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# Control by state observer of PEMFC anodic purges in dead-end operating mode

**Maxime Piffard** *,** **Mathias Gerard** *,** **Eric Bideaux** ***
**Ramon Da Fonseca** *,** **Paolo Massioni** ***

* *CEA LITEN, F-38054 Grenoble, France (e-mail: maxime.piffard@cea.fr)*
** *Univ. Grenoble Alpes, F-38000 Grenoble, France*
*** *Ampere Laboratory, Institut National des Sciences appliques de Lyon (INSA-Lyon), 69621 Villeurbanne cedex, France*

Abstract
A Proton Exchange Membrane Fuel Cell (PEMFC) needs an active system to control all the ancillaries and ensure optimal operating conditions, especially in a fuel cell vehicle. For the fuel cell system architecture, dead-end anode is the cheapest architecture for the hydrogen line and also the one that leads to important reversible and irreversible degradations if not appropriately managed. To address the cost and durability issues on fuel cell vehicles, this study proposes a state observer which aims at estimating online the nitrogen saturation in the anode side in order to trigger the purge at a given criterion. This observer is based on a simple set of equations extracted from a detailed 2D-meshed model. Nitrogen buildup is evaluated in simulation with different road profiles with less than 5% error. Moreover the fuel cell system efficiency increases compared to the other existing purge strategies, so as the mileage. The observer can also be used to develop other optimal strategies to minimize the irreversible degradations of the fuel cell.



*Keywords:*
Fuel Cell Vehicles, PEM, State observer, Anode purging

## 1. INTRODUCTION

Proton-exchange-membrane fuel cell (PEMFC) is the most promising technology for transportation applications due to the high power density and low operating temperatures. It is considered as an alternative to internal combustion engines as it provides the same mileage range with no emissions of greenhouse gases on site. A fuel cell system is composed of four mains supply sub-system: the air, hydrogen, cooling and the electric supply sub-systems (Figure 1). The fuel cell needs active ancilliaries (compressor, pump, valves, power electronic) to obtain a high level of efficiency (performance and durability). The optimization of the system components and the control laws associated are essential to reach the targets of performances and lifetime of a fuel cell.

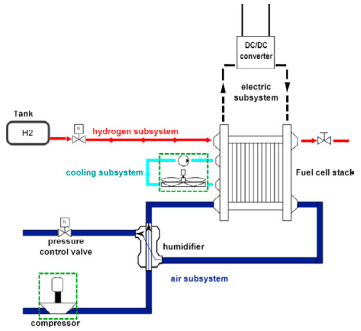


Figure 1. Fuel cell with its four sub-systems (Fonseca, 2013)

To achieve the cost target for a PEMFC system, the dead-end anode (DEA) architecture is a simple solution since only a pressure regulator at the inlet and a solenoid valve at the outlet are required for the anode side. The hydrogen injected in the anode is supposed to be fully consumed in DEA operations, which theoretically means 0% hydrogen losses. However nitrogen and water permeation through the membrane induce performance drops and irreversible degradations, decreasing the efficiency.

According to Strahl et al. (2014), reversible degradations are due to excess nitrogen and water in the outlet anode side that lead to a lower hydrogen concentration (stratification phenomena). The main consequence is a voltage drop and thus a lower output power or a lower efficiency. The performance can be recovered by purging the anode outlet to remove accumulated nitrogen and water. Moreover, irreversible degradations could be accelerated during stratification effect. The accumulation of nitrogen and water at the anode outlet induces the presence of oxygen (permeation through the membrane) that can accelerate the cathode carbon corrosion. This measurement is confirmed by Matsuura et al. (2013), where a strong correlation is developed between cathode carbon corrosion and presence of oxygen in the anode side after long purge intervals.

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Consequently, purge intervals must be calibrated to achieve a performance criterion and/or a lifetime criterion. Hydrogen loss may occur during purges according to the operating conditions and increase with short purge intervals. On the other hand, we have just seen that long purge intervals lead to irreversible degradations. Chen et al. (2013) have investigated the optimization of the purge strategy to reach these two objectives, taking into account actuators constraints (opening/closing delay). This study therefore show an optimal tuning of the purge interval/purge duration for a given operating power. However, the tuning is highly related to the operating conditions, and the optimality may not be obtained with varying-power. Ahluwalia and Wang (2007) has studied the build up of nitrogen for a 90kW automotive stack in recirculation mode. They found an optimum purge that minimizes the performance drop, mainly based on the nitrogen buildup. The optimal purge strategy is also link to the relative humidity, according to Nikiforow et al. (2013).

