ABSTRACT QUESTIONNAIRE

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Title:	Design and Validation of a new DC-DC Converter for optimsation of PEM Fuel Cells efficiency				
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EXPECTED CLASSIFICATION:

	MAIN SESSION
X	PEM fuel cells
	SO fuel cells
	Other fuel cells
	Batteries
	Supercapacitors
X	Hydrogen
	Other

	SUB-CLASSIFICATION
X	Numerical simulation
	New materials
	New processes
X	Prototipe development
X	Engineering & Integration
	Industrial project
	Marketing analysis
	Standards and regulations

Design and Validation of a new DC-DC Converter to optimize the efficiency of PEM Fuel Cells

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1 Introduction

Fuel cells produce electricity from hydrogen through an electrochemical process; which efficiency can reach 90% in some applications. This process is virtually free of emissions and noise and only water and heat are the results beyond the electricity. In addition, the fuel cells have other advantages; high efficiency compared to the conventional systems, silent, high potential for cogeneration applications, adaptable to a wide range of powers and applications.

The recent developments on fuel cells combine various elements, namely; new proton exchange membranes, better catalysts, and better design of the cells, new static and dynamic models and better control methods of power electronic converters are also important development in the field.

Therefore the main objective of this paper is to present a high efficiency power converter. In this context, an accurate topology for the DC-DC power electronic converter and implement the correct control strategy for obtaining the maximum efficiency of the set system composed by: fuel cell, DC-DC converter, DC bus with storage of energy and power factor compensation.

2 Model of the PEM fuel cell

2.1 Mathematical model of the PEM

The analysis of the dynamical behavior of a PEM fuel cell can be made by the electrochemical equivalent circuit represented in Figure1. 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.

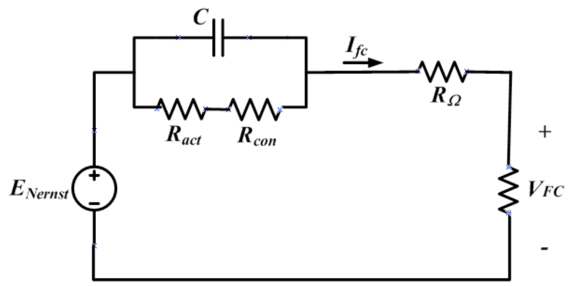

Fig. 1. Electrical equivalent circuit of a PEM fuel cell.

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:

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

Where:

ENernst is the thermodynamic potential of the cell in open circuit, which represents its reversible voltage. Is defined by;

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

PH2 and PO2 are the partial pressures (atm) of hydrogen and oxygen, respectively. T is the cell temperature in Kelvin.

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

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

$$C_{O_2} = \frac{P_{O2}}{5.08\times10^6 \times e^{-\left(\frac{498}{T}\right)}} \quad (3)$$

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.

$$V_{ohmic} = i_{FC}\,\left(R_M + R_C\right) \quad (4)$$

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;

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

$$R_M = \frac{\rho_M \times l}{A} \quad (5)$$

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).

$$V_{con} = -B\times\ln\left(1-\frac{J}{J_{\max}}\right) \quad (6)$$

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

$$V_s = n\times V_{FC} \quad (7)$$

2.2 MATLAB/SIMULINK model of the PEM

As the equivalent circuit of the PEM already established, a model has be performed using MatLab/Simulink software. The PEM model is composed by two subsystems, whose scheme can be shown in Figure 2. Two subsystem models 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.

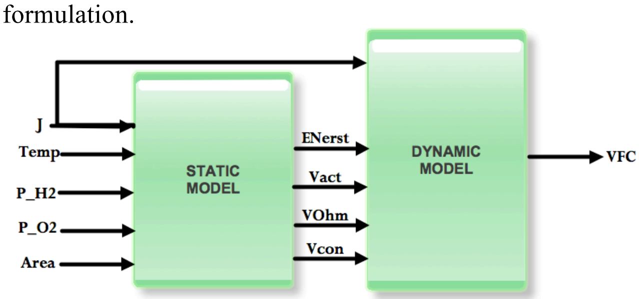

Fig. 2. Fuel cell subsystem models implemented in MatLab/Simulink

2.3 Efficiency and fuel comsumption of the PEM

1. Efficiency

All energy conversions will lead to a certain amount of degradation of energy quality. All input energy will not come out as output. Maximizing the output power means minimizing the losses. Some of the energy is lost as heat. There are two kinds of losses: hydrogen losses and electrical losses. Small amounts of hydrogen that feed in the stack to be converted to electric power will however be purged out of the system. The net power delivered from the system will be slightly lower because of this loss. The overall efficiency of the system must take all these losses into account.

