A Low Cost Soft-Switched DC/DC Converter for Slid Oxide Fuel Cells

Monthly Report

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Prepared for

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1. TASKS ACCOMPLISHED: SUBTASK 2.1 AND 2.2.

Figure 1 shows the proposed three-phase power circuit for dc/dc converter. The 3-phase bridge inverter consists of 6 MOSFET switches. In order to reduce I^2R losses, it is necessary that each switch current be as small as possible. Thus, paralleling multiple switches is more effective than using a large size MOSFET. However, the parasitic components in parallel connections can cause additional losses. Our approach is to use insulated metal substrate (IMS) board and surface mount devices to minimize the interconnect parasitics.

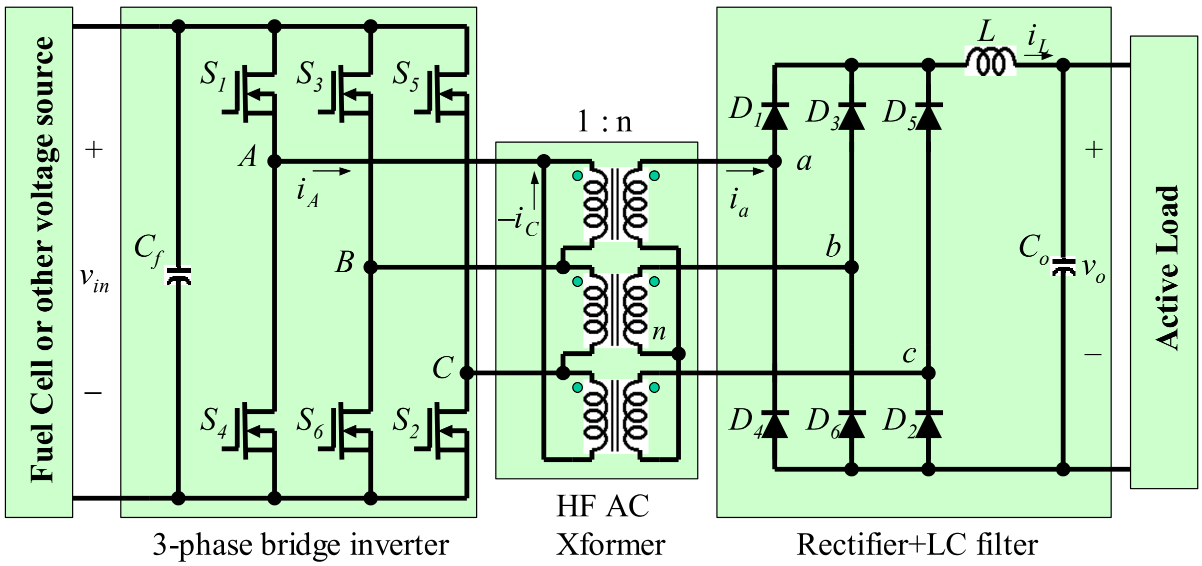


Figure 1. Proposed three-phase power circuit for dc/dc converter.

<u>Subtask 2.1: Design the power circuit</u>

According to previous studies, the device suitable for this application can be secured from different vendors at a reasonable cost. The surface-mount device that has equivalent electrical characteristic to TO-220 package is in TO-263 package. This package is most cost effective today because it's widely used in automotive industry and uninterruptible power system (UPS) industry. Among commercially available devices, Fairchild FDB045AN080A0 and Vishay Siliconix SUM110N08-05 have nearly identical characteristic. The first one is rated 75 V, 4.5 mΩ, and the second one is rated 75 V, 4.8 mΩ. The cost of Fairchild device is $1.60 in 100,000 quantity. This price can be negotiated down to less than 50¢ each. Thus, increasing the number of paralleling device will not be a major cost burden in the final produce. Based on simulation results, to achieve 97% efficiency, we need at least four devices in parallel per switch. Thus, to start with, we decided to lay out the circuit with six switches in parallel to give more margin in efficiency gain.

Figure 2 shows the printed circuit board (PCB) layout for the power circuit. The use of IMS board restricted the layout to be single layer, and thus all the device pins need to be connected on the top layer of the board. To carry high current, heavy copper (4 oz) board was selected. Middle section of the circuit board is for gate drive connections. Figure 3 shows the completed power circuit board. Brass bolts and all the devices were soldered with wave solder equipment. Temperature profile of wave soldering needs to be carefully controlled to avoid poor connections.

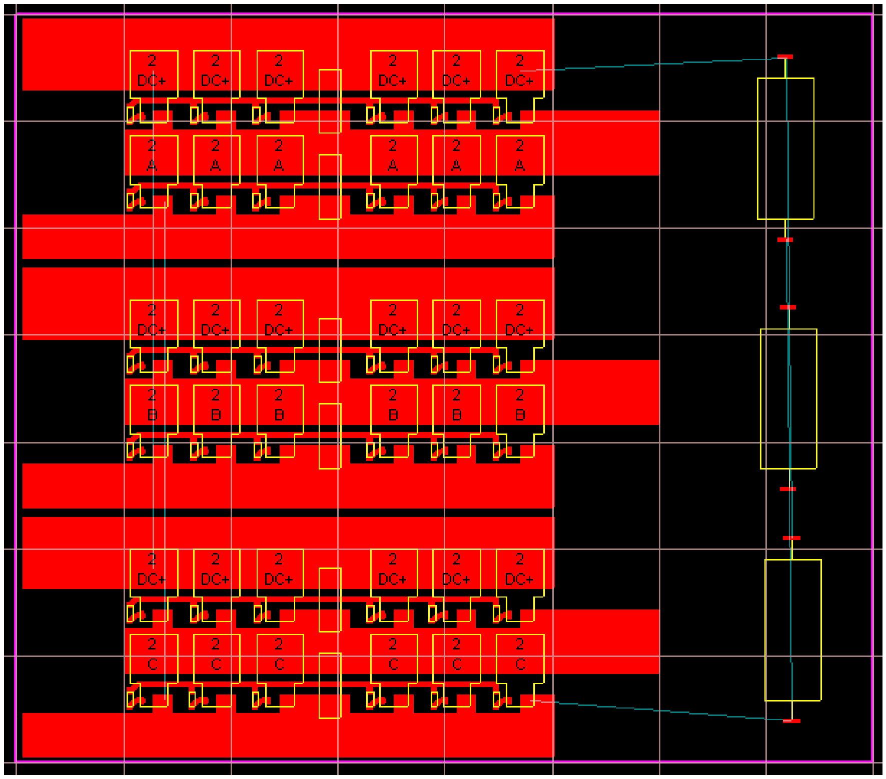


Figure 2. Printed circuit board layout for the power circuit.

