ANNOUNCEMENT

PART I: STI PRODUCT DESCRIPTION (To be completed by Recipient/Contractor)

A. STI Product Identifiers

1. REPORT/PRODUCT NUMBER(s)

2. DOE AWARD/CONTRACT NUMBER(s)

DE-FG36-04GO14329

3. OTHER IDENTIFYING NUMBER(s)

B. Recipient/Contractor

Ceramatec, Inc.

C. STI Product Title

A Novel Bidirectional Power Controller for Regenerative Fuel Cells

D. Author(s)

Joseph Hartvigsen

Sudip Mazumder

E-mail Address(es):

jjh@ceramatec.com

mazumder@ece.uic.edu

E. STI Product Issue Date/Date of Publication

10/10/2005 (mm/dd/yyyy)

F. STI Product Type (Select only one)

☒ 1. TECHNICAL REPORT

☒ Final ☐ Other (specify) _____

☐ 2. CONFERENCE PAPER/PROCEEDINGS

Conference Information (title, location, dates)

☐ 3. JOURNAL ARTICLE

a. TYPE: ☐ Announcement Citation Only

☐ Preprint ☐ Postprint

b. JOURNAL NAME

c. VOLUME _____ d. ISSUE _____

e. SERIAL IDENTIFIER (e.g. ISSN or CODEN)

☐ OTHER, SPECIFY

G. STI Product Reporting Period (mm/dd/yyyy)

9/30/2004

Thru

9/30/2005

H. Sponsoring DOE Program Office

Golden Field Office

I. Subject Categories (list primary one first)

Keywords

Fuel Cell, Hydrogen, SOFC, RFC, Power Electronics

J. Description/Abstract

Power electronics test with SOFC/RFC stack

K. Intellectual Property/Distribution Limitations

(must select at least one; if uncertain contact your Contracting Officer (CO))

☒ 1. UNLIMITED ANNOUNCEMENT (available to U.S. and non-U.S. public; the Government assumes no liability for disclosure of such data)

☐ 2. COPYRIGHTED MATERIAL: Are there any restrictions based on copyright? ☐ Yes ☒ No
If yes, list the restrictions as retained in your contract

☐ 3. PATENTABLE MATERIAL: THERE IS PATENTABLE MATERIAL IN THE DOCUMENT
INVENTION DISCLOSURE SUBMITTED TO DOE:
DOE Docket Number: **S-**
(Sections are marked as restricted distribution pursuant to 35 USC 205)

☐ 4. PROTECTED DATA: ☐ CRADA ☐ Other
If other, specify

Release date (mm/dd/yyyy)

☐ 5. SMALL BUSINESS INNOVATION RESEARCH (SBIR) DATA

Release date (Required,

No more than 4 years from date listed in part 1.E above)

☐ 6. SMALL BUSINESS TRANSFER (STTR) DATA

Release date (Required,

No more than 4 years from date listed in part 1.E above)

☐ 7. OFFICE OF NUCLEAR ENERGY APPLIED TECHNOLOGY

L. Recipient/Contractor Point of Contact Contact

for additional information (contact or organization name to be included in published citations and who would receive any external questions about the content of the STI Product or the research contained therein)

Name and/or Position

Joseph Hartvigsen

Senior Engineer SOFC & Hydrogen Technologies

E-mail **jjh@ceramatec.com** Phone **801-978-2163**

Organization **Ceramatec, Inc.**

UNITED STATES DEPARTMENT OF ENERGY (DOE)
Scientific and Technical Information (STI) For Financial
Assistance Recipients and Non-M&O/M&I Contractors

ANNOUNCEMENT

**PART II: STI PRODUCT MEDIA/FORMAT and
LOCATION/TRANSMISSION**

(To be completed by Recipient/Contractor)

A. Media/Format Information:

1. MEDIUM OF STI PRODUCT IS:
☒ Electronic Document ☐ Computer medium
☐ Audiovisual material ☐ Paper ☐ No full-text
2. SIZE OF STI PRODUCT _____
3. SPECIFY FILE FORMAT OF ELECTRONIC
DOCUMENT BEING TRANSMITTED, INDICATE:
☐ SGML ☐ HTML ☐ XML ☒ PDF Normal ☐ PDF Image
☐ WP-Indicate Version (5.0 or greater) _____
Platform/operating system _____
☐ MS-Indicate Version (5.0 or greater) _____
Platform/operating system _____
☐ Postscript _____
4. IF COMPUTER MEDIUM OR AUDIOVISUAL
 - a. Quantity/type (*specify*) _____
 - b. Machine compatibility (*specify*) _____
 - c. Other information about product format a user
needs to know: _____

B. Transmission Information:

STI PRODUCT IS BEING TRANSMITTED:

- ☒ 1. Electronic via Elink
☐ 2. Via mail or shipment to address indicated
in award document (*Paper products,
CD-ROM, diskettes, videocassettes, et.*)

☐ 2a. Information product file name
(*of transmitted electronic format*)

Ceramatec_UIC_CatI_final.pdf

**PART III: STI PRODUCT REVIEW/RELEASE
INFORMATION**

(To be completed by DOE)

A. STI Product Reporting Requirement Review:

- ☐ 1. THIS DELIVERABLE COMPLETES ALL
REQUIRED DELIVERABLES FOR THIS AWARD
- ☐ 2. THIS DELIVERABLE FULFILLS A
TECHNICAL REPORTING REQUIREMENT,
BUT SHOULD NOT BE DISSEMINATED
BEYOND DOE.

B. DOE Releasing Official

- ☐ 1. I VERIFY THAT ALL NECESSARY
REVIEWS HAVE BEEN COMPLETED AS
DESCRIBED IN DOE G 241.1-1A, PART II,
SECTION 3.0 AND THAT THE STI
PRODUCT SHOULD BE RELEASED IN
ACCORDANCE WITH THE INTELLECTUAL
PROPERTY/DISTRIBUTION LIMITATION
ABOVE.

Released by (*name*) _____

Date _____
(mm/dd/yyyy)

E-mail _____

Phone _____

Title Page

Project Title
A Novel Bidirectional Power Controller for Regenerative Fuel Cells

Contract No.
DE-FG36-04GO14329

Category 1 Final Report

Period of Covered by Report
9/30/2004 to 9/30/2005

Ceramatec, Inc.
2425 South 900 West
Salt Lake City, UT 84119

Technical Contacts

Joseph Hartvigsen
Senior Engineer, SOFC and Hydrogen Technologies
Ceramatec, Inc.
2425 South 900 West
Salt Lake City, UT 84119
Phone: 801 978-2163
Fax: 801 972-1925
Email: jjh@ceramatec.com

Dr. Sudip K. Mazumder
Assistant Professor, Sr. Member, IEEE
Director, Laboratory for Energy and Switching-Electronics Systems
Power Electronics Research Center (PERC)
Department of Electrical and Computer Engineering
University of Illinois
851 S. Morgan Street, MC: 154,
1020 Science and Engineering Offices
Chicago, IL: 60607-7053
Phone: 312-355-1315 (office)/312-996-8541 (lab.)
Fax: 312-996-6465
Email: mazumder@ece.uic.edu

Executive Summary	3
Project Summary	4
1. Project Introduction and Background	5
1.1. Cost and Energy Efficiency	5
2. Project Description and Approach	6
3. Project Task Performance	8
3.1. System Response (Ceramatec)	8
3.2. RFC PES Fabrication and Testing (UIC)	8
3.2.1. Description of the PES	8
3.2.1.1. Operation of the Zero-Ripple Boost Converter (ZRBC)	9
3.2.1.2. Operation of the DC/AC Converter	11
3.2.2. Device Fabrication	18
3.2.2.1. Sub-scaled (1 kW) First Generation Prototype	18
3.2.2.2. First Generation 5 kW Prototype	19
3.2.3. Debugging/Design Optimization Cycle	20
3.2.3.1. Second Generation 5 kW Prototype	22
3.2.4. Prototype Testing	23
3.2.4.1. Performance of ZRBC	23
3.2.4.2. Performance of DC/AC	26
3.2.5. Manufacturing Cost Analysis	27
3.3. Device Testing with RFC Stack (UIC ñ PES, Ceramatec- Stack)	32
3.3.1. Stack Construction and Performance Characterization	32
3.3.2. PES Performance Characterization	35
3.3.3. PES-Stack Interaction Effects	37
4. Project Results Supporting Economic and Environmental Benefits	43
5. Project Results Supporting Commercialization - Market Potential	43
Appendix 1: Schematics	44
References	49

Executive Summary

Hydrogen fuel-cells (FC) are among the front-runner alternative-energy solutions proposed by the DOE EERE to address and alleviate the critical problems at hand posed by existing fossil-fuel-energy systems: *environmental pollution due to high emission levels, and rapid depletion of fossil fuels*¹. The framework for integrating these i zero-emissionâ alternative-energy sources to the existing energy infrastructure has been provided by the concept of distributed generation (DG), which provides an additional advantage: *reduced reliance on existing and new centralized power generation, resulting in significant savings in generation, transmission and distribution capital costs*. Additional capacity can then be added in smaller increments as needed, offering reduced risk and more rapid payback to the investors and lower rates to the consumers.

