directly the fuel stack to grid. Main requirements to be considered in the selection of the topology are: efficiency, cost, voltage and current ripple and stable operation under transient loading conditions.

Adoption of a soft-switching topology privileges the efficiency as switching losses can be reduced or eliminated. This type of topology is very interesting to be applied to operation control of fuel cells, having been analyzed by different researchers [35, 37, 40, 41].

A particular case with efficiency optimal performance is the topology based on resonant converters as the switching loss is minimized and it is proportional to the switching frequency. These converters exhibit sinusoidal voltages or currents, what leads to transistor switching transitions under the ideal conditions. A variety of possible topologies can be implemented to realize the resonant operation, implementing a zero-current switch (ZCS) [30, 31, 35, 36, 40], which takes place the near zero current switching, and the zero-voltage switch (ZVS) [31, 35, 39, 45], with dual operation characteristics. The scheme below gives a modular perspective of the topology with the resonant converter taking control on generated power by fuel cell system.

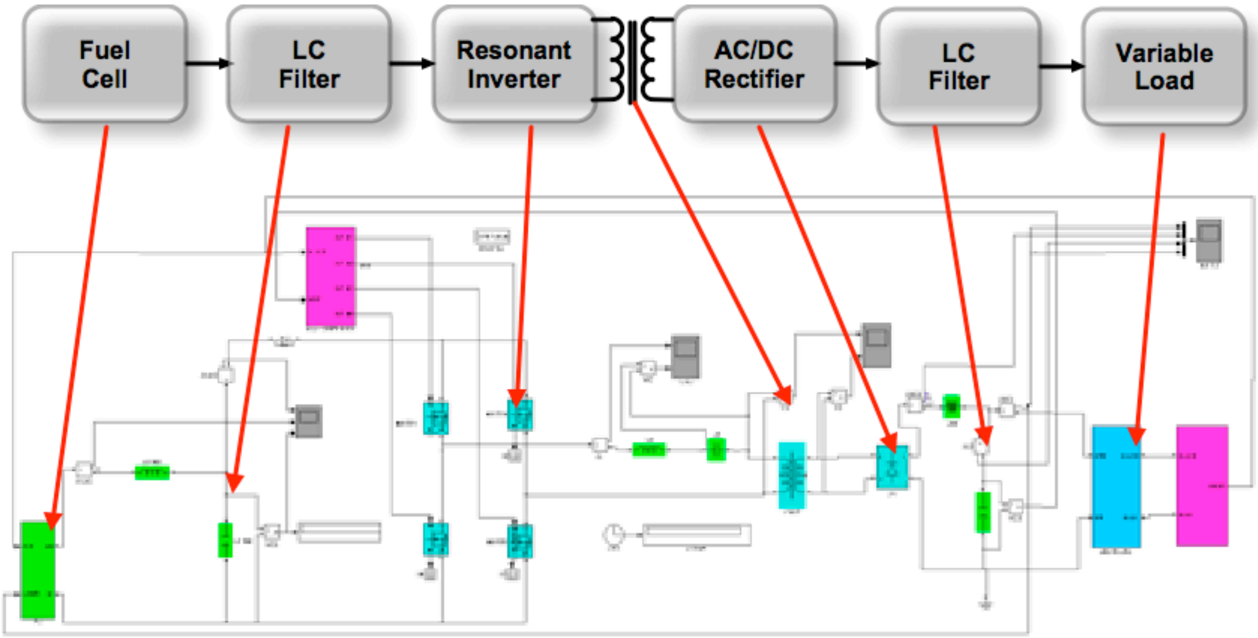

Figure 4 –Schematic of the main blocks of the power converter circuit and the correspondent MatLab/Simulink implementation model.

2. Experimental section

The experimental setup consists of an EC-certified system [43], integrating a PEM (Proton Exchange Membrane) fuel cell stack, rated to 1kW electrical power and 1kW thermal power, enabling micro cogeneration investigation and appropriated to exploitation of operating characteristics of a fuel cell. It provides fully integrated applications to ensure a large variety of experiments. Technical characteristics of the system are:

- Nominal Electrical power: 500 W (U = 23 V / I = 22 A) to 1000 W (U = 20 V - I = 50 A)
- Maximum Electrical power: 1200 W (U = 19 V - I = 62 A)
- Thermal power: up to 1 kWth
- H2 consumption: 5.5 Nl/min at 500 W and 11.2 Nl/min at 1000 W
- H2 and N2 supply at 7 bar pressure (H2 and N2 quick connect plug)
- Start up time lower than 1 minute
-

Operation modes: As a demonstration system, it allows to carry out operation of three distinct forms during practical works and experiments namely; 1) PC simulation: it allows simulation of the fuel cell system operation from any computer; 2) Semi automatic mode: enabling to break up the different starting phases of the system and to launch miscellaneous profiles, and 3) Automatic mode: automatic system operation (start/load profiles/stop) based on parameters defined by the user.

Load: the system allows at programming different electronic load profiles.

Measurements: Input and output data of variables are recorded as well as efficiency calculations and statistics are made by the system; namely: measured variables are; stack current, stack voltage, stack temperature profile, air flow profile (stoechiometry), H2 pressure, water flow, and calculations are made for; H2 flow, thermal and electrical power and electrochemical efficiency.

