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كفاءة نموذج خلية أكسيد الوقود الصلب (SOFC) والمعدل حرارياً تحت ظروف مختلف لتيار الحمل المباشر

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الخلاصـة

في هذا البحث، تم تقديم نموذج ديناميكي بأسس حرارية لخلية أوكسيد الوقود تحت ظروف مختلفة لتيار الحمل المباشر باستخدام نموذجنا السابق لخلية الوقود والتي تشمل الأومية، والتفعيل وخسائر الجهد والتركيز، والديناميكا الحرارية، وميثانول المعدل. ونموذج المعدل لخلية الوقود الصلبة يغطي تقييد عامل استخدام الوقود. وبالتالي، فإن الجهد وقوة خلية الوقود الصلبة تقتصر على تجنب تدفق الوقود المفرط ودرجة الحرارة. وتم تطوير نموذج أكسيد خلية الوقود الصلبة باستخدام برنامج Matlab/Simulink وجرى اختبار تحت ظروف مختلفة للحمل المباشر للتيار، وهي خطوات المنحدر والأحمال العشوائية المتدرجة. وتبين نتائج المحاكاة بأن أكسيد خلية الوقود الصلبة يمكن أن تستخدم لتتبع بدقة متغيرات التيار المباشرة. وهذا متوقع لأن الوصول إلى حالة الاستقرار للنظام تأخذ وقت أقل لتحميل المنحدر، بينما تأخذ وقت أطول لتحميل المتدرج. إلى جانب ذلك، فإن محدودية معامل استخدام الوقود يمكن أن ينظر إليها على أنها أكثر وضوحاً من نظام تحميل المتدرج.

The performance of thermal based modified solid oxide fuel cell (SOFC) model under different DC load conditions

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ABSTRACT

In this paper, a thermal-based dynamic model of a Solid Oxide Fuel Cell under different direct current load conditions is improved by using our previously developed fuel cell model, which includes ohmic, activation and concentration voltage losses, thermal dynamics and methanol reformer. The modified Solid Oxide Fuel Cell model covers restriction of fuel utilization factor. Hence, the voltage and power of the Solid Oxide Fuel Cell stack are limited to avoid excessive fuel flow and temperature. The Solid Oxide Fuel Cell model is developed in a Matlab/Simulink environment and tested for different direct current load conditions, which are step, ramp, random and stair-case loads. The simulation results show that the modified Solid Oxide Fuel Cell model can be used to precisely follow the direct current load variations. This is true, because reaching the steady state of the system takes a shorter time for the ramp load, and takes a longer time for the step load. Besides, the limitation of the fuel utilization factor can be seen more clearly from the system with the stair-case load.

Keywords: Different load types; load following; solid oxide fuel cell; thermal model.

INTRODUCTION

Fuel cells are one of the energy convertors that have high efficiency and very low emission. According to the type of electrolyte used in fuel cell systems, they are classified as proton exchange membrane fuel cells, solid oxide fuel cells, molten carbonate fuel cells, phosphoric acid fuel cells and alkaline fuel cells. The solid oxide fuel cell (SOFC) is preferred due to its high efficiency, low pollutant emissions, flexible fueling strategies, ability to operate at high temperatures and power plant applications. The thermal dynamics of the SOFC system must be considered because it operates at a high temperature (EG & G Services, 2002; Kang *et al.,* 2008).

In recent years, many dynamic models of SOFC have been reported by researchers (Padulles *et al.,* 2000; Zhu & Tomsovic, 2002; Sedghisigarchi & Feliachi, 2004; Li *et al.,* 2005; Goel *et al.,* 2006; Wang & Nehrir, 2007a). Padulles *et al.* presented a basic SOFC dynamic model which considers only ohmic voltage loss. But, in this model, the fuel cell temperature was kept constant and a reformer was not used. Also, Zhu and Tomsovic added a CO reformer and a power section to same model mentioned in (Padulles *et al.,* 2000). Sedghisigarchi and Feliachi developed a SOFC model, that contains three voltage losses (ohmic, activation and concentration) and thermal dynamics. But, a fuel reformer was not considered in their model. Li *et al.,* (2005) only added a methanol reformer to the model proposed in Padulles *et al.,* (2000). They suggested two control schemes as constant utilization control and constant voltage control for the SOFC model. Goel *et al.,* (2006) presented a dynamic model which considers all voltage losses, thermal dynamics and a fuel reformer. But, their reformer model is based on a first-order transfer function (Goel *et al.,* 2006). In another study, electrochemical, material conservation, diffusion, thermal and double layer charging effect equations were used to develop a SOFC model (Wang & Nehrir, 2007a). The SOFC model in our previous work (Gelen & Yalcinoz, 2013) includes all voltage losses, modified thermal dynamics and a second-order transfer function based fuel reformer. But; this model was developed to keep the fuel utilization factor constant (Gelen & Yalcinoz, 2013)**.**

