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Flatness control strategy for the air subsystem of a hydrogen fuel cell system

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Abstract—In this paper, a non linear control strategy is applied to the air supply subsystem of a polymer electrode membrane fuel cell (PEMFC). Based on a simplified control model and using the differential flatness control theory, a controller is designed in order to regulate the most important variables in the air supply subsystem: the oxygen stoichiometry and the cathode pressure. The non linear control approach is validated using a real fuel cell system, presenting a good response compared with a PID classical approach.

I. INTRODUCTION

PEMFC technology is considered as the best adapted for transport application [1]. In this work, this technology is used for the development of a 7kW (90 cells) fuel cell stack for vehicle applications. In order to operate the fuel cell, its state variables should be controlled and regulated by a conditioning system. Some of the most important components of the fuel cell system are integrated in the air subsystem. Therefore, the control of these elements is necessary to avoid some harmful effects that can accelerate the degradation of the fuel cell stack. One of these phenomena is the oxygen starvation, presented by Gerard et al. in [2]. It is caused by the lack of oxygen in the cathode during the electrochemical reaction. Generally, the cause of this oxygen starvation is the difference between the air supply subsystem dynamics and the electric response demanded to the stack, which means that the low dynamics of the elements in the air group limits the oxygen flow towards to the cathode.

Concerning the air group, a control strategy must be implemented such that the stoichiometry (ratio of the input oxygen flow over the reacted oxygen flow) is maintained around a constant desired value, whatever the power demand. Moreover, the control of the oxygen flow should be coupled to the regulation of the pressure in the cathode, such that a pressure equilibrium is maintained between cathode and anode.

Several authors dealt with this subject with different approaches. Tekin et al. [3] adopted the fuzzy logic with particle swarm approach to control the motor compressor; Grujicic et al. [4] applied static and dynamic feedforward control techniques for the air flow control. Nonlinear approaches using passivity, sliding mode and prediction control techniques were developed in [5], [6], [7] respectively. These approaches obtained good results in terms of oxygen flow, but do not take into account the pressure control at the cathode.

In order to implement a robust solution for the control of the air supply system, this work proposes a non linear control design that enables stoichiometry and pressure control to be coupled. The control design is based on the differential flatness theory [8]. The differential flatness strategy is designed using a simplified fuel cell system model and is tested using a real fuel cell system.

This paper is built up as follows: The real fuel cell system is presented in section 2. Section 3 presents the control model and the proposed non linear control strategy. The results are presented in section 4. Conclusions are given in Section 5.

II. FUEL CELL SYSTEM (PROSPAC)

In order to evaluate the proposed control strategy, a real fuel cell system called PROSPAC (figure 1) is used. It was designed and constructed by the CEA (Commissariat à l’Energie Atomique) and is composed by 7kW PEMFC fuel cell system (90 cells) and two packs of LiFePO4 battery composing 55.4V and 2kWh.



Figure 1. PROSPAC system

The battery and Fuel cell system are arranged in a series architecture using an electric bus, which has its voltage imposed by the battery. The fuel cell system has its interface made by an unidirectional DC/DC converter in order to adapt the voltage level and to protect the fuel cell.

Concerning the pressure adopted in the cathode and anode, an equilibrium value of 1.2 bar is demanded to the system. On the hydrogen side, a mechanical valve in the anode upstream imposes this pressure, while a purge valve is used to eliminate the water created during the operation. On the cathode side, the oxygen is delivered by an air compressor. A pressure valve at the downstream of the cathode is used to regulate the pressure in this chamber.

The control and supervision of this system is effectuated by a DSPACE microautobox II, where the control laws of the fuel cell sub systems (cooling, hydrogen, air, electric, etc) and supervision are designed using the environment Simulink.

III. CONTROL MODEL AND CONTROL STRATEGY

A. Control model

In order to design a control law for the air group, a simplified model has been designed based on the real fuel cell system presented previously. Some assumptions were made to reduce the model complexity and dimension:

- The humidifier is represented only by its equivalent pressure drop without dynamics and transport phenomena.
- The transport phenomena inside the fuel cell are not taken into account.
- The temperature inside the fuel cell is homogeneous and perfectly controlled.
- The cathode is represented by a global volume and a pressure drop from the inlet to the outlet (figure 2).

