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The modeling and simulation of thermal based modified solid oxide fuel cell (SOFC) for grid-connected systems

Ayetül Gelen[1*] and Tankut Yalcinoz[2]

*[1]Department of Electrical and Electronics Engineering, Gaziosmanpasa University, Taslıciftlik campus, 60150, Tokat, Turkey. [2]Department of Electrical and Electronics Engineering, Mevlana University, Konya, Turkey. *Author for correspondence. E-mail: aygelen@outlook.com*

ABSTRACT. This paper presents a thermal based modified dynamic model of a Solid Oxide Fuel Cell (SOFC) for grid-connected systems. The proposed fuel cell model involves ohmic, activation and concentration voltage losses, thermal dynamics, methanol reformer, fuel utilization factor and power limiting module. A power conditioning unit (PCU), which consists of a DC-DC boost converter and a DC-AC voltage-source inverter (VSI), their controller, transformer and filter, is designed for grid-connected systems. The voltage-source inverter with six Insulated Gate Bipolar Transistor (IGBT) switches inverts the DC voltage that comes from the converter into a sinusoidal voltage synchronized with the grid. The simulations and modeling of the system are developed on Matlab/Simulink environment. The performance of SOFC with converter is examined under step and random load conditions. The simulation results show that the designed boost converter for the proposed thermal based modified SOFC model has fairly followed different DC load variations. Finally, the AC bus of 400 Volt and 50 Hz is connected to a single-machine infinite bus (SMIB) through a transmission line. The real and reactive power managements of the inverter are analyzed by an infinite bus system. Thus, the desired nominal values are properly obtained by means of the inverter controller.

Keywords: solid oxide fuel cell, thermal modified model, power conditioning unit, infinite bus, grid connected.

O modelamento e a simulação de célula de combustível de óxido sólido (CCOS) modificado para sistemas conectados por grids

RESUMO. Esse artigo apresenta um modelo dinâmico modificado baseado em temperatura de uma Célula de Combustível de Óxido Sólido (CCOS) para sistemas conectados por grids. O modelo de célula de combustível envolve ativação e concentração ôhmica, perda de voltagem, dinâmica termal, reformador de metanol, fator de utilização de combustível e módulo limitante de potência. A unidade condicionadora de potência (UCP), a qual consiste em um conversor DC-AC e um inversor de fonte de voltagem DC-AC (IFV), o controlador, transformador e filtro, foi modelado para sistemas conectados por grids. O inversor de fonte de voltagem com seis interruptores de Transistor Bipolar de Portal Insulado (TBPI) inverte a voltagem DC oriunda do conversor para a voltagem sinusoidal sincronizada com o grid. As simulações e os modelos do sistema são desenvolvidos num ambiente Matlab/Simulink. O funcionamento de CCOS com o conversor é analisado sob condições de carregamento aleatório e avanço. Os resultados mostram que o conversor para o modelo CCOS seguiu variações diferentes de carga DC. A distribuição de rede AC de 400 Volts e 50 Hz é conectada a uma rede infinita de máquina única por linha de transmissão. A administração de potência real e reativa do conversor é analisada por um sistema infinito de distribuição. Portanto, os valores nominais são adequadamente ordenados pelo controlador do inversor.

Palavras-chave: célula de combustível de óxido sólido; modela térmico modificado; unidade de condicionamento de potência; distribuição infinita; conectado a grid.

Introduction

Solid Oxide Fuel Cells (SOFCs) are used in many applications such as auxiliary power units and stationary power systems. The total efficiency of SOFC systems that operate at high temperature is increased with combined heat power system (EG&G TECHNICAL SERVICES, 2002). The voltage and frequency characteristics of the single-machine infinite bus (SMIB) are constant in the case of any load variation. Some researchers have considered on the dynamics of SOFCs power plant connected to a SMIB system for AC test. Hybrid power sources, adaptive control schemes, effect of firing angle on real power, power flow control, microgrid applications, grid fault conditions, real-reactive power management and inverter control strategies related to the infinite bus have been studied by several researchers (SEDGHISIGARCHI; FELIACHI, 2004a; JURADO; VALVERDE, 2005; SEDGHISIGARCHI; FELIACHI, 2006; LI et al., 2007; WANG; NEHRIR, 2007; HAJIZADEH; GOLKAR, 2009; STEWARD et al., 2010). However, researchers have considered only thermal aspects of fuel cells. Moreover, these models have included neither all voltage losses nor a fuel reformer module. The SOFC model in our previous work (GELEN; YALCINOZ, 2013) has all voltage losses, modified thermal dynamics and a second-order transfer function-based fuel reformer unit.

