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

Performance and Control of V6 Converter

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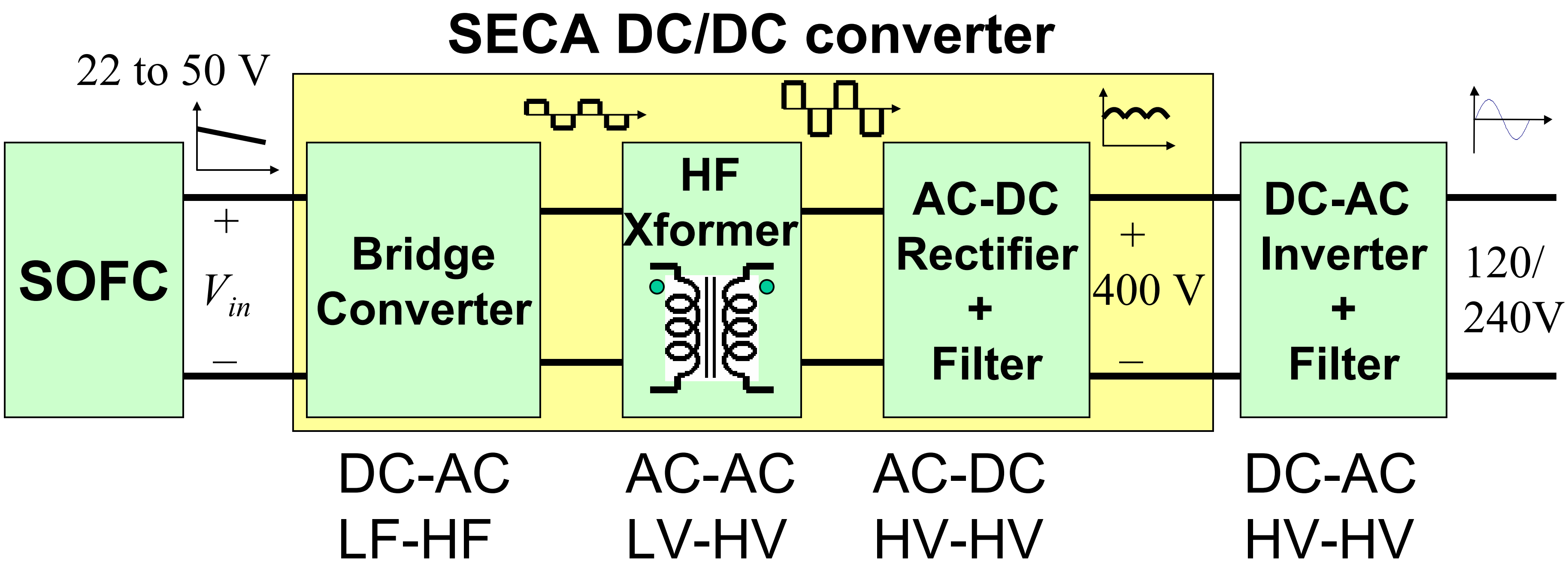
Acknowledgement

- **Technical support and encouragement of Don Collins of DOE NETL are greatly appreciated.**
- **Also quoted by Don Collins that a 1% increase in efficiency is worth $75/kWe given a $6.50/mbtu gas cost for a SOFC power plant of the size about 150kW – A motivation to high-efficiency power converter design**

Outline

1. Fuel Cell Power Plant and DC/DC Converter Topology Options
2. Features of V6 Converter
3. Calorimeter Setup and Test
4. Testing with PEM Fuel Cells
5. Conclusion

1. Block Diagram of the SOFC Power Plant

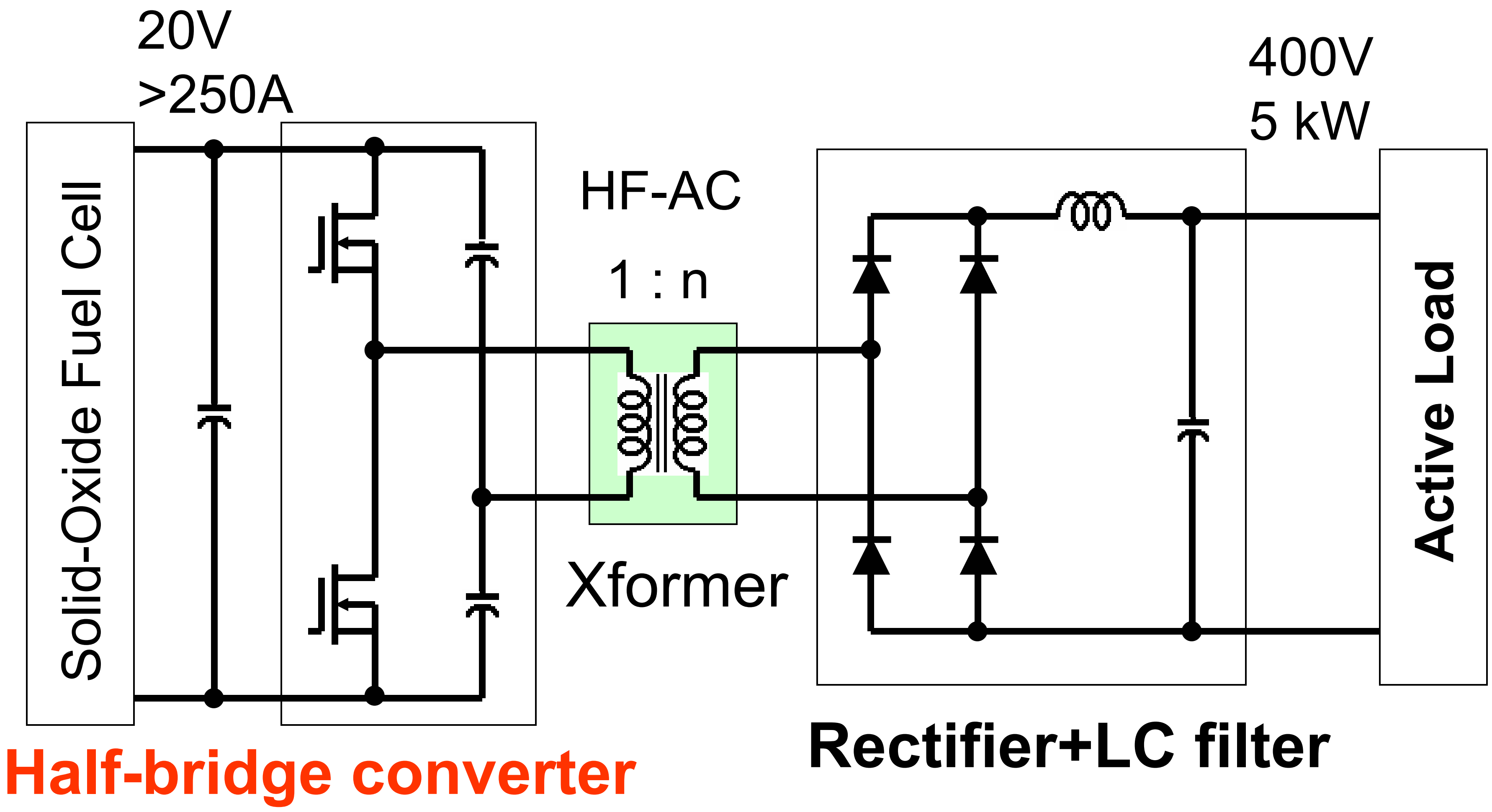


- **Fuel cell output or converter input is low-voltage DC with a wide-range variation**
- **Plant output is high-voltage ac**
- **Multiple-stage power conversions including isolation are needed**

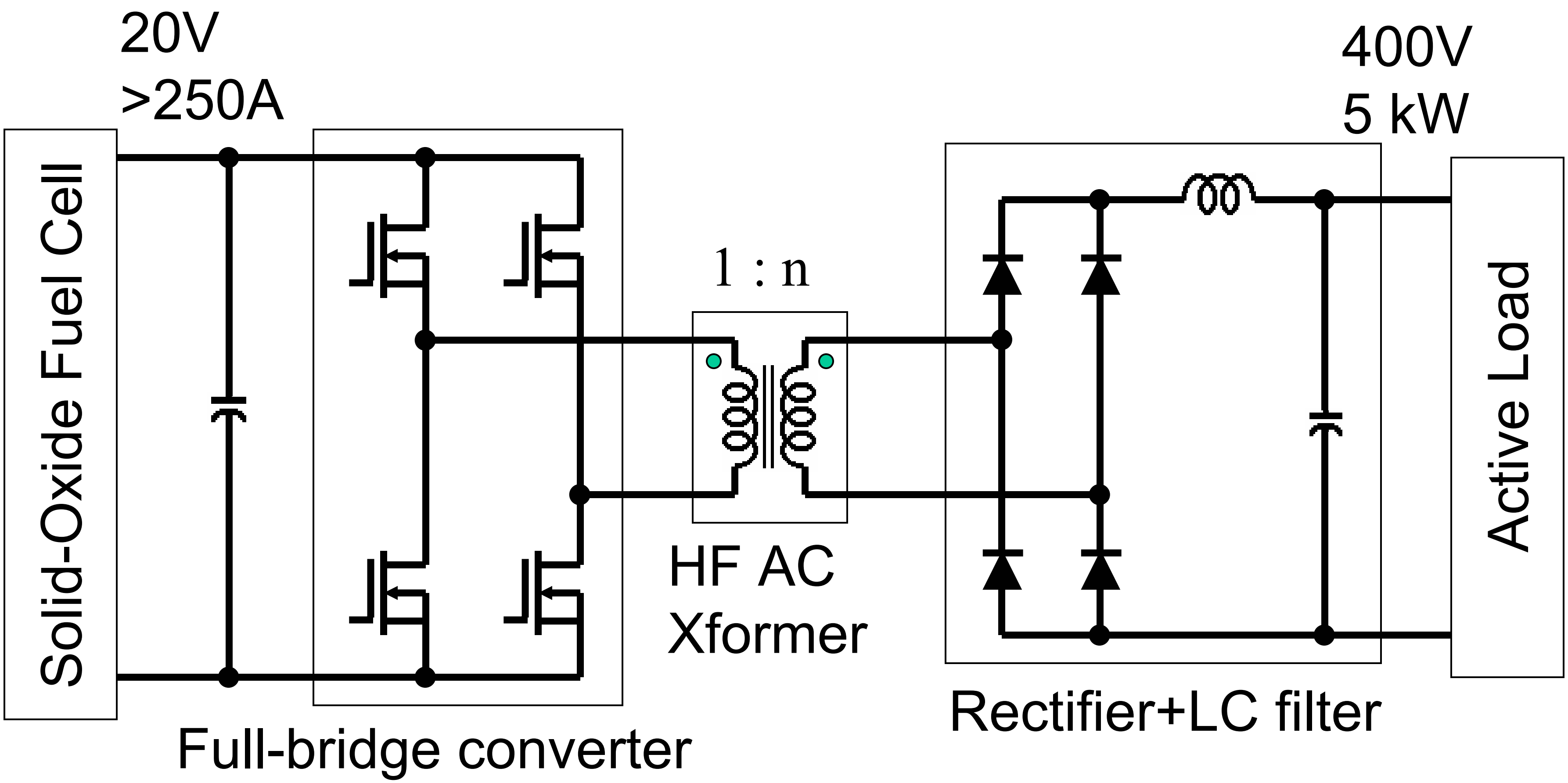
DC/DC Converter Topology Options

- **Single-phase – Half-bridge converter**
- **Two-phase – Full-bridge converter**
- **Three-phase – Three-phase bridge converter**
- **Six-phase – The proposed V6 converter**