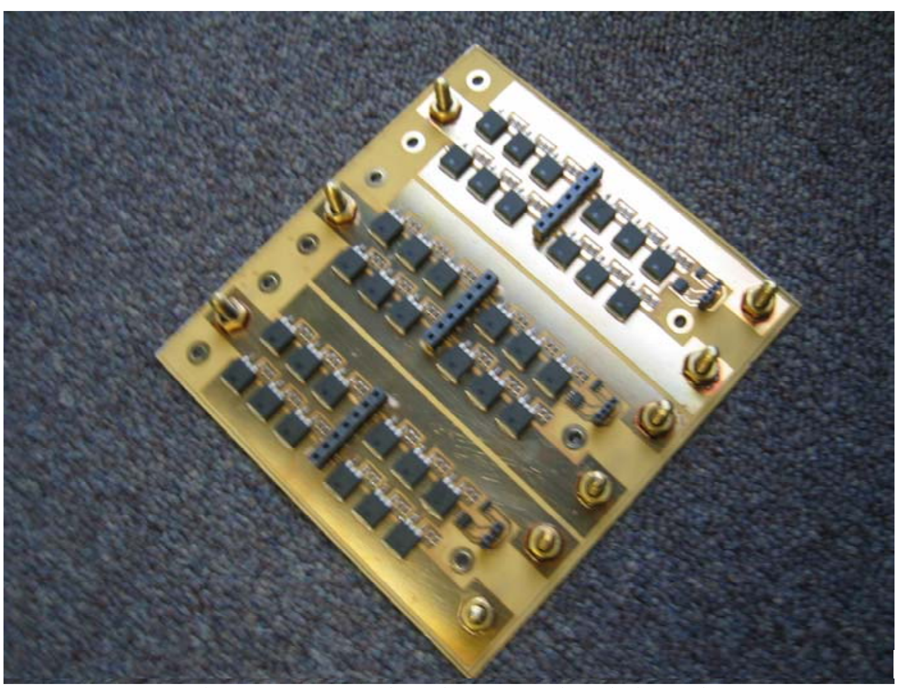


Figure 3. Completed power circuit board.

Subtask 2.2 Design and fabricate the transformer and magnetic components

Transformer is the key to successful design of the isolated dc/dc power supply. Three-phase high-frequency transformer is not standard off-the-shelf product. We have to design from scratch. A MATHCAD program has been developed for the transformer design. In this program, different core sizes were calculated to see which one gives highest efficiency while maintaining a reasonable size. The comparison results indicated that Planar E64 core is the best choice. For the specified 5-kW power level, we started with 6-kW continuous and 10-kW peak to avoid saturation. Detailed specification and features are listed as follows.

Specifications:
Peak power rating: 10 kW for 1 minute
Continuous power rating: 6 kW
Total loss at 6 kW: 39 W

Features:
Low leakage inductance (<27 nH)
Low core loss (<20 W)
Low copper loss (<20 W)
Low cost (<$60 in 1000 quantity)

Figure 4 shows the final assembly of the three-phase transformer. Three pairs of planar E64 cores were used with heavy copper for the primary winding and thinner copper for the secondary. Overall size is about half of a standard letter size paper.

Figure 4. Three-phase transformer assembly.

Both power circuit board and transformer will be tested next month to show their performance. Once test is completed, the complete converter will be assembled together for the entire converter performance test. Figure 5 shows the Autocad drawing for the planned final assembly of the entire dc/dc converter.

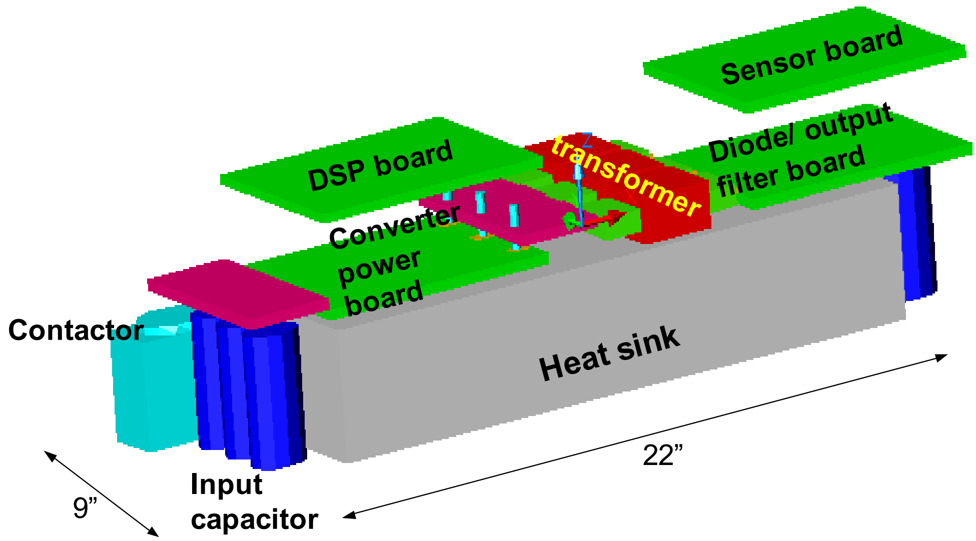


Figure 5. Autocad drawing for the planned final assembly of the entire dc/dc converter.

2. KEY MILESTONE UPDATE

The following table identifies key milestones that are completed and to be completed. The completed are marked with thick solid lines, and tasks to be completed are marked with dash lines.

	Aug-02 Oct-02	Oct-02 Jan-02	Jan-02 Apr-02	Apr-02 Jul-03	Jul-03 Oct-03	Apr-03 May-03
1 Computer modeling and simulation						
2 Design Optimization **2.1 Power circuit** **2.2 Magnetic components** 2.3 Thermal management 2.4 Auxiliary power supply						
3 Design and Fabricate the Controller Circuit						
4 Integrate and Test the Alpha Version DC/DC Converter Prototype						
5 Test the DC/DC Converter with Fuel Cell Source						

3. Discussion Topics

Not applicable in this period.

4. Significant Accomplishments

Major power circuit components were designed and fabricated with significant reduction in size and parasitic components.

5. Science & Technology Transfer

A presentation was given in SECA Program Review Meeting in Sacramento, CA on February 20, 2003. Participants were all the SECA Industry Team members and Core Technology Program participants.

6. Presentation & Publications

The presentation file for the SECA Program Review is attached.

7. Site Visits

Not application in this period.

8. Travel

Travel was completed from February 18 to 21, 2003 to present the progress report to SECA Team Members in Sacramento, CA.