In addition to the model in reference (GELEN; YALCINOZ, 2013), the modified SOFC model used in this paper includes a limiting module for the fuel utilization factor (U_f). The feedback current, voltage and power of fuel cell are varied indirectly by this addition module because the feedback current varies with limited U_f. Thus, these parameters are limited to avoid excessive fuel flow and temperature. In addition, the employed reformer is based on second-order transfer function as in reference (EL-SHARKH et al., 2004). The thermal module used in the SOFC model is modified as based on reference (GELEN; YALCINOZ, 2013). SOFC parameters are taken from Refs. (PADULLES et al., 2000; SEDGHISIGARCHI; FELIACHI, 2004b; GELEN; YALCINOZ, 2013; WU et al., 2008; UZUNOGLU; ONAR, 2008). This newly developed SOFC model complements the existing models and is reliable. A power conditioning unit (PCU), which consists of a DC-DC boost converter, a DC-AC voltage-source inverter (VSI), their controller, a transformer and a filter, is employed to connect the SOFC model to the grid. A mathematical model of the boost DC-DC converter is established for the PCU. The simulation model of the inverter was examined mathematically in many previous studies. In this study, the inverter is developed using an electrical circuit model. The first contribution of this paper is to illustrate the AC behavior of the modified SOFC model. A DC load tracking ability of the boost converter for two different load types is examined and this is the second contribution. The AC performance of the SOFC model connected to a SMIB is then investigated by using designed PCU. The simulation results present several measurements of the SOFC, the converter and the inverter. The fuel cell model, PCU and test systems are implemented in Matlab/Simulink environment.

Grid-connected modified SOFC power system

Model of modified SOFC system

Expressions and equations of fuel reformer model, electrochemical model, modified thermal dynamics and Nernst voltage are given in detail in Refs. (PADULLES et al., 2000; GELEN; YALCINOZ, 2013). The stack output voltage is presented as follows (SEDGHISIGARCHI; FELIACHI, 2004b; SORDI et al., 2006):

$$V_{dc} = V_o - \eta_{ohm} - \eta_{act} - \eta_{conc} \quad (1)$$

where:
V_o is the open-circuit reversible potential (V) in Equation (2). It is based on temperature and reactant-product partial pressures that are based on the flow rate; it is also based on the feedback current. Therefore, if these quantities are variables, the behavior of the fuel cell stack is more realistic. In this paper, all quantities are chosen as variables.

$$V_o = N\left(E + \frac{RT}{2F}\ln\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}} \right) \quad (2)$$

The SOFC parameters used in this paper are obtained from Refs. (PADULLES et al., 2000; SEDGHISIGARCHI; FELIACHI, 2004b; WU et al., 2008; UZUNOGLU; ONAR, 2008; GELEN; YALCINOZ, 2013) and the parameters are given in Appendix A. The completely modified SOFC system is obtained by cascade connecting of above-mentioned modules. The thermal module is modified by using 'unit delay block' instead of 'memory block'. Particularly, in the grid-connected systems, the simulation time suffers from memory block. In this paper, the 'unit delay block' is used to solve this problem. Further, if an AC bus system is designed as an electrical circuit, the efficiency of this block is much increased.

The existing fuel cell model presented in reference (GELEN; YALCINOZ, 2013) is modified by adding the limiting stage for the fuel utilization factor and the stack power. The controlling of the fuel reformer is based on the feedback current and this new block given in Figure 1 is used to limit 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, which is function of the feedback current and temperature, is limited between 280 and 330 V. When stack voltage is below a certain value and the system feeds the load; anode materials can be oxidized electrochemically. Thus, an effective voltage control must be made to prevent anode oxidations (MUELLER et al., 2007). Further, 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. Consequently, this modification complements the existing SOFC models.

