Virginia Tech Research on Power Electronics for Fuel Cells

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Outline

- Energy Management Issues
- Non-isolated Bidirectional DC/DC Converter for Fuel Cell Energy Management
- Isolated Bidirectional DC/DC converter for Fuel Cell Energy Management
- 2001 Future Energy Challenge – Single-Phase 10-kW Fuel Cell Inverter
- Discussions

Why Fuel Cells Need Auxiliary Energy Source or Energy Storage?

- **For standalone power supplies: need energy storage for load transient**
- **For grid-connected power supplies: need auxiliary energy source for start-up**
- **For all systems: need auxiliary energy source to provide power for control signals**

Problems of a Fuel Cell System without Energy Storage

- **Fuel cell does not have storage capability**
- **Slow response, output voltage fluctuates with loads**
- **Source may not be continuously available**
- **Size (or capacity) needs to be higher than the peak load**
- **When sized enough for the maximum load, excess energy will be wasted**

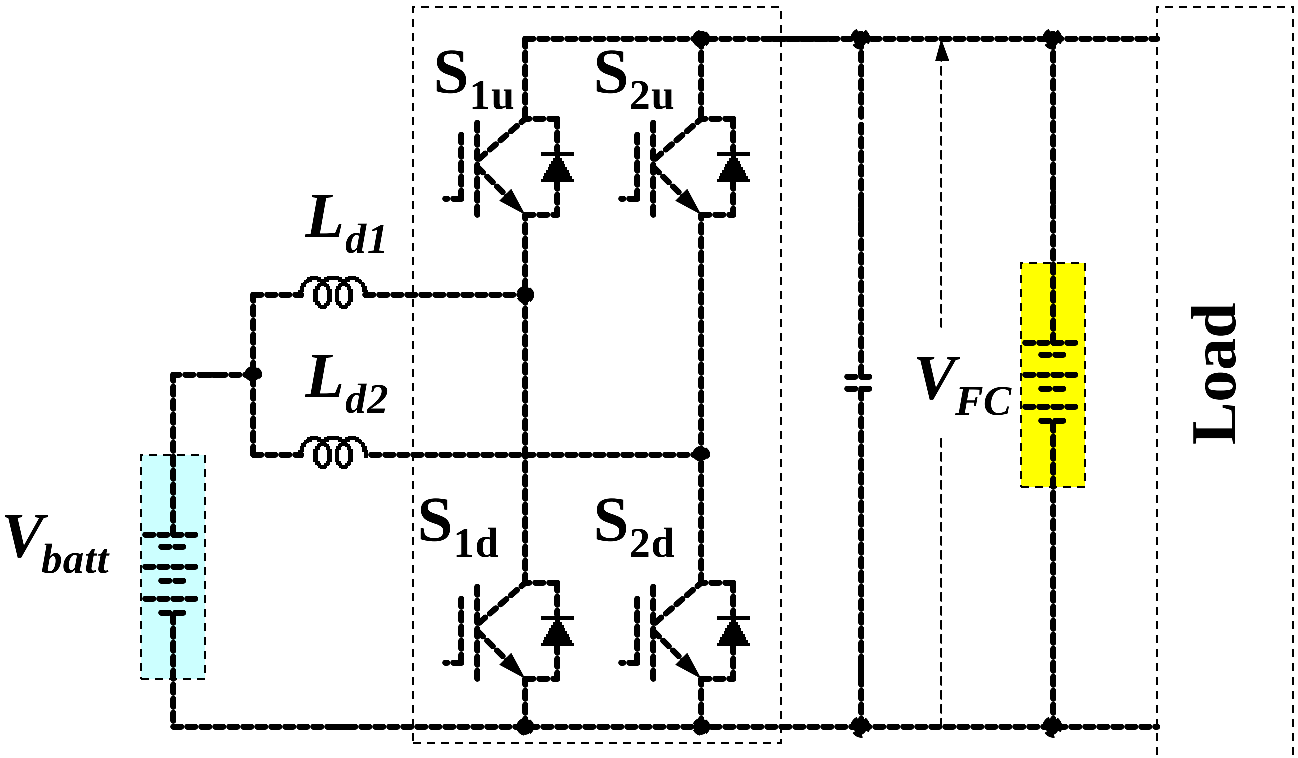
Energy Management with Energy Storages

- Optimum energy usage control
- Start-up control
- Load transient control
- Charging and discharging (bi-directional) controls for auxiliary energy storages

Design Considerations for Hybrid-Source Systems

1. *Utilization* of Primary Source
2. *Simple Power Circuit* (as simple as possible)
3. Voltage ratio
4. *Isolation* Requirement
5. *Energy Storage* Requirement
6. Inverter *DC Bus Voltage* Requirement
7. *Cost*

Non-isolated Bidirectional DC/DC Converter for Fuel Cell Energy Management



Interleaved operation for both boost and buck modes ➔

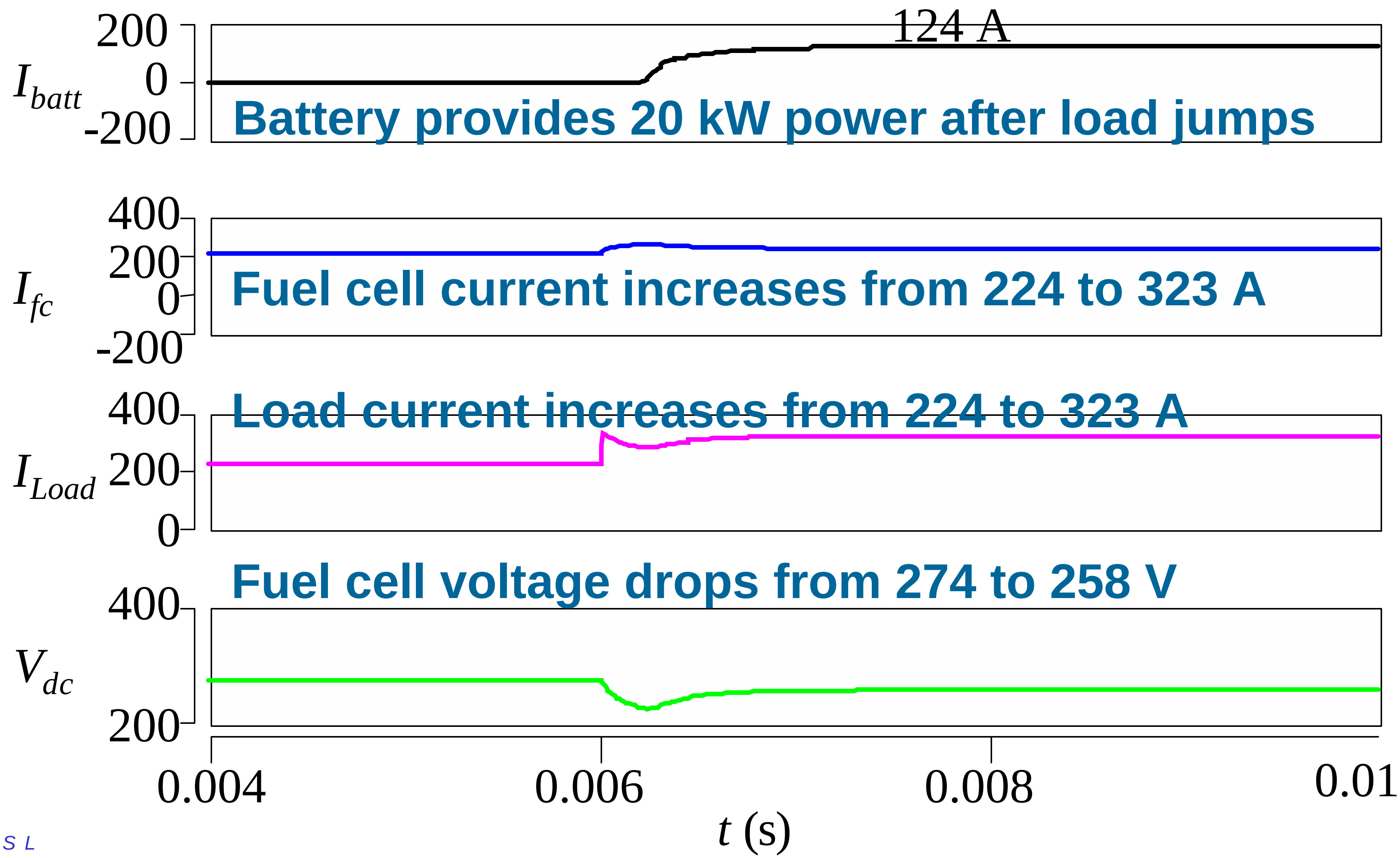
- **smaller passive components;**
- **less battery ripple current**

An Example of Bi-Directional DC-DC Converter with Interleaved Control

- LV side battery voltage range: 140 – 240 V
- HV side fuel cell voltage range: 250 – 425 V, nominal: 300 V
- HV DC bus voltage is unregulated
- Fuel cell power: up to 60 kW
- Battery power: up to 20 kW
- Load power level: up to 80 kW
- HV DC bus voltage is unregulated