9. Inventions

Not applicable in this period.

A High-Efficiency Low-Cost DC-DC Converter for SOFC

February 19-20, 2003

SECA Core Technology Program Review Meeting

Presented by

Dr. Jason Lai

Virginia Polytechnic Institute and State University

The Bradley Department of Electrical and Computer Engineering

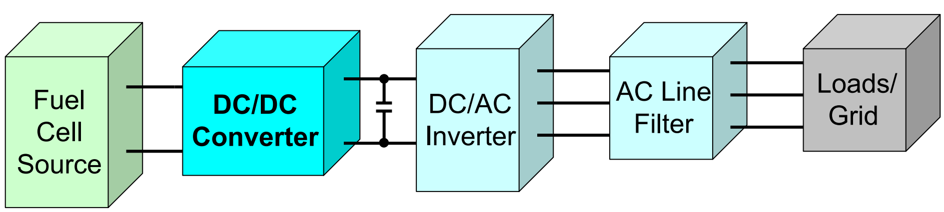
Outline

- Fuel Cell Power Conditioning
- State-of-the-Art High-Power DC/DC Converter Technologies
- Proposed DC/DC Converters
- Performance Evaluation
  - Efficiency
  - Cost
  - Ripples
  - Dynamic Response
- Project Status

Part 1: Overview of DC/DC Converters

- DC/DC Converter Requirement in a Typical Power Plant
- Isolated versus Non-isolated
- Uni-directional versus Bi-directional
- Voltage Source versus Current Source
- Design Calculation for Voltage Source Converter
- Design Calculation for Current Source Converter
- Overall features of Voltage and Current Source Converters

A Typical Fuel Cell Power Plant

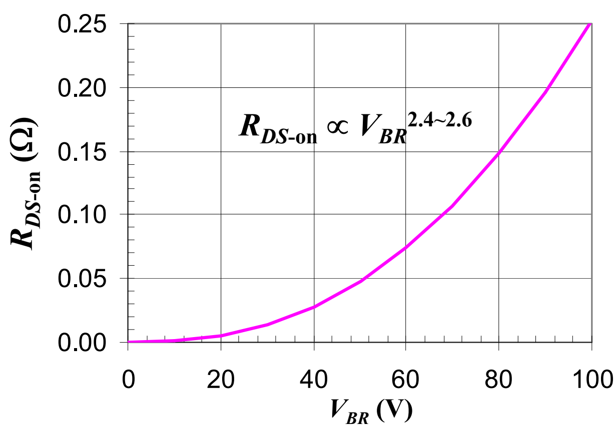


- The DC/DC converter is the most crucial electrical interface to the fuel cell source
- Requirements for the DC/DC Converter:
  - ✓ High efficiency
  - ✓ High reliability
  - ✓ Low ripple current
  - ✓ Capable of start-up with auxiliary source
  - ✓ Capable of communicating with fuel cell
  - ✓ Low electromagnetic interference (EMI) emission

Selection of DC/DC Converters

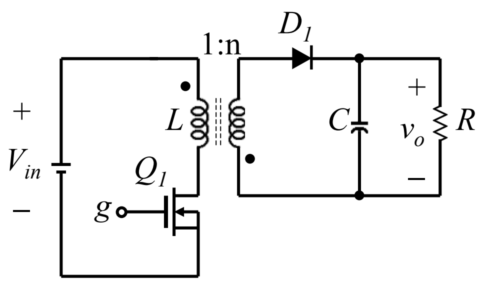
- Linear mode versus switched mode
- Switched mode versus switched capacitor
- Isolated versus non-isolated
- Uni-directional versus bi-directional
- Voltage source versus current source
- Single stage versus multiple stages
- Single phase versus multiple phases
- Single level versus multiple levels

MOSFET Conduction Loss as a Function of Breakdown Voltage Rating

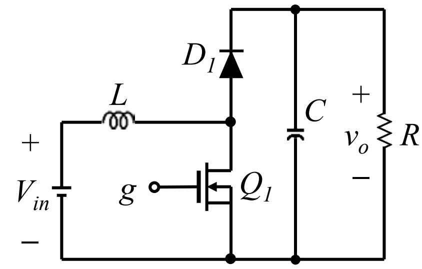


Power MOSFET is more cost effective at lower voltages
Selection of circuit topology should take into account the voltage stress of the device.

