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Susan Rogers
Advanced Power Electronics and Electric Machines (APEEM) R&D Program Overview

Office Of Vehicle Technologies

Susan Rogers

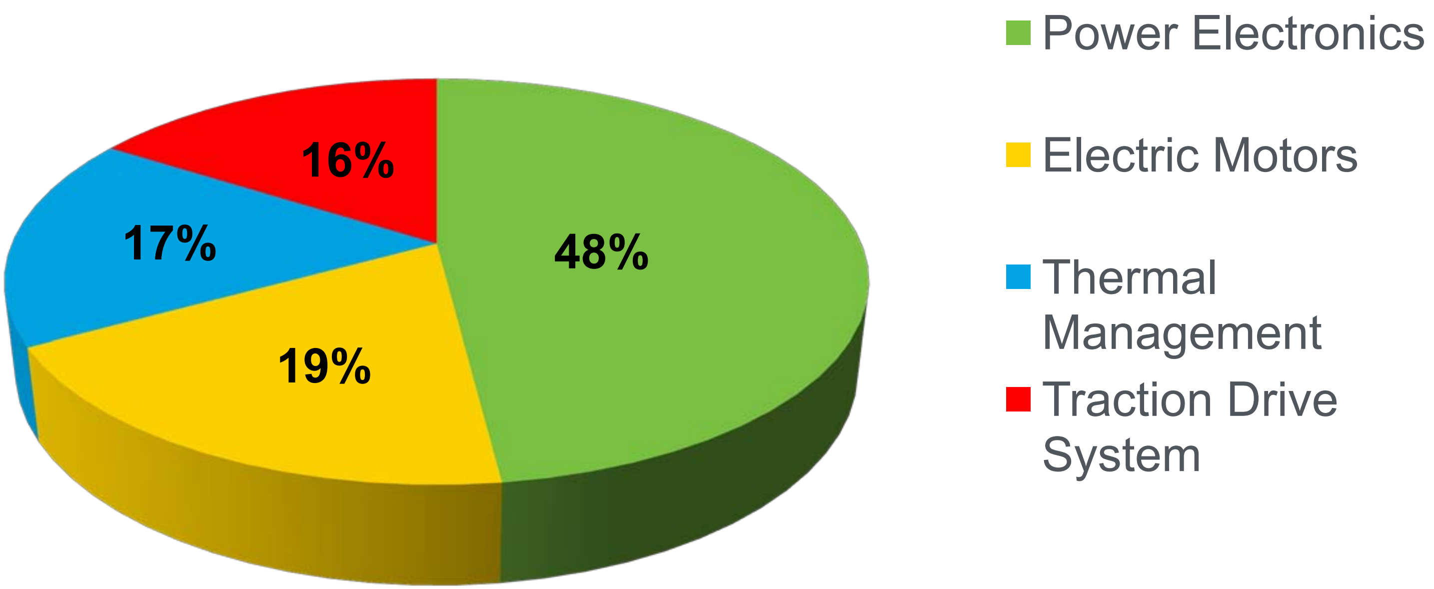
Technology Development Manager

2010 DOE Hydrogen Program and Vehicle Technologies AMR

June 10, 2010

Project ID: APE000

Advanced Power Electronics FY2010 $22,294,764



