Boost-Half Bridge Single Power Stage PWM DC-DC Converter for Small Scale Fuel Cell Stack

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Boost-Half Bridge Single Power Stage PWM DC-DC Converter for PEM-Fuel Cell Stack

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ABSTRACT

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

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

1. Introduction

In general, a typical PEM fuel cell stack produces low voltage, 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 to interface stack output power to the DC bus, a battery or super-capacitor bank with bidirectional DC-DC converter that maintain voltage within a 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, this super-capacitor bank requires recharging when the fuel cell can generate surplus power and utility connected DC-AC converter to produce sinusoidal 110Vrms to supply required AC voltage to the AC load. A 300V DC bus for interconnecting the system blocks to allow efficient power transfer between them. This power conditioner prototype architecture uses 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 relatively low-voltage large current DC output into a reliable and efficient DC voltage source of power that is comparable 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 the electrochemistry. In addition, a 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.

A variety of topologies have been considered for high frequency isolated DC-DC converter, in this paper, boost half bridge converter topology to generate a symmetrical ac waveforms at the primary side of the transformer, in which the core flux is excited bidirectionally. This topology has an advantage of better utilization of the core. And then 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 the power switching devices are required to block only the input voltage. This paper presents a boost half-bridge ZVS DC-DC converter with high frequency link for small scale PEM fuel cell attack power conditioner. The PEM fuel cell model is introduced, a simulation analysis of this DC power conditioner are discussed and 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 reference [3]. This paper proposes unidirectional operation of the dc-dc converter. Even though the circuit topology is not novel, It seems to be a good candidate for application to step-up converter for fuel cells.
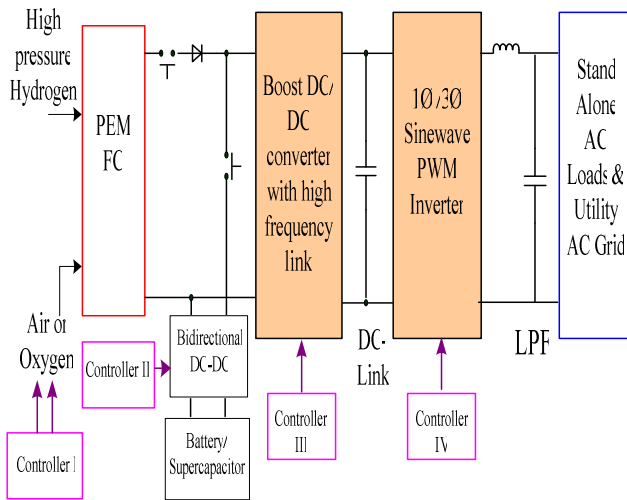
Fig. 1 A schematic block diagram of fuel cell power conditioning system

2. Boost-Half Bridge One Stage Dc-Dc Converter For Fuel Cell Stack

A- 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 switch only which includes 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 transformer, bridge voltage-doubler 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 proposed here, the switching block Q_1 (SW_1/D_1) performs the operation of both boost chopper converter and high frequency ZVS high frequency PWM inverter in one stage.
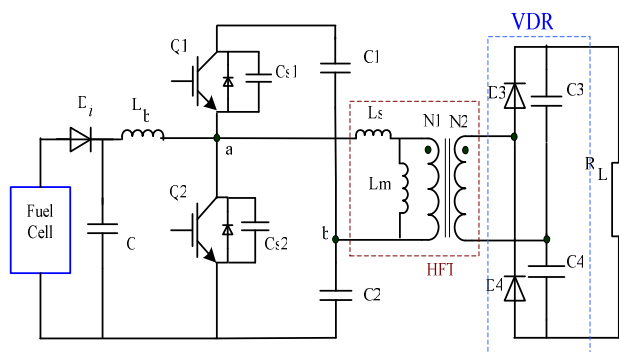

Fig. 2 A voltage-fed half-bridge ZVS PWM high frequency DC-DC converter with a transformer link with voltage doublers rectifier.