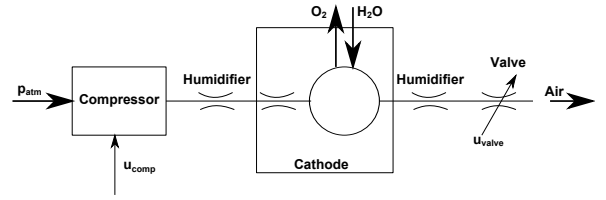


Figure 2. Simplified model of air supply subsystem

The compressor air flow results from the compressor characteristics in a nonlinear stationary condition model (1). The parameters a , b , ψ_1 and ψ_2 are obtained by fitting the experimental characteristics of the real compressor, operating in the fuel cell working domain.

$$q_{cp} = (a\omega^2 + b\omega) \left\{ \frac{\psi_1}{\psi_2} - \frac{1}{\psi_2 \left[1 - \left(\frac{p_{sm}}{p_{atm}} - 1 \right)^{\frac{\gamma-1}{\gamma}} \right]} \right\} \quad (1)$$

Finally, the model used for the control synthesis is given by equation 2.

$$\begin{cases} \frac{d\omega}{dt} = \frac{1}{J} \left(\alpha u_{mot} - \frac{C_p T_{atm}}{\omega \eta_{cp}} \left[\left(\frac{p_{sm}}{p_{atm}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] q_{cp}(\omega, p_{sm}) - \varphi \omega \right) \\ \frac{dp_{cath(out)}}{dt} = \frac{RT_{cath}}{V_{cath} m_{molar}} (q_{cp}(\omega, p_{sm}) - q_{O_2} + q_{H_2O} - q_{valve}) \\ \dot{q}_{valve} = \frac{1}{\tau_{valve}} (-q_{valve} + k_{valve} u_{valve}) \end{cases} \quad (2)$$

Where J is the inertia of the motor, u_{mot} is the voltage control input of the motor, α and φ are specific parameters of the motor. C_p is the specific heat capacity of the air, T_{atm} is the atmospheric temperature, η_{cp} is the compressor efficiency, p_{sm} is the outlet pressure, p_{atm} is the atmospheric pressure, γ is the ratio of the air specific heats ($\gamma = 1.4$).

In the cathode equation T_{cath} is the temperature at the cathode, V_{cath} is the volume in the cathode and m_{molar} is the molar mass of the air. Concerning the valve equation, τ_{valve} is the time constant of the valve, k_{valve} is the gain and u_{valve} is the control variable of the valve.

The oxygen flow consumed by the fuel cell q_{O_2} and the water flow q_{H_2O} are known disturbances, which are calculated in function of the fuel cell current i_{FC} (equations 3 and 4) [9]. N_{cell} are the number of cells in the stack, F is the Faraday number. The air to be supplied by the compressor to maintain the oxygen stoichiometry St_{O_2} is calculated as a function of the fuel cell current i_{FC} (eq 5).

$$q_{O_2} = \frac{N_{cell} i_{FC}}{4F} \quad (3)$$

$$q_{H_2O} = \frac{N_{cell} i_{FC}}{2F} \quad (4)$$

$$q_{air} = \frac{St_{O_2} N_{cell} i_{FC}}{\chi_{O_2} 4F} \quad (5)$$

This model is used to design the control strategy, where the outputs to be controlled are the cathode outlet pressure $p_{cath(out)}$ and the compressor air flow q_{cp} . However, there is a coupling between these two variables that complicates the task. Therefore, a non-linear control strategy is applied to decouple the outputs, linearize the system and thereafter apply a classical control strategy for the new linear system.

p_{atm}	1 bar	φ	0.0000385 Nm.rpm ⁻¹
a	0.0081	R	8.31 Pa.m ³ .mol ⁻¹ .K ⁻¹
b	0.59	V_{cath}	0.00008 m ³
ψ_1	15.3	T_{cath}	348 K
ψ_2	15.5	τ_{valve}	0.1 s
γ	1.4	ζ_1	9
J	32.10 ⁻⁶ kg.m ²	ζ_2	-4.5
α	3.45 Nm.V ⁻¹	N_{cell}	90
C_p	1 kJ.kg ⁻¹ .K ⁻¹	F	96400 C.mol ⁻¹
T_{atm}	300 K	St_{O_2}	2
η_{cp}	0.75	χ_{O_2}	0.21
k_{hu}	0.0084 bar.m ⁻³ h	k_{FC}	0.008 bar.m ⁻³ h

