DESIGN AND CONTROL OF A POWER GENERATION SYSTEM FOR A FUEL-CELL POWERED AUTOMOBILE

Panini K. Kolavennu, Srinivas Palanki [1]
John C. Telotte

Department of Chemical and Biomedical Engineering, FAMU-FSU College of Engineering, Florida State University, Tallahassee, FL 32310-6046, USA

Abstract: In this paper, we consider design and control issues in a fuel-cell powered automobile that utilizes methane as a source of hydrogen. A power generation system is designed based on a steady state model of a PEM fuel cell that is capable of generating 50 kW of power. The transient behavior of the fuel cell is captured via a transfer function model and an appropriate adaptive controller is tuned to follow a time varying power profile that mimics realistic road conditions. Finally, a logic-based controller is designed and tested that switches to a battery backup that provides power to the electric motor when the fuel cell is unable to meet the necessary power demand.

Keywords: fuel processor, PEM fuel cell, power generation system

1. INTRODUCTION

Fuel cell power systems for automotive applications have received increased attention in recent years because of their potential for high fuel efficiency and lower emissions [Zalc and Loffler, 2002]. In particular, a fuel cell converts hydrogen and oxygen into water, directly generating electrical energy from chemical energy without being restricted by efficiency limits of the Carnot thermal cycle [Larminie and Dicks, 2000]. This interest in automotive applications has primarily been the result of the breakthroughs made in polymer electrolyte membrane (PEM) fuel cells which have several attractive features such as low operating temperatures (around 80 ^oC), relatively low cost, simple maintenance requirements, and high efficiency.

While there have been significant advances in fuel cell technology, one reason this technology has not seen wide-spread applications in the automotive industry has been the lack of an efficient hydrogen distribution center and the difficulties associated with storing hydrogen onboard an automobile [Lovins and Williams, 1999]. One option to alleviate these problems is to develop a system that utilizes a commonly available carbon-based hydrogenous fuel such as gasoline or methane to generate the necessary hydrogen *in situ* on an "as needed" basis. Hydrocarbon fuels are relatively easy to store onboard a vehicle and a nationwide infrastructure to supply these fuels already exists. In this paper, we consider the design of a fuel-cell powered automobile that utilizes methane as a source of hydrogen.

[1] Corresponding author: palanki@eng.fsu.edu

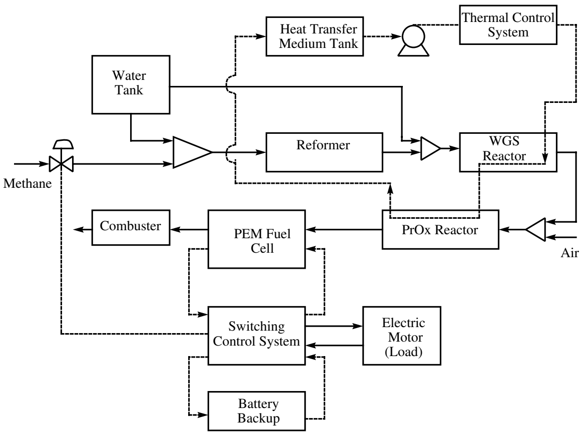

Fig. 1. Schematic of Fuel Cell System

2. SYSTEM DESIGN CONSIDERATIONS

A schematic of the fuel cell system under consideration is shown in Fig. 1. The two main components of the overall system are (1) the fuel processing subsystem and (2) the power generation subsystem. Methane enters the fuel processing subsystem and is converted to hydrogen. Hydrogen enters the fuel cell where it mixes with oxygen to generate electrical power which drives an electric motor.

In addition to the fuel cell, there is a battery backup that the electric motor switches to when the hydrogen delivered to the fuel cell is insufficient to meet the *instantaneous* power demands of the electric motor. This battery backup is essential because significant load transitions occur frequently as a result of sudden acceleration on highway ramps as well as terrain changes [Zalc and Loffler, 2002].

In an earlier paper [Kolavennu *et al.*, 2004], the primary components of a fuel cell power system, that utilizes methane to generate hydrogen, were analyzed. In particular, basic chemical engineering principles were utilized to design a reactor train that converts methane to hydrogen of the desired purity. The relation between power produced by a PEM fuel cell and methane entering the reactor train *at steady state* was calculated. However, a typical automobile does not operate at steady state. The power demand for an automobile motor undergoes significant variations due to acceleration, changes in road surface and traffic conditions.

