A soft-switching DC/DC converter to improve performance of a PEM fuel cell system

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***Abstract-* This paper presents a soft-switching dc/dc converter with ZCS to improve the performance of a PEM fuel cell as a power generation system.**

The first part of the paper presents an appropriate model for the fuel cell behavior based on analytical formulation of chemical processes behind fuel cell operation and the design of an equivalent and analogue electrical circuit describing the fuel cell operation. A method to extract the set of parameters needed for modeling and to optimize their values is also presented. For the validation of this approach experimental tests are performed with a commercial fuel cell system. The dynamics of the fuel cell model and the dependency on operation point are analyzed. In fact, the dynamics of the fuel cell must be taken in account for an accurate characterization of the fuel cell as a power generation unit.

As a power generation unit the fuel cell must be integrated with a dc/dc converter able of controlling the system operating as a dc regulated Voltage source and controlling the fuel cell MPPT, maximizing the generated energy. Authors purpose in the second part of the paper a topology this dc/dc converter based on resonant operation, which allows a soft-switching commutation, and consequently a high efficiency operation. Analysis on selected topology choice, the control and design of the converter are performed. Carried out results show that the controller needs to have a dynamic derivative component in order to ensure a good regulation of output voltage for different load conditions and disturbances on them. The overall system is validated using Matlab/Simulink models.

NOMENCLATURE

A	cell active area (cm^2)
C	equivalent electrical capacitance (F)
E_{Nernst}	thermodynamic potential
J_{max}	maximum current density (A/cm^2)
n	number of cells in stack
P_{O2}	oxygen partial pressure (atm)
P_{H2}	hydrogen partial pressure (atm)
R_C	contact resistance (Ω)
T	cell operating temperature (K)
V_{act}	activation voltage drop (V)
V_{ohmic}	ohmic voltage drop (V)
V_{con}	concentration voltage (V)
ξ_i , ψ	parametric coefficients
λ	membrane thickness (μm)

I. INTRODUCTION

The efficiency of a FC as power generating system can be significantly improved by using optimum operating conditions. In this context two areas are of significant interest: first, the optimization of the electrochemical process, characterized by some parameters with unknown values, which must be precisely determined in order to obtain accurate simulated results; and second, power electronic converters requires an adequate control in order to know the load applied to the FC.

To model the electrochemical process, many models have been reported in the literature to describe the physical phenomena that occur inside the fuel cells, in particular in PEM fuel cells [1-5]. These models are usually based on analytical formulations of the electrochemical process. The models can be classified as: 1) mechanistic models, describing the heat, mass transfer and electrochemical phenomena found in the fuel cell; 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 operation. Taking into consideration the importance of the FC modeling and how the parameter values may affect significantly its dynamic characteristics, this paper analyses the influence of some of these parameters such as capacitance, temperature and hydrogen pressure on the voltage supplied by the FC. The power and efficiency provided by the FC for certain load current are also investigated.

In the conversion area, the power electronic converters plat an important role on the performance and efficiency of the FC system. A several types of converters in cascade can be found in the literature [6-11]. Two cascade topologies are usually used: DC/DC together with DC/AC and DC/AC.

A topology for the DC/DC converter is presented and the control method allowing the characterization of the load applied to the PEMFC is discussed. The PEM fuel cell and converter models are implemented in Matlab/Simulink software. To validate these models experimental tests are performed with a commercial system of 1.2kW.

II. ELECTROCHEMICAL PEMFC MODEL

A. Model equations

The analysis of the dynamical behavior of a PEM fuel cell can be made by the electrochemical equivalent circuit represented in Fig. 1. 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.

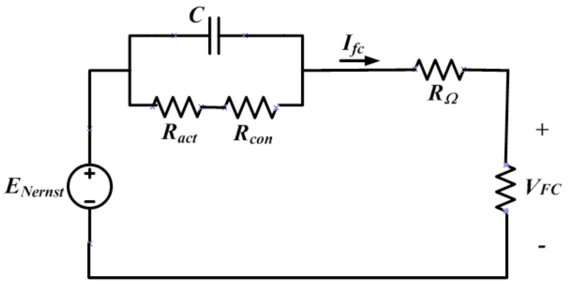

Fig. 1 – Electrical equivalent circuit of PEMFC.