Table 1
PARAMETERS VALUES FOR THE CONTROL MODEL

B. Control strategy

A non linear control strategy called differential flatness [8] is applied to the non linear system presented previously. This control strategy permits to define the control inputs u directly from the desired output trajectories y and its derivatives. Differently from other approaches, the differential flatness strategy permits to compensate the known non-linearities of the system, setting a trajectory for the flat outputs and ensuring performance for the system. However, a stabilization adopting feedback loops are required to ensure robustness to the system.

Considering the two outputs ω and $p_{cath(out)}$, it is possible to define the desired trajectory for these variables and to obtain the control in function of these desired trajectories. $p_{cath(out)}$ has a stationary profile ($p_{cath(out)}^d = cte$) in order to keep the balance between the cathode and anode. The definition of ω depends on the current I_{FC} demanded to the fuel cell and stoichiometry. This current is converted in air flow that should be delivered by the compressor as can be seen in the equation 6. Thus, the compressor speed ω can be obtained by an approximation of the compressor behavior (equation 7). p_{sm}^d is the desired supply manifold pressure, which is obtained by the equation 8 that takes into account the pressure drop at the fuel cell stack k_{FC} and the humidifier k_{hu} (the same pressure drop at inlet and outlet of the cathode).

$$q_{air}^d = \frac{St_{O_2} N_{cell} i_{FC}^d}{\chi_{O_2} 4F} \quad (6)$$

$$q_{air}^d = q_{cp}^d = \left(a (\omega^d)^2 + b \omega^d \right) \dots$$

$$\dots \left\{ \begin{array}{l} \frac{\psi_1}{\psi_2} - \frac{1}{\psi_2 \left[1 - \left(\frac{p_{sm}^d}{p_{atm}} - 1 \right)^{\frac{\gamma-1}{\gamma}} \right]} \end{array} \right\} \quad (7)$$

$$p_{sm}^d = p_{cath(out)}^d + q_{air}^d (k_{hu} + k_{FC}) \quad (8)$$

Applying these trajectories to the first dynamic equation (motor-compressor equation), the control input u_{mot} is obtained in function of the desired flat outputs (equation 9)

$$u_{mot} = \frac{\frac{dy_1}{dt} + \lambda_2 \frac{1}{y_1^d} \left[\left(\frac{y_2^d + f_1(y_1^d, y_2^d)(\lambda_3)}{p_{atm}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] f_1(y_1^d, y_2^d)}{\lambda_1} \dots \dots \dots \quad (9)$$

$$\dots \frac{+\lambda_4 y_1^d}{\lambda_1}$$

In this equation, the parameters λ_i were used to simplify the presentation and f_1 calculates the air desired flow supplied by the compressor (q_{cp}^d).

The second control variable is calculated in two steps. The first derivative of the flat output y_2 allows to calculate q_{valve} (equation 10). The second derivative allows to obtain the control input of the valve u_{valve} , when the dynamics of the valve in (2) replaces the variable \dot{q}_{valve} . In the resulting equation, the value of q_{valve} is replaced by the obtained equation 10.

$$q_{valve} = \left[q_{cp}^d (y_1^d, y_2^d) - q_{O_2} + q_{H_2O} - \frac{1}{\lambda_5} \frac{dy_2^d}{dt} \right] \quad (10)$$

$$\frac{d^2 y_2^d}{dt^2} = \lambda_5 \left[\dot{q}_{cp}^d (y_1^d, y_2^d) - \dot{q}_{O_2} + \dot{q}_{H_2O} - \dot{q}_{valve} \right] \quad (11)$$

$$\frac{d^2 y_2^d}{dt^2} = \lambda_5 \left[\dot{q}_{cp}^d (y_1^d, y_2^d) - \dot{q}_{O_2} + \dot{q}_{H_2O} \dots \dots \dots \left(\frac{1}{\tau_{valve}} (-q_{valve} + k_{valve} u_{valve}) \right) \right] \quad (12)$$