Isolated versus Non-isolated DC/DC Converter

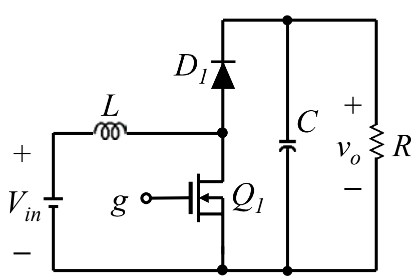


An isolated flyback converter

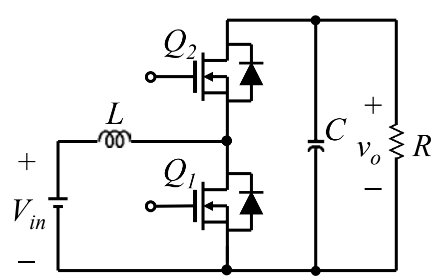


A non-isolated boost converter

Uni-directional versus Bi-directional Converters

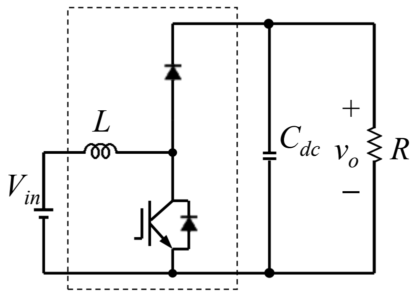


Uni-directional boost converter

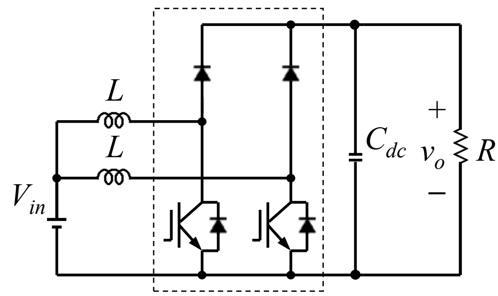


Bi-directional dc/dc converter

Single-Phase versus Two-Phase Boost Converters

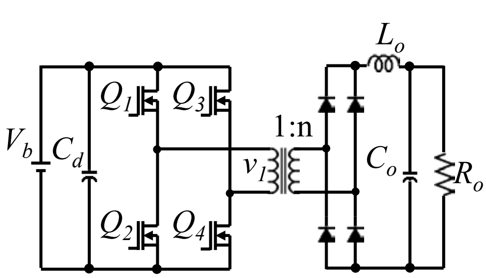


Single-phase boost converter

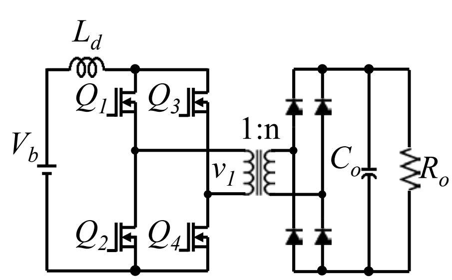


Two-phase boost converter

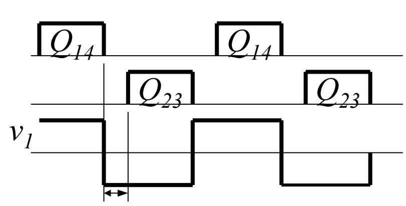
Voltage-Source versus Current-Source Converters



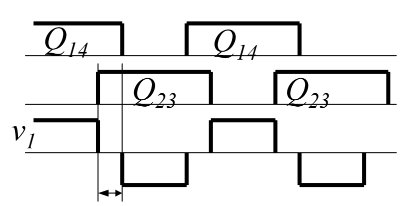
Voltage-source converter



Current-source converter

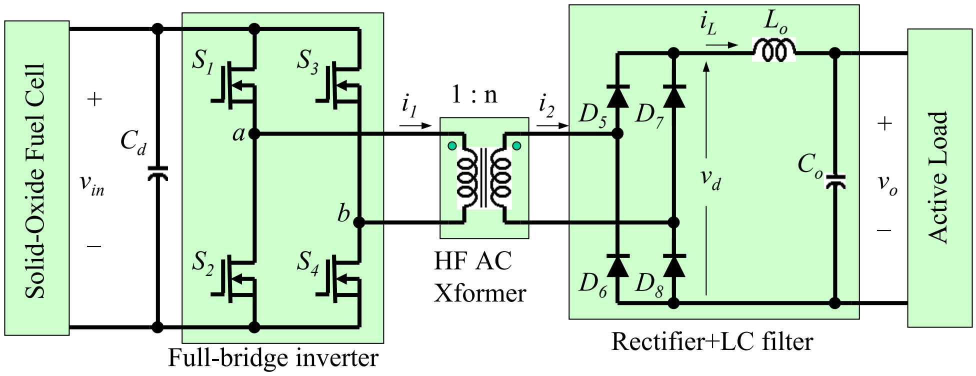


dead-time, energy circulating thru anti-paralleled diodes



overlap-time, energy charging to inductor

Voltage Source Full-Bridge DC/DC Converter Circuit

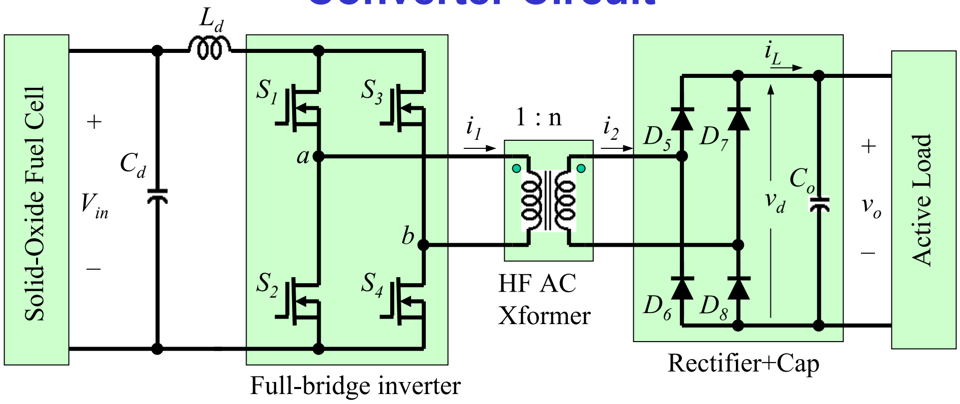


- ✓ **Capacitor C_d+full-bridge circuit = voltage source inverter**
- ✓ **HF Transformer converts voltage to a different level**
- ✓ **Rectifier bridge converts HF ac to pulsating dc**
- ✓ **Voltage $V_d + L_o + C_o$ = a buck converter**
- ✓ **Overall is an "isolated buck" converter**

Design Calculation for Voltage Source Converter

- **Fuel cell power: 6 kW for 5 kW load + 1 kW parasitic and losses**
- **Fuel cell (low side) output voltage: 22 to 50 V, 25 V as nominal**
- **Fuel cell output current = 6000/25 = 240 A**
- **High side voltage = 400 V**
- **High side average current = 6000 / 400 = 15 A**
- **Low-side switch peak voltage = 50 V + overshoot, choose 75 V**
- **Low-side switch avg. current = 240 /2 = 120 A**
- **Transformer turns ratio = 400/25/0.9 = 1:18 (assume max duty cycle = 0.9)**
- **High side diode peak voltage = 50 × 18 = 900 V + overshoot, choose 1200 V**
- **High side diode avg. current = 15 / 2 = 7.5 A**
- **High side inductor average current = 15 A**

Current Source Full-Bridge DC/DC Converter Circuit



- ✓ Inductor L_d + full bridge circuit = current source inverter
- ✓ Transformer converts HF AC current to a different level
- ✓ Rectifier converts ac current to dc and charge to C_o
- ✓ Overall is considered as "isolated boost" converter

Design Calculation for Current Source Converter

- **Fuel cell power: 6 kW for 5 kW load + 1 kW parasitic and losses**
- **Fuel cell (low side) output voltage: 22 to 50 V, 25 V as nominal**
- **Fuel cell output current = 6000/25 = 240 A**
- **Low side inductor average current = 240 A**
- **High side voltage = 400 V**
- **High side average current = 6000 / 400 = 15 A**
- **Transformer turns ratio, n = 400/25 × (1 – 0.6) = 1:7 with 60% duty**
- **Low-side switch peak voltage = 400/7 = 55 V + overshoot, >100 V**
- **Low-side switch avg. current = 240/2 = 120 A**
- **High side diode peak voltage = 400 V, choose 600 V**
- **High side diode avg. current = 15/2 = 7.5 A**

Note: The reflected voltage from secondary 400 V back to primary, 400 / n, should be higher than the maximum input voltage, 50 V for the "boost" function. Smaller n is not desirable because the switch voltage stress is higher.

