Title: A Low-Cost Soft-Switched DC/DC Converter for Solid-Oxide Fuel Cells

SECA Technical Program Final Report

Initial Date: August 15, 2002

End Date: June 11, 2009

Prepared by Dr. Jason Lai

Report Issued: June 11, 2009

DOE Award Number: DE-FC26-02NT41567

Submitting Organization:

Virginia Polytechnic Institute and State University

302 Whittemore Hall

Blacksburg, Virginia 24061-0111

Telephone: 540-231-4741

FAX: 540-231-3362

Subcontractors: Electric Power Research Institute

Southern California Edison

ABSTRACT

A highly efficient DC to DC converter has been developed for low-voltage high-current solid oxide fuel cells. The newly developed “V6” converter resembles what has been done in internal combustion engine that split into multiple cylinders to increase the output capacity without having to increase individual cell size and to smooth out the torque with interleaving operation. The development was started with topology overview to ensure that all the DC to DC converter circuits were included in the study. Efficiency models for different circuit topologies were established, and computer simulations were performed to determine the best candidate converter circuit. Through design optimization including topology selection, device selection, magnetic component design, thermal design, and digital controller design, a bench prototype rated 5-kW, with 20 to 50V input and 200/400V output was fabricated and tested. Efficiency goal of 97% was proven achievable through hardware experiment. This DC to DC converter was then modified in the later stage to converter 35 to 63 V input and 13.8 V output for automotive charging applications. The complete prototype was tested at Delphi with their solid oxide fuel cell test stand to verify the performance of the modified DC to DC converter. The output was tested up to 3-kW level, and the efficiency exceeded 97.5%. Multiple-phase interleaving operation design was proved to be reliable and ripple free at the output, which is desirable for the battery charging. Overall this is a very successful collaboration project between the SECA Core Technology Team and Industrial Team.

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

This report is to describe the basic principle and summarize the test results of a high-efficiency DC-DC converter. The DC-DC converter was developed under SECA core technology program and tested with the SOFC developed by a SECA industrial team. The development was started with topology overview to ensure that all the DC to DC converter circuits were included in the study. Efficiency models for different circuit topologies were established, and computer simulations were performed to determine the best candidate converter circuit. Through design optimization including topology selection, device selection, magnetic component design, thermal design, and digital controller design, a bench prototype was fabricated and tested. Efficiency goal of 97% was proven achievable through hardware experiment. This DC to DC converter was then modified to converter 35 to 63 V input and 13.8 V output with necessary interfaces for automotive charging applications. The converter was tested at Delphi with their solid oxide fuel cell test stand to verify the performance of the modified DC to DC converter. The output was tested up to 3-kW level, and the efficiency exceeded 97.5%. Multiple-phase interleaving operation design was proven to be reliable and ripple free at the output, which is desirable for the battery charging. Overall this is a very successful collaboration project between the SECA Core Technology and Industrial Teams.

1. INTRODUCTION

Virginia Tech has developed high efficiency DC-DC converters for low-voltage fuel cells for the SECA core technology program. The original Virginia Tech 6-phase DC-DC converter (V6 converter) was designed for 20 to 50 V input and 400 V output for a typical DC-AC inverter that can output 220 V AC power. However, the SOFC developed by Delphi is aimed for automotive applications, which has a similar fuel cell voltage range, from 35V to 63V, but the output is for 12-V vehicle battery and associated DC loads. Therefore, some modifications are needed for the V6 DC-DC converter to work with the Delphi SOFC.

The major modification is to change the 6-phase output to 3-phase output to reduce the number of inductors, and then to replace the transformer with the inductor to serve as a step-down converter. Furthermore, a new interface board needs to be designed and built so the new converter can communicate with the Delphi SOFC controller. The interface board takes frequency command signals from Delphi SOFC control signals and converts them to internal voltage and current commands for the DC-DC converter control.

Major efforts include:

(1) Modify existing V6 DC-DC converter to change from nominal 400 V to 13.8 V output
(2) Design and build an interface board for communication
(3) Test the new converter with VT SOFC simulator
(4) Test the new converter with Delphi SOFC simulator
(5) Test the new converter with Delphi SOFC
(6) Final reporting

Basic specifications of the converter are listed as follows:

(1) Input: 35V to 63V with 36V as nominal
(2) Output: 13V to 16V with 13.8V as nominal
(3) Power: 3 kW
(4) Efficiency: >96%
(5) Cooling: Forced air cooling
(6) Size: Standard rack mount unit 5.25”H×19”W×16”D
(7) Interface: 20 to 900-Hz frequency for 0 to 200-A current setting

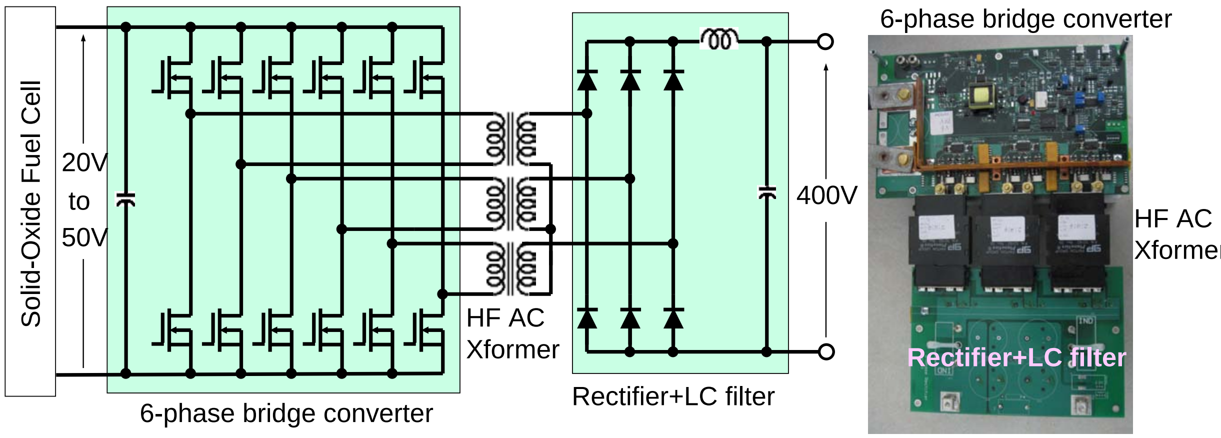
During the preparation of modifying DC-DC converter, Virginia Tech received tremendous help from Delphi technical team, especially from Rajaey Kased, who visited Virginia Tech on August 28, 2008 to check out the functionality of the modified DC-DC converter and then provided necessary suggestions for further modification so the test can be smoothly conducted during the visit.

The final test was performed on September 25, 2008. Again, the Virginia Tech received strong support from the Delphi technical team during the visit. The first test was performed with Delphi SOFC controller but running with a DC power supply as the source. The test essentially mimics the actual SOFC test condition. After rigorous tests with high voltage level (60 V) and high current level (200 A) using power supply as the source and final calibration of the controller parameters, the DC-DC converter was proven working very well under both steady-state and dynamic conditions. The current ramp can also be precisely controlled. From no load to full load, test results showed a voltage regulation of ±0.01 V for the 13.8-V output range and a current regulation of ±1 A for the 200-A output range. Efficiency was consistently higher than 97% for the load above 1-kW conditions. No significant temperature rise or hot spot was observed after the test. The temperature of key power components remains lower than human body temperature after full load test. With the confidence of the converter performance, the converter was then tested with actual SOFC. Entire converter test with SOFC was very smooth, and the performance agreed with the test results obtained from fuel cell simulators.

2. EXPERIMENTAL

2.1 MODIFY EXISTING V6 DC-DC CONVERTER TO CHANGE FROM 400 V TO 13 V OUTPUT

The current V6 DC-DC converter output is connected to transformers for isolation and voltage boost. After transformer, there is a rectifier board that converts high frequency AC to DC and filter to 400-V DC. The new design needs 13 V, so the major change is to connect the original 6-phase (V6) converter output through inductors to the battery and reduce the number of phases to three (V3) to reduce the amount of magnetic components. Figure 1(a) shows the circuit diagram of the original V6 converter, which contains a 6-leg bridge converter, a high frequency AC transformer, and a rectifying and filtering stage. The input voltage was originally designed for 20 to 50-V SOFC, and the output voltage was regulated at 400 V. Figure 1(b) shows the photograph of the entire V6 DC-DC converter. The voltage boost function is obtained through the high turns-ratio of the high frequency transformer.



(a) **(b)**

Figure 1. Original Virginia Tech V6 DC-DC converter: (a) circuit diagram, and (b) photograph.

Figure 2(a) shows circuit diagram of the modified three-phase (V3) DC-DC converter designed for Delphi SOFC. The power circuit is simplified from six phases to three phases, so the number of output inductor remains three. The three phases are operated 120° apart; therefore, the original programmed phase sequence in V6 converter does not need to be changed. The input voltage is higher than the original design level, so the devices need to be changed to a higher voltage rated MOSFET. The new device is rated 75 V, which should be sufficient to handle 63-V input. Notice that the bottom side MOSFET switches of the 3-phase bridge are paralleled with Schottky diodes to reduce the switching loss. The buck converter requires only diode for the bottom side. However, a typical diode has a fixed voltage drop of 0.7 V at light load conditions, which accounts for 2% conduction loss. Even with Schottky diode, the voltage drop is about 0.4 V at light load conditions. Under the rated load condition, Schottky diode will see at least 0.7-V drop. With additional upper MOSFET switch conduction voltage drop, switching loss, inductor loss, capacitor loss, and parasitic losses, the theoretical maximum efficiency will be less than 95%. Therefore, we propose to use power MOSFET as the bottom switch to operate under synchronous rectification mode, while keeping Schottky diode to reduce the switching loss under light load condition, so the efficiency maintains high over the entire load range. The calculated efficiency is higher than 97% in most load conditions.

