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Nonlinear observation of internal states of fuel cell cathode utilizing a high-order sliding-mode algorithm

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HIGHLIGHTS

- A comprehensive nonlinear isothermal model of the air-feed system is introduced.
- A nonlinear state observation algorithm based on HOSM is deduced.
- Mathematical skills to make the observer operate online are described.
- Robustness against uncertainties in initial values and parameters is analyzed.

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ABSTRACT

A scheme for designing a second-order sliding-mode (SOSM) observer that estimates critical internal states on the cathode side of a polymer electrolyte membrane (PEM) fuel cell system is presented. A nonlinear, isothermal dynamic model for the cathode side and a membrane electrolyte assembly are first described. A nonlinear observer topology based on an SOSM algorithm is then introduced, and equations for the SOSM observer deduced. Online calculation of the inverse matrix produces numerical errors, so a modified matrix is introduced to eliminate the negative effects of these on the observer. The simulation results indicate that the SOSM observer performs well for the gas partial pressures and air stoichiometry. The estimation results follow the simulated values in the model with relative errors within $\pm$ 2% at stable status. Large errors occur during the fast dynamic processes (<1 s). Moreover, the nonlinear observer shows good robustness against variations in the initial values of the internal states, but less robustness against variations in system parameters. The partial pressures are more sensitive than the air stoichiometry to system parameters. Finally, the order of effects of parameter uncertainties on the estimation results is outlined and analyzed.

1. Introduction

Nowadays, hydrogen is regarded as an important potential energy vector for meeting the increasing demands placed on renewable energy as a primary power source. Polymer electrolyte membrane fuel cells (PEMFCs), which use hydrogen as fuel, have substantial potential as alternative power sources in applications such as automobiles [1–3]. Compared with traditional internal combustion engines, PEMFCs are highly efficient, quiet and environmentally friendly [4]. Extensive research into this technology is being conducted around the world, and in the past decades great progress has been made [5]. However, the durability, reliability and cold-starting capability of PEMFCs remain bottlenecks to the commercialization of this technology.

These dimensions of a PEMFC system relate to its internal operating conditions, e.g., the temperature, pressure, gas species concentrations in the channels, gas diffusion layers (GDLs) and catalyst layers (CLs). The performance of the electrochemical system is greatly affected by these conditions. Unexpected changes in internal operating conditions lead to global or local

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reactant starvations and ultimately the performance decay of the fuel cell [6,7]. To avoid global or local fuel starvations, it is critical to know the internal states of a PEMFC stack. The measurement of internal states is demanding even under laboratory conditions and by extension almost impossible for a vehicular system, because PEMFCs are hermetic systems. It is therefore necessary to develop virtual sensors that estimate the internal states within a PEMFC from peripherally measurable signals. These virtual sensors are usually developed on the basis of nonlinear observers and are regarded as an essential part of a control or fault diagnosis system. Further to this, small number of studies on state observers of PEMFCs have been published.

