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Highly-Efficient Power-Conditioning System for Grid-Tied Fuel Cell Power Generation

B. Han[1] and J. Lee[2]

[1, 2] Department of Electrical Engineering
Myongji University
Seoul, Korea.
e-mail: erichan@mju.ac.kr

Abstract. This paper proposes a grid-tied power conditioning system for the fuel cell power generation, which consists of a 2-stage DC-DC converter and a 3-phase PWM inverter. The 2-stage DC-DC converter boosts the fuel cell stack voltage of 26-48V up to 400V, using the hard-switching boost converter and the high-frequency unregulated LLC resonant converter. A laboratory experimental set-up was built with the 1.2kW PEM fuel-cell stack to verify the feasibility of hardware implementation. The developed power conditioning system shows high efficiency of 91%, which is very positive result for the commercialization.

Key words

LLC resonant DC-DC converter, PEM(Proton Exchange Membrane) fuel cell, Nernst model, DSP(Digital Signal Processor).

1. Introduction

Fuel cell is a clean energy source to generate the electricity like a solar cell. Many kinds of fuel cell were developed for supplying the electricity to the car or the home. PEM fuel cell, which has simple structure and high power density, is considered as a promising DC power source for the distributed generation and the passenger car.[1],[2],[3] Fuel cell stack shows non-linear characteristic in electrical operation due to the polarization phenomena of electro-chemical reaction. The terminal voltage at the rated load drops to the half value at no load. So, the DC-DC converter can boost the low terminal voltage up to the high DC voltage.[4],[5],[6]

Full-bridge converter, push-pull converter, or boost converter has been widely used as a DC-DC converter for the fuel cell stack. Full-bridge converter has a disadvantage of high switching loss due to large number of switching units. Push-pull converter has lower switching loss due to lower number of switching units, but it has rather low efficiency of 88% because it requires double winding structure in the primary side. Boost converter has lower switching loss due to small number of switching units, but it has lower voltage boosting ratio of 3 to 4 times. Recently, multi-stage boost converter without transformer was developed to obtain high voltage boosting ratio. But its efficiency is located between 86～90%. Isolated boost converter was also developed to obtain high voltage boosting ratio, of which the efficiency is located between 86～90%. However, it requires large number of switching units and transformers. In order to increase the efficiency and to reduce the number of components, various types of converter were proposed and are being proposed by many researchers [7],[8],[9],[10],[11].

This paper proposes a new power conditioning system to interconnect the fuel cell stack with the power grid. The power conditioning system consists of the 2-stage DC-DC converter and three-phase PWM inverter. The 2-stage DC-DC converter consists of a hard-switching boost converter cascaded with an unregulated LLC resonant converter. The feasibility of hardware implementation is verified through experimental results with a laboratory prototype.

2. Proposed System

Fig. 1 shows the configuration of proposed power conditioning system including the whole system controller. Power conditioning system for the fuel cell power generation requires a high boost-ratio, high efficiency DC-DC converter because the fuel cell stack has a severe voltage variation between at no-load and at full load condition. In order to satisfy this condition this paper proposes a new DC-DC converter composed of a conventional boost converter and a 2-stage LLC resonant converter with high-frequency transformer. The proposed converter has high efficiency because the LLC converter operates in soft switching mode with resonance even though the boost converter operates in hard-switching pattern. It has a simple control structure to regulate the output voltage up to 400V by controlling the duty ratio of boost converter. The overall controller for proposed power conditioning system is divided into the control part for DC-DC converter and the control part for grid-tied inverter.

