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Modelling, Design and Control of a Single Phase Solid Oxide Fuel Cell based Power System

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ABSTRACT*:* In an industrial power generation, power conversion is a significantly important concern. The power flow is seamless transmitted from fuel cell (FC) to electric grid through power converter components. This paper presents modelling and simulation of grid connected FC system. One of the most important types of FCs is that solid oxide fuel cell (SOFC) which has high-temperature technology, and fuel-flexible economic entitlement has been selected. The interconnection of the SOFC with a DC-DC converter and a DC-AC inverter for interfacing with the electric grid are modelled and simulated. DC-DC Boost converter is controlled by current and voltage based cascaded PI controller. Single phase adaptive filter based phase-locked loop (PLL) algorithm and pulse width modulation (PWM) is used for control of single phase DC-AC inverter. The simulation results show that the adaptive filter-PLL based control strategy is implemented for the control and synchronizing of the single phase electric grid connected SOFC system, successfully. All system components are developed by PSCAD/EMTDC simulation software.

Keywords: Adaptive filter, PLL, single phase inverter, solid oxide fuel cell

Tek Fazlı Katı Oksit Yakıt Hücresi tabanlı Güç Sisteminin Modellenmesi, Tasarlanması ve Kontrolü

ÖZET: Endüstriyel bir enerji üretiminde, güç dönüşümü önemli bir ilgi konusudur. Güç akışı, güç dönüştürücü bileşenleri tarafından yakıt hücresinden (YH) elektrik şebekesine kesintisiz olarak iletilir. Bu çalışmada, şebekeye bağlı YH sisteminin modellenmesi ve benzetim çalışması sunulmaktadır. Yüksek sıcaklık teknolojisine ve esnek yakıt ekonomisine sahip en önemli YH' den biri olan katı oksit yakıt hücresi (KOYH) seçilmiştir. KOYH' yi elektrik şebekesine bağlanmak için bir DA-DA dönüştürücü ve bir DA-AA evirici ile ara bağlantıları modellenmiş ve benzetim çalışması yapılmıştır. DA-DA yükseltici dönüştürücü, akım ve gerilim tabanlı artarda bağlanmış oransal integral (OI) ile kontrol edilmiştir. Tek fazlı DA-AA eviricinin kontrolü için tek fazlı uyarlanabilir süzgeç- faz kilitlemeli döngü (FKD) tabanlı kontrol stratejisi ve darbe genişlik modülasyonu (DGM) kullanılmıştır. Benzetim sonuçları, uyarlanabilir süzgeç-FKD tabanlı kontrol stratejisinin, tek fazlı elektrik şebekesine bağlı KOYH sisteminin kontrolü ve senkronizasyonu için başarıyla uygulandığını göstermektedir. Sistemin tüm bileşenleri PSCAD/EMTDC benzetim programı ile geliştirilmiştir.

Anahtar Kelimeler: FKD, katı oksit yakıt hücresi, tek fazlı evirici, uyarlamalı süzgeç

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INTRODUCTION

The world energy consumption, population growth, industrialization based on technological development is rapidly increasing. Nowadays, declining reserves, polluting nature by fossil energy sources, the use of renewable resources have been raised. These resources are solar, wind, water power (hydrogen power, geothermal energy,) wave energy, tidal energy and hydrogen based fuel cells (FCs) system. Wind energy and solar system are depending on whether conditions. Therefore, they are intermittent and not reliable and these cause limiting the optimal utilization of these sources (Chandrakar, 2013). And so, FCs are significant energy source for those problems and FC is preferred in many existing applications such as transportation and stationary applications in recent years (Boccaletti et al., 2006; Shouman et al., 2012).

In electric grid connected systems, FC can be easily placed at any side in a power system. Therefore, proper controllers are required to tie FC system to electric grid with interface devices (boost converter and single phase inverter) (Salam et al., 2009). Some different studies are presented for single phase grid connected FC system in literature (Sharma and Mishra, 2017). Zhao et al. (2011) proposed a current based proportional integral (PI) and proportional resonant (PR) controllers for currentregulation at steady state error. Jang et al. (2011) and (2013) presented a second order generalized integrator based PR controller for active and reactive power controller in single phase system.