Battery and Fuel Cell Current Responses

from 60 kW to 80 kW Step Load Jump



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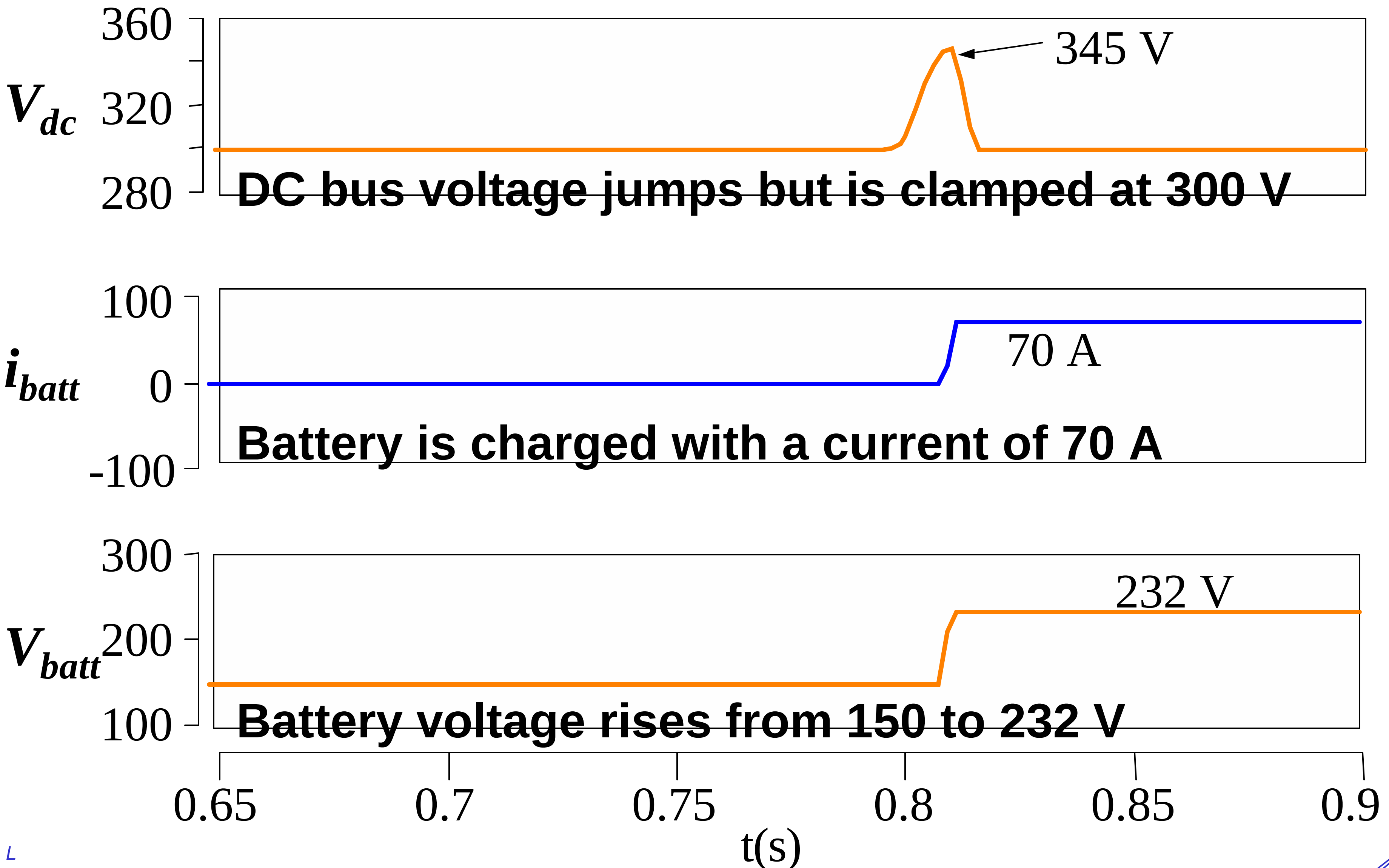
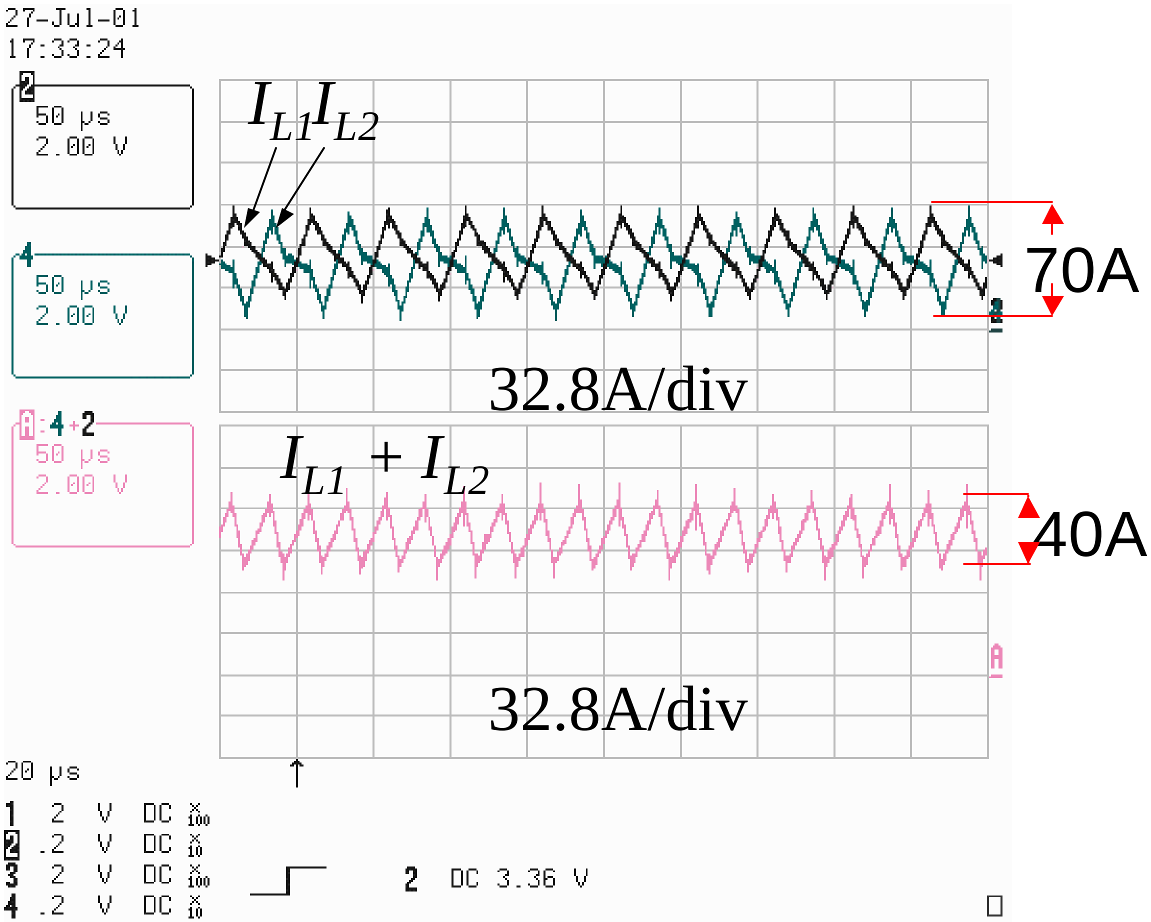
Voltage Loop Control Response During Load Dump