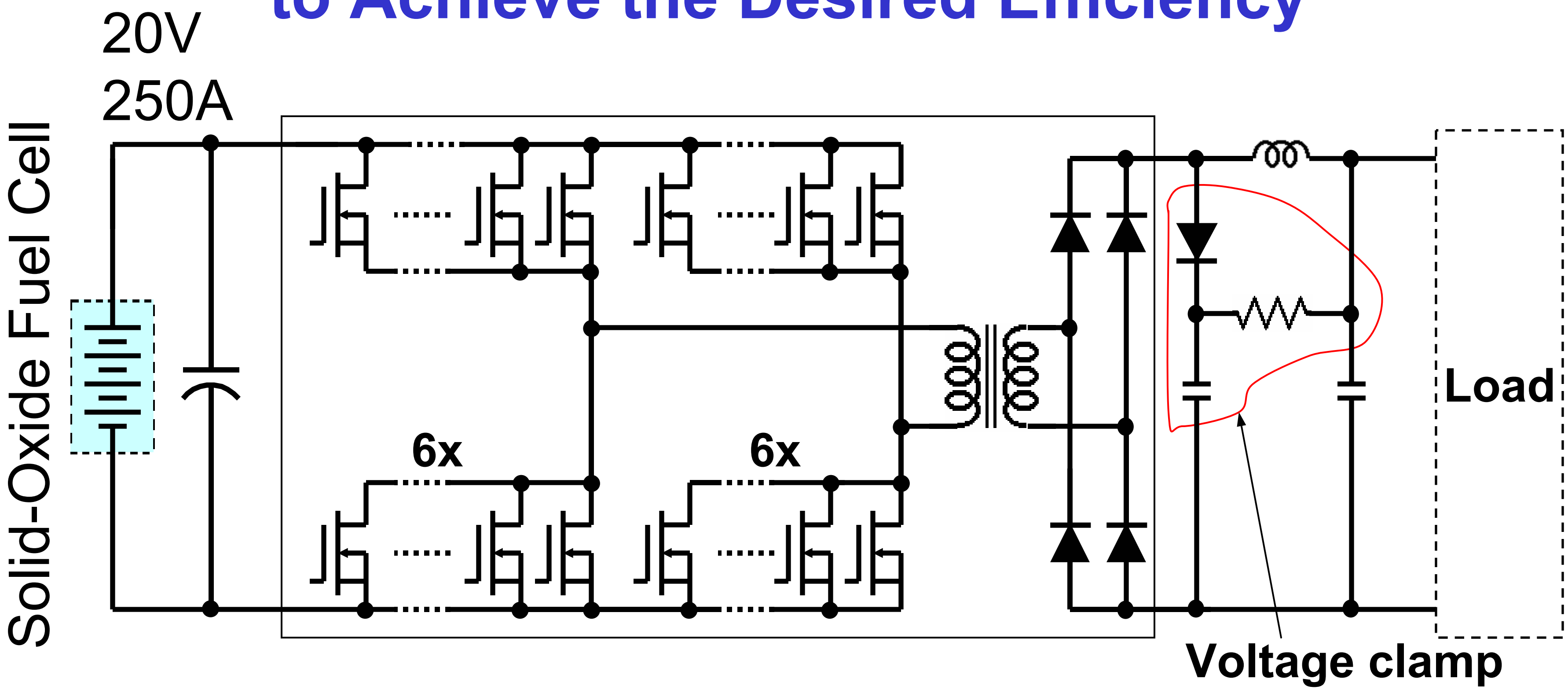
Single-Phase Half-Bridge Converter



Two-Phase Full-Bridge Converter

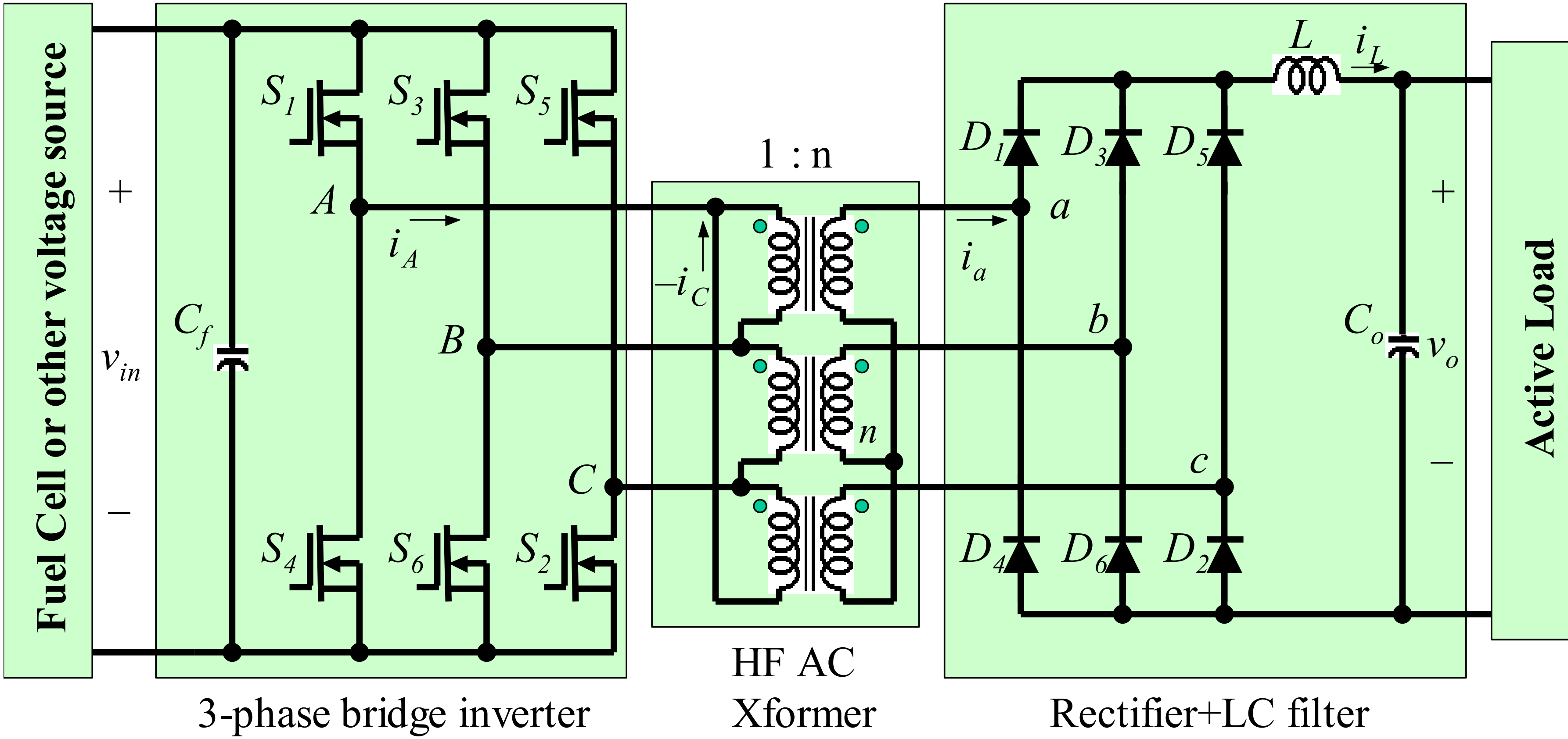


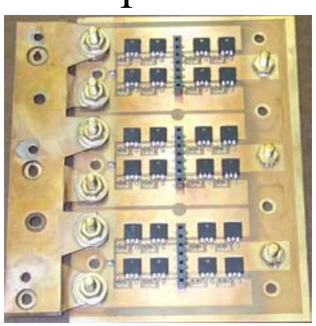
Full-Bridge Converter with Paralleled Devices to Achieve the Desired Efficiency



- **With 6 devices in parallel, the two-leg converter can barely achieve 97% efficiency**
- **Problems are additional losses in parasitic components, voltage clamp, interconnects, filter inductor, transformer, diodes, etc.**

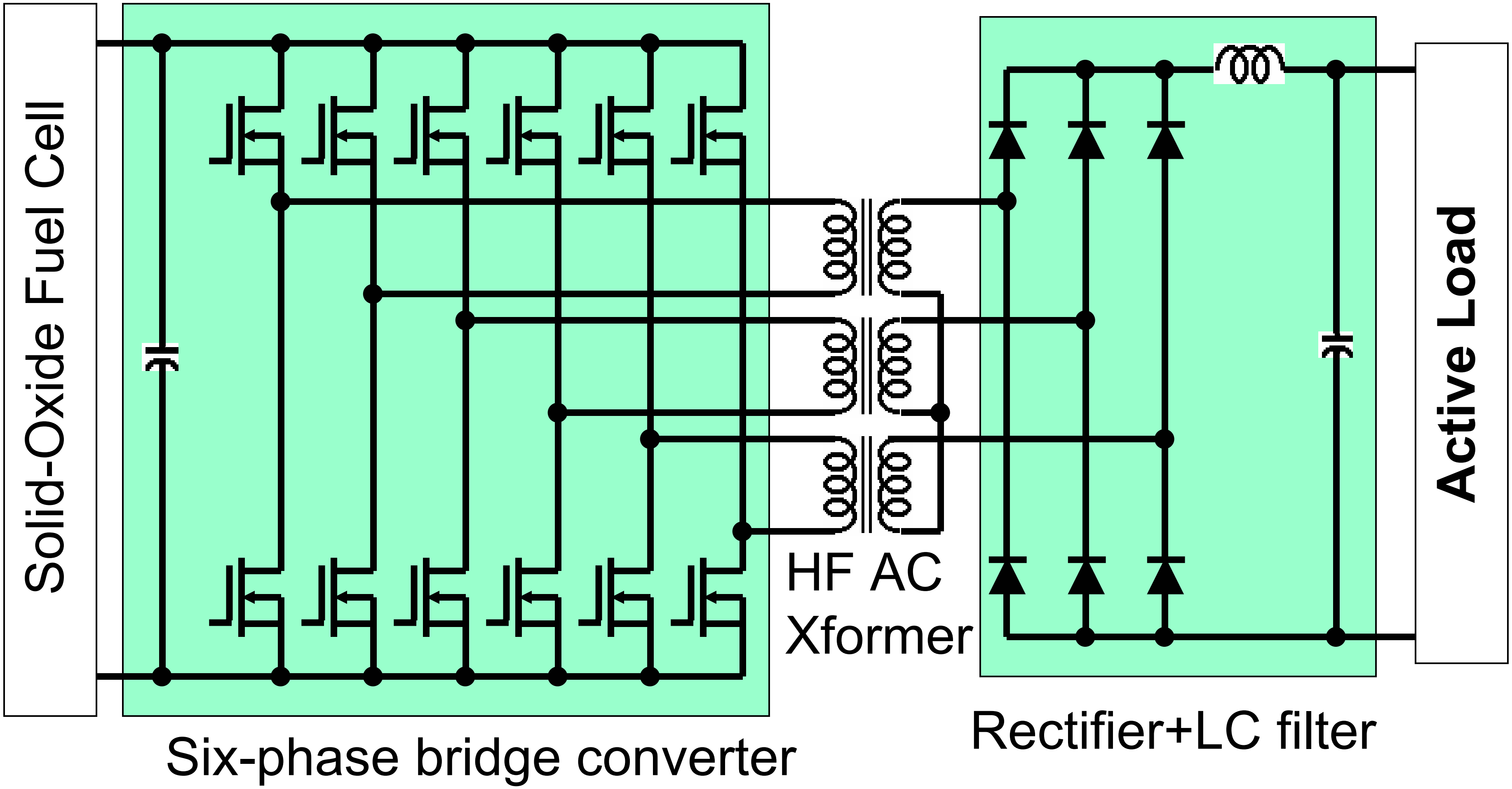
A Three-Phase Bridge Converter





- **Hard switching**
- **With 4 devices in parallel per switch**
- **Efficiency ≈ 95%**

