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

The First Introduction of V6 Converter

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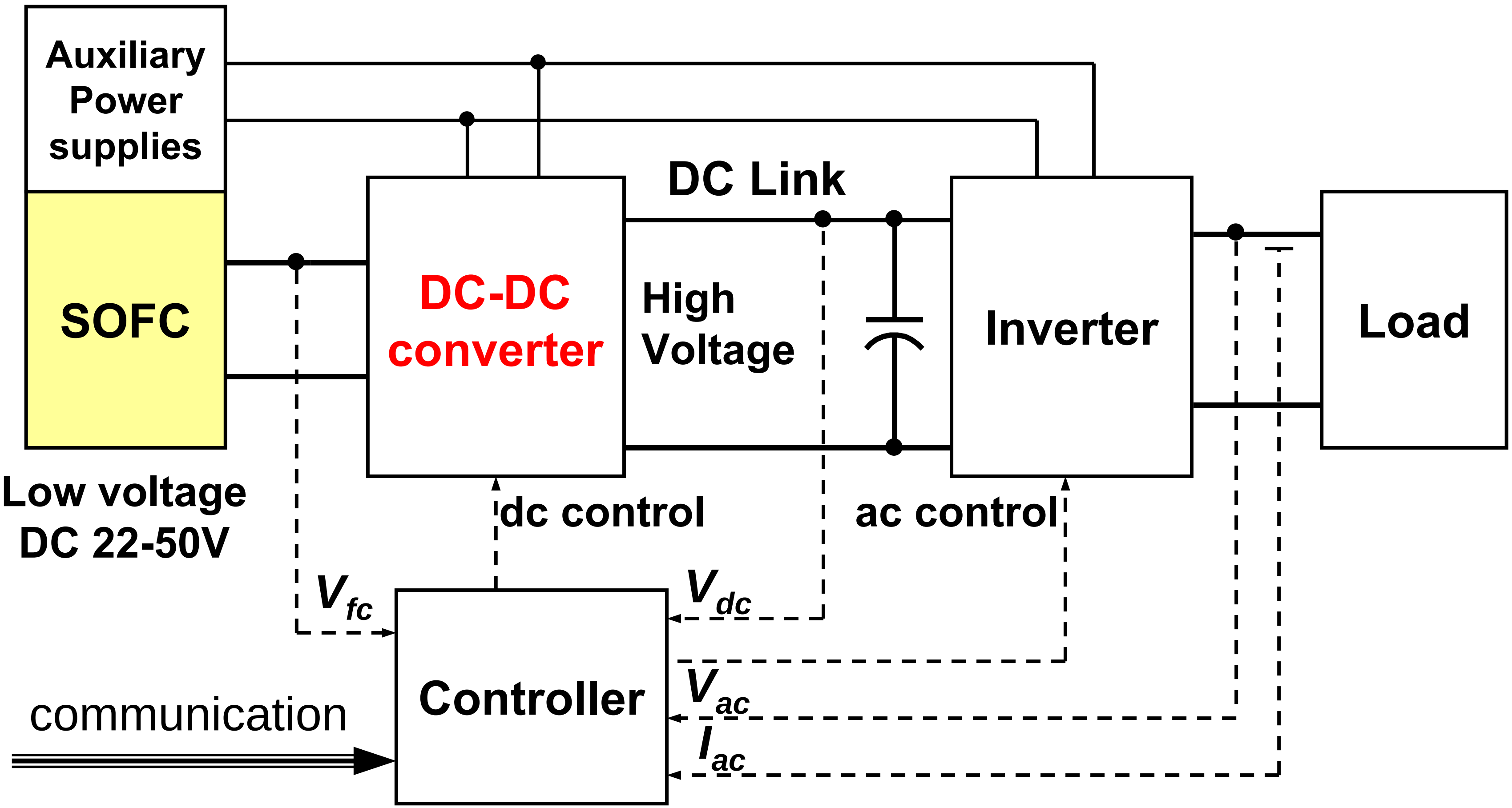
Outline

- Introduction of V6 Converter
- State-of-the-Art DC/DC Converter Technologies
- Hardware Implementation of V6 Converter
- Sensorless Control Design and Implementation
- Fuel Cell Current Ripple Issue
- Conclusion

The Role of DC-DC Converter in an SOFC Power Plant



The DC/DC converter is the most crucial electrical interface to the fuel cell source

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

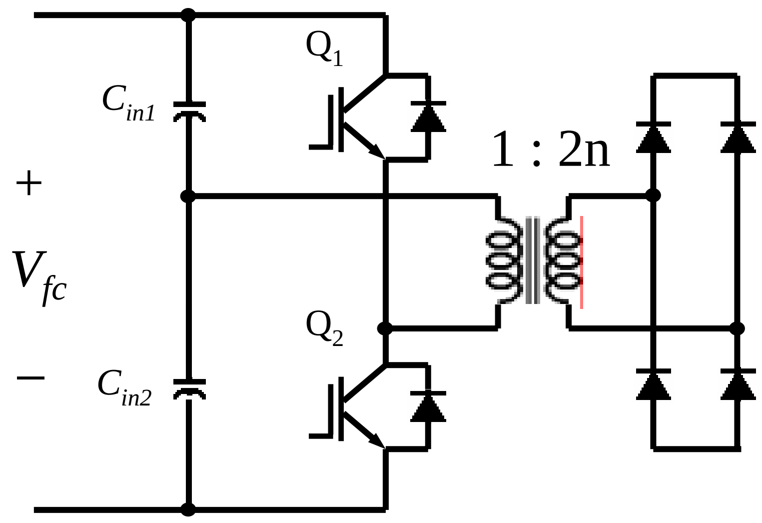
Why V6 Converter?
Analogy to Automotives

Automotives	Fuel Cell Converters
• Single Cylinder • Motorcycle • <500 c.c.	• Single Phase • Low power converters • <1kW
• Six Cylinders (V6) • Midsize vehicles • >2500 c.c.	• Six Phases (V6) • Mid power converters • >5kW

How to Categorize Converters?

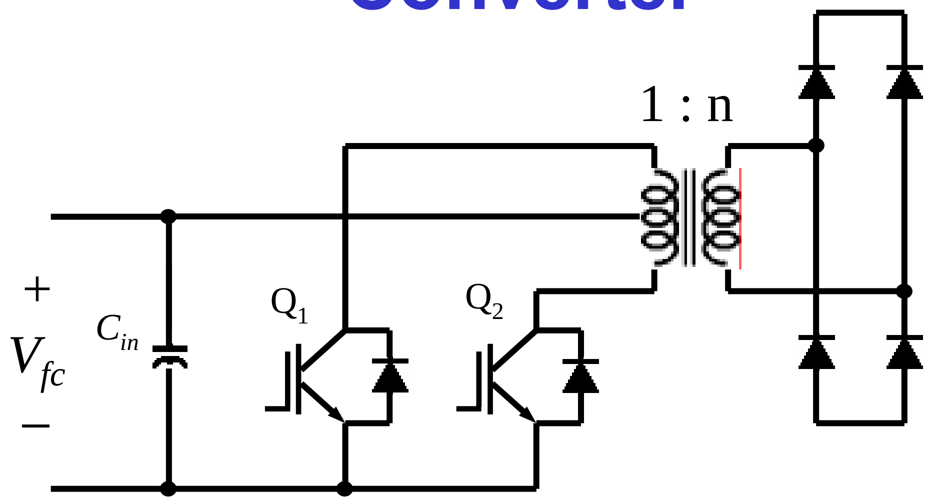
- Single-Phase Converters
  - Half-Bridge Converter
  - Push-Pull Converter
- Two-Phase Converters
  - Full-Bridge Converter
- Three-Phase Converters
- Four-Phase Converters
- Six-Phase Converters

Half-Bridge Converter – A Single-Phase Converter



- ✓ Low device count
- ✓ Low voltage device
- ✗ Device sees twice current
- ✗ Split capacitors
- ✗ Twice transformer turns ratio

Push-Push Converter – A Single-Phase Converter



+ Low component count – misleading when power level is high!

+ Simple non-isolated gate drives

+ Suitable for low-voltage low-power applications

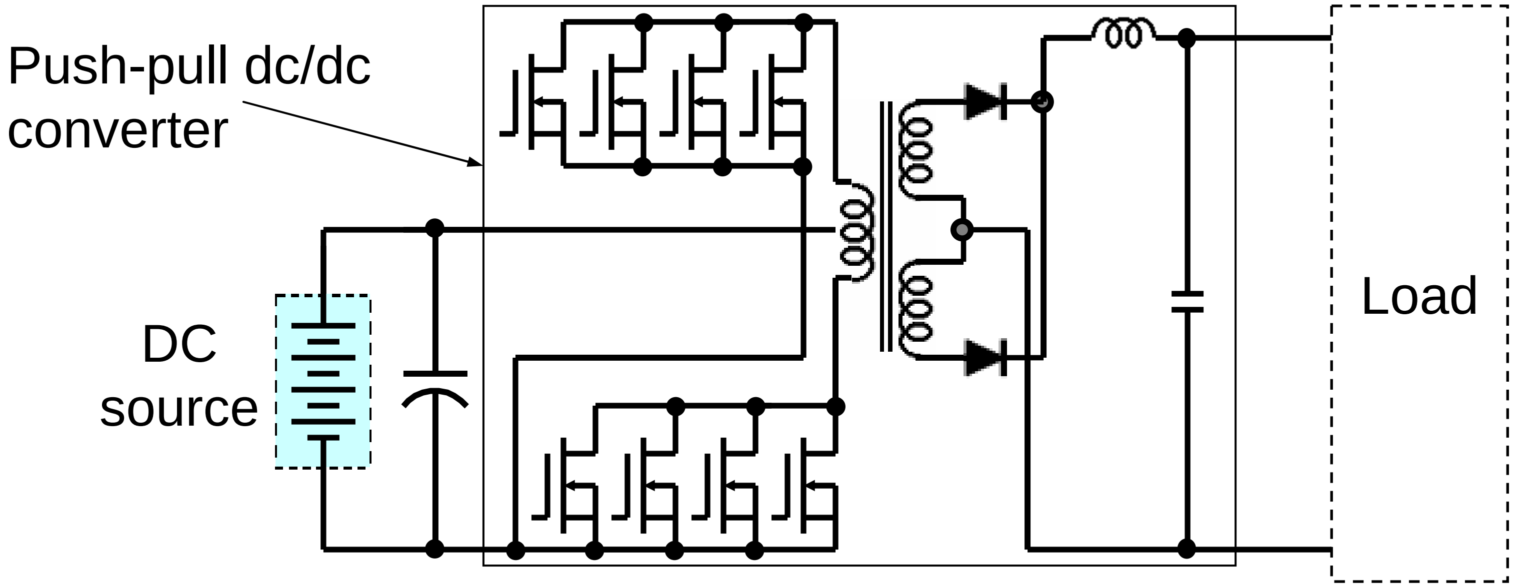
– Device sees twice input voltage – high voltage MOSFET is needed

  - ➢ High conduction voltage drop, low efficiency

– Center-tapped transformer

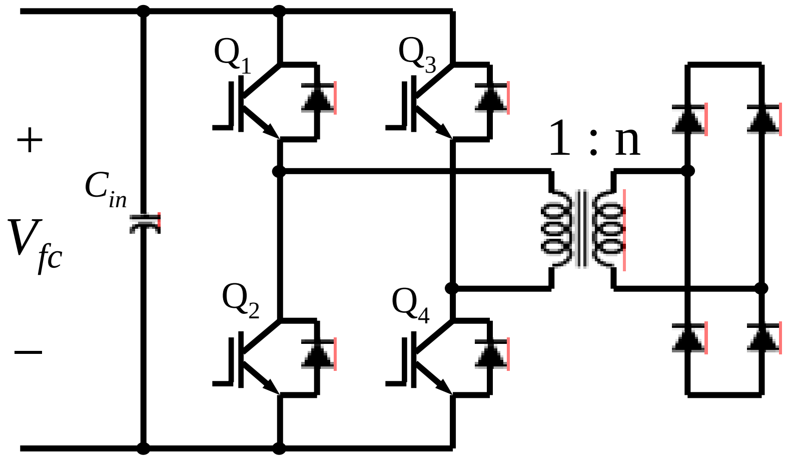
  - ➢ Difficult to make low-voltage high-current terminations
  - ➢ Prone to volt-second unbalance (saturation)

A Commercial Off-the-Shelf 1-kW Push-Pull Converter for Fuel Cell Applications



- **Input – 28 to 35 V**
- **Device voltage blocking level – 100 V**
- **Efficiency – <85% even with 4 devices in parallel**

Full-Bridge Converter – A Two-Phase Converter

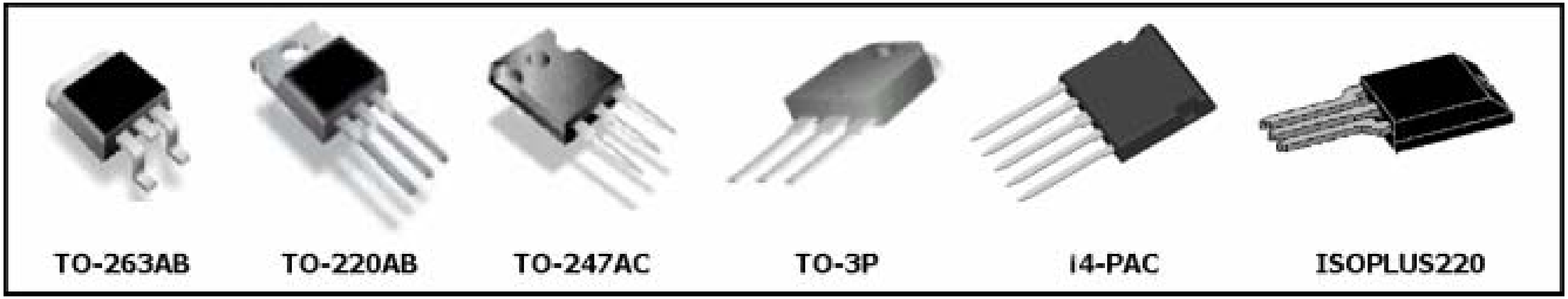


- ✓ **Most popular circuit today for high-power applications**
  - ➢ **Soft switching possible**
  - ➢ **Reasonable device voltage ratings**
- × **High component count from the look**
- × **High conduction losses**

