On the Anode Pressure and Humidity Regulation in PEM Fuel Cells: a Nonlinear Predictive Control Approach

**Noè Rosanas-Boeta, Carlos Ocampo-Martinez,
Cristian Kunusch**

*Universitat Politècnica de Catalunya - BarcelonaTech,
Institut de Robòtica i Informàtica Industrial, CSIC-UPC
Llorens i Artigas, 4-6, 08028 Barcelona, Spain
{nrosanas, cocampo, ckunusch}@iri.upc.edu*

Abstract: In this paper, a nonlinear model predictive control (NMPC) strategy is proposed to regulate the humidity in a Proton Exchange Membrane Fuel Cell (PEMFC) anode. The proposed control strategy uses two controllers in cascade to regulate the humidity and pressure in the anode, separately. With this strategy, safety and performance constraints for pressure and humidity can be guaranteed and external disturbances, as changes in stack current demand, are rejected.

1. INTRODUCTION

Hydrogen fuel cells are one of the most promising technologies regarding energy production thanks to their high efficiency and due to the fact hydrogen is a clean source of energy. Particularly, proton exchange membrane fuel cells (PEMFC) provide high power density making them viable for portable and vehicular power applications, as well as for stationary plants. A typical PEMFC power system is composed of several auxiliary interconnected components, as presented in Pukrushpan et al. (2004). The energy is produced in the cell stack subsystem where the hydrogen, supplied from the anode, and the oxygen, supplied from the cathode, react. The energetic efficiency of this reaction depends on several factors such as the concentrations of the reactants, the degradation of the membrane, the temperature in the cell stack, the pressure of the gases and the humidity across the membrane. It is therefore necessary a control system to maintain optimal conditions in order to avoid a degradation in the membrane while maximizing the closed-loop performance. The control problem is complex due to the numerous variables that affect the process and the interconnections among them. Short life of the membrane is a barrier for its massive commercialization so extending its lifespan is one of the main interests in this field.

The relative humidity (RH) in both anode and cathode channels has a capital importance both in the preservation of the membrane and in the energetic performance of the PEMFC. The importance of RH lies in the need of high humidity in the anode for high proton conductivity without saturating the ambient that could cause flooding in the membrane, blocking the channels and pores of the gas diffusion layers. The flooding of the membrane results in a poor performance and it also leads to corrosion. As the water is produced in the cathode, the flooding is a phenomenon appearing more frequently in the cathode than in the anode. In this paper, a control system is presented to achieve the suitable regulation of both the RH and the pressure in the anode while rejecting the disturbances produced by the electrochemical reaction. Ideally, partial pressure of hydrogen in the anode must be high enough to avoid starvation in the PEMFC, a phenomenon produced by the lack of the required reactant reducing the lifetime of the fuel cell and its general performance. The excess of hydrogen pressure first implies an excess of mechanical stress in the MEA (membrane electrode assembly). Being this field important for the preservation of the lifespan of the PEMFC, there are several studies covering different issues regarding the degradation of the membrane. Karnik et al. (2009) use a gain scheduling control and a ejector-based anode recirculation system to control the humidity and pressures in the anode and cathode, assuming perfect knowledge of the dynamics of the plant, taking into account scenarios with both subsaturated and saturated conditions. In the line of this work, Gruber et al. (2012) proposes an NMPC for the airflow in a PEMFC in order to guarantee the oxygen excess in the cathode and ensure performance and safety conditions. The work from Vahidi et al. (2004) tackles the issue of oxygen starvation in the cathode by using a linear MPC with an auxiliary power source, showing the capabilities of anticipating the possible energy shortages produced by oxygen starvation. The requirements of humidity and stoichiometric conditions to avoid early degradation and to extend the life of fuel cells are presented in Schmittinger and Vahidi (2008), remarking the importance of water management where humidity regulation is a quite important issue.