The basic concept of calculating the electrical efficiency of a fuel cell power system is the same as for any power generating system. The formula used for percent electrical efficiency of the fuel cell system is:

$$\eta el = \left(\frac{net\_electrical\_energy\_output}{total\_energy\_input}\right)\times 100\% \quad (8)$$

Or, related to the fuel cell stack voltage (VFC), the efficiency of the fuel cell system is:

$$\eta_{el} = \mu_f \times \left(\frac{V_{FC}}{1.48}\right)\times 100\% \quad (9)$$

Which is defined as the percentage of the fuel that is converted to electrical energy or, the output electrical energy related to the consumed chemical energy.

The efficiency of a fuel cell system is defined as the percentage of the fuel that is converted to electric energy. This is making by comparing the output electric energy with the consumed chemical energy. The common value of chemical energy is the lower heating value (LHV) of the fuel.

2. Fuel consumption

A high efficiency of the fuel cell means low hydrogen consumption.

The calculation of fuel consumption is made by the difference between the flow fuel output and the flow fuel input. During the experimental tests, a ventilator is used to inject the oxidant flow necessary into the stack in order to produce the electrochemical reaction. This is not measured. The hydrogen consumption of the presented case is plotted in the results section of the paper.

3 Power Scheme of the DC-DC converter

A modular power DC-DC converter is represented in Figure 3. It is composed by; a resonant inverter, HF transformer, rectifier and filters in the output of the PEM and to the load were projected, simulated and a prototype was then implemented in the lab. The operation of this converter can be described as follows; the voltage supplied by the fuel cell stack, which is typically low

(29V - 42V), must be converted to the 400VDC in order to be used in several applications, namely generation power to the grid thought an inverter. The HF transformer is a step up transformer voltage, used also for galvanic isolation between the high and low level voltage circuits. DC/AC resonant converter with its LC series resonant circuit gives the sinusoidal waveforms of voltage and current in the primary side of the transformer. Appropriate values for L and C 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.

4 Control strategy

In a fuel cell system the performance of the DC-DC converter is very dependent on the unknown variations of process parameters. These changes will degrade the performance of the converter and as a result it is required that the controller not be affected from these disturbances [85]. Also, the transformers turns ratio, the coupling coefficient, the leakage inductance of the transformer, and the series resistance of the filter inductor are parameters that can not be controlled closely and consequently they vary with the load variations, input source, and operating frequency. Fuel cells have limited ripple current capability and have a slower response time, which must be taken into account in the control strategy. The DC/DC power converter must react to load steps faster than the fuel cell; otherwise it will demand more power than instantly available.

Then, the variation of the current is much faster than the variation of the output voltage. So, in this context, the controller has to be fast and noise immune and should have good disturbance rejection, to ensure minimum of losses, minimum of disturbances of the converter, and optimum operating points of the cell.

5 PEM control

While the voltage-loop is responsible of controlling the output voltage of the converter, the PEM-loop is responsible of controlling the operation of the PEM, keeping it in its optimal operation point. This controller is implemented in MatLab/Simulink and works as follows; once characterized an operation point of the PEM, assuming for example that is point P in Figure 4, the PEM-loop has the task of improving the performance of the system, defining a new point P ' or P" that best optimizes the PEM performance, i.e. which maximizes the energy produced with a minimum of consumption of hydrogen. The algorithm of control that satisfies these conditions of operation is represented by the flowchart of Figure 4, is given its descriptive explanation.

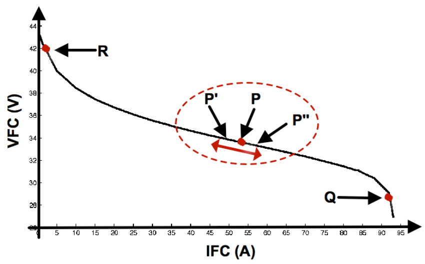

Fig. 3. Main characteristic of a PEM fuel cell.