In this paper, single phase AF-PLL based power controller is proposed for control of single phase electric grid connected FC system. After the model of SOFC stack is developed in PSCAD/EMTDC software, it is connected to the electric grid via boost converter and single phase inverter. The current and voltage based cascaded PI controller is presented under variable DC load. The performance of proposed AF-PLL is examined under various cases such as start-up and voltage harmonics.

MATERIALS AND METHODS

Single phase SOFC is tied electric grid through by boost converter and single phase inverter (Figure 1). Cascaded PI controller and AF-PLL based power controller are developed for control of grid connected SOFC system. All system modules and controllers are developed by PSCAD/EMTDC software package. The parameters of the proposed test system for simulation are given in Table 1.

Table 1. The parameters of proposed test system

Parameters		Values
Converter input voltage		110 V
Converter output voltage		220 V
Grid		220V
System frequency		50 Hz
Load power		24 kW
Load values		10-12.5
	L	0.3 mH
Filter	C	1.5 uF

Solid oxide fuel cell (SOFC) model

In this paper, solid oxide fuel cell (SOFC) model is developed with fuel cell (FC) stack provided by PSCAD/EMTDC software. The equations for SOFC module is given between (1) and (9). The FC stack current is proportional to fuel flow. The flow rates of hydrogen and oxygen determine partial pressure of hydrogen, oxygen and water (Tao et al., 2009). The stack voltage is depending on stack current, fuel flow and pressure of gases (Akkinapragada, 2007; Yang et al., 2014).

The partial pressure of hydrogen, oxygen and water (Yang et al., 2014) are given between equations (1) and (3) as follows;

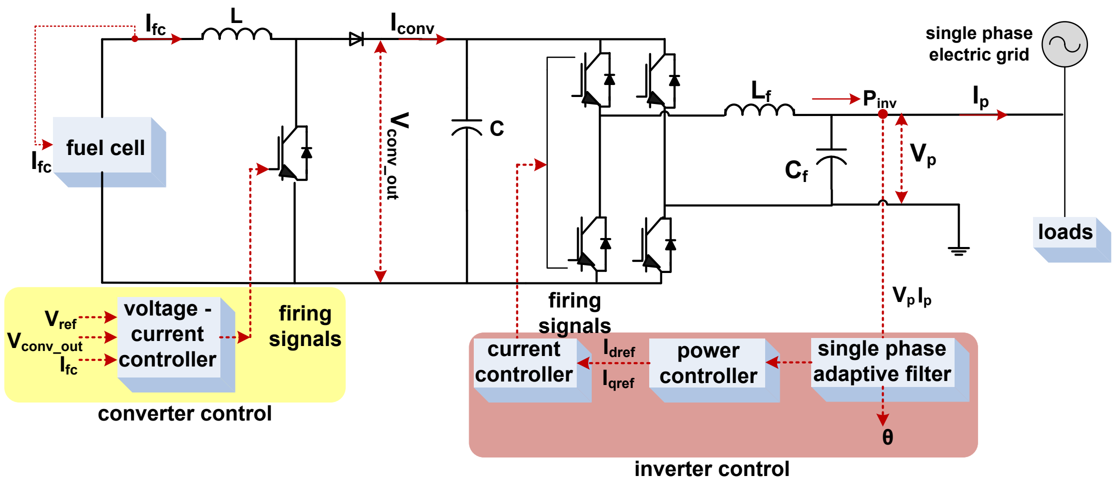

Figure 1. The proposed entire system configuration

$$P_{H_2} = \left(\frac{\frac{1}{KH_2}}{1+\tau_{H_2}S}\right)\left(qH_2 - 2K_r.I_{fc}\right) \tag{1}$$

$$P_{O_2} = \left(\frac{\frac{1}{KH_2O}}{1+\tau_{H_2O}S}\right)\left(qO_2 - 2K_r.I_{fc}\right) \tag{2}$$

$$P_{H_2O} = \left(\frac{\frac{1}{KH_2O}}{1+\tau_{H_2O}.S}\right)\left(2K_r.I_{fc}\right) \tag{3}$$