List of Available Power MOSFETs for up to 50-V Fuel Cell Converters

Manufacturer	Part Number	V_{DSS} (V)	R_{DS-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

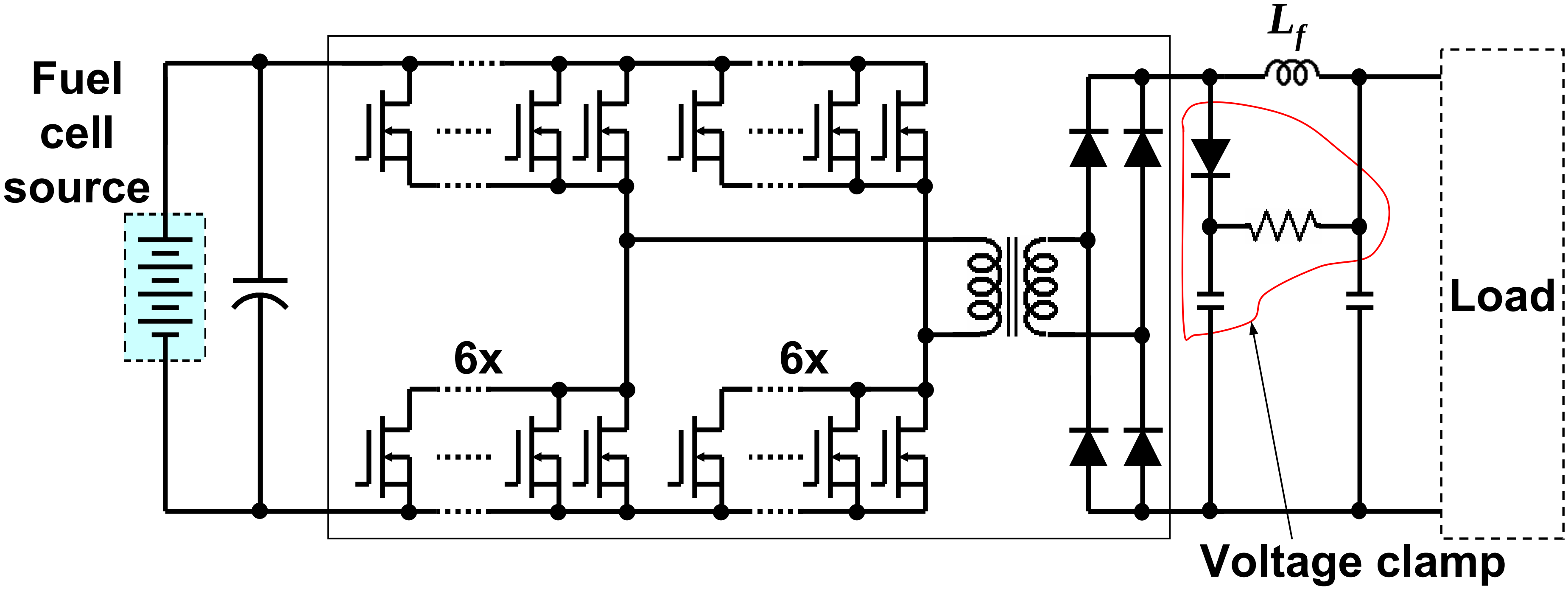
*Note: IXYS FMM 150-0075 is a dual pack (half bridge) device.



Efficiency Consideration with Conventional Full Bridge Converter

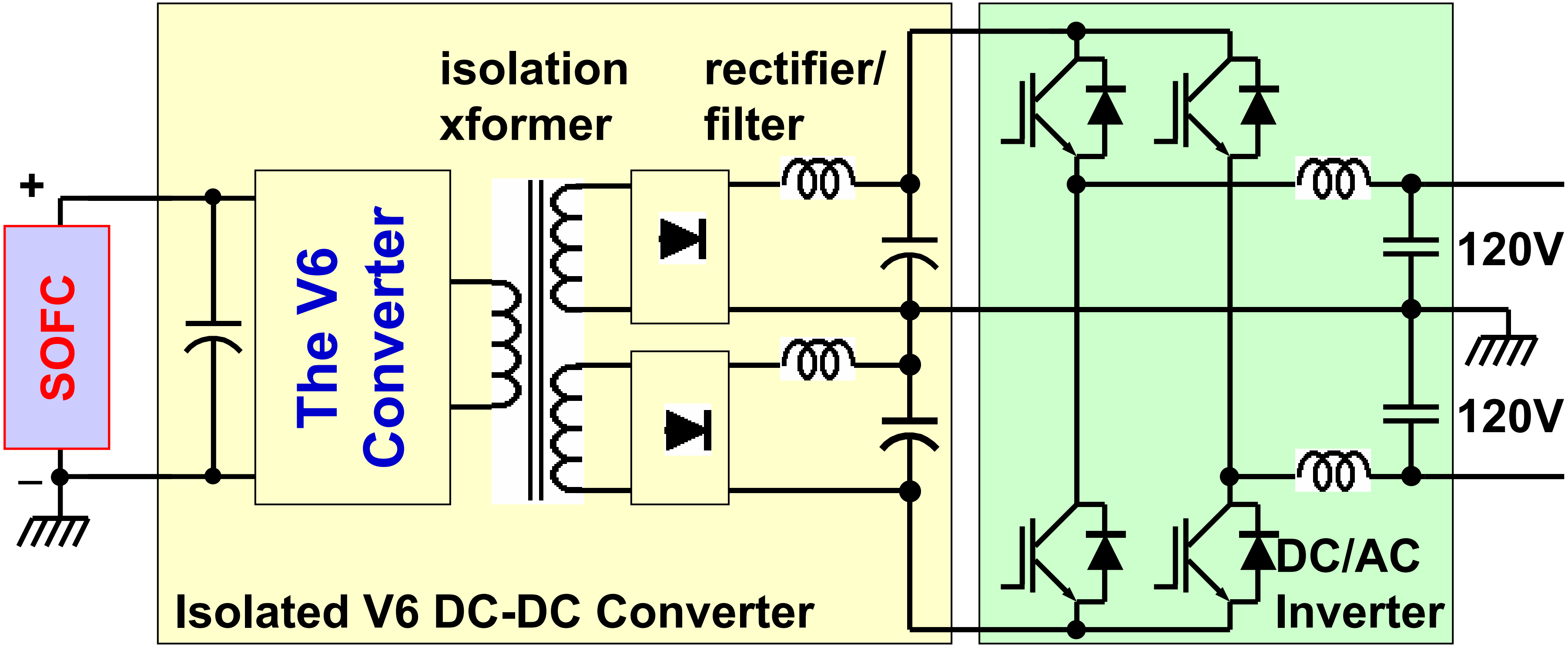
- **At 6kW fuel cell power output condition**
- **Input voltage: 25 V**
- **Input current: 240 A**
- **Device conduction resistance = 4.5mΩ at 25°C and 9mΩ at 125°C**
- **Device conduction voltage drop: V_{on} = 9mΩ×240×2 = 4.32V**
- **Maximum achievable efficiency: 82% (18% loss)**
- **Minimum number of parallel devices to achieve 97% efficiency: 6 ➔ V_{on} = 0.72 V (assuming no parasitic and switching losses and no output stage losses)**
- **Minimum total number of devices to achieve 97% efficiency: 24 ➔ Equivalently 12 phases are needed to achieve efficiency goal**

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



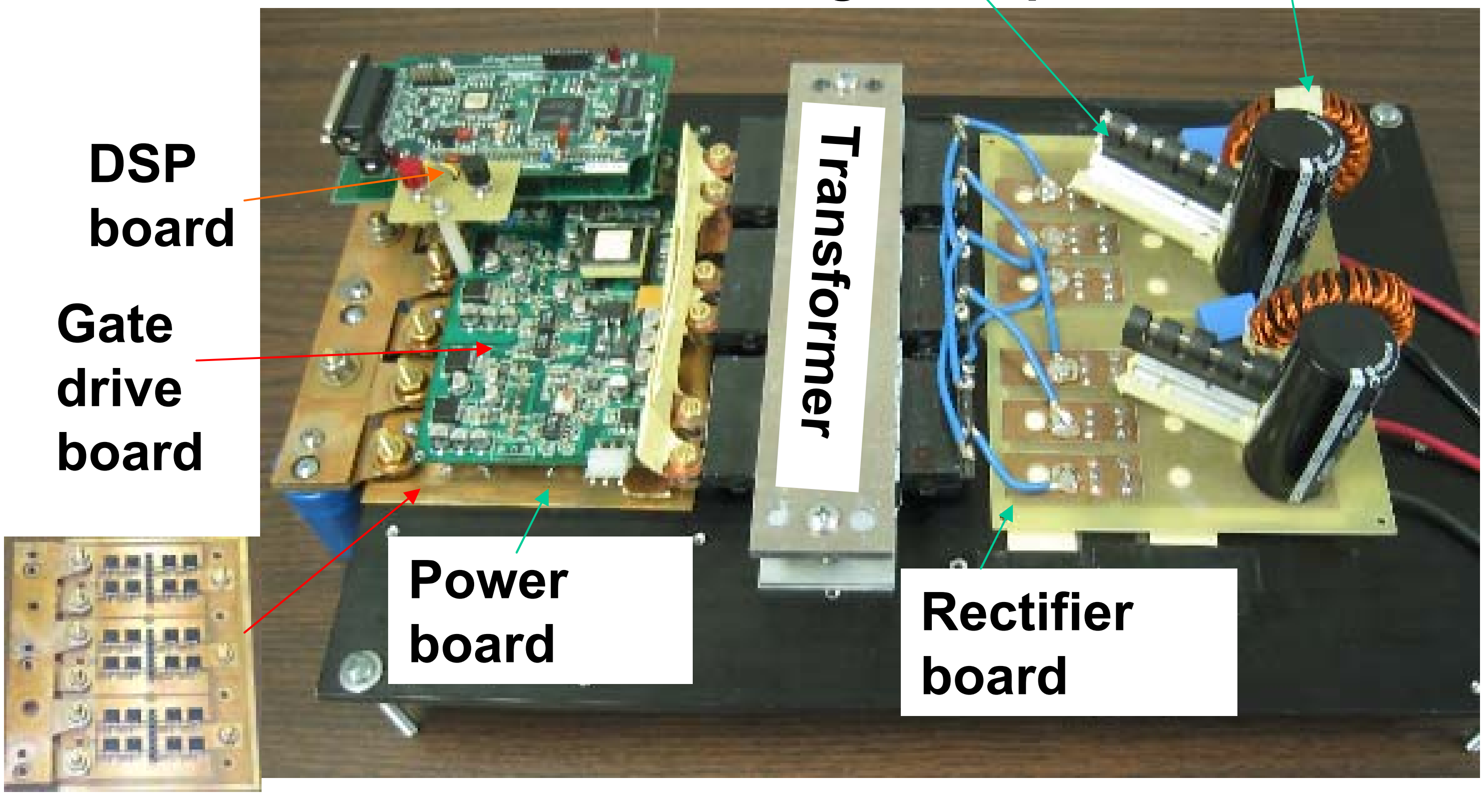
- **With 6 devices in parallel, the two-leg converter can barely achieve 97% efficiency**
- **Problems are additional losses in parasitic components, voltage clamp, interconnects, filter inductor, transformer, diodes, etc.**

