Development of a Low Cost Fuel Cell Inverter System With DSP Control

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***Abstract*—In this paper, the development of a low cost fuel cell inverter system is detailed. The approach consists of a three-terminal push-pull dc–dc converter to boost the fuel cell voltage (48 V) to ±200 VDC. A four switch [insulated gate bipolar transistor (IGBT)] inverter is employed to produce 120-V/240-V, 60-Hz ac outputs. High performance, easy manufacturability, lower component count, safety and cost are addressed. Protection and diagnostic features form an important part of the design. Another highlight of the proposed design is the control strategy, which allows the inverter to adapt to the requirements of the load as well as the power source (fuel cell). A unique aspect of the design is the use of the TMS320LF2407 DSP to control the inverter. Two sets of lead-acid batteries are provided on the high voltage dc bus to supply sudden load demands. Efficient and smooth control of the power drawn from the fuel cell and the high voltage battery is achieved by controlling the front end dc–dc converter in current mode. The paper details extensive experimental results of the proposed design on Department of Energy (DoE) National Energy Technology Laboratory (NETL) fuel cell.**

***Index Terms*—Current mode, dc–dc converter, fuel cell.**

I. INTRODUCTION

DISTRIBUTED power systems offer a potential increase in efficiency by localizing power generation. Distributed power also offers increased reliability, uninterruptible service, and energy cost savings [1]. In general, the energy source in a distributed power scheme is a fuel cell, a microturbine, or a photo-voltaic cell. These energy conversion devices produce a dc voltage, which must be converted to an ac voltage for residential or industrial application. This paper focuses on energy conversion aspects associated with a fuel cell, but could be extended to the previously mentioned sources.

In general, a fuel cell produces a dc voltage from hydrogen-rich fuel gas and air that flow over two cell electrodes. The principal by-products are water, carbon dioxide and heat. Fuel cells are similar to batteries in that both produce a direct current by using an electrochemical process. Fuel cells convert the energy in a hydrogen-rich fuel directly into electricity and operate as long as they are supplied with fuel. Fuel cells emit almost none of the sulfur and nitrogen compounds released by conventional generation methods, and can utilize a variety of fuels: natural gas, coal-derived gas, landfill gas, bio-gas, or alcohols. Fuel cells also have many advantages, one of which is efficiency.

Even though this environmentally friendly, highly efficient energy resource is promising, the high cost of installing a fuel cell power plant is one of the main obstacles hindering its widespread deployment. Currently, fuel cell production costs are decreasing, and have nearly achieved energy costs that are competitive with local utility rates. To further assist the reduction of cost, the price of the inverter portion of the fuel cell system must also decrease, while at the same time increasing efficiency, increasing reliability, and maintaining suitable power quality levels [2]. The low cost inverter approach will help to enable small-scale fuel cell system commercialization and will in turn encourage the development and advancement of distributed power systems.

In view of this, this paper outlines the design and development of a low cost fuel cell inverter system. The advantages of this design are as follows.

a) Lower parts count, easy manufacturability, and lower cost resulting in an economically viable design.
b) Protection and diagnostic features provide safety and convenience for the operator.
c) Flexibility and intelligence are incorporated to suit varying system and control requirements.

This paper outlines the technical approach adopted to meet the specifications laid down for the 2001 Future Energy Challenge (FEC'01) organized by the Department of Energy and IEEE in August 2001 [2]. Following the specifications outlined in [2], the objective of this contest was to design a 10-kW fuel cell inverter costing less than $500, and to build a 1.5-kW fuel cell inverter prototype for demonstration purposes.

II. PROPOSED FUEL CELL INVERTER

This part of the paper begins with an overview of the solution followed by details of each aspect of the inverter.

A. Topology and Operation

Fig. 1 shows the schematic for the TAMU fuel cell inverter system comprising a dc–dc boost circuit, a dc–ac inverter