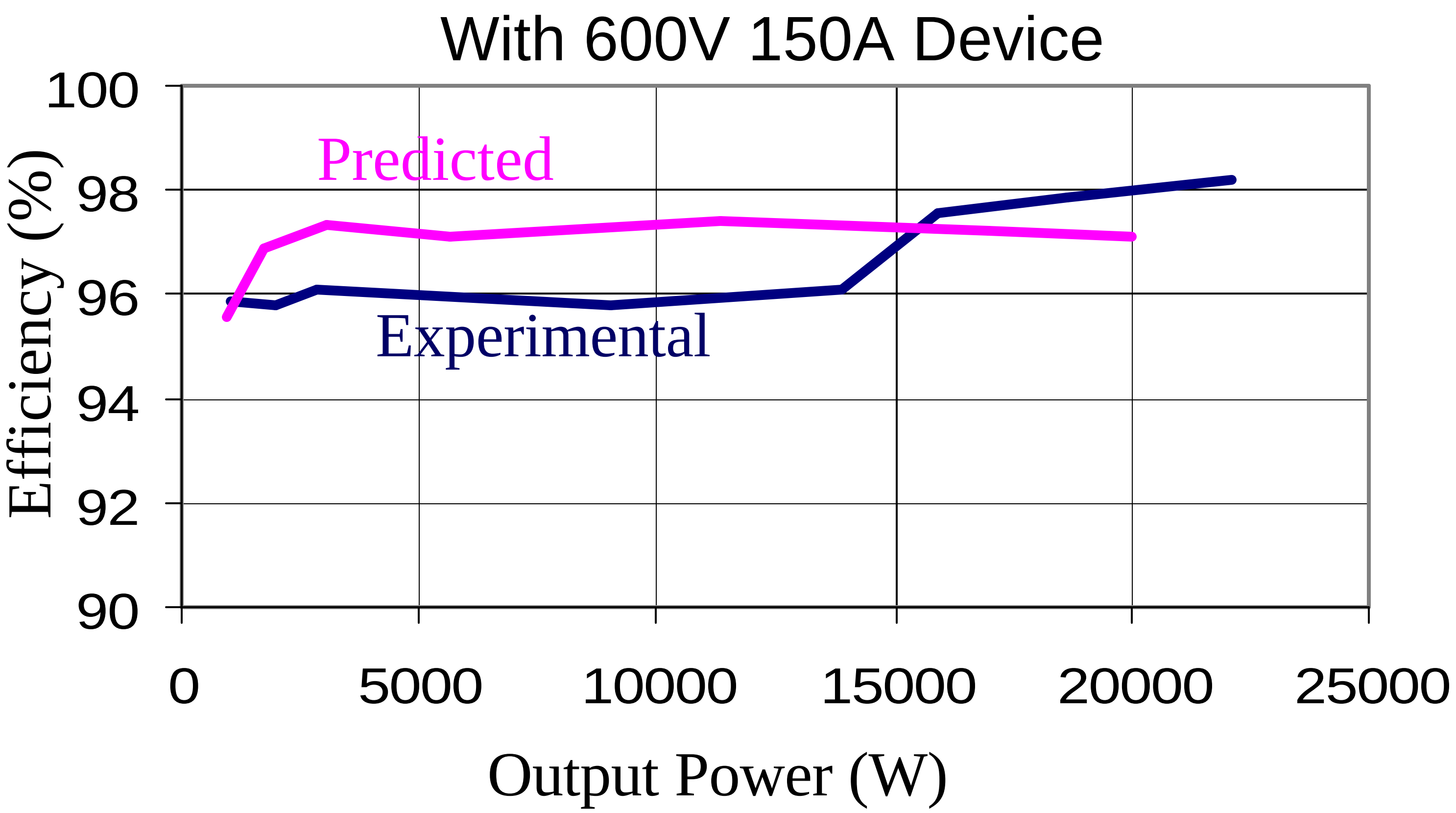


Ripple Current Cancellation with Interleaved Operation

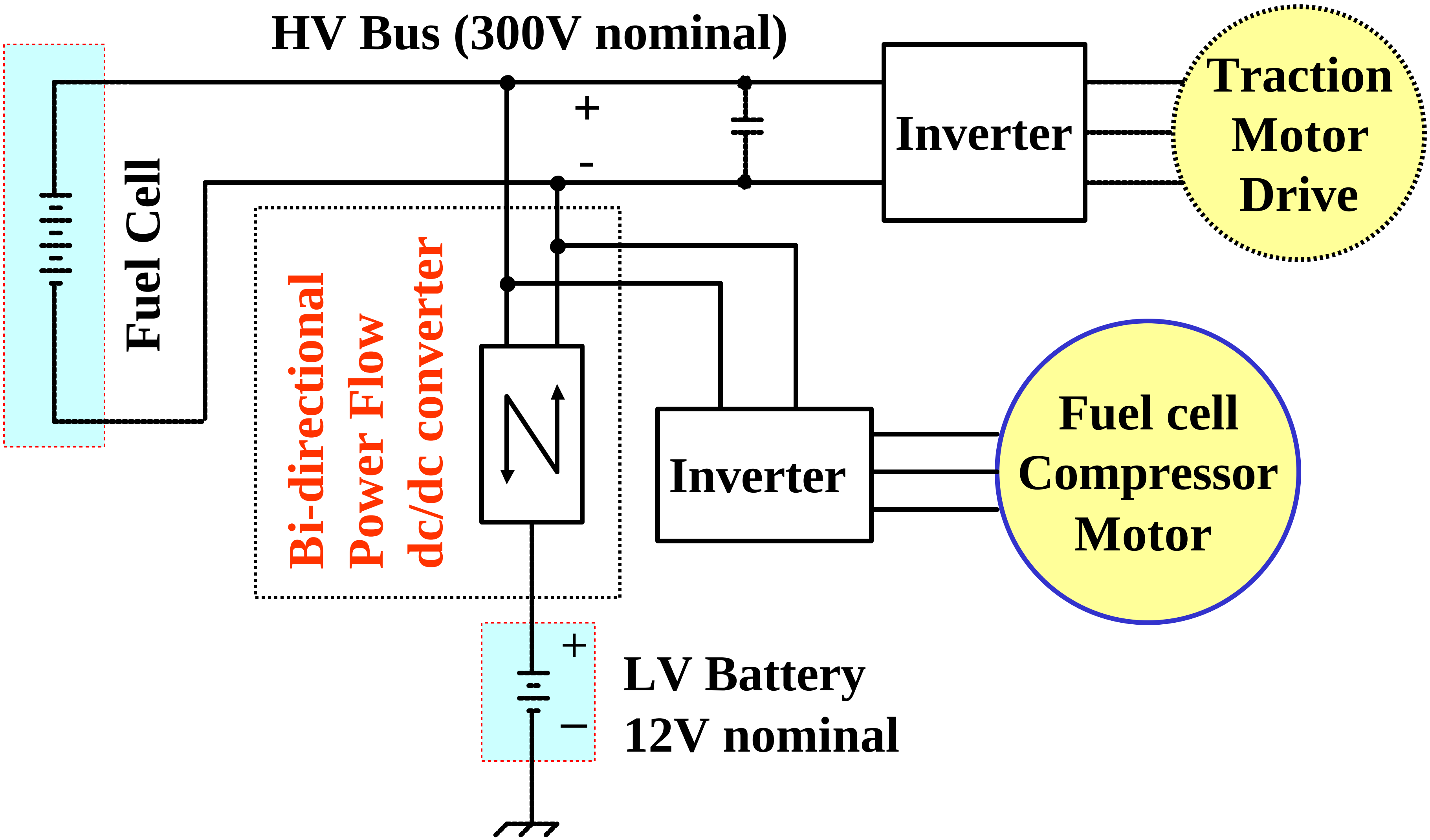
V_{batt} = 190 V, V_{dc}= 282V, P_o = 20 kW



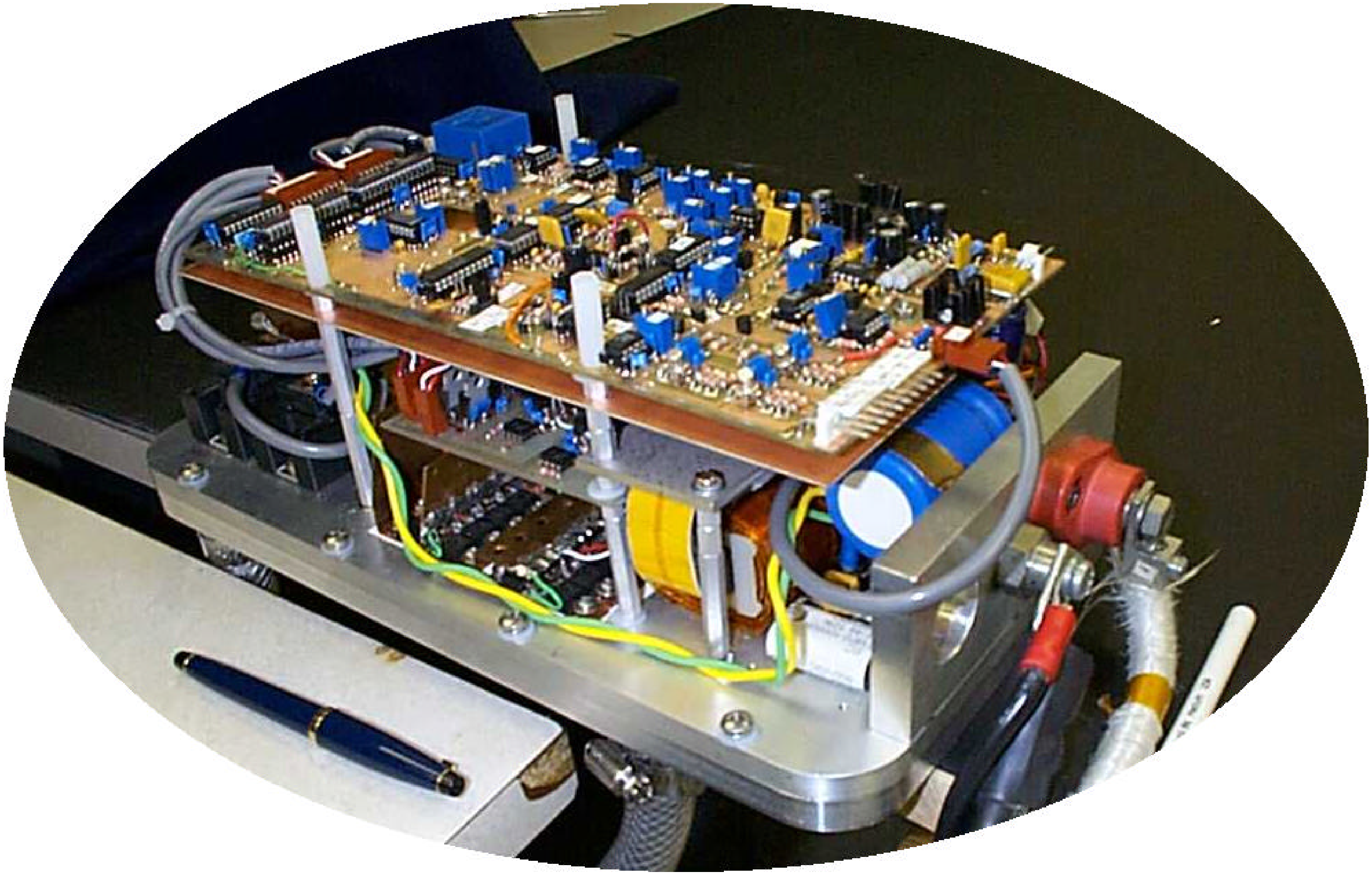
Efficiency Evaluation Results for Boost Mode Operation



