Electrochimica Acta 177 (2015) 237–249

Contents lists available at ScienceDirect

Electrochimica Acta

journal homepage: www.elsevier.com/locate/electacta

Control strategy for power management, efficiency-optimization and operating-safety of a 5-kW solid oxide fuel cell system

Lin Zhang, Jianhua Jiang, Huan Cheng, Zhonghua Deng, Xi Li *

School of Automation, Key Laboratory of Education Ministry for Image Processing and Intelligent Control, Huazhong University of Science & Technology, Wuhan, 430074, China

A R T I C L E I N F O

Article history:
Received 14 January 2015
Received in revised form 3 February 2015
Accepted 6 February 2015
Available online 7 February 2015

Keywords:
Solid oxide fuel cell(SOFC)
Optimal operating points(OOPs)
pre-conditioning current strategy
feedback power reference control scheme
load step-up transients

A B S T R A C T

The slow power tracking, operating safety, especially the fuel exhaustion, and high efficiency considerations are the key issues for integrated solid oxide fuel cell (SOFC) systems during power step up transients, resulting in the relatively poor dynamic capabilities and make the transient load following very challenging and must be enhanced. To this end, this paper first focus on addressing the efficiency optimization associated with simultaneous power and thermal management of a 5-kW SOFC system. Particularly, a traverse optimization process including cubic convolution interpolation algorithm are proposed to obtain optimal operating points (OOPs) with the maximum efficiency. Then this paper investigate the current implications on system step-up transient performance, then a two stage pre-conditioning current strategy and a feedback power reference control scheme is proposed for load step-up transients to balance fast load following and fuel starvation, after that safe thermal transient is validated. Simulation results show the efficacy of the control design by demonstrating the fast load following ability while maintaining the safe operation, thus safe; efficient and fast load transition can be achieved.

1. Introduction

Solid oxide fuel cells (SOFCs) offer high electrical efficiency, quiet operation and low emissions compared to conventional power production technologies by generating electrical power directly from hydrocarbon fuels without burning and mechanical transmission [1,2]. Thus given the global focus on energy and environmental issues, SOFCs are attracting more attentions.

The operational challenge of SOFCs arises from two competing goals, namely, the optimization of the steady state efficiency versus the fast and safe load transitions. Maximizing SOFCs' electrical efficiency is one of the main goals for SOFC stand-alone power system. Firstly, higher system efficiency means lower cost [3]. Secondly, higher efficiency also results in lower emissions. The output efficiency is tight coupling with thermal characteristics, the electric current density would be more and output efficiency would be higher with higher temperature. Then, a medium-high temperature environment should be sustained for the electrochemical reaction in SOFCs. However, excessively high temperature and gradients with thermal stresses would possibly cause failure of the fuel cell during transient operation [4,5]. Thus the cooperative consideration of operating safety and efficiency optimization is the key issue for SOFC power system load following applications.

Multiple studies show that the steady state efficiency increases by minimizing fuel consumption for a given load or maximizing power production for a given fuel supply [6,7]. However, all these works are completed from the point of view of maximizing the SOFC system efficiency, where there is no mature thermoelectric analysis for thermo-safety and efficiency-optimization. The safe temperature zones of individual system component is neglected. The operating temperature of SOFC system components should be controlled in safe range where the system efficiency is maximal. For this objective, Handa [8] has analyzed steady-state optimization and concluded that the OOPs can be determined by maximizing the system efficiency while enforcing the operating constraints on maximum PEN temperature and its gradient. In this way, OOPs for partial and full load operation conditions by considering two temperature constrains are found out. However, in Handa's work, the tail-burner and heat exchangers are not included and the SOFC system considered is simplified, thus burner temperature constrains and the balance of plant (BOP) of

Abbreviations: BOP, Balance of Plant; OOP, Optimal operation point; PEN, Positive electrolyte negative; SOFC, Solid oxide fuel cell.

* Corresponding author. Tel.: +86 13296629989; fax: +86 027 87557273.
E-mail address: lixi_wh@126.com (X. Li).