The feedback current varies with a limited fuel utilization factor (U_f). Therefore, the U_f needs a proper control to safely balance load variations for the stack operations. The first contribution of this paper is the restriction of the fuel utilization of SOFC stack. Therefore, the voltage and power of the SOFC stack are limited to avoid excessive fuel flow and temperature. The response of the fuel cell for different load types, which is studied in this paper, has not been previously reported in the literature. Researchers generally examined the fuel cell applications for a single load type such as step load (Sedghisigarchi & Feliachi, 2004; Qi *et al.,* 2006; Wang & Nehrir, 2007b; Wu *et al.,* 2008b; Wang *et al.,* 2008; Chakraborty, 2009), ramp load (Lu *et al.,* 2007) and stair-case load (Wang & Nehrir, 2007a; Wu *et al.*, 2008a). Zhang *et al.,* (2008) investigated two load types as step and stair-case. The modified SOFC model with limited U_f is tested on four DC load types, which are step, ramp, random and stair-case. That is the second contribution of this paper. SOFC model is developed in the Matlab/Simulink environment.

DYNAMIC MODEL OF THERMAL BASED SOFC SYSTEM

In this paper, the proposed SOFC dynamic model includes all properties such as a methanol reformer, electrochemical properties, voltage losses as ohmic, activation and concentration. In the majority of previous studies, the first-order transfer function is used to develop the reformer model. The fuel reformer, which is based on second-order transfer function, is used in this paper. In a fuel cell system, especially stationary fuel cells such as SOFC and MCFC (molten carbonate fuel cell), fuels produced from hydrocarbon rather than pure hydrogen have been used. For example, use of natural gas in city gas network as fuel has been much preferred (EG & G Services, 2002). Therefore, in this manuscript, a fuel reformer is used because both SOFC is stationary type fuel cell and H_2-rich fuel produced from hydrocarbon is preferred in real time. Peters et al. modeled the reformer dynamics (including the evaporator-superheater and gas clean up stage) by assuming a second-order transfer function (Peters *et al.,* 1998). The dominant characteristic of the fuel flow response to an input step of methanol flow is increased by using second-order transfer function model. The response time depends on the specific reformer design. In the case of steam reformers, the heat transfer limitations within the reformer dominate the overall reformer dynamics together with the reaction kinetics at the catalyst sites (Ohl, 1995; Hauer, 2001). Due to these reasons, in this study, the fuel reformer based on second-order transfer function is chosen as a reformer model. Consequently, the related fuel reformer model is given in Ref. (El-Sharkh *et al.,* 2004). Its mathematical form can be written in Equation (1) as seen in Table 1. The modeling equations and definitions are given in Table 1 and Table 2, respectively. A proportional integral (PI) controller is used to control flow rate of methanol in the reformer. The feedback signal is the SOFC stack current. The hydrogen flow rate for the reformer can be written in Equation (2) as in Table 1. And, this parameter can be used to control the methanol flow rate as seen in Equation (3) (El-Sharkh *et al.,* 2004).

Expressions of molar flow and partial pressure of species for electrochemical model are presented in detail in Padulles *et al.,* (2000). As seen in Equation (4), the molar flow of any gas through the valve is proportional to its partial pressure inside the channel. According to the basic electrochemical relationships, the molar flow of hydrogen that reacts can be calculated as in Equation (5). According to Equation (6); the hydrogen partial pressure is a function of τ_{H_2} and $\tau_{H_2} = V/(K_{H_2}RT)$ in Equation (7), which is expressed in seconds, is the value of the system pole associated with the hydrogen flow (Padulles *et al.,* 2000).

SOFC models, which concentrate on effects of temperature dynamics, were previously investigated in the literature (Sedghisigarchi & Feliachi, 2004; Goel *et al.,* 2006; Wang & Nehrir, 2007a; Wu *et al.,* 2008a; Ren *et al.,* 2010; Gebregergis & Pillay, 2010; Yang *et al.,* 2009). The output power of fuel cell is closely related to the temperature of the fuel cell unit (Sedghisigarchi & Feliachi, 2004). Heat transfers occur mainly as conduction, convection and radiation (Wang & Nehrir, 2007a). The energy balance equation for each cell is given in Equation (8) (Sedghisigarchi & Feliachi, 2004; Achenbach, 1995). The coefficients of the specific heats C_P seen in Equation (9) can be met in standard reference tables (Wu *et al.,* 2008a). According to Equation (10), the output temperature of the SOFC stack is determined considering the existing temperature and the relaxation time. In this paper, this thermal model is adapted to the proposed SOFC model.

The stack output voltage can be derived by using Nernst's equation and Ohm's law taking into account ohmic, concentration and activation losses as in Table 1 (Sedghisigarchi & Feliachi, 2004; Gebregergis & Pillay, 2010; Akkaya, 2007; Larminie & Dicks, 2003).

The complete SOFC system is obtained by a cascade connection of methanol reformer, electrochemical module, voltage losses module and modified thermal module. The modified SOFC system is shown in Figure 1. The temperature of the SOFC stack is computed by the existing temperature. This computation was performed by using "memory block" in (Goel *et al.,* 2006). Especially in the AC operation conditions, the simulation time suffers from this block. In this paper, the "unit delay" block is used to solve this problem. The thermal module is given in detail in (Gelen & Yalcinoz, 2013).