The V6 DC-DC Converter and the Associated the Output Stage DC-AC Inverter



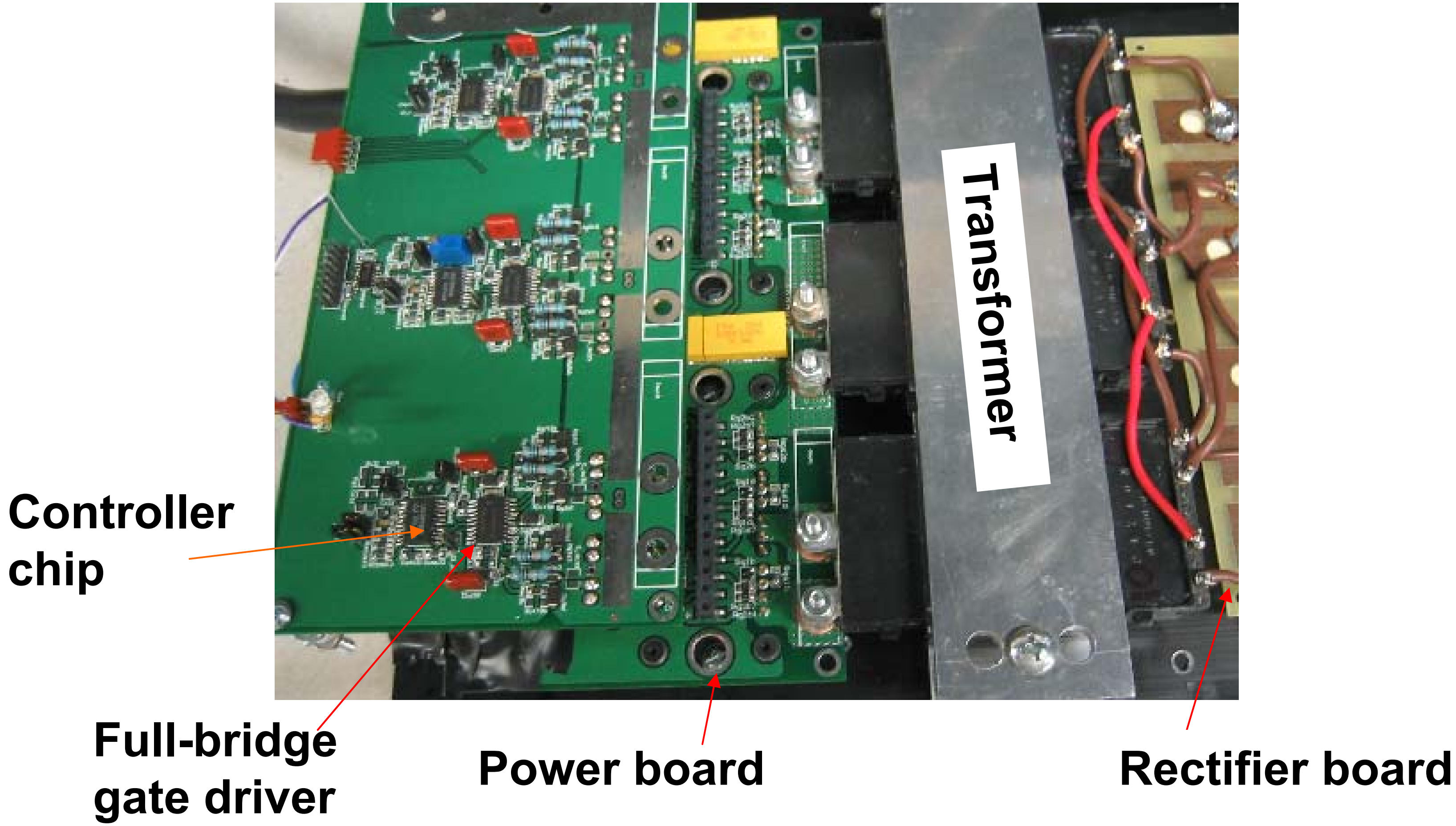
- ✓ Low-voltage high-current input
- ✓ High-voltage low-current output
- ✓ Dual output dc voltages provide neutral point for grounding
- ✓ Residual current in non-switching phases allows zero-voltage switching at light load condition

Photograph of a Three-Phase Hard-Switched DC-DC Converter



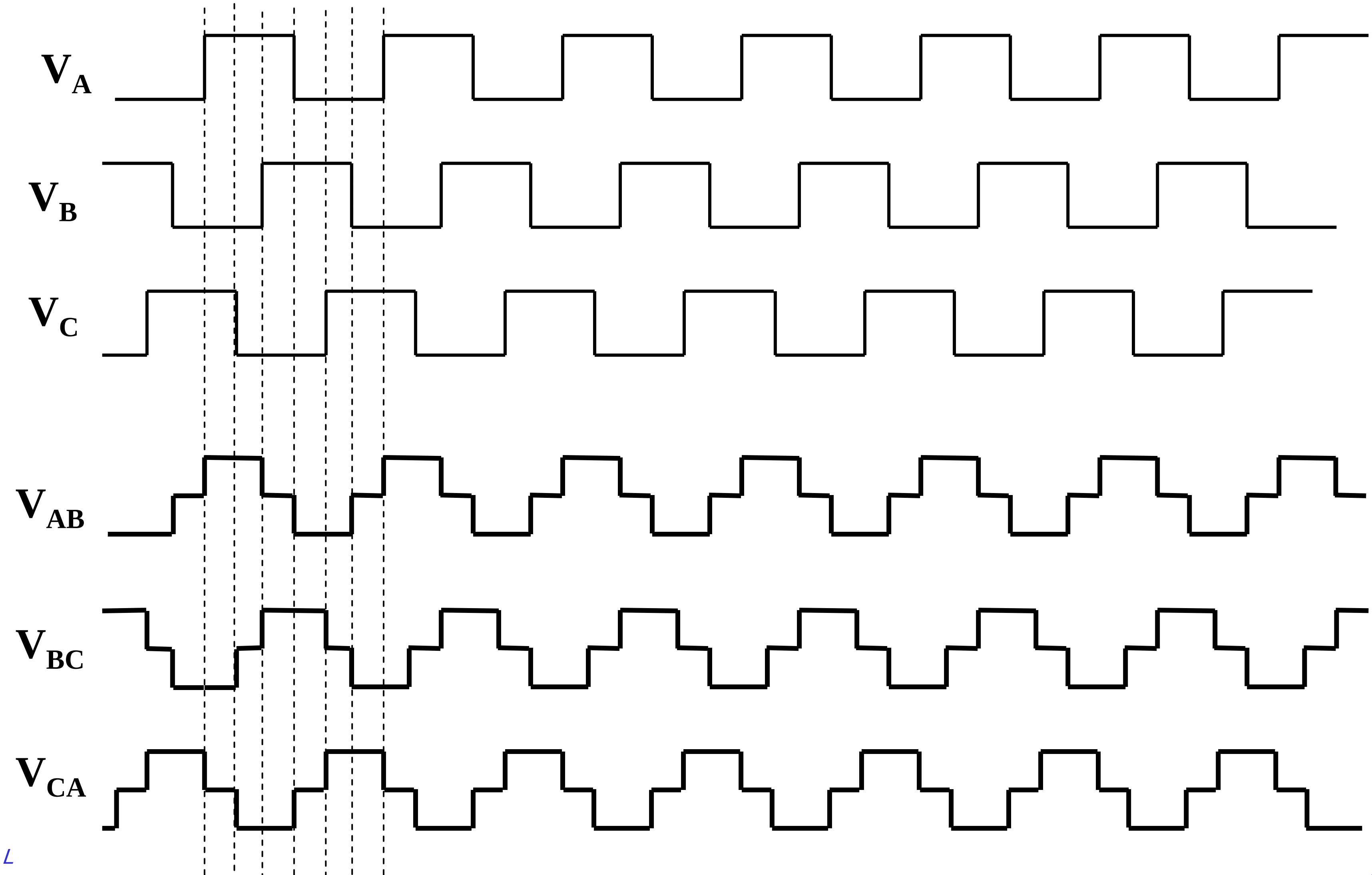
Note: The power switch has four TO-263 devices in parallel

Photograph of the Soft-Switched V6 DC-DC Converter

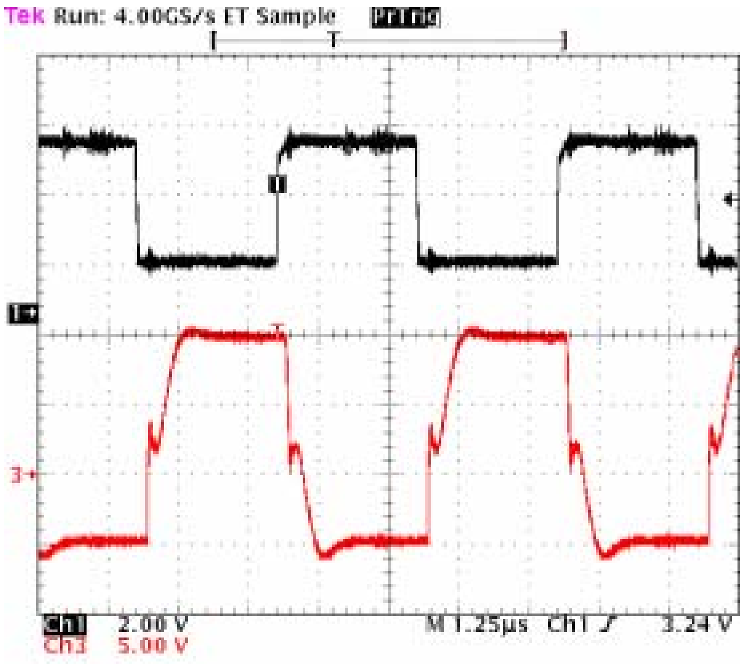


Note: The power switch is single device without paralleling to avoid parasitic losses

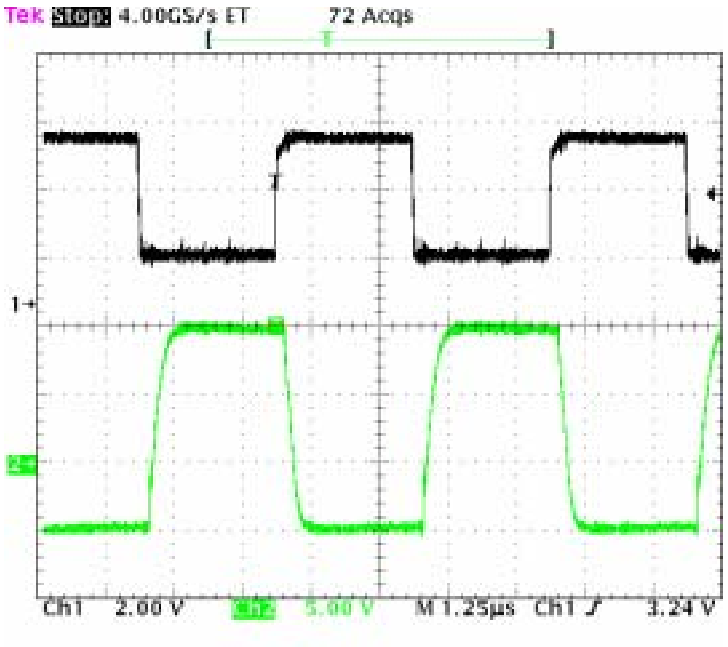
Phase Shifted Controller Signals



Significance of Parasitic Components



Gate drive with twisted wire

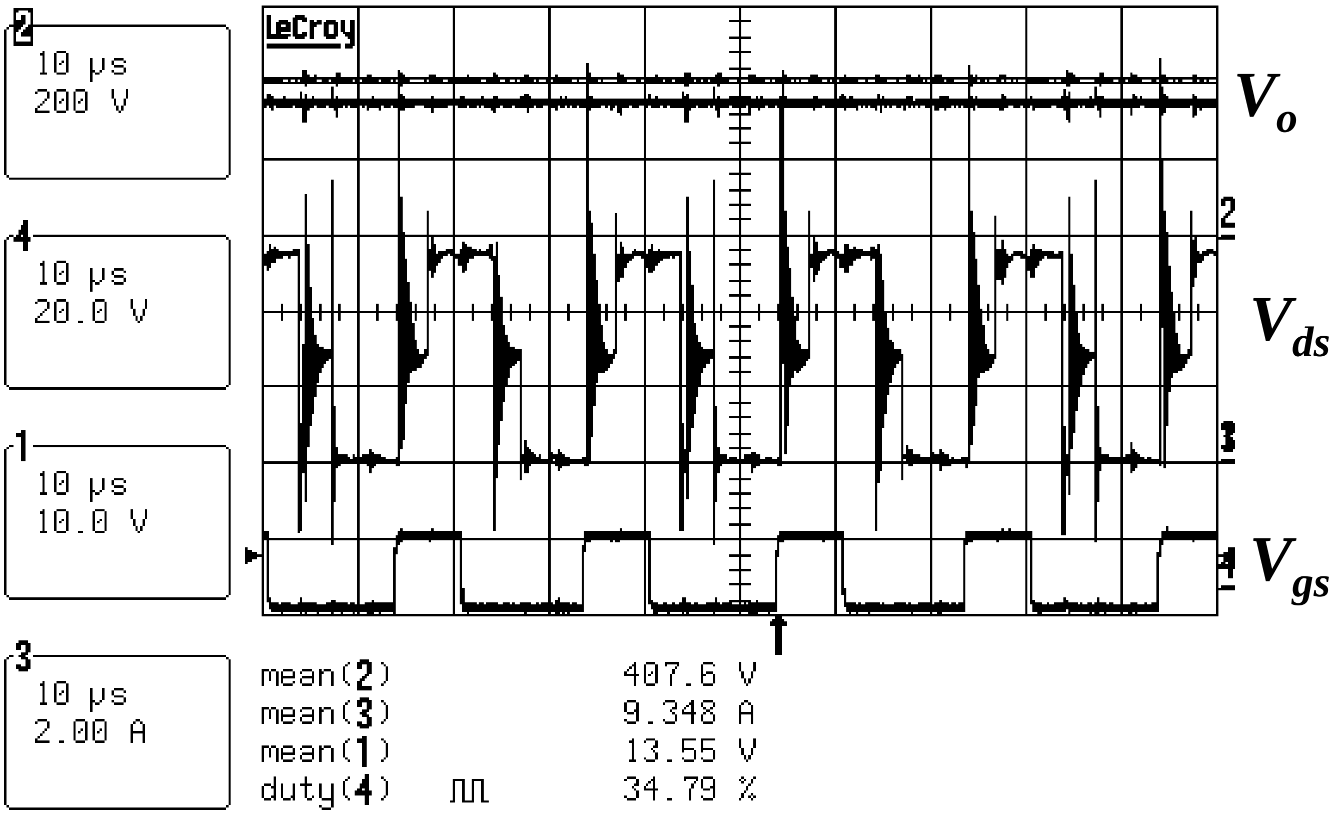


Direct plug in type

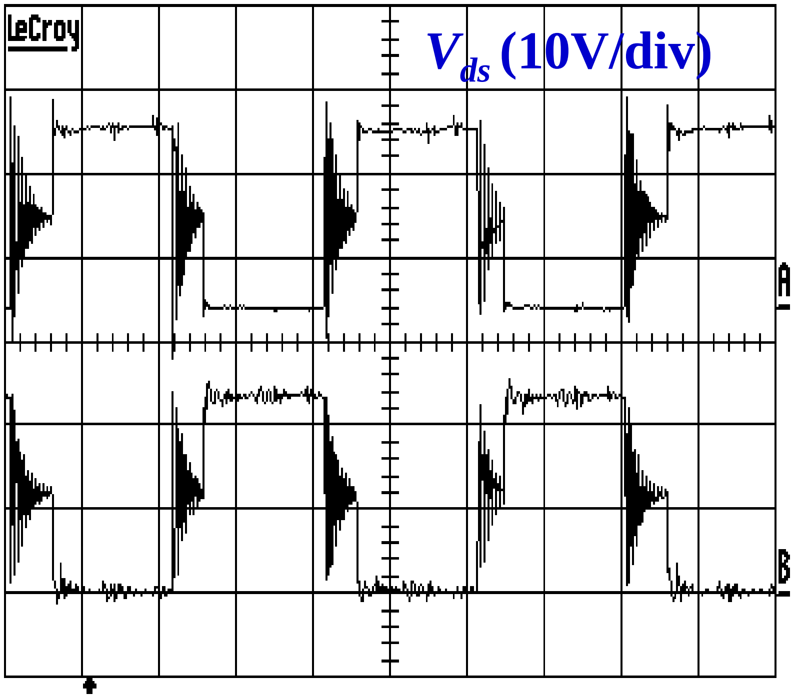
Potential Problems:

- **High frequency ringing and EMI**
- **Additional transformer loss**
- **Additional switching loss**

Voltage Overshoot and Ringing on Primary Side under Hard Switching Condition



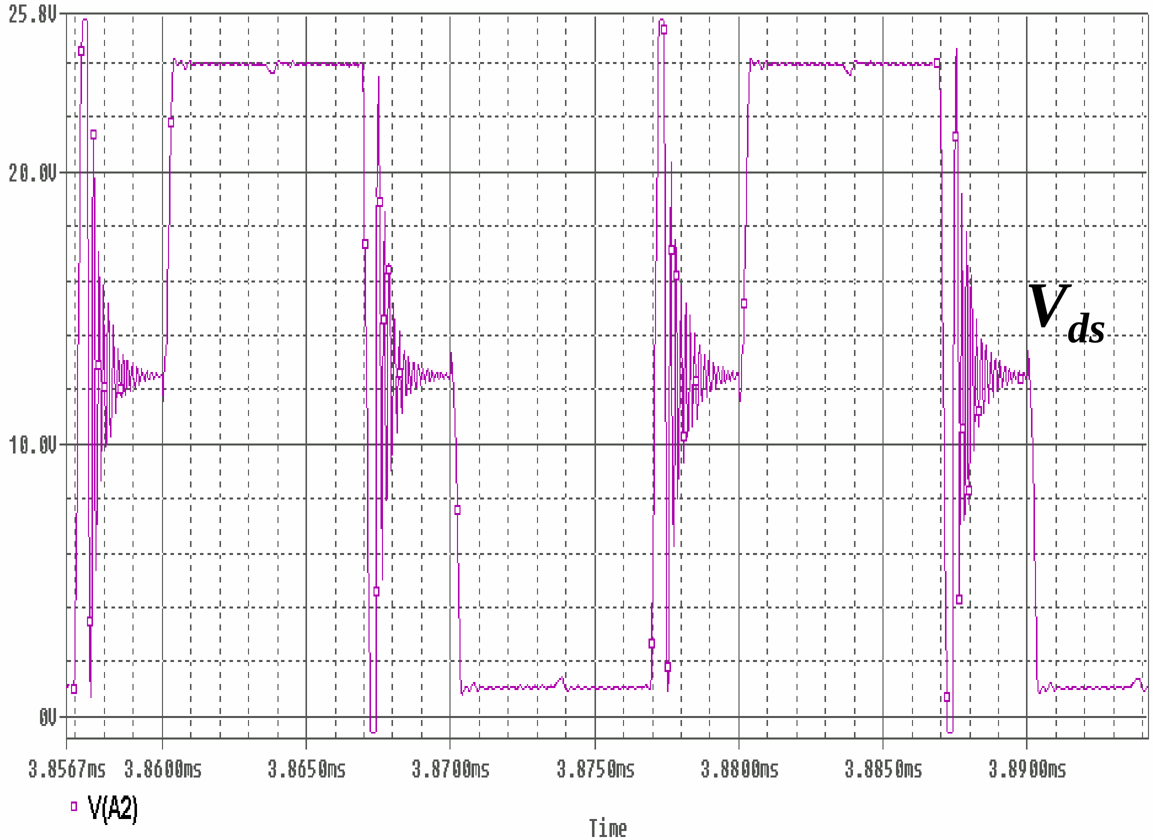
Hard Switched Full-Bridge Converter Device Voltage Waveform at Lighter Load



At lighter load, for the primary side device voltage

- **Severe parasitic ringing remains**
- **Resulting substantial EMI propagation**

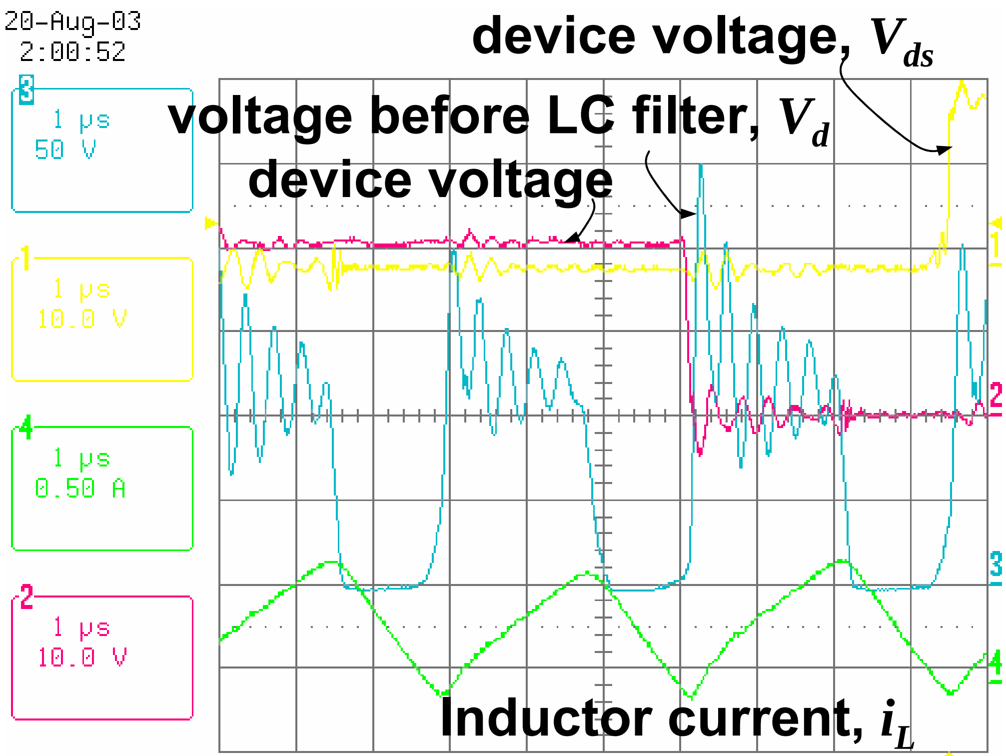
Simulation Verification of Hard Switched Converter Voltage Overshoot and Ringing



Causes of voltage overshoot and ringing

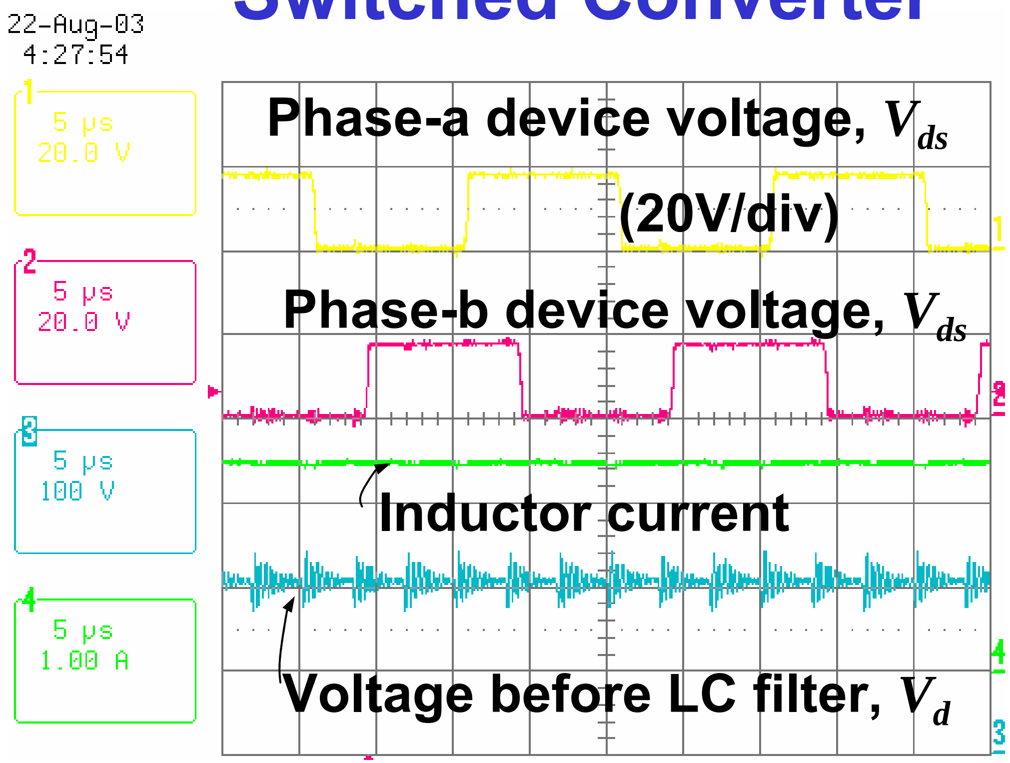
1. **Circuit parasitic inductance**
2. **Output capacitance of the device**
3. **Transformer leakage inductance**

“Conventional Full-Bridge” Soft-Switched Converter Voltage and Current Waveforms



- ✓ Primary side soft switching without voltage overshoot and parasitic ringing
- × Secondary side has high voltage swing from 0 to 2.5V_o and severe ringing with single-phase operation
- × High inductor current requires large inductor to smooth it out

Voltage and Current of the V6 Soft-Switched Converter



- ✓ Primary side soft switching without voltage overshoot and parasitic ringing
- ✓ Secondary inductor current is rippleless; and in principle, no dc link inductor is needed
- ✓ Secondary voltage swing is eliminated with <40% voltage overshoot

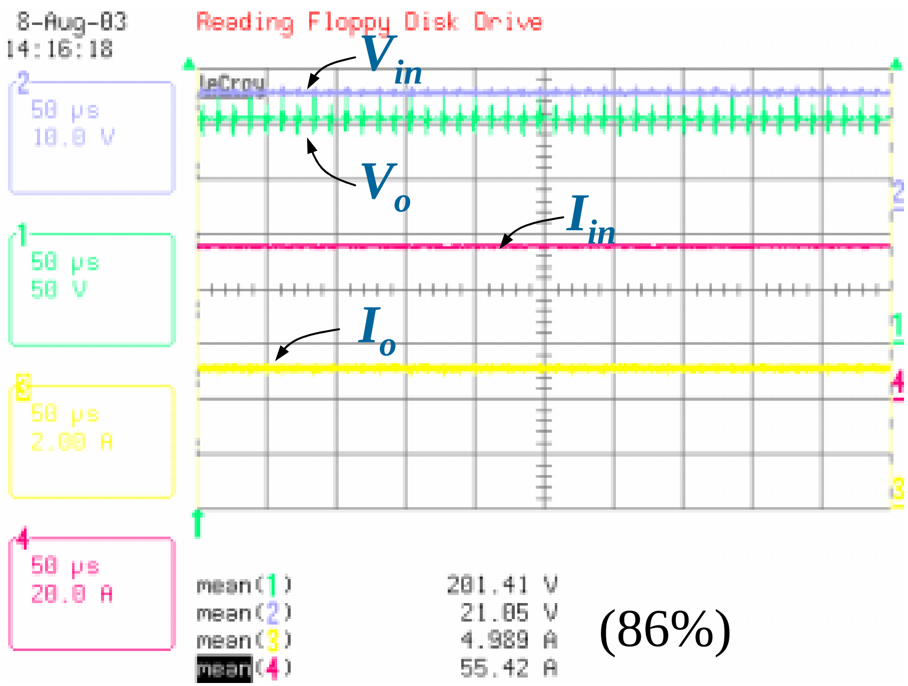
Significant DC link Inductor Size Reduction as Compared to Full-Bridge Converter