Circuit Diagram of the Proposed V6 Converter



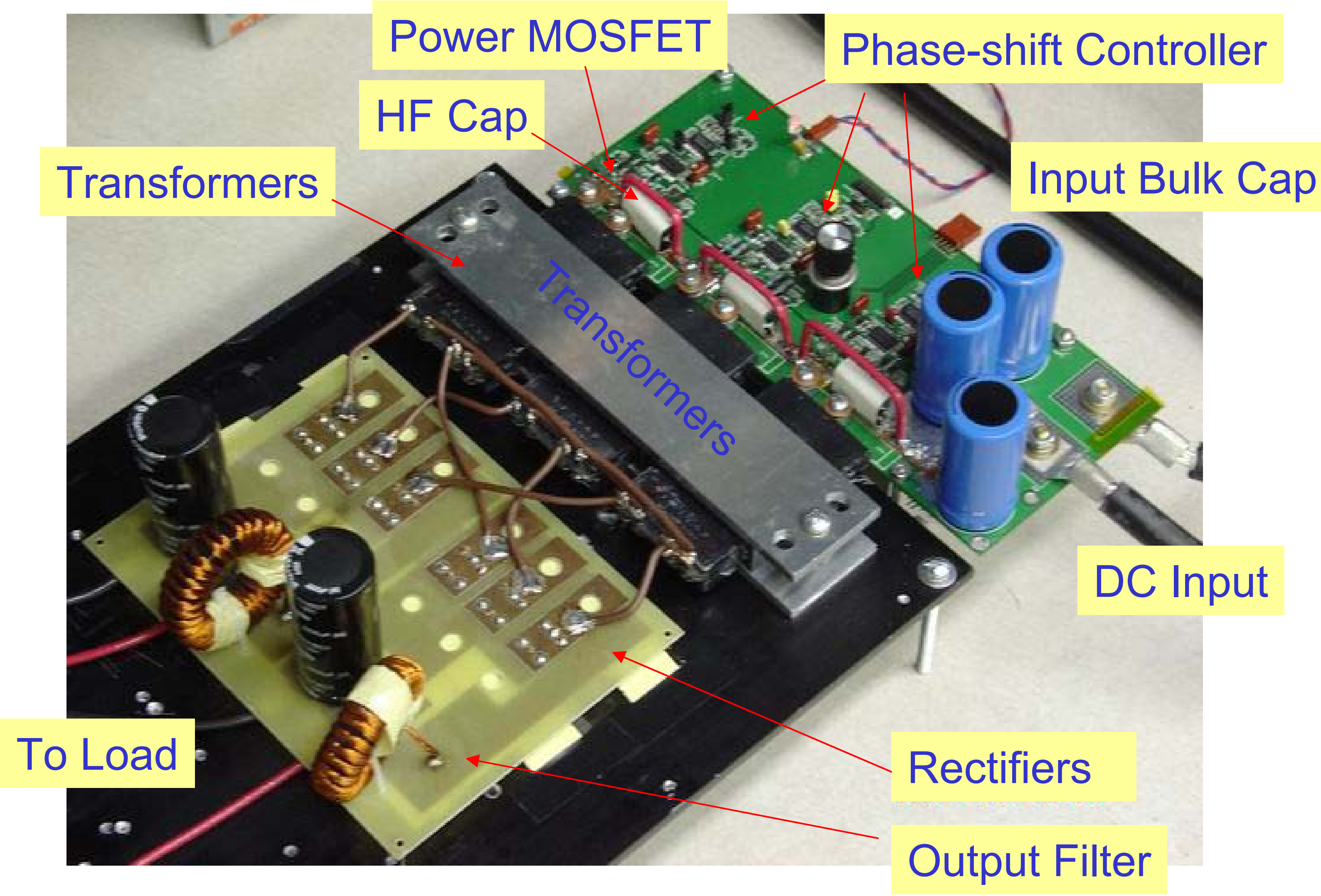
Major Issues Associated with the DC/DC Converter

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

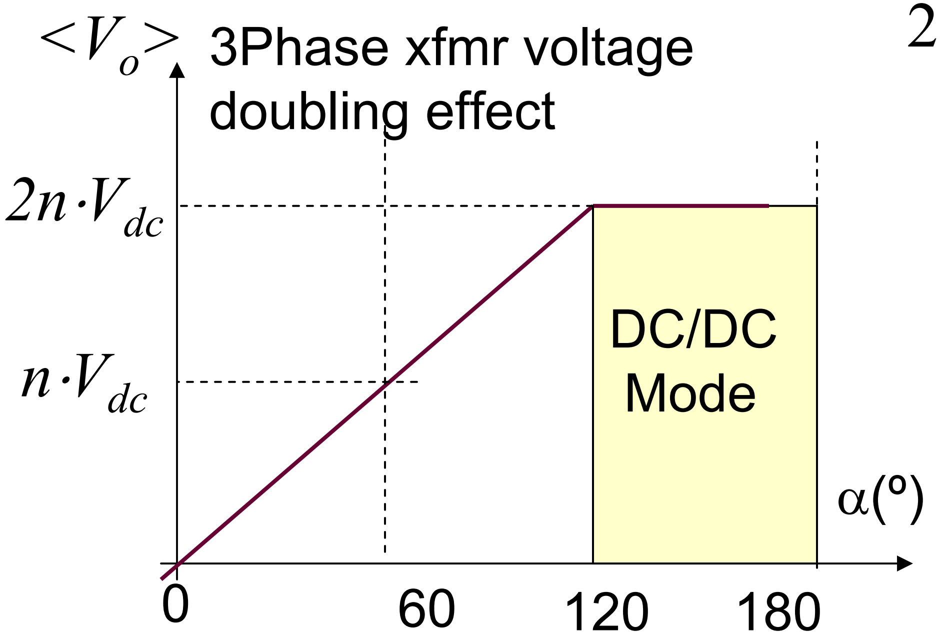
2. Key Features of the V6 Converter

- 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

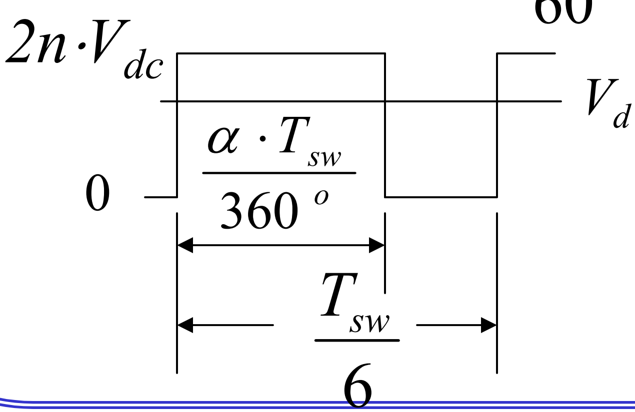
Photograph of the V6 Converter



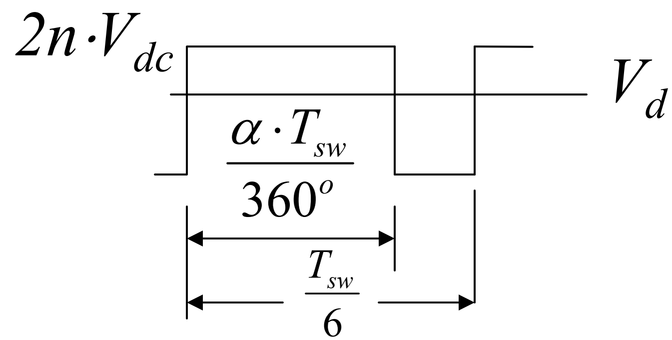
Voltage Conversion Ratio



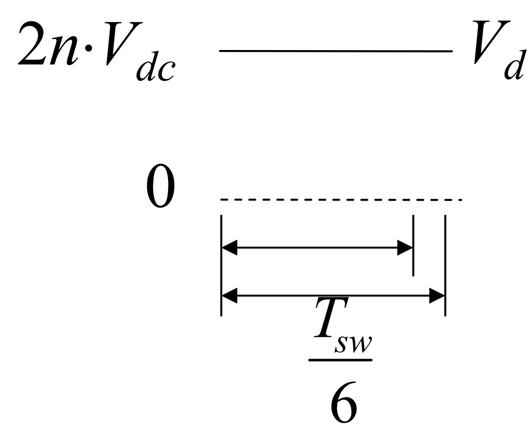
$$1.\ 0° < \alpha < 60° \qquad <\overline{V_o}> = \frac{\alpha}{60^o} \cdot n \cdot V_{dc}$$



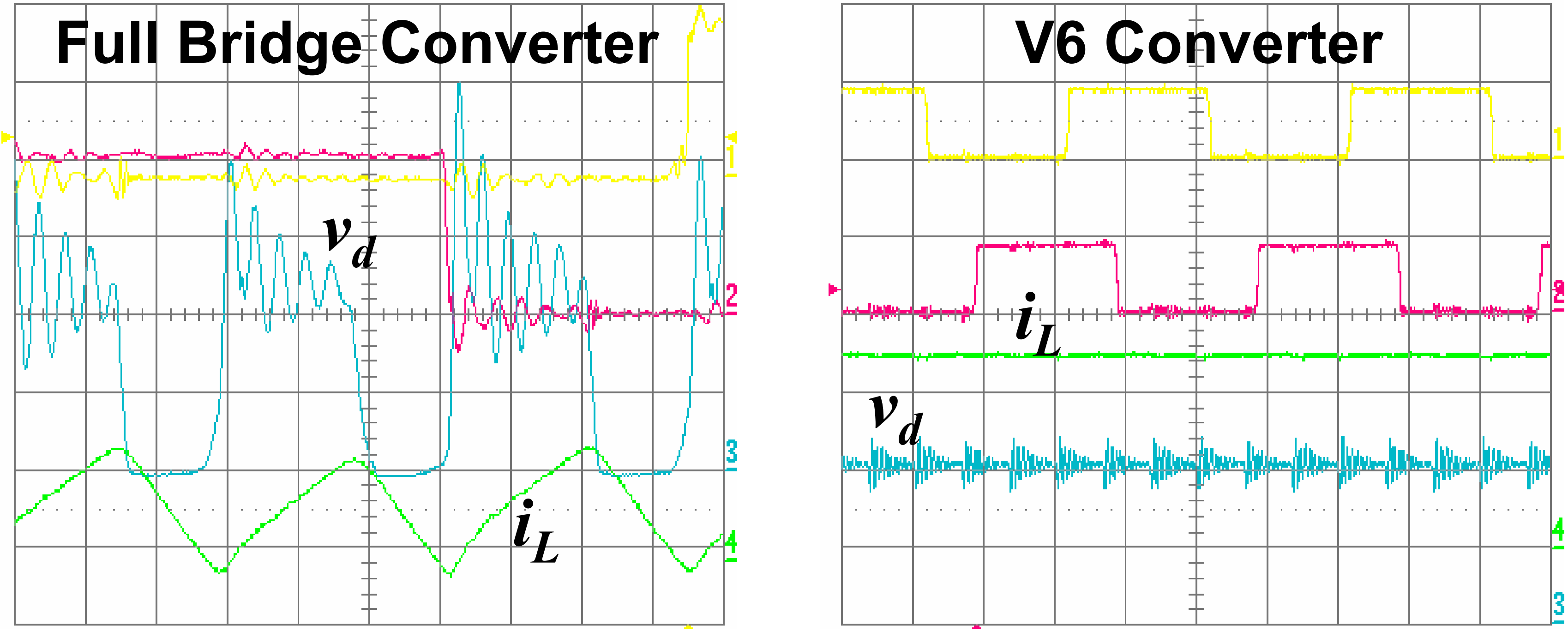
$$2.\ 60° < \alpha < 120° \qquad <\overline{V_o}> = \frac{\alpha}{60^o} \cdot n \cdot V_{dc}$$