This model can be described as follows [1]. The output voltage of a single cell can be calculated by the following expression, according to the Nernst's equation and Ohm's law:

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

Where:

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

$$E_{Nernst} = 1.229 - 0.85\times10^{-3}\times(T-298.15) + \\ +4.31\times10^{-5}\times T\times\left[\ln(P_{H2}) + \frac{1}{2}\ln(P_{O2})\right] \quad (2)$$

P_{H2} and P_{O2} are the partial pressures (atm) of hydrogen and oxygen, respectively. T is the cell temperature in Kelvin.

V_{act} is the voltage drop due to the activation of the anode and cathode (also known as activation over-potential);

$$V_{act} = -[\xi1 + \xi2\times T + \psi + \\ +\xi3\times T\times\ln(C_{O2}) + \xi4\times T\times\ln(i_{FC})] \quad (3)$$

With C_{O2} 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 ξ_1, ξ_2, ξ_3 and ξ_4.

$$C_{O_2} = \frac{P_{O2}}{5.08\times10^{6}\times e^{-\left(\frac{498}{T}\right)}} \quad (4)$$

V_{ohmic} 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;

$$V_{ohmic} = i_{FC}\left(R_M + R_C\right) \quad (5)$$

R_C is the equivalent contact resistance to electron conduction.
R_M is the equivalent membrane resistance to proton conduction:

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

Where ρ_M is the membrane specific resistivity given by:

$$\rho_M = \frac{181.6\left[1+0.03\times\left(\frac{i_{FC}}{A}\right)+0.062\times\left(\frac{T}{303}\right)^2\times\left(\frac{i_{FC}}{A}\right)^{2.5}\right]}{\left[\psi-0.634-3\times\left(\frac{i_{FC}}{A}\right)\right]\times\exp\left[4.18\times\left(\frac{T-303}{T}\right)\right]} \quad (7)$$

ψ is considered an adjustable parameter.

V_{con} 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). It is given by:

$$V_{con} = -B\times\ln\left(1-\frac{J}{J_{max}}\right) \quad (8)$$

Where B (V) is a parameter dependent on the cell type and its operation state.

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

$$V_s = n\times V_{FC} \quad (9)$$

Therefore, based on the equations above, the parameters of the model can be summarized as:

A – Area of the membrane;

B – Parameter dependent on the cell type and its operation state; λ – Thickness of the membrane; R_C – Equivalent contact resistance; C – Equivalent capacitor; ξ's – Model coefficients; ψ – Empirical parameter; J_{max} –Maximum current density;

The input model variables are the partial hydrogen pressure P_{H2}, the partial oxygen pressure P_{O2}, the operating temperature T and the number of cells n.

The FC model parameter values must be precisely defined and they are specific to particular FC. The identification is not an easy task. Some technological parameters can be set if provided from manufacturer or form literature. From remaining parameters this is not possible since they are of empirical nature. It has been proved by this research team that the use of an optimization-based approach to identify the parameters is a promising solution [1] The Simulated Annealing (SA) algorithm seems to be appropriated for this task.

B. Parameter extraction method

The Simulated Annealing algorithm is used to find the minimum value of an objective function and corresponding input values that will produce this minimum.

The implementation requires the definition of some parameters:

1) Initial population (or initial guess);
2) Initial temperature (T0);
3) Perturbation mechanism – a method to create new trial vector of values for parameters;
4) Objective function – a scalar equation to measure the goodness of each trial vector;
5) Cooling schedule (s) – a method that controls how temperature decreases. Note that temperature must be large enough to move off a local minimum but small enough not to move off a global minimum;
6) Terminating criterion – a method to control termination of algorithm. It could be a maximum number of iterations, a minimum temperature, a minimum value of objective (cost) function, or a combination of three.

