Electric Vehicles and Power Electronics

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Outline of Presentation

- **Part A: Background and Introduction**
  - What are Electric Vehicles?
  - Why Electric Vehicles?
  - Partnership for Next Generation Vehicles
- **Part B: Overview of EV/HEVs on the Market**
  - GM EV1
  - Ford Ranger
  - Honda EVPlus, Insight
  - Toyota Prius
  - Ford P2000
- **Part C: Power Electronic Technologies in EV/HEV**
  - Energy Sources
  - Traction Motors/Inverters
  - Auxiliary Motors/Inverters
  - Bi-directional Chargers
  - Basic Structure of a Fuel Cell Vehicle

Part A: Background and Introduction

- **What are Electric Vehicles?**
- **Why Electric Vehicles?**
- **Partnership for a New Generation of Vehicles**
- **Specification of “Supercar”**
- **EV/HEV Configurations**

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EV/HEV Definitions

- **An Electric Vehicle is**

  A vehicle fueled with mains electricity. An EV usually requires a battery pack as energy storage.

- **A Hybrid Vehicle is**

  A chemically fueled vehicle equipped with at least one bi-directional energy reservoir. The fueled hybrid power unit (HPU) is usually a heat engine, but may be a fuel cell. Energy storage and delivery is usually electric.

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Driving Forces for EV/HEV

- ✓ Simplicity (1910)
- ✓ Energy Security (1970)
- ✓ Environmental Concerns (1990)
- ✓ Customer Expectations (2000)

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US Customer Expectations for EV/HEVs

✓ Range:	Minimum 160 km/charge
✓ Safety:	Same as ICE Vehicles
✓ Performance:	Same as ICE Vehicles
✓ Cost:	No more than ICE vehicles
✓ Features:	No less than ICE vehicles

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Partnership for a New Generation of Vehicles

Technology Areas

- **Hybrid/electric vehicle drive trains**
- **Direct-injection engines**
- **Fuel cells**
- **Lightweight materials**

LONG-TERM GOAL – Development of a Supercar

- **Gas mileage: 3X average of Concorde/Taurus/Lumina, or 80 mpg**
- **Load: Six passengers + 200 pounds of luggage**
- **Range: Similar to today's models**
- **At least 80 percent recyclable**

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Specifications of Baseline Vehicle and Supercar

	Baseline	Supercar
Curb Weight	3200 lbs	40% less
Drag coeff.	0.32	0.20
Friction:	0.005	0.008
Engine:	Internal Combustion	flywheel, battery, ultracapacitor
Fuel Efficiency:	26.6 mpg	80 mpg (3X)
Recycleability:	75%	80%
Range (HWY):	380 miles	same or better
Accel (0-62 mi):	12 seconds	same or better
Luggage:	168 ft^3	same or better
Load:	6 passengers + 200 lb	same or better
Life:	100,000 miles	same or better

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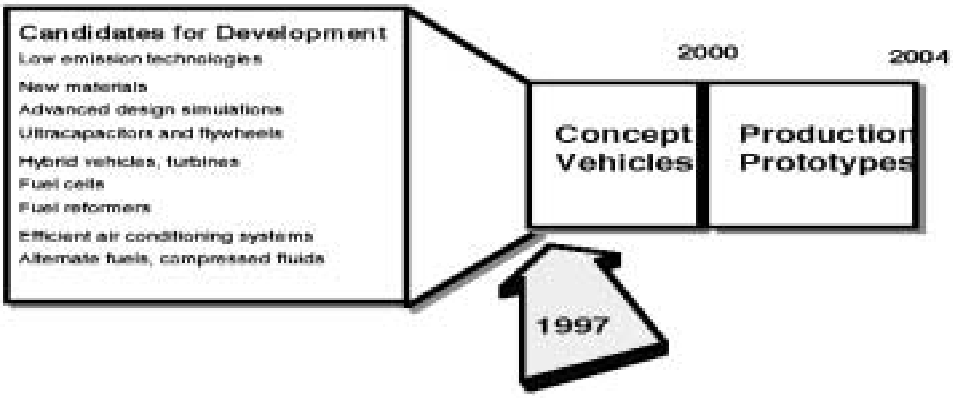
PNGV Time Table



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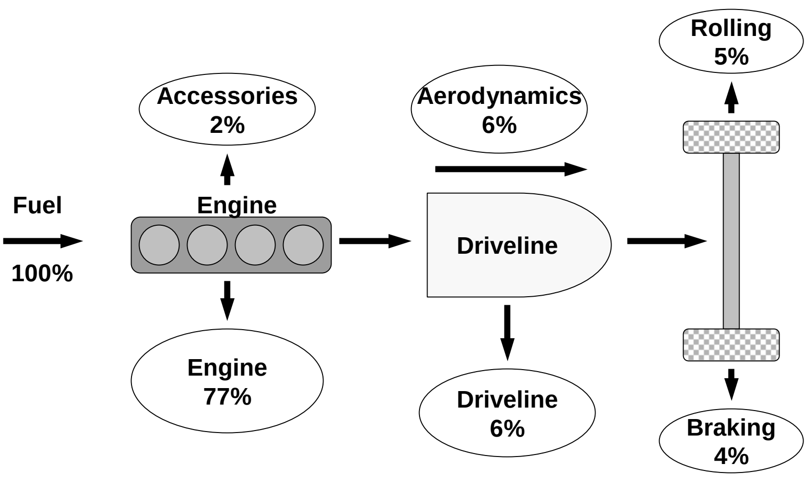
Where are the Energy Goes in a Conventional Car? For Metro-Highway Driving Cycle



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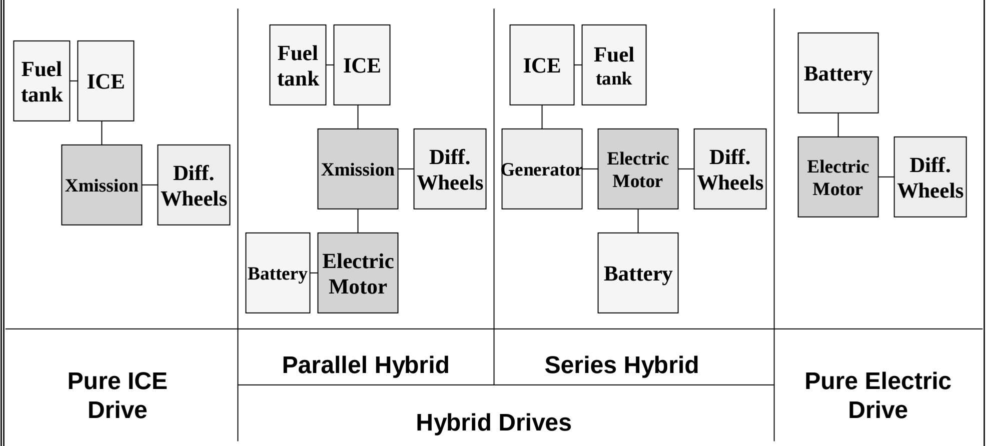
Electric/Hybrid Electric Vehicle Configurations



ICE: Internal Combustion Engine
Xmission: Transmission
Diff.: Differential gear

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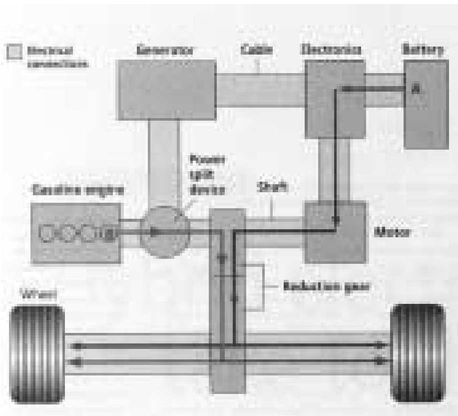
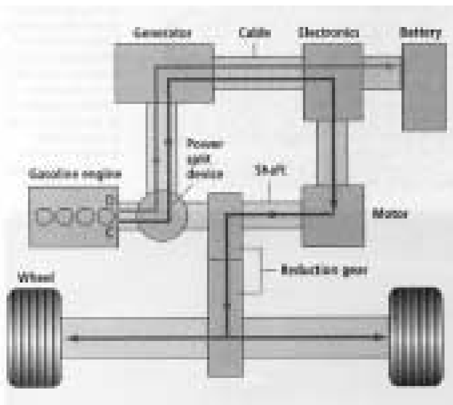
How Does a Hybrid Electric Vehicle Work?



(a) Shaft driven by both ICE and electric motor



(b) Shaft driven by electric motor and battery is charged

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Part B: Overview of EVs on the Market

- GM EV1
- Ford Ecostar, Ranger
- Honda EVPlus, Insight
- Toyata Prius
- Ford P2000

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General Motor EV1

Price:	$33,995 MSRP
Lease:	$424 - $574 / mo 36-month lease $0.20/mile over 30,000 miles

http://www.gmev.com/index.htm

Power:	137 hp
Top speed:	80 miles per hour
Drag coeff.:	0.19
Acceleration:	0 to 60 miles, less than 9 seconds
Range:	55 to 95 miles with 26 lead-acid battery pack 75 to 130 miles with Nickel-Metal Hydride (NiMH) battery pack
Charging:	220 V, 6.6 kW non-contact inductive charging, 6 hours
Braking:	front disk, rear drum, and regenerative

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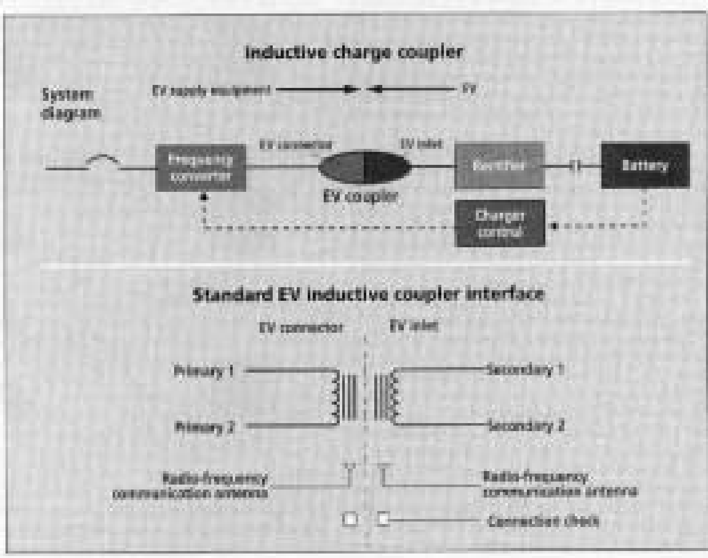
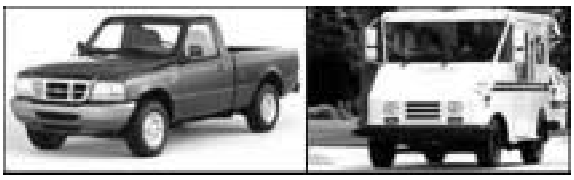
GM Inductive Charge Coupler



