Power Electronic Technologies for Fuel Cell Power Systems

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Dr. Jih-Sheng (Jason) Lai
Director, Future Energy Electronics Center
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0111
TEL: 540-231-4741
FAX: 540-231-3362
Email: laijs@vt.edu

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2. Non-isolated DC-DC Converters
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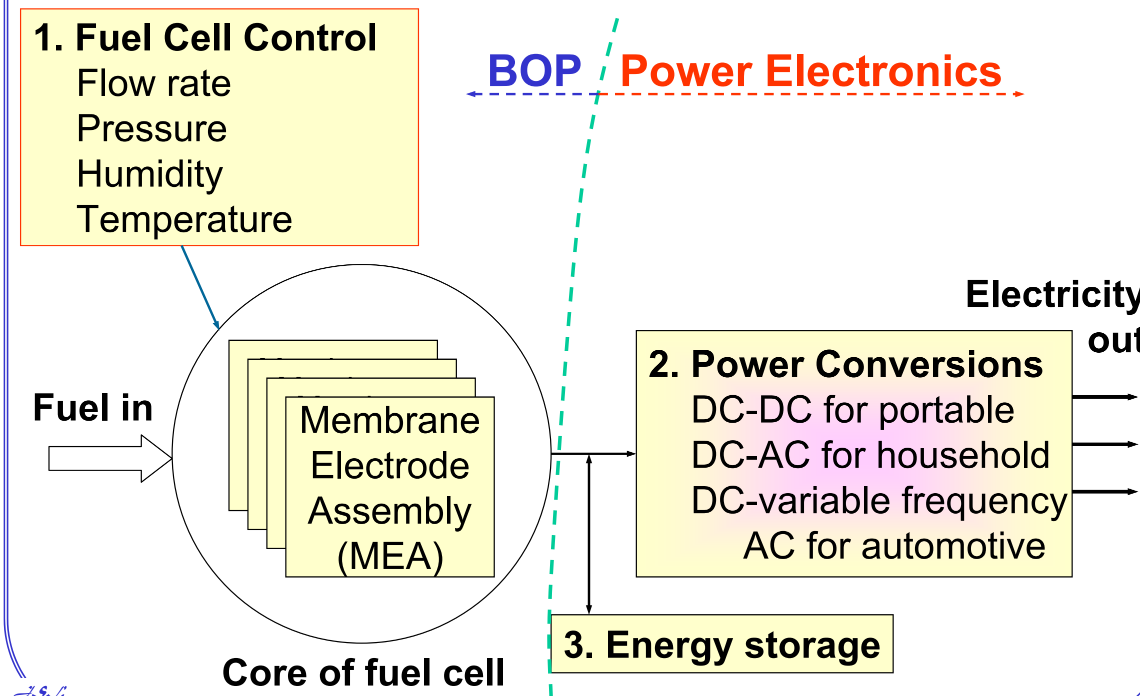
5. Basic DC-AC Inverters
6. Fuel Cell and Converter Interactions
7. Fuel Cell Energy Management Issues
8. Advanced V6 DC-DC Converter
9. Fuel Cell Current Ripple Issues
10. Recap

1. Basic Fuel Cell Power Systems



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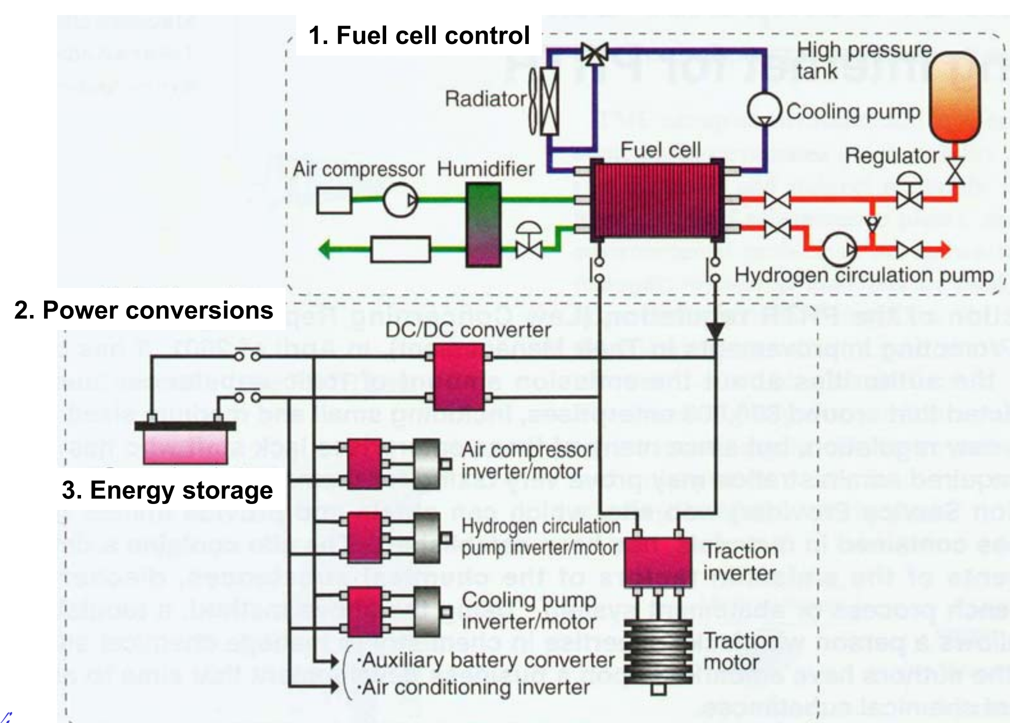
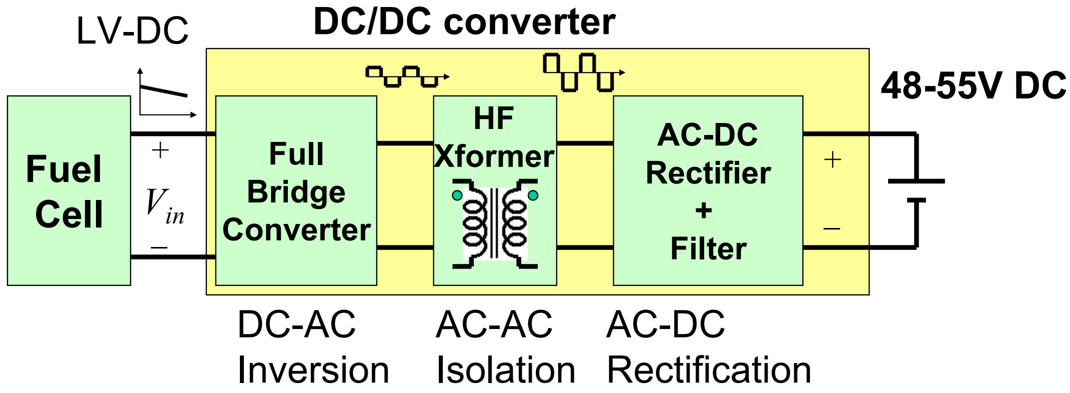
Automotive Fuel Cell Power System

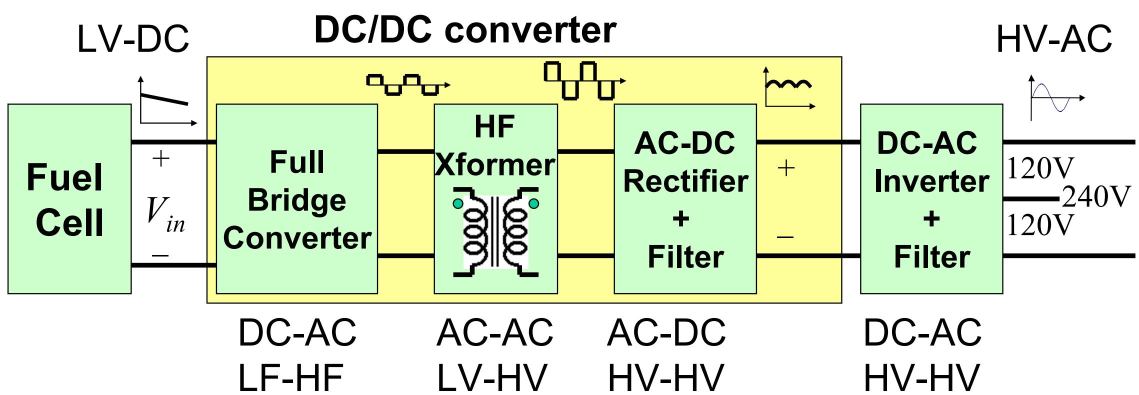


Stationary Fuel Cell Power Plant for Telecom Applications



- **Fuel cell output or converter input is low-voltage DC with a wide-range variation**
- **Plant output is 48-V DC**
- **Isolation may or may not be needed**

Stationary Fuel Cell Power Plant for Household Applications



- **Plant output is high-voltage ac**
- **Multiple-stage power conversions including isolation are needed**

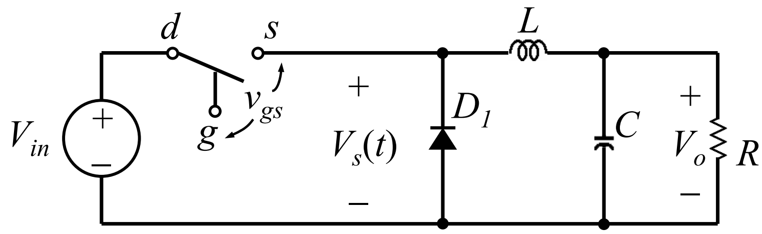
Major Issues Associated with the Power Conditioning Systems

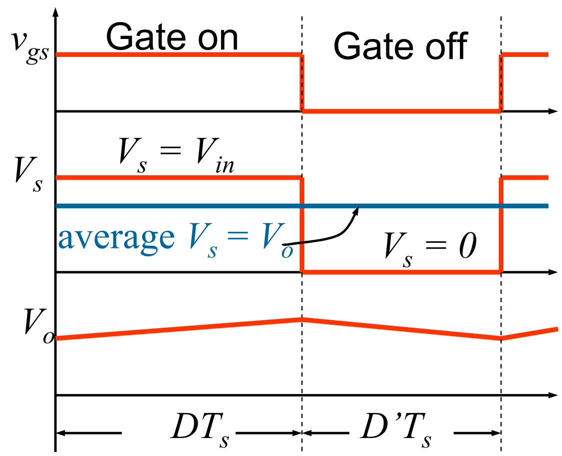
- Cost
- Efficiency
- Reliability
- Isolation
- Fuel cell ripple current
- Transient response along with auxiliary energy storage requirement
- Communication with fuel cell controller
- Electromagnetic interference (EMI) emission

2. Basic Non-Isolated DC-DC Converters

- Buck Converter – Output voltage is always lower than input voltage
- Boost Converter – Output voltage is always higher than input voltage
- Buck-boost Converter – Output voltage can be either lower or higher than input voltage

Basic Principle of Buck Converter





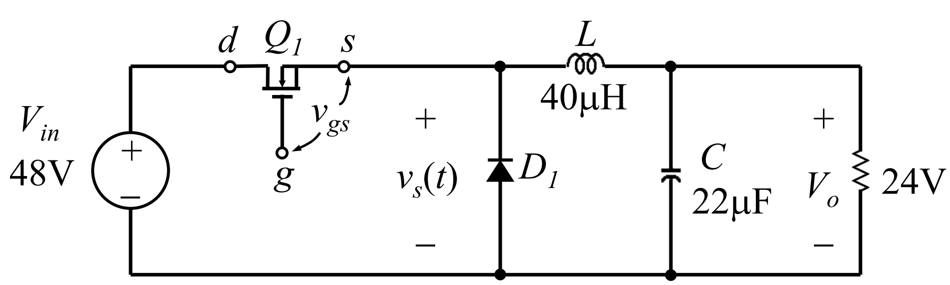
Average output voltage:

$$V_o = DV_{in}$$

where *D* is the duty ratio. Because *D* < 1, V_o is always less than V_{in} ➔ buck converting

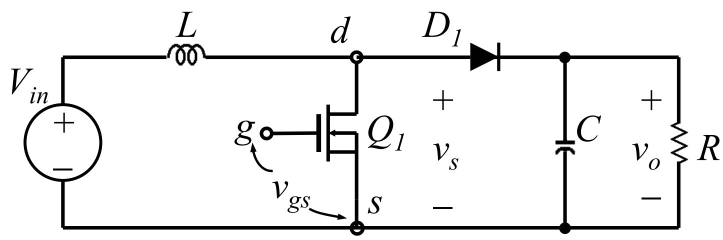
T_s: switching period = $1/f_s$ (s)
f_s: switching frequency (Hz)

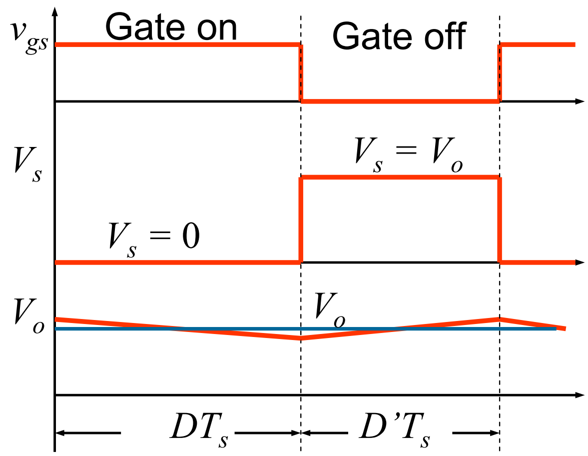
A Buck Converter Example



- **Input is 48 V, and output is 24 V**
- **Duty cycle $D = V_o/V_{in} = 0.5$**
- **Switching frequency = 100 kHz**
- **Output power = 150 W**
- **Inductor and capacitor are designed to limit the current and voltage ripples**

Basic Principle of Boost Converter



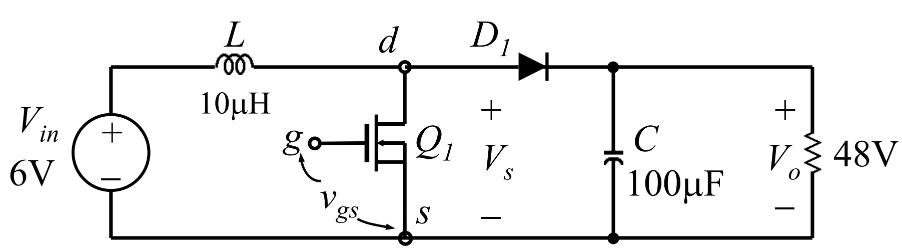


Average output voltage:

$$V_o = \frac{1}{1-D} V_{in} = \frac{1}{D'} V_{in}$$

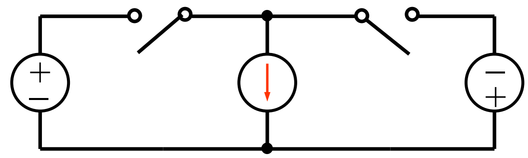
where D is the duty ratio, and $D' = 1 - D$. Because $D' < 1$, V_o is always greater than V_{in} ➔ boost converting

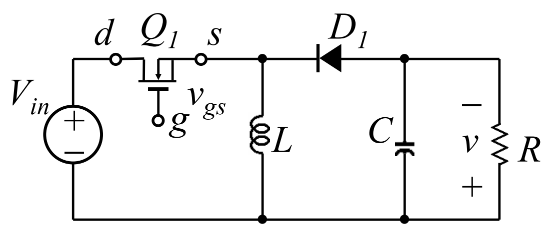
A Boost Converter Design Example



- **Input is 6 V, and output is 48 V**
- **Duty cycle $D = 1 - V_{in}/V_o = 0.875$**
- **Switching frequency = 100 kHz**
- **Output power = 180W**
- **Inductor and capacitor are designed to limit the current and voltage ripples**

Circuit Diagram of Buck-boost converter

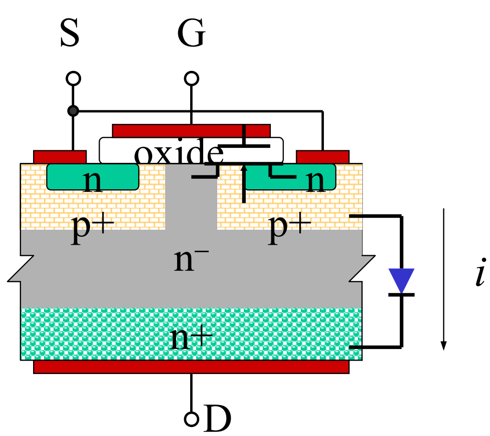


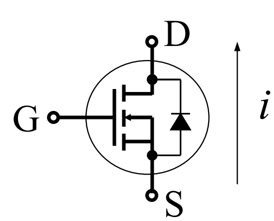


The output voltage can be expressed as

$$V = \frac{D}{1-D} V_{in} = \frac{D}{D'} V_{in}$$

Synchronous Rectifier



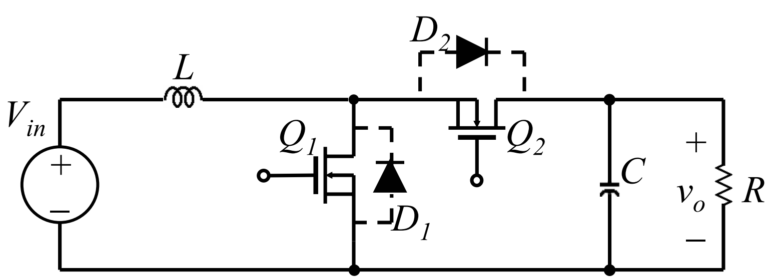


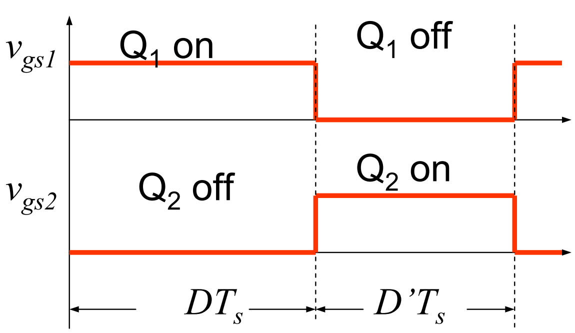
- MOSFET can be used as a diode by shorting G-S
- However, when running under diode mode, gating between G-S would allow current to flow through S-D channel in reverse direction ➔ synchronous rectification

Features of Synchronous Rectification

- MOSFET voltage drop is resistive and can be as low as possible, such as <0.1 V.
- The voltage drop is very crucial to the converter efficiency in a low voltage system. For example, a diode with a fixed voltage drop of 0.7 V represents 3.5% loss of a 20-V system.
- Synchronous rectification allows the voltage drop to be a function of MOSFET resistance and current and cuts the conduction loss substantially. For example, a MOSFET with 5 mΩ running at 20 A condition, the voltage drop is 0.1 V, much less than diode voltage drop.
- Suitable for low-voltage systems.

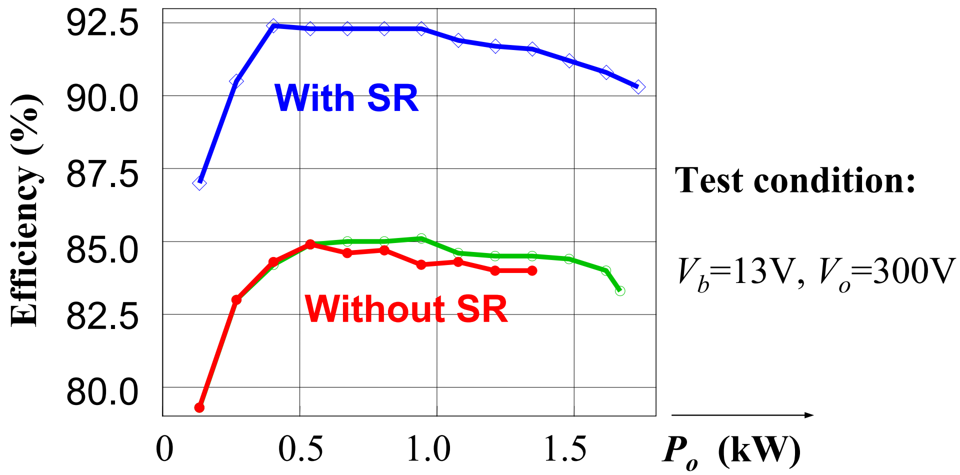
Circuit configuration of a Boost Converter with Synchronous Rectification





- ***D*₁ and *D*₂ are body diode of *Q*₁ and *Q*₂.**
- ***Q*₁ and *Q*₂ switch complimentary**

Experimental Results of a DC-DC Converter with and without SR



Efficiency is improved by 7% with Synchronous Rectification

3. Isolated DC-DC Converters

- **Why isolation is needed?**
- **Push-pull DC-DC converter**
- **Half-bridge DC-DC converter**
- **Full-bridge DC-DC converter**

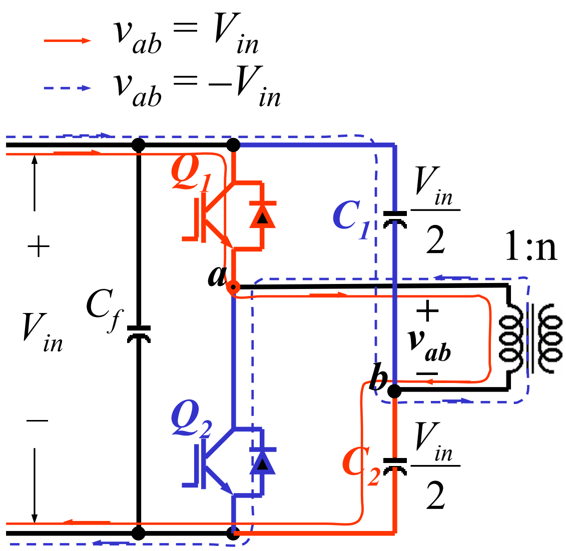
Isolation is Required for Most Systems

- High voltage conversion ratios
  - Isolation allows better device utilization
- Grounding requirement
  - Isolation avoids noise coupling
- Safety requirement
  - Isolation allows meeting safety standards
- Multiple outputs
  - Isolation transformer allows multiple secondary windings

Problems with Isolation

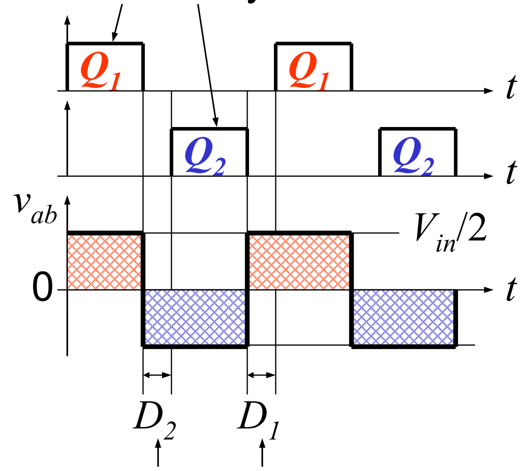
- Magnetic component design and cost are non-trivial
- Transformer saturation due to unbalance input
- Additional losses
- Additional terminations

