Sensor and Online Diagnostic Needs in Automotive Fuel Cells

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Abstract
Considerable research and development efforts have been devoted to fuel cell operation and systems. In particular, in the area of polymer electrolyte membrane (PEM) fuel cells for mobile and stationary applications. This paper discusses the advances needed for sensor and actuator technology to improve and accelerate fuel cell development. The sensitivities of process parameters to sensor and actuators dictate the accuracy and response requirements of sensors for fuel cell application. Theoretical analysis of these sensitivities are discussed to illustrate this. Finally, an industrial perspective for need for research activities in the area of on-line diagnostic is presented. To illustrate this, a pattern based diagnostic is described for fuel cells for early detection of onset of stack instability due to non-uniform cell-to-cell water management.

1. Introduction

The high-level control requirements for a fuel cell based propulsion system (FCPS) for automotive applications are derived from those of traditional internal combustion based IC engines. These can be classified as: (a) performance, (b) reliability, (c) durability, and (d) cost.

Performance metrics are often associated with transient response (e.g. acceleration), efficiency (e.g. fuel efficiency) and turndown (ratio of th maximum to minimum power) capability of FCPS. Turndown capability is directly related to turndown capability of sensors and actuators. Moreover the fuel efficiency is a key performance metric. Reliability metrics are associated with stability. Moreover the emission constraint of unutilized hydrogen has to be met. Reliability of sensors and actuators also affect the reliability of the FCPS.

All of the above requirements affect the design of the fuel cell stack and system but they also directly translate into operational and control requirements. For example, meeting the transient requirements (response to changes in power level demand) while maximizing the efficiency over the drive cycle are conflicting objectives. Transient requirements may prefer higher excess reactants to the fuel cell which may hurt the overall fuel efficiency. A control strategy has to consider all the objectives and constraints. For the same hardware design, the control system can be adapted to weight one objective over another.

Figure 1 below shows a high-level block diagram of a fuel cell control system. In an automotive system the power request may be proportional to the accelerator pedal position. Thus, a control system has to follow the power request while staying within the durability, emission and performance constraints. The response of the fuel cell system is limited by plant dynamics and control parameters.

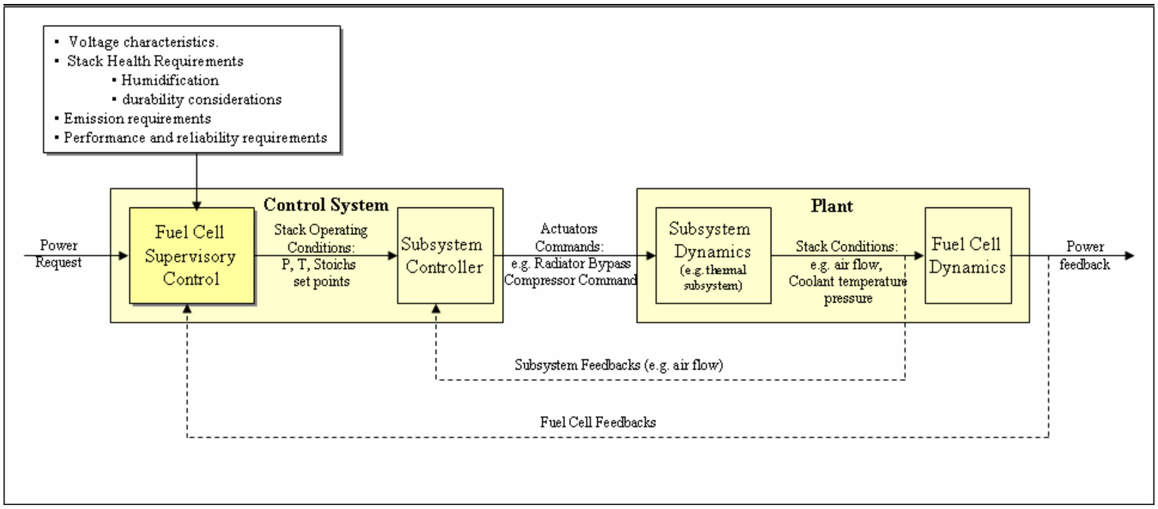

Figure 1: A high-level conceptual schematic of a fuel cell control system.