http://dx.doi.org/10.1016/j.electacta.2015.02.045
0013-4686/

Nomenclature

AR	Air excess ratio [–]
BP	Bypass valve opening ratio [–]
FU	Fuel utilization [–]
I_s	Stack current [A]
$Max.\|\Delta T_{PEN}\|$	Maximum PEN temperature gradient [K cm^{-1}]
$Max.\|T_{PEN}$	Maximum PEN temperature [K]
ΔT_{inlet}	Stack inlet temperature difference [K]
T	Absolute temperature [K]; time constant [s]
$\triangle E_0$	Standard electrode potential [V]
SE	System efficiency [%]
t_d	Gas transmission delay time [s]
F	Faraday's constant [96485 C mol^{-1}]
LHV_{H2}	Low heating value of hydrogen [241.83 kJ mol^{-1}]
$\dot{N}$	Molar flow rate [kmol s^{-1}]
N_0	Number of fuel cells [–]; 134
p	Pressure [bar]
P	Power [kW]
$\dot{Q}$	Heat transfer [kW]
R	Universal gas constant [8314 kJ kmol^{-1} K^{-1}]
T	Absolute Temperature [K]; time constant [s]
U	Voltage [V]
$\dot{W}$	Work [W]
X	Species mole fraction
i_0	Exchange current [A cm^{-2}]
A	Surface area of discretization units of the cell calculated [cm^2]
k	The index of discretization units of the cell calculated
K	The user-defined number of cell nodes; 5

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

Subscript

amb	Ambient
act	Activation
B	Burner
bl	Blower
con	Concentration
ohm	Ohmic
net	System net output power
s	Stack
HE	Heat exchanger
by	Bypass
cond	Conduction
conv	Convection
cell	Fuel cell

SOFCs are neglected. Xi H. [9] considered the temperature constraints during the optimization for a simplified SOFC system, but only addressed two representative load conditions (part load and full load). H. L. Cao [10] took an analysis on optimization of a kW scale SOFC stand-alone system for maximum system efficiency and considered four temperature constraints, but instead of a proposed optimization method, the maximum system efficiency is obtained at the two dimensional planes. What's more, it only discussed the thermal management oriented steady state analysis where ignored electrical characteristics analysis.

Due to SOFCs operate at elevated temperatures (~1000 K) to sustain for the electrochemical reaction. Since 1990 s, SOFC technology has made great progress in materials and design, especially in single cell and seal materials, cell fabrication, stack design, control and system integration. As a result, the efficiency and life cycle performance have been improved dramatically. However, high performance and stability of SOFCs are demonstrated mostly on test platforms, there is no physically feasible method to achieve cooperative control of operating safety and efficiency optimization for a stand- alone SOFC system oriented to load following in practice.

Thus the parametric study which allows SOFCs operate safely while retaining cell performance and high efficiency must be revealed. The operating parameters usually including fuel utilization (*FU*), air excess rate (*AR*) [8,10]. For a simple SOFC system that consists of a blower, a heat exchanger, an SOFC stack and an exhaust burner, its degree of freedom for control and dynamic operation is very limited. Research has shown that the spatial temperature variations of the fuel cell over a large fuel cell operating envelope can be effectively managed by optimally manipulating the cathode air flow rate the stack cathode inlet temperature [6,7,10,11]. Based on the above research, by adjusting the cathode inlet gas temperature using a bypass valve (*BP*), Fardadi [4] indicated that the SOFC system can be designed and controlled to contain the spatial temperature distribution deviation within a small range so that thermal stress problems can be mitigated. Further, L. Zhang [12] analyzed the positive effect of the *BP* on the system thermal management and system efficiency under various output power conditions. Thus *BP* is also involved in the operating parameters in this paper.

As the shortcomings of existing methods for analyzing and summarizing achievements already realized, i.e. the incomplete SOFC system thermal constrains, incomplete physical realization of efficiency-optimization and operating-safety oriented control, the problems such as time delay and fuel exhaustion during power step-up transient. Existing results cannot provide a practical alternative for use in an effective control method for SOFC systems, especially a thermoelectric control system with perfect security, life and efficiency indexes.

Multiple studies from the literature [13–16] and our study have revealed that the relatively poor dynamic capabilities of the SOFCs are often the results of integrated system characteristics and stringent operation safety requirements. The relatively negative impact on the components and system life cycle are as follows: (1) when the load is suddenly increased, the SOFC may not be able to provide sufficient fuel and heat to sustain the operation under the new load condition. (2) large thermal inertia of the high temperature SOFC and fuel path dynamics often lead to slow transient response. (3) while the SOFC is generally able to response to quick load changes, a sudden large change in SOFC operation condition could seriously impact the components and their life cycle due to thermally induced stress. Thus fast load following and safe transient operation are considered most critical here for reliable performance of SOFC system in working conditions. Some authors [17–20] have focused on investing the behavior of SOFC plants by taking into account the load following and operating conditions, but the research is very far from obtaining satisfactory results given the facts that the optimal set-points are located at the boundary of the feasible operation region [21].

According to the key problems discussed above, this research attempts to ensure an independent power supply for the stand-alone SOFC system from the perspectives of thermoelectric control for power management, efficiency-optimization and operating-safety. On the one hand, in order to maximize fuel cell efficiency