B- Fuel Cell Modeling

The fuel cell can stack for distributed power supply be generally modeled as a voltage source in series with source resistance but this circuit model is accurate in the middle region of fuel cell V-I characteristic curve (resistance polarization region), but not accurate in activation polarization region and concentration polarization region. A more accurate model to model the fuel cell using dynamic link library (DLL) which is linked to PSIM program. The variables to be passed from PSIM by value to DLL are time step and feedback current. The DLL uses these values to determine the fuel cell output voltage and then sent 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 connected to 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 VCCS current controlled voltage source, which controlled by the value passed from DLL, The voltage source is controlled by the branch current is. With a gain of unity, 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 modeling of fuel cell V-I has been used. This program contains the equations of the three regions of Fuel cell V-I curve. Each region represented by straight line equation, the numerical values of these equations are determined by experimental data, the middle region is accurate but the first and last region is approximated to be linear. Fig. 4 represent the flow chart of DLL dynamic model of PEM Fuel cell The fuel cell model V-I characteristic is shown in Fig. 5. In the fuel cell modeling, the V-I characteristics in Fig. 5 which was developed using Fig. 3 and 4, shows the steady-state characteristics only, but implementation of this steady-state V-I curve is not a issue and some other researchers already demonstrated better ways to express V-I curve using polynomial equations. However the proposed method is very simple and it is accurate in the operating range of fuel cell. In the future work the dynamic characteristics will be considered.
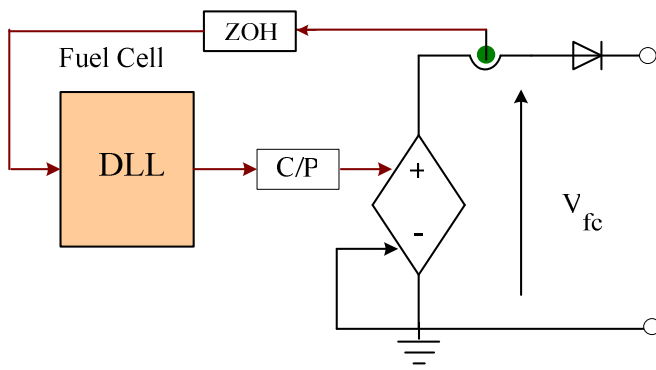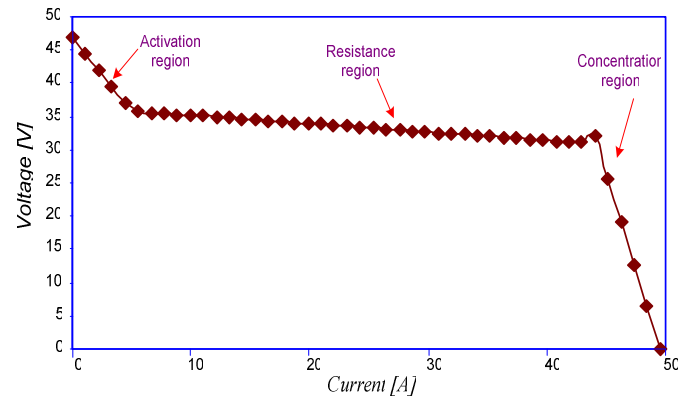
Fig 3 Fuel cell stack model using DLL algorithm.
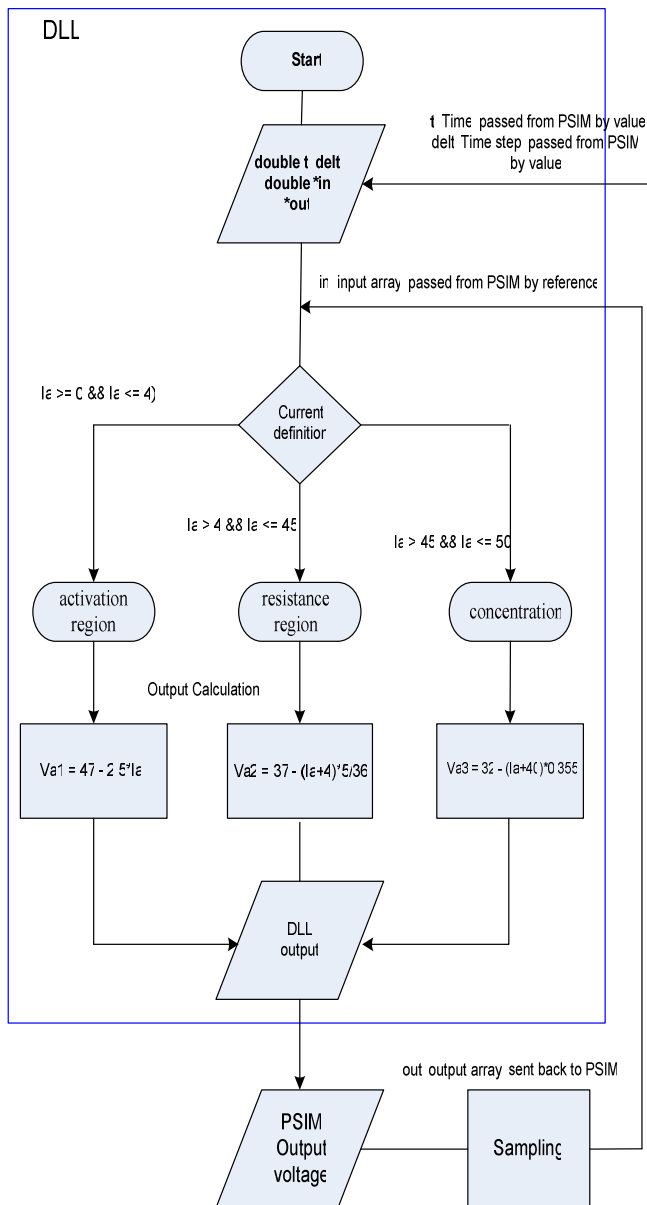