Two key application areas of FC energy systems (FCES) are in residential and commercial power systems, where the projected worldwide market is \$50 billion by 2015. However, to achieve this projected target, the FCES have to address *three key issues: cost, durability and reliability, and energy efficiency*. Currently, the higher cost of electricity from FCES (as compared to conventional energy systems) are primarily due to the energy sources (FCs) and related subsystems. *A big part of the power-systems cost is due to the power-electronics technology*. For instance, a recent DOE-sponsored study has shown that unless the cost of power-electronics for FCES reduces to \$40/kW (which is about 40% of the present commercial cost), FC energy systems are not economically viable. The issue of durability of the fuel cell is also of key importance. Recent comprehensive studies by National Energy Technology Laboratory (NETL) and Mitsubishi have shown that *power-electronics, which interface directly to the cell stacks, have a significant impact on the long-term durability (life) and reliable energy efficiency of the FC cells*. Energy-conversion efficiency of the FC is power electronics system is of great importance in light of the lower capital costs (\$/kW) of conventional energy systems, a few of which (e.g., combined cycle plants), have achieved comparable efficiencies in recent years. Today, the efficiencies of power-electronics conversion technology have exceeded 90%; however under severe cost constraints, most of these technologies are not economically viable. As such, *achieving high power-conversion efficiency at significantly low cost for the viability of FCES is a potentially rewarding challenge*.

This project has successfully demonstrated a novel power-electronics system design, which achieves (a) *efficiencies of 94% for single-phase full load from 72 Vdc and as high as 98% from 600 Vdc sources*, (b) *50% reduction in voltage stresses on the power devices (as compared to best commercial technology)* which leads to higher reliability, (c) *ripple-current elimination from the FC source current without using any filter*, thereby significantly enhancing the life and energy efficiency of the FCs, and (d) *direct power conversion, i.e., does not require any intermediate energy-storage bulk capacitors*, thereby significantly reducing the size of the power-electronics package. *All the advantages outlined in (a)-(d), are achieved with reduced cost as compared to the best available commercial technology*.

A 5 kW prototype regenerative FCES/RFCES has been built to verify these advantages by comparison of the experimental and projected performances. The device has been tested at Ceramtec with a 25-cell SOFC stack, which was operated in both SOFC and electrolysis (RFC) modes.

¹ In his latest state-of-the union address, President George W. Bush has stressed the need for reduced dependence on foreign oil and lower emission, by laying out his vision for a hydrogen (fuel cell) economy. EERE and DOE has recognized the need for alternative energy sources (even earlier) due to immense energy crisis and the growing emissions problems due to burgeoning population and growing economy.

Project Summary

1. Innovation, viability and performance data from bench-scale model: The PES innovation comprises i) a zero-ripple DC-DC bidirectional boost converter (ZR-DC-DC-BBC), ii) a high-frequency inverter (HFI), and iii) an AC-AC converter. The PES design and scaled prototype development has been accomplished, and a provisional patent (UIC Tech ID CW074) has been procured for industry licensing. A cost target of \$40/kW at high volume has been projected, which is at least \$15/kW less than any conventional technology. Following are the technical advantages of the PES over state-of-the-art (SoA) conventional technology: (a) ~ 94% overall energy efficiency (as compared to 92% for SoA) at full load yielding high power density and enhanced thermal management; the high efficiency is due to zero-voltage switching (ZVS) of both the HFI and the AC-AC converter; (b) isolation is achieved between energy source and the load using only a small high-frequency transformer (a bulky and expensive 60 Hz line transformer is used for the SoA converter); (c) 50% reduction in device voltage stresses for the HFI, leading to higher reliability of PES; (d) at least 90% reduction in RFC-current ripple without using any bulky and expensive filter; and (e) DPC - direct power conversion - (as compared to high-frequency-link converter requiring intermediate bus capacitor) leading reduced package size.
2. Engineering and scientific basis of the technology: RFC technology is of key interest to DOE and FC industries because of FC/RFC's unique ability to generate power to supply electrical loads, and also sink power to generate hydrogen. However, to achieve this projected target, the fuel-cell energy systems have to address three key issues: cost, durability (of fuel cells) and reliability (of power-conditioning systems), and energy efficiency. The new invention addresses all of these at reduced cost. The scientific basis for this are threefold: a ZR-DC-DC-BBC designed based on a unique integrated-magnetics principle to practically eliminate switching ripple, ZVS soft-switching of HFI and AC-AC converter to significantly minimize the switching losses and boost efficiency, multilevel HFI topology to reduce device stress and cost, DPC to reduce package size.
3. Accomplishments during the Category I program: i) Completed PES design and fabrication layout; ii) measured the efficiency of PES and its subsystems at no to full load ; iii) experimental unit tested to 5 kW in a complete load test setup; iv) completed bill of materials and cost analysis; v) UIC provisional patent obtained and commercialization agreement negotiated between UIC and Ceramtec ; vi) tested the system with actual SOFC/RFC hardware at Ceramtec, and vii) presented in leading IEEE and ASME conferences for visibility and peer review.

1. PROJECT INTRODUCTION AND BACKGROUND

Hydrogen fuel cell (FC) energy systems are among the front-running alternative-energy solutions being developed to address and alleviate the imminent and critical problems of existing fossil-fuel-energy systems: environmental pollution due to high emission level and rapid depletion of fossil fuel. However, to make the FC energy systems viable and to achieve the projected world-wide target of \$50 billion by 2015 [1], the FC power electronics has to meet three key requirements: (a) cost (less than \$40/kW for producing high volume), (b) energy efficiency (of greater than 90%), and (c), reliability over 40,000 hours of operation.

1.1. Cost and Energy Efficiency: The DOE cost targets for FC system ranges from \$400/kW to \$600/kW [2]; of which the cost allocation for power electronics is less than 10%. Therefore, meeting the stringent cost constraint and the energy-efficiency requirement is a substantial challenge. So far, research in power electronics for (primarily 1-10 kW) residential FC power systems have tried to address cost and energy-efficiency requirements [3-13]. The choice of power-electronic topologies can be broadly categorized as push-pull and full-bridge based topologies. In [3-6], low cost push-pull topology for power levels > 1 kW is proposed. Push-pull based topology, by virtue of a low parts count, is a good candidate for a low-cost FC converter and can achieve an efficiency of 90% for low and medium power. However, at higher power it suffers from transformer flux imbalance and core-saturation problems. For current-fed topologies, the main limitation comes at power levels > 3 kW, where leakage inductance of the transformer poses a problem, unless soft switching is used. Further the limited allowable range of switch duty cycle also makes it difficult to track variations in the input voltage. In [7-13], full-bridge based FC inverter topologies are discussed. Because of the symmetrical transformer flux and equal electrical stress distribution, several variations of full-bridge inverter topologies have been found to be useful from the cost and efficiency point of view, especially when implemented for power levels greater than 3 kW. A 1.8 kW prototype of a boost converter followed by a two-stage DC/AC converter is discussed in [8]. The two-stage DC/AC converter comprises a full-bridge high-frequency (HF) inverter and a cycloconverter, both operating at the same switching frequency, is based on a novel multi-carrier PWM. A similar two-stage DC/AC converter is discussed in [12], which incorporates a zero-current switched cycloconverter; while the full-bridge HF inverter is switched with a fixed 50% duty cycle. An improved version of the prototype in [12], comprising a soft-switched sine wave pulse-width modulated (SPWM) full-bridge HF inverter followed by a cycloconverter (operating at line frequency) is proposed in [13]. Among all the low-cost FC inverters [3-13] which aim to achieve an efficiency of $> 90\%$, a maximum full-load efficiency of 87 % and 89% is demonstrated in [3] and [12] respectively.

We present, a low-cost and energy efficient PCS, which is capable of reducing the FC ripple current, and the voltage stress on the PCS. The front end of the PCS is a zero-ripple boost converter (ZRBC), which reduces the PCS input current ripple by a factor of five. A two-stage DC/AC converter comprising a soft-switched phase-shifted SPWM multilevel HF inverter and a line-frequency switched cycloconverter follows the ZRBC. The multilevel arrangement of the HF inverter switches reduces the voltage stress and cost of semiconductor switches. The cycloconverter is switched at AC line frequency based on the power-flow information and hence, it results in extremely low switching losses. Therefore, the heat-sinking requirement of

the cycloconverter switches is significantly reduced. In this report, we present the design and performance of the bidirectional fuel cell power conditioning system.