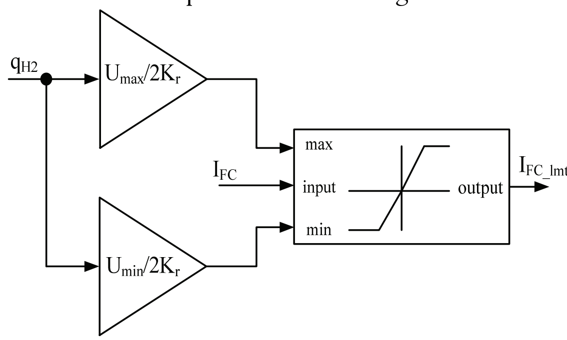

Figure 1. U_f and power limiting block.

The designing power conditioning unit

The designed PCU consists of a DC-DC boost converter, a DC-AC inverter and their controller. Then, the SOFC system with the PCU for testing AC performance of the SOFC model is connected to a SMIB. This system consists of transformer, LC filter and 3 km length short transmission line. In this case, the AC system is simulated without considering a load unit. Figure 2 demonstrates the modified fuel cell model, the PCU and a SMIB. The transformer, which is connected to the output of the PCU, achieves isolation between the PCU and the infinite bus. The LC filter is connected between the PCU and the transmission line. Finally, at nominal frequency of 50 Hz, the infinite bus at a voltage of 400 V is connected to end of the transmission line.

In this paper, the DC-DC boost converter is designed as a mathematical model by using Matlab/Simulink, and used in AC grid applications. The fuel cell power source is considered as DC power supply of 400 V with the DC-DC converter. The simulation model of SOFC is constituted by using mathematical equations. Therefore, by using this type converter, it does not require using any conversion block between two units. In addition, the modeling of the converter as electrical circuit has enhanced notably simulation time. The output voltage of the boost converter is regulated at 400 V value by a proportional integral (PI) type controller.

The regulated DC voltage of 400 V is fed to input of a voltage-source DC-AC inverter with IGBTs. A three-phase AC voltage at fundamental frequency is obtained by applying sinusoidal pulse-width-modulation (SPWM) technique to the voltage-source inverter (VSI). The inverter is synchronized with the grid by controlling properly the output voltage and frequency of the inverter. Phase-locked loop (PLL) is employed. The inverter is characterized with the Park-transformation (abc/dq0)-based real-reactive power controller. This transformation technique is a mathematical conversion used to simplify analysis of three-phase circuits. At balanced three-phase systems, three AC components are reduced to two DC components by the Park-transformation. Synchronous data of the system voltage is needed for the conversion of *abc* to *dq0*. When the obtained ωt by feeding source voltages to input of the PLL synchronizes with system ωt, *dq0* synchronizes with the system frequency. The Park-transformation which is applied to three-phase current as matrix is seen in Equation (3) (ANDERSSON, 2003).

$$I_{dq0} = T I_{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} Cos(\theta) & Cos(\theta - \frac{2\pi}{3}) & Cos(\theta + \frac{2\pi}{3}) \\ -Sin(\theta) & -Sin(\theta - \frac{2\pi}{3}) & -Sin(\theta + \frac{2\pi}{3}) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (3)$$

At the three-phase systems, the component on d-axis of current, which is transformed to *dq0* at same phase with voltage, is *Id* that is positive-sequence real current. *Iq* component on q-axis is negative-sequence reactive current, since it is right-angled according to *Id*. *I0* component on 0-axis is zero-sequence component of the current. If *Iq* is negative, load includes inductive component and, if it is positive, load includes capacitive component (ANDERSSON, 2003).

