연료전지의 정전압 특성을 위한 적응제어기 설계

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Design of an Adaptive Controller for Steady Voltage Characteristics of the Fuel Cell

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Abstract - In this paper, the dynamic models of a SOFC are rearranged. It consists of electrochemical model, thermal model, voltage equation and several loss equations. Experiment results of the real SOFC system are shown to evaluate the steady voltage characteristics. Control problems 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 in 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 so analysis of such a behavior or design of a controller 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) and each has a specific dynamic model.[1] Most of the published models, however, concentrate on stand-alone fuel cells. An important performance of fuel cell are steady power characteristics and cell utilization, especially, guarantee to steady stack voltage withstand the variation of stack current and load.[2]

The dynamic model rearranged in this paper which 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. Experiment results of the real SOFC system are shown to evaluate the steady voltage characteristics. Control problems on tracking reference voltage by operation for air flow is discussed and an adaptive controller is designed to withstand to the variation of stack current. Computer simulations are done to prove the effectiveness of the control algorithms.

2. Dynamic Modelling for SOFC

The dynamic model of SOFC is based on the chemical, thermal and electrical principles and has two inputs fuel(H_2), air(O_2) and three outputs DC voltage(V_{dc}), water(H_2O) and heat(T), respectively. The electrochemical model of fuel, water and air will be represented by the component material balance equations as follows.

$$\dot{x}_1 = -\frac{1}{\tau_1}x_1 + \frac{1}{\tau_1 K_1}N_1^i - \frac{K_r}{\tau_1 K_1}I_{st} \quad : \text{fuel}(H_2) \tag{1}$$

$$\dot{x}_2 = -\frac{1}{\tau_2}x_2 + \frac{K_r}{\tau_2 K_2}I_{st} \quad : \text{water}(H_2O) \tag{2}$$

$$\dot{x}_3 = -\frac{1}{\tau_3}x_3 + \frac{1}{\tau_3 K_3}N_3^i - \frac{K_r}{\tau_3 K_3}I_{st} \quad : \text{air}(O_2) \tag{3}$$

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

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

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

$$M_p C_p \dot{T} = q_e W_e + \sum Q_j \tag{6}$$

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

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

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

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

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

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

Using the above all equations, a dynamic model of SOFC will be represented as Fig 1.

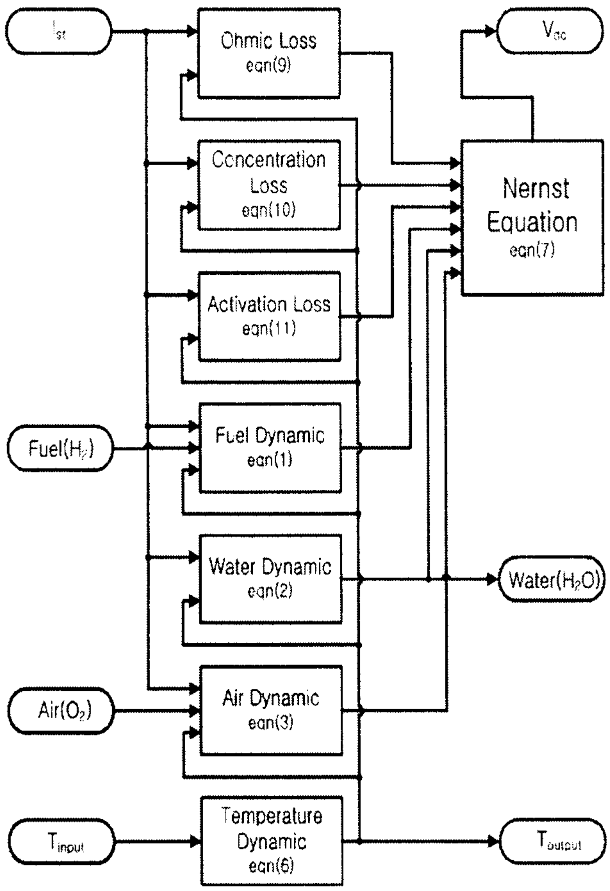
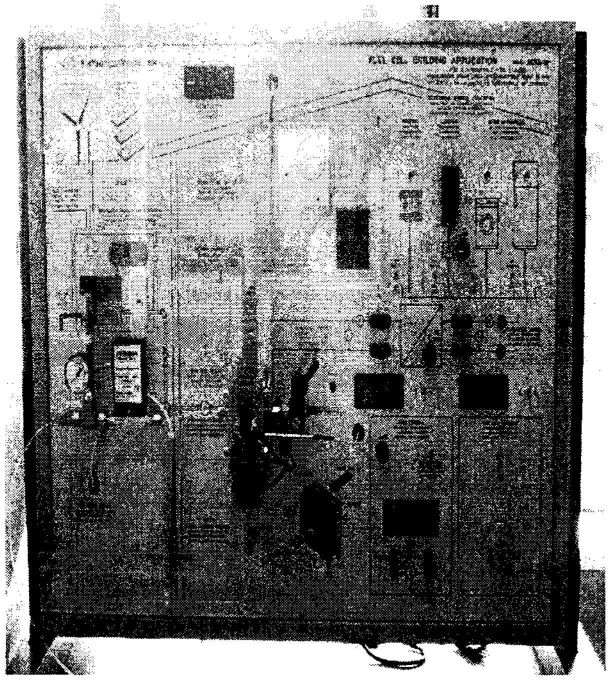