Basic Operating Principle of a Half-Bridge Converter Circuit



Half-bridge converter

Switches conduct alternately



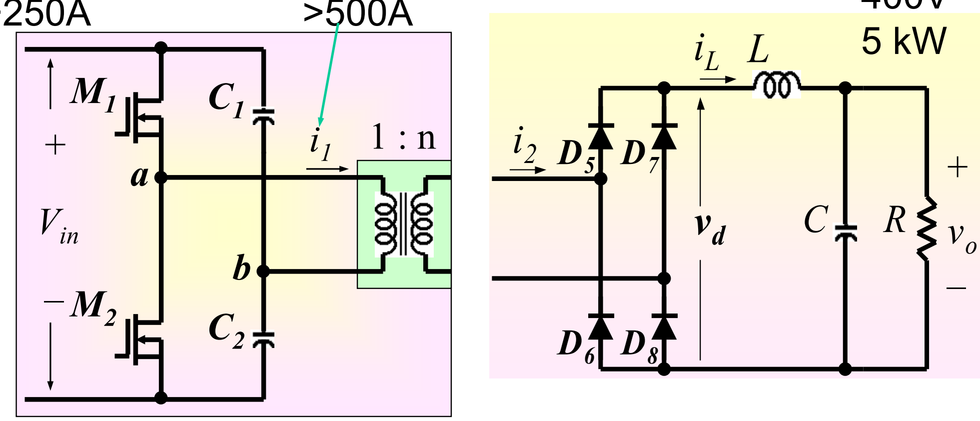
dead-time, current circulating thru anti-paralleled diodes

Half-Bridge DC/DC Converter

20V
>250A

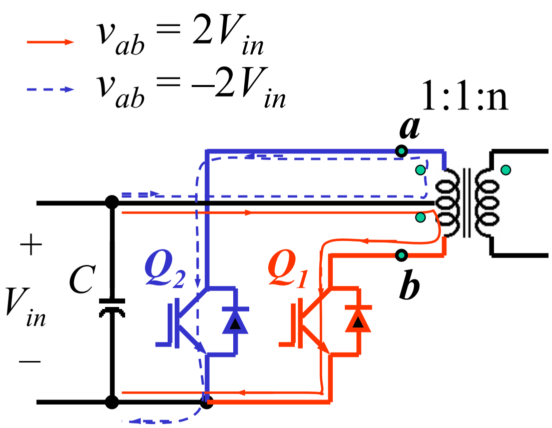
10V
>500A

400V
5 kW

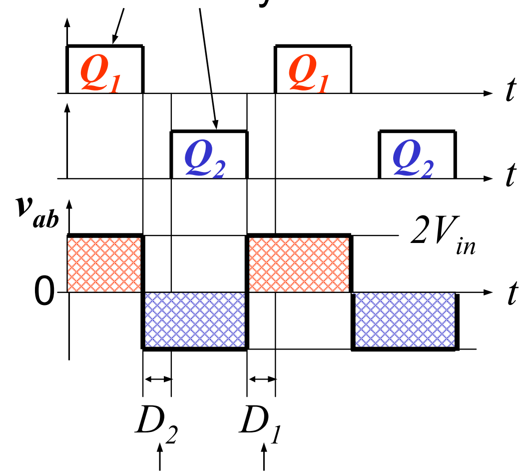


- ✓ Low device count
- ✓ Low voltage device
- × Device sees twice current
- × Unbalance due to split capacitors
- × High leakage due to twice transformer turns ratio

Basic Operating Principle of a Push-Pull Converter



Push-Pull converter



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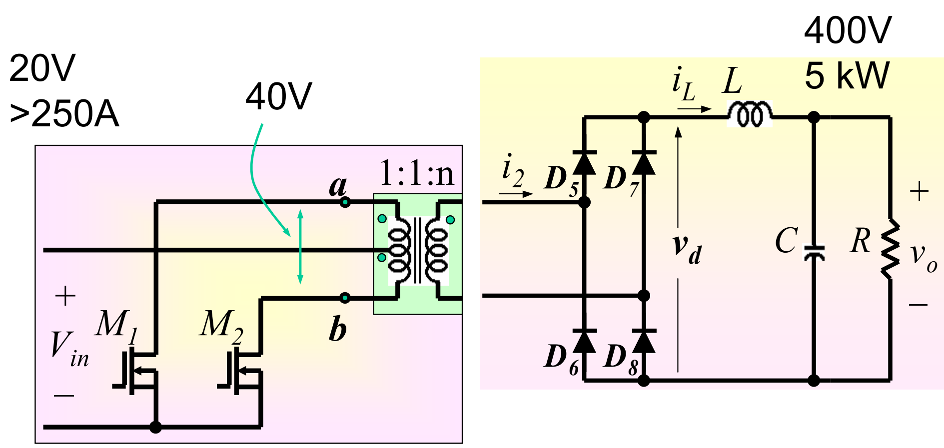
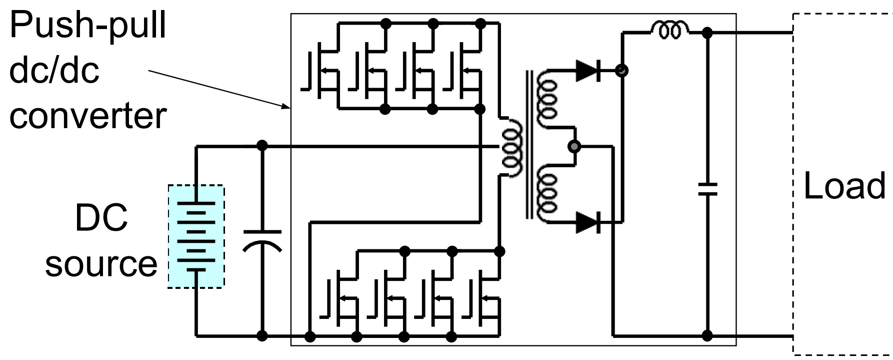
Push-Pull DC/DC Converter



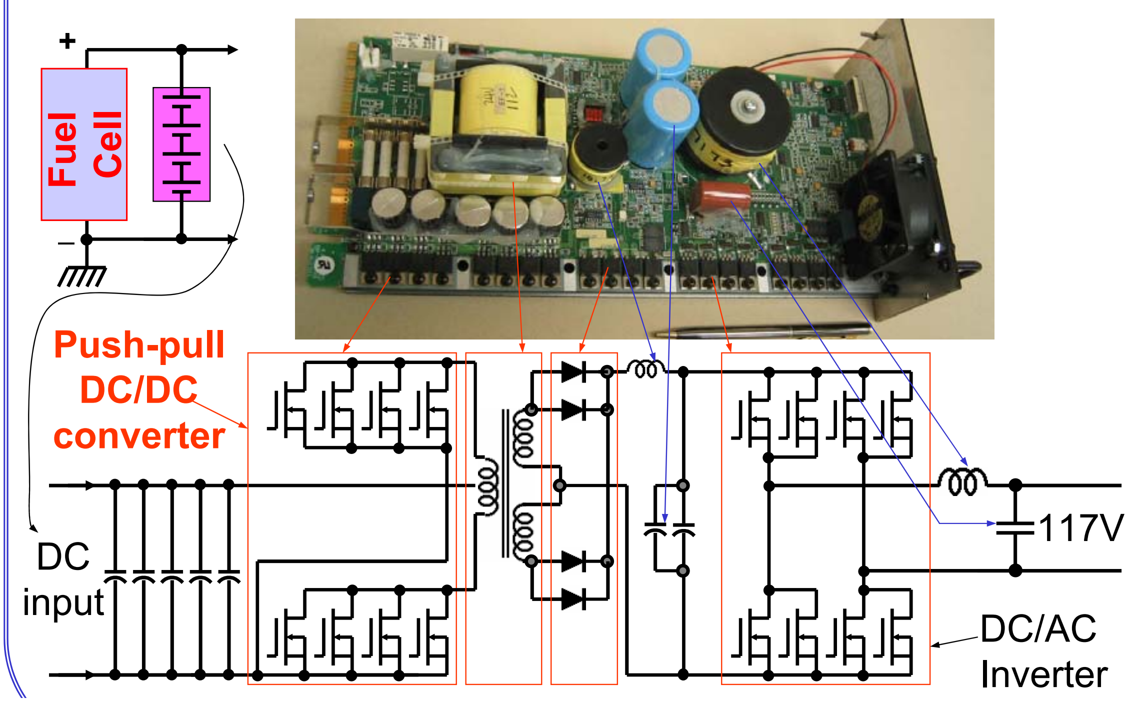
- + Simple non-isolated gate drives
- + Suitable for low-voltage low-power applications
- – Device sees twice input voltage – need high voltage MOSFET
  - **High conduction voltage drop, low efficiency**
- – Center-tapped transformer
  - **Difficult to make low-voltage high-current terminations**
  - **Prone to volt-second unbalance (saturation)**

A Push-Pull Converter with Paralleled Devices

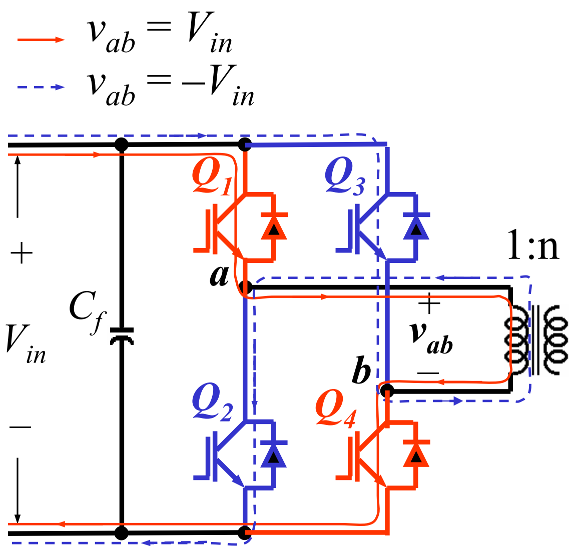


- Input – 28 to 35 V
- Device voltage blocking level – 100 V
- Efficiency – <85% even with 4 devices in parallel

A Commercial Off-the-Shelf 1-kW Fuel Cell Power Plant Using Push-Pull Converter

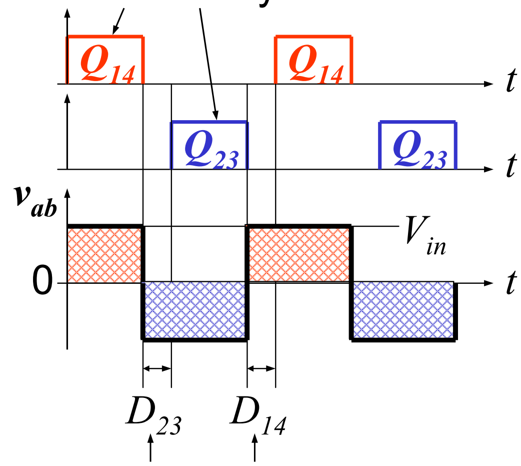


Basic Operating Principle of a Full-Bridge Converter Circuit



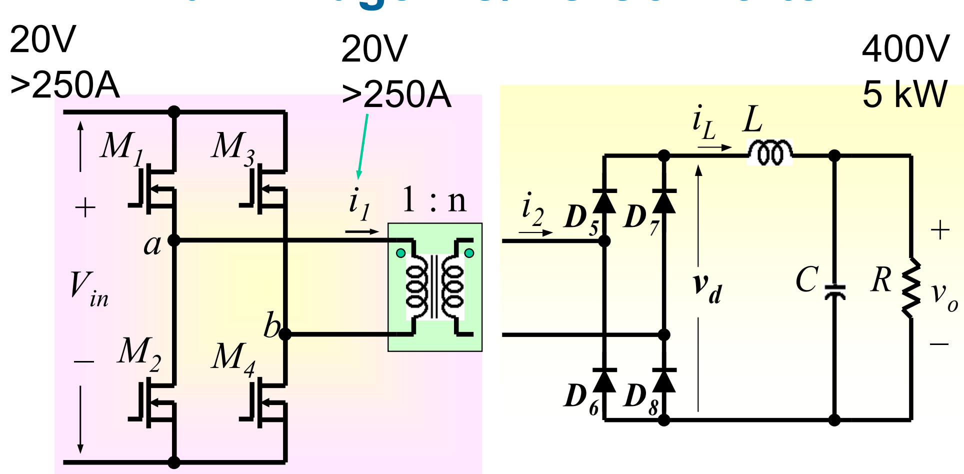
Full-bridge converter

Switches conduct alternately



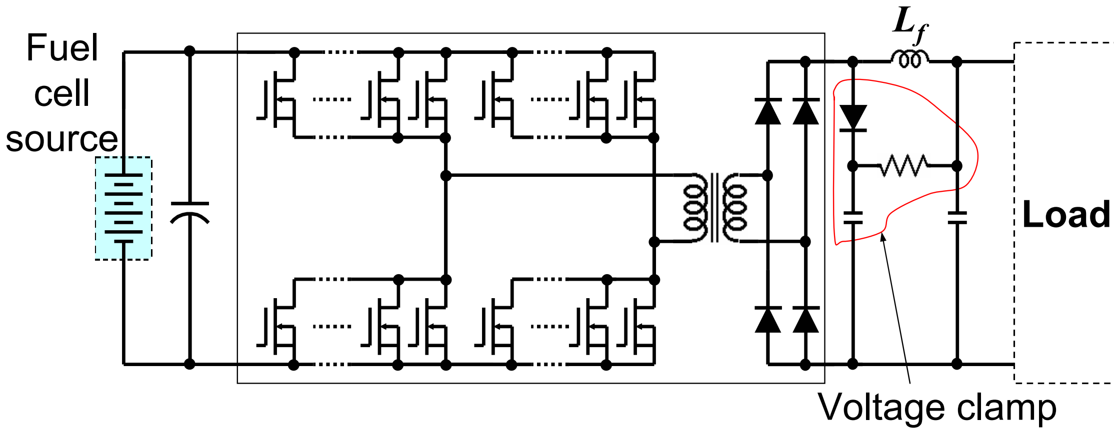
dead-time, current circulating thru anti-paralleled diodes

Full-Bridge DC/DC 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

Full-Bridge Converter with Paralleled Devices to Achieve Desired Power Levels



- Multiple devices in parallel to achieve desired high efficiency
- Problems are additional losses in parasitic components, voltage clamp, interconnects, filter inductor, transformer, diodes, etc.

Design Considerations for Isolated DC-DC Converters

- **Transformer turns ratio**
- **Transformer core utilization**
- **Device voltage stress**
- **Device current stress**
- **Output diode voltage stress**
- **Voltage clamping**

Pulse Width Modulation for Isolated DC-DC Converters

The average output voltage

$$V_o = DnV_{in}$$

Where

n = transformer turns ratio = n_2/n_1

D = duty ratio = t_{on}/T

and

n_1 = number of turns of primary winding

n_2 = number of turns of secondary winding

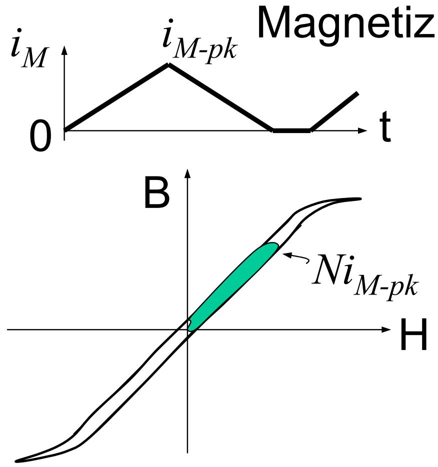
t_{on} = switch turn-on time

T = switching period

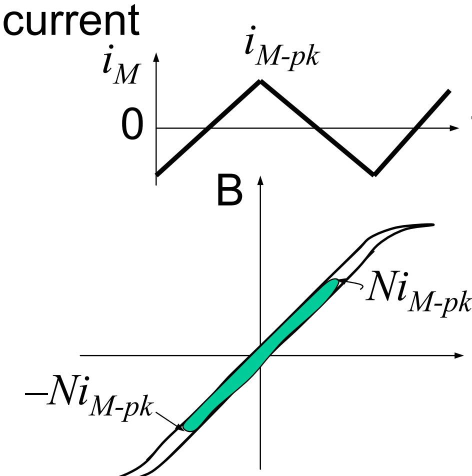
Transformer Core Utilization

- ✗ **Forward: <50%**
- ✗ **Flyback: <50%**
- ✓ **Half-bridge: 100%**
- ✓ **Push-pull: 100%**
- ✓ **Full-bridge: 100%**

Magnetizing current



Core is half utilized



Core is fully utilized

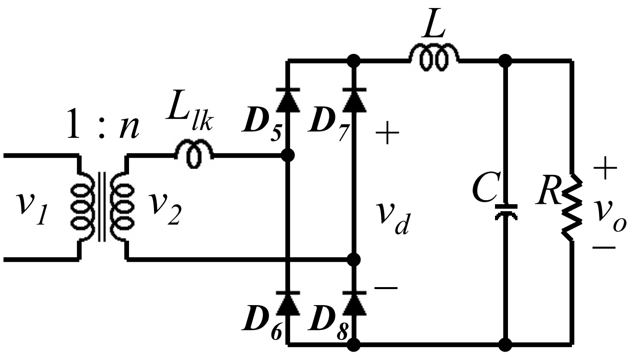
Device Voltage and Current Stresses

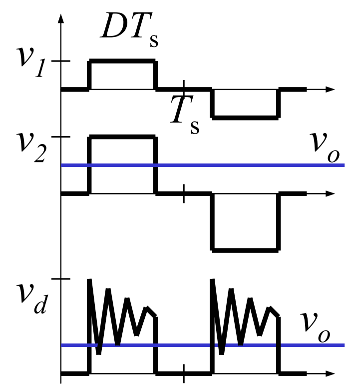
- Device voltage stress
  - ✗ Push-pull: 200%
  - ✓ Half-bridge: 100%
  - ✓ Full-bridge: 100%
- Device current stress
  - ✗ Half-bridge: 200%
  - ✓ Push-pull: 100%
  - ✓ Full-bridge: 100%
- Output diode voltage stress
  - ✗ Center tap: 200%
  - ✓ Bridge: 100%

Voltage Clamping

- Problems of diode over voltages
  - Full-bridge
  - Center-tapped
- Voltage clamping methods
  - Passive clamping method
  - Active clamping method

Over-Voltage Caused by the Transformer Leakage Inductance



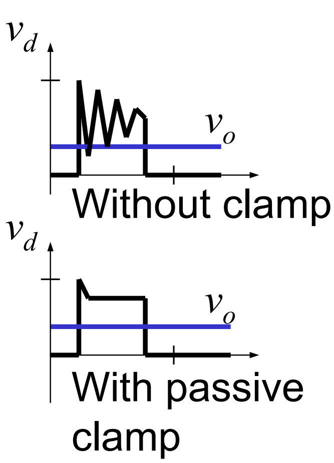


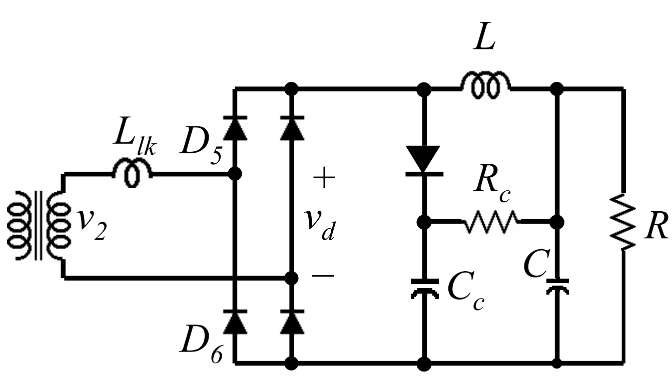
v_1: Primary side voltage

v_2: Secondary side voltage v_2, $v_2 > v_o$.

v_d: Voltage stress of upper diodes (D_5 , D_7) when lower diodes (D_6 , D_8) conduct, or vice versus, $v_{d\text{-}pk} > v_{2\text{-}pk} > v_o$, due to leakage inductance voltage drop.

Full-Bridge Diode Rectifier Over-Voltage Clamping





Advantage: Diode voltage stress is significantly reduced.

Disadvantage: Added cost and complexity.

Fuel Cell System Example for Topology Selection

Question: With 48 V fuel cell voltage and 400 V dc output, what topology is the best?

Answer: Intuitively, push-pull converter is the best because of least parts count. However, with device availability and cost consideration, full-bridge converter may be a better choice.

Reason: For low-side power MOSFET, lower voltage is more cost effective. Similarly, for high-side diode, lower voltage is more cost effective.