Apart from maintaining system operating conditions the control system monitors real time data from sensors and actuators for diagnostic and remedial actions. Some of these include:

- Fuel cell stack health monitoring and trigger a "limp home" mode operation. For example in a fuel-processor based fuel cell system high level of CO can cause reversible degradation of catalysts and the control system can transition to a "limp home" mode by reducing power level.
- Catalyst or material degradation may cause the control system to adapt its operating strategy. For example as fuel cell voltage degrades the control system may draw more and more current to meet the same power requirements.
- Finally one of the supervisory functions of control system is to perform real-time tradeoff for optimal setpoint trajectory to maximize objectives such as fuel efficiency.

2. Sensor Requirements Driven by Control

Sensors and actuators for a fuel cell application have their own unique requirements. Some requirements are driven by the operational sensitivity of fuel cell stack while other are driven by automotive vehicle requirements. These requirements include:

- Sensor accuracy, resolution and response time.
- Reliability in harsh automotive conditions in terms of temperature, exposure to water, air quality etc.
- Robustness: i.e. variability from sensor to sensor caused by sensor itself or installation.
- Durability and Maintainability (time variance characteristics and ability to adapt/tune the calibrations)
- Integration and cost

Following are some examples of fuel cell sensing applications:

2.1 Cell Voltage Monitoring (CVM)

Abnormal low cell voltage can cause irreversible damage to a fuel cell stack. Since the heat generation is inversely proportional to cell voltage, cell with a very low voltage can cause hot spots. Monitoring and detection of voltage distribution within a stack require individual cell voltage to be measured. Such a vector of sensors enables control strategy that manages the "weakest" cell and improves the reliability of a fuel cell stack. However there is need for sensing technology that provides a similar functionality without the need of individual cell monitoring via hardware sensor technology or via fault detection algorithms. Thus there is a need for a cost-effective approach to monitor cell voltages.

2.2. Chemical Specie Monitoring

For a fuel cell with an onboard fuel processor, e.g. converting gasoline to hydrogen, online monitoring of hydrogen quality is important. Presence of carbon monoxide (CO) or non-methane hydrocarbons affect the platinum catalyst in the fuel cell stack. Thus these concentration of these species need to be detected in the reformate stream. This can then be used to modify the operating parameters of the fuel processor to minimize CO, e.g. by increasing the airflow to the CO cleanup unit (Preferential Oxidizer, PrOX reactor).

Moreover the fuel processor subsystem has to track the desired hydrogen flow rate to the fuel cell stack to meet a changing electric power demand. Hence, a feedback signal of hydrogen concentration in the reformate can be utilized by the fuel processor control system. Also accurate and responsive tailpipe hydrogen concentration is important from H_2 emissions perspective.

2.3. Temperature Sensing Requirements Driven by Humidification Requirements

One of the key to successful fuel cell operation is water management. The basic control approach for water management is controlling the humidity of the gases entering and leaving the stack. A mass balance model [Springer et. al. 1991] can be used to investigate the sensitivity of process parameters such as temperature, pressure and cathode stoichiometry on relative humidity of the air stream exiting the fuel cell.

$$RH\_out = \frac{y * P}{P^{sat}(T)};$$

$$y = \frac{[1 + 2.38 * \nu * (\frac{y_{w\_in}}{1 - y_{w\_in}})]}{[0.5 + 2.38 * \nu * (\frac{y_{w\_in}}{1 - y_{w\_in}})] + 2.38\nu}$$

where:

y_{w_in} : is the mole fraction of water at cathode inlet calculated based on inlet RHcondition,

ν is the cathode stoichiometry

P is the pressure at cathode outlet

T is the fuel cell cathode outlet temperature

Heat rejection and other system and fuel cell constraints (Fronk et. al. 2000) result in typical nominal fuel cell operation between 60-80C with relative humidity of cathode exhaust between 80 – 120%. Nominal operation may target RH close to but not exceeding 100% to prevent cell flooding. Or other fuel cell design may target RH higher than 100% to maximize MEA hydration. In either case accurate monitoring of fuel cell operational parameters that affect RH is essential.

