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

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SECA Core Technology Program Review Meeting

Sacramento, California

Presented by Dr. Jason Lai

Virginia Polytechnic Institute and State University

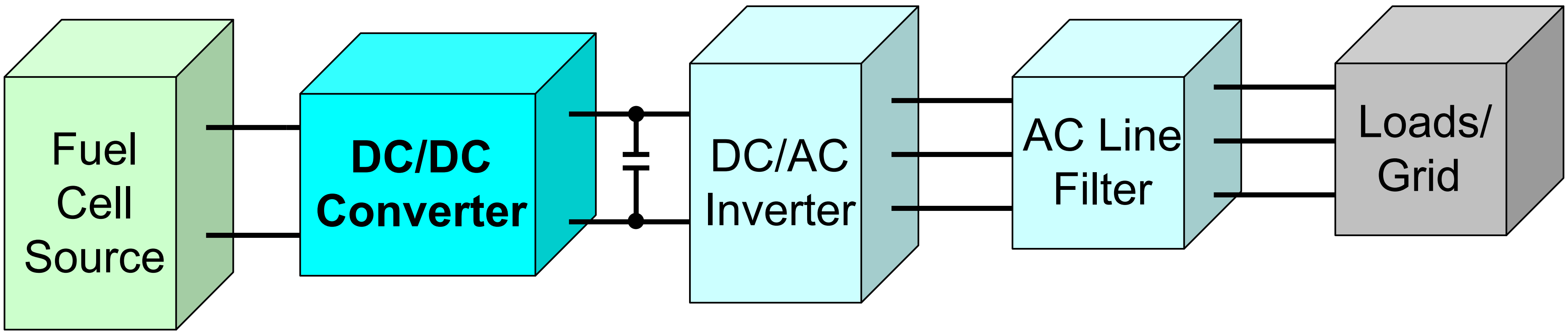
Project Team

- **Technical Team:**
  - Virginia Tech
    - Jason Lai: PI
    - Damian Urciouli: Power circuit design, simulation, and implementation
    - Elton Pepa: Magnetic circuit design, soft switching, conditioning circuit design, and testing
    - Chris Smith: Control design, digital signal processor (DSP) controller design and implementation
  - EPRI Power Electronics Applications Center
    - Tom Key: Test protocol development
    - Tom Geist: Fuel cell setup and testing
    - Haresh Kamath: Fuel cell testing
- **Sponsor:**
  - Don Collins, DOE National Energy Technology Laboratory

Technical Issues

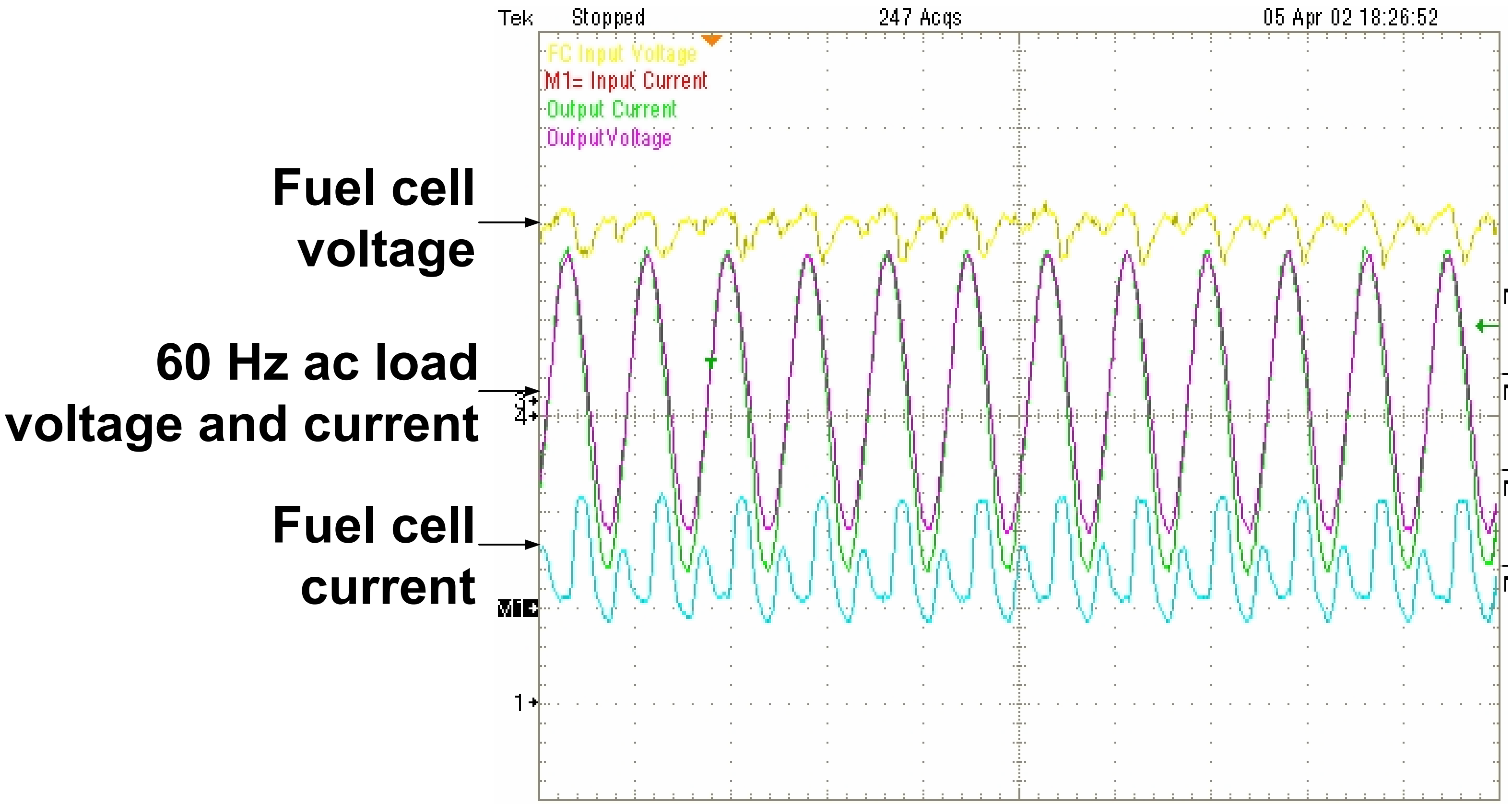
1. **Low Voltage – SECA SOFC voltage is as low as 20 V, and silicon band-gap is 0.7 V. Any device junction means 3.5% conduction loss.**
2. **High Converter Cost – Typical commercial power supply sold $1/W. It is desirable to drop the cost down to 4¢/W or $40/kW for the SECA 5-kW SOFC.**
3. **Interfacing Converter and Fuel Cell – Power converters draw tremendous current ripple from fuel cell. What are the impacts? Is there a need for a better or more fuel cell friendly power converter?**
4. **Slow Fuel Cell Dynamic – Power converters experience frequent and fast load transients, but the fuel cell source has a slow dynamic response. What are the impacts? How to deal with energy imbalance between source and load?**