L_f for V6 converter

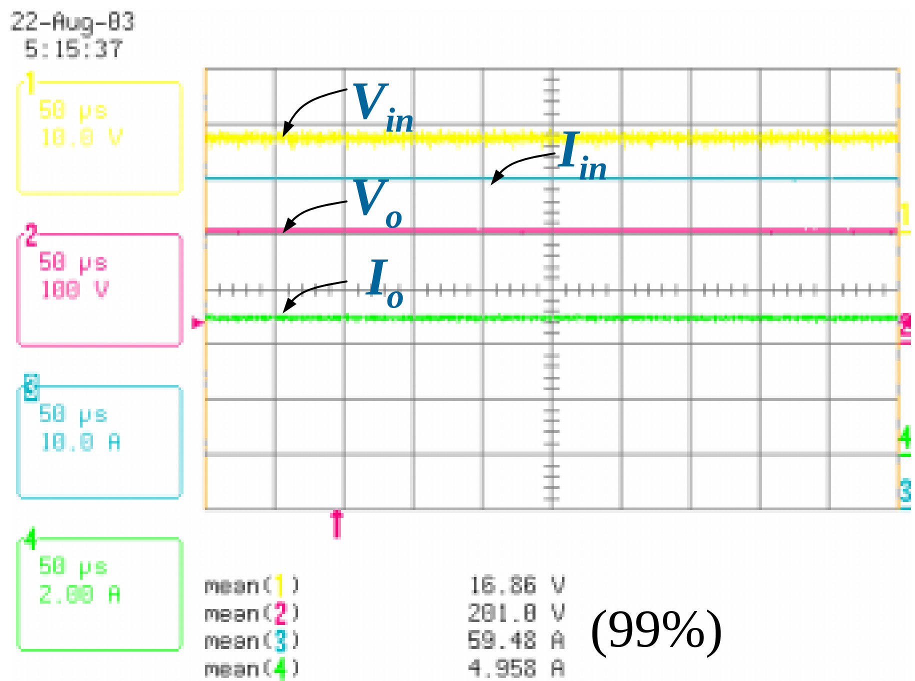
L_f for full-bridge converter

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

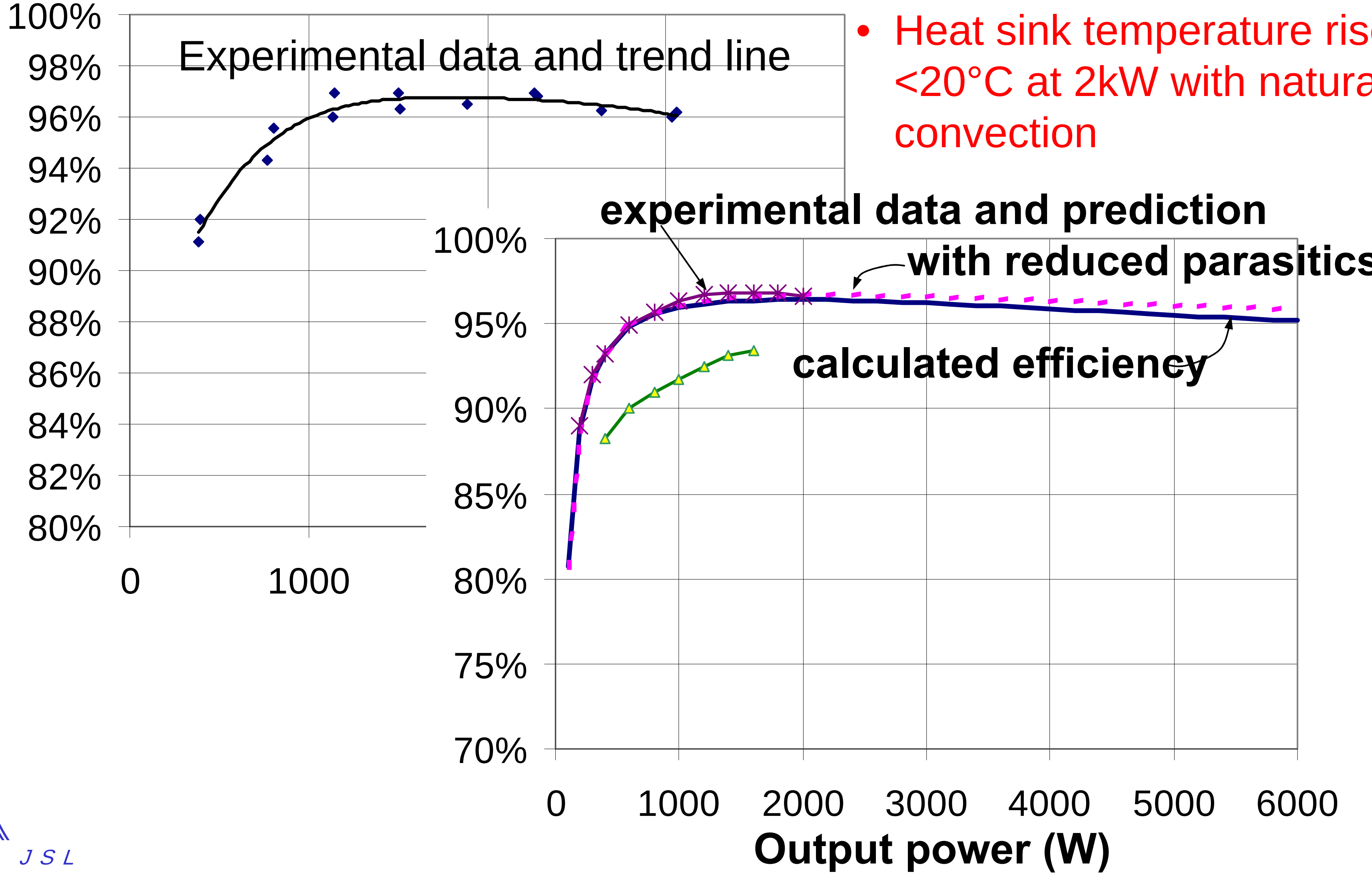
Significant improvement with multiphase converter

✓ Less EMI

✓ Better efficiency (97% versus 87% after calibration)

Efficiency Measurement Results

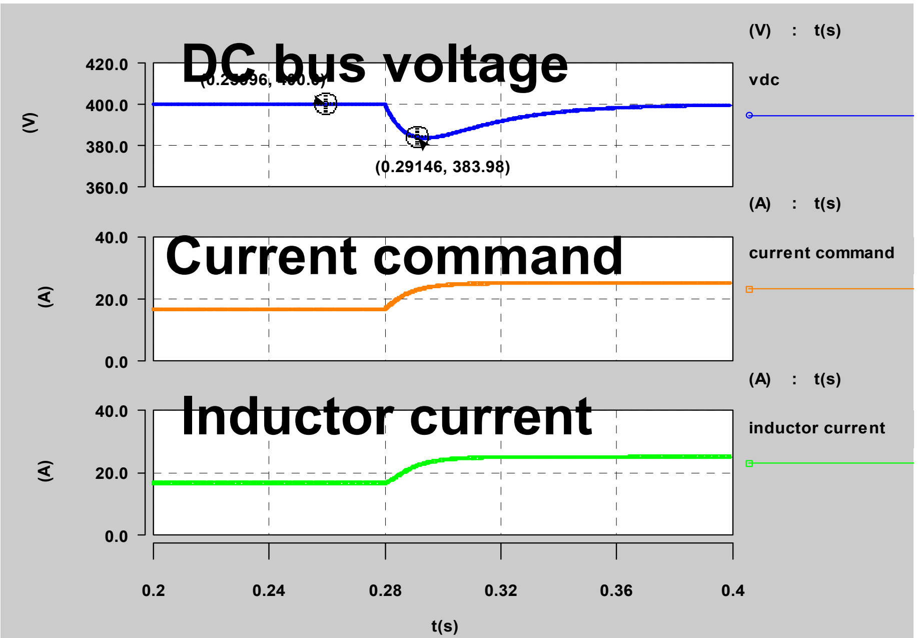
- Measurement error: within 1%
- Heat sink temperature rise: <20°C at 2kW with natural convection



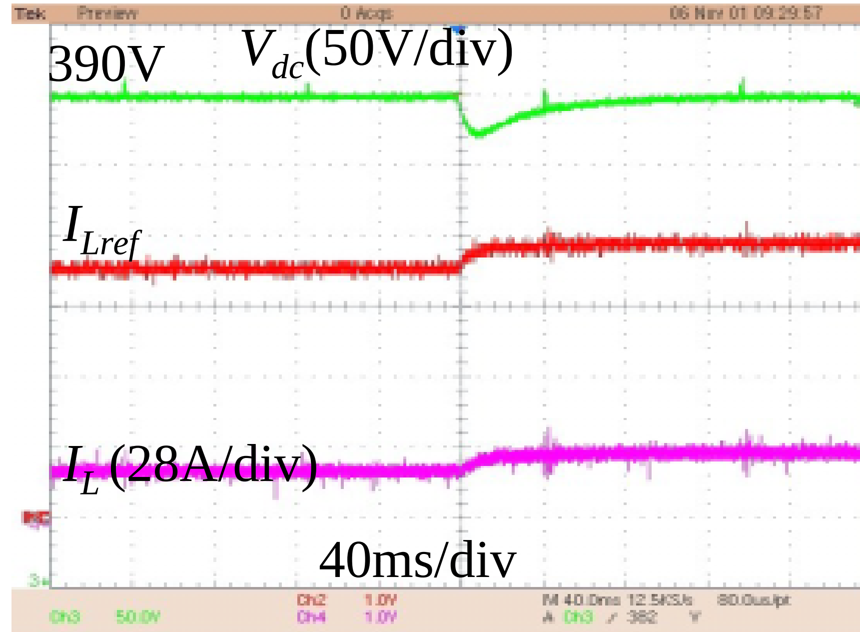
Current Sensorless Control Design

- **To regulate dc bus voltage, current loop may not be necessary. However, with added current loop the control response is faster, and the voltage regulation is more stable.**
- **The problem with adding a current control loop is the cost associated with the current sensor**
- **In this project, a novel current sensorless control is developed with superior performance to the conventional voltage loop control system**

