INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 34 (2009) 3953–3964

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Multi-loop nonlinear predictive control scheme for a simplistic hybrid energy system

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ARTICLE INFO

Article history:
Received 29 December 2008
Received in revised form
19 February 2009
Accepted 22 February 2009
Available online 3 April 2009

Keywords:
Temperature regulation
Oxygen excess ratio
Nonlinear predictive control
PEM fuel cell
Wind turbine

ABSTRACT

A simplistic hybrid energy system is composed of the wind turbine, electrolyzer, and PEM fuel cell stack. In view of the high current demand and fast load changes, the hybrid dynamic simulation shows that the fuel cell may be in risk of oxygen starvation and overheating problems. Regarding the safe operation as well as long lifetime of the fuel cell, the effective control manner is expected to regulate both the stack temperature and oxygen excess ratio in the cathode at the desired level. Under the multi-loop nonlinear predictive control framework, the controlled output variables are specified independently by manipulating air (oxygen) and water flowrates, respectively. The dynamic modeling and control implementation are realized in the Matlab–Simulink™ environment.

1. Introduction

In general, the proton exchange membrane fuel cell (PEMFC) is quite suitable for residential or automotive applications [1]. The reasons including; (i) it can operate at relatively low temperature; (ii) it has relatively high power density; (iii) its maintenance is simple. However, the performance of the PEMFC is strictly affected by the unsteady hydrogen feed flow, oxygen starvation, temperature, and humidity. Although the pure hydrogen fuel could be replaced by hydrogen-rich fuel streams, the fuel reformer was usually added [2,3]. As for the oxygen starvation problem, the air flow control was used to regular the oxygen excess ratio in the cathode to improve the fuel cell system's performance [4–6]. Recently, Lauzze and Chmielewski [7] used the cascade PI control structure to achieve the power set-point tracking of the PEMFC system in the face of the oxygen starvation, membrane flooding or dehydration, and Zhong et al. [8] also presented a two-loop cascade controller with the self-optimizing extremum algorithm to keep the fuel cell working at the maximum power point. To address the clean and stand-alone power generation system, the fuel reforming design may be replaced by the conventional electrolyzer. In other words, the wind turbine [9,10] or photovoltaic system [11,12] would be connected to the fuel cell as an alternative hybrid power generation combination.

Regarding the fuel cell stack system, the partial pressure of oxygen is hardly accessible by measurement, and heat effect as well as dehydration could quickly degrade the capability of membrane. Thereby the specific control implementations are often utilized to improve the efficiency of power generation. Since the multivariable control design can accurately manipulate the multi-loops simultaneously, Wang et al. [13]

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doi:10.1016/j.ijhydene.2009.02.060

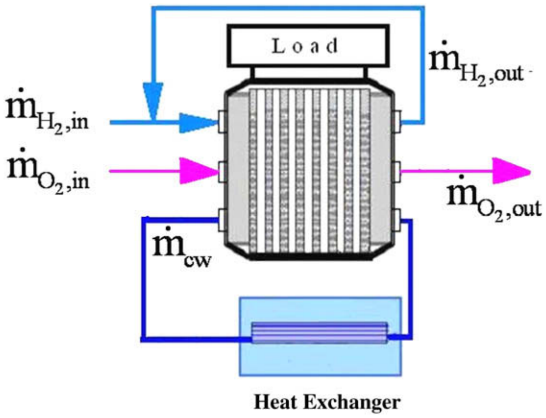

Fig. 1 – Diagram of the PEMFC stack system.

proposed the multivariable robust controllers to ensure robust performance as well as to reduce the hydrogen consumption of this system, Sheng et al. [14] used the cascade PID control to guarantee the solid temperature of molten carbonate fuel cell (MCFC) system under a prescribed temperature, and Zhang et al. [15] used a nonlinear model predictive controller to control the output power, fuel utilization and temperature of the solid oxide fuel cell (SOFC) system. In those approaches, the model equations for MCFC or SOFC system were reduced into the linear model or steady-state model [16,17]. Coincidentally, they indicated that the temperature regulation problem is another critical issue for the study of efficiency of fuel cell systems.

Table 1 – Parameter values for the Ballard 5 kW PEMFC system.