Duty	With 22-V input		With 50-V input	
cycle	n	Vpri	n	Vpri
0.8	3.6	110	1.6	250
0.7	5.5	73	2.4	167
0.6	7.3	55	3.2	125
0.5	9.1	44	4.0	100
0.4	10.9	37	4.8	83
0.3	12.7	31	5.6	71
0.2	14.5	28	6.4	63
0.1	16.4	24	7.2	56

Voltage and Current Rating Comparison of Major Devices and Components

		Voltage rating (V)	Current rating (A)
Voltage Source Converter	LV switch	75	120
	Transformer 1:18	22:400	240:15
	HV inductor	–	15
	HV diode	1200	7.5
Current Source Converter	LV switch	100	120
	LV inductor	–	240
	Transformer 1:7	22:400	240:15
	HV diode	600	7.5

Overall Features of Voltage-Source and Current-Source Converters

Voltage-Source Converter

- ✓ Use bulk capacitor C_d in parallel with dc bus
- ✓ Need dead time to avoid shoot-thru
- ✓ Low switch voltage stress
- ✓ No startup problem
- × Output needs an inductor
- × High transformer turns ratio ➔ poor magnetic utilization
- × High diode voltage stress

Current-Source Converter

- ✓ Use inductor choke L_d in series with dc bus
- ✓ Need overlap to avoid over-voltage
- ✓ No need for output inductor
- × High switch voltage stress, poor device utilization
- × High LV side inductor current ➔ heavy copper, hard to manufacture
- × Cannot start with low output voltage

Part 2: Semiconductor Cost Estimation and Efficiency Modeling

- Survey of Power Devices
- Device Conduction Loss Model
- Separation of Power Losses
- Efficiency Comparison
- Loss Comparison at 6 kW Output

Survey of High Current Power MOSFETs

Manufacturer	Part Number	V_{DSS} (V)	$R_{DS\text{-}on}$ (mΩ)	Package
Fairchild	FDB045AN08A0	75	4.5	TO-263
International Rectifier	IRFP2907	75	4.5	TO-247
Fairchild	FDP047AN08A0	75	4.7	TO-220AB
IXYS	FMM 150-0075P	75	4.7	ISOPLUS i4-PAC*
Vishay Siliconix	SUM110N08-05	75	4.8	TO-263
IXYS	IXUC160N075	75	6.5	ISOPLUS 220
International Rectifier	IRF3808	75	7.0	TO-220AB
Fairchild	FQA160N08	80	7.0	TO-3P

Quantity	1	100	1000	25,000	50,000	100,000
FDB045AN08A0	$3.50	$2.50	$2.40	$2.30	$2.10	$1.60
IRFP2907	$4.49	$3.96	$3.07	$3.07	$3.07	$2.89
FDP047AN08A0	$3.50	$2.50	$2.40	$2.30	$2.10	$1.60
FMM 150-0075P	$8.00	$7.00	$6.19	$5.79	$5.30	$5.03
SUM110N08-05	$2.70	$2.50	$2.50	$2.35	$2.19	$2.19
IXUC160N075	$4.00	$3.00	$2.05	$1.65	$1.49	$1.40
IRF3808	$2.29	$2.16	$1.80	$1.50	$1.30	$1.17
FQA160N08	$4.00	$3.00	$2.90	$2.60	$2.50	$2.20

*Note: IXYS FMM 150-0075 is a dual pack (half bridge) device.

Survey of Ultrafast Reverse Recovery Diodes

Manufacturer	Part Number	V_F	t_{rr}	I	Package
Fairchild	RHRG5060	1.5 V	45ns (max)	50 A	TO-247
International Rectifier	HFA50PA60C	1.9 V	23ns (typ)	50 A	TO-247AC
IXYS	DSEK 60-06A	1.6 V	35ns (typ)	60 A	TO-247AD

Quantity	1	100	1000	25,000	50,000	100,000
RHRG5060	N/A, (300 part min)		$3.50	$1.75	$1.50	$1.50
HFA50PA60C	$8.81	$8.22	$7.71	$7.61	$7.25	$4.00
DSEK 60-06A	$4.00	$3.00	$2.50	$2.07	$1.99	$1.90

Total Cost of Semiconductors at 100,000 Production Quantity

1. For full-bridge converter, assume 6 power MOSFETs in parallel along with four output diodes.

   Cost = 6 × 4 × $1.60 + 4 × $1.50 = $44.4

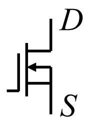
2. For the proposed converter, assume 4 power MOSFETs in parallel along with six output diodes.

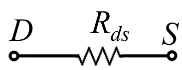
   Cost = 4 × 6 × $1.60 + 6 × $1.50 = $47.4

For a quantity of >1 million, semiconductor cost is based on the amount of silicon and plastic. For example, the TO-220 type package MOSFET and TO-247 diode can be negotiated down to ~30¢ each. The total semiconductor cost becomes $8.40 and $9.00, respectively.

