Electric Traction Drive R&D at the Oak Ridge National Laboratory

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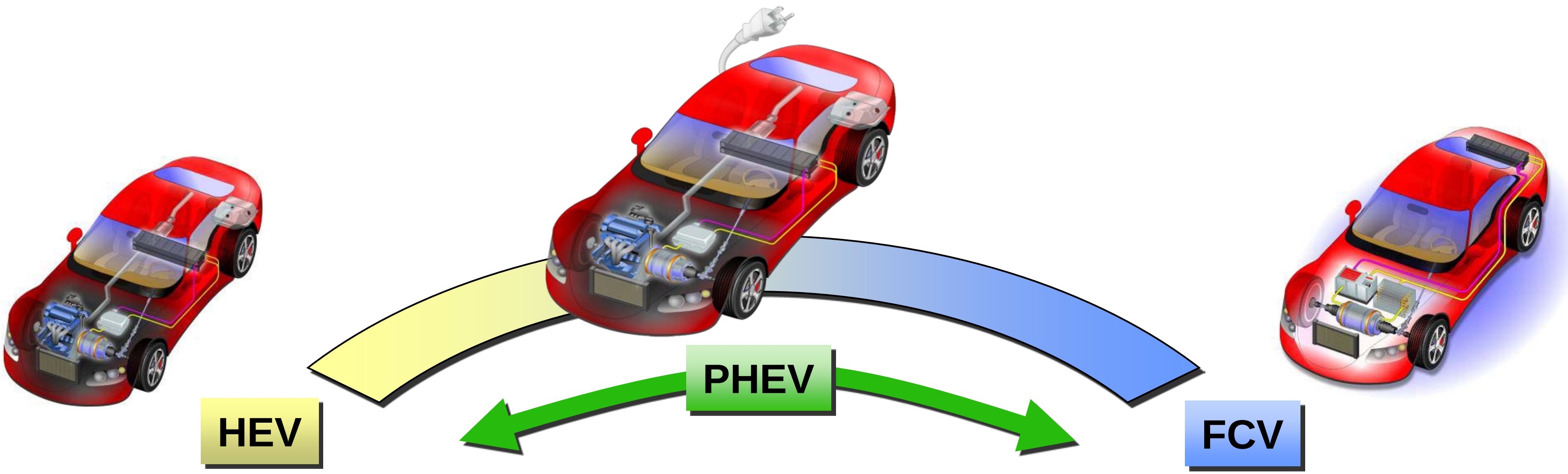
Advanced Vehicle Applications

APEEM is a critical system of all HEVs/PHEVs/FCVs



Blended ICE/Electric
– Power requirement ≥ 55 kW
– Parallel architecture
– Intermittent short operation

Sized for Electric Only
– Power required increases (up to 200 kW)
– Series architecture
– Always “on”

PHEV Position in Spectrum Depends on Design

Advanced Power Electronics and Electric Machines Research

Reduce Dependence on Oil
Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life; coolant (air or 105ºC WEG)

Technology Targets

Year	Traction Drive System				Power Electronics			Motors		
	($/kW)	(kW/kg)	(kW/l)	Efficiency	($/kW)	(kW/kg)	(kW/l)	($/kW)	(kW/kg)	(kW/l)
2010	19	1.06	2.6	>90%	7.9	10.8	8.7	11.1	1.2	3.7
2015	12	1.2	3.5	>93%	5	12	12	7	1.3	5
2020	8	1.4	4	>94%	3.3	14.1	13.4	4.7	1.6	5.7

Challenges

size cost weight

Research Focus Areas

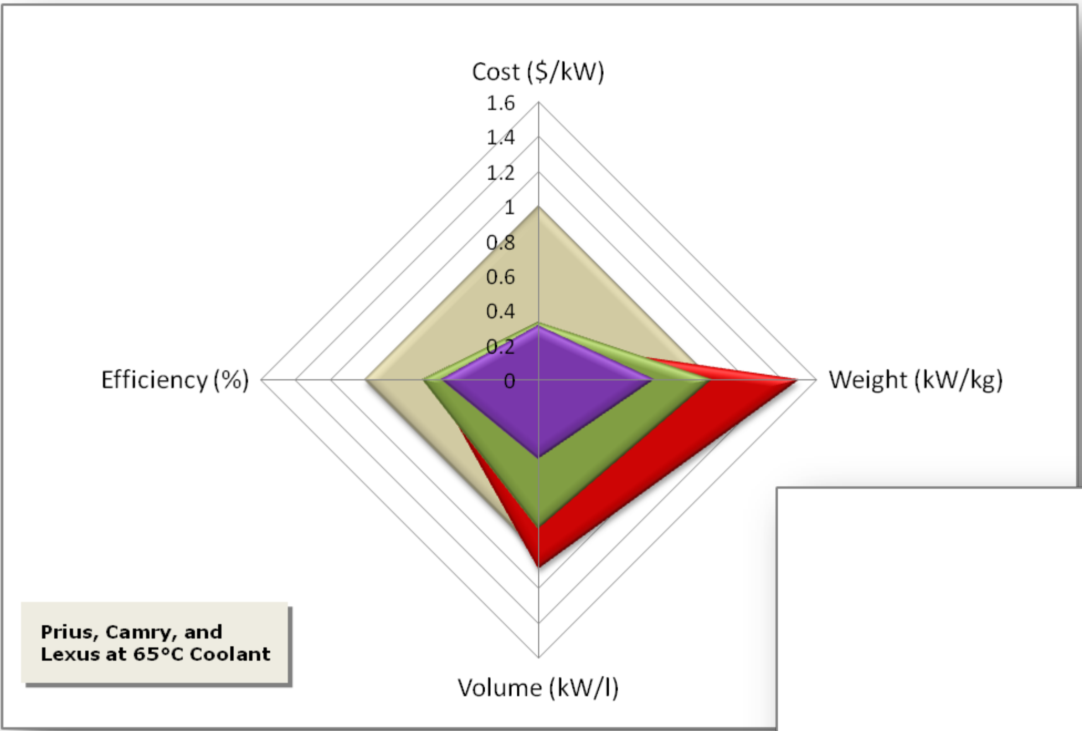
Power Electronics
- inverters and converters
- innovative topologies
- packaging
- temperature-tolerant devices
- capacitors