APEEM Activity Covers the Full Range of Vehicle Electrification Applications

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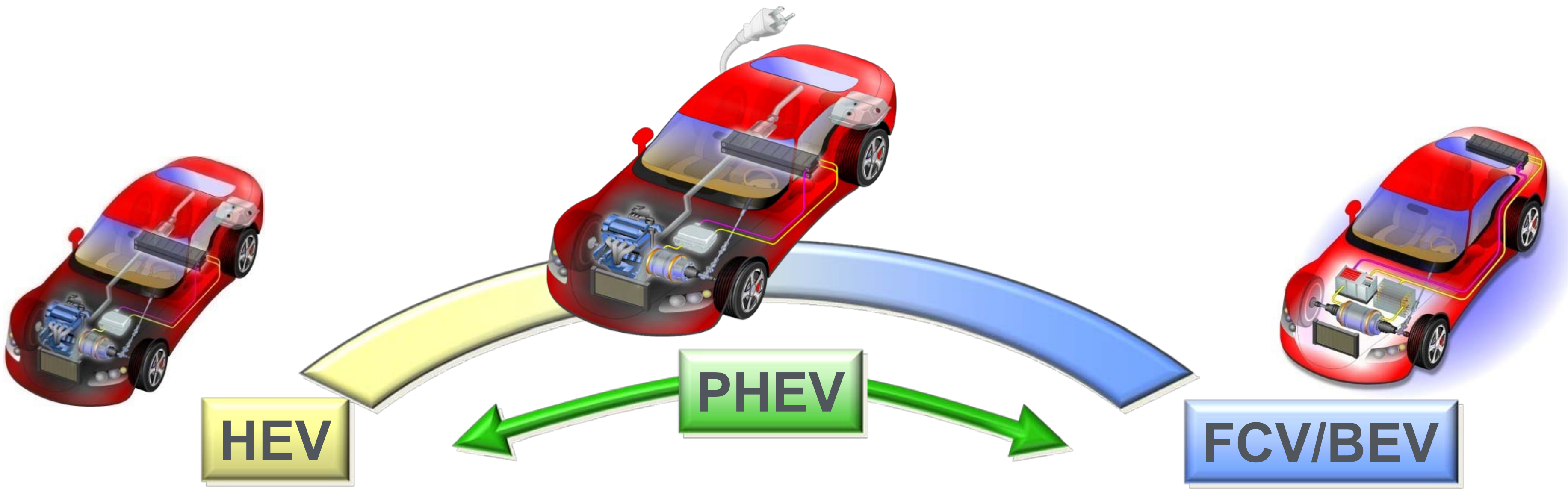
APEEM (Advanced Power Electronics and Electric Machines)



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

APEEM Components are Critical and Unique to Electric Drive Vehicles

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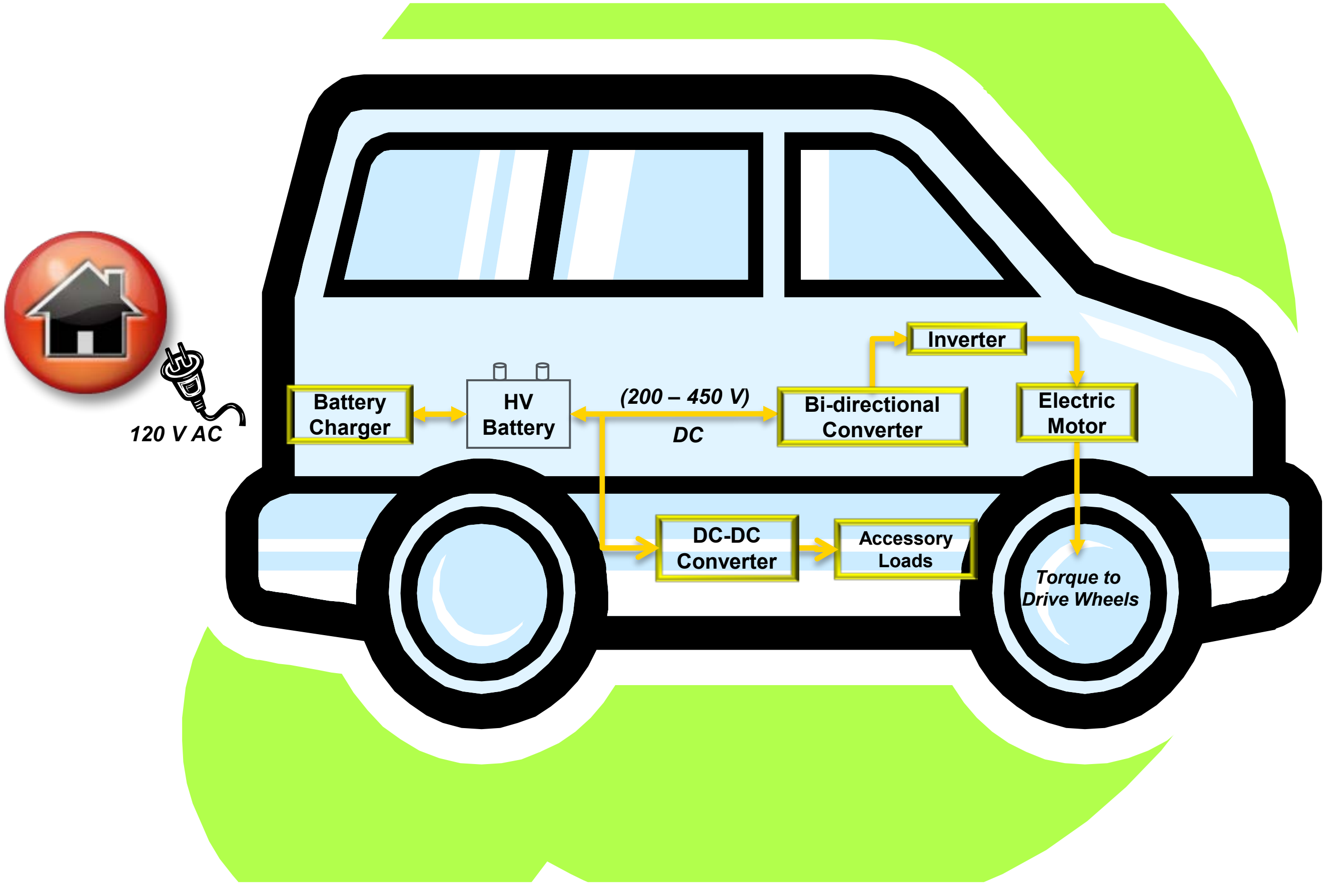