DC Bus Voltage under 15% Load Step *without Current Loop*



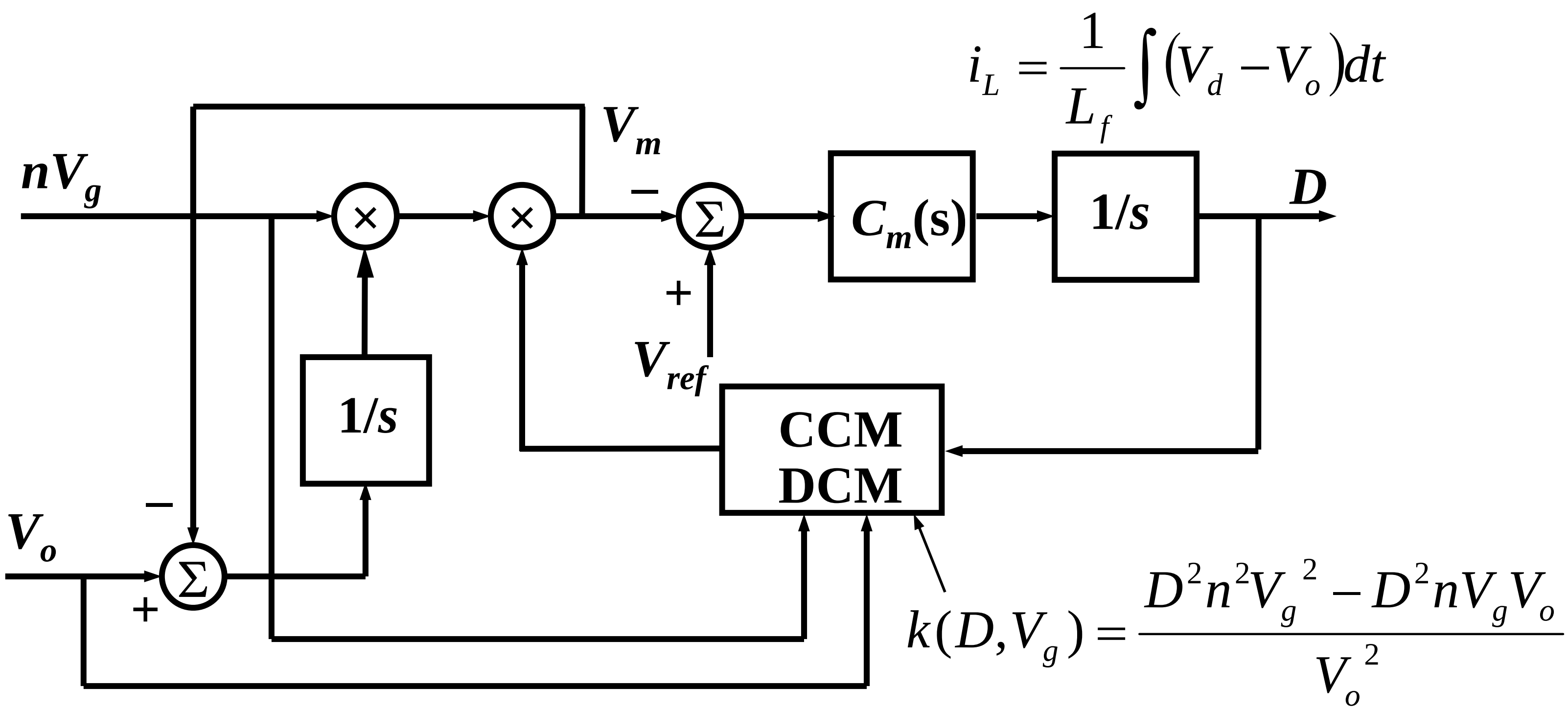
Simulation results



Experimental results

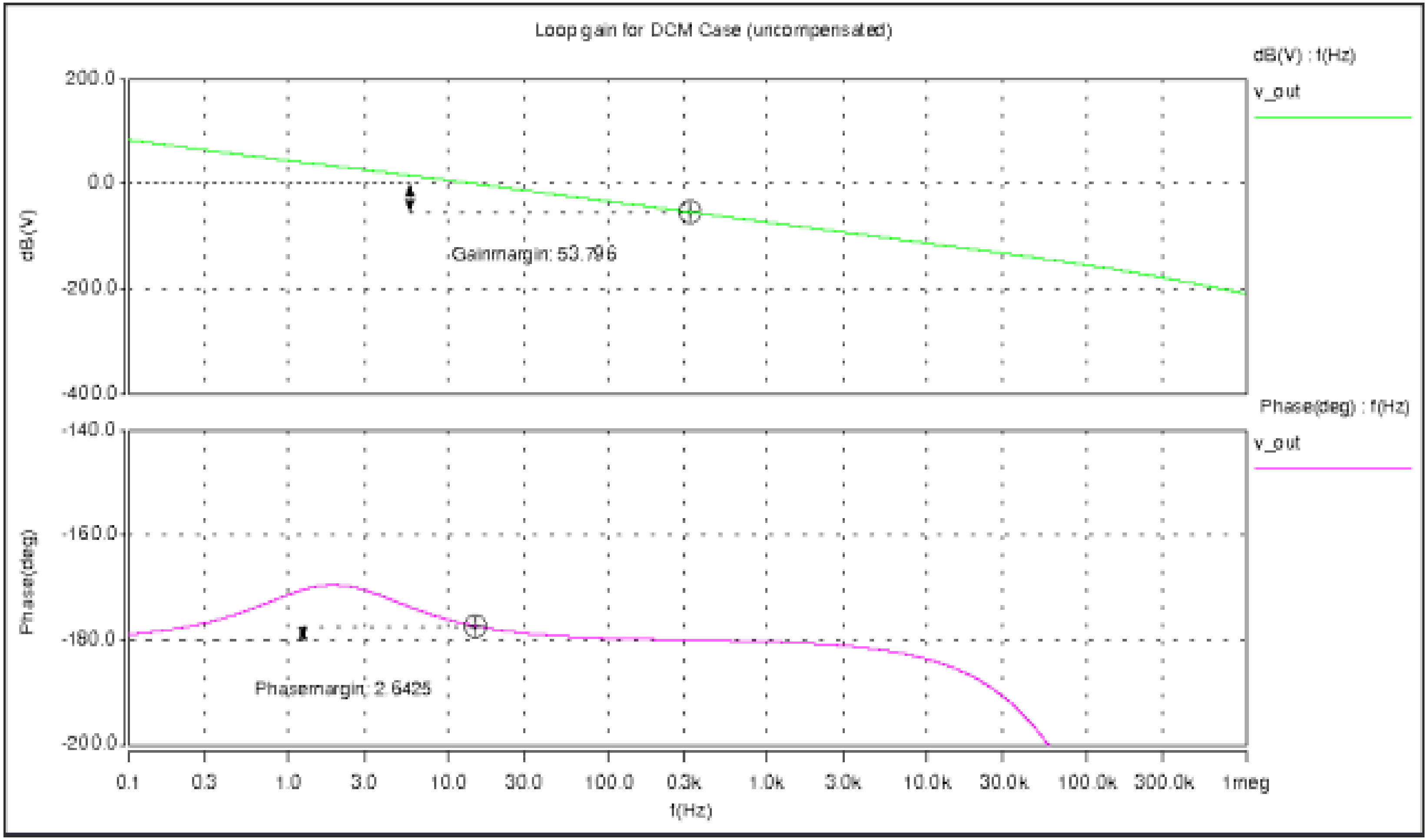
- Without current loop, voltage fluctuates during load transients
- Both simulation and experiment agree each other

A Novel Current Sensorless Control

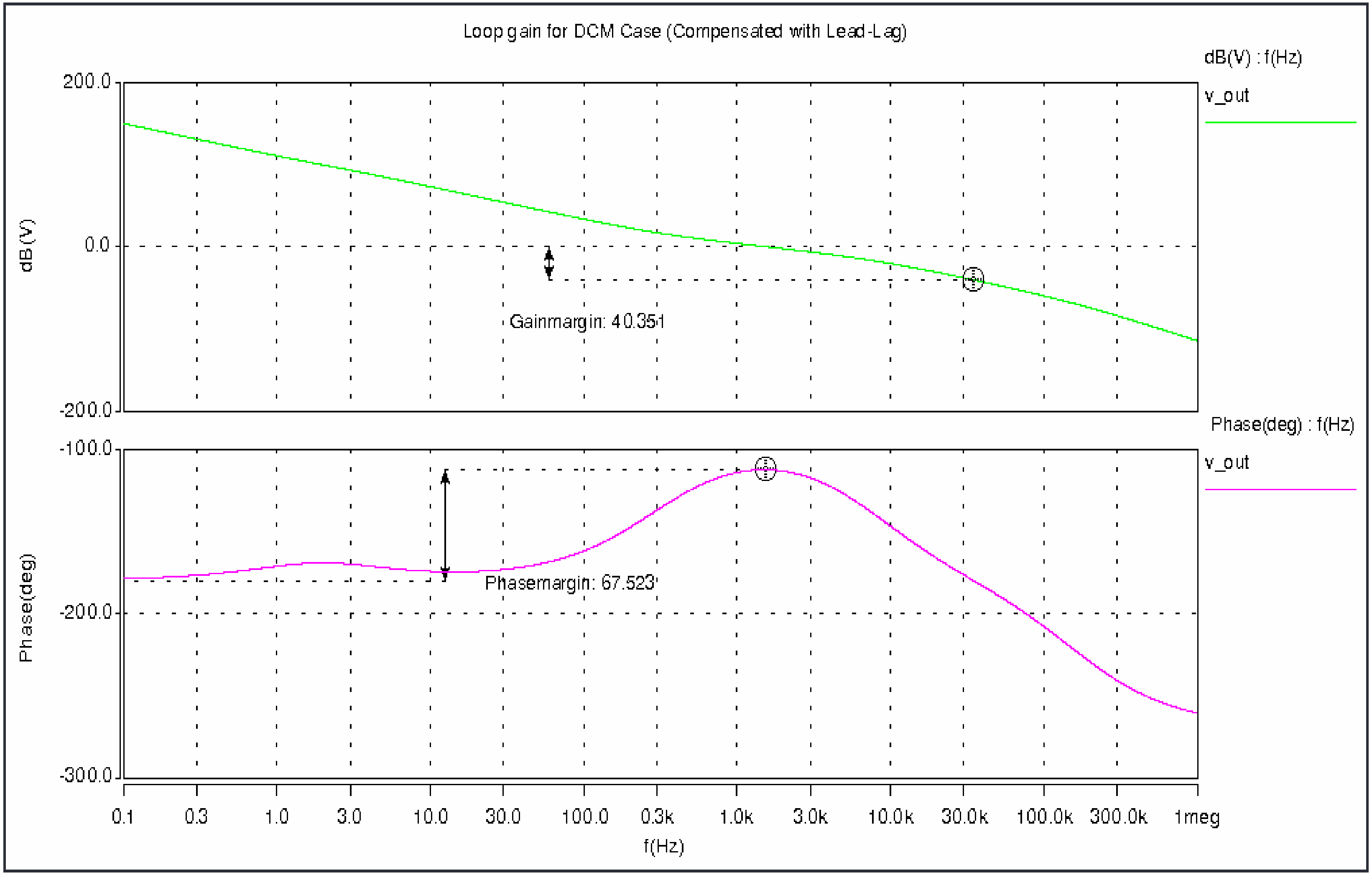


- A plant model based on known inductance and operating mode, continuous and discontinuous conducting mode (CCM and DCM)
- A simple lead-lag compensator is designed to achieve fast dynamic control without the need for the current sensor

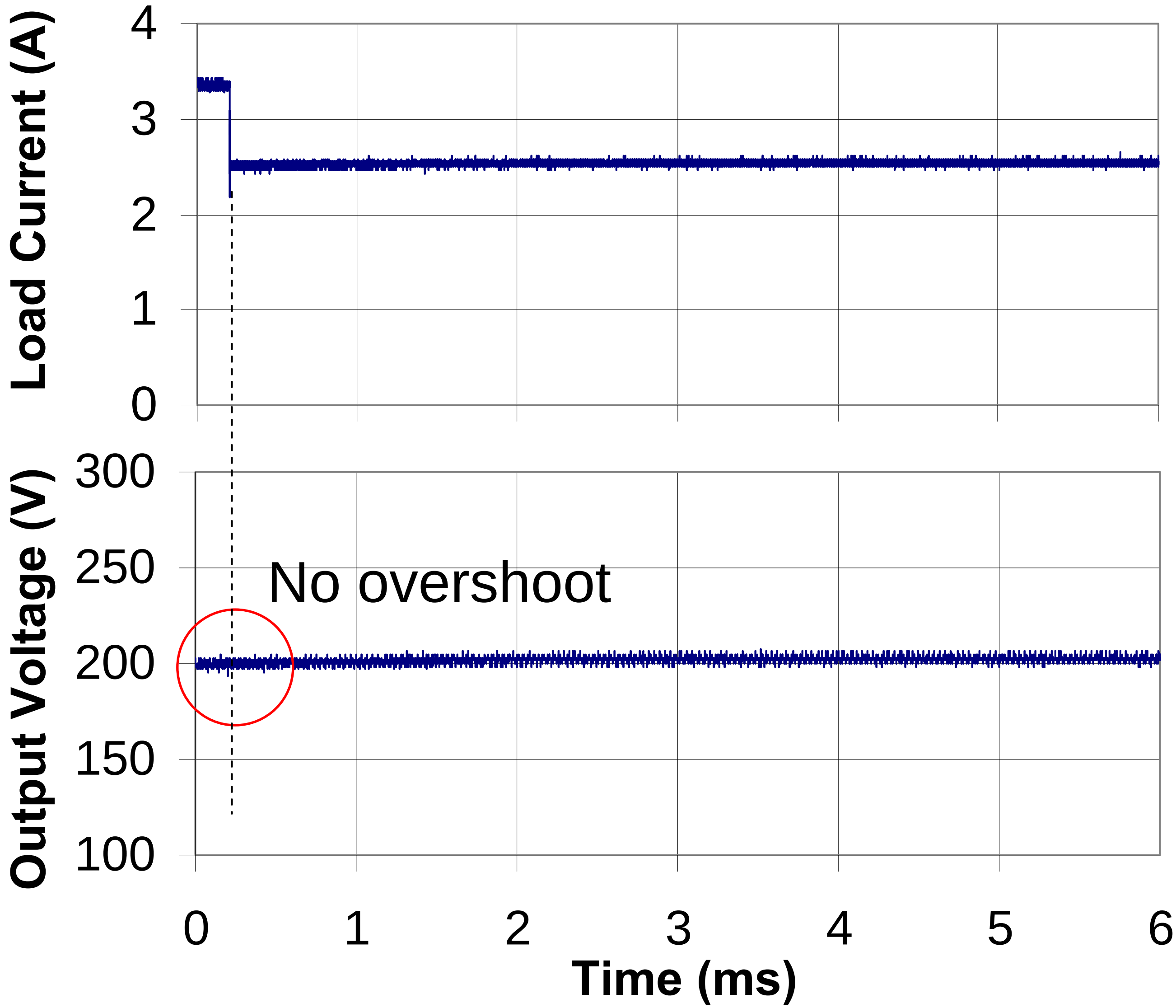
Uncompensated Loop Gain Plot
Phase Margin = 2.6°



