Control Engineering Practice 56 (2016) 92–100

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Active disturbance rejection control for voltage stabilization in open-cathode fuel cells through temperature regulation

Nima Lotfi [*,1], Hesam Zomorodi [2], Robert G. Landers

Mechanical and Aerospace Engineering Department, Missouri University of Science and Technology, 207 Toomey Hall, 1870 Miner Circle, Rolla, MO 65409, USA

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form
3 July 2016
Accepted 13 August 2016

Keywords:
Open-cathode PEM fuel cell
Temperature control and estimation
Observer design
Uncertainty estimation
Adaptive voltage regulation

ABSTRACT

Temperature regulation is an important control challenge in open-cathode fuel cell systems. In this paper, a feedback controller, combined with a novel output-injection observer, is designed and implemented for fuel cell stack temperature control. The first functionality of the observer is to smooth the noisy temperature measurements. To this end, the observer gain is calculated based on Kalman filter theory which, in turn, results in a robust temperature estimation despite temperature model uncertainties and measurement noise. Furthermore, the observer is capable of estimating the output voltage model uncertainties. It is shown that temperature control not only ensures the fuel cell temperature reference is properly tracked, but, along with the uncertainty estimator, can also be used to stabilize the output voltage. Voltage regulation is of great importance for open-cathode fuel cells, which typically suffer from gradual voltage decay over time due to their dead-end anode operation. Moreover, voltage control ensures predictable and fixed fuel cell output voltages for given current values, even in the presence of disturbances. The observer stability is proved using Lyapunov theory, and the observer's effectiveness in combination with the controller is validated experimentally. The results show promising controller performances in regulating fuel cell temperature and voltage in the presence of model uncertainties and disturbances.

1. Introduction

While open-cathode Polymer Electrolyte Membrane Fuel Cells (PEMFCs) possess the advantages of closed-cathode PEMFCs, such as high efficiency and power density, long cell and stack life, low electrolyte corrosion, low noise levels, and low operating temperatures, they differ because they have cathode channels exposed to the atmosphere. In closed-cathode PEMFCs, the air is supplied by a compressor at pressures from near ambient to approximately 6 atm. On the other hand, open-cathode PEMFCs are usually operated near atmospheric pressure with the air being supplied by either convection or low-power fans. Higher pressures in closed-cathode PEMFCs mandate simultaneous cathode and anode pressure regulation in order to minimize their pressure difference and avoid potential damage. However, in open-cathode PEMFC systems, due to near-atmospheric operating pressures, pressure regulation is not required. It should also be noted that although operating at higher pressures results in higher voltages, it induces considerable parasitic loads (e.g., compressor, cooling system, humidification system) and corresponding costs. However, open-cathode fuel cells do not require humidification and are usually supplied with dry reactants; therefore, open-cathode PEMFCs have become popular due to their portability and reduced number of required Balance-Of-Plant (BOP) components: compressors, supply or return manifolds, pumps and radiators for cooling, and humidifiers.

In spite of the numerous advantages of fuel cells, their safe, reliable, and efficient operation is still among the main challenges facing their widespread commercialization. The use of advanced and robust control methodologies capable of considering the complex interactions between different subsystems in fuel cells can greatly help overcome those obstacles and simplify their further development and employment. Open-cathode fuel cells, in particular, have not received much attention in the fuel cell literature. Due to their low cost, they are typically equipped with simple controllers which, in turn, results in their underutilization.

The majority of the papers on the control of PEMFCs focus on the challenges in closed-cathode PEMFC systems, specifically, their application in hybrid fuel cell-battery/supercapacitor systems and

* Corresponding author.
E-mail address: nlb6f@mst.edu (N. Lotfi).
[1] Present address: Mechanical Engineering Department, Southern Illinois University Edwardsville, USA.
[2] Present address: Automotive Engineering Department, Clemson University, USA.

http://dx.doi.org/10.1016/j.conengprac.2016.08.006
0967-0661/

the optimization of the energy flow between different system components (Greenwell & Vahidi, 2010; Jiang & Dougal, 2006). Another important control problem in closed-cathode fuel cells has been the cathode air flow management in order to prevent oxygen starvation and improve the overall system efficiency. Suh and Stefanopoulou (2006) proposed a decentralized controller in order to minimize oxygen starvation by properly manipulating air flow. An explicit constrained model predictive controller was proposed in Arce and Ramirez (2007), Arce, Real, Bordons and Ramírez (2010) for this purpose. Oxygen excess ratio i.e., the ratio of the supplied oxygen to the oxygen used in the fuel cell reaction, has been used as an indicator of the sufficiency of the oxygen supply (Pukrushpan, Peng, & Stefanopoulou, 2004). A feedforward controller was developed in Grujicic, Chittajallu, Law, and Pukrushpan (2004) in order to control the oxygen excess ratio, while the authors in Pukrushpan, Stefanopoulou, and Peng (2002), Pukrushpan et al. (2004) augmented the feedforward controller with a linear quadratic regulator structure for this purpose. The desired oxygen excess ratio was maintained using a nonlinear model-based controller in Danzer, Wilhelm, Aschemann, and Hofer (2008). Finally, a supervisory fault diagnosis system, based on Bayesian networks, was introduced in Riascos, Cozman, Miyagi, and Simoes (2006). This system was proposed to detect faults in the fans, refrigeration system, hydrogen pressure, and fuel crossover and internal current.