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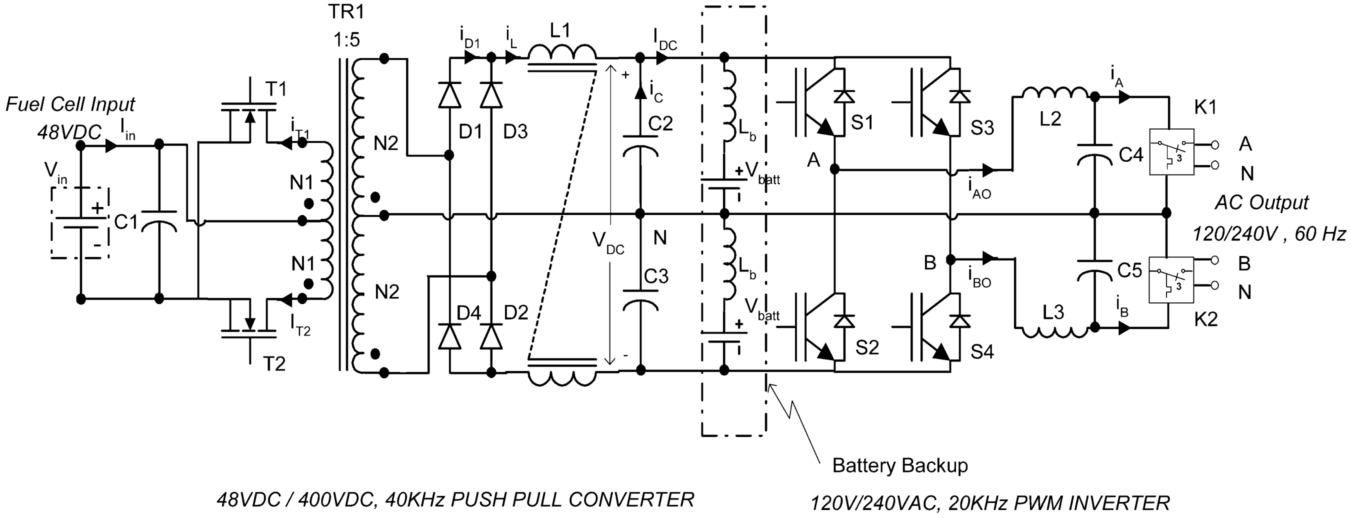


Fig. 1. Schematic of the TAMU fuel cell inverter system.

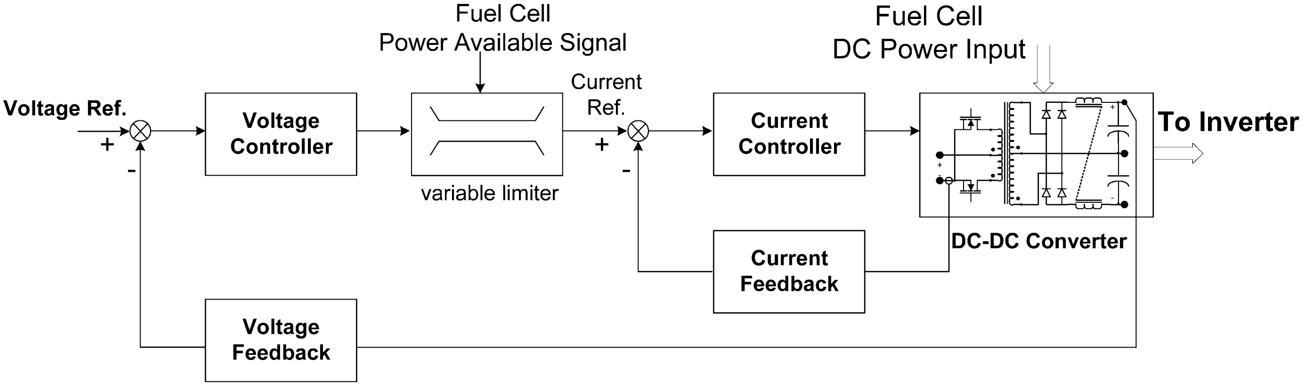


Fig. 2. Block diagram for dc–dc converter control.

circuit, and an output filter. The dc input from the fuel cell (48 VDC nominal, $+50\%$, -12.5%) is first converted to a regulated 400 VDC using a three-terminal push-pull dc–dc converter switching at 40 kHz. The dc–dc conversion stage consists of a high-frequency transformer. Isolation is provided for safety, system protection, and to meet the stringent FCC Class-A standards. The 400-V dc–dc converter output is converted to 120-V/240-V, 60-Hz, single-phase ac by means of a PWM driven inverter stage. To obtain independent single phase outputs, two half-bridge inverters operating at 20-kHz switching frequency are used.

An output LC filter stage is employed to produce a low THD ac waveform. Low loss, high switching frequency MOSFET and IGBT switches have been employed to achieve a higher efficiency, lower size and volume of the fuel cell inverter system.