The molar fuel flow for hydrogen reacting and oxygen reacting is given in equation (4) and (5) (Meral and Çelik, 2016);

$$qH_2^{rec} = 2K_r.I_{fc} \tag{4}$$

$$qO_2^{rec} = \frac{qH_2}{rHO} \tag{5}$$

I_{ref} is the reference current ,

$$I_{\mathrm{ref}} = \frac{P_{\mathrm{ref}}}{V_{\mathrm{fc}}} \tag{6}$$

$$I_{\mathrm{fc}} = \frac{I_{\mathrm{ref}}}{1+\tau_e S} \tag{7}$$

The FC power can be derived as follow;

$$P_{\mathrm{fc}} = N_0 V_{\mathrm{fc}} I_{\mathrm{fc}} \tag{8}$$

FC stack voltage is given by the Nernst equation.

$$V_{fc} = N_0 \left(E_{\mathrm{o}} + \frac{RT}{2F} \left(In \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \right) - r I_{\mathrm{fc}} \tag{9}$$

Nomenclatures for FC stack equations:

E_o Standard reversible cell potential (V),

r: Internal resistance of stack (Ω),

N_0: Number of FC cell,

R: Universal gas constant (J/mol K),

T: FC stack temperature (K),

F: Faraday's constant (C/mol),

P_{H_2}: Partial pressure of hydrogen, oxygen and water

P_{O_2}: Partial pressure of oxygen

P_{H_2O}: Partial pressure of water

K_r: constant

Single-phase PLL

A PLL is a closed loop frequency control system that synchronizes for grid voltage and phase voltage. Adaptive filters (AF) provide fast tracking amplitude and phase angle of the input signal. This filter ensures many advantages, such as including generality, less complexity and computational burden and near optimum performance under distorted grid conditions. AF based phase locked loop (AF-PLL) extracts amplitude and phase angle of input signal. The measured output signals from proposed AF-PLL can be used for fast synchronising and control of grid tied inverter.

The error signal from AF-PLL represents the deviation of the input signal from the output signal. Vp is the line to phase voltage of grid voltage as input signal to the PLL. θ is the phase angle of the tracked signal (Meral et al., 2014). The block diagram of a single phase AF-PLL is given In Figure 2. The estimated phase angle and amplitudes of output signals can be expressed as follows;

$$Apl(t+1) = Apl(t) + k_1 e(t) \sin\left(\theta(t) - \frac{\pi}{2}\right) \tag{10}$$

$$\theta(t+1) = \theta(t) + k_p k_v e(t) \sin\big(\theta(t)\big) + w(t) \tag{11}$$

The output signal of proposed PLL is termed as Vα which are given in discrete time in following.

