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고체산화 연료전지의 동특성 모델링과 제어

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Dynamic Modelling and Control of Solid-Oxide Fuel Cell

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Abstract - In this paper, the dynamic models of SOFC are suggested. It consists of electrochemical model, thermal model, voltage equation and several loss equations. Control problem on tracking steady voltage by air flow is discussed and an adaptive controller is designed to withstand to the variation of stack current. Simulation is done to prove the solution of control algorithms.

1. INTRODUCTION

Fuel cells are attractive as the electric power production of the future because they are modular, efficient, and environmentally friendly. However, fuel cells are dynamic devices which will affect the dynamic behavior of the power system to which they are connected and hence analysis of such a behavior requires an accurate dynamic model.

Two types of fuel cells are likely to be used as power plants namely solid-oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). Each has a specific dynamic model. Most of the published models, however, concentrate on standalone fuel cells. The model proposed in this paper includes the electrochemical and thermal aspects of chemical reactions inside the stack of SOFC and voltage losses due to activation, concentration, ohmic losses are account for.

In this paper, the dynamic model of SOFC will be suggested and dealt on some control problem. Simulation will also be done to prove the applicability of the solution of control algorithms.

2. MAIN SUBJECT

2.1 Dynamic Modelling for SOFC

The proposed dynamic model of SOFC is based on the chemical, thermal and electrical principles and has multiple input and output as shown in Fig.1.

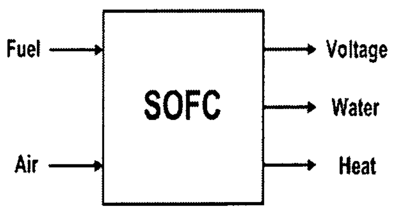


Fig.1 Inputs and outputs of SOFC

The two inputs are fuel(H_2) and air(O_2) and three outputs are DC voltage(V_{dc}), water(H_2O) and heat(T).

The electrochemical model of fuel, water and air will be represented by the component material balance equations as follows.

$$\dot{x}_1 = -\frac{1}{\tau_1}x_1 + \frac{1}{\tau_1 K_1}\dot{N}_1 - \frac{K_r}{\tau_1 K_1} I_{st} \quad \text{: fuel flow} \tag{1}$$

$$\dot{x}_2 = -\frac{1}{\tau_2}x_2 + \frac{K_r}{\tau_2 K_2} I_{st} \quad \text{: water flow} \tag{2}$$

$$\dot{x}_3 = -\frac{1}{\tau_3}x_3 + \frac{1}{\tau_3 K_3}\dot{N}_3 - \frac{K_r}{\tau_3 K_3} I_{st} \quad \text{: air flow} \tag{3}$$

$$\tau_1 = \frac{W}{K_1 RT},\ \tau_2 = \frac{W}{K_2 RT},\ \tau_3 = \frac{W}{K_3 RT} \tag{4}$$

$$K_1 = \frac{N_1}{x_1},\ K_2 = \frac{N_2}{x_2},\ K_3 = \frac{N_3}{x_3} \tag{5}$$

where, x_1, x_2, x_3 are mole fractions, τ_1, τ_2, τ_3 are time constants and K_1, K_2, K_3 are molar constants with fuel, water and air, respectively. $\dot{N}_1, \dot{N}_3$ are flow rates at the input cell and N_1, N_3 are reaction rates of fuel and air, respectively. $K_r = 0.25N/F$ is a constant dependent on Faraday's constant(F) and number of electrons(N) in the reaction, I_{st} is a stack current, W is a compartment volume, R is a gas constant and T is a cell temperature.

The thermal model will be represented by the energy balance equations as follows.

$$M_p C_p T = q_e W_e + \sum Q_j \quad \text{: thermal dynamics} \tag{6}$$

where, M_p is a mass, C_p is a heat capacity, W_e is a volume, q_e heat generation of the cell unit and Q_j is a total heat between cell and separators.