The push-pull dc–dc converter is controlled by means of a high-speed PWM controller UC3825B. The special features of this controller are suitability for current control, soft start, over current and under voltage protection, low propagation delay, high current dual outputs, and low cost. Current mode control has numerous advantages over simple voltage mode control, including making the converter respond faster to load changes. In particular the UC3825B is suitable for the fuel cell inverter application because it allows direct control over the power drawn from the fuel cell. The error amplifier output in the outer voltage loop defines the level at which the primary current (in the inner current loop) will regulate the pulse width and output voltage. Pulse-by-pulse symmetry correction is a feature of current mode control and thus is essential for flux balancing the transformer in the push-pull topology [3]–[5].

Two sets of batteries are connected on the dc-link (Fig. 1) to supply sudden demand in output power. The inductor L_b blocks the high frequency ripple current from the inverter being circulated in the battery circuit.

Fig. 2 shows the block diagram for the current control of the dc–dc converter. Differential voltage feedback is provided using a voltage scaling circuit. For current sensing, a dc current sensor or precision resistors may be used. The power available signal (analog) from the fuel cell is used to adjust the current limit of the dc–dc converter. This ensures that the power drawn from the fuel cell does not exceed its capability. The remaining power is then provided by the battery backup system (Fig. 1). The inverter DSP control determines the actual power drawn by the loads and communicates to the fuel cell to either increase or decrease its power output. This ensures the fuel cell has sufficient time to adjust its power generation to meet the changes in load demand.

High frequency film capacitors on the 400-VDC bus are used for filtering the 40-kHz switching frequency components. Bulk (electrolytic) capacitors serve to balance the ±200 V voltages for the single-phase inverters. In addition, power resistors are connected across the dc link for safe discharge of the capacitors upon shut down.

Fig. 1 also depicts the dc–ac inverter schematic. Texas Instruments TMS320LF2407 DSP was implemented to obtain the closed loop control and PWM functions via software that maximizes the overall performance of the fuel cell inverter system, while allowing the low cost objective to be achieved (the TMS320LF2407 costs less than $2 in OEM quantities). Mixed signal (both analog and digital) techniques were employed to develop the four-layer printed circuit board [6] to mount the DSP. The DSP system has a high-speed A/D converter, nine PWM output channels, and serial communication capabilities. In addition, the TMS320C240X series contains a 10-bit analog-to-digital converter (ADC) having a minimum conversion time of 500 ns that offers up to 16 channels of analog input. The auto sequencing capability of the ADC allows a maximum of 16 conversions to take place in a single conversion session without any CPU overhead. Further, the processor has two modules, which can each accomplish a task such as centered and/or edge-aligned PWM generation, programmable dead band to prevent shoot-through faults, and synchronized analog-to-digital conversion. By implementing the control via DSP, the proposed approach offers increased flexibility, insensitivity to temperature drifts and minimizes component cost.

Both the dc–dc converter and the dc-ac inverter design includes the capability to detect any over-currents, over-temperatures, overvoltages or other shut down conditions to prevent damage to the inverter system.

B. Data Exchange and Handshaking With the Fuel Cell

The inverter uses an RS232 cable to link the DSP's serial port to a PC operating under Windows. This interface is used to transfer voltage and current values from the inverter to the PC so they can be displayed for real time viewing. The data is also stored into text files for data processing (or could be posted on the Internet if the PC is also a server).

A control interface [2] with the fuel cell control system provides for coordinated power transfer to the load. The following signals were provided.

a) Fuel cell trip—Digital TTL level, high = fuel cell operable/ready, low = fuel cell trip/not ready.
b) Available power level—Analog 0–5 V signal representing the maximum power available from the source.
c) Inverter On/Off—Digital TTL level, high = On, low = Off. Commands fuel cell to start up or to shut down.
d) Power level control—Analog 0–5 V signal to request a power level from minimum (idle) to maximum on a linear scale, where 1800 W corresponds to 5 V.

C. Battery Backup System

The fuel cell control system continuously adjusts the fuel flow rate to match the power output. However, these control systems involve pumps and compressors that are slow. The time constants involved in responding to a load change are several tens of seconds, depending on the size of the system. Hence it becomes necessary to use a temporary energy storage element to support sudden load changes. Battery banks, supercapacitors or flywheel based energy storage schemes can be considered. Our proposed design employs a ±192 V battery backup system connected to the dc-link. A series connection of sixteen 12-V, 1.2-Ah sealed rechargeable lead-acid batteries (Fig. 1) are employed to form $+192$ V. Another string of sixteen batteries of the same rating form -192 V. Each string of batteries is also connected in series with an inductor, and each sixteen battery/inductor combination is placed in parallel with the dc-link capacitors on the dc side of the inverter.