$$V_\alpha(t) = Apl(t) \sin\left(\theta(t) - \frac{\pi}{2}\right) \tag{12}$$

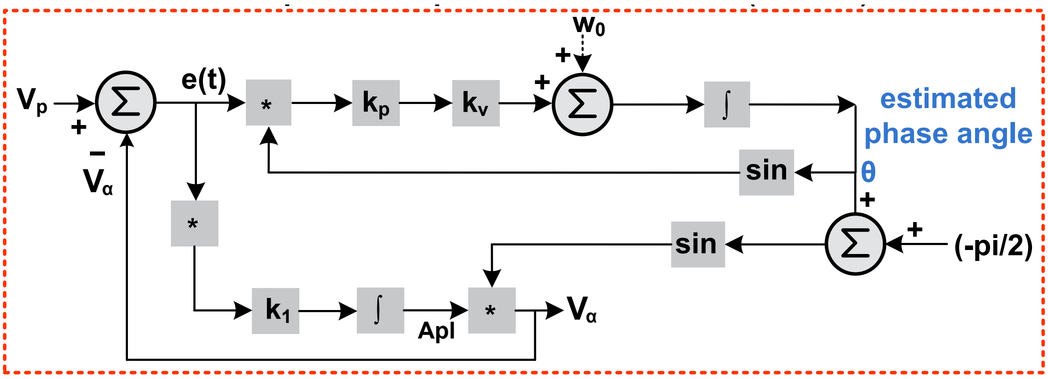

Figure 2. Block diagram of an adaptive filter based PLL

The control of fuel cell based power system

The control of grid-connected SOFC system is designed in Figure 3. As shown in Figure 3a and 3b, current and voltage based cascaded PI controllers are used for boost converter. The proposed AF-PLL based power controller is used for single phase inverter. The input current of boost converter is used for feedback control of FC system. In the control system, proposed AF-PLL synchronizes the electric grid connected single phaseinverter. AF-PLL generates phase angle to use in coordinate transformation for active and reactive power control. The difference between the reference active-reactive power and injected active-reactive power is regulated by inner-loop power controller. The reference currents are received from the outer-loop current PI controller. The reference voltage from PI controller is used into the control signal component of pulse width modulation (PWM).

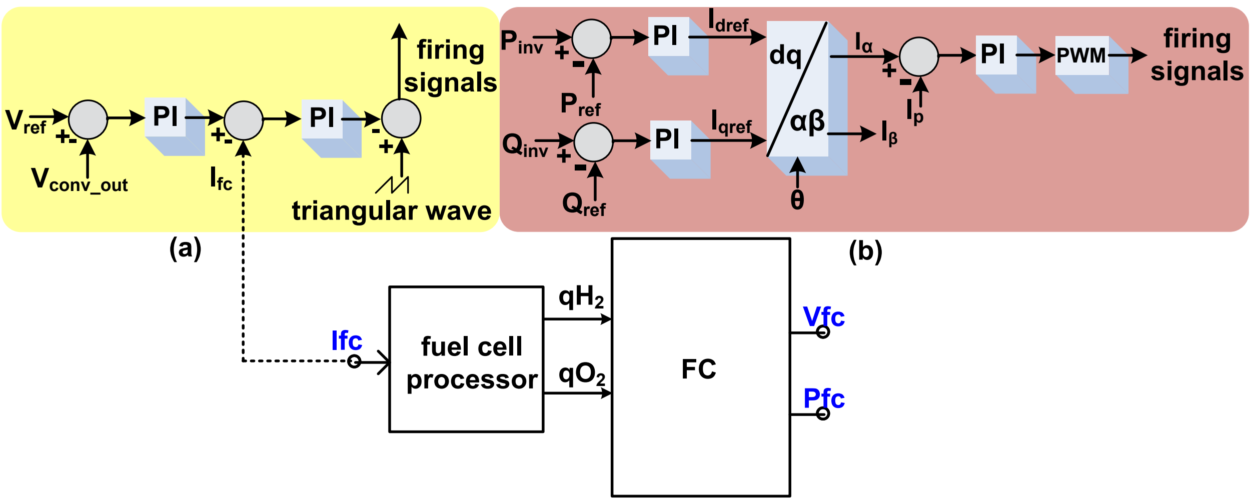

Figure 3. Control block diagram of; a) boost converter and b) grid connected single phase inverter

RESULTS AND DISCUSSIONS

The results show that, as stated in Figure 4a, the steady state error signal is almost zero for start-up of AF-PLL. It is possible to observe that the input reference signal (V*p*) is fast tracking the output signals (Vα) of AF. The AF-PLL provides fast dynamic response (less than one period-14ms). The performance of AF- PLL is examined under voltage harmonics. When voltage harmonics (5^{th} and 7^{th}) are injected to the electric grid, the proposed PLL extracts pure sinusoidal signals with low harmonic ripple errors in Figure 4b. Therefore, the phase error between input and output signals is highly low.