The work reported in Kunusch et al. (2013) considers a series of observers for the water transport across the membrane that are essential in order to estimate the RH at the anode. Moreover, Kunusch et al. (2012) present

a analytical model designed for non-linear control and observation purposes. This model has been validated experimentally in laboratory PEMFC test-bench. The approach followed in the design of the model is a combination between a theoretical, shown by Pukrushpan et al. (2004), and empirical based on experimental data. This approach is quite useful in this paper since it provides deep detail of the significant physical variables of the system and reduces the complexity of non-relevant features of the system using linearizations rather than the non-linear complex description.

The main contribution of this paper consists in presenting a cascade control architecture that regulates both the pressure and the humidity in the anode. In this paper, the capacity of the non-linear model predictive control (NMPC) is used to take advantage of the analytical model and the natural ability of the control strategy to include the system physics. The goal is to provide optimal conditions to preserve the lifespan of the membrane in the fuel cell stack. This objective is achieved tackling the problem of pressure and humidity as two separate problems and designing a controller for each one of them. Hence, with this strategy two dynamic processes highly coupled can be tackled separately.

2. PROBLEM STATEMENT

The goal is to develop a control system for a PEMFC anode subsystem that regulates the RH in the anode channels. The characteristics of the fuel cell system under study has several measured variables that provide information about the system. In the anode part, the measured variables are: the pressure in the anode channels (P_{an}) and the pressure in the anode humidifier $P_{hum,an}$. In the fuel cell stack, the temperature (T_{st}), the current (I_{st}) and voltage (V_{st}) are also available. Also, the hydrogen inflow (W_{H2}) and the power supplied to the anode humidifier ($\Pi_{hum,an}$) are controlled and measured. Additionally, the measurement of the RH in the anode (RH) is also available.

To achieve the desired RH in the anode at steady state, two inputs are used: $\Pi_{hum,an}$ and W_{H2}. The dynamic nature of W_{H2} and $\Pi_{hum,an}$ are quite different and the response time of the system to a change of the hydrogen inflow is orders of magnitude faster than the response time to a change in the temperature of the humidifier set-point.

There is strong interaction between both controlled variables. Variations in $T_{hum,an}$, produced by $\Pi_{hum,an}$, will cause a variation in $P_{hum,an}$ that will change the inflow to the anode thus changing P_{an}. The same chain effect can be seen when a variation in W_{H2}, which changes $W_{v,inj}$ causing, in turn, a variation of the RH. This two phenomena will be addressed separately: an inner control loop will regulate the pressures in the system and a outer loop will regulate the water vapour added to the system in the humidifier.

2.1 Problem Formulation

The control problem will be formulated as an non-linear constrained optimization problem. Apart of the bounded constrains related to the system variables, there is an additional constraint regarding $T_{hum,an}$ that is worth of particular attention: the humidifier has only a heating system but not a cooling system. This means that its temperature can be actively increased by providing energy to the heating system but it only decreases passively by dissipating the heat.

The analytical model of the anode channels, obtained from Kunusch et al. (2013) and Kunusch et al. (2012), can be described as follows:

$$\dot{m}_{H2} = f_1(W_{H2}, m_{H2}, P_{an}),$$
$$\dot{P}_{an} = f_2(m_{H2}, P_{amb}, I_{st}, W_{v,mem}, RH),$$
$$\dot{RH} = f_3(m_{H2}, P_{an}, W_{v,mem}, RH, T_{hum,an}, \Pi_{hum,an}),$$

where P_{amb} is the ambient pressure and m_{H2} is the mass of hydrogen in the humidifier. This latter variable is closely related to the pressure in the humidifier ($P_{hum,an}$), as it will be shown later. The analytical model is composed by continuous-time equations and it needs to be discretized in order to design an NMPC controller in discrete time. Assuming the time between samples (Δt) small enough, the discrete model will keep the properties of the continous model. The discretization of the model is carried out using the Euler method. The discrete-time system will have the following form:

$$m_{H2}(k+1) = m_{H2}(k) + f_1 \Delta t,$$
$$P_{an}(k+1) = P_{an}(k) + f_2 \Delta t,$$
$$RH(k+1) = RH(k) + f_3 \Delta t,$$

where k denotes the discrete-time variable. A cascade loop architecture, as seen in Figure 1, is used in order to be able to regulate both the pressure and the humidity of the system. The inner loop handles the pressure of the anode by using the hydrogen inflow as control action while the humidity controller uses the humidifier temperature. It can also set the pressure reference for the inner controller.

