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Boost-Half Bridge Single Power Stage PWM DC- DC Converters for PEM-Fuel Cell Stacks

Soon Kurl Kwon† and Khairy F. A. Sayed*

†*Dept. of Electrical Eng., Kyungnam University, Korea

ABSTRACT

This paper presents the design of 1 kW prototype high frequency link boost half bridge inverter-fed DC-DC power converters with bridge voltage-doublers suitable for small scale PEM fuel cell systems and associated control schemes. The operation principle of this converter is described using fuel cell modeling and some operating waveforms. The switching mode equivalent circuits are based on simulation results and a detailed circuit operation analysis at soft-switching conditions.

Keywords : DC-DC converter, High frequency transformer link, Boost half-bridge circuit topology, Voltage doublers-rectifier, PEMFC power conditioner

1. Introduction

In general, a typical PEM fuel cell stack produces low voltage and large current DC output. A schematic of the power conditioning system for practical application is shown in Fig. 1. The power conditioner system consists of a fuel cell stack, electrically isolated fuel cell DC-DC converter. The fuel cell DC-DC converter is aim to interface stack output power to the DC bus, a battery or super-capacitor bank with a bidirectional DC-DC converter .The battery or super-capacitor bank will maintain voltage within certain set limits during load transients, and PEM FC stack. When the fuel cell temporarily cannot supply required stable DC voltage to the DC load the super-capacitor bank requires recharging when the fuel cell can generate surplus power and utility. The utility is a connected DC-AC converter and produces sinusoidal 110Vrms to supply required AC voltage to the AC load. A 300V DC interconnecting bus blocks the system to allow efficient power transfer between them [1].

This power conditioner prototype architecture uses a proton exchange membrane (PEM) fuel cell module that converts hydrogen and oxygen from air into 1200 watts of unregulated DC electrical power. To transform this low-voltage large current DC output into a reliable and efficient DC voltage source of power that is a comparable fuel cell is relatively slow to respond to load changes, due to the mass of its reactants, thermal lags, and reaction time of its hydrocarbon reformer. They are best suited for relatively steady loads. For this application, an isolated topology is favored for converter optimization. Isolated converter topologies provide advantages in applications requiring large voltage conversion ratios [2]. Transformer isolation can reduce switch and diode device stresses and

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† Corresponding Author: soonkurl@kyungnam.ac.kr
Tel: +82-55-249-2633, Kyungnam University
*Dept. of Electrical Eng., Kyungnam University

allow multiple windings or taps to be used for multiple converter outputs.

A variety of topologies have been considered for high frequency isolated DC-DC converters. In this paper, the topology of the boost half bridge converter is generating symmetrical ac waveforms at the primary side of the transformer, in which the core flux is excited bidirectional. This topology has an advantage because it better utilizes the core. In contrast to the half bridge converter the full bridge topology also has the same advantage but the full bridge configuration is more suitable for high input voltage applications and higher switch rating since it requires the power switching devices to block only the input voltage. This paper presents a boost half-bridge ZVS DC-DC converter with a high frequency link for a small scale PEM fuel cell attack power conditioner. The PEM fuel cell model is [3].

This paper proposes unidirectional operations of the introduced and simulation analyses in performance and cost with the conventional AC grid, a carefully designed electrical subsystem must be developed that accounts for the unavoidable characteristics of a fuel cell. It is noted that the dc output of the cells varies with their load with a polarization curve that is a function of its electrochemistry. In addition, a of this DC power conditioner is discussed. It is evaluated along with its operating principle and operating performance analysis using operating waveforms and equivalent circuit for each mode. The basic power circuit topology is originally from the ZVS bidirectional dc-dc converter in the reference dc-dc converter. Even though the circuit topology is not novel, it seems to be a good candidate for an application to step-up a converter for fuel cells.