The performance of the method is measured by the evolution of the objective function. Equation 10 defines the general equation of the objective function.

$$f_{obj} = \sqrt{\sum_i \left(\frac{\left(g^e(x_i) - g^s(x_i)\right)^2}{g^e(x_i)} \right)} \tag{10}$$

$g^s(x_i)$ is the simulated data and $g^e(x_i)$ is the experimental data.

TABLE I
FUEL CELL PARAMETERS

Parameter	**Value**
A	69.4 cm^2
λ	128 μm
B	0.0165 V
R_C	15×10^{-4} Ω
C	2.5 F
ξ_1	-0.514
ξ_2	Equation*
ξ_3	0.41×10^{-4}
ξ_4	-0.92×10^{-4}
ψ	27.7
J_{max}	1815 mA/cm^2
Objective fonction value :	**2.851**

Considering an initial set of parameters, the PEM fuel cell model compares simulated and experimental waveforms, producing an error value. Then, parameters are varied and simulation is re-executed to produce new waveforms. This is again compared with measured data and optimization continues accordingly. Once parameters have converged to give a minimum error, optimization process stops and the optimal set of model parameters for the PEMFC are obtained.

Table I gives the optimum values of the parameters for a commercial fuel cell system of 1.2kW. Please see [1] for further details.

C. Dynamic Analysis of the PEM

Activation (V_{act}) and concentration (V_{con}) voltage drops in the equivalent circuit of the PEMFC are affected by a delay due to the capacitor C in parallel. This aspect is extremely important in the analysis of the dynamics of the cell and can be explained as follows. The interface between the electrode and the electrolyte acts as storage of electrical charges and energy, i.e. behaves as a capacitor. This effect causes a delay in the dissipation of electrical charges at the interface electrode/electrolyte. So, for an increase of current in the cell there is a delay until the voltage decreases and the same appends for the reduction of current and the increase of voltage. The ohmic drop (V_{ohmic}) is not affected by this delay.

The capacitor affects the dynamics of the cell, which is represented in the electrical equivalent circuit of Fig. 1 and corresponds to the phenomenon known as "charge double layer". Therefore, the dynamics of the PEMFC model can be represented by the equation:

$$\frac{dV_d}{dt} = \left(\frac{1}{C} \times i_{FC}\right) - \left(\frac{1}{\tau} \times V_d\right) \tag{11}$$

Where V_d corresponds to the dynamical voltage across the capacitor and τ is the fuel cell electrical time constant defined as:

$$\tau = C \times Ra = C \times \left(R_{act} + R_{con}\right)$$

$$= C \times \left(\frac{V_{act} + V_{con}}{i_{FC}}\right) = C \times \left(\frac{V_d}{i_{FC}}\right) \tag{12}$$

Figure 2 shows the detail of the Simulink implementation of the dynamic model of the PEMFC. The integration block "1/s" obtains the voltage Vd accordingly to equations 11 and 12.

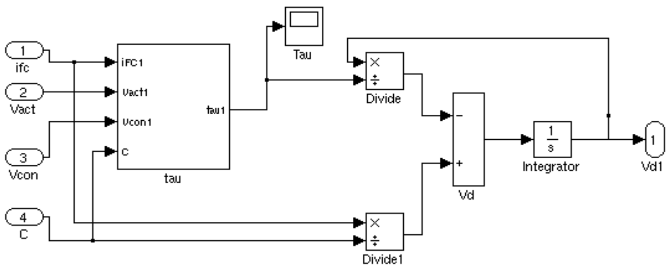

Fig. 2 –Dynamic block model implemented in Simulink.

The dynamics of the PEMFC model is analyzed for several variables that characterize the fuel cell. These results correspond to a commercial system, which a rated voltage of 22 to 45V, rated current of 45A and rated efficiency of 22% - 33%. All the analysis in centered in the step-up current at instant time represented in Figure 3. More information about this system in [5].