In this paper, we analyze the power generation subsystem in the face of fluctuating power demand. In particular, we design a controller that adjusts the hydrogen flow into the fuel cell in response to changing power demand. When power demand goes down, the excess hydrogen can be diverted from the fuel cell. However, a sudden *increase* in power demand requires an instantaneous increase in hydrogen flow rate into the fuel cell. However, the conversion of methane to hydrogen takes several seconds which leads to an unacceptable lag between power demand of the motor and the power supplied by the fuel cell. For this reason, a backup battery is required that takes over this power load during the time it takes for the fuel cell to generate the necessary power. In this paper, a logic-based switching controller is designed that switches to the battery backup when the fuel cell is unable to provide the necessary power to the motor. This design is tested via simulations for a typical power profile of an automobile motor.

Reactor Name	T(K)	P (atm)	Size (l)
Steam Reformer	1000	5	10
Water-Gas Shift	700 (HT) 490 (LT)	2	41.8
Preferential Oxidation	473	2	0.35

Table 1. Fuel Processing Subsystem

2.1 Fuel Processing Subsystem

In this subsystem, methane is converted to hydrogen. In a previous publication [Kolavennu *et al.*, 2004], we utilized basic chemical engineering principles to design a reactor train that produced hydrogen of the desired purity. The design operating conditions of this series of reactors are summarized in Table 1.

The steam reformer operates at 1000 K and 5 atm and utilizes a steam to carbon ratio of 3:1. The water gas shift reactor operates at 2 atm and has two temperature zones. The initial 1 liter is operated at 700 K (HT) to promote high reaction rate and the remaining 40.8 liters are operated at 490 K (LT) to promote high conversion. The preferential oxidation reactor operates at 473 K and 2 atm. It was shown [Kolavennu *et al.*, 2004] that the relation between methane utilized and hydrogen produced was linear and could be represented by the following relation:

$$F_{H_2} = 3.12 F_{CH_4} \tag{1}$$

2.2 Design of Power Generation Subsystem

The current generated by the fuel cell stack is directly proportional to the hydrogen consumption rate. The voltage generated by a cell depends on the current density in the cell, thermodynamic parameters (temperature and partial pressures) and the cell materials and design. For a given cell design and thermodynamic state a detailed calculation of the voltage versus current density can be performed. In this work we have utilized a semi-theoretical model first proposed by Larminie and

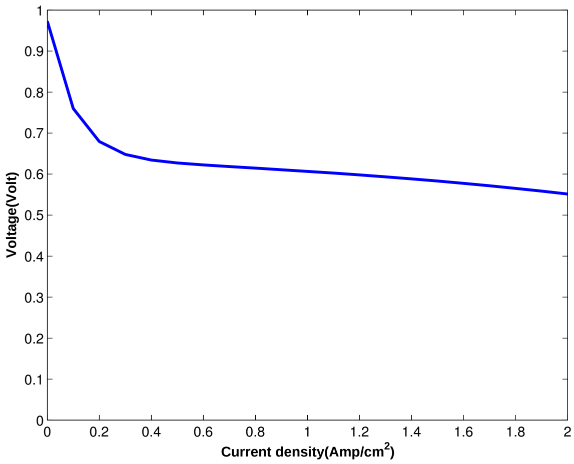

Fig. 2. Voltage vs. Current Density

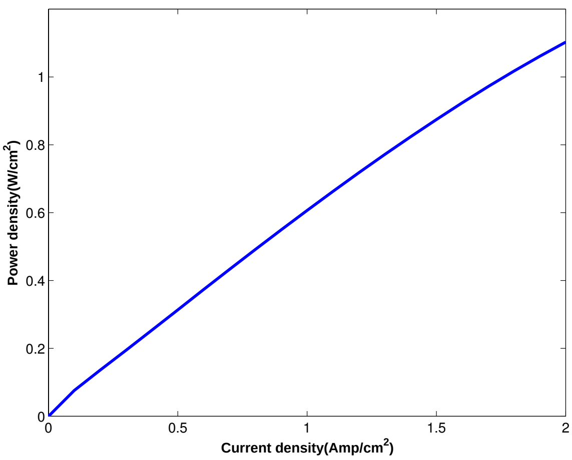

Fig. 3. Power Density vs. Current density

Dicks [2000] and later parameterized by Pukrushpan [2003]. For a fuel cell operating at 353 K with an anode partial pressure of hydrogen of 3 atm and air fed to the cathode at 5 atm, the following cell polarization curve is obtained:

$$V = 0.6405 + 0.3325e^{-10i} - 0.03036i - 0.00355i^3 \tag{2}$$

For these conditions that there is a sharp drop-off in cell voltage at small current densities but a very flat region to the polarization curve with cell voltages being nearly 0.6 V over a wide range of current densities as shown in Figure 2. This is desirable characteristic as this produces a power density that varies nearly linearly with current density, as seen in Figure 3.

The design objective for this project has been for a 50 kW fuel cell stack. We have based our design on a cell voltage of 0.6 V. This occurs for a current density of 1.15 A/cm^2. If one desires a system with a 300 volt output [Pukrushpan, 2003], then 500 cells in series are required. To generate 50 kW of power then requires 166.67 A of current which requires an active cell area of 145 cm^2. The required hydrogen flow per cell is calculate from

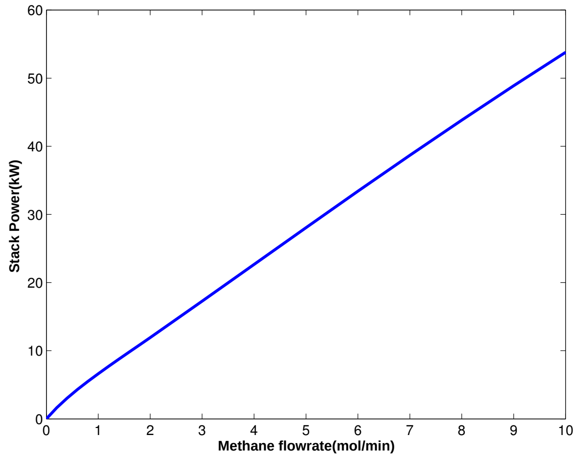

Fig. 4. Effect of Methane Flow on Power Generated

$$I = 2FX\dot{N}_{H_2} \tag{3}$$

The conversion is assumed to be 90%, which yields a maximum required hydrogen flow of 0.001 moles/sec/cell. This corresponds to a total required methane flow of 9.2 moles/min. The power curve for the combined fuel processor and fuel cell stack system is shown in Figure 4. To construct this curve a methane flow rate was selected and the resultant hydrogen flow from the fuel processor was calculated using equation (1). Using equation (3), the cell current was then determined. With the cell area specified at 145 cm^2, the current density could then be found and the stack power was finally calculated using equation (2).

3. CONTROLLER DESIGN FOR POWER GENERATION SUBSYSTEM

For the fuel cell systems to operate at levels comparable to existing internal combustion engines, the key issue that should be addressed is the *transient* behavior of fuel cell systems. Automobiles are subjected to significant load transitions during operation and the fuel cell system should be able to produce power which can follow this varying load profile. Hydrogen from the fuel processing subsystem comes at the anode and splits into hydrogen ions and electrons. The electrons pass through an external circuit towards the cathode thereby producing the current. The whole process involves electrochemical, mass and heat transport phenomena and there has been considerable research effort in modeling fuel cells to capture this phenomena [Nguyen and White, 1993; Kim et al, 1995]. Power produced by the fuel cell is dependent on the voltage current characteristics. Hence for control related studies a dynamic model which can mimic the voltage-current characteristics of the fuel cell system is required. Pukrushpan [2003] proposed a dynamic nonlinear model which can be