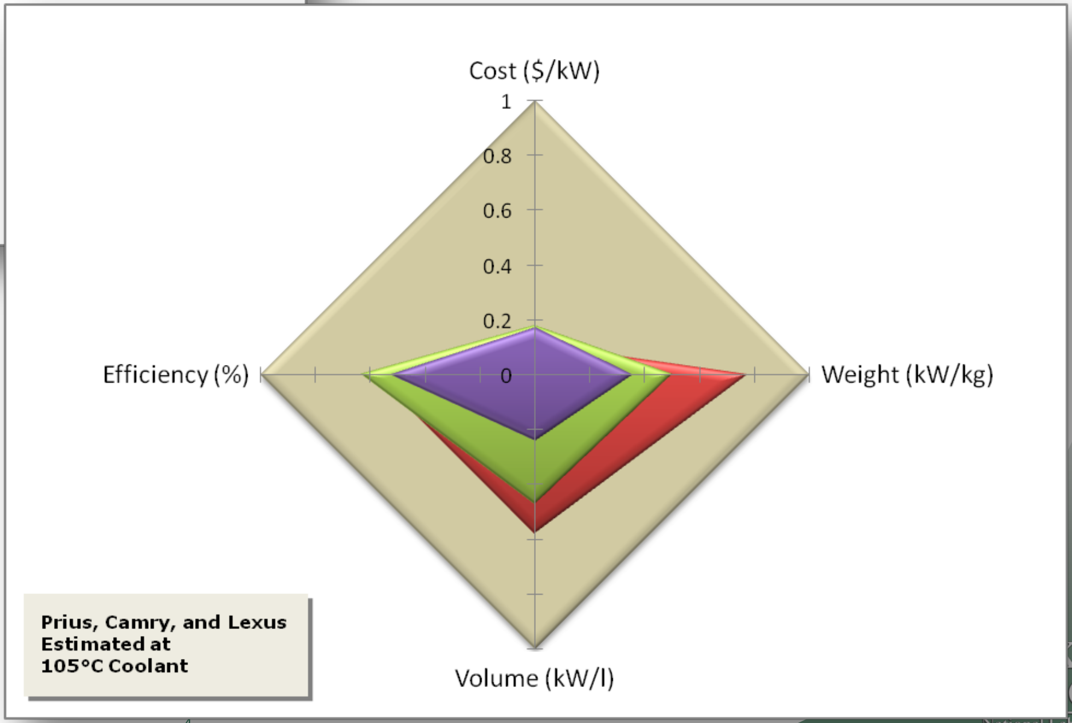
Motors
- permanent magnet (PM) motors
- high performance non-PM motors
- permanent magnets

PEEM Thermal Control
- heat transfer techniques
- materials
- area enhancement
- alternative coolants

Integrated Traction Drive System
- benchmarking technologies
- innovative system designs

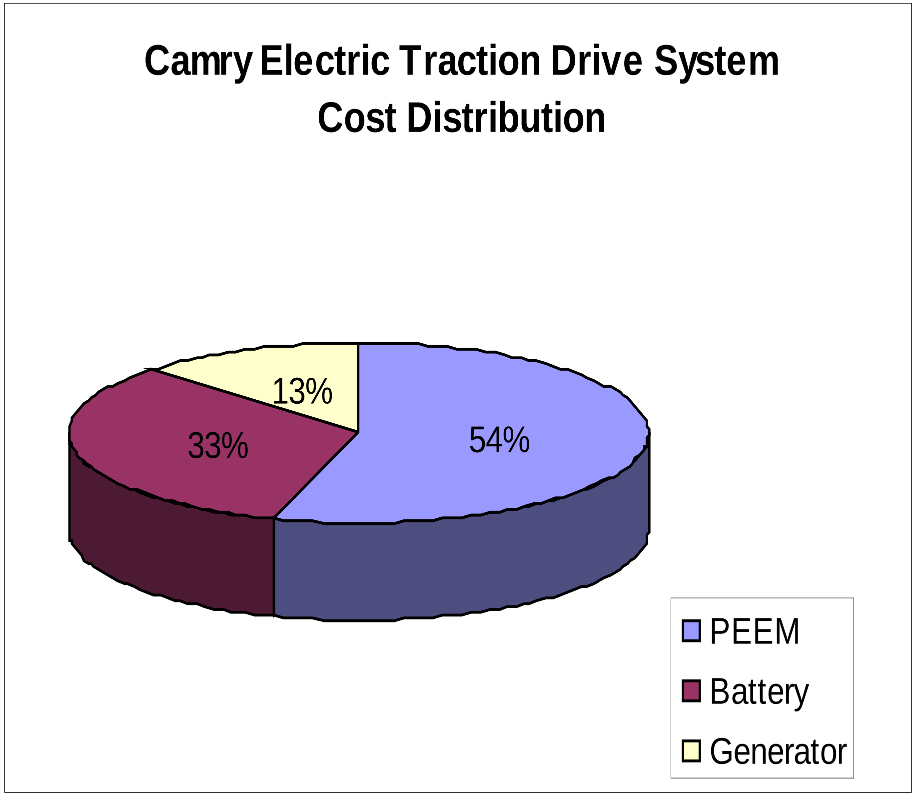
Today's On-Road Technology Shows That Significant Challenges Exist