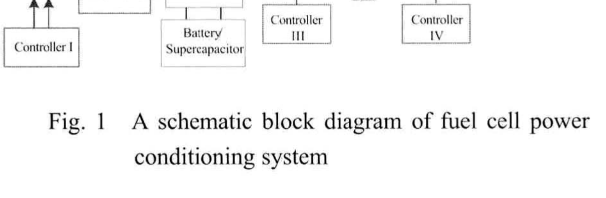

Fig. 1 A schematic block diagram of fuel cell power conditioning system

2. Boost-half Bridge One Stage DC-DC Converter for Fuel Cell Stack

2.1 Power Circuit Description

Figure 2 represents a novel circuit configuration of the proposed one stage zero voltage soft switching PWM DC-DC converter incorporating two switches which includes a boost chopper and half-bridge inverter hybrid circuit topology. The boost-half bridge one stage high frequency DC-DC converter is composed of two active power switch blocks Q_1 (SW_1/D_1), Q_2 (SW_2/D_2), divided capacitors C_1 and C_2, two winding high frequency step up transformers, a bridge voltage-doublers rectifying circuit, which can achieve boosted output voltage in addition to the voltage boosted block composed of the boost inductor L_b and active switch Q_1 (SW_1/D_1). The diode at the output of the fuel-cell stack is necessary to prevent the negative current going into the stack. As can be seen from the circuit configuration of the proposed, the switching block Q_1 (SW_1/D_1) performs the operation of both a boost chopper converter and a high frequency ZVS high frequency PWM inverter in one stage.

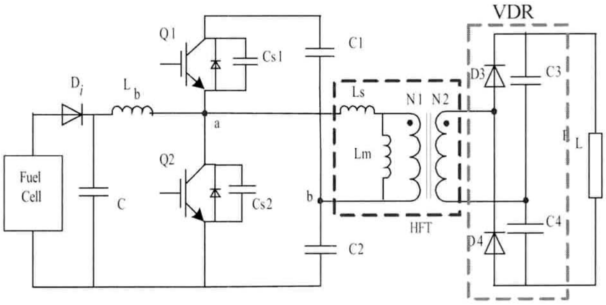

Fig. 2 A voltage-fed half-bridge ZVS PWM high frequency DC-DC converter with a transformer link with voltage doublers rectifier

2.2 Fuel Cell Modeling

The fuel cell can stack for distributed power supply can be generally modeled as a voltage source in a series with source resistance but this circuit model is accurate in the middle region of the fuel cell's V-I characteristic curve (resistance polarization region), but not accurate in the activation polarization region and the concentration polarization region. A more accurate way to model the fuel cell using the dynamic link library DLL is linked to the PSIM program. The variables to be passed from PSIM by value to DLL are the time step and the feedback current. The DLL uses these values to determine the fuel cell output voltage and then sends it back from DLL to PSIM. The DLL block has one input and one output. The input variable of the DLL block is the feedback current value, which is connected to a discrete element ZOH (zero-order hold). The DLL block is called only at the discrete sampling times. The ZOH samples the input at the beginning of a clock cycle, and holds the sampled value until the next clock cycle.

Figure 3 shows the schematic diagram of the fuel cell stack model. The fuel cell output connects to the C/P Control-power interface block. In PSIM, the power conversion circuit and control processing circuit are separated. The control-power interface block allows a control circuit quantity to be passed unchanged to the power circuit. The output of the interface block is treated as a constant voltage source in the power circuit. By using this block, some of the functions can be passed to a VCCS current controlled voltage source, which is controlled by the value passed from DLL. The voltage source is controlled by the branch current with a gain of unity and in this way; a current quantity can be converted to a voltage quantity.

A program was developed in C programming language, compiled and linked to the DLL block. A piecewise linear model of fuel cell V-I has been used. This program contains the equations of three regions of Fuel cell V-I curve. Each region is represented by a straight line equation and the numerical values of these equations are determined by experimental data. The middle region is accurate but the first and last regions are approximated to be linear. Fig. 4 represents the flow chart of the DLL dynamic model of PEM Fuel cell. The fuel cell model V-I characteristic is shown in Fig. 5. In the fuel cell model, the V-I characteristics in Fig. 5 were developed using Fig. 3 and 4. It shows the steady-state characteristics only, but implementation of this steady-state V-I curve is not an issue. Some other researchers already demonstrated better ways to express the V-I curve using polynomial equations. However, the proposed method is very simple and it is accurate in the operating range of the fuel cell. Future work includes studying the dynamic characteristics.

