Fuel Cell Current Ripple Reduction with Active Control Technique

January 27 – 28, 2005
SECA Core Technology Program Review Meeting
Tampa, Florida

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JSL

Outline

1. **Review of V6 DC-DC converter**
2. **Prototype Development**
3. **Current Ripple Reduction**
4. **Summary of V6 Converter Prototype**
5. **Accomplishments and Future Work**

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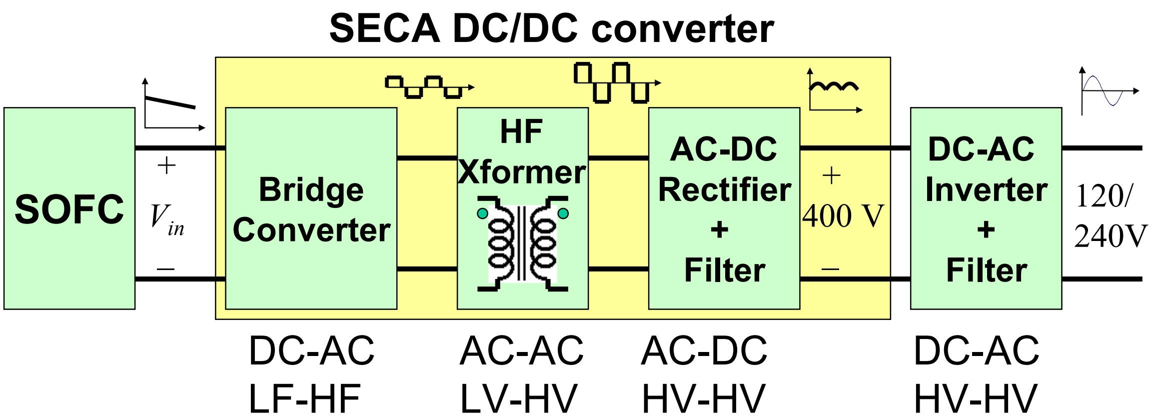
Block Diagram of the SOFC Power Plant



- **Fuel cell output or converter input is low-voltage DC with a wide-range variation**
- **Plant output is high-voltage ac**
- **Multiple-stage power conversions including isolation are needed**

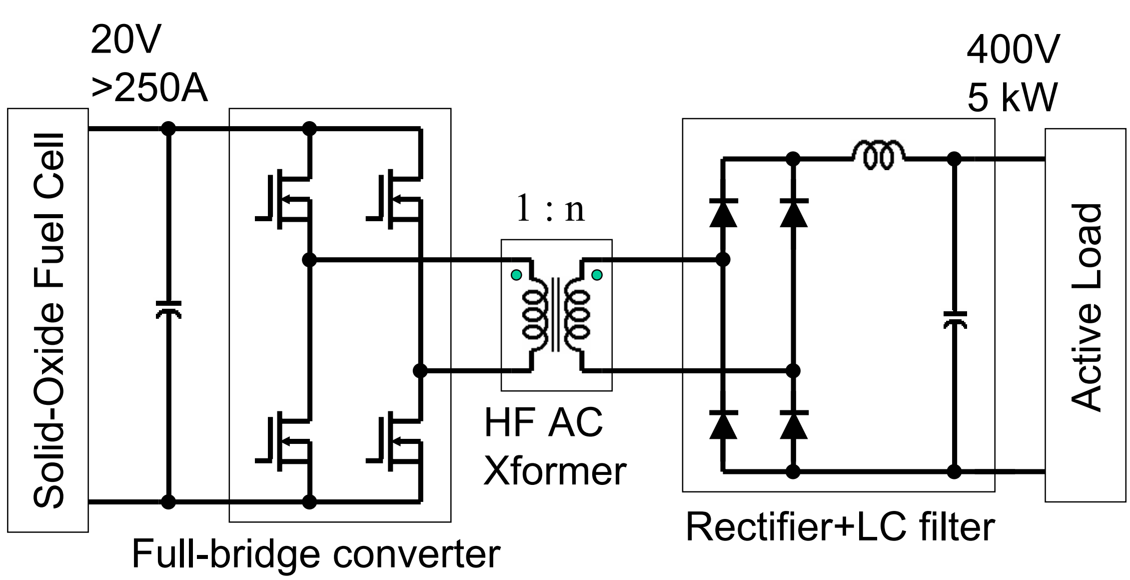
Major Issues Associated with the DC/DC Converter

- **Cost**
- **Efficiency**
- **Reliability**
- **Ripple current**
- **Transient response along with auxiliary energy storage requirement**
- **Communication with fuel cell controller**
- **Electromagnetic interference (EMI) emission**