Current power electronics and electric machine technologies must advance to achieve lower cost, smaller and lighter footprints, and higher efficiency to meet marketplace demands.

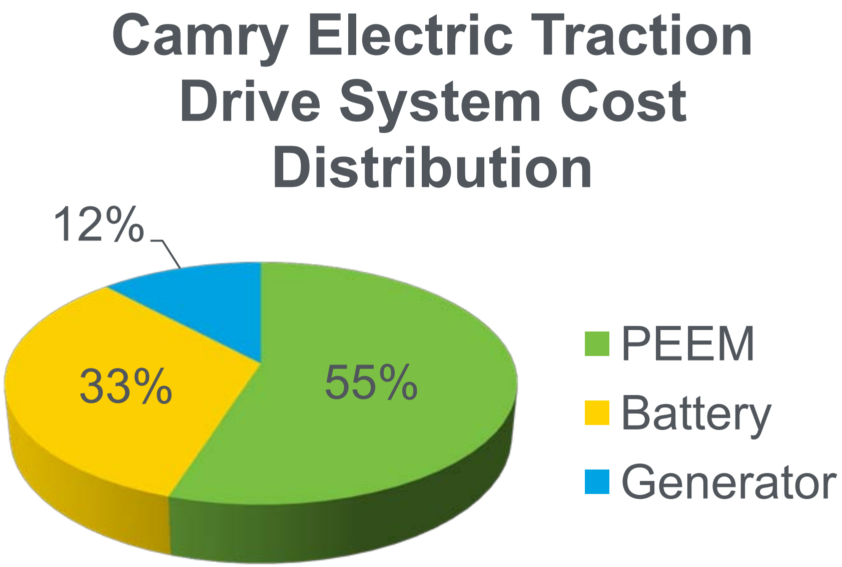
Traction Drive Components
(varies with vehicle architectures)

