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On dynamic operation modes of fuel cell: A comparison between the single-loop and multi-loop controls

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ABSTRACT

Solid Oxide Fuel Cell (SOFC) is a promising alternative in power generation due to its reliable, efficient, and pollution free characteristics. However, the existing operation modes proposed for the SOFC dynamic control remain inconsistent and even conflicting. To this end, this paper compares the existing control schemes, detailing the merits and deficiencies, respectively. The dynamic model of a tubular SOFC is developed by formulating the disturbance input as load resistance instead of the load current, because the load current is coupled with the voltage during the transient. Different operation modes, i.e., constant fuel flow, constant fuel utilization, and constant voltage operation, are respectively investigated under load fluctuation. Simulation results show that constant fuel flow is advantageous in terms of simplicity; constant fuel utilization is superior in terms of efficiency; constant voltage operation will ease the necessity of using a converter. Finally, based on the nonlinearity, pairing, and coupling analyses, a multivariable operation strategy is explored to maintain fuel utilization and terminal voltage, simultaneously. The results show that this proposed operation strategy is able to achieve the merits of both the constant fuel utilization and constant voltage operation.

Introduction

Solid Oxide Fuel Cells (SOFCs) are advanced electrochemical energy conversion devices playing an important role in a micro-grid due to its reliability and environmental friendliness [1]. They are superior to conventional power generation in the prospects of wide applications in stationary distributed power generation, transportation and military market sectors [2,3]. When combined with heat and power applications, the energy conversion efficiency of SOFCs can be up to 65% [4], and release very low levels of NO_x and SO_x emissions. Recently, numerous papers were concerned with advanced materials technologies for SOFC [5–7]. Besides, some researchers were working on the field of SOFC low temperature operation [8–10]. However, Researches on safe, stable and efficient operation of SOFC are also very important.

During the last decades, dynamic model studies and controller design highly promote the developments of SOFC in theory and provides previous reference for the researches and practitioner [11–19]. Padullés, Ault and McDonald [11] created a simulation model of SOFC power plant intended for a power

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Nomenclature

A	Area (m^2)
b	Constant material resistance (K)
h	Heat transfer coefficient $[W/(m^2 \cdot K)]$
i_0	Exchange current (A)
l_c	Distance from cathode to reaction (m)
m	Mass (kg)
P, p	Pressure (atm)
R	Gas Constant, or resistance
V	Volume (m^3), or Voltage (V)
ε	Emissivity
a	Constant material resistance ($\Omega \cdot m$)
C	Specific heat capacity $[J/(mol \cdot K)]$
I, i	Current (A)
l_a	Distance from anode to reaction (m)
M	Mole flow rate (mol/s)
M_{mw}	Molecular weight (kg/mol)
q	Energy (J)
T	Temperature (K)
υ	Stoichiometric coefficient in reaction
δ	Thickness (m)

Superscripts and subscripts

AST	Conditions for air supply tube
act	Activation
air	Conditions for air
ca	Cathode
con	Concentration
ele	electricity
Fuel	Conditions for fuel
g	Vapor
H_2	Hydrogen
in	Conditions of input/inlet
O_2	Oxygen
out	Conditions of output/outlet
Red	reduction reaction
a	Air
an	Anode
air, AST	Conditions for air in AST
cell	Conditions for a single cell
conv	Convective
flow	Flow heat exchange
f	Fuel (Hydrogen and Vapor)
H_2O	Vapor (water)
itc	interconnection between cells
Net	Net values
ohm	Ohmic
Ox	oxidation reaction
rad	Radiation

system analysis package. However, the influence of reaction temperature was not considered in these models. Wang and Nehrir presented a dynamic model for tubular SOFCs based on electrochemical and thermodynamic properties [12], which illustrated the dynamic process of fuel cell effectively and integrally. Despite lacking of the speed of simulation, many nonlinear models describe the characteristics of SOFCs more accurately [13–15]. Moreover, Aguiar, Adjiman and Brandon [16] were devoted to exploring the influence of temperature in different parts in a distributed parameter model. Chakraborty [17] built an SOFC system model based on genetic programming approach by describing the electrochemical and thermal characteristic. In addition, Murshed, Huang and Nandakumar proposed lumped and detail model, and analyzed performance of transient system [18]. In order to further improve the efficiency of system, the control oriented modeling and analysis of the integrated SOFC/gas turbine system were included in Refs. [20,21].

Although plenty of models have been studied and considered, the change of load resistance has rarely been considered in the model. The change of load resistance is the main influence factor in the user side, which should be considered in simulation. Therefore, one achievement of this paper is to use load resistance instead of load current to study the transient dynamic of SOFC.

In addition, plenty of operation schemes have been developed to explore the performance of SOFC. In general, these schemes can be classified into two categories.

i) The single operation mode [22–28], which selects different variables to realize corresponding requirements. For example, the problem of input saturation and fuel utilization can be solved by adaptive neural network based adaptive constrained control scheme in Ref. [22]. In order to track voltage, model predictive controller was designed to for SOFC in Ref. [23]. The distribution of SOFC temperature was estimated by nonlinear sliding mode observer in Ref. [25]. However, those operation schemes are still inconsistent and controversial among published studies. Only a few pieces of researches have been proposed to expound merits and deficiencies of the operation schemes. Therefore, different operation strategies are discussed and compared in this paper to make guidance for further understanding to the dynamic tubular SOFC model. However, these operating modes cannot meet the requirements of multiple objectives.
ii) The multivariable operation mode, which improves dynamic performance of SOFC. Even though plenty of advanced optimization algorithms were used [29–31], there are few studies on multivariate modes of SOFC operations [32–34]. Y. Komatsua, S. Kimijimab and J. S. Szmydc employed multi-loops method to control the fuel utilization, output power and temperature based on a multivariable SOFC model in Ref. [32]. Cao and Li proposed adaptive PID controller combined with feedforward controllers to control the temperature of stack and fuel utilization in Ref. [33]. In Ref. [34], a multiple model predictive was presented to keep the output voltage and fuel utilization at constant. However, these control strategies did not consider the coupling between these objects and nonlinearity of SOFC under operation range. Therefore, this paper not only analyzes the nonlinearity, pairing, and coupling of SOFC, but also ensures the stability of fuel utilization and output voltage.

The paper is organized as follows: Section Multivariable SOFC model will improve the model obtained in Ref. [24] in the MATLAB/Simulink environment, where the