Isolated Bidirectional DC/DC Converter for Fuel Cell Energy Management

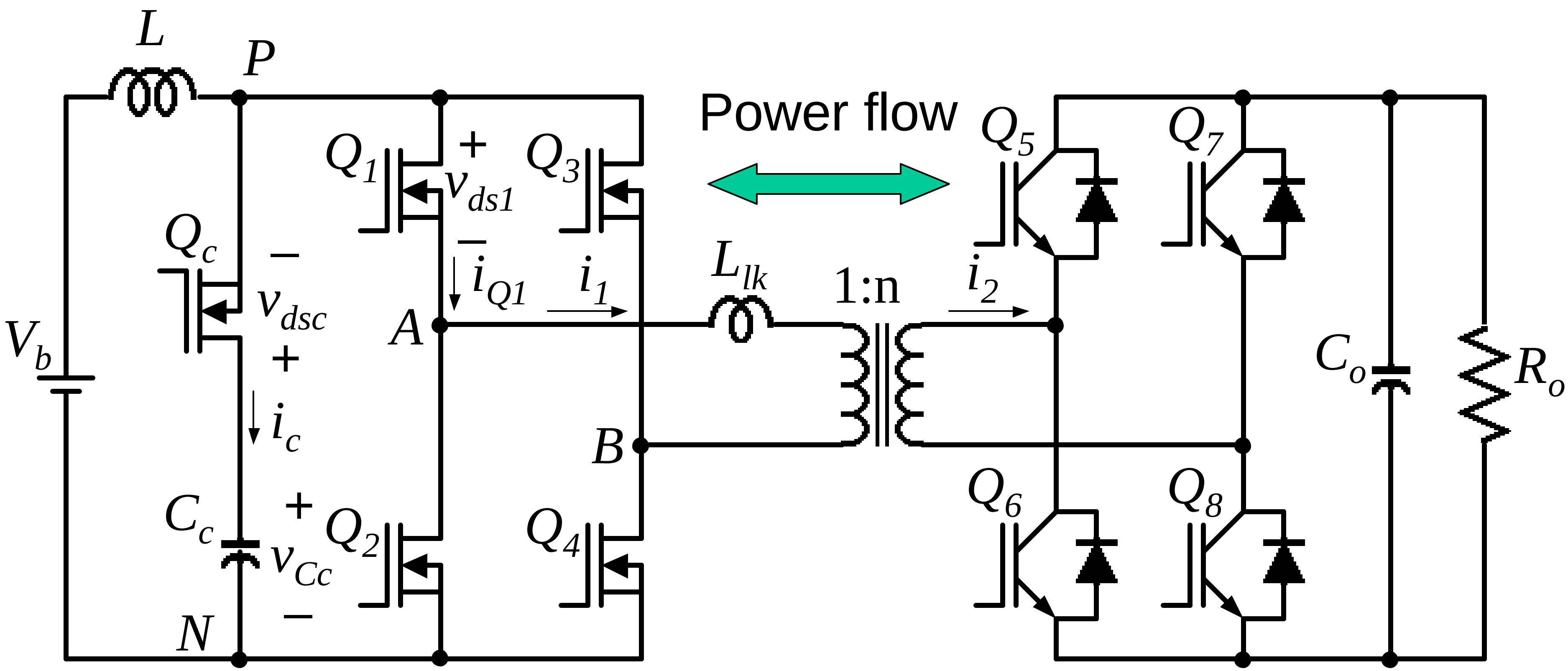


Prototype of a Liquid Cooled 5-kW Bi-directional DC-DC Converter



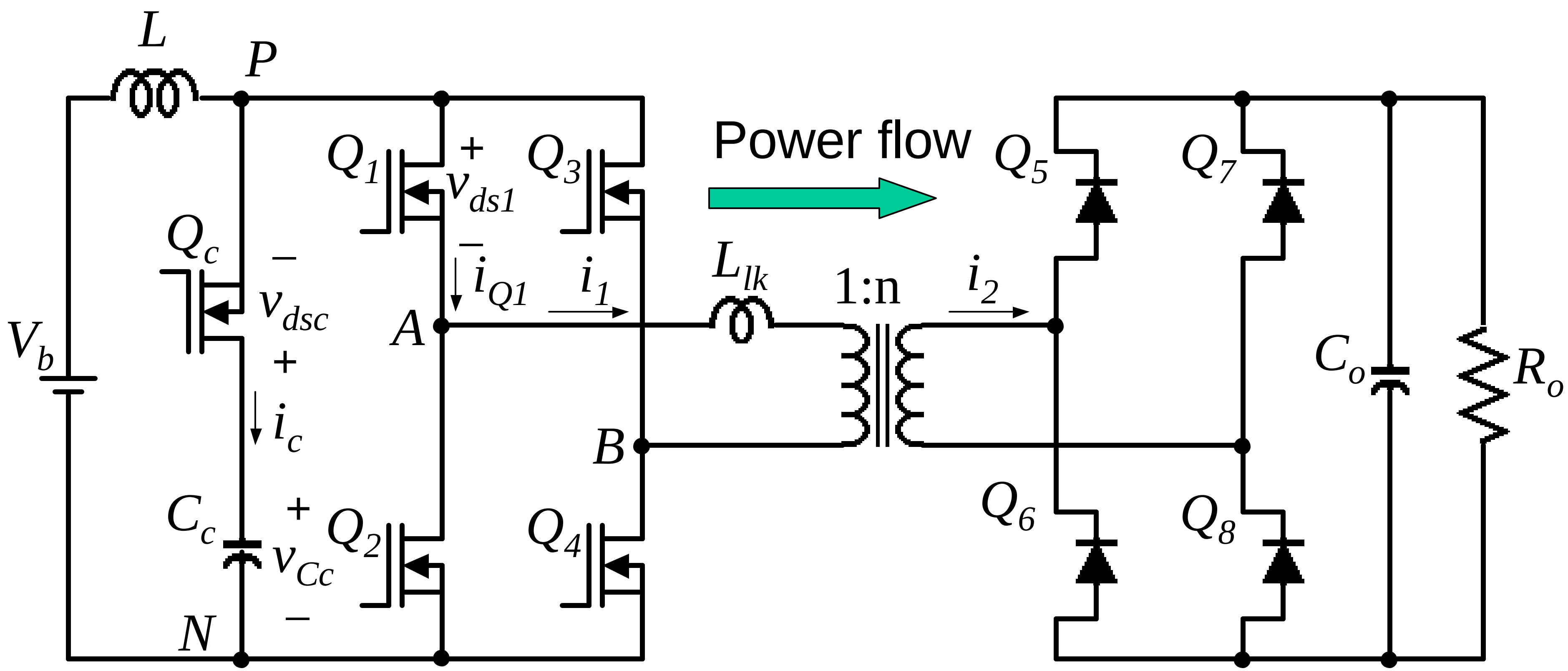
An Isolated Bi-directional DC-DC Converter

LV-Side "Current Source" and HV-Side "Voltage Source"

