A High Frequency Link Direct DC-AC Converter for Residential Fuel Cell Power Systems

Yu Jin Song Prasad N. Enjeti, IEEE Fellow

Power Electronics and Fuel Cell Power Systems Laboratory
Department of Electrical Engineering
Texas A&M University
College Station, TX 77843-3218, USA
e-mail: enjeti@ee.tamu.edu

Abstract— **This paper describes a boost converter cascaded high frequency link direct dc-ac converter suitable for fuel cell power sources. A new multi-loop control for a boost converter to reduce the low frequency input current harmonics drawn from the fuel cell is proposed. A new PWM technique for the cycloconverter at the secondary to reject the low order harmonics in the output voltages is presented in detail. The front-end boost converter regulates the dc bus voltage effectively where the fuel cell voltage varies widely depending on the power demand, and provides a constant dc voltage to the high frequency link dc-ac converter. The proposed multi-loop control reduces the low frequency (120Hz) input current harmonic of the boost converter without additional filter requirement in order to improve the performance of fuel cell system. The proposed PWM technique for the cycloconverter cancels the low order harmonics in the output voltage caused by the low frequency voltage ripple in the dc bus and guarantees the high quality of the output voltage. The trade-offs of proposed scheme are described in detail with mathematical evaluation approach.**

I. INTRODUCTION

Fuel cell has been considered as one of the highly promising alternatives for environmentally friendly renewable energy generation due to its high efficiency, modularity, and cleanness. One of its applications for medium power is the residential power system, where a compact dc-ac converter with galvanic isolation is required [1]-[4].

The high frequency link power conversion technique is attractive for this application because a bulky 60Hz transformer can be replaced with a compact high frequency transformer, and a high frequency link direct dc-ac converter which consists of a high frequency inverter, a cycloconverter, and a high frequency transformer between them, presents a possible way to build a compact direct dc-ac converter without the dc link capacitor and provides high conversion efficiency due to the reduced conversion step [6][7][11].

Since the dc voltage generated by a fuel cell stack varies widely and is low in magnitude (36V to 60V), a front-end step-up dc-dc conversion stage is required to provide a regulated higher dc voltage to the high frequency link direct dc-ac converter. Due to the nature of the fuel supply process, the fuel cell response time to changes in power demand is slow and varies from few seconds to few minutes. Therefore, it is necessary to improve the dynamics of the system by introducing the auxiliary power source [8]. In addition, it is crucial to reduce the low frequency current harmonics drawn from the fuel cell by high frequency link dc-ac converter because the varying reactant conditions surrounding the cells due to the low frequency current ripple may impose a severe impact to the performance of the fuel cell [5]. The dominant harmonic of the low frequency current harmonics drawn from the fuel cell is a 120Hz harmonic by a single phase high frequency link dc-ac converter whose output frequency is 60Hz, and the limit of 120Hz current harmonic is specified as 0.15 per-unit (i.e. 15% of its rated current) from 10% to 100% load in [12]. The low frequency voltage ripple in the dc bus caused by the substantial low frequency current ripple and a conventional sinusoidal PWM technique assuming a ripple-free dc voltage are the primary contributors for the appearance of low order harmonics in the high frequency link dc-ac converter output not present in the PWM switching functions, and are responsible for the deterioration in the quality of output voltage. A simple straightforward solution to this problem is to increase the output filter capacitance of the step-up dc-dc conversion stage, which makes it bulky and contributes to slow response, increased cost and losses [9].

In order to overcome these problems, a boost converter connected in series high frequency link direct dc-ac converter is proposed in this paper. A new multi-loop control to reduce the low frequency current harmonics drawn from the fuel cell and a new sinusoidal PWM technique for the cycloconverter at the secondary to reject the low order harmonics in the output voltage caused by the low frequency input voltage ripple are presented with proposed topology. The proposed multi-loop control reduces the 120Hz input current ripple of the boost converter dramatically without additional filter requirement, and the proposed PWM technique guarantees the high quality of the ac output voltage.