Therefore, the control variable u_{valve} is obtained in function of the known disturbances and the desired flat outputs (equation 13).

$$u_{valve} = \frac{q_{cp}^d (y_1^d, y_2^d) - q_{O_2} + q_{H_2O}}{k_{valve}} \dots \dots \dots \frac{-\tau_{valve} \left(\frac{1}{\lambda_5} \frac{d^2 y_2^d}{dt^2} - \dot{q}_{cp}^d + \dot{q}_{O_2} - \dot{q}_{H_2O} \right)}{k_{valve}} \quad (13)$$

In equations 9 and 13, the terms $\frac{dy_1}{dt}$ and $\frac{d^2 y_2^d}{dt^2}$ represents the new inputs W_1 and W_2 . The application of these two open loop control inputs in the model leads to find a new open loop structure of the system, consisting of an integrator chain (14).

$$\left\{ \begin{array}{l} \dot{Z}_1^d = W_1 \\ \dot{Z}_2^d = Z_3^d \\ \dot{Z}_3^d = W_2 \end{array} \right. \quad (14)$$

For the new linear system in 14 it is possible to apply classic control approaches such as a state feedback procedure (system 15). Feedback loops and negative gains can then be used to place the poles in a stable condition, to provide robustness to the system response against uncertainties and to set a desired dynamic for each flat output.

$$\begin{cases} \dot{Z}_1^d = W_1 = -k_1 (y_1^d - \omega) \\ \dot{Z}_2^d = Z_3^d \\ \dot{Z}_3^d = W_2 = -k_2 (y_2^d - p_{cath(out)}) \end{cases} \quad (15)$$

IV. RESULTS

The performance of the control law, proposed in the last section, were tested in the real fuel cell system PROSPAC presented in section 2. The reference for the oxygen stoichiometry is 2 and for the cathode outlet pressure is 1.2 bar. The most important variables to be observed are:

- Compressor speed profile.
- Pressure valve behavior.

A current demanded profile in the figure 5 was imposed to the fuel cell system, in order to verify the response of two control strategies:

- a classical approach using two PID control loops (figure 3):
 - speed control ω applied in u_{mot}
 - pressure control $p_{cath(out)}$ applied in u_{valve}
- the flatness control strategy (figure 4)

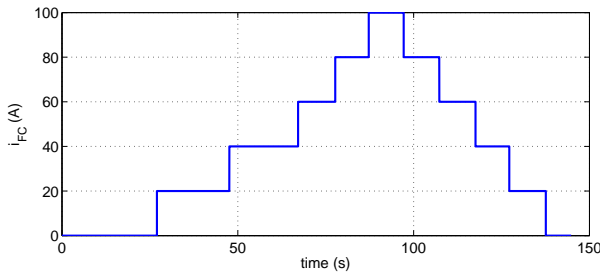


Figure 5. Demanded current profile

The speed and pressure responses in the figures 6 to 9 presents a better behavior of the flatness strategy, with a good performance characteristics. As can be seen the decoupling procedure in the flatness approach avoids the interference of one variable on the other, as presented in the PID strategy.