2. PROJECT DESCRIPTION AND APPROACH

This project utilized a team approach to develop and demonstrate this novel bidirectional fuel cell power conditioning system. The concept of this PES topology originated within Professor Mazumder's group at the University of Illinois Chicago (UIC) Power Electronics Research Center (PERC). An early embodiment of the device was based on a single directional (Fuel Cell to AC inverter) converter being developed at the PERC. Ceramtec has been a leading developer of Solid Oxide Fuel Cells (SOFC) for nearly twenty years, with many current SOFC programs including a key role in a DOE SECA CTP system analysis and modeling project led by Professor Mazumder. Ceramtec also has a key role in the Idaho National Laboratory's (INL) project under the DOE Nuclear Hydrogen Initiative (NHI) using SOFC stacks for high temperature steam electrolysis (HTE also known as reversible or regenerable fuel cell RFC). The common need for efficient, affordable and durable power electronics, capable of both sourcing power to the stack from the grid in RFC mode, and conditioning the SOFC power (DC-DC and DC-AC) to the load while taking care not to take the SOFC out of its optimal operating range was noted. The realization that with slight changes to the PES design under development at UIC, it could be made to move power to and from the stack as needed for a RFC/SOFC system, and the plans to test such a stack under the SECA CTP program provided a unique opportunity for a combined demonstration of the reversible power controller coupled to an operating SOFC/RFC stack.

After some bureaucratic delays within the organizations of these two teams, the UIC group made the required circuit modifications, and with a few iterations showed the desired performance and operational characteristics in bench testing at the UIC PERC. The completion of the prototype circuit was well timed to match the test schedule of a 25 cell stack being built at Ceramtec, for impedance testing and thermal electrochemical model validation for UIC under the SECA CTP program. The PES was designed and bench tested for a power level of 5kW, however the available stack size was only a few hundred Watts. As it was a 25 cell stack, the operating voltage was also considerably lower than the design voltage for the PES, so full load efficiency testing was done in the PERC laboratory.

The stack was started at Ceramtec in mid August. During the first week of its operation it was subjected to a battery of tests to probe its response to and interaction with the PES. Professor Mazumder, and his Ph.D. student Rajni Burra came to Ceramtec with several hundred pounds of instrumentation and the PES prototype, and spent a busy week of long days testing with the stack. The stack performance was excellent, as were the results obtained from the PES operation with the stack. The stack continued in RFC mode until reaching 800 hours of operation. Following that, a period of 200 hours of constant resistance load data was acquired. At approximately the 1000 hour mark, stack operation commenced a load profile shifting every 15 minutes from a low level constant resistance load to a high level constant voltage (using a switchmode DC-DC converter). It will continue in this mode through 2000 hours at the end of October.

An overview of the PES tests comprises the remainder of this section.

Steady State Measurements (5 kW Fuel Cell Mode): For the purpose of steady state and transient measurements at 5 kW, a programmable DC power supply (ARAGNTIX XDS80-62) was used. The programmable power supply can be tuned to imitate the fuel cell characteristics. Once the operation of the power electronics at full load condition was tested, all the power stage and controller parameters were fine tuned in order to ensure the optimum performance of the converter. Efficiency results were obtained and compared with the estimated figures. For the purpose of efficiency measurements, a resistive load was used (as shown in Figure A) and the inverter was operated at near unity power factor.

Transient Measurements (Fuel Cell Mode): For the transient measurements, a switched resistor was used to alternate between two predetermined load levels. The load was switched using a relay, which was controlled using a microcontroller PIC16F877A (as shown in Figure A).

Figure A: Test setup for inverter (FC) mode of operation and transient testing

Steady State Measurements (5 kW Electrolysis Mode): For the electrolysis mode of operation, an AC power supply is connected and to simulate the reversible fuel cell, a combination of the programmable DC power supply and a parallel resistor was connected as shown in the Figure B. The parallel combination of the DC power supply and the resistor imitates an RFC as it sinks current in electrolysis mode.

Figure B: Test setup for electrolysis (RFC) mode of operation

PES Validation on the SOFC Stack (Fuel cell and Electrolysis Mode): For the purpose of PES performance validation on the reversible SOFC stack, the PES was shipped to the Ceramtec test facility. An actual SOFC stack was used instead of the programmable DC supply shown in the above Figures A and B. However, since the 25 cell stack will operate from 12.5Vdc (peak power in SOFC mode) to 32Vdc (electrolysis mode at the thermal

neutral voltage), the validation was performed at approximately 200 watts for the fuel cell mode of operation and 400 watts in the electrolysis mode of operation.

3. PROJECT TASK PERFORMANCE

3.1. System Response (Ceramatec)

The PI, as noted and listed in the proposal, has published a number of papers in the field of SOFC modeling and performance analysis, using both highly detailed 3-D finite element models as well as closed form parametric analytical solutions. In the first week of June, a seminar was presented to team members at UIC to explain the relevant thermodynamic principles of SOFC/RFC operation and the resulting electrochemical and thermal performance characteristics of these devices as pertaining to their operation and interaction with the reversible PES.

Ceramatec has fabricated, assembled and tested over 400 SOFC stacks in a variety of SOFC research projects since the late 1980s. The 25-cell stack tested under this program was stack number 437 (25UIC437). Based on experimental results of stack tests immediately preceding stack 437, expected voltage-current (V-I) characteristics of a 25-cell stack were computed and communicated to UIC. These values were used to prepare the PES for operation in the lower voltage regime of a 25-cell stack compared with the PES design point SOFC voltage condition of approximately 72V (representative of stacks having 100 to 120 cells, depending on selected operating point).

3.2. RFC PES Fabrication and Testing (UIC)

3.2.1. Description of the PES

In this section, we describe a low cost PES, which is capable of operating over a wide power range, protects the fuel cell from the harmful ripple currents and reduces the voltage stress on the PES. The front end of the PES is a zero-ripple boost converter, which reduces the PES input switching current ripple by a factor of five. The ZRBC is followed by a 2-stage DC/AC converter comprising a soft-switched phase shifted SPWM multilevel HF inverter and a line frequency switched cycloconverter. The multilevel arrangement of the HF inverter switches reduces the voltage stress on the power semiconductors by half and reduces the cost of semiconductor switches. Therefore, for high voltage DC ($> 500\text{V}$) operation, such an arrangement would result in improved system reliability. The cycloconverter is switched at AC line frequency based on the power flow information and hence it results in extremely low switching losses. Therefore, the heat-sinking requirement of the cycloconverter switches is significantly reduced.

Fig.1: RFC Bidirectional PES (a) block diagram (b) circuit schematic.

A schematic of a 5 kW fuel-cell powered PES unit, shown in Fig.1, comprise (a) a DC/DC zero-ripple boost converter (ZRBC), which generates a 350 V DC at its output, and (b) a soft-switched, transformer isolated DC/AC inverter, which generates a 110 V AC at its output using the 350 V DC input. The multilevel arrangement of switches (S_1 - S_4) on the primary of the high-frequency (HF) transformer are modulated to create a HF, 2-level or 3-level square AC voltage and a pair of bidirectional switches on the secondary of the center tapped HF transformer are modulated to generate a 60 Hz sinusoidal AC at the output. The multi-level arrangement results in a reduced voltage stress across the switches, thereby, improving the reliability and facilitating the use of low cost switches. Multi-level arrangement of switches is particularly useful when the intermediate DC voltage greater than 500 V.

3.2.2.1. Operation of the Zero-Ripple Boost Converter (ZRBC)

Fig. 2 Modes of ZRBC operation (a) switch S is ON (b) switch S is OFF.

The ZRBC is a standard non-isolated boost converter, with the conventional inductor replaced by a zero-ripple inductor (ZRI). The ZRI is a two winding inductor; with primary winding conducting the DC input current and the secondary winding conducts the AC current. The secondary winding of the ZRI is connected to an external trimming inductor and a filter capacitor as shown in Fig. 1. Similar to the conventional inductor the ZRBC has two modes of operation as shown in Fig. 2.