Figure 2(b) shows photograph of the V3 DC-DC converter and its test setup. The physical size is significantly reduced from the original V6 converter because of the elimination of transformers and the rectifier stage. Fig. 2(c) shows detailed view of the V3 DC-DC converter. The overall circuit structure remains the same as the original V6 DC-DC converter, but the output section is replaced with three inductors.

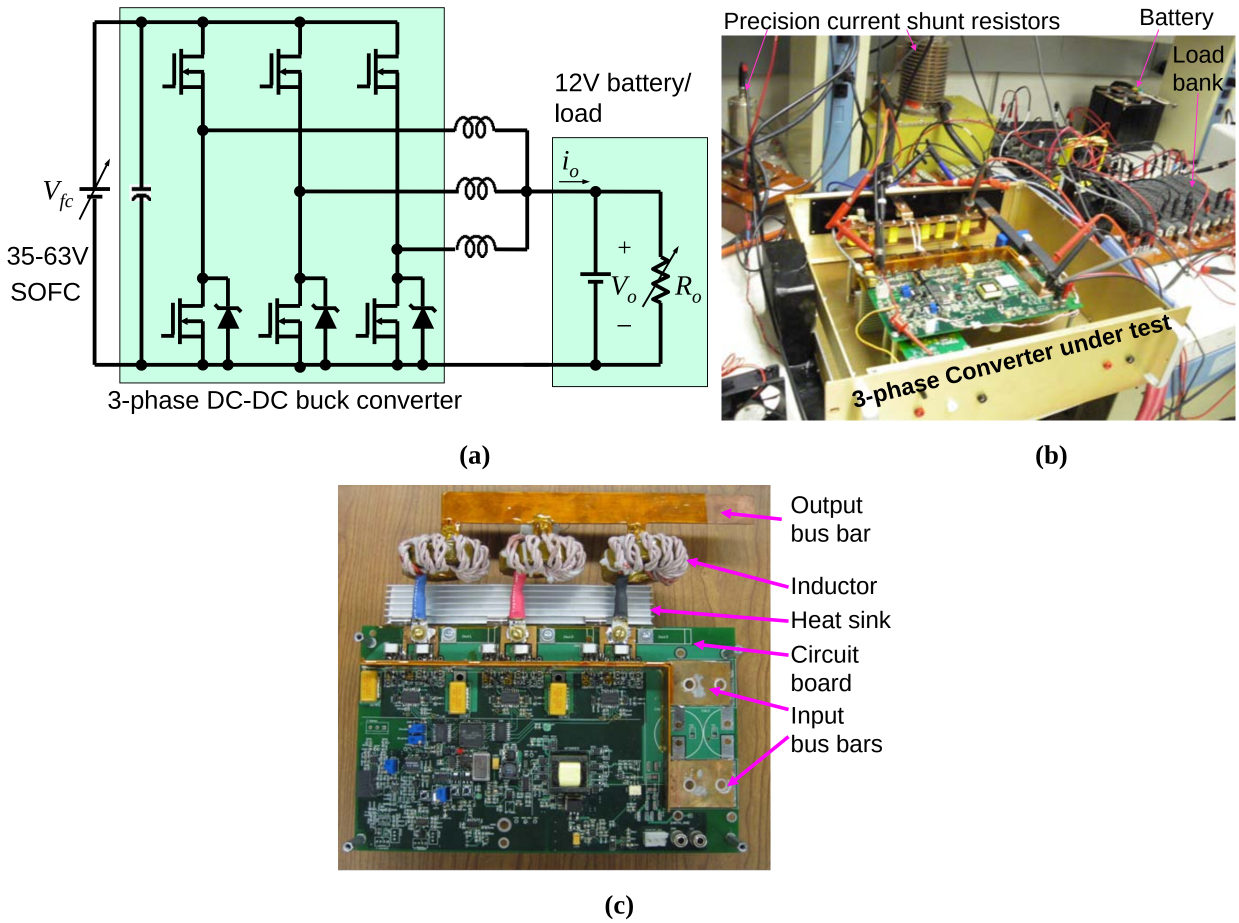


Figure 2. Modified V3 DC-DC converter for step-down applications: (a) circuit diagram, (b) photograph showing V3 converter under test, and (c) detailed view of V3 converter.

2.2 Design and Build Interfaces

The interface between SOFC and DC-DC converter involves power and control and communication. The power connections include input and output terminals. We added two DC contactors to help startup control for both input and output connections. The input contactor cannot be turned on without output connected to a 12-V battery, while the output connector cannot be turned on when the converter output and battery voltage difference is too high. A high voltage difference tends to spark over the contacts of the DC contactor and damage the mechanical contacts. If the converter output voltage is less than the battery voltage, turning on the contactor can also damage power MOSFET because the circuit functions like a boost converter that produces excessive voltage and can damage the power devices.

For the control and communication interface, the design options can be digital or analog. Digital interface is less sensitive to noise interference but requires additional conversion. Analog interface is simple, but the signal can be easily corrupted by the noise. Therefore, our choice is a more reliable digital interface, which should be compatible with the Delphi fuel cell controller's 20 Hz to 900 Hz. For the current control or current limit, this frequency range represents 0 to 200 A. For the voltage control, the frequency range can be specified to cover the battery voltage state of charge range, typically from 11 V to 16 V.

3. RESULTS AND DISCUSSION

3.1 EFFICIENCY TEST

The new DC-DC converter has been packaged in a standard rack-mount case and tested with the SOFC simulator at Virginia Tech. The first test was to test efficiency at different switching frequency to see what frequency yields the best efficiency. Figure 3 shows the tested efficiency profiles results under fixed input of 36 V and fixed output of 13 V but different switching frequencies, i.e., 33-, 40-, and 50-kHz conditions.

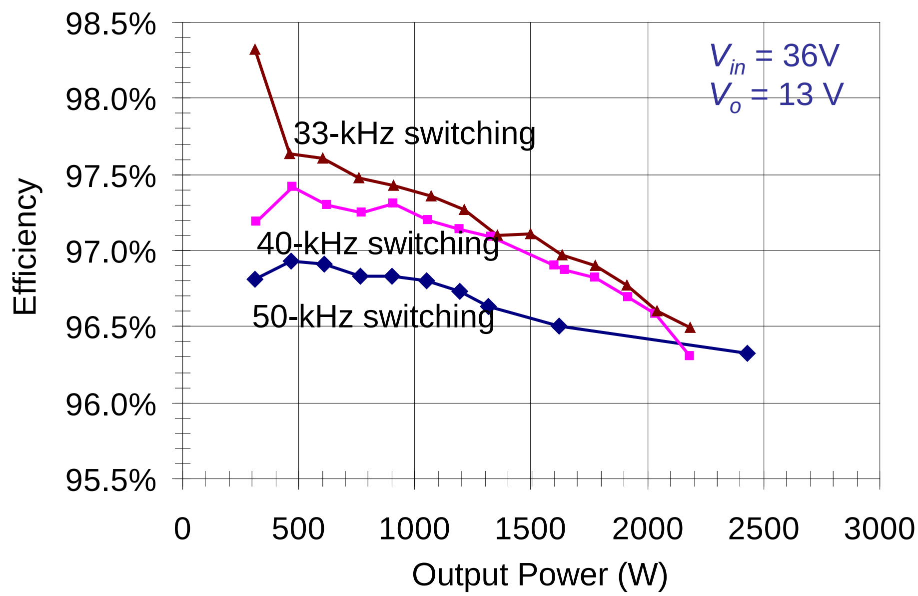


Figure 3. Fixed input and output voltages test under different switching frequency conditions.

Lower switching frequency tends to yield higher efficiency over the entire load range. However, the efficiency gain with further reduction of switching frequency seems to be diminished, especially at the heavy load condition, which can be attributed to the increase of the inductor loss. Therefore, we decided to use 33 kHz as the switching frequency for the subsequent tests.

Figure 4 shows the efficiency evaluation results under variable fuel cell input voltage and fixed output voltage condition. The fuel cell voltage is reduced from 50 V to 35 V from light load to heavy load. The efficiency is going upward as the load increases. The efficiency is above 97% in most load conditions.

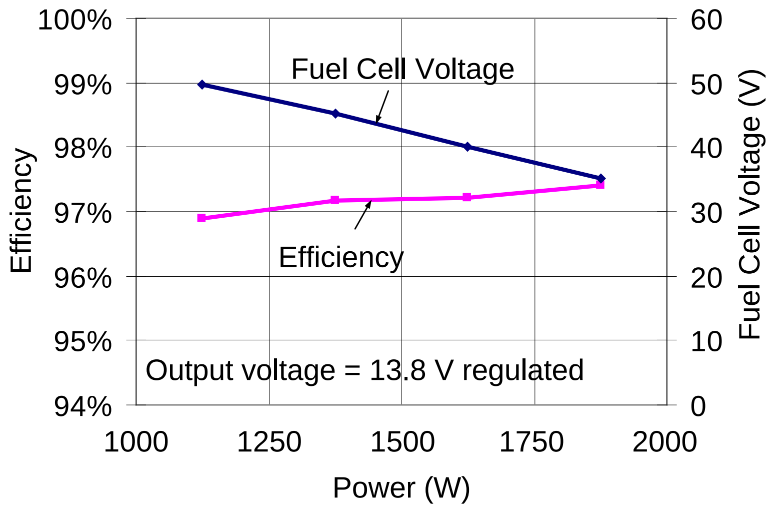


Figure 4. Efficiency evaluation under variable fuel cell input voltage and fixed output voltage condition.