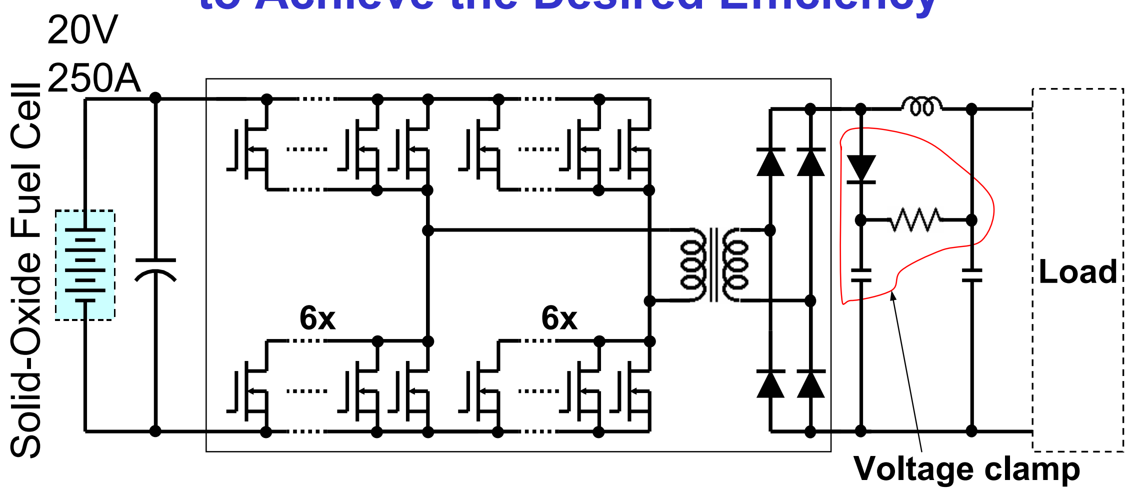
Virginia Tech Approaches

- Efficiency improvement to reduce fuel consumption
- V6 multiphase control to reduce passive components for cost reduction
- Ripple current elimination to reduce size of fuel cell stack
- Soft start and current control to reduce the inrush current so as to improve reliability
- Soft switching to reduce EMI

State-of-the-Art Full-Bridge Converter

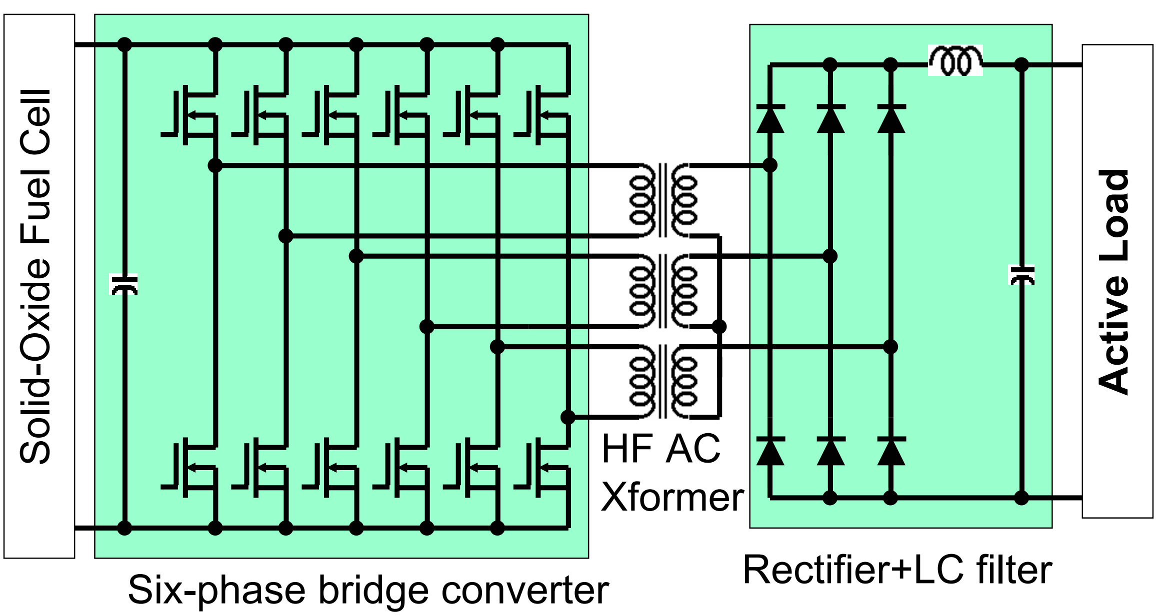


Full-Bridge Converter with Paralleled Devices to Achieve the Desired Efficiency



- With 6 devices in parallel, the two-leg converter can barely achieve 95% efficiency
- Problems are additional losses in parasitic components, voltage clamp, interconnects, filter inductor, transformer, diodes, etc.

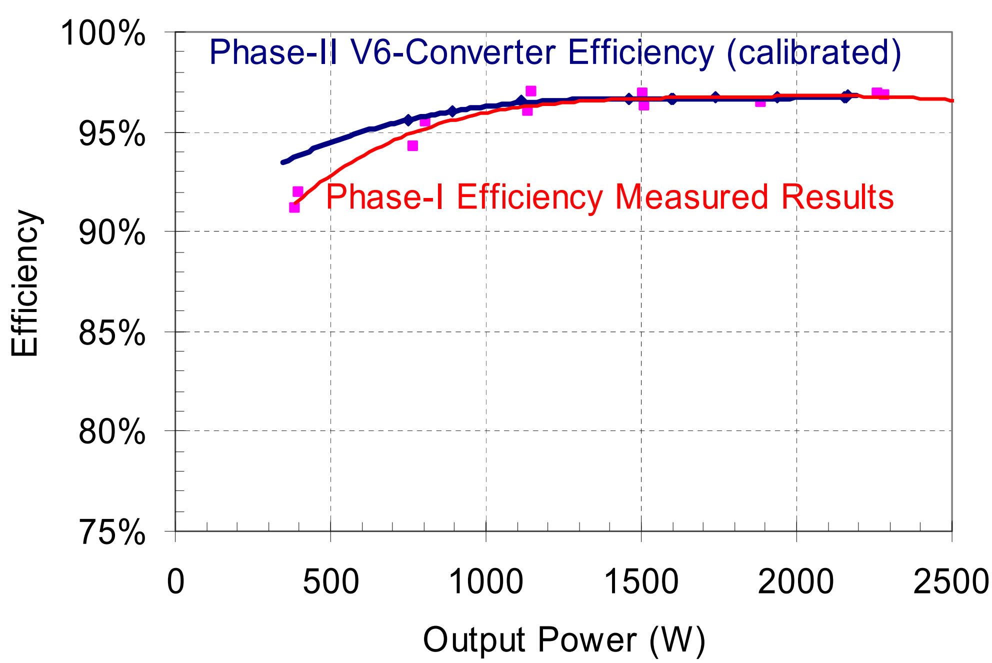
Circuit Diagram of the Proposed V6 Converter



