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Nonlinear observer design for PEM fuel cell power systems via second order sliding mode technique

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ABSTRACT

In this paper, a nonlinear observer is proposed for a PEMFC system, based on Second Order Sliding Mode (SOSM) techniques. The goal is to estimate the hydrogen partial pressure in the anode channel of the PEMFC, using the measurements of stack voltage, stack current, anode pressure and anode inlet pressure. The proposed observer employs a nonlinear error injection term, where the error is obtained from the difference between the system voltage output obtained from an experimental validated nonlinear model and estimated voltage output obtained from the designed observer. The robustness of this observer against parametric uncertainties and load variations is studied, and the finite time convergence property is proved via Lyapunov analysis. Simulation results illustrate the effectiveness and robustness of the proposed approach.

1. Introduction

Polymer electrolyte membrane fuel cell (PEMFC) is an electrochemical device that produces electricity from the chemical reaction between hydrogen and oxygen [1,2]. The electrolyte membrane of a PEMFC has a special property that allows only positive protons to pass through while blocking electrons. They are under intensive development in the past few years as they are regarded as potential alternative power sources in automotive applications due to their relatively small size, low temperature (40–180 °C), quick start up and easy manufacturing [3]. Recent developments in PEM and catalyst technology have greatly increased the power density of fuel cells, made them one of the most prominent technologies for future's automotive world [4]. 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.

In PEMFC, hydrogen which is generated from the fuel processing system is fed into the anode side of the cell stack, while air is pumped into the cathode side through an air compressor. On one hand, it is well known that the fuel cell stack life is reduced due to the so-called starvation phenomenon of the cell, because of insufficient supply of oxygen and hydrogen [5]. On the other hand, excessive supply is also undesirable due to the reduction of its efficiency. Pressure regulation remains one of the most challenging control problems. The main objective is to ensure minimum pressure difference between the anode and cathode side of the PEMFC, avoid the membrane from damage and increase the fuel cell stack life [6]. Several model based control approaches have been proposed for solving this problem, such as H_∞ robust control [7], feedback linearization plus pole placement [8], proportional integral (PI) plus static feed-forward controller [3] and static feedback controller [9]. To evaluate the performance of these controllers, a major obstacle is the absence of reliable measurements of hydrogen partial pressure, specially in the conditions of humidified gas streams inside the cell stack. 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. The sensors that do provide satisfactory performance usually suffer from slow response times, low accuracy, bulky and high cost [10]. Therefore, state observers serve as a replacement for physical sensors, are of great interest.

During the recent years, an increasing research activity has been addressing observation problems in fuel cell systems. Several kinds of Kalman Filters (KF) have been applied to the state estimation of fuel cell systems, i.e. classical KF [11,12], Unscented Kalman Filter (UKF) [13,14] and adaptive UKF [15]. It should be noted that these methods are based on model linearization around pre-defined operating points of the system, depending upon the operating conditions such as air flow, humidity and temperature. In addition, the calculation of Jacobian matrix of complex models like fuel cells is time consuming, making it difficult in real time implementation [16–19]. In [20], a

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Luenberger observer was employed to estimate the membrane water content in PEMFCs. However, it only ensures the convergence to a neighborhood of the real system states in the presence of external disturbances. Arcak et al. [10] developed an adaptive observer for hydrogen partial pressure estimation based on the fuel cell voltage. Following this work, Görgün et al. developed an algorithm which consists of two adaptive observers, for estimating partial pressures and the membrane water content in PEMFCs based on the resistive cell voltage drop [21]. However, both of them lack robustness against the fuel cell voltage's measurement noise and the model uncertainties.

Sliding mode observers (SMOs) have found wide application in the areas of parameter estimation [22], state estimation [23,24] and fault detection and isolation [17,25–27] in recent years. Their well-known advantages are robustness and insensitivity to external disturbance. Higher order Sliding Mode Observers have better performance as compared to classical sliding mode based observers because their output is continuous and does not require low pass filters. The super-twisting algorithm (STA), which is an unique absolutely continuous sliding mode algorithm among the SOSM algorithms, therefore it does not suffer from the problem of chattering [28,29]. The main advantages of the STA are the following: it does not need the evaluation of the time derivative of the sliding variable; its continuous nature suppresses arbitrary disturbances with bounded time derivatives.

In this paper, we present a nonlinear observer based on STA for the hydrogen partial pressure in the anode of the PEMFC, from the measurements of stack voltage, stack current, total cathode and anode pressures and supply manifold pressure. The main advantages of this paper are as follows:

- The finite time convergence of the observation error is proven via Lyapunov analysis.
- Only one parameter of the proposed algorithm has to be tuned.
- Robustness against voltage measurement noise is demonstrated via Lyapunov analysis.