Conduction Loss Modeling

(a) MOSFET



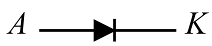


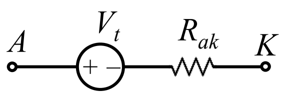
$V_{ds} = I_{on}R_{ds}$

Example: For FDB045AN08A0 power MOSFET,

R_{ds}: 4.5 mΩ at T_j = 25ºC
11 mΩ at T_j = 175ºC

(b) Diode





$V_{ak} = V_t + I_{on}R_{ak}$

Example: For RHRG5060 diode, at T_j = 100ºC

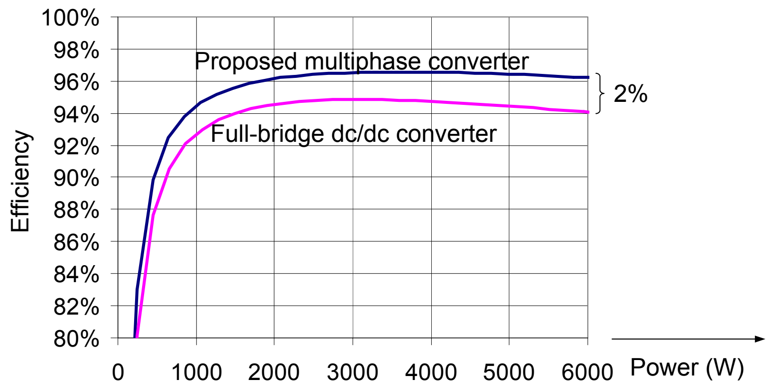
R_{ak}: 16 mΩ

V_t: 0.6 V

Separation of Power Losses

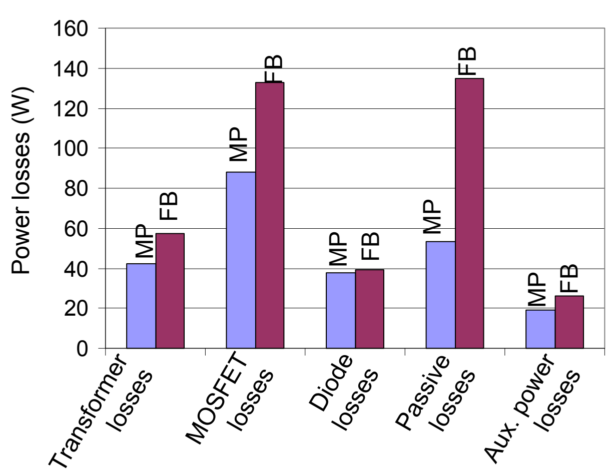
1. MOSFET conduction loss $P_{sw} = (\sqrt{D}I_1)^2R_{ds}$
2. MOSFET conduction loss $P_{sw} = (\sqrt{D}I_1)^2R_{ds}$
3. Transformer copper loss $P_{Tr\text{-}copper} = (\sqrt{D}I_1)^2R_{Tr1} + (\sqrt{D}I_2)^2R_{Tr2}$
4. Transformer core loss $P_{Tr\text{-}core} = k_{Tr}B^2f_{sw}$
5. Diode loss $P_{diode} = \sqrt{D}I_2(V_t + \sqrt{D}I_2R_{ak})$
6. Inductor copper loss $P_{Tr\text{-}copper} = I_2^2R_{Lo}$
7. Inductor core loss $P_L = k_L(\Delta i)^2f_{sw}$
8. Capacitor loss $P_{cap} = I_{ripper}{}^2R_{esr} + V_1^2\tan\delta$
9. Parasitic loss $P_{para} = \text{sqrt}(I_1)R_{para}$
10. Auxiliary power supply loss $P_{aux} = P_{const} + nQ_GV_Gf$

Efficiency Comparison Between Full-Bridge and Proposed Converters



- Assume the same condition for: the amount of silicon, transformer iron and copper, switching frequency, and ripple voltage and current, etc.
- The proposed multiphase converter peaks at **97%** and maintains 96% at full load, while the convention full-bridge converter peaks at **95%** and drops to 94% at full load.

Loss Comparison Between Full-Bridge and Proposed Multiphase Converters

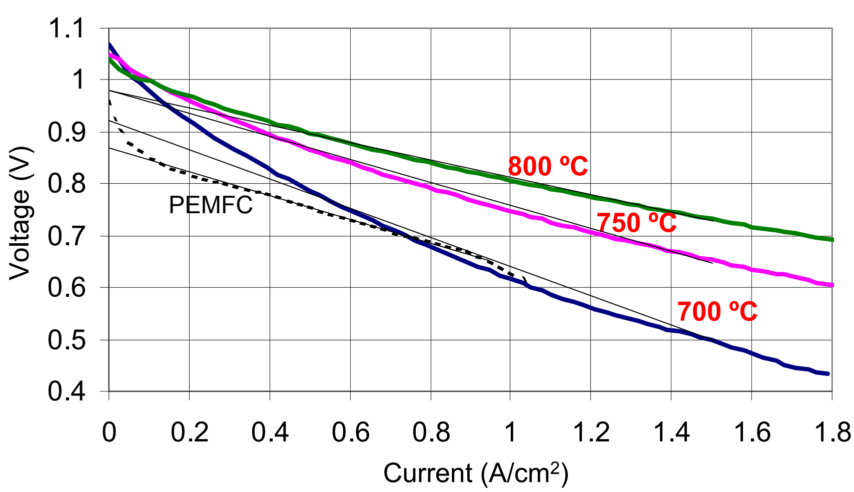


- Comparing the proposed multiphase and conventional full-bridge converters, major loss reductions are in **parasitic components** and **device switching and conduction**

Part 3: Solid Oxide Fuel Cell Modeling

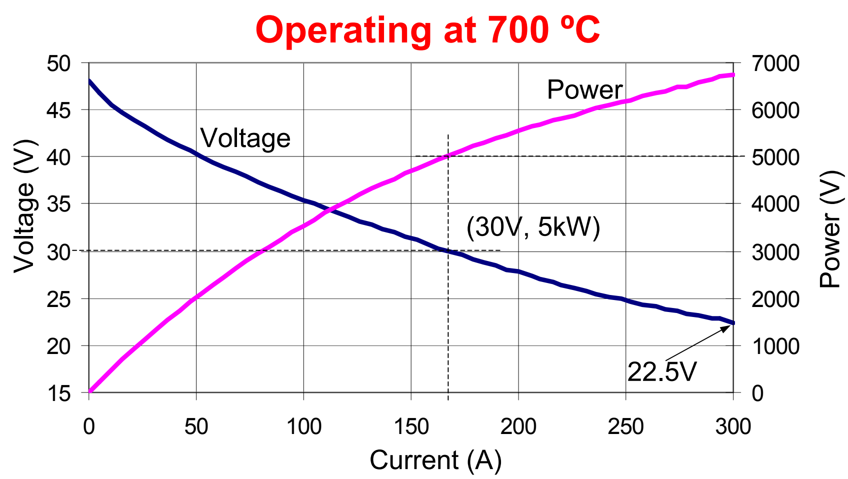
- Solid Oxide Fuel Cell (SOFC) Static Model
- SOFC Stack Modeling
- Example Static Models for Different Stack Configuration
- SOFC Dynamic Modeling
- Time Domain Response of SOFC

Fuel Cell Static Modeling

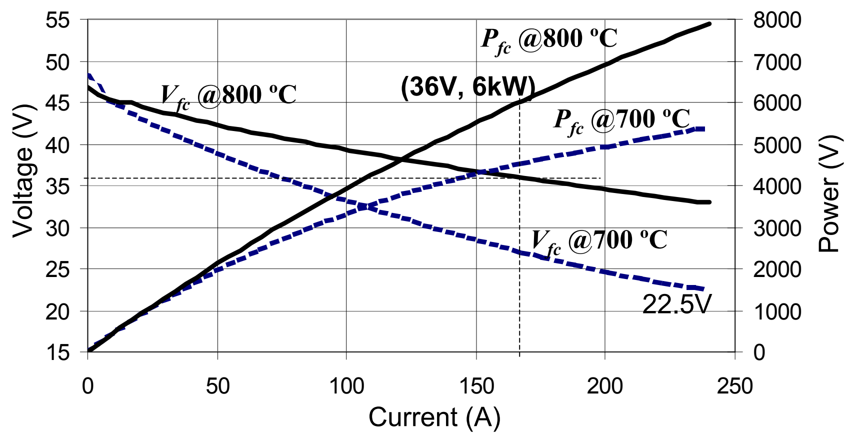


Data source: DOE SECA Modeling team report at Pittsburgh Airport, 10/15/2002

SOFC Static Characteristic with 200-cm² Area, 45-Cell Stack



SOFC Static Characteristic with 160 cm² Area, 45 Cells in Stack, 700 and 800 ºC Operating Conditions