Symbol	Description	Value	Unit
A_{fc}	Cell active area	232	cm^2
V_{an}	Anode volume	0.005	m^3
V_{ca}	Cathode volume	0.01	m^3
k_{an}	Flow constant at the anode	0.065	$mol\,s^{-1}\,atm^{-1}$
k_{ca}	Flow constant at the cathode	0.065	$mol\,s^{-1}\,atm^{-1}$
$\dot{m}_{H_2,in}$	Hydrogen inlet flowrate	0.8	$mol\,s^{-1}$
$\dot{m}_{O_2,in}$	Oxygen inlet flowrate	2	$mol\,s^{-1}$
$P_{H_2,in}$	Hydrogen pressure at the inlet	3	atm
l_m	Membrane thickness	178×10^{-4}	cm
R	Universal gas constant	8.314	$J\,mol^{-1}\,K^{-1}$
F	Faraday constant	96,485	$C\,mol^{-1}$
C_{dl}	Double layer capacitance	0.035×232	F
ΔH	Hydrogen consumption enthalpy	285.5	$kJ\,mol^{-1}$
C_t	Thermal capacitance	17.9	$kJ\,K^{-1}$
h_{cond}	Heat exchanger conductive coefficient	35.55	$W\,K^{-1}$
h_{conv}	Heat exchanger convective coefficient	0.025	$W\,K^{-1}\,A^{-1}$
T_{amb}	Ambient temperature	25	°C
$T_{c,in}$	Inlet water temperature	25	°C
UA	Overall heat transfer index	241	$W\,K^{-1}$
C_{pw}	Heat capacity of water	4.184	$kJ\,kg^{-1}\,K^{-1}$
ρ_w	Water density	1000	$kg\,m^{-3}$
V_w	Water volume	2.5×10^{-3}	m^3
τ	Time constant	2.06	s

In this article, the dynamic modeling and simulation of a simplistic hybrid energy system are constructed in the Matlab–Simulink™ environment. Whereas the high current demand may challenge the response capability of hybrid power generation and degrade the performance of fuel cell stack, a multi-loop feedback control scheme for a PEMFC system is utilized. In our study, the amount of hydrogen is assumed to be regularly produced from electrolyzer. Under the restriction at windy district at specified time period, the wind turbine is assumed to produce an abundant power and provide the regular hydrogen inlet flow. Assumed that direct measurement of partial pressure of oxygen is avoided, and the manipulation of hydrogen flow is reduced according to the inlet hydrogen flow through throttle and re-circulating designs. Regarding our approach, state estimations are not required, both controlled output variables are specified independently, and the nonlinear predictive control design subject to input/output constraints is efficiently achieved. By the closed-loop simulation results, the manipulation of both air (oxygen) and water flowrates is verified to accurately dominate the operation and performance of the PEM fuel cell system.

2. System description

The isolated power generation system is composed of four major units including an AIR 403 wind turbine, a 5 kW PEM fuel cell stack, an electrolyzer, and controller devices. Regarding the hybrid energy complementary circulation, the wind turbine must serve as the transient power supply and meanwhile the excess wind power can drive the electrolyzer to produce the pure hydrogen regularly.

2.1. *PEM fuel cell stack with heat exchanger system*

According to Fig. 1 with the empirical-type fuel cell stack model by [18,19], the pure hydrogen is fed to the anode and its excess gas can be re-circulated, the air used as the oxidant is kept flowing through the stack, the system is internally humidified by a circulating water system, and the temperature of water flowrate at the inlet is changed by the external heat exchanger device. The output voltage of a single fuel cell (V_{fc}) is formulated by

$$V_{fc} = E - V_{act} + V_{ohm} \tag{1}$$

where the thermodynamic potential (E) and the ohmic overvoltage (V_{ohm}) are written as

$$E = 1.229 - 8.5 \times 10^{-4}(T - 298.15) + \frac{RT}{2F} \ln\left[P_{H_2}(P_{O_2})^{0.5}\right] \tag{2}$$

$$V_{ohm} = -\frac{181.6I\left[1 + 0.03\left(\frac{I}{A_{fc}}\right) + 0.062\left(\frac{T}{303}\right)^2\left(\frac{I}{A_{fc}}\right)^{2.5}\right] l_m}{A_{fc}\left[11.866 - 3\left(\frac{I}{A_{fc}}\right)\right]\exp\left[4.18\left(\frac{T - 303}{T}\right)\right]} \tag{3}$$

and the activation overvoltage (V_{act}) is described by a first-order dynamic with the effects of double layer capacitance charging at the electrode–electrolyte interfaces