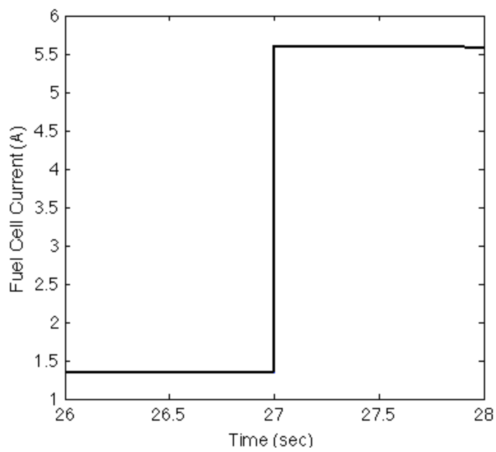

Fig. 3 – Step-up current applied to the fuel cell.

1. Fuel cell voltage

For an increase of the fuel cell current the voltage drops with a delay of first order because of the capacity. The delay increases whit the increase of the capacitor value, as can be observed in Figure 4. If there is a decrease in the fuel cell current the voltage raises showing similar delay effect for different values of the capacitor. However the delay due to the capacitor does not affect the polarization curve of the fuel cell, because each point on the curve is obtained when the voltage has reached its steady state.

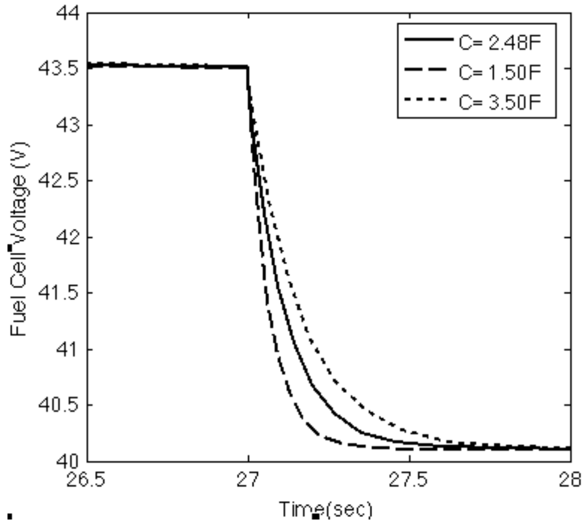

Fig. 4 – Fuel cell voltage showing the effect of the capacitor value.

2. Electrical power and efficiency

The instantaneous electrical power (P_{FC}) supplied by the cell and the efficiency (η) are determined by the following equations:

$$P_{FC} = i_{FC} \times V_{FC} \tag{13}$$

and,

$$\eta = \mu_f \times \frac{V_{FC}}{1.48} \tag{14}$$

The dynamic effect already observed for the fuel cell voltage is also present in the electrical power and efficiency. As can be observed in figures 5 and 6 for the electrical power and efficiency, there is a delay of first order, which varies with the capacitor value correspondingly. The efficiency is directly proportional to the fuel cell voltage accordingly to the equation 14.

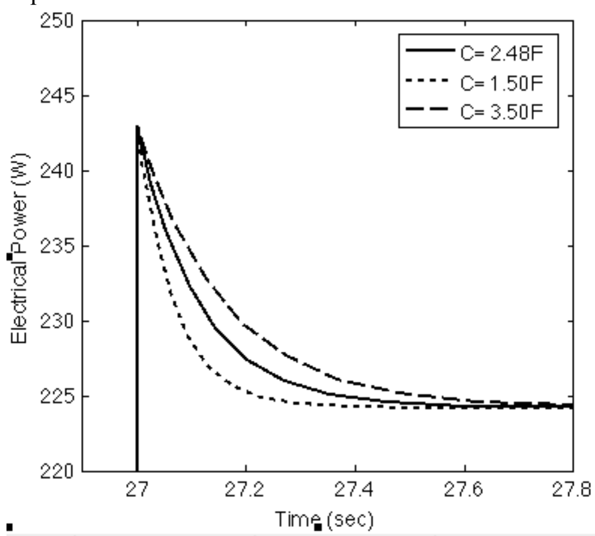

Fig. 5 – Fuel cell power showing the effect of the capacitor value.

