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Review

Dynamic modelling and control of planar anode-supported solid oxide fuel cell

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Abstract

Most solid oxide fuel cell (SOFC) modelling efforts emphasize steady-state cell operation. However, understanding the dynamic behaviour is essential to predict the performance and limitations of SOFC power systems. This article presents the development of a SOFC dynamic model and a feedback control scheme that can maintain output voltage despite load changes. Dynamic responses are determined as the solutions of coupled partial differential equations derived from conservation laws of charges, mass, momentum and energy. To obtain the performance curve, the dynamic model is subjected to varying load current for different fuel specifications. From such a model, the voltage responses to step changes in the fuel concentration and load current are determined. Low-order dynamic models that are sufficient for feedback control design are derived from the step responses. The development of the partial differential equation model is outlined and the limitations of the control system are discussed.

Keywords: Solid oxide fuel cell; Dynamic modelling; Simulation; Load change; Control

Contents

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1. Introduction

A fuel cell is a device that converts a constant supply of fuel directly to electrical power. Solid oxide fuel cells (SOFC) have emerged as one of the leading fuel cell technologies which can be used in a wide range of commercial applications. Their solid electrolyte is made of a ceramic material which requires the operating temperature range of 800–1000 °C. In recent years, the number of computational models of SOFC has been gradually increasing. Since SOFC operations are often subjected to transient condition such as changes in power demand, fuel cell dynamics have been increasingly considered in modelling activities. By developing a physically based dynamic model, the transient behaviour of SOFC can be accurately predicted and the design envelopes can be optimized. The dynamic model is especially beneficial for control testing in the development stage of SOFC.

Most of the existing dynamic models were developed for prediction of SOFC performance and limitations. Additionally, the majority of dynamic models for process control have focused on large-scale operation such as an integrated-SOFC power plant system. For instance, Stiller, Thorud, Bolland, Kandepu, and Imsland (2006) and Thorud, Bolland, and Kvamsdal (2002) have presented a dynamic model for control of the integrated SOFC and turbine systems. It has been shown that the power supplied by the SOFC system can be controlled by manipulating the fuel flow using a proportional–integral–derivative (PID) type controller. In other work by Aguiar, Adjimana, and Brandon (2005), the temperature control of a stack-level SOFC model was presented. A PID controller was implemented to maintain the outlet fuel temperature and the fuel utilization during load changes by varying the air flow rates. The findings from these models emphasize the need for the process control to enhance the reliability and minimize the degradation of SOFC.

A physically based three-dimensional (3D) dynamic model of a single SOFC is presented in this article. To investigate the transient performance and limitations of SOFC, this dynamic model is subjected to step changes in inlet gas concentrations and external load currents. Low-order models capable of capturing the main dynamic behaviour of the SOFC system are derived from the step responses. Feedback PI controllers are simulated with the low-order models in the voltage control-loop. An approach to control the output voltage such that it is close to the set-point voltage despite external load changes is outlined.

The remaining of this article is organized as follows: Section 2 presents a review of the SOFC operating principles; Section 3 presents the numerical formulation for the dynamic model; Section 4 discusses the steady-state and dynamic modelling results; Section 5 addresses the control of the SOFC output voltage in the presence of varying load by implementing a PI controller. The concluding remarks are presented in Section 6.

2. SOFC operating principles

In SOFC, the oxygen ion (O^{2-}) is the mobile ion transferred through a solid electrolyte in the following half-cell reactions at the cathode and anode, respectively.

$$\tfrac{1}{2}O_2 + 2e^- \leftrightarrow O^{2-} \tag{1}$$

$$H_2 + O^{2-} \leftrightarrow H_2O + 2e^- \tag{2}$$

The overall reaction is then

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{3}$$

A schematic diagram presenting the flow of mass and charges for a SOFC is shown in Fig. 1.

2.1. Thermodynamics of solid oxide fuel cells

The amount of voltage that an electrochemical fuel cell produced is determined from the change in Gibbs free energy of an overall chemical reaction. The change in Gibbs free energy is dependent on the partial pressure of the reactants and products. For a hydrogen–oxygen fuel cell, the change in Gibbs free energy is

$$\Delta G(T) = \Delta G^{\circ}(T) + RT \ln\left(\frac{P_{H_2O}}{P_{H_2} P_{O_2}^{1/2}}\right) \tag{4}$$

where $\Delta G^{\circ}(T)$ is the Gibbs free energy change at standard state. At equilibrium, the change in Gibbs free energy is related to the electrochemical work done by electrons according to the equation

$$\Delta G(T) = -n_e F E(T) \tag{5}$$