3. MODEL ANALYSIS

The following natural step towards designing the controller is to describe analytically the model used as a baseline of this paper. The model used is focused on the auxiliary systems around it: the humidifiers, the manifolds and line heaters. The dynamics of the electrochemical reaction are simplified. This was modelled in the previous work of Kunusch et al. (2012) and Kunusch et al. (2013). The model reported includes many variables and parameters that would make the control problem quite complex. Therefore, its simplified version, with the focus on the anode and anode huidifier, is used.

3.1 Pressure Control-Oriented Model

This control-oriented model (COM) describes two phenomena: how the supplied hydrogen is humidified and what happens in the anode of the fuel cell with this humidified hydrogen. These phenomena are described from the point of view of mass balances taking into account the conservation mass principle and the ideal gases law.

For the objective of this paper, it is important to know the mass and behaviour of m_{H2}, whose change is represented by the dynamic process:

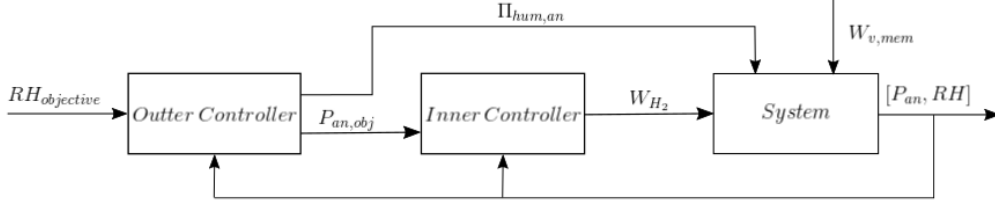$$\dot{m}_{H2} = W_{H2} - W_{H2,an,in}. \tag{1}$$

Fig. 1. Block diagram of the control system

The behaviour of W_{H2} is set externally and will be used as a control action for the system. Moreover, $W_{H2,an,in}$ is a variable obtained after the linearisation of the nozzle equation. The approximation is the polynomial:

$$W_{H2,an,in} = C_0 + C_1(P_{hum} - P_{an}), \qquad (2)$$

where C_0 and C_1 are values determined experimentally (Kunusch et al., 2012) and they are shown in Table 1. The values of P_{hum} and P_{an} are measured from the system. Besides, P_{hum} is related directly to the m_{H2} by the ideal gas law and will be described as

$$P_{hum} = K_1 m_{H2}, \qquad K_1 = \frac{G_h T_{hum}}{V_{hum}},$$

where K_1 is the factor obtained by ideal gases law that relates mass and pressure, V_{hum} is the volume of the humidifier and G_h is the molar mass of hydrogen.

The focus of interest is the pressure dynamics in the anode expressed as a function of the different inputs, outputs and stack current. This is given by

$$\dot{P}_{an} = ((W_{H2,an,in} - W_{H2,react} - W_{h2,out})R_h +$$
$$+ (W_{v,inj} - W_{v,out} - W_{v,mem})R_v)\frac{T_{st}}{V_{an}}. \quad (3)$$

The term $W_{v,inj}$ is the amount of vapour added, dependent on the hydrogen flux, temperature and pressure in the anode:

$$W_{v,inj} = \frac{G_v RH_{hum} P_{sat}(T_{hum})}{G_h P_{hum}} W_{H2,an,in}. \qquad (4)$$

The terms RH_{hum} and $P_{sat}(T_{hum})$ are the RH and saturation pressure in the humidifier respectively. The RH_{hum} is quite close 100% when the humidifier works under nominal operation. Hence, $P_{sat}(T_{hum})$ is expressed as follows:

$$P_{sat,hum}(T_{hum}) = 10^{3+\gamma(T_{hum})}, \qquad (5)$$

where

$$\gamma(T_{hum}) = \alpha_0 + \alpha_1 T_{hum} + \alpha_2 T_{hum}^2 + \alpha_3 T_{hum}^3 \alpha_4 T_{hum}^4.$$

The coefficients of this polynomial are found in Table 1.