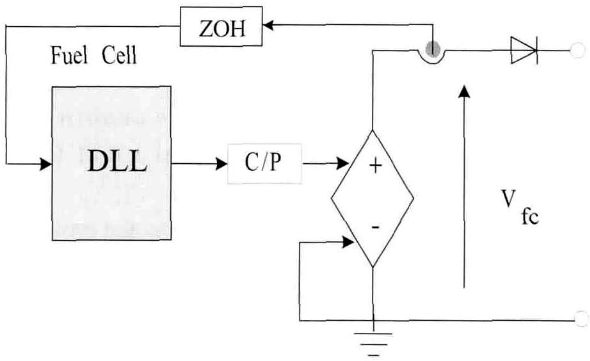

Fig. 3 Fuel cell stack model using DLL algorithm

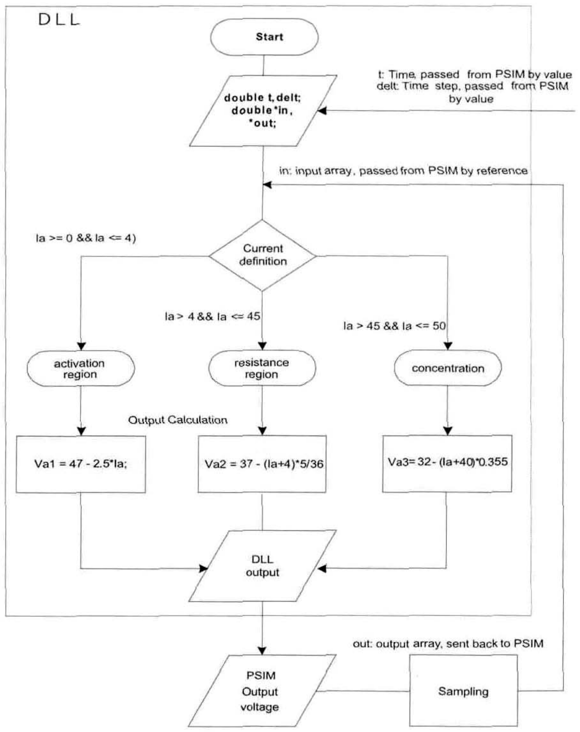

Fig. 4 Flow chart of DLL model of PEM Fuel cell

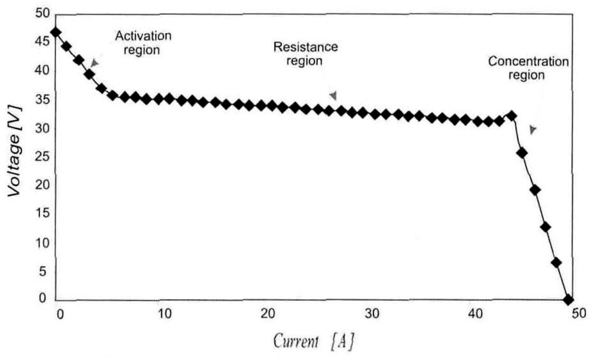

Fig. 5 Fuel cell model-based V-I Characteristic

2.3 Feedback control circuit

In the boost-half bridge DC-DC converter, the duty ratio can be used as a control parameter. Fig. 6 indicates the block diagram for feedback voltage control of the boost-half bridge type asymmetrical PWM DC-DC converter

Generally, a control parameter is a value that provides an approach to changing the output or the other desired variables. In the DC-DC power converter treated here, the conventional control parameters include phase and the duty ratio mentioned above. Sometimes control parameters appear as functions. In a PWM inverter, in the second stage, the modulating function can be treated as the control parameter. In order to control the DC output voltage by PWM switching, a feedback control loop is applied to one single output voltage control loop providing the control of output voltage. It is assumed that smooth ripple-free voltages are in a steady state due to the voltage doublers capacities.