Input Switching Current Ripple Reduction

The generalized reluctance model of the ZRI is shown in Fig. 3. The currents i_1 and i_2 are respectively the primary and the secondary AC currents, fluxes ϕ_1 and ϕ_2 are respectively the primary and the secondary leakage fluxes, and ϕ_m is the flux associated with the magnetic core. Using the reluctance model the expression for the input AC current is given by

$$i_1 - i_2 = \frac{\phi_o}{N_1^2 \left(\frac{1}{R'_m R_1} + \frac{1}{R'_m R_2} + \frac{1}{R_1 R_2} \right)} \left[n \left(\frac{1}{R'_m} + \frac{1}{R_2} \right) - \frac{1}{R'_m} \right] \quad (1)$$

where N_1 is the primary turns
 N_2 is the secondary turns

$n = N_2/N_1$ is the turns ratio

R'_m is the reluctance of the core including the air gap

R_1 is the primary leakage reluctance

R_2 is the secondary leakage reluctance

Fig. 3: Reluctance model of ZRI using an E-E core

From (2) the condition for the zero AC input current can be expressed as:

$$n = k = \frac{R_2}{R_2 + R'_m} \quad \text{and } n < 1 \quad (2a)$$

$$\text{where } R'_m = R_{g1} + \frac{R_{g2}}{2} + \frac{R_m}{4} \quad (R_{g1} \text{ and } R_{g2} \text{ are the air gap reluctances}) \quad (2b)$$

From (2a) and (2b), we observe that the condition for zero input current ripple depends on the choice and shape of the core, the turns ratio, and the coupling coefficient. Theoretically, the input zero-current ripple condition is valid for all values of $n < 1$, $k < 1$. However, because of tolerances and temperature variations, it may not be possible to adjust the secondary leakage reluctance to a very high degree of accuracy by only adjusting the air gap. Therefore, an external trimming inductance is used to achieve the zero-ripple condition.

Table 1: Effective reluctance expressions for commonly used coupled inductor cores

Core type	Expression
E-E (3 limbs and symmetrical outer limbs)	$R'_m = R_{g1} + \frac{R_{g2}}{2} + \frac{R_m}{4}$
E-I (3 limbs and symmetrical outer limbs)	$R'_m = R_{g1} + \frac{R_{g2}}{2} + \frac{R_m}{4}$
U-U	$R'_m = R_{g1} + R_{g2} + R_m$
U-I	$R'_m = R_{g1} + R_{g2} + R_m$
Gapped Toroid	$R'_m = R_{g1} + R_m$

3.2.1.2. Operation of the DC/AC Converter

In this section, the ZVS operation of the DC/AC converter is discussed. A trade off between the achievable ZVS range and duty ratio loss is performed towards the end of this section. Such a study is necessary for energy efficient design of transformer-isolated topologies.

Fig. 4(a) and 4(b) shows the schematic waveforms of the five operating modes of the HF converter for a positive primary current. Modes 2 and 4 show the ZVS turn-on mechanism for switches S4 and S3 respectively. The AC/AC stage comprises a single-phase cycloconverter and an output LC filter. The cycloconverter has two bi-directional switch pairs Q1 and Q2 and Q3 and Q4 for single-phase outputs. Unlike conventional control scheme [12], which modulates the switches at HF, the proposed cycloconverter operates at line frequency. The switches are commutated at high frequency only when the polarities of output current and voltage are different [13]. Usually this duration is very small and therefore, the switching loss of the AC/AC cycloconverter is considerably reduced compared to the conventional control method.

Fig. 4: (a) Schematic waveforms for the inverter operation (b) schematic waveforms for the HF inverter (c) overall control scheme for the HF inverter

Inverter Mode of Operation

In this section, five modes of the DC/AC converter operation are discussed for positive primary current. A set of five modes exists for a negative primary current as well.

Fig. 5: Topologies corresponding to the five operating modes of the DC/AC converter for positive primary current and for power flow from the input to the load.

Mode 1 (Fig. 5(a)): During this mode, switches S1 and S2 of the HF inverter are on and the transformer primary current I_{pri} is positive. The output current I_{out} is positive and flows through the bidirectional switch pair Q1 and Q2 the output filter, and the center-tap of the transformer secondary. Switches S3 and S4 and Q3 and Q4 are turned off during this interval.

Mode 2 (Fig. 5(b)): At the beginning of this interval the gate voltage of the switch S1 undergoes a high-to-low transition. As a result, the output capacitance of S1 begins to accumulate charge

and at the same time the output capacitance of switch S4 begins to discharge through the external fly capacitor (C_{fly}). Once the voltage across S4 goes to zero, it is can be turned on under ZVS. The transformer primary current I_{pri} and the output current I_{out} continue to flow in the same direction. Switch S2 and the bidirectional switch pair Q1 and Q2 are ON while S3 and S4 and Q3 and Q4 are OFF. This mode ends when the switch S1 is completely turned off and its output capacitance is charged to $V_{in}/2$.

Mode 3 (Fig. 5(c)): This mode initiates when S1 turns off. The transformer primary current I_{pri} is still positive, and free wheels through the diode D1 as shown in Fig. 5(c). Also the output current continues to flow in the same direction as in Mode2. Mode3 ends at the commencement of turn off S2.

Mode 4 (Fig. 5(d)): At the beginning of this interval, the gate voltage of S2 undergoes a high to low transition. As a result of this the output capacitance of S2 begins to accumulate charge and at the same time the output capacitance of switch S3 begins to discharge as shown in the Fig. 5(d). The charging current of S2 and discharging current of S3 together add up to the primary current I_{pri} . The transformer current makes a transition from positive to negative. Once the voltage across S3 goes to zero, it is turned on under ZVS. The output current flows in the same direction as in Mode3, but makes a rapid transition from the bidirectional switches Q1 and Q2 to Q3 and Q4 and during this process I_{out} splits between the two secondaries of the transformer and flows through Q1 and Q2 and Q3 and Q4. Mode 4 ends when the switch S2 is completely turned off and its output capacitance is charged to $V_{in}/4$. At this point, it is necessary to note that since S1 and S2 are off simultaneously, each of them support a voltage of $V_{in}/4$.

Mode 5 (Fig. 5(e)): This mode starts when S2 turns off. The primary current I_{pri} is positive, and while the output current is positive as shown in Fig. 5(e).

Rectifier Mode of Operation

The schematic waveforms and the controller structure for the rectifier mode operation are shown in Fig. 6(a) and Fig. 6(b). For the rectifier mode of operation, input AC-current mode controller is implemented and is the current injected at near unity power factor as shown in Fig. 6(a). Therefore, no changes need to be made to the logic operator block and the controller structure of Fig. 4(c).

(a)

(b)

Fig. 6: Schematic waveforms for the rectifier operation (b) schematic waveforms for the HF inverter (c) overall control scheme for the rectifier mode of operation

ZVS Range of the HF Inverter

For the HF inverter, the SPWM results in the loss of ZVS for each switch, twice in every line cycle. The extent of loss of ZVS is a function of the output current I_{out} (3) and the load power factor ($\cos\phi$). Equation (4) is the expression of the available ZVS range as a percentage of the line cycle.

$$I_{out} = \frac{\sqrt{2}P_{in}}{V_o \cos \phi} \quad (3)$$

$$\frac{t_{ZVS}}{t_{LineCycle}} = \frac{2}{\pi} \sin^{-1} \left(\left(\frac{1}{4} \frac{V_{in}^2 \left(\frac{4}{3} C_{oss} + \frac{1}{2} C_T \right)}{I_{out}^2 L_{lk}} \right)^{1/2} \right) \quad (4)$$

where,

P_{in} is the input power

V_o is the output voltage

V_{in} is the input voltage

L_{lk} is the leakage inductance of the primary transformer

C_{oss} is the effective output capacitance of the MOSFETs of the HF inverter

C_T is the equivalent parasitic capacitance of the HF transformer

$t_{LineCycle}$ is the line-cycle time period (i.e. for a 60 Hz line frequency it is 16.67 ms)

3.2.2. Device Fabrication

The fabrication of the prototype was carried out in 3 stages. A sub-scaled 1 kW first generation prototype was fabricated to (a) verify the concept of operation, (b) estimate the electrical and thermal stresses on the power stage components, and (c) fine tune the analog controller components. A first generation full scale prototype was fabricated to demonstrate the operation at a full load of 1 kW. Following that a first generation of 5 kW was designed and fabricated. The 1 kW and 5 kW prototypes were fabricated on commercially available 2 oz copper boards. The copper boards designed for the second generation prototype were found to be resistive and were not suitable for testing beyond 3 kW. The efficiency decreased significantly below 90% at 2.2 kW of output power. Therefore, a 2nd generation 5 kW prototype was fabricated on commercially available 4 oz printed circuit boards (PCBs). However, no changes were made to the board layouts. The schematics, and the component listings for the 2nd generation 5 kW prototype are shown in Section 3.2.5 and Appendix I respectively.