D. Design and Calculations for the 10 kW TAMU Fuel Cell Inverter System

Fig. 1 shows the schematic of the TAMU fuel cell inverter system comprising of the dc–dc converter, inverter, output filter, and the battery banks.

DC–DC Converter Design: In this section design of the dc–dc converter is detailed.

The power output P_o of the inverter is 10 000 W. Assuming an efficiency of 95% for the inverter and the dc–dc converter, we have an input power P_{in}

$$P_{\text{in}} = \frac{10\,000\text{ W}}{0.95 \cdot 0.95} = 11\,050\text{ W}. \tag{1}$$

A nominal fuel cell input voltage, $V_{in} = 48$ VDC, is assumed. The output voltage of the converter is 400 VDC. Designing for the low input line condition ($V_{in} = 42$ VDC), input current I_{in} from the fuel cell is,

$$I_{in} = \frac{11\,050\text{ W}}{42\text{ V}} = 263\text{ A}. \tag{2}$$

At the maximum duty ratio of 0.45, rms current rating I_T of the switches is,

$$I_T = I_{in}\sqrt{0.45} = 176\text{ A}. \tag{3}$$

For obtaining an output voltage of 400 VDC for the push-pull converter, a turns ratio of $K = 5$ is selected for the high frequency transformer. Center taps are available on both the primary and secondary sides. The VA rating of the transformer is defined as half of the sum of total primary and secondary winding VA

$$\begin{aligned} VA_{\text{Tr}} &= \frac{1}{2}\left(\frac{V_{\text{in}}}{\sqrt{2}} \cdot \frac{I_{\text{in}}}{\sqrt{2}} \cdot 2 + V_{\text{in}} \cdot K \cdot \frac{I_{\text{in}}}{K} \cdot 2\right) \\ &= 1.5\text{ V}_{\text{in}} \cdot I_{\text{in}} = 16\,600\text{ W} \cong 17.0\text{ kVA}. \end{aligned} \tag{4}$$

Voltage ratings are selected as 80 V for the primary side and 400 V for the secondary side of the transformer. The reverse blocking voltage for the diodes is equal to the dc link voltage 400 V. Since each diode is clamped to the mid-point of the dc-link (±200 V), each diode can be rated for 300 V. The rms current through the diode, I_D, is given by

$$I_D = \frac{I_{\text{in}}}{K \cdot \sqrt{2}} = 37.2\text{ A}. \tag{5}$$

The dc–dc converter uses the three-terminal push-pull topology to boost the 48 V from the fuel cell to ±200 V at a switching frequency of 40 kHz. The push-pull dc–dc converter is controlled by means of a high speed current mode PWM controller UC3825B. Selecting a proper input capacitor C_1 contributes to the reduction in fuel cell input current ripple. The average input current I_{avg} at full load is 263 A. Assuming a square wave input current, for a duty ratio of 0.9, the peak current I is

$$I = \frac{263}{0.9} = 292\ \text{A} \tag{6}$$

and the RMS current I_{rms} is

$$I_{\text{rms}} = 292\sqrt{0.9} = 277\ \text{A}. \tag{7}$$

Therefore the RMS capacitor current $I_{\text{c,rms}}$ is

$$I_{\text{c,rms}} = \sqrt{I_{\text{rms}}^2 - I_{\text{avg}}^2} = 92\ \text{A}. \tag{8}$$

Based on the rated ripple current, four aluminum electrolytic capacitors 22000 μF, 100 V each are selected.