The stack output voltage and ohmic, concentration, activation losses will be represented by the Nernst equation as follows.

$$V_{dc} = V_0 - \eta_{ohm} - \eta_{con} - \eta_{act} \tag{7}$$

$$V_0 = N_0\left[E_0 + \frac{RT_0}{2F}\ln\frac{x_1\sqrt{x_3}}{x_2}\right] \quad \text{: output voltage} \tag{8}$$

$$\eta_{ohm} = rI_{st} \;\; at \;\; r = \alpha \exp\left[\beta\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \; : \text{ohmic loss} \tag{9}$$

$$\eta_{con} = \frac{RT}{nF}\ln\left(1 - \frac{I_{st}}{i_L}\right) \; : \text{concentration loss} \tag{10}$$

$$\eta_{act} = \frac{RT}{\alpha nF}\ln\left(\frac{I_{st}}{i_0}\right) \approx a + b\ln(I_{st}) \; : \text{activation loss} \tag{11}$$

where, V_0 : open-circuit reversible potential
N_0 : number of cells in stack
E_0 : standard reversible cell potential
T_0 : constant temperature
r : ohmic resistance
α, β : constant coefficients
n : number of electrons in reaction
i_L : limiting current
a, b : Tafel constant and Tafel slope

The above all equations is based on the following assumptions.

1) Stack is fed with hydrogen and air
2) A uniform gas distribution among cells
3) There is no heat transfer among cells
4) The ratio of pressures between the interior and exterior of the channel is large enough to consider that orifice choked

Using the above all equations and Laplace transformation, a dynamic model of SOFC will be represented as fig.2.

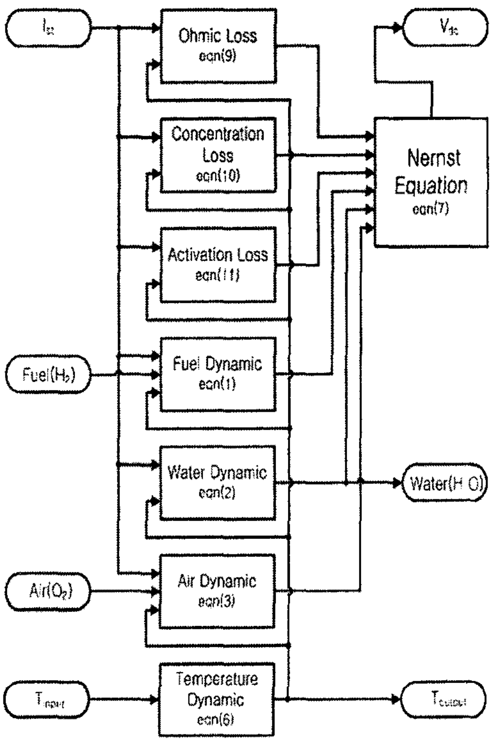


Fig.2 Block Diagram for SOFC model

2.2 Adaptive Control for Tracking Problem

The simulation result for output voltage of the stack was presented in Fig.3 if the stack current should be maintained at constant value. The target system of SOFC has rated power of 100[kW], rated stack voltage of 286.3[V] and rated stack current of 300[A] and assume that the variation of temperature can be negligible. System parameters and several data need to simulation are arranged at Table.1.

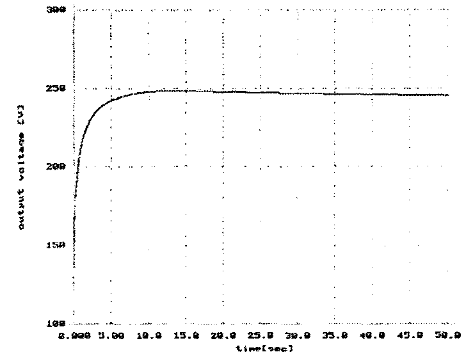


Fig.3 Simulation result for output voltage (V_{dc})

Table.1 System parameters and data for simulation

SYMBOL	VALUE[UNIT]	SYMBOL	VALUE[UNIT]
τ_1	1.0[sec]	T	1000[°C]
τ_2	2.0[sec]	T_0	923[°C]
τ_3	1.5[sec]	N_0	384
K_1	0.8	E_0	0.8[V]
K_2	0.2	α	0.2
K_3	0.9	β	-2870
N_1	12.0[mole/sec]	I_{st}	300[A]
N_3	24.0[mole/sec]	i_L	500[A]
K_r	0.01	a	0.05
R	8.31[J/mole°K]	b	0.11

Stack output voltage in Fig.3 can be converge to some steady value, however, a little error of output voltage will be exist by the variation of system parameters (espectially, stack current). Hence, it is need to design adaptive controller to meet reference output voltage withstand to variation of parameters.