3.2 STEADY-STATE TEST WITH CURRENT LIMIT CHECKING

The purpose of test is to make sure that the current limit command does not change after removing the input source. Figure 5(a) indicates that the initial test has a current limit of 48 A and the battery is charged with 8-A input. The fuel cell input source is removed for 8 minutes. Figure 5(b) shows that after 8 minutes, the current limit remains unchanged. This proves that the current loop control is stable and is not affected by the fuel cell voltage condition.

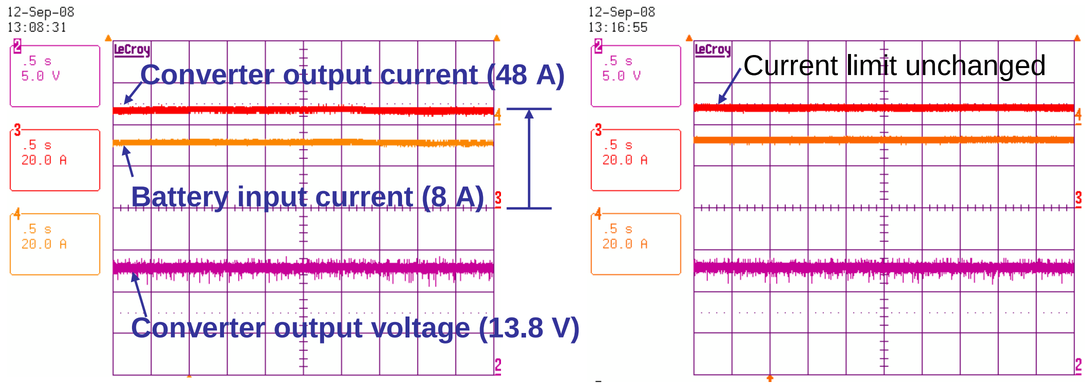


Figure 5. Current limit unchanged 8 minutes after input source is removed when battery is charged: (a) initial current limit of 48 A and (b) 8 minutes after the source is removed and reapplied back.

The same test was conducted at a higher current level with battery discharging the current to the load. Figure 6(a) indicates that the initial test has a total load current of 67 A, and the battery is outputting 7 A. The input source is removed to allow the battery sourcing the load. Figure 6(b) shows that after 8 minutes, the current limit remains unchanged. Therefore, no matter the battery status is in charging or discharging mode, the current loop control is stable and is not affected by the fuel cell voltage condition.

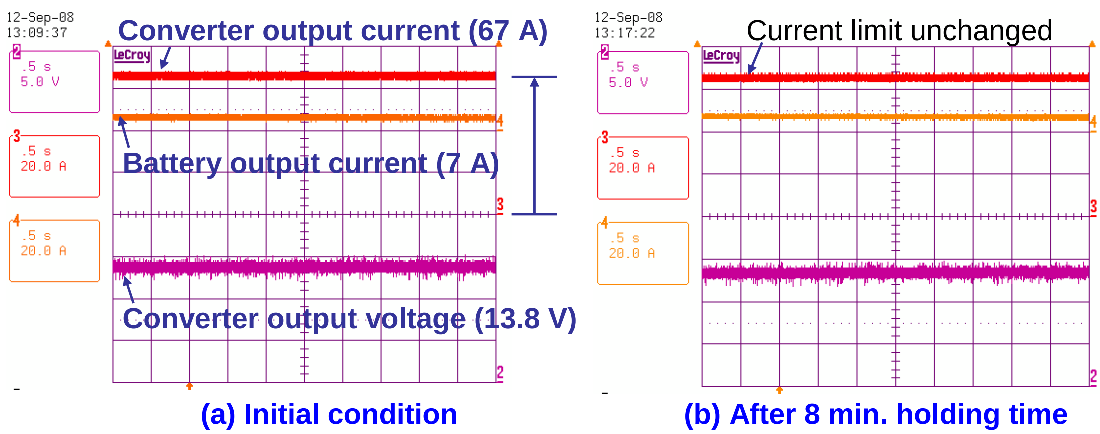


Figure 6. Current limit unchanged 8 minutes after input source is removed when battery is discharging: (a) initial current limit of 67 A and (b) 8 minutes after the source is removed and reapplied back.

Figure 7 shows the voltage and current waveforms of three-phase mode under 60-V input voltage and 100 kHz switching frequency. Voltage overshoot and undershoot at turn-off and turn-on are observed, but since the peak overshoot voltage is less than the device rating of 75 V, the device should operate safely. Note that the converter is capable of operating at 100 kHz, but the actual operating frequency was determined to be 33 kHz to ensure high efficiency operation.

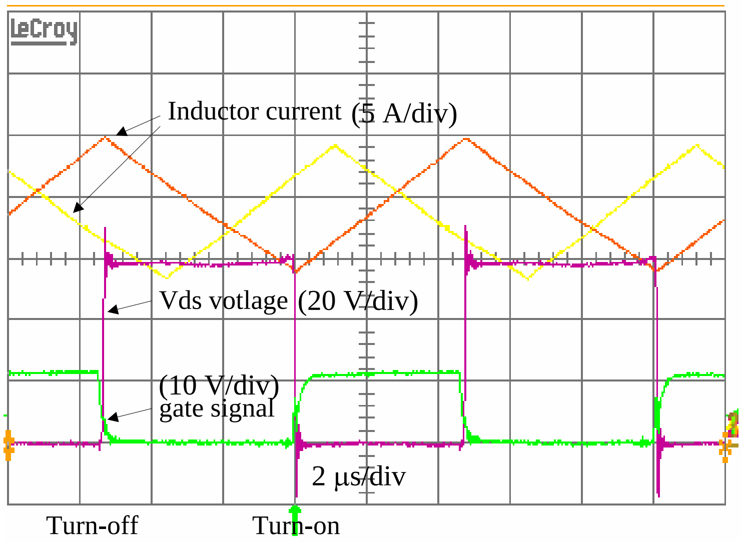


Figure 7. Switch voltage and inductor current waveforms.

3.3 DYNAMIC TEST

Under the current limit condition, increasing the voltage command will not increase the voltage because the duty cycle is saturated. However, for the same current limit condition, decreasing the voltage command will reduce the voltage and current, as shown in Figure 8. The initial output current limit was set at 56 A, and the voltage was 11V. By reducing the voltage command to 7 V, the current limit is reduced to 38A.

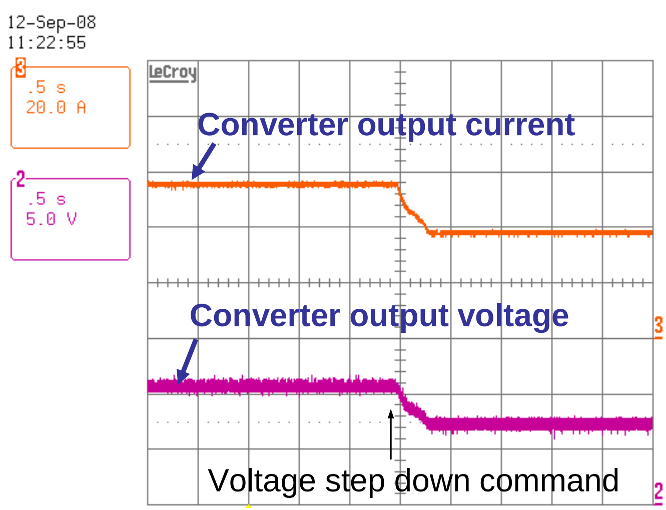


Figure 8. Dynamic voltage regulation under different voltage command conditions.

Figure 9 shows the battery voltage under severe load dump condition. The initial load current is 143 A, and the battery is 13.8 V, or 2-kW condition. The test is to dump the 2-kW completely to see how battery voltage will react. Without current loop control, this normally implies an excessive amount of energy will charge to the battery, which will increase the battery voltage to a dangerous level. However, our design adopts a fast current loop control with 1-kHz control loop bandwidth. The output voltage is also well regulated with 90-Hz control loop bandwidth. Therefore, the battery voltage spike is very well contained during such a server load dump. The measured voltage spike is no more than 3.5 V, which is mainly due to parasitic ringing, and the actual battery cell voltage level should be much less. Therefore, the designed fast control loop allows output voltage well regulated, and thus protecting the battery from over-voltage damage even under the most severe load transient condition.

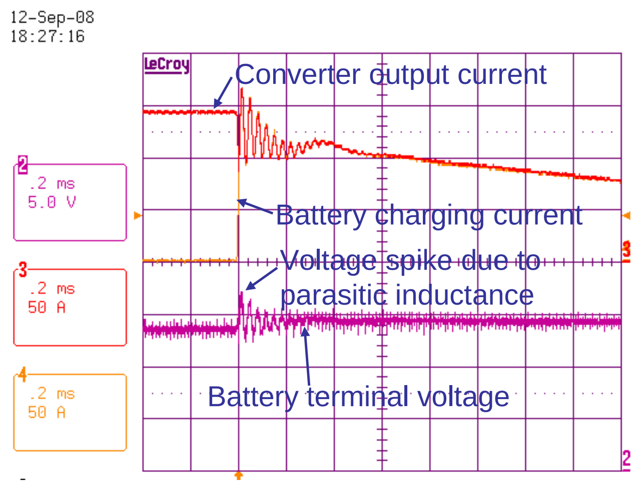


Figure 9. Battery voltage after 2-kW load dump.