Table 1. Units of the SOFC system used in the dynamic model

Units	Equation No	Formulas	Explanation
Fuel reformer	**1**	$\frac{q_{H_2}}{q_{methanol}} = \frac{CV}{\tau_1\tau_2 s^2 + (\tau_1 + \tau_2)s + 1}$	Fuel is methanol, Controller is PI
	2	$q_{H_2}^{req} = \frac{NI}{2FU}$	
	3	$q_{methanol} = \left(k_3 + \frac{k_3}{\tau_3 s}\right)\left(\frac{NI}{2FU}\right)$	
SOFC stack	**4**	$\frac{q_{H_2}}{p_{H_2}} = K_{H_2}\ \frac{q_{H_2O}}{p_{H_2O}} = K_{H_2O}$	Electrochemical model
	5	$q_{H_2}^r = \frac{NI}{2F} = 2K_r I$	
	6	$P_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}(q_{H_2}^{in} - 2K_r I)$	
	7	$\tau_{H_2} = V/(K_{H_2}RT)$	
	8	$M_P C_P \frac{dT}{dt} = q_e V_e + \sum Q_i$	Energy balance equation
	9	$C_{P,i} = a_i + b_i T + c_i T^2$	
	10	$T_o = T + \left(\frac{T_{in} + \Delta T - T}{t}\right)dt$	
	11	$V_{dc} = V_o - \eta_{ohm} - \eta_{act} - \eta_{conc}$	Nernst's voltage equation
	12	$V_o = N\left(E + \frac{RT}{2F}\ln\frac{p_{H_2}p_{O_2}^{1/2}}{p_{H_2O}}\right)$	

The nominal power of the modified SOFC system is 100 kW. Output power and U_f of the described fuel cell model are limited by a new block which is added to the model presented in Gelen & Yalcinoz (2013). The controlling of the fuel reformer is based on the feedback current and this new block given in Figure 2 is used to limit

feedback current. The nominal value of U_f is 0.85 and it is limited between 0.8 and 0.9. The inputs of the power limiting block are fuel flow rate and feedback current. The limited output current of fuel cell is obtained by dynamic saturation block and this is fed as an input to all modules. The stack voltage is restricted between 280 V and 330 V because it is a function of the feedback current and temperature. When stack voltage is below a certain value and the system feeds the load, anode materials can be oxidized electrochemically. This situation continues with fuel decreasing and this type of repeated reactions can damage the cell anode seriously. Thus, an effective voltage control must be made to prevent anode oxidations (Mueller *et al.,* 2007). Also, inputs of thermal module of the SOFC stack are the fuel cell voltage and current, therefore the fuel cell stack is protected from over temperature. SOFC parameters are obtained from (Padulles *et al.,* 2000; Sedghisigarchi & Feliachi, 2004; Goel *et al.,* 2006; Wu *et al.,* 2008b; Uzunoglu & Onar, 2008) and they are given in Table 2.