A Typical Fuel Cell Power Plant



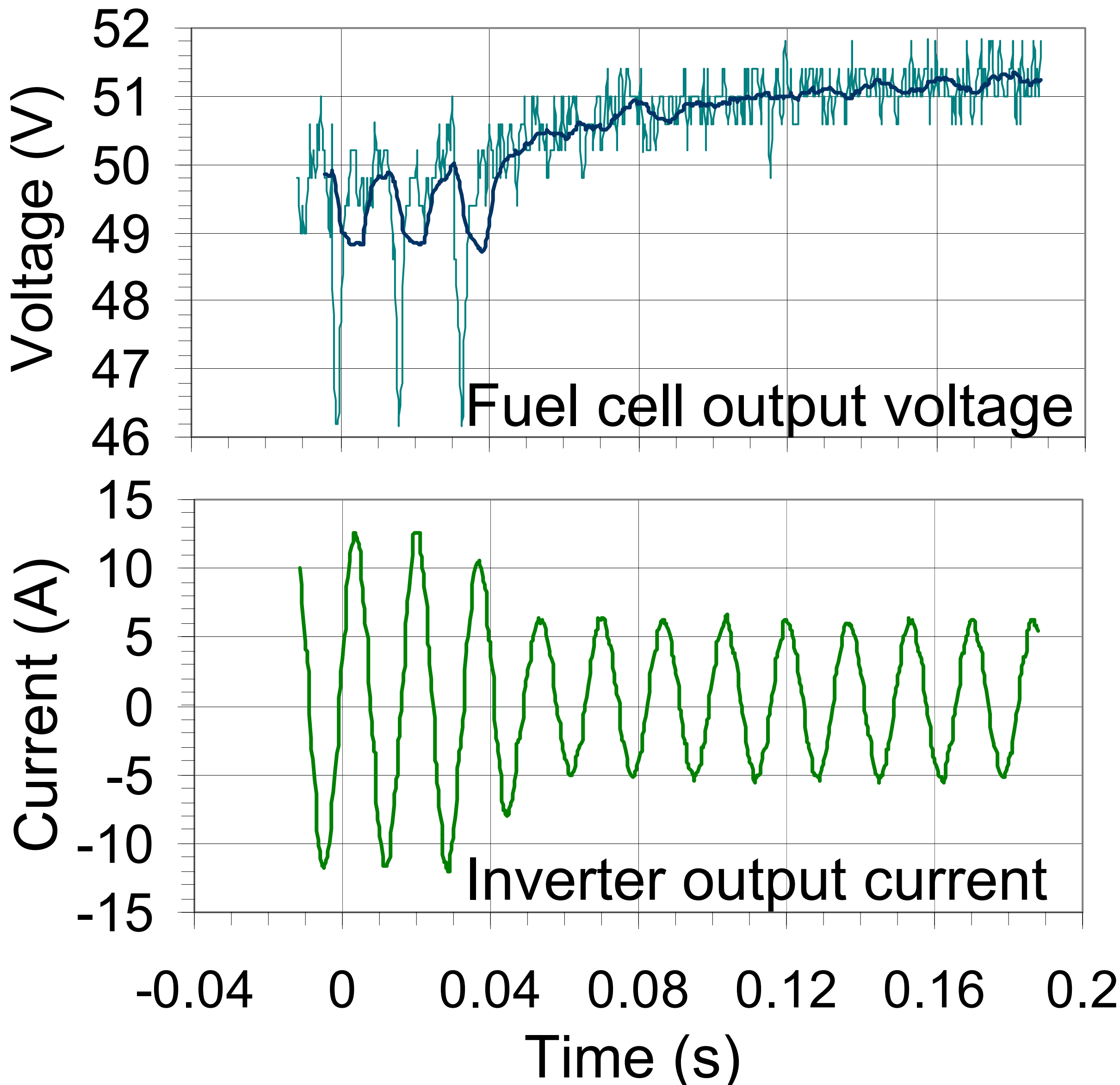
- The DC/DC converter is the most crucial electrical interface to the fuel cell source
- Requirements for the DC/DC Converter:
  - ✓ High efficiency
  - ✓ High reliability
  - ✓ Low ripple current
  - ✓ Capable of start-up with auxiliary source
  - ✓ Capable of communicating with fuel cell
  - ✓ Low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

Steady-State Fuel Cell Test Results



- Significant 120 Hz voltage and current ripple present

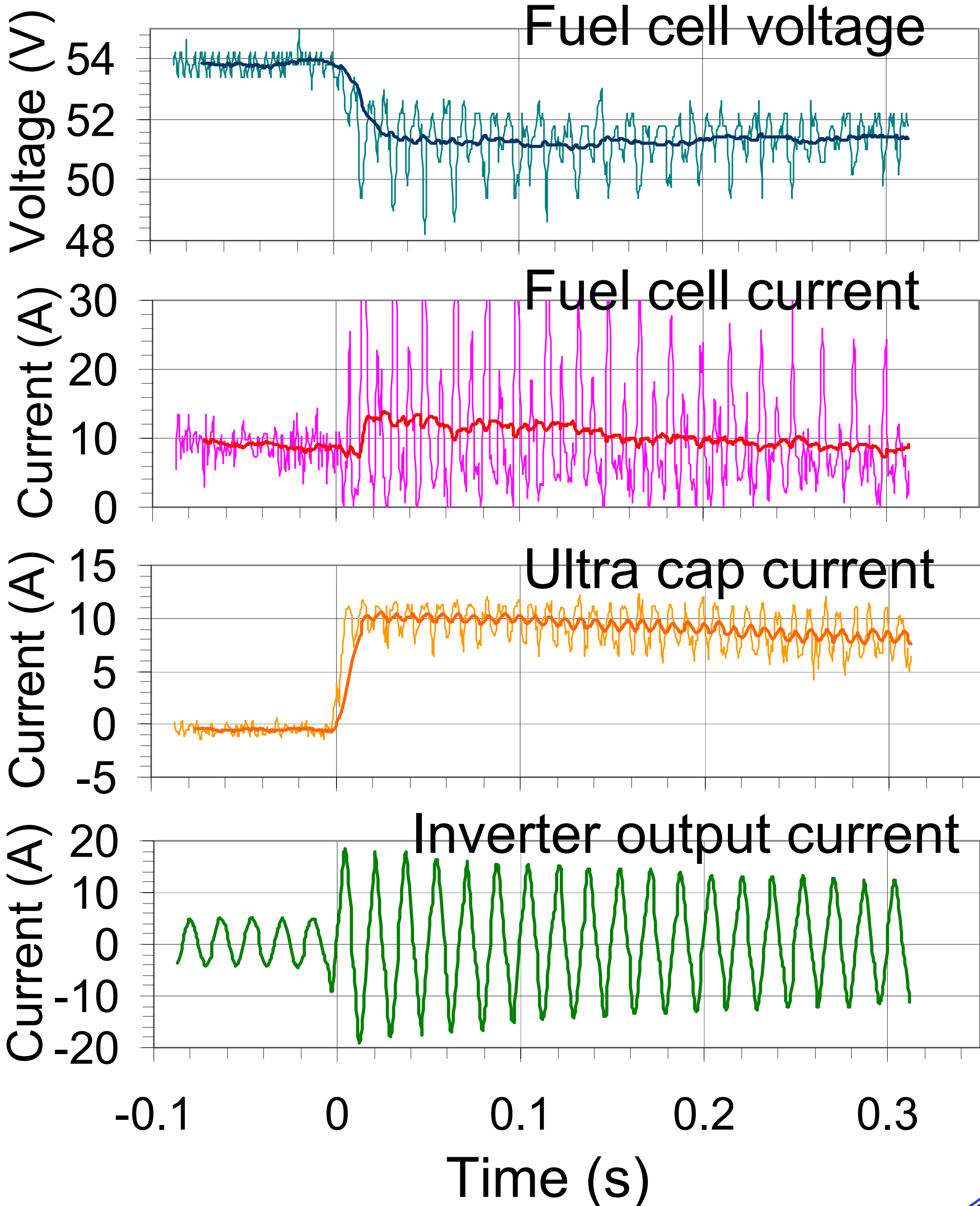
Fuel Cell Voltage During Load Dump
From 1.1 kW to 500 W



- Experiment with a 3-kW PEM fuel cell and a 3.3-F ultra capacitor.
- Use incandescent lamps as the load.
- Ultra cap smoothes the load transient effectively.
- Fuel cell time constant is reasonably fast, in millisecond range.