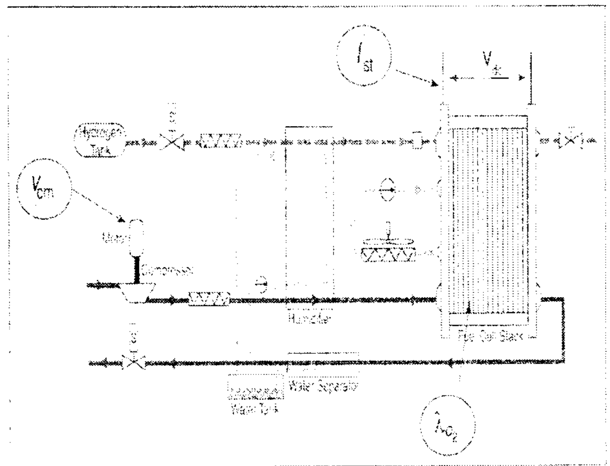
Fig 1. Result of the modelling for SOFC

3. Experiments for Steady Stack Voltage

Experiments were conducted to evaluate the characteristics of steady voltage for SOFC which is made in ITALY(ElettronicaVaneta) and has rated power of 20[W], rated stack voltage of 2.8[V] and rated stack current of 7[A]. Outside configuration and inside functional diagram of the fuel cell system for experiments are shown in Fig 2. The experimental result for output voltage of the stack was presented in Fig 3 and we can see that the stack output voltage can be converge to some steady value, however, a little decrease of output voltage will be exist by the variation of some system parameters (espectially, stack current).



(a) Outside configuration



(b) Inside functional diagram

Fig 2. Fuel cell systems for experiment

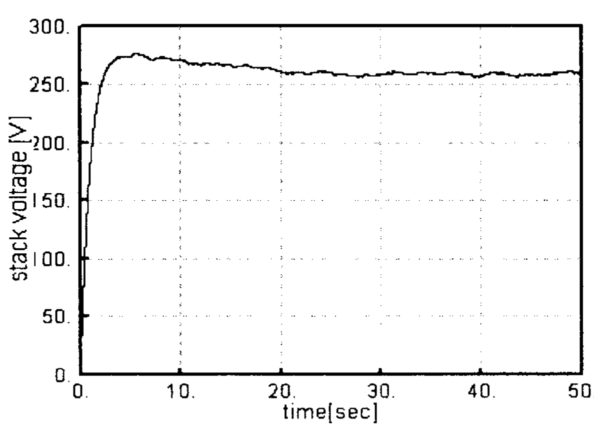


Fig 3. Measurement result of the stack output voltage

4. Design of an Adaptive Controller

It is clearly shown in Fig 3 that the stack output voltage has a little decrease by the variation of several system parameters. Hence, it is need to design an adaptive controller to meet reference output voltage withstand to variation of parameters. It is assume that the fuel flow(N_1^i) is constant, stack current I_{st} is unknown parameter(θ) and air flow(N_3^i) is control input(u) to track output voltage(V_{dc}) to reference voltage(V_{dc}^*). For the control objective, define the tracking and estimation error as follows.