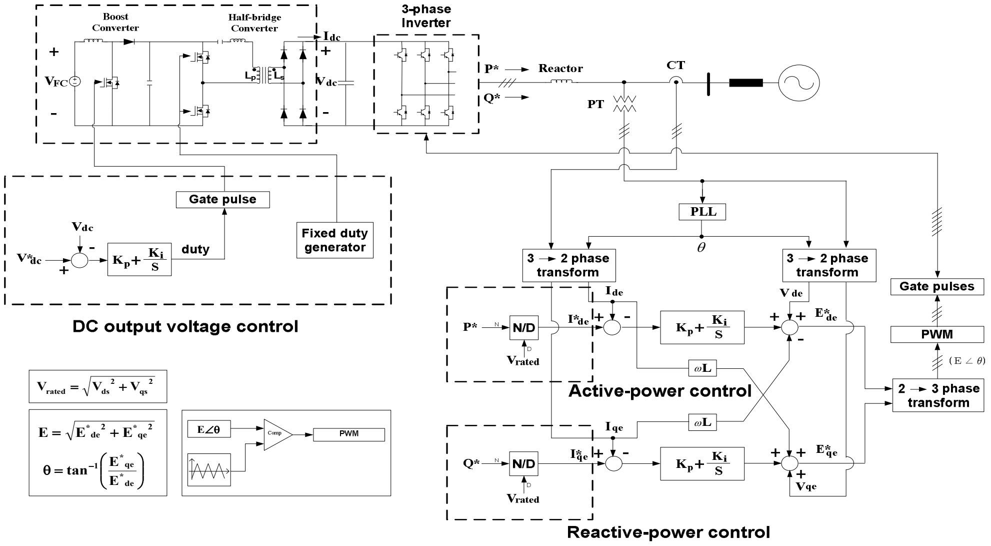


Fig. 1. Configuration of Proposed System

The control part for the DC-DC converter is to maintain the DC output voltage constant, while the control part for the grid-tied inverter is to control the active power P and the reactive power Q which flow into the grid.

The control part for DC-DC converter compares the measured DC capacitor voltage with the reference value, and generates an error signal. The error signal is sent to the PI control to determine the duty ratio. The boost converter maintains the output voltage at 80V, and the high-frequency resonant LLC converter increases the 80V up to the 400V.

The control part for the inverter measures the 3-phase voltage and current and performs the d-q transform with the phase-locked angle. It generates the reference values of d-axis current and q-axis current dividing the reference values of active power P and the reactive power Q by the rated voltage. These d and q reference currents are sent to the current control part for generating the d and q reference voltage of inverter. These d and q reference voltages are converted into the 3-phase voltages by inverse d-q transform, and used for generating the PWM pulses.

3. 2-stage DC-DC Converter

Fig. 2 shows the configuration of 2-stage DC-DC converter, which is composed of a hard switching boost converter and a soft switching half-bridge LLC resonant converter. The controller is composed of an output voltage sensor, boost converter control, and fixed-duty gate pulse generator. The proposed 2-stage DC-DC converter offers several benefits to reduce the complexity of controller design and to decrease the size of resonant converter transformer by high frequency operation over 100*kHz*. Since each converter has a separated function, it can be designed at the optimal operating point, which helps to increase the overall efficiency.

The input voltage is determined to be 24～48V by considering the output voltage characteristic of fuel cell. This voltage is boosted up to 80V by controlling the duty ratio of boost converter. The half-bridge LLC resonant converter boosts the input voltage of 80V up to 400V by operating a fixed duty ratio.

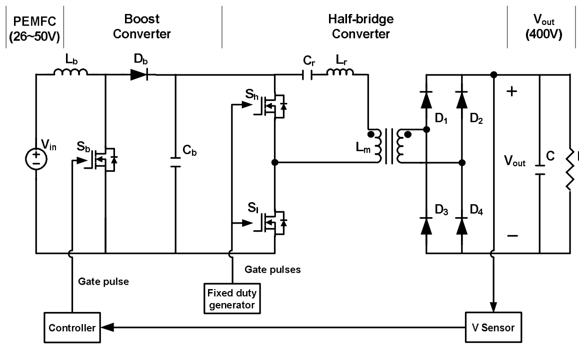


Fig. 2. Circuit Diagram of 2-stage DC-DC Converter

The control part of boost converter compares the reference voltage 400V with the measured converter output voltage, and the error signal is passed through the PI control to generate the gate pulse for the boost converter.