3.2.2.1. Sub-scaled (1 kW) First Generation Prototype

Specifications: FC stack voltage: 72-150 V; Output voltage: ~ 110 V, signal phase, 60 Hz; Output power: 1 kW; Frequency (DC/DC): 20 kHz; Frequency (DC/AC): 20 kHz; Overall efficiency: $> 90\%$

(a)

Fig. 7: Working prototype of the proposed PES (a) complete setup (b) 2 Module ZRBC (c) DC/AC converter (d) Zero ripple inductor (ZRI).

3.2.2.2. First Generation 5 kW Prototype

Specifications: FC stack voltage: 72-150 V; Output voltage: ~ 110 V, signal phase, 60 Hz; Output power: 5 kW; Frequency (DC/DC): 20 kHz; Frequency (DC/AC): 20 kHz; Overall efficiency: $> 90\%$

(a)

(b)

Fig. 8: 5 kW working prototype (a) the complete setup (b) magnetics for the 5 kW PES obtained from Inplot Electronics Inc.

3.2.3. Debugging/Design Optimization Cycle

Leakage optimization for Energy Efficient Design: From equation (4), it can be concluded that for a given output current larger leakage is necessary for improving the ZVS range of the HF inverter switches. In here, we show that large values of leakage inductances result in a

significant reduction in the duty ratio, resulting in reduced transformer and overall DC/AC converter efficiency. The effective duty ratio for the DC/AC converter is expressed as

$$D_{eff} = D - D_{CH} + D_{ZVS} \quad (5a)$$

$$D_{eff} = \frac{2t_{on}}{T_s} - \frac{2}{T_s} \frac{2L_{lk}NI_{out}}{V_{in}} + \frac{2}{T_s} \frac{V_{in}C}{2NI_{out}} \quad (5b)$$

where

t_{on} is time during which a non zero voltage is applied across the transformer primary
 T_s is the switching time period.

The magnitude of D_{ZVS} is usually very small as compared to the D_{CH} .

$$D_{eff} = 2\left(\frac{t_{on}}{T_s} - \frac{2L_{lk}NI_{out}}{T_s V_{in}} + \frac{V_{in}C}{2T_s NI_{out}}\right) \quad (5c)$$

$$V_{out} = D_{eff} V_{in} \quad (5d)$$

From the second term in expression (5c), it is obvious that a higher leakage improves the ZVS operating range, but significantly degrades the effective duty ratio. Further, at higher power levels a significant duty ratio loss can occur even at low values of leakage. Therefore, transformer design and winding arrangement plays a key role in energy efficient design of the isolated DC/AC converter.

Fig.9: (a) Parametric plot showing the percentage ZVS achievable versus load current for different values of leakage inductances (b) Transformer efficiency versus output power for various values of leakage inductances

The ZVS range is predicted using equation (4) shows that for a given average power the load power factor does not have much of an impact on the duration of ZVS operation obtained as a percentage of the time period line cycle. Fig.9(a) is the plot for available ZVS range for various values of leakage inductances. It can be seen that for low values of leakage inductance the ZVS is lost for a large output power range (upto 40% loss in ZVS for 100 nH of leakage). However, such low values of leakage may not be achievable for a 20 kHz transformer design. Therefore, for leakage values of 500 nH and above significant reduction in the turn-on losses can be achieved over the entire range of operation. Fig.9(b) is plotted for 6 different values of

leakage inductances, using expression 9(d) for output voltage of the DC/AC converter. It is seen that with increase in leakage and output power, the efficiency of the transformer degrades significantly. Therefore, it is necessary to design and wind a transformer for very low leakage inductance values. Two possible winding arrangements are shown in Fig.10 and obtained values of leakage inductances for Figs.10(a) and 10(b) are 1.2 μ H and 450 nH respectively.

3.2.3.1. Second Generation 5 kW Prototype

Specifications: FC stack voltage: 72-150 V; Output voltage: $\sim$ 110 V, signal phase, 60 Hz; Output power: 5 kW; Frequency (DC/DC): 20 kHz; Frequency (DC/AC): 20 kHz; Overall efficiency: > 90 %

(a)

(b)

(c)

Fig. 10: (a) 5 kW working prototype experimental setup. Two different winding arrangements for a 5 kW, 25 kHz isolation- transformer using P-49925-UC, Ferrite Core (b) Primary and

secondary windings on the same leg using a AWG 10 solid copper wire. The leakage inductance was measure to be 1.2 μH (c) Primary and secondary windings distributed over the entire length of the core using a two strand AWG 14 copper wire. The leakage inductance was measure to be 450 nH.

3.2.4. Prototype Testing

3.2.4.1 Performance of ZRBC

(b)

(c)

Fig. 11: Illustration of the Zero-ripple inductor used in the 1st generation 1 kW PES prototype. (a) Simulated result showing the performance of the zero-ripple inductor. (b) The current split between the AC winding (secondary winding N_s in Fig. 1(b)) and the DC winding (primary winding N_p in Fig. 1(b)). (c) Experimentally observed input ripple current variation in the DC winding with variation in external inductance.

Fig. 12: ZRBC and conventional boost input current ripple performance with load variation (a) input peak to peak AC current comparison between the conventional boost and the ZRBC for an optimum value of external inductance (b) fuel cell hydrogen utilization for variation in input current ripple.

Fig. 12 shows the percentage of ripple reduction achieved by the coupled inductor as the external inductance is tuned. As evident from the Fig. 12(a) the performance of the coupled inductor was tested at the boundary of continuous and discontinuous conduction, which is the maximum ripple condition. For an external inductance of $7.6 \mu\text{H}$ a minimum ripple of 20% of the switching ripple current flows in the DC winding of the coupled inductor. In practice it is not possible to obtain the exact values of leakage inductances; therefore, the use of an external tuning inductor is inevitable.

Such a reduction in fuel cell current ripple will possibly enhance the life of the fuel cell. In order to study the effect of load variation on the fuel cell output current ripple, the load was varied from full load to 20% load and the peak to peak ripple current sharing between the AC and DC windings is plotted in Fig. 12(a). A peak to peak current ripple of 2.7 A is drawn from the fuel cell while a similar curve for a boost converter with an equivalent inductor results in approximately 18 A of peak to peak current ripple.

Even at very low load conditions the ZRBC draws a continuous current from the fuel cell as opposed to the conventional boost which would be forced to operate in discontinuous conduction mode. Fig. 12(b) is the plot for the fuel cell hydrogen utilization for a fixed fuel flow rate for peak input currents for different load conditions. The values of the hydrogen utilization are obtained using the model described in [14 and 15]. Clearly, the use of the zero-ripple inductor will result in a reduced variation in fuel utilization and hence it prevents the thermal cycling of the fuel cell electrodes.

Fig. 13: Illustration of the Zero-ripple inductor used in the 3rd generation 5 kW PES prototype showing approximately 5-fold reduction in the current ripple. (a) ZRBC output voltage (Top, 100 V/div), input current (with an inductor $N = N_1 + N_2$) (Center, 100 V/div), and the switch (S in Fig. 1(b)) gating pulses (Bottom, 5 V/div). (b) ZRI output voltage (Top, 100 V/div), input current (with the ZRI) (Center, 100 V/div), and the switch (S in Fig. 1(b)) gating pulses (Bottom, 5 V/div).

Table 1: Parameters for a ZRI and an equivalent boost inductor for the 5 kW prototype

ZRI Parameters	Measured Values (ZRBC)	Measured Values (Conventional Boost)
Turns	$N_p=73, N_s=70$	$N = N_p + N_s = 143$
L (μH)	-	1192
L_{11} (μH)	298	-
L_{22} (μH)	273.20	-
M (μH)	277.23	-
L_1 (μH)	9.45	-
L_2 (μH)	6.84	-
L_M (μH)	288.55	-
k	0.9716	-
C_1 (μF)	1000	-
r_1 (Ω)	0.06	-
C_2 (μF)	110	110
r_2 (Ω)	0.06	0.06

Fig. 14: ZRBC start-up transient (for an input voltage of 80 V) showing the output voltage (Top, 100 V/div, 50 ms/div) and input current (Bottom, 10 A/div, 50 ms/div)

3.2.4.2. Performance of DC/AC: For the HF inverter, the PSZVS SPWM is implemented using the UC3875. The gating pulses for all four switches and the transformer primary current and voltage waveforms are shown in Figs. 15(a) and 15(b) respectively.

(a)

(b)

Fig. 15: Illustration of the HF inverter operation; (a) gating pulse for HF inverter switches (b) transformer primary voltage and current waveforms.