DC-AC Inverter Design: The inverter produces two single-phase outputs, Phase-A and Phase-B (Fig. 1). It is comprised of two half bridge inverters each supplying a separate single-phase load at 120 VAC, 60 Hz. Consider the case when Phase-B is not loaded and Phase-A is supplying full load (5000 VA). The peak amplitude of the fundamental frequency component is the product of m_a and $(1/2)V_{\text{DC}}$, where m_a is the modulation index. A modulation index of 0.9 is assumed for this design. The fundamental component of the inverter Phase-A output voltage V_{AO} is

$$V_{\text{AO},1} = m_a \cdot \frac{V_{\text{DC}}}{2}\sin(\omega_1 t) \quad 0 < m_a < 1. \tag{9}$$

Assuming the load current i_A to consist of fundamental (I_1) and third harmonic component (I_3 for nonlinear load), we have

$$I_{\text{A,rms}} \cong \sqrt{I_1^2 + I_3^2}. \tag{10}$$

Further, assuming $I_3 = 0.7I_1$ (which is typical of a single phase rectifier type nonlinear load) we have, $I_{\text{A,rms}} = 1.22 \cdot I_1$. Since

$$I_{\text{A,rms}} = \frac{5000}{120} = 41.7\ \text{A} \tag{11}$$

the current I_1 is

$$I_1 = \frac{41.7}{1.22} = 34\ \text{A}. \tag{12}$$

Therefore, the largest component of the dc-link capacitor current i_c is the fundamental frequency current, the rms value of which equals

$$i_{\text{c,rms}} = \frac{1}{2} \cdot I_1 = 17\ \text{A}. \tag{13}$$

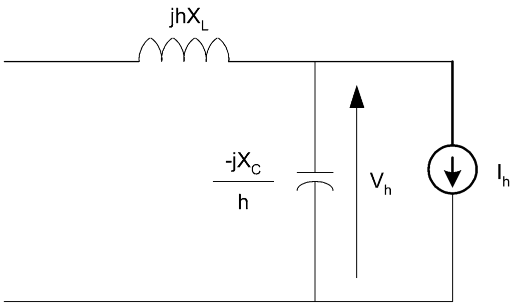


Fig. 3. Equivalent circuit for a nonlinear load.

For a voltage ripple ΔV_c less than 5% or 10 V we have

$$\Delta V_c = \frac{i_{\text{c,rms}}}{\omega C} \tag{14}$$

$$C = \frac{i_{\text{c,rms}}}{\omega \Delta V_c} = \frac{17}{10 \cdot 2\pi \cdot 60} \cong 4500\ \mu\text{F}. \tag{15}$$

Electrolytic capacitors rated 100 V, 4500 μF are selected for this design. The rms current is$_A$ is 41.7 A. Thus, rms current rating I_T of each switch is

$$I_T = \frac{41.7}{\sqrt{2}} = 30\ \text{A}. \tag{16}$$

Inverter L–C Output Filter Design: Fig. 1 shows the topology for the output L–C filter. It is assumed here that the output filter is lossless and the third harmonic current is 70% of the fundamental. The transfer function for this type of filter is described by

$$H_n = \frac{V_{\text{o,n}}}{V_{\text{i,n}}} = -\frac{jX_C \cdot Z_{\text{L,n}}}{nX_L X_C + jZ_{\text{L,n}}(n^2 X_L - X_C)} \tag{17}$$

where $V_{\text{o,n}}$ and $V_{\text{i,n}}$ are output and input voltage harmonic components. X_C and X_L are capacitive and inductive components of impedance $Z_{\text{L,n}}$. For $H_1 \to 1$; or $X_L \ll X_C$, then

$$H_1 \le \frac{-jX_C \cdot Z_{L,1}}{-jZ_{\text{L},1} \cdot X_C} \cong 1. \tag{18}$$