When the switch S_b of boost converter is ON, current flows through the reactor L_b and energy is charged in the reactor. When the switch S_b is OFF, this energy is discharged into the capacitor C_b through the diode D_b.

Fig. 3 shows four operation modes of the LLC resonant converter, which is composed of two MOSFET switches, resonant capacitor C_r, leakage inductance of transformer L_r and magnetizing inductance L_m. The secondary side of transformer is connected to the full-bridge diode rectifier.

Fig. 4 shows the voltage and current waveforms at each component of the LLC resonant converter. The converter operation can be divided into the four modes according to the time interval.

A. Operation Mode 1 (t_0-t_1)

Fig. 3(a) shows the operation mode in the powering section, which starts at the instant when the MOSFET S_l turns on. The resonant current flows through MOSFET S_l and the energy is transferred to the secondary side of transformer. The resonant capacitor C_r is charged and the resonant frequency f_r is determined by equation (1), because the magnetizing inductance L_m does not involve in resonant.

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

In the secondary side, diode D_1 and D_4 are on conduction and the current through the magnetizing inductance L_m is linearly increased.

B. Operation Mode 2 (t_1-t_2)

Fig. 3(b) shows the operation mode in the dead time section, which starts at the instant when the switch S_l turns off. The current that was flown through the switch S_l flows through the diode inside the switch S_h. This allows the zero-voltage switching condition at switch S_h. At this section the magnetizing current does not increase any more, and the energy transfer to the secondary side of transformer is cut off.

C. Operation Mode 3 (t_2-t_3)

Fig. 3(c) shows the operation mode in the powering section, which starts at the instant when the switch S_h turns on. The energy that is charged in C_r transferred to the secondary side of transformer, in which the resonant frequency is determined by equation (7). In the secondary side, diode D_2 and D_3 are on conduction, and the current through the magnetizing inductance L_m is linearly decreased.

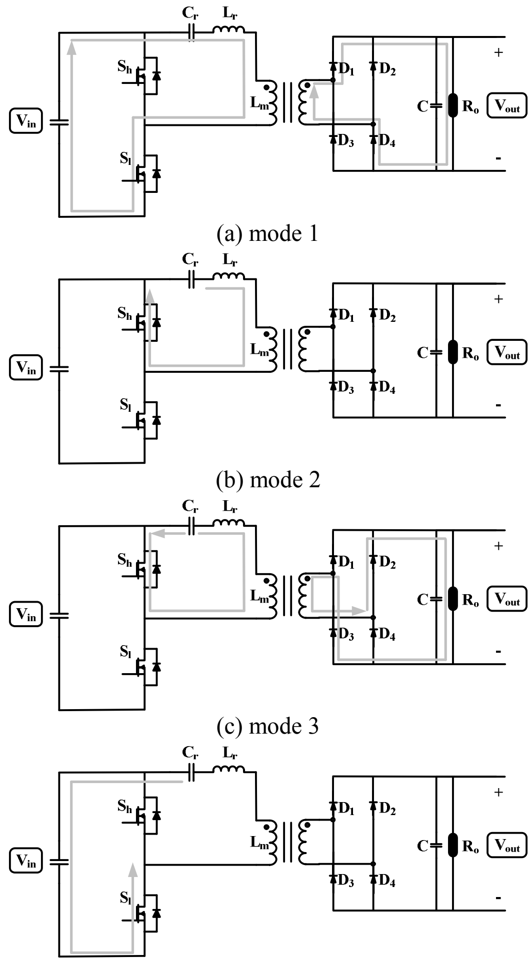
D. Operation Mode 4 (t_3-t_4)

Fig. 3(d) shows the operation mode in the dead time section, which starts at the instant when the switch S_h turns off. The current that was flown through the switch S_h flows through the diode inside the switch S_l. This allows the zero-voltage switching condition at switch S_l. At this section the magnetizing current does not increase any more, and the energy transfer to the secondary side of transformer is cut off.