Fig. 16: Illustration of the AC/AC converter operation; (a) gating pulse for cycloconverter switches (b) PCS output voltage and current (top), reactive power information (center), gating pulse for switch Q1 (bottom) (c) an expanded view of the rectangular portion of plot (b).

Fig.17(a) shows the operation of the cycloconverter at near unity power factor. It can be clearly seen that during active power transfer the converter is switching at line frequency and during the reactive power transfer it switches at the 20 kHz. Such a switching mechanism results in a significant reduction in the switching losses of the cycloconverter. Fig.17(a) shows the output waveforms at the rated voltage of ~ 162 V peak and output current is 50 A peak. Fig.17(b) is the transient performance of the proposed PCS.

Fig. 17: (a) PCS output voltage and current waveforms during steady state operation. (b) PCS output voltage and current waveforms for a load transient waveforms from 1000 W to 4500 W and back to 1000 W; output voltage (Top, 100 V/div 40 ms/div), output current (bottom, 25 A/div 40 ms/div).

3.2.5. Manufacturing Cost Analysis

ZRBC COMPONENTS

Designator	Manufacturer	Manufacturer Part #	Description	Cost /Unit	Extended Cost/ units
C1	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C2	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C3	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C4	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C5	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C6	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C7	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C8	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C9	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C10	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C11	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C12	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C13	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C14	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C15	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C16	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C17	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C18	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C19	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C20	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C21	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C22	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C23	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C24	Murata Electronics	GRM32NR71H564KA01I	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C25	Panasonic - ECG	EET-HC2D102BA	1000 uF, 200 V Polarized Capacitor	2.37000	0.93200
C26	Panasonic - ECG	EET-HC2D102BA	1000 uF, 200 V Polarized Capacitor	3.55000	0.93200
C27	Panasonic - ECG	EET-HC2D102BA	1000 uF, 200 V Polarized Capacitor	3.55000	0.93200
C28	Panasonic - ECG	EET-HC2D102BA	41000 uF, 200 V Polarized Capacitor	3.55000	0.93200
C29	Panasonic - ECG	EET-UQ2C102BA	1000 uF, 160 V Polarized Capacitor	3.55000	1.44045
C30	Panasonic - ECG	EET-UQ2C102BA	1000 uF, 160 V Polarized Capacitor	3.55000	1.44045
C31	Panasonic - ECG	EET-UQ2C102BA	1000 uF, 160 V Polarized Capacitor	3.55000	1.44045
C32	Panasonic - ECG	EET-UQ2C102BA	1000 uF, 160 V Polarized Capacitor	3.55000	1.44045
C33	Panasonic - ECG	EEU-FC1H100	10 uF, 50 V Polarized Capacitor	0.28000	0.05800
C35	Panasonic - ECG	EEU-FC1H100	10 uF, 50 V Polarized Capacitor	0.28000	0.05800
CURRENT SENSE1	LEM	LTS 25-NP	TRANSDUCER CURRENT CLOSE L 25A	20.20	5.21
CURRENT SENSE2	LEM	LTS 25-NP	TRANSDUCER CURRENT CLOSE L 25A	20.20	5.21
CURRENT SENSE3	LEM	LTS 25-NP	TRANSDUCER CURRENT CLOSE L 25A	20.20	5.21
CURRENT SENSE4	LEM	LTS 25-NP	TRANSDUCER CURRENT CLOSE L 25A	20.20	5.21
D1	Infineon Technology	SDT12S60	SCHOTTKY 600V 12A TO220-2-	13.69400	3.2
D2	Infineon Technology	SDT12S60	SCHOTTKY 600V 12A TO220-2-	13.69400	3.2
D3	Infineon Technology	SDT12S60	SCHOTTKY 600V 12A TO220-2-	13.69400	3.2
D4	Infineon Technology	SDT12S60	SCHOTTKY 600V 12A TO220-2-	13.69400	3.2
GD1	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8DI	1.40000	0.97000

GD2	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8DI	1.40000	0.97000
GD3	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8DI	1.40000	0.97000
GD4	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8DI	1.40000	0.97000
JP1			Header, 2-Pin	0.78	0.24
JP2			Header, 20-Pin, Dual row	1.5	0.75
L1	Inglot				2.34
L2	Inglot				2.34
L3	Inglot				2.34
L4	Inglot				2.34
OP1	Agilent Technologie	HCPL-2630	OPTOCPLR 2CH LOG-OUT 10MBI DIP	2.81000	1.62500
OP2	Agilent Technologie	HCPL-2630	OPTOCPLR 2CH LOG-OUT 10MBI DIP	2.81000	1.62500
Q1	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q2	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q3	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q4	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
R1	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R2	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R3	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R4	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R9	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R10	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R11	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R12	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R13	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R14	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R15	Yageo	CFR-25JR-2K0	1 k, Resistor	0.00894	0.00426
R16	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R17	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R18	Yageo	CFR-25JR-2K0	1 k, Resistor	0.00894	0.00426
R19	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R20	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R21	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R22	Yageo	CFR-25JR-2K0	2 k, Resistor	0.00894	0.00426
R24	Yageo	ERD-S2TJ1R5V	1.5 Ω , Resistor	0.00683	0.00420
R25	Yageo	ERD-S2TJ1R5V	1.5 Ω , Resistor	0.00683	0.00420
R26	Yageo	ERD-S2TJ1R5V	1.5 Ω , Resistor	0.00683	0.00420
R27	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R28	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R31	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R32	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R33	Yageo		1.5 Ω , Resistor	0.00894	0.00426
T1	Inglot	Magnetics	# 58867-A2 ($\mu=60$) x 2		4.23
T2	Inglot	Magnetics	# 58867-A2 ($\mu=60$) x 2		4.23
T3	Inglot	Magnetics	# 58867-A2 ($\mu=60$) x 2		4.23
T4	Inglot	Magnetics	# 58867-A2 ($\mu=60$) x 2		4.23

HF INVERTER COMPONENTS

Designator	Manufacturer	Manufacturer Part #	Description	Cost /Uni	Extended C 5000 uni
C2	Panasonic - ECG	ECO-S2DP221BA	220 uF, 200 V Polarized Capacito	2.37000	0.93200
C4	Panasonic - ECG	ECO-S2DP221BA	220 uF, 200 V Polarized Capacito	2.37000	0.93200
C5	Panasonic - ECG		2 uF, 600 V		0.4
C7	Panasonic - ECG		2 uF, 600 V		0.4
C21	Murata Electronic	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C23	Murata Electronic	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C39	Murata Electronic		2 uF, 50 V, Bypass Capacitor		
C41	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C44	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C47	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C49	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C52	Murata Electronic		2 uF, 50 V, Bypass Capacitor		0.07
D1	International Rectif	32CTQ030	Schottky Rectifier		2.1
D2	International Rectif	32CTQ030	Schottky Rectifier		2.1
D5	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D6	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D7	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D8	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D9	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D10	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D11	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
D12	Fairchild	1N5820RLOSCT	DIODE SCHOTTKY 20V 3A DO20	0.36400	0.17290
J1	Jumper	Jumper Wire	RAD-0.1		
JP2	Header 10	Header, 10-Pin	HDR1X10		0.20
Q1	International Rectif	IRFB260N	DIODE MOSFET 200V 56A TO-220	3.90000	1.57300
Q2	International Rectif	IRFB260N	DIODE MOSFET 200V 56A TO-220	3.90000	1.57300
Q3	International Rectif	IRFB260N	DIODE MOSFET 200V 56A TO-220	3.90000	1.57300
Q4	International Rectif	IRFB260N	DIODE MOSFET 200V 56A TO-220	3.90000	1.57300
R42	Yageo[L2]	RC0603FR-0710RL	10 Ω , Resistor	0.00480	0.00216
R43	Yageo	CFR-12JR-11K	11 k, Resistor	0.01495	0.00713
R44	Yageo	CFR-12JR-11K	11 k, Resistor	0.01495	0.00713
R45	Yageo	CFR-25JR-10R	10 Ω , Resistor	0.00894	0.00426
R46	Yageo	CFR-12JR-11K	11 k, Resistor	0.01495	0.00713
R47	Yageo	CFR-12JR-11K	11 k, Resistor	0.01495	0.00713
R70			Short Circuit		
R71			Short Circuit		
R90	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R93	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R96	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
R97	Res1	Resistor	AXIAL-0.4		
R101	Ohmite	OA101K	RESISTOR 100 OHM 1W CARB CC	1.92000	1.23000
T1	Inglot	Magnetics Core	# P-49925-UC		5.41
T2	C&D Technologie	1003 YYWW	2:1:1 Pulse Transformer, Primary Inductance 12 mH, 400 Vus		2.13