Summary of SOFC Static Modeling

- Higher temperature, higher output power
- Cell voltage level at 700°C resembles that of PEMFC
- Internal resistance at 750°C resembles that of PEMFC
- From 0.5 to 1.5 A/cm^2, the electrical models can be approximated by
  - At 700°C, V_{fc} = 0.92 V/cell – 0.289 Ω-cm^2
  - At 750°C, V_{fc} = 0.98 V/cell – 0.222 Ω-cm^2
  - At 800°C, V_{fc} = 0.98 V/cell – 0.172 Ω-cm^2
- For comparison purpose, from 0.3 to 0.9 A-cm^2, the electrical model of PEMFC can be approximated by
  - V_{PEMFC} = 0.87 V/cell – 0.215 Ω-cm^2
- PEMFC voltage tends to collapse at 0.9A/cm^2, SOFC won't collapse until after 2A/cm^2

JSL

Example Static Models for 160-cm^2 Area, 45 Cells in Stack

At 700°C

V_{fc} = (0.92 V/cell – 0.289 Ω-cm^2 / 160 cm^2) x 45 cells

$V_{fc} = 41.4 - 0.0813 \times I_{fc}$

At 750°C

V_{fc} = (0.98 V/cell – 0.222 Ω-cm^2 / 160 cm^2) x 45 cells

$V_{fc} = 44.1 - 0.0624 \times I_{fc}$

At 800°C

V_{fc} = (0.98 V/cell – 0.172 Ω-cm^2 / 160 cm^2) x 45 cells

$V_{fc} = 44.1 - 0.0484 \times I_{fc} \rightarrow I_{fc} = (44.1 - V_{fc})/0.0484$

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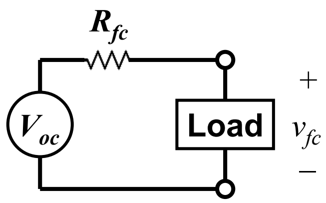
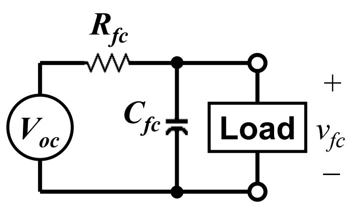
First Order Dynamic Modeling of SOFC



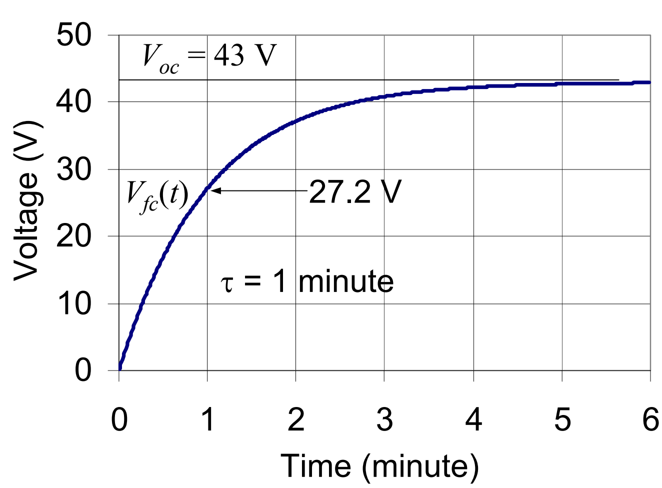
(a) Model without dynamic:
Select V_{oc} = 43 V, R_{fc} = .07 Ω, approximately at 725 °C.



(b) Model with first-order dynamic:
Select V_{oc} = 43 V, R_{fc} = 0.07 Ω, C_{fc} = 857 F. This assumes time constant = 60 s or 1 minute.

<u>Case study:</u>
V_{fc} = 29 V, I_{fc} = (43 – 29)/0.07 = 200 A, $P_{fc} = V_{fc} \times I_{fc}$ = 5.8 kW
With 95% dc/dc converter efficiency, dc output = 5.5 kW
If downstream inverter efficiency = 95%, then ac output = 5.2 kW

Time-Domain Response of SOFC Using 1-minute Time-Constant

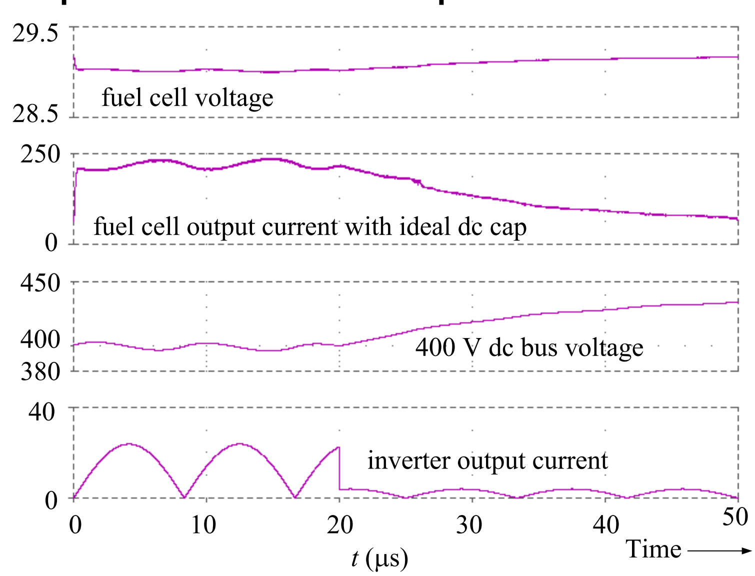


Part 4: Dynamic Simulation for the Complete System Including Fuel Cell

- **Dynamic Response of a Full-Bridge Converter with 1-min SOFC Time Constant**
- **Dynamic Response of a Full-Bridge Converter with 1-s SOFC Time Constant**
- **Dynamic Response of the Proposed Converter with 0.1-s SOFC Time Constant**
- **Dynamic Simulation Result Comparison Between Full Bridge and the Proposed Circuit.**