$$3.\ 120° < \alpha < 180° \qquad <\overline{V_o}> = 2 \cdot n \cdot V_{dc}$$

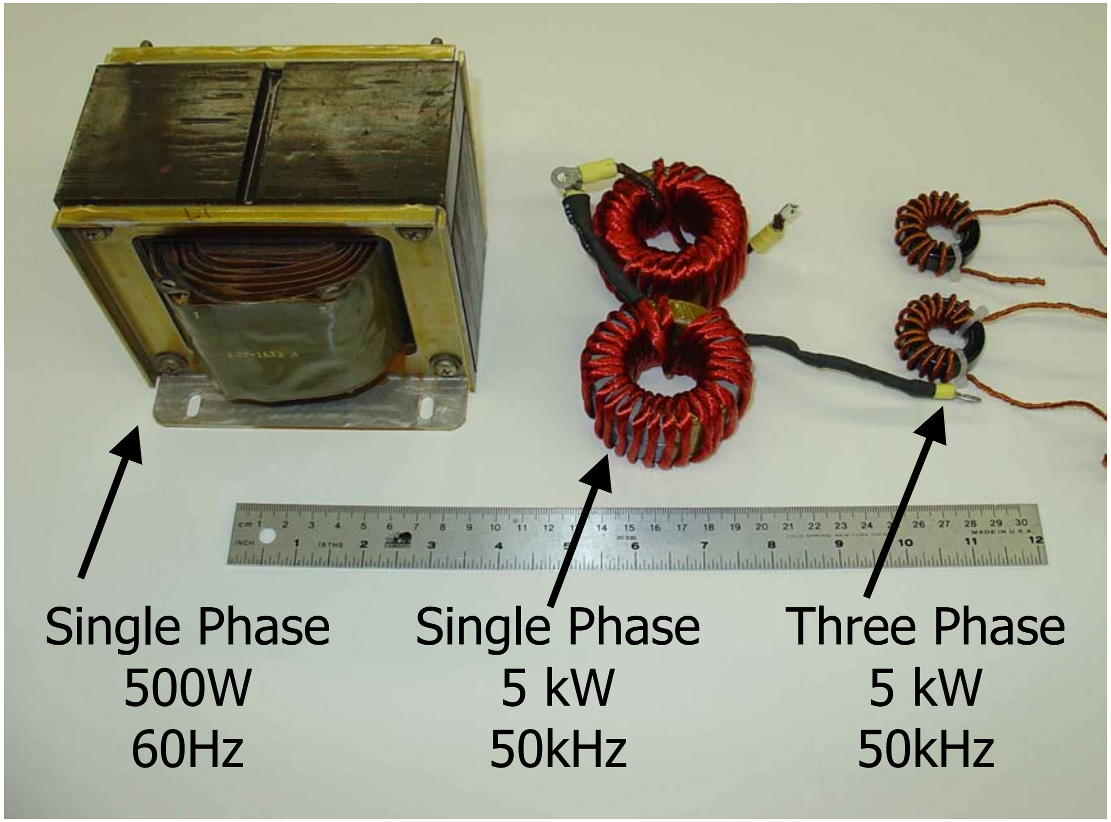


Comparison between Full-Bridge and V6 Converters



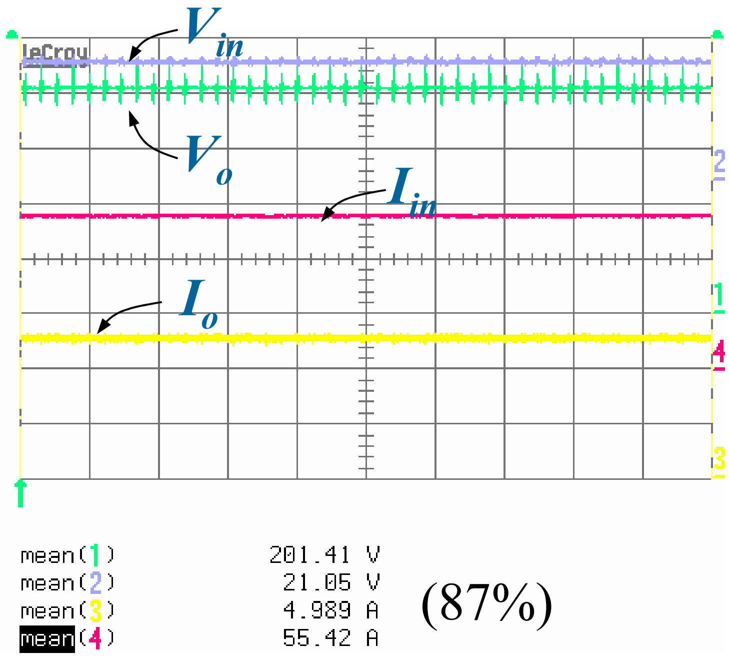
- Secondary inductor current is ripple-less; and in principle, no dc link inductor is needed
- Secondary voltage swing is eliminated with <40% voltage overshoot as compared to 250%

Significant DC link Inductor Size Reduction

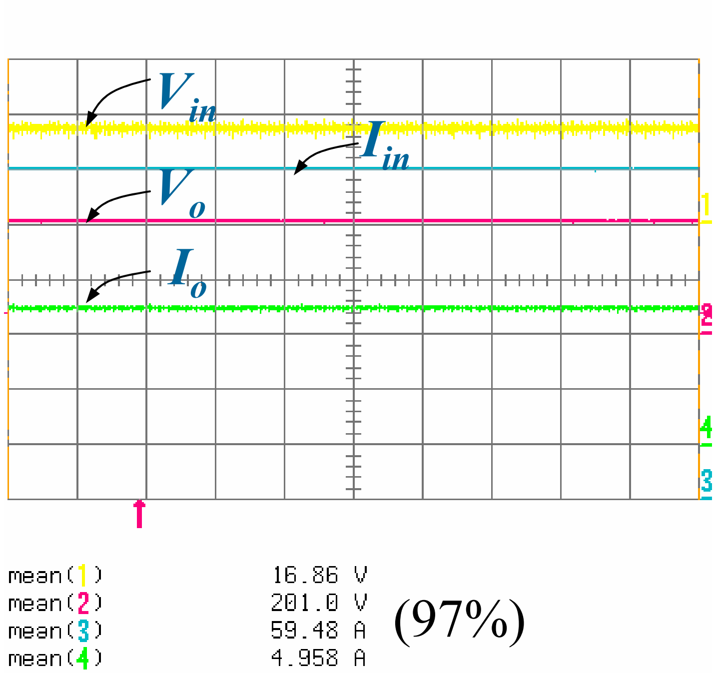


With V6 converter, an effective 10x reduction in DC link filter inductor in terms of cost, size and weight

Input and Output Voltages and Currents at 1kW Output Condition



(a) Full bridge converter

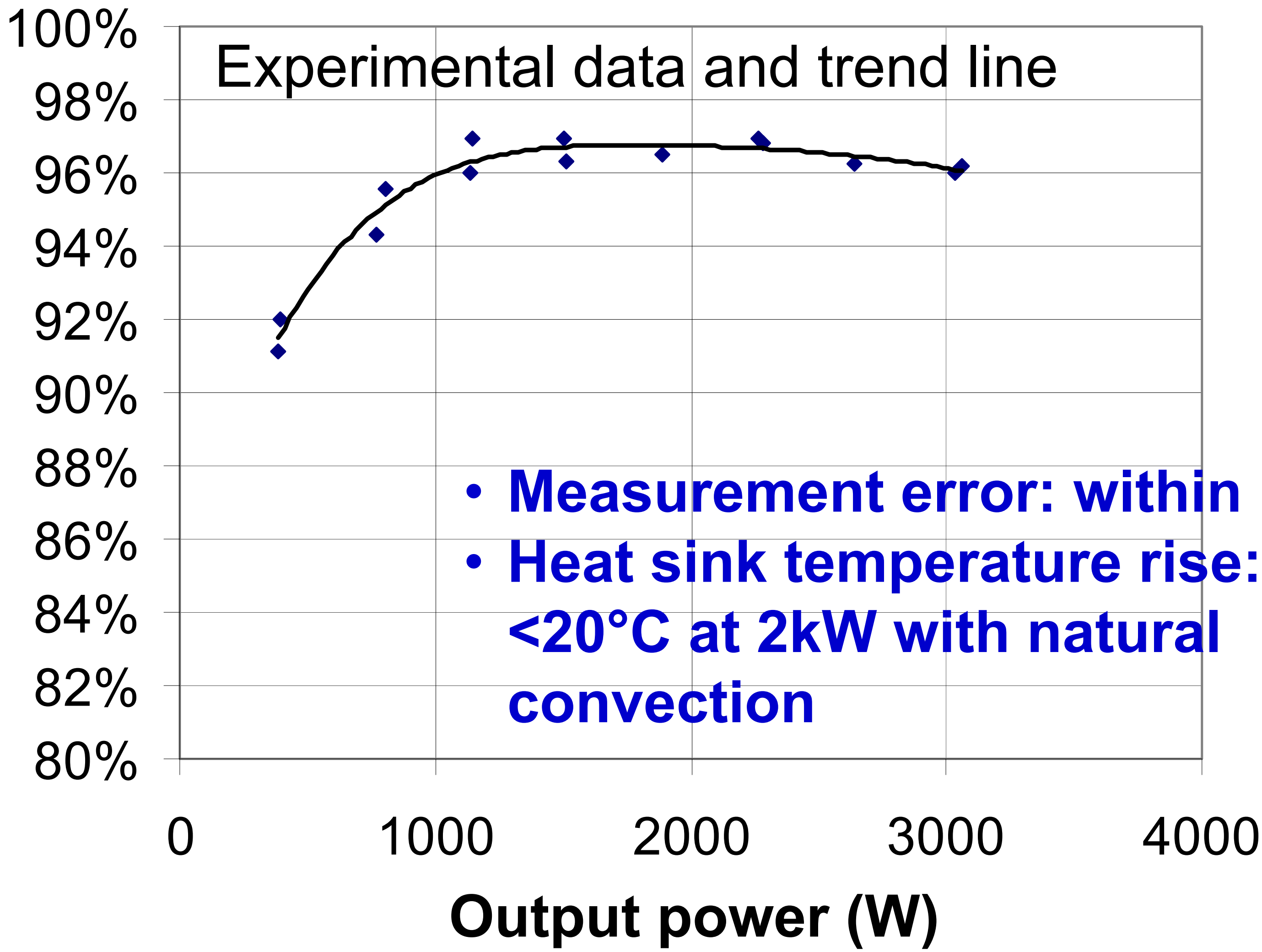


(b) V6 Converter

Significant improvement with V6 converter

- ✓ Less EMI
- ✓ Better efficiency (97% versus 87% after calibration)

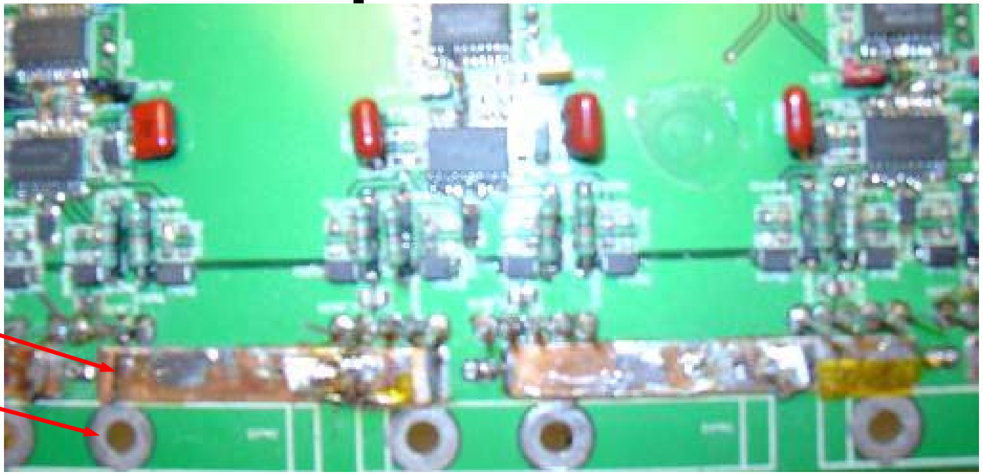
Efficiency Measurement Results



- **Measurement error: within 1%**
- **Heat sink temperature rise: <20°C at 2kW with natural convection**

Where are the Losses?

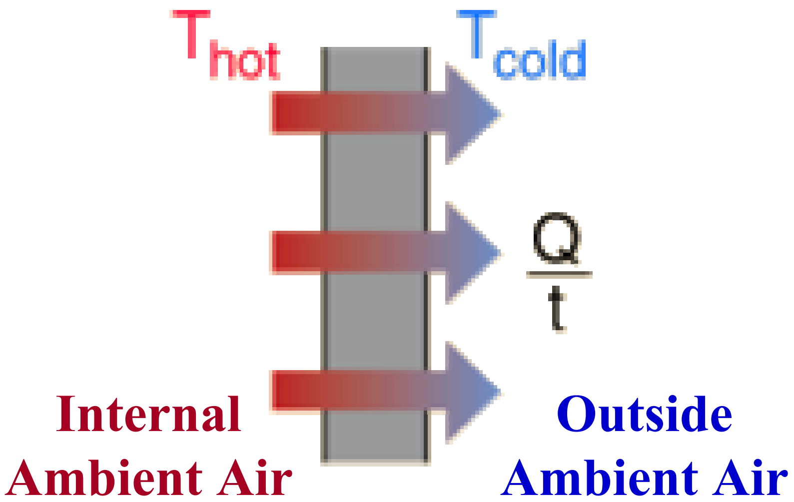
- Switch conduction
- Diode conduction
- Transformer
- Output rectifier
- Output filter inductor and capacitor
- Input capacitor
- Parasitics
  - Copper traces
  - Interconnects



3. Calorimetry for Accurate Loss Measurement

- A 50-liter calorimeter
- Calibration of the 50-liter calorimeter
- A 160-liter calorimeter
- Calibration of the 160-liter calorimeter