The switching frequency of LLC converter f_{sL} is selected to be same as the resonant frequency f_r calculated as $1/(2\pi\sqrt{L_r C_r})$ to reduce the switching loss. The output voltage can be represented by the following equation.

$$\frac{V_o}{V_{in}} = \frac{V_b}{V_{in}} \cdot \frac{V_o}{V_b} = \frac{1}{(1-D)} \cdot \frac{n}{2} \tag{2}$$

Where, D means the duty-ratio of the boost converter.



(a) mode 1

(b) mode 2

(c) mode 3

(d) mode 4

Fig. 3. Operation of LLC Resonant Converter

These four operation modes are sequentially repeated according to the switching frequency of 100*kHz*. Although the switching frequency is rather high, the switching loss is quite small because of choosing the zero-voltage switching scheme.

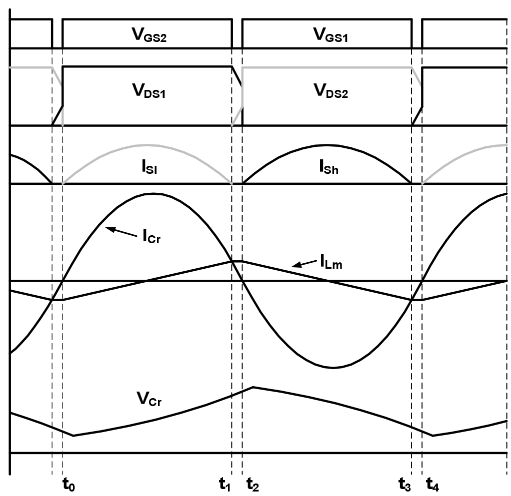


Fig. 4. Operation analysis of LLC Resonant Converter

A hardware prototype of proposed DC-DC converter was built and tested to verify the application feasibility for fuel cell power generation. The circuit parameters are shown in Table I.

Table I. – Circuit Parameters for 2-Stage DC-DC Converter

Input Voltage	25~50[V]
Output Voltage	400[V]
Output Current	2.5[A]
Switching Frequency	100[kHz]
Resonant Frequency	100[kHz]
Resonant Capacitor	0.8[μF]
Resonant Reactor	2.9[μH]

Fig. 5 shows a picture of proposed DC-DC converter which was built in the lab. The physical size of DC-DC converter is 150mm*150mm.

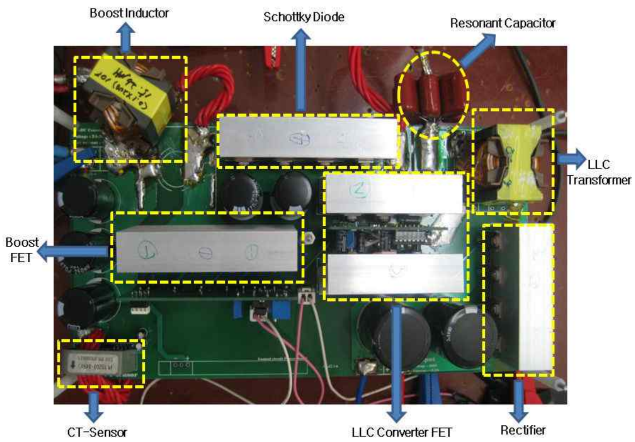


Fig. 5. Picture of proposed DC-DC converter

Fig. 6 shows the drain-source voltage accross each MOSFET in the LLC resonant converter, and the resonant current through the primary winding of transformer. The switching frequency is fixed at 100kHz, and the LC resonant frequency is also fixed at 100kHz. Through this experimental result, it is confirmed that the resonant LLC converter operates properly.