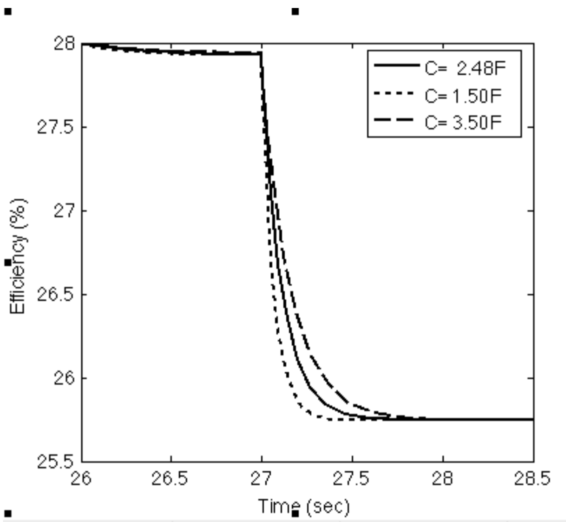

Fig. 6 – Fuel cell efficiency showing the effect of the capacitor

III. POWER CONVERTER

C. Considerations of the topology choice

The major considerations to take into account in the choice of the topology for the fuel cell converter are: the cost, the efficiency, the output ripple and stable operation under transient loading conditions [8, 9]. The cost and efficiency are related to the conduction and switching losses and can be reduced or eliminated through the use of an adequate control, with a soft-switching commutation. Due to the type of application with a high step-up conversion ratio, a high-frequency (HF) transformer is necessary. This allows reducing the size of the reactive components like; transformer and filters. It is clear from the analysis of previous figures that the dynamics of the FC system, as well as its static behavior, must be taken in account for an accurate description of the FC behavior. Using the proposed optimized model that goal can be achieved successfully. From the operational point of view, the fuel cell may produce a large output power variation under variable load conditions. However, in order to maximize the energy generated by the PEMFC the control strategy of the converter must track the maximum power point.

B. Proposed power scheme

Figure 9 shows the proposed scheme of the fuel cell power system, which is composed by a resonant inverter, followed by the HF transformer and rectifier. Two low pass filters are also represented; the one in the primary side is used to protect the fuel cell from current-ripple and for storage, and the other in the secondary side, is used to improve the quality of the energy supplied by the power system.

The operation of the converter can be described as follows; the voltage supplied by the fuel cell stack is typically low 29-42V, and must be converted to 400V in order to be used in several applications, namely power generation to low voltage grid. The HF transformer is used for this proposal and for galvanic isolation between the high and low level voltage circuits. The LC series resonant circuit gives sinusoidal waveforms to voltage and current signals in the primary side. Appropriate values for L and C components establish the resonant frequency of the circuit. Then, the fuel cell dc voltage is firstly inverted in primary side of HF transformer, being rectified in secondary side. The LC filter in the primary side allows protecting the PEM fuel cell from the ripple current and voltage produced by the converter and also allowing the storage of energy in the DC bus. The LC filter in the secondary side is used to reduce the ripple of current and voltage to the output, respectively. The right operation of the power system converter depends of the PI controllers together with the voltage control oscillator (VCO) blocks as explained in the next section.

C. Proposed control structure

In a DC-DC resonant converter the variation of the current is much faster than the variation in output voltage. Using a cascaded control structure composed by two control loops this problem can be solved; an inner loop controls the current and an outer loop controls the output voltage. The scheme of the control structure proposed in this paper is represented in Figure 10. Both the feedback loops uses PI controllers followed by a voltage control oscillator block – VCO.

The operation of the proposed control structure can be described as follows; the system is designed to comprehend two limit actuators, one limiting maximum voltage through minimizing operating frequency of the converter, the other one limiting minimum voltage through maximizing operating frequency of the converter.

The reference signal to the voltage control oscillator block (VCOref) is made by the cascaded control structure. The output voltage (Vout) of the converter is got and compared with the reference value (Vref=400V); an error signal is generated and processed slowly by the P - proportional and I - integral controller producing a reference value to the current (ILref).

The current value of the inductor filter current (iLf) is got and compared with its reference value (ILref), an error signal is generated and processed by the fast P - proportional and I - integral controller producing the reference value for the voltage control oscillator (VCOref).