Fuel Cell Dynamic Response During Single-Phase Motor Start-up Transients

- Ultra cap absorbs significant current during load transient
- Dynamic fuel cell input current and voltage ripples are severe



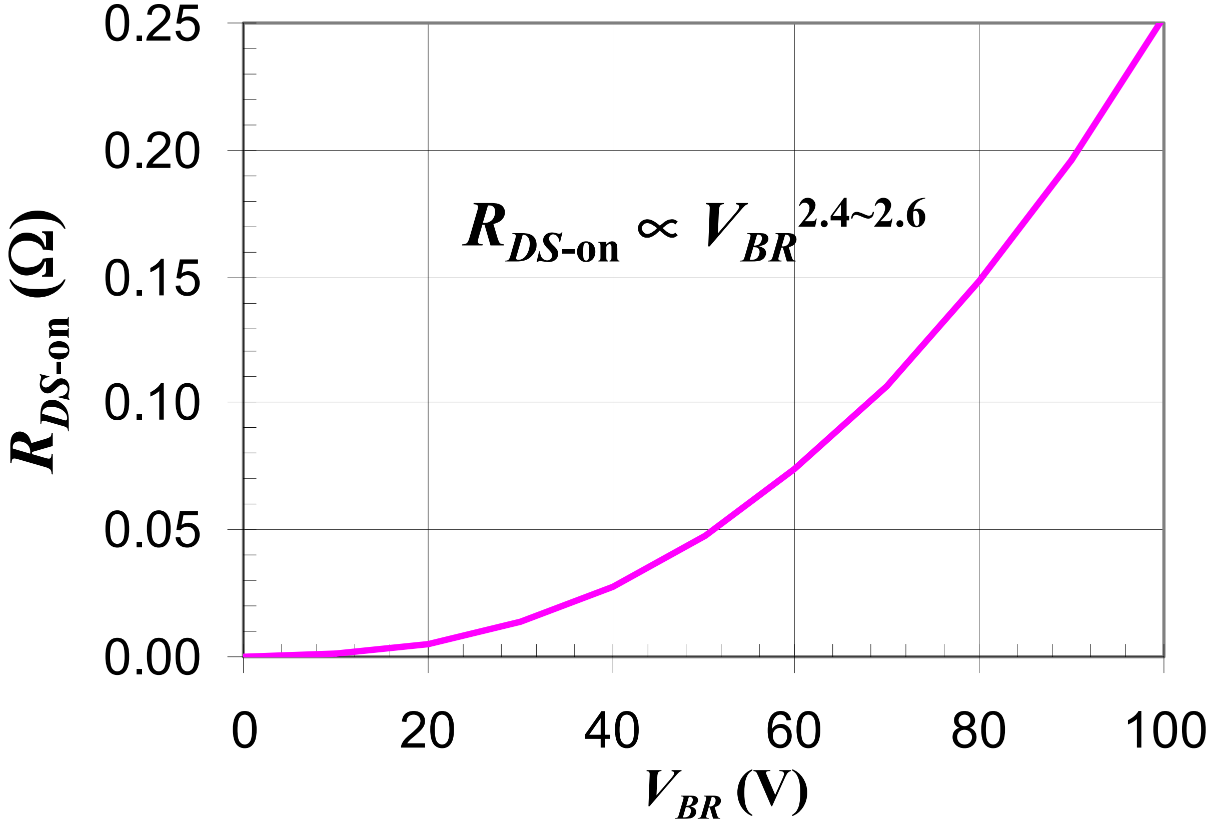
R&D Objectives

1. Efficiency Improvement
2. Cost Reduction
3. Ripple Current Reduction
4. Fuel Cell System Dynamic Response Study

R&D Approaches for Efficiency Improvement

- Selection of circuit topology and control method
- Soft switching to eliminate switching losses
- Better utilization of power semiconductor devices
- Fully utilization of magnetic materials

MOSFET Conduction Loss as a Function of Breakdown Voltage Rating

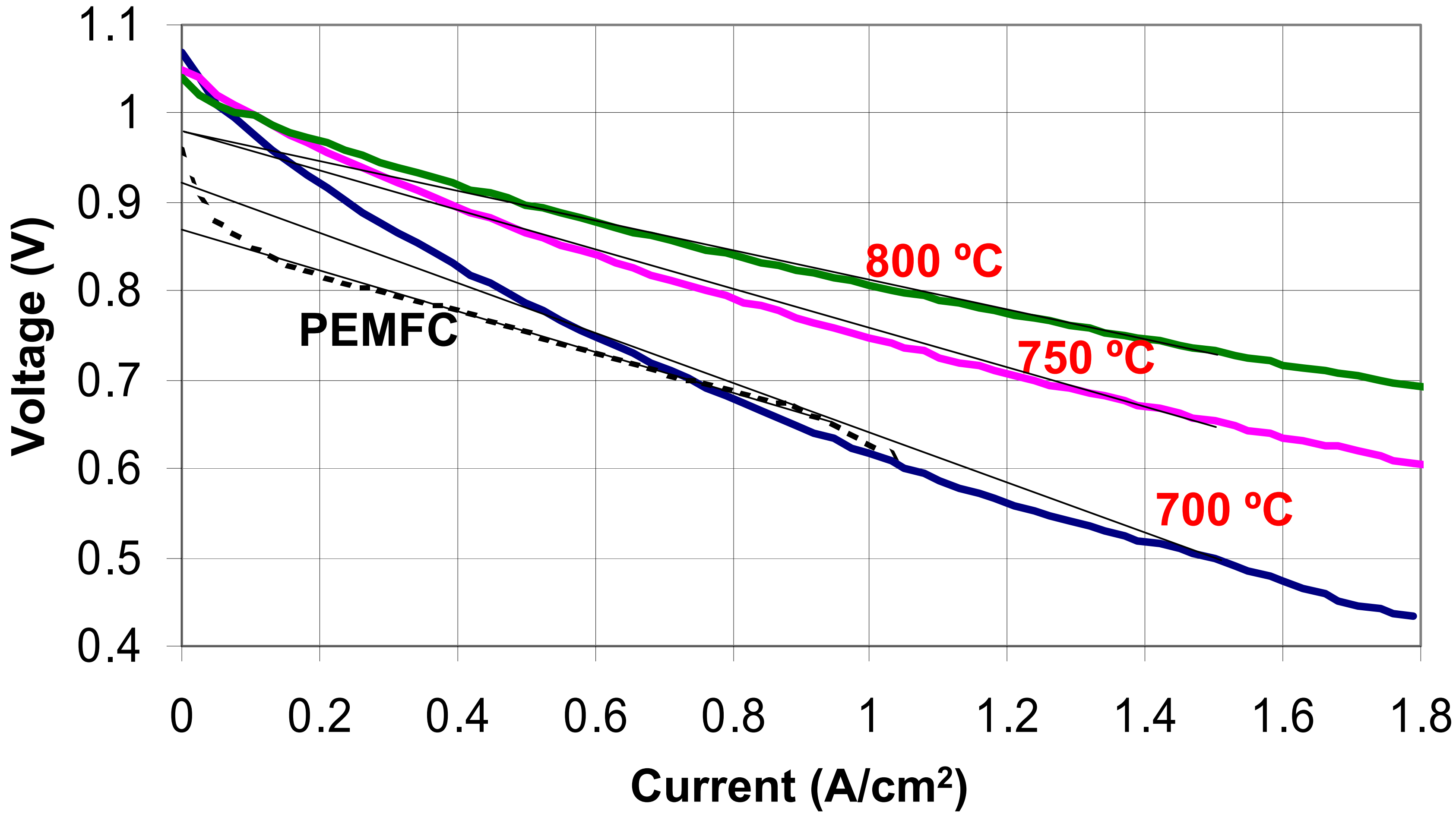


Power MOSFET is more cost effective at lower voltages
Selection of circuit topology should take into account the voltage stress of the device.