Basic Calorimeter Principle



$$\frac{Q}{t} = \frac{k \cdot A \cdot \left(T_{hot} - T_{cold}\right)}{d}$$

where

$\frac{Q}{t}$: heat flow (W)

k: thermal conductivity of the barrier

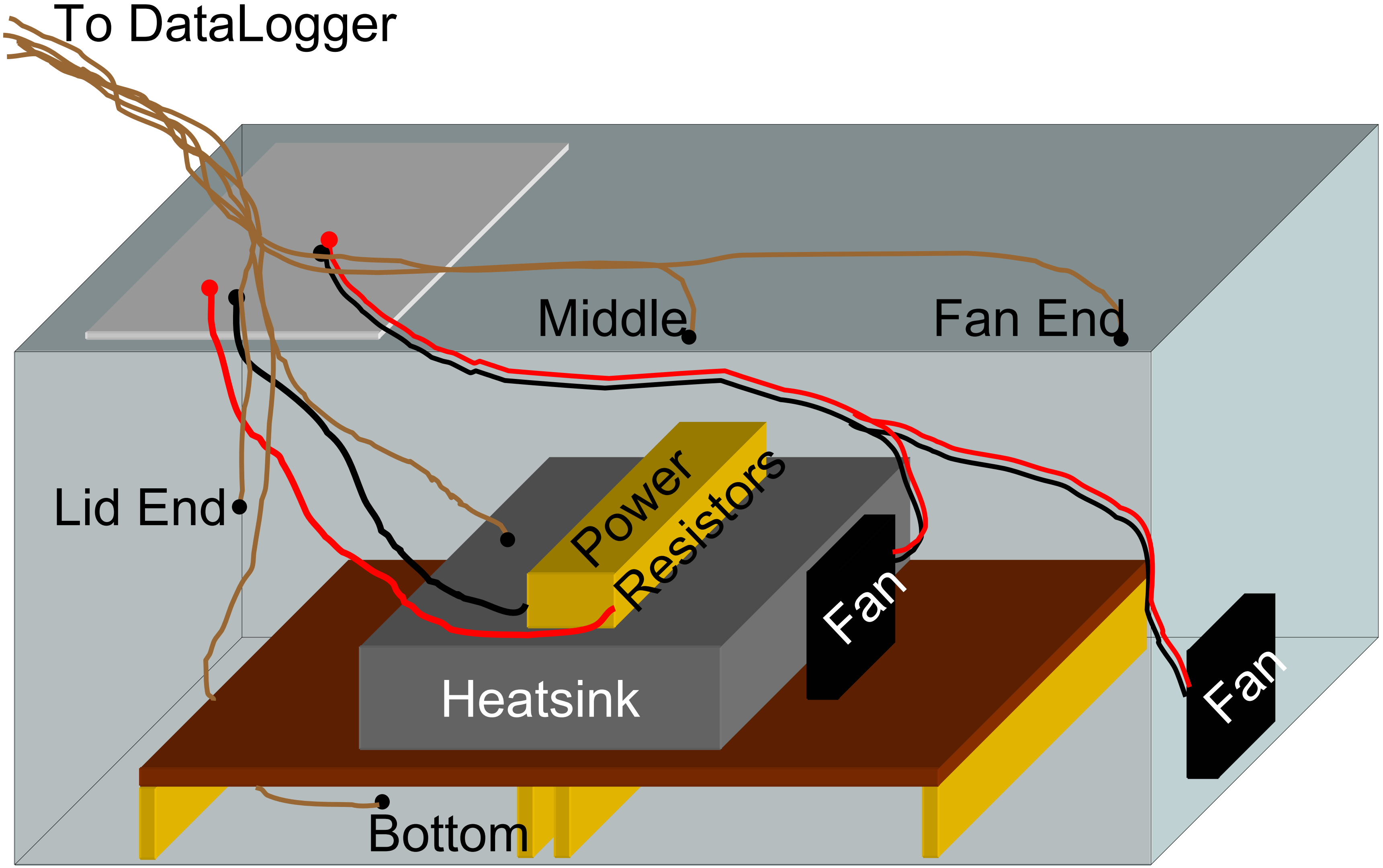
$k \cong 0.029 \text{ W/m} \cdot \text{K}$ for styrofoam

A: surface area (m^2)

T: temperature ($^\circ$C)