Table 1. Coefficient values for (2) and (5)

Coefficient	Value	Coefficient	Value
C_0	1.0836×10^{-5}	α_2	3.39×10^{-4}
C_1	3.3510×10^{-9}	α_3	0.143×10^{-9}
α_0	-1.69×10^{-10}	α_4	20.92
α_1	3.85×10^{-7}		

The hydrogen consumed in the electrochemical reaction, $W_{H2,react}$, only depends on I_{st} and constant parameters, i.e.,

$$W_{H2,react} = I_{st}\frac{G_h n}{2F},$$

being n the number of cells and F the Faraday's constant. The outflow from anode, W_{out}, is dependent on a nozzle

constant, the differential pressure between P_{an} and P_{amb} and $W_{out} = K_{an,n}(P_{an} - P_{amb})$. With the measurement of RH, the proportion of vapour in W_{out} can be known as follows:

$$W_{v,out} = (1 - \omega)W_{out},$$
$$W_{H2,out} = \omega W_{out},$$
$$\omega = \frac{1}{\frac{G_v R_v}{G_h R_h}\frac{m_{v,an}}{m_{H2,an}} + 1},$$
$$m_{v,an} = \frac{P_{sat}(T_{st})RHV_{an}}{T_{st}},$$
$$m_{H2,an} = \frac{(P_{an} - P_{sat}(T_{st})RH)V_{an}}{R_h T_{st}},$$

where $m_{v,an}$ and $m_{H2,an}$ are the mass of vapour and hydrogen in the anode, respectively. The last variable concerning the anode mass balance is the water transport in the membrane $W_{v,mem}$ which has unmodelled dynamics due to its complexity but it can be also observed. The parameter ω indicates the mass relation of hydrogen and vapour in the anode. The remaining of terms in (3) are: R_h, hydrogen specific constant; R_v, vapour specific constant; T_s, PEMFC stack temperature and V_{an}, anode volume.

3.2 Humidity Control-Oriented Model

This model describes the changes of humidity in the anode in relation to the temperature in the humidifier. The dynamics of the temperature model is two orders of magnitude slower than the dynamics of the humidifier and anode masses, thus they will be considered as instantaneous changes seen like observable perturbations. The same basic ideas are used in the pressure COM but assuming that the pressures are instantaneously self-regulated. The heating model is assumed to be a first-order system where the input $\Pi_{hum,an}$ is the power supplied to the heating resistor. The discrete-model of the heating system is

$$T_{hum}(k+1) = -\Omega T_{hum}(k1) + \Pi_{hum,an}\Delta t, \qquad (6)$$

where Ω is the heat dissipation rate. The humidity system can be described as

$$\dot{RH} = (-W_{v,an,out} - W_{v,mem} + W_{v,inj}),$$

where all the terms are previously described.

3.3 Complete Model

The complete model has 8 states. It models the whole system including the cathode dynamics and a model of $W_{v,mem}$ so it can be considered as an accurate reference to apply the control. The original model has as input the voltage of the air compressor that relates to the input air flux and the hydrogen input flux. This model

assumes the temperature of the anode humidifier remains constant so some slight modifications are performed to adapt the model. This modifications are regarding the implementation of the model but its theoretical approach of exactly the same. The description of this model is found in Kunusch et al. (2012) and Kunusch et al. (2012). The model presented was validated experimentally and provides a useful information about how the controller would perform on a physical setup. This model is used for simulations purposes with the sampling time equal to the pressure COM model's sampling time. The cathode part is not studied in this paper but is configured to provide the complete operating conditions.