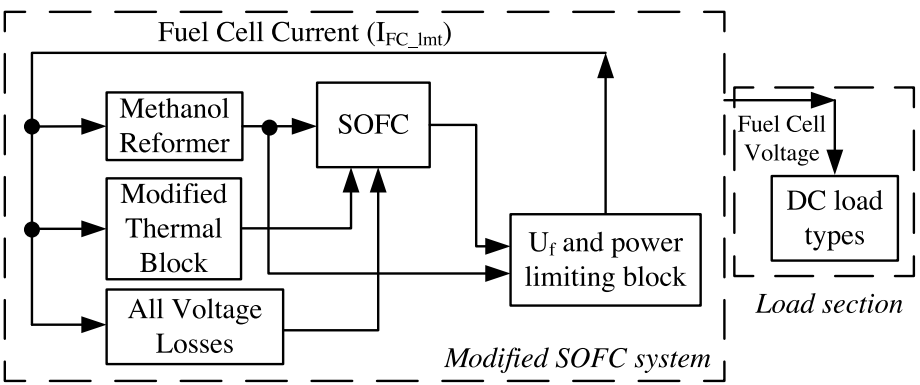

Fig. 1. Proposed modified model for SOFC system

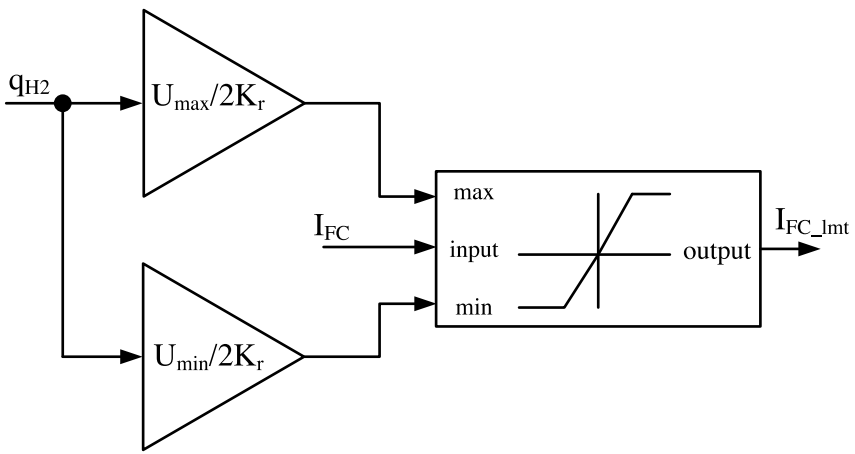

Fig. 2. U_f and power limiting block

Table 2. Parameters of the SOFC system used in the model

Variable	Specification	Value	Reference
P_{stack}	stack power	100 kW	(Padulles et al., 2000)
T	cell temperature	Variable	-
F	Faraday's constant	96484600 C mol^{-1}	-
R	gas constant	8314.47 J $kmol^{-1}$ °K^{-1})	-
E	ideal standard potential	0.935 V	(Sedghisigarchi & Feliachi, 2004)
N	number of cells in stack	384	(Padulles *et al*., 2000)
K_r	constant $K_r=N/4F$	9.9498x10^{-7} kmol s^{-1} A^{-1}	-
K_{H_2}	valve molar constant for hydrogen	8.43x10^{-4} kmol s^{-1} atm^{-1}	(Padulles *et al*., 2000)
K_{H_2O}	valve molar constant for water	2.81x10^{-4} kmol s^{-1} atm^{-1}	(Padulles *et al*., 2000)
K_{O_2}	valve molar constant for oxygen	2.52x10^{-3} kmol s^{-1} atm^{-1}	(Padulles *et al*., 2000)
τ_{H_2}	response time for hydrogen flow	26.1 s	(Padulles *et al*., 2000)
τ_{H_2O}	response time for water flow	78.3 s	(Padulles *et al*., 2000)
τ_{O_2}	response time for oxygen flow	2.91 s	(Padulles *et al*., 2000)
R_{int}	ohmic loss	0.126 Ω	(Padulles *et al*., 2000)
r_{H_O}	ratio of hydrogen to oxygen	1.145	(Wu *et al*., 2008b)
B	activation voltage constant	0.04777 A^{-1}	(Uzunoglu & Onar *et al*., 2008)
C	activation voltage constant	0.0136 V	(Uzunoglu & Onar *et al*., 2008)
τ_1	reformer time constant	4 s	-
τ_2	reformer time constant	4 s	-
τ_3	reformer time constant	4 s	-
CV	conversion factor	2	(Uzunoglu & Onar *et al*., 2008)
k_3	PI gain constant	1/(2CV)	-
I_L	limiting current	800 A	(Wu *et al*., 2008b)
h_{eff}	thickness	0.05 m	-
λ_s	thermal conductivity	27 W m^{-1} °K^{-1}	(Goel *et al*., 2006)
η	efficiency	0.8	Sedghisigarchi & Feliachi, 2004
σ	density	7800 kg m^{-3}	(Goel *et al*., 2006)
t	relaxation time	200 s	(Goel *et al*., 2006)

RESULTS AND DISCUSSION

In this section, the simulation examples are presented for four different DC load types to show feasibility of the proposed modified SOFC model. Step, ramp, random and stair-case DC load types are examined and their simulation results are given in Subsections, respectively.

Case study 1: DC Step load

In this study, the SOFC model with U_f limiting is tested for step changing of 25 kW in the load. The change of the load power, load voltage, load current and stack temperature are shown in Figs. 3a-d. Figures show variations of quantities in a test period of 2000 seconds.

The stack voltage has changed with step changes at levels 308 V-300 V in 1000 seconds time interval as shown in Figure 3b. According to Figure 3c, the increase in the load current causes a decrease in the output voltage of SOFC. Besides, as seen from Figure 3d, the stack temperature follows load power variations in Figure 3a and it varies between 1200 °K (927 ºC) and 1230 °K (957 ºC). As seen from Figure 3c and Figure 3d, the fuel cell's temperature increases when the load current increases. Temperature reaches to the steady state value after 500 seconds for the first load level. According to the other stack quantities, this situation has resulted from time constants and relaxation time of the thermal block. Also, a steep change in the fuel cell temperature is an undesirable state because it is harmful for the cell. This result shows that the thermal block given in (Goel *et al.,* 2006) has been successfully adapted to our model.