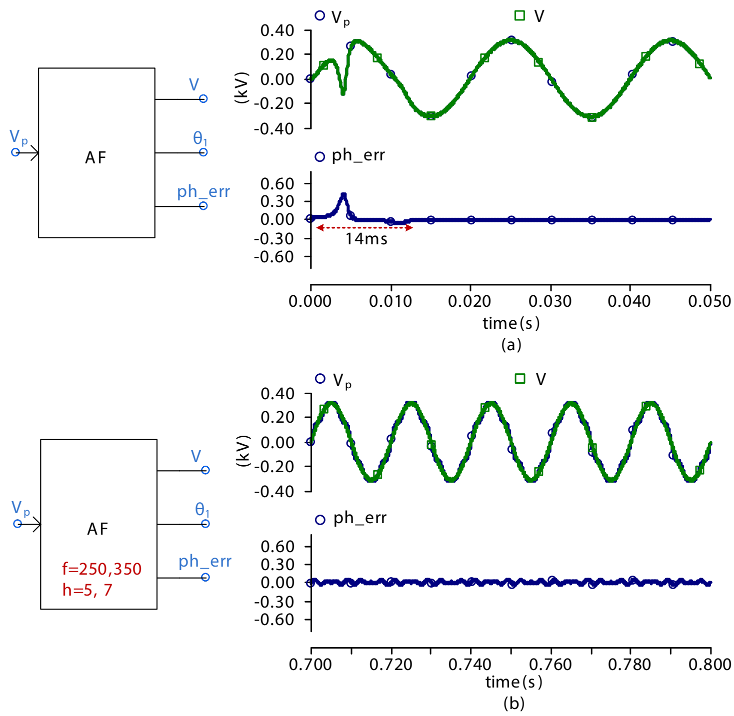

Figure 4. The results for AF-PLL; a) phase tracking for start-up and b) impact of voltage harmonics

The characteristic behaviour of SOFC system under various DC load condition is given Figure 5. The load values are changed from 10 ohm to 12.5 ohm. With increasing load values, FC output power and current decrease and voltage increases, proportionally (Figure 5a). In SOFC connected boost converter, the impact of variable load on output voltage is examined. While converter output voltage is kept constant by favour of converter control under variation of load, converter output power and current change, inversely as shown in Figure 5b.