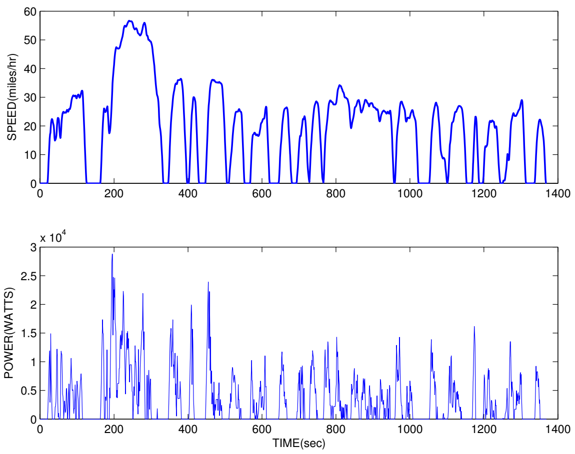

Fig. 5. Speed and Power Profile for UDDS

used for this purpose. For a given current demand the model calculates the voltage produced and thereby the power output of the fuel cell. The model also takes into account the effects of humidity on cell performance. The transient response data from the nonlinear model was generated by subjecting the nonlinear system to a series of step inputs in the current around the 100 Amperes operating point. Utilizing this input output data from the nonlinear model system identification techniques were employed to derive a linear second order model was fit between the current demand and the voltage produced by the fuel cell stack. The transfer function G_p is given below

$$G_p = \frac{-390.78}{s^2 + 27.291s + 2068.8} \tag{4}$$

This transfer function is used in this paper to design a controller to regulate the power output of the fuel cell to the power demand. The control problem is to track the power demand of the motor using current as the manipulated variable.

To get a more realistic power vs time profile we obtained the power profile for a small car from an existing speed vs time profile using ADVISOR software package [NREL, 2002] as shown in Figure 5. The Urban Dynamometer Driving schedule(UDDS) which is designed for light duty vehicle testing in city driving conditions was used.

4. MODEL REFERENCE ADAPTIVE CONTROLLER

Model reference adaptive control (MRAC) is derived from the model reference control (MRC) problem. The objective of MRC is to find the feedback control law that changes the structure and dynamics of the plant so that its I/O properties are exactly the same as those of a reference model. The structure of an MRC scheme for a

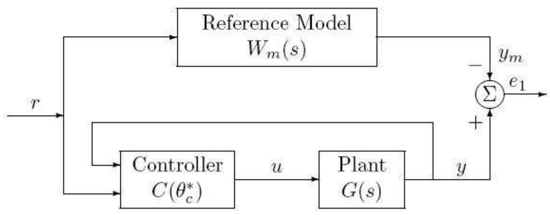

Fig. 6. Model Reference Adaptive Control

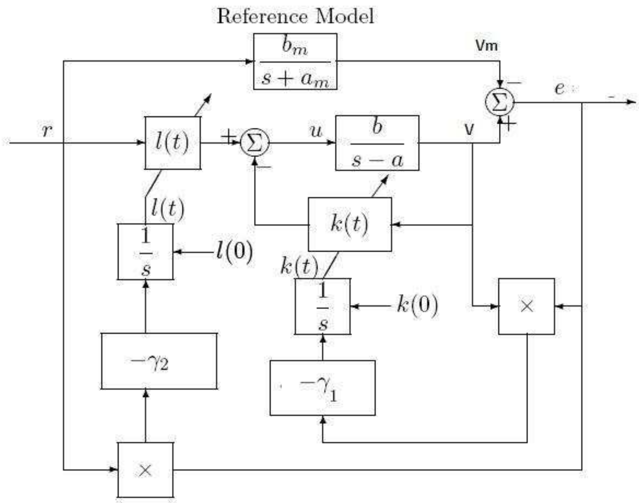

Fig. 7. Implementation of Model Reference Adaptive Control

LTI, SISO plant is shown in Fig. 6 [Ioannou and Sun, 1996]. Here, $W_m(s)$ is the transfer function of the reference model, $r(t)$ a given reference input signal, $y_m(t)$ the output of the reference model and $y(t)$ is the plant output. The feedback controller, denoted by $C(\Theta_c)$, is designed so that all signals are bounded and the closed-loop plant transfer function from r to y is equal to $W_m(s)$. This transfer function matching guarantees that for any given reference input $r(t)$, the tracking error $e = y - y_m$, which represents the deviation of the plant output from the desired trajectory ym, converges to zero with time.