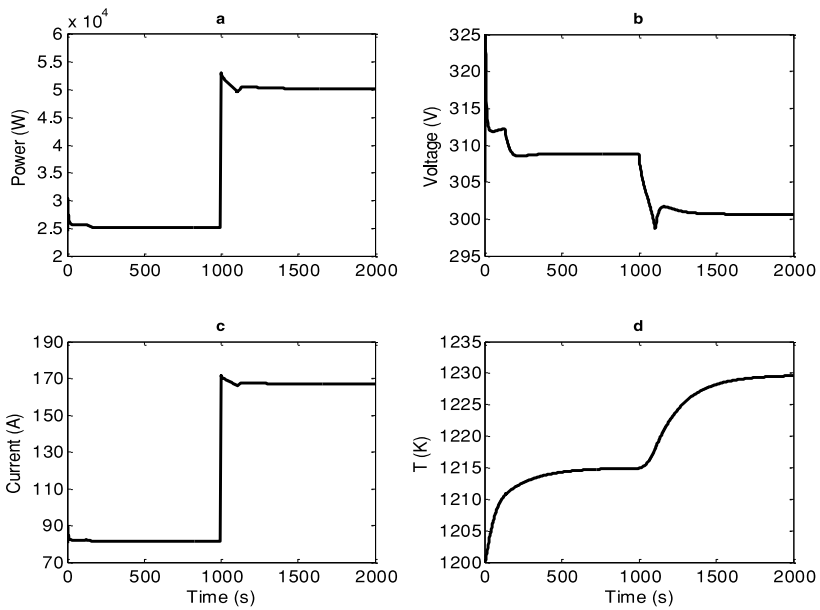

Fig. 3. For step load type a- power, b- voltage, c- current d- temperature

The obtained simulation results for the hydrogen (H_2) and oxygen (O_2) flow rate, U_f and the partial pressures of H_2, O_2 and water (H_2O) are given in Figures 4a-d. As seen from Figure 4a, the flow rate of H_2 and O_2 can follow variations of the load power. Thus, U_f based on second-order transfer function provides smooth load tracking as seen from Figure 4a. The U_f is 0.8 during transient state of about 180 seconds as shown in Figure 4b. It becomes 0.85 for the first load level of 25 kW. This is the expected situation because it is the nominal value. Then, it becomes 0.9 after 150 seconds, when the load of 50 kW switched on. Finally, it reaches again to 0.85, that expected value after transient state finished. In the previous model (Gelen & Yalcinoz, 2013), U_f was not limited between 0.8 and 0.9. In this paper, the remarkable point is that the U_f is limited to 0.9, while load is increased. The partial pressures of H_2 and O_2 for the step load type are given in Figure 4c. The variation of partial pressures of H_2 and O_2 is very close to one another, so that DC load variations can be followed as seen from Figure 4c. Also, the load tracking is clearly seen at the partial pressure of H_2O that is given in Figure 4d.

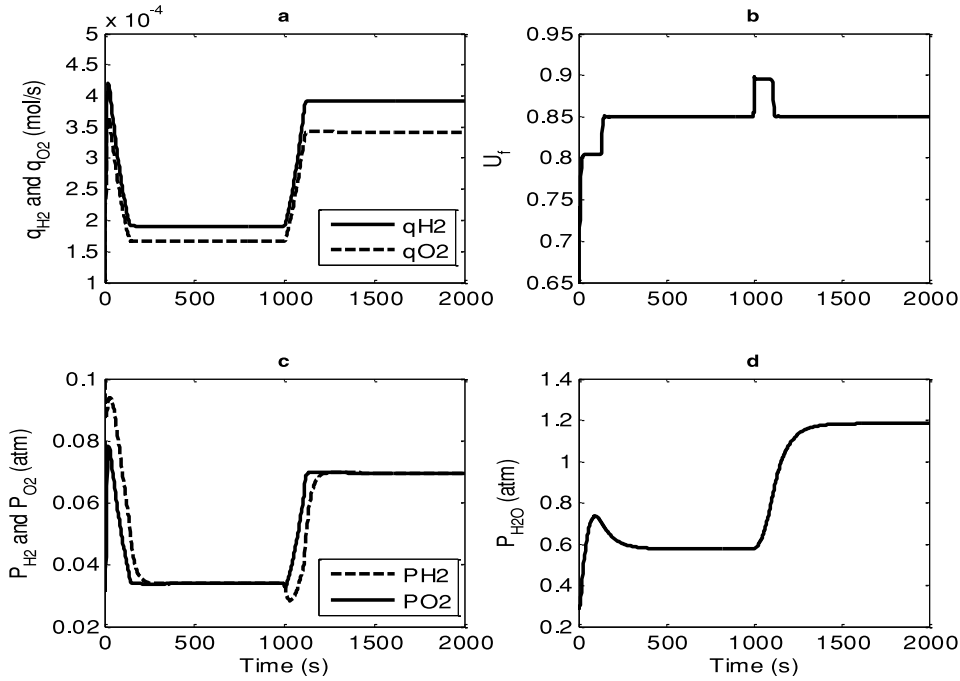

Fig. 4. For step load type a- H_2 - O_2 flow rate, b- fuel utilization factor, c- H_2 - O_2 partial pressures d- H_2O partial pressure

Case study 2: DC Ramp load

The ramp load type is used to test load-tracking of the new SOFC model. The load is 25 kW in the first 1500 seconds and reaches 50 kW in the second 1500 seconds.

Finally, the ohmic load becomes 50 kW. The changes of the load power, load voltage, load current and stack temperature are shown in Figures 5a-d. Figures show variations of quantities in a test period of 4500 seconds. In 1500 seconds time interval, Figure 5b demonstrates the stack voltage and it varies approximately between of 308 V-300 V. The power and current of the stack have shown same behavior as seen from Figure 5a and Figure 5c. The temperature response of the SOFC model is given in Figure 5d and it varies between 1200 ºK (927 ºC) and 1235 ºK (962 ºC). According to these figures, the thermal based modified SOFC model has a good response to variations in the ramp load powers.