3.4 Test the New Converter with Delphi Power Supply

3.4.1 Efficiency Test

With well proven steady-state and dynamic performance, the newly modified converter was first tested with the Delphi power supply using actual SOFC controller. Therefore, the test is considered as under SOFC simulator condition. To test efficiency under actual fuel cell voltage condition, we selected some high voltage low current points and moved down the voltage but increased the current command until full load condition. Figure 10 shows efficiency evaluation results for the voltage range of 60 V down to 35 V and output current from 5 A up to 200 A. The efficiency is generally higher under heavier load conditions. For the first point with load less than 250 W, the efficiency is only 70%. At 500 W, the efficiency quickly moves to 90%, and at 1 kW, the efficiency reaches 97%. There are two unusual efficiency points that indicate an efficiency of >99% between 1 kW and 1.5 kW range. We believe that these two points are invalid due to potential measurement error. As a comparison, we added three points measured with VT fuel cell simulator, the efficiency should be around 97%. As the load increases to full load (3 KW) range, the efficiency stays around 97.5%, which is consistent with what was measured in VT lab. This result confirms that the proposed approach with synchronous rectification operated power MOSFET in parallel with Schottky diode can break the theoretical efficiency limit of 95% when only Schottky diode is used.

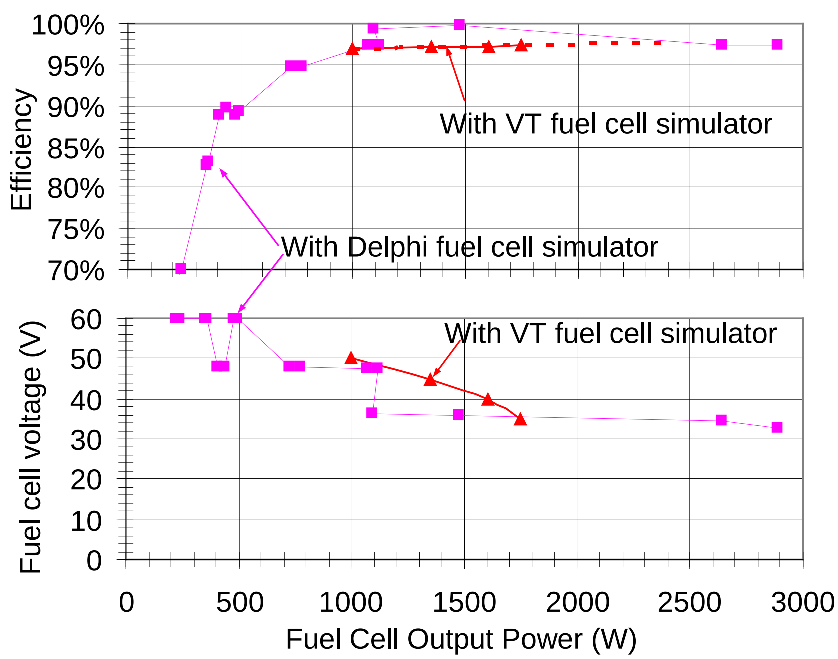


Figure 10. Efficiency test results with SOFC simulators.

3.4.2 Steady-State Test

Figure 11 shows the steady-state tested voltage and current waveforms at 13.4-V, 28-A output condition. With a high initial battery voltage, the load is mostly supplied by the battery, not by the fuel cell because a small current limit is commanded by the converter, and thus the output of fuel cell current is nearly zero, or 0.13 A as indicated in the chart. Under such a light load condition, the switch duty cycle is quite small (23.7%), which is enough to maintain a stable battery voltage of 13.4 V.

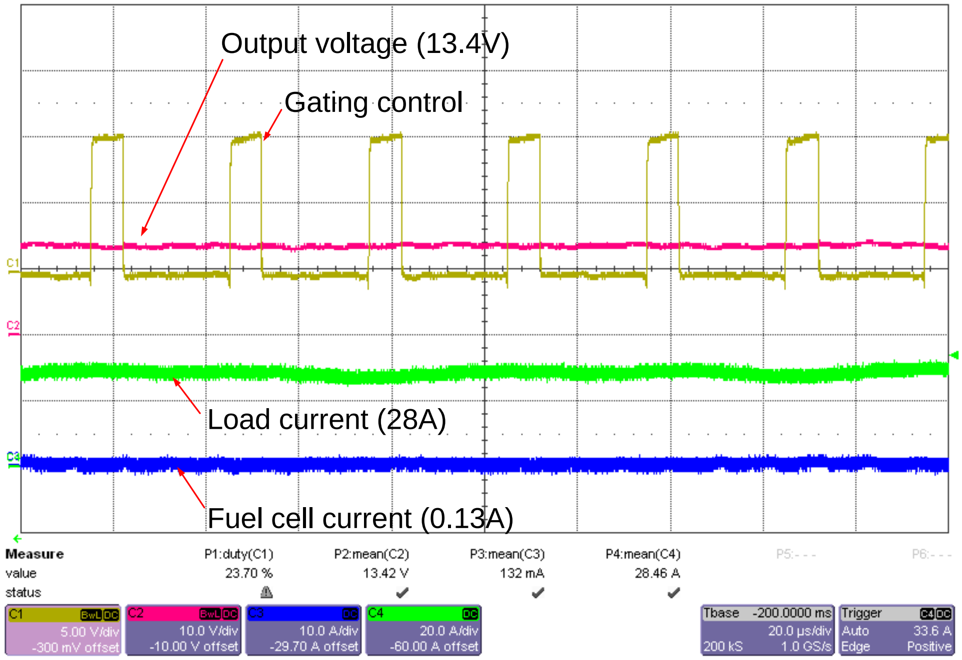


Figure 11. Steady-state voltage and current waveforms at 13.4 V, 28 A output test condition.

As fuel cell simulator continues charging the battery with a higher output current command, the duty cycle and battery voltage also continue increasing. Figure 12 shows the test condition at 13.8-V battery voltage and 186-A load current condition. The duty cycle is increased to 40.8%, and the fuel cell voltage and current are 34.6 V and 76.2 A, respectively.

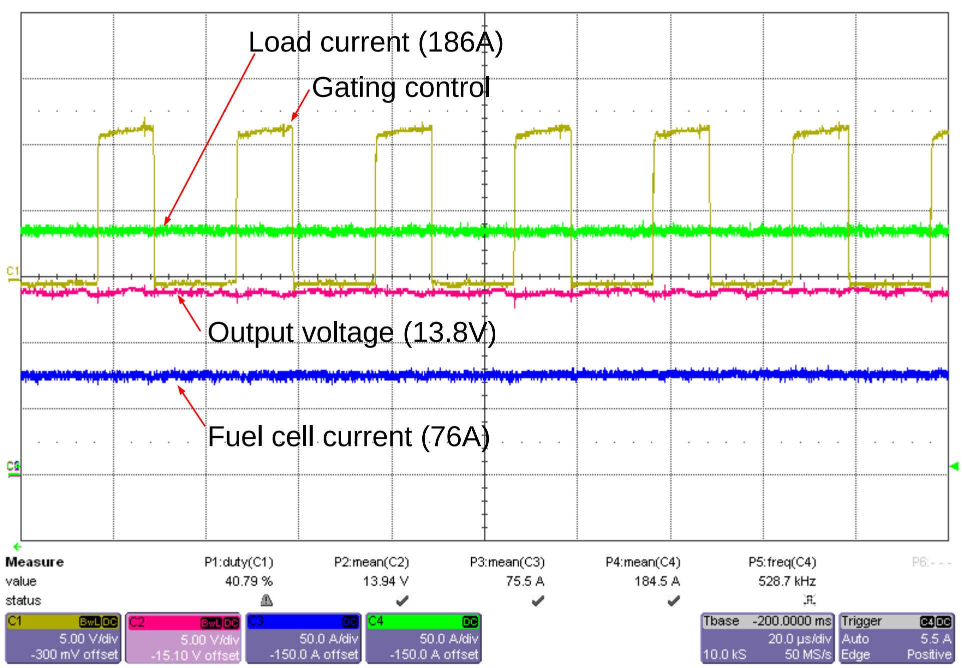


Figure 12. Steady-state voltage and current waveforms at 13.9 V, 185 A output test condition.

3.4.3 Dynamic Test

Figure 13 shows voltage and current waveforms under load step test condition. The load current is increased from 20 A to 60 A. The ramp is controlled to have a rise time of 60 ms. With fast current loop control, the load current, and thus the fuel cell current rise smoothly without any overshoot. The output voltage maintains well regulated at 13.8 V under such a dynamic load step condition.