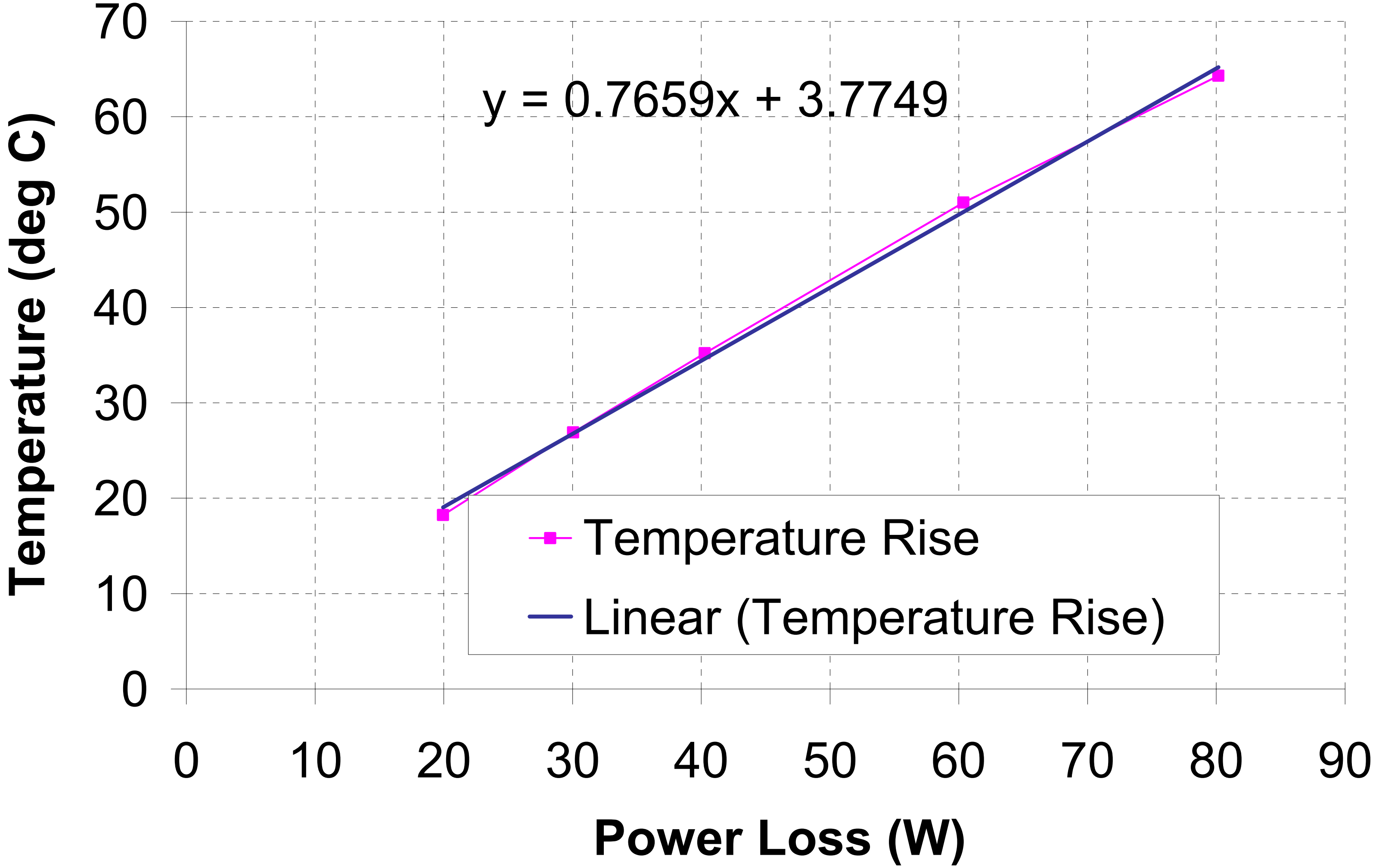
d : thickness of barrier

Calorimeter Setup Diagram

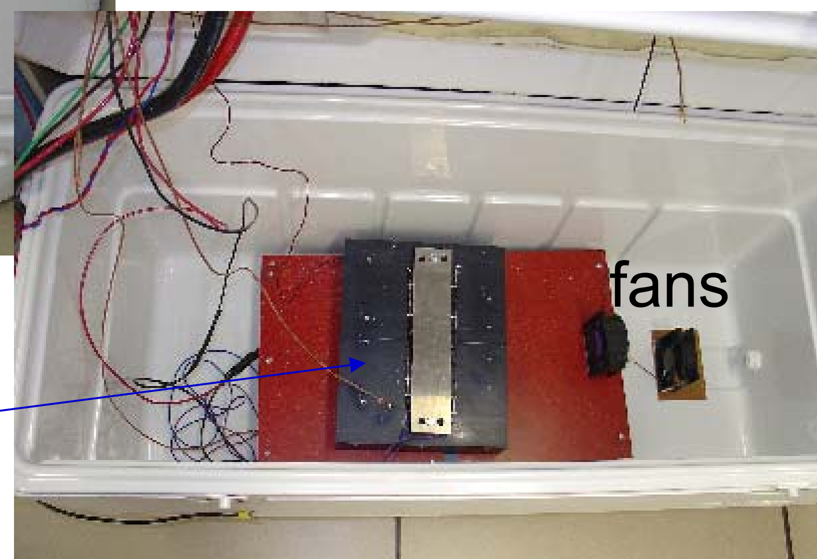


A 50-liter Calorimeter

Calibration Results of the 50-Liter Calorimeter

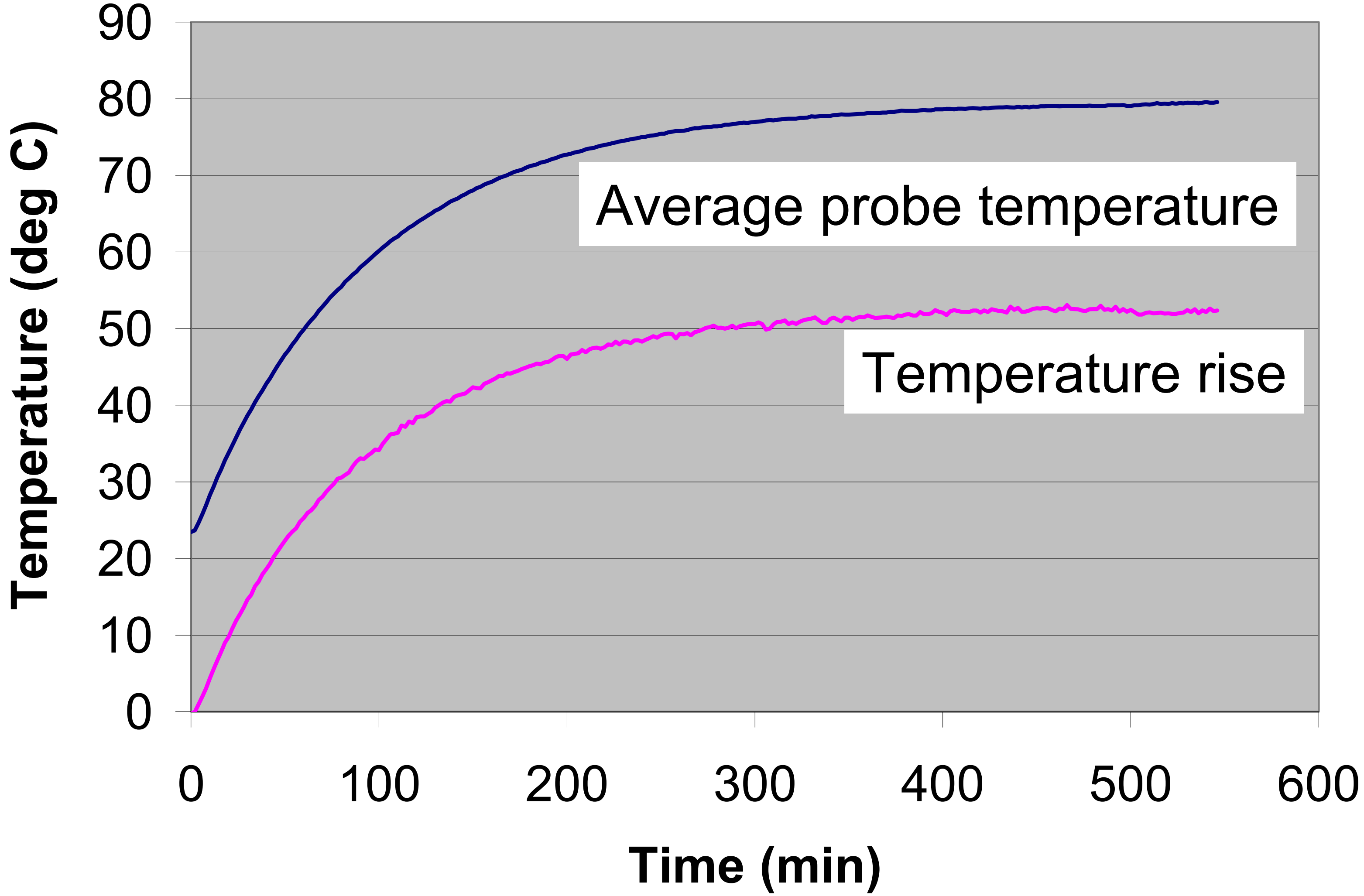


A 160-Liter Calorimeter Setup

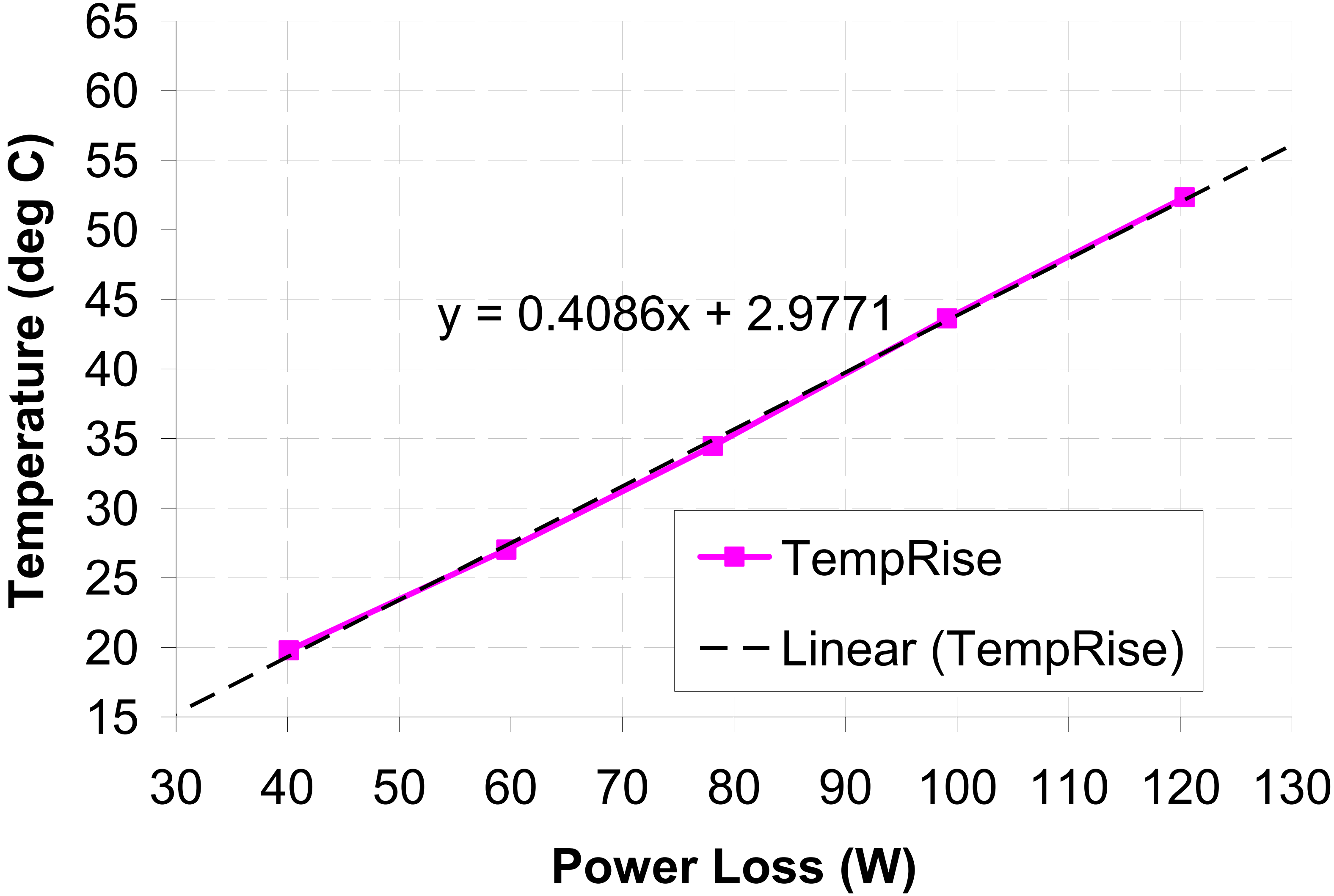


Calibration with resistor bank

Test the 160-Liter Calorimeter at 120-W Condition



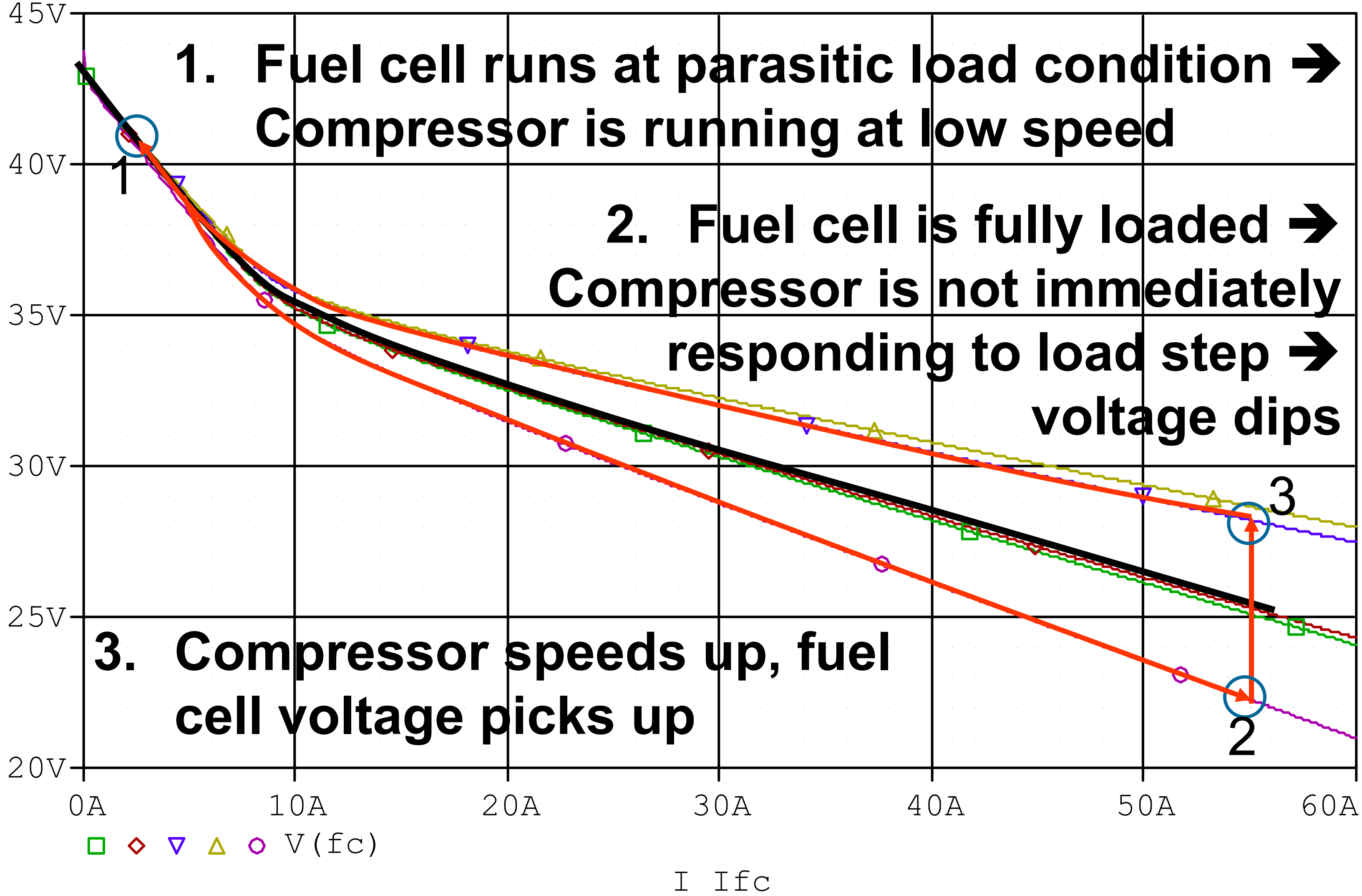
Temperature Rise Versus Power Loss



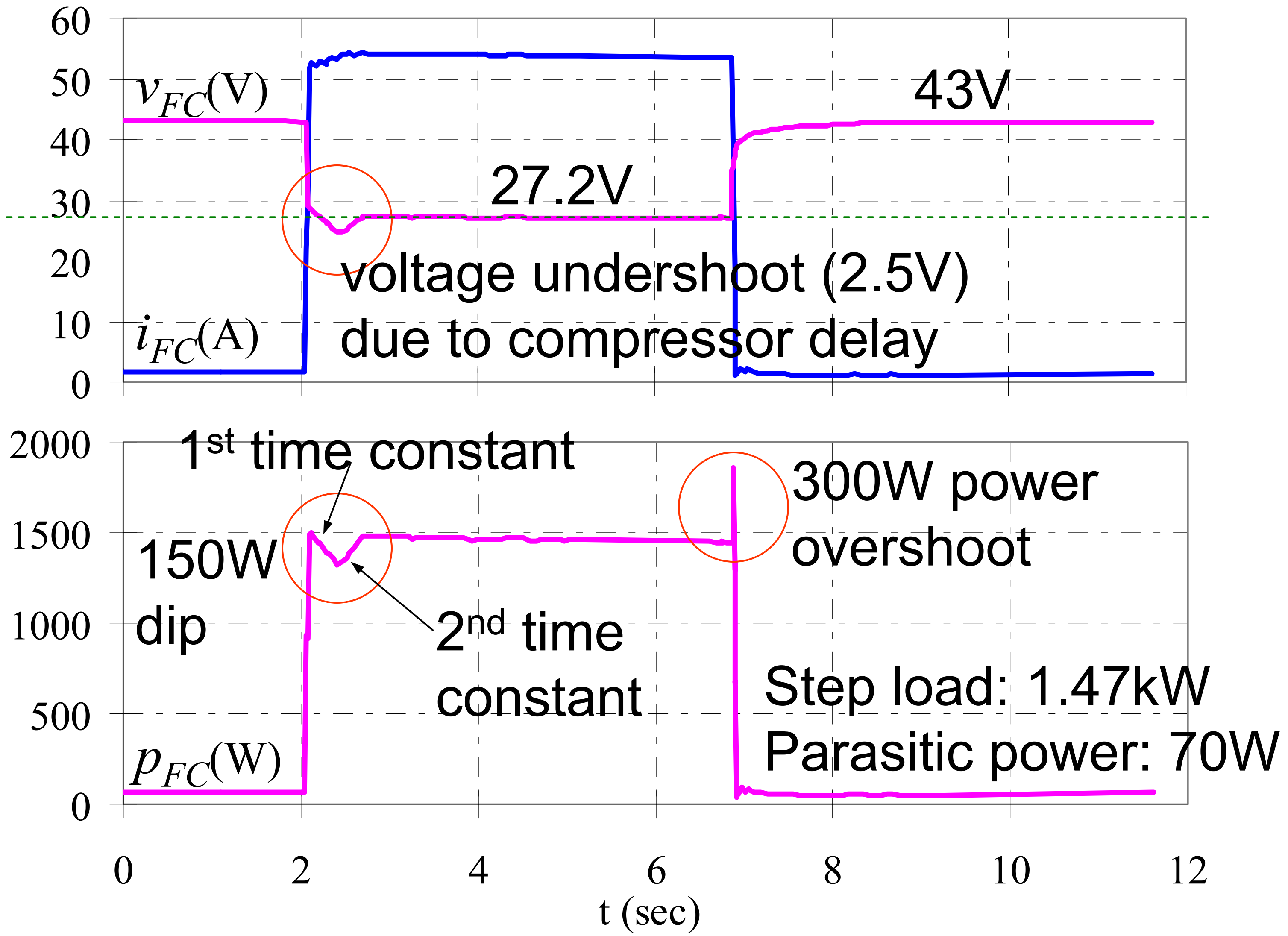
4. Test DC/DC Converter with a PEM Fuel Cell

- Fuel cell polarization curve
- Dynamic fuel cell voltage and current output
- Dynamic fuel cell model in electrical circuit
- Model verification
- Comparison with slow time constant power supply test