Thus, knowing the internal parameters of the stack (nitrogen, humidity, liquid water) seems to be the first step to build an optimal purge strategy for a dynamic power cycle. Humidity sensors used in Farcas and Dobra (2014) are expensive for a widespread commercialization and the durability of such sensors is not appropriate for industrial fuel cells systems. Hydrogen concentration sensors are already used in recirculation mode and located in the recirculation loop. Their implementation is more difficult in DEA in a non-intrusive manner. Another solution is to use a model correlated with experimental measurements to fit precisely the studied stack (Chen et al., 2014; Steiner et al., 2011). This solution relies on a strong data base to deliver appropriate results.

The solution developed here is a state observer that combine a simplified physical model with online measurements to update the states estimation. The state observer delivers in real time the nitrogen buildup which can be used to trigger the purge at the right moment. The observer and associated purge strategy are tested and validated by simulation with a 2D dynamic model to simulate the fuel cell response.

## 2. FUEL CELL DYNAMIC MODEL DESCRIPTION

### *2.1 General model setting*

A detailed fuel cell model has been used in this study to simulate the stack and its system in a dead-end mode. This model has been described in several studies (Schott and Baurens, 2006; Gerard et al., 2010; Robin et al., 2013; Fonseca et al., 2014) and it is efficient to capture the dynamics of the local conditions of the fuel cell. It is 2D-meshed along the surface of the MEA (Membrane Electrode Assembly) and based on pseudo bond graph theory to describe transport phenomena, mass and energy balance, heat transfer through the channel, the GDL (Gas Diffusion Layer) and the membrane. The flow balances are represented by a multi-physic capacity (**C**). The **C** element calculates the effort variables (temperature, partial pressure). The transport of flow or heat is represented by a resistive element (**R**). Through the channel the **R** element calculates the flow variables by the difference of pressure, a drop pressure coefficient and the geometry. Through the GDL (porous media), the diffusion flux computed by a **R** element is based on Stefan-Maxwell's equations for the diffusion and on Darcy's laws for the convective terms (gas and liquid phases). Through the membrane, the two mass transfer processes of water (diffusion and electro-osmose) are taken into account.

### *2.2 Membrane transport model*

Our study focuses on the nitrogen build up in the anode side, therefore we need to model the nitrogen permeation through the membrane, which is according to Matsuura et al. (2013), a function of $\lambda_m$ the membrane water content and $T_{cell}$ the cell temperature:

$$K_{N_2}(\lambda_m, T_{cell}) = \alpha_{N_2}\left(0.0295 + 1.21 f_v - 1.93 f_v^2\right) \times e^{-14} \times \exp\left[\frac{E_{N_2}}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{cell}}\right)\right] \quad (1)$$

where $\alpha_{N_2}$ is a tuned scale factor fixed at 1.5 here, $R$ is the universal gas constant, $E_{N_2}$ is the nitrogen molar energy ($E_{N_2} = 24\, kJmol^{-1}$), $T_{ref} = 303\, K$ and $f_v$ is the volume fraction of water in the membrane given by:

$$f_v = \frac{\lambda_m V_w}{V_{mb} + \lambda_m V_w}$$

where $V_{mb} = EW/\rho_{dry}$ is the dry membrane volume, $EW$ the equivalent weight, $\rho_{dry}$ the dry density of the membrane and $V_w$ the molar volume of water.

The key parameter of the nitrogen permeation is the membrane water content $\lambda_m$, given by:

$$\lambda_m = \int \left(\frac{EW}{\rho_{dry}} \frac{1}{e_m S} \sum F\right) dt \quad (2)$$

with $\sum F$ the algebraic sum of the different fluxes (back-diffusion and electro-osmosis) through the membrane. The electro-osmotic drag and the back diffusion flux are calculated with the following equations (Schott and Baurens, 2006):

$$F_{eo} = \left(1.0 + 0.028\lambda_m + 0.0026\lambda_m^2\right) \frac{I}{F} \quad (3)$$

$$F_{d,i} = \frac{\rho_{dry}}{EW} \frac{S}{e_m} \left(6.707e^{-8}\lambda_m + 6.387e^{-7}\right) \times \exp\left(\frac{-2416}{T}\right)(\lambda_m - \lambda_i) \quad (4)$$

where $I$ is the fuel cell current, $F$ the Faraday constant and $\lambda_i$ the membrane water content at the interface between the membrane and the electrode active area. $\lambda_i$ is given by:

$$\lambda_i = 0.043 + 17.81a - 39.85a^2 + 36a^3 \quad (5)$$

where $a = P_{vap}/P_{sat}(T)$.

### *2.3 Simulation of the stratification effect*

Only the fuel cell hydrogen sub-system is modeled with dead-end mode architecture. The other sub-sytems are