Other research in the closed-cathode PEMFC controls field has considered the minimization of fuel and consumed energy. In these studies, the hydrogen and/or oxygen flow rates are adjusted in such a way that minimum auxiliary and fuel consumption is achieved. Tekin, Hissel, Pera, and Kauffmann (2006) used fuzzy logic in determining an air flow set-point in order to minimize energy consumption. In Ramos-paja, Bordons, Romero, Giral, and Martínez-salamero (2009), air flow rate and output current were used as control variables to minimize fuel consumption for different load demands. Air and hydrogen flow rate adjustments have also been employed for output voltage regulation. An adaptive air flow rate controller capable of the voltage regulation in the presence of plant uncertainties was developed in Yang, Wang, Chang, Ma, and Weng (2007). Furthermore, Wang, Chen, Yang, and Yen (2008) used a multivariable H_∞ controller to regulate the output voltage by adjusting air and hydrogen flow rates.

Another important consideration for fuel cell performance is to maintain the stack temperature in a desired range. A PI controller was proposed in Choe and Ahn (2008) for temperature regulation, whereas the authors in Kolodziej (2007) achieved this objective by manipulating the coolant mass flow rate using a feedback linearization controller. Furthermore, an incremental fuzzy controller with integral action was proposed in Hu, Cao, Zhu, and Hu (2010). In Riascos and Pereira (2009), a systematic approach was introduced to calculate the optimal temperature as a function of input air relative humidity and stoichiometry, which was then used as the temperature reference for the controller.

Although some of these works can readily be applied to open-cathode fuel cells, there are few studies specifically addressing their real-world control challenges. Strahl, Husar, and Puleston (2014) proposed an extremum seeking algorithm in order to determine the maximum voltage of an open-cathode fuel cell for a given current draw considering coupled temperature and humidity effects. The authors combined the extremum seeking algorithm with a PI controller in order to regulate the fuel cell voltage at its maximum value. Although the authors demonstrated promising simulation results, practical implementation of the proposed controller requires further investigation. A detailed procedure for the design and analysis of the cooling fans in a 2 kW air-forced open-cathode fuel cell was presented in Lopez-Sabiron, Barroso, Roda, Barranco, Lozano, and Barreras (2012). Also, Barreras, Maza, Lozano, Bascones, Roda, Barranco, Cerqueira, and Verges (2012) proposed a non-model-based temperature control strategy for an open-cathode PEMFC used in a fuel cell hybrid vehicle. The controller adjusts the fans' speed to some predefined setpoints when the temperature exceeds a threshold.

Another important control challenge for open-cathode fuel cell systems is the design of purging strategies. Purging is mainly intended to remove excess water and other impurities in the anode channels, thereby maintain the desired humidity level. Purging is traditionally performed with a constant duration and period, as recommended by the fuel cell manufacturer. It can also be performed in a closed-loop manner using the fuel cell current as the feedback signal (Mokmeli & Asghari, 2010). Recently, optimization strategies have been used in order to determine the optimal purging schedule based on its effect on the fuel cell active area, hydrogen consumption, voltage response and, therefore, the overall fuel cell system efficiency (Chen, Siegel, Stefanopoulou, & Waldecker, 2013; Pokphet, Khan-ngern, & Charoensuk, 2010; Ripaccioli, Siegel, Stefanopoulou, & Cairano, 2009).

In this paper, temperature and voltage control, two of the important control problems in open-cathode fuel cells, will be investigated. Temperature has an important effect on fuel cell performance. Higher operating temperatures result in an increased fuel cell output voltage, larger voltage variations during purging, and even cathode catalyst layer drying in the case of extreme temperatures (Strahl, Husar, & Franco 2014). Therefore, a controller capable of dynamically maintaining the desired temperature, while considering model and process uncertainties, is required in order to ensure the fuel cell's desired performance. Temperature control in open-cathode fuel cells is typically handled in an open-loop fashion by running the fans continuously at a constant speed (Matian, Marquis, & Brandon, 2011), which induces undesirable auxiliary power consumption. At lower current demands where increased temperature is actually desirable, the fans can operate at lower speeds, thereby minimizing power consumption. However, a non-zero minimum fan speed is essential in order to guarantee the minimum air flow required to prevent oxygen starvation. In spite of the aforementioned advantages of operating open-cathode fuel cells at constant temperatures, a gradual voltage decrease over time is observed during this mode of operation. This phenomenon, along with the strong dependence of the fuel cell voltage on operating conditions, causes large voltage uncertainties for any given current draw; thereby increasing the complexity and cost of the required power electronics circuitry. In a previous work by authors (Lotfi, Zomorodi, & Landers, 2015), this issue was addressed by manipulating the temperature reference in order to maintain a constant output voltage. In this paper, this objective is achieved by augmenting a novel observer to the feedback temperature controller. The observer is capable of simultaneously estimating both the internal fuel cell temperature and the output voltage uncertainties. The observer stability is proved using Lyapunov stability and its effectiveness, as part of the control scheme, is shown experimentally. The proposed observer/controller set is robust against model uncertainties and ensures a fixed and predictable output fuel cell voltage as the operating conditions change. This feature can greatly simplify the design of open-cathode fuel cell systems and the power electronics to which they interface.

2. Temperature control

2.1. Experimental system

The open-cathode fuel cell used in this work is a 500 W air-forced open-cathode PEMFC stack with 40 cells and an active area of 50 cm^2. The auxiliary components for the fuel cell stack include