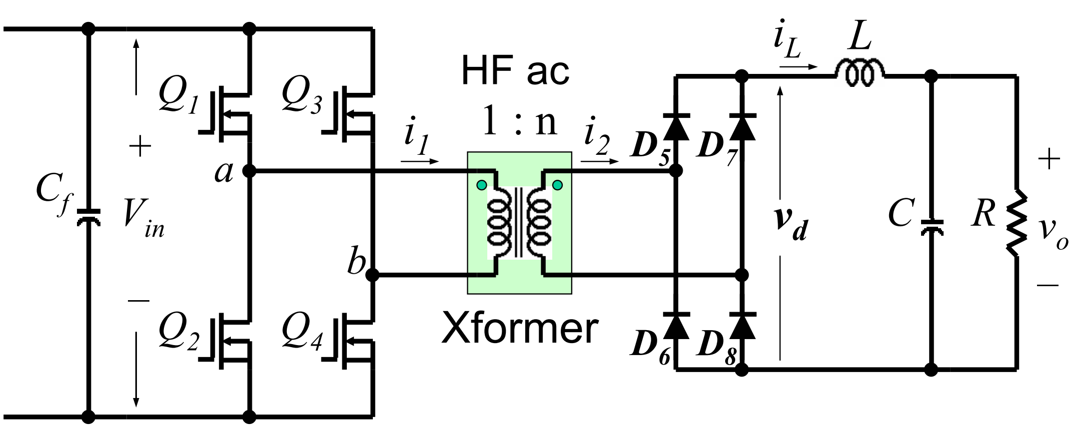
4. Implementation Issues in High Power DC/DC Converters

- **Controller output duty cycles tend to be unbalanced due to internal chip layout, resulting transformer saturation.**
- **Voltage sensing problem:**
  - **Feedback voltage signal tends to be corrupted by noises**
  - **Hall sensor is expensive**
  - **Common mode and isolation are difficult to deal with resistor dividers**
- **Current sensing problems:**
  - **Lossy with resistor sensing**
  - **Difficult to insert Hall sensor for device current measurement**

Full-bridge Converter Design Example

- Specifications:
  - Input fuel cell voltage ranges from 36 V to 60 V
  - Output: 400 V, 10 kW
- Current
  - Output: 25 A
  - Input: 208 A

Power Stage Design



Component Design and Selection:

- Power MOSFET
- Rectifier diode
- Transformer
- Filter inductor
- Filter capacitor

Survey of High Current Power MOSFETs

Manufacturer	Part Number	V_{DSS} (V)	$R_{DS\text{-}on}$ (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

Quantity	1	100	1000	25,000	50,000	100,000
FDB045AN08A0	$3.50	$2.50	$2.40	$2.30	$2.10	$1.60
IRFP2907	$4.49	$3.96	$3.07	$3.07	$3.07	$2.89
FDP047AN08A0	$3.50	$2.50	$2.40	$2.30	$2.10	$1.60
FMM 150-0075P	$8.00	$7.00	$6.19	$5.79	$5.30	$5.03
SUM110N08-05	$2.70	$2.50	$2.50	$2.35	$2.19	$2.19
IXUC160N075	$4.00	$3.00	$2.05	$1.65	$1.49	$1.40
IRF3808	$2.29	$2.16	$1.80	$1.50	$1.30	$1.17
FQA160N08	$4.00	$3.00	$2.90	$2.60	$2.50	$2.20

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

Survey of Ultrafast Reverse Recovery Diodes

Manufacturer	Part Number	V_F	t_{rr}	I	Package
Fairchild	RHRG5060	1.5 V	45ns (max)	50 A	TO-247
International Rectifier	HFA50PA60C	1.9 V	23ns (typ)	50 A	TO-247AC
IXYS	DSEK 60-06A	1.6 V	35ns (typ)	60 A	TO-247AD

Quantity	1	100	1000	25,000	50,000	100,000
RHRG5060	N/A, (300 part min)		$3.50	$1.75	$1.50	$1.50
HFA50PA60C	$8.81	$8.22	$7.71	$7.61	$7.25	$4.00
DSEK 60-06A	$4.00	$3.00	$2.50	$2.07	$1.99	$1.90

Output Filter Capacitor Selection
- Typically based on the output voltage ripple

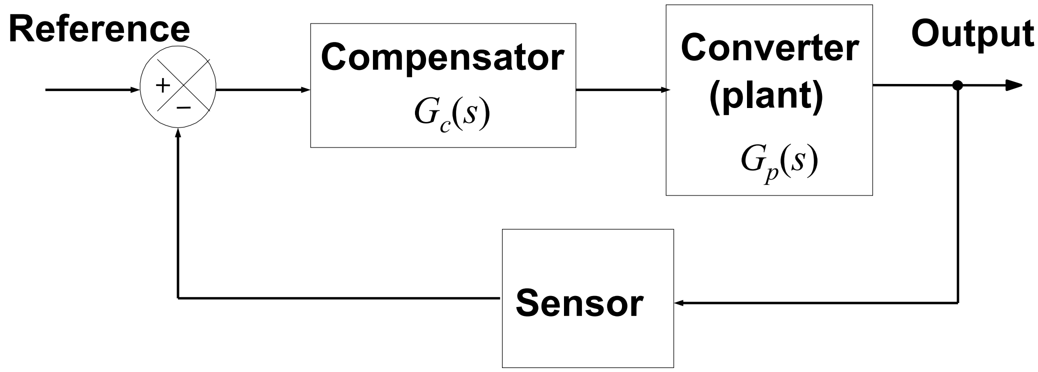
- The output filter capacitor needs to handle 120 Hz, 22 A ripple current generated from the next stage inverter.
- Assume the voltage ripple is limited to 5%. The capacitance can be calculated as

$$C = \frac{\Delta I}{8 f \cdot \Delta V} = \frac{22}{8 \cdot 60 \cdot 400 \cdot 0.05} = 2.2\,\text{mF}$$

Digital Computer Implementation for High Power DC/DC Converters

- **Digital computer such as DSP has become a good option for high power DC/DC converter control implementation**
- **Feedback voltage signal can be converted to digital and through PWM feeding back to DSP to avoid noise corruption**
- **Even if commercial PWM or PSM chips are used, the control signal can be obtained from DSP through D/A conversion**
- **Communication with digital signals has become the essential part between the dc/dc converter and the fuel cell controller or other power converters**

Controller Design for a Typical Converter



$$G_p(s) = \frac{K}{1 + s/Q + s^2}$$

$$s = j\omega = 2\pi f \qquad j = \sqrt{-1} \qquad f = \text{frequency}$$

$$G_c(s) = K_p + \frac{K_i}{s}$$ (A standard PI controller)

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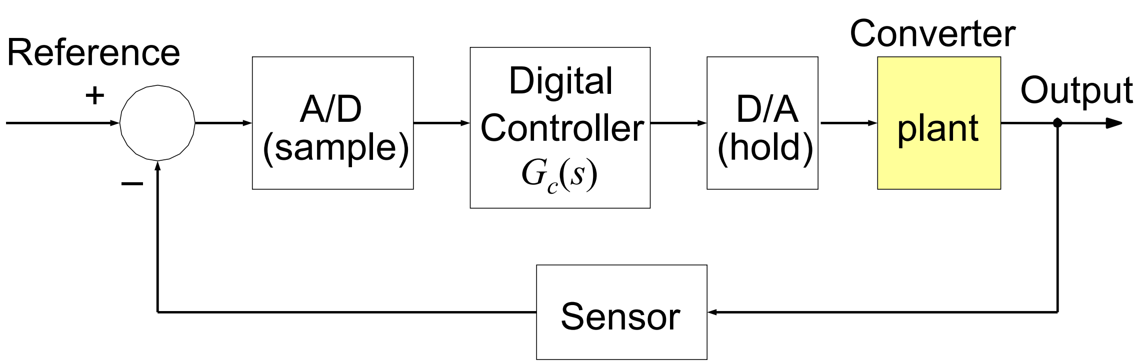
Digital Controller for a Typical Converter

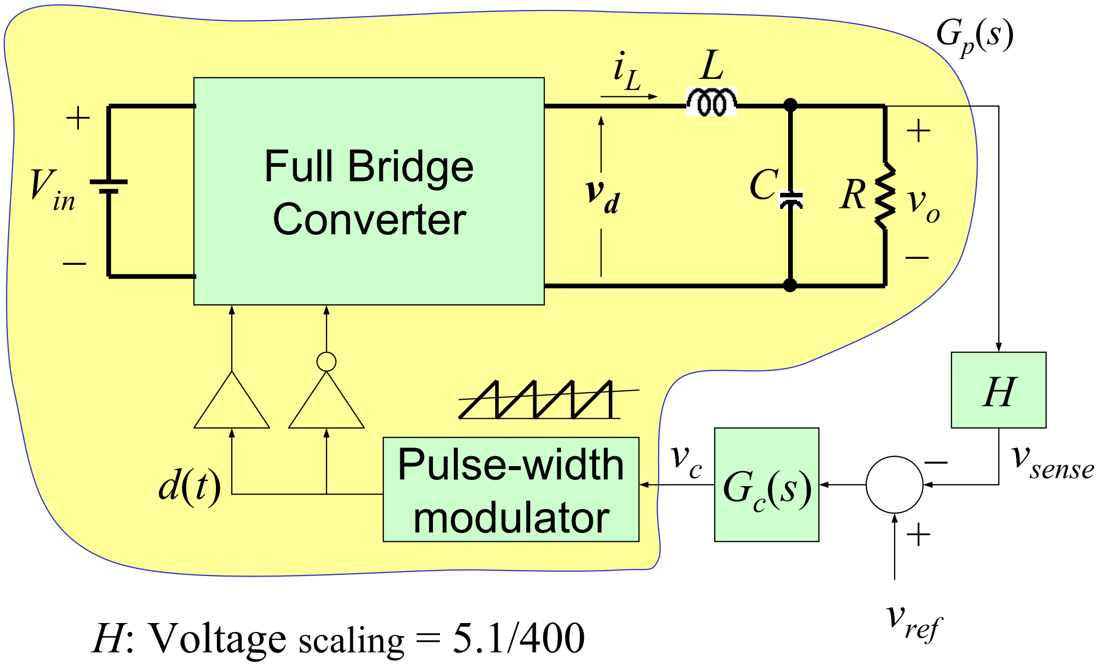


$$G_c(z) = K_p + K_i \frac{T_s}{2} \frac{z+1}{z-1}$$

T_s = switching frequency

$$s = \frac{2}{T_s} \frac{z-1}{z+1}$$

Voltage Loop Controller Block Diagram

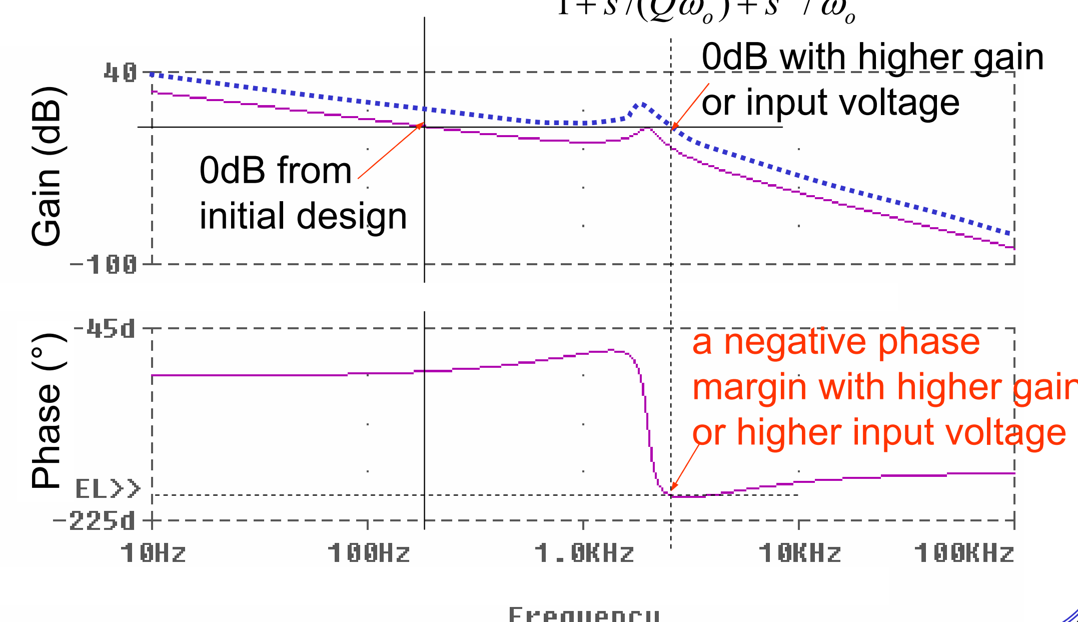


H: Voltage scaling = 5.1/400

$G_c(s)$: PI or PID Controller

Phase Margin Shifts due to Fuel Cell Input Voltage Variation: 42 to 60 V

$$G_{vd}(s) = \frac{nV_{in}}{1 + s/(Q\omega_o) + s^2/\omega_o^2}$$



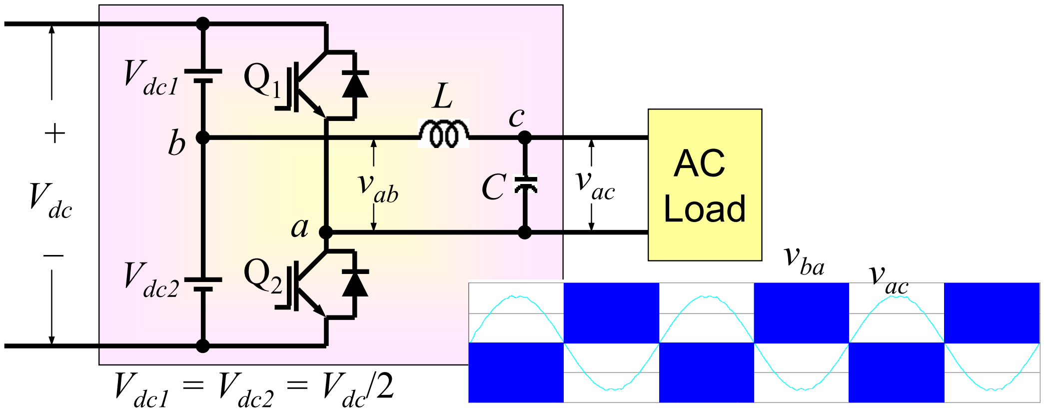
DC-DC Converter Control System Design is Challenging with the Fuel Cell Source

- A typical controller is designed with low input voltage and heavy load condition.
- When the load is reduced, the fuel cell voltage increases, and the original controller design may be inadequate due to input voltage variation.
- Increasing the input voltage is equivalent to increase the closed-loop gain and tends to worsen the phase margin, and the system can eventually become unstable.

5. DC/AC Inverters

- Single-phase output
  - Half-bridge
  - Full-bridge
- Dual single-phase outputs
  - Dual half-bridge
  - Three-leg inverter
- Load Effect
  - Linear loads
  - Nonlinear loads

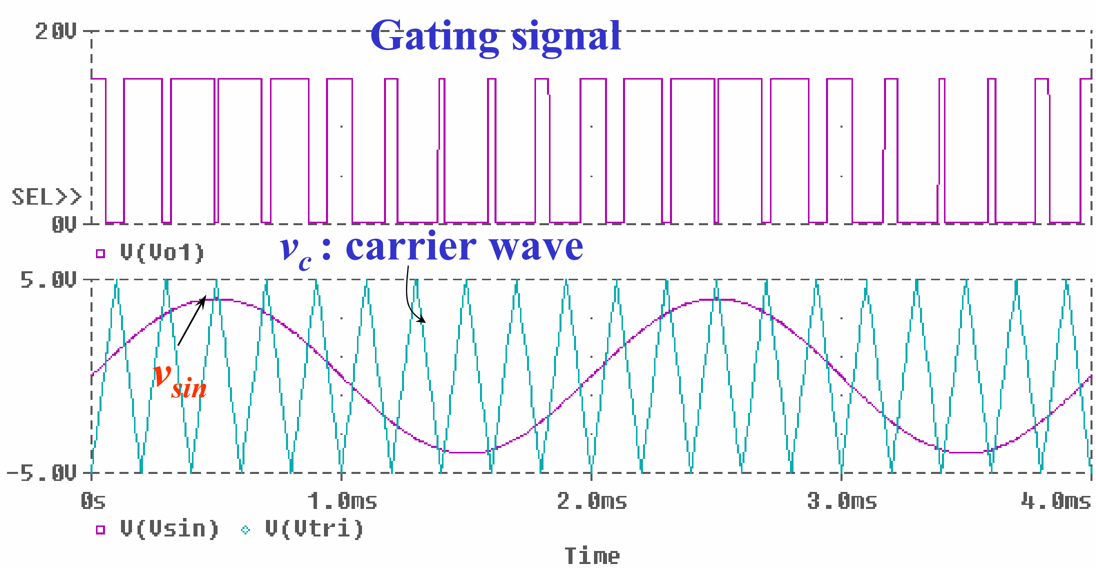
Half-Bridge DC-AC Inverter with Split DC Buses



Maximum output peak voltage $V_{max} = V_{dc}/2$

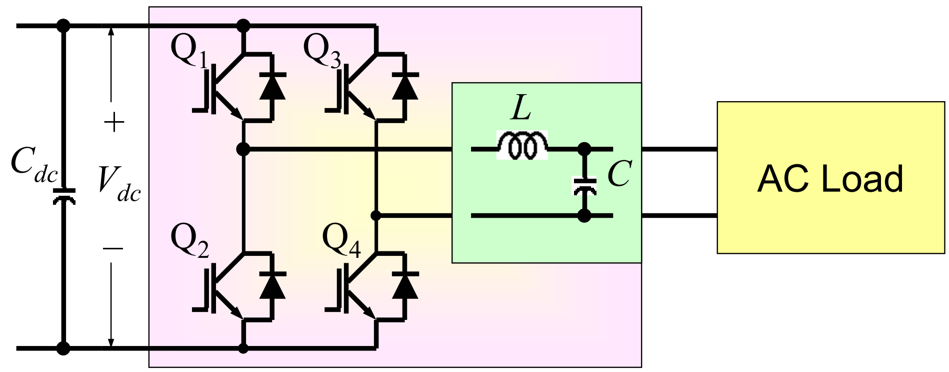
- **Simple dc-ac Inverter with minimum switch counts**
- **Split dc buses should be very stiff and balance to avoid dc or even harmonics at the ac output**
- **Control is limited to the ordinary sinusoidal pulse width modulation (SPWM)**
- **Cost burden is in passive components**

Sinusoidal Pulse Width Modulation



When $v_{sin} > v_c$, gate signal is high, and IGBT is turned on; Otherwise, gate signal is low and IGBT is turned off.

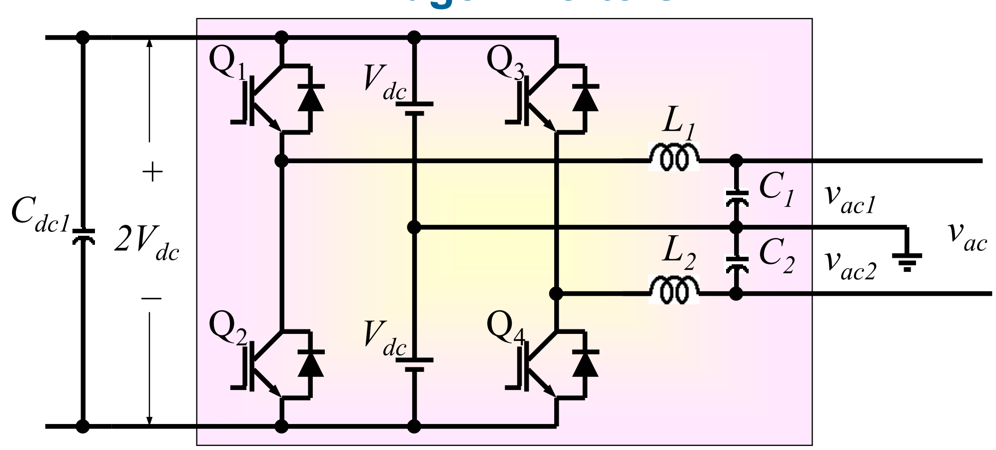
Single-Phase Full-Bridge DC-AC Inverter



Compared with Half-Bridge inverter, FB inverter features

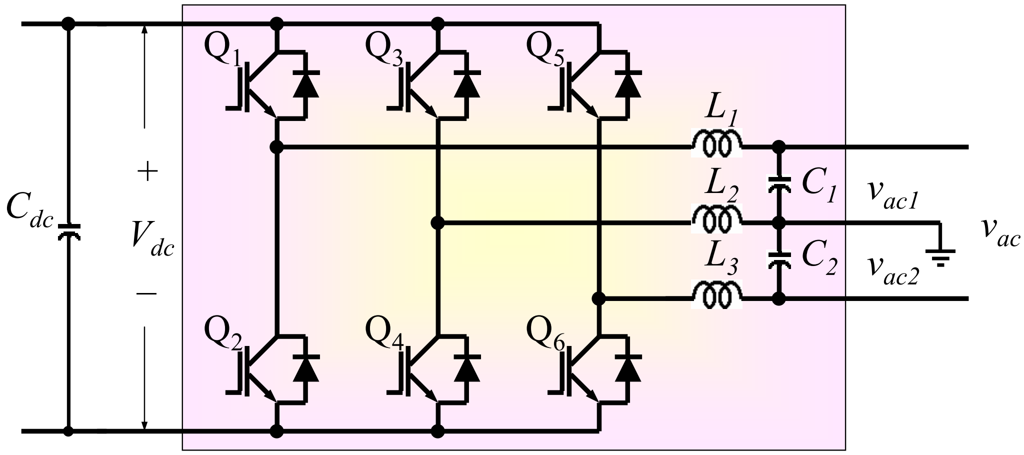
- **Simple dc-ac Inverter with more switch counts, but less bulky capacitors**
- **Control is more flexible to have phase-shifted SPWM for two individual legs – Dual Modulation Method.**
- **Size of passive components may be reduced**

Dual Single-Phase Outputs with Dual Half-Bridge Inverters



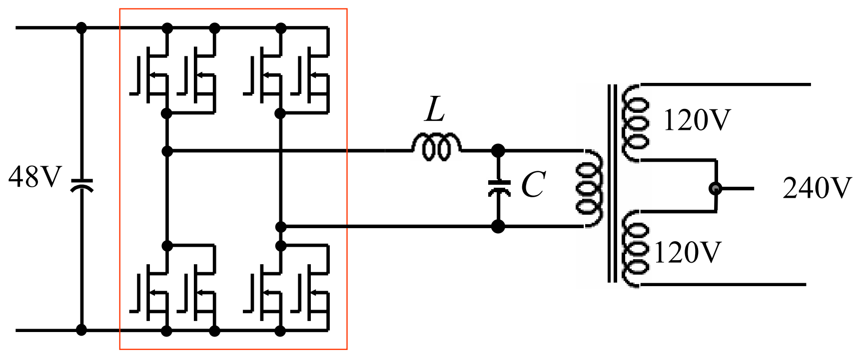
- ✓ Only one set of split dc buses are required
- ✓ Q_1-Q_2 and Q_3-Q_4 pairs need to be switched complementary so that the total $v_{ac} = v_{ac1} + v_{ac2}$.
- ✗ Possible unbalanced output ac voltages under unbalanced load conditions

Three-leg Inverter for Dual AC Outputs with Single DC Bus



- Similar to full-bridge inverter with **more switch counts, but less bulky capacitors**
- Outer legs do SPWM to produce vac output. Middle leg is controlled to equalize v_{ac1} and v_{ac2}
- Control is more complicated to ensure output voltage balance
- Size of **passive components** may be reduced

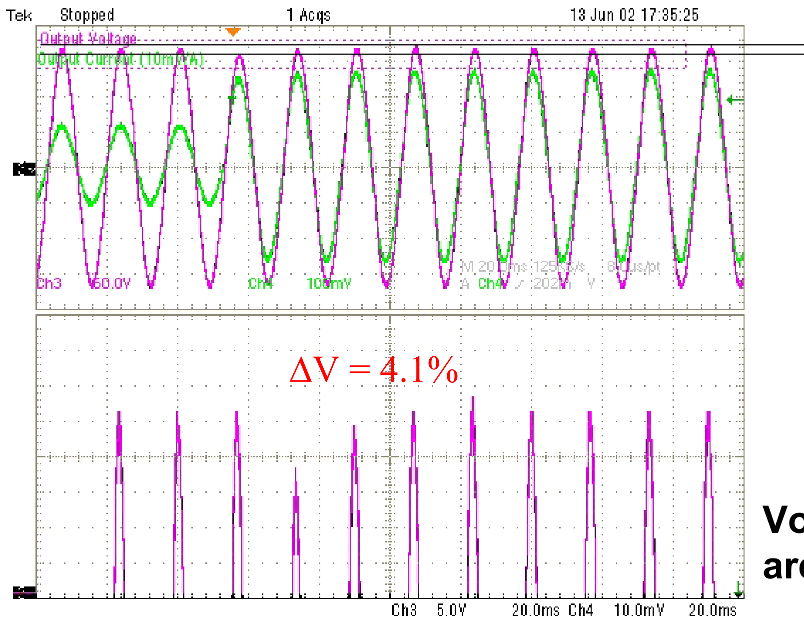
Using Low-Frequency Transformer for Low-Voltage AC Inverter Output

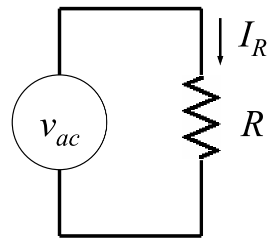


Features:

- Low-frequency transformer allows low-voltage DC to be directly converted to AC
- Output can be single or dual
- Size is the major concern