Figure 2.1 shows the sensitivity of relative humidity (RH) on the temperature of the fuel cell. For example, at a nominal condition of 70 ^{o}C an increase in 1 ^{o}C results in a decrease of 5% RH. The sensitivity of RH with temperature decreases with increase in operating temperature. This relationship can be used to derive the necessary resolution of a temperature sensor to meet humidification criteria. For example if the fuel cell needs to be operated at 90% nominal RH but not exceed 100% to avoid cell flooding, the temperature sensor should be accurate to within 2 ^{o}C from the mean.

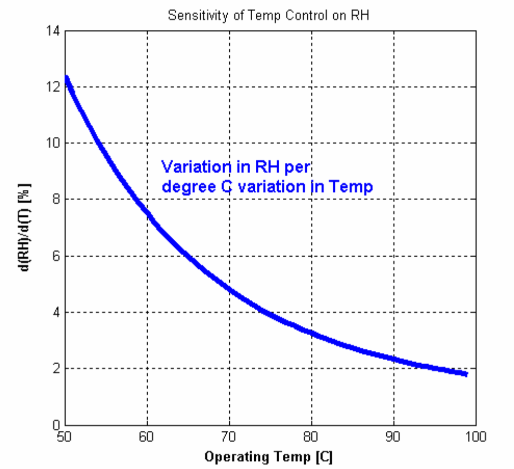

Figure 2.1: Sensitivity of relative humidity of cathode stream to temperature at different base operating temperature.

Figure 2.2 shows iso-RH lines with respect to temperature and pressure and illustrates the relative sensitivity of RH to these state properties and sensor readings.

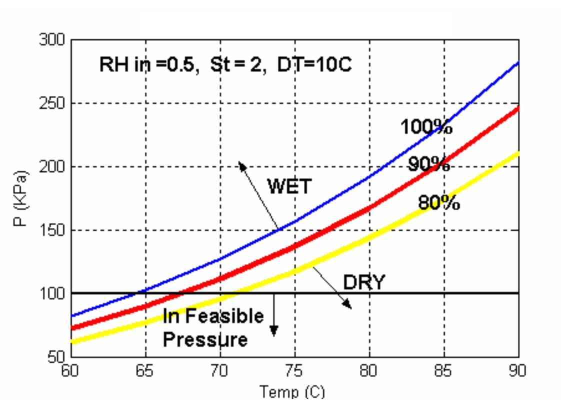

Figure 2.2: Iso-RH curves with respect to temperature and pressure for a fuel cell system (Inlet RH: 50%, St: 2 and a 10^oC rise).

2.4. Air Flow Sensing Requirements Driven by Humidification Requirements

Cathode stoichiometry is defined at the ratio of actual air flow to the theoretical air flow required to sustain the fuel cell reaction of $H_2 + 1/2\ O_2 <-> H_2O$. Sensitivity of stoichiometry (stoich) to errors in airflow increases as the overall power level decreases. For example a 100 cell stack operating at a stoich of 2 at 500Amps will require 36 grams/second of air. A 2 g/s error in airflow translates to an error in stoich of 0.06 (i.e. Stoich between 1.97 and 2.03). If the system has turndown of 50, then the required airflow at 10Amps at stoich of 2 would be nominally be 1.4 g/s. Suffice to say that even a small error in airflow will result in large fluctuation in stoich.

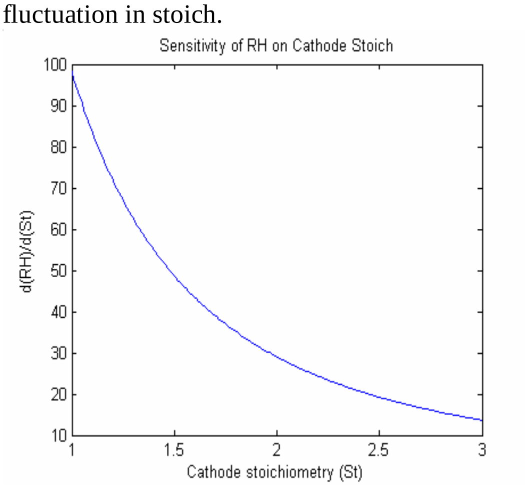

Figure 2.3 illustrates the sensitivity of stoich to RH.

For example, a system running nominally at a stoich of 2 will have a decrease in 2.5% RH for 0.1 increase in stoich. The sensitivity of stoich on humidification increases as the stoich is reduced.