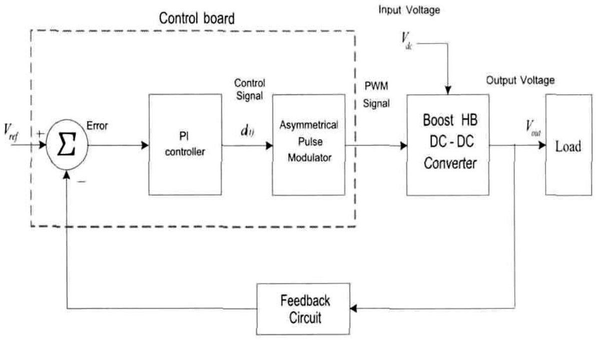

Fig. 6 Block diagram for feedback voltage control system including boost half bridge PWM DC-DC converter

In this system, a PI standard feedback loop component is used. It measures the "output" of the boost-half bridge DC-DC converter and controls t for maintaining the output at a target value, as the "setting-value" or reference values. Although it can be used to control any measurable variable which can be affected upon manipulating some other process variables such as pressure and temperatures in a fuel cell system, the output voltage can be regulated and controlled by using UC3825 PWM IC.

The PWM IC is equipped with two high frequency PWM outputs. In a pulse width modulated signal the period of the signal is kept to be fixed, while the duty ratio can be varied according to the output voltage feedback signal. In this application, a PI control algorithm is introduced, and then the control signal is modulated to obtain a PWM control signal, which is amplified for the IGBT gating driver.

3. Principle of Operation and Equivalent Circuit Switching mode

Fig. 7 shows the operating voltage and current waveforms as well as the operation switching modes of the proposed one stage high frequency link DC-DC power converter during one switching cycle. Its corresponding equivalent circuits are represented in Fig. 8. The operation modes include eight switching modes during one switching period, which will be explained by the following:

Mode 1: *At t=t0,* the gate signal is applied to SW1, The anti-parallel diode D1 of SW1 conducts, two current loops in the equivalent circuit are composed of L_s-D_1-C_1-L_s in which the primary current is a negative value and is decreasing linearly toward zero. The second loop is FC- L_b-D_1-C_1-C_2-FC, a series capacitor C2 resonates with leakage inductance Ls and the input current I_{Lb} decreases linearly according to the following equations:

$$i_p = \frac{V_2 - V_p}{L_s}(t - t_0) \tag{1}$$

$$i_L = \frac{V_s - (V_1 + V_2)}{L_b}(t - t_0) \tag{2}$$

Where V1, V_2 are the voltages across the divided capacitors C1, C_2 , V_P and is the HFT primary side voltage.

After the primary current reaches zero, the diode D1 still conducting, this mode terminates when t=t1

Mode 2: (t_1<t<t_2) At t=t1, the diode D_3 starts to conduct. The primary current is changed to the positive direction; D_4 commutates naturally, the current through C_1 decreases toward zero to change its direction in the next mode.

Mode 3: (t2<t<t3) At t=t2, SW_1 is turned on with ZVZCS, and D_1 is turned off. The current through the

capacitor C_1 reverses its direction to the negative direction,. In this mode the voltage across C1 now decreases until it reaches its minimum value because the current through C1 is reversed. At the same time the secondary circuit current through C3 is changed to a positive value and increases gradually. Consequently the D3 and current through the secondary side of the high frequency transformer (HFT) increases.

Mode 4: The gate pulse signal is removed for SW1 and consequently the current through C1 decreases toward zero. Cs1, Cs2, C1 and C2 resonates with the leakage inductance Ls, therefore SW1 turns off at zero current soft switching. This mode terminates when $v_{Cs1} = V_1 + V_p$, $v_{cs2} = 0$.

Mode 5: At the same time capacitor C1 stops to discharge, the diode D2 starts to conduct, the current through the primary circuit of HFT and the current through C2 decreases and no current flows through C1.At the end of this mode, D2 naturally commutates therefore the voltage across SW2 will be zero.

Mode 6: The switch SW2 starts to conduct and consequently the current through C2 decreases towards zero. The current reverses its direction through C3, and current iD3 decreases, the resonant capacitor C2 resonates with the leakage inductance.