T3	C&D Technologie	1003 YYWW	2:1:1 Pulse Transformer, Primary Inductance 12 mH, 400 Vus		2.13
U3	Texas Instruments	UC3875N	3 PHASE SHIFT CONTROLLER 20	9.70000	5.91700

CYCLOCONVERTER COMPONENTS

Designator	Manufacturer	Manufacturer Part #	Description	Cost /Unit	xtended Cost/ units
C1	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C2	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C3	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C4	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C5	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C6	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C7	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C8	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C9	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C10	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C11	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C12	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C13	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C14	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C15	Cap	Capacitor	AC Capacitor		
C16	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C17	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
C18	Panasonic - ECG	ECK-D3A102KBP	1 nF, 1 kV, Snubber Capacitor	0.29800	0.10200
C19	Murata Electronics	GRM32NR71H564KA01	500 nF, 50 V, Bypass Capacitor	0.12960	0.09576
GD1	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8D	1.40000	0.97000
GD2	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8D	1.40000	0.97000
GD3	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8D	1.40000	0.97000
GD4	Microchip	TC4420CPA	IC MOSFET DRIVER 6A HS 8D	1.40000	0.97000
JP1	Header 10X2	Header, 10-Pin, Dual row	HDR2X10		0.20
L1	Inglot		Laminated 60 Hz		10.23
OP1	Agilent Technology	HCPL-2630	PTOCPLR 2CH LOG-OUT 10MB DIP	2.81000	1.62500
OP2	Agilent Technology	HCPL-2630	PTOCPLR 2CH LOG-OUT 10MB DIP	2.81000	1.62500
Q1	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q2	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q3	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q4	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q5	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q6	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q7	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
Q8	IXYS	IXFX55N50	MOSFET N-CH 500V 55A PLUS-2	23.81000	4.1
R1	Yageo	CFR-25JR-5R1	5 Ω , Resistor	0.00894	0.00426
R2	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R3	Ohmite	OA101K	ESISTOR 100 OHM 1W CARB CO	1.92000	1.23000
R4	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713
R5	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713

R6	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R7	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R8	Ohmite	OA101K	ESISTOR 100 OHM 1W CARB C0	1.92000	1.23000
R9	Ohmite	OA101K	ESISTOR 100 OHM 1W CARB C0	1.92000	1.23000
R10	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713
R11	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713
R12	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R13	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R14	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00426
R15	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713
R16	Ohmite	OA101K	ESISTOR 100 OHM 1W CARB C0	1.92000	.23000
R17	Yageo	CFR-25JR-5R1	5 Ω , Resistor	0.00894	0.00426
R18	Ohmite	OA101K	ESISTOR 100 OHM 1W CARB C0	1.92000	1.23000
R19	Yageo	CFR-25JR-5R1	5 Ω , Resistor	0.00894	0.00426
R20	Ohmite	OA101K	ESISTOR 100 OHM 1W CARB C0	1.92000	1.23000
R21	Yageo	CFR-25JR-1K0	1 k, Resistor	0.00894	0.00426
R22	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713
R23	Yageo	CFR-12JR-2K0	2 k, Resistor	0.01495	0.00713
R24	Yageo	CFR-25JR-5R1	5 Ω , Resistor	0.00894	0.00426

The extended cost estimates obtained are for 5000 units. The total cost of the PCBs is \$ 15.26 for 5000 units. The lumped cost the DC/DC controller and DC/AC controller components approximately cost \$ 9.0 and \$ 12.5.

3.3. Device Testing with RFC Stack (UIC ñ PES, Ceramtec- Stack)

3.3.1. Stack Construction and Performance Characterization

Stack 25UIC437 was constructed for the SECA CTP, for testing of stack impedance, interaction of stack and PES, model validation, and load profile testing. The cells are 10x10 cm with a 64cm² active electrode area. The electrolyte, approximately 180 μ m thick, is produced at Ceramtec by tape casting and sintering of commercially available scandia stabilized zirconia powder. The electrodes are proprietary compositions which are synthesized at Ceramtec and applied by screen printing and sintering operations. The interconnects are fabricated using a ferritic stainless alloy which is treated using a process developed by Ceramtec over the past 15 years in a number of programs. The stack was installed in a test stand fitted with the needed reactant feed measurement, control and preheat systems. A thin gage thermocouple was installed near the center of the stack by insertion into an interconnect channel on the air exhaust face of the stack. Voltage tap leads were similarly provided every 5 cells. Voltages (overall stack and 5 cell groups), current, temperatures (air inlet plenum which acted as the controller process value measurement, furnace enclosure, and stack core) were measured and recorded using a custom developed LabView application. Steam generation for electrolysis mode was by means of saturation of a hydrogen/nitrogen fuel stream in a controlled temperature water bubbler. Photographs of cell and interconnect components, a similar 22 cell stack (tested in RFC mode at INL in July), and its installation in the test fixture are shown in Figure 18.

Figure 18. SOFC stack, components and installation photos.

The initial performance is shown in a V-I sweep from electrolysis through open circuit to fuel cell mode in Figure 19. The area specific resistance (ASR) in RFC mode was 1.3 ohm-cm^2 at an average core temperature of 815°C . The fuel cell ASR was lower (1.0 ohm-cm^2) due to the higher operating temperature resulting from fuel cell operation and limited cooling air flow in a test station originally designed for 10 cell stacks. Note the smooth and continuous transition from one mode to the other about the open circuit (zero current) point indicating the reversibility of the SOFC/RFC device. The period of steady operation (hours 816-1005) under a fixed resistance load, and a segment of the load profile data (hours 1005-1275 as of 08 Oct).

Figure 19. 25-cell stack initial V-I characteristics

Figure 20. Initial 800 hours of stack operation, predominantly in RFC mode

Figure 21. Steady state operation period under fixed resistance load

Figure 22. Expanded segment of load profile data

3.3.2. PES Performance Characterization

Fig. 23(b) shows a comparison of the energy efficiency between the estimated and the measured values over the entire range power range for all the three prototypes that were fabricated. The 1st and 2nd generation prototypes show a efficiency of 88% at 1 kW and 92% at 2 kW respectively. The 3rd generation prototype achieved an overall efficiency of 92.1% at full load and a maximum efficiency of 92.6% at 3 kW. The 5 kW PES maintains a flat efficiency for more that 60% of the entire operating range. Also the individual subsystem efficiencies are close to the estimated values. The mismatch in efficiency is because of unaccounted parasitic resistive loss, winding resistance of the magnetic components and tare losses. All the measured efficiency results are accurate within $\pm 1.3\%$.

Fig. 23: Efficiency comparison of measured and estimated values for individual subsystems (a) 1st generation prototype (b) 2nd generation prototype and (c) 3rd generation prototype

3.3.3. PES-Stack Interaction Effects

Fig. 24: PES test setup powered by SOFC stack at Ceramatec Inc.

Fig. 25: (a), (b) and (c) SOFC Performance in electrolysis/regenerative mode and the PES operating in the rectifier mode (d) SOFC stack temperature variation for the current/voltages in (a), (b) and (c).

Fig. 25: Variation of the FC output voltage (Ch: A, top, 5 V/div) and current (Ch: D, bottom, 5 A/div) when operated in FC mode and the PES operating in inverter mode.

3.3.3.1. Effect of Low Frequency Ripple

The ripple with frequency on the order of 60 to 200 Hz is defined as the low-frequency ripple in terms of power electronics. An inverter converts DC to AC voltages at 50 or 60 Hz, and a low-frequency (100 or 120 Hz) ripple current is drawn from the PSOFC stack. Fig. 26 shows the effect of low frequency ripple on the operable fuel utilization of a 5 kW PSOFC stack. The increasing magnitude of the low frequency ripple increases the peak of the current drawn from the stack, leading to an increase the peak of the hydrogen utilization of the cell. Therefore, the operating fuel utilization of the cell needs to be lowered so as to avoid the low reactant condition inside the PSOFC stack. Hence, the efficiency of the stack decreases with increase in the magnitude of the ripple current.

Fig. 26: Effect of ripple on the PSOFC stack efficiency.

Because the frequency of the ripple on the current, (120 Hz), is very high as compared to the thermal time constant of the cell, the temperature rise in the stack due to ripple is minimal as can be shown in Fig. 27. A further study on the current ripple is being carried out to quantify the electrochemical effects on the PSOFC and the ageing.

Fig. 27: Effect of low frequency current ripple magnitude on the mean PSOFC temperature.