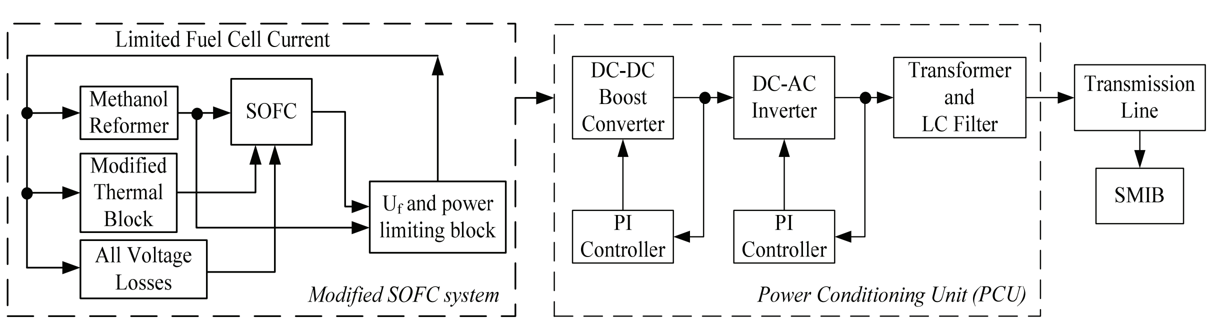

Figure 2. Modified SOFC power system connected to grid.

Figure 3 shows a block diagram of the three-phase PCU and its control structure. The inverter output is in the form of square wave. A three-phase transformer of 220/400 V is used to convert this output into sinusoidal waveform. The LC filter is used to reduce ripples. They are transformed to *dq* values by measuring three-phase AC bus voltage and current by '*abc/dq0* transformation block'. Reference *dq* values are obtained by taking into account real-reactive power demands of a grid. These values are fed to the current controller, which produces a controller signal. This signal is transformed to *abc,* which is an input signal of trigger, by '*dq0/abc* transformation block'. In addition, the angular frequency, which is needed for synchronization, is fed to this block as a second input. Switches of the inverter are fired by using trigger. Hence, an AC voltage of nominal value can be produced. Thus, the PCU is modeled for the fuel cell system of 100 kW.

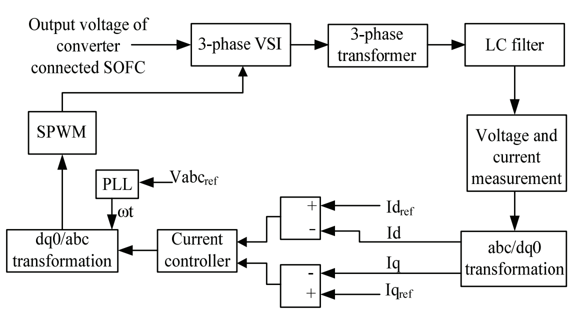

Figure 3. Three-phase PCU and its control structure.

Results and discussion

In this section, simulation studies are carried out in Matlab/Simulink to show performance of the designed power conditioning unit for the modified SOFC model. Initially, DC load tracking of the DC-DC boost converter is investigated for both step and random load types. Then, the inverter is merged into the converter for grid-connected applications. Moreover, a SMIB is used for AC test studies.

The step load-tracking of DC-DC boost converter

A step load profile is used to test load-following ability of cascade-connected SOFC model and the DC-DC boost converter. Figure 4 shows the obtained stack voltage for a step load. The changes of the current, voltage, power and duty cycle of the converter are shown in Figure 4a-d. The simulation results are obtained during 2000 s.

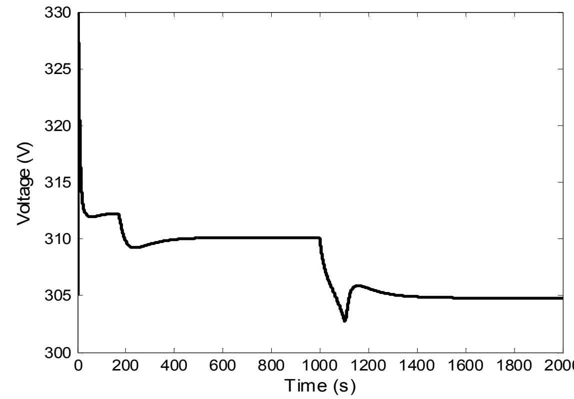

Figure 4. SOFC stack voltage for a step load.