The current isw2 is defined as:

$$i_{sw2} = i_L - i_p \tag{3}$$

$$i_L = \frac{V_s}{L_b}(t - t_5) \tag{4}$$

$$i_p = \frac{V_2 - V_p}{L_s}(t - t_5) \tag{5}$$

The current through C3 and D3 will be zero at the end of this mode at t6

Mode 7: The capacitor C1 resonates with the leakage inductance Ls, as it discharges energy to Ls. The primary and secondary currents of the HFT invert its direction at this operating mode and the primary current will be defined by:

$$i_p = \frac{V_2 - V_p}{L_s}(t - t_6) \tag{6}$$

The current isw2 is defined as :

$$i_{sw2} = (i_L + i_p)(t - t_6) \tag{7}$$

The input current iL is linearly increasing and given by:

$$i_L(t) = \frac{V_s}{L_b}[(t - t_6) + T_5] \tag{8}$$

Where T5 is the duration of mode 5.

In the secondary circuit, the diode D4 is turned on and D3 is turned off because the primary current inverts its direction. This mode terminates when the switch SW2 turns off.

Mode 8: at t= t8, SW2 is tuned off and at this moment Cs1 discharges and Cs2 charges. Cs1, Cs2, C1 and C2 resonate.

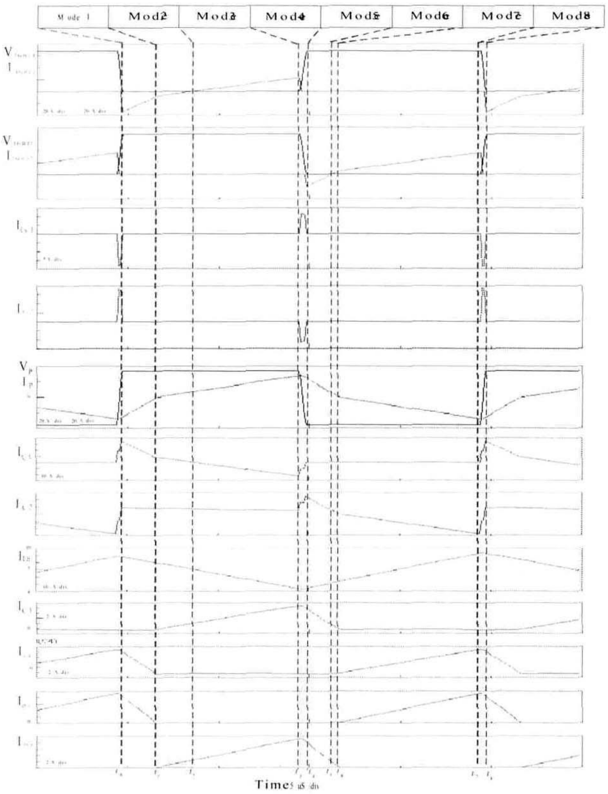

Fig. 7 Voltage and current operating waveforms

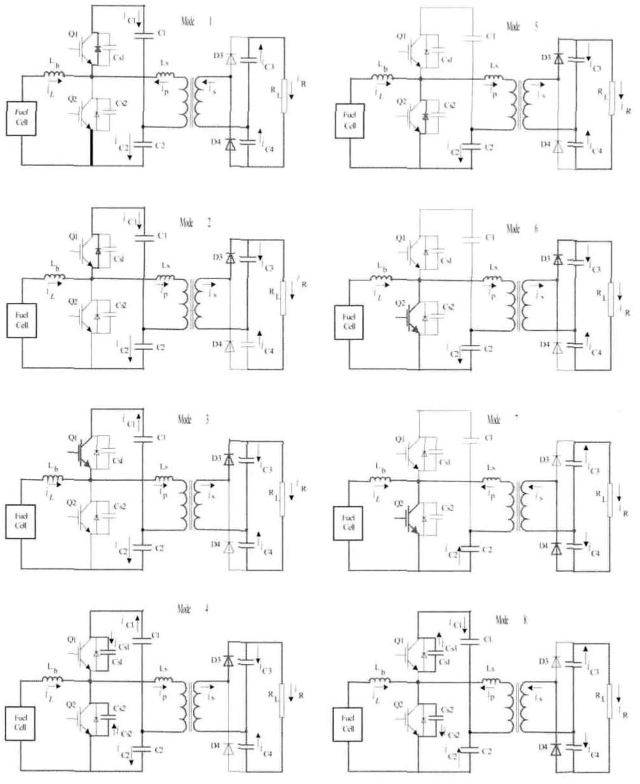

Fig. 8 Operating switching mode equivalent circuits of the proposed high frequency link DC-DC converter with voltage doublers-rectifier

4. Operating Performances and Discussions

In order to achieve ZVS operation in this topology the dead time should be introduced during the switching transition of both IGBTs. During the dead time between the turn-off of Q1 and turn-on of Q2, the transformer leakage inductance discharges the voltage across the snubber capacitor Cs1. Similarly during the dead time between the turn-off of Q2 and turn-on of Q1, the transformer leakage inductance discharges the voltage across the snubber capacitor Cs2.

In this topology the switching frequency is designed for 50 kHz. The high frequency switching suppresses the harmonics and is easier to filter, producing high power quality without large filter capacitors.

