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

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.
Driving Forces for EV/HEV

- Simplicity (1910)
- Environmental Concerns (1990)
- Customer Expectations (2000)

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
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

Specifications of Baseline Vehicle and Supercar

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Supercar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb Weight</td>
<td>3200 lbs</td>
<td>40% less</td>
</tr>
<tr>
<td>Drag coeff.</td>
<td>0.32</td>
<td>0.20</td>
</tr>
<tr>
<td>Friction</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Engine</td>
<td>Internal Combustion</td>
<td>flywheel, battery, ultracapacitor</td>
</tr>
<tr>
<td>Fuel Efficiency</td>
<td>26.6 mpg</td>
<td>80 mpg (3X)</td>
</tr>
<tr>
<td>Recycleability</td>
<td>75%</td>
<td>80%</td>
</tr>
<tr>
<td>Range (HWY)</td>
<td>380 miles</td>
<td>same or better</td>
</tr>
<tr>
<td>Accel (0-62 mi)</td>
<td>12 seconds</td>
<td>same or better</td>
</tr>
<tr>
<td>Luggage</td>
<td>168 ft³</td>
<td>same or better</td>
</tr>
<tr>
<td>Load</td>
<td>6 passengers + 200 lb</td>
<td>same or better</td>
</tr>
<tr>
<td>Life</td>
<td>100,000 miles</td>
<td>same or better</td>
</tr>
</tbody>
</table>
PNGV Time Table

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

- Accessories: 2%
- Aerodynamics: 6%
- Rolling: 5%
- Braking: 4%
- Engine: 77%
- Driveline: 6%
### Electric/Hybrid Electric Vehicle Configurations

<table>
<thead>
<tr>
<th>Pure ICE Drive</th>
<th>Parallel Hybrid</th>
<th>Series Hybrid</th>
<th>Pure Electric Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel tank</td>
<td>ICE</td>
<td>ICE</td>
<td>Battery</td>
</tr>
<tr>
<td>Xmission</td>
<td>Diff. Wheels</td>
<td>Diff. Generator</td>
<td>Electric Motor</td>
</tr>
<tr>
<td>Battery</td>
<td>Electric Motor</td>
<td>Battery</td>
<td>Diff. Wheels</td>
</tr>
<tr>
<td>Diff. Wheels</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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
Part B: Overview of EVs on the Market

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

General Motor EV1

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

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

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

Drivetrain of Honda Insight
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

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.
Power Flow in Prius

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

Emission Comparison of Prius and Corolla

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Curb Weight (kg)</th>
<th>Nonmethane Organic gases (NMOG), g/km</th>
<th>Carbon Monoxide g/km</th>
<th>Nitrogen Oxide g/km</th>
<th>Carbon Dioxide g/km</th>
<th>Fuel Economy</th>
<th>Accel From 0-60 mi/h</th>
<th>Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prius</td>
<td>1237</td>
<td>0.002 0.033</td>
<td>0.025 0.062</td>
<td>0.001 0.063</td>
<td>112 155</td>
<td>20.8</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>Corolla</td>
<td>1143</td>
<td>0.025 0.068</td>
<td>0.808 0.864</td>
<td>0.124 0.205</td>
<td>157 217</td>
<td>14.7</td>
<td>10.3</td>
<td></td>
</tr>
</tbody>
</table>

Note:
- “Car” values are vehicle exhaust (tailpipe) emissions
- “TE” values are total emissions-Car plus upstream, including fuel cycle emission
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

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

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

Fuel: Methanol
Emission: zero
Top Speed: 90 mph
Range: 280 miles
Part C: Power Electronic Technologies in EV/HEV

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

Energy Sources and Storages

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

VRLA Battery Charging Voltage and Current
for a Typical Tubular Gel Product

<table>
<thead>
<tr>
<th>Typical State of Charge</th>
<th>Voltage</th>
<th>Charging Voltage at diff temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>2.13 V</td>
<td>0°C 2.35 V</td>
</tr>
<tr>
<td>70%</td>
<td>2.09 V</td>
<td>10°C 2.28 V</td>
</tr>
<tr>
<td>50%</td>
<td>2.06 V</td>
<td>20°C 2.23 V</td>
</tr>
<tr>
<td>20%</td>
<td>2.02 V</td>
<td>30°C 2.20 V</td>
</tr>
</tbody>
</table>

* 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

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

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

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.
Fuel Cell Vehicle Configurations with Different Sources

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

Basic Hydrogen-Oxygen Fuel Cell

Electrical loads

Fuel (H₂)

Oxidant

(Air O₂)

