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Study of nonlinear control schemes for an automotive traction PEM fuel cell system

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ABSTRACT

To be practical in automotive traction applications, fuel cell systems must provide power output levels of performance that rival that of typical internal combustion engines. In so doing, transient behavior is one of the keys for success of fuel cell systems in vehicles. The focus of this paper is on the air/fuel supply subsystem in tracking an optimum variable pressurization and air flow for maximum system efficiency during load transients. The control-oriented model developed for this study considers electrochemistry, thermodynamics, and fluid flow principles for a 13-state, nonlinear model of a pressurized fuel cell system. For control purposes, a model reduction is performed, and several multi-variable control designs are examined. The first technique uses an observer-based linear optimum control which combines a feed-forward approach based on the steady-state plant inverse response, coupled to a multi-variable LQR feedback control. An extension of that approach, for control in the full nonlinear range of operation, leads to the second technique, nonlinear gain-scheduled control. Some enhancements were applied to overcome the fast variations in the scheduling variable. Finally, a rule-based, output feedback control, implemented with fuzzy logic, is coupled with a nonlinear feed-forward approach, and is examined under the same conditions applied to the first two techniques. The control designs developed are compared in simulation studies to investigate robustness to disturbance, time delay, and actuator limitations.

1. Introduction

A fuel cell (FC) is an electrochemical device that converts chemical energy to electrical energy by combining a gaseous fuel and oxidizer. Lately, new advances in membrane material, reduced usage of noble metal catalysts, and efficient power electronics have put the fuel cell system under the spotlight as a direct generator for electricity [1].

Compared to internal combustion engines (ICEs) or batteries, fuel cells (FCs) have several advantages. The main advantages are efficiency, low emissions, and dual use technology. FCs are more efficient than ICEs, since they directly convert fuel energy to electrical energy, whereas ICEs need to convert the fuel energy to thermal energy first, then to mechanical energy. Due to the thermal energy involved, the ICE conversion of energy is limited by the Carnot Cycle, which is not the case with FCs [2]. Fuel cells are considered zero emission power generators if pure hydrogen is used as fuel.

Obtaining the desired power response requires air flow, pressure regulation, heat, and water management to be maintained at certain optimal values according to each operating condition. Moreover, the fuel cell control system has to maintain optimal temperature, membrane hydration, and partial pressure of the reactants across the membrane in

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order to avoid harmful degradation of the FC voltage, which reduces efficiency [1]. While stack pressurization is beneficial in terms of both fuel cell voltage (stack efficiency) and of power density, the stack pressurization (and hence air pressurization) must be done by external means, i.e., an air compressor. This component creates large parasitic power demands at the system level, with 10–15% of the stack power being required to power the compressor under some operating conditions which can considerably reduce the system efficiency. Hence, it is critical to pressurize the stack optimally to achieve best system efficiency under all operating conditions. In addition, oxygen starvation may result in a rapid decrease in cell voltage, leading to a large decrease in power output, and "torque holes" when used in vehicle traction applications [3].

To avoid these phenomena, regulating the oxygen excess ratio in the FC is a fundamental goal of the FC control system. Hence, the fuel cell system has to be capable of simultaneously changing the air flow rate (to achieve the desired excess air beyond the stoichiometric demand), the stack pressurization (for optimal system efficiency), as well as the membrane humidity (for durability and stack efficiency) and stack temperature. All variables are tightly linked physically, as the realizable actuators (compressor motor, back-pressure valve and spray injector or membrane humidifier) are located at different locations in the systems and affect all variables simultaneously. Accordingly, three major control subsystems in the fuel cell system regulate the air/fuel supply, the water management, and the heat management. The focus of this paper will be solely on the first of these three subsystems in tracking an optimum variable pressurization and air flow for maximum system efficiency during load transients for future automotive traction applications.

There have been several excellent studies on the application of modern control to fuel cell systems for automotive applications; see, for example, [1,3–6], and [7]. In this work, several nonlinear control ideas are applied to a multi-input, multi-output (MIMO) PEM-FC system model, to achieve good tracking responses over a wide range of operation. Working from a reduced order, control-oriented model, the first technique uses an observer-based linear optimum control which combines a feed-forward approach based on the steady-state plant inverse response, coupled to a multi-variable LQR feedback control. Following this, a nonlinear gain-scheduled control is described, with enhancements to overcome the fast variations in the scheduling variable. Finally, a rule-based, output feedback control design is coupled with a nonlinear feed-forward approach. These designs are compared in simulation studies to investigate robustness to disturbance, time delay, and actuators limitations. Previous work (see, for example, [1,4,5] and references therein) has seen results for single-input examples, using direct feedback control, where linearization around certain operating conditions led to acceptable local responses. The contributions of this work, therefore, are threefold: Control-oriented modeling of a realistic fuel cell system, extending the range of operation of the system through gain-scheduled control and rule-based control, and comparative studies under closed-loop control for realistic disturbances and uncertainties in typical operation.

2. PEM fuel cell system model

Having a control-oriented model for the PEM-FC is a crucial first step in understanding the system behavior and the subsequent design and analysis of a model-based control system. Because the main focus of this paper is on the control aspects of pressurized automotive PEM fuel cells, only a brief description of the stack and auxiliaries model is provided here. The model used throughout this paper was derived and thoroughly detailed in [4,8].

2.1. *Model overview*

The PEM fuel cell consists of a polymeric electrolyte membrane sandwiched between two electrodes: an anode and a cathode. It has been observed that the efficiency of the fuel cell can be increased slightly by pressurizing the fuel gasses, leading to higher power densities needed for automotive applications [9]. Additionally, the membrane needs to be humidified in order to operate properly, which is generally provided by humidification of supplied air flow [10]. Furthermore, to achieve optimal performance, the modern automotive fuel stacks should operate typically around 80 °C or 85 °C [8]. To satisfy these requirements, a compressor is used to supply pressurized air, a humidification system for the air stream, a heat exchanger or intercooler to remove heat from the air, and a back-pressure valve to control system pressure [8]. Also, a very similar setup is required for the anode. These systems are powered by the fuel stack itself, leaving the net power of the overall fuel cell system for use in traction systems. The objective is to track trajectories of best net system efficiency, while avoiding flooding or oxygen starvation. Fig. 1 offers a schematic of the modeled system.

The primary motivation for these assumptions is to result in a control-oriented model that considers only the critical dynamics for automobile operations. The model has been described in detail in [11] and [4]. However, for clarity, a summary of the model is presented here. The following are the primary assumptions that characterize the fuel cell system model: (i) a lumped-parameter modeling approach is used; (ii) all cells are lumped into one equivalent cell; (iii) all volumes are assumed to be under isothermal conditions; (iv) slow dynamics (temperature regulation and heat dissipation) are neglected; (v) fast dynamics (electrochemistry) are represented by empirical maps or equations.

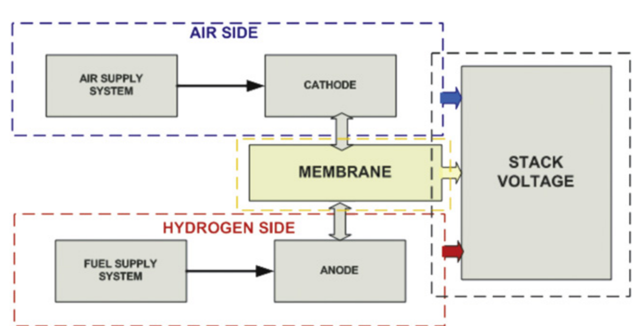

Fig. 1 – Fuel cell system blocks [4].