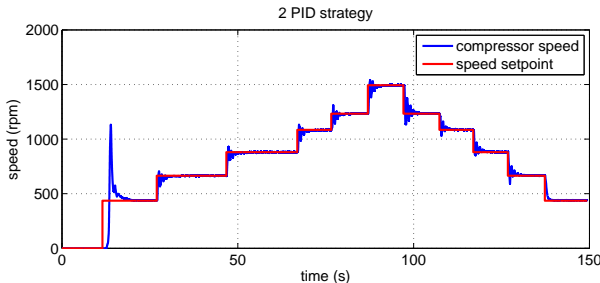


Figure 6. 2 PID strategy - speed

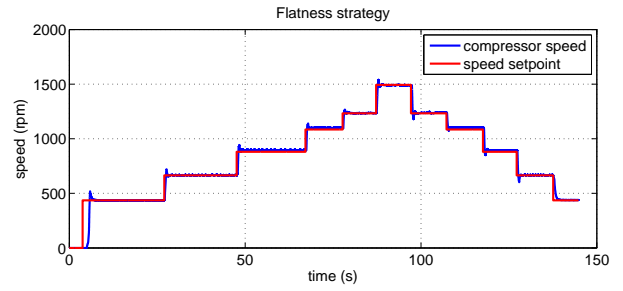


Figure 7. flatness strategy - speed

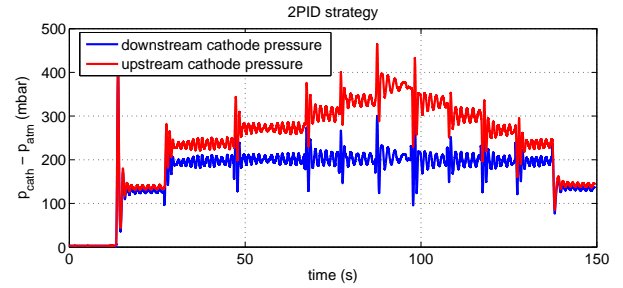


Figure 8. 2 PID strategy - cathode pressure

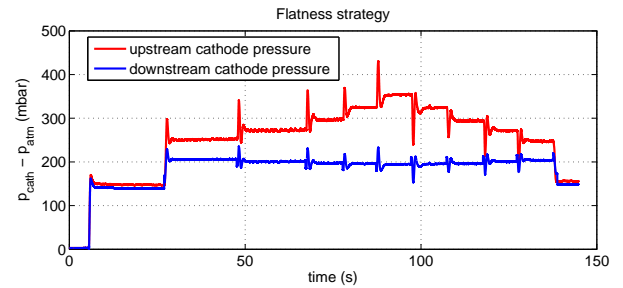


Figure 9. Flatness strategy - cathode pressure

Another important result is about the control signal of the pressure valve. Differently from the PID approach (figure 10), the flatness strategy (figure 11) presents a stable profile, which is better in terms of ageing and reliability.