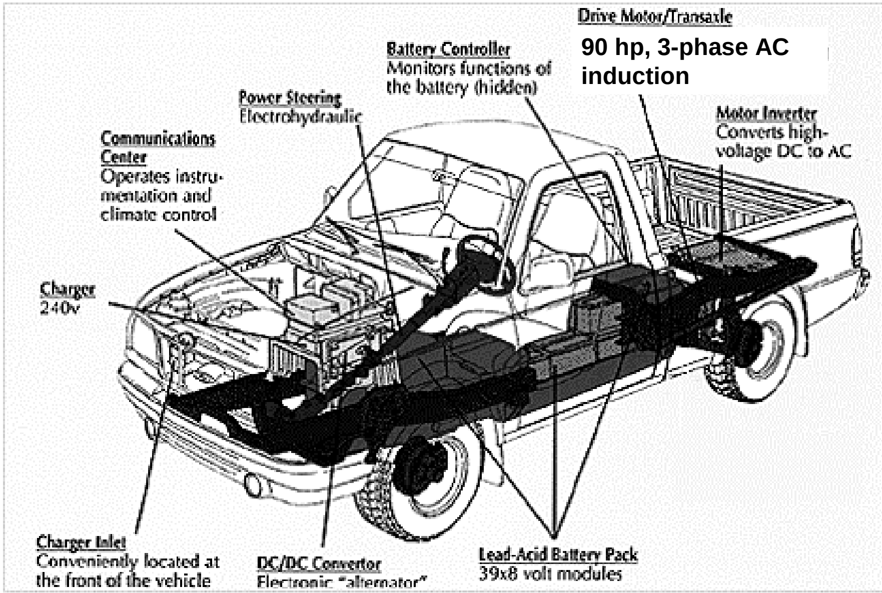
Ford Ranger and US Post Office Electric Vehicles



Battery:
- **Fourth generation "sealed lead acid"**
- **39x8 volt modules; 312 volt system**
- **Capacity rating @ FUDS:** **23 kWh (18 kWh at 80% discharge)**
- **On-board Charger:** **On-board, 240 V/30 A**

Performance:
- **0-50 mph acceleration:** **13 seconds**
- **Rated top speed (governed) :** **75 mph**
- **Customer range @ 72F:** **50 miles**
- **Range - FUDS cycle @ 72F:** **58 miles without A/C or heater operation**

Ford Ranger Schematic



Honda EVPlus

New Technology Features

- Nickel-metal hydride batteries
- Permanent-magnet motor
- Single-speed, direct-drive transmission
- Regenerative braking
- On-board charger – 110- or 220-volt
- Heating and air conditioning
- High-intensity headlights

Standard Features

- EPA City: 100 miles; Highway: 84 miles (Use 80% battery capacity)
- Meets all federal motor vehicle safety standards
- Dual airbags and 3-point seat belts
- Anti-lock braking system (ABS)
- Power windows, door locks and mirrors
- AM/FM/CD audio system
- Remote keyless entry and security system
- Cargo area with "fold-flat" rear seats
- Walk-in feature for rear seat access

Honda Insight Hybrid Electric Vehicle

Integrated Motor Assist:	**1.0-liter, 3-cylinder gasoline engine + electric motor**
EPA mileage ratings:	**61 mpg city/70 mpg highway**
Driving range:	**600 - 700 miles**
Drag coefficient:	**0.25**
Electric motor:	**36 ft-lb, 10-kW DC-brushless motor, 2.3” wide, sits between the engine and transmission, mounted directly to the engine's crankshaft**
Battery:	**A 144-volt nickel metal-hydride battery pack**
Inverter:	**An advanced electronic Power Control Unit (PCU), adopted from Honda EV PLUS**

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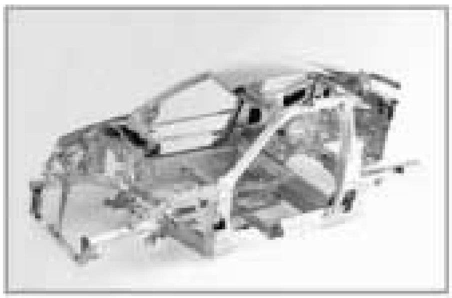
Drivetrain of Honda Insight



Insight's aluminum hybrid body is constructed from extruded aluminum for an ideal balance of light weight, strength and rigidity.

An inside look at Insight's innovative Integrated Motor Assist (IMA) ultra-thin electric motor and 1.0 liter, 3-cylinder VTEC™-E lean-burn gasoline engine.

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Toyota Prius - A Hybrid Vehicle

Engine:	**1.5-liter, DOHC, 16-valve, EFI 4-cylinder with Variable Valve Timing with intelligence (VVT-i)**
Maximum Engine Output:	**58 hp at 4,000 rpm**
Maximum Speed:	**100 mph (engine and motor combined)**
Motor Type:	**permanent magnet, 30 kW/40 hp at 940—2,000 rpm**
Battery Type:	**sealed nickel-metal hydride with 40 modules**
Combined Horsepower:	**58 hp engine + 40 hp motor + 3 hp batteries = 101 hp**
Fuel Efficiency:	**66 mpg (Japanese 10—15 city drive mode)**
Maximum Range:	**850 miles (combined city/highway)**
Regeneration Braking:	**Front disc/rear drum brakes with ABS**

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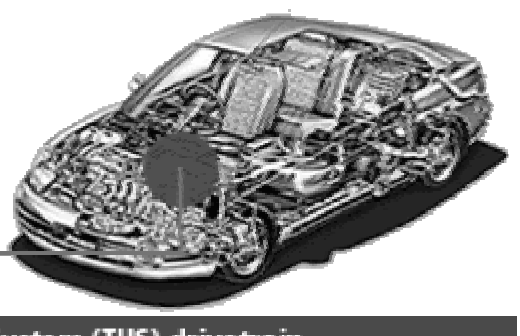
Prius Hybrid Drivetrain



Toyota Hybrid System (THS) drivetrain

The engine, a 1.5-liter, DOHC, 16-valve, EFI 4-cylinder with Variable Valve Timing with intelligence (VVT-i). The motor type, a permanent magnet. They work in tandem, depending on the driving situation, to complement, augment and even defer to one another.

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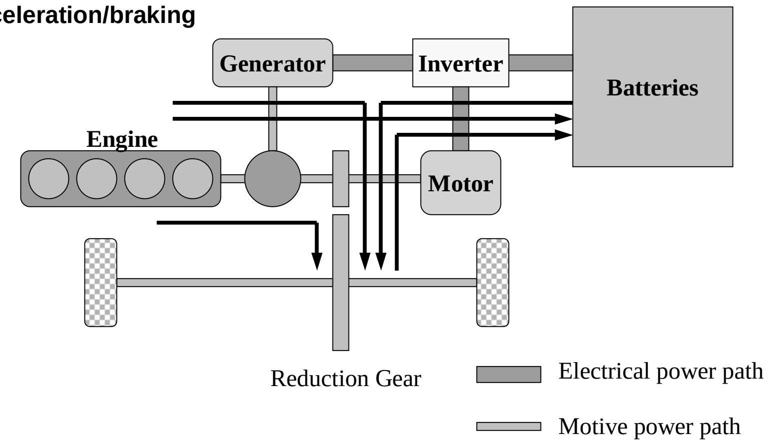
Power Flow in Prius

Engine Flow

Starting from rest/low speeds
Full-throttle acceleration
Normal driving
Deceleration/braking



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Emission Comparison of Prius and Corolla

Vehicle	Curb Weight (kg)	Nonmethane Organic gases (NMOG), g/km		Carbon Mononxide g/km		Nitrogen oxide g/km		Carbon dioxide g/km		Fuel Eco-nomy	Accel From 0-60 mi/h
		Car	TE	Car	TE	Car	TE	Car	TE	Km/L	Sec.
Prius	1237	0.002	0.033	0.025	0.062	0.001	0.063	112	155	20.8	12.7
Corolla	1143	0.025	0.068	0.808	0.864	0.124	0.205	157	217	14.7	10.3

Note:

- **“Car” values are vehicle exhaust (tailpipe) emissions**
- **“TE” values are total emissions-Car plus upstream, including fuel cycle emission**
- **Source: IEEE Spectrum, March 2001, Pages 47 – 50.**

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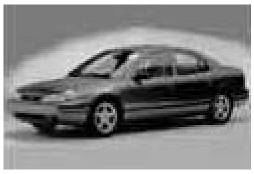
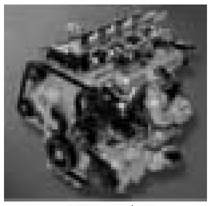
Ford P2000 Low Storage Requirement (LSR) Car





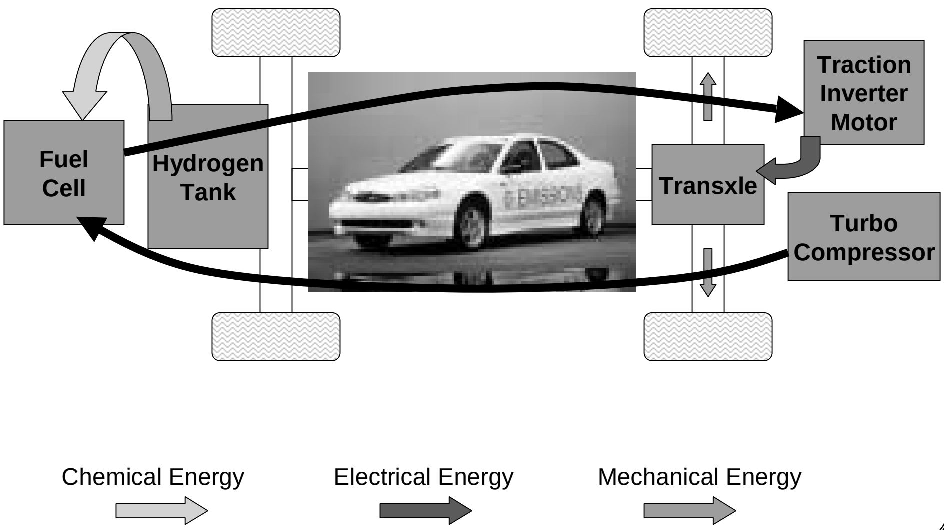
Features:

