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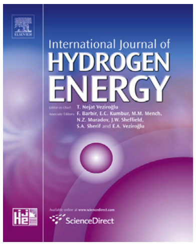

Review

Dynamic modeling and analysis of a 5-kW solid oxide fuel cell system from the perspectives of cooperative control of thermal safety and high efficiency

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ABSTRACT

One of the key problems for a solid oxide fuel cell (SOFC), which is a high-temperature power-generation plant, is the cooperative control of safe operation and system efficiency during load tracking. Within the constraints of thermal safety, the SOFC plant should have the maximum output efficiency under various static conditions. Moreover, the SOFC system can switch between these different static working conditions smoothly, safely, and quickly when the external load power changes. To achieve cooperative thermoelectric control, a second air bypass manifold from the primary air manifold has been added in this research to regulate temperature and improve system efficiency. An integrated SOFC model has also been developed to perform both steady-state and dynamic analysis. Taking a 5 kW stand-alone SOFC system as the research object, the optimal operating points (OOPs) that meet thermal safety requirements and provide maximum system efficiency under different levels of static output power are determined by a transverse optimization process. According to the optimal static strategy designed in this research, the effect of the bypass valve on SOFC system performance has been analyzed. Furthermore, the optimal power-switching scheme is discussed for SOFC system power switching between OOPs during load tracking, in which the system can switch smoothly, safely, and quickly without fuel exhaustion and while satisfying thermal constraints. In particular, the power-switching scheme is validated to demonstrate that the scheme proposed in this paper can solve these key problems for international applications.

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Nomenclature

AR	air excess ratio, –
BP	bypass valve opening ratio, –
C	specific heat capacity, kJ $kmol^{-1}$ K^{-1}
ΔE_0	standard electrode potential, V
FU	fuel utilization, –
F	Faraday's constant, 96,485 C mol^{-1}
h	convective heat transfer coefficient, kW cm^{-2} K^{-1}
I	current, A
i	current density, A cm^{-2}
LHV_{H2}	low heating value of hydrogen, 241.83 kJ mol^{-1}
Max.$\lvert\Delta T_{PEN}\rvert$	maximum PEN temperature gradient, K cm^{-1}
Max.T_{PEN}	maximum PEN temperature, K
ΔT_{inlet}	stack inlet temperature difference, K
N	control volume mole number, kmol
$\dot{N}$	molar flow rate, kmol s^{-1}
N_0	number of fuel cells, –; 134
p	pressure, bar
k_{ss}	solid conduction heat transfer coefficient, kW cm^{-1} K^{-1}
P	power, kW
$\dot{Q}$	heat transfer, kW
R	universal gas constant, 8.314 kJ $kmol^{-1}$ K^{-1}
T	absolute temperature, K; time constant, s
U	voltage, V
$\dot{W}$	work, W
X	species mole fraction
L	distance between control volume, cm
C_D	current density, A cm^{-2}
i_0	exchange current, A cm^{-2}
S	surface area of the heat transfer, cm^2
j	the index of discretization units of the cell calculated
J	the user-defined number of cell nodes

Greek letter

τ	effectiveness
γ	specific heat ratio, 1.4
δ	number of electrons participating in the electrochemical reaction
α	charge transfer coefficient, 0.5
ε	specified tolerance constant, 1e-5
η	efficiency, %
ρ	density, kg m^{-3}

Subscript

amb	ambient
act	activation
B	burner
bl	blower
con	concentration
ohm	ohmic
i	species
in	inlet
out	outlet
net	system net output power
s	stack; solid control volume
v	volume
g	gas control volume
ca	cathode
an	anode
cond	conduction
conv	convection
cell	fuel cell

Introduction

Solid oxide fuel cells (SOFCs) generate electrical power directly from hydrocarbon fuels without burning and mechanical transmission, which could bring a number of advantages, such as high electrical efficiency, low emissions and quiet operation [1–4]. As such, SOFC power systems are becoming to be the focus of research.

Based on the requirement for a high-temperature environment, the SOFC stand-alone power system should take full advantage of the heat from electrochemical reactions to achieve self-sustainability and promote efficiency [5]. Therefore, the hydrogen-fueled SOFC system proposed in this paper is consist of the SOFC stack, the control system, and the balance of plant (BOP), as shown in Fig. 1(a). Among these, the stack is the core power-generation component, and the control system manages and optimizes the stack output performance according to criteria like safety, high efficiency, and stability by taking advantage of the BOP.

In a SOFC system, a medium–high temperature environment should be sustained for the electrochemical reaction. However, excessively high temperature causes thermal stresses during transient operation, with excessive temperature gradients possibly causing failure of the fuel cell [6,7]. The electrical characteristics are tightly coupled with the thermal characteristics. The higher the temperature, the denser will be the electric current and the higher the output efficiency, the thermoelectric coupling relationship can be described as Fig. 1(b).

Therefore, cooperative control of thermal safety and optimization efficiency is the key issue for an SOFC power system.

Since the 1990s, SOFC technology has made great progress in materials and design, especially in single-cell and sealing materials, cell fabrication, and stack design. Efficiency and life-cycle performance have been improved on test platforms which depend on the stable temperature environment of furnaces to provide the necessary thermal operating conditions. However, without the furnace environment, for a stand-alone SOFC system oriented to load following, there is no physically feasible way to achieve cooperative control of thermal safety and optimization efficiency.

It was clearly pointed out in Refs. [8,9] that cooperative control of thermal safety and optimization efficiency of an SOFC system is the key issue for load-following applications.

To ensure system safety given the thermal characteristics, four constraints should be satisfied, including maximum PEN (Positive electrode-electrolyte-negative electrode) operating temperature, maximum PEN temperature gradient, stack inlet gas temperature difference and maximum burner temperature.