The complete model is slightly different than the COM because no assumptions of are made regarding the constant values of the perturbations or instant changes in the pressure. The simulation model is used to close the control loop. Both COM are used to compute the optimal inputs and, once they are obtained, they are applied to the simulation model. The outputs obtained from it are used as initial conditions for the optimization problem in the next iteration.

4. CONTROLLER DESIGN

In this section, two controllers needed are designed separately and individually tested in different scenarios to demonstrate their effectiveness. The two loops have different time constants and can be seen separately. The inner loop, in charge of pressure regulation, will assume constant values for RH_{hum}, RH and T_{hum}. In the outer loop, P_{hum} and P_{an} will be assumed to change instantaneously. The inner loop is able to reach the set point of the pressures fast enough to ignore their transient behaviour in the outer loop. This values, considered constant in the optimization process, are updated at each time step even though the dynamics of the change are ignored.

4.1 Pressure Controller (Inner Loop)

The objective is to find the optimal value of W_{H2} supplied to the system to obtain the desired value of P_{an}. The model is described as a discrete-time non-linear state space as follows:

$$m_{H2}(k+1) = \dot{m}_{H2}(k)T_s + m_{H2}(k),$$
$$P_{an}(k+1) = \dot{P}_{an}(k)T_s + P_{an}(k),$$
$$y_1(k) = K_1 m_{H2}(k),$$
$$y_2(k) = P_{an}(k).$$

It is necessary to define the prediction horizon (H_p) for the NMPC controller. If the COM, referred also as reduced model, is compared with the full model, it shows that both have a similar behavior until the time mark of 2 seconds approximately (Figure 2). Taking into account that both models are discretized with $T_s = 0.1$ s, it is safe to use controllers with a H_p up to 20.

The optimization problem is expressed as follows:

$$\min_{W_{H2}\in\mathbb{R}^{H_p}} \quad \sum_{k=0}^{H_p} J(P_{an}(k), W_{H2}(k)) \qquad (7a)$$
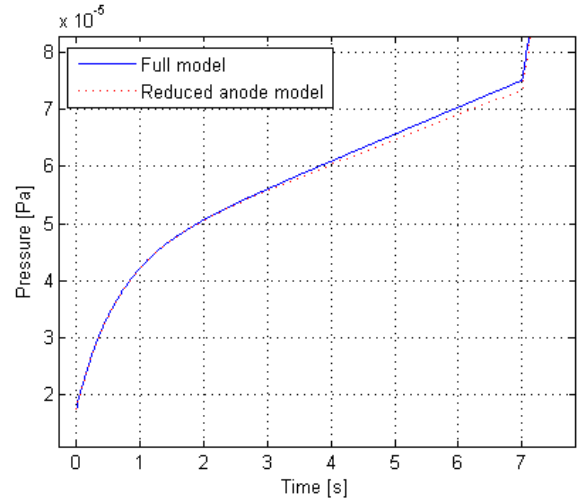
subject to

Fig. 2. Comparison between full model and reduced model

$$P_{amb} \leq P_{hum} \leq P_{hum,max}, \qquad (7b)$$
$$P_{hum} \leq P_{an} \leq P_{an,max}, \qquad (7c)$$
$$P_{an} \leq P_{hum}, \qquad (7d)$$
$$\Delta W_{H2,min} \leq \Delta W_{H2} \leq \Delta W_{H2,max}, \qquad (7e)$$
$$0 \leq W_{H2} \leq W_{H2,max}, \qquad (7f)$$
$$m_{H2}(k+1) = f_1(k)T_s + m_{H2}(k), \qquad (7g)$$
$$P_{an}(k+1) = f_2(k)T_s + P_{an}(k), \qquad (7h)$$

with

$$J(P_{an}(k), W_{H2}(k)) = (P_{an}(k) - P_{an,ref}(k))^2 w_{P_{an}}$$
$$+ \Delta W_{H2}(k)^2 w_{\Delta W_{H2}},$$

with $w_{P_{an}}$ and $w_{\Delta W_{H2}}$ being the weighting matrices. The way of finding the optimal value for these matrices (controller tuning) is out of the scope of this paper. For the purposes of this paper, suitable values have been found from simulation results.