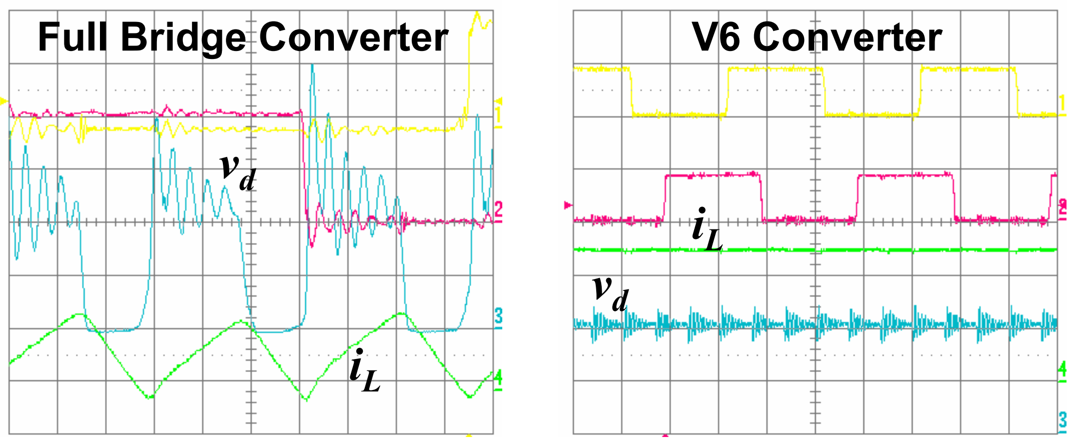
Key Features of the V6 Converter

- Double output voltage ➔ reduce turns ratio and associated leakage inductance
- No overshoot and ringing on primary side device voltage
- DC link inductor current ripple elimination ➔ cost and size reduction on inductor
- Secondary voltage overshoot reduction ➔cost and size reduction with elimination of voltage clamping
- Significant EMI reduction ➔ cost reduction on EMI filter
- Soft switching over a wide load range
- High efficiency ~97%
- Low device temperature ➔ High reliability