Inverter Output with Resistive Load

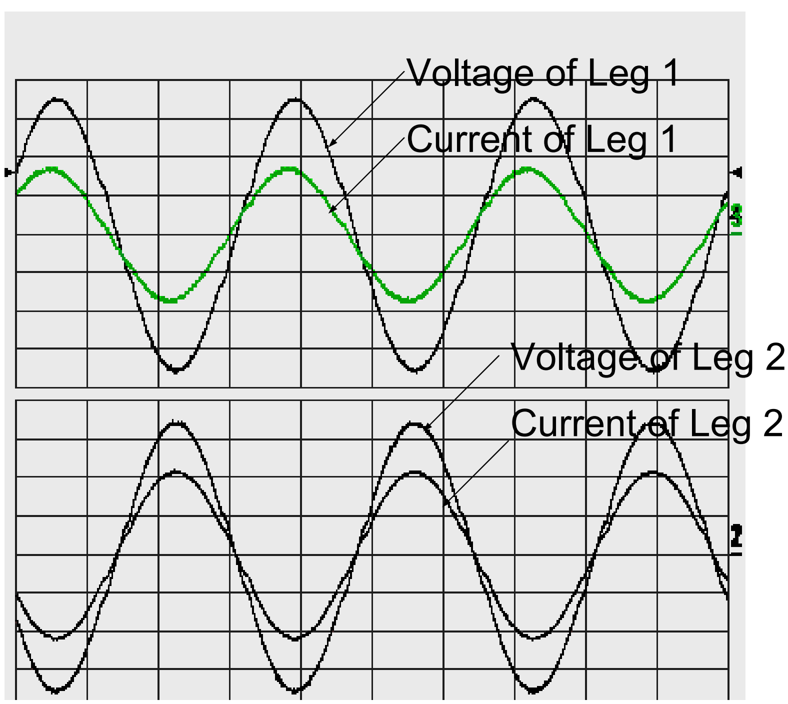




$$I_R = \frac{v_{ac}}{R}$$

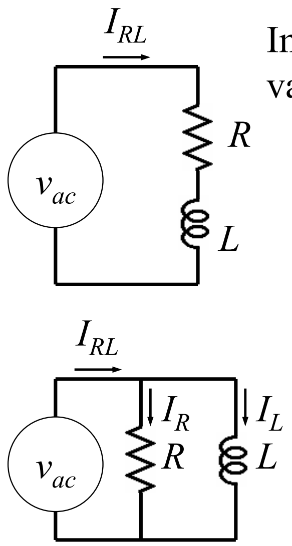
Voltage and current are in phase

Dual Output Voltage and Current with Unbalanced and Reactive Loads

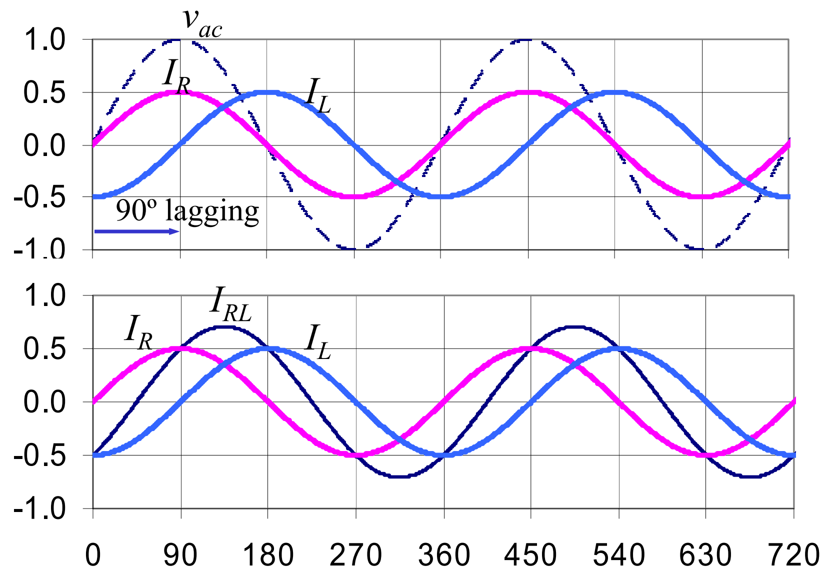


Majority of Power System Loads is Inductive

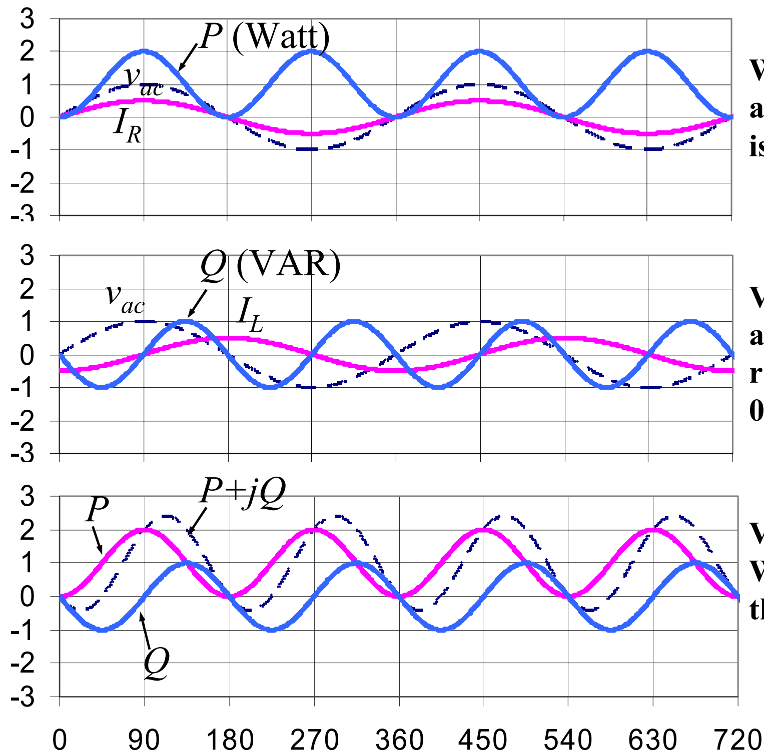
Impedance of inductor is imaginary (90º apart from real value)



$$X_L = j\omega L = j2\pi fL$$



What about Watt and VAR?



Watt is real V×A, average Watt > 0, and is the average (V×A).

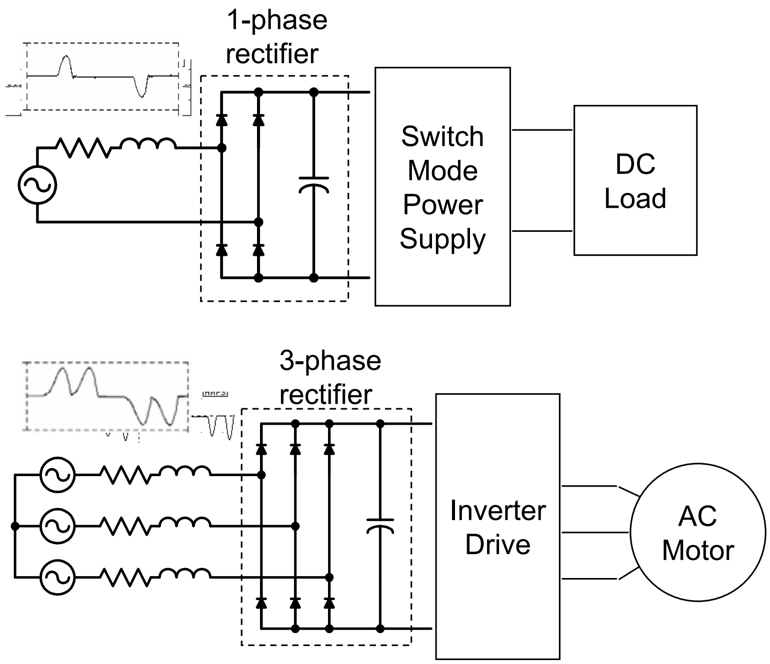
VAR is reactive V×A, average VAR = 0, but reactive current is not 0.

VA = Watt+jVAR, not Watt+VAR because they are not in phase.

Implications of VAR

- Average VAR = 0 ➔ No real power output
- VAR loads are typically inductive such as motors, magnetic ballasts, relays, etc.
- The current associated with VAR causes additional heat losses in the wiring and the internal impedance of the source
- Inductive VAR can be compensated with capacitive VAR, but not without complexity
- Nonlinear loads also introduce VAR

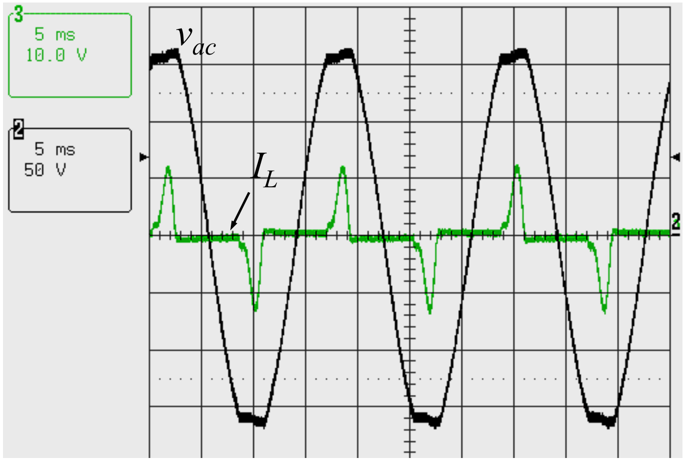
Majority of Electronic Loads is Nonlinear



Used for:
Computers,
Printers, Fax,
most ITE
Electronic Lighting
Communications
Food Preparation

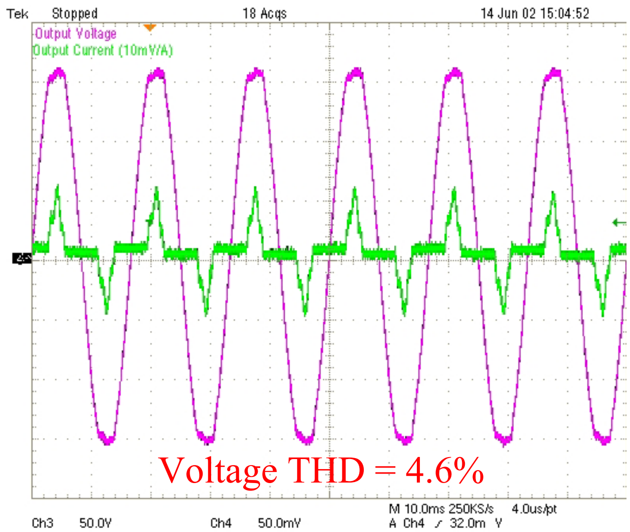
Used for:
HVAC, Battery
Charging, Food
Preparation,
Elevators

Inverter Output Voltage Under Nonlinear Rectifier Load



- Single-phase nonlinear load current is rich with odd harmonics (3,5,7,…) especially with the 3rd harmonic
- The voltage waveform is flatten up due to nonlinear current.

Voltage Waveform Quality may be Improved with Closed-loop Control

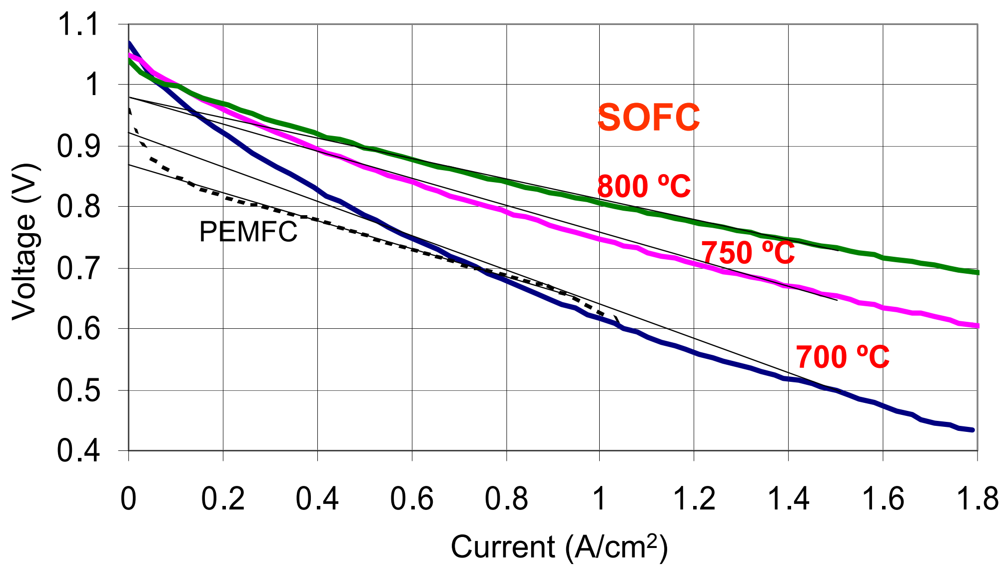


Closed-loop control can smooth the voltage waveform but the nonlinear current waveform remains nasty.

6. Fuel Cell and Converter Interactions

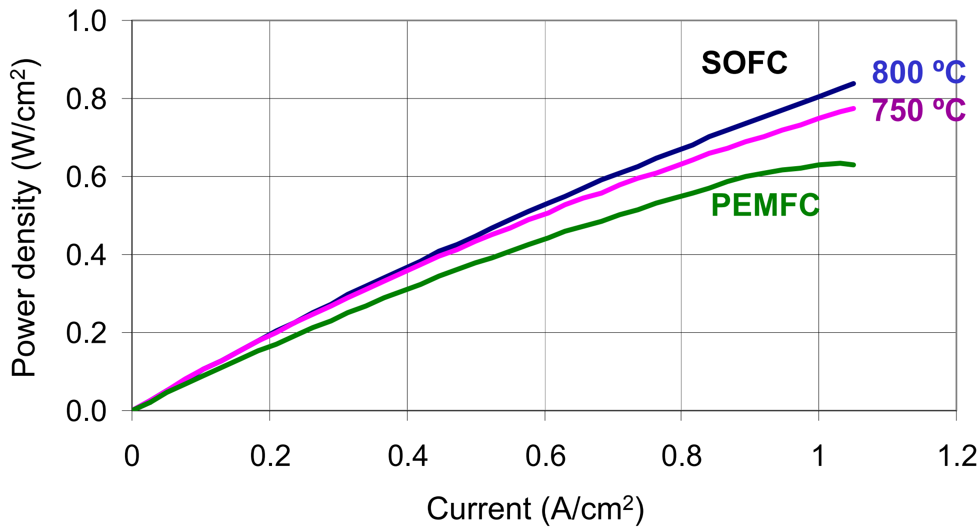
- **Static modeling**
- **Dynamic modeling**
- **Fuel cell dynamic response with and without converters**

SOFC Voltage-Current Characteristic as a Function of Temperature



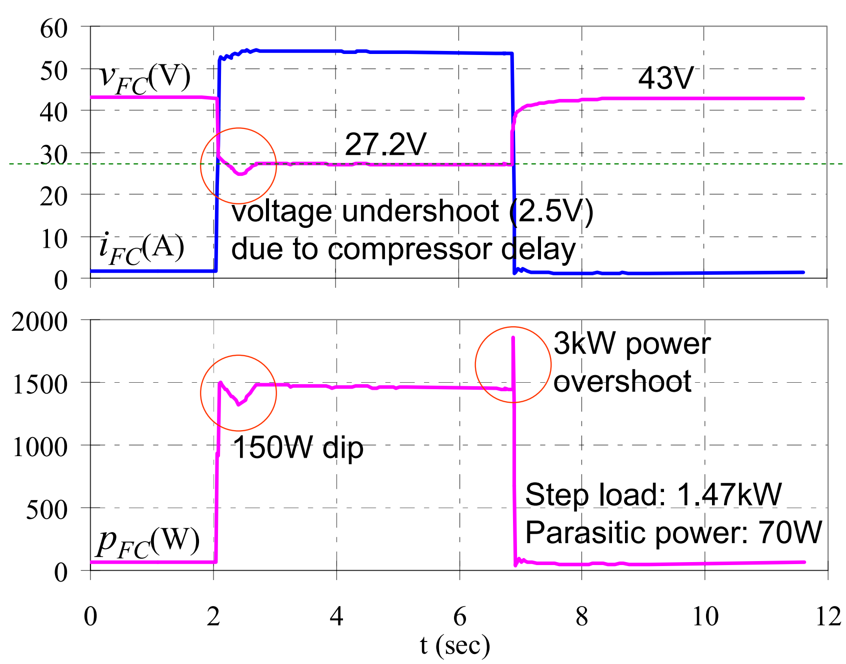
Data source: DOE SECA Modeling team report at Pittsburgh Airport, 10/15/2002

Power Density of SOFC and PEMFC

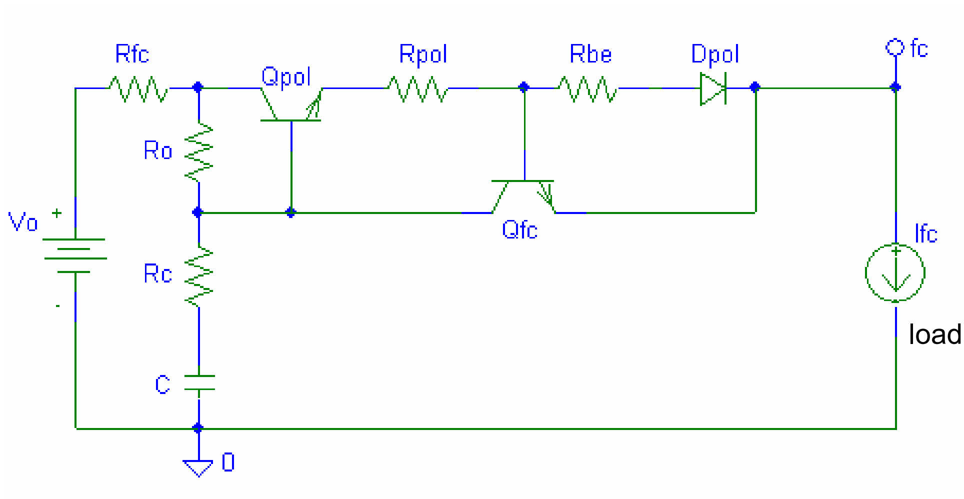


PEM Fuel Cell Dynamic Characteristics

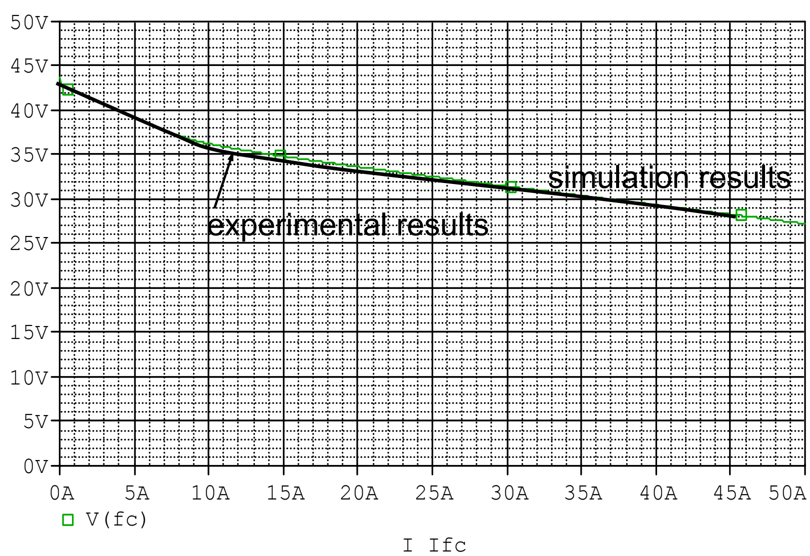
Nexa 1.2kW Unit



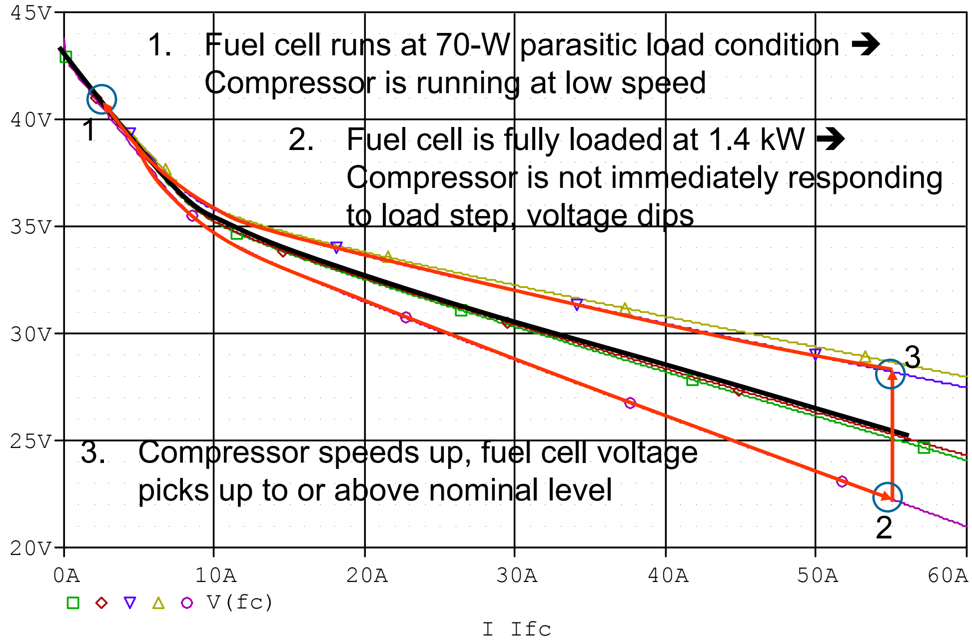
Fuel Cell Modeling with Electrical Circuit



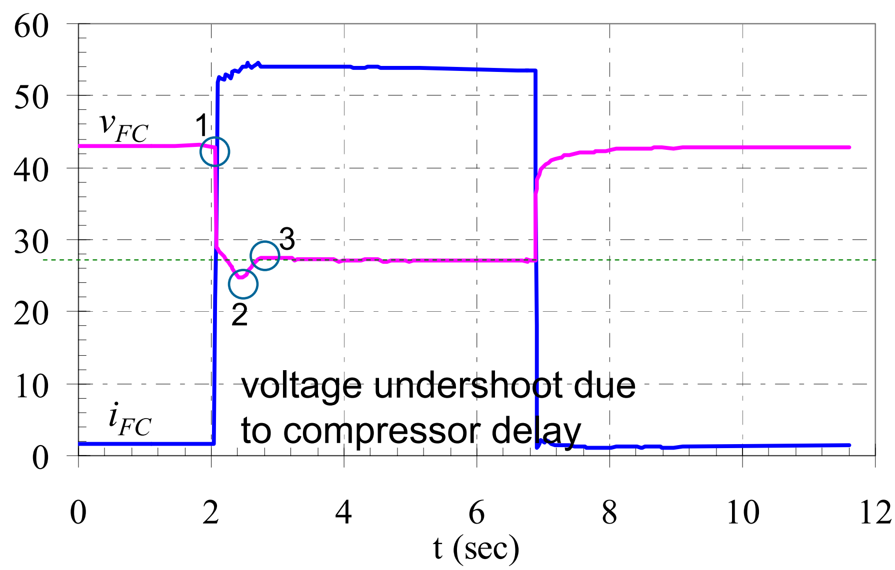
Nexa1200 Polarization Curve



Polarization Curves for Nexa PEM FC

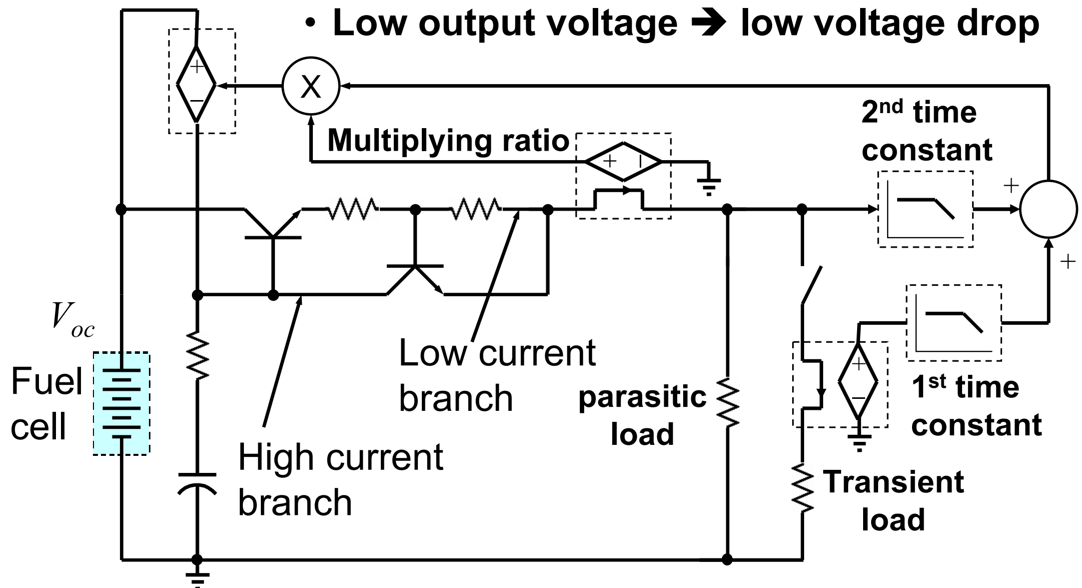


Time Domain Response



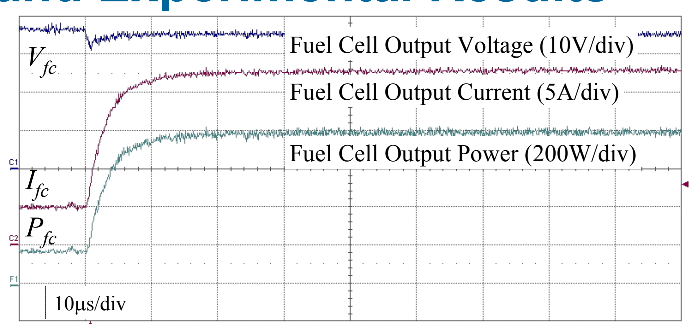
PEM Fuel Cell Dynamic Simulation Diagram