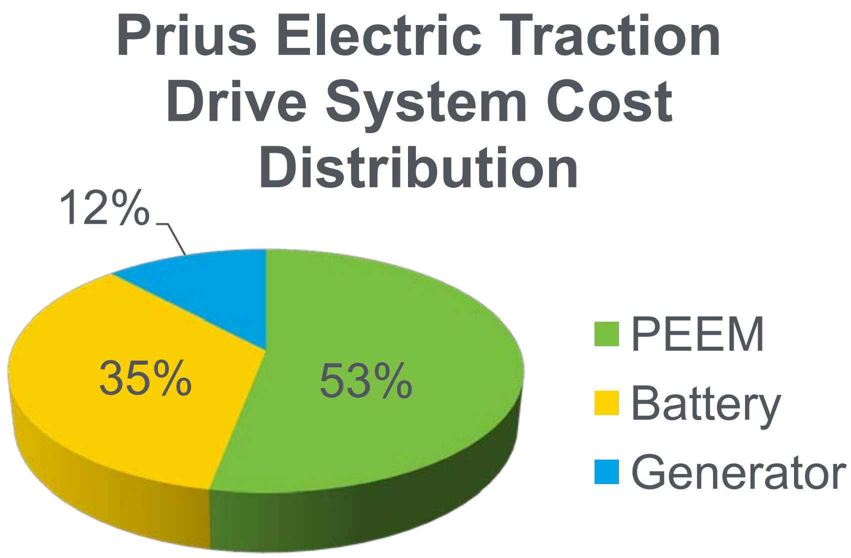
- ***Battery charger*** – PEVs vehicles require a battery charger.
- ***Bi-directional converter*** – step up the battery voltage for the motor and step down the bus voltage for regeneration to the battery.
- ***Inverter*** – convert direct current (DC) to alternating current (AC) to provide phased power for vehicle traction motors and generators.
- ***Electric motor*** - provide power for driving.

Power Management
(varies with vehicle architectures)

- ***DC-DC converter*** – provides power to auxiliary vehicle buses to operate accessories, lighting, air conditioning, brake assist, power steering, etc.

PEEM is Important Cost Component in Electric Drive for HEVs





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

APEEM Research Targets, Challenges, and Research Areas

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Reduce Dependence on Oil

Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life

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 Areas

Power Electronics

- Innovative topologies
- Temperature-tolerant devices
- Packaging
- Capacitors
- Vehicle charging

Electric Machines

- Permanent magnet (PM) motors
- Magnetic materials
- High-performance non-PM motors
- New materials

PEEM Thermal Management

- Thermal system integration
- Heat transfer technologies
- Thermal stress and reliability

Traction Drive System

- Benchmarking technologies
- Innovative system designs

Research Focus Areas

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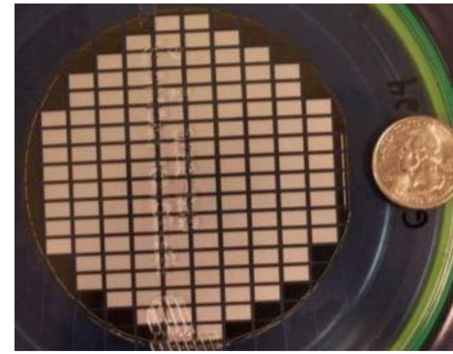
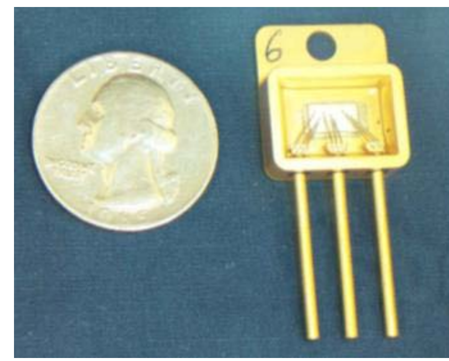
Power Electronics