At no load, $Z_{\text{L},1} \to \infty$, therefore (17) is

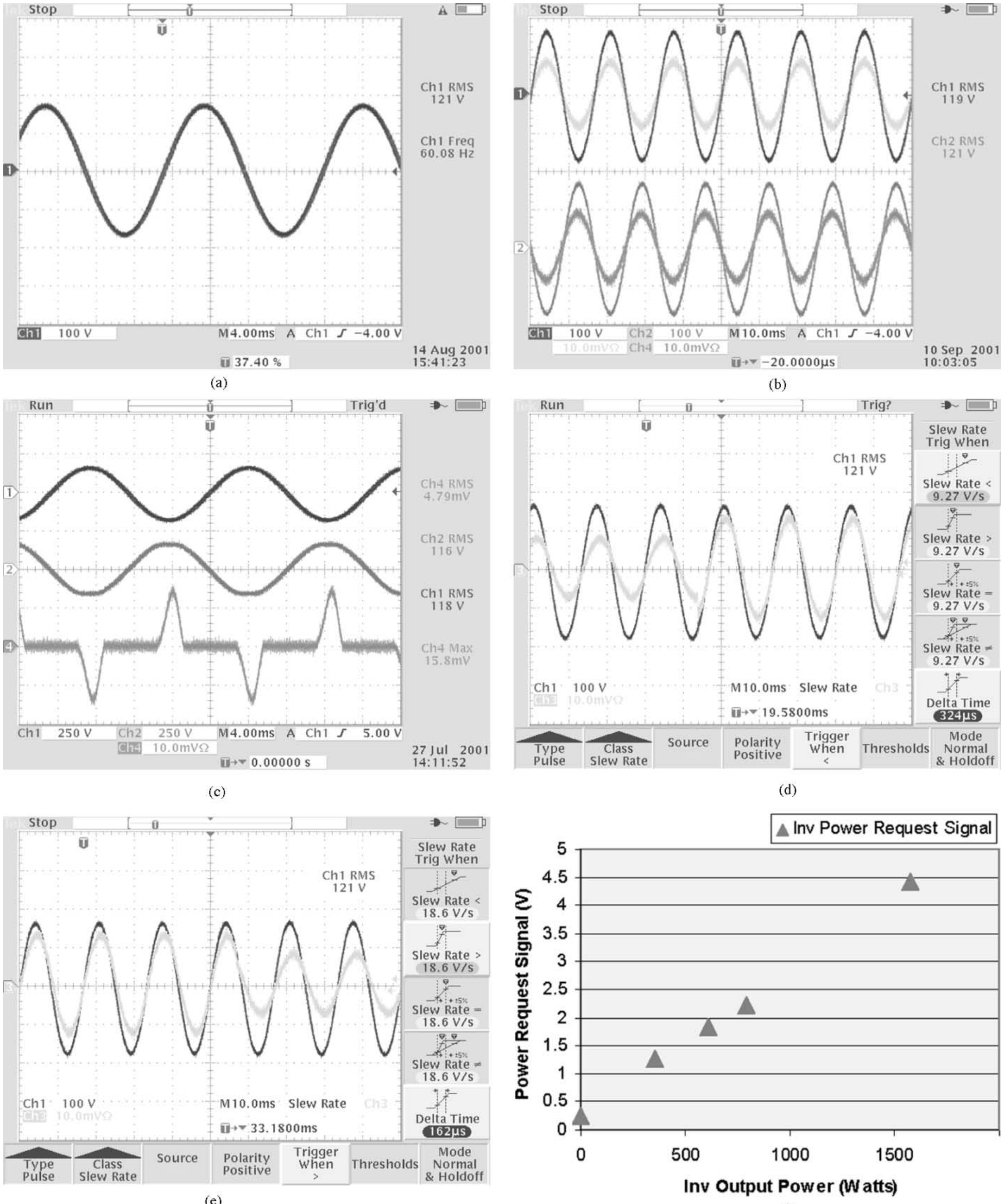
$$|H_n| = -\frac{X_C}{n^2 X_L - X_C} = \frac{1}{n^2 \cdot \frac{X_L}{X_C} - 1}. \tag{19}$$

In order to satisfy a THD requirement of less than 3%

$$\frac{1}{n^2 \cdot \frac{X_L}{X_C} - 1} \le 0.03 = \frac{X_L}{X_C} \ge \frac{34.333}{n^2}. \tag{20}$$

The load for the inverter is assumed to be nonlinear, i.e., a combination of single phase rectifier loads as well as lighting/heating loads. An equivalent circuit used in finding filter characteristics for a nonlinear load is shown in Fig. 3. The transfer function for this schematic is described by

$$V_h = \frac{jhX_L \cdot X_C}{X_C - h^2 X_L} \cdot I_h \tag{21}$$



(a) (b) (c) (d) (e) (f)

Fig. 4. Experimental results of the TAMU fuel cell inverter system. (a) Inverter output voltage waveform when running off the fuel cell at NETL on August 14, 2001. (b) Inverter output waveforms (voltage & current) when supplying 800 W/phase. Both phase-A and phase-B were loaded equally. (c) Inverter output waveforms with phase A on 800 W/phase and phase B on 150 W switching power supply load. (d) Inverter output waveforms (voltage and current) when a step change in load was applied from 360 W to 610 W on phase A. (e) Inverter output waveforms (voltage and current) when a step change in load was applied from 610 to 360 W on phase A. (f) Inverter power request signals.