The performance of the proposed schemes is verified by the various simulation and experiment results, and their trade-offs are described in detail using mathematical evaluation approach.

II. PROPOSED HIGH FREQUENCY LINK DC-AC CONVERTER

Fig. 1 shows the proposed boost converter cascaded high frequency link dc-ac converter for residential fuel cell power system applications. Since the fuel cell terminal

0-7803-8399-0/04/$20.00 ©2004 IEEE.

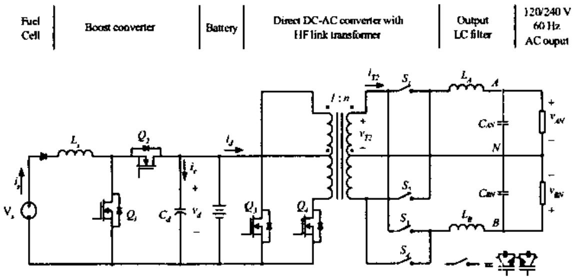


Fig.1 Proposed high frequency link dc-ac converter

voltage varies significantly depending on the load change, it is required to boost and regulate the fuel cell voltage. The high frequency link transformer needs to be designed to accommodate the lowest magnitude of the fuel cell voltage. During the normal operation the nominal input voltages are typically much higher than the minimum value and the transformer does not operate optimally [8]. Therefore, the boost converter step-up the fuel cell voltage to 84V, regulates and supplies a constant dc voltage to the input terminal of high frequency inverter at the primary, which allows the inverter to operate with a fixed duty ratio and does transformer to operate optimally. A battery pack is connected to the dc bus to provide fast system dynamic response. The high frequency inverter in push-pull connection at the primary generates a rectangular voltage waveform with 50% duty ratio and provides it to the secondary side through a high frequency link transformer. The cycloconverter with a new PWM technique produces sinusoidally modulated 60Hz split single phase output voltage waveforms with high quality.

III. MULTI-LOOP CONTROL FOR BOOST CONVERTER

The main propose of the front-end boost converter is to step-up the fuel cell voltage and regulate the output voltage and the input current. The magnitude of the low frequency (120Hz) input current ripple is highly dependent on the voltage control loop characteristic and the size of capacitor, C_d, in the dc bus.

The output voltage and current of high frequency link dc-ac converter are defined simply as follows,

$$v_o(t) = \sqrt{2}V_{o,rms}\sin(\omega_o t)$$
$$i_o(t) = \sqrt{2}I_{o,rms}\sin(\omega_o t - \phi) \qquad (1)$$

, where ϕ is power factor angle.

The instantaneous output power, $P_o(t)$, is

$$P_o(t) = v_o(t)i_o(t)$$
$$= V_{o,rms}I_{o,rms}\cos\phi - V_{o,rms}I_{o,rms}\cos(2\omega_o t - \phi)$$

Considering power balance with assumption that $v_d(t)$ is a constant dc value, V_d, the dc current $i_d(t)$ is

$$i_d(t) = I_d + i_{d,rppl}(t)$$
$$= \frac{V_{o,rms}I_{o,rms}}{V_d}\cos\phi - \frac{V_{o,rms}I_{o,rms}}{V_d}\cos(2\omega_o t - \phi) \qquad (2)$$

$$i_c(t) = -i_{d,rppl}(t) \qquad (3)$$

, where 120Hz ripple current as large as fundamental current is included in the current of dc bus terminal. The dc bus voltage with a voltage ripple caused by the 120 Hz current ripple across C_d is expressed as follows,

$$v_d(t) = V_d + \frac{1}{C_d}\int i_c(t)dt = V_d(1 + k\sin(2\omega_o t - \phi))$$

$$\text{, where } k = \frac{V_{o,rms}I_{o,rms}}{2\omega_o C_d V_d^2} \qquad (4)$$

The steady state voltage error calculated in the voltage control loop of boost converter becomes

$$v_{err}(t) = V_d - v_d(t) = -\frac{V_{o,rms}I_{o,rms}}{2\omega_o C_d V_d}\sin(2\omega_o t - \phi) \qquad (5)$$

