Online Identification of Time Varying Parameters in PEM Fuel Cells

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Abstract: this article tackles some ideas about parameters identification in the anode line of a typical PEM fuel cell test station. The approach is focused in the nonlinear model structure and solves an observation problem using a system transformation and Kalman filtering. Simulation results are presented to show the feasibility of the proposal.

1. INTRODUCTION

Fuel cell based devices are extremely complex dynamical systems, usually described by nonlinear uncertain models. During the years, an increasing research activity has been addressing observation problems in fuel cells, in order to reduce sensoring and estimate inaccessible variables. In [2], the authors design observers for hydrogen partial pressure estimation based on the stack output voltage. The approach is interesting, but the strategy relies on the internal model of the fuel cell voltage, which is usually unknown. Görgün et al have also presented an observation algorithm for the membrane water content in a polymer electrolyte membrane, but it is also based on the voltage internal model [3]. McKay and Stefanopoulou have employed open loop nonlinear observers based on lumped dynamic models for estimating the anode and cathode relative humidities [1]. This last work also presents experimental results, which is a major breakthrough in PEM fuel cells water content estimation.

In the current manuscript, another approach to the anode line estimation problem of water transport in the polymeric membranes is presented. Based on a validated lumped parameters model, the estimation of the membrane water transport is solved to reconstruct the system state. The idea is neither using the internal model of the membrane, nor the stack voltage, because it may lead to lack of robustness due its complex unknown time-variant models. The presented approach relies on the system structure but not on its parameters, using three standard available measurements. Based on Kalman filtering, the proposal robustly solves the estimation problem.

From the presented observation/identification approach and following an appropriate system transformation, the water transport of polymeric membranes in PEM fuel cells can be robustly online. The only requirement is the use of three sensors in the plant (humidifier pressure sensor, anode pressure sensor and stack current sensor). From these three measurements, the complete state can be recovered as well as water transference across the membrane ($W_{v,mem}$). This result can be validated in different PEM fuel cell test stations because it is not based on uncertain internal models.

2. SYSTEM MODEL

A necessary first step, previous to the design of observers or controllers, deals with the rearrangement of the equations presented in [4] and [5], in order to obtain a reduced state space model of the anode subsystem, suitable for nonlinear observers design purposes. This procedure involves coupling the presented differential equations with their auxiliary equations in order to represent the system only in terms of the space states, external inputs (fuel cell stack current I_{st} and hydrogen supply W_{H2}) and measured outputs (anode humidifier pressure P_{hum} and anode stack pressure P_{an}). Further information about how the overall state space equations were obtained and validated, as well as all the parameters can be found in [4] and [5]. Taking the system state $x \in R^3$:

$$\dot{x}_1 = W_{H_2} - W_{H_2,an,in} \tag{1}$$

$$\dot{x}_2 = W_{H_2,an,in}(W_{H_2}, P_{an}) - W_{H_2,an,out}(x_1, x_2, x_3) - W_{H_2,react}(I_{st}) \tag{2}$$

$$\dot{x}_3 = W_{v,an,in}(W_{H_2}, P_{an}) - W_{v,an,out}(x_1, x_2) - W_{v,mem} \tag{3}$$

where $x_1 = m_{hum}$ is the air mass inside the anode humidifier; $x_2 = m_{H2,an}$ is the hydrogen mass in the anode channels; $x_3 = m_{v,an}$ is the vapour mass in the anode channels. In this system, the input (W_{H2}) is known and the measured outputs are the humidifier pressure (P_{hum}), the anode pressure (P_{an}) and the stack current (I_{st}). Note that $P_{hum}=k_1x_1$ and $P_{an}=k_2(k_3x_1+k_4x_2)$.

3. PARAMETERS IDENTIFICATION PROBLEM

The strong dependency of the proton conductivity of Nafion® membranes, which are the most widely used in PEM fuel cells, on the water content and the large amount of swelling due to water uptake makes the understanding of the water transport mechanism in these membranes crucial for analyzing the performance and the durability of fuel cell stacks and developing more reliable systems. Nevertheless, the mechanism of proton and water transport in Nafion® has not been yet fully understood because of the lack of comprehensive knowledge on the Nafion® microstructucture and the interaction among the polymer matrix, protons and water molecules which are highly coupled to each other [7]. In this context, $W_{v,mem}$ is a crucial variable to observe because it takes into account the water flow that crosses the membrane, due to both back diffusion and electrosmotic drag, which are the main inputs to the membrane water content model. It is important to stress that because of the unreliable internal model of this term, it should be treated as a perturbation or unknown input.