Fig.5 Fuel cell model-based V-I Characteristic

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

C- Feedback control circuit

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

Generally, a control parameter is a value that provides an approach to vary the output or the other desired variable. In 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 one single output voltage control loop provides the control of output voltage. It is assumed that smooth ripple-free voltages in steady state due to the voltage doubler capacitances.

In this system, PI standard feedback loop component is used. It measures the "output" of the boost-half bridge DC-DC converter and controls PWM signal, with a goal of maintaining the output at a target value, as the "setting-value" or reference value.
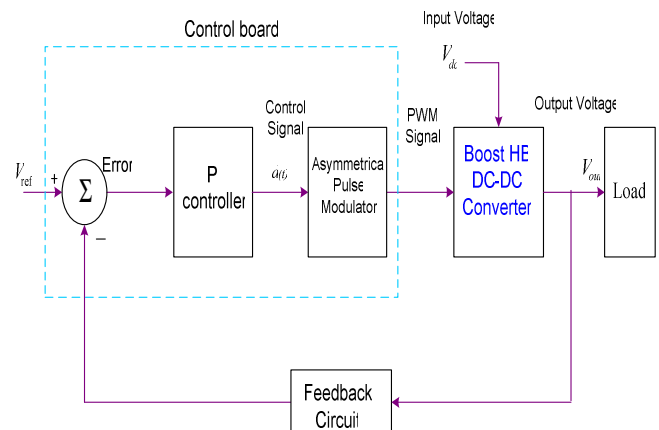

Fig. 6 Block diagram for feedback voltage control system including boost half bridge PWM DC-DC converter

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, PI control algorithm is introduced, then the control signal is modulated to obtain PWM control signal, which is amplified for 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 represented in Fig. 8. The operation modes include eight switching modes during one switching period, which will be simply explained in the following:

Mode 1: At t=t0, the gate signal is applied to SW1, The antiparallel 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 decreasing linearly toward zero. The second loop is FC-L_b-D_1-C_1-C_2-FC., 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   , after the primary current reaches zero, the diode D1 still conducting, this mode terminates when t=t1

Mode 2: (t1<t<t2) At t=t1, the diode D_3 starts to conduct, The primary current is changed to be 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 ZVS, D_1 is turned off The current through capacitor C_1 reverse its direction to 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 in the secondary circuit current through C3 is changed to a positive value and increases gradually and consequently current through D3 and current through the secondary side of the high frequency transformer (HFT) increases.