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

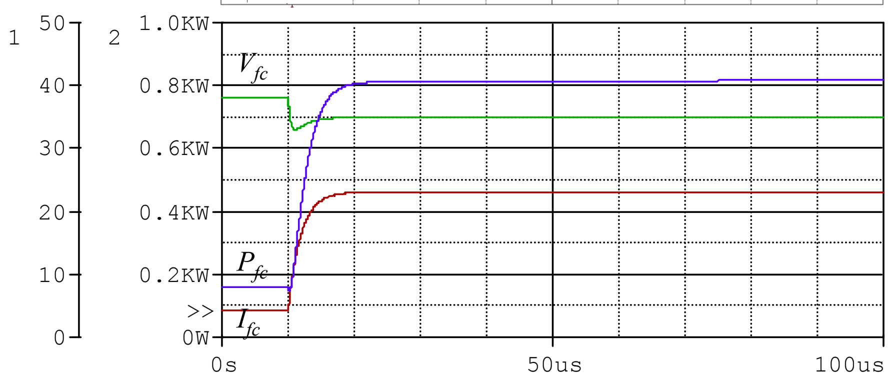


Fuel Cell Stack Output Dynamic Simulation and Experimental Results

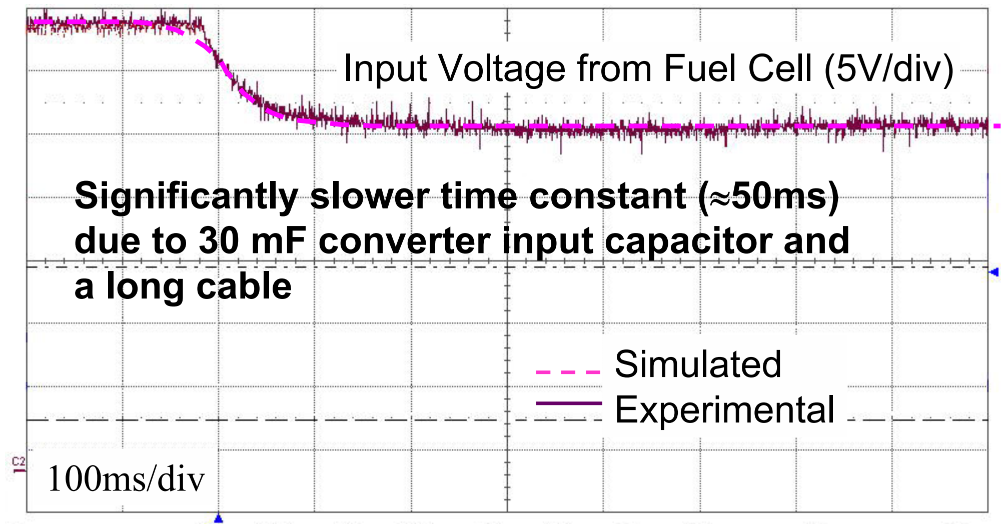
(a) experimental results



(b) simulation results

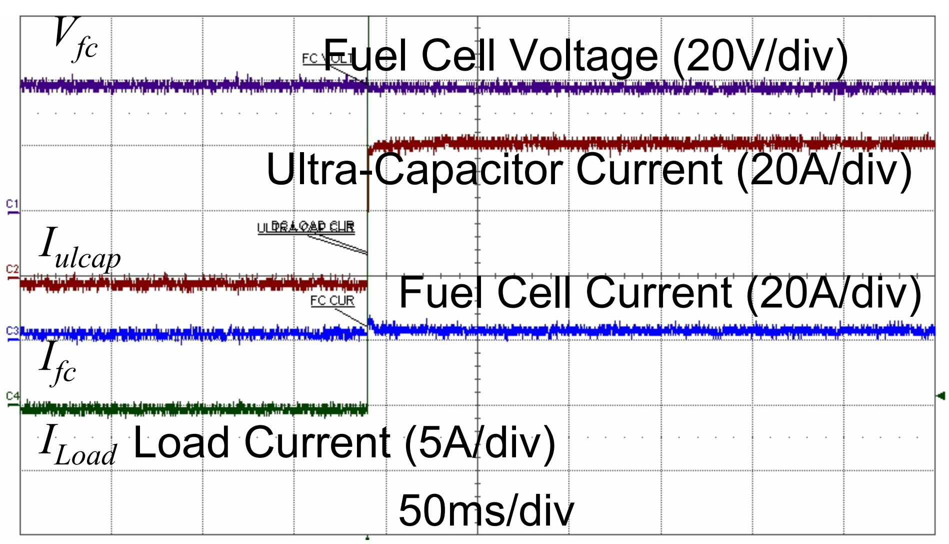


Fuel Cell Voltage Dynamic with Converter Load Transient

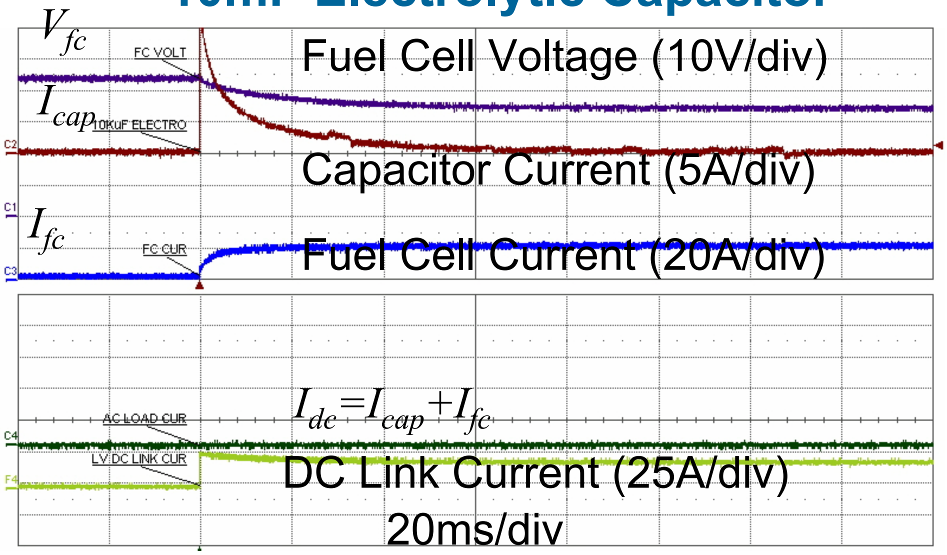


Future Energy Electronics Center

Fuel Cell Responds with a Paralleled 140F Ultra Capacitor Capacitor



Fuel Cell Responds with a Paralleled 10mF Electrolytic Capacitor



Note: Fuel cell output voltage response is slowed down to 30ms. Capacitor takes over the transient current.

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**

Issues to be Resolved in a Fuel Cell Power Conditioning System

- Energy management system options – Sizing of converters and auxiliary sources
- Advanced Bidirectional dc-dc converter technologies
- 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

7. Fuel Cell Energy Management Issues

- Problems without Slow Fuel Cell Response and Auxiliary Energy Storage
- Options of Energy Storage Placement
- Energy Management options with Bidirectional DC/DC Converters

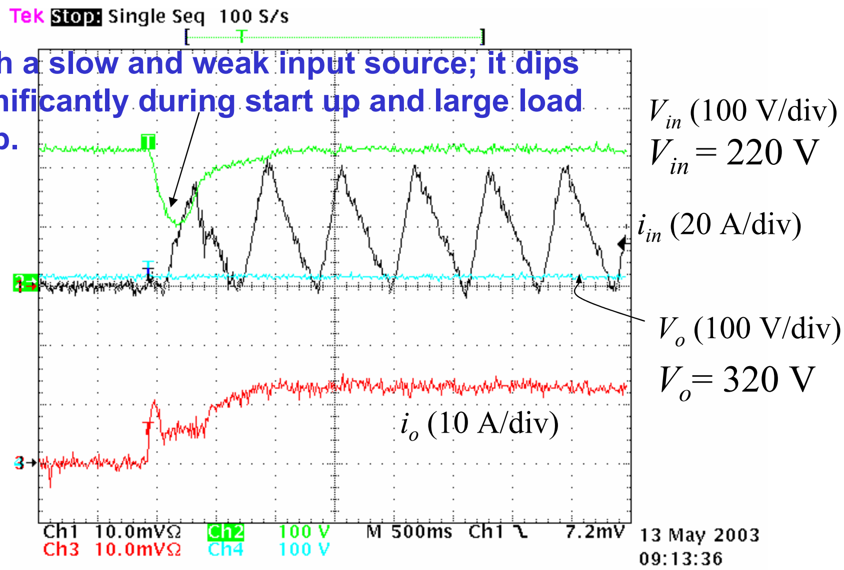
Why Fuel Cells Need Auxiliary Energy Source or Energy Storage?

- 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

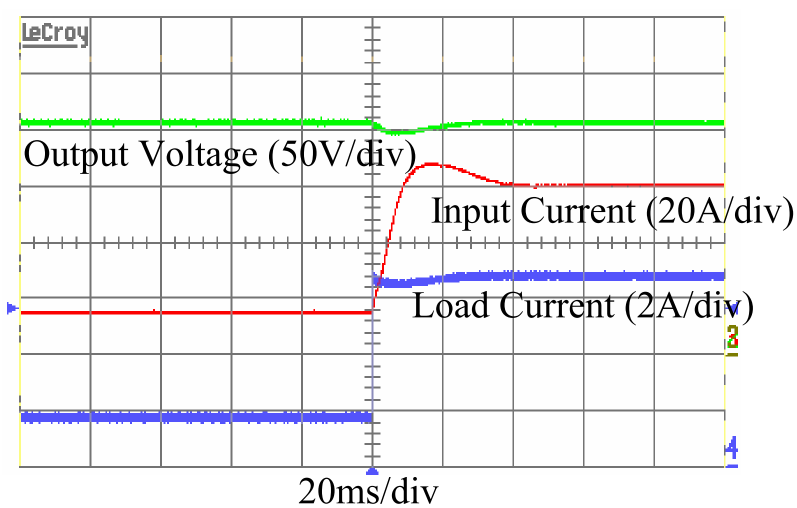
Problems of a Fuel Cell System without Energy Storage

- 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

A Slow and Weak Energy Source During Startup and Large Load Transient

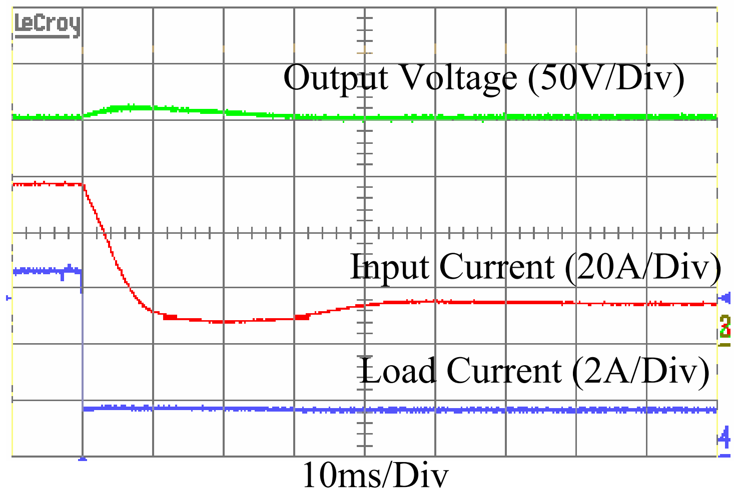


Converter Step Load Response with Stiff Voltage Source and Voltage Loop Control



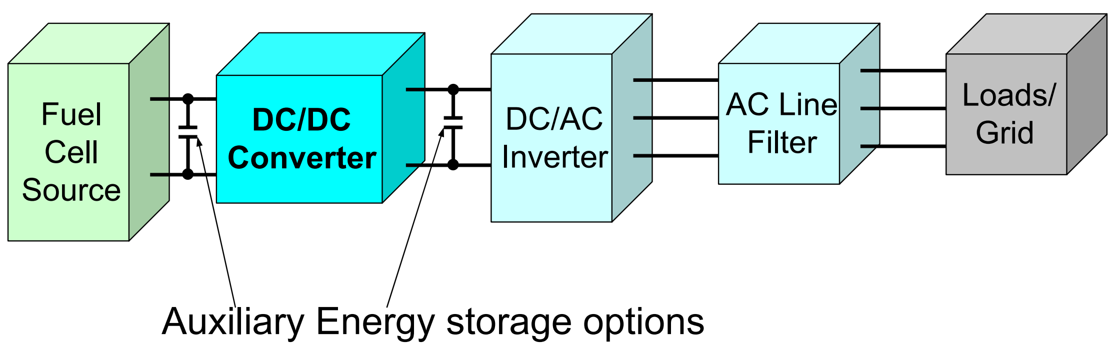
With voltage control loop bandwidth designed at 20 Hz, settling time is about 40ms under load step

Converter Load Dump Response with Stiff Voltage Source and Voltage Loop Control



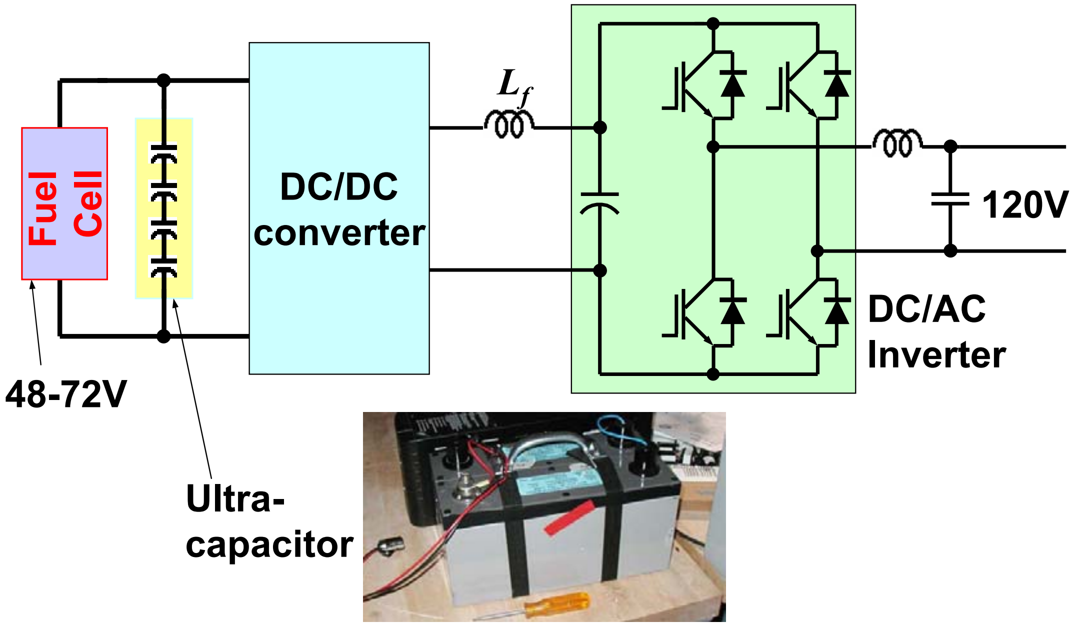
With voltage control loop bandwidth design at 20 Hz, settling time is about 40ms under load dump

A Fuel Cell Power Plant with Energy Storage

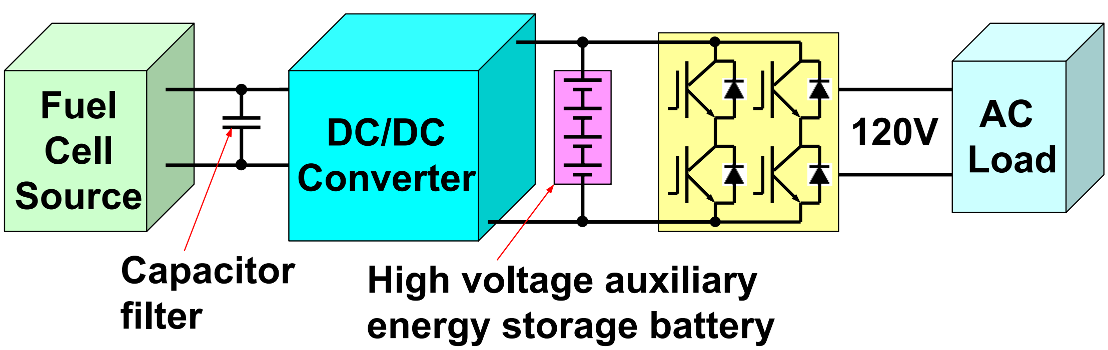


Fuel Cells Need Auxiliary Energy Storage for energy management

Low-Voltage Ultra-Capacitor Energy Storage Configuration



Use High-Voltage Battery as the Auxiliary Energy Storage



Photograph of a 96V battery bank

Potential Problems with Passive Energy Storage

- **Low-side ultracap option:**
  - Two voltage sources are paralleled – not a good engineering practice
  - Time to reach equilibrium point is too long because dynamic characteristics of both sources are different
  - Ultra capacitor helps transient current sharing, but creates significant voltage and current ripples due to interaction between two voltage sources
  - Dynamic current sharing problem
- **High-side battery option:**
  - Battery cell voltage balance problem
  - Battery state-of-charge management
  - Long-term battery life expectancy
  - Cost of battery is a concern

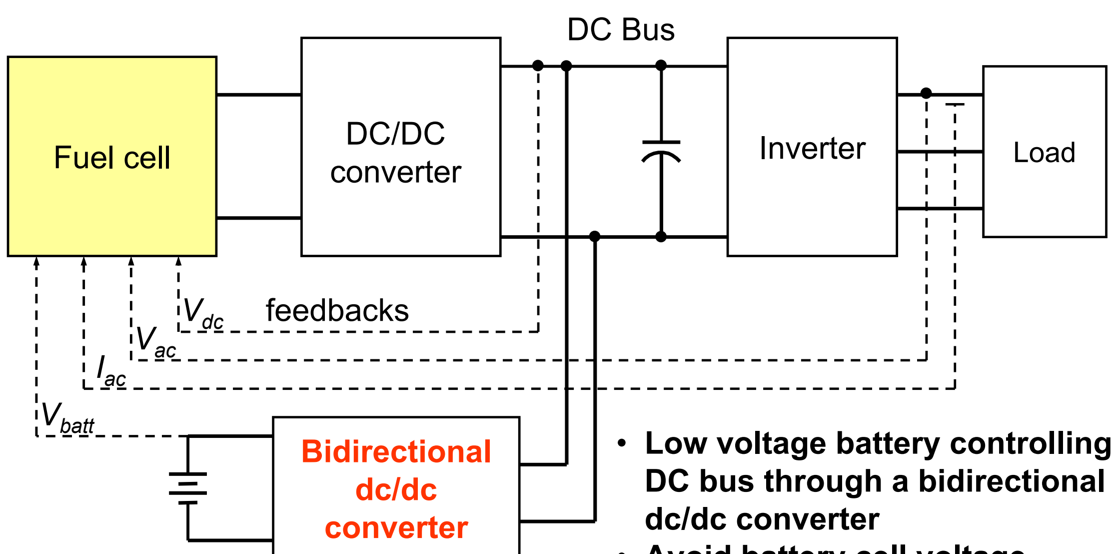
Energy Management Options with Energy Storages and Power Electronics

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

Design Considerations for Hybrid-Source Systems

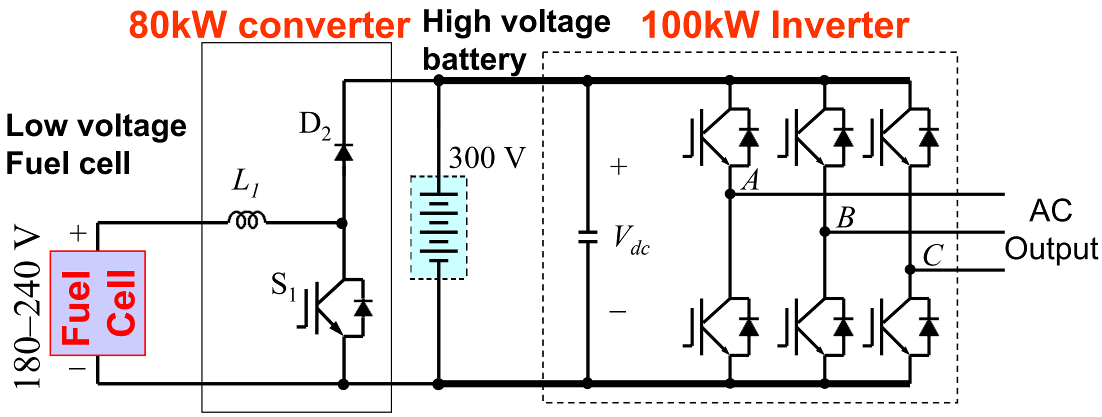
1. *Utilization* of Primary Source
2. *Simple* ***Power Circuit*** (as simple as possible)
3. Voltage ratio
4. *Isolation* Requirement
5. *Energy Storage* Requirement
6. Inverter *DC Bus Voltage* Requirement
7. *Cost*

Energy Management Using Low Voltage Battery and Bidirectional DC/DC



- Low voltage battery controlling DC bus through a bidirectional dc/dc converter
- Avoid battery cell voltage balancing problem
- Complicated control

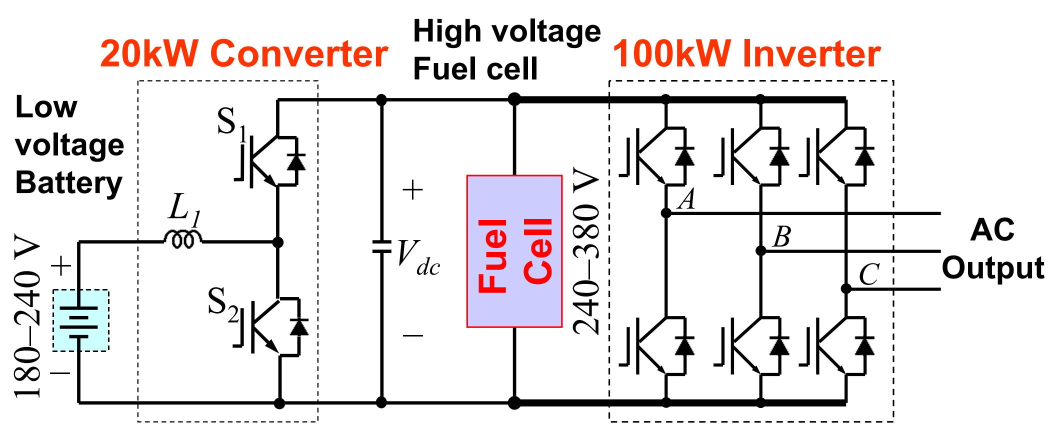
Dual-Source Energy Management Using a Unidirectional Boost Converter



