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IFAC-PapersOnLine 48-30 (2015) 445–449

A Practical Compound Controller Design for Solid Oxide Fuel Cells

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Abstract: Solid oxide fuel cell (SOFC) has emerged as a promising technology in the family of clean electricity generation methods. However, it is challenging to control the output voltage at the desired value due to the strong nonlinearity, slow dynamics and actuator saturation. The biggest difficulty comes from the constraint on the fuel utilization in a transient response. This paper is dedicated to develop an engineering friendly control structure to fulfill the comprehensive objectives. A basic PI feedback controller is utilized to accommodate the nonlinearity. The dynamic response is accelerated via a feedforward action. A compensation block is designed to satisfy the constraint requirement. The simulation shows that the resulting performance is similar to that of the latest model predictive control (MPC) design, demonstrating that the various difficulties can be effectively handled under the framework of conventional control.

Keywords: Solid oxide fuel cell (SOFC), Distributed Control System (DCS), PI controller, Feedforward controller.

1. INTRODUCTION

Fuel cell electricity generation attracts a growing attention during the past decade in that it produces water, heat, no noise and negligible amounts of pollutants with higher energy efficiency than fossil fuel combustion plant. Among various types of fuel cells, solid oxide fuel cell (SOFC), characterized by its solid electrolyte and high-operating temperature, has the advantage of fuel flexibility, long-term stability and excusing the necessity of a precious platinum catalyst (Stambouli and Traversa, 2002).

In terms of improving the operation level of the SOFC system, much attention is exercised on the constant voltage regulation in the presence of external current disturbance. However, the controller design is significantly challenging because of the system nonlinearity, sluggish dynamics and rigorous constraint on the fuel utilization. Based on the benchmark model proposed by (Padullés, Ault, and McDonald, 2000), it was revealed in (Li, Choi, and Rajakaruna, 2005) and (Knyazkin, Soder, and Canizares, 2003) that the PI controller and even the $\mathcal{H}_\infty$ optimal control are not sufficient to satisfy the performance and constraint requirements simultaneously. To this end, the research focus was tuned to Model Predictive Control (MPC) to fulfil the requirements with on-line constrained optimization. Wang, Huang, and Chen (2007) proposed a data-driven linear MPC strategy with the model identified from subspace methods. To further improve the performance, many researchers resorted to nonlinear MPC based on the fuzzy model (Jurado, 2006), Hammerstein model (Huo et al., 2008), neural network model (Wu, Zhu, Cao, and Tu, 2008) and support vector machine model (Li, Shen, and Lu, 2011). All these methods can of course achieve quite reasonable results but at the cost of the huge amount of calculation. There are at least 3 factors limiting the practical utilization of the algorithms above: (i) These methods should be realized in the programmable logic controllers (PLCs), through certain protocols and ports, which need to communicate with the industrial Distributed Control System (DCS) (Wu, Shen, Li, and Lee, 2014). The additional hardware complexity will bring more security risks, which is not preferred by the field engineers. (ii) The complex nonlinear MPC with advanced modelling techniques is very difficult to be understood by the field engineers. It means that they are not able to re-tune the parameters or operate confidently when faced with perturbed or dangerous conditions. (iii) Usually there is no theoretic or even gradient-based numerical solution to the constrained nonlinear optimization, thus heuristic optimization is used. But the stochastic search procedure may be time-consuming and bring non-determinacy to the system, which makes it unrealistic in real-time process control.

In contrast to the active research in MPC, most industrial applications, however, still rely on more conventional control strategies. So it is always of high practical meaning to design an efficient but engineering friendly control strategy for wide implementation of SOFC. This paper strives to accomplish all the goals with a simple structure, consisting of linear PI controller and two compensation blocks. The resulting control strategy can be easily configured by function blocks of contemporary DCS and be of direct physical meaning to the engineers.

The remainder of the paper is organized as follows: The SOFC system is described in Section 2. A linear transfer function model is obtained in Section 3. Section 4 designed

10.1016/j.ifacol.2015.12.419

the engineering friendly controller step by step. Some concluding remarks are given in Section 5.

2. SOFC SYSTEM DESCRIPTION

2.1 Electrochemical Basics of SOFC

The SOFCs are unique in that the circuit loop is closed by delivering negatively charged oxygen ions from the cathode to the anode instead of positively charged hydrogen ions travelling from the anode to the cathode, which is the scheme of other types of fuel cells. Thus the SOFC system can provide electricity continuously via the electrochemical reactions as follows:

Anode Reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode Reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$

Overall Cell Reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Although pure hydrogen gas is necessary for the anode reaction, the high-temperature SOFC is capable of internally reforming light hydrocarbons such as natural gas (CH_4) into H_2. The advantage on fuel flexibility makes SOFC interesting as power units in many application fields.