According to Figure 4, the fuel cell stack voltage has varied at levels 310-305 V in 1000 s time interval. The stack voltage is an input of the boost converter. In addition, it is required that the converter boosts this input voltage to 400 V by means of the controller. Gains of the designed PI controller are KP = 0.2, KI = 10. A step load variation is seen clearly in Figure 5a and 5c, respectively. The converter output voltage could hold constant at 400 V in despite of this load change, as seen in Figure 5b. The converter output power is 25 kW and 50 kW in a 1000 s time interval. Lastly, the duty cycle value is measured as 0.225 and 0.235 in same interval as observed in Figure 5d. This simulation results show that designed PI controller is used to regulate the converter output voltage.

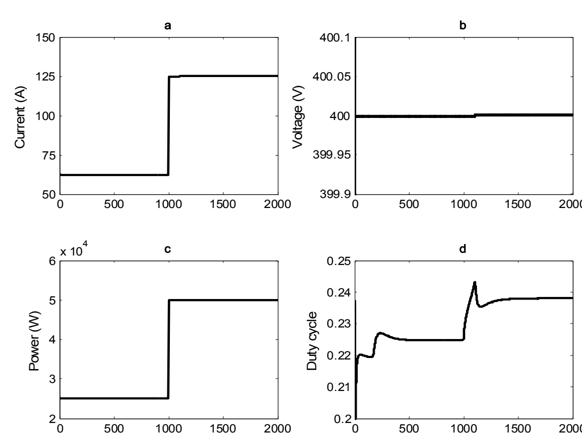

Figure 5. For a step load a: current; b: voltage; c: power and d: duty cycle.

The random load-tracking of DC-DC boost converter

The random loads, which have different power values in different time, are used to test the load tracking of the new SOFC model. The simulated stack voltage is given in Figure 6. Figure 7a-d show the variations in current, voltage, power and duty cycle for the converter. The simulation results are acquired during 2000 s.

According to Figure 6, the stack voltage changes at levels between 290 and 310 V during simulation. The gains of the PI controller are chosen as K_P = 0.2, K_I = 10. As seen in Figure 7b, the converter output voltage is held constant at around 400 V in despite of load currents and power changing. The converter output power varies at levels between 25 and 100 kW during simulation as shown in Figure 7c. Besides, according to this figure, effectiveness of U_f limiting block in the modified fuel cell model is observed clearly with maximum power level of 100 kW because the limited U_f is a variable of the power. Finally, the duty cycle value changes at levels between 0.225 and 0.275 in the same interval as seen in Figure 7d. These simulation results show that designed PI controller regulates outputs of the converter for both step and random load type.

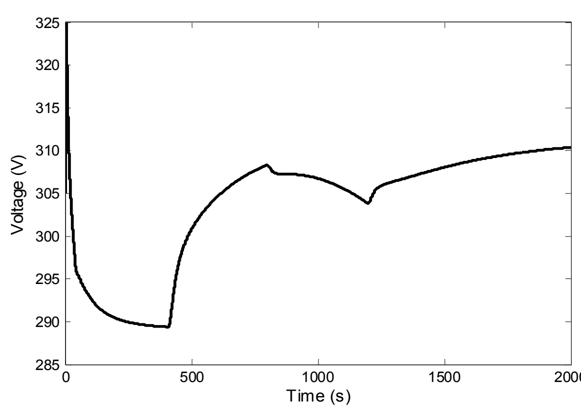

Figure 6. SOFC stack voltage for random loads.