It is assume that the fuel flow(N_1) is constant, stack current I_{st} is unknown parameter(θ) and air flow(N_3) is control input(u) to track output voltage (V_{dc}) to reference voltage(V^*_{dc}). For the control objective, define the tracking error as

$$e = V_{dc} - V^*_{dc} \tag{12}$$

and estimation error as

$$\tilde{\theta}=\theta-\hat{\theta} \tag{13}$$

where, θ is a real constant value and $\hat{\theta}$ is estimated value of unknown stack current. The Lyapunov function is chosen as

$$U_L=\frac{1}{2}e^2+\frac{1}{2\gamma}\tilde{\theta}^2 \tag{14}$$

where, γ is an adaptation gain. If the losses in eqn(9)~(11) are very little, then the derivative of U_L is

$$\begin{aligned}\dot{U}_L &= e\dot{e}+\frac{1}{\gamma}\tilde{\theta}\dot{\tilde{\theta}}=e\dot{V}_{dc}-\frac{1}{\gamma}\tilde{\theta}\dot{\hat{\theta}}\\ &=ce(g_1+g_2\hat{\theta}+g_3u)+g_2\tilde{\theta}-\frac{1}{\gamma}\tilde{\theta}\dot{\hat{\theta}}\end{aligned} \tag{15}$$

where,

$$\begin{aligned}g_1&=-\frac{1}{\tau_1}+\frac{1}{\tau_2}-\frac{1}{2\tau_3}+\frac{\dot{N}_1}{\tau_1K_1x_1}\\ g_2&=-\frac{K_r}{\tau_1K_1x_1}+\frac{K_r}{\tau_2K_2x_2}-\frac{K_r}{2\tau_3K_3x_3}\\ g_3&=\frac{1}{2\tau_3K_3x_3}\end{aligned} \tag{17}$$

and $c=\frac{N_0RT_0}{2F}$. Now, the adaptive and control law are chosen as follows

$$\dot{\hat{\theta}}=\gamma g_2 \quad \text{: adaptive law} \tag{18}$$

$$u=-\frac{1}{g_3}\left(\frac{k}{c}e+g_1+g_2\hat{\theta}\right) \quad \text{: control law} \tag{19}$$

where, k is a control gain. The derivative of U_L at eqn(2.10) will be as

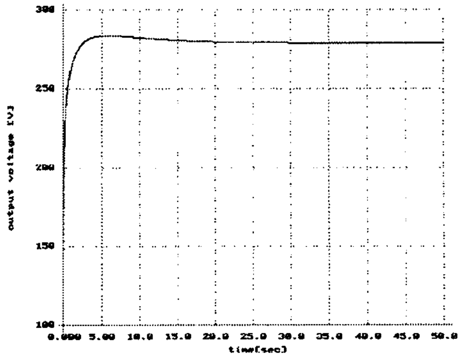
$$\dot{U}_L=-ke^2\le 0 \tag{20}$$

Using Barbalat's lemma [6], it can be shown that $U_L(t)$ tends to zero as $t\to\infty$. Therefore, tracking error e will also converge to zero as $t\to\infty$. As a result, the stability of the proposed adaptive control system can be guaranteed.

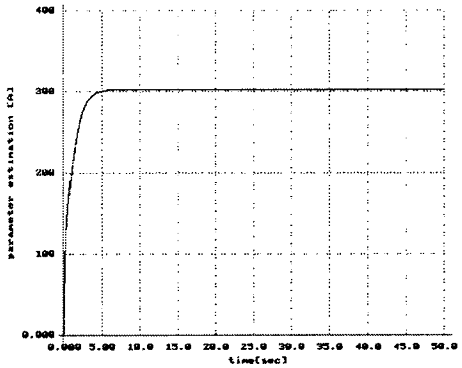
Simulation was done with $k=1$, $\gamma=0.1$, $V^*_{dc}=280[V]$ and the results are depicted at Fig.4. It shows that stack output voltage is converge to reference voltage and parameter estimation value is also converge to constant value.

3. CONCLUSION

In this paper, the dynamic models of SOFC are presented and it consists of electrochemical model, thermal model, voltage equation and several loss equations. Control problem on tracking steady voltage by air flow is solved by proposed adaptive controller which designed to withstand to the variation of stack current. The appropriate adaptive and control law are designed and the effectiveness of the proposed controller is proved by simulation results. Experiments will be performed to confirm to this results in the near future.



(a) stack output voltage (V_{dc})



(b) parameter estimation (θ ⇒ stack current (I_g)

Fig.4 Simulation results for the proposed controller

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