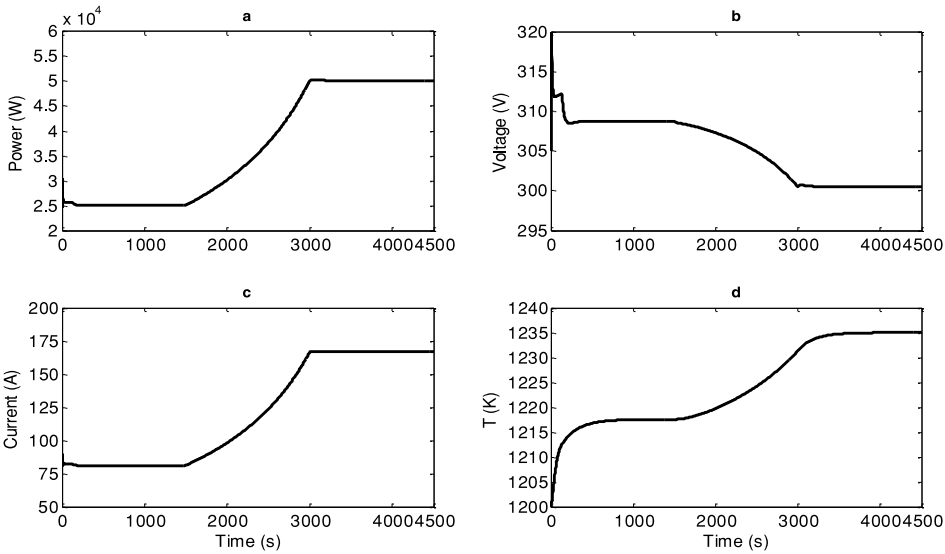

Fig. 5. For ramp load type a- power, b- voltage, c- current d- temperature

The obtained simulation results for the H_2 and O_2 flow rate, U_f and the partial pressures of H_2, O_2 and H_2O are shown in Figures 6a-d. As seen from Figure 6a, the flow rate of H_2 and O_2 can follow variations of the load power as expected. U_f is about 0.8 during transient state for first 180 seconds. It becomes 0.85 until 1500 seconds and it is 0.85 after 3000 seconds and this is an expected situation as at the step load condition. Finally, the partial pressures of H_2, O_2 and H_2O for ramp load type are given in Figure 6c and Figure 6d, respectively. The variations of the partial pressures of H_2 and O_2 are very close to each other. They follow the DC load variations as seen from Fig. 6c. Also, the load tracking is clearly seen at the partial pressure of H_2O. As seen from figures, in the system with ramp load takes shorter time to reach steady state condition than the step loaded; the reason for this is that the load does not change suddenly.

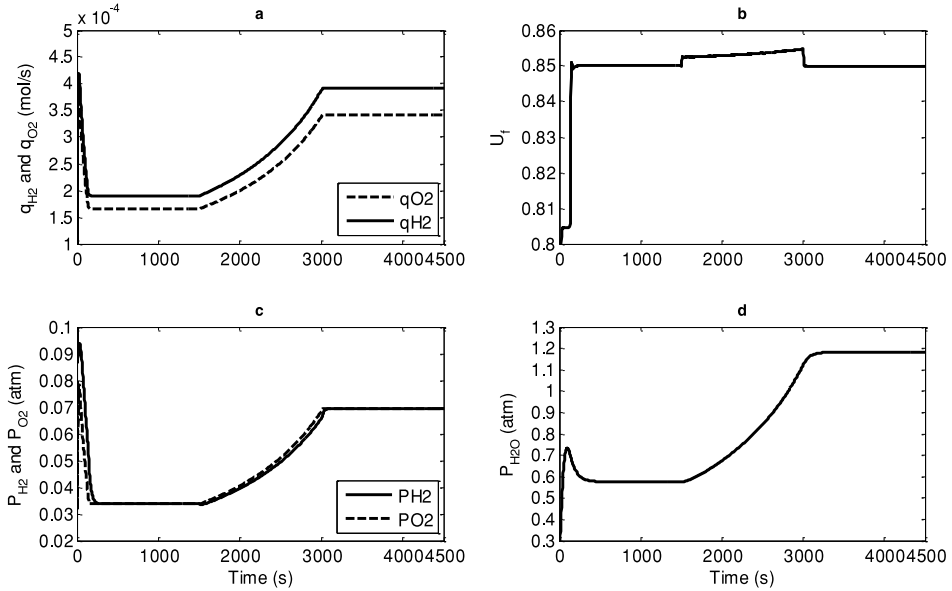

Fig. 6. For ramp load type a- H_2 - O_2 flow rate, b- fuel utilization factor, c- H_2 - O_2 partial pressures d- H_2O partial pressure

Case study 3: DC Random load

In this case study, the random load type is used for the DC load-tracking testing of the SOFC model with U_f limiting. The system has a load of 25 kW for period of first 1500 seconds, a load of 40 kW is suddenly switched on at 1500 seconds and finally the system has a load of 65 kW after 3000 seconds. The change of the stack power, voltage, current and temperature are shown in Figures 7a-d. The simulation results are obtained for 4500 seconds. Figure 7a illustrates the stack voltage. There is a ramp behavior at the period between 1500 seconds and 3000 seconds. The stack voltage is 308 V for the first 1500 seconds. It is at 301 V, when switched on and it is measured as 295 V for a load of 65 kW, as seen in Figure 7b. The temperature response of this model is given in Figure 7d. The temperature varies between 1200 ºK (927 ºC) and 1245 ºK (972 ºC). From Figure 7d, a sudden increase in load of 15 kW at 1500 seconds causes a slight increase in temperature. This result is important because the fuel cell system is maintained from sudden temperature variation. According to these figures, the SOFC model has a desired behavior and follows variations of the load power.