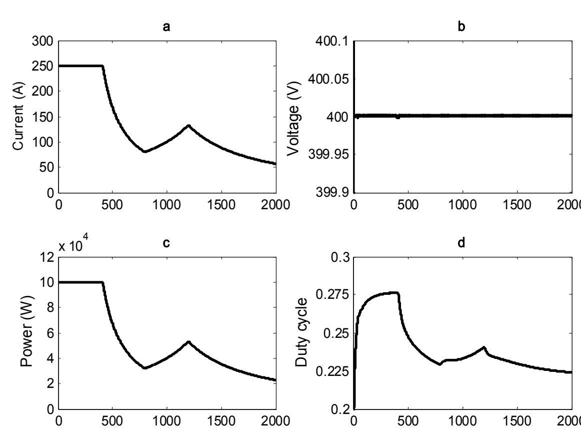

Figure 7. For random load a: current; b: voltage; c: power and d: duty cycle.

AC test of fuel cell system with SMIB

A PI type controller is designed to control firing angles of the IGBT-based voltage-source inverter. The gains of the PI controller are chosen as K_P = 10, K_I = 3000. In addition, the gains of the PI controller for the boost converter are selected as K_P = 1.6, K_I = 0.02. The variations of voltage, power, hydrogen (H_2) and oxygen (O_2) flow rate, fuel utilization factor (U_f), partial pressures of H_2-O_2-water (H_2O) and stack temperature for a power system with the SOFC connected to an infinite bus system are given in Figure 8a-f, respectively.

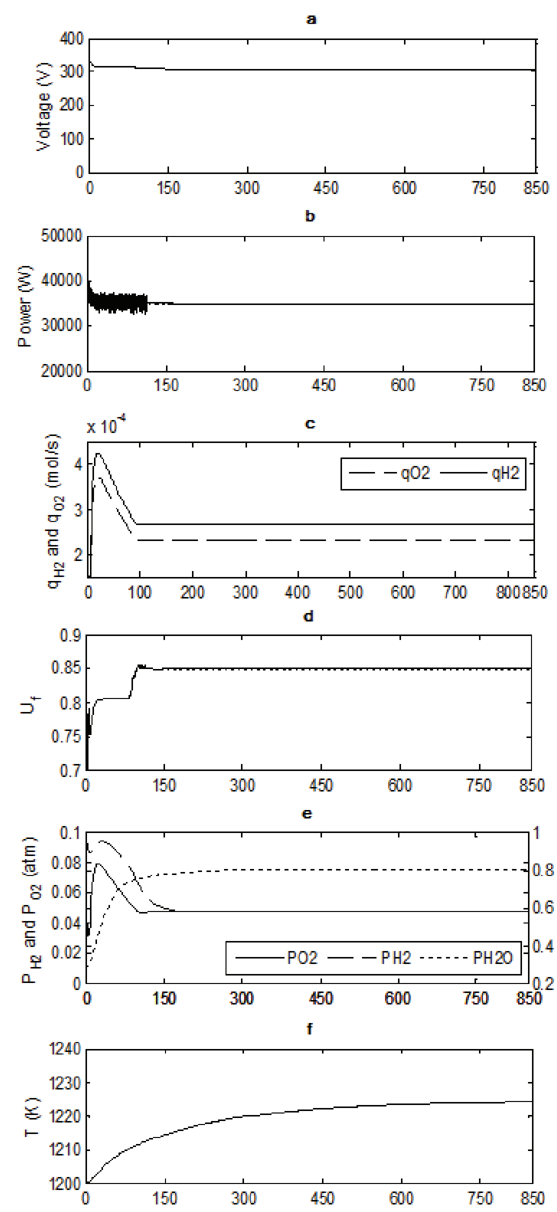

Figure 8. a: voltage; b: power; c: H_2-O_2 flow rate; d: U_f e: H_2-O_2-H_2O partial pressures and f: temperature for the system with SMIB.

The simulation results are obtained during 850 s. The stack voltage is 306 V; the stack power is 35 kW; the H_2 flow rate is 0.27 mol s^{-1}; the O_2 flow rate is 0.23 mol s^{-1}; fuel utilization factor is 0.85; the H_2 and O_2 partial pressures are 4.74×10^{-2} atm; the H_2O partial pressure is 0.806 atm and the stack temperature is 1224°K for the SOFC. The U_f is 0.85 that is nominal value for fuel cell systems. There are ripples within acceptable limits and the fuel cell feeds to the converter.