The main problem with humidity sensors is that they have considerably slow time constants, which makes the dynamic measuring difficult to handle. Another problem is that humidity sensors are difficult to keep stable when working at high gas relative humidities. This is because they are usually affected by water condensation and the recovery is very slow. Therefore, the interesting case for real applications is to estimate $W_{v,mem}$ without measurement of x_3. In this second case, the only output is a linear combination $y = P_{an} = k_2(k_3x_1+k_4x_2)$. This case is more challenging since the anode output flow $W_{an,out} = W_{H2,an,out} + W_{v,an,out}$ is not measured, neither the states x_2 and x_3.

Considering the following linear transformation of the system $z = k_2(k_3x_1+k_4x_2)-P_{amb}$, equations (2) and (3) can be summarized as follows:

$$\dot{z} = U - zk_{an}k_2\left(k_3 + \frac{k_4 - k_3}{k_5\frac{x_3}{x_2}+1}\right) - k_2k_3W_{v,mem} \tag{4}$$

being P_{amb} the ambient pressure and U a known input of the problem, $U = k_2[k_4(W_{H2,an,in} - W_{H2,react}) + k_3W_{v,an,in}]$. It is important to stress that $W_{H2,react}$ can be directly measured, while the flows $W_{H2,an,in}$ and $W_{v,an,in}$ can be determined from the estimate of $W_{H2,an,in}$. Assuming $dW_{v,mem}/dt = 0$ and defining new variables θ_1 and θ_0 as

$$\theta_1 = k_{an}k_2\left(k_3 + \frac{k_4 - k_3}{k_5\frac{x_3}{x_2}+1}\right);\ \theta_0 = k_2k_3W_{v,mem} \tag{5}$$

the system can be reduced to the following non-linear affine in the unknown state system.

$$
\begin{aligned}
&\dot{z} = U - z\theta_1 - \theta_0 \\
&\dot{\theta}_0 = 0 \\
&\dot{\theta}_1 = \theta_2 \\
&\dot{\theta}_2 = 0
\end{aligned} \tag{6}
$$

note that in this first approach the approximation has order 1 ($d\theta_0/dt = 0$), but in a more general framework the system order can be extended. Then, the following linear time variant model is equivalent to the previous one:

$$
\begin{aligned}
&\dot{x}' = A(y')x' + Bu \\
&y' = Cx'
\end{aligned} \tag{7}
$$

being

$$
\begin{aligned}
\dot{x}' &= \begin{bmatrix} \dot{z} \\ \dot{\theta}_0 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} 0 & -1 & -y' & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} x' + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} U \\
y' &= \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} x' = z
\end{aligned} \tag{8}
$$

In this context, the following Kalman based full state observer can be built for the system:

$$
\begin{aligned}
\dot{\hat{x}}' &= A(y')\hat{x}' + Bu + P(t)C^T R^{-1} C(x' - \hat{x}') \\
&= A(y')\hat{x}' + Bu + P(t)C^T R^{-1}(z - \hat{z})
\end{aligned} \tag{9}
$$

with

$$
\begin{aligned}
\dot{P}(t) &= P(t)A(y') + A^T(y')P(t) - P(t)C^T R^{-1} C P(t) + Q \quad , \quad P \in \mathbb{R}^{4\times 4} \\
P(t_0) &= P_0 > 0 \\
Q &> 0 \ , \quad \in \mathbb{R}^{4\times 4} \\
R &> 0 \ , \quad \in \mathbb{R}
\end{aligned} \tag{10}
$$

Note that *P(t)* is the covariance matrix of the observation error *P(t) = E*

$$
P(t) = E\left\{(x' - \hat{x}')(x' - \hat{x}')^T\right\}
$$

and the Kalman filter minimizes the variance error of the estimation. If the pair *[A(t),C]* in uniformly observable, then *P(t)>0* exists for all $t > t_0$ and the observer guarantees that

$$
\tilde{x}' = (x' - \hat{x}') \to 0 \quad as \quad t \to \infty
$$

4. SIMULATION RESULTS

A representative simulation was conducted varying the hydrogen mass flow entering the humidifier. The variation was set as a sinusoidal signal, in order to produce a sinusoidal change in *z(t)*. In this way, the persistence in the excitation is guaranteed. In Figure 1, the persistent excitation to the system in appreciated, and both the variable z and its estimate is depicted. This first figure is complemented with Figure 2, where the asymptotic convergence to zero of the estimation error is shown. I.e. the difference between the measured output (*z*) and the reconstructed output from equation (9).