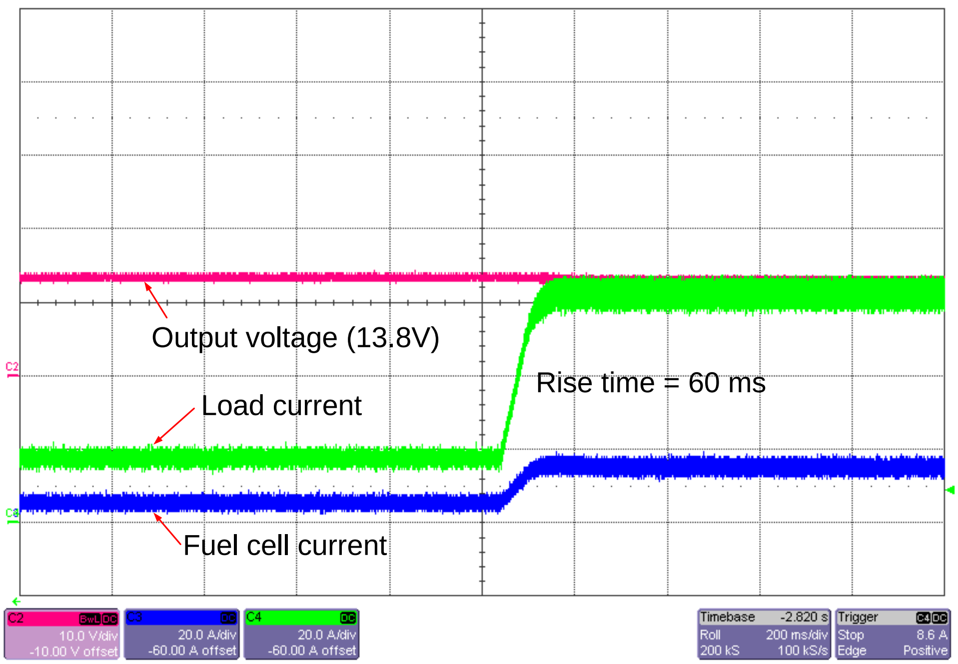


Figure 13. Voltage and current waveforms under load step test from 20-A to 60-A condition.

Figure 14 shows voltage and current waveforms under load dump condition. The load current is reduced from 85 A down to 25 A. Since the SOFC controller does not set the ramp rate, the response under load dump is faster than the load step. As can be seen from Figure 13, the current fall time is 50 ms for a 60-A load dump, as compared to 60 ms for a 40-A load step.

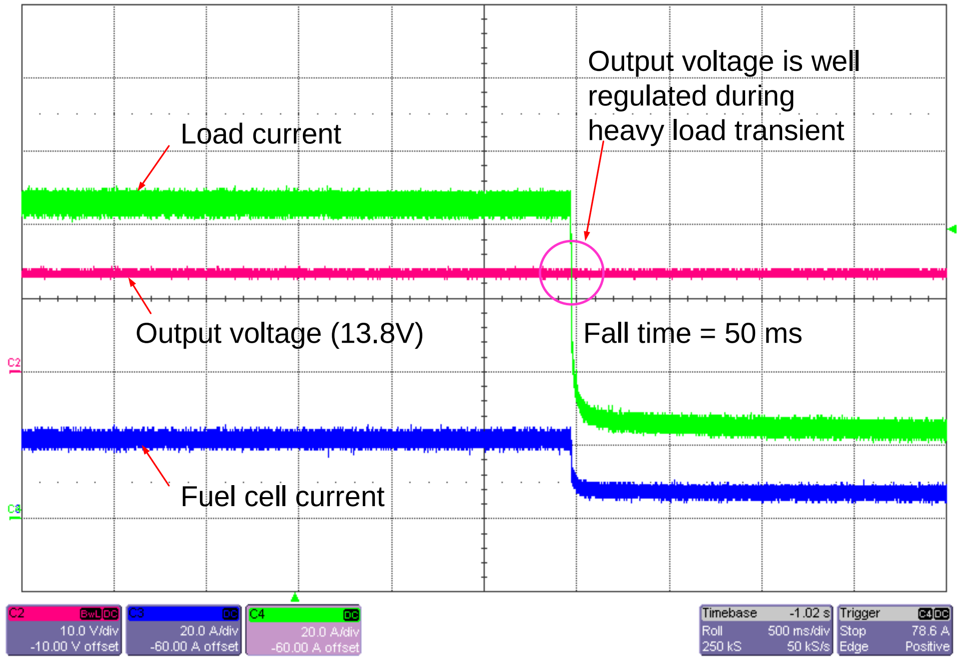


Figure 14. Voltage and current waveforms under load dump test from 85-A to 25-A condition.

3.5 Test the New Converter with Delphi SOFC

3.5.1 Efficiency Test

After the converter test with Delphi SOFC simulator, the converter was proven to have the claimed efficiency and to be able to communicate with the Delphi SOFC controller. The converter was then moved to the fuel cell test stand. Figure 15 shows photograph of the test setup with VT DC-DC converter and the Delphi SOFC. The fuel cell output is monitored and controlled by setting a set of fuel cell parameters. The load contains a 12-V battery pack and a programmable electronic load. The entire test condition is the same as that under SOFC simulator test, except that the source voltage and available current are dependent on the SOFC condition. For every test point, the SOFC parameters need to be adjusted to match the output.

Three efficiency points were tested to compare with the results obtained from the SOFC simulator test. Figure 16 shows the efficiency and fuel cell output voltage as a function of the output power. The first point starts at about 600-W condition, and the efficiency is about 95%. This is slightly better than the one obtained from fuel cell simulator test (94.5%) because its voltage is lower. The second point runs at about 900-W condition, and the efficiency is about 97%, which agrees the test result obtained from the simulator test very well. The third point is measured at about 1.3 kW, and the efficiency reaches 98.5%. This agrees with the results obtained from Delphi fuel cell simulator, but is more than 1% higher than the one measured with VT fuel cell simulator. It appears that the instrumentation tends to favor output power between 1 and 1.5 kW range. Nevertheless, the VT converter has demonstrated a superior efficiency under both SOFC and SOFC simulator test conditions.

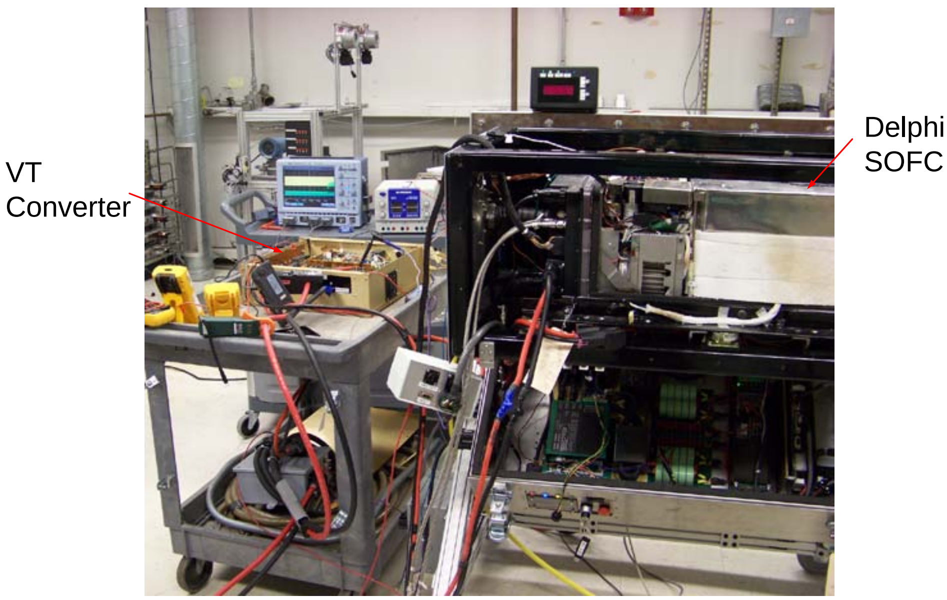


Figure 15. Photograph showing setup of VT DC-DC converter tested with Delphi SOFC.

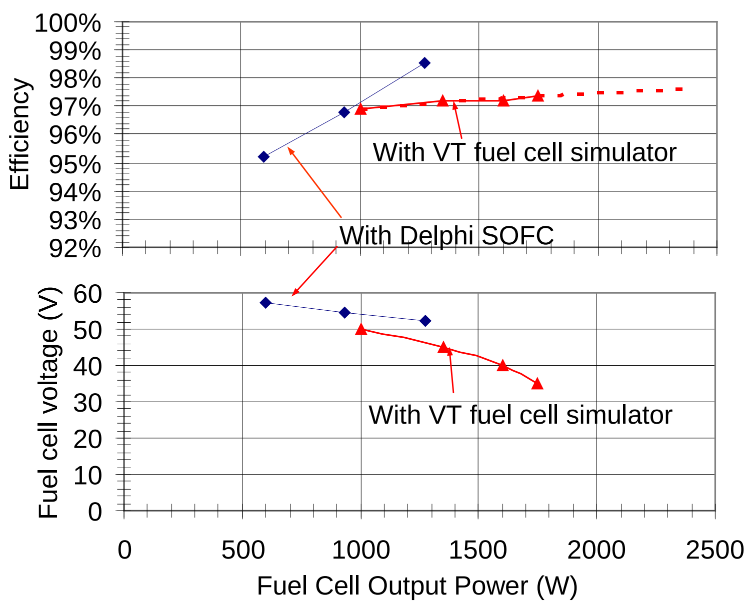


Figure 16. Efficiency evaluation results with Delphi SOFC.

3.5.2 Current Ramp Test

The fuel cell power availability depends on various factors. With temperature as the dominant factor, the fuel cell output current ramp needs to be slowed down with proper control. Although the previous fuel cell simulator tests indicated that the VT converter has a fast current loop control, and the current ramp can be achieved within 10's of milli-second, the actual fuel cell output ramp needs to be controlled in 10's of second. Figure 17 shows test result using Delphi SOFC controller to obtain the current ramp control of 40A/40s rise rate.