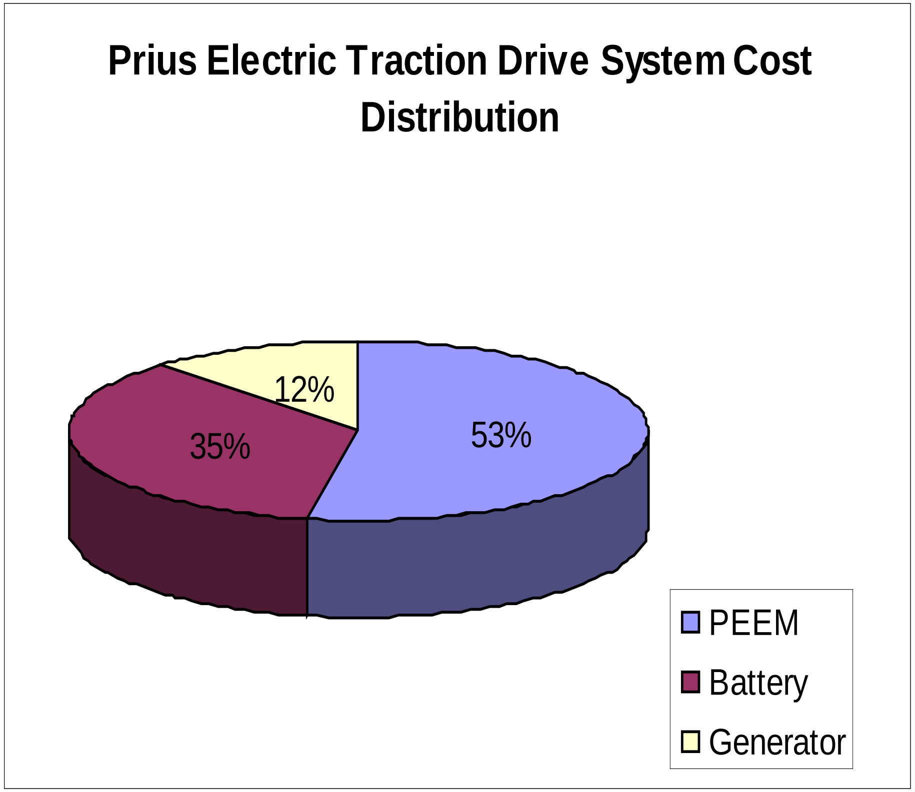




- 2015 Targets
- Lexus (110 kW)
- Camry (70 kW)
- Prius (50 kW)

PEEM is Important Cost Component in Current HEVs



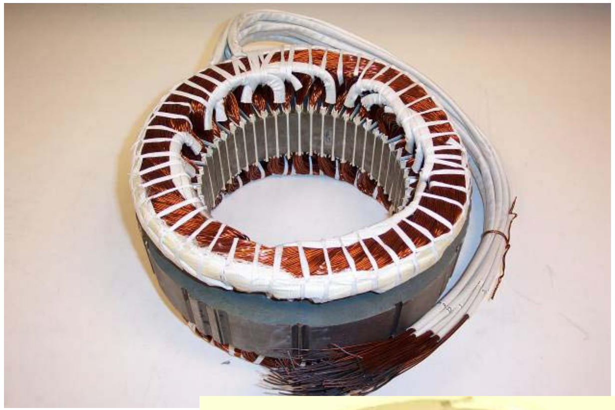


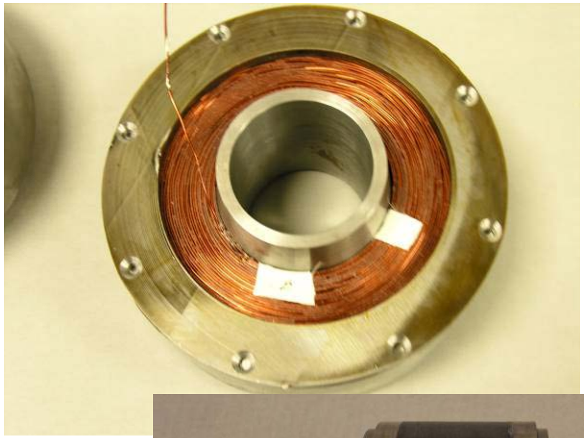
For PHEV application PEEM cost projected to be 15-40% depending on vehicle design

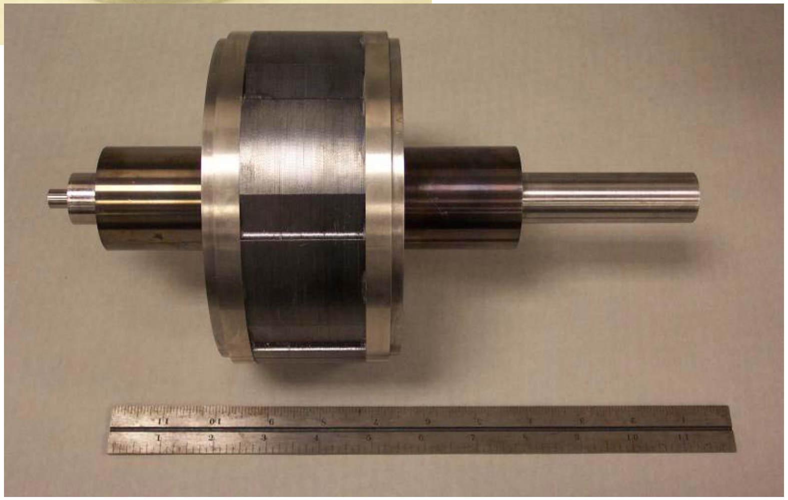
Sources:
1. K.G. Duleep, Technology and Cost of MY 2007 Toyota Camry HEV, ORNL/TM-2007/132, 2007
2. Rick McGill's Toyota, Knoxville, TN

Completed Technology Development

16,000 RPM IPM Rotor







- **Concept provides stationary field excitation at both ends of the rotor**
- **Enables the elimination of the boost converter and the decrease of core losses at high speeds**
- **At low speed, the field can be enhanced.**
- **Produces high starting and accelerating torque and better performance over the entire speed range.**