Efficiency Modeling Approach

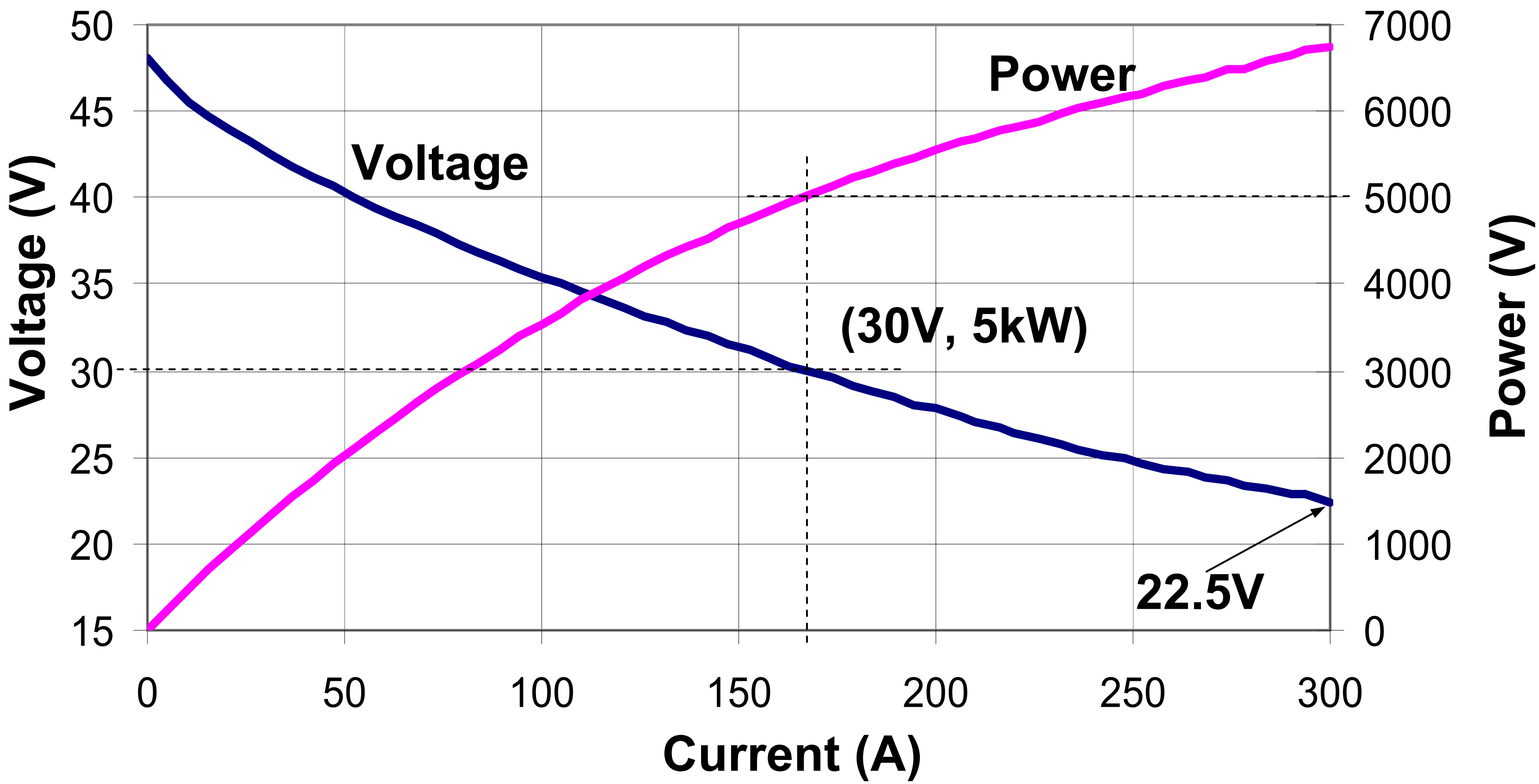
- **Fuel cell circuit modeling**
- **Transformer modeling**
- **Device modeling**
- **System loss modeling**

Fuel Cell Static Modeling



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

Voltage and Power Characteristics used in System Simulation



Transformer Core Loss Estimation

$$B_{\max} = \frac{D \cdot V_{in}}{N_1 A_e f}$$

Determine flux density, B_{max}

- **D: duty cycle**
- **V_{in}: input voltage**
- **N_1: primary turns**
- **A_e: cross section area**
- **f: frequency**