Mode 4: The gate pulse signal is removed for SW_1 at the same time capacitor C1 stop to discharge, the diode D_2 starts to conduct, the current through the primary circuit of HFT and current through C_2 decreases and no current flows through C_1, at the end of this mode D_2 naturally commutates.
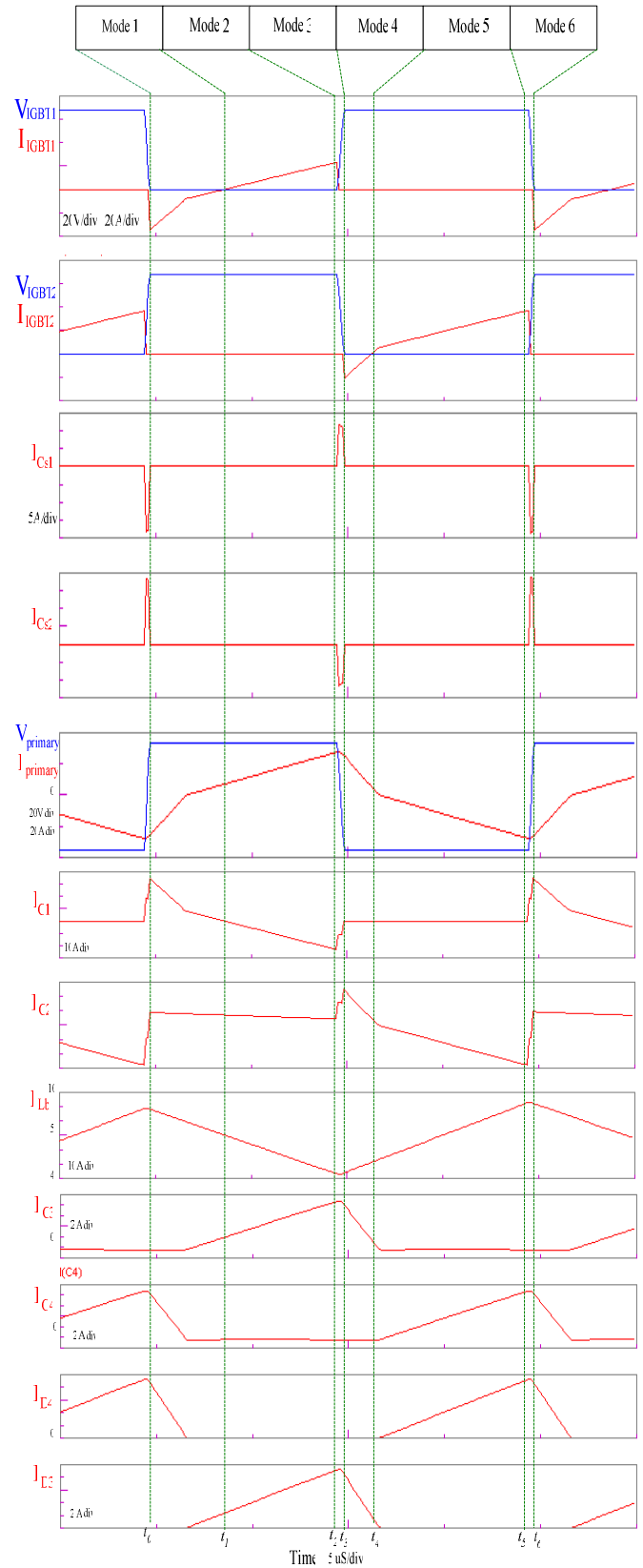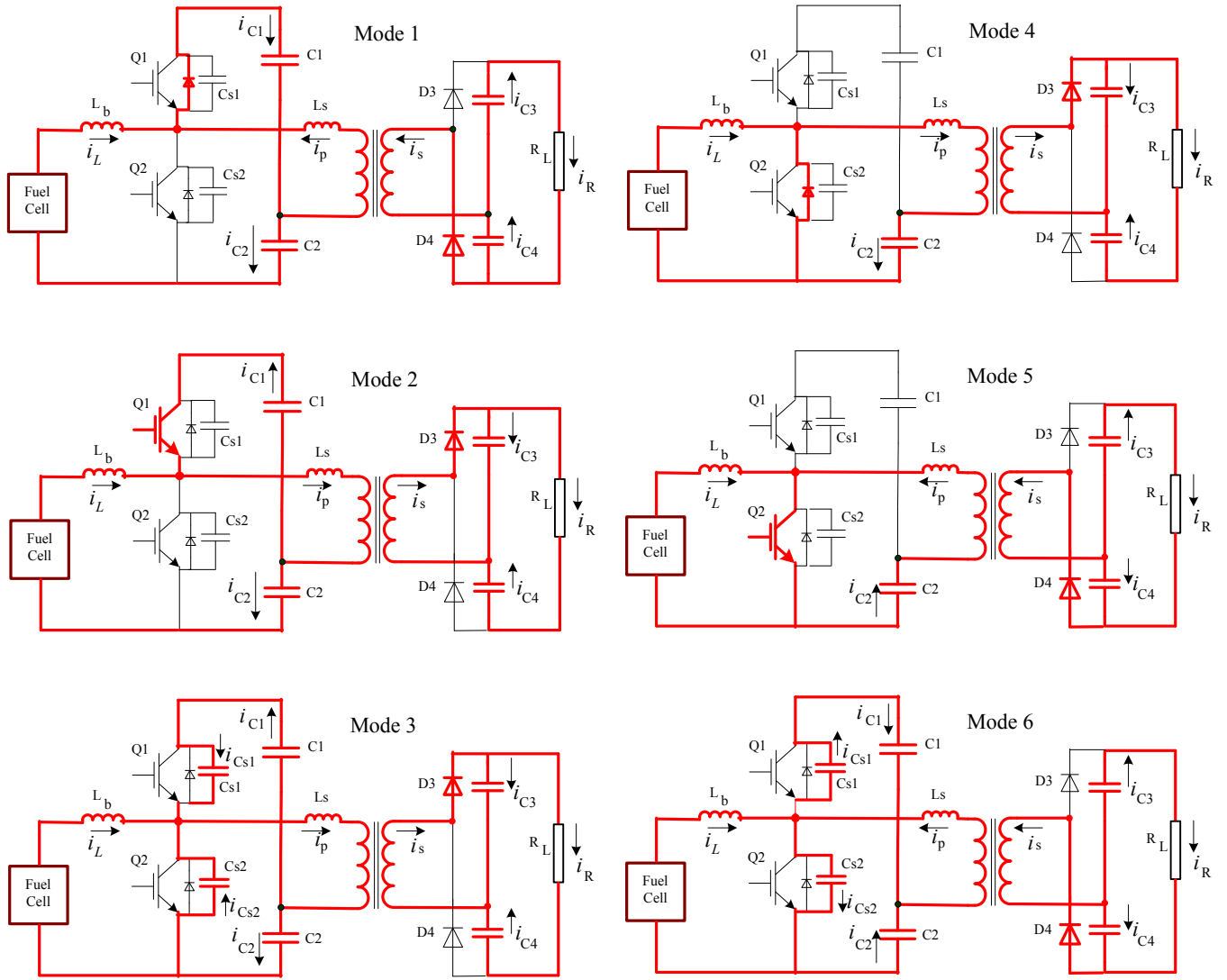