- Battery voltage > Fuel cell voltage
- Simple boost converter regulates the battery state of charge
- DC bus voltage is constant

Total power electronics: 80-kW DC/DC + 100-kW DC/AC
Total energy sources: 20-kW battery + 80-kW fuel cell

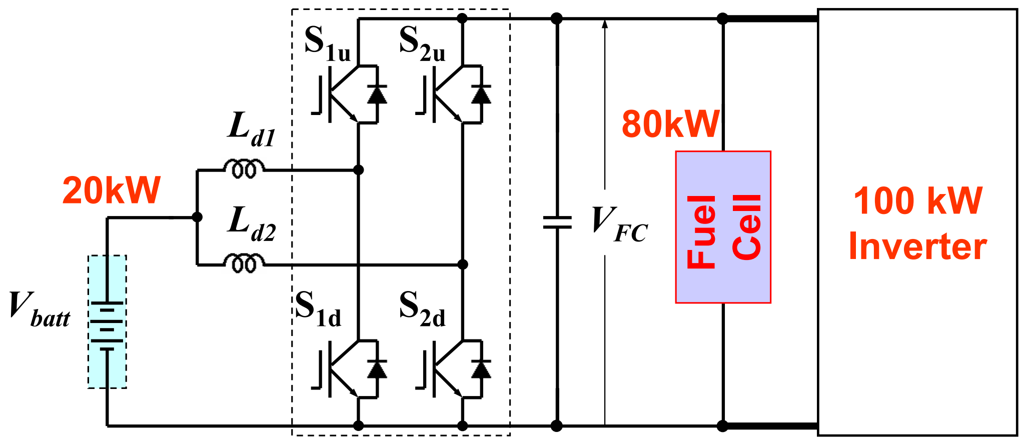
An Example of Dual Sources with a Bidirectional DC-DC Converter



Battery voltage < fuel cell voltage ➔ needs a boost converter to supply energy during transient load **and a buck converter** to charge the battery
Fuel cell voltage = dc bus voltage ➔ **not regulated**

- **Total power electronics: 20-kW DC/DC + 100-kW DC/AC**
- **Total energy sources: 20-kW battery + 80-kW fuel cell**

Interleaved Bidirectional DC/DC Converter for Fuel Cell Energy Management

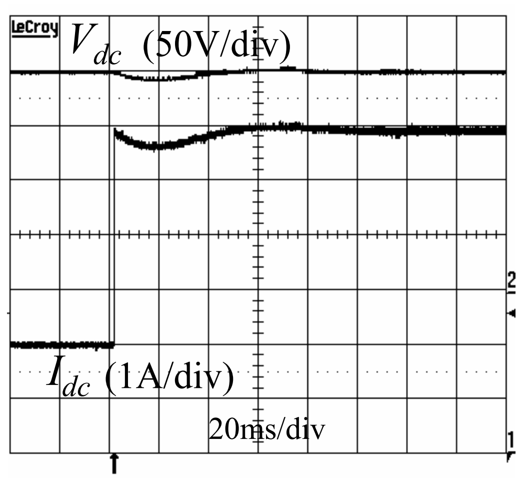


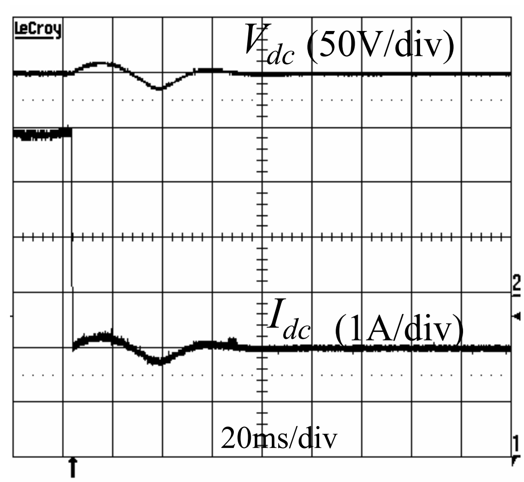
Interleaved operation for both boost and buck modes ➔

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

- **Total power electronics: 20-kW DC/DC + 100-kW DC/AC**
- **Total energy sources: 20-kW battery + 80-kW fuel cell**

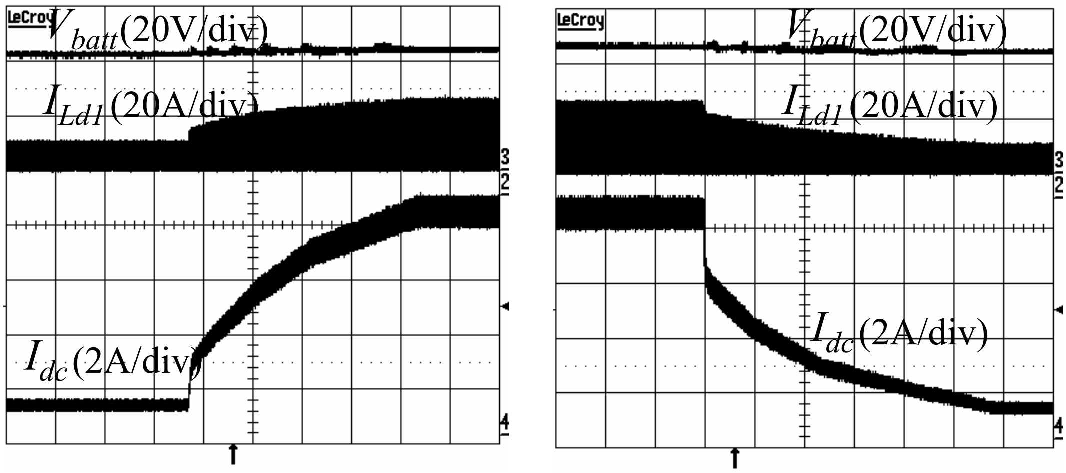
DC Bus Voltage During 800-W Load Step and Load Dump Under Boost Mode Operation





DC bus voltage fluctuates but returns to original setting after load transients

Battery Voltage During 800-W Battery Charge Command Step under Buck Mode Operation

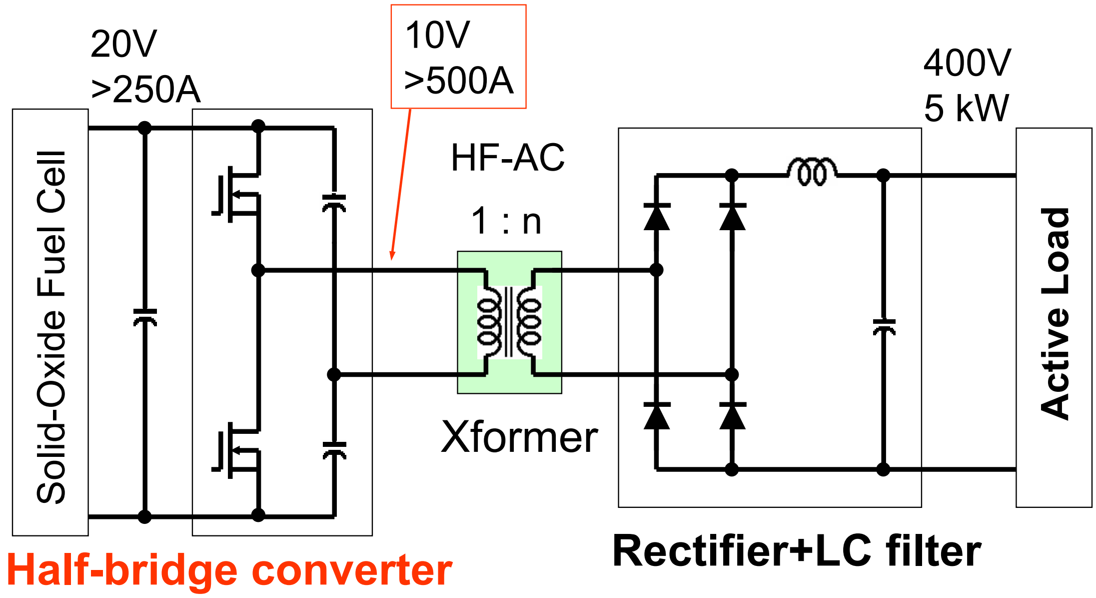


Battery voltage keeps constant during severe charging and discharging current conditions

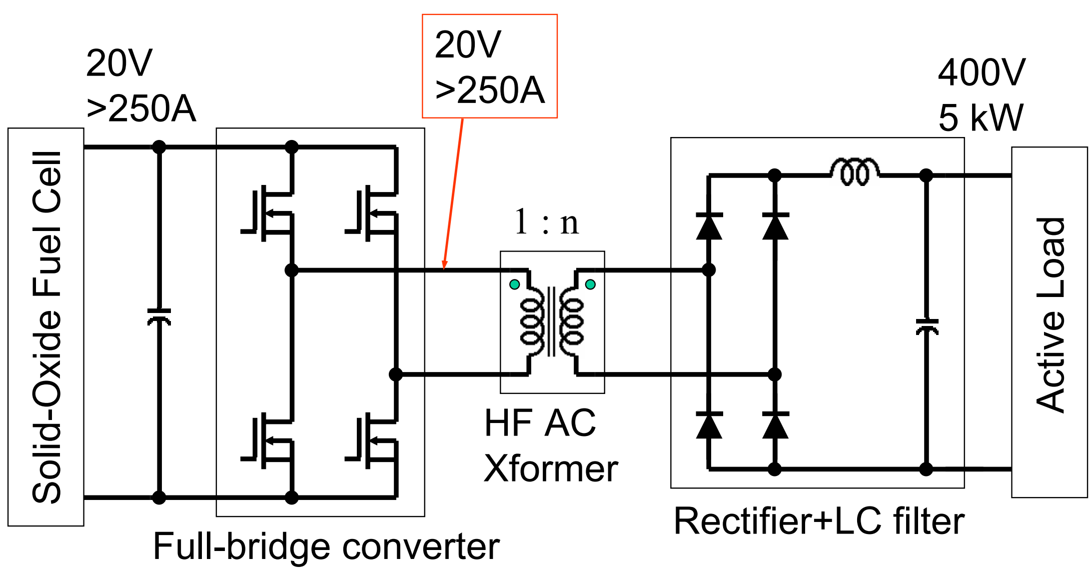
8. Advanced V6 Converter

- **Single-Phase Half-Bridge Converter**
- **Two-Phase Full-bridge Converter**
- **Three-Phase Converter**
- **V6 Converter**
- **Test Results with V6 Converter**
- **V6 Converter Prototype**

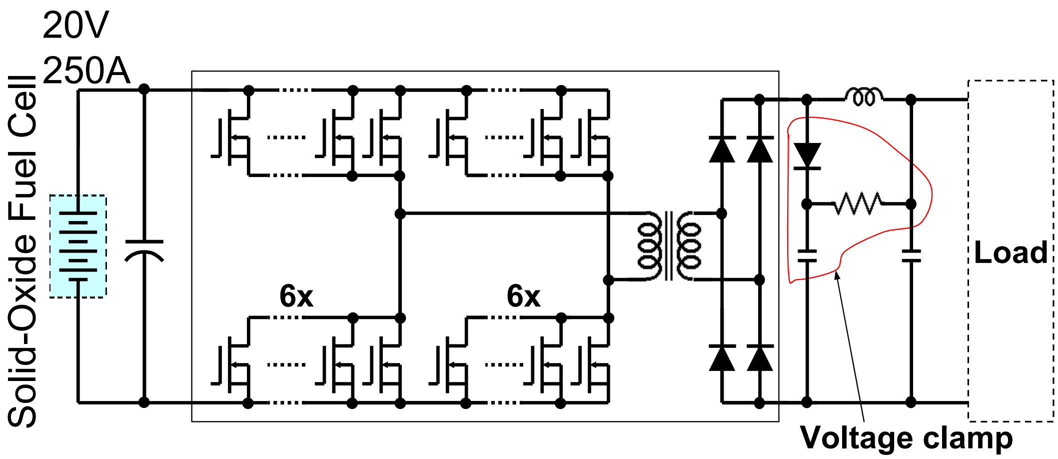
Half-Bridge Converter – A Single-Phase Converter



Full-Bridge Converter – A Two-Phase Converter

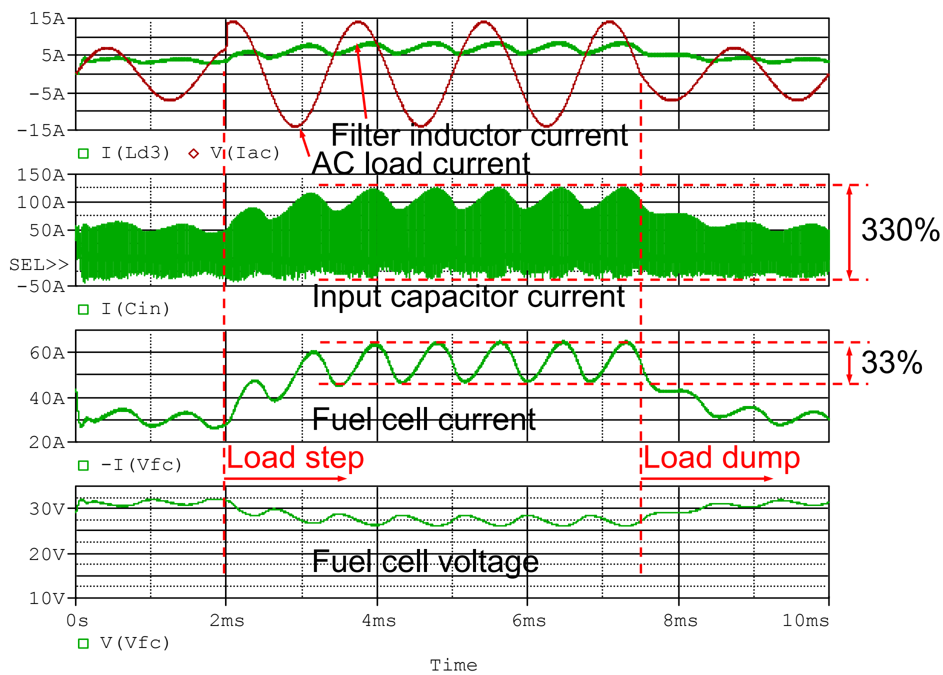


Full-Bridge Converter with Paralleled Devices to Achieve Desired Power Levels

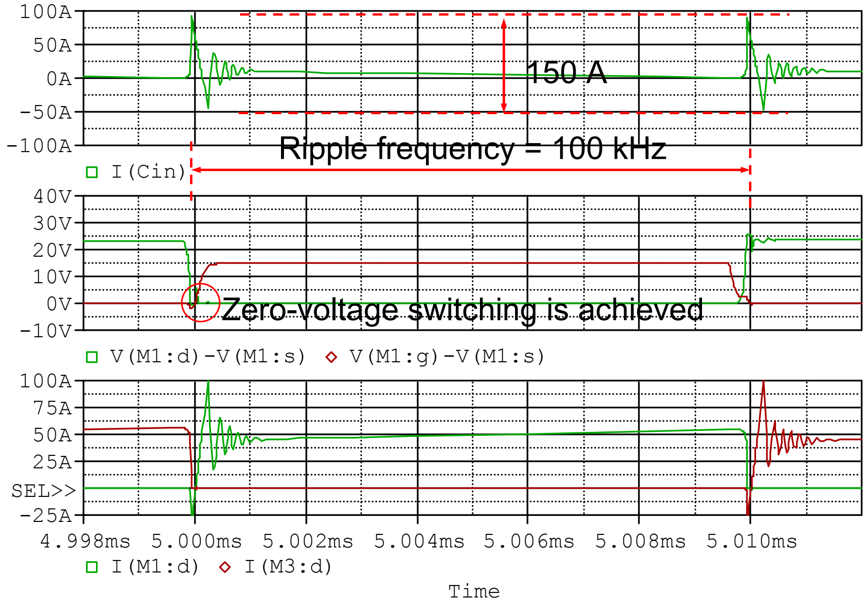


- **With 6 devices in parallel, the two-leg converter can barely achieve 95% efficiency**
- **Problems are additional losses in parasitic components, voltage clamp, interconnects, filter inductor, transformer, diodes, etc.**

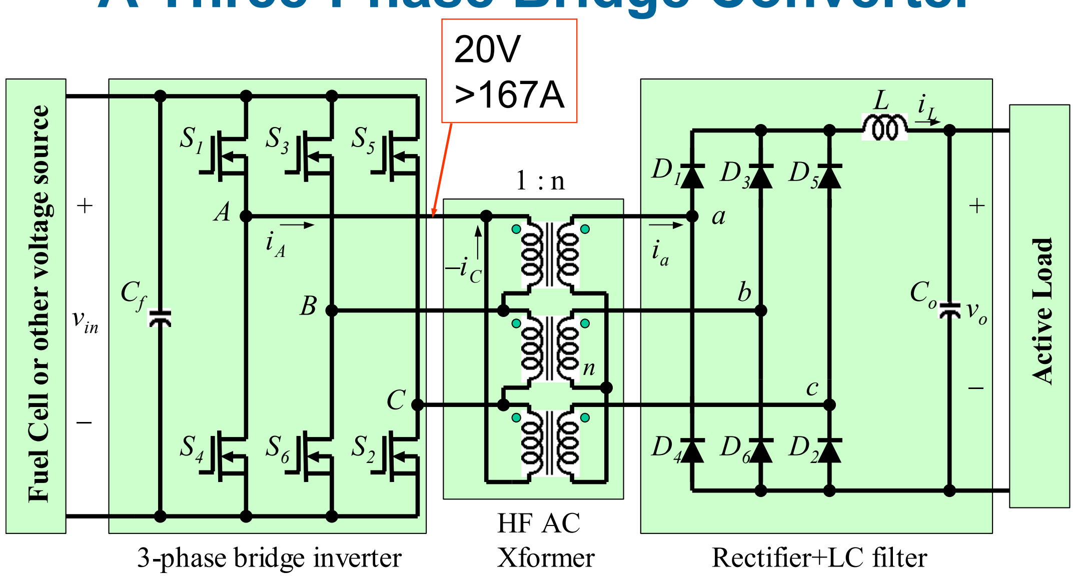
Fuel Cell Voltage and Current with Full Bridge Converter Case



Switching Waveforms with Full-Bridge Converter

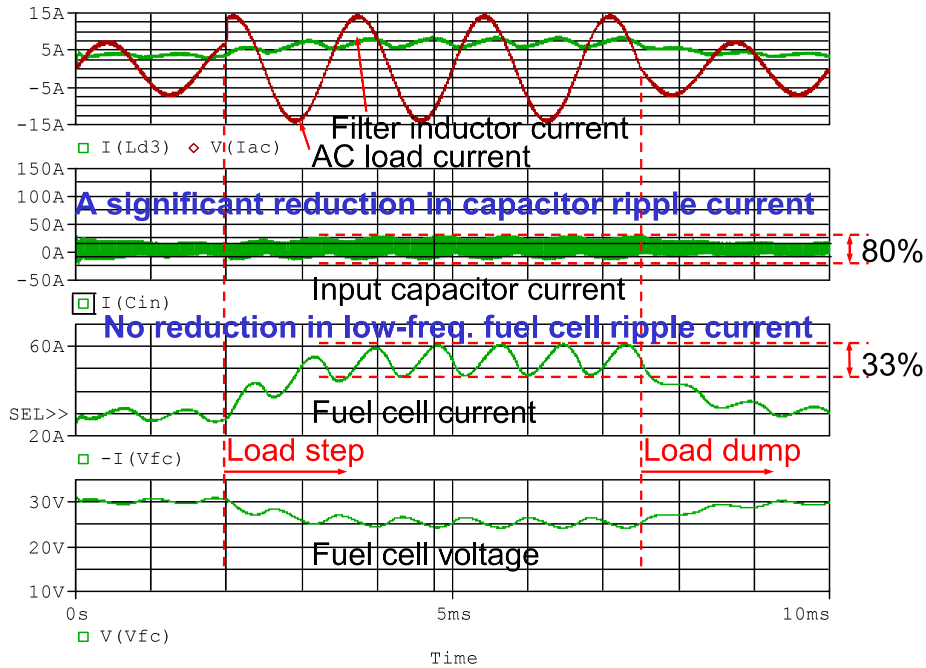


A Three-Phase Bridge Converter

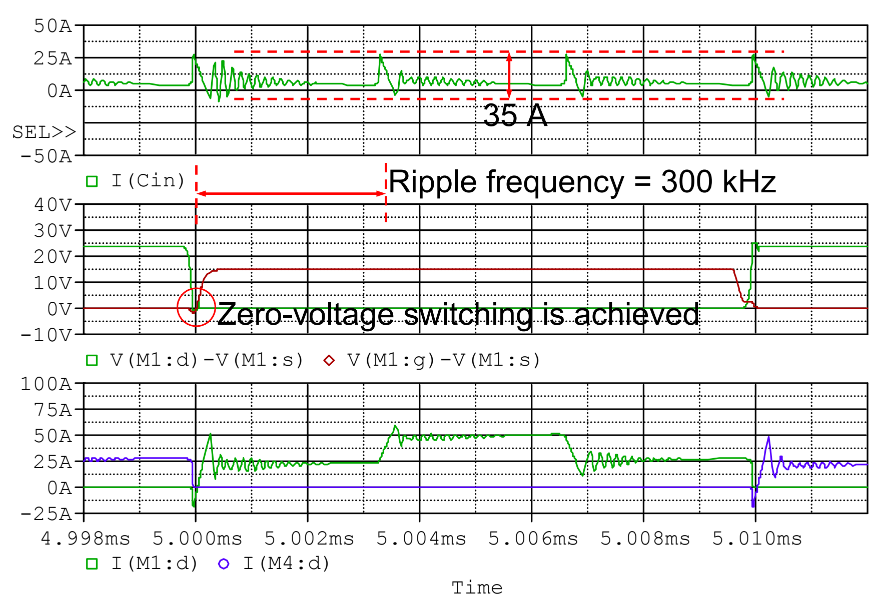


- **Hard switching**
- **With 4 devices in parallel per switch**
- **Efficiency ≈ 95%**

Fuel Cell Voltage and Current with 3-Phase Bridge Converter Case



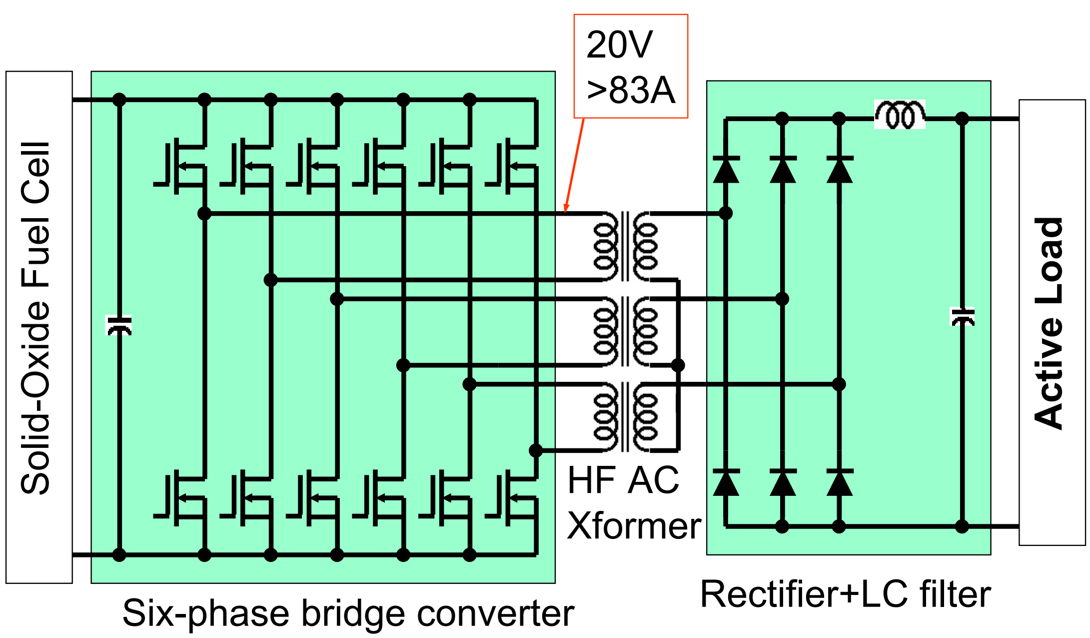
Switching Waveforms with 3-Phase Bridge Converter



Key Features of Multiphase Converter

- Device is switched at a lower current, while maintaining zero-voltage switching.
- High-frequency capacitor ripple current is reduced by >4x, and its frequency is increased by 3x. This translates to significant capacitor size reduction and cost saving.
- No effect on low-frequency AC current ripple, which remains an issue to be solved.