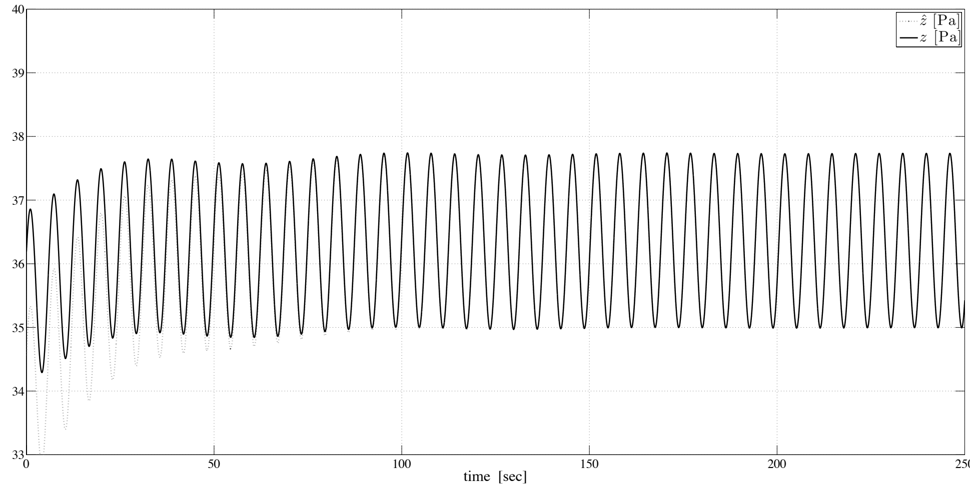

Figure 1: z(t) vs. its estimate.

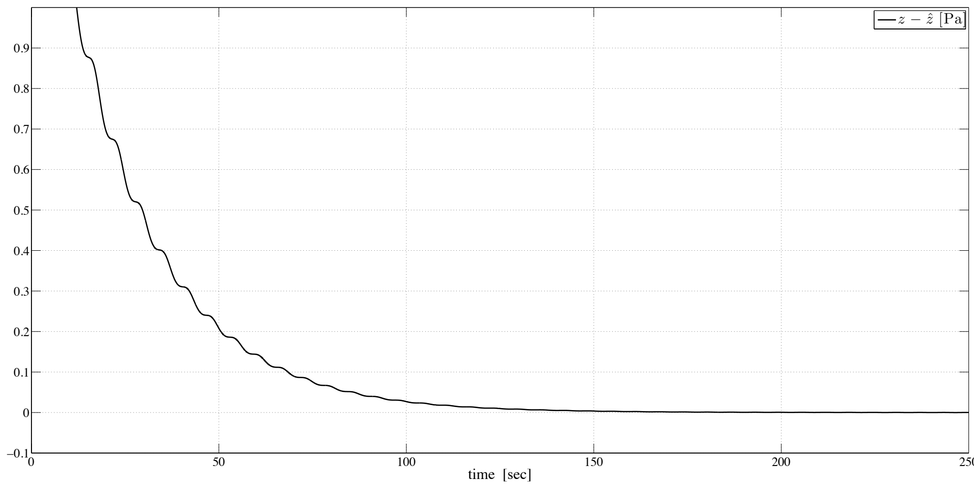

Figure 2: performance of the estimation error.

In the second set of figures (figs. 3 and 4), the observer performance is presented. Where the variables θ_1 and θ_0 are reconstructed, so the system state is recovered. Note that θ_1 has no physical significance, but it is necessary to determine θ_0, which is an estimation objective that allows to get the variable $W_{v,mem}$.