where V_h is the equivalent voltage and I_h is the current at the hth harmonic. Equation (21) can then be shown as

$$|V_h| = \frac{hX_L}{1 - h^2 \frac{X_L}{X_C}} \cdot I_h. \tag{22}$$

Here, X_L/X_C is very small making $h^2(X_L/X_C) \ll 1$, therefore

$$|V_h| \leq hX_L \cdot I_h. \tag{23}$$

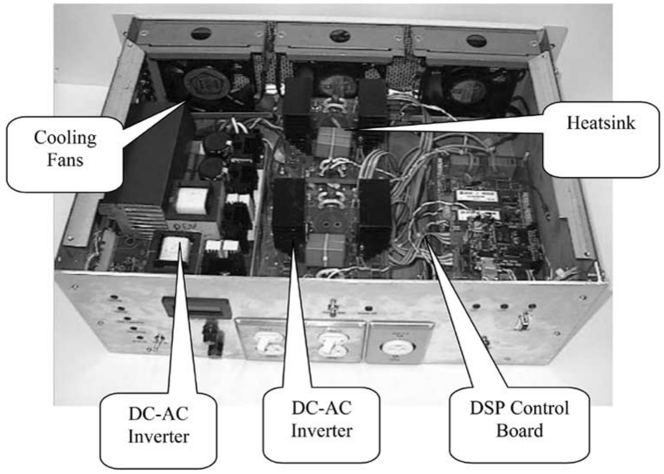


Fig. 5. Photograph of the packaged TAMU fuel cell inverter.

For the third harmonic $h = 3$, we have $|V_3|/V_1 = 3X_L \cdot I_3/V_1$, where THD is $|V_3|/V_1 = 0.03$ or 3%. Inductor impedance can be found by

$$X_L = \frac{0.03 \cdot V_1}{3I_3}. \tag{24}$$

Let f_s be defined as the switching frequency and f_1 be defined as the fundamental frequency. Then for $f_s = 20$ kHz, $f_1 = 60$ Hz, and $n = f_s/f_1 = 333.3\overline{3}$, $X_L/X_C \geq 3.09 \times 10^{-4}$ the filter resonant frequency f_r can be found with

$$\frac{f_r}{f_1} = \sqrt{\frac{X_C}{X_L}} \leq \sqrt{\frac{n^2}{34.333}} \leq 56.89 \tag{25}$$

where $f_r \approx 3413$ Hz. The 10-KW inverter (5 KW per Phase) with $V_1 = 120$ V, produces $I_{\rm rms} = 41.67$ A, $I_3 = 25.95$ A. Use (24) to find $X_L = 0.046$. Then, using

$$L = \frac{X_L}{2\pi f_1} \tag{26}$$

where L is the inductance, which will be $L = 123\ \mu$H. To find the capacitor impedance, use (20) to get $X_C = 148.9$, then using

$$C = \frac{1}{2\pi f_1 \cdot X_C} \tag{27}$$

where C is the capacitance, which will be $C = 18\ \mu$F.

E. Experimental Results

The 2001 FEC allowed the teams to submit a 1.5-kW proof-of-concept design for laboratory evaluation. TAMU team developed a fully functional 1.5-kW inverter shown in Fig. 5. Testing of the inverter system was completed in the DOE NETL facility on August 14, 2001. In this section, experimental results from the prototype are discussed. Fig. 4(a) depicts the performance of the inverter running on the fuel cell at the NETL facility. Fig. 4(b) shows the inverter output voltage and current waveforms when supplying 800 W/phase. Voltage waveforms for the inverter with Phase A supplying 800 W and Phase B on a 150-W switching power supply load is shown in Fig. 4(c). The current for Phase B supplying the nonlinear load is also shown. Fig. 4(d) and (e) depict the performance of the inverter when step changes in load were applied. Fig. 4(f) shows the power request signal (0–5 V) generated by the inverter DSP control. This signal is interfaced to the fuel cell controller.

III. COST

The cost analysis was based on the schematic shown in Fig. 1 and the 10-kW design procedure detailed in this paper. The cost analysis was based on the 10-kW design detailed in this paper, the schematic for which is shown in Fig. 1.