- **Low Storage Requirement (LSR)**
- **Direct Injection Aluminum Through-bolt Assembly (DIATA) engine**
- **Integrated Starter/Alternator**
- **Engine shut-down during braking and at rest**
- **Very fast engine restart**
- **Improve engine dynamics and shift fell**
- **Modified shift strategy for reduced emissions**
- **Weight and cost penalties low relative to “full” hybrid**
- **enables limited re-generative braking**

Comparison of P2000 LSR and Hybrid Vehicles

	Series		Parallel	P2000
Platform	5 + passenger, Al-Intensive, Sedan		5 passenger, Light-weight prototype	5 passenger, Light-weight prototype
HPU	55 kW, Turbo-Alternator		55 kW, 1.2 L, CIDI	55 kW, 1.2L, CIDI
Transmission	none		Auto 5-speed	Auto 5-speed
Traction Motor	75 kW, EV transaxle		18/30 kW motor on 4x4 transfer case	8 kW starter/alternator
Battery	180 kW x 6 kWh		48 kW x 2 kWh	15 kW x 0.4 kWh
Weight	1401 kg		1258 kg	1000 kg
Fuel Economy (v. Taurus) City:	Metal 1.8x	Ceramic 2.4x	2.9x	2.5x
Highway	1.4x	1.9x	2.2x	1.9x

Ford P2000
Hydrogen Fuel Cell Car



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Daimler-Chrysler NECAR IV
A Fuel Cell Electric Vehicle with Built-in Reformer

Fuel:	**Methanol**
Emission:	**zero**
Top Speed:	**90 mph**
Range:	**280 miles**

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Part C: Power Electronic Technologies in EV/HEV

- **Energy Sources and Storages**
  - ✓ **Batteries**
  - ✓ **Fuel Cells**
- **Traction Motors**
- **Soft-Switching Inverters**
- **Bi-Directional Chargers**

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Energy Sources and Storages

- **Lead Acid Batteries**
- **Nickel Metal-Hydride (NiMH) Batteries**
- **Lithium Batteries**
- **Fuel Cells**

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Lead Acid Batteries

Flood type:

- **First design in 1880's**
- **With flat pasted plate immersed in a dilute sulfuric acid electrolyte**

Valve Regulated Lead Acid (VRLA) type:

- **Original development in 1960's with sealed lead acid batteries**
- **The gases produced during operation are recombined to minimize water losses**
- **Typical gas recombination efficiency is 95%**
- **Gas recombination cell can be made with Absorptive Glass Mat separator or Gel Electrolyte**

Electric Vehicles use "deep charge/discharge" type VRLA batteries

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Source: www.hawker.invensys.com

VRLA Battery Charging Voltage and Current

for a Typical Tubular Gel Product

Typical State of Charge	Voltage	Charging Voltage at diff temp.	
100%	2.13 V	0°C	2.35 V
70%	2.09 V	10°C	2.28 V
50%	2.06 V	20°C	2.23 V
20%	2.02 V	30°C	2.20 V
		35 °C	21.7 V

* Measuring open ckt voltage after battery rested >24 hr.

Charging Current

- **Typically 10% of the 10-hour capacity, C_{10}**
- **In general, not exceed 30% of C_{10}**
- **For fast charge, keep 2.35 V per cell with 10% of C_{10} as the current limit**

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Source: www.hawker.invensys.com

Nickel Metal-Hydride (NiMH) Batteries

- **Negative Electrode:**
  - **rare earth/nickel alloys LaNi5 (AB5 alloys)**
  - **titanium and zirconium (AB2 alloys)**
- **Positive Electrode: Sintered-type positive electrodes are economical and rugged while exhibiting excellent high-rate performance, long cycle life, and good capacity**
- **Electrolyte**: **Alkaline, a dilute solution of potassium hydroxide**
- **Energy Density: Improved energy density (up to 40 percent greater than Nickel Cadmium cells)**
- **GM EV1 Test Range: 55 to 95 miles with 26 lead-acid battery pack 75 to 130 miles with Nickel-Metal Hydride (NiMH) battery pack**

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Comparison of Nickel-Metal Hydride to Nickel Cadmium Batteries

Nominal Voltage	Same (1.25V)
Discharge Capacity	NiMH up to 40% greater than NiCd
Discharge Profile	Equivalent
Discharge Cutoff Voltages	Equivalent
High Rate Discharge Capability	Effectively the same rates
High Temp (>35ºC) Discharge Capability	NiMH slightly better than NiCd cells
Operating Temperature Limits	Similar, NiMH slightly better at cold temp
Self-Discharge Rate	Similar to NiCd
Cycle Life	Similar to NiCd
Mechanical Fit	Equivalent
Selection of Sizes/Shapes/Capacities	Equivalent
Environmental Issues	Reduced with NiMH because of elimination of cadmium toxicity concerns. Collection of spent NiMH batteries is not mandated

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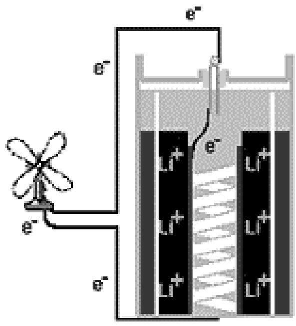
Lithium/Thionyl Chloride Batteries

Negative Electrode: mixture of carbon, Teflon, fiberglass, alcohol, and water

Positive Electrode: Lithium

Electrolyte: Thionyl Chloride

Lithium batteries have been widely used in computers and communications and will be competing with NiMH batteries for EV applications



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Fuel Cell Vehicle - Future Trend

A fuel cell produces electricity by combining hydrogen and oxygen in an electrochemical reaction. Fuel cells require no combustion, unlike a conventional gasoline- or diesel-powered engine. The only emission from hydrogen fuel cells is water vapor.

Fuel Cell Electric Vehicles (FCEVs) are similar to a battery-powered EV except that fuel cells replace batteries. As with batteries, fuel cell emit no **carbon dioxide**, although carbon dioxide and other emissions may be created in vehicle manufacturing and fuel production.

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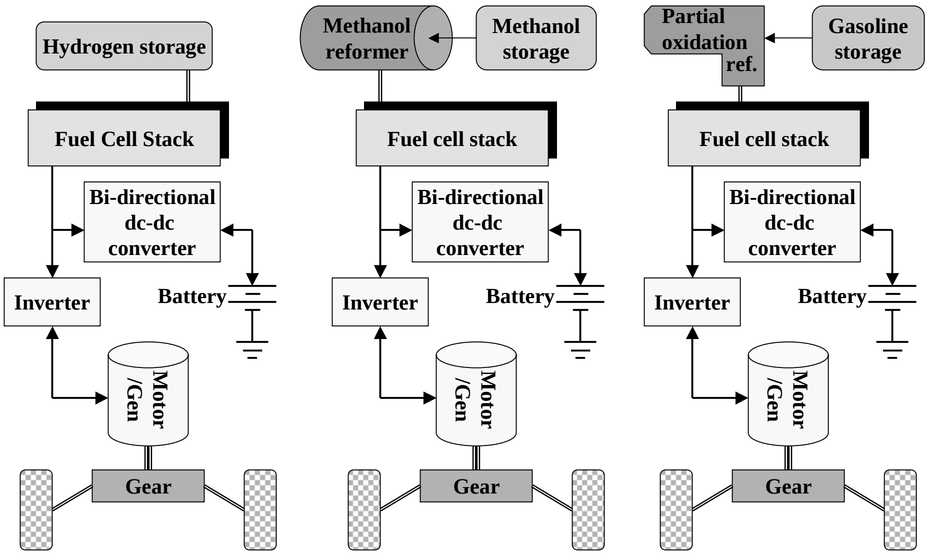
Fuel Cell Vehicle Configurations with Different Sources



(a) With hydrogen (b) With Methanol (c) With Gasoline

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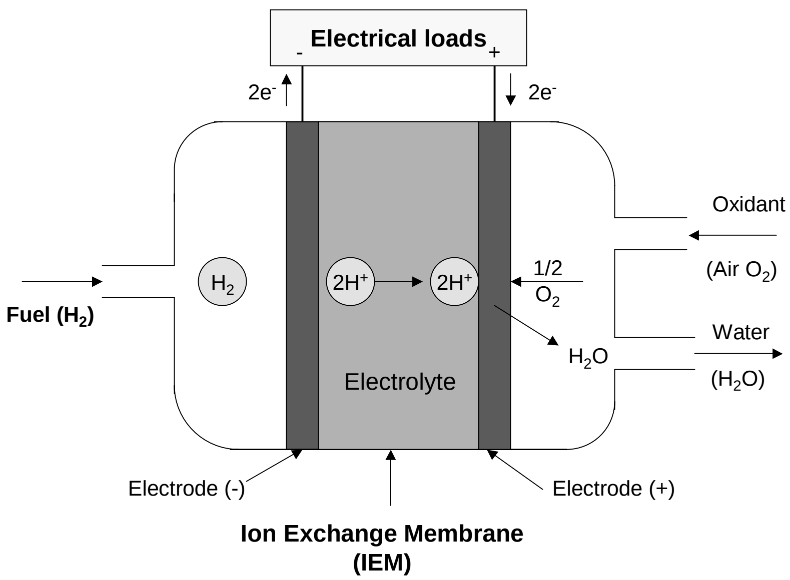
Basic Hydrogen-Oxygen Fuel Cell