Fig. 7 Voltage and current operating waveforms.

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

Mode 5: The switch SW$_2$ starts to conduct and consequently current through C$_2$ decreases toward zero. The current reverses its direction through C$_3$, and current i_{D3} decreases, the resonant capacitor C$_2$ resonates with the leakage inductance. The primary and secondary currents of the HFT invert its direction at this operating mode and the primary current will defined by:

$$i_p = \frac{V_2 - V_p}{L_s}(t - t_4)$$

Mode 6: at t= t$_5$, SW1 is tuned off, at this moment Cs1 discharges and Cs2 charges. Cs1, Cs2, C1 and C2 resonates with the leakage inductance Ls, therefore SW1 turns off at zero current soft switching

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

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

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

The current through C$_3$ and D$_3$ will be zero at the end of this mode at t$_6$

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

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

The current i_{sw2} is defined as :

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

(7)

The input current i_L is linearly increasing and given by:

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

(8)

where T_5 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= t_8, SW2 is tuned off, at this moment Cs1 discharges and Cs2 charges. Cs1, Cs2, C1 and C2 resonates with the leakage inductance Ls, therefore SW2 turns off at zero current soft switching. This mode terminates when $v_{Cs2} = V_2 + V_p$, $v_{cs1} = 0$

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 much 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 and 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 help the designer to decrease the turns ratio of the transformer, which reduces leakage inductance and makes the system more efficient and easier to control. And at the same time, the voltage and current stresses on the low voltage side are also minimized. Capacitive type rectifier can construct voltage-doubler, which is suitable to the applications with characteristic of 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 is 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.

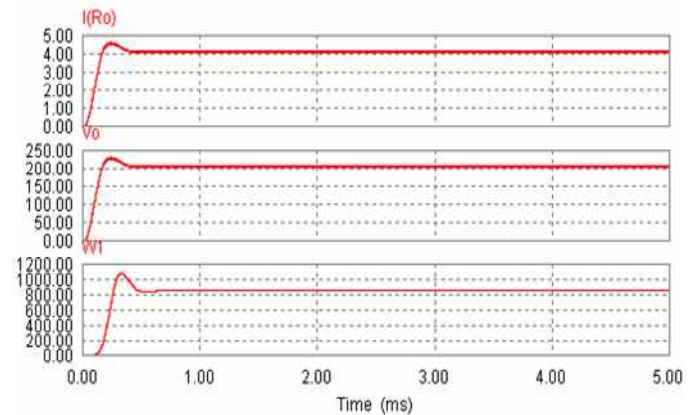| Item	Symbol	Value
Switching frequency	f_s	50 kHz
Inductance of boost inductor	L_b	50[μH]
Divided series capacitor	C_1 , C_2	500 [μF]
Snubber Capacitances	C_{s1}, C_{s2}	50 [nF]
Primary and secondary leakage inductances of HFT	L_1 , L_2	1 [μH]
HFT Turns Ratio	N1:N2	1: 5
Capacitors of voltage doublers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

Fig. 9 Output waveforms of the proposed DC-DC converter.
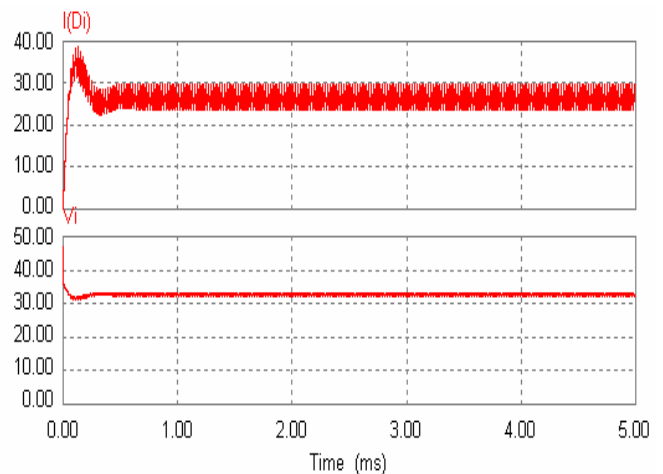
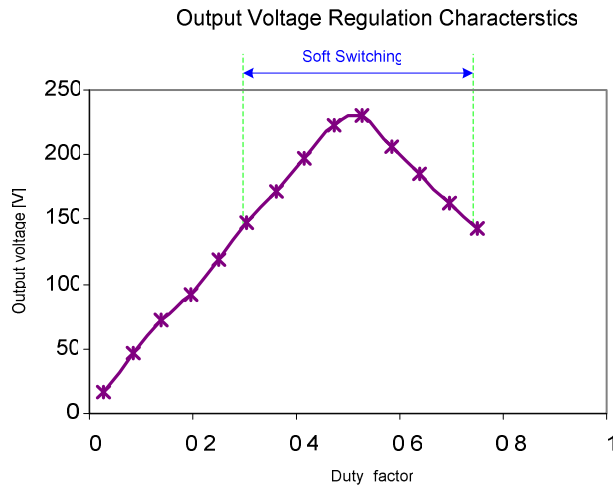Fig.10 Input voltage and current dynamic operating waveforms

Output Voltage Regulation Characterstics

Fig. 11 Output power regulation characteristics with asymmetrical PWM

Fig. 13 Output voltage

5.   Experimental Results

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 output voltage is presented in Fig. 13.