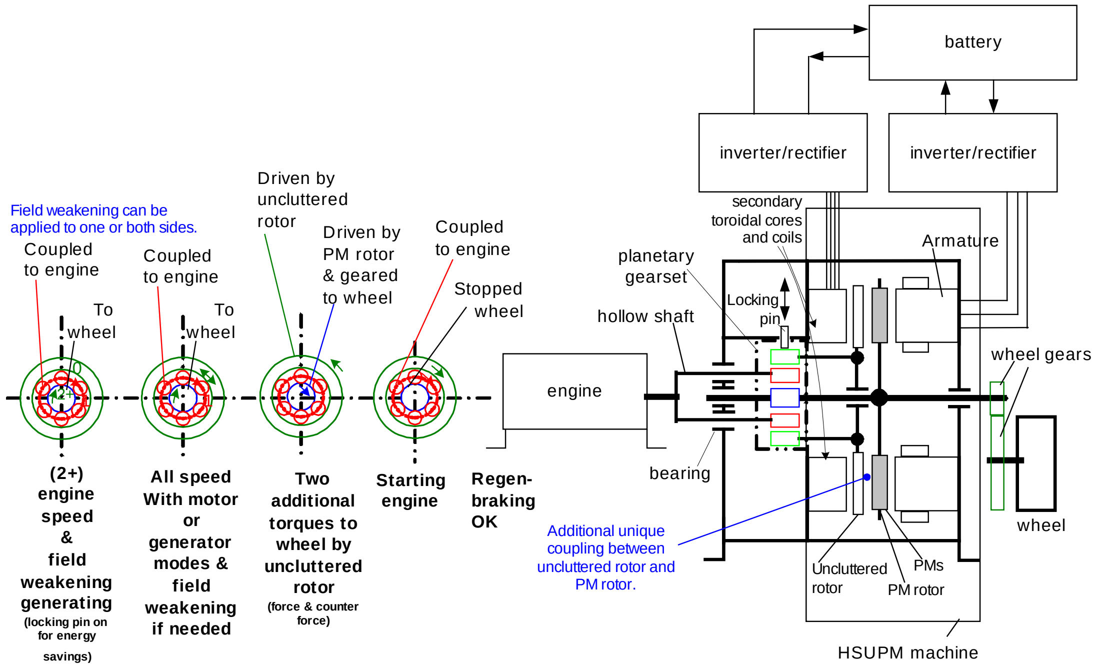
Integrated Machine Design

The Technology

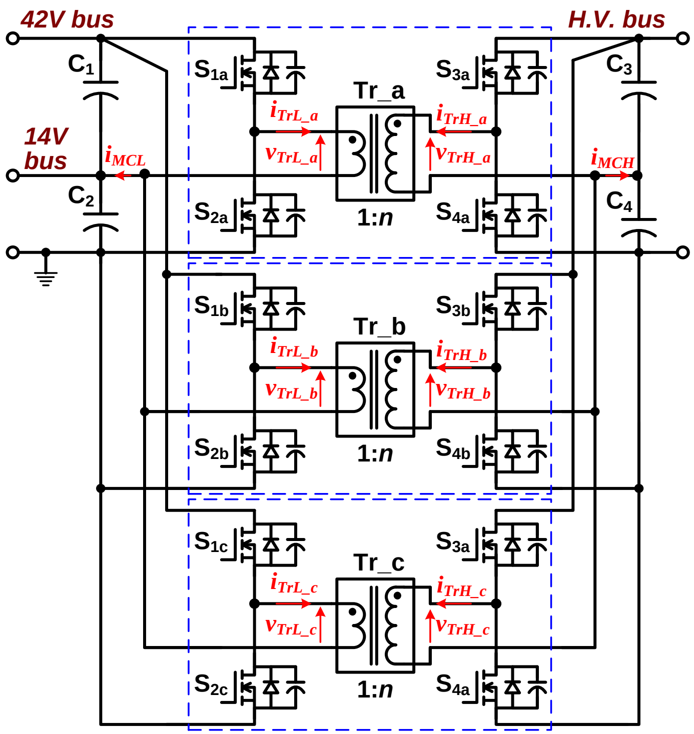
The machine contains an uncluttered rotor and a PM rotor. The two rotors and the engine are coupled to a planetary gear set.

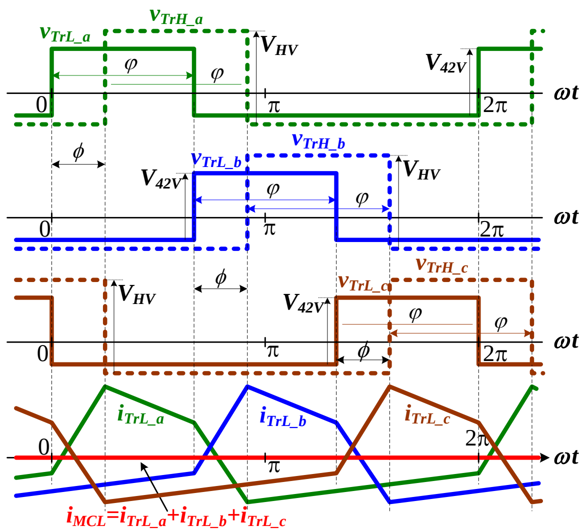
The PM rotor and the armature form one machine while the uncluttered rotor with the PM rotor forms a second machine.

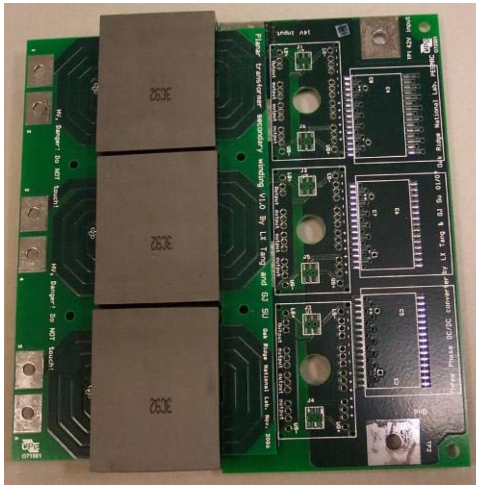
As the armature drives the PM rotor to produce torque to drive the wheel, the uncluttered rotor can also drive the PM rotor for a higher wheel torque. The uncluttered rotor sees a reaction torque that further increases the wheel torque via the gears.