, and the current reference of the current loop is the voltage error multiplied by voltage loop gain. Therefore, a large 120Hz ripple current which is 180° phase shifted from the 120Hz ripple voltage in the dc bus is induced at the fuel cell terminal with a conventional PI control, and deteriorates the performance of fuel cell power system. In order to reduce the 120Hz input ripple current, a new multi-loop control is proposed (Fig. 2). An additional control loop with gain K_c is added to the PI voltage control loop, and the voltage error multiplied by K_c cancels the 120Hz ripple component of the current reference of the current control loop and eliminates the 120Hz input ripple current at the fuel cell terminal. A limiter on the current reference limits the sudden large current reference command during start up or load change and prevents the inductor from saturating and does the switching devices from being damaged.

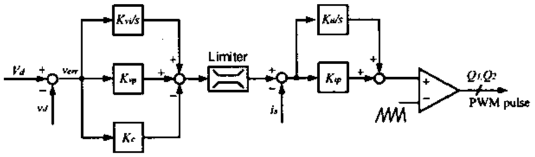
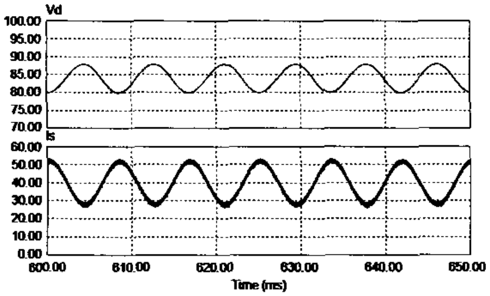
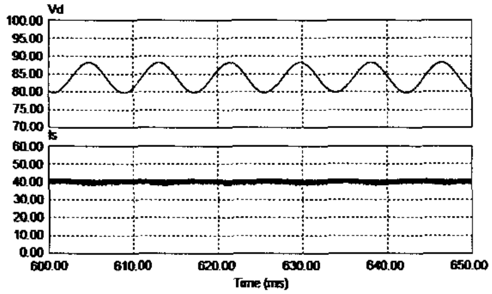


Fig.2 Block diagram of proposed multi-loop control

Fig.3 shows the simulation results obtained with 10% voltage ripple at the output of boost converter. The input current ripple with the proposed multi-control scheme is reduced from $i_{s,pp}$=27.2 to $i_{s,pp}$=3.8A, and the 120Hz harmonic of input current is reduced from $I_{s,h2}$=0.3p.u. to $I_{s,h2}$=0.008p.u., while the output voltage ripple, $v_{d,pp}$, is increased by 2.1%. The increased voltage ripple in the dc bus is counted into designing a new PWM scheme for the cycloconverter at the secondary. During load transition, the maximum overshoot of v_d is increased by multi-loop control, but its effect is mitigated by the battery in parallel with C_d and the independent voltage control with a new PWM technique for the cycloconverter.



(a) v_d and i_s with conventional PI control



(b) v_d and i_s with proposed multi-loop control

f_{sw}= 40kHz, L_s= 60uH, C_d= 5.5mF and P_o=1.5kVA

Fig.3 Waveforms of i_s and v_d

IV. PROPOSED PWM TECHNIQUE FOR CYCLOCONVERTER

In this section, the performance of the proposed PWM technique for the cycloconverter at the secondary is analyzed using a switching function approach. The PWM switching signals of cycloconverter are obtained by converting the level of the PWM switching signals of the single phase inverter composed of unidirectional switches according to the polarity of the ac link voltage. The PWM switching signals of cycloconverter are same as those of single phase inverter when the polarity of ac link voltage is positive. On the other hand, when the polarity of ac link voltage is negative, the PWM switching signals of cycloconverter are generated by reversing the level of PWM switching signals of the inverter [6]. Therefore, the PWM switching functions and output voltages of the cycloconverter can be expressed in the same manner as those of single phase inverter using Fourier series. The switching functions can be written as

$$\begin{bmatrix} S_a(t) \\ S_b(t) \end{bmatrix} = \begin{bmatrix} \sum_{m=1}^{\infty} A_m \sin m(\omega_o t) \\ \sum_{m=1}^{\infty} A_m \sin m(\omega_o t - \pi) \end{bmatrix} \qquad (6)$$