2.5. Sensing RH in Presence of Liquid Water

The sections above discuss the importance of monitoring temperature, pressure and air flow and their sensitivity to fuel cell humidification. Performance and durability of fuel cell may dictate humidification of air stream. Monitoring relative humidity of inlet and outlet streams is critical to any humidification strategy and thus fuel cell operation. During transient operation the air streams may see liquid water and the RH sensor has to be robust to such an environment. Thus the RH sensor for fuel cells need to be able to accurately measure RH at high temperature and humidity conditions and responsive to changes in RH during drive cycles. Cycling of RH has shown to correlate with membrane life (Lai, 2005).

2.6. In-situ Monitoring of MEA and DM Humidification

Membrane hydration affects the protonic conductivity of a PEM fuel cell. The membrane conductivity decreases as λ (defined as moles of water per sulphonic acid site in the nafion membrane) increases [Springer et. al 1991]. However, high humidification could lead to electrode flooding resulting in performance degradation due to mass transport losses and cause fuel cell instability. RH cycling (λ cycling) has shown to correlate to poor durability due to crossover failure (Mathias et. al. , 2005). Thus there is a need for online approaches to monitor the fuel cell water buffer, i.e. extent of water holdup in the MEA and diffusion media in the fuel cell.

Use of impedance spectroscopy has been proposed to measure membrane resistance during online operation. One realization of such a technique is to measure the high frequency resistance of fuel cell stack and correlating the high frequency resistance to membrane hydration (λ).

2.6. Sensor to detect cell-to-cell variation?

A small variation in plate design or stack assembly could result in variation in pressure drop across the cathode flowfield and/or coolant flowfield. This may translate to cell-to-cell variation in airflow rate or coolant flow rate and consequently different cells may see different humidification. Thus a sensor, akin to the CVM, that monitors process condition (T, ν, RH etc) of each cell could provide valuable information regarding stack variability. Such information could trigger a control system to take remedial actions if the variability would impact stack performance. Most of the control strategies cannot control to a single cell. However approach to individually control the airflow to each cell in a stack has been reported [Knobbe et. al., 2004] for small stacks.

However such a the sensor itself should be simple to integrate into the fuel cell engine and be cost effective. No such sensor has been reported, probably due to engineering issues associated with development and integration.

3. Illustration of Online Diagnostic: Variation in Cell Hydration

As described in section 2.6, a sensor to detect cell-to-cell variation may not be feasible from a hardware sensor perspective. This section discusses an algorithmic approach to detect such variation is a fuel cell-stack.

3.1. Motivation: Fuel Cell System Reliability

Reliability of fuel cell system strongly depends on water management. A typical fuel cell stack may have 100-500 cells based on application. Sections 2 discussed the sensitivity of airflow and temperature on humidification. Reliability of a fuel cell stack is a product of reliability of each of its individual cells since cells are connected in series (Wilkinson, 2003).

$$R_{system} = R_1(t) \times R_2(t) \times ....\times R_n(t)$$

where $R_i(t)$ is the reliability of i^{th} cell at time (t), and n is the number of cells.

Consequently if the reliability of all cells are same then

$$R_{system} = [R(t)]^n$$

Hence there is need for on-line diagnostics that can improve reliability of fuel cell systems.

Online detection of process faults in the fuel cell system is key to reliability of fuel cells. At the basic level, detecting faults in functioning of sensors and actuators are needed. If they are functioning, the next level is to detect process faults in the fuel cell plant. Examples of such faults include instability due to water management. Next section illustrates how cell-to-cell variability in hydration can be detected as an on-line diagnostic.

3.2. Online Diagnostic Concept

Water management at a stack level does not necessarily translate to water management in each and every cell. Variability in state of hydration of from cell-to-cell results in issues such as low power instability and low performing cells. Small variability in design and assembly of cells each cell result in different pressure drops in the air, hydrogen flowfield and also the coolant flowfield. This in-turn causes variability in stoichs and temperatures that a cell sees. Moreover, as a cell partially floods it causes more pressure drop and reduction of stoich thus resulting in a runaway condition leading to stack failure resulting in shutdown. The dynamics of this runaway is a function of cell-to-cell variability.