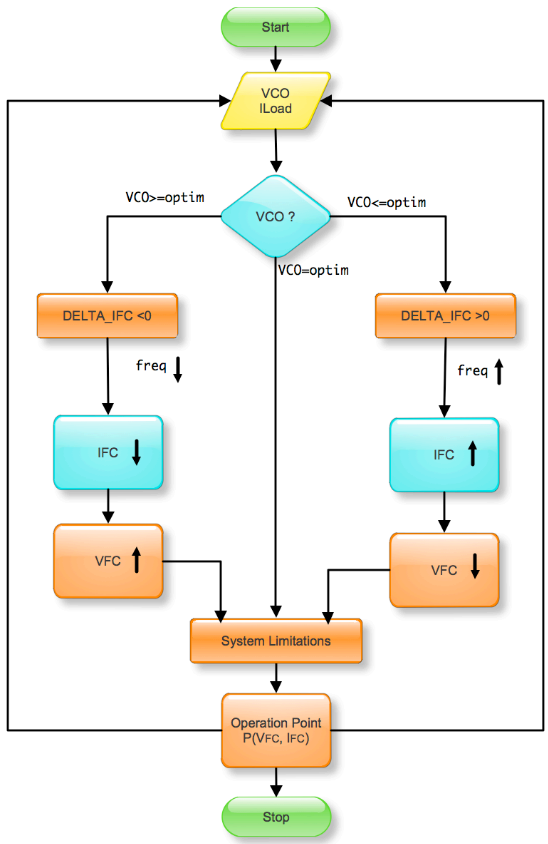

Fig. 4. Flowchart of the PEM fuel cell control.

5.1 Explanation of the algorithm

The outer loop control of the PEM is as an "observer of the system," i.e., once characterized a point P of output characteristic of the PEM, this induces small perturbations in the system thus leading the cell to operate under conditions of maximum efficiency of the PEM, in other words, providing maximum power with minimal consumption of hydrogen.

However, a minimum consumption of hydrogen, means the operation of the PEM with minimum current, i.e.: IFC minimum and VFC maximum, just in the sense of P' of the output characteristic of the PEM, as exemplified in the graph above.

A lowering of the current cell implies a lowering of the operating frequency of the resonant converter, so the search condition from the point of optimum operation of PEM requires the lowering of the resonant frequency of the converter. Once you find the optimum for the present conditions of load, the resonant converter is operating at a frequency that is also the minimum frequency that ensures the load conditions imposed on the system. The process is repeated whenever there is a variation of the conditions imposed by the load.

6 Experimental execution of PEM controller

Accordingly to the circuit shown in figure 6, the operation point of the PEM can be controlled actuating on pin5 of the NE555 repeatedly and automatically while the stable point of the PEM is not reached. This action arises from the application of the two parallel resistances R//R '= 2.5KΩ to pin 5. Consequently a change in the threshold level and frequency operation of the converter appends. Then, assuming that the converter is working with frequency f_P of the PEM controller is to move the operation point from P to P ' according to the nomenclature presented in Figure 3. Thus, the ON pulse of the NE555 should be of order.

$$T1 \simeq 5 \times \tau_{PEM} \simeq 5 \times 2.5 \sec = 12.5 \sec$$

Consequently, the values for R_A, R_B and C must guarantee this condition. Thus, according to the above considerations and the availabilities of stock lab, the components are: RA = 1KΩ, RB =330KΩ, and C =47µF

$$t_{ON} \simeq 0.7 \times (RA + RB) \times C \simeq$$
$$= 0.7 \times (1 + 330) e10^3 \times 47 e10^{-6} = 10.88 ms$$

$$t_{OFF} \simeq 0.7 \times (RB) \times C \simeq$$
$$= 0.7 \times (330) e10^3 \times 47 e10^{-6} = 10.85 ms$$

$$f_{PEM} = \frac{1.44}{(RA + 2 \times RB) \times C} =$$
$$= \frac{1.44}{(1 + 2 \times 330) \times 10^3 \times 47 \times 10^{-6}} =$$
$$= \frac{1.44}{31.067} = 0.000046 Hz (\ll 1Hz)$$

7 Actions that arise while the NE555 remains in T_{ON}

During T_{ON} the Relay inductance is covered by the current i. SW 4&6 which is NC opens, SW 4&8 which is NO closes. Accordingly, the capacitor C ' charges via R' from the voltage source +15 V to its maximum value VC=Vcf = +15 V when i=0A, with a time constant, t= R'C'. The Vcontrol signal is applied to pin5 of the NE555 and Vcontrol> 2/3Vcc.

