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PEM fuel cell air-feed system observer design for automotive applications: An adaptive numerical differentiation approach

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ABSTRACT

In this paper, an adaptive algebraic observer is proposed for a Polymer Electrolyte Membrane Fuel Cell (PEMFC) air-feed system, based on Higher Order Sliding Mode (HOSM) differentiators. The goal is to estimate oxygen and nitrogen partial pressures in the fuel cell cathode side, using measurements of supply manifold pressure and compressor mass flow rate. As the proposed technique requires the time derivatives of the states, Lyapunov-based adaptive HOSM differentiators are synthesized and implemented for estimating these derivatives without *a-priori* knowledge of the upper bounds of their higher order time derivatives. The performance of the proposed method is validated through experiments on a Hardware-In-Loop (HIL) test bench. These results illustrate the feasibility and effectiveness of the proposed approach.
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Introduction

PEM fuel cells have emerged as the most prominent technology for energizing future's automotive world [1–4]. Due to their relatively small size, light weight and easy manufacturing, they have been widely studied in automotive applications over the past two decades [5–10]. As the cost of hydrogen production through renewable energy sources is also continuously decreasing, fuel cells are expected to lead the world towards fossil-fuel independent hydrogen economy in terms of energy and electro-mobility. Automotive fuel cell applications have more rigorous operating requirements than stationary applications [11], therefore these applications need precise control of performance, in order to guarantee reliability, health and safety of both, the fuel cell and the user. Along with control, health monitoring and safety systems are essential for the application of fuel cells in automotive systems. Both control and health-monitoring systems require precise measurements of different physical quantities in the fuel cell. However, it is not always possible to use sensors for measurements, either due to prohibitive costs of the sensing technology or because the quantity is not directly measurable. In both these cases, state observers serve as a replacement for physical sensors, for obtaining the unavailable quantities.

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It is known that low oxygen partial pressure in the cathode reduces the generation capacity of fuel cell systems and affects the fuel cell stack life [12,13]. Therefore, the observation of oxygen partial pressure is essential for the feedback control and fault detection, in order to ensure the safety and longevity of the fuel cells [14–16]. However, most of the commercially available oxygen sensors do not operate properly in presence of humidified gas streams inside the fuel cell stack [17]. The sensors that do provide satisfactory performance are usually too big and costly. Therefore, observer designs for estimating the unmeasurable partial pressures are of great interest.

Many research endeavors have been focused during the recent years, on observation problems in fuel cell systems [18,19]. Arcak et al. [17] developed an adaptive observer for hydrogen partial pressure estimation based on the fuel cell voltage. Görgün et al. [20] developed an algorithm for estimating partial pressures and the membrane water content in PEMFCs based on the resistive cell voltage drop. This algorithm has incorporated two adaptive observers for hydrogen and oxygen partial pressures, adapted from the work of [17]. However, both of the above works lack robustness against the fuel cell voltage's measurement noise and the internal model relies upon unmeasurable values. Several kinds of Kalman Filters (KF) have been applied to the state estimation of fuel cell systems, i.e. classical KF [21], Unscented Kalman Filter (UKF) [22] and adaptive UKF [23]. These approaches are based on model linearization around pre-defined operating points of the system. Moreover, the calculation of Jacobian matrix of complex models like fuel cells are time consuming, and therefore difficult in real time implementation [24,25]. Ingimundarson et al. [26] proposed a model based estimation approach to hydrogen leak detection in PEMFCs. More recently, Linear Parameter Varying (LPV) observer was proposed by Lira et al. [27] for the application to fault detection in PEMFC systems, where the stack current was taken as the scheduling variable. Kunusch et al. [28] proposed an approach based on super-twisting algorithm, in order to estimate the hydrogen input flow at the anode of the stack and the water transport across the membrane. A Luenberger observer was employed by Ref. [29] in order to estimate the membrane water content in PEMFCs. The main limitation of this method is that it can only converge to a neighborhood of the real system states in the presence of disturbances.

Due to the lack of a straightforward observer design method for a given nonlinear system, many observation methods are generally dependent upon state transformations, the structure of the system, the form of the nonlinearities and the boundedness of the system states [30]. Among the popular strategies, high gain observers [31–33] are usually employed to estimate the system states under the assumption that the nonlinearity vector is globally or locally Lipschitz. However, in practice, the Lipschitz constraint is not easy to obtain, which prevents the global convergence of the high gain observer. Although the circle-criterion observer design [34,35] relaxes the requirement of Lipschitz constant, it remains limited to systems with positive-gradient nonlinearities.

Motivated by the results on algebraic observability [36–39], showed that the system state variables can be expressed in terms of inputs, outputs and their time derivatives up to some finite number. When the algebraic observability condition is verified, the state estimation is obtained by means of algebraic calculation of the input and output derivatives irrespective of the form of the nonlinearities and is more attached to the estimation of time derivatives of the inputs and outputs. Therefore, the accuracy and robustness of the differentiation method are the key element of the algebraic observer design. Several techniques have been proposed for differentiation, such as high gain differentiators [40,32,41] and sliding mode differentiators [42,43]. The high gain differentiators can furnish exact signal derivatives only if their gains tend to infinity. However, this infinitely amplifies their sensitivity to small high frequency noise and results in peaking phenomenon. The sliding mode differentiator ensures finite-time robust differentiation of noisy signals. Levant [43] has shown that the sliding mode differentiation error depends on the magnitude of the noise and not its derivative or frequency. However, this differentiation method requires the knowledge of the upper bound of the higher order derivatives, i.e. the Lipschitz constant. In many practical cases this boundary can not be easily obtained.

In this paper, we present an algebraic observer based on adaptive sliding mode differentiators for the partial pressures of oxygen and nitrogen in the cathode of the PEMFC. The motivation behind this work is that algebraic observers [36,38] are precise and easily implementable in automotive embedded systems. We have demonstrated that the states of the PEMFC air-feed system is algebraically observable i.e. the system states (oxygen and nitrogen partial pressures) can be presented in terms of a static diffeomorphism [44] involving system outputs (supply manifold pressure and compressor flow rate) and their time derivatives. New Lyapunov-based adaptive sliding mode differentiators are proposed for practical implementation of our algebraic observation scheme, which forms the main contribution of the paper. The gains of the adaptive differentiator are adapted dynamically based on the quality of the sliding motion, therefore the Lipschitz constant is not required during the design, as compared to Levant's design mentioned before [43]. Initial developments and preliminary results of this work were first published in Ref. [45]. In continuation of this work, the problems related to practical implementation have been resolved, and are the main focus of this paper. Namely, Lyapunov-based adaptive first and second order sliding mode differentiators are proposed for practical implementation of our algebraic observation scheme, experimental results are presented and the robustness of the proposed algorithm against parametric variation and measurement noise have been validated.

The Lyapunov functions for these differentiators are inspired from the work of Moreno et al. [46] on fixed-gain sliding mode differentiators. These functions are used to proof the finite time stability of the differentiators. The performance of the proposed observer is evaluated by implementing on an instrumented Hardware in Loop (HIL) test bench [47] that consists of a commercial twin screw compressor based physical PEMFC air-feed system and a real time PEMFC emulation system. In our experimental study, the main emphasis has been maintained on the robustness of the proposed observer against measurement noise and parameter variations. The use of the PEMFC emulation system permits to conduct experiments on fuel cell auxiliary systems in real time, while avoiding the risk of accidents (during worst case

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