The transformer primary current and primary voltage between points a,b are shown in Fig. 14. In voltage and current across the main switch are shown in Fig. 15. Fig. Voltage and current across capacitor C1 are shown in Fig. 16.
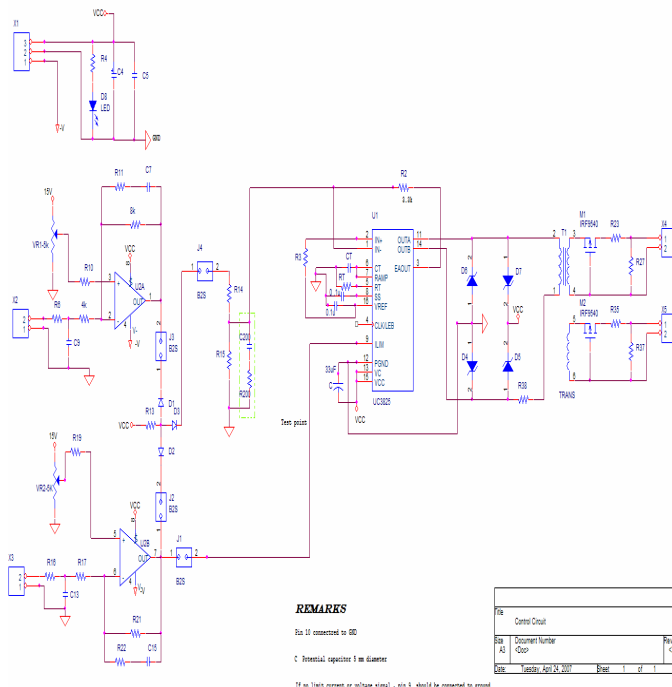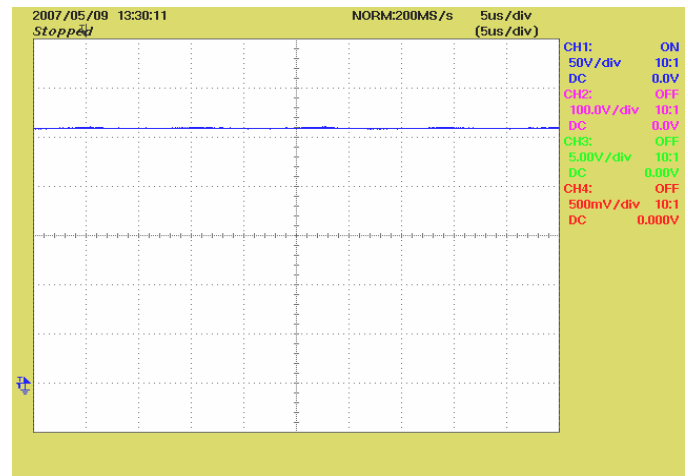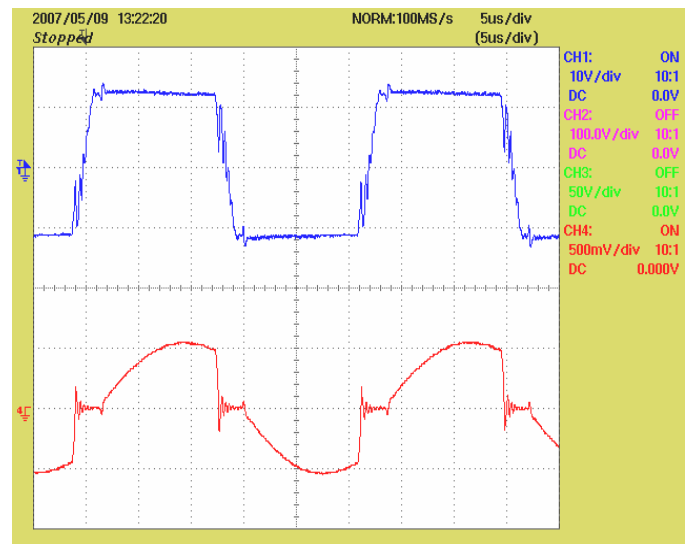