2.2 Model description

In this paper, we adopted a SOFC dynamic model, which is originally proposed in (Padullés, Ault, and McDonald, 2000) and widely accepted as a benchmark model (Sedghisigarchi and Feliachi, 2004; Wang, Huang, and Chen, 2007; Li, Shen,and Lu, 2011).

The block diagram of the MATLAB/Simulink based SOFC model is shown in Fig. 1. The output variable is V_{dc}, denoting the stack output voltage (V), which should be controlled as a constant. The manipulated variable is natural gas flow rate (mol/s), denoted as q_f. The disturbance comes from the external current load, denoted as I (A). The input flow rates of the oxygen, $q_{O_2}^{in}$, is proportional to that of the hydrogen, $q_{H_2}^{in}$, produced by the reformer. The partial pressures of hydrogen, oxygen, and steam (Pa) in the cell are denoted as p_{H_2}, p_{O_2} and p_{H_2O}, respectively. The meanings and values of the other parameters of the SOFC model are listed in Table 1.

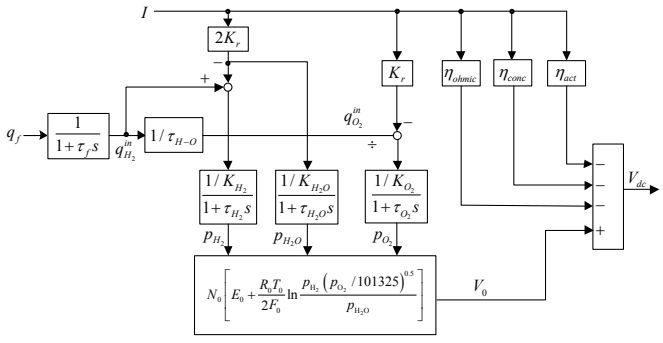

Fig. 1. The MATLAB/ Simulink realization of SOFC model.

Table 1. Parameters in the SOFC system.

Parameter	Value	Unit	Representation
T_0	1273	K	Absolute temperature
F_0	96,485	$C\ mol^{-1}$	Faraday's constant
R_0	8.314	$J\ mol^{-1}K^{-1}$	Universal gas constant
E_0	1.18	V	Ideal standard potential
N_0	384	–	Number of cells in series in the stack
K_r	0.996×10^{-3}	$mol\ s^{-1}A^{-1}$	Constant,
K_{H_2}	8.32×10^{-6}	$mol\ s^{-1}Pa^{-1}$	Valve molar constant for hydrogen
K_{H_2O}	2.77×10^{-6}	$mol\ s^{-1}Pa^{-1}$	Valve molar constant for water
K_{O_2}	2.49×10^{-5}	$mol\ s^{-1}Pa^{-1}$	Valve molar constant for oxygen
τ_{H_2}	26.1	s	Response time of hydrogen flow
τ_{H_2O}	78.3	s	Response time of water flow
τ_{O_2}	2.91	s	Response time of oxygen flow
τ_{H-O}	1.145	–	Ratio of hydrogen to oxygen
r	0.126	Ω	Ohmic loss
τ_f	5	s	Time constant of the fuel processor
α	0.05	–	Tafel constant
β	0.11	–	Tafel slope
I_L	800	A	Limiting current density

It can be found that the system nonlinearity mainly stems from the Nernst's equation:

$$V_0 = N_0\left[E_0 + \frac{R_0T_0}{2F_0}\ln\frac{p_{H_2}\left(p_{O_2}/101{,}325\right)^{0.5}}{p_{H_2O}}\right] \tag{1}$$

where, the partial pressures can be approximately expressed as the following transfer functions,

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}\left(\frac{1}{1+\tau_f s}q_f - 2K_rI\right) \tag{2}$$

$$p_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2}s}\left(\frac{1/\tau_{H-O}}{1+\tau_f s}q_f - K_rI\right) \tag{3}$$

$$p_{H_2O} = \frac{1/K_{H_2O}}{1+\tau_{H_2O}s}2K_rI \tag{4}$$

Usually, the real output voltage may be reduced because of ohmic, activation, and concentration losses, which can be expressed as

$$V_{dc} = V_0 - \eta_{act} - \eta_{ohmic} - \eta_{conc} \tag{5}$$

Where,

$$\eta_{ohmic} = Ir \tag{6}$$