Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/he

An MCFC operation optimization strategy based on PID auto-tuning control

Donghyeon Lee [a], Yujin Cheon [a], Jun-Hyung Ryu [b,*], In-Beum Lee [a]

[a] Department of Chemical Engineering, Pohang University of Science and Technology, Pohang, 37673, South Korea
[b] Department of Nuclear & Energy System Engineering, Dongguk University, Gyeongju, 38666, South Korea

ARTICLE INFO

Article history:
Received 21 March 2017
Received in revised form
25 August 2017
Accepted 26 August 2017
Available online xxx

Keywords:
MCFC
Operation optimization
Load adjustment
PID control
Auto-tuning

ABSTRACT

Molten Carbonate Fuel Cell (MCFC) has been emerging as a promising renewable power system. It is still challenging to operate the MCFC to meet its varying demands because of its nonlinearity and complex dynamics. This paper proposes a novel MCFC operation framework based on PID auto-tuning control. A case study is presented to illustrate the applicability of the strategy with some comments.

Introduction

Molten carbonate fuel cell (MCFC) is drawing an increasing attention as a promising renewable power system. The attention is caused by its strengths against fossil fuel based ones: it can provide power only through chemical reactions without generating environmentally hazardous byproducts. It can be employed in various sectors such as industries, commercial and residential buildings. A variety of fuels including biogas or even carbon dioxide can be used as fuels.

In order to take full advantage of such strengths, it should be easy to use them in practice. When customer demand is changed, it should be possible to obtain the corresponding operation adjustment in a straightforward manner. It should not require too much time delay or additional high cost. So far MCFC has been operated to obtain the fixed maximum capacity. Most works on MCFC thus focused on obtaining high performance, or searching for more efficient component materials. For example see the review by Bischoff (2006) [1].

The task of adjustment is not easy because dynamics of MCFC operation is highly complex and nonlinear [2,3]. The MCFC operation should be flexible enough to cope with changing environments. The operation under the assumption of a constant demand is not economically desirable because any redundant energy more than demand is wasted. The operation adjustment with regards to varying demand should be orchestrated in the operation framework. This can be done by modifying the operation variables based on the rigorous framework. This paper aims to develop the framework by transforming the MCFC operation into a control optimization problem.

* Corresponding author.
E-mail address: jhryu@dongguk.ac.kr (J.-H. Ryu).
http://dx.doi.org/10.1016/j.ijhydene.2017.08.184

Nomenclature

$a_{max,k\text{-}1}$	maximum value at the k-1st period in the excitation step
$a_{min,k\text{-}1}$	minimum value at the k-1st period in the excitation step
f_l	radial basis function of lth node in the hidden layer
G_m	identified frequency response model
g_{RBF}	function symbol
k	static gain of the frequency response model
L	number of hidden nodes
LHV	lower heating value
$\dot{m}_{air}$	air flowrate, mole/sec
$\dot{m}_{fuel}$	fuel flowrate, mole/sec
n	number of the operating regions
P_f	period of the final cyclic steady state part
P_i	period of the initial cyclic steady state part
P_{net}	fuel cell stack net power, kW
P_{on}	relay on value of the net power, kW
P_{off}	relay off value of the net power, kW
P_{ref}	relay reference value of the net power in the excitation step, kW
P_{ss}	net power output at steady state
P_{max}	maximum net power output
ΔP	difference of the net power
r	region index
rm	reduced model
t_i	starting time of the initial steady state
t_f	starting time of the final steady state
$u_1(t)$	deviation variable of the fuel flowrate, mole/sec
$u_2(t)$	deviation variable of the air flowrates, mole/sec
$u_{ref}(t)$	fuel flowrate reference value, mole/sec
$u_{ref,k}$	reference value of the fuel flowrate at the kth period
$v(t)$	relay output in the biased-relay feedback control system
$w_{m,l}$	weight factor connecting the lth hidden node response to the mth output
$\overline{x}_{l,n}$	center of the lth hidden node corresponding to the nth input
x_n	nth input vector in the neural network model
$y(t)$	deviation variable of the stack output power
$y_{ref}(t)$	deviation variable of the reference value regarding relay on/off
$\hat{y}_m$	predicted value of the mth node of the neural network output layer

Greek symbols

α	tuning parameter of the excitation step
α_{rm}	order of the reduced model
β	reference decision parameter
η_{sys}	overall system efficiency
θ	time delay
τ	time constant
ω	frequency of the relay signal
ω_i	frequency of the relay signal at index i
ω_u	ultimate frequency

In the literature, research on the modeling of high temperature fuel cells such as MCFC and SOFC has been actively conducted. Lukas et al. developed a lumped-parameter mathematical stack model of a direct carbonate fuel cell [4]. Works have been reported to increase the accuracy of the fuel cell model. A semi-empirical model was developed to accurately determine the parameters that reflect the results of experiments [5], and numerical models of fuel cells and systems were developed and validated with experimental data [6,7]. Some studies investigated a range of feed compositions [8–10]. MCFCs have been investigated in terms of life cycle assessment [11], combined heat and power plants [12–15], and hybrid systems with gas turbines [16,17]. One strong advantage of MCFCs over other fuel cells is that they can be used in carbon capture and storage (CCS) [18–20].

To take the best advantage of the flexible MCFC, demand load adjustment should be addressed in the operation strategy. A rigorous operation framework that can provide operation direction of MCFS should be developed. For the rigorous operation of fuel cells, a number of control strategies have been employed in the literature including proportional-integral-derivative (PID) control [21,22], fuzzy control [23] and model predictive control (MPC) [24,25]. MPC had been employed to control fuel cells although PID control also shows good performances in terms of simplicity, applicability and robustness. Moreover, its computational burden is lighter compared to other control schemes.

The parameters in the PID controllers were tuned as a result of four steps: (1) excitation, (2) model identification, (3) model reduction, and (4) PID tuning [26,27]. In the model identification, frequency components are identified from excitation results using a range of methods [28]. The model incorporates various forms of process data, from both initial steady state and final one to both initial cyclic steady state and final one. For model reduction, the frequency response model could be reduced to several dynamic models like first-order plus time delay model (FOPTD) and second-order plus time delay model (SOPTD) according to Sung and Lee [29]. The SOPTD model generally shows a good approximation results for usual industry process. Nevertheless, these methods show poor performance when the process has fractional-order dynamics or strong zeros. A variety of analytic PID tuning rules to map between the PID tuning parameters and the reduced models were investigated such as internal model control, Ziegler-Nichols, and the integral of time-weighted absolute error (ITAE) [26]. The tuning rule based on the ITAE method for the SOPTD model is known to show the best performance for both over-damped and under-damped process [30].

As MCFCs are subject to highly complex dynamics, approximation of the dynamics to first-order or second-order dynamic models is difficult. Alternatively fractional calculus may describe various physical dynamic systems more accurately than integer-order models [31]. Therefore, a fractional-order dynamic model is adopted for the model reduction [32]. Previously Cheon et al. [33] presented a control method for the MCFC operation. It was novel in a sense that it approached the MCFC problem using control principles. On the other hand, some of their simulation result was not realistic. This paper improved their model with the detailed description of the framework.

Please cite this article in press as: Lee D, et al., An MCFC operation optimization strategy based on PID auto-tuning control, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.08.184