Fig. 14 Primary voltage and current of the HF transformer

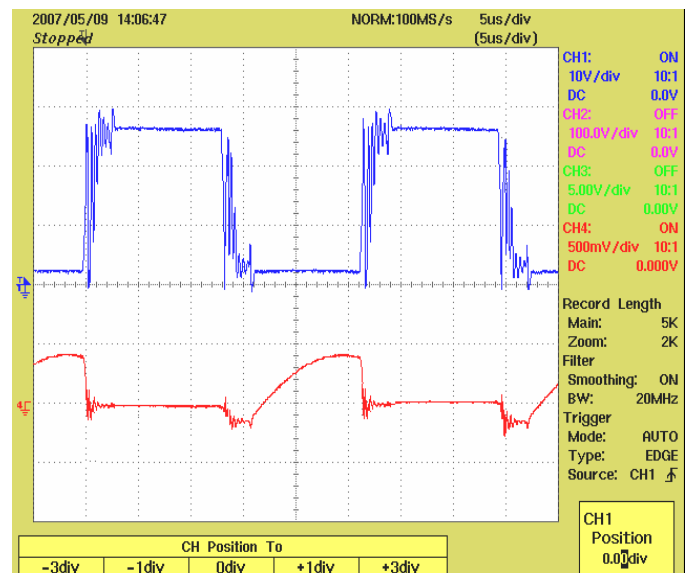Fig. 12 PWM IC and control board

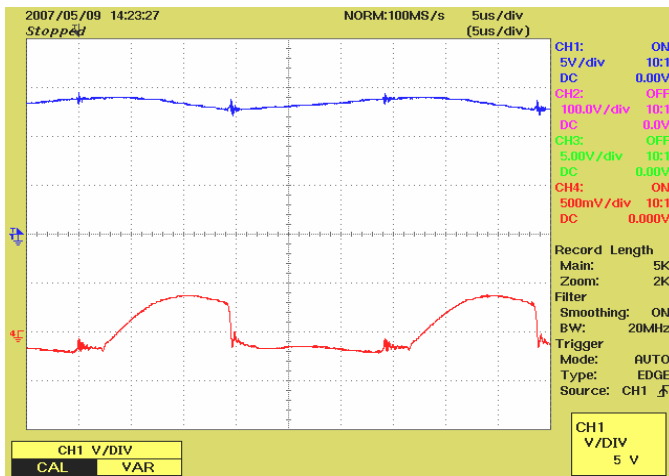Fig. 15 Switch Q2 voltage and current

Fig. 16 Voltage and current across capacitor C1.

6. Conclusions

In this paper, a high frequency link soft-switched PWM DC-DC converter with boost-half bridge one stage topology for PEM-FC power conditioner has been presented. With boost half-bridge topology the advantage that a fewer switching devices as compared with the boost converter and full-bridge inverter type converter topologies, this one stage inverter type DC-DC converter has half the number of switching devices. This simplified converter could also leads to significant savings on the gate drivers and heat sink. No auxiliary circuit or complex control required for soft switching. Extensive simulation based on a detailed circuit analysis and fuel cell model proved about the circuit operation and soft-switching conditions. A prototype rated at 1 kW was designed. This converter topology provides a solution for low-cost, lightweight, compact, higher efficiency and reliable DC-DC converter designed for automotive application and other applications areas could be also in uninterrupted DC power feeder and battery charging and discharging systems.

In the future, the boost-half bridge one stage high frequency linked soft switching PWM DC-DC power converter with a current doublers type rectifier for the small scale PEM fuel cells stack interfaced power conditioner should be evaluated and discussed as compared with the boost-half bridge high frequency linked DC-DC converter treated here, which has a voltage doubler-rectifier configuration. In addition the SiC-SBD or GaN-SBD in place of fast recovery PN junction diode should be introduced and evaluated.

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