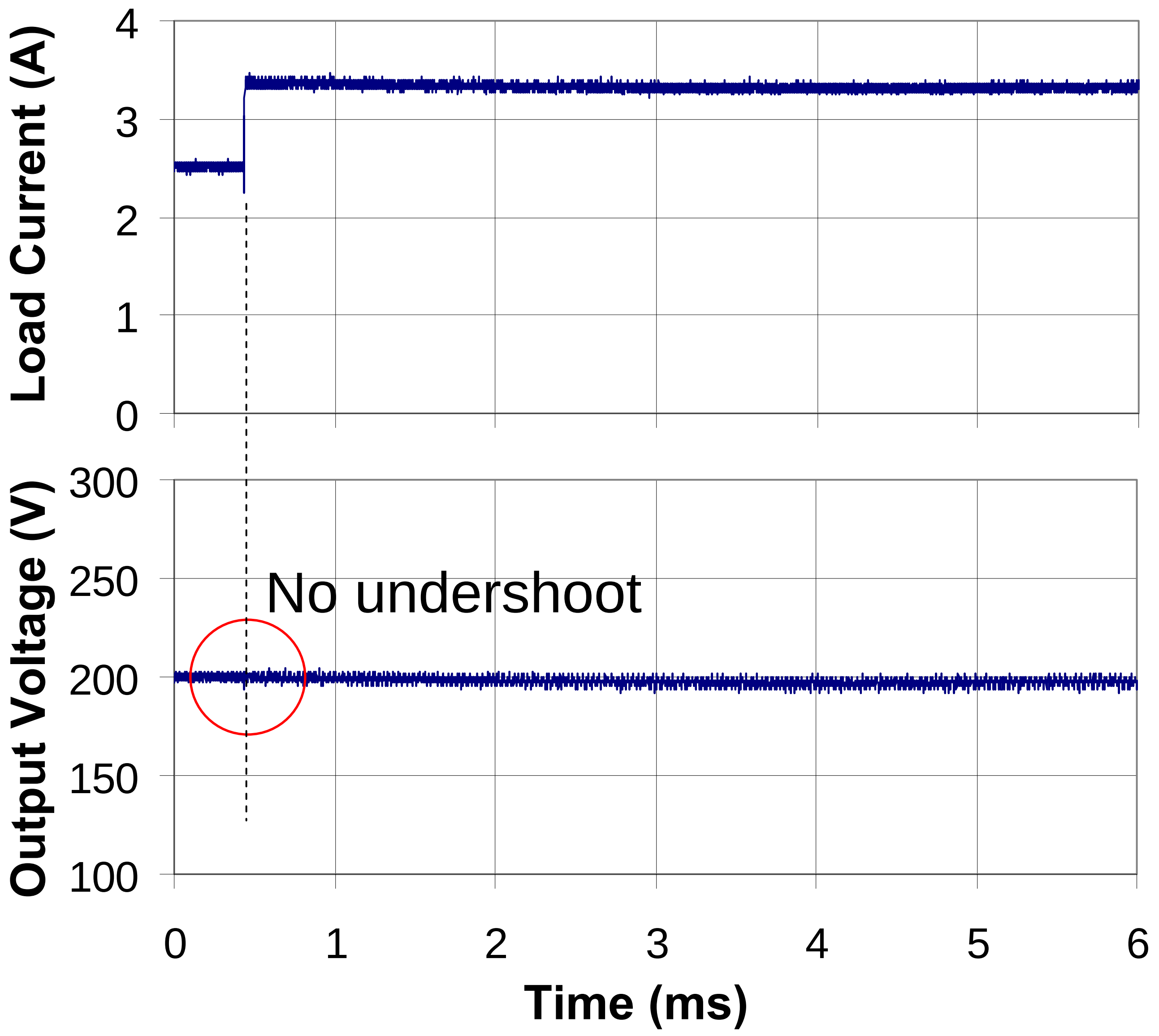
Compensated Loop Gain Plot
Phase Margin = 67.5°



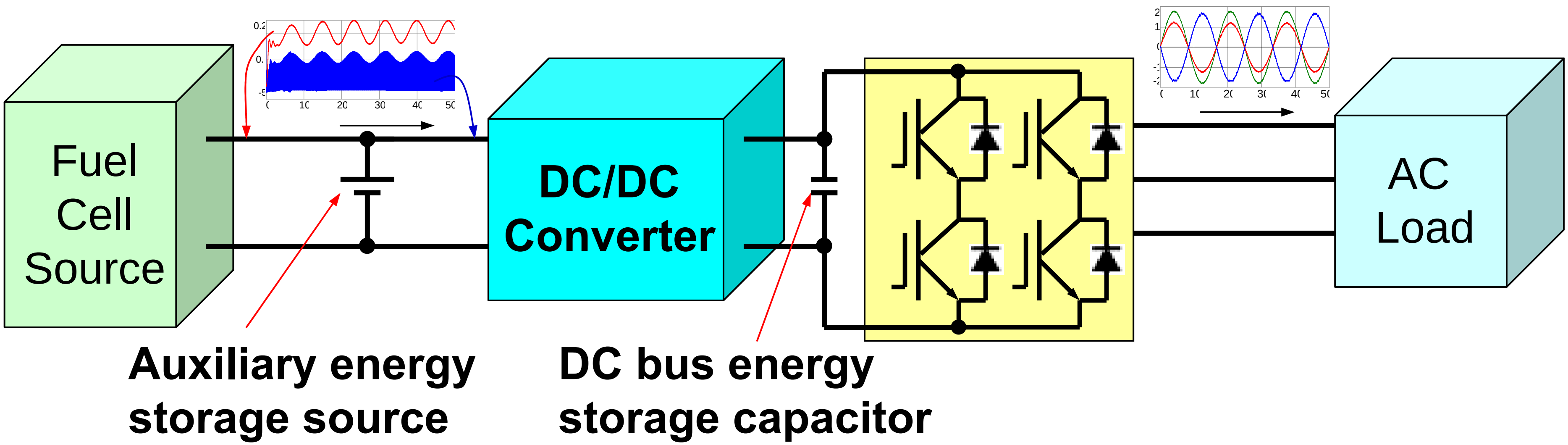
Load Dump with Sensorless Control



Load Step with Sensorless Control

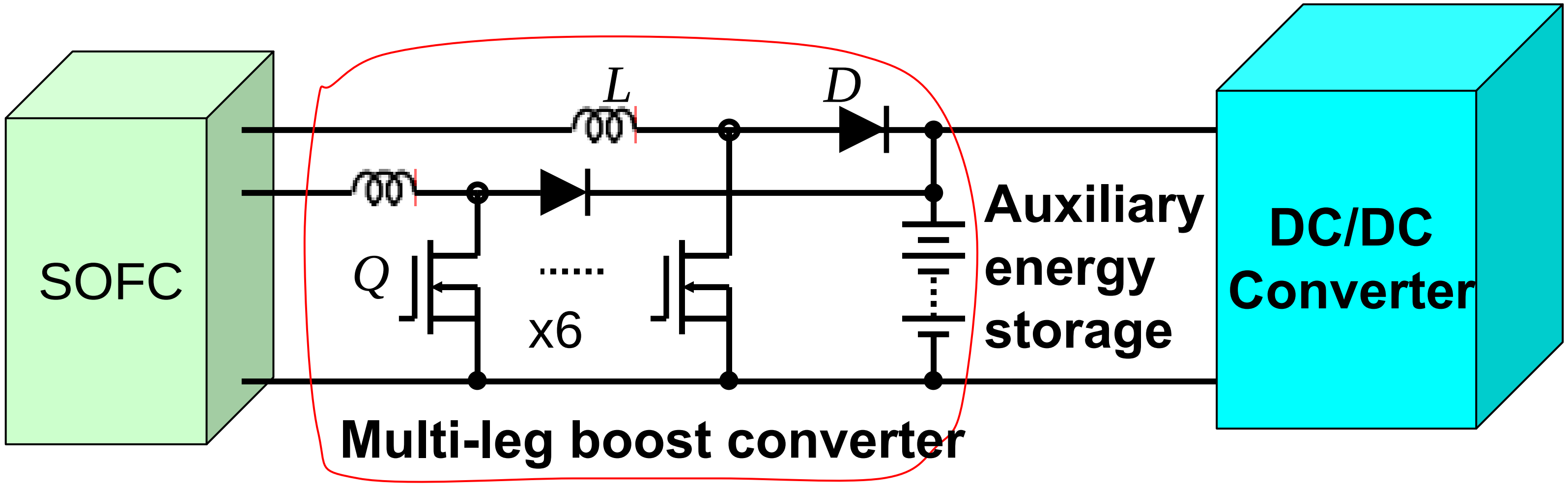


Fuel Cell Current Ripple Issue



- The inverter output 60 Hz current tends to reflect back to fuel cell source with 120 Hz ripple if there is not enough energy buffer in between.
- On the other hand, the auxiliary energy storage source tends to interact with the fuel cell source given unequal time constant between them.

Solving Current Ripple Problem with Additional Boost Converter



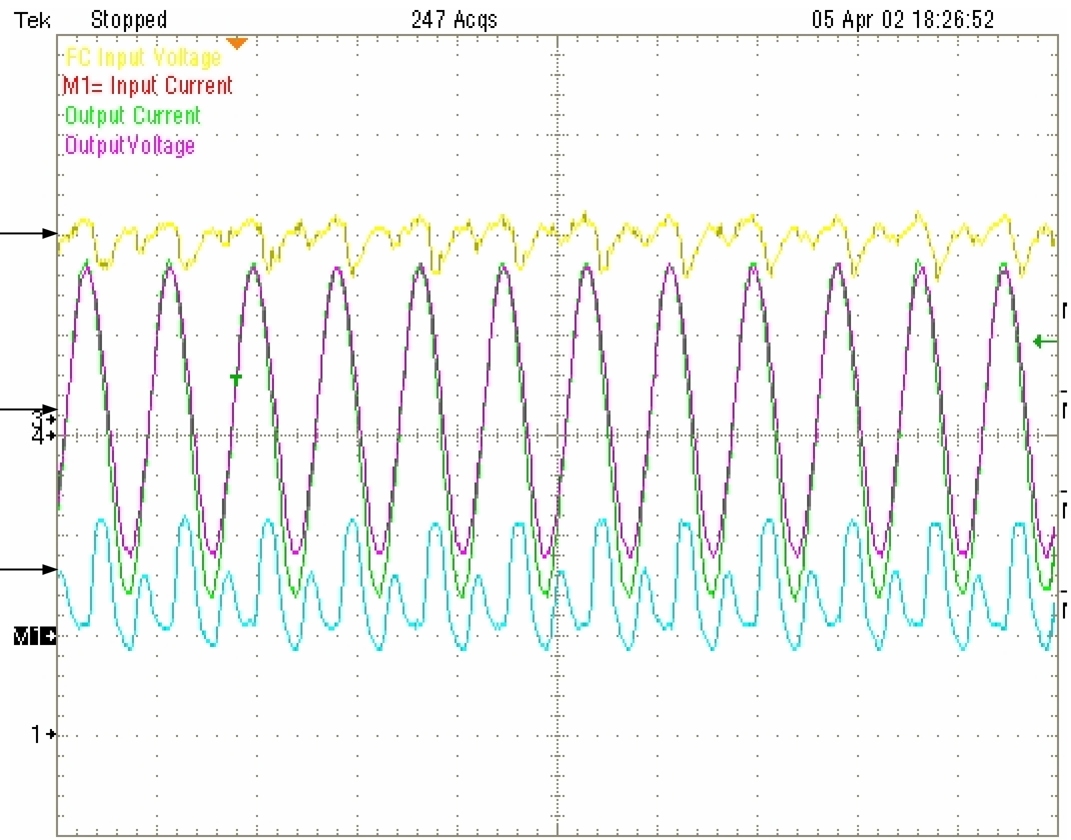
- Fuel cell current ripple can be avoided by adding a boost converter in between dc/dc converter and auxiliary battery.
- The boost converter must be sized equally as the SOFC.
- Main problem is additional power conversion losses and cost.
  ➔ Other ways of energy buffering can be better solutions.