Water

(H₂O)

Electrolyte

Ion Exchange Membrane (IEM)
Proton Exchange Membrane (PEM) Fuel Cell

Methanol Fuel \( \text{CH}_3\text{CH}_2\text{OH} \)
Water \( \text{H}_2\text{O} \)

Vaporizer
Methanol Reformer
\( \text{CO}_2 \)
Oxidation Catalyst

CO\(_2\) \( \rightarrow \) \( \text{H}_2\text{O} \)
Water \( \rightarrow \) \( 3\text{H}_2\text{O} \)
Oxidant \( \rightarrow \) \( (\text{H}_2\text{O}, \text{N}_2, \text{O}_2) \)

Electrode (-)

Electrode (+)

Fuel Cell Output Voltage and Current Characteristic

Stack Voltage(V)

Stack Current(A)
Fuel Cell Output Power and Current Characteristic

![Graph showing net power (kW) against stack current (A).]

20 kW Future Car Stack

![Image of a 20 kW future car stack.]

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

Motor Design Consideration 1
Using Federal Urban Driving Schedule to Find Most Critical Speed and Torque Regions

FUDS CYCLE

- Speed (mph)
- Battery Current (Pos=Discharge)
- Time (seconds)
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%

Motor Types

- Induction Motor
- Permanent Magnet Motor
- Switched Reluctance Motor
- Other Combinations
Inverter Partitioning for Integrated Inverter-Motor

Inverter Design and Partitioning
Using Optical Fiber to Link Integrated Power Stage and Control Interface

Compact Gate Driver with Optical Fiber Link
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

Turn-on Loss Reduction with Soft-Switching
**Turn-off Loss Reduction with Soft-Switching**

<table>
<thead>
<tr>
<th>Is(10A/div)</th>
<th>Vce(100v/div)</th>
<th>Is(10A/div)</th>
<th>Vce(100v/div)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

**A Zero-Voltage-Transition Inverter for AC Motors**

Auxiliary Resonant Commutated Pole (ARCP)

![Diagram](image5.png)
Basic Operating Principle of ZVT Soft-Switching

From \( t_1 \) to \( t_2' \)

From \( t_2' \) to \( t_2 \)

From \( t_2 \) to \( t_3 \)

From \( t_3 \) to \( t_4 \)

ARCP ZVT Inverter Test Results

\( A \) : \( v_{S2} \) (20 V/div)

\( B \) : \( i_L \) (200 A/div)

\( C \) : \( i_{ax} \) (200 A/div)

\( D \) : \( v_{S2} \) (200 V/div)
Zero Current Transition Inverter

Basic Operation of ZCT Soft Turn-on
Test Results of 30-kW Soft-Switching Inverters

ARCP ZVT

ZCT

Basic Operation of ZCT Soft Turn-off
Soft-Switching Inverter Assembled in EV1 Chassis

Development...

Testing...

On the Road...

Bi-directional Charger for Fuel Cell Powered Electric Vehicles

Fuel Cell

Voltage Clamp

High Voltage Bus (>300V)

Energy Storage Cap.

Inverter

Motor

Bi-directional Power Flow dc-dc Converter

CMEU Controller

Compressor Motor Expanding Unit

Other Loads

Battery for Startup
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)
4. 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:

\[ V = DV_s \]

where \( D \) is the duty ratio. Because \( D < 1 \), \( V \) is always less than \( V_g \) \( \rightarrow \) buck converting.

Non-Isolated Boost Converter

Average output voltage:

\[ V = \frac{1}{1-D} V_s = \frac{1}{D} V_s \]

where \( D \) is the duty ratio, and \( D' = 1-D \). Because \( D' < 1 \), \( V \) is always greater than \( V_g \) \( \rightarrow \) boost converting.
Non-Isolated Single-Directional Boost Converter
Non-Interleaved vs. Interleaved

(a) Non-Interleaved

(b) Interleaved

A Non-Isolated Bi-Directional DC-DC Converter
with Interleaved Control
Ripple Current Cancellation Effect in a 20 kW Interleaved Boost Converter

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.
### Isolated Buck Converter

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

### Isolated Boost Converter

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

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

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

Vo = 12 V, Il = 161 A, Vc = 280 V, Pd = 1.83 kW in steady state

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

Vb = 8 V, Il = 228 A, Vc = 288 V, Pd = 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.
4. L-type converter is lossy due to passive clamp circuit.

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

\[ V_o = 15 \text{ V}, \ I_L = 335 \text{ A}, \ V_o = 425 \text{ V}, \ P_{cp} = 5 \text{ kW} \]
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

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