Triple Voltage DC/DC Converter

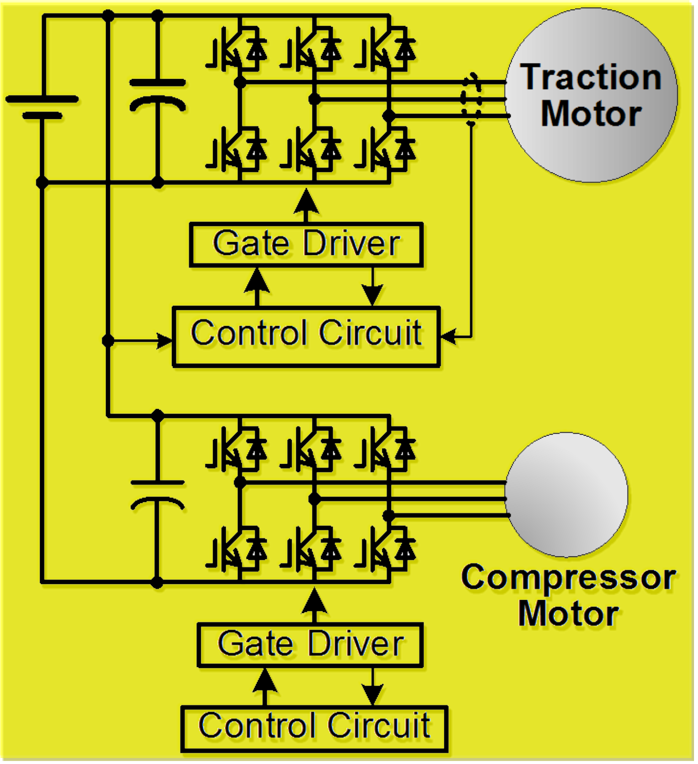






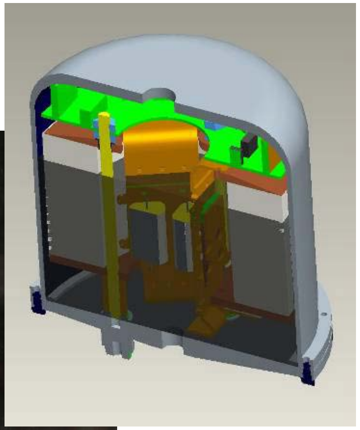
- Employ a 3-phase configuration
  - Reduce dc bus capacitor requirements (i_{MCL}, i_{MCH}→0)
  - Increase dynamic response
  - Increase power density by spreading heat sources

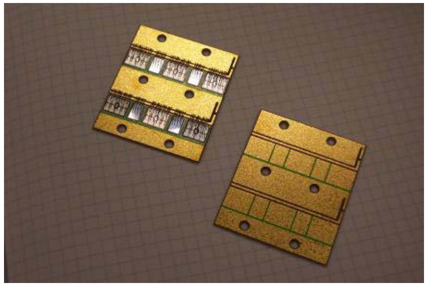
Integrated Inverters for HEVs and FCVs



- **Background**
  - Electrical motor driven compressors for HVAC are favored in HEVs because of their superior performances over the conventional engine driven counterparts
    - efficient variable speed operation
    - flexible packaging
    - low refrigerant emissions
  - FCVs require an electrical motor driven compressor
  - Existing HEVs employ two separate inverters
  - Purpose of the project is to reduce the system cost

Direct-Contact, Two-Phase Cooled Inverter





FY09 Portfolio

FY09 APEEM Focus - *Power Electronics*

FY09 Emphasis

- **Reduce Cost**
  - **Eliminate separate boost converter**
  - **Reduce capacitor size**
- **Enable High-Temperature Operation**
  - **Switches**
  - **Gate drives**
  - **Passive components (e.g., capacitors)**
  - **Packages**
- **Charging System for PHEVs**

FY09 Approaches

- **Inverter Topologies**
  - **Integrate multiple functionality into one unit (e.g., boost converter and inverter)**
  - **Minimize/eliminate need for DC bus capacitor**
- **Inverter Packaging**
  - **Design to accommodate high temperature coolants**
- **High-Temperature, High-Performance Components**
  - **Gate drives**
  - **Capacitors**
  - **Switches**

FY09 APEEM Focus - *Electrical Machines*

FY09 Emphasis

- **Reduce motor cost**
- **Enhance security of raw material supply**
  - **Reduce dependency on rare earth materials where China has monopoly**
- **Reduce PE cost by eliminating need for voltage boost**

FY09 Approaches

- **High-Speed designs using no PM material**
  - **No boost needed**
  - **Eliminate cost/supply security concern of PM**
- **High performance IPM**
- **Magnet effort to reduce cost and improve temperature capability**

Current Source Inverter for HEVs and FCVs

Research Focus Area: Power Electronics
➔ innovative topology
➔ innovative packaging

Projected Benefits

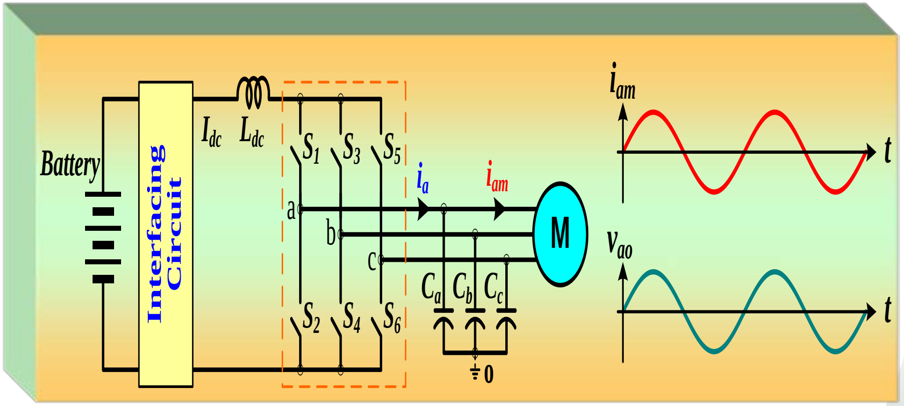
- Reduce cost and volume by 25% compared to standard voltage source inverter (VSI)
- Reduce DC link bus capacitor size and cost by >75% (caps about 25% of cost and 33% of volume of VSI)
- Eliminate external boost converter by incorporating 3X boost in inverter ($325 savings)
- Enable high temperature operation