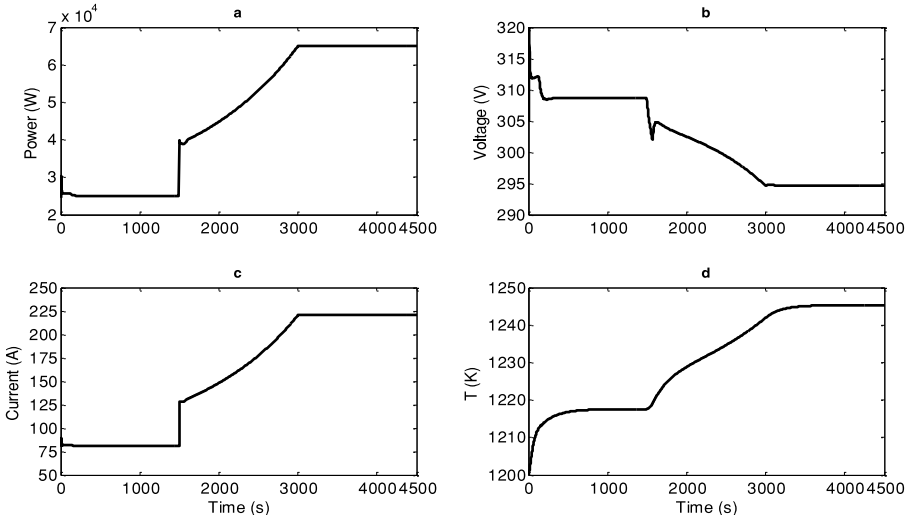

Fig. 7. For random load type a- power, b- voltage, c- current d- temperature

As seen from Figure 8a, the flow rate of H_2 and O_2 can follow load power variations fairly. U_f is 0.8 during transient state for first 180 seconds. It is 0.85 in the time interval between 180 seconds and 1500 seconds. It is 0.9 at switching on the load of 40 kW and this is the highest value. And, it is obtained as 0.85 after 3000 seconds as expected. In Figure 8b, especially, transient times for step or sudden load changes have clearly increased. The partial pressures of H_2, O_2 and H_2O for random load type are given in Figure 8c and Figure 8d, respectively. The variation of partial pressures of H_2 and O_2 is very close to each other and the load tracking is clearly seen at the partial pressure of H_2O.

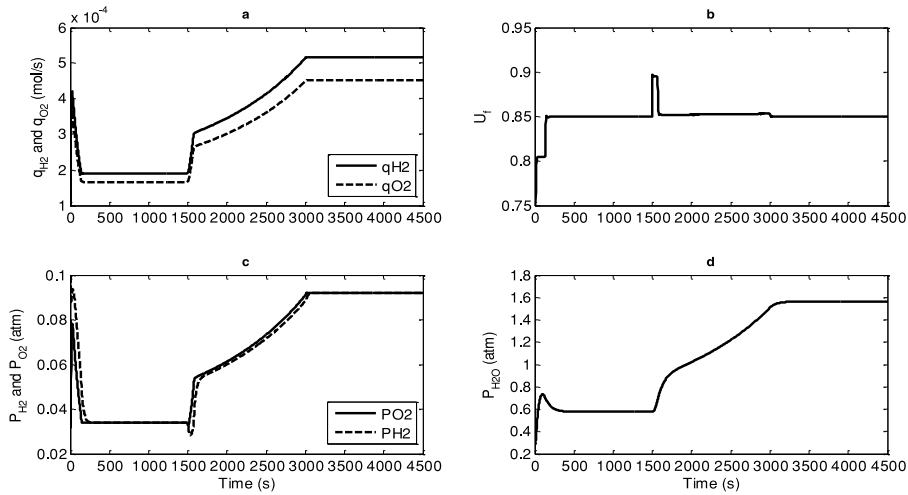

Fig. 8. For random load type a- H_2 - O_2 flow rate, b- fuel utilization factor, c- H_2 - O_2 partial pressures d- H_2O partial pressure

Case study 4: DC Stair-case load

Finally, in this case study, the stair-case load type is used for the DC load-tracking test of the SOFC model with U_f limiting. The ohmic loads of 25-45-65-45-25 kW are changed in 1500 seconds time interval in the system. The change of the stack power, voltage, current and temperature are shown in Figures 9a-d. The simulation results are obtained for 7500 seconds. To this power profile, the stack voltage has changed at levels 309-302-295-302-309 V in same interval as shown in Figure 9b. The stack temperature varies between 1200 ºK (927 ºC) and 1245 ºK (972 ºC). The increasing of the load current causes an increase in the temperature of SOFC stack.