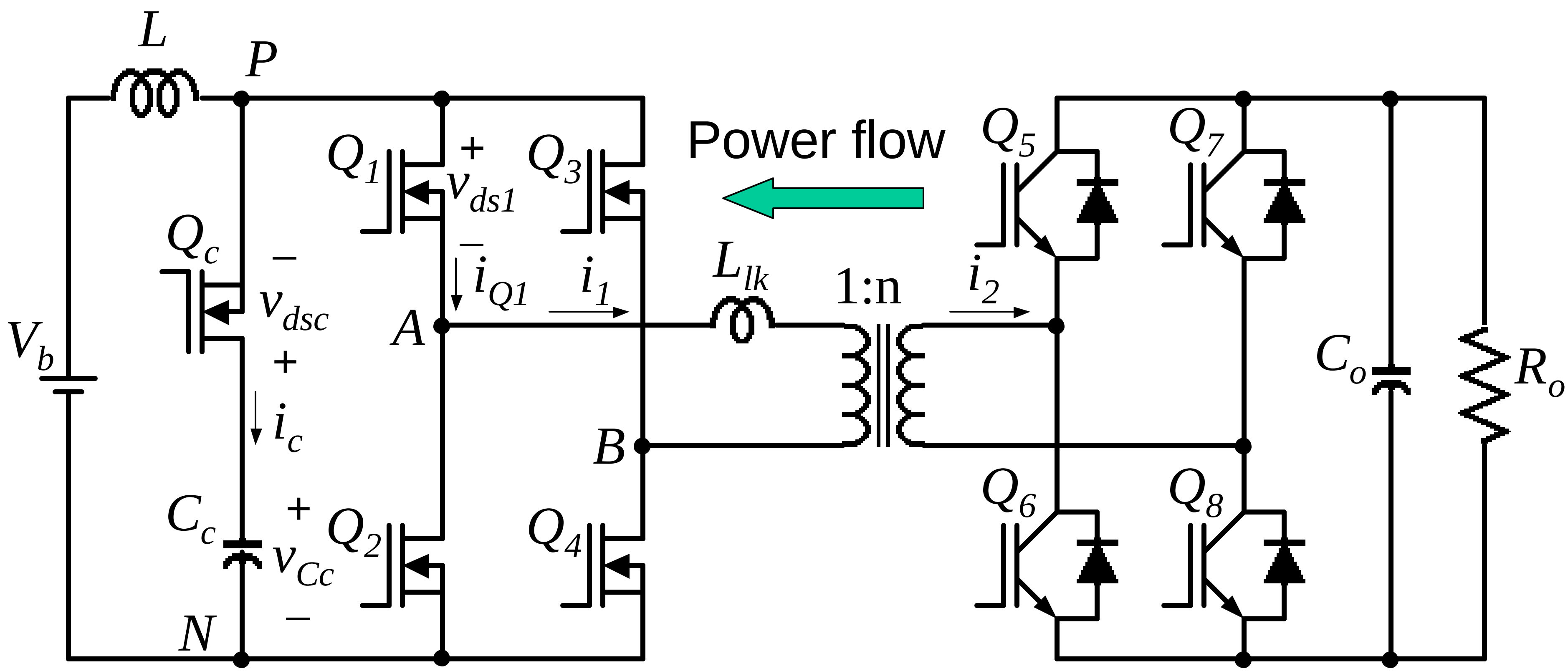


- ✓ Simple voltage clamp circuit implementation
- ✓ Simple transformer winding structure and low turns ratio
- ✓ High choke ripple frequency ($2f_s$)
- × Start-up problem

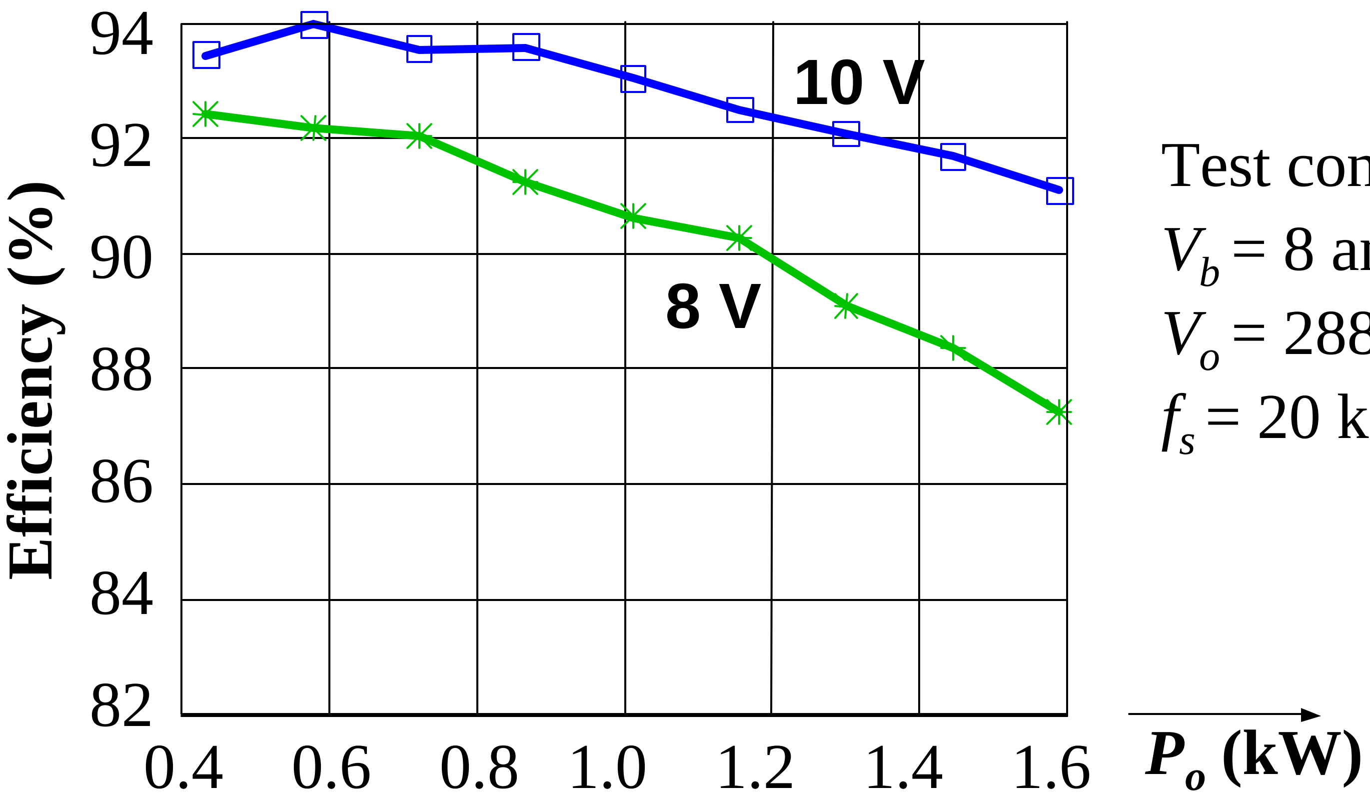
Boost Mode Operation



Buck mode Operation



Measured Efficiency of a Full-Bridge Boost Converter



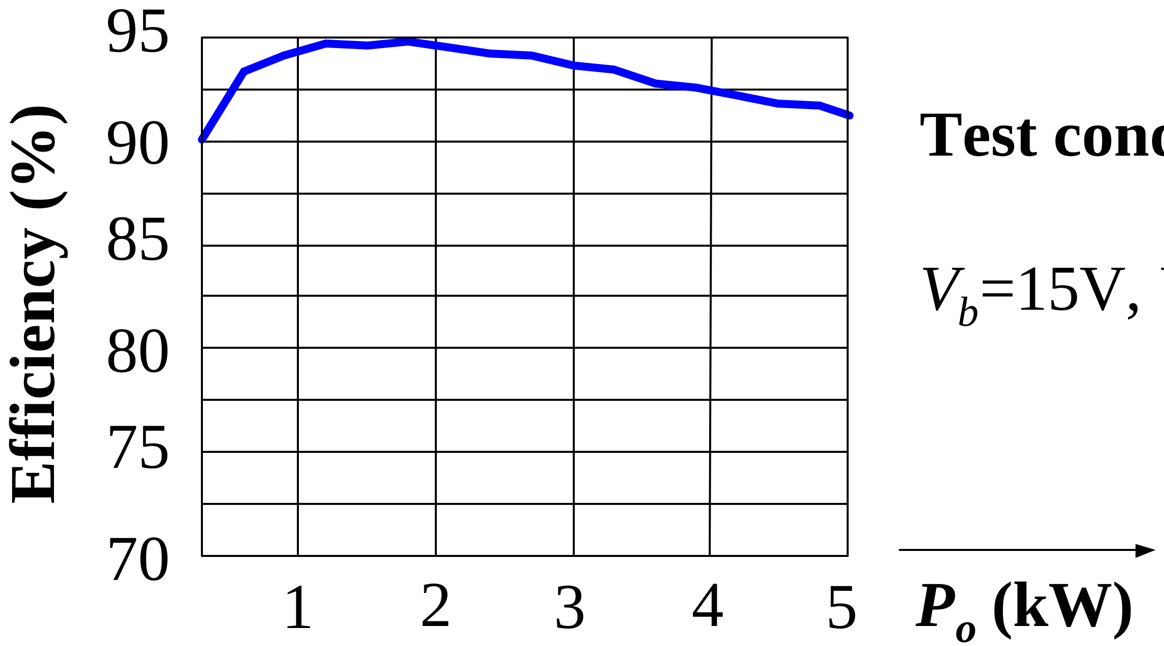
Test conditions:

V_b = 8 and 10V

V_o = 288V

f_s = 20 kHz

Measured Efficiency under Buck Mode Operation



Test condition:

V_b=15V, V_o=425V

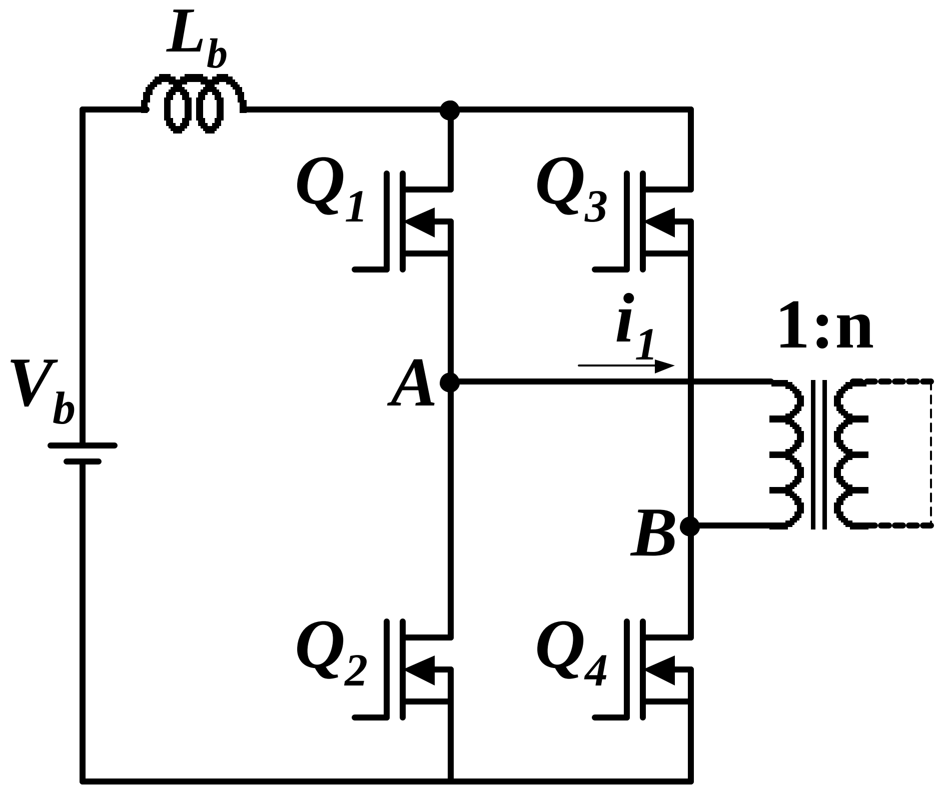
High efficiency because

(1) more devices in parallel on the LV side,

(2) the active clamp circuit provides lossless snubbing and soft-switching operations, and

(3) synchronous rectification.

Startup is a Problem with Isolated Boost

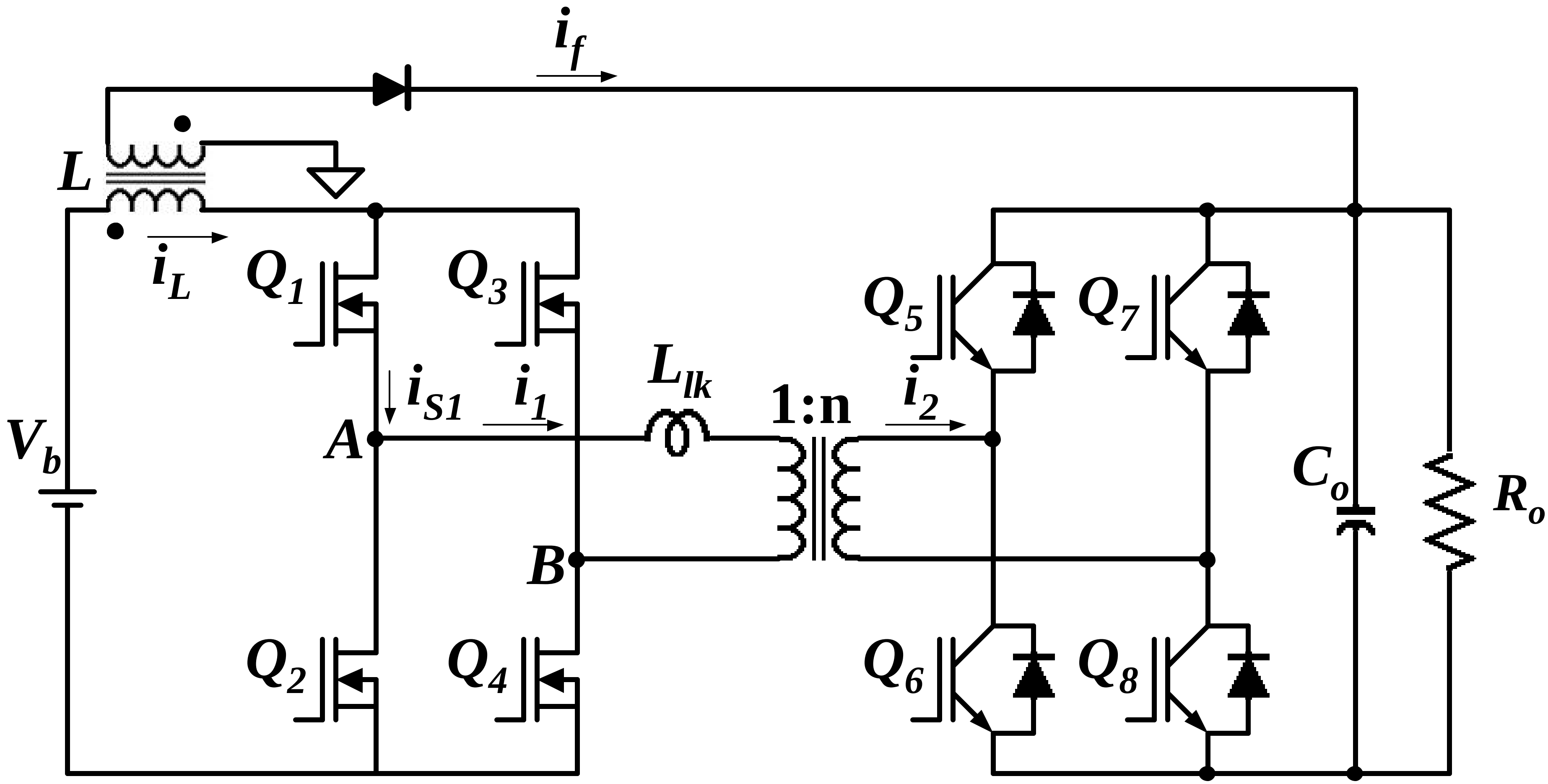


Initially
$V_o = 0$

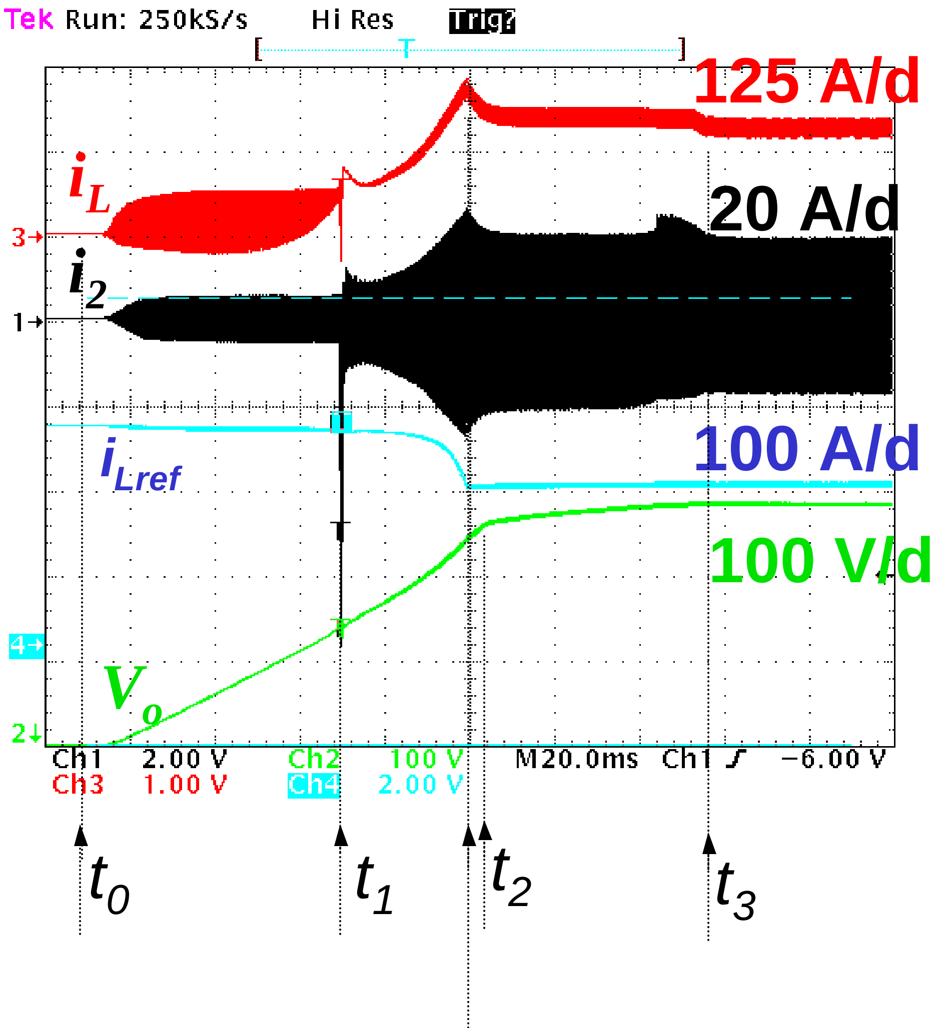
During startup

- **Initial output voltage is zero, or short-circuited**
- **Energy charged in L_b can't be transferred to secondary until $V_o > nV_b$**