For the ripple-free dc bus voltage, V_d, the respective output voltages are given by

$$v_{AN}(t) = nVdSa(t) = nVd\sum_{m=1}^{\infty} Am \sin m(\omega o t)$$

$$v_{BN}(t) = nVdSb(t) = nVd\sum_{m=1}^{\infty} Am \sin m(\omega o t - \pi)$$

, where n is transformer turn ratio (7)

However, the dc bus voltage of single phase high frequency link dc-ac converter has 120Hz voltage ripple caused by the inherent 120Hz input current ripple as mentioned in the third section. The output voltages with 120Hz voltage ripple in the dc bus can be written as follows using (4) and (6)

$$\begin{aligned} v_{AN}(t) &= nvd(t)Sa(t) = nVd\sum_{m=1}^{\infty} Am \sin m(\omega o t) \\ &+ \frac{nVdk}{2}\sum_{m=1}^{\infty} Am(\cos(2\omega o t - \phi - m\omega o t) \\ &- \cos(2\omega o t - \phi + m\omega o t)) \\ v_{BN}(t) &= nvd(t)Sb(t) = nVd\sum_{m=1}^{\infty} Am(\sin m(\omega o t - \pi) \\ &+ \frac{nVdk}{2}\sum_{m=1}^{\infty} Am(\cos(2\omega o t - \phi - m(\omega o t - \pi)) \\ &- \cos(2\omega o t - \phi + m(\omega o t - \pi))) \end{aligned} \qquad (8)$$

It is apparent that low order harmonics at ($2\omega_o t - \phi \pm m \omega_o t$) and ($2\omega_o t - \phi \pm m(\omega_o t - \pi)$), not present in the PWM switching functions, appear in the output voltages due to the dc-link voltage ripple. The simulation is carried out with 120 Hz voltage ripple of 20% (i.e., k=0.1) in the dc bus. Fig.4 illustrates that the conventional PWM technique with 120Hz voltage ripple in the dc bus generates the 3rd harmonics in the output voltages and distorts the output waveforms.

A. Proposed PWM technique to cancel the low order harmonics

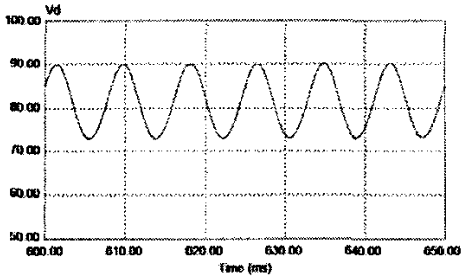
In order to eliminate the low order harmonics in the output voltages caused by the conventional PWM switching functions, (6), with 120Hz voltage ripple in the dc bus, new PWM switching functions are proposed as follows,

$$\begin{bmatrix} S_{a.new}(t) \\ S_{b.new}(t) \end{bmatrix} = \frac{1}{1 + k\sin(2\omega_o t - \phi)} \begin{bmatrix} \sum_{m=1}^{\infty} A_m \sin m(\omega_o t) \\ \sum_{m=1}^{\infty} A_m \sin m(\omega_o t - \pi) \end{bmatrix} \qquad (9)$$

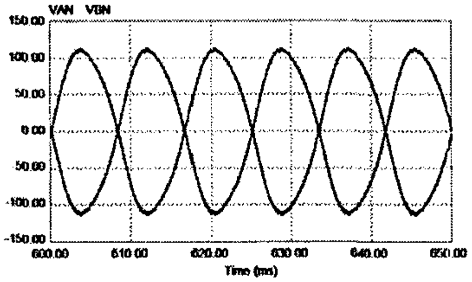
The respective output voltages then become

$$v_{AN}(t) = nvd(t)Sa.new(t) = nVd\sum_{m=1}^{\infty} Am \sin m(\omega o t)$$

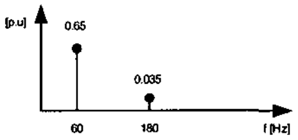
$$v_{BN}(t) = nvd(t)Sb.new(t) = nVd\sum_{m=1}^{\infty} Am \sin m(\omega o t - \pi) \qquad (10)$$