Objectives

- Develop a 55 kW current source inverter prototype to:
  - integrate boost converter and inverter functionality
  - be capable of using a low voltage battery and controlling a PM motor
  - be capable of regeneration function
  - use topology that improves fault tolerance
  - substantially reduce the capacitor requirements

FY09 Focus

- Design hardware of a 55 kW inverter
- Design DSP control and gate driver PCBs
- Fabricate prototype
- Conduct preliminary testing of the prototype



High-Temperature, High-Voltage Fully Integrated Gate Driver Circuit

Research Focus Area: Power Electronics
➔ temperature-tolerant devices

Projected Benefits

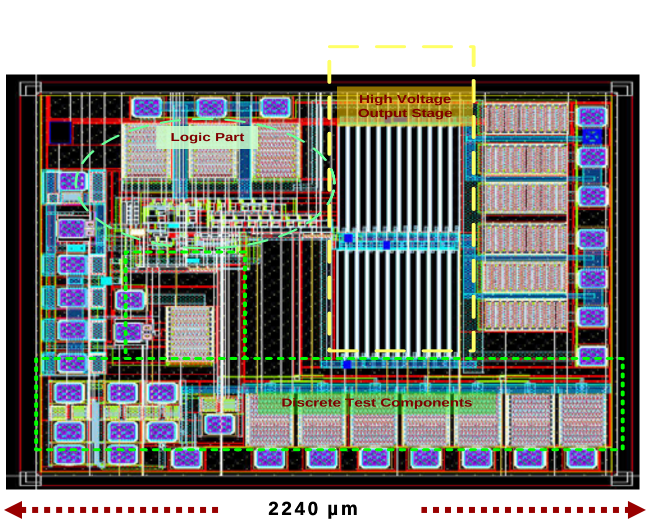
- Silicon on insulator (SOI) gate drive electronics enable high temperature operation

FY09 Focus

- Demonstrate a fully integrated, reliable, high-temperature, high-voltage SOI gate driver circuit capable of driving SiC-based MOSFET and JFET power switches at 200°C ambient temperature
- Incorporate greater functionality (voltage regulator, fault current detection and temperature sensor) on chip

Objectives

- Develop a “universal” SOI-based high-temperature, high-voltage gate driver
  - Function from -40°C to 200°C ambient without heat sinks or cooling mechanisms
  - Capable of driving various types of SiC switches



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Utilizing the Traction Drive Power Electronics System to Provide Plug-in Capability for HEVs

Research Focus Area: Power Electronics
➔ innovative topology

Projected Benefits

- Use traction drive system power electronics and motor windings for charging
  - Minimize components for charging
  - Provide rapid charging and low-power charging capability from the same system
- Provide cost and volume reduction of 90% over existing standalone chargers

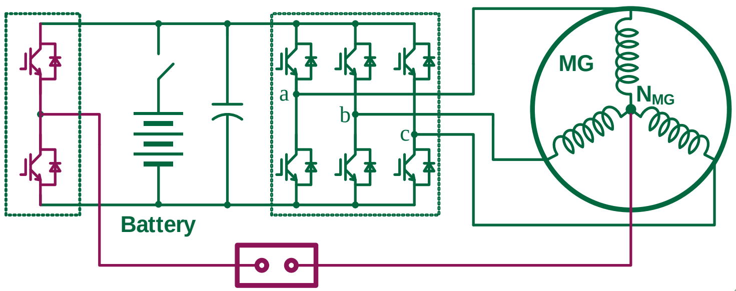
FY09 Focus

- Modify the 55 kW inverter prototype built in FY08 to incorporate mobile power generation capability
- Assure consistency with the development in codes and standards for smart charging

Objectives

- Develop a 55 kW prototype capable of:
  - both overnight or rapid charging at greater than 20 kW
  - 90% reduction in cost and volume compared to standalone battery chargers
  - mobile power generation

For HEVs using single inverter and motor



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Wide Bandgap Materials

Research Focus Area: Power Electronics

➔ temperature-tolerant devices

➔ innovative topologies

Projected Benefits

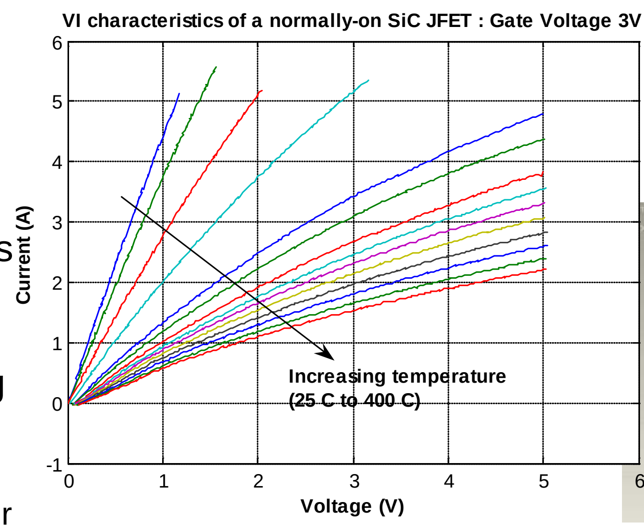
- Wide bandgap (WBG) device characteristics
  - Faster switching times (nanosecond vs. microsecond for Si devices)
  - Higher junction temperatures (500°C compared to 175°C for Si)
  - Higher frequencies (up to MHz vs kHz for Si)
- Allows power density and specific power levels exceeding 20 kW/kg and 20 kW/L, respectively for inverters