Adding a Flyback Winding for Start-up Operation



Start-up Operating Waveforms



Start Up Process:

- t_0-t_1 **Start up mode, open loop controlled**
- t_1-t_2 **Boost mode, open loop controlled**
- t_2-t_3 **Boost mode, inner current loop regulated**
- t_3- **Boost mode, outer voltage loop regulated**

Average current loop regulated

$V_b = 12$ V,

$I_L = 161$ A,

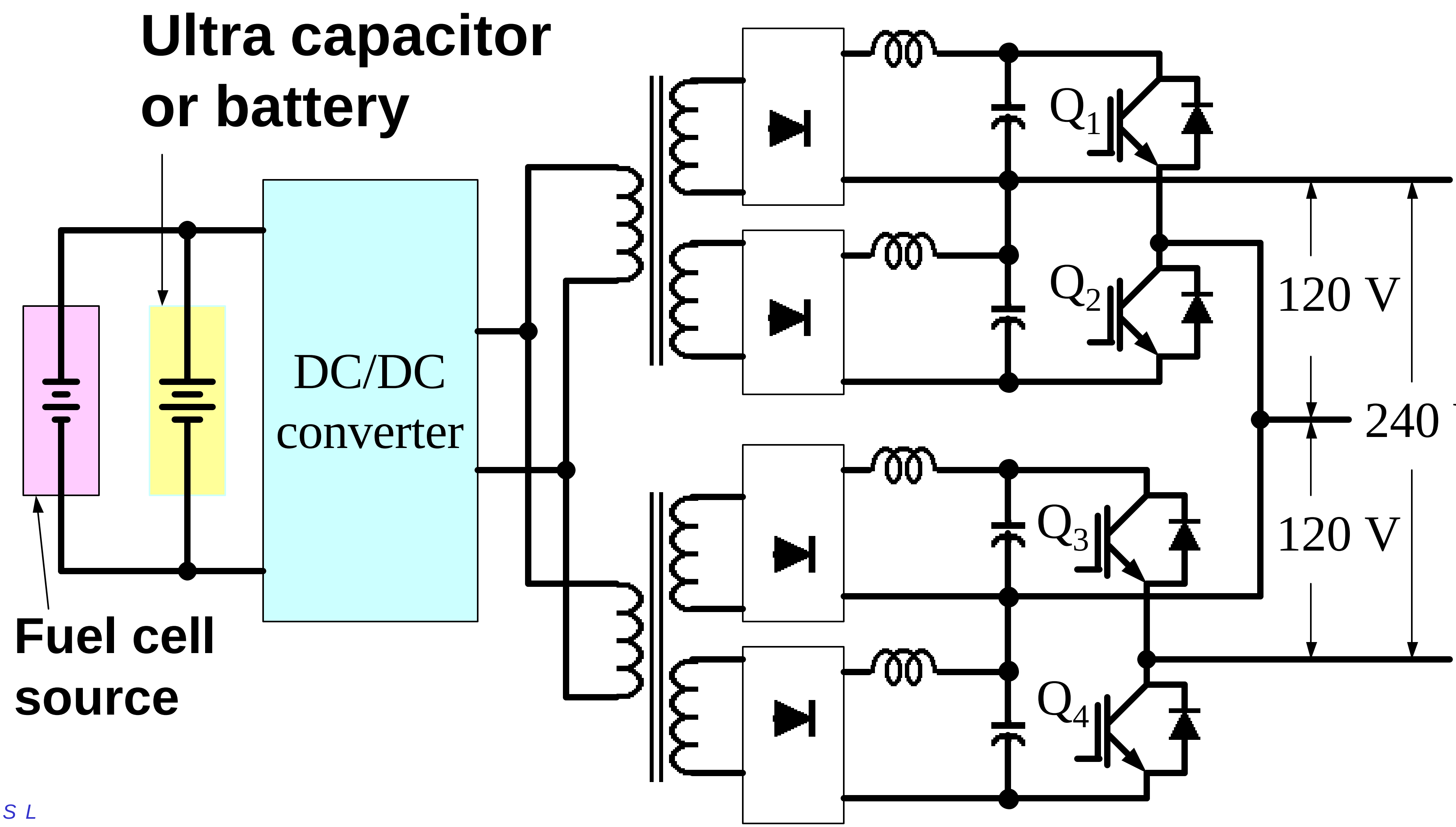
$V_o = 280$ V,

$P_o = 1.83$ kW

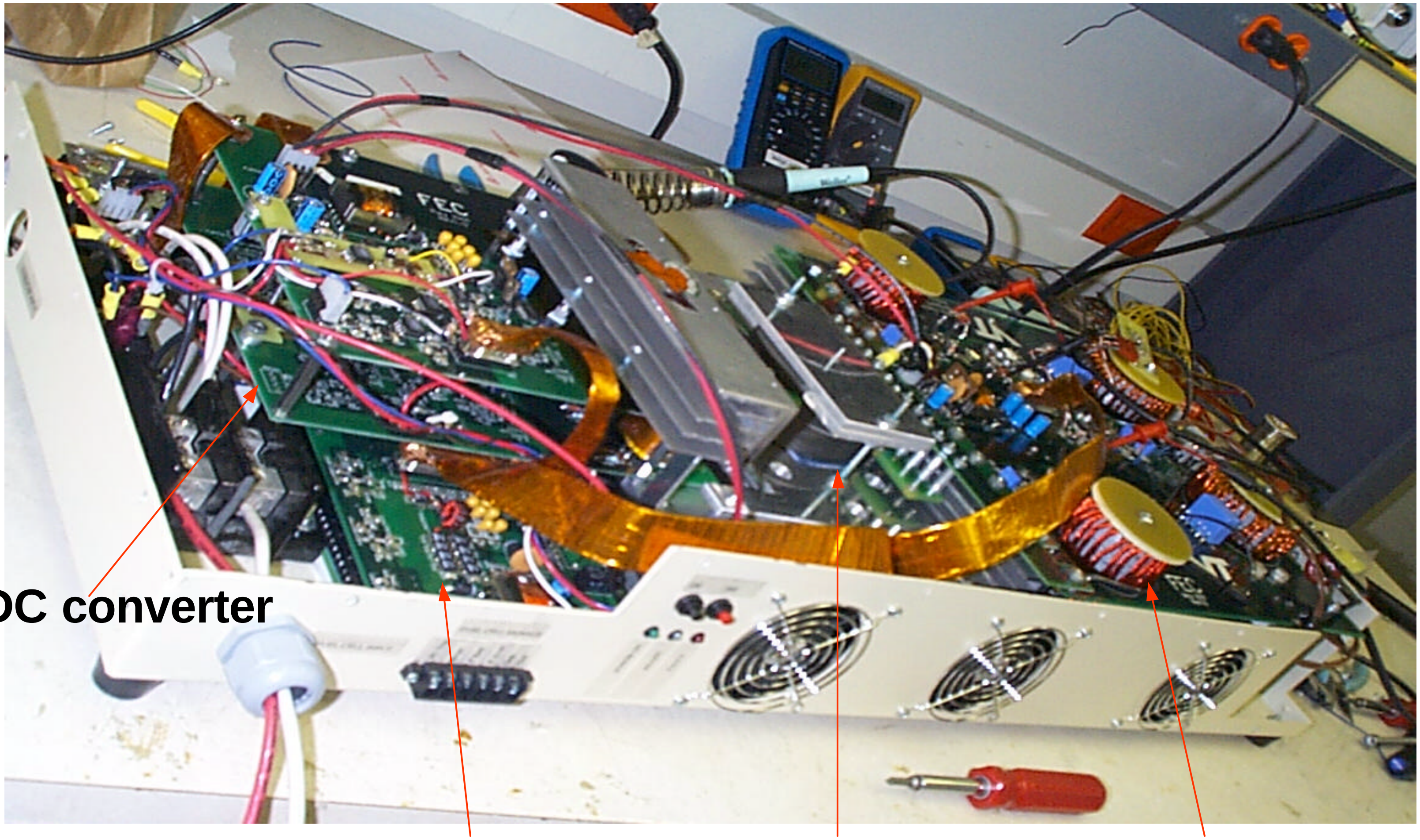
2001 Future Energy Challenge Inverter

- Cost: <$500 for 10 kW design
- Input: 42 to 72 V
- Output: 120/240 V, 60 Hz, 10 kW
- Size: <50 L
- Weight: <32 kg
- Efficiency: >90%
- THD: <5%
- Voltage regulation: ±6%
- Protections: voltage, current, temp., etc.