Similar planar transformers with ferrite cores are used in the two units. These operate efficiently at high frequencies with low conduction, eddy current losses and low hysteresis losses. The leakage inductance of the high frequency transformer is adjusted so as to match its inductance required for the resonant circuit commutation.

The transformer provides voltage isolation between the fuel cell stack and the DC or AC output voltage improving overall safety of the power conditioning system. The voltage doubler-rectifier on the high voltage side helps the designer to decrease the turn ratio of the transformer, which reduces leakage inductance and makes the system more efficient and easier to control. At the same time, the voltage and current stresses on the low voltage side are minimized. A Capacitive type rectifier can construct voltage-doublers, which is suitable to the applications with characteristic high output voltage.

The design specifications and circuit parameters of the proposed power conditioner system in Fig. 2 are listed in Table 1.

The ripple current delivered by the fuel-cell stack due to the switching of the boost half bridge converter has to be reduced. It is inversely proportional to boost inductor values.

Fig. 9 shows the output voltage, output current and output power dynamic operating waveforms.

The transient output voltage and current waveforms are shown in Fig. 10. The fuel cell voltage drops from no load output voltage which is 47 V to 32 V according to load current.

The output power regulation characteristics are shown in Fig. 11. By varying the duty cycle from 0 to 1 for the main switch SW2, the output power can be regulated.

Table 1 Design Specifications and Circuit Parameters

Item	Symbol	Value
Switching frequency	f_s	50 kHz
Inductance of boost inductor	L_b	50[μH]
Divided series capacitor	C_1 , C_2	500 [μF]
Snubber Capacitances	C_{s1}, C_{s2}	50 [nF]
Primary and secondary leakage inductances of HFT	L_1 , L_2	1 [μH]
HFT Turns Ratio	$N1:N2$	1: 5
Capacitors of voltage doublers type rectifier	C_3 , C_4	500 [μF]
Load resistance	R_L	50 [Ω]