The rest of the paper is divided as follows: the dynamic model of the PEMFC system is described Section 2. In Section 3, a nonlinear observer is designed for estimating the hydrogen partial pressure using SOSM technique. In Section 4, simulation results of the proposed observer are discussed. Finally, the major conclusions are presented in Section 5.

2. Nonlinear dynamic model of PEMFC

Fig. 1 shows a block diagram of a typical PEM fuel cell system [18]. It consists of four major subsystems: the hydrogen supply subsystem, the air feed subsystem, the humidifier subsystem and the cooling subsystem. As our study is related to the hydrogen supply subsystem, we will restrict the model for observer design specifically to the states of the hydrogen supply system and PEMFC anode. Certain assumptions have been imposed on the operating conditions, as follows:

*A*1 The stack temperature and humidity in the fuel cell cathode and anode are well controlled.

*A*2 The anode pressure is well controlled to follow the cathode pressure.

*A*3 The temperatures inside the anode and the cathode are equal to the stack temperature [11].

*A*4 The flow channel and the cathode backing layer are lumped into one volume which assumes uniform conditions inside the anode channel [10].

*A*5 Vapor partial pressure in the stack is considered equal to the saturation pressure.

Remark 1. The first two assumptions are valid from practical point of view as the temperature, humidity and anode pressure are usually regulated externally in PEMFC applications. The third assumption is justified as the temperature dynamics of a PEMFC stack are slow [11]. Assumption 4 is employed because we are interested in estimating the hydrogen partial pressure in the exit, and not its distribution along the channel [10]. Assumption 5 means that if the gas humidity drops below 100%, liquid water will either evaporate into the cathode gas or it will accumulate in the cathode.

2.1. Gas dynamics of hydrogen partial pressure

Under these considerations, a lumped model is given as follows:

$$\dot{p}_{H_2} = \frac{RT_{fc}}{V_{an}M_{H_2}}(W_{H_2,in} - W_{H_2,out} - W_{H_2,react}), \tag{1}$$

where M_{H_2} is the molar masses of hydrogen, $W_{H_2,in}$ is the mass flow rate of hydrogen gas entering the anode, $W_{H_2,out}$ is the mass flow rate of hydrogen gas leaving the anode, $W_{H_2,react}$ is the rate of hydrogen reacted, R is the universal gas constant, and V_{an} is the anode volume.

The inlet and outlet mass flow rates of hydrogen are given as follows:

$$W_{H_2,in} = \frac{1}{1+\omega_{an,in}} W_{an,in}, \tag{2}$$

$$W_{H_2,out} = \frac{1}{1+\omega_{an,out}} W_{an,out}, \tag{3}$$

where $\omega_{an,in}$ and $\omega_{an,in}$ are the anode inlet and outlet humidity ratios, respectively. $W_{an,in}$ and $W_{an,out}$ are anode inlet and outlet mass flow rates, respectively. Given that the purge of the anode gas is zero, they can be expressed as

$$\begin{aligned} \omega_{an,in} &= \frac{M_v}{M_{H_2}} \frac{\phi_{an,in} p_{sat}(T_{fc})}{p_{an} - \phi_{an,in} p_{sat}(T_{fc})}, \\ W_{an,in} &= K_{an,in}(p_{an,in} - p_{an}), \\ W_{an,out} &= 0, \end{aligned} \tag{4}$$

where M_v is the molar masses of vapor, $\phi_{an,in}$ is the relative humidity on the anode, $p_{sat}(T_{fc})$ is the saturation pressure at fuel cell stack temperature. $K_{an,in}$ is the nozzle inlet flow constant for the anode side, $p_{an,in}$ is the anode inlet pressure, and p_{an} is the anode pressure.

The reacted mass flow rate is defined by

$$W_{H_2,react} = M_{H_2} \frac{nI_{st}}{2F}, \tag{5}$$

where F is the Faraday constant, and I_{st} is the stack current, which is considered as a measurable disturbance variable.

2.2. Fuel cell stack voltage

Our observer is based on the voltage output, which is modeled by

$$V_{fc} = n(E - v_{act} - v_{ohm} - v_{conc}), \tag{6}$$

where n is the number of cells in the stack, E is the open circuit voltage, v_{act}, v_{ohm} and v_{conc} present the activation loss, ohmic loss and concentration loss, respectively.

The open circuit voltage E is expressed as

$$\begin{aligned} E &= E_0 + \frac{RT_{fc}}{2F}(\ln p_{H_2}) + \frac{RT_{fc}}{4F}\ln(p_{O_2}), \\ &= 1.229 - 0.85 \cdot 10^{-3}(T_{fc} - 298.15) \\ &\quad + 4.3085 \cdot 10^{-5} T_{fc}\left[\ln(p_{H_2}) + \frac{1}{2}\ln(p_{O_2})\right], \end{aligned} \tag{7}$$