The reference to the frequency of the resonant converter is established in the VCO block, which works as follows: Once it is known the input signal, interpreted as a voltage (VCOref), established by the PI controllers, the continues-time VCO generates a sinusoidal signal whose frequency shifts from the Quiescent frequency parameter (*fc*) with a sensitivity to the input parameter (*kc*) and amplitude *Ac*. The inverter topology is a full-bridge; then four output signals need to be generated by this subsystem, one for each transistor respectively (Mi, i =1,2,3,4). They are synchronized by φ, which is the initial phase parameter and assumes zero or π value in the case.

$$y(t) = A_c \cos\left(2\pi f_c + 2\pi k_c \int_0^t u(\tau) d\tau + \varphi\right) \quad (15)$$

D. Design considerations

1. Series resonant circuit

The series resonant circuit is characterized by the L*C* series circuit, which as the natural frequency f_0 and impedance Z_0, also called the characteristic of the resonant circuit.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (16)$$

$$Z_0 = \sqrt{\frac{L}{C}} \quad (17)$$

Considering the dc nominal voltage from the fuel cell equal to 35Vdc (29-42V) and maximum current through the semiconductors equal to 100A, the resonant frequency f_0=50000Hz, and using the two equations below,

$$\begin{cases} \frac{I_{max}}{Vdc} = \sqrt{\frac{L}{C}} \\ f_0 = \frac{1}{2\pi\sqrt{LC}} \end{cases} \quad (18)$$

A possible set of values for the resonant circuit elements are as follows:

$$\begin{cases} C_r = 5.1153\mu F \\ L_r = 1.9245\mu H \end{cases} \quad (19)$$

Which correspond exactly to the frequency and impedance values of;

$$f_0 \approx 50723Hz \quad (20)$$

$$Z_0 = 0.788\Omega \quad (21)$$

2. Transformer

The HF transformer is placed in series with the resonant circuit, then the same current of the resonant inductor covers it's primary winding. As part of the converter, the transformer must be able to transmit the power flow from the source to the load, so it should not adversely affect this power flow.

In case of the core transformer saturation, an increase in the input power does not result in an increased of output power, even acting in the controller gains, this will not be possible. In this situation the transformer acts as a limiter circuit.

Thus, in terms of frequency response, the poles must be sufficiently far from the zone of converter operation. Then the choice of the cut off frequency of transformer elements is about 5kHz, the frequency operation is 50kHz, primary side voltage: V_{rms}=26V, and secondary side voltage: V_{out}=400V.

3. PEM filter

In the design of the PEM filter, the worst situation is considered, ie, the one for which a maximum amplitude of ripple current is presented to the PEM (Imax). This situation accurs at the nominal power, 1200W which current in secondary side is 3A and in primary side its maximum is about 144.45A. In addition the filter should be calculated to the minimum converter frequency, 1900Hz. Then, considering at least a ripple voltage of 1% of their nominal value (ΔV_C) and a cut off frequency of 190Hz, and using equations below,

$$\begin{cases} \Delta Vc = \frac{1}{C} \times \frac{2}{\pi} \times \frac{I_{max}}{2 \times f} \\ L = \frac{1}{4\pi^2 \times f_{filter}^2} \end{cases} \quad (22)$$

Then, the elements that chacterizes the PEM filter are as follows:

$$\begin{cases} C_{Fcell} = 57.44mF \\ L_{Fcell} = 12.21\mu H \end{cases} \quad (23)$$

4. Output filter

The component values of the output filter must be much larger than the resonant circuit so, it can be considered constant values in voltage and current, during a switching cycle. For the charaterization of the LC filter the output voltage of the converter must be considered, which should be 400V in this case. The nominal power to transfer is 1200 W, then the maximum current on the bus is 3A (assuming an ideal converter). To simulate this current a resistive load of 134 Ω is considered.