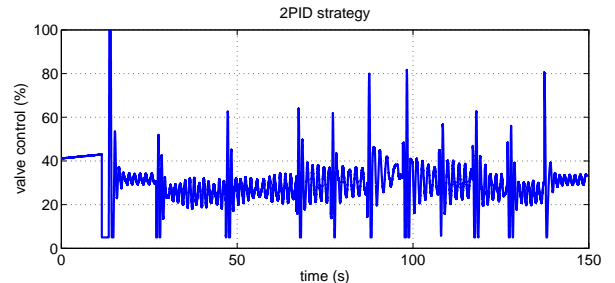


Figure 10. 2 PID strategy - valve control

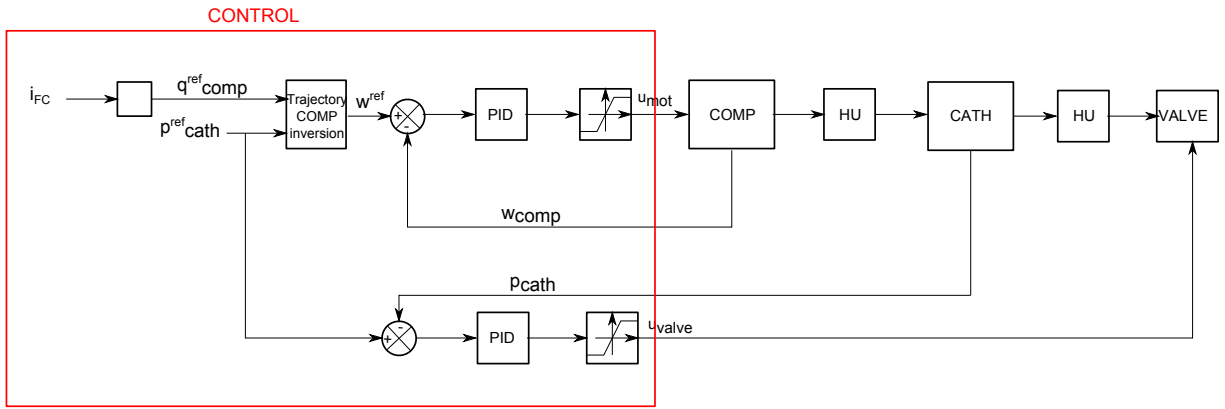


Figure 3. 2 PID control block

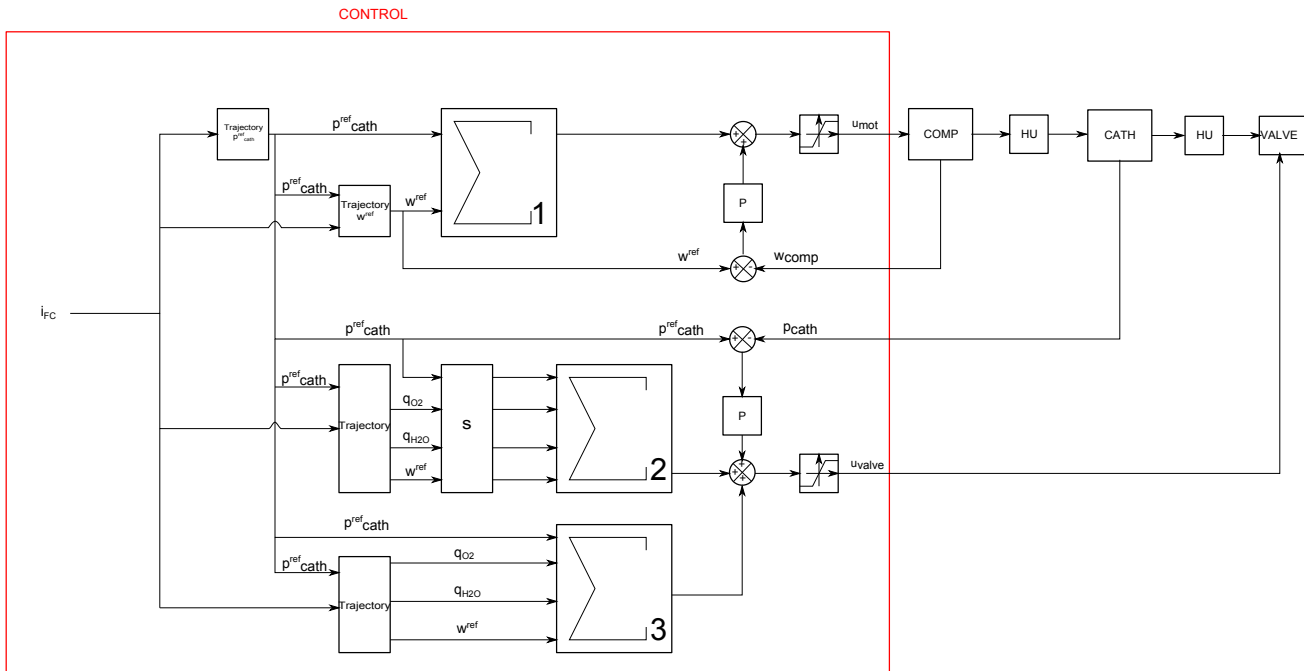


Figure 4. Flatness control block

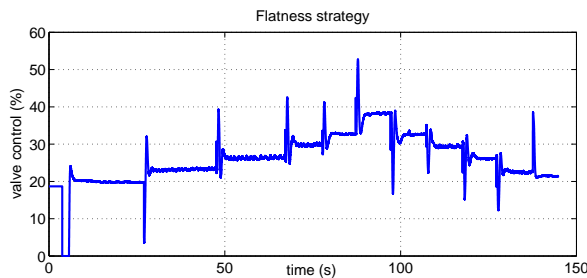


Figure 11. Flatness strategy - valve control

V. CONCLUSIONS

A non linear control law strategy was applied to the air circuit of a fuel cell system. Two important variables are the main objectives of this control: oxygen stoichiometry and cathode pressure. Adopting the differential flatness theory and

a simplified model, a non-linear control law was designed, which results in a decoupling and a linearization of the system. This non-linear strategy is applied in a real system and compared with a classical control approach. The differential flatness strategy presents good results that justify the adoption of this method for this kind of dynamic application.

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