Upon closer examination of the dynamic equations of the system, one can notice that the humidifier acts as a buffer between the input (W_{H2}) and the actual output of the system (P_{an}). This coupled with a short H_p produces a big control action that increases the pressure in the humidifier putting the system close to the constraints. This extra pressure in the humidifier will cause an increase in the humidified hydrogen inflow to the anode making the system difficult or even impossible to control. The buffer effect could be avoided providing also a set point for the humidifier but this would make the system slower if the set point is constant. In order to provide a dynamic set point, another level of optimization would be required, wicho would increase the complexity of the system prohibitively. A softer response could be achieved with a penalty on the control action but this would include a steady state error also undesired. As a result, the better option is to choose a large H_p without compromising the performance of the system. By simulation, it is found that $H_p = 15$ provides a satisfactory results and performance. In Figure 3, it is shown the response of the system with different H_p lengths.
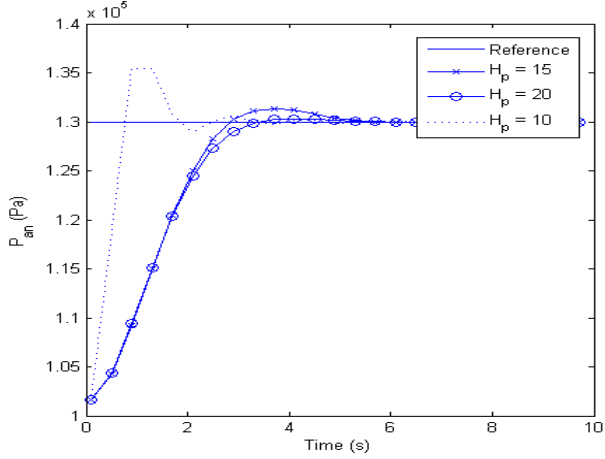
Fig. 3. Comparison between different H_p lengths

4.2 RH Controller (Outer Loop)

This external controller provides two signals to the pressure controller: $\Pi_{hum,an}$ and $P_{an,ref}$. In the previous section, a fully detailed model was used as internal model. In the outer loop, the dynamics of P_{hum} and P_{an} are ignored, and P_{an} is assumed to follow exactly $P_{an,ref}$. The objective to regulate the RH is achieved mostly by the change of the temperature of the humidifier but, as mentioned in Section 3, the temperature can only be decreased passively, the control action $\Pi_{hum,an}$ only provides positive increments of temperature, so the extra manipulable $P_{an,ref}$ can help achieving the desired RH. Between the two inputs, it is desirable to use the temperature primarily and avoid the excess expenditure of H_2 that would result in an excessive $P_{an,ref}$. Hence, the optimization problem related to this controller is expressed as follows:

$$\min_{\gamma \in \mathbb{R}^{2H_p,ext}} \sum_{k=0}^{H_p} J_{ext}(k) \tag{8a}$$

subject to

$$RH_{min} \leq RH \leq RH_{max} \tag{8b}$$
$$P_{an,min} \leq P_{an} \leq P_{an,max} \tag{8c}$$
$$\Pi_{hum,an,min} \leq \Pi_{hum,an} \leq \Pi_{hum,an,max} \tag{8d}$$
$$\Delta\Pi_{hum,an,min} \leq \Delta\Pi_{hum,an} \leq \Delta\Pi_{hum,an,max} \tag{8e}$$
$$T_{hum,an,min} \leq T_{hum,an} \leq T_{hum,an,max} \tag{8f}$$
$$RH(k+1) = RH(k) + f_3(k)T_s, \tag{8g}$$