3. Results

Figures 5 shows the effect of capacitance on the dynamic behavior of the fuel cell. This is measured through step load variations of the current. Effect of the temperature and hydrogen pressure on the dynamic response of the model are also investigated and shown in Figures 14 and 15. Shown results allow at analyzing fuel cell dynamic behavior:

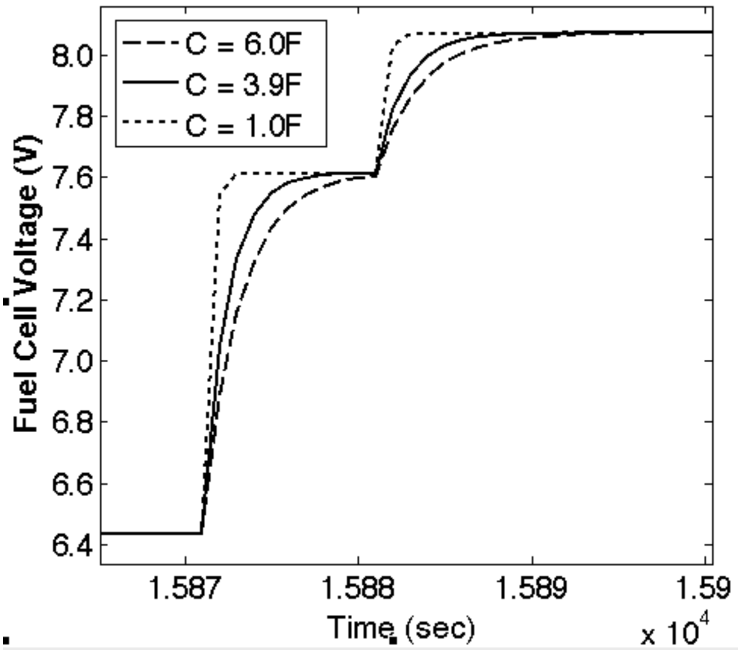

Figure 5 –Effect of the capacitor value on the dynamic response of the model to a step down current.

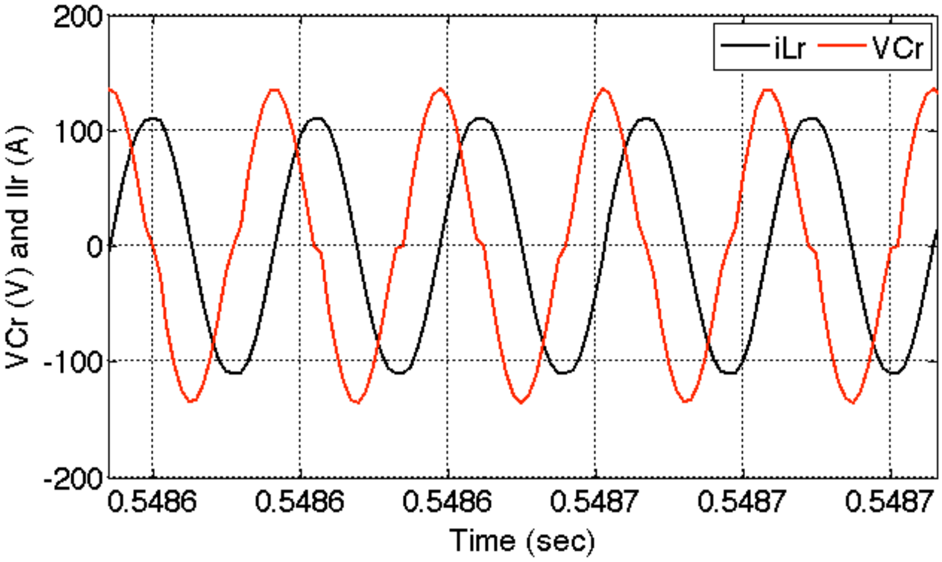

Figure 6 – Typical series resonant tank converter waveforms of the converter

3. Conclusions

This paper presents a successful methodology to adopt to the design of electrical power generation systems based on fuel cells. The paper is divided in two parts; in the first one the authors discusses the methodology for accurate a model for the fuel cell stack including its static and dynamical behavior. Because this is an essential aspect in the design of electrical power generation based on fuel cells. The design tool adopted is the MatLab/Simulink, which proves to be a very common and easy tool for the design of electrical control systems.

However, due to the lack of manufacturers data-sheet about the exact values of the parameters needed for modeling it. It is necessary to adopt a methodology in order to determine the optimum set of these parameters. The method adopted by the authors is the Simulated Annealing (SA) optimization algorithm, which proves to be well adapted to satisfy the goal of a fast convergence to establish the right values for the cell parameters. The good agreement between the simulation and the experimental results shows that the proposed model provides an accurate representation of the static and dynamic behavior for the PEM fuel cell.

On the second part of the paper the authors gives an overview of the possible topologies to be adopted for the DC/DC converter which are appropriate to take control and optimization of operation point of the Fuel Cell. In that sense, the soft switching proves to be particularly attractive and in particular the series resonant topology converters because they allows reduce the switching losses and consequently increase the efficiency. The simulation results are compared with real data got from a commercial system. Finally, the combination of a good power converter with a well-defined controller together with the well –optimized fuel stack model, makes de electrical generation systems by FC indeed very attractive.

Acknowledgments

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