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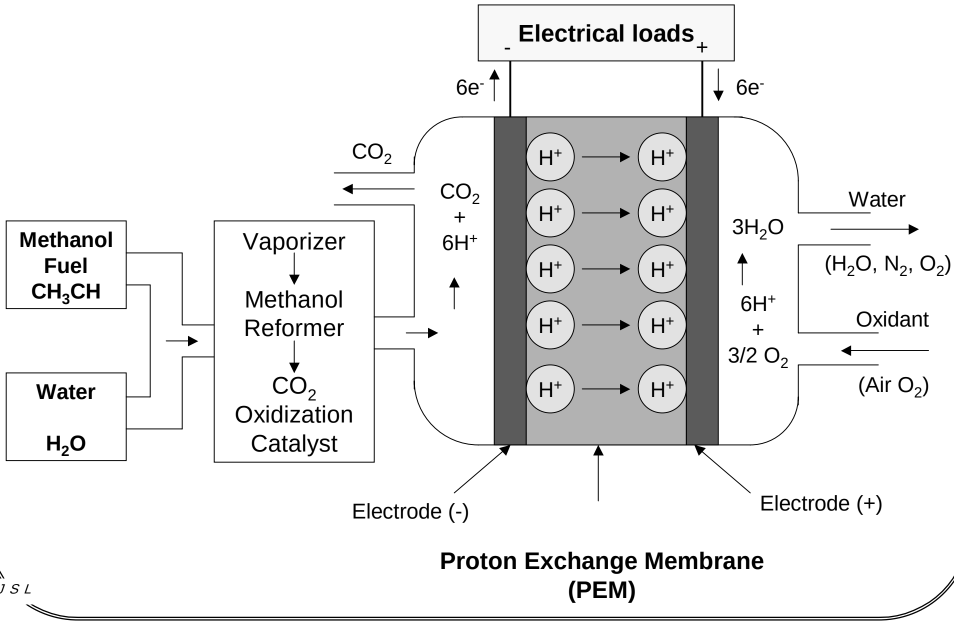
Proton Exchange Membrane (PEM) Fuel Cell



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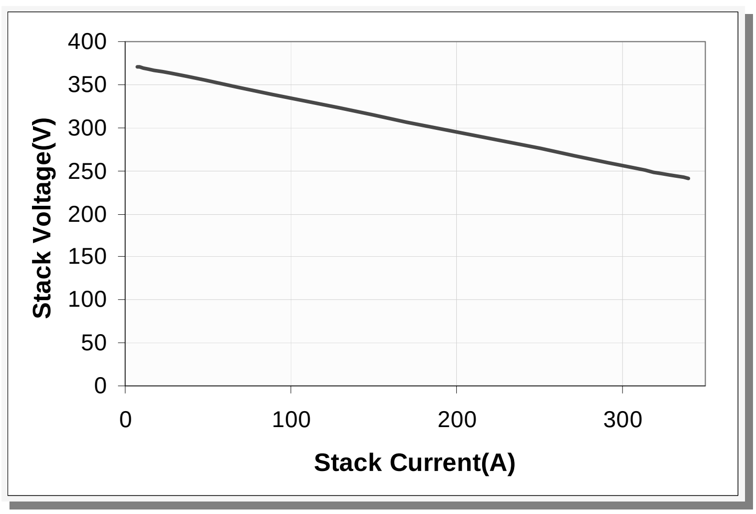
Fuel Cell Output Voltage and Current Characteristic



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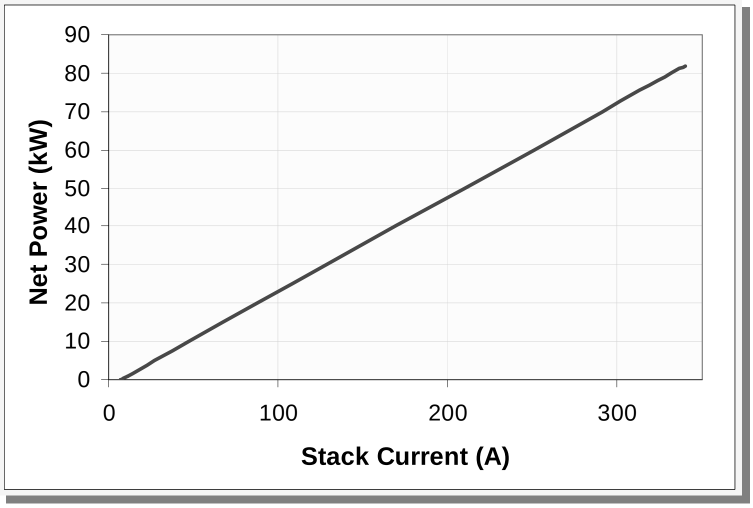
Fuel Cell Output Power and Current Characteristic



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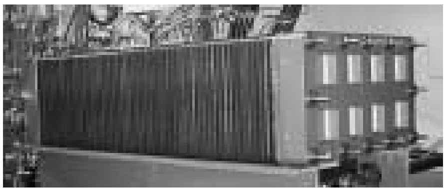
20 kW Future Car Stack



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Traction Motors/Inverters

- **Motor Design Consideration**
  1. **Using Federal Urban Driving Schedule to Find Most Critical Speed and Torque Region**
  2. **Optimize Motor Design in Proper Torque-Speed Regions**
- **Motor Types**
- **Inverter Partitioning for Integrated Inverter-Motor**
- **Soft-Switching Inverter Considerations**
- **Bi-directional Chargers for Fuel Cell Vehicles**
  1. **A 20-kW Non-isolated Bi-directional Converter**
  2. **A 5-kW Isolated Bi-directional Converter**

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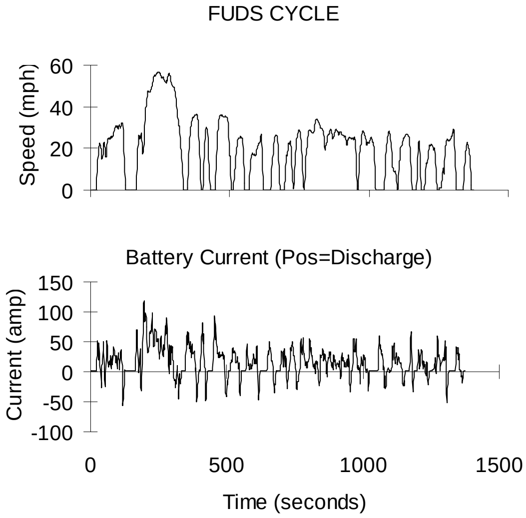
Motor Design Consideration 1

Using Federal Urban Driving Schedule to Find Most Critical Speed and Torque Regions



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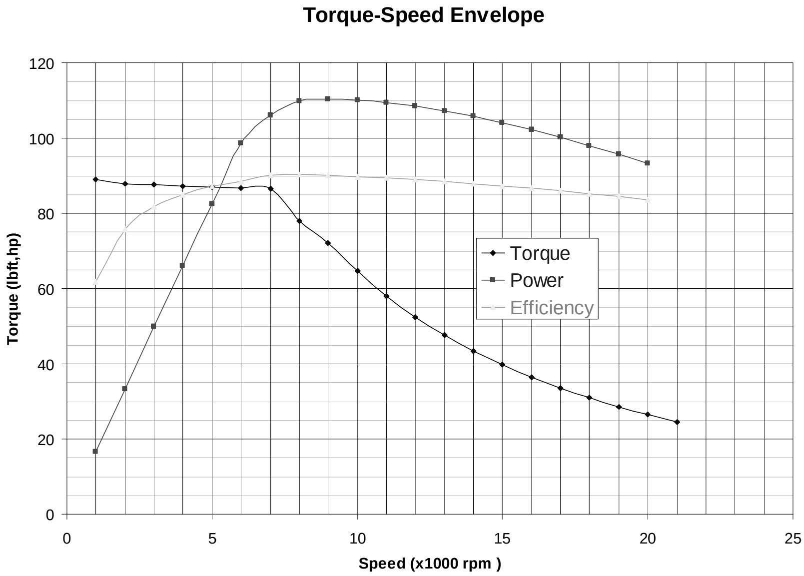
Motor Design Consideration 2

Optimize Motor Design in Proper Torque-Speed Regions Resulting High-Speed (20,000 rpm) Design that Cuts Size and Weight by 30%



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Motor Types

- **Induction Motor**
- **Permanent Magnet Motor**
- **Switched Reluctance Motor**
- **Other Combinations**

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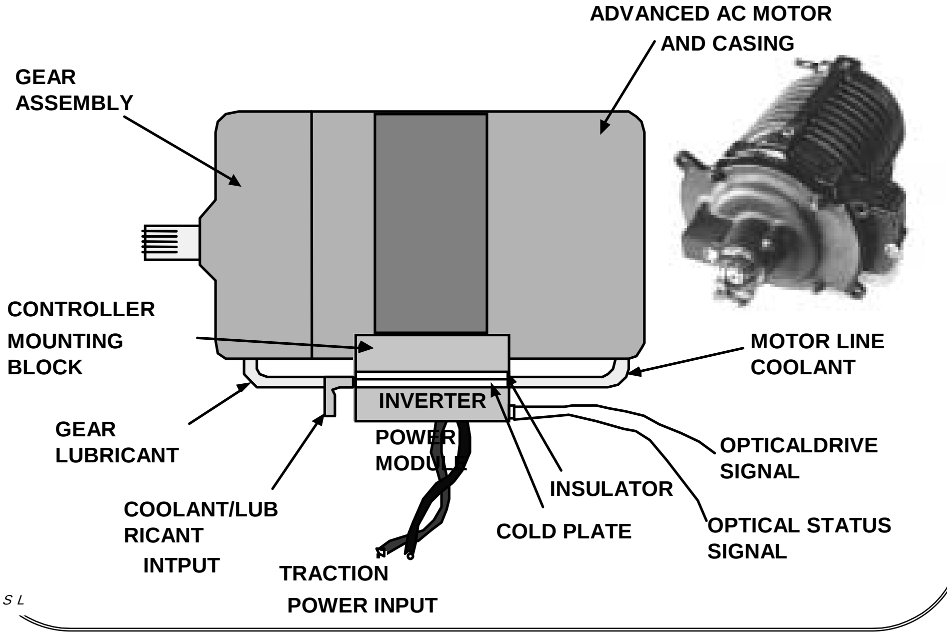
Inverter Partitioning for Integrated Inverter-Motor