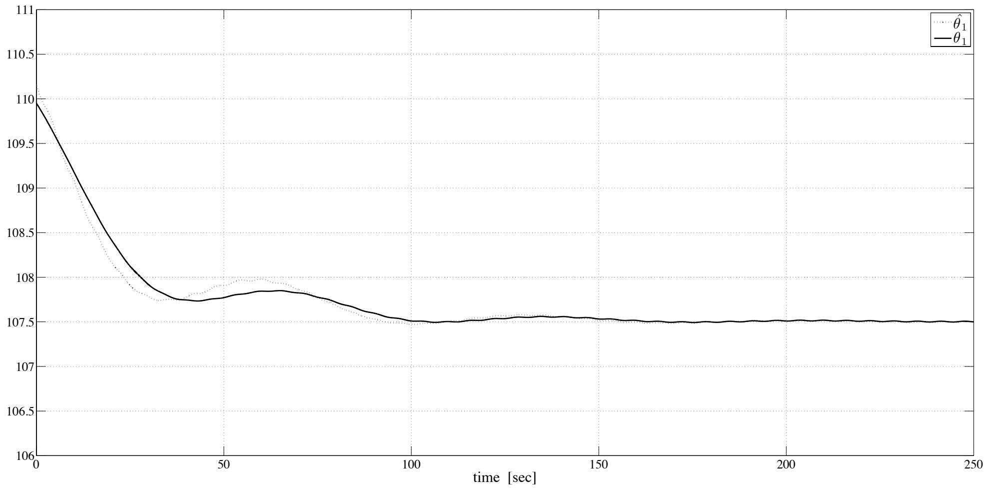

Figure 3: performance of the estimated varying parameter θ_1.

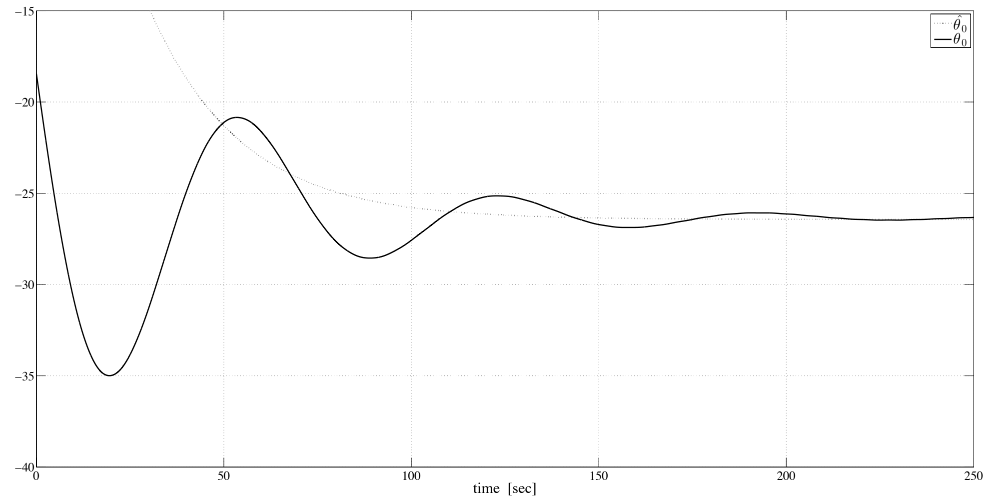

Figure 4: performance of the estimated varying parameter θ_0.

5. CONCLUSIONS AND DISCUSSION

From the presented observation/identification approach, the water transport of polymeric membranes in PEM fuel cells can be estimated. The only requirement is the use of three sensors in the plant (humidifier pressure sensor, anode pressure sensor and stack current sensor). From these three measurements, the complete state of the anode line can be recovered as well as $W_{v,mem}$ which is an important performance variable in PEM fuel cell stacks. Initial results using an experimental validated model and Kalman filtering were shown to analyze the proposal suitability for real applications. The presented approach only depends on the system structure, being robust against model uncertainties.

NOMENCLATURE AND CONSTANTS VALUES

I_{st}	stack/cell current	[A]
G_h	hydrogen molar mass	[kg/mol]
G_v	hydrogen molar mass	[kg/mol]
P_{amb}	ambient pressure	[Pa]
P_{an}	stack/cell anode pressure	[Pa]
P_{hum}	anode humidifier pressure	[Pa]
R_h	hydrogen specific constant	[Nm/kg/mol]
R_v	vapour specific constant	[Nm/kg/mol]
T_{st}	stack/cell temperature	[K]
V_{an}	anode lumped volume	[kg/s]
$W_{an,out}$	gas mass flow leaving the stack/cell anode	[kg/s]
W_{H2}	hydrogen supply mass flow	[kg/s]
$W_{H2,an,in}$	hydrogen mass flow entering the stack/cell anode	[kg/s]
$W_{H2,an,out}$	hydrogen mass flow leaving the stack/cell anode	[kg/s]
$W_{H2,react}$	hydrogen mass flow reacting at the anode	[kg/s]
$W_{v,an,in}$	vapour mass flow entering the stack/cell anode	[kg/s]
$W_{v,an,out}$	vapour mass flow leaving the stack/cell anode	[kg/s]
$W_{v,mem}$	membrane water transport	[kg/s]

MODEL CONSTANTS

k_{an} anode flow restriction

$k_1=T_{st}R_h/V_{an}$

$k_2=T_{st}/V_{an}$

$k_3=R_v$

$k_4=R_h$

$k_5=G_vR_v/ G_hR_h$

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