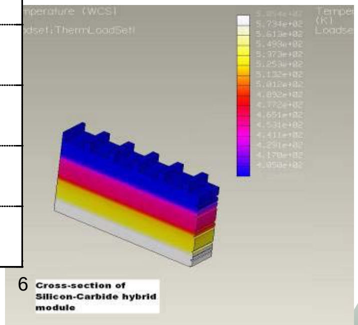
Objectives

- Monitor the state-of-the-art in WBG materials and assess their impact on electric traction drive system design
- Develop a novel inverter design fully utilizing the advantages of SiC devices that will achieve:
  - 140°C ambient temperature operation with air cooling
  - greater than 98% efficiency
  - power density of 24 kW/kg

FY09 Focus

- Characterize new devices as they become available; utilize them in simulations to ascertain their benefits in inverters/converters
- Perform a feasibility study of the concepts developed in FY08 for an air cooled, SiC-based traction inverter





FEA results for the SiC hybrid IPMs heat flow analyses

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Segmented Drive System with a Small DC Bus Capacitor

Research Focus Area: Power Electronics
➔ innovative topology

Projected Benefits

- Reduce the inverter bus capacitance by 50% or more (capacitor is 33% of volume and 25% of cost)
- Reduce battery losses and improve battery lifetime by minimizing battery ripple current
- Reduce switching losses by 50% or more
  - Reduce motor torque ripple
  - More efficient drive system

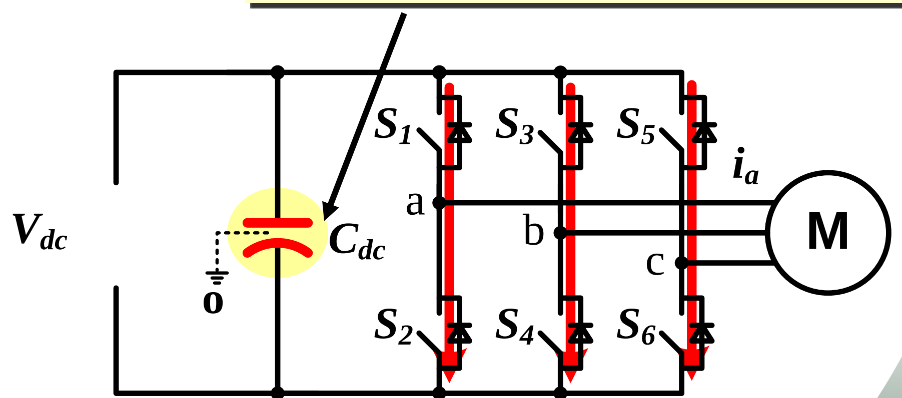
FY09 Focus

- Assess the effect of various pulse width modulation (PWM) schemes on the reduction of ripple current via simulation study
- Complete conceptual design for a 55 kW inverter prototype

Objectives

- Develop a 55 kW inverter prototype that can:
  – reduce the bus capacitance by at least 60%
  – reduce motor torque ripple up to 50%
  – reduce switching losses by 50%

- **Costly and bulky**
- **A major hurdle for high-temperature operations**



An Active Filter Approach to the Reduction of the DC Link Capacitor

Research Focus Area: Power Electronics
➔ innovative topology

Projected Benefits

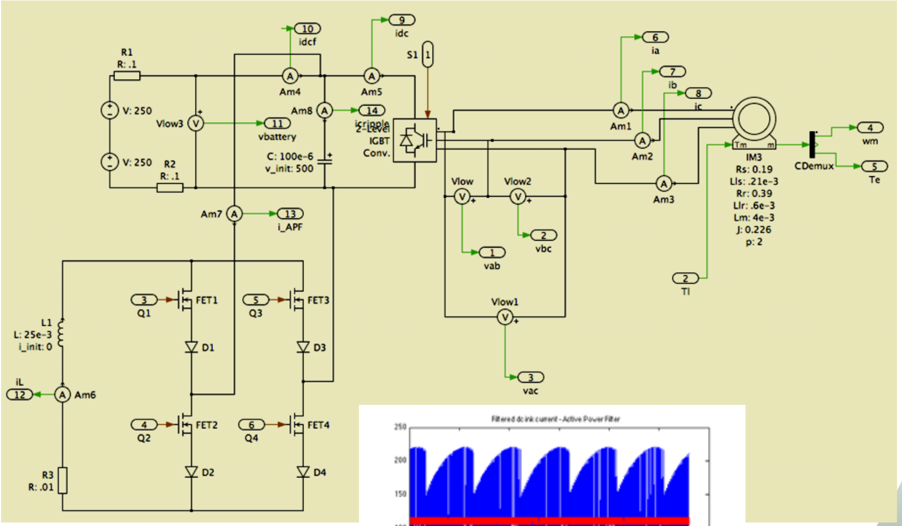
- Eliminate DC capacitor requirements (cap is 33% of inverter volume and 25% of cost)
- Enables high-temperature operation earlier
  - Progress on high-temperature switches appears more promising than high-temperature capacitors

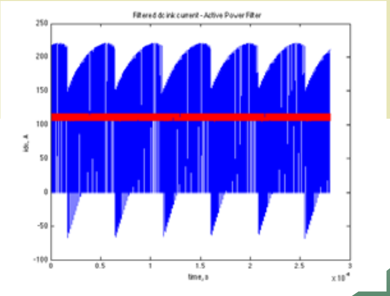
FY09 Focus

- Design and build an active filter to demonstrate:
  - the successful operation of the active filter replacing the DC link capacitor
  - the reduction in the weight, volume, and cost of the traction inverter

Objectives

- Develop an active filter to replace the DC link capacitor to enable more cost effective high temperature operation achieving:
  - 50% reduction in weight
  - 50% reduction in volume