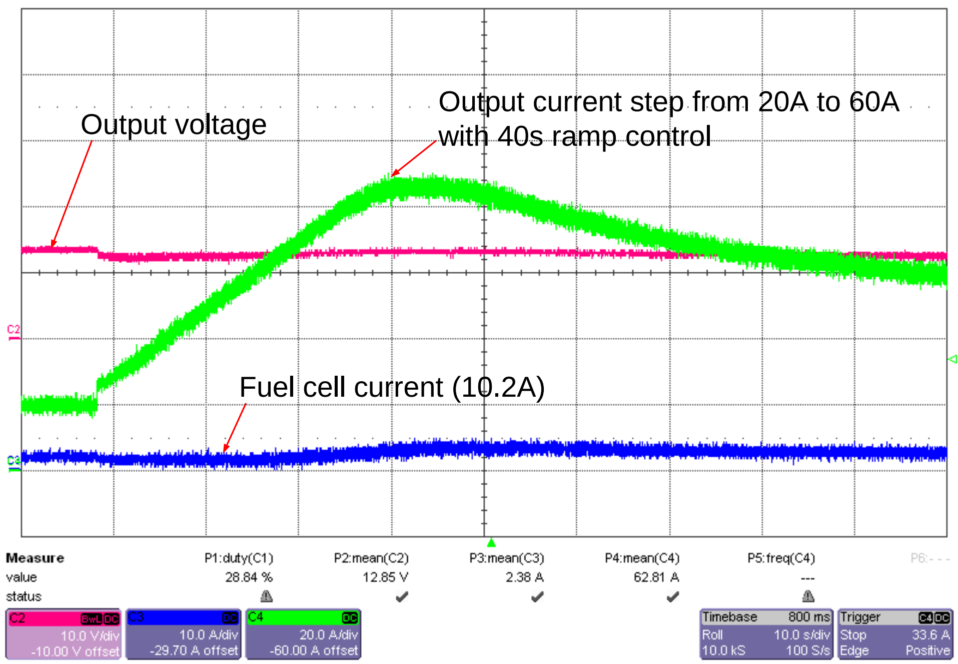


Figure 17. Voltage and current waveforms under current ramp control using Delphi SOFC controller.

3.5.3 Steady-State Test

Figure 18 shows steady-state voltage and current waveforms of the DC-DC converter tested with Delphi SOFC under light load condition. The fuel cell voltage and current are 57.3 V and 10.2 A, respectively. The output load has a battery voltage of 13.1 V and the total load current of 43 A. The switch duty cycle is 25.4% in this case.

Figure 19 shows steady-state voltage and current waveforms of the DC-DC converter tested with Delphi SOFC under medium load condition. The fuel cell voltage and current are 52.4 V and 24.3 A, respectively. The output voltage and current are 13.1 V and 95 A, respectively. The duty cycle is increased to 36.4%.

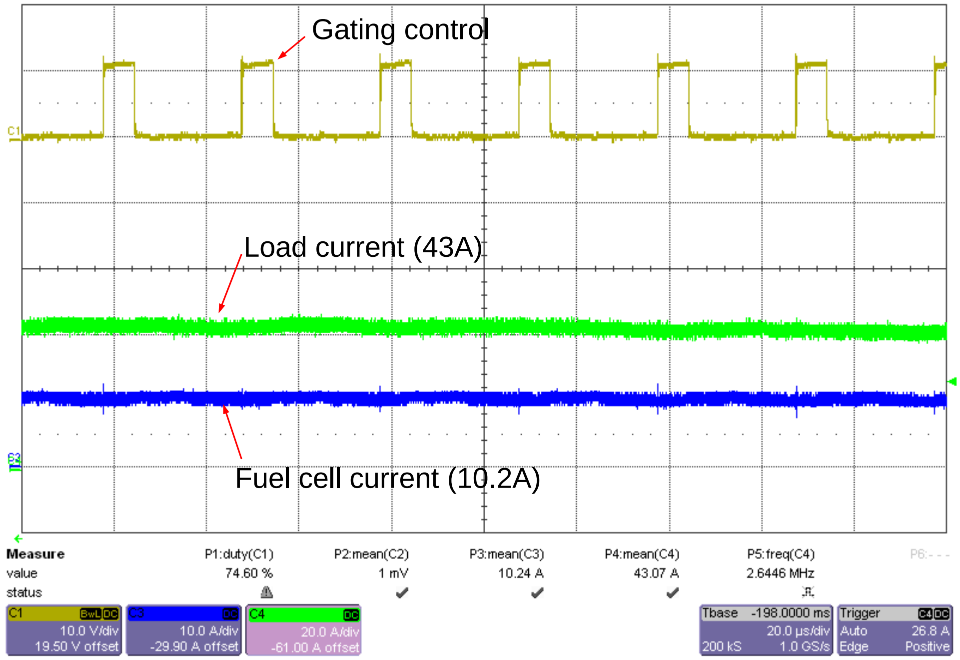


Figure 18. Steady-state voltage and current waveforms of DC-DC converter tested with SOFC under light load condition.

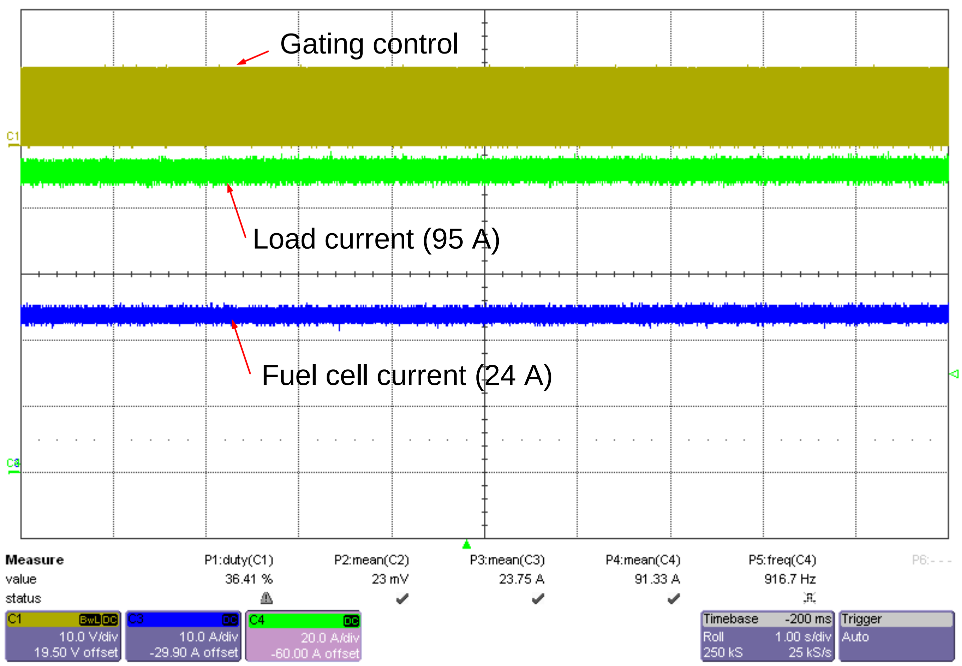


Figure 19. Steady-state voltage and current waveforms of DC-DC converter tested with SOFC under medium load condition.

3.5.4 Dynamic Test

With proper tuning of fuel cell parameters, the Delphi SOFC allows load step and load dump tests with reasonable current rise or fall rate. Figure 20 shows voltage and current waveforms under load step from 16 A to 28 A. The load and fuel cell currents rise smoothly with a rate controlled by the SOFC controller. This test also proves that the communication between the VT converter and Delphi SOFC is working properly.

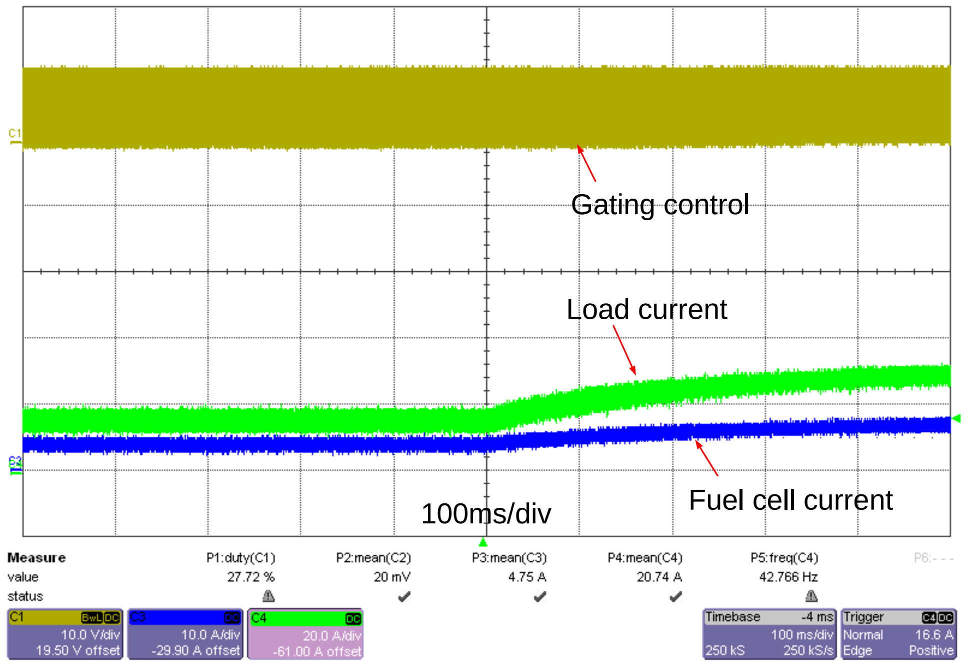


Figure 20. Voltage and current waveforms under load step from 16-A to 28-A test with Delphi SOFC.

Figure 21 shows voltage and current waveforms under load dump from 95 A to 60 A. The load dump process was performed continuously with several steps, and the scope time scale was changed to 1 s/div to capture the current waveforms. Again, the fuel cell and load currents smoothly reduce and follow the command precisely.