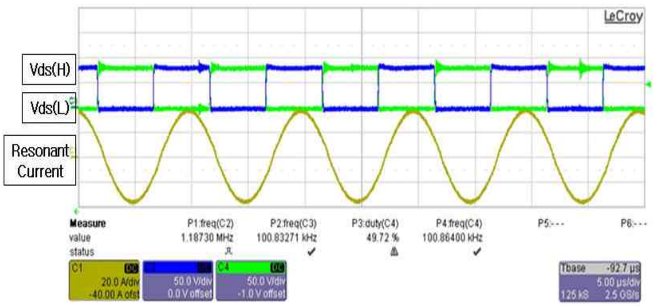


Fig. 6. Drain-source voltage and resonant current of LLC converter

4. Experimental Work

A prototype of proposed system was built and tested to confirm the feasibility of hardware implementation as shown in Fig. 7. The fuel-cell power unit used in the experiment is the 1.2kW Ballard Nexa PEM Module. It has a monitoring system with PC, which monitors the operation status of the fuel cell module through communication link.

The 2-stage DC-DC converter was mounted on the rack together with the 3-phase inverter. The controller for the 2-stage DC-DC converter was designed and built with OP amps. It adjusts the duty ratio of 2-stage DC-DC converter to boosts the output voltage up to 400V.

The first boost gain is obtained from the boost converter, and the additional boost gain is obtained by the fixed boost gain from the LLC resonant converter and the winding ratio of high-frequency transformer. The boost converter stage was designed to operate with 30*kHz* of switching frequency and the LLC stage was designed to operate with 100*kHz* of switching frequency.

The controller for the grid-tied inverter was designed and built with a floating-point DSP (Digital Signal Processor), TMS320vc33-150 and EPLD (Erasable Programmable Logic Device), EP1K100QC208. The control board has 24ch of ADC, 4ch of DAC, 4ch of Digital Input, 4ch of Digital Output, 1module of Encoder pulse input, 1port of RS232, and 2port of RS485.

The actual fuel-cell stack can not track the fast variation of active power in the grid because the chemical reaction in the fuel cell stack is relatively much slower. In order to confirm a safe and reliable operation, the duration of active power variation was determined by 100sec in the actual experiment as described in Table II.

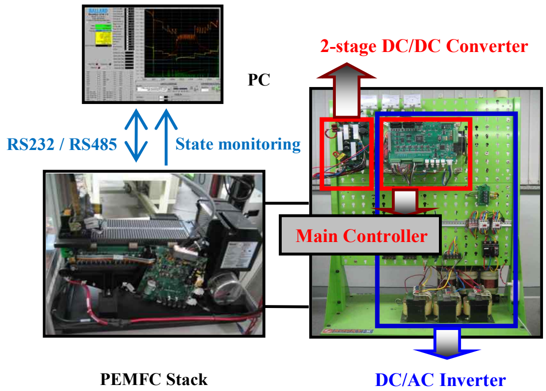


Fig. 7. Experiment Set-Up of Prototype

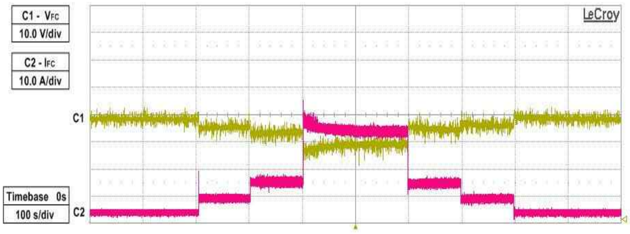
Table II. – Operation Scenario for Hardware Experiment

Time [s]	100	200	300	400	500	600	700	800
P [W]	100	300	500	1000	1000	500	300	100
Q [Var]	0	300	100	0	0	300	100	0

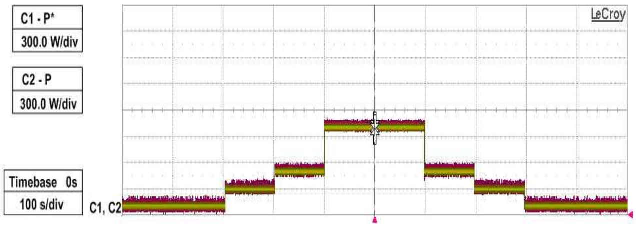
Fig. 8 shows the experimental results to verify the operation of proposed system. Fig. 8(a) shows the operation voltage and current of fuel cell module with 10V(A)/div. The time div was selected by 100s same as the duration period of active or reactive power. As the active power increases, the fuel cell voltage decreases while the fuel cell current increase. Fig. 8(b) shows that the measured active power tracks the reference value accurately without severe transient.