Focus Area	Benefits
New Topologies for Inverters and Converters *(Decrease size, cost, and improve reliability)*	Avenue to achieve significant reductions in PE weight, volume, and cost and improve performance . • Reduce capacitance need by 50% to 90% yielding inverter volume reduction of 20% to 35% and cost reduction. • Reduce part count by integrating functionality thus reducing inverter size and cost and increasing reliability. • Reduce inductance, minimize electromagnetic interference (EMI) and ripple, reduce current through switches all result in reducing cost.
Temperature – Tolerant Devices *(Wide Bandgap Semiconductors)*	Produces higher reliability, higher efficiency, and enables high-temperature operation.
Packaging *(Greatly reduced PE size, cost, and weight with higher reliability)*	Provides opportunity for greatly decreased size and cost • Module packaging can reduce inverter size by 50% or more, cost by 40%, enable Si devices to be used with high-temp coolant for cost savings of 25%, and enable use of air cooling. • Device packaging to reduce stray inductance, improve reliability and enable module packaging options. When coupled with heat transfer improvements gains are enhanced.
Capacitors *(Reduced inverter volume)*	Improved performance can reduce capacitor size by 25% reducing inverter size by 10% and increase temperature limit.
Vehicle Charging *(Provide function at minimum cost)*	Provide the vehicle charging function in a policy neutral manner at virtually no additional cost with bi-directional capability.



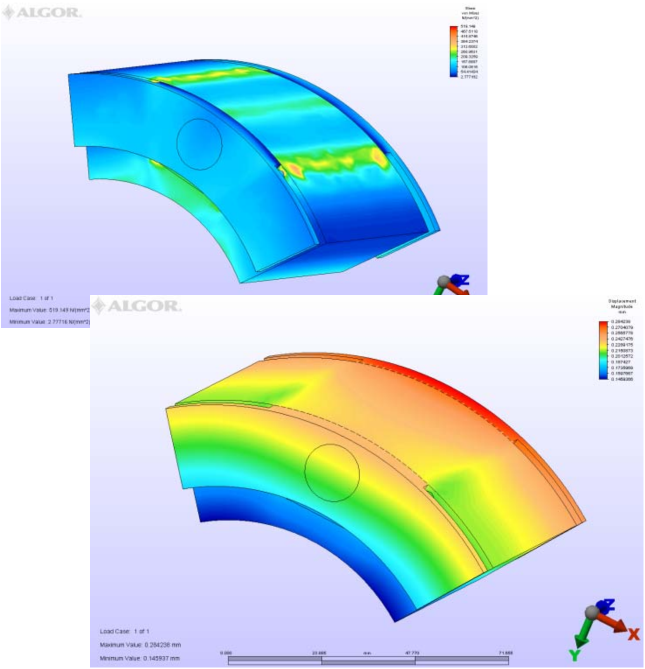


Wide Bandgap Semiconductors

Research Focus Areas

Electric Machines

Focus Area	Benefits
High Performance Permanent Magnet (PM) Motors ***(Reduce cost and maintain performance)***	Cost is major concern for interior permanent magnet (IPM) motor (cost reductions of 75% are required to meet 2020 target). Work on all aspects of motor design may reduce cost by 25% to 40%.
Magnetic Materials ***(Reduce cost and increase temperature)***	Magnetic material cost 50 to 75% of the motor targets for 2015 and 2020, respectively. Work focusing on reducing cost and increasing temperature capability could reduce motor cost by 5 to 15%.
Non-PM Motors ***(Greatly reduce cost in motor and power electronics)***	Non-PM machine technology matching the performance of IPM machines yields the greatest opportunity for motor and system cost reduction. • PM cost of about $200 is about 75% of the 2020 motor cost target, eliminating PMs reduce motor cost by 30%. • Back emf of IPM requires boost converter which adds cost component to PE greater than 2015 or 2020 cost target, eliminating boost saves 20% in PE cost. • Poor power factor of IPM cause larger currents increasing size and cost of PE, save 15% PE cost. • Increase the constant power speed range (CPSR) to 8:1 (current systems are 4:1) to effect savings in transmission.
New Materials ***(Reduce motor cost)***	Other materials in motor must be addressed because PMs are about 30% of current IPM cost. New materials for laminations, cores, etc. could save 20% of motor cost.