Efficiency Measurement Results

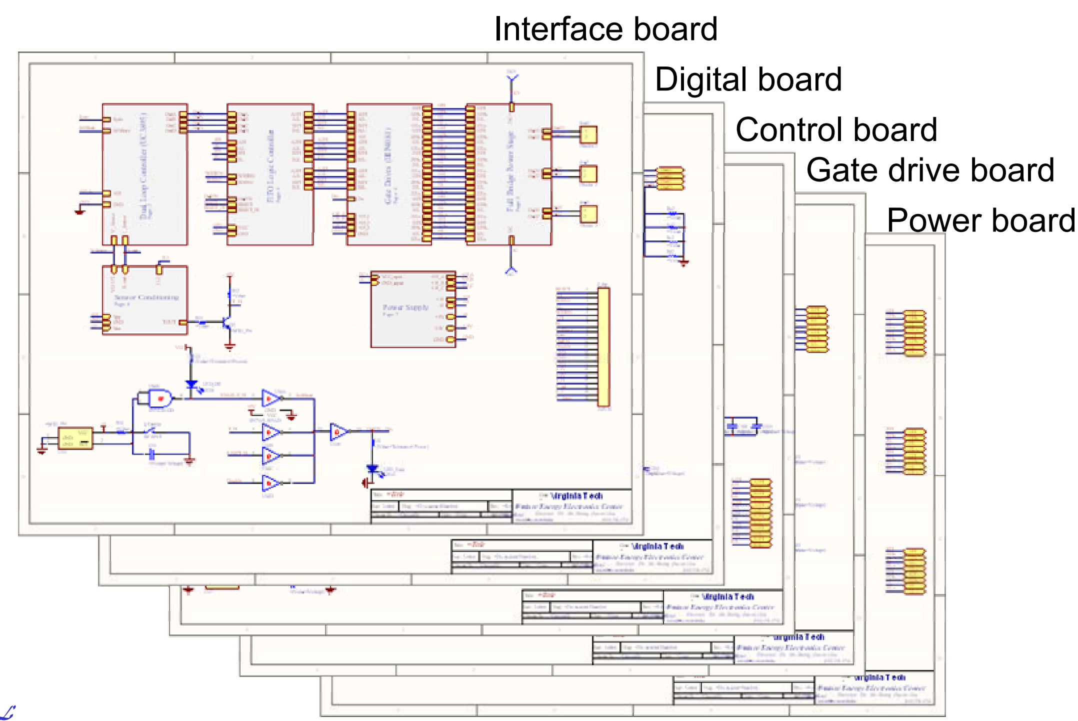


Waveform Comparison between Full-Bridge and V6 Converters

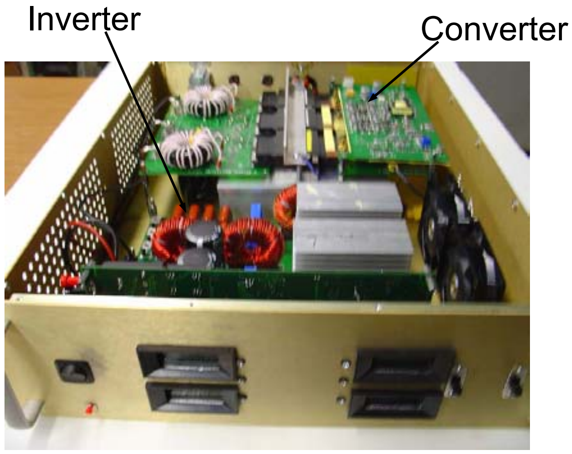


- **Secondary inductor current is ripple-less; and in principle, no dc link inductor is needed**
- **Secondary voltage swing is eliminated with <40% voltage overshoot as compared to 250%**

Schematic Circuit Diagrams



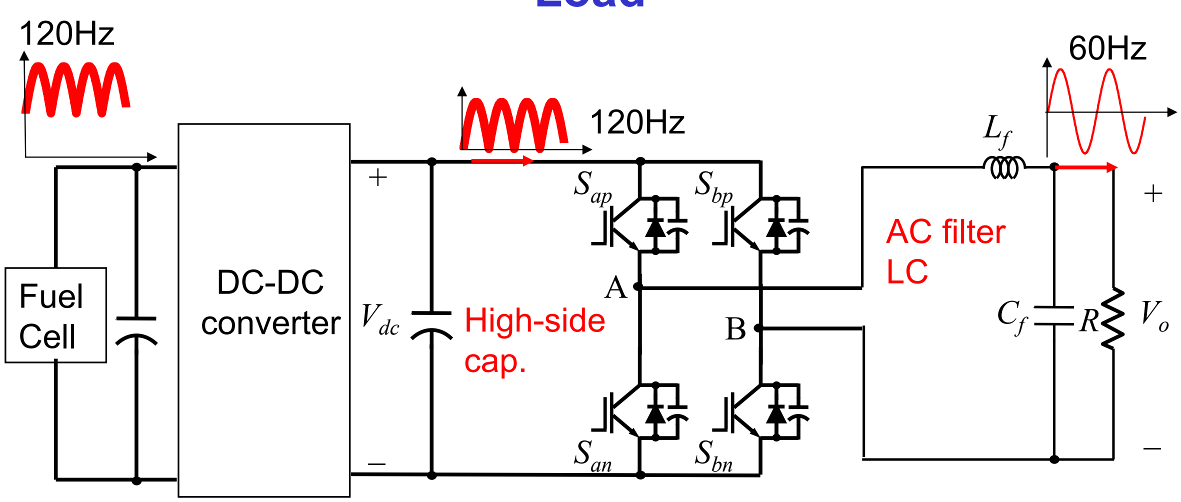
Photographs of V6-Converter Together with DC-AC Inverter Prototype



Front View

Rear View

Current Ripple Issues with DC-AC Inverter Load

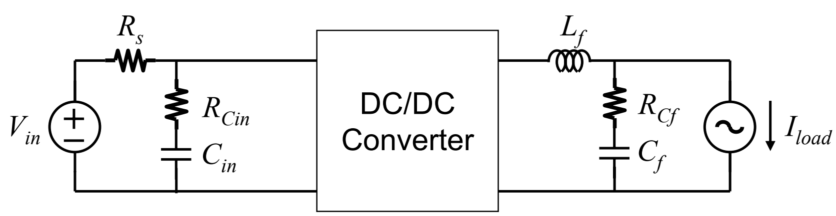


- **Current Ripple Propagates from AC Load back to DC side**
- **With rectification, ripple frequency is 120 Hz for 60 Hz systems**
- **Low-frequency ripple is difficult to be filtered unless capacitor is large enough**

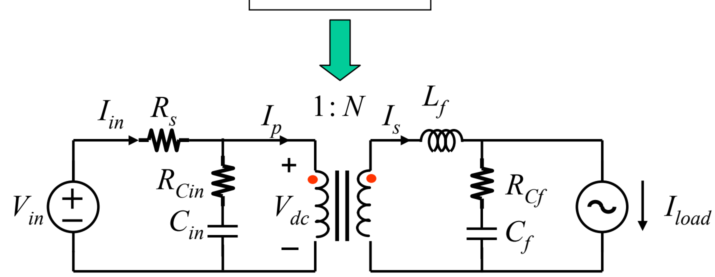
AC Current Ripple Problems

- **Inverter AC current ripple propagates back to fuel cell**
- **Fuel cell requires a higher current handling capability ➔ Cost penalty to fuel cell stack**
- **Ripple current can cause hysteresis losses and subsequently more fuel consumption ➔ Cost penalty to fuel consumption**
- **State-of-the-art solutions are adding more capacitors or adding an external active filters ➔ Size and cost penalty**
- **Virginia Tech solution is to use existing V6 converter with active ripple cancellation technique to eliminate the ripple ➔ No penalty**