with

$$J_{ext}(k) = (P_{an,ref}(k) - P_{an,optim}(k))^2 w_{P_{an,ref}}$$
$$+ \Delta\Pi_{hum,an}(k)^2 w_{\Delta\Pi_{hum,an}}$$
$$+ (RH(k) - RH_{ref}(k))^2 w_{RH}$$

and $\gamma = [\Pi_{hum,an}, P_{an,ref}]'$. Matrices $w_{P_{an,ref}}$, $w_{\Delta\Pi_{hum,an}}$ and w_{RH} are the weight matrices. $\Delta\Pi_{hum,an}$ is the increment of the control action in relation to the last control action. This value is bounded by $\Delta\Pi_{hum,an,min}$ and $\Delta\Pi_{hum,an,max}$. Besides, RH is bounded by RH_{min} and RH_{max}, which provide safety and performance bounds for the membrane. The variable $P_{an,optim}$ is the optimal pressure, set externally, regarding FC durability and safety. The constraint in $P_{an,ref}$ could be bounded to a single value set externally and then the controller would just adjust the humidity in the anode via the temperature of the anode.

In order to determine $H_{p,ext}$ for this controller, it is necessary to take into account two factors: the settling time of the pressure subsystem and the time constant of the humidifier temperature. The sampling time is 20s, five times the time the inner loop takes to reach steady state. With the sampling time in mind, a balance must be found between an H_p that allows to make predictions long enough, in time units, to make significant predictions without being too expensive computationally. The balance is found with $H_{p,ext} = 15$, allowing predictions of events 5 minutes ahead of the current time-instant. It is important to achieve RH without increasing excessively the temperature because it is hard to decrease it, this implies avoiding overshooting at expense of a slower system. A rule of thumb to set the weighting matrices in such a way is to penalize heavily the state representing the pressure in the anode and the slew rate of the power of the resistor of humidifier. Given this external controller has two degrees of freedom, a fixed anode pressure could be set to control the RH via $T_{hum,an}$.

5. RESULTS AND DISCUSSION

5.1 Simulation Scenario

Simulations have been carried out using `fmincon` routine in MATLAB® 2010b 64-bits running on an Intel® Core™2 Duo CPU E8600 @ 3.33 GHz with 8GB of RAM. The simulation conditions are set to a fixed set-point of RH to provide optimal performance for the PEMFC. The process assumes observability of the variables $W_{v,mem}$ and RH, the observability of the former is solved by Kunusch et al. (2013) and the later can be measured with a humidity sensor in the outlet flow. The system will be simulated first with two degrees of freedom for the controller and the second with a fixed low pressure so the controller only regulates the temperature of the humidifier. Both simulations will face a perturbation in the form of a change of I_{st} demand, the demand in I_{st} will be doubled.

5.2 Main Results

The main challenge the pressure controller faces is the changes in the $P_{an,obj}$ and the disturbance introduced by a change in I_{st}. There will be a step change in the current drawn and also in the $P_{an,obj}$ and both perturbations are rejected with no steady state error with a suitable transient behaviour, no overshoot and fast response. As stated before, this response allows the external controller to assume the values change instantaneously, the settling time of this subsystem is orders of magnitude smaller than the sampling time of the external controller. The change of I_{st} has a small impact over the pressure subsystem, which can be seen in Figure 4 at 5s. There is a slight change in the pressure but the effects are rejected quite fast. The change in the pressure is due to the change in hydrogen demand when stack current increases.