Placement of Low Voltage Energy Storage for Energy Management



A 10-kW Split Single-Phase Fuel Cell Inverter for Residential Applications



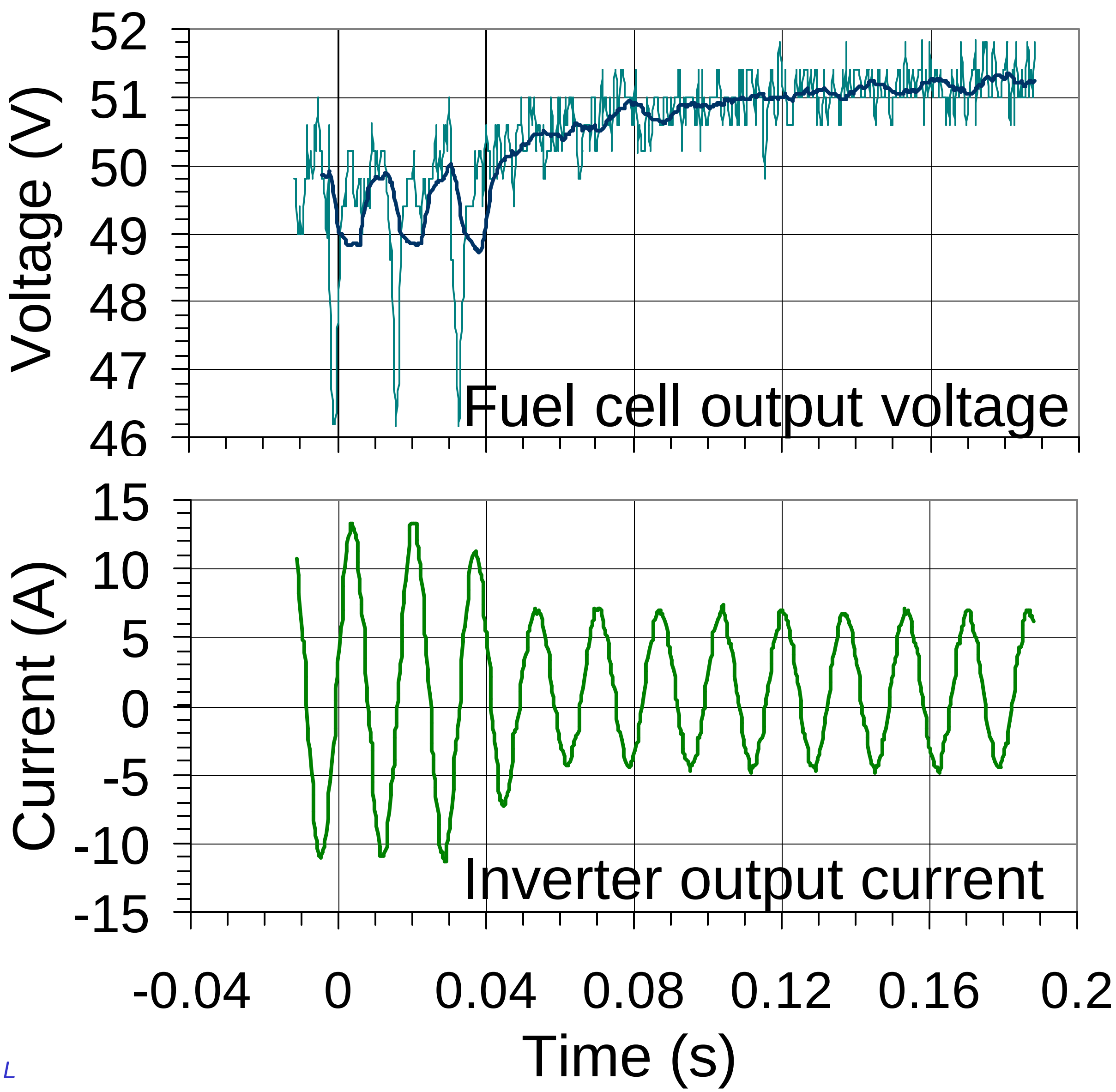
DC-DC converter

Digital controller

High-frequency transformer

DC-AC inverter

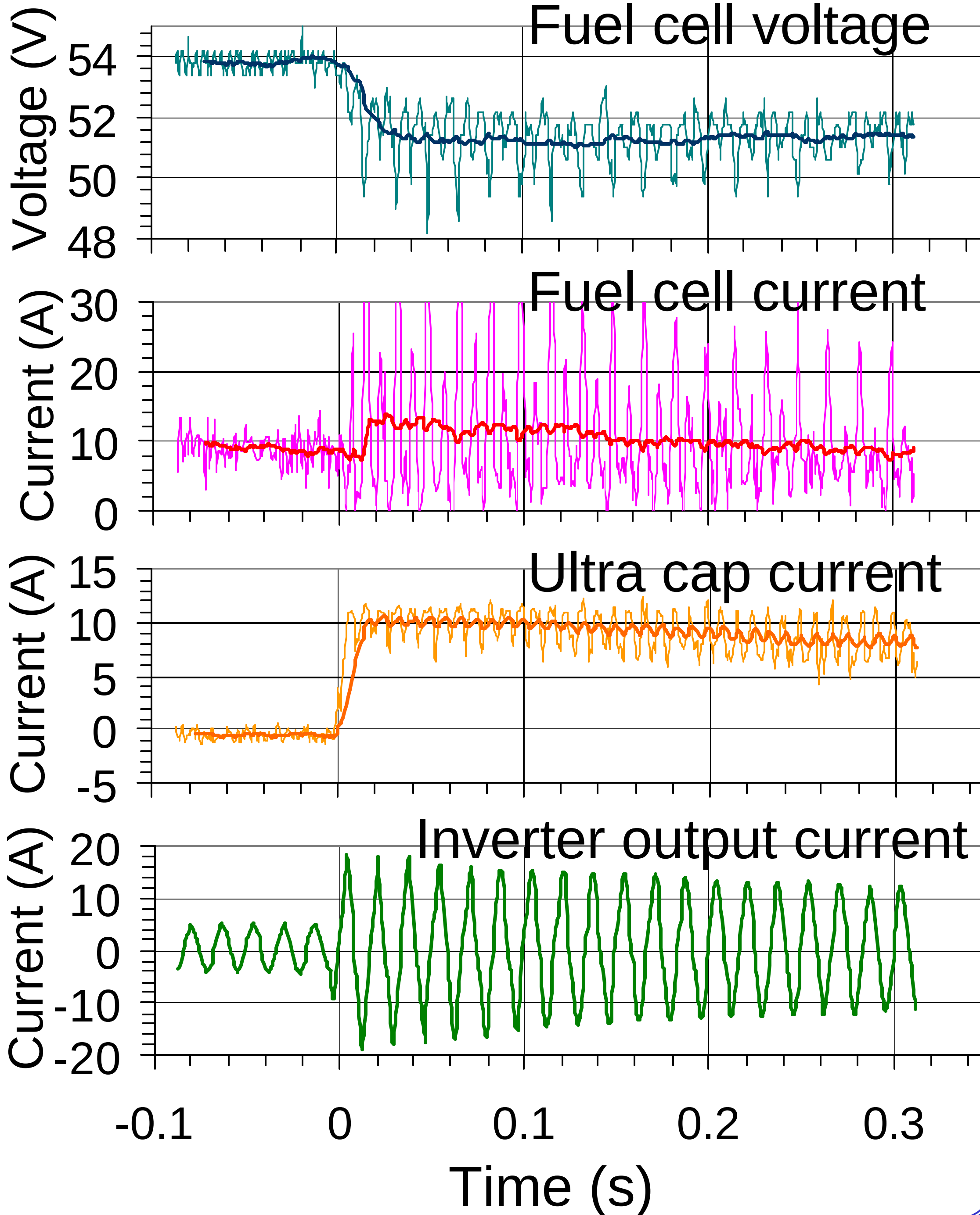
Fuel Cell Voltage During Load Dump
From 1.1 kW to 500 W



- 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



Issues to be Discussed in Fuel Cell Power Conditioning

- Advanced Bi-directional dc-dc converter technologies
- High power interleaved control and associated technologies
- Digital control for high power dc-dc converters
- Fuel cell voltage standardization
- Fuel cell ripple current specifications
- Fuel cell output voltage dynamic
- Fuel cell and power conditioning interface and communication protocol
- Fuel cell system and utility interconnection