$$e = V_{dc} - V_{dc}^* \ , \qquad \tilde{\theta} = \theta - \hat{\theta} \tag{12}$$

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

$$U_L = \frac{1}{2}e^2 + \frac{1}{2\gamma}\tilde{\theta}^2 \tag{13}$$

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

$$\dot{U}_L = e\dot{e} + \frac{1}{\gamma}\tilde{\theta}\dot{\tilde{\theta}} = e\,\dot{V}_{dc} - \frac{1}{\gamma}\tilde{\theta}\dot{\hat{\theta}} \tag{14}$$
$$= ce\,(g_1 + g_2\hat{\theta} + g_3 u) + g_2\,\tilde{\theta} - \frac{1}{\gamma}\tilde{\theta}\dot{\hat{\theta}}$$

$$g_1 = -\frac{1}{\tau_1} + \frac{1}{\tau_2} - \frac{1}{2\tau_3} + \frac{N_1^i}{\tau_1 K_1 x_1} \tag{15}$$
$$g_2 = -\frac{K_r}{\tau_1 K_1 x_1} + \frac{K_r}{\tau_2 K_2 x_2} - \frac{K_r}{2\tau_3 K_3 x_3}$$
$$g_3 = \frac{1}{2\tau_3 K_3 x_3}$$

where, $c = \dfrac{N_0 R T_0}{2F}$. Now, the adaptive and control law are chosen as follows

$$\dot{\hat{\theta}} = \gamma g_2 \qquad : \text{ adaptive law} \tag{16}$$
$$u = -\frac{1}{g_3}\left(\frac{k}{c}e + g_1 + g_2\hat{\theta}\right) \quad : \text{ control law} \tag{17}$$

where, k is a control gain. The derivative of U_L at eqn(14) will be as follows

$$\dot{U}_L = -ke^2 \le 0 \tag{18}$$

Using Barbalat's lemma, 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. The block diagram of the overall system contained adaptive controller for SOFC is given in Fig 4.

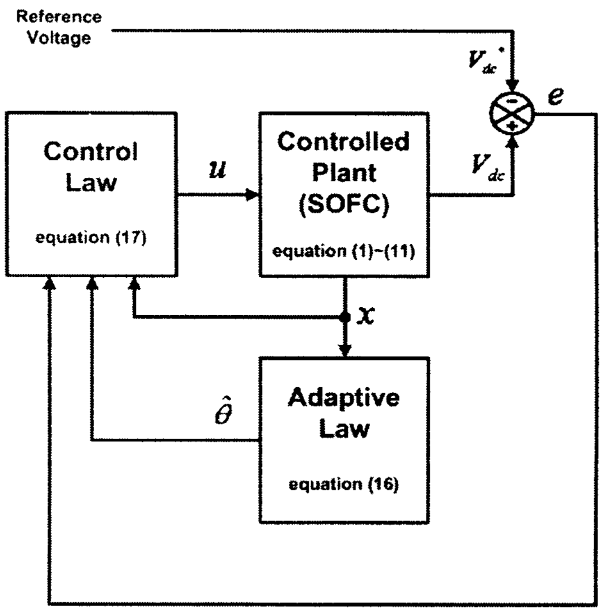


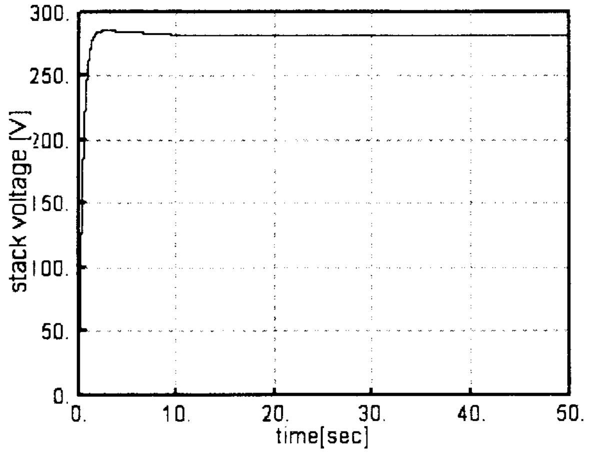
Fig 4. Block diagram of the overall system