Luna [8–11] studied nonlinear distributed parameter observers (NDPOs) using distributed parameter models [8,9] and applied them to the control of a PEMFC system to improve the efficiency and durability of system [10]. Water flux through the membrane was regarded as an uncertainty of the observation problem, and a disturbance estimation algorithm and high-order sliding mode (HOSM) [12] algorithm were incorporated into the NDPOs so as to estimate the molar concentrations of hydrogen, oxygen, and water vapor on the anode and cathode sides. An observer with a Luenberger structure [13] was also designed for the internal states of the anode channels and predictive controls based on state observation were developed [11]. Schultze [14] proposed state estimation algorithms based on a sigma point Kalman filter for a PEMFC system that was fed with oxygen-depleted air. The oxygen concentration, water loading and temperature were then estimated using a lumped parameter model. Pilloni [15] studied an HOSM observer, which was between the second and third order in order to reconstruct the states of a PEMFC in a finite time using a lumped parameter model. The internal states of the cathode side, including the air mass in the supply manifold, oxygen mass on the cathode side, nitrogen mass on the cathode side and air stoichiometry, were estimated online and controlled by means of a feedback control algorithm. Piffard [16] presented a nonlinear observer for the nitrogen concentration on the anode side using an unscented Kalman filter. The nitrogen concentration on the anode side was regarded as a function of the cell temperature and water content in the membrane, and a nonlinear model was established on this basis. The state observer was then incorporated into a closed-loop control algorithm for dead-end operation. Rakhtala [17] designed an HOSM state observer for the air stoichiometry using a lumped parameter model and measurable variables, i.e., the compressor angular speed, the supply and return manifold pressures and cell current. The observer had increases in the response time and improved accuracy with respect to flow sensors. Kunusch [18] designed state observers for the hydrogen flux on the anode side and water flux through the membrane using a generalized super-twisting algorithm based on a lumped parameter model. Meanwhile, Mangold [19] incorporated a heuristic observer into a passivity-based control algorithm for a PEMFC. A one-dimensional, spatially-distributed model was presented and used to develop algorithms. A suitable Lyapunov function was chosen and a state feedback law that guarantees stability over a wide range of operational conditions was derived. Görgün [20] investigated reduced-order observers for molar fractions of gas species in fuel processing reactors of a PEMFC power system. On this basis, the convergence of the observers was analyzed and proved. Bressel [21] studied nonlinear observers based on an extended Kalman filter and degradation model of a PEMFC. The state of health of the PEMFC and the lifespan of the PEMFC were thereby estimated.

In summary, most nonlinear observers for internal states within PEMFCs are designed on the basis of lumped parameter models, which can be traced back to models developed in other papers [22,23]. Distributed parameter models, especially one-dimensional ones, have begun to be introduced to develop state observers that obtain the spatial details of internal states. However, the effectiveness of these models must be further verified in experiments. Gas species concentrations on the anode and cathode sides, air stoichiometry, and gas species fluxes are the most commonly considered aspects of the internal state. States on the anode and cathode sides are observed separately, and water transport flux is usually considered as an uncertainty variable in the problem. Variables that are related to permanent degradation in cell voltages are rarely taken into account. Most studies have adopted nonlinear state observers (e.g., the sigma point Kalman filter, unscented Kalman filter and HOSM) to estimate internal states. Among them the second order sliding mode (SOSM) algorithm, which is a typical kind of HOSM algorithm, has been favored recently, because it guarantees fast convergence and relatively high accuracy.

The present paper studies nonlinear observers for internal states on the cathode side of a PEMFC. A nonlinear isothermal model based on work from other studies [22–24] is introduced. Internal-state observers are designed on the basis of an SOSM algorithm. The algorithm is simulated in a stepped cycle, and its robustness against variations in initial values and system uncertainties is analyzed. The main contributions of this paper are as follows:

(1) The paper outlines a system-level isothermal one-dimensional two-phase flow model. Most of the system-level models nowadays are based on the one proposed by Pukrushpan [23], which is generally a one-phase zero dimensional model that can capture the filling-and-emptying process of a fuel cell system. In this paper, the model is improved in two aspects. Firstly, the electrochemical model is improved. The influence of liquid water saturation ratio of the cathodic GDLs on the cell voltage, is considered. Secondly, the one-dimensional two-phase water transport process in the membrane electrolyte assembly (MEA) is considered.
(2) It suggests an available observability matrix, finds a method for solving the problem of the singularity of the observability matrix, and proposes a method for calculating the inverse of the observability matrix online. There are two critical problems relating to an SOSM observer, namely: 1) how to find the observability matrix; and 2) how to calculate the inverse matrix of the observability matrix online. Based on Rakhtala's [17] work, this paper proposes one available observability matrix. Then, this paper provides a new methods to avoid the singularity of the matrix by introducing several linear mapping coefficients. An on line algorithm for the Moore-Penrose pseudo inverse matrix is developed for the inverse observability matrix.
(3) Furthermore, the paper simulates and analyzes robustness of the state observer against uncertainties about initial values and system parameters, and outlines the order of the effects of system uncertainties on estimation results.

The remainder of the paper is organized as follows. Section 2 briefly introduces a nonlinear isothermal model for the PEMFC system. Section 3 defines the problem of internal state observation and designs an SOSM-based observer. Section 4 simulates the performance of the observer and checks its robustness. Section 5 presents some conclusions and proposes future work.