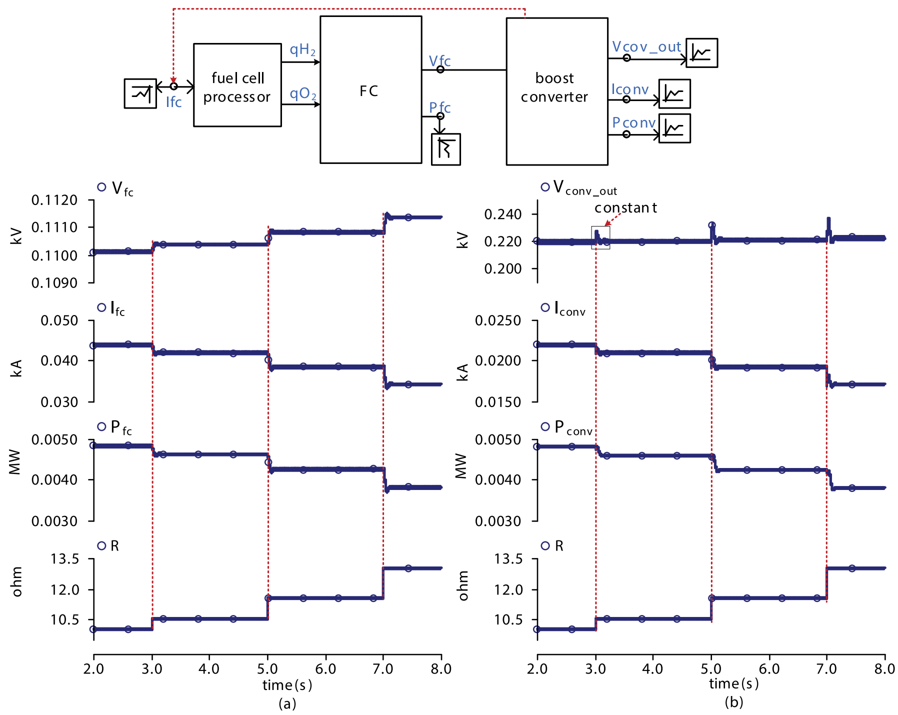

Figure 5. Using variation of DC load for; a) behaviour of SOFC system and b) converter output voltage, current and power

Figure 6 shows the SOFC output power, single phase inverter output power, electric grid power and load power. The SOFC supply power to inverter. AF-PLL based power control algorithm provides a power balanced among single phase inverter, electric grid and load.

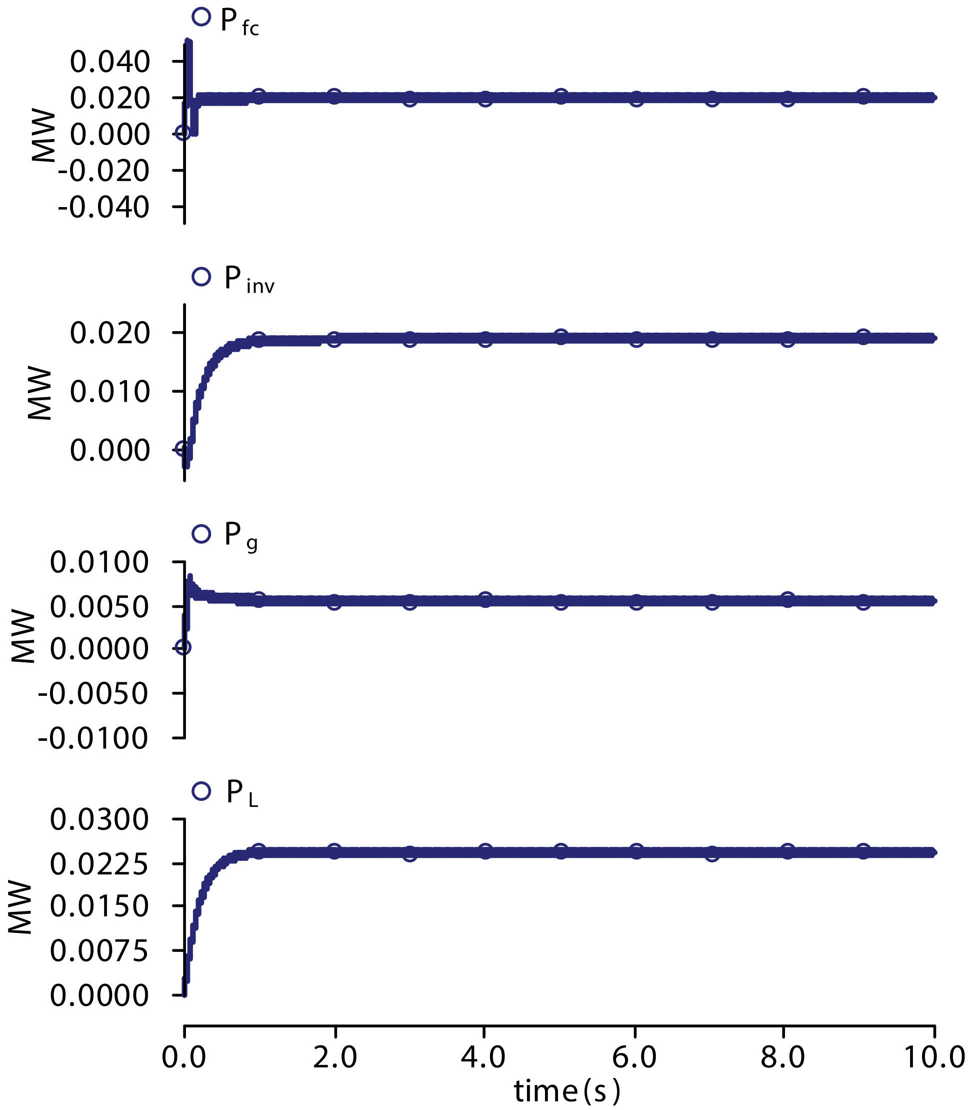

Figure 6. Results for power values of SOFC, inverter output, electric grid and load