In terms of frequency analysis, the LC circuit is a low-pass filter that reduces the ripple voltage and current associated with switching frequency as lower the cut-off frequency is. Ideally this filter rejects all the flutuations, due to the switching frequency and only the average DC components is send to the load. In the frequency domain, the cut-off frequency is much lower than the operating frequency of the converter (typically a decade below). Then, the elements that chacterizes the output filter are as follows:

$$\begin{cases} C_f = 10mF \\ L_f = 0.1\mu H \end{cases} \quad (24)$$

Which correspond to the frequency and impedance values;

$$f_0 \approx 503Hz \quad (25)$$

$$Z_0 = 0.0316\Omega \quad (26)$$

E. Simulation Results

A model of the scheme of the fuel cell power system presented by figures 12 and 13 was implemented using Matlab/Simulink software. the following parameters of simulation were considered:

Simulation method: ode23t (Stiff/ Trapezoidal)
Tolerances: 1e-3 (Rel.) 1e-6 (Abs.)
Max step size: 1e-5
Load: 1200Ω (≅0.33A)
Initial output voltage of capacitor = 400.1V
Voltage control (outer loop): kp=1, ki= 100
Current control (inner loop): kp=0.001, ki= 100
Quiescent frequency parameter (*fc*):1900Hz
Sensitivity to the input parameter (*kc*):45100Hz
Amplitude (*Ac):* 2

Figures 11 and 12 shown the actuation of the control block explained above. In Figure 11 the reference value to the VCO block is in steady-state 0.08V for the case considered. Figure 12 shows the actuation of the PI controller's, which aim to maintain the value of the output voltage of the converter at 400V. As can be seen, this goal is achieved in 0.14s and remains stable in the steady-state operation.

Figure 13 is the correspondent output current waveform of case study. The analysis of these figures also show that even with the connection of a load well below the nominal load, the controller needs to have a dynamic derivative component in order to ensure a good regulation of output voltage.

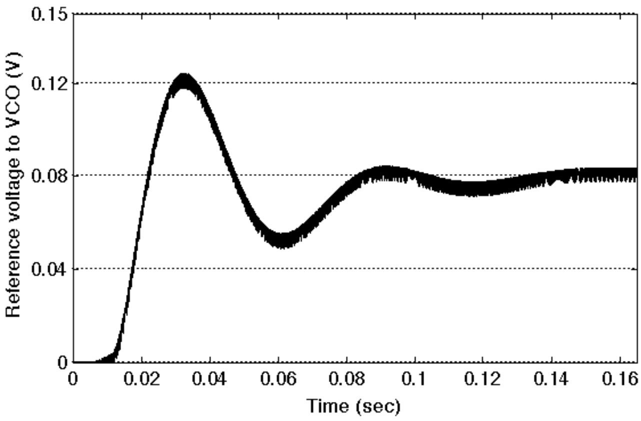

Fig. 11 –Control of the reference to VCO (RP=0.33V)

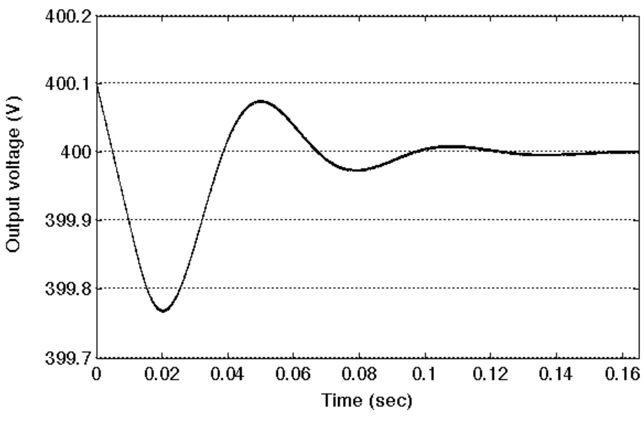

Fig. 12 – Output voltage for the control reference = 400V

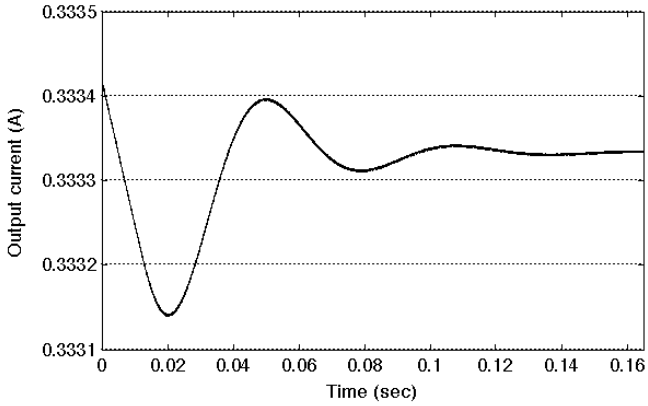

Fig. 13 – Series resonant converter waveforms.