Fig. 8(c) shows the output voltage and current variation of fuel cell. The output current has same variations as the active power while the capacitor voltage is maintained at

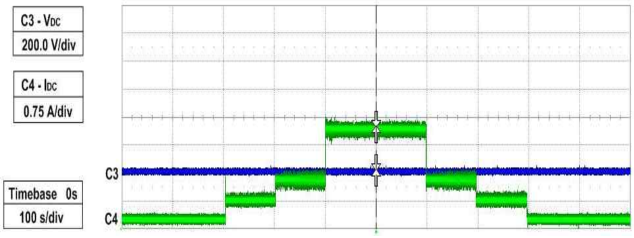
400V. This confirms that the DC-DC converter can accurately control the output voltage without the variation of active power. Fig. 8(d) shows that the measured reactive power tracks the reference value accurately without severe transient.



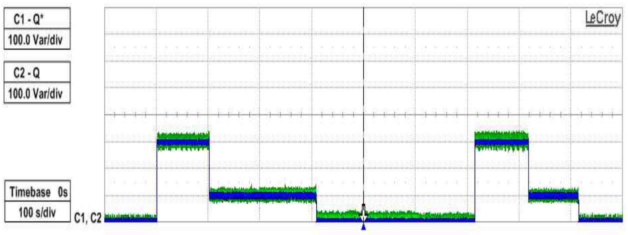
(a) Fuel-Cell Operation Voltage and Current



(b) Active-Power Control



(c) DC Output Voltage and Current



(d) Reactive-Power Control

Fig. 8. Experimental Results of Hardware Prototype

Fig. 9 shows the voltage-current characteristic curve for the fuel cell module used in the experiment. The no-load voltage of fuel cell is about 50V and the terminal voltage goes down while the output current increases, as the active power increases. At the active power of 1kW, the fuel cell voltage is 27.3V, and the fuel cell current is 34.41A.

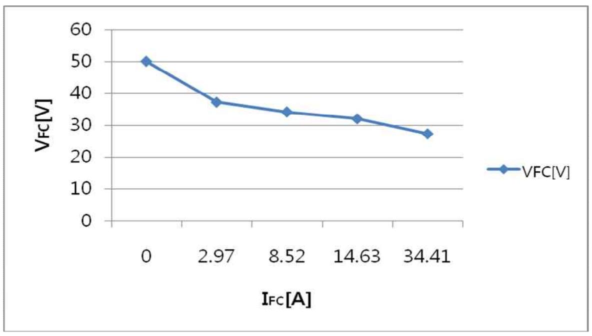


Fig. 9. Measured Fuel Cell Voltage and Current

Fig. 10 shows the efficiency of 2-stage DC-DC converter which was measured through experimental works. The efficiency was measured with respect to the lowest input voltage of 24V and the highest input voltage of 48V. The efficiency of proposed converter is 93.5% when the input voltage is 24V and the output power is 1kW. Since the actual fuel cell voltage is 27.4V at the output of 1kW, it can be confirmed that the efficiency of DC-DC converter is approximately 94%. Assuming the efficiency of grid-tied inverter is 97%, the total efficiency of proposed power conditioning system could be about 91%.

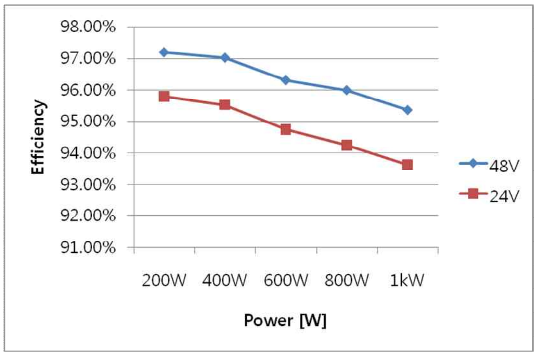


Fig. 10. Measured Efficiency of 2-Stage DC-DC Converter

5. Conclusion

This paper proposes a new grid-tied power conditioning system for the fuel cell power generation. The proposed power conditioning system consists of a 2-stage DC-DC converter and a 3-phase inverter.