Polarization Curves with Different Compressor Speeds

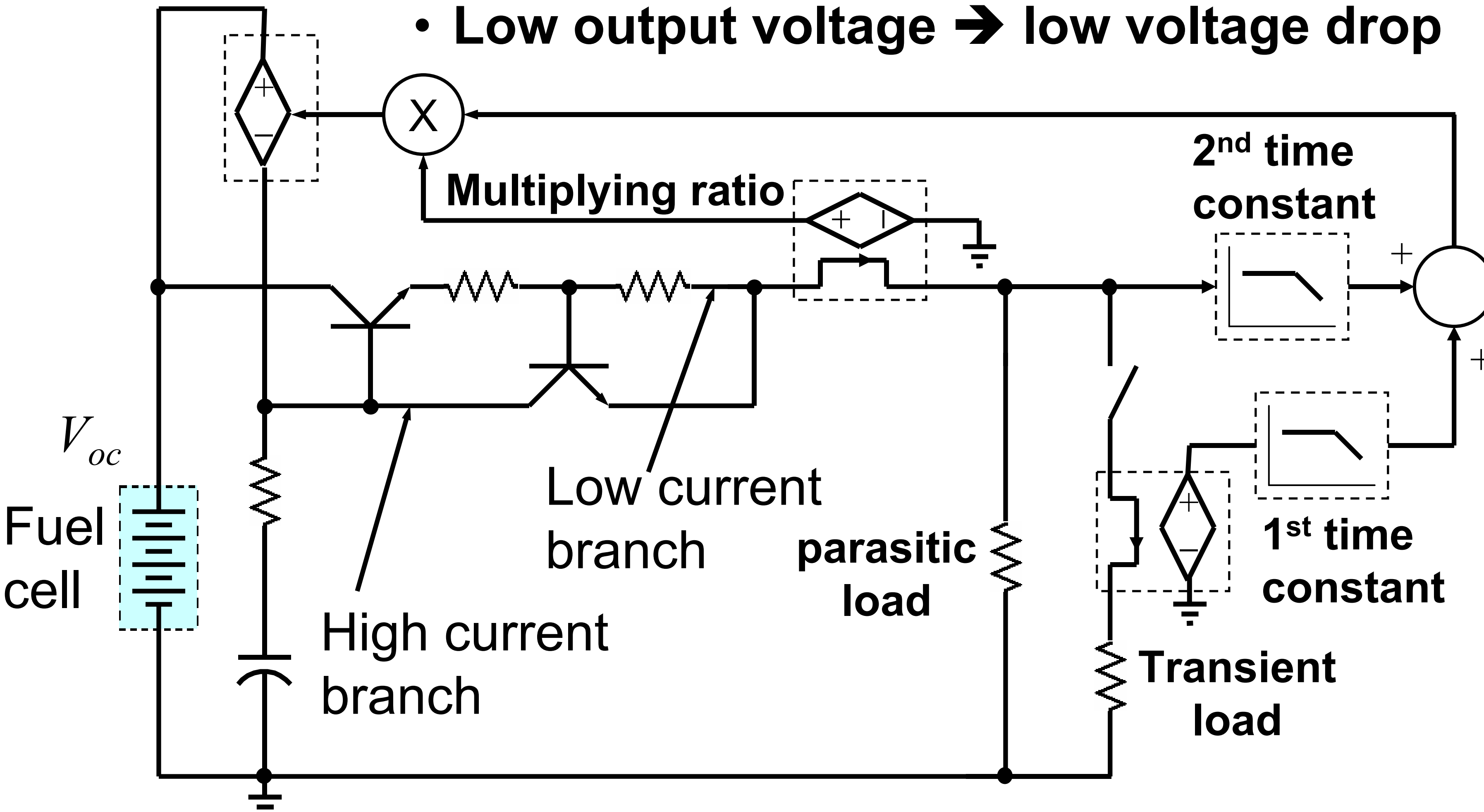


Fuel Cell Dynamic Characteristics



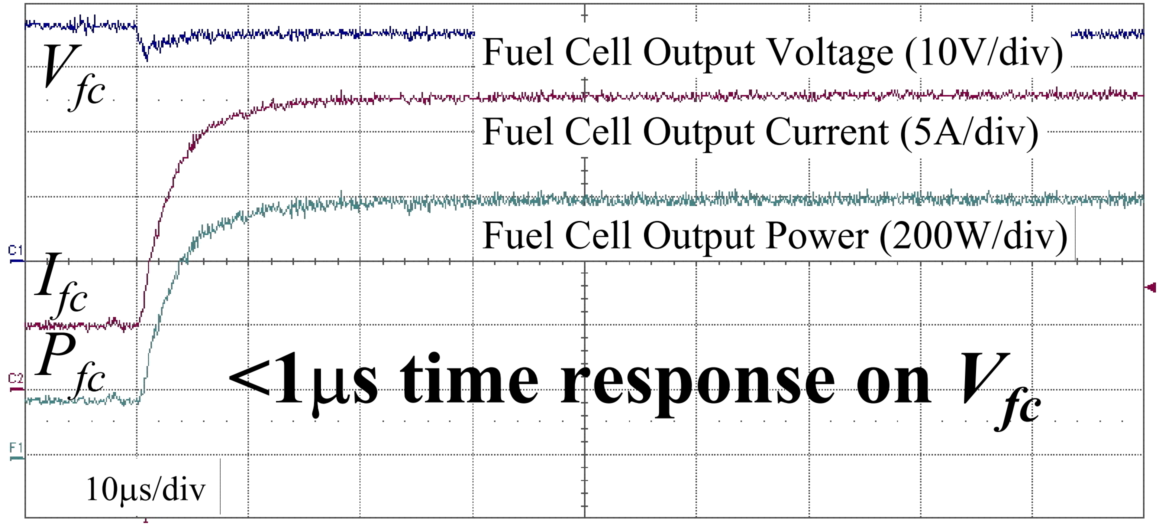
Fuel Cell Dynamic Circuit Model

- **High load current → high voltage drop**
- **Low output voltage → low voltage drop**