8 Actions that arise while the NE555 remains in T_{OFF}

During T_{OFF} any current does not cover the Relay inductance. The SW 4&6 is NC and remains in this state. The same state remains also for the SW 4&8. Accordingly, the capacitor C ' which has however its maximum charge, Vcf puts the diode D in conduction and through its and the SW 4&6 establish a closed circuit allowing fast discharge of the capacitor C'. During this interval no signal is applied to pin 5 of the NE555 and the discharge of C ' with time constant t= r_FC' (r_F of diode is very small) happens very quickly. The energy is transferred from C' to the Diode that is;

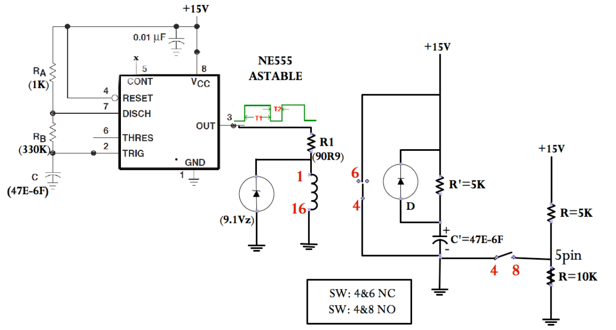

Fig. 5 Circuit principle to modify the threshold value of the NE555 (PEM control)

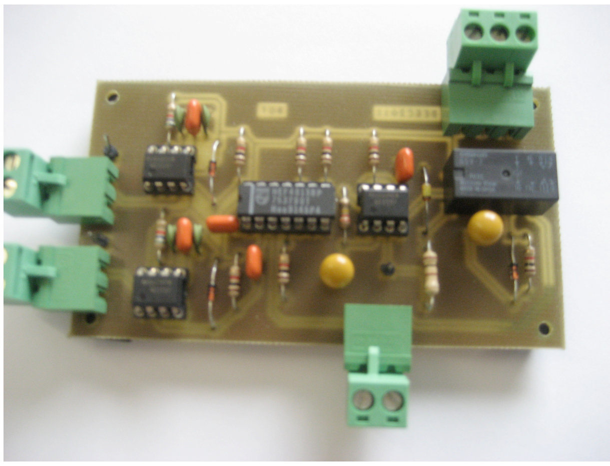

Fig. 6. Implementation board the PEM controller

9 Experimental Results

The experimental results of the PEM were taking with a 28-cells model stack - MARK1020 from Ballard, the output voltage is measured by directly connecting with the Fuel Cell. This is an uncontrolled DC voltage, which fluctuates with load variations as well as with changes in the fuel input of the system. So, the fuel cell system provides a DC-DC converter, which will control the output voltage. Figures 7 and 8 show the stack voltage and stack power respectively.
As can be observed, the stack voltage decreases slightly with the increase of the stack current. This decrease on the stack voltage is due to: 1) the voltage drop associated with the activation of anode and cathode, Vact, 2) the voltage drop result-

ing from the resistances of the conduction of protons through the solid electrolyte and the electrons through its path, Vohmic, and 3) the voltage drop resulting from the decrease in the concentration of the oxygen and hydrogen, Vcon. This characteristic of the stack is also referred to as the polarization curve of the stack. The stack voltage decays from 26.8V to 18.9V, which is in accordance with the information provided by the manufacturer datasheet. The stack power information represented in Figure 8 is also in accordance with the information provided by the manufacturer. That is, for 26A of demanded load, the stack provides 493W of power. The maximum power supplied by this PEM stack is 1259W for a load current of 65A.

The couple between the DC-DC Converter and the PEM fuel cell results is represented in Figures 9, 10 and 11, which were obtained with oscilloscope Tektronix TDS2024. For the measurement of the current, a Tektronix A622 is used for DC current measurement wile for the AC current measurement is used a CWT -Rogowski coil range from Powertek.

