

Dynamic Modeling of Fuel Cell Systems for Use in Automotive Applications

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ABSTRACT

This paper describes a proton-exchange-membrane Fuel Cells (FC) system dynamic model oriented to automotive applications. The dynamic model allows analysis of FC system transient response and can be used for: a) performance assessment; b) humidification analysis; c) analysis of special modes of operation, e.g., extended idle or freeze start; d) model based FC control design and validation. The model implements a modular structure with first principle based components representation. Emphasis is placed on development of a 1-D membrane water transport model used to simulate gas to gas humidification and stack membrane water diffusion. The Simulink implementation of the model is discussed and results showing FC system transient behavior are presented.

INTRODUCTION

Recent advances in fuel cell system technology make fuel cell systems very promising as an alternative power source for automotive application. In particular, Proton Exchange Membrane (PEM) Fuel Cells are at a level of maturity where major automotive manufactures are actively pursuing FC vehicle development programs. Increasingly stringent government regulations on vehicle fuel economy and emissions, including CO₂, further highlight the criticality of FC system development.

The application of FC systems to ground vehicles is a very challenging technical problem because of wide and highly dynamic load variation which affects FC system life and performance. Because of the inherent complexity of FC systems the design and development of hardware and controls must be supported by a model based development (MBD) process. A dynamic FC system modeling capability is essential to the MBD process for fuel cell systems and fuel cell vehicles.

The basic requirements for a FC system dynamic modeling capability include capture of essential system dynamics such as bulk pressure transients, membrane hydration variation (spatial as well as temporal), cathode/anode loop humidification and stack temperature variation. On the other hand a dynamic FCS model must be computationally efficient to allow full drive cycle analysis and application to hardware in the loop (HIL) testing.

Despite the recent flurry of activity in FC system research, only a few publications address transient modeling of fuel cell systems, e.g. [1-3]. A control oriented model developed at the University of Michigan [4] captures the main dynamics of pressure, compressor speed and flow and stack membrane hydration. Also, this work includes a physics based formulation of stack membrane diffusion and stack voltage calibrated to available FC system data. The complexity of FC system dynamic modeling is emphasized in [5] due to the heterogeneous nature of the system which really stretches the capability of simulation tools. In this work, Dymola is selected as the modeling tool and the FCS dynamic models are developed for design and analysis.

The dynamic model presented in this paper has been developed for:

- Vehicle control design and verification
- Analysis of special FCS operating modes, e.g. start-up,
- FCS performance assessment.

The model features multiphase gas flow with liquid water condensation in both the cathode and anode loops, bulk pressure dynamics, stack membrane hydration, and stack membrane gas diffusion. The model is modular and features separate component models for the balance of plant (BOP) external to the stack. This provides the means for accurate air and fuel transient flow prediction.

Also included in the FCS model described here is a unique 1-D membrane water diffusion model which has been developed to represent the hydration process.

the gas-to-gas humidifier membrane and the stack membrane. This model is a significant improvement over zero-dimensional, lumped parameter membrane diffusion models. Zero dimensional models typically overestimate membrane water transfer because they assume water transfer is driven exclusively by the concentration difference between the inlet flows. The implementation of the 1D membrane model is also unique in that it can be used in real time applications.

MODEL FORMULATION

Model Architecture

A fuel cell system plant model architecture was developed to:

- Reflect consistent, generic subsystem decomposition for the fuel cell system plant in model form
- Establish a model plug-and-play structure to support a range of system model applications
- Enable collaborative model-based system development
- Enable sharing and re-use of models through common interface definitions
- Improve the quality of FCS models and understanding of the system

The architecture features a modular structure with well defined interfaces. The approach taken to developing the architecture is similar to the approach used at Ford to create the Vehicle Model Architecture (VMA) [6], [7].

The Simulink implementation of the fuel cell plant model architecture is shown in Figure 1. It includes the following major subsystems which are identified by their essential functionality:

Cathode Module - The cathode module includes all plant elements outside of the stack that are part of the cathode flow circuit. The main function of the cathode module is to manage the air flow to and from the stack. This includes:

- Generate the air mass flow
- Maintain air pressure
- Deliver feedback signals for control
- Maintain air humidity
- Maintain air temperature

Stack Module – The stack module includes all flow (anode, cathode, coolant) and structural elements of the stack, including the membrane electrode assembly (MEA). The main function of the stack module is to react hydrogen and oxygen to produce stable electrical current flow. Additional functions include:

- Providing flow paths for the reactants
- Providing a mechanism for rejecting waste heat

Anode Module – The anode module includes all of the plant elements of the anode outside of stack that are part of the anode flow circuit. The main function of the

anode module is to manage the hydrogen flow to and from the stack. This includes:

- Maintain anode hydrogen flow
- Maintain anode gas pressure
- Maintain anode gas hydrogen concentration
- Maintain anode gas humidity

Electrical Module - The Electrical Module includes all of the electrical components necessary to distribute electrical power to the fuel cell system electrical components and to conduct electrical power to/from vehicle electrical system.