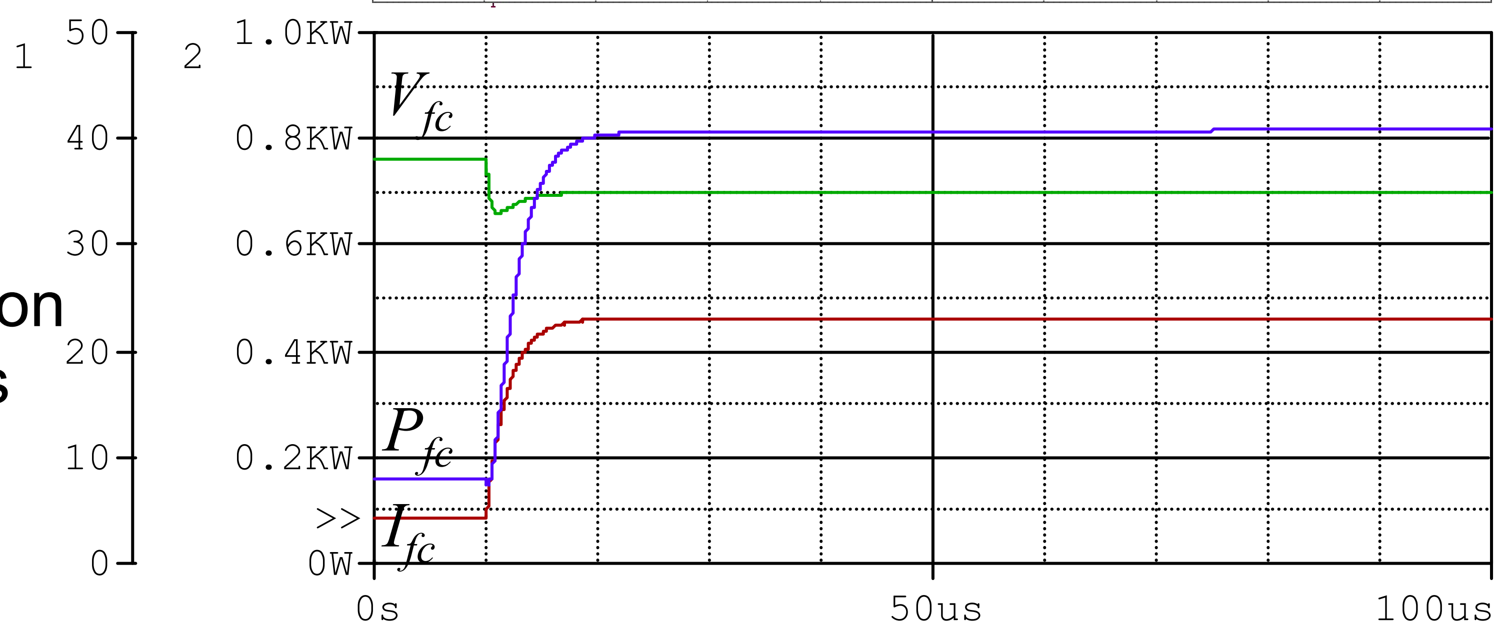


Verification of Fuel Cell Model with Resistive Load Transient

(a)
Experimental results

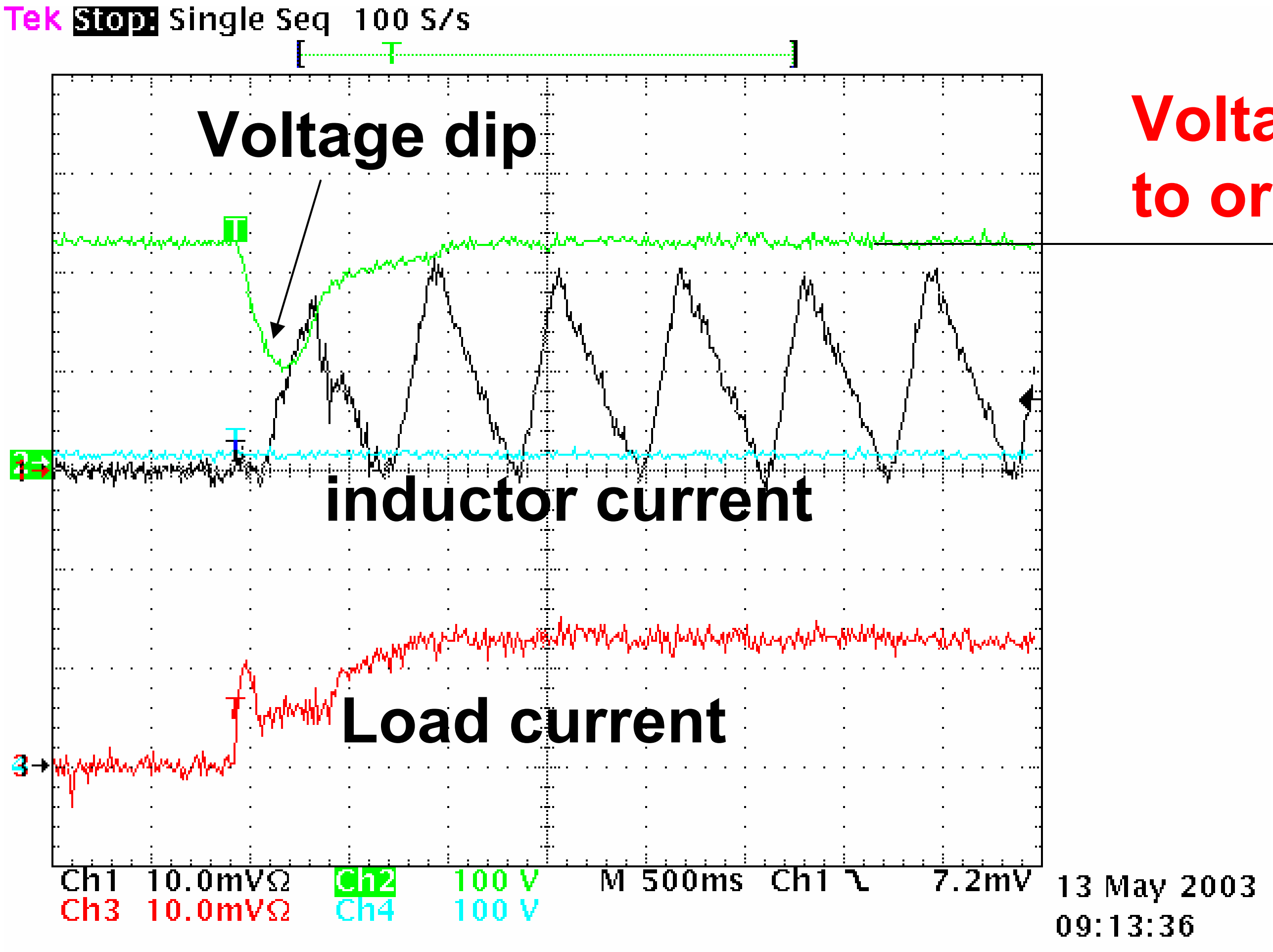


(b)
Simulation results



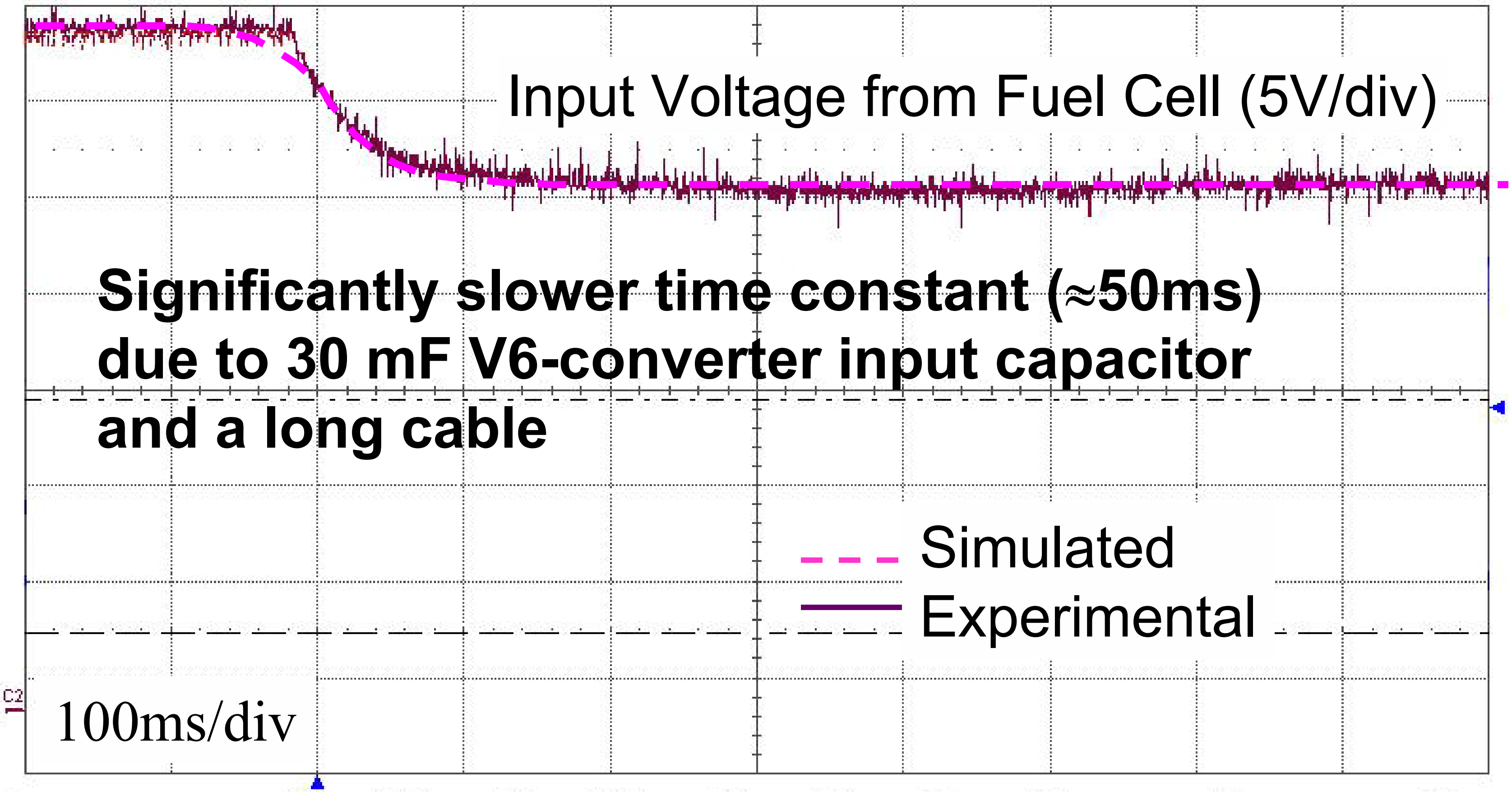
Test Load Transient with a Slow Power Supply

Voltage maintains constant after transient

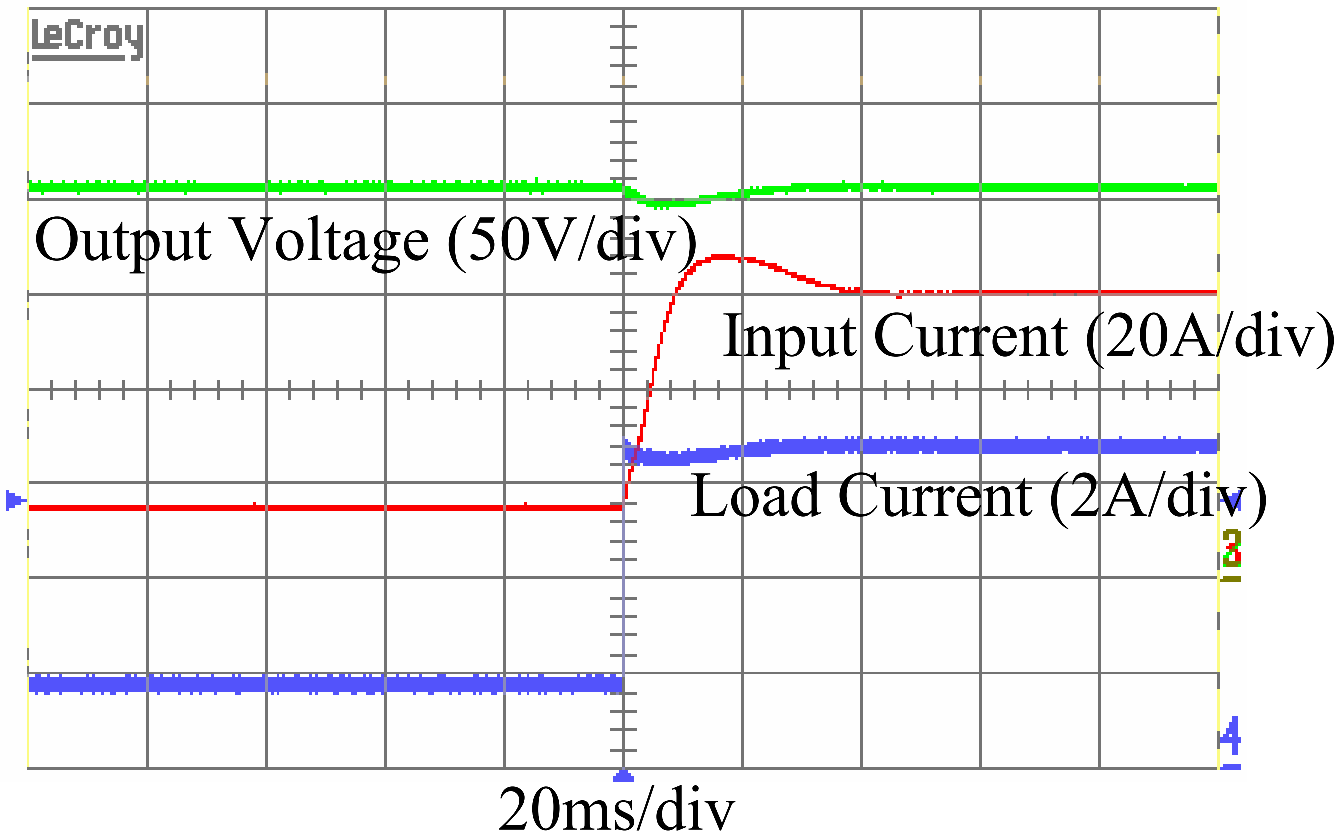


Voltage returns to original level

Fuel Cell Voltage Dynamic with V6 Converter Load Transient

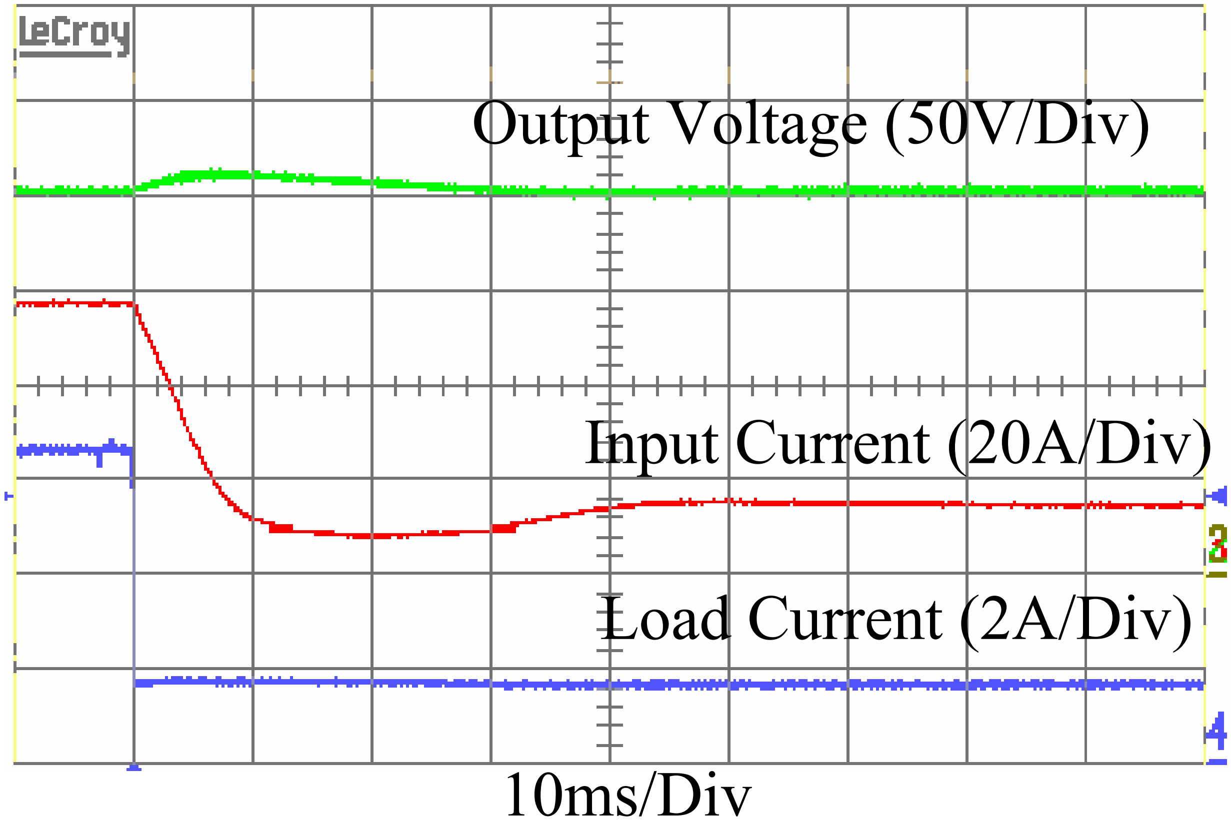


V6-Converter Output under Load Step



With voltage control loop bandwidth designed at 20 Hz, settling time is about 40ms under load step

V6-Converter Output under Load Dump



With voltage control loop bandwidth design at 20 Hz, settling time is about 40ms under load dump

Findings of Fuel Cell Modeling and Converter Test Results

- **Fuel cell stack shows very fast dynamic, nearly instantly without time constant**
- **Perception of slow fuel cell time constant is related to ancillary system not fuel cell stack**
- **Output voltage dynamic is dominated by the converter interface capacitor and cable inductor**
- **Output current dynamic is dominated by the load**

Summary

- Static and dynamic performances of a new V6 converter has been presented
- Two calorimeters were built and calibrated
- PEM fuel cell has been tested under dynamic conditions for controller design purpose
- A circuit model has been verified for fuel cell dynamic study

Future Work

- **Test V6 converter with Calorimeter**
- **Incorporate DC/AC inverter for current ripple evaluation**
- **Work with PNNL for SOFC dynamic modeling in electrical circuits and test V6 converter with SOFC**
- **Develop energy balancing and control strategies with SOFC**
- **Test EMI performance at EPRI-PEAC**