Several groups (including *Giesecke*, et. al. 2003) have proposed that intermittent increase of cathode stoich has shown to help instability caused by water management. This intermittent increase in stoich to remedy instability is termed cathode pulse in this work.

When cathode of a fuel cell is pulsed with an increased air flow, the cell voltage responds due to following factors:

(a) increase in partial pressure of oxygen,
(b) reduction in partial pressure of water,
(c) increase in pressure due to increased pressure drop at higher flows, and finally
(d) increased MEA protonic resistance as it dries.

The first three factors result in increase in voltage while the fourth factor results in decrease in voltage. The overall voltage is superposition of the four factors. Thus the cell that has higher water buffer will take longer to dry out and thus the reduction in voltage will be delayed or may not even show. Thus cells having different water buffers show different voltage pattern in response to a cathode flow pulse.

The core concept is detection of cell-to-cell variation in water buffers via individual voltage patterns trends of the cells (Patent Filed- Sinha, 2005). Figure below shows the voltage pattern exhibited by the 17 cells of a short stack in response to large cathode flow pulse.

Figure on the left is a response for an stack that is progressively going unstable. The figure on the left is the same stack after a few cathode pulse that have remedied the instability.

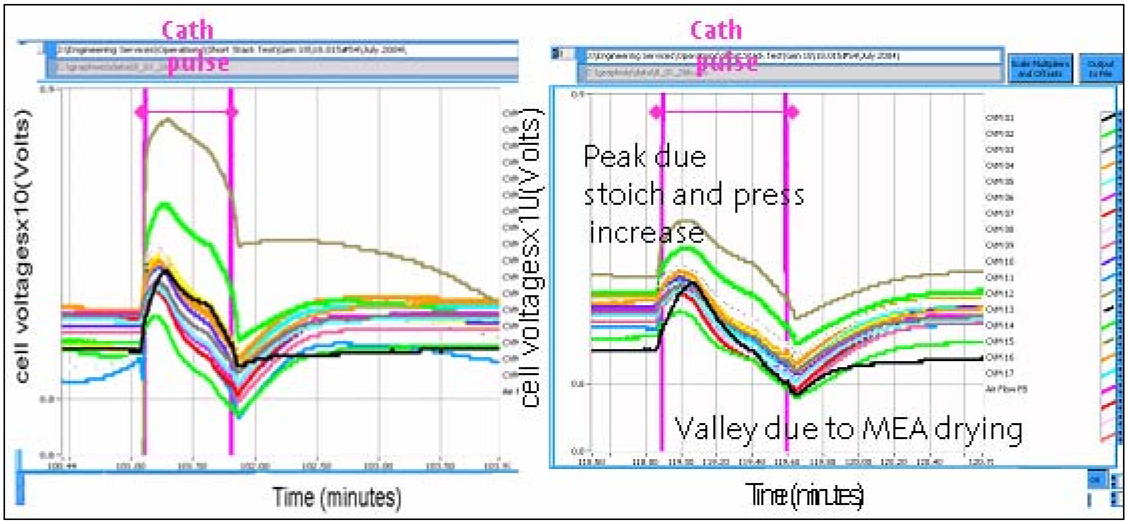

Figure 3.1: Comparison of voltage signatures with and significant (left) and minimal (right) variation in cell-to-cell water holdup.

Most of the cells show a typical peak and valley pattern. Cells that are flooded show a larger peak and no valley. This is confirmed by our internal dynamic model. The pattern on the left shows some cells exhibit a peak and valley while other cells show a larger peak and no valley. This could be a "fingerprint" of a stack with variation in water buffer. In comparison, the figure on the right shows uniform peak and valley in all the cells indicating uniformity in hydration amongst the cells. Patent application US Patent: 11/215196 discusses the algorithm development for this on-line diagnostic in detail.

Summary

This paper describes a high level view of control system for automotive fuel cells and discusses the requirements of sensors for use within the control system. Implication of sensor inaccuracies on fuel parameters such as relative humidity is discussed. Finally need for online diagnostics to improve reliability of fuel cell power plants is discussed. To illustrate this, and provide motivation, an example of how voltage pattern trends in response to a cathode flow pulse can be used to diagnose cell to cell variation in stacks is discussed.

Acknowledgement

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