The TAMU design team made well-informed design decisions to aggressively lower the cost of the final 10-kW design and 1.5-kW prototype. By use of the push-pull topology the number of MOSFETs was minimized to half that needed by a full bridge topology. IGBTs were reduced in the inverter by use of the half bridge topology as opposed to the full bridge topology. The analog PWM controller provided a low cost solution to control the dc–dc converter. It provides a single chip control solution opposed to complex discrete analog hardware. DSP control of the dc–ac inverter provides efficiency of time and control. Readily programmable, the DSP enables easy design changes to account for various applications and allows a seamless interface with other components of the power management system. Programming capability translates into efficiency in human capital reducing costs of analysis, troubleshooting, development and manufacturing of the inverter. The topology of the TAMU Fuel cell Inverter System employs a high voltage battery floating on the dc-link. This approach does not add any additional power processing cost for management of transient loads.

As per the cost analysis spreadsheet provided by the FEC'01 organizing committee [7], the cost of the dc–dc converter was \$317.80 and that for the dc-ac inverter section was \$208.50. The total cost of the TAMU 10-kW system was \$526.30. We believe that with a detailed analysis of the control circuit and the ancillary components, this design can be mass produced and marketed below the target cost of \$500 [2].

IV. CONCLUSION

In this paper, development of a low cost fuel cell inverter has been presented. The main objective of the design was to explore strategies that would result in a significant cost reduction of the inverter. The proposed approach has been shown to meet the performance and cost targets set for the 2001 FEC competition. Finally, experimental results have been presented to validate the design for linear and nonlinear loading conditions.

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In 1988, he became an Assistant Professor in the Department of Electrical Engineering, Texas A&M University (TAMU), College Station. In 1994, he was promoted to Associate Professor and in 1998 he became a Full Professor. His primary research interests are advance converters for power supplies and motor drives, power quality issues and active power filter development, converters for fuel cell, microturbine, and wind energy systems, power electronic hardware for flywheel, and ultracapacitor type energy storage/discharge devices for ride-through and utility interface issues. He holds four U.S. patents and has licensed two new technologies to the industry. He is the Lead Developer of the Power Electronics/Power Quality & Fuel Cell Power Conditioning Laboratories, TAMU, and is actively involved in many projects with industries while engaged in teaching, research and consulting in the area of power electronics, motor drives, power quality, and clean power utility interface issues.

Dr. Enjeti received the IEEE-IAS Second and Third Best Paper Awards in 1993, 1998, 1999, 2001, and 1996, respectively, the second best IEEE-IA Transaction Paper, 1994 to 1995, the IEEE-IAS Magazine Prize Article Award in 1996, the "Class of 2001 TAMU Faculty Fellow" Award for demonstrated achievement of excellence in research, scholarship, and leadership in the field, and the 2001 Future Energy Challenge Award Grand Prize from the Department of Energy (DoE). He is a Registered Professional Engineer in the state of Texas.

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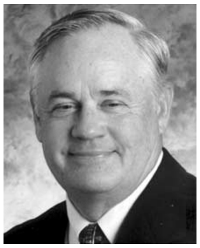
In 1995, he was with IBM, Austin, TX, as a member of the Microprocessor Development Team. As a graduate student, he served as a Teaching and Research Assistant. Following his graduation in 1999, he continued to be a member of the DSP Group and a Lecturer in the Department of Electrical Engineering, TAMU. Since the Fall of 2002, he has been an Assistant Professor in the Department of Electrical and Computer Engineering, University of Oklahoma, Norman. He has spent the summers of 2002, 2003, and 2004 at Raytheon as a Faculty Research Engineer. His contributions include the design an all-digital system-on-a-chip scheme for a KA band radar. His research, teaching, and consulting interests are in the areas of customized embedded DSP systems and digital signal processing as applied to radar signal processing, digital communications, image processing, adaptive filter design, and real-time systems.

Dr. Yeary received the Dean's Outstanding Student Award, the Outstanding Teaching Assistant Award from the local IEEE Student Chapter two years in a row, and was also nominated to be an NSF/FIE 1998 New Faculty Fellow. He is a member of Tau Beta Pi and Eta Kappa Nu. He was a Session Chairman of the 2001 IEEE International Symposium on Intelligent Signal Processing and Communication Systems. In 2001, he served on the Steering Committee of the 2001 Future Energy Challenge. He has also served as a Session Chairman at 2003 IEEE-IMTC and as a Technical Committee Member of the 2003 and 2004 IEEE-ICIP.



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He served as Program Chairman for the 2003 International Future Challenge, sponsored by IEEE, DoE, DoD, and various companies.