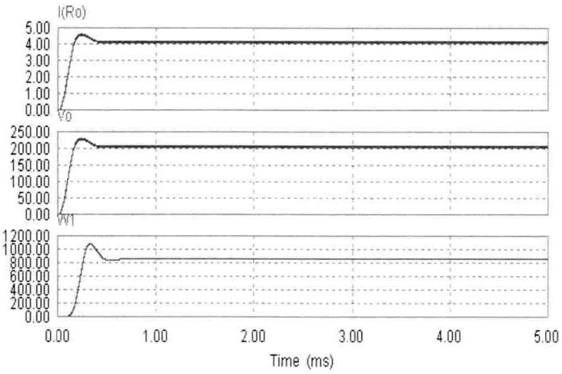

Fig. 9 Output waveforms of the proposed DC-DC converter

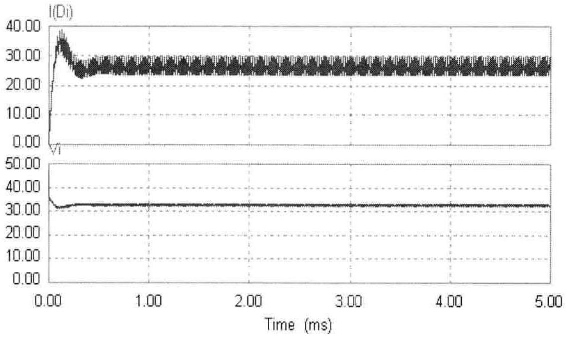

Fig. 10 Input voltage and current dynamic operating waveforms

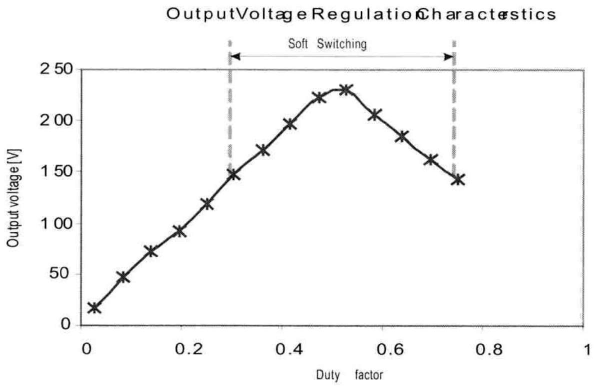

Fig. 11 Output power regulation characteristics with asymmetrical PWM

The experimental results for the proposed DC-DC converter are presented. A pulse frequency of 50 kHz is used. In this application both current and voltage control can be applied. The PWM IC and control board are shown in Fig. 12. The PWM controller used is the UC3825, the gate drive circuit consists of the dual totem pole outputs of the UC3825 that drives a small toroidal transformer with two secondary ones that have opposite polarity outputs. The output voltage is presented in Fig. 13. The transformer primary current and primary voltage between points a and b are shown in Fig. 14. In voltage and current across the main switch are shown in Fig. 15. The voltage and current across capacitor C1 are shown in Fig. 16.