(a) v_d with 20% ripple



(b) v_{AN} and v_{BN}



(c) Frequency spectrum of v_{AN}

f_{sw}=20kHz and modulation index, m_a= 0.7

Fig.4 Output voltage waveforms with conventional PWM technique

Equation (10) is identical to (7) where the 120Hz voltage ripple is zero. Therefore, the proposed PWM technique cancels the low order harmonics in the output voltages without increasing the filter capacitor (C_d), and guarantees the output voltages with high quality. Fig.5 shows the simulation results obtained with proposed PWM switching functions, where the PWM technique is implemented by changing the modulation index according to the voltage ripple adaptively (Fig.5 (b)). Fig.5 (d) illustrates the frequency spectrum of output voltage and depicts the cancellation of low order harmonics.

B. Evaluation of proposed PWM technique

(a) Current ripple in the dc bus: The dc current, $i_d(t)$, in the dc bus with proposed switching technique is given by

$$i_d(t) = n(S_{a.new}(t)i_{AN}(t) + S_{b.new}(t)i_{BN}(t)) \tag{11}$$

The magnitude of dc component and the low order harmonics can be obtained using a geometric series. The simplified dc term and the low order harmonics are given by

$$I_d = nI(A_1 + \frac{A_1k^2}{2}) \tag{12}$$

$$I_{h2} = -nI((A_1 + \frac{A_1k^2}{4})\cos 2\omega_0 t + (A_1k + \frac{3A_1k^3}{4})\sin 2\omega_0 t) \tag{13}$$

$$I_{h4} = -nI(\frac{A_1k^2}{2}\cos 4\omega_0 t - (\frac{A_1k}{2} + \frac{3A_1k^3}{8})\sin 4\omega_0 t) \tag{14}$$

, where I is a peak value of each phase current and m=1.

Fig.6 shows the frequency spectrum of dc current, i_d, with 20% voltage ripple in the dc bus. For a modulation index m_a=0.7 (i.e., A_1=m_a/2=0.35), I_{h2}=0.36 p.u. at 120Hz and I_{h4}=0.036 p.u. at 240Hz. Thus, it can be concluded that the proposed PWM technique effectively eliminates the low order harmonics of the output voltages, but the dc current of the dc bus, i_d, will be distorted by the increased I_{h2} and I_{h4}. For reasonable magnitude of voltage ripple in the dc bus, the magnitudes of I_{h2} and I_{h4} are not high.

(b) Voltage gain of high frequency link dc-ac converter: The 120Hz voltage ripple of the dc bus(Fig5.(a)) also appears in the ac link voltage at the secondary with an amplitude multiplied by the transformer turn ratio (n), and reduces the margin to incorporate higher instantaneous values of the modulating signal given by the proposed switching functions (9). Moreover, this insufficient margin is proportional to the magnitude of voltage ripple. Thus, there is an upper limit to which the modulation index can be raised with proposed switching functions for a particular magnitude of voltage ripple, which results in losses of voltage gain. Therefore, considering the increased voltage ripples by the multi-loop control and the increased I_{h2} and I_{h4} resulted from the proposed PWM technique, Δk_1 and Δk_2 each, the percentage voltage gain of high frequency link dc-ac converter with voltage ripple of magnitude k is given by,

$$Gv = (1 - (k + \Delta k_1 + \Delta k_2)) \times 100\% \tag{15}$$

The reduced voltage gain at 20% voltage ripple is 11.5% in Fig.7.