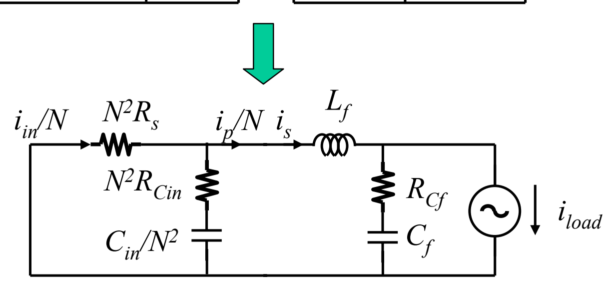
Circuit Model for AC Current Ripple



DC Model



AC Ripple Model

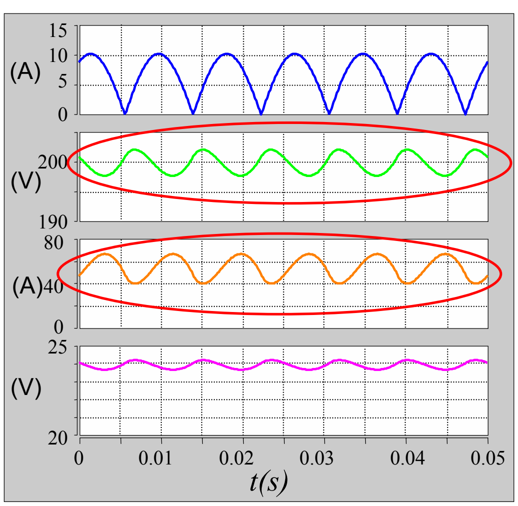


Benchmark DC/DC Converter Parameters for Ripple Study

- Input Voltage: 25V
- Output Voltage: 200V
- Input DC Capacitor: 6mF
- Output DC Capacitor: 2200mF
- Filter Inductor: 84mH
- Inverter Modulation Index: 0.86
- Inverter Load Resistor: 16.7Ω