$$P_{core} = af^{c} B_{\max}{}^{d} V_e \frac{VD \cdot V_{in}}{N_1 A_e f}$$

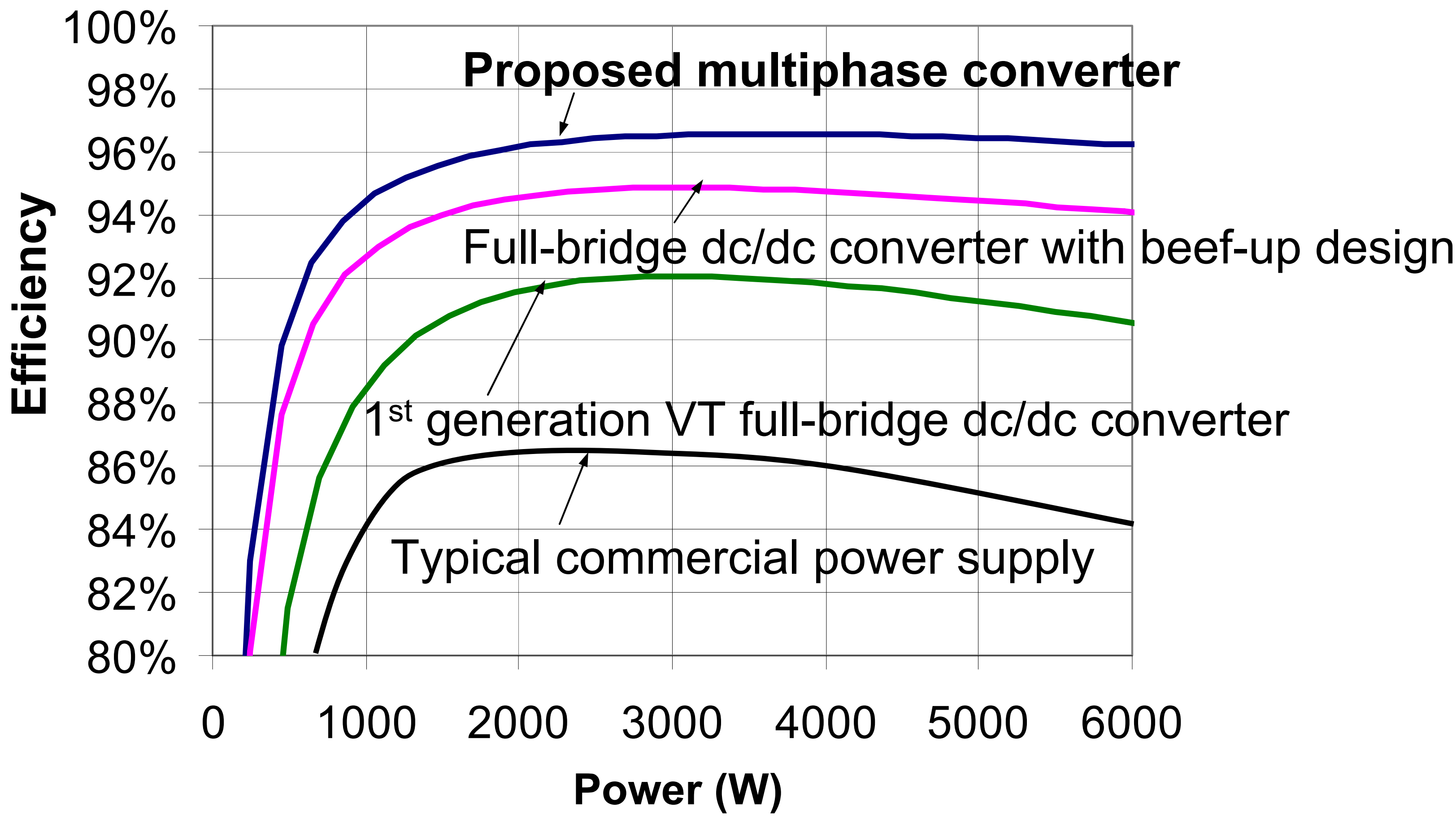
For EE64 planar core

- **d: 3.15**
- **c: 1.6**
- **a: 0.053**
- **V_e: 40.7 cm^3**

Entire Converter System Loss Modeling

1. **MOSFET conduction loss** $P_{sw} = (\sqrt{}DI_1)^2 R_{ds}$
2. **MOSFET conduction loss** $P_{sw} = (\sqrt{}DI_1)^2 R_{ds}$
3. **Transformer copper loss** $P_{Tr\text{-}copper} = (\sqrt{}DI_1)^2 R_{Tr1} + (\sqrt{}DI_2)^2 R_{Tr2}$
4. **Transformer core loss** $P_{Tr\text{-}core} = k_{Tr} B^2 f_{sw}$
5. **Diode loss** $P_{diode} = \sqrt{}DI_2 (V_t + \sqrt{}DI_2 R_{ak})$
6. **Inductor copper loss** $P_{Tr\text{-}copper} = I_2{}^2 R_{Lo}$
7. **Inductor core loss** $P_L = k_L (\Delta i)^2 f_{sw}$
8. **Capacitor loss** $P_{cap} = I_{ripper}{}^2 R_{esr} + V_1{}^2 tan\delta$
9. **Parasitic loss** $P_{para} = \mathrm{sqrt}(I_1) R_{para}$
10. **Auxiliary power supply loss** $P_{aux} = P_{const} + nQ_G V_G f$

Efficiency Comparison Among Different Technologies



R&D Approaches for Cost Reduction

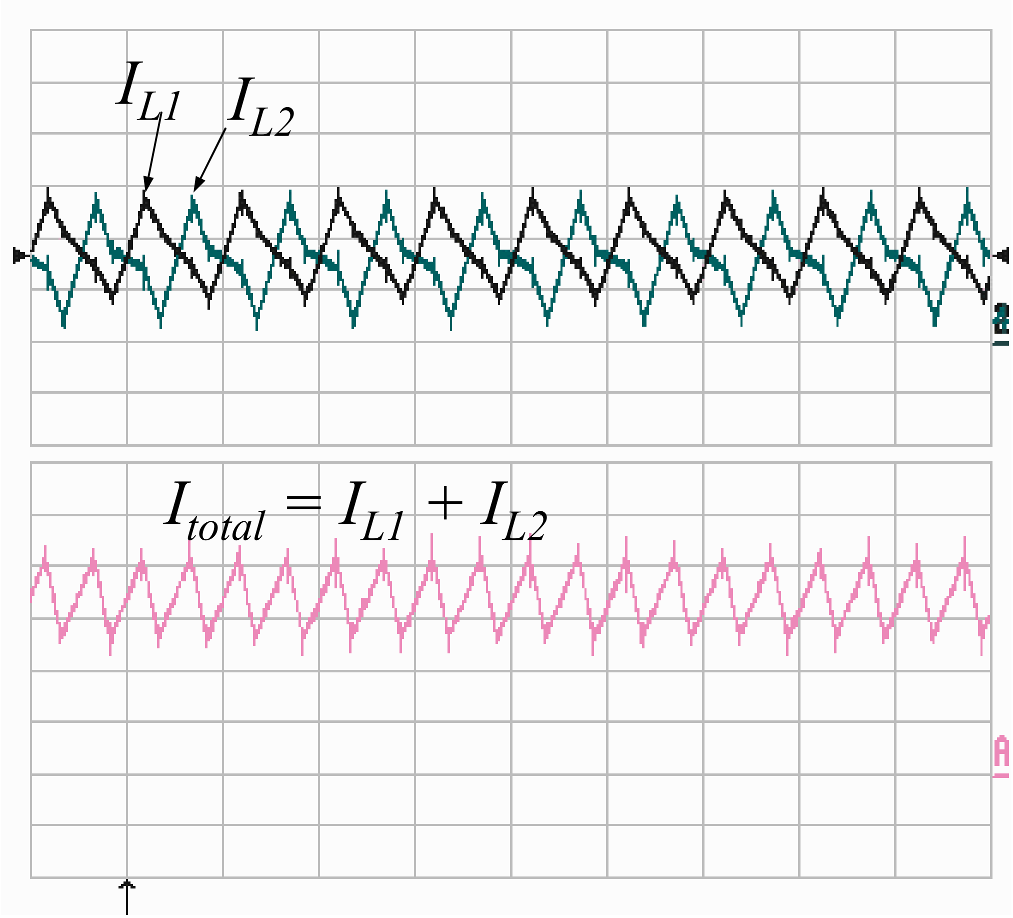
- **Sensorless control technique development**
- **More integration to eliminate interconnects and associated manufacturing**
- **Design optimization to fully utilize devices and components**
- **Standardize interface to simplify connections**