3.3.3.2. Effect of the Load Power Factor

The power factor of the load dictates the phase lag or lead between the voltage across the AC load and the current through it. At lower lagging power factors, the AC load draws both reactive and active power from the source. This unnecessarily increases the burden on the PSOFC and degrades its performance by decreasing the available power from the stack.

Fig. 28 shows the effect of load power factor on the hydrogen utilization at constant active output power to the utility. It shows that the fuel utilization ripple and the mean fuel utilization increase at lower power factors. However, since the active power output into the load is kept constant; this indicates that the external loss in the PES increases with lower power factor. At lower power factors, the additional loss is mainly attributed to the additional circulating current in the circuit as shown in Fig. 29(a).

Fig. 28: Hydrogen utilization ripple of the PSOFC stack at various load power factors.

Fig. 29: Effect of variation of load power factor on a) average PSOFC stack current, b) current ripple magnitude.

Fig. 29(b) shows that the magnitude of the current ripple increases at lower power factor. As described in Section 1.1, the increase in the current ripple degrades the efficiency of the stack.

3.3.3.3. Effect of the Load Transients

We analyze the effects of load transient on the performance and durability of the PSOFC stack. Fig. 30(a) shows the drop in the output voltage of the stack, due to the load transient. The voltage drop is attributed to the enhanced polarization losses owing to a surge in the current density. Because the response time of the BOPS is significantly lower than that of the PES/PSOFC stack, the input fuel-flow rates of the stack will not change soon after the load-transient. This leads to sudden increase in fuel utilization inside the PSOFC stack so as to attain a new electrochemical steady state. Fig. 26(b) shows that, hydrogen (fuel) utilization increases very sharply immediately after the load transient, and decreases at a slower rate in pace with the increase in the fuel supply by the BOPS. The peak in the hydrogen utilization is attributed to the period of inactivity of the BOPS.

Fig. 30: Current transient (10 A to 85 A) which results in (a) a sudden drop in the PSOFC stack output voltage and (b) a sudden surge in the hydrogen utilization.

An increase in the heat rate (Q) (because of increased rate of the exothermic reaction) and almost no change in flow rates in the stack (until the BOPS flow rates adjust to the increased demand of fuel and air), increases the fuel-cell temperature with time. However, the thermal time constant of the stack being much larger than that of the SOFC electrochemistry/PES time constant, the increase in the cell temperature just after the load transient is minimal, And the mean temperature increases to a higher thermal steady state value after approximately 600 seconds as shown in Fig. 31.

Fig. 31: Variation of mean PSOFC temperature with time

The analysis here provides a detailed insight into the effects of various electrical-feedback effects on the planar solid-oxide fuel cell (PSOFC) stack and the PSOFC power conditioning system (PCS) as a whole. This allows the determination of the required response time of the BOPS, and power buffering mechanism and control to avoid any degrading effect on the PCS. Specifically, we conclude the following:

- The no-load to full-load transient increases the current density abruptly and immediately. The higher level of current density increases the fuel utilization and the polarization voltage leading to a drop in the stack voltage;
- The thermal time constant of the PSOFC stack is very high and hence takes a long time to reach a steady-state after any load transient.
- Lower power factor of the load increases the fuel utilization of the stack unnecessarily, to cater to the loss due to the circulating AC current in the circuit. This again reduces the efficiency of the stack by increasing the current ripple magnitude.
- The higher ripple current magnitude decrease the operating fuel utilization of the stack, and hence, lowers the efficiency of the stack.

4. Project Results Supporting Economic and Environmental Benefits

The economic and environmental benefits of this technology in the envisioned application are contingent on the emergence of fuel cell and RFC hydrogen generation devices from R&D laboratories into mainstream commerce. The low cost and high efficiency of the design are in line with the aggressive DOE targets. At the projected costs, PES cost will not be a barrier to the commercialization of FC/RFC technologies.

The low ripple characteristics of this topology enable operation of the FC/RFC at optimal conditions, since the RMS and instantaneous peak current values are practically identical. This in turn allows higher power operation at higher values of mean fuel utilization (efficiency) with less concern for degradation induced by localized and or transient reactant depletion conditions that can adversely affect the electrode state.

RFC technology has the potential to generate hydrogen from surplus renewable energy sources that are typically 'use or lose', such as wind, concentrator photovoltaic (CPV), non-storage hydro, as well as advanced nuclear energy systems. Energy produced by such carbon free sources displaces CO₂ emissions from coal, oil or gas fired generation at the rate of 8 metric tons per kW-year. More efficient conversion of carbon-based fuels to electric power using SOFC systems can reduce the CO₂ emissions rate by 2-3 tons/kW-year.

5. Project Results Supporting Commercialization - Market Potential

While the immediate market for a bi-directional PES product designed for SOFC/RFC is limited to developers and demonstration sites, other current markets may exist. There is a rather large market for inverters and charge controllers for use with solar PV systems, in both stand alone (grid independent) and grid inter-tied configurations. The bi-directional capabilities of this system would allow a grid connected PV system with a modest amount of battery backup to control the amount of power delivered to the grid (according to the PV production) as well as to supply the installed site with backup power in the event of a local blackout on the grid. The DC-DC converter section of the PES allows efficient operation and stable output voltage even with variable input voltage. For example in order to charge the batteries on hot days, PV arrays are usually designed with a much higher voltage than the nominal battery voltage. The difference between PV array voltage on a bright cold day, and the battery voltage under discharge conditions, can be as high as 2:1. After a blackout, the PES can function as a grid powered battery charger similar to its operation in RFC mode. Ceramatec has negotiated commercialization rights with UIC, and intends to explore these near term markets in parallel with conducting a desired Category II program.

NB: The diodes D1-D4 were replaced by MOSFETs IXFX55N50 for rectifier mode of operation

SHEET #5 **DC/AC** **Controller Board**

Rev	By	Date
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10

REFERENCES

1. <http://www.eren.doe.gov/distributedpower>.
2. http://www.materialsworld.net/PASI/reading/Pages_369_to_451_from_FCHandbook6.pdf.
3. G.K. Andersen, C. Klumpner, S.B. Kjaer, and F. Blaabjerg, A new green power inverter for fuel cells, *IEEE Power Electronics Specialists Conference*, 2002, pp. 727-733.
4. R. Gopinath, S.S. Kim, and P. Enjeti et al., Development of a low cost fuel cell inverter with DSP control, *IEEE Power Electronics Specialists Conference*, 2002, pp. 1256-1262.
5. G.W. Pradeep, H. Mohammad, and P. Famouri, et al., High efficiency low cost inverter system for fuel cell application, *Fuel Cell Seminar*, 2003. (available at <http://www.energychallenge.org/FuelCellSeminar.pdf>).
6. J. Mazumdar, I. Batarseh, and N. Kutkut et al., High frequency low cost DC-AC inverter design with fuel cell source for home applications, *IEEE Industry Applications Conference*, 2002, pp. 789-794.
7. A.M. Tuckey, and J.N. Krase, A low-cost inverter for domestic fuel cell applications, *IEEE Power Electronics Specialists Conference*, 2002, pp. 339-346.
8. P.T. Krein, and R. Balog, Low cost inverter suitable for medium-power fuel cell sources, *IEEE Power Electronics Specialists Conference*, 2002, pp. 321-326.
9. H. Ertl, J.W. Kolar, and F.C. Zach, A novel multicell dc-ac converter for applications in renewable energy systems, *IEEE Transactions on Industrial Electronics*, 2002, pp. 1048-1057.
10. J. Wang, and F.Z. Peng, , A new low cost inverter system for 5 kW fuel cell, *Fuel Cell Seminar*. (available at <http://www.energychallenge.org/FuelCellSeminar.pdf>), 2003.
11. T.P. Bohn, and R.D. Lorenz, A low-cost inverter for domestic fuel cell applications, *Fuel Cell Seminar*, 2003. (available at <http://www.energychallenge.org/FuelCellSeminar.pdf>).
12. T. Kawabata, H. Komji, and K. Sashida et al., High frequency link DC/AC converter with PWM cycloconverter, *IEEE Industrial Application Society Conference*, 1990, pp. 1119-1124.
13. S. Deng, and H. Mao, A new control scheme for high-frequency link inverter design, *IEEE Applied Power Electronics Conference and Exposition*, 2003, pp. 512-517.
14. C. Haynes, and W.J. Wepfer, Characterizing heat transfer within a commercial-grade tubular solid oxide fuel cell for enhanced thermal management, *International Journal of Hydrogen Energy*.
15. K. Acharya, S.K. Mazumder, and R.K. Burra et al., System-interaction analyses of solid-oxide fuel cell (SOFC) power-conditioning system, *IEEE Industrial Application Society Conference*, 2003, pp. 2026-2032.