The output voltage, the duty cycle and the output power of the DC-DC boost converter at the system with SMIB are illustrated in Figure 9a-b. The output voltage is 400 V, the duty cycle is 0.235 and the output power is 45.5 kW. These simulation results show that the output of the converter is regulated and the signal is a suitable input for the inverter. From Figure 9b, the transient time of the fuel cell, which is about 120 s, affects the converter power and these ripple values are acceptable.

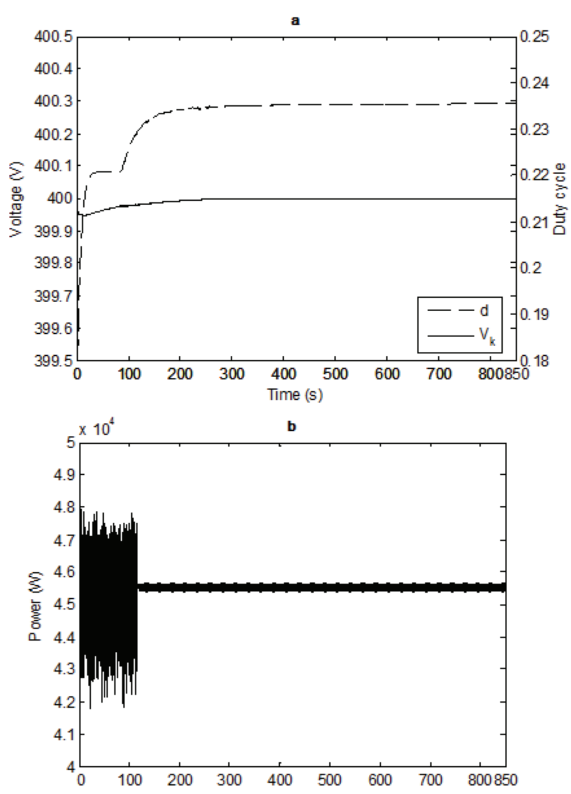

Figure 9. a: voltage and duty cycle and b: power for the system with SMIB.

Figure 10a-f present AC bus quantities, which are inverter output, filter output and sinusoidal infinite bus voltage waveform with rms values, filter and infinite bus frequency, real and reactive power for the system with SMIB. Square wave with amplitude of 400 V acquired by firing six IGBT switches is seen in Figure 10a.