From Theoretical Study and Simulation

Input Capacitor has Very Little Effect to Current Ripple Reduction

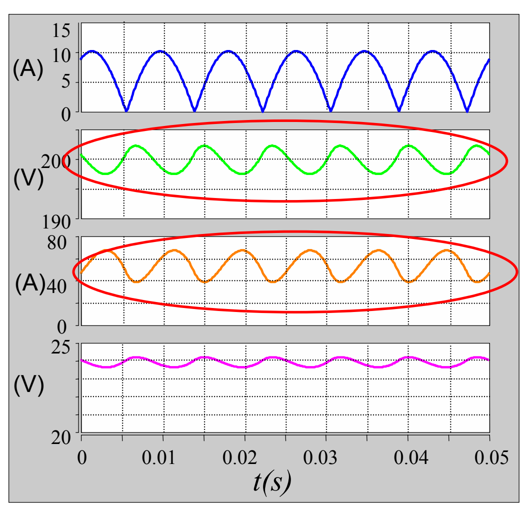


HV DC Current

HV DC Voltage

LV DC Current

LV DC Voltage

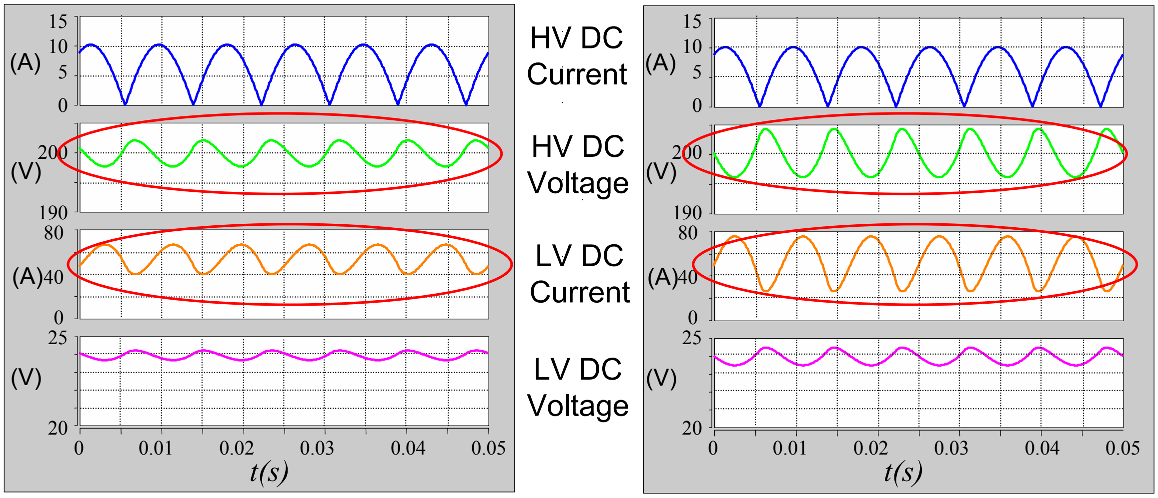


Input Cap 6mF

Input Cap Reduced to 136μF

Output Capacitor can be Used as Passive Solution to Current Ripple Reduction

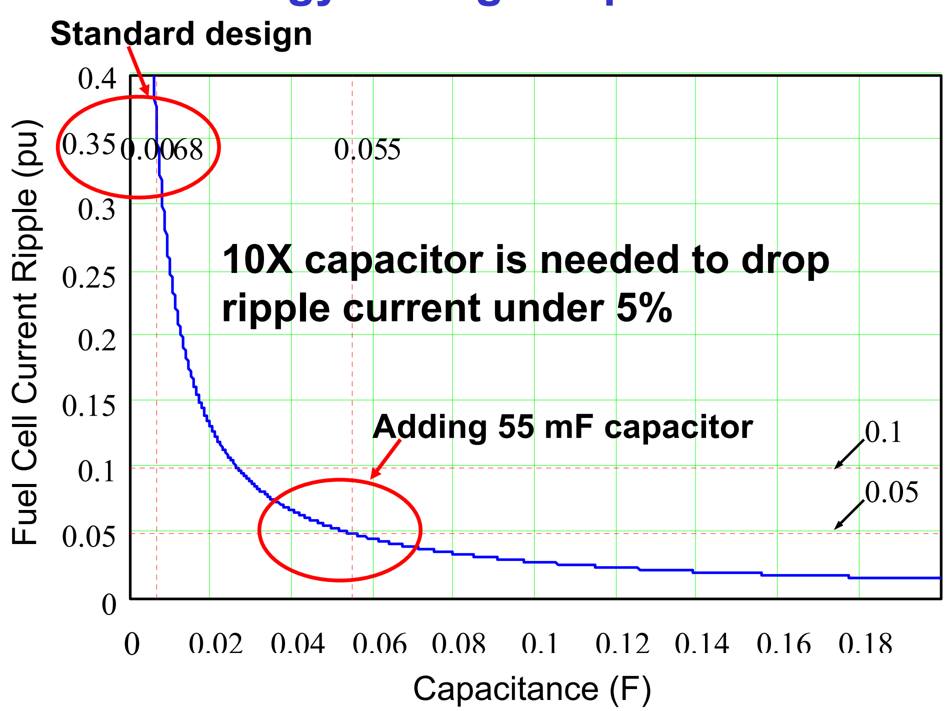
– Cost is a Concern



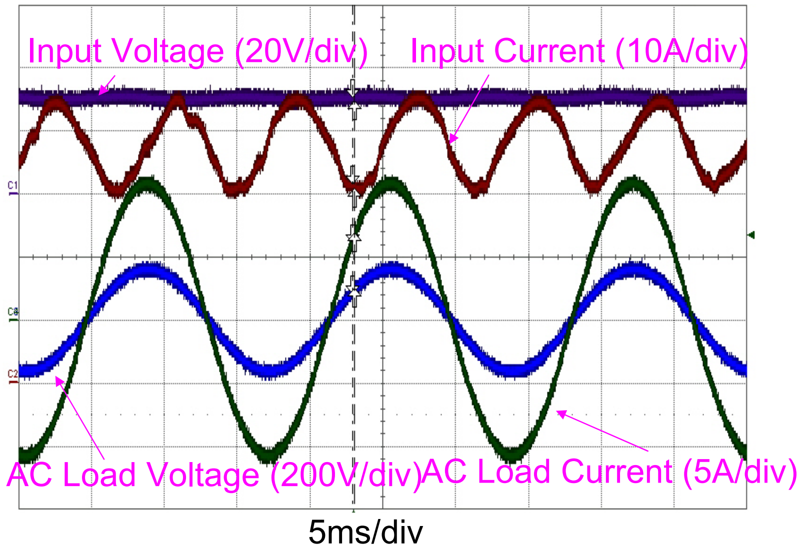
Output Cap 2.2mF

Output Cap Reduced to 820µF

Current Ripple Reduction with High-Side Energy Storage Capacitor



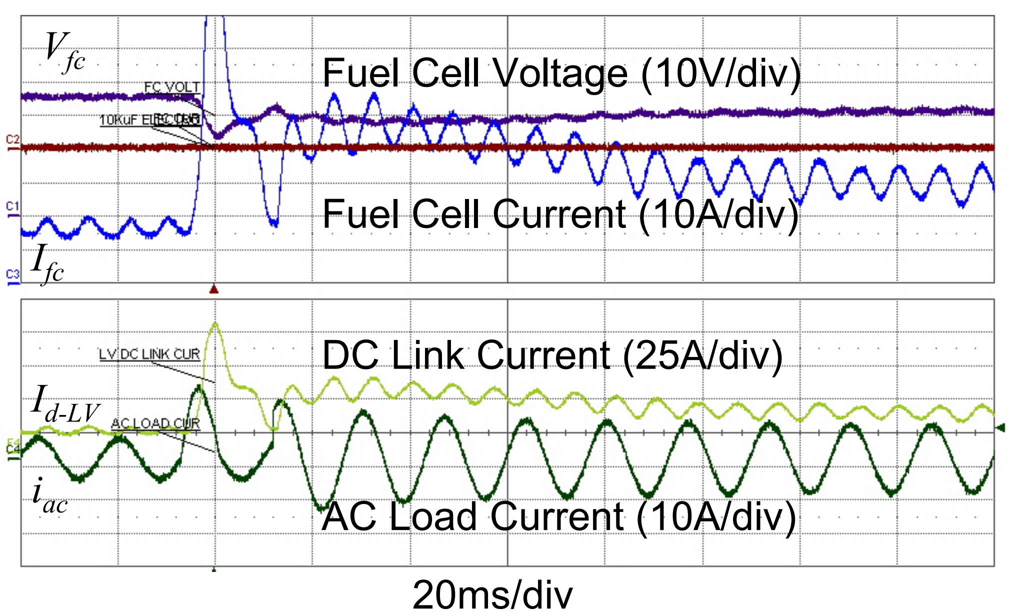
Experimental Current Ripples without Adding Capacitors or Controls