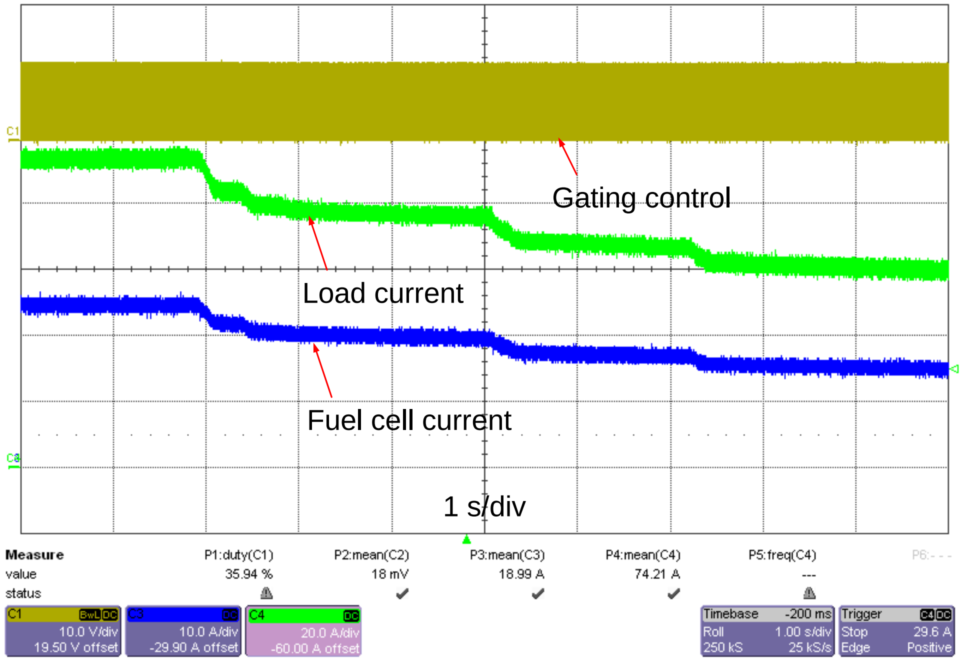


Figure 21. Voltage and current waveforms under load dump from 95-A to 60-A test with Delphi SOFC.

4. CONCLUSION

The entire test with VT DC-DC converter operating under Delphi SOFC controller was very smooth and successful. The VT DC-DC converter communicates with the Delphi SOFC controller very well with current control scale well calibrated. Major test items are summarized as follows:

- Tested voltage range: 32 to 60 V
- Test current range: 0 to 203 A
- Voltage regulation from 0 to 3kW test condition is within 0.01V.
- Current regulation from 0 to 200A test condition is within 1A.
- Efficiency exceeds 97% at load higher than 1 kW and peaks at 97.5% at 3-kW full load condition.
- Dynamic load step and load dump follow the command rate precisely and operate smoothly.

Some of the test conditions are actually tougher than the original specification. For example, the low-end tested voltage of 32 V is lower than the original specified 35 V. The highest current tested was 203 A, which is higher than the specified 200 A, and actually caused the damage on the mechanical contactor during the test. The DC-DC converter ran robustly even after the failure of the mechanical contactor. The efficiency exceeds the SECA goal of 97%. Multiple-phase interleaving operation design was proved to be reliable and ripple free at the output, which is desirable for the battery charging. The numbers are consistent throughout all the tests in VT-FEEC lab and Delphi test stand. Overall this is a very successful collaboration project between the SECA Core Technology Team and Industrial Team.

5. BIBLIOGRAPHY

[1] C. Liu and J.S. Lai, "Low Frequency Current Ripple Reduction Technique with Active Control in a Fuel Cell Power System with Inverter Load," *IEEE Transactions on Power Electronics*, Jul. 2007, pp.1429 – 1436.

[2] S.-R. Moon and J.-S. Lai, "Multiphase Isolated DC-DC Converter for Low-Voltage High-Power Fuel Cell Applications," in *Proceedings of IEEE APEC,* Anaheim, CA, Feb. 2007, pp. 654 – 660.

[3] R.-Y. Kim and J-S. Lai, "A Seamless Mode Transfer Maximum Power Point Tracking Controller for Thermoelectric Generator Applications," *IEEE Trans. on Power Electronics,* Sep. 2008, pp. 2310 – 2318.

[4] R. P. O'Hayre, S.W. Cha, W. G. Colella, and F.B. Prinz, Fuel Cell Fundamentals, New Jersey: Wiley, 2009.

[5] M. A. Peavey, Fuel from Water, 10th ed., Louisville: Merit, Inc.

[6] R. McAlister, The Solar Hydrogen Civilization, 2nd ed., Mesa: American Hydrogen Association, 2005.

6. PATENT ISSUED

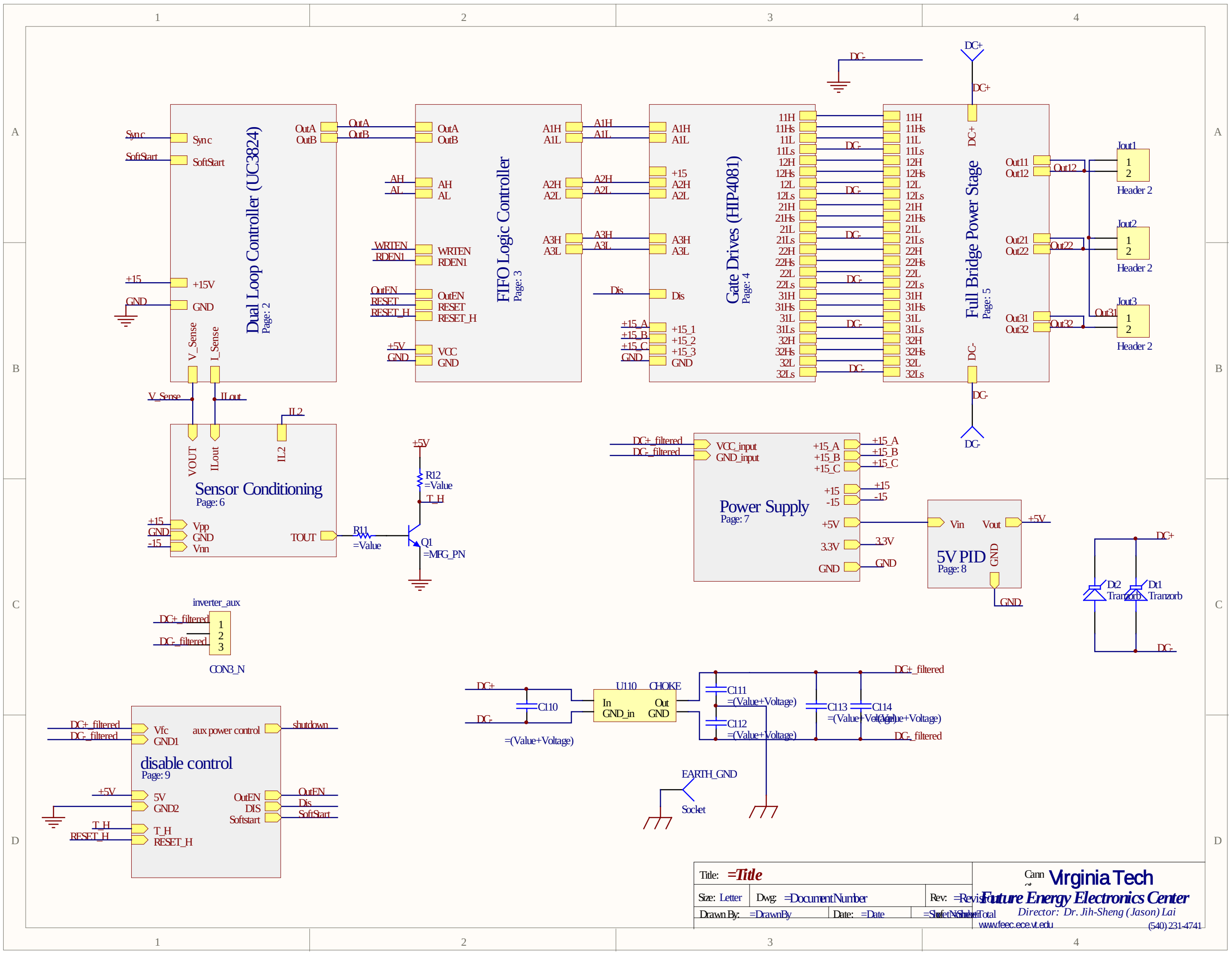
Jih-Sheng Lai et. al., "Multiphase soft switched DC/DC converter and active control technique for fuel cell ripple current elimination," U.S. Patent #7,518,886, April 2009.