As can be see the fuel cell voltage in Figure 9 is 20.6V and the current of the fuel cell is in this case 11.3A. Considering two points of the experimental PEM polarization represented in Figure 7, (10A, 20.88V) and (12A, 20.68V9. It can be seen that the measured values in the output of the PEM, during of the operating of the resonant converter, are in accordance with the respective polarization curve for a given request load.

in Figure 10 there are schow the voltage and current waveforms at the output of the full bridge IGBTs inverter As can be seen, these waveforms correspond to that expected for this type of inverter, that is the voltage is alternated square-wave and the current is sinusoidal. Refer to the particular question of the frequency of switching IBGTs as may be read that is 32.75kHz, with all the advantages associated with using this type control (soft-switching).

As is explained above in the papper, the PEM controller is as an "observer of the system" then, when the system working in steady-state operation and once well defined the point P in the PEM characteristic, small perturbations are introduced into the system. As is explained in the flowchart of Figure 4 and experimentally implemented in Figures 5 and 6. Then, Figures 11 to 13 orresponds to the operation of this circuit part namely; Figure 11 shows the output (pin3) of the oscillator NE555 (CH4) and the threshold voltage of THRES (pin6) input (CH2), Figure 12 shows the discharge of the capacitor C' with is very quickly, with the time constant t= rFC' (CH3) and the oscillator output NE555 (CH4) finnaly a plot showing in more detail the effect of the discharge of the capacitor C', with t= rFC' is presented in Figure 13.

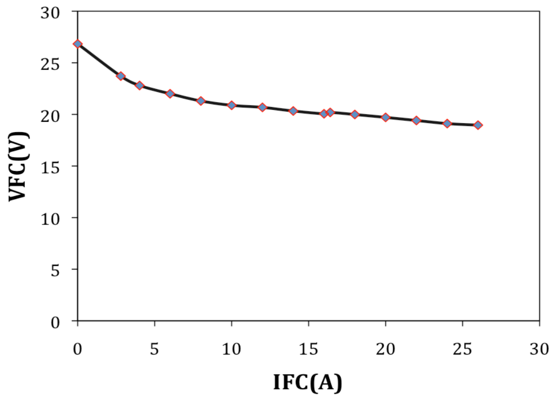

Fig. 7. Fuel cell voltage of Mark1020 stack .

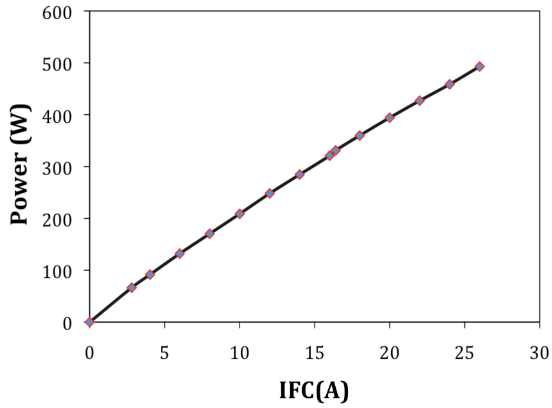

Fig. 8. Electrical power of Mark1020.

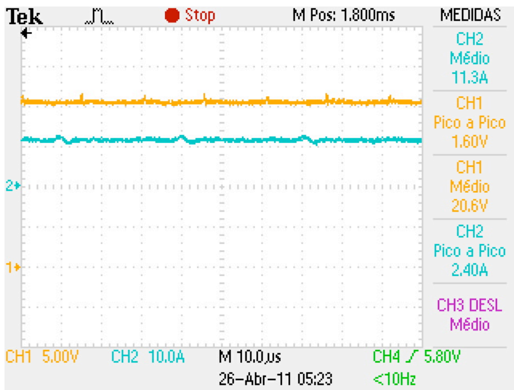

Fig. 9. Plots showing the fuel cell voltage (CH1) and current (CH2) for for a given request load to the converter.

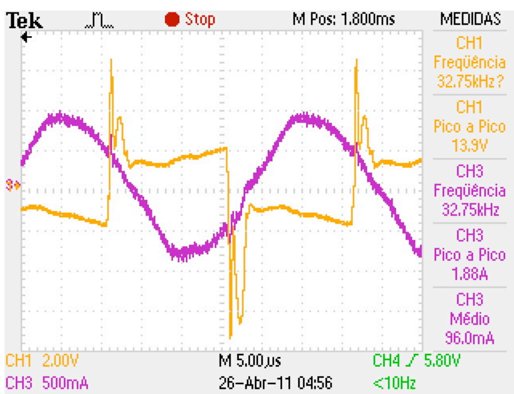

Fig. 10. Plots showing the voltage (CH1) and current (CH3) waveforms in the output of the full bridge IGBTs inverter.