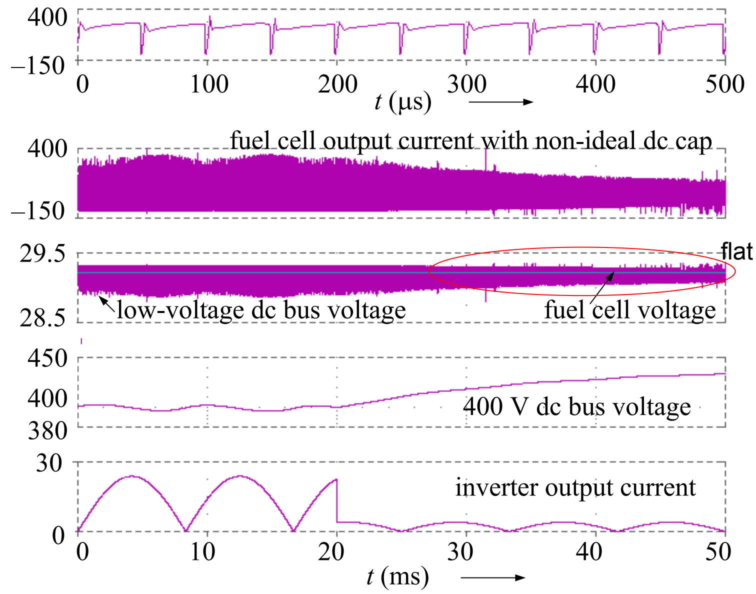
Full-Bridge Converter Responses (τ_{fc}=1 min)

Output condition: Load dump from 6 kW to 1 kW



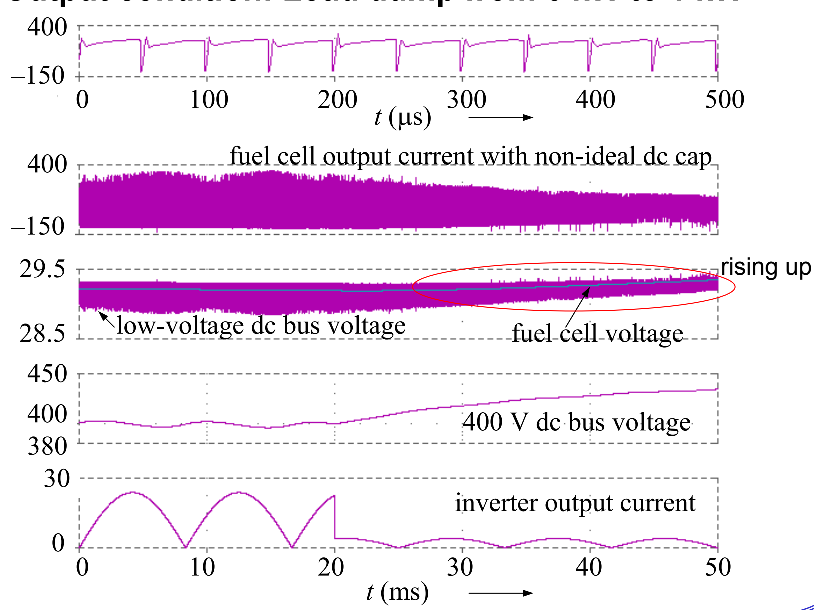
Full-Bridge Converter Responses (τ_{fc}=1 min)

Output condition: Load dump from 6 kW to 1 kW

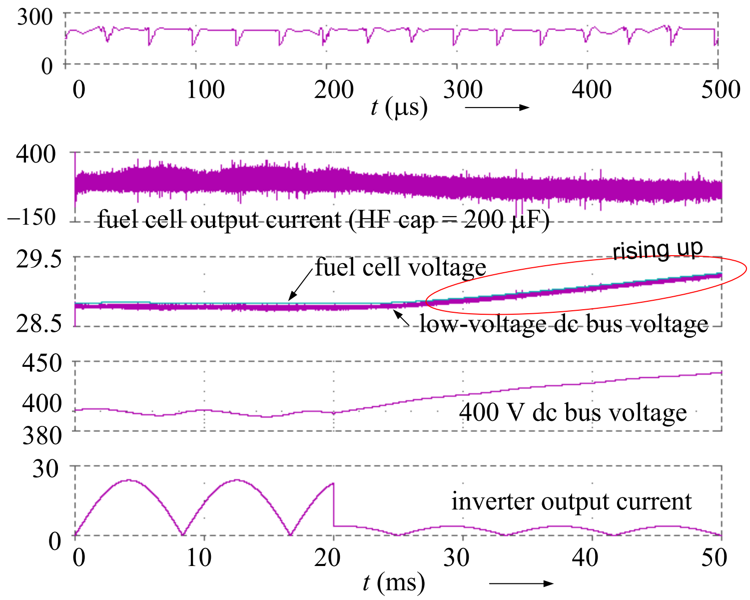


Full-Bridge Converter Responses (τ_{fc}=1 s)

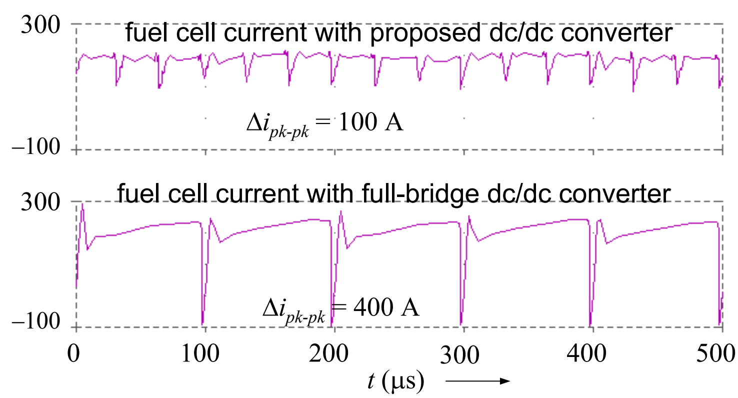
Output condition: Load dump from 6 kW to 1 kW



Proposed Converter Responses (τ_{fc}=.1 s)



Fuel Cell Current Ripple Comparison for Full-Bridge and Proposed Converter



Fuel cell voltage: 29 V
Fuel cell output power: 6 kW
DC Bus Cap: 47 mF electrolytic + 100 μF film capacitors

Prototype Multiphase Planar Transformer

Features:
- Low leakage inductance (<27 nH)
- Low core loss (<20 W)
- Low copper loss (<20 W)
- Low cost (<$60 in 1000 quantity)

Specifications:

Peak power rating: 10 kW for 1 minute
Continuous power rating: 6 kW
Total loss at 6 kW: 39 W

Complete DC/DC Converter Assembly