Steady State Fuel Cell Current and Voltage Ripples with Inverter Load

Fuel cell voltage

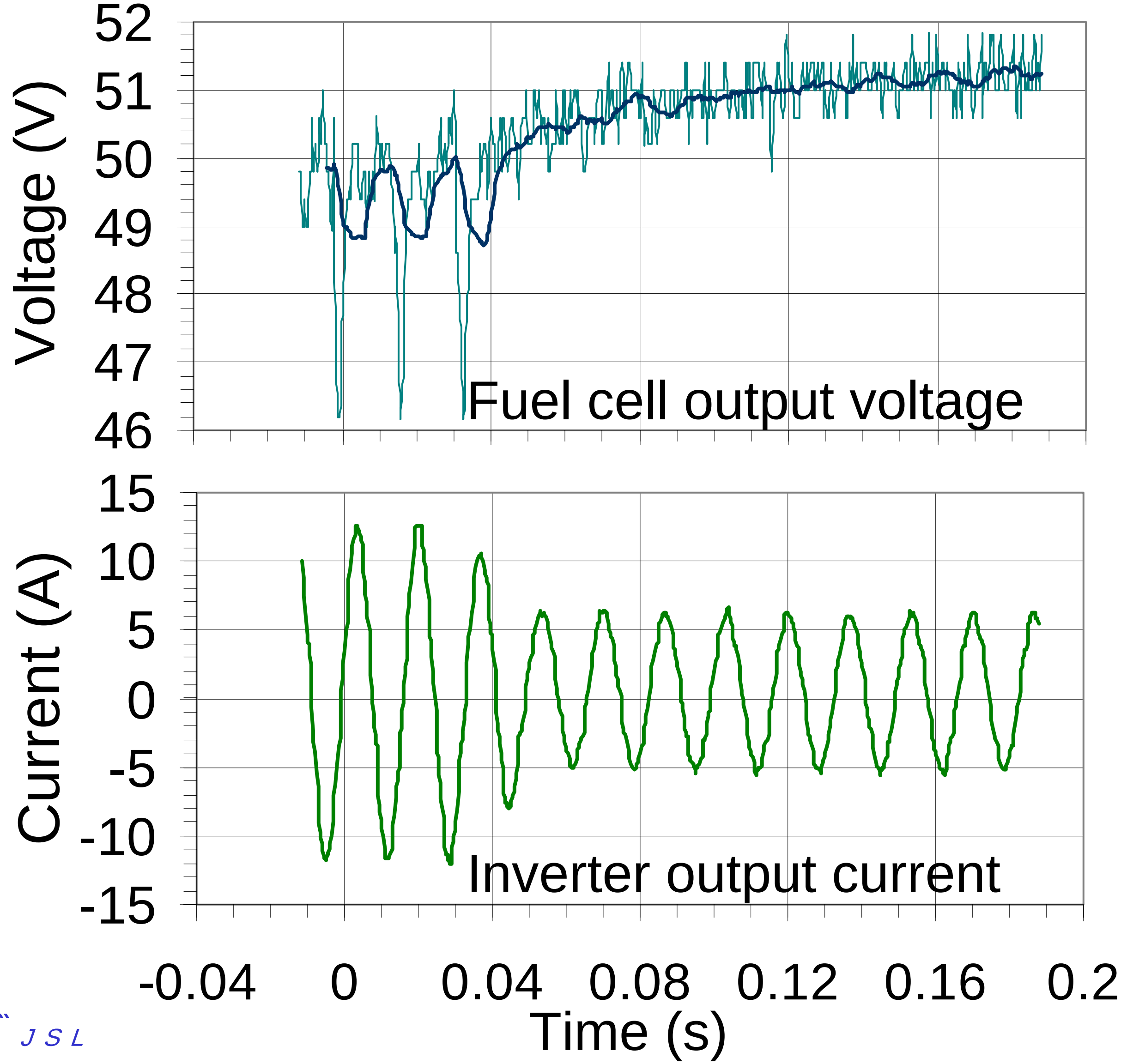
60 Hz ac load voltage and current

Fuel cell current



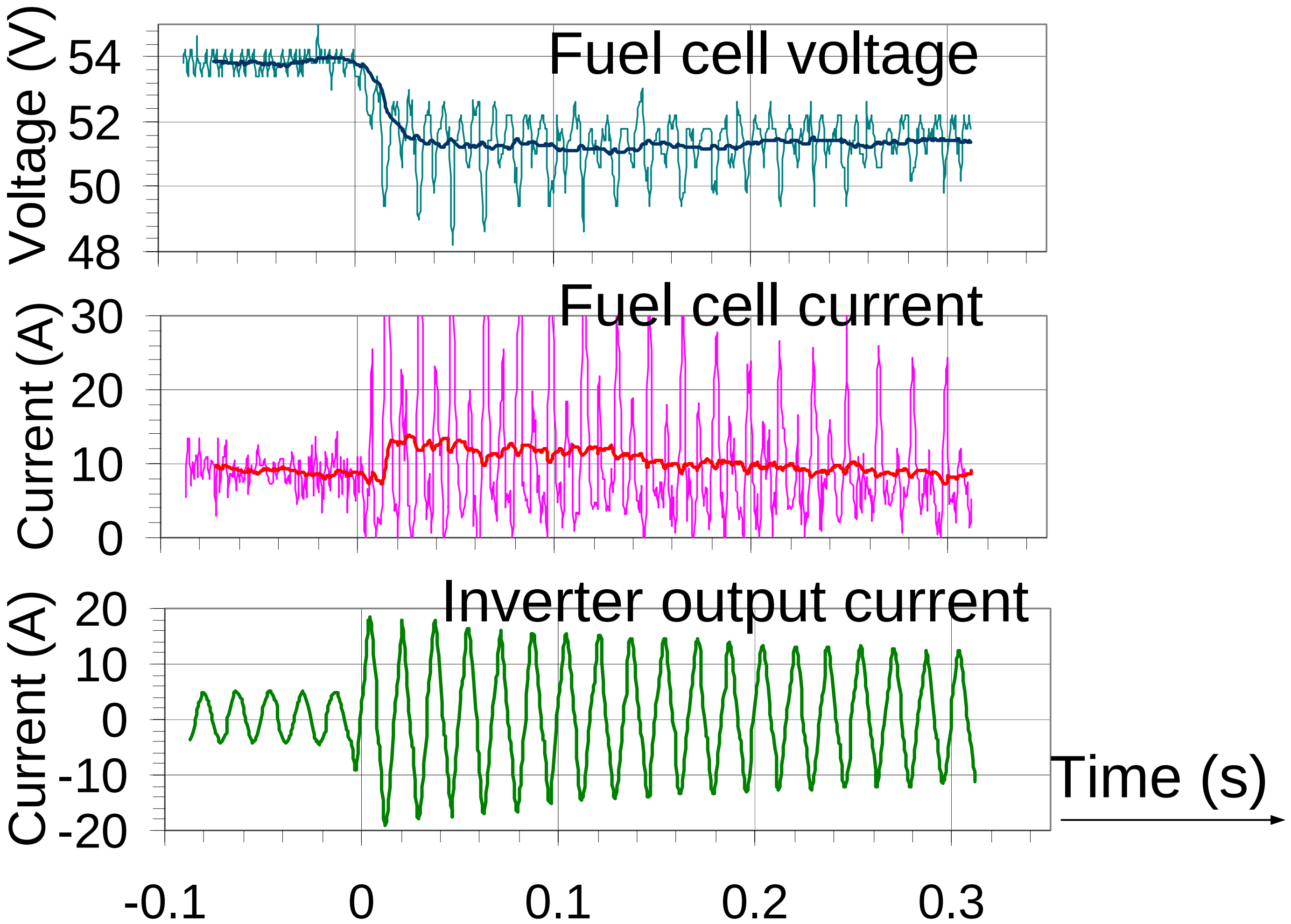
- **Significant 120 Hz voltage and current ripple present**

Fuel Cell Output Voltage During Load Dump

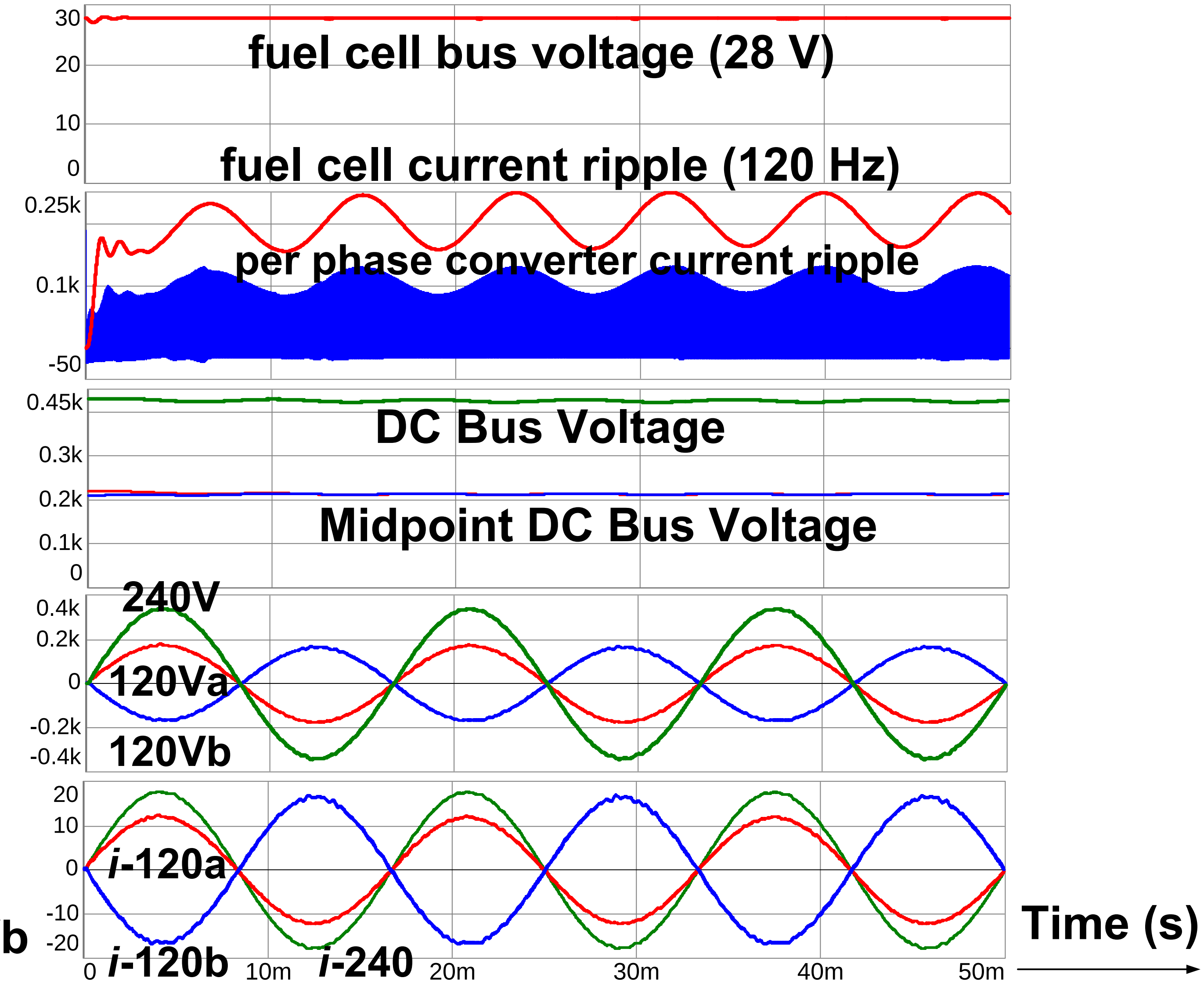


- **Experiment with a 3-kW PEM fuel cell and a 3.3-F ultra capacitor.**
- **Use incandescent lamps as the load.**
- **Ultra cap smoothes the load transient effectively.**
- **Fuel cell time constant is reasonably fast, in millisecond range.**

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

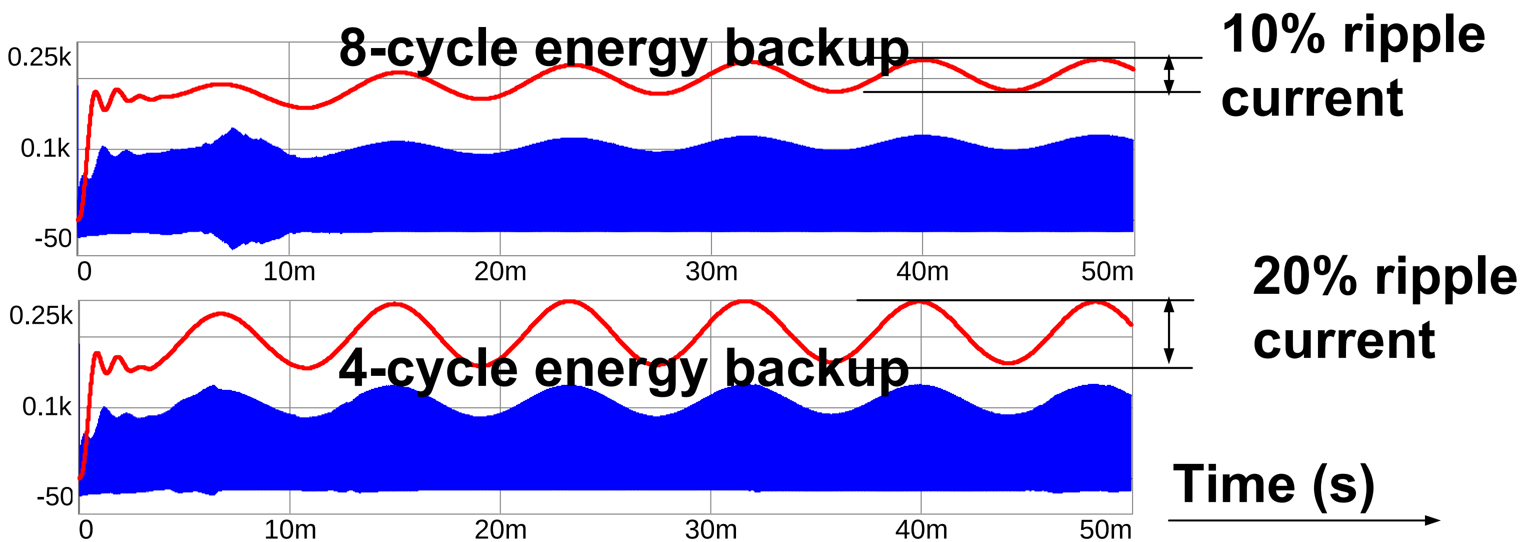


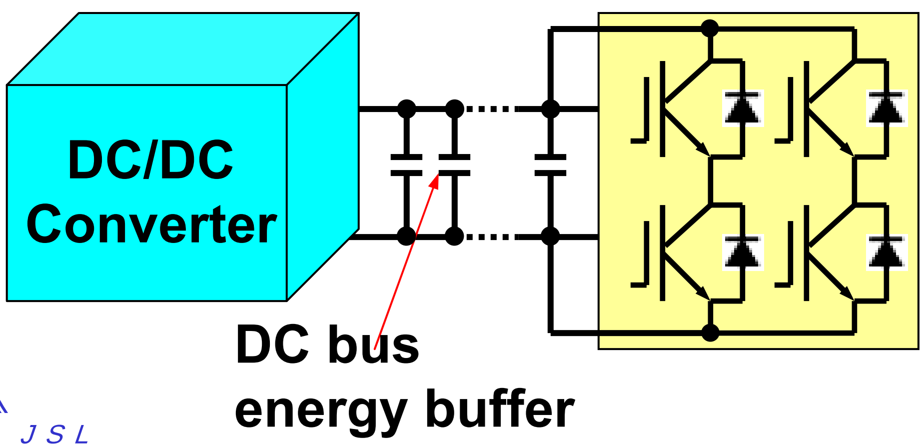
Fuel Cell Current Ripple with Inverter Load



3kW-240V
1kW-120Va
1.44kW-120Vb

Adding Energy Storages at DC Bus is Another Alternative





Adding energy storage capacitors at the DC bus not only smoothes out the inverter load transient, but also reduces fuel cell current ripple proportionally.

Summary

A V6 DC-DC converter has been successfully developed and tested to demonstrate

- Soft switching over a wide load range
- High efficiency ~97%
- Low device temperature → High reliability
- 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
- Fast dynamic response with sensorless control → cost reduction on current sensor
- Significant EMI reduction → cost reduction on EMI filter

Future Work

- Test V6 converter with SOFC
- Define fuel cell and converter interface
- Develop interface and communication protocol
- Design package for the beta version
- Develop energy balancing strategy
- Facilitate Standardization!