(c) Output voltage quality: Fig.8 presents the total harmonic distortion (THD) of the output voltage (v_{AN}) at various percentage of dc voltage ripple, both with a conventional PWM technique and with the proposed PWM technique. For 50% voltage ripple, the total increased voltage ripple by the multi-loop control and the proposed PWM technique is 63.4% (i.e., k+Δk_1+Δk_2=0.32) at the modulation index, m_a=0.7, where the margin to incorporate higher instantaneous values of the modulating signal is insufficient and the THD of output voltage is increased to 11.6%. Thus, the margin of modulating signal should be larger than the total voltage ripple of the dc bus to avoid a severe distortion of output voltage.

$$1 - m_a \geq k + \Delta k_1 + \Delta k_2 \tag{16}$$

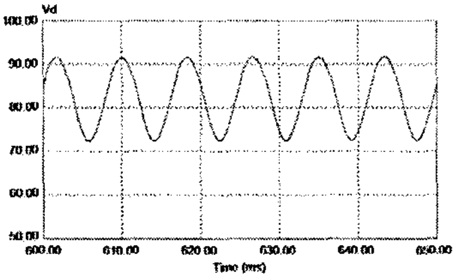
C. Calculation of C_d

The required capacitance of C_d for a desired voltage ripple ($2kV_d$) is calculated using the equation (4) as follows

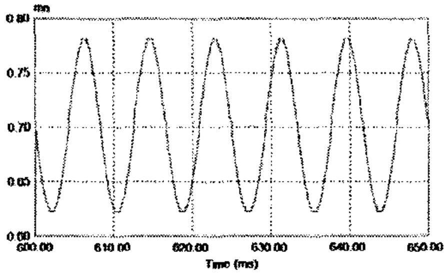
$$C_d = \frac{P_o}{(k-(\Delta k_1+\Delta k_2))2\omega_o V_d^2} \tag{17}$$

In addition, the capacitance of C_d also satisfies the following equation for the proper operation of the boost converter.

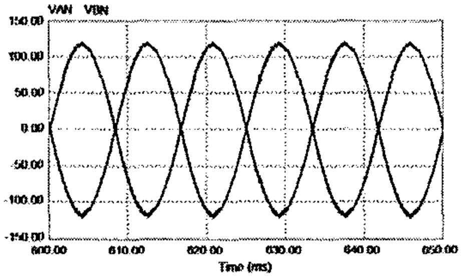
$$C_d = \frac{I_{s.pk}L_s}{2kV_d(V_d-V_s)} \tag{18}$$



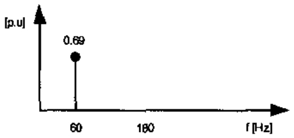
(a) v_d



(b) Modified modulation index, m_a



(c) v_{AN} and v_{BN}



(d) Frequency spectrum of v_{AN}

Fig.5 Output voltage waveforms with proposed PWM technique

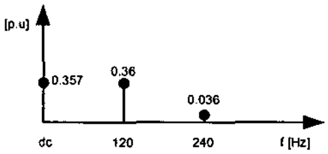


Fig.6 Frequency spectrum of i_d

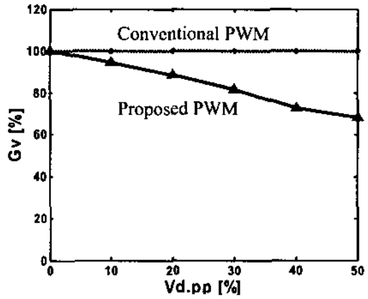


Fig.7. Voltage gain versus $V_{d,pp}$

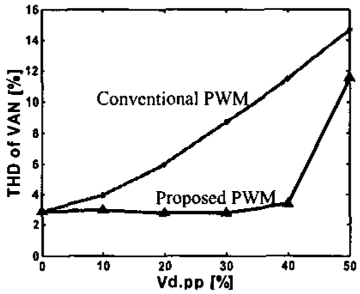
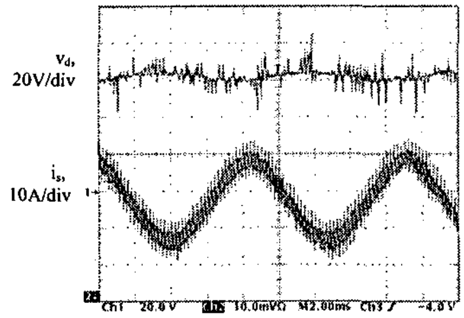