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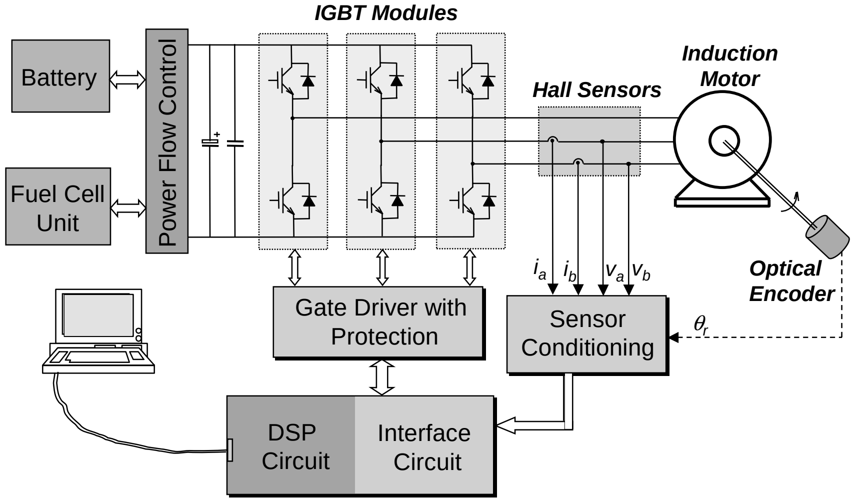
Inverter Design and Partioning



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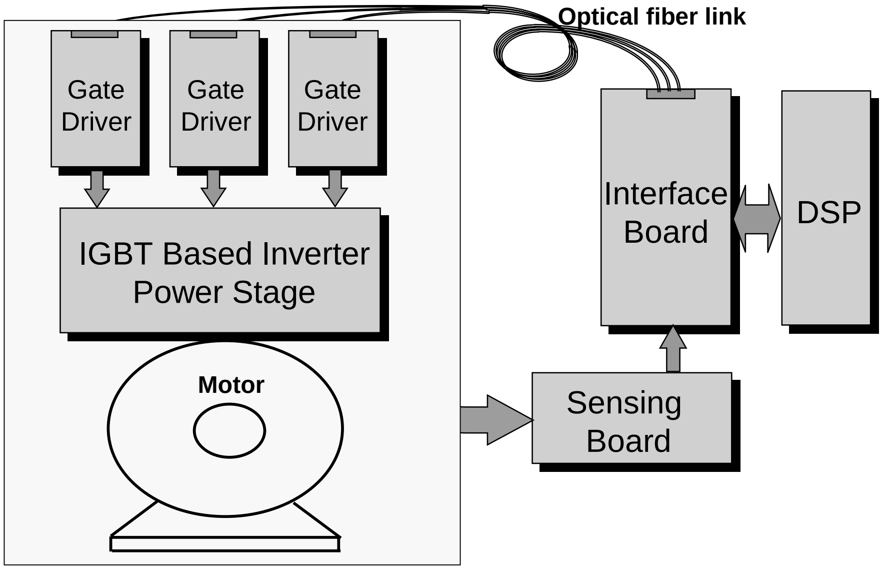
Using Optical Fiber to Link Integrated Power Stage and Control Interface



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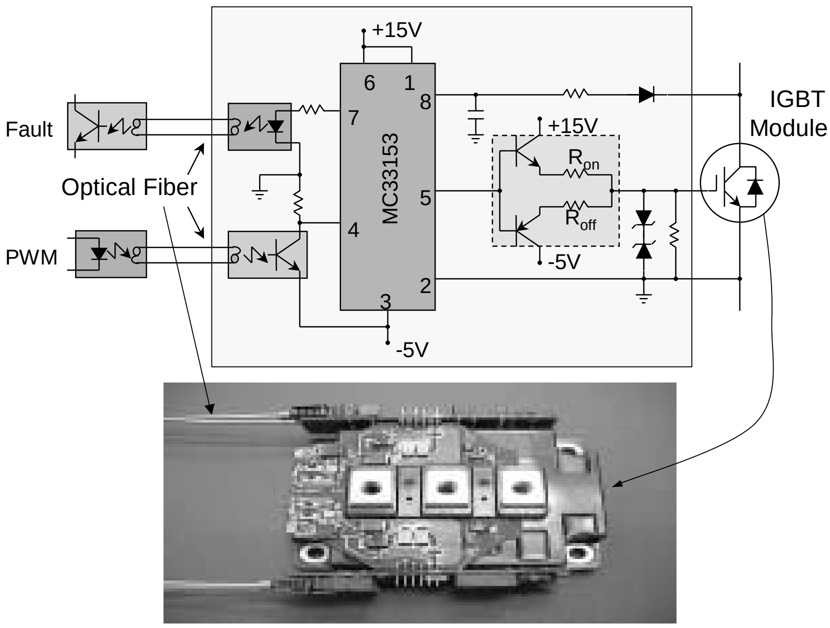
Compact Gate Driver with Optical Fiber Link



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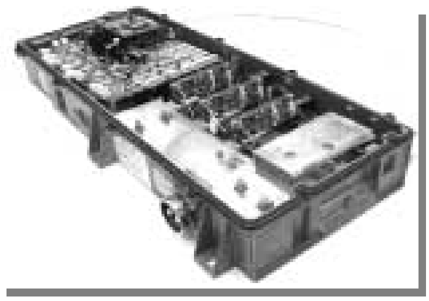
Soft-Switching Inverter Considerations

- Zero-Voltage-Transition – Auxiliary Resonant Commutated Pole (ARCP) Inverter for AC Motor Drives
- Zero-Current Transition (ZCT) Inverter
- Advantages:
  - Allow high switching frequencies
  - Low switching losses
  - Low EMI



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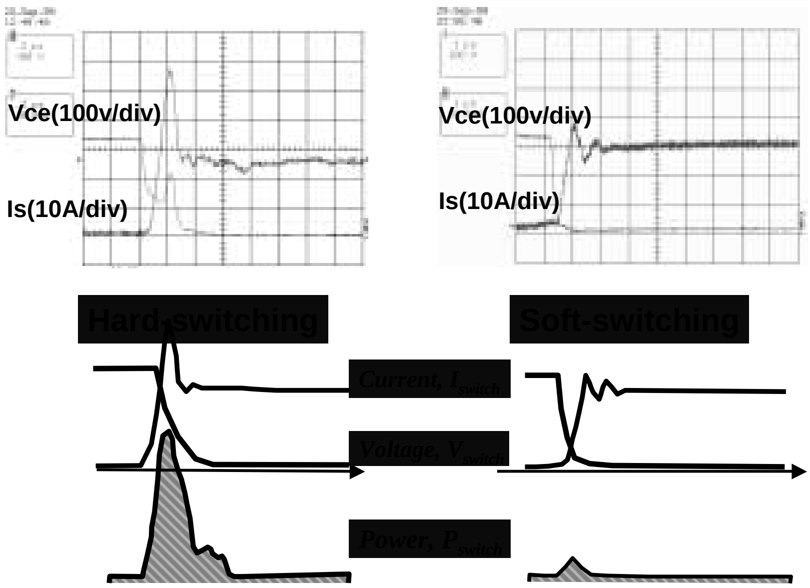
Turn-on Loss Reduction with Soft-Switching



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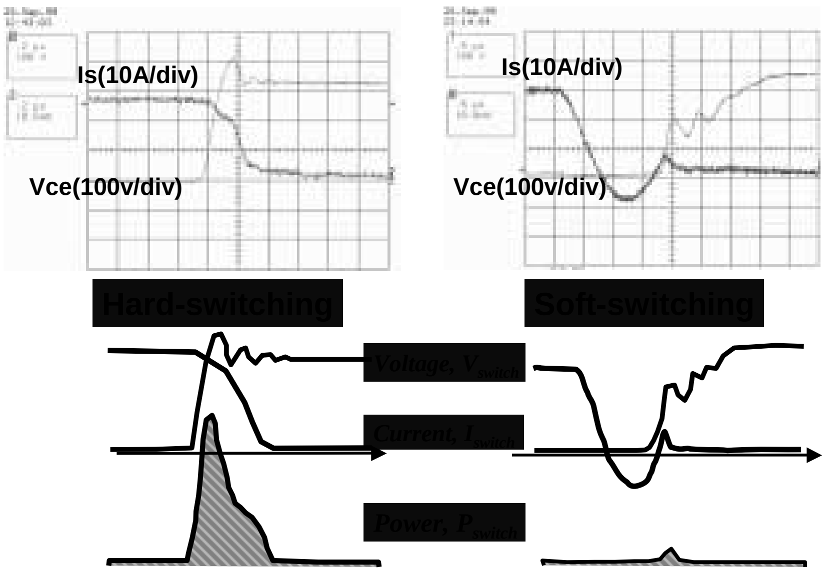
Turn-off Loss Reduction with Soft-Switching



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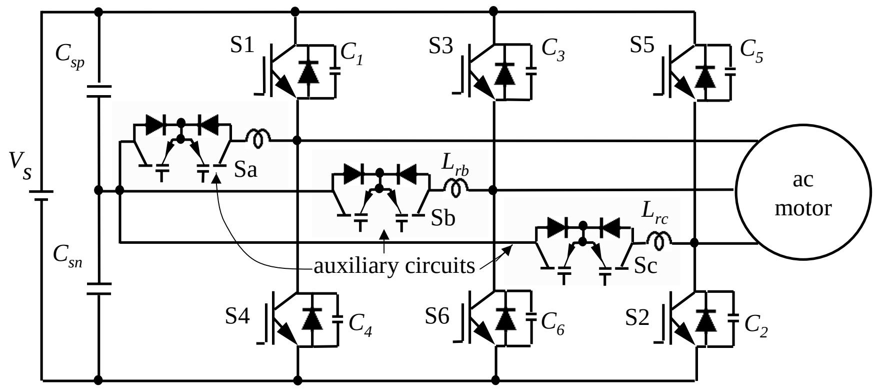
A Zero-Voltage-Transition Inverter for AC Motors

Auxiliary Resonant Commutated Pole (ARCP)