IV. CONCLUSIONS

In this paper, dynamical performance of a PEMFC is analyzed. Effects of some key parameters are shown through comparison between simulation results based on an appropriate electrochemical model and real data from a commercial system to. The method adopted in order to determine the optimum set of parameters is SA algorithm, which proves to be well adapted to satisfy the goal of a fast convergence to establish the correct values for the cell parameters. Using the optimum parameter set, the polarization curve is obtained, and influences of the temperature and hydrogen pressure are analyzed.

A power generation unity based on fuel cells has to integrate a DC/DC converter in order to guarantee a global behavior as a dc regulated voltage source. The paper discusses DC/DC converter topology considering the major requirements to be taking into account in this type of application: cost, efficiency, ripple and stable operation under transient loading conditions. The choice is based on resonance operation of the converter which allows a soft-switching commutation and consequently a high efficiency besides the fundamental characteristics of high quality of the energy injected into grid.. The overall system is validated using the developed models programmed in Matlab/Simulink environment. Carried out results show that the controller needs to have a dynamic derivative component in order to ensure a good regulation of output voltage for different load conditions and disturbances on them as well as to allow at implementing MPPT algorithms for controlling of fuel cell operation.

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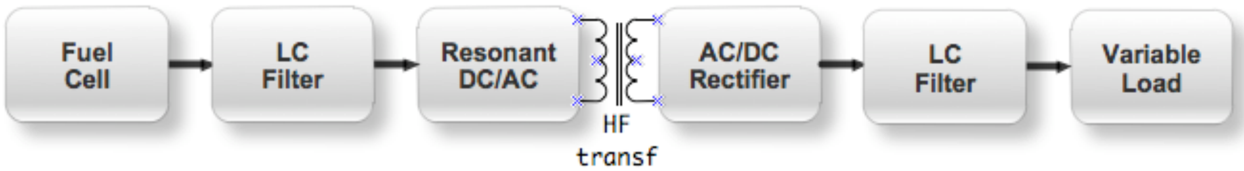

Fig. 9. – Proposed power scheme.

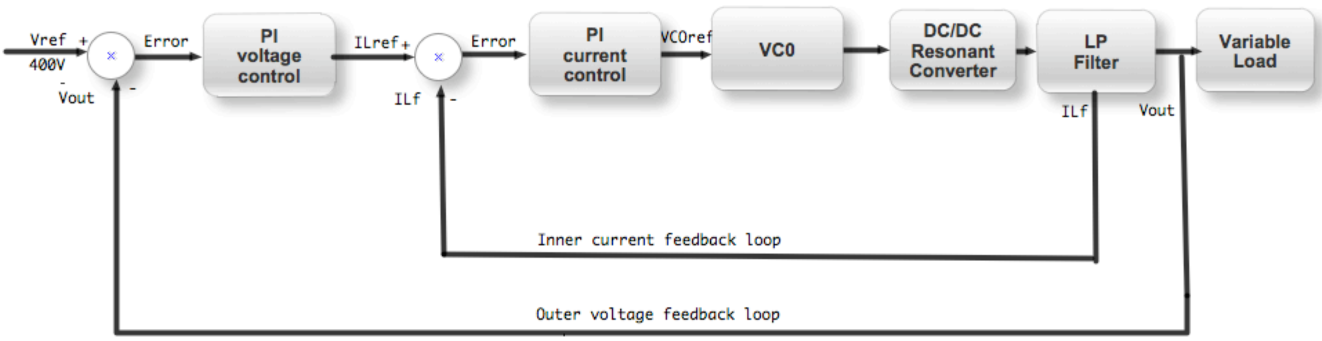

Fig. 10. – Proposed control structure with two PI control loops.