Novel Flux Coupling Machine w/o PMs

Research Focus Areas

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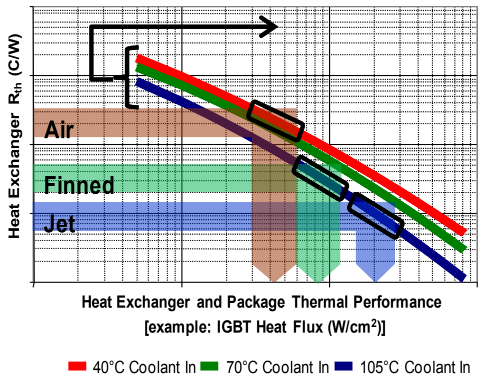
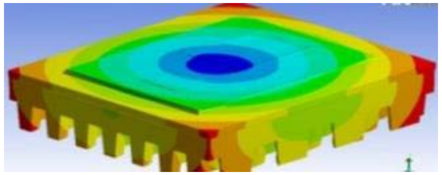
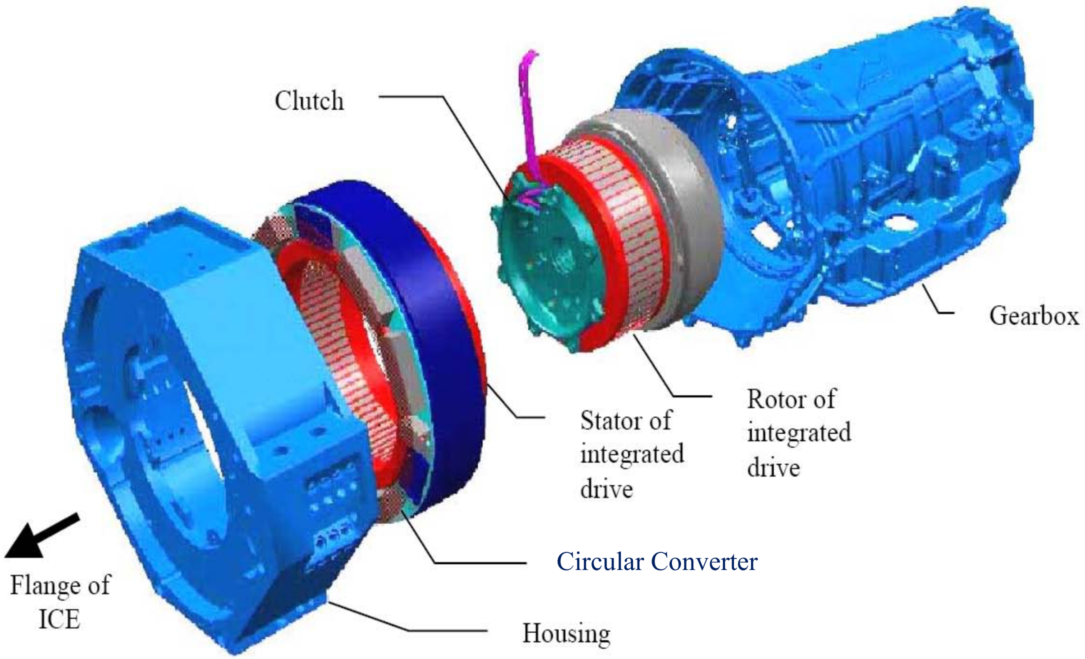
Thermal Management	
Focus Area	**Benefits**
Thermal System Integration *(Technology integration at lower system cost)*	• Guides thermal research objectives. • Defines thermal requirements. • Facilitates viable thermal solutions. • Links thermal technologies to electric traction drive systems.
Heat Transfer Technologies *(Enable increased power density at lower cost)*	• Detailed characterization of the thermal performance of candidate heat transfer technologies. • Provides experimental data and fundamental thermal models. • Develops and demonstrates promising technologies to enable program targets.
Thermal Stress and Reliability *(Improve reliability of new technologies)*	• Develops advanced predictive thermal stress and reliability modeling tools. • Application will guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals.