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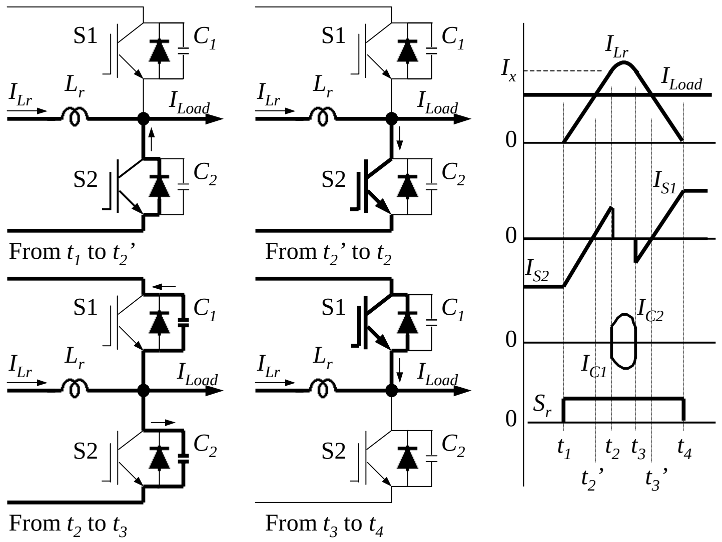
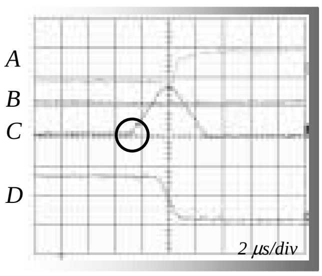
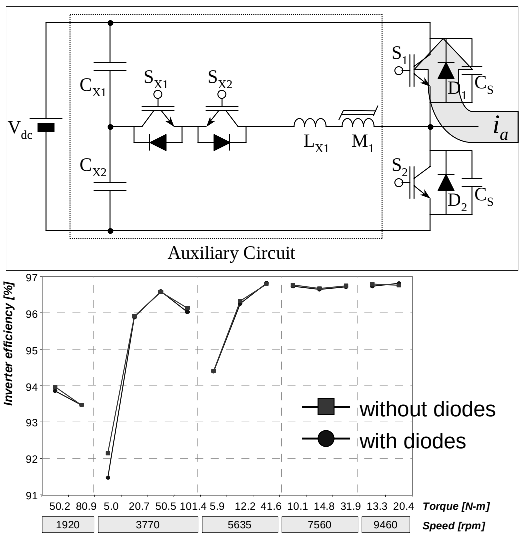
Basic Operating Principle of ZVT Soft-Switching



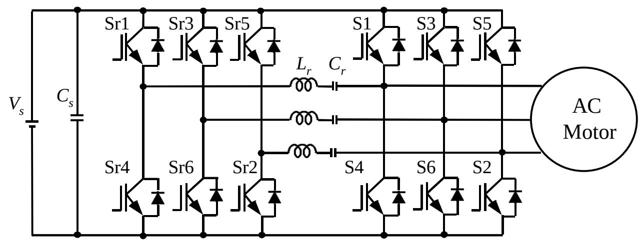
ARCP ZVT Inverter Test Results



A : $v_{g(S2)}$ (20 V/div)
B : i_a (200 A/div)
C : i_{ax} (200 A/div)
D : v_{S2} (200 V/div)



Zero Current Transition Inverter



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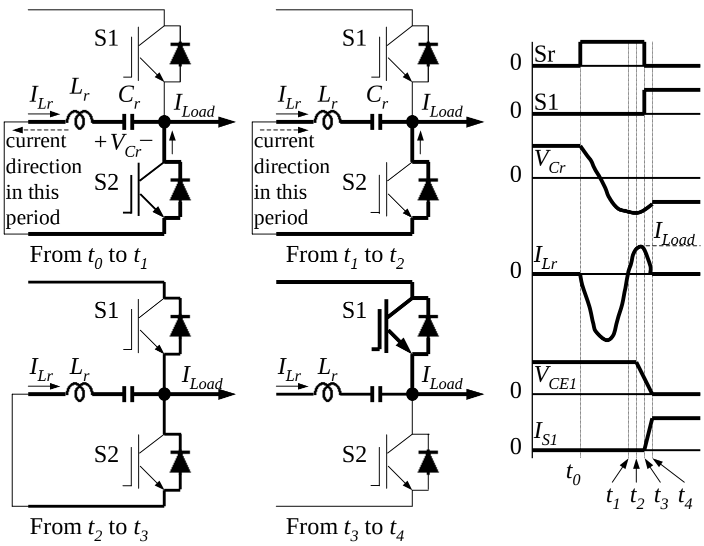
Basic Operation of ZCT Soft Turn-on



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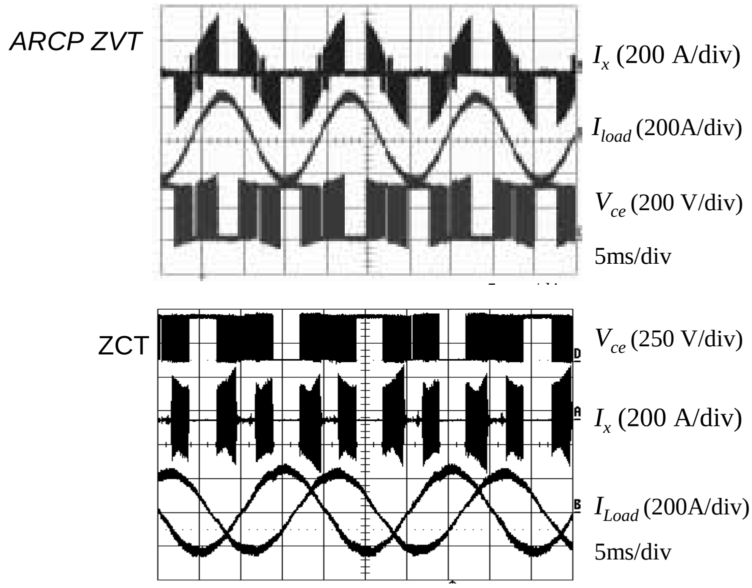
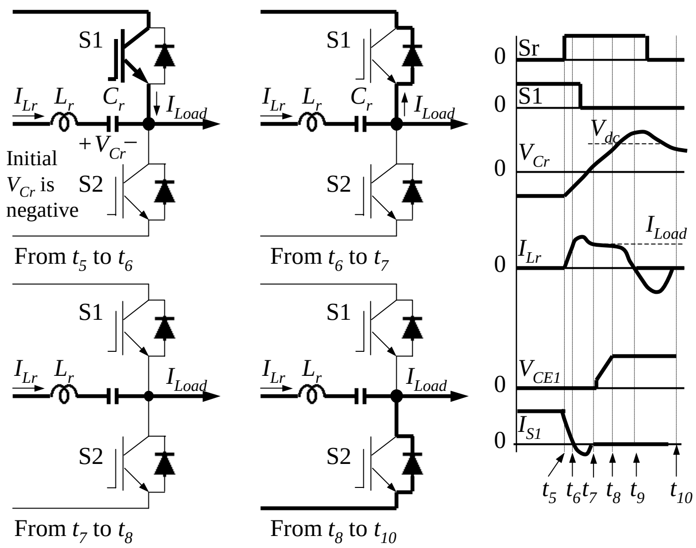
Test Results of 30-kW Soft-Switching Inverters

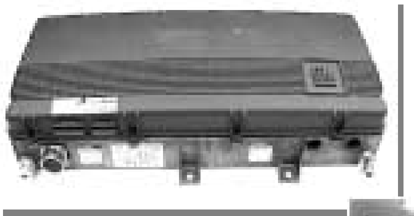


Basic Operation of ZCT Soft Turn-off



Soft-Switching Inverter Assembled in EV1 Chassis

Development...



Testing...

On the Road...

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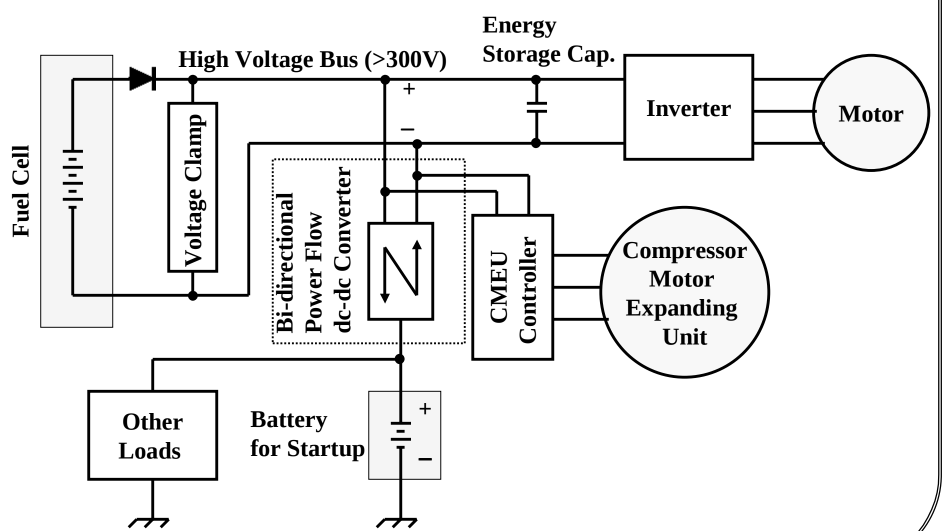
Bi-directional Charger for Fuel Cell Powered Electric Vehicles



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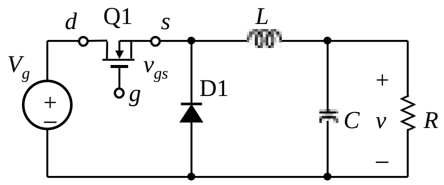
Why Bi-directional DC-DC Converter is Needed?