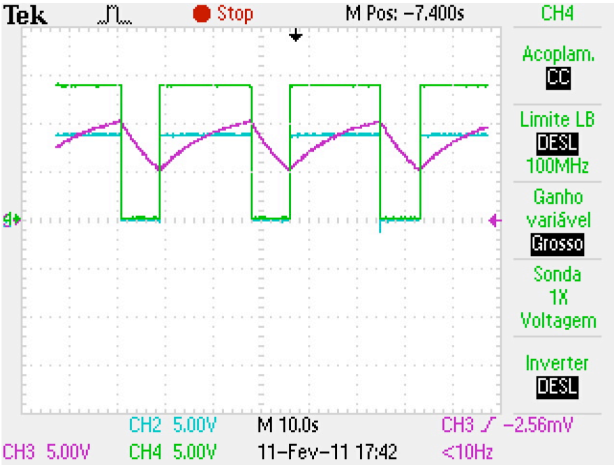

Fig. 11. Plots showing the output (pin3) of the oscillator NE555 (CH4) and the threshold voltage of THRES (pin6) input (CH2).

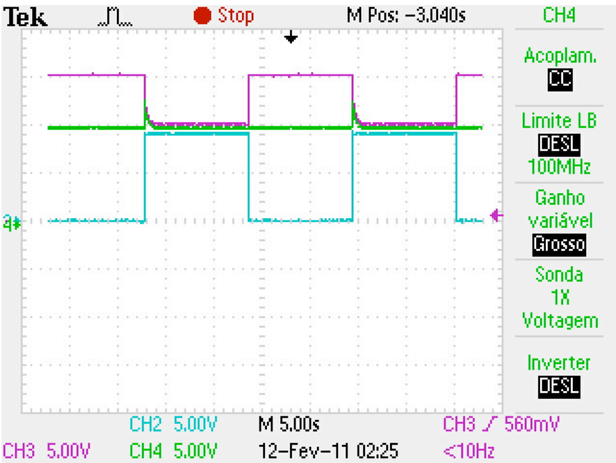

Fig. 12. Plots showing the very quickly discharge of the capacitor C' with the time constant t= r_FC' (CH3) and the output of the oscillator NE555 (CH4)

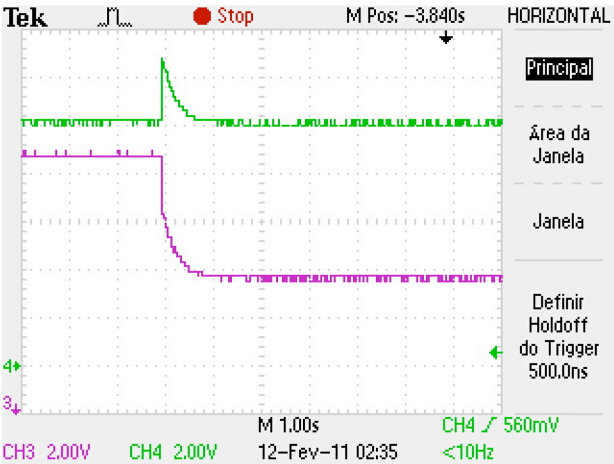

Fig. 13. Plots showing in more detail the effect of the discharge of the capacitor C', with t= r_FC'.

10 Conclusions

In this paper, the design and validation of an experimental setup based on a DC-DC converter with a particular controller with allows to optimize the performance of a PEM fuel cell is presented.

The current–voltage (I–V) curve, also known as a polarization curve of a PEM fuel cell, defines normally its behavior, but it is highly nonlinear. In this context, it is important to incorporate proceses of nonlinearity to control design and process the optimization. Thus, this paper was presented in a first phase the numerical model of the PEM and its simulation in Matlab/Simulink, and then its performance is characterized through an experimental model (the MARK1020 of Ballard). Once validated the PEM characteristics by experimental results it is join to the DC-DC converter, specially designed and implemented for the PEM, and a variable load. The experimental results obtained with this set were then analyzed and discussed. In addition, this paper focuses in particular the analysis and the details of implementation of the PEM controller. Experimental results of the PEM controller were also obtained and discussed.

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