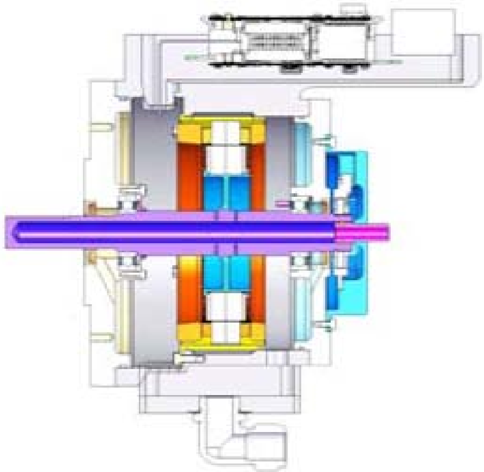




Research Focus Areas

Traction Drive System	
Focus Area	**Benefits**
Innovative Systems Design *(Meet future system targets)*	Modular and integrated solutions to meet size, weight, and cost 2015 and 2020 targets for drive system.
Benchmarking *(Program planning)*	Vital to program planning and project performance activities.





Integrated Motor and Inverter Concept

FY10 Emphasis

- **Inverter topologies to reduce volume and cost**
  - Reduce capacitor requirements
  - Integrate functionality
- **High-temperature components, packaging, and reliability for long-term transformation technologies**
- **Motor research addressing limitation of rare earth materials**
  - Advanced magnet materials
  - Non-permanent magnet motor concepts
- **Thermal management technologies to reduce volume and enhance thermal reliability**

FY10 Power Electronics Focus Responsive to Evolving Needs

- **Initially power electronics (PE) only included inverter and focused on voltage source inverter (VSI)**
- **Use of high-speed interior permanent magnet motors (IPMs) added need for boost converter**
- **Increasing cost sensitivity created desire to reduce current and Silicon (Si)**
- **PHEV application added charging function**
- **Desire to reduce cost and volume by eliminating separate cooling loop led to consideration of high-temperature coolants and;**
  - **elevated component temperature tolerance**
  - **packaging innovations**
  - **capacitor advances**

FY10 Emphasis

- **Reduce Cost and Volume**
  - Eliminate separate boost converter
  - Reduce capacitor size
- **Enable High-Temperature Operation**
  - Packages and components
- **Charging System for PHEVs**

FY10 Approaches

- **Inverter Topologies**
  - Integrate multiple functionality into one unit
  - Minimize capacitance need
- **Inverter Packaging**
  - Design to use high-temp coolant
- **High-Temperature Components**
  - Gate drives, capacitors

FY10 Electrical Machines Focus Builds on Evolving Path

- **Initially induction motor favored due to cost consideration**
- **As volume became greater consideration IPM became motor choice because of high power density and efficiency**
- **PM cost and market supply constraints have resulted in reexamination of IPM**

FY10 Emphasis

- **Reduce motor cost and eliminate voltage boost (which also reduces PE cost)**

FY10 Approaches

- **High-Speed designs using no PM material**
  - No boost needed
  - Eliminate cost/supply security concern of PM
  - High-speed results in smaller motor which due to lack of PMs grows
- **High performance IPM**
- **Magnet effort to reduce cost and improve temperature capability**

FY10 Thermal Management Focus Responsive to Developing Needs

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- **Range of vehicle platforms gives rise to coolant temperature range of 65 C to 105 C (liquid) or air cooling**
- **Excessive heat can degrade the performance, life, and reliability of power electronic components**
- **Advanced thermal control technologies are critical to enabling higher power densities and lower system cost**

FY10 Focus

- **Enable increased power density and lower system cost**
- **Increase the rate of heat transfer**
- **Decrease thermal resistance**
- **Evaluate impacts on life and reliability early in the development process**

FY10 Approaches

- **Conduct analysis of thermal stress and fatigue life of APEEM packages**
- **Characterize and develop advanced liquid cooling technologies**
- **Complete assessment of state-of-the-art thermal interface materials**
- **Demonstrate advanced air-cooling heat transfer and system level performance**

FY10 Systems Focus
Moving to Demo Meeting 2010 Targets

- **Initial emphasis was on discrete power electronics and electric motor modules**
- **Expanded focus towards integration for cost and volume savings**

FY10 Emphasis

- **Document performance of current state-of-