Major Component Costs in Quantity Production

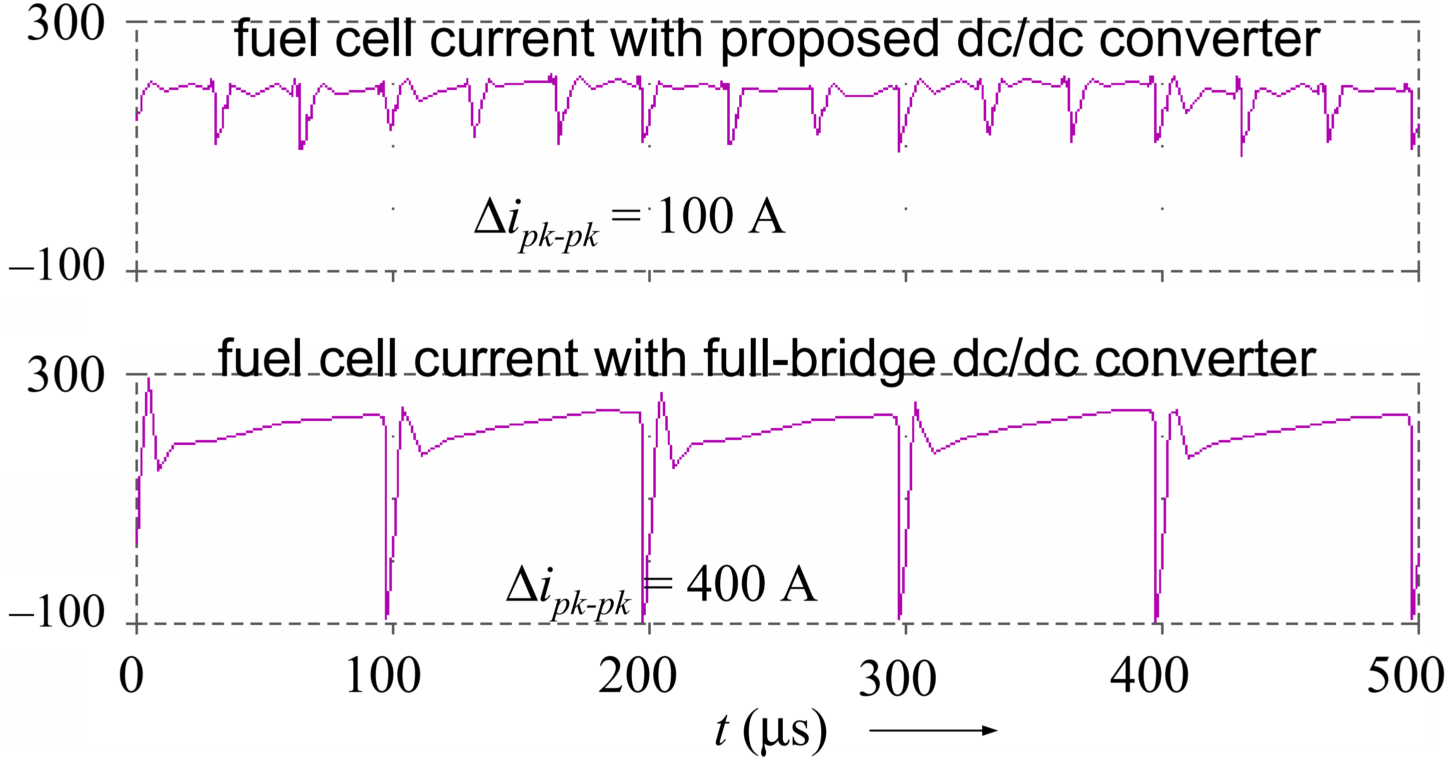
- For the proposed converter, assuming 4 power MOSFETs in parallel along with six output diodes. At 1,000 quantity, total semiconductor cost = $4 \times 6 \times \$2.4 + 6 \times \$2.05 = \$69.9$
- For the planar transformer at 1,000 quantity, transformer cost = $60.
- For a quantity of >1 million, semiconductor 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 $9.00. Similarly transformer cost is based on the amount of copper and iron (~$4/lb). The transformer cost will be less than $20.
- It should be noticed that in large quantity production price drops faster with semiconductor devices than with passive components.
- The complete converter cost of $200/5kW is difficult to meet with small quantity production, but not a problem with large enough quantity.

R&D Approaches for Ripple Reduction

- Adopt a multiphase converter with interleaved control to cancel ripples



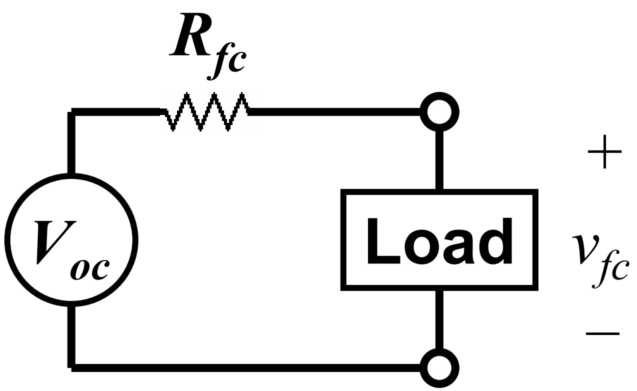
Fuel Cell Current Ripple Comparison for Full-Bridge and the Proposed Converter



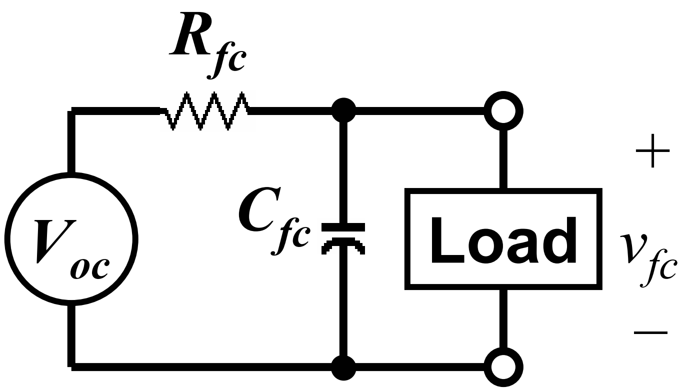
R&D Approach for Fuel Cell System Dynamic Response Study

- First-order SOFC modeling with a finite time constant
- Dynamic system modeling and simulation to understand the impact of load transient and to optimize the design

First Order Dynamic Modeling of SOFC



(a) **Model without dynamic:**
Select V_{oc} = 43 V, R_{fc} = .07 Ω.



(b) **Model with first-order dynamic:**
Select V_{oc} = 43 V, R_{fc} = 0.07 Ω, C_{fc} = 1.43 F. This assumes time constant = 0.1 second = 6 electrical cycles.