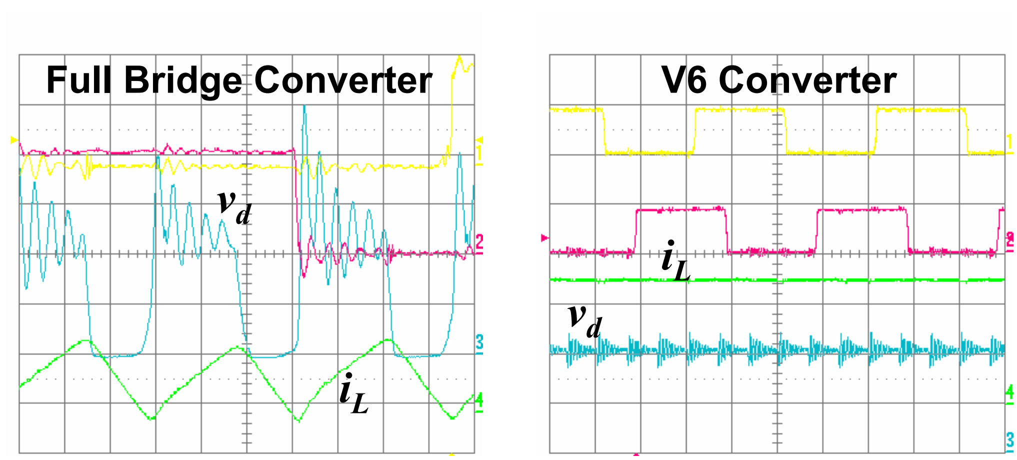
Circuit Diagram of the Virginia Tech V6 Converter



Key Features of V6 Converter

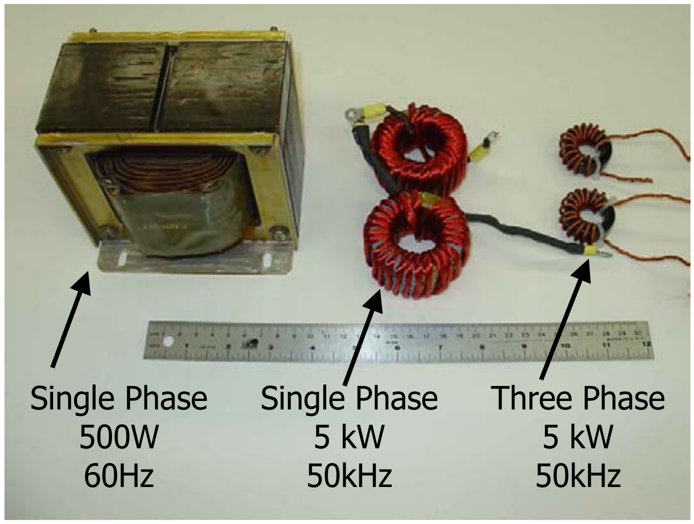
- Double output voltage ➔ reduce turns ratio and associated leakage inductance
- No overshoot and ringing on primary side device voltage
- Input side high-frequency ripple current elimination ➔ cost and size reduction on high-frequency capacitor
- Output DC link inductor current ripple elimination ➔ 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

Waveform Comparison between Full-Bridge and V6 Converters



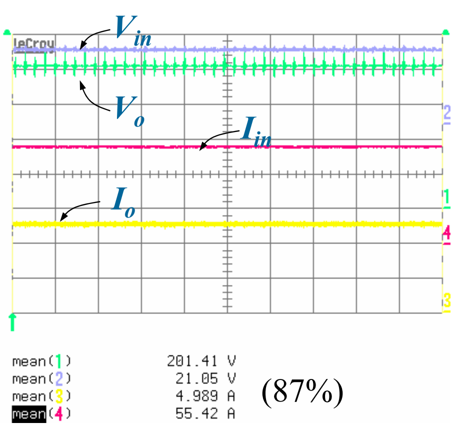
- Secondary inductor current is ripple-less; and in principle, no dc link inductor is needed
- Secondary voltage swing is eliminated with <40% voltage overshoot as compared to 250%

Significant DC link Inductor Size Reduction

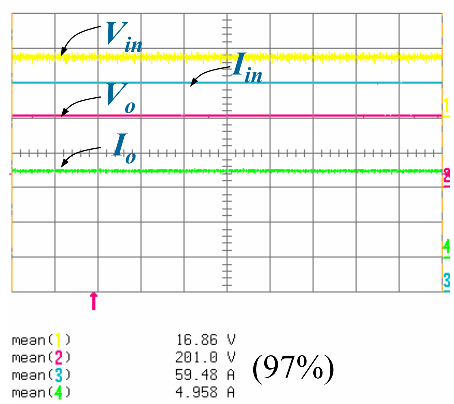


With V6 converter, an effective 10x reduction in DC link filter inductor in terms of cost, size and weight

Input and Output Voltages and Currents at 1kW Output Condition



(a) Full bridge converter



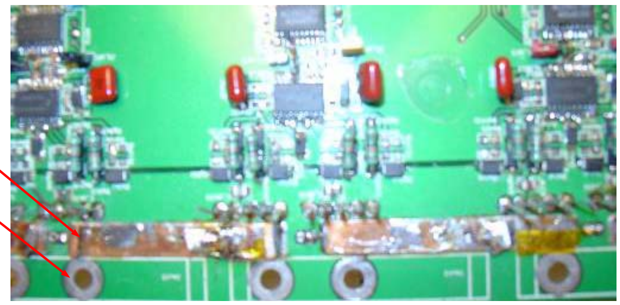
(b) V6 Converter

Significant improvement with V6 converter

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

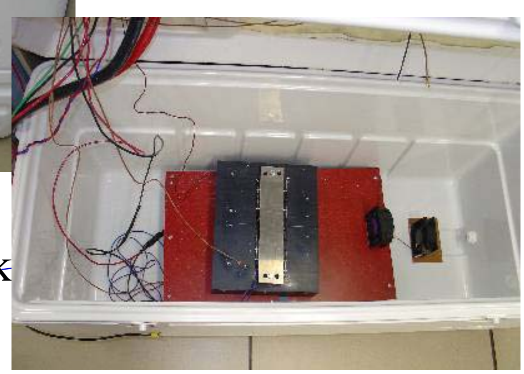
Where are the Losses?

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

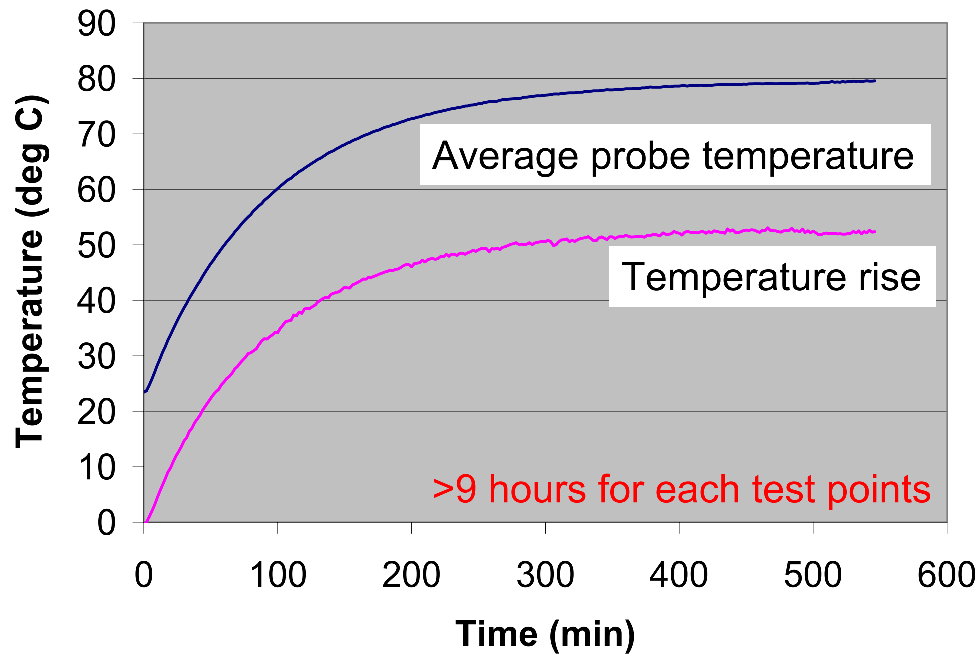


Calorimetry for Accurate Loss Measurement

Calibration with resistor bank

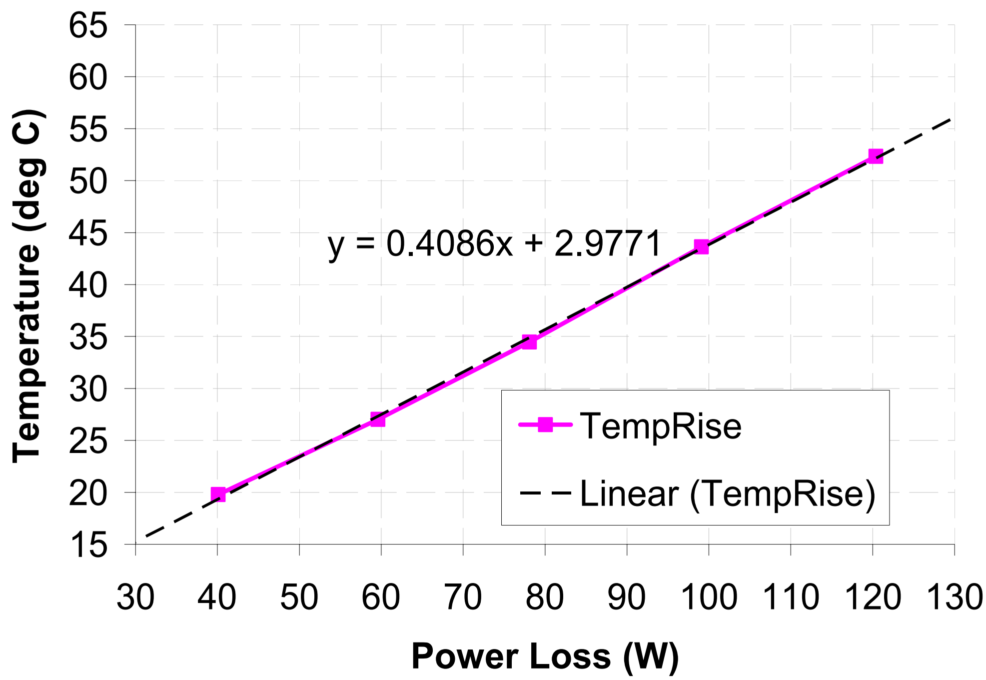


Test the 160-Liter Calorimeter at 120-W Loss Condition

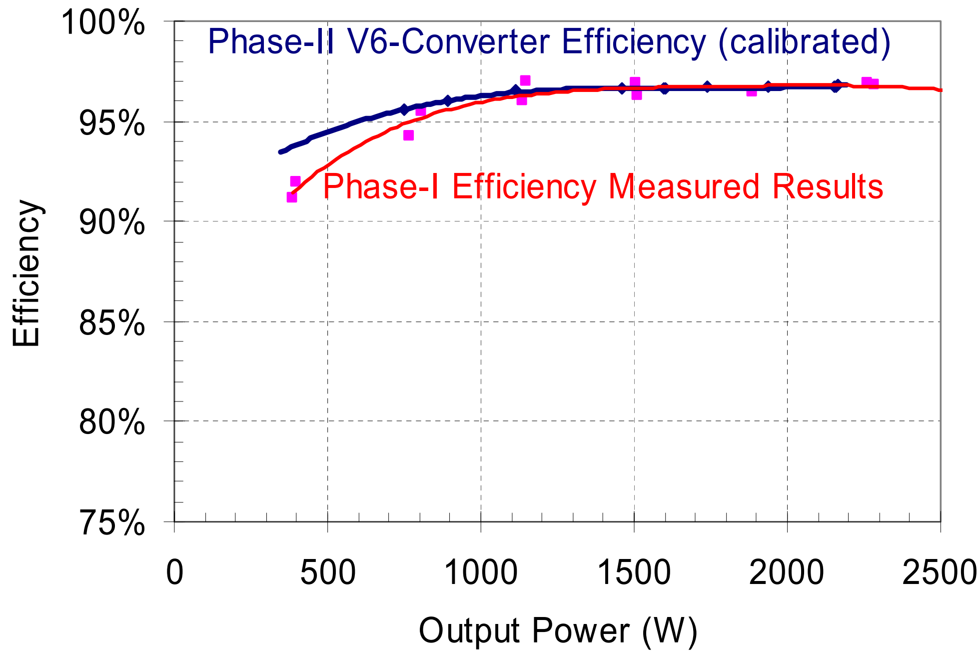


Future Energy Electronics Center

Temperature Rise Versus Power Loss



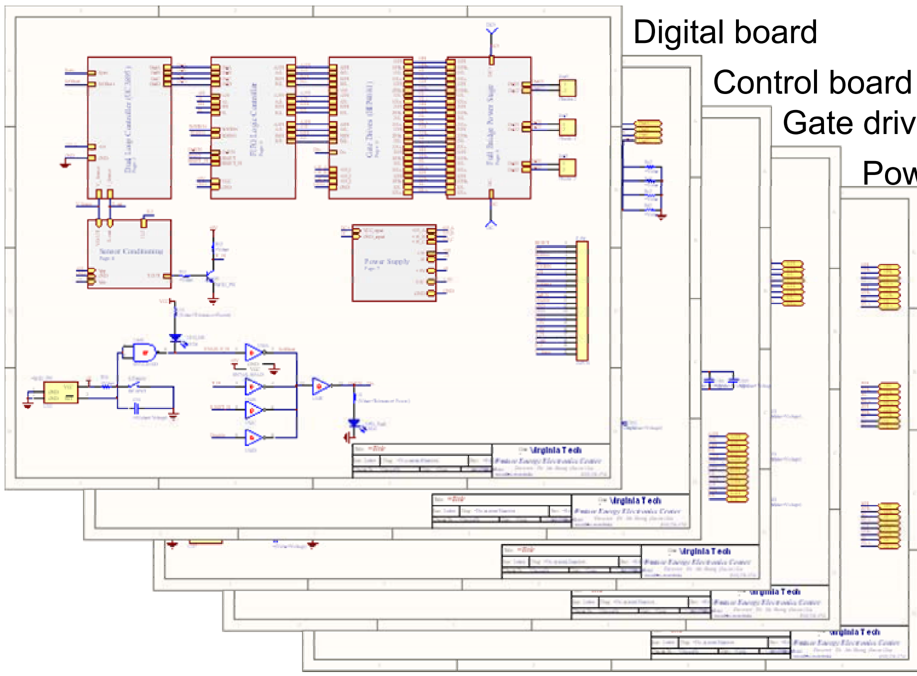
Efficiency Measurement Results



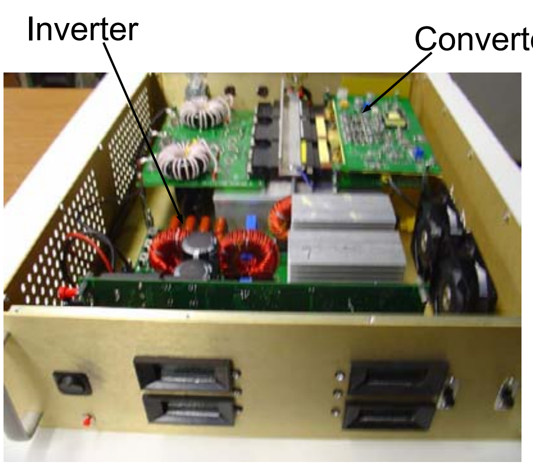
The Beta Version Prototype Converter

- Schematic Circuit Diagrams
- V6 Cost Estimate
- Summary of Beta Version Prototype

Schematic Circuit Diagrams



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



Front View

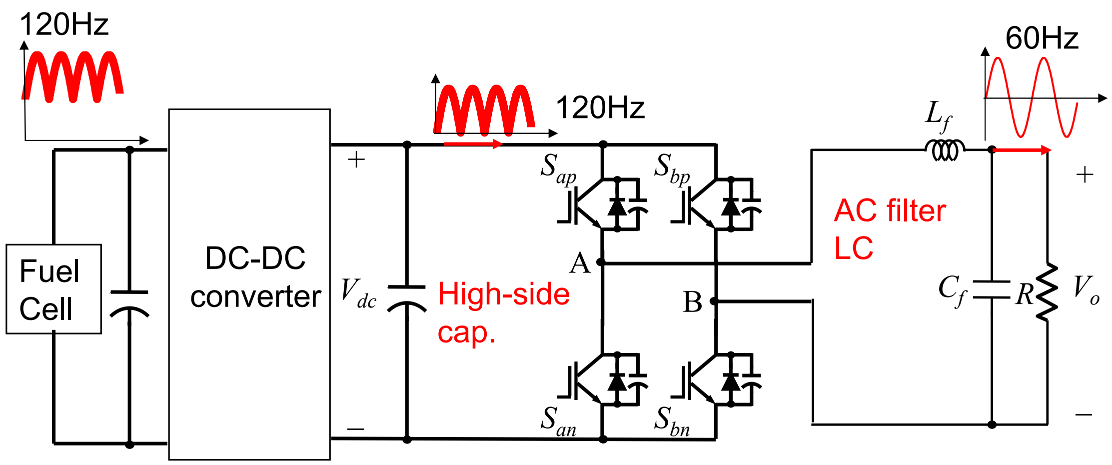
Rear View

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

9. Fuel Cell Current Ripple Issues

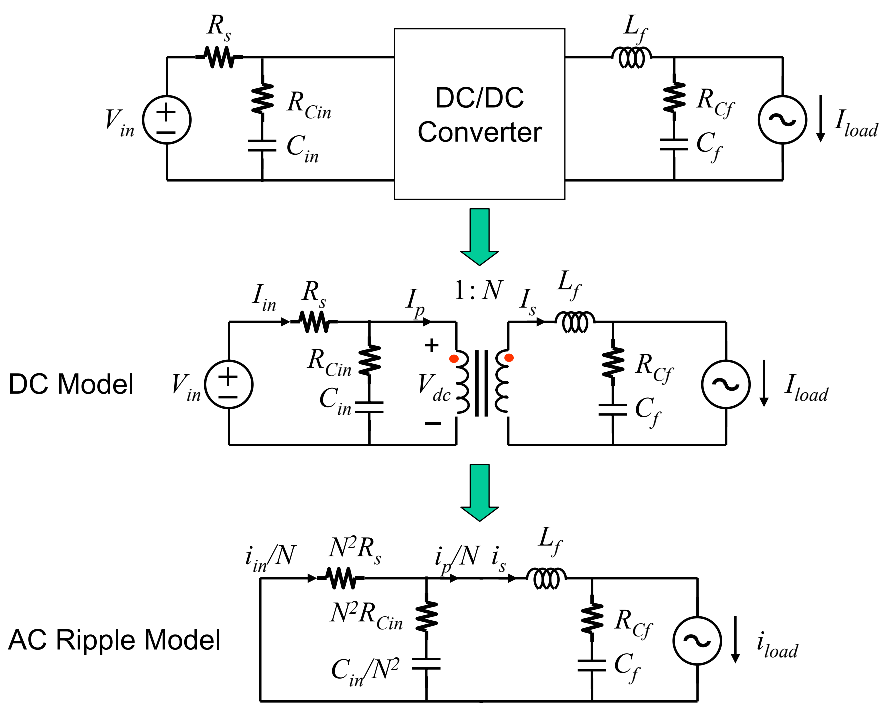


- **Current ripple propagates from AC load back to DC side**
- **With rectification, ripple frequency is 120 Hz for 60 Hz systems**
- **Low-frequency ripple is difficult to be filtered unless capacitor is large enough**

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



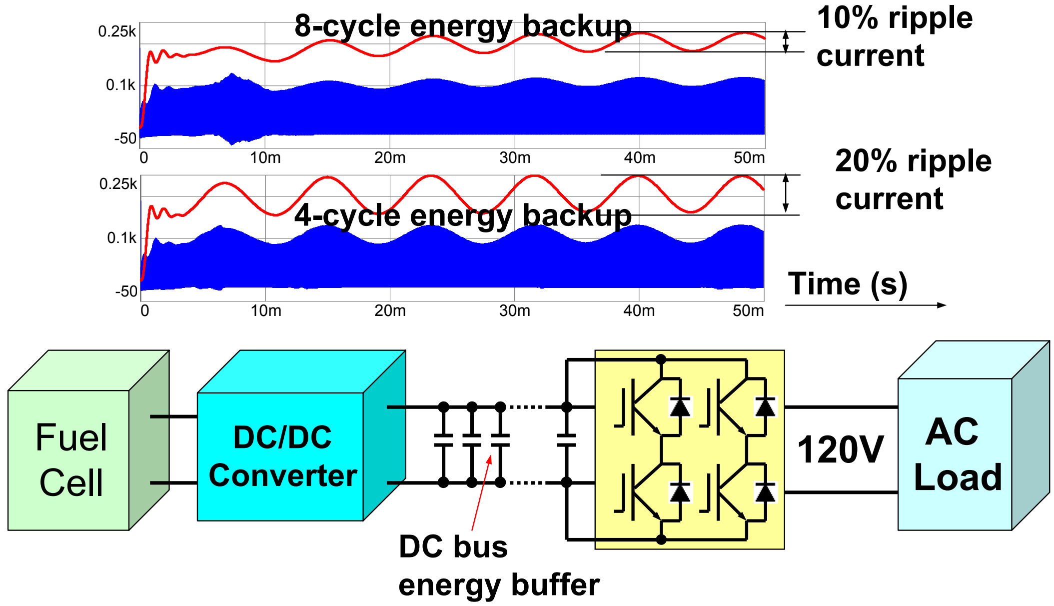
Solutions to Ripple Currents

- Add more capacitors (ultra capacitor) on the low-side dc bus
- Add more capacitors on the high-side dc bus
- Add one more stage DC-DC converter
- Add an active ripple cancellation circuit
  - with a bidirectional DC-DC converter to stabilize the high-side dc bus voltage
  - with a built-in control function in the DC-DC converter