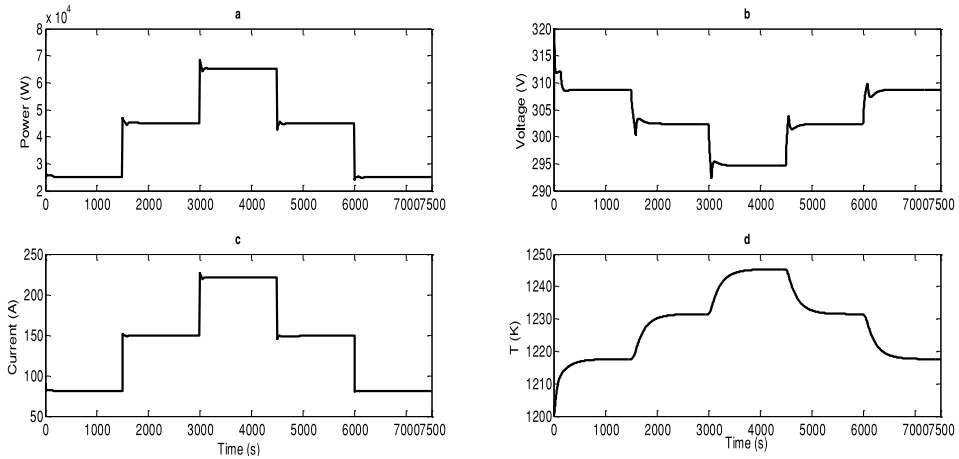

Fig. 9. For stair-case load type a- power, b- voltage, c- current d- temperature

As seen from Figures 10a-d, the SOFC stack quantities can follow variations of the load power. The fuel flow rate has changed at levels 0.19-0.35-0.52-0.35-0.19 mol/s in 1500 seconds time interval as seen from Figure 10a. The U_f values occur at between 0.8 and 0.9 at switching on-off loads. But, going out from 0.8-0.9 interval of U_f can cause damage to the fuel cell system and this situation will cause excessive fuel use. So, the limited situation of U_f can be seen clearly for especially stair-case load type. Lastly, the partial pressures of H_2, O_2 and H_2O for stair-case load type are given in Figure 10c and Figure 10d, respectively. The variations of partial pressures of H_2 and O_2 are very close to each other and the load tracking are clearly seen at the partial pressure of H_2O as in the other load types.

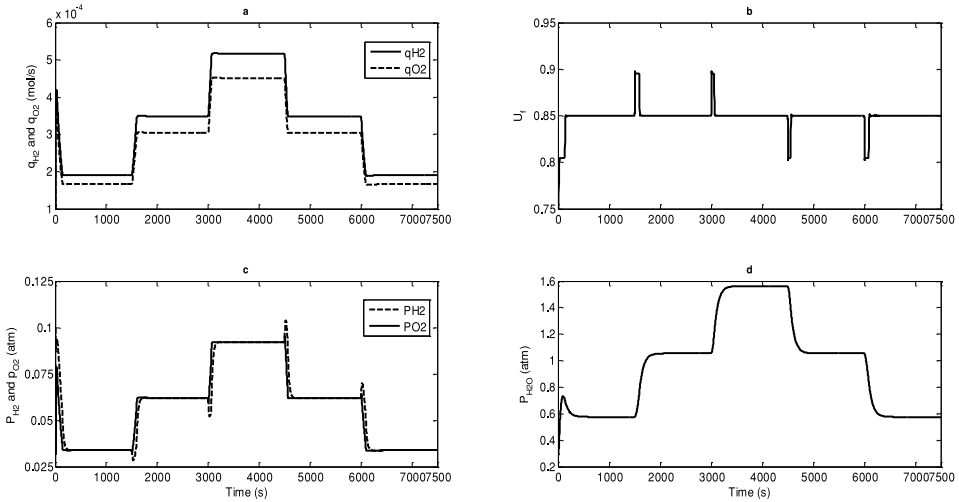

Fig. 10. For stair-case load type a- H_2 - O_2 flow rate, b- fuel utilization factor, c- H_2 - O_2 partial pressures d- H_2O partial pressure

CONCLUSIONS

This paper presents a thermal based SOFC model with fuel utilization factor limiter. The modified SOFC model is tested for different DC load types, which are step, ramp, random and stair-case to show load tracking performance.

The simulation results show that the new SOFC model has a proper DC load tracking capability. Especially, reaching a steady state of the system takes a shorter time in the ramp load according to the step load. Besides, the limitation of U_f can be seen more clearly from the system with stair-case load. Especially, transient times in fuel utilization factor for step or sudden load changes have clearly increased. At sudden load variations, the fuel cell systems must be protected by using these limiter blocks. These results show that the use of U_f limiter block has adapted successfully to the proposed dynamic model. The future work will investigate performance under AC load conditions of the proposed SOFC model.

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