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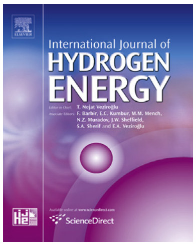

A nonlinear sliding mode observer for the estimation of temperature distribution in a planar solid oxide fuel cell

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ABSTRACT

Compliance to certain temperature constraints is essential for the long life and stable operation of solid oxide fuel cells (SOFCs). However, it is difficult and costly to measure the temperature inside a high temperature, well-sealed cell directly. A nonlinear sliding mode observer has been designed in this paper for estimating the temperature distribution in a hydrogen fed SOFC stack. The observer design is based on a finite-volume parameter SOFC model, which is simplified by quasi-static mass balance assumption. In the observer design, a decoupling pole placement method that applies to multi-timescale systems is proposed to obtain a suitable observer gain. And a quasi-sliding mode control method is adopted to eliminate the chatter caused by the discontinuous control actions of sliding mode control. Theoretical analysis and simulation results are presented to prove the convergence and good performance of the designed observer for estimating the temperature distribution in a SOFC stack during steady-state and transient operation.

Introduction

Solid oxide fuel cells (SOFCs) have emerged as a promising alternative to traditional power generation because of factors such as their high efficiency, low emissions and flexible fueling strategies. Among the different types of SOFCs, planar SOFCs are most attractive because they are easy to fabricate and assemble and can offer a higher power efficiency. Although substantial progress has been made in planar SOFC technology development, many technical obstacles still have to be overcome to realize its widespread application and commercialization [1]. The most notable of these challenges for planar SOFC system development is to monitor and control the temperature and temperature gradient in the stack [2].

Because of the high operating temperature (600–1000 °C), the maximum temperature in the SOFC must be limited to

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Nomenclature

A	area, m^2
C	specific heat capacity, J mol^{-1} K^{-1} or constant
d	distance, m
E_N	Nernst's voltage, V
F	Mole flow rate, mol s^{-1} or Faraday's constant, $=96{,}485$ C mol^{-1}
h	enthalpy, J mol^{-1}
I_{tot}	total electrical current of the stack, A
i_k	electrical current of the kth node, A
k	heat transmission coefficient, k WK^{-1} m^{-2}
L	gain
N	mole number
P	intensity of pressure, Pa
R	ideal gas constant, $=8.314$ J mol^{-1} K^{-1}
R_s	equivalent electric resistance, Ω
T	temperature, K
V	volume, m^3
V_{cell}	the voltage of single cells, V
x	mole fraction

Greek letters

ρ	density, kg m^{-3}
τ	thickness, m

Signs

→	converge to
α	proportional to

Subscripts

in	inlet
act	activation
an	anode
ca	cathode
con	concentration
ic	interconnector
k	k th node
load	electronic load
ohm	ohmic
pen	Positive electrode-Electrolyte-Negative electrode
sol	solid structure
tot	total

Abbreviation

PCS	power control system
PEN	Positive electrode-Electrolyte-Negative electrode
SOFC	solid oxide fuel cell

guarantee the security of the material and the system performance [1,2]. The sandwiched structure of the positive electrode–electrolyte–negative electrode (PEN) assembly consists of three solid layers, which are tightly attached together and have different thermal expansion coefficients [1,3]. Large temperature gradients in the stack can give rise to significant thermal stresses in the PEN structure because of a mismatch in thermal expansion coefficients between these components [3]. Such thermal stresses can cause delamination and cracks in the critical layers of the PEN [4] and shorten the cell life. It is therefore important to maintain the maximum temperature and the temperature gradient of the stack within the required range.

As the two most important temperature indices, the maximum temperature and the temperature gradient in a SOFC stack could be monitored and controlled if the temperature distribution in the stack can be obtained. However, a direct measurement of the temperature distribution in a high-temperature stack is usually not practically feasible. It is undesirable to place too many thermocouples in a well-sealed SOFC stack because of the difficulty in implementation and cost. Therefore, designing an observer that can estimate the temperature distribution accurately with limited and easily accessible measurements would be preferred.

In this paper, a co-flow planar SOFC stack is taken as the study object. It is composed of 30 single cells and is designed to produce a 1000 W output. The cell size is 10 × 10 cm^2 with a 9 × 9 cm^2 active area for reaction. The basic structure and operating principle of a single cell is shown in Fig. 1 [16]. Since the reaction processes in each stack cell are assumed to be the same, the model has been developed for a single cell before being extended to the stack. To obtain the temperature distribution, the cell is divided equidistantly into five nodes along the gas flow direction from the inlet to outlet and then the finite-volume method is applied to derive the model of a single cell (shown in Fig. 2 [6]). This model is expanded to a model of the SOFC stack comprised of 30 single cells. The stack model is used as the virtual plant, namely the reference model, to design a nonlinear observer. In the observer designing process, the stack inlet conditions, including temperatures, mole fractions and inlet fuel and air flow rates, are assumed to be given and three easily accessible measurements are used, namely, the cell voltage and the temperatures of the fuel and air at the stack outlet. Simulation shows that the observer that was designed could estimate the temperature distribution effectively during steady-state and transient operations. According to the temperature distribution in the stack, the maximum temperature and temperature gradient in the PEN can be obtained easily.

This paper is organized as follows: the SOFC model used for the observer design is presented in section 2, where an electronic load working on a constant current mode is added. In section 3, a nonlinear sliding mode observer is developed,

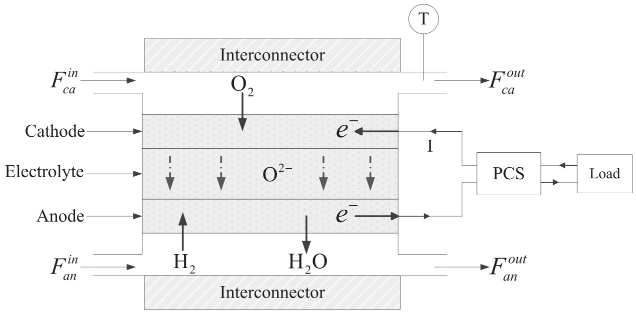

Fig. 1 – Schematic showing SOFC construction and operation.