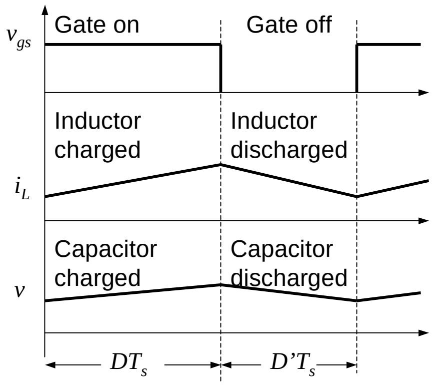
1. Need to have high voltage to start up the CMEU controller.
2. Need to stabilize the bus voltage during transient conditions.
3. Need battery to charge the dc bus bus for the initial startup power (Boost operation)
3. Need to keep battery charged (Buck operation)

Circuit Topology Considerations for the Bi-directional DC-DC Converter

1. Single-directional vs. bi-directional
2. Isolated vs. non-isolated
3. Multiple-leg Interleaved vs. single-leg
4. Voltage source vs. current source for either primary or secondary side
5. Low side battery with 12 V, 42 V, or 180 V vs. high side fuel cell at about 300 V

Non-Isolated Buck Converter





Average output voltage:

$$V = DV_g$$

where *D* is the duty ratio. Because *D* < 1, *V* is always less than V_g ➔ buck converting

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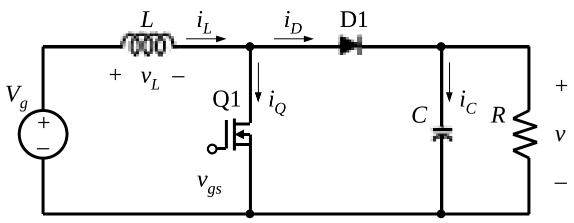
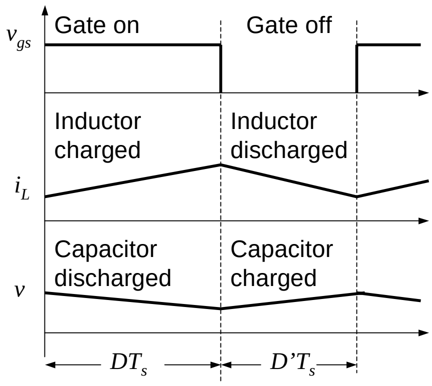
Non-Isolated Boost Converter





Average output voltage:

$$V = \frac{1}{1-D}V_g = \frac{1}{D'}V_g$$

where *D* is the duty ratio, and *D’* = 1 – *D*. Because *D’* < 1, *V* is always greater than V_g ➔ boost converting

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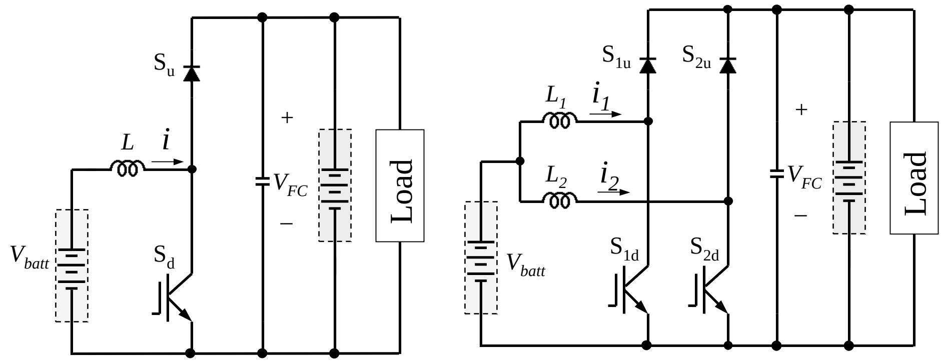
Non-Isolated Single-Directional Boost Converter

Non-Interleaved vs. Interleaved



(a) Non-Interleaved **(b) Interleaved**

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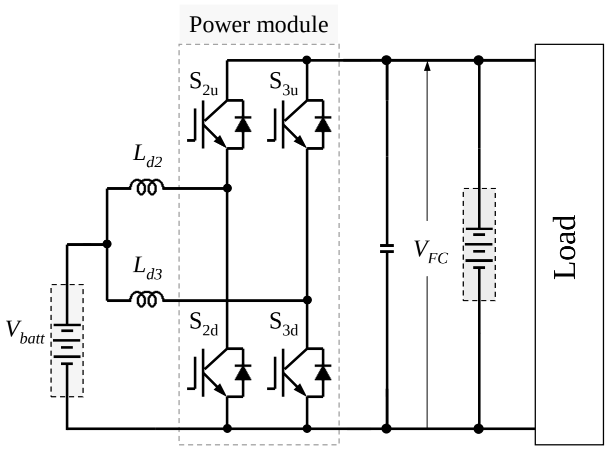
A Non-Isolated Bi-Directional DC-DC Converter with Interleaved Control



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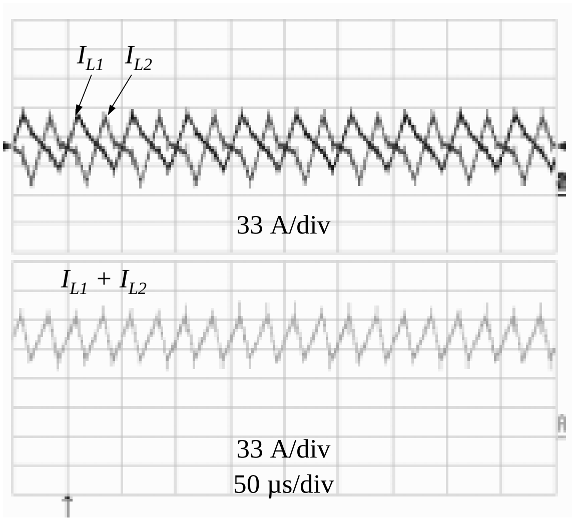
Ripple Current Cancellation Effect in a 20 kW Interleaved Boost Converter



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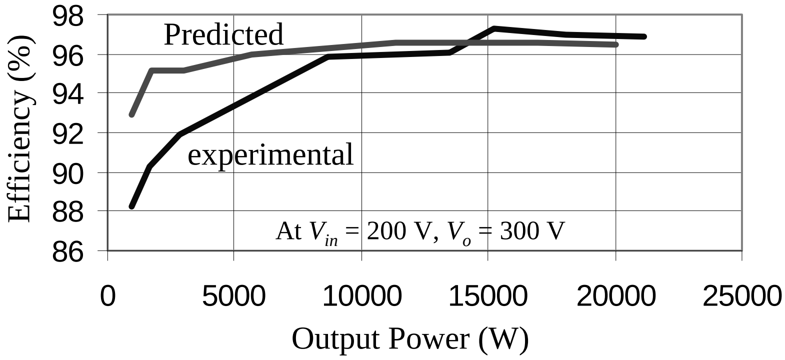
Efficiency Test Results of a 20 kW Interleaved Boost Converter



DCM operated converter has parasitic ringing losses at the light load condition, and the efficiency is suffered.

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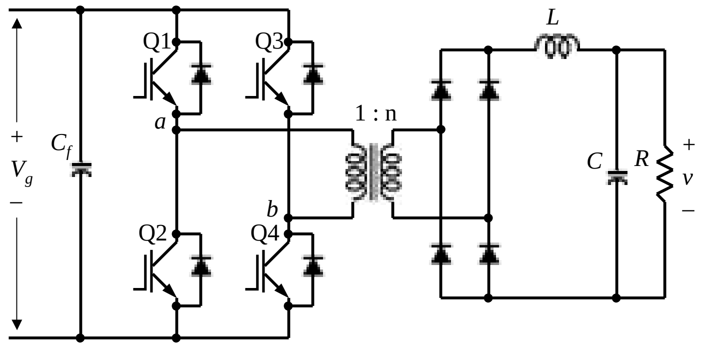
Isolated Buck Converter



- Suitable for high voltage input and low voltage output
- Zero-voltage switching can be achieved with phase-shift modulation

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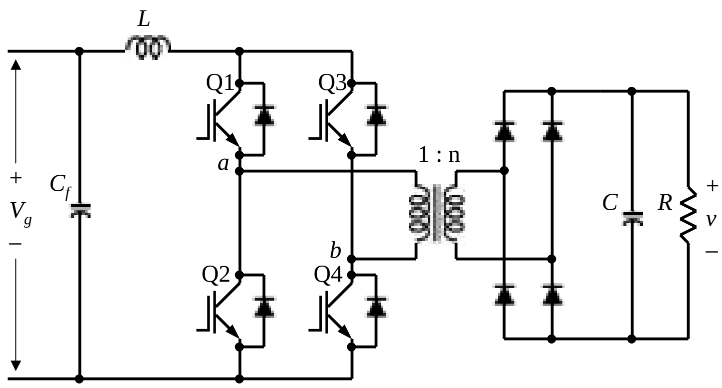
Isolated Boost Converter



- Suitable for low voltage input and high voltage output
- The main problem is high voltage stress on the switching devices

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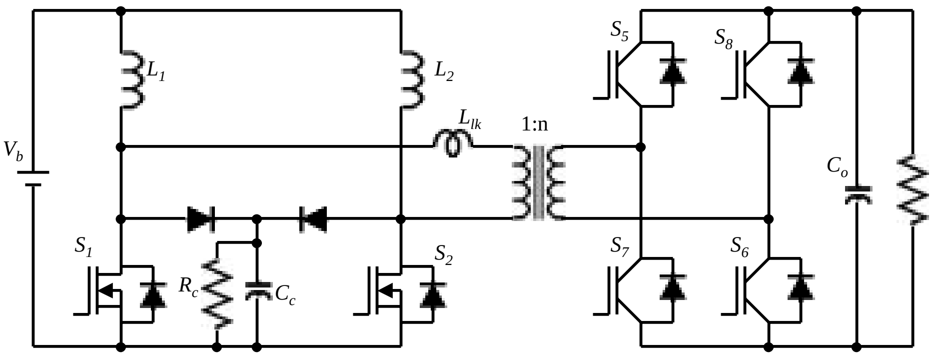
Low-Voltage Side "Half-Bridge Current-Fed" Isolated Bi-directional Converter



- ✓ **Low switch counts**
- ✓ **Simple transformer winding structure**
- ✓ **Low transformer current**
- × **Start-up problem**
- × **Low choke ripple frequency (f_s)**
- × **Duty cycle limitation**
- ✖ **Passive clamp is easy to implement but lossy**

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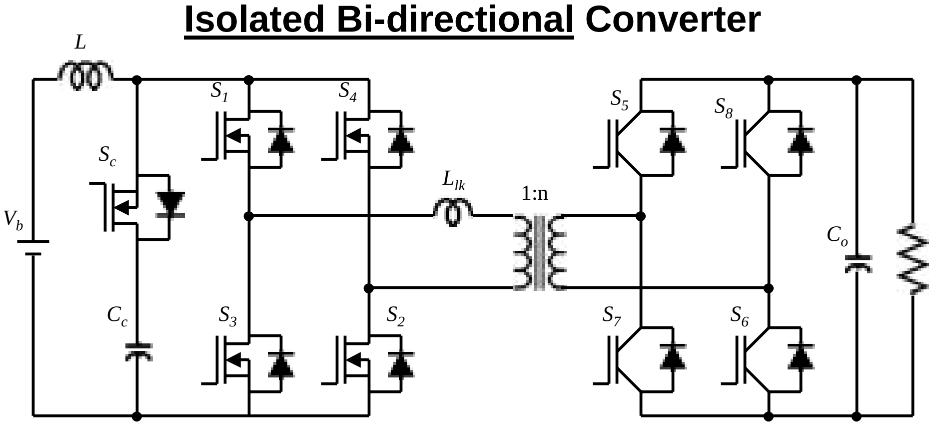
Low-Voltage Side "Full-Bridge Current-Fed" Isolated Bi-directional Converter