More than 35% ripple current at the input

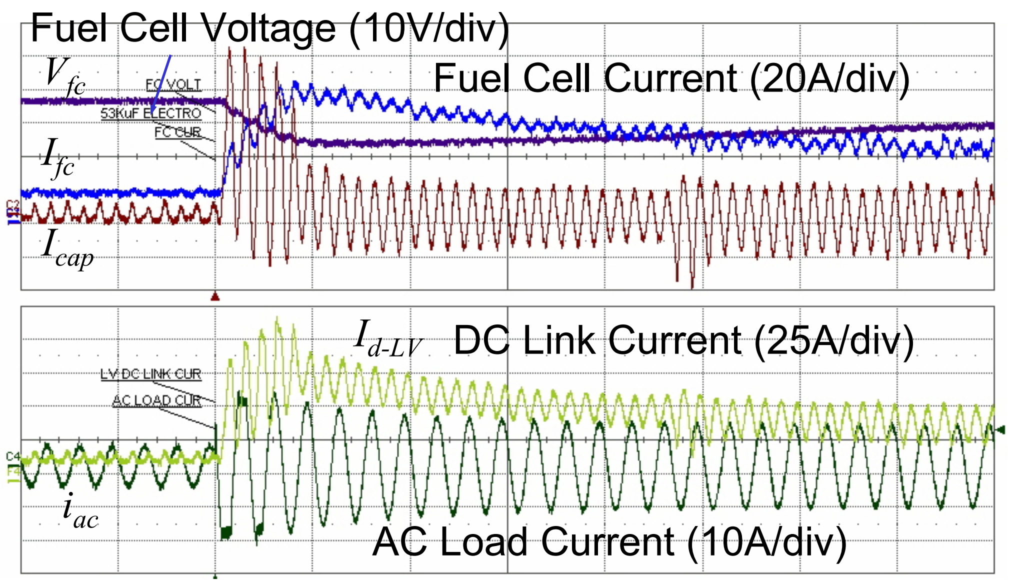
Current Ripple Under Dynamic Condition without Adding Capacitors

Fuel Cell Current Ripple is 35% plus Overshoot



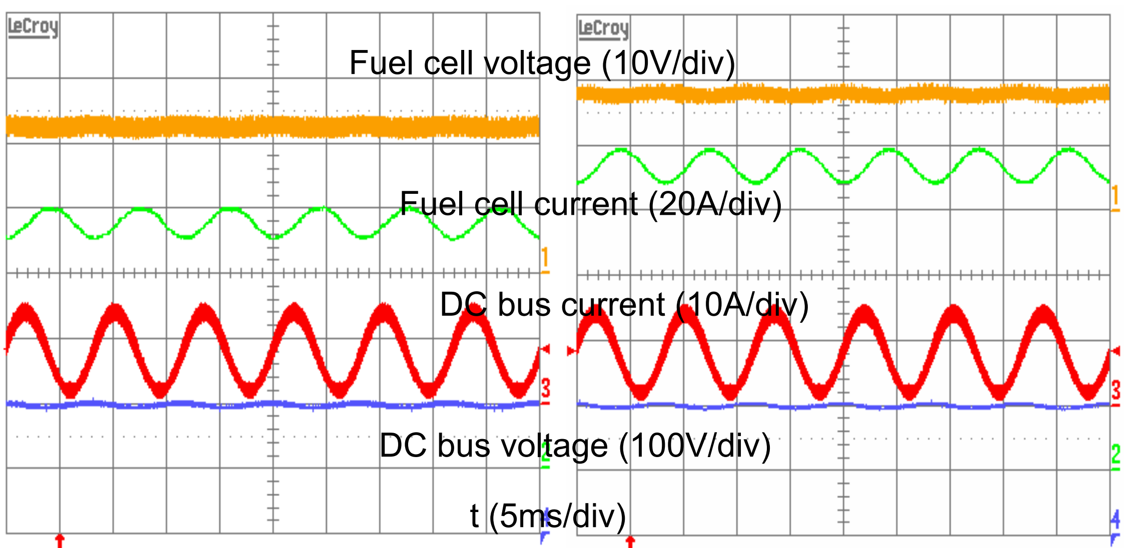
AC Load Transient Response for Fuel Cell with 53-mF Added Capacitors