CONCLUSION

In this paper, SOFC and its power electronic device have been developed in PSCAD software. It has been seen that boost converter is required to regulate and boost the FC' s output voltage. This paper ensures that:

- The behaviour of SOFC is analysed and examined under various DC loads.
- Current-voltage based cascaded PI controller provides constant voltage under variable DC loads. However, instead of PI controller, an advanced current controller can be used for current regulation at steady state.
- The proposed AF-PLL is effective technique that provides fast tracking (its start-up time is less than 14ms) and less affected voltage harmonic in single phase applications. However, the phase error between input and output signals is not completely minimized.
- AF-PLL based power control strategy has been used to control of single phase grid connected inverter, successfully.

REFERENCES

Akkinapragada N, 2007. Dynamic modelling and simulations of solid oxide fuel cells for grid-tied applications, Faculty of the Graduate School of The University of Missouri-Rolla, Master Thesis, 93p.

Boccaletti C, Duni G, Fabbri G, Santini E, 2006. Simulation models of fuel cell systems. 17th International Conference on Electrical Machines, July, Roma, Italy.

Chandrakar Y, 2013. Comparison of open loop and closed loop models for dual input DC-DC boost converter. International Journal of Emerging Technology and Advanced Engineering, 3: 307-311.

Jang M, Ciobotaru M, Agelidis VG. 2011. Grid-connected fuel cell system based on a boost-inverter with a battery back-up unit. Power Electronics and ECCE Asia (ICPE & ECCE), 30 May-3 June, Jeju, South Korea.

Jang M, Ciobotaru M, Agelidis VG, 2013. A single-phase grid-connected fuel cell system based on a boost-inverter. IEEE transactions on power electronics, 28: 279-288.

Meral ME, Cuma MU, Teke A, Tümay M, Bayındır KÇ, 2014. Experimental and simulation based study of an adaptive filter controlled solid state transfer switch. Electrical Engineering, 96: 385-395.

Meral, ME, Çelik, D, 2016. Grid Tied Fuel Cell System Using Single Phase PLL Based SOGI with PI and PR Current Controllers. Universal Journal of Electrical and Electronic Engineering, 4: 91-96.

Salam AA, Mohamed A, Hannan MA, 2009. Improved control strategy for fuel cell and photovoltaic inverter in a microgrid. Wseas Transactions on Power Systems, 4: 331-340.

Sharma RK, Mishra S, 2017. Dynamic power management and control of PV PEM fuel Cell based standalone AC/DC microgrid using hybrid energy storage. IEEE Transactions on Industry Applications, 1-12.

Shouman N, Hegazy Y, Sakr S. 2012. PSCAD Modeling and analysis of PEM fuel cell based distributed generators. Engineering and Technology (ICET), 10-11 October, Cairo, Egypt.

Tao Z, Bi L, Yan L, Sun W, Zhu Z, Peng R, Liu W, 2009. A novel single phase cathode material for a proton-conducting SOFC. Electrocemistry Communication, 11: 688-690.

Yang Y, Luo X, Dai C, Chen W, Liu Z, Li Q, 2014. Dynamic modeling and dynamic responses of grid-connected fuel cell. International Journal of Hydrogen Energy, 39: 14296-14305.

Zhao, W, Lu DDC, Agelidis VG, 2011. Current control of grid-connected boost inverter with zero steady-state error. IEEE Transactions on Power Electronics, 26: 2825-2834.