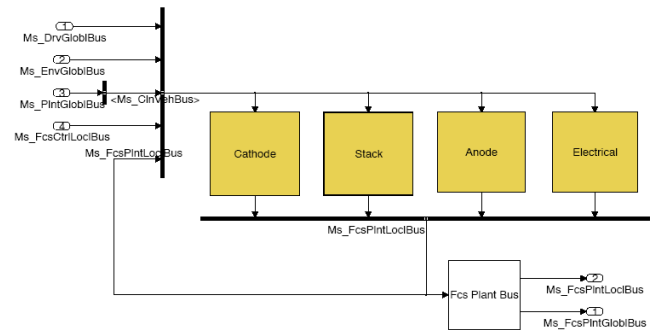


Figure 1: Top level implementation of the dynamic Fuel Cell model in a Matlab/Simulink® environment

Each subsystem outputs a bus containing a number of scalar signals unique to that subsystem. These subsystem buses are combined into a single bus which is fed back to the inputs of each subsystem. The subsystem buses are also combined with buses external to the fuel cell system, which include:

- a) Local bus from the FC controller;
- b) Vehicle level plant bus;
- c) Environmental bus;
- d) Driver bus;

These external buses are consistent with the VMA interfaces, thus allowing the FCS plant model to be integrated into a VMA-based vehicle system model.

Selected signals from the FCS plant bus are also bundled into separate local and global plant buses that are output from the FCS plant model. The local bus can be fed back to a FCS control model for combined FCS plant-control simulation. The global bus is necessary for integration with a VMA-based vehicle system model.

Dynamic Model Requirements

The required pressure, temperature and humidity conditions at the inlet of the stack will vary significantly with stack load. Further, for automotive propulsion, stack loads are highly dynamic and vary over a wide

range. Therefore, an essential requirement of the FCS plant model is that it captures the pressure, temperature and humidity dynamics that affect system performance. The main elements of the present modeling methodology that have been established to address these dynamics are:

- Tracking of gas species and liquid water content
- Inlet and stack volumes
- Membrane hydration

Each of these is described in the following sections.

Gas Species and Liquid Water Content

The dynamic FCS model features complete tracking of all relevant gas species and liquid water content. This is enabled by the flow interface definition given in Table 1. This interface definition is applied to each component.

As indicated by Table 1, liquid water content is tracked across interfaces between components. It is assumed that the liquid water exists in the form of highly dispersed liquid drops that move with the flow. Accumulation of liquid water on surfaces is neglected. Liquid water can be evaporated into a flow if the vapor content of the flow drops below saturated levels. Liquid water can also be removed from the flow (and system) through water knockout devices.

Quantity	Units
Pressure	Pa
Temperature	K
O ₂ molar flow	Mol/s
N ₂ molar flow	Mol/s
H ₂ molar flow	Mol/s
H ₂ O vapor molar flow	Mol/s
H ₂ O liquid molar flow	Mol/s

Table 1. Physical quantities associated with component flow interfaces.

Inlet and Stack Volumes

In order to represent important bulk pressure and temperature dynamics within a given flow circuit (anode or cathode), two thermodynamic control volume submodels are included. One is associated with the inlet flow external to the stack and one is associated with flow within the stack.

The inlet volume includes dynamic states associated with the temperature and pressure within the volume. The accumulated masses of gas (e.g. air, hydrogen), water vapor and liquid water are calculated to define the

average volume pressure. An enthalpy balance is used to calculate the average volume temperature.

The stack volume has a single dynamic state associated with pressure. Similar to the inlet volume, conservation of mass is used to define an equation for this pressure. The stack volume temperature is assumed to be equal to the bulk stack temperature. This is determined from an overall stack heat balance including cooling system inlet and outlet enthalpy flows.

Membrane Hydration

Membrane hydration dynamics are critical to the assessment of FC system design, since dry stack membrane operation results in increased ohmic resistance and, as a consequence, increased membrane heat that can cause membrane degradation. Further, inlet flow humidification can be accomplished using gas-to-gas (G2G) humidification where moisture from the typically saturated outlet flow from the stack is transferred to the inlet flow. This involves diffusion of moisture between two gas flows across a membrane within a G2G humidifier. Hence, membrane hydration dynamics within the humidifier become important to overall system performance.

In order to properly represent membrane hydration dynamics, a one dimensional membrane hydration and diffusion model has been developed. The model follows a similar formulation as one reported in [8].

The 1D membrane model is shown in Figure 4 for the case of parallel flow. There are two gas flows: a wet side gas flow; and a dry side gas flow. In the case of a G2G humidifier, the dry side flow would be associated with the stack inlet flow and the wet side flow would be associated with the stack outlet flow. As shown in Figure 4, the membrane is divided into N_{grid} segments along the flow direction and the model calculates the water content at the membrane nodes. It is assumed that the liquid water on the wet side is in the form of small droplets that move with the flow and do not accumulate on the membrane surface.

The membrane water balance at each segment is given by:

$$\dot{m}_{v,m}^i = \dot{m}_{d,w}^i - \dot{m}_{d,d}^i \quad (1)$$

where $\dot{m}_{v,m}^i$ is the rate of the water mass at node i of