Fuel Cell Current Ripple is 5% plus Overshoot



20ms/div

Experiment with Open-Loop and with only Voltage Loop Control

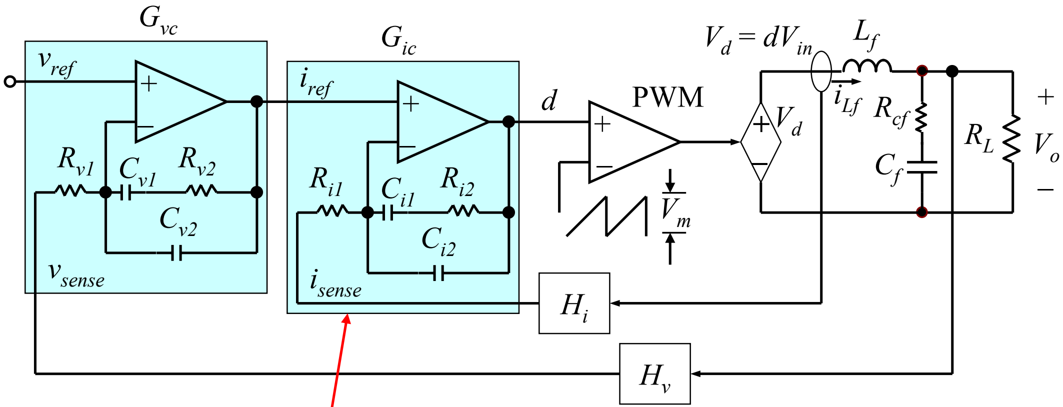


(a) Open loop

(b) With voltage loop control

No improvement on current ripple reduction with voltage loop control

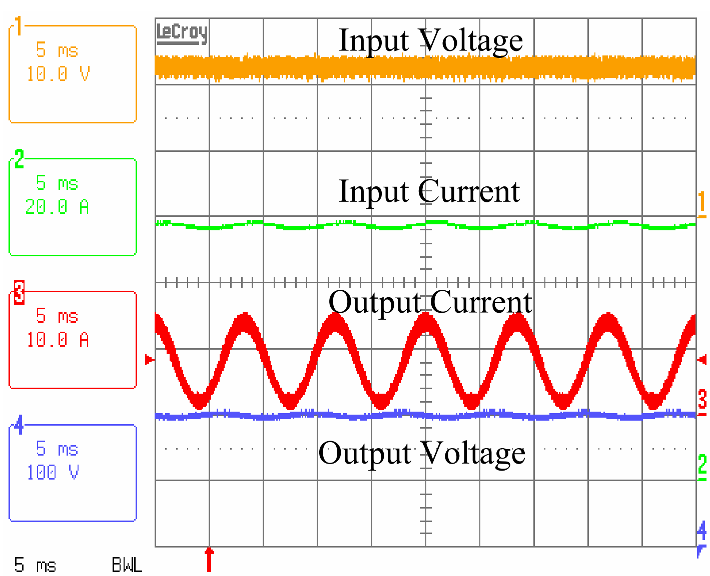
Virginia Tech Solution to Ripple Reduction



Adding a current loop to regulate the output current

Fuel Cell Current Ripple Reduction with the Proposed Active Control Technique

Fuel Cell Current Ripple is Reduced to 2%



Summary of V6 DC-DC Converter Prototype

- **High efficiency with a wide-range soft switching: 97%**
- **Cost reduction by cutting down passive components**
  - **Output inductor filter reduction with three-phase interleaved control: 6X**
  - **Input high frequency capacitor reduction: 6X**
  - **Output capacitor reduction with active ripple reduction: 10X**
- **Reliability enhancement**
  - **No devices in parallel**
  - **Soft-start control to limit output voltage overshoot**
  - **Current loop control to limit fuel cell inrush currents**
- **Significance to SECA Program and SOFC design**
  - **Stack size reduction by efficient power conversion and ripple reduction: 20%**
  - **Inrush current reduction for reliability enhancement**

Prototype and Production Cost Estimate for the 5-kW V6 DC-DC Converter

Quantity	100	1000	10000
Material cost	$475	$347	$227
Tooling, Assembly & Testing	$1,424	$347	$114
Production Cost	$1,899	$694	$341

Key Materials	Parts Count	Qty 1	Qty 10000
Power Circuit	22	$571.00	$154.40
Devices	8	$201.00	$38.40
Capacitors	6	$84.00	$30.00
Transformers	3	$180.00	$45.00
Inductors	2	$24.00	$8.00
Sensors	2	$32.00	$8.00
Contactor	1	$50.00	$25.00
Control Circuit	325	$113.70	$33.22
Resistors	164	$18.59	$2.71
Capacitors	110	$46.61	$17.41
Discretes	27	$8.00	$2.42
IC's	24	$40.50	$10.68
Miscellaneous	55	$174.80	$52.44
Total	402	$840.50	$227.05

Accomplishments

- Low-cost V6 DC-DC converter prototype has been developed to demonstrate 97% efficiency and tested with PEM fuel cells
- Two invention disclosures have been filed
  1. V6 DC-DC converter topology – already licensed to PEMDA, Knoxville, Tennessee for renewable energy applications
  2. Active current ripple reduction technique

Future Work

- Define SOFC interface protocol and design interface hardware and software
- Test V6 converter with SOFC simulator
- Test V6 converter with SECA SOFC
- Test EMI performance at EPRI-PEAC