The 2-stage DC-DC converter is composed of a hard-switching boost converter cascaded with an unregulated LLC resonant converter. The fuel cell output voltage of 26-48V is boosted up to 80V by controlling the duty ratio of hard-switching boost converter. The half-bridge LLC resonant converter boosts the input voltage of 80V up to 400V by operating a fixed duty ratio.

A laboratory experimental set-up was built with the 1.2kW PEM fuel-cell stack to verify the feasibility of hardware implementation.

The developed power conditioning system shows high efficiency of 91%, which is very positive for the commercialization. It can be applied for implementing the micro-grid with fuel cell power generation.

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References

[1] Bo Yang and Fred C. Lee. Alpha J. Zhang, Guisong huang, "LLC Resonant Converter for Front End DC/DC Conversion", Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE Volume 2, 10-14 March 2002 Page(s):1108 - 1112.

[2] Tae-Won Lee; Sung-Ho Kim; Yong-Ho Yoon; Su-Jin Jang; Chung-Yuen Won, “A 3 kW fuel cell generation system using the fuel cell simulator”, Industrial Electronics, 2004 IEEE International Symposium on Volume 2, 4-7 May 2004 Page(s):833 – 837

[3] Bouneb, B.; Grant, D.M.; Cruden, A.; McDonald, J.R., “Grid connected inverter suitable for economic residential fuel cell operation”, Power Electronics and Applications, 2005 European Conference on 0-0 0 Page(s):10 pp. - P.10

[4] Wingelaar, P.J.H. Duarte, J.L. Hendrix, M.A.M “Dynamic Characteristics of PEM Fuel Cells”, Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th, 16-16 June 2005 Page(s):1635 - 1641.

[5] Wang, C.; Nehrir, M.H., “Distributed Generation Applications of Fuel Cells”, Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, 2006. PS '06 14-17 March 2006 Page(s):244 – 248

[6] Polenov, Dieter; Mehlich, Heiko; Lutz, Josef, “Requirements for MOSFETs in Fuel Cell Power Conditioning Applications”, Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International Aug. 30 2006-Sept. 1 2006 Page(s):1974 – 1979

[7] Rathore, A.K, Bhat, A.K.S. Oruganti, R, “A Comparison of Soft-Switched DC-DC Converters for Fuel Cell to Utility Interface Application”, Power Conversion Conference - Nagoya, 2007. PCC '07 2-5 April 2007 Page(s):588 – 594.

[8] Mousavi, A.; Das, P.; Moschopoulos, G, “A ZCS-PWM Full-Bridge Boost Converter for Fuel-Cell Applications”, Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE 15-19 Feb. 2009 Page(s):459 – 464.

[9] Yu, X.; Starke, M.R.; Tolbert, L.M.; Ozpineci, B., “Fuel cell power conditioning for electric power applications: a summary”, Electric Power Applications, IET Volume 1, Issue 5, Sept. 2007 Page(s):643 – 656

[10] Sung-Yeul Park; Chien-Liang Chen; Jih-Sheng Lai, “Wide range active and reactive power flow controller for a solid oxide fuel cell power conditioning system”, Applied Power Electronics Conference and Exposition, 2008. APEC 2008. Twenty-Third Annual IEEE 24-28 Feb. 2008 Page(s):952 – 958

[11] Jung-Min Kwon; Eung-Ho Kim; Bong-Hwan Kwon; Kwang-Hee Nam, “High-Efficiency Fuel Cell Power Conditioning System With Input Current Ripple Reduction”, Industrial Electronics, IEEE Transactions on Volume 56, Issue 3, March 2009 Page(s):826 – 834.

[12] Gregor Hoogers, "FUEL CELL TECHNOLOGY HANDBOOK", CRC Press, 2003.