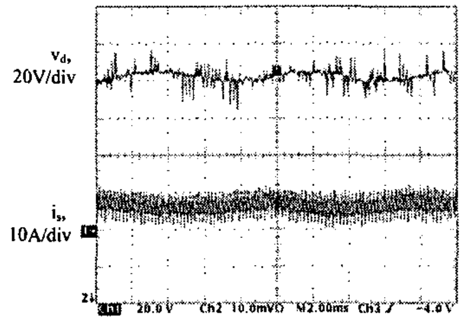
Fig.8. THD of output voltage (v_{AN})

V. EXPERIMENTAL RESULTS

In order to provide experimental verification of the proposed scheme, a boost converter cascaded high frequency link direct dc-ac converter has been built with TMS320LF2407 and FPGA chip, where the fuel cell voltage (36V) is converted to the 60Hz, $120V_{rms}$ split single-phase ac output voltages. The boost converter and dc-ac converter operate at 40kHz and at 20kHz each. The input inductor of boost converter is 60uH, and the output capacitor, C_d, is 3.3mF which was properly designed using equations (17, 18) for a 20% voltage ripple in the dc bus. Fig.9. shows that the waveforms of the output voltage and input current obtained from the boost converter, and illustrates that the proposed multi-control scheme reduces the 120Hz input current ripple harmonic to the magnitude less than 10% of dc value, which improves the performance

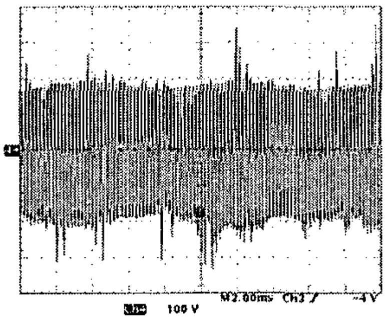


(a) Conventional PI control

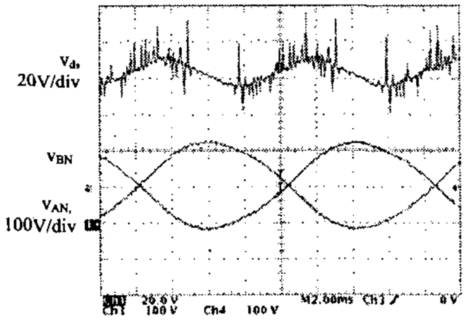


(b) Multi-loop control

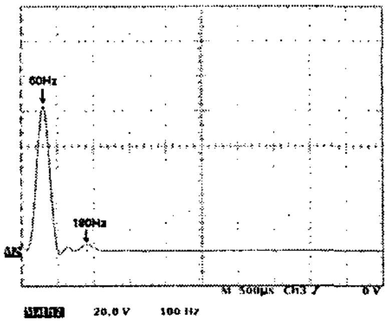
Fig.9. Output waveforms of boost converter



(a) AC link voltage, v_{T2}, 100V/div

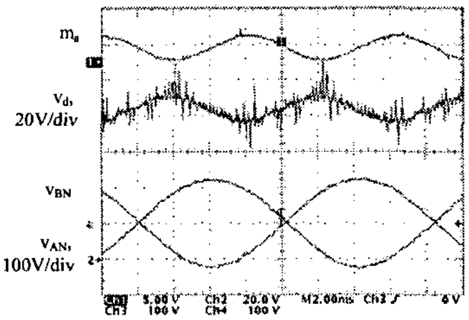


(b) Output voltage waveforms

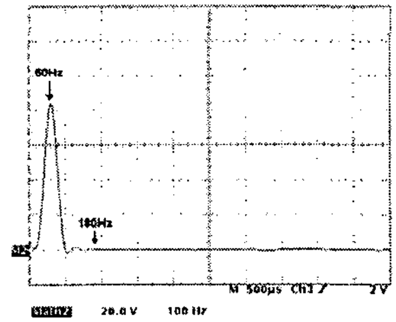


(c) Frequency spectrum of v_{AN}, $20V_{rms}$/div

Fig.10. Output voltage waveforms of dc-ac converter with a conventional PWM technique under 20% voltage ripple and m_a=0.7