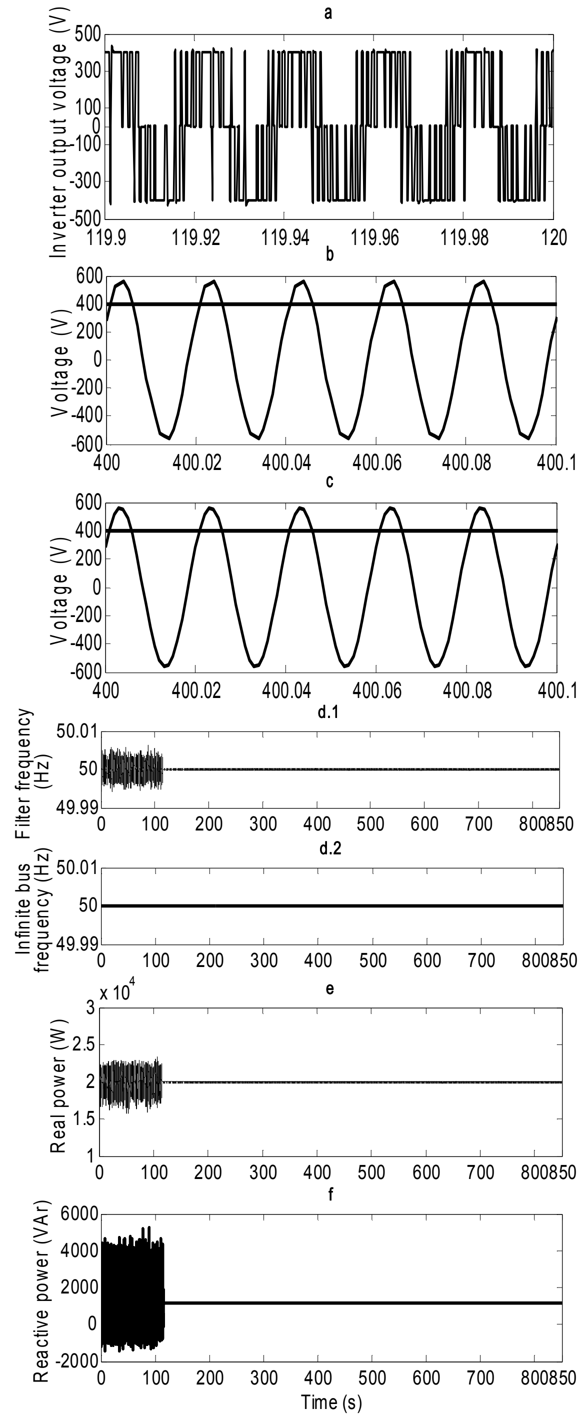

Figure 10. The system with SMIB a: inverter output voltage; b: filter output voltage as sinus and rms; c: infinite bus voltage as

sinus and rms; d: filter and infinite bus frequency; e: real power and f: reactive power.

Moreover, its input is the converter output voltage of 400 V. The form after transformer and filter of this square wave is given in Figure 10b. The peak and effective value of the filter output voltage are 565 V and 400 V_{rms}, respectively. Besides, the filter removes undesired fluctuations on voltages at the head of the transmission line. Figure 10c shows the signals related to the measured voltage on the infinite bus at the end of the transmission line. The obtained nominal value of 400 V_{rms} is expected for the infinite bus. Frequencies of the PCU output and the infinite bus are acquired as 50 Hz as given in Figure 10d. The frequency ripple at the head of transmission line during the steady state time is considerably low. Therefore, the inverter controller produces the desired nominal voltage and frequency. Real and reactive powers are given in Figure 10e-f, respectively. The real power and reactive power values, given as the reference value to the inverter controller, are 20 kW and 0 kVAr, respectively. The real power is reached to its desired value. The value of 1 kVAr at the reactive power results from transformer, filter and transmission line. According to these results, the real-reactive power management of the inverter, which is designed as an electrical circuit, is done successfully. Hereby, suitable power conditioning unit and their controllers for the proposed SOFC model are designed and AC tests are carried out.

Conclusion

In this paper, a thermal-based modified dynamic model of a Solid Oxide Fuel Cell has been proposed for grid-connected systems. A power conditioning unit, which includes a DC-DC boost converter, a DC-AC inverter, their controller, a transformer and a filter, is designed for the thermal-based SOFC model with limiter of the fuel utilization factor. The Matlab/Simulink environment is used for developing the SOFC system and simulation studies for the DC-DC boost converter and three-phase voltage-source inverter. The simulation results demonstrate that the new SOFC model with the power conditioning unit successfully operates for grid-connected systems.

The DC step and random loads are used for simulation studies. The designed PI controller for the boost converter regulates its output by changing duty cycle for both step and random load types. In other words, if the load is changed on the system; it is not required to adjust controller parameter again. Thus, the feasibility of designed controller is shown and the modified SOFC-based DC power source of 400 V is obtained.

Finally, the SOFC system is connected to a single-machine infinite bus through a short transmission line for AC performance tests. The PI controller is used to control of the inverter, which is designed as an electrical circuit. The frequency values at the head and the end of the transmission line are obtained as 50 Hz by synchronizing by a phase-locked loop. The frequency ripple at the head of transmission line during the steady state time is considerably low. Thus, the inverter controller produces the desired nominal values of 400 V_{rms} and 50 Hz and it is fed to the grid. According to the simulation results, the real-reactive power management of the inverter is performed satisfyingly and the modified SOFC-based AC power source is acquired. Furthermore, the fuel utilization factor (U_f) is hold as 0.85 in the grid-connected system. Therefore, this shows that the fuel reformer block and its controller successfully perform this duty.

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Appendix A. Parameters of the SOFC system used in the dynamic model.

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