Benchmark DC/DC Converter Parameters for Ripple Study

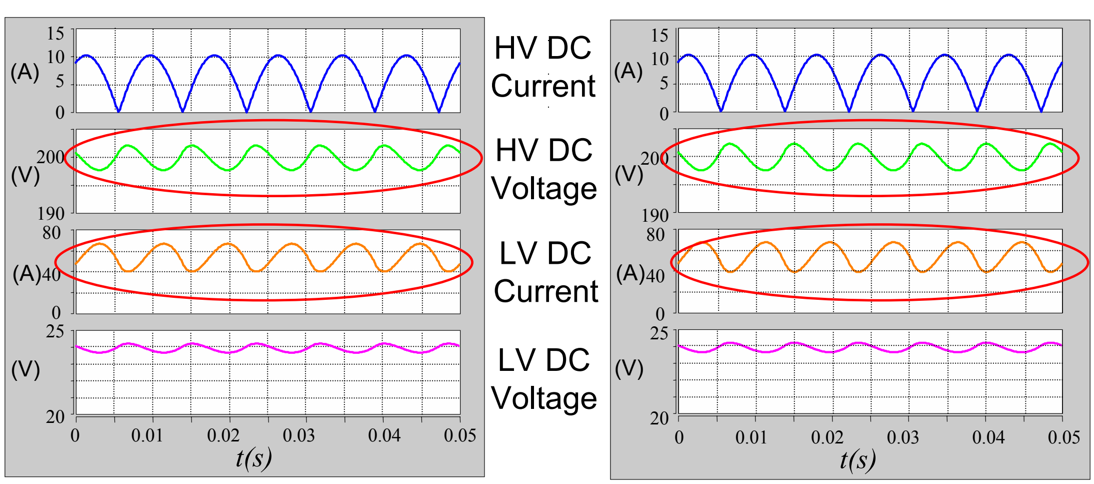
- Input Voltage: 25V
- Output Voltage: 200V
- Input DC Capacitor: 6mF
- Output DC Capacitor: 2200mF
- Filter Inductor: 84mH
- Inverter Modulation Index: 0.86
- Inverter Load Resistor: 16.7Ω

Adding Hide-Side Energy Storages on DC Bus Helps Reduce Ripple Current



Simulation Results with LV-Side Capacitor

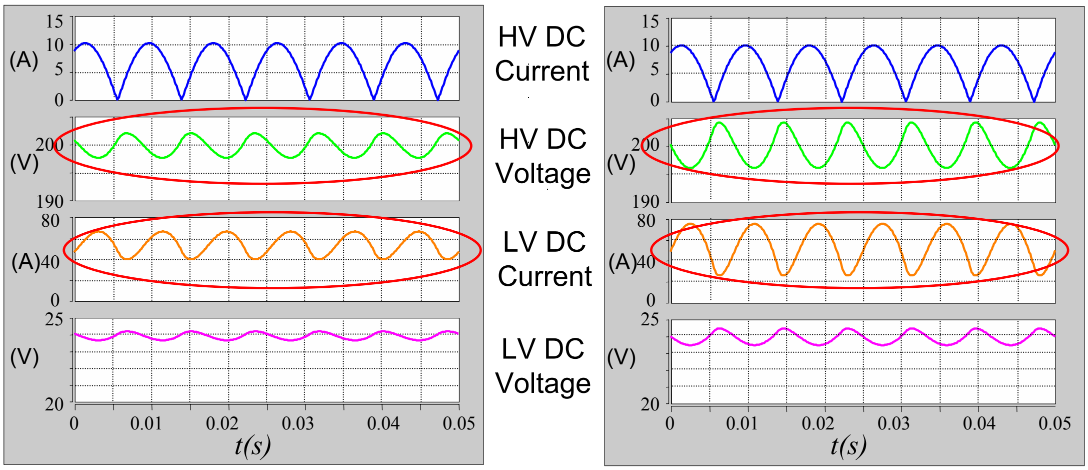
Input Capacitor has Very Little Effect to Current Ripple Reduction



Input Cap 6mF

Input Cap Reduced to 136µF

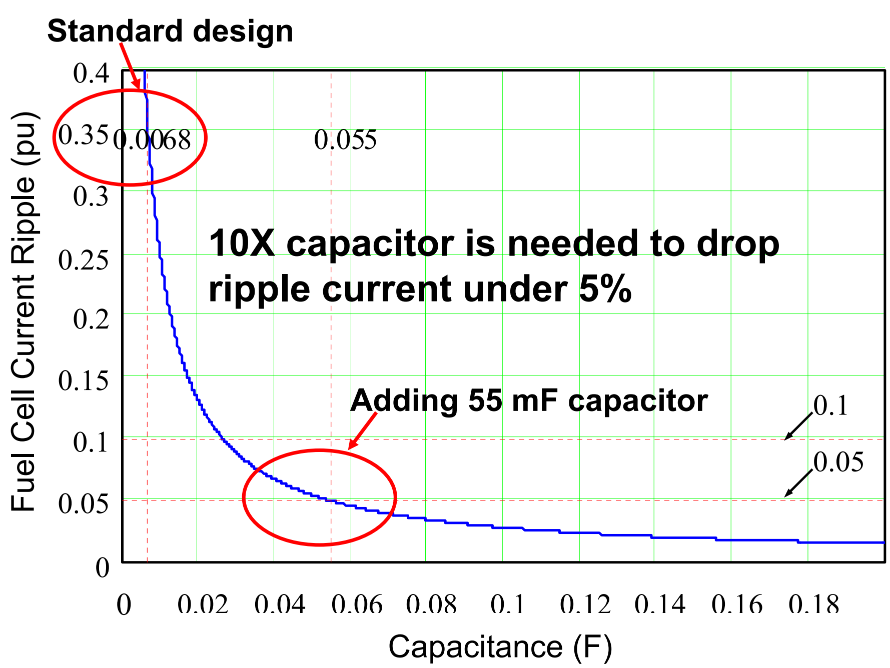
Output Capacitor can be Used as Passive Solution to Current Ripple Reduction – Cost is a Concern



Output Cap 2.2mF

Output Cap Reduced to 820μF

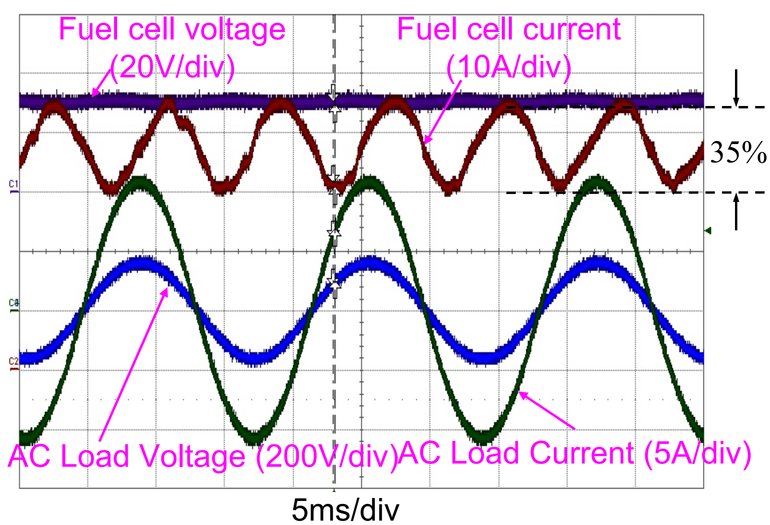
Current Ripple Reduction with High-Side Energy Storage Capacitor



Features of High-Voltage DC Bus Energy Storage Capacitors

- Fuel cell voltage is low, typically from 36 to 60 V.
- High voltage dc bus voltage is split into two 200 V.
- For a single-phase dual ac outputs such as 120/240 V in US residential systems, the transformer secondary and dc bus can be split in two halves. Each phase leg of the full-bridge along with the split-capacitors becomes a half-bridge inverter to supply 120 V ac output. Summing two 120 V outputs becomes 240 V.
- Multiple capacitors are paralleled for the high-voltage dc bus to store more energy and to provide more transient handling capability during dynamic load change conditions. Energy storage is proportional to CV2.
- Size and weight are dominated by passive components. With split DC buses, the volume of energy storage capacitors becomes an issue.

Experimental Current Ripples without Adding Capacitors or Controls

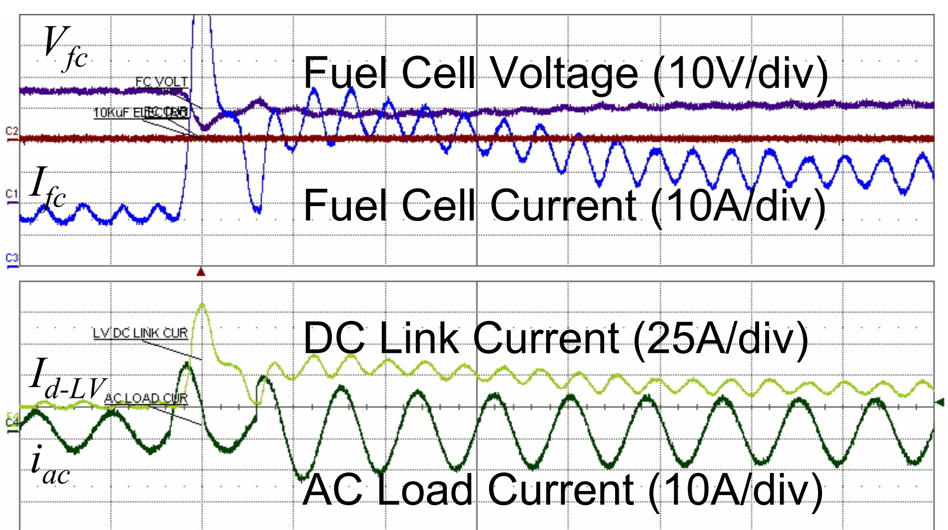


More than 35% ripple current at the input

Fuel Cell Ripple Current Problem is Severe During Load Transients

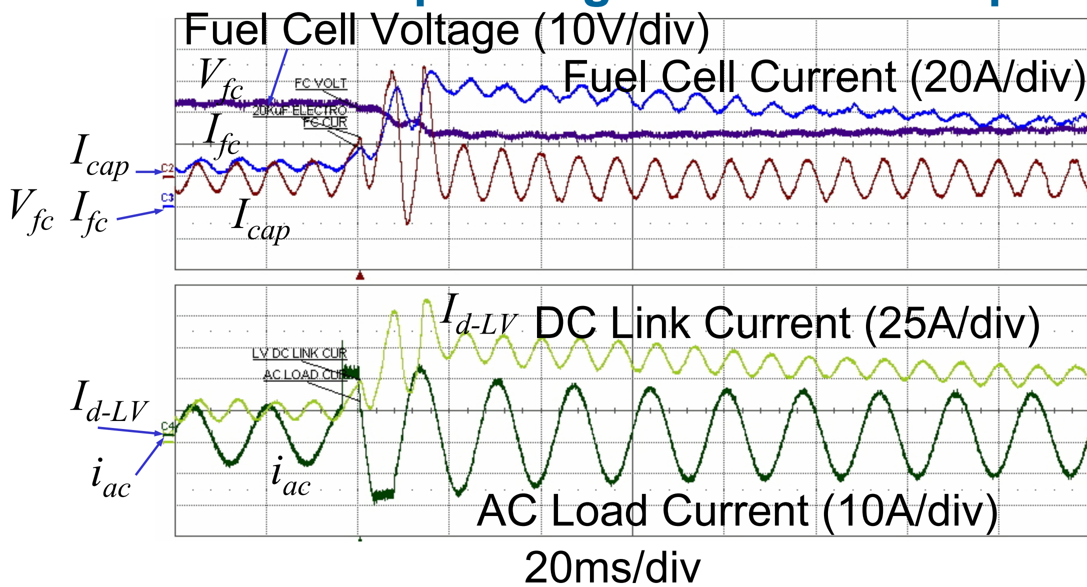
- **For single-phase ac loads, 120 Hz (twice the fundamental frequency) current ripple can reflect back to fuel cell.**
- **During load transients such as turning on light bulbs or starting up motors, the transient initial current is typically more than 5 times the steady-state current, and the fuel cell ripple current exceeds more 100% or even 200% in some cases.**

Fuel Cell Responds to AC Load Steps (without Externally Added Capacitor)



Fuel cell sees severe current transient (spike) and current ripple in steady state (35%)

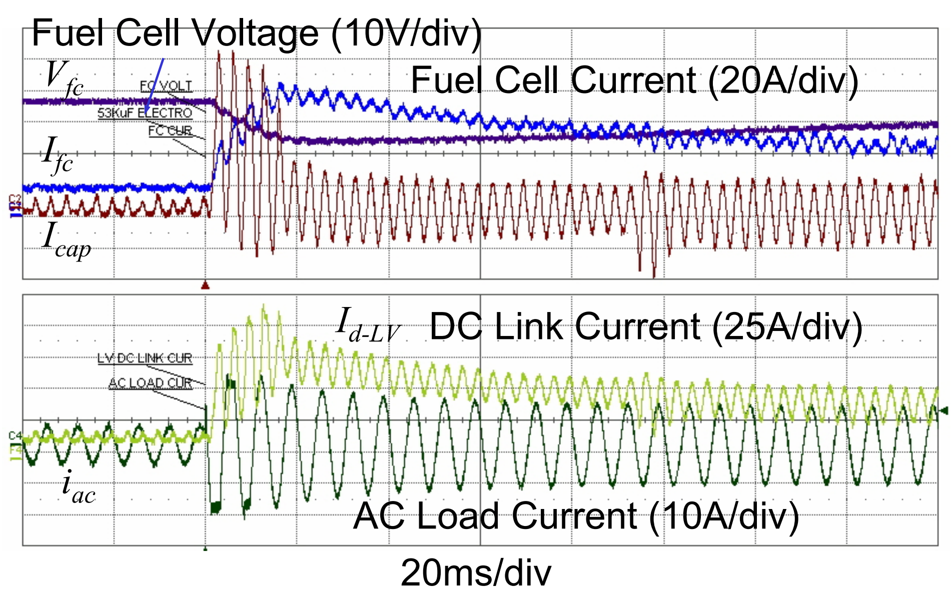
Using Electrolytic Capacitor to Smooth Fuel Cell Responding to AC Load Steps



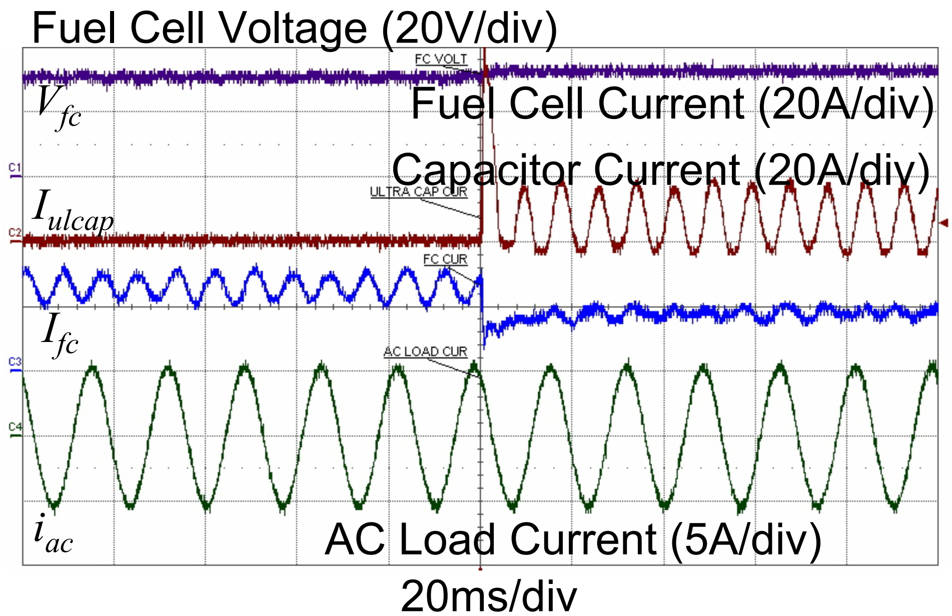
With 20 mF capacitor, fuel cell current transient is reduced, but the current ripple remains

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

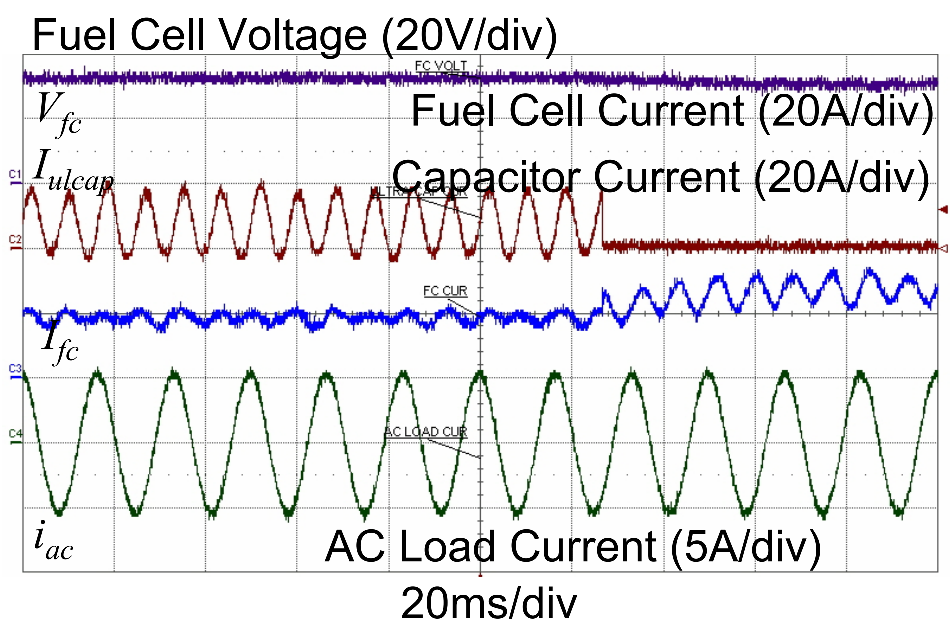
Fuel Cell Current Ripple is 5% plus Overshoot



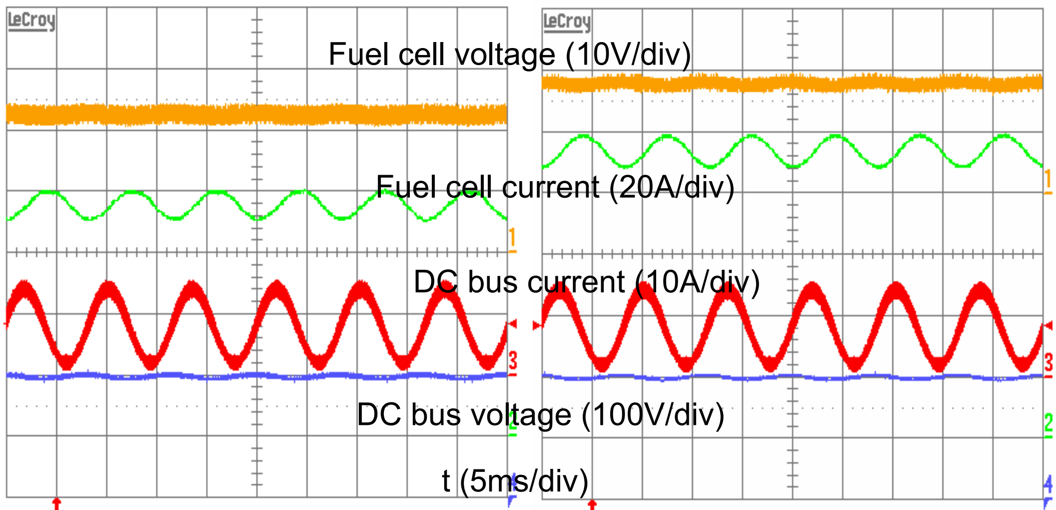
Fuel Cell Output Response with an Ultra Capacitor Cut-in



Fuel Cell Output Response with an Ultra Capacitor Dropout



Experiment with Open-Loop and with only Voltage Loop Control

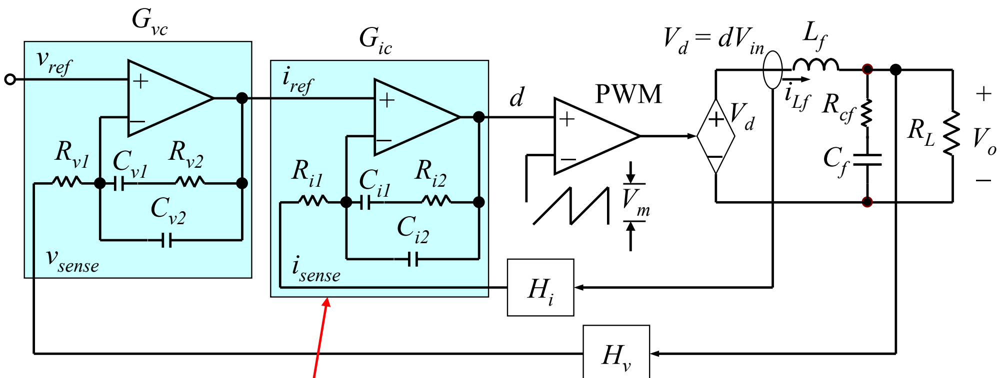


(a) Open loop

(b) With voltage loop control

No improvement on current ripple reduction with voltage loop control

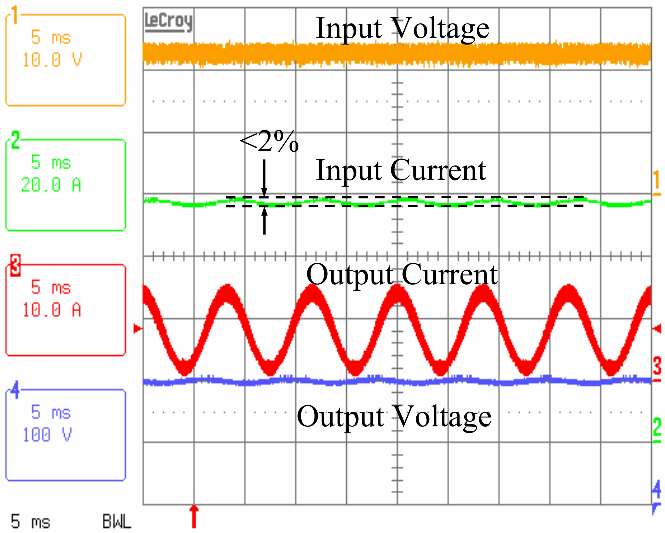
Solving Current Ripple with Added Current Loop inside the Voltage Loop



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 with Active Ripple Cancellation

- 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 SOFC design
  - Stack size reduction by efficient power conversion and ripple reduction: 20%
  - Inrush current reduction for reliability enhancement

10. Recap

1. Basic DC-DC converters and DC-AC inverters are introduced
2. Circuit topology selection can be misled by schematic diagram. Some important considerations are
   - Device voltage and current stresses
   - Number of paralleled devices
   - Parasitic components and losses
3. Advanced V6 DC-DC converter not only shows superior performance but also low production cost
4. Fuel cell current ripple issue can now be solved with advanced current control developed by Virginia Tech without adding cost penalty