(a) Output voltage waveforms



(b) Frequency spectrum of v_{AN}, $20V_{rms}$/div

Fig.11. Output voltage waveforms of dc-ac converter with a proposed PWM technique

of fuel cell system. Fig.10. shows that the voltage ripple in the dc bus with a conventional PWM technique assuming ripple-free voltage in the dc bus generates distorted output voltages with the 3^{rd} harmonic at 180Hz. The proposed PWM technique is implemented by DSP, where an adaptive modulating signal is generated based on the sensed dc voltage ripple, and it eliminates the 3^{rd} harmonic of output voltage effectively and produces the output voltage waveforms with high quality (Fig. 11.).

VI. CONCLUSION

In this paper, a boost converter cascaded high frequency link direct dc-ac converter for fuel cell power sources has been proposed. The boost converter has been shown to regulate the dc bus voltage effectively when the fuel cell voltage varies widely depending on the load condition. Further, the proposed multi-loop control of the boost converter has been shown to reduce the 120Hz input current harmonic drawn from the fuel cell to less than 10% without additional filter requirements. The evaluation of proposed PWM technique illustrates that immunity to voltage ripple in the dc bus can be achieved only at the expense of loss of voltage gain in the dc-ac converter and marginal dc current distortion. Experimental results have been shown to validate the feasibility of the proposed approach.

REFERENCES

[1] Dept of Energy, 2001 Future Energy Challenge Final Report, http://www.energychallenge. org

[2] T. A. Nergaard, J. F. Ferrell, L. G. Leslie, and J.-S. Lai, "Design considerations for a 48V fuel cell to split single phase inverter system with ultracapacitor energy storage," Conf. Rec. IEEE PESC'02, pp. 2007-2012, 2002.

[3] G. K. Andersen, C. Klumpner, S. B. Kjar, and Frede Blaabjerg, "A new green power inverter for fuel cells," Conf. Rec. IEEE PESC'02, pp. 727-733, 2002.

[4] P. T. Krein and R. Balog, "Low cost inverter suitable for medium-power fuel cell sources," Conf. Rec. IEEE PESC'02, pp. 321-326, 2002.

[5] Randall S. Gemmen, "Analysis for the effect of inverter ripple current on fuel cell operation condition," ASME 2001 International Mechanical Engineering Congress and Exposition, Nov.11-16, NY

[6] I. Yamato, N. Tokunaga, Y. Matsuda, H. Amano, and Y. Suzuki, "New conversion system for UPS using high frequency link," Conf. Rec. IEEE PESC'88, pp. 658-663.

[7] M. Matsui, M. Nagai, M. Mochizuki and A. Nabae, "High-frequency link DC/AC converter with suppressed voltage clamp circuits-naturally commutated phase angle control with self turn-off devices," IEEE Trans. on Ind. Appl., vo. 32, no. 2, March/April 1996.

[8] M.H. Todorovic, L. Palma and P. Enjeti, "Design of a wide input range DC-DC converter with a robust power control scheme suitable for fuel cell power conversion," APEC, 2004.

[9] P. Enjeti and W. Shireen, "A new technique to reject DC-link voltage ripple for inverters operating on programmed PWM waveforms," IEEE Trans. Power Electr., vol. 7, no. 1, pp. 171-180, 1992.

[10] C. Liu, T. Nergaard, L. Leslie, J. Ferrell, X. Huang, T. Shearer, J. Reichl, J. Lai and J. Bates, "Power balance control and voltage conditioning for fuel cell converter with multiple sources," PESC'02, IEEE 33rd Annual, vol.4, P2001-2006.

[11] Divan, D.M, "The resonant DC link converter- a new concept in static power conversion," IEEE trans. On Industry Applications, vol. 25, March-April 1989, p317-325

[12] DOE future energy challenge : 2001 and 2003, Low cost fuel cell inverter design competition : http://www.energychallenge.org