- ✓ **Simple voltage clamp circuit implementation**
- ✓ **Simple transformer winding structure and lower turns ratio**
- ✓ **Low transformer current**
- ✓ **High choke ripple frequency ($2f_s$)**
- × **Start-up problem**
- × **High switches count**

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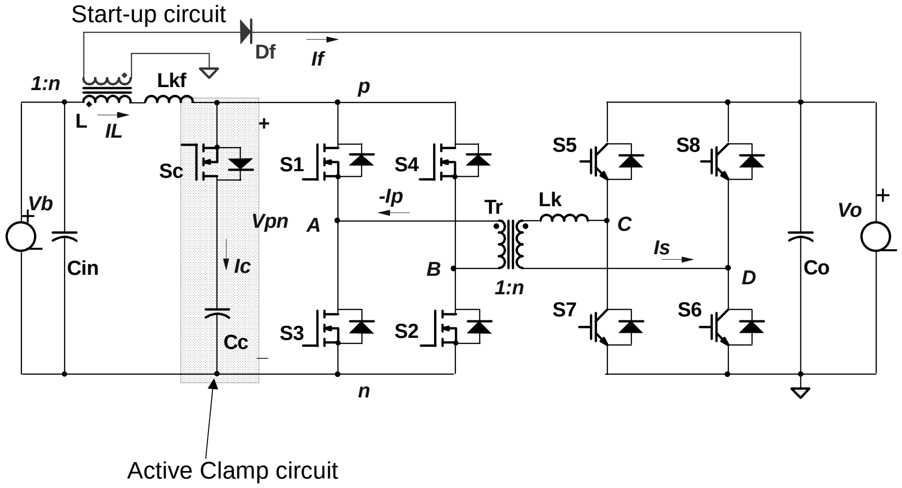
Complete Bi-directional dc-dc Charger with Clamping and Start-up Circuits



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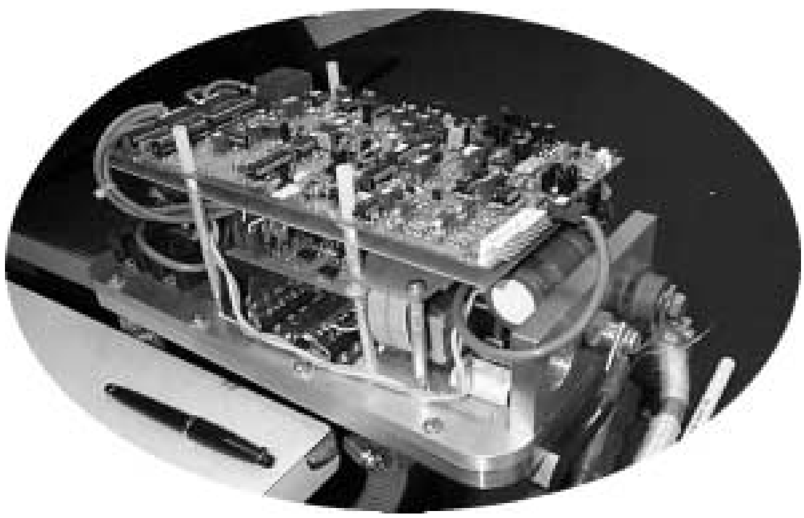
Prototype of a Liquid Cooled Bi-directional DC-DC Converter to be Installed in a Fuel Cell Vehicle



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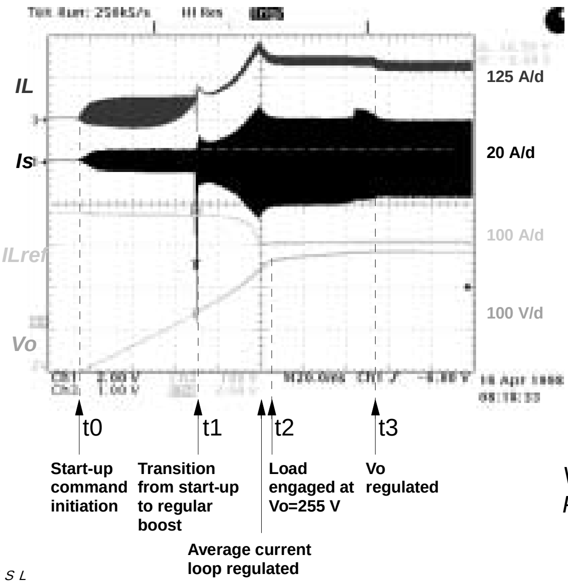
Start-up Mode Operation

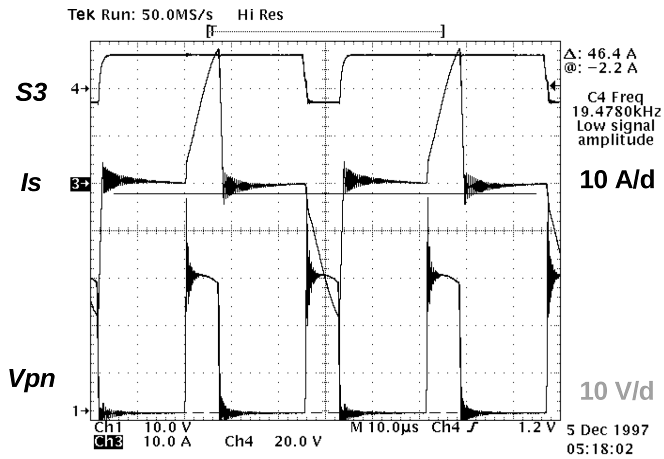


Start Up Process:

t0-t1	Start up mode, open loop controlled
t1-t2	Boost mode, open loop controlled
t2-t3	Boost mode, inner current loop regulated
t3-	Boost mode, outer voltage loop regulated

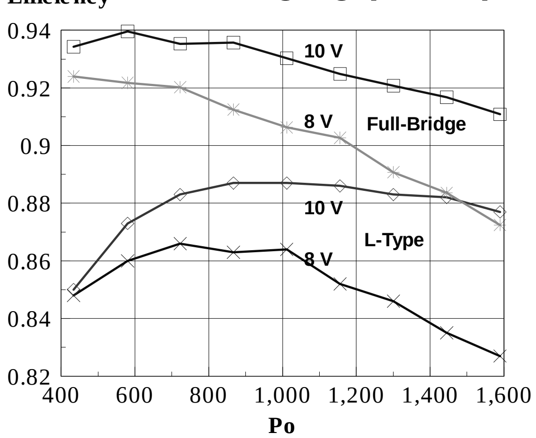
V_b = 12 V, I_L = 161 A, V_o = 280 V, P_d = 1.83 kW in steady state

Switch Voltage and Current Waveforms in Boost (Discharging) Mode Operation



V_b = 8 V, I_L = 228 A, V_o = 288 V, P_d = 1.55 kW

Comparison of Measured Efficiency Profile for Discharging (Boost) Mode Operation



Test conditions:

Start-up, battery discharging

Battery voltage: V_b = 8 and 10 V
High side voltage: V_o = 288 V
Switching freq.: f_s = 20 kHz

1. **Higher battery voltage, higher overall efficiency.**
2. **Full bridge is more efficient than the L-type half-bridge converter in overall operating range.**
3. **Efficiency at light-load exceeds 90% with full-bridge version.**
4. **L-type converter is lossy due to passive clamp circuit.**

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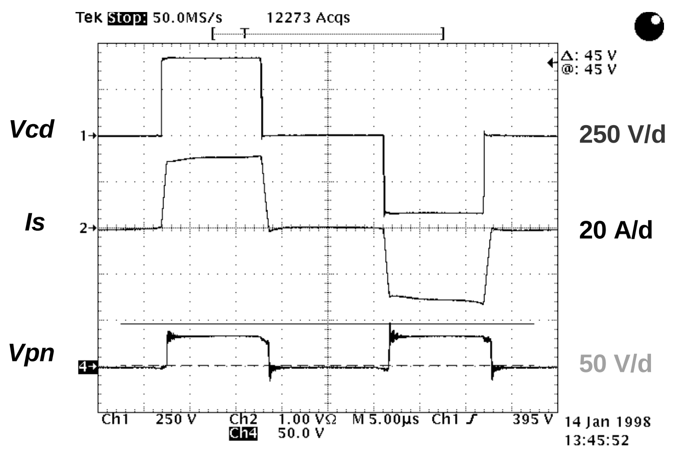
Switch Voltage and Current Waveforms in Buck (Charging) Mode Operation



V_b = 15 V, I_L = 335 A, V_o = 425 V, P_{cp} = 5 kW

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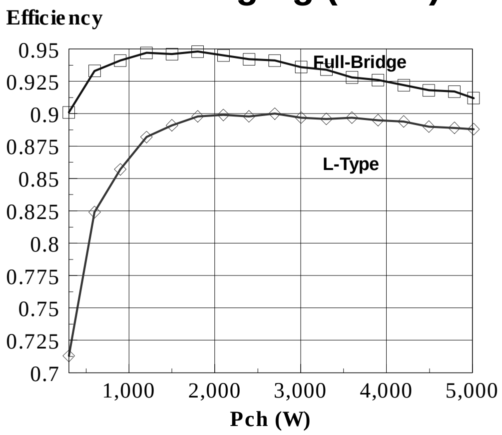
Comparison of Measured Efficiency Profile for Charging (Buck) Mode Operation



Test conditions:

Regenerative Mode
Battery voltage: V_b=15 V
High voltage bus: V_o=425 V

1. **L-type half-bridge efficiency reaches only 90%**
2. **Full bridge converter is more efficient with peak efficiency 95% because**
   - **more devices in parallel on low-voltage side**
   - **active clamp circuit provides lossless snubbing**
   - **soft-switching with zero-voltage zero-current operations**

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Summary and Discussions

- **Development of EV/HEV is very vital in recent years**
- **HEV has hit the market since 1999**
- **Fuel cell is becoming the choice of energy source for future EVs**
- **Power electronics is the main driver of EV/HEV**
- **Key power electronics technologies are traction motor/inverter drives and bi-directional chargers**
- **Power electronics engineers are in great demand**

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