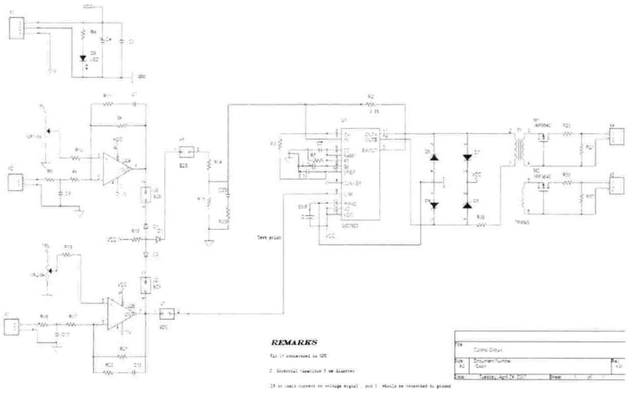

Fig. 12 PWM IC and control board

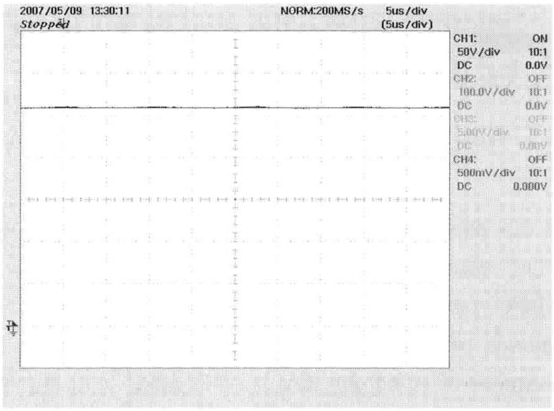

Fig. 13 Output voltage

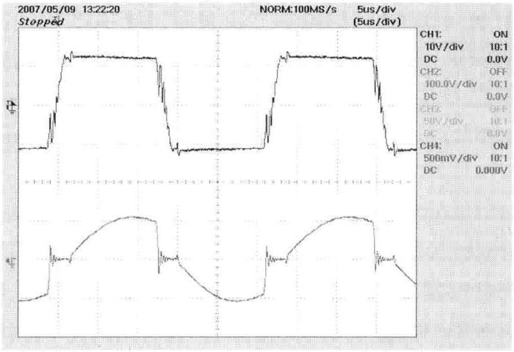

Fig. 14 Primary voltage and current of the HF transformer

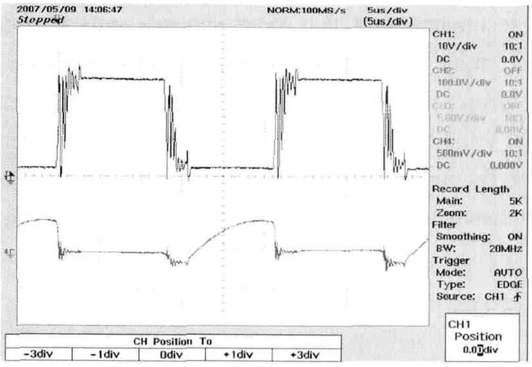

Fig. 15 Switch Q2 voltage and current

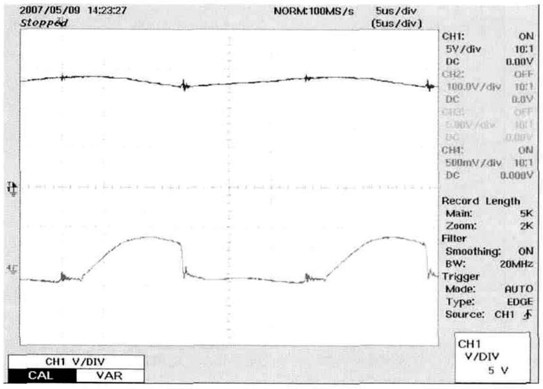

Fig. 16 Voltage and current across capacitor C1

5. Conclusions

In this paper, a high frequency link soft-switched PWM DC-DC converter with boost-half bridge topology for PEM-FC power conditioners has been presented. The advantage of having a boost half-bridge topology is half the number of switching devices compared with the boost converter and full bridge inverter type topologies. This simplified converter could also lead to significant savings on the gate drivers and heat sink. There are no an auxiliary circuit or complex control required for soft switching. Extensive simulation based on a detailed circuit analysis and fuel cell model proved the circuit operation and soft-switching conditions. The designed prototype rating is 1KW.

This converter topology provides a solution for low-cost, lightweight, compact, highly efficient and reliable DC-DC converters designed for automotive applications. Other applications areas could be also an uninterrupted DC power feeder and battery charging and discharging systems.

Acknowledgment

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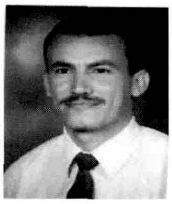
Soon-Kurl Kwon received his B.E. degree in Electrical Engineering from Young-Nam University, Daegu, Korea, and received his M.S. degree in Electrical Engineering from Busan National University, Busan, Korea, He received his Ph.D. (Dr-Eng) degree in

Electrical Engineering from Young-Nam University, Daegu, Korea. He joined the Electrical Engineering Department of Kyungnam University, Masan, Korea in 1983 as a Professor. He was a Visiting Professor in VPEC at Virginia Polytechnic Institute and State University, USA in 1997. His research interests include application developments of power electronics circuits and system. He is a member of KIEE and KIPE.



Khairy Fathy Abd El-Sayed received his B.S. degree in Electrical Power and Machines in 1997 from Assiut University, Assiut, Egypt. He is now working towards his Masters degree at the Graduate School of Electrical Engineering, Kyungnam University, Masan, Korea. His research interests include soft switching DC-DC power converter topologies, high frequency inverter applications, renewal energy related power conditioners. He received the 2001 Best Student Paper Award at the 57th annual conference of the International Appliances Technical Conference IATC2006 held at Crowne Plaza, Chicago, USA, March 27-29. He is a student member of KIEE, KIPE and IEEE.