The MRAC control law equation can be implemented as shown in Fig. 7. The initial conditions $l(0)$; $k(0)$ are chosen by an *a priori* guess of the unknown parameters k and l respectively.

To make a quantitative comparison between the adaptive controller and a PID controller, the Integrated Time Averaged Error (ITAE) is calculated by the following equation.

$$ITAE = \sum_{i=0}^{n} \frac{t_i \, |e_i(t)|}{n} \tag{5}$$

where n stands for the number of time steps. e_i is the error at time t_i.

Table 2. Average ITAE error in kW obtained for the nonlinear model

Controller	UDDS	US HWY
PID	91.46	unstable
Adaptive	40.5	55.6

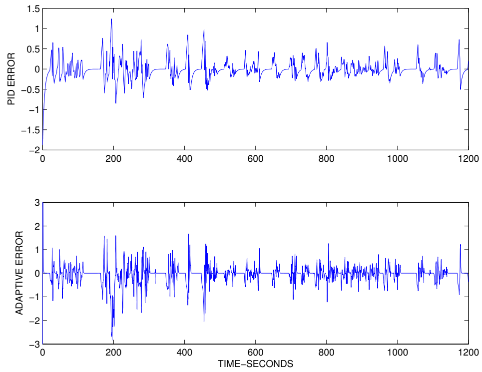

Fig. 8. Error obtained for the PID and Adaptive controllers implemented on the nonlinear model

After designing the controllers for the linear model it was implemented on the nonlinear model. The PID controller and the adaptive controller were fine-tuned for the nonlinear model and the errors obtained for the UDDS profile are shown in Fig. 8. The adaptive controller error has a larger overshoot compared to the PID controller but the error comes back to zero quickly when compared with the PID controller. An important aspect of designing a controller for an automotive purpose is we do not know the trajectory of the power profile *a priori* and so the controller tuned for one profile should work for several other typical road profiles. This is where the adaptive controller scores over the PID controller. The PID controller has to be retuned for each different power profile to meet the performance specifications whereas the adaptive controller can adapt to the new power profile. To test this the controller designed for the UDDS profile was implemented on a US06-HWY profile which simulates highway driving instead of city driving represented by UDDS. When the US06-HWY profile is used on the controllers designed for the UDDS profile the PID controller failed as the system became unstable whereas the adaptive controller works well as shown in Table 2.

4.1 Switching to Battery Backup

When the power demand increases suddenly (e.g. due to sudden acceleration), this requires an instantaneous increase in hydrogen. However, since it takes time for reactants and products to go through the reactor train, there is a time delay in producing the hydrogen. If the reactions are not kinetically limited, this time delay can be estimated from the space time of the reactor train

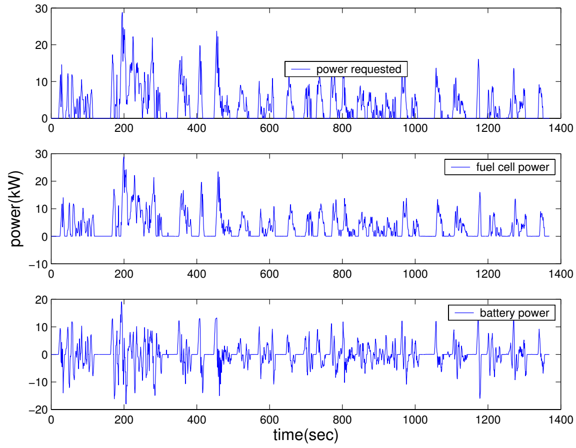

Fig. 9. Power Profiles for the UDDS

which was estimated to be about 4 seconds based on the maximum flow rate of 10 moles/min of methane. Thus, it is necessary to have a battery backup that provides power to the motor during this time lag while sufficient hydrogen is generated. Since the battery is charged and discharged continuously, knowledge of the transient behavior of the batteries is very important. Dynamic modeling of batteries is a major concern for electric vehicles and fuel cell hybrid vehicles. For control oriented studies we require models which can be simulated quickly and so in this paper we utilize an equivalent electric circuit model developed along the lines of [He and Hodgson, 2002] which gives an accurate prediction of state-of-charge (SOC) of the battery.