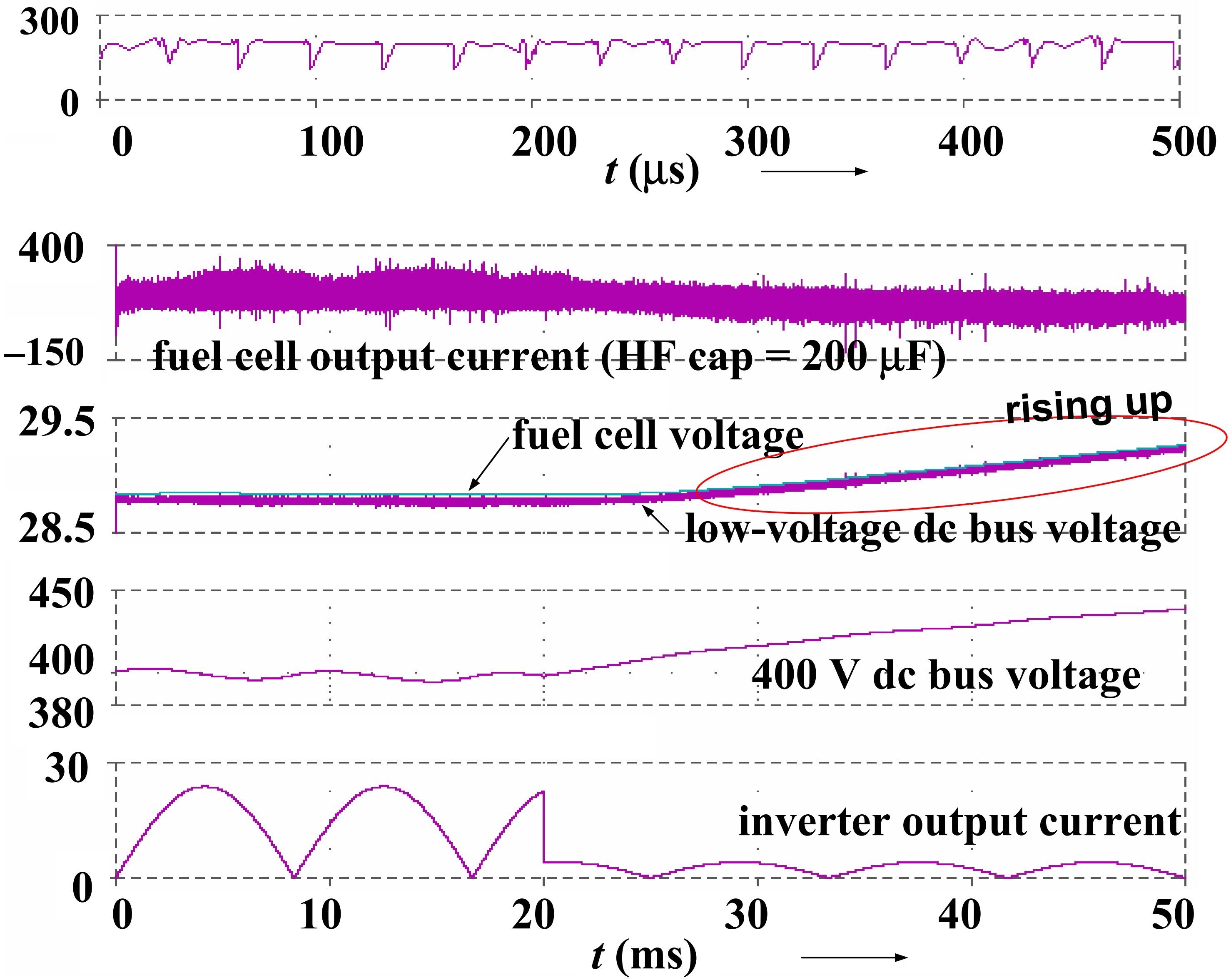
<u>Case study:</u>

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

Simulated Converter Responses under Load Dump Condition with τ_{fc}=.1 s



Results to Date

- Circuit topology has been selected for design optimization
  - A patent disclosure regarding multiphase converter control has been prepared for filing
- Complete system has been simulated for performance evaluation
  - Efficiency: 97% peak
  - Ripple: <100 A peak-to-peak
- Power circuit board and transformer have been designed and built

Prototype Multiphase Planar Transformer

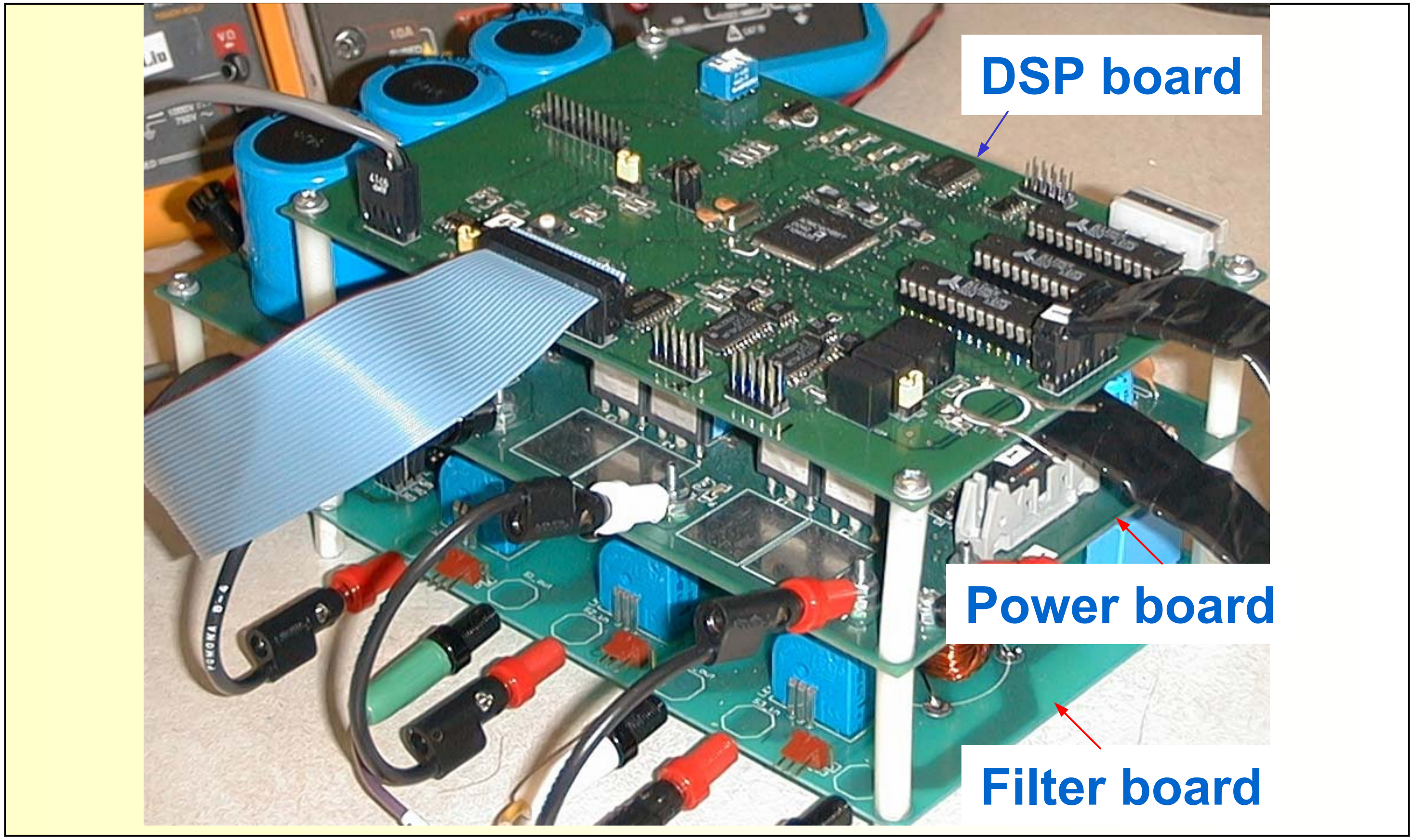
Features:

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

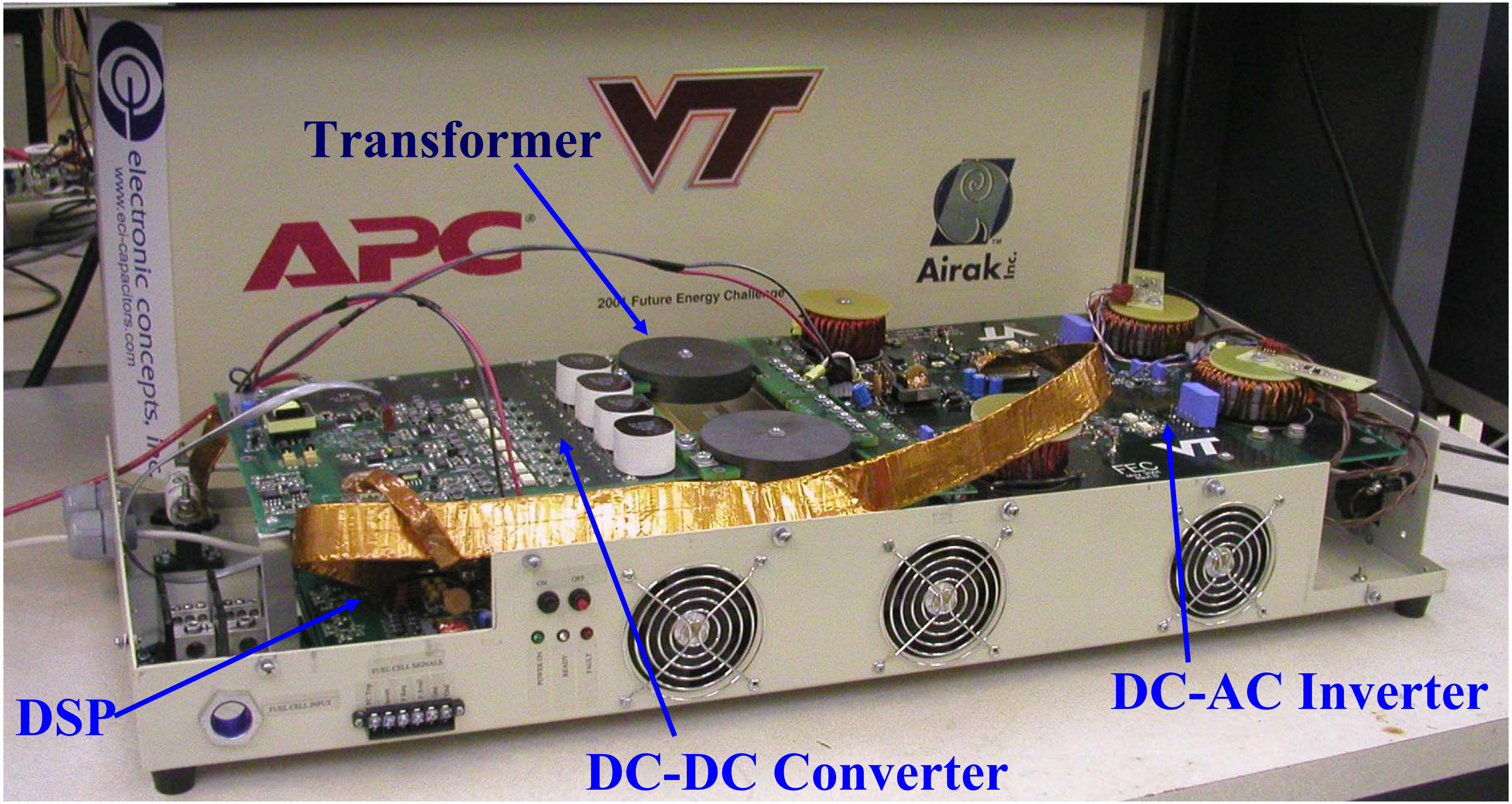
Specifications:

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

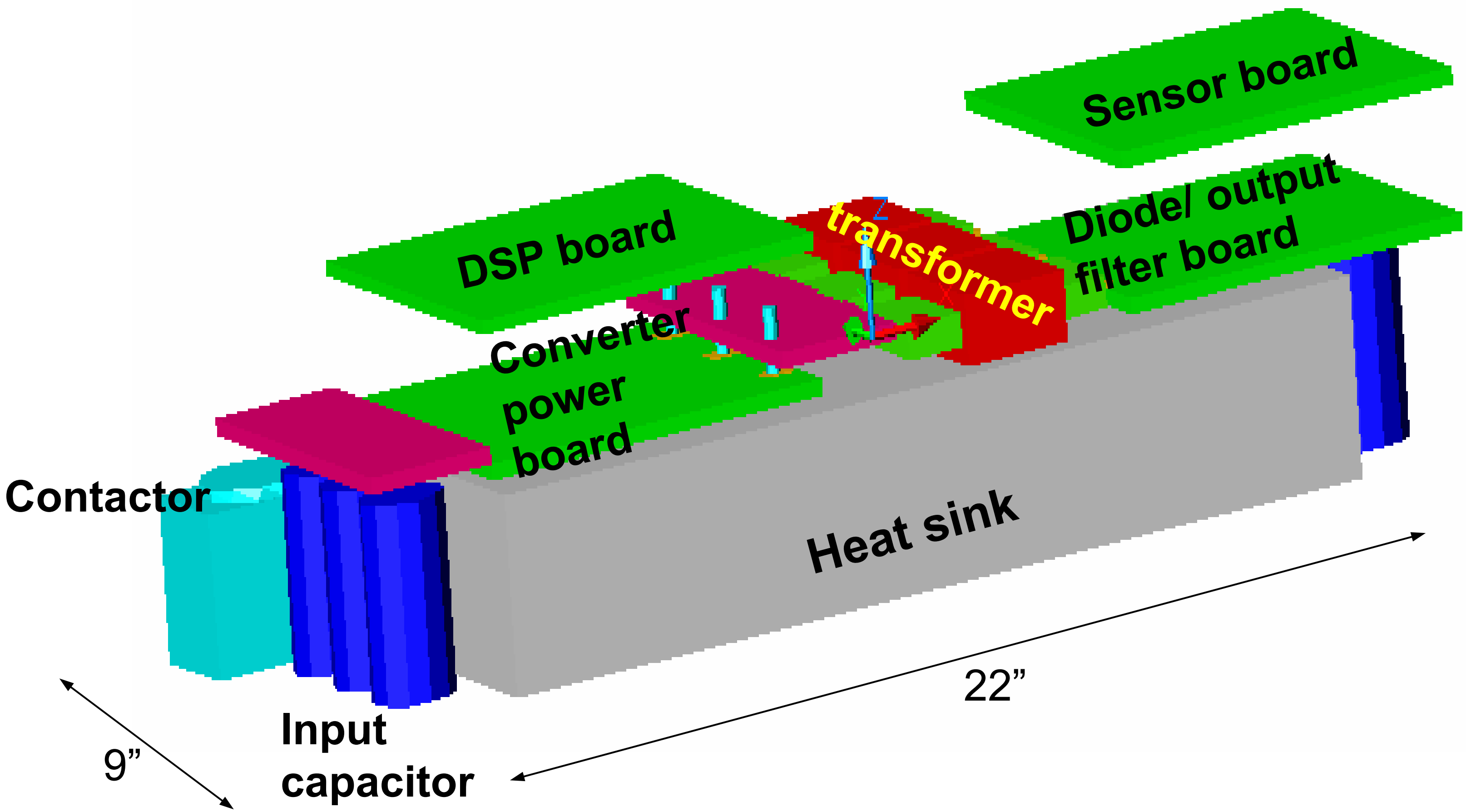
Virginia Tech DSP Board and Inverter Assembly



Virginia Tech First Generation Full-Bridge Based Fuel Cell Converter



New Design with Highly Integrated DC/DC Converter Assembly



Summary of the Proposed Converter

- Fuel cell current ripple reduction: from 400 $A_{pk\text{-}to\text{-}pk}$ to 100 $A_{pk\text{-}to\text{-}pk}$ and no negative spike as compared with full-bridge converter
- Output current ripple reduction: reduced passive component losses
- High efficiency: 97% peak efficiency at half load; 96% efficiency at full-load
- Maintain soft switching over a wide load range
- DC bus voltage ripple reduction
- Sensorless control to reduce cost

Applicability to SOFC Commercialization

- **Lower the complete SOFC system cost by increasing power conversion efficiency**
- **Provide a low-cost and SOFC friendly dc/dc converter**
- **Path the way for defining power electronics and SOFC interface protocol**
- **Show dynamic load response and lead to energy balancing strategy between SOFC and output loads**

Activities for the Next 6-12 Months

- Complete power circuit testing
- Complete sensorless control software coding
- Complete converter integration
- Test with dc power supply source and ac inverter load
- Work with SECA industrial team members to evaluate converter performance running under SOFC source
- Define fuel cell and converter interface (→phase II)
- Develop interface and communication protocol (→phase II)
- Design package for the beta version (→phase II)
- Develop energy balancing strategy (→phase II)