The whole system with the ability to set the pressures in the anode produces an interesting result, when the RH objective is increased there is an increase also in P_{an}, Figure 5. This is makes the settling time longer
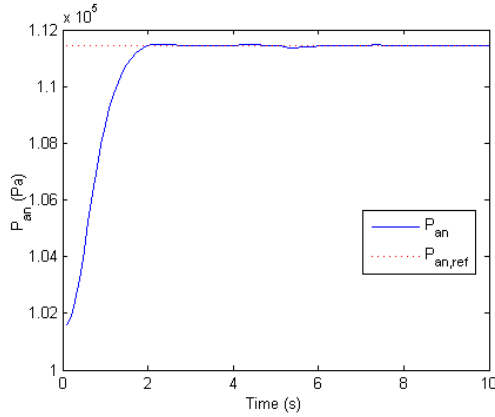
Fig. 4. Response of the internal loop with a disturbance at 5 seconds mark the current demand is doubled.
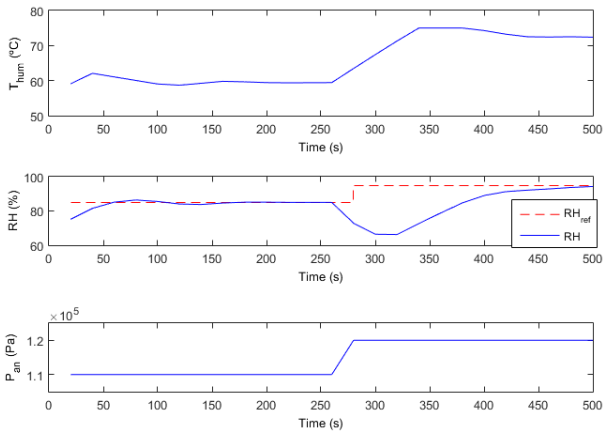

Fig. 5. Response of the external loop with a step change in the RH objective with the freedom to set the pressure in the anode.

but provides useful extra pressure to avoid constraint violation. The effect of the external disturbance (stack current variation) is completely rejected. The controller without the possibility to set the reference of the pressure in the anode has a quite similar behaviour to the general configuration, with the freedom to set the anode pressure. The controller tuning gets easier but when the working operations is quite close to the saturated anode, the system will not have the possibility to purge the excess of hydrogen. This action can decrease fast the quantity of vapour in the anode. The simulations results are shown in Figure 6.

The computation of the optimal solution in average took 15.64 s per iteration for the internal loop and 0.91 s per iteration for the outer one. On one hand, the computational time in the outer loop is satisfactory because it stays below the response time of the system and it could be applied in real time. On the other hand, the computational time for the inner loop must be drastically decreased in order to be applied to a real time system, the computation time is too high compared to the sampling time of the pressure.

6. CONCLUSION

The NMPC controller has been designed and applied satisfactorily in the PEMFC anode subsystem, allowing the
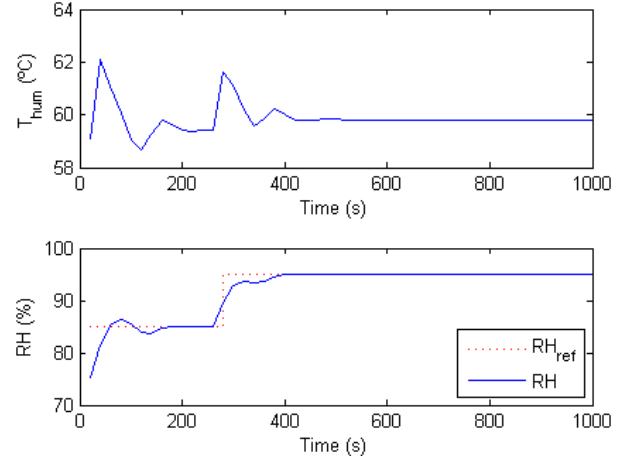

Fig. 6. Response of the external loop with a step change in the RH objective and a step change in the current drawn, doubling the initial demand.

control of critical variables for the lifespan of the membrane. Promising results have been obtained in the simulation scenario. The results have shown a better performance of the controller with a fixed pressure in the anode, a condition that makes sense physically and economically. Note that this approach is an interesting option regarding future works where the control of both anode and cathode humidity will be performed. In that case, the pressure could be set externally to satisfy safety reasons or it could be imposed by the cathode. An improvement of the current system could be achieved by finding suitable weighting matrices for the cost function, taking into account fine details of the membrane and overall PEMFC degradation.

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