The switching controller is a logic based on-off controller that switches back and forth between the fuel cell and the battery to meet the power demand. The logic controller addresses the following issues:

- The power produced by the fuel cell comes with a certain time delay and hence any deficit in power demand is handled by switching to the battery until the fuel cell can produce sufficient power.
- The excess power produced by the fuel cell during deceleration or decrease in power demand should be routed to the battery.
- When the SOC of the battery falls below a specified target the controller should direct the fuel cell to produce power to charge the battery in addition to the power demand.
- Since the fuel processor and the fuel cell system were designed for a maximum power output of 50 kW. The controller should make sure that the power demand is not greater than 50 kW.

The time profiles of power requested, fuel cell power and battery power are plotted in Fig. 9. The power supplied by the battery also depends on

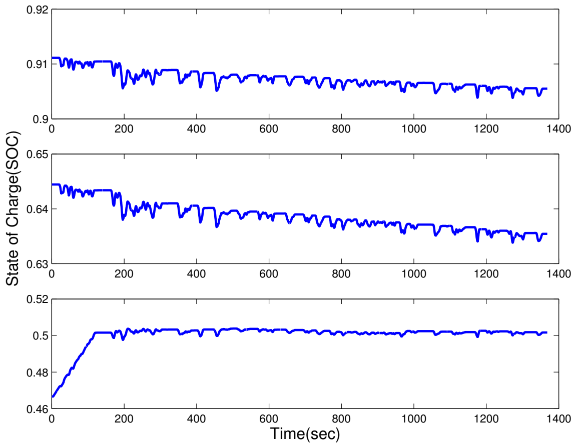

Fig. 10. State of Charge for Different Initial Conditions

the initial SOC of the battery. For the same cycle the system was simulated for different initial SOC as shown in Fig. 10. The controller was designed to maintain the SOC above 0.5. For the initial conditions where the battery is almost charged (SOC=0.9) and semi charged (SOC=0.64) the profiles look similar. But for the case where the initial SOC is less than 0.5 the controller is activated and brings the SOC level to above 0.5.

5. CONCLUSIONS

A power generation system for a methane-powered automobile is designed that consists of a fuel cell and a battery backup. The hydrogen flow to the fuel cell is adjusted via an adaptive controller depending on the power demand of the electric motor. A logic-based controller switches to the battery backup when the fuel cell is unable to meet the power demand. These controllers are tested via simulation on realistic power demand profiles.

Currently, the effect of thermal transients on the fuel processor and the power generation system are being studied.

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REFERENCES

[1] He, X. and Hodgson, J.W., " Modeling and simulation for hybrid electric vehicles. i. modeling." *Intelligent Transportation Systems*, volume 3, 235-243, (2002)

[2] Ioannou P. and J. Sun, *Robust Adaptive Control*, Prentice Hall, Inc., 1996

[3] Kim, J., Lee, S.M., Srinivasan, S., "Modeling of Proton Exchange Membrane Fuel Cell Performance with an Empirical Equation," *J. Electrochem. Soc.*, 142, 8, 2670 (1995)

[4] Kolavennu, P.K., Telotte, J.C., and Palanki, S., "Modeling and Control of a Fuel Cell Power System for Automotive Applications," *European Symposium for Computer Aided Process Engineering-14*, Lisbon, Portugal, May 16-19, 2004

[5] Larminie, J., and Dicks, A., *Fuel Cell Systems*, Wiley, New York, 2000

[6] Lovins, A.B., and Williams, B.D., "A strategy for the hydrogen transition," *10th Annual U.S. Hydrogen Meeting*, Vienna, Virginia, April 1999

[7] National Renewable Energy Laboratory, "ADVISOR (Advanced Vehicle Simulator)", 2002

[8] Nguyen, T.V., and White, R.E., "A water and heat management model for proton-exchange-membrane fuel cells," *J. Electrochem. Soc.*, 140, 8, 2178-2186 (1993)

[9] Pukrushpan, J. T., *Modeling and Control of Fuel Cell Systems and Fuel Processors*, PhD thesis, The University of Michigan, Ann Arbor, 2003

[10] Zalc, J.M., and Loffler, D.G., "Fuel processing for PEM fuel cells: transport and kinetic issues of system design," *J. Power Sources*, 111, 58-64 (2002)