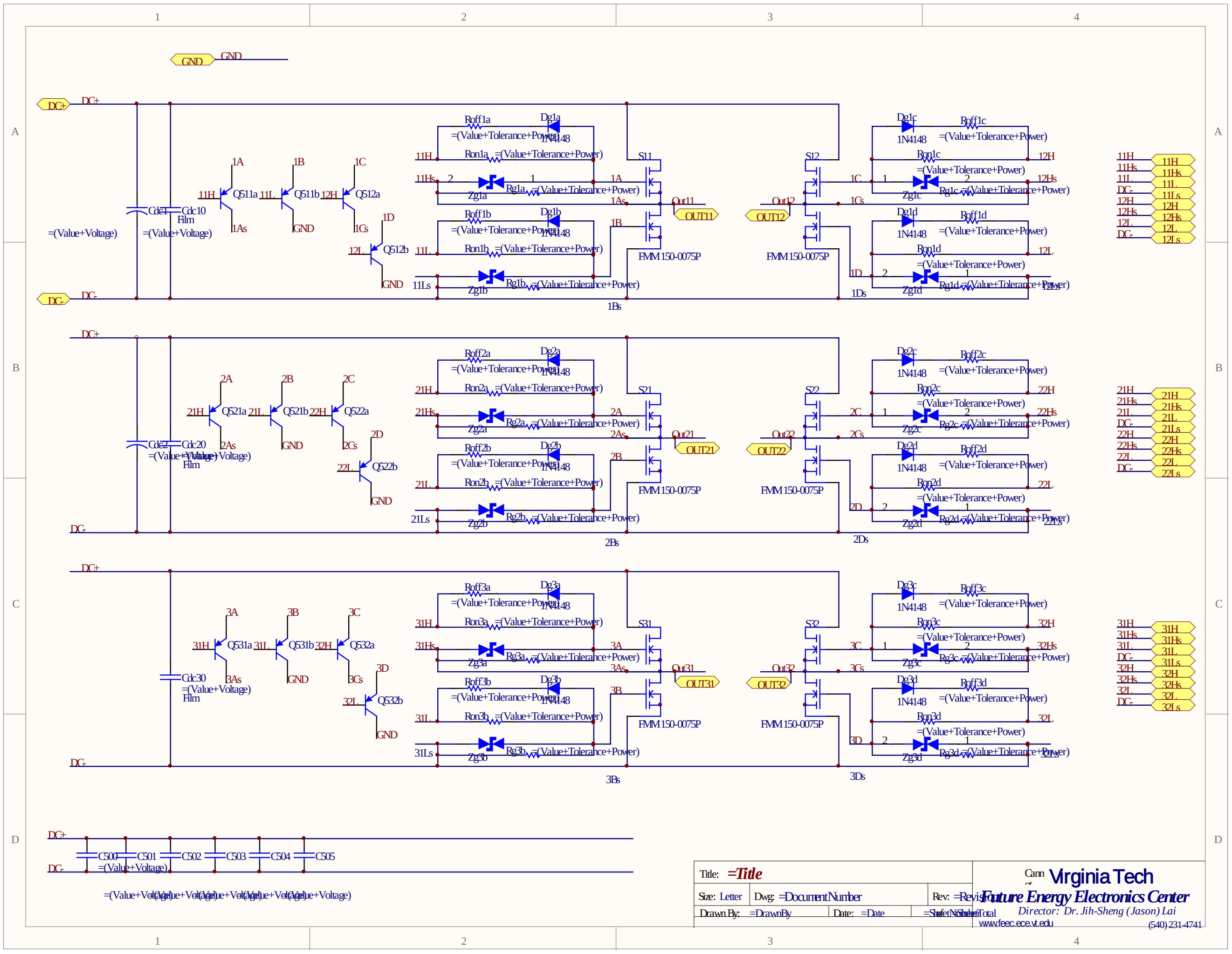
7. LIST OF ACRONYMS AND ABBREVIATIONS

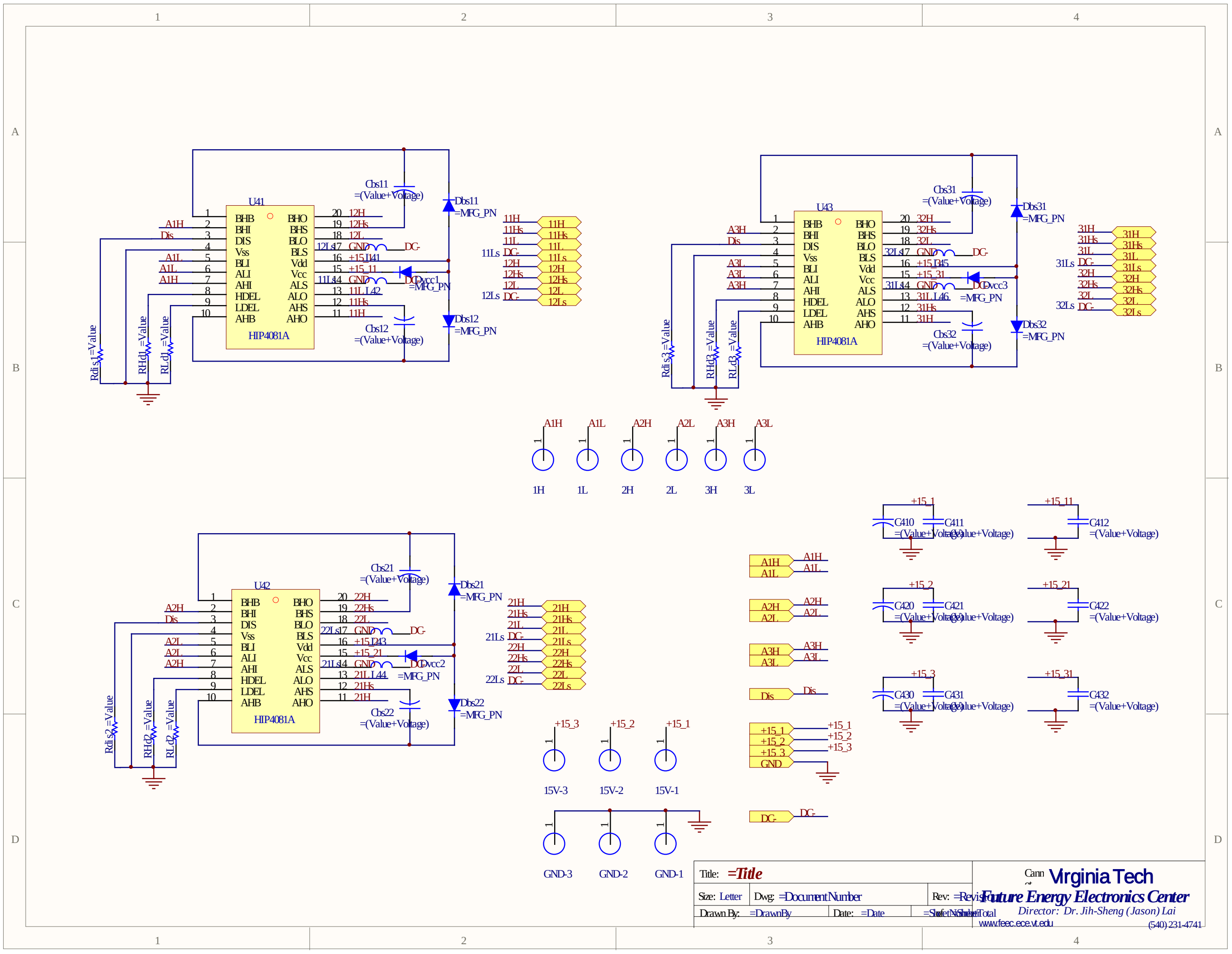
AC – Alternate current
CB – Circuit breaker
DC – Direct current
DG – Distributed generation
DOE – Department of Energy
DSP – Digital signal processor
EPRI – Electric Power Research Institute

IEEE – Institute of Electrical and Electronics Engineering
kVAr – kilo Volt-Ampere reactive
kW – kilo watts
LC – inductor-capacitor
LCL – inductor-capacitor-inductor
PCS – Power conditioning system
PLL – Phase locked loop
QPR – Quasi-proportional-resonant
SECA – Solid-State Energy Conversion Alliance
SOFC – Solid oxide fuel cell
V – Volt
VAr – Volt-Ampere reactive
Virginia Tech – Virginia Polytechnic Institute and State University
W – Watt

APPENDIX: Key Schematic Circuit Diagrams




GND
DC+
DC-
OUT11
OUT12
OUT21
OUT22
OUT31
OUT32
FMM150-0075P
Title: =Title
Size: Letter
Dwg: =DocumentNumber
Rev: =Revision
Drawn By: =DrawnBy
Date: =Date
Virginia Tech
Future Energy Electronics Center
Director: Dr. Jih-Sheng (Jason) Lai
www.feec.ece.vt.edu
(540) 231-4741


U41
HIP4081A
U42
HIP4081A
U43
HIP4081A
BHB
BHI
DIS
Vss
BLI
ALI
AHI
HDEL
LDEL
AHB
BHO
BHS
BLO
BLS
Vdd
Vcc
ALS
ALO
AHS
AHO
Cbs11
Cbs12
Cbs21
Cbs22
Cbs31
Cbs32
=(Value+Voltage)
Dbs11
Dbs12
Dbs21
Dbs22
Dbs31
Dbs32
=MFG_PN
Dvcc1
Dvcc2
Dvcc3
Rdis1 =Value
RHd1 =Value
RLd1 =Value
Rdis2 =Value
RHd2 =Value
RLd2 =Value
Rdis3 =Value
RHd3 =Value
RLd3 =Value
A1H
A1L
A2H
A2L
A3H
A3L
Dis
DC-
GND
+15_1
+15_2
+15_3
+15_11
+15_21
+15_31
C410
C411
C412
C420
C421
C422
C430
C431
C432
1H
1L
2H
2L
3H
3L
15V-3
15V-2
15V-1
GND-3
GND-2
GND-1
Title: =Title
Size: Letter
Dwg: =DocumentNumber
Rev: =Revision
Drawn By: =DrawnBy
Date: =Date
Virginia Tech
Future Energy Electronics Center
Director: Dr. Jih-Sheng (Jason) Lai
www.feec.ece.vt.edu
(540) 231-4741