Computer simulations were done by Turbo-C language to prove the effectiveness of the proposed controller. System parameters and several data need to simulation are arranged at Table 1 and assume that the variation of temperature can be negligible.

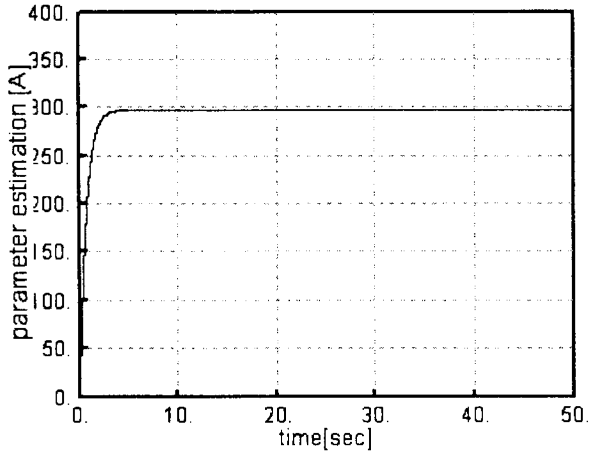
Table 1. System parameters for the simulations

Nomenclature	Setting Value	Nomenclature	Setting Value
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^i	12.0[mole/sec]	I_{st}	7[A]
N_3^i	24.0[mole/sec]	i_L	5[A]
K_r	0.01	a	0.05
R	8.31[J/mole°K]	b	0.11

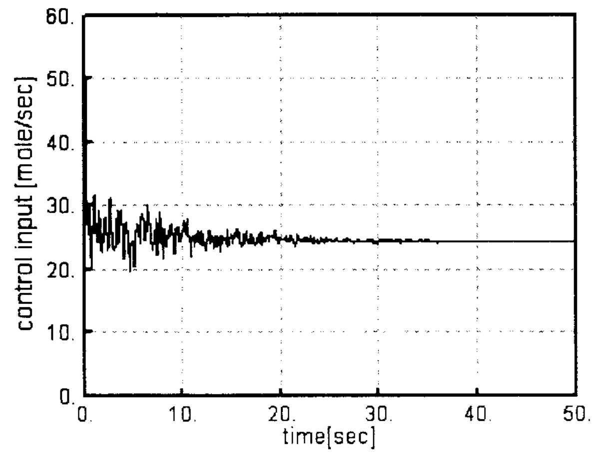
Simulation was done with $k = 1$, $\gamma = 0.1$, $V_{dc}^* = 2.8[V]$ and the results are depicted at Fig 5. It shows that stack output voltage is exactly tracking to reference voltage after 5[sec] and parameter estimation value (stack current) is also converge to constant value.



(a) Output voltage of the stack (V_{dc})



(b) Parameter estimation (θ) ⇒ stack current (I_{st})



(c) Control input (u) = flow rate of air (N_3^i)

Fig 5. Simulation results of the proposed controller

5. CONCLUSIONS

In this paper, the dynamic models of a SOFC were rearranged. It consists of electrochemical model, thermal model, voltage equation and several loss equations. Experiment results of the real SOFC system are shown to evaluate the steady voltage characteristics and the stack output voltage has a little decrease by the variation of several system parameters. Hence, we were to design an adaptive controller to meet reference output voltage withstand to variation of parameters. Control problems on tracking steady voltage by air flow was proposed and an adaptive controller was designed to withstand to the variation of stack current. Simulation were done to prove the solution of control algorithms.

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