Uncluttered Rotor Machine Without Permanent Magnets - U Machine

Research Focus Area: Motors
➔ high performance non-PM motors

Projected Benefits

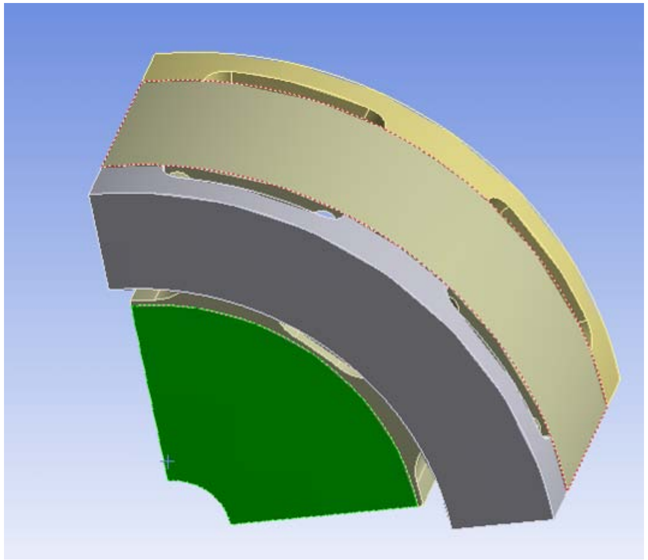
- Concept achieves the benefits of permanent magnet (PM) machines without rare earth magnets
  - Reducing dependency on China for PMs
  - 20% cost reduction
  - 3% overall efficiency increase

Objectives

- Develop a traction motor without PMs achieving specific power and power density similar to PM machines but at lower cost and with higher efficiency

FY09 Focus

- Design motor by conducting electromagnetic and mechanical simulations



New Class of Switched Reluctance (SR) Motors

Research Focus Area: Motors
➔ high performance non-PM motors

Projected Benefits

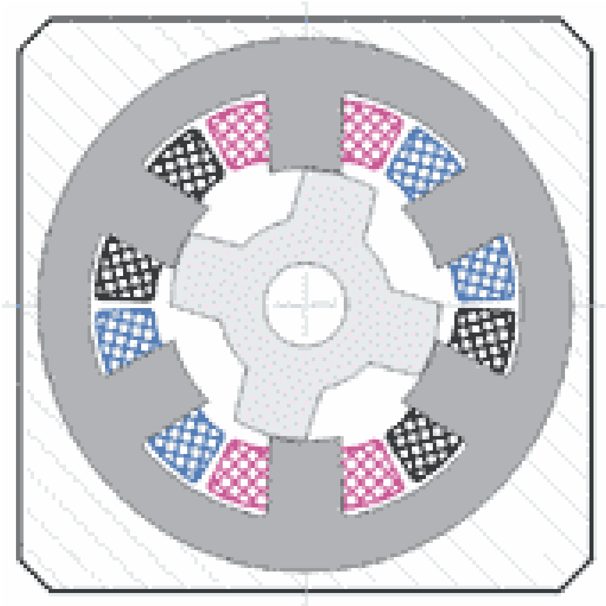
- Eliminate PMs in motor
  - Reduce dependency on China for PMs
- Overcome torque cogging of traditional SRM
- Achieve:
  - power density of 5-7.5 kW/L
  - specific power of 1-2.2 kW/kg
  - cost of $7-9.5/kW

Objectives

- Design and develop a SR motor of at least 55 kW peak that incorporates a novel flux path design with an enhanced air gap technique and uses a continuous conduction control method.
- Develop a high power density motor without permanent magnets or the limitations of conventional SR motors

FY09 Focus

- Develop base SR motor
- Verify though thorough finite element analyses and basic feasibility assessments
- Design novel converter topology for the base SR motor design



Direct-Cooled Power Electronics Substrate

Research Focus Area: PEEM Thermal Control

➔ heat transfer techniques
➔ materials
➔ area enhancements

Projected Benefits

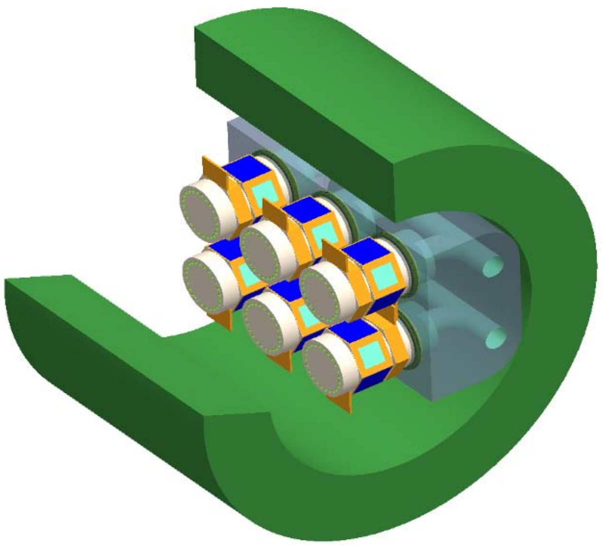
- Packaging concept with reduced thermal resistance
  - Enables use of 105ºC coolant for silicon-based electronics
  - Achieves inverter power density of 8 kW/L

FY09 Focus

- Finalize the design requirements for the selected architecture for the electronics substrate
- Fabricate and assemble a single leg prototype design
- Instrument and test the prototype design using 105°C WEG coolant

Objectives

- Develop a power electronics substrate that is directly cooled with water/ethylene glycol (WEG) coolant that eliminates the base plate, TIM, and cold plate from traditional inverter package and enables novel three-dimensional inverter designs



Future R&D Directed at Improved Technology

- **Innovative PE packaging and topology to reduce volume and cut cost**
- **Reducing need for capacitor**
- **Motor concepts to reduce/ eliminate costly PMs and preserve performance**
- **Working with industry to increase manufacturability of modules**