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Experimental investigation of fuel cell dynamic response and control

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Abstract

An experimental study of the dynamic response of a commercial fuel cell system is presented in this work. The primary goal of the research is an examination of the feasibility for using fuel cells in a load-following mode for vehicular applications, where load-following implies that the fuel cell system provides the power necessary for transient responses without the use of additional energy storage elements, such as batteries or super-capacitors. The dynamic response of fuel cell systems used in the load-following mode may have implications for safe and efficient operation of vehicles. To that end, a DC–DC converter was used to port the power output of the fuel cell to a resistive load using a pulse-width-modulating circuit. Frequency responses of the system were evaluated at a variety of DC offsets and AC amplitudes of the PWM duty cycle from 1 out to 400 Hz. Open-loop transient responses are then evaluated using transitions from 10% to 90% duty cycle levels, followed by dwells at the 90% level and then transitions back to the 10% level. A classical proportional–integral controller was then developed and used to close the loop around the system, with the result that the fuel cell system was driven to track the same transient. The controller was then used to drive the fuel cell system according to a reference power signal, which was a scaled-down copy of the simulated power output from an internal combustion engine powering a conventional automobile through the Federal Urban Driving Schedule (FUDS). The results showed that the fuel cell system is capable of tracking transient signals with sufficient fidelity such that it should be applicable for use in a load-following mode for vehicular applications. The results also highlight important issues that must be addressed in considering vehicular applications of fuel cells, such as the power conditioning circuit efficiency and the effect of stack heating on the system response.

Keywords: Fuel cells; Dynamic response; Fuel cell vehicles

1. Introduction

It is generally accepted that fuel cells have the potential for being a primary power source in automobiles. A number of technical issues remain before widespread fuel cell use can be realized, including reducing the capital cost of the fuel cell systems and improving hydrogen storage. Another important issue is determining the most appropriate way to utilize the fuel cell power plant. For example, it may be appropriate to utilize the fuel cell system as a mobile battery charger, such that the fuel cell is essentially a range-extender for what may be a plug-in electric vehicle. Alternatively, it may be that the fuel cell system may be the dominant source of power for the drivetrain, with batteries or other auxiliary energy sources used only for fuel cell system startup and shutdown. There is then a continuum of implementation approaches between those two extremes, where fuel cells and other electrical energy sources are more or less dominant powerplants in a given vehicle design.

Depending on the extent to which the fuel cell is the primary power source, the dynamic response of the complete fuel cell system can be quite important. For example, in the range-extender paradigm, a delay of several seconds in starting the fuel cell may not be significant. In that application, it may be that the fuel cell will be started, run at a constant load for a required period of time and then shut down until needed again. In contrast, if a fuel cell system is a vehicle's primary power source, then the system dynamics are quite important, as power demands can fluctuate quite rapidly during the drive cycle. In that application, time lags or sluggish responses may be unacceptable or even hazardous. The dynamic response of a fuel cell system can

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therefore be an important part of realizing safe operation of fuel cell vehicles.

Fuel cell dynamics have been studied from a variety of different perspectives. For example, a number of authors have examined the interactions between fuel cells and power conditioning circuits, including Gemmen [1], Fontes et al. [2], Choi et al. [3] and Schenck et al. [4], to name a few. In those works, the authors were generally concerned with obtaining an understanding of how the power conditioning circuits, including DC/AC inverters and boost and DC–DC converters, can affect the ripple current of a fuel cell system. Gemmen [1] provides a definition of ripple current as a deviation of the system current away from the current, which is theoretically obtainable for a given set of reactant flows. He noted that inverter loads can, in some cases, cause ripple that is potentially damaging to fuel cell membranes.

Another approach to studying the interactions between fuel cells and power conditioning was taken by Fontes et al. [2] and Choi et al. [3], who performed experiments to determine the dynamic impedance of a fuel cell systems. Fontes et al. concluded that the charge double layer (CDL) capacitance of the fuel cell was sufficient to filter the high-frequency ripple, but the lower frequency interactions may be of concern. Choi et al. examined the effect of the low-frequency ripple on fuel cell power output and proposed limits on the allowable ripple so as to minimize fuel cell power losses. Those authors also proposed the use of their model to optimize fuel cell/power conditioning unit design in future work.

Fuel cell transient responses have also been studied by a number of authors. Morner and Klein [5] examined the influence of temperature, humidity and air flow rate on the transient performance of a fuel cell stack. Wang and Wang [6] developed a simulation model to study the influence of operating parameters on fuel cell system performance. Those authors included a determination of time constants for both the CDL capacitance effect of the fuel cell, gas transport within the cells and water content of the membrane, with the intent of using the information in future works dealing with the design of power circuits and fuel cell system control.

The response of a fuel cell system subjected to large load variations was studied by Hamelin et al. [7]. The authors reported that the fuel cell system was able to respond to load variations within 0.15 s, although they also noted the presence of large current and voltage transients that may require filtering. Pei et al. [8] described the development of a test stand for testing vehicle-scale fuel cells. The authors reported on the use of the system to test a 50 kW fuel cell and presented results on the fuel cell efficiency. Transient responses were also reported by some of the authors examining fuel cell/power conditioning interactions. Fontes et al. [2] examined the transient responses of a 200 W fuel cell to 20 kHz switching. Schenck et al. [4] studied fuel cell responses for 60 Hz inverter loads and also for step load changes. In working with the step loads, the authors examined not only the large time-scale (integer seconds) responses, but also the response at a fairly small time-scale (tens of micro-seconds). The authors suggested the use of ultra capacitors to reduce the ripple of the output signal.

In examining the literature, it is apparent that there is a growing interest in the dynamic and transient responses of fuel cell systems. A good deal of the research has focused on the development of models so that simulation studies can be performed to determine the appropriate methods for designing fuel cell and power conditioning system interactions. Comparatively fewer works have been found that deal with the transient response of fuel cell systems to arbitrary load changes, although a great deal of simulation work has been carried out in that area. For example, Pukrushpan et al. [9] and Guezennec et al. [10] have developed fuel cell system simulations that are used to study the dynamics and control of fuel cell systems in vehicular applications. A more recent work that has dealt with the dynamic response of fuel cells is the paper by Lemes et al. [11], who discussed the development of a system for performing hardware in the loop simulation with fuel cell system components. The intent of that work is the development of a platform such that individual components can be implemented and optimized as if they were in a complete physical system, even though part of the system is actually implemented in simulation, rather than in physical hardware. Another work that deals with fuel cell dynamics is the report produced by Ottesen [12]. In that work, the author describes basic testing of a Nexa fuel cell system identical to the one described in this paper. The Nexa was loaded using a resistor bank that was switched to one of three resistance values. By monitoring the voltage and current, the author was able to observe the basic behavior of the Nexa system in response to step changes in load. The data collection for that work was done at 10 Hz, however, indicating that the examination of the fuel cell dynamics was limited to frequencies below 5 Hz. In addition, as noted, the load variations were restricted to three distinct levels, while in vehicular applications, a more continuous range of load levels is anticipated. There still seems to be room, therefore, for an experimental work that deals with fuel cell system dynamics across a wide range of operating conditions and an examination of the corresponding implications for using the fuel cell system in vehicular applications.

The goal of the research presented in this work is an examination of the dynamic response of a fuel cell system and its implications for the applicability of a fuel cell powerplant as the primary power source in a vehicle. For the purposes of this work, this method of implementing the fuel cell in a vehicle is termed “load-following,” as the fuel cell power plant is required to track a given power load demand. To that end, a series of experiments were performed using a commercially available 1.2 kW fuel cell system equipped with a pulse-width-modulated (PWM) DC–DC converter, specifically, a chopper, to regulate the power dissipated over a resistive load. It is understood that automotive applications will require significantly higher power levels than 1.2 kW. However, the smaller fuel cell system is a good start for understanding fuel cell system dynamics; it is more economical and is readily available for researchers in the field. Also, while it is accepted that it may not be possible to directly scale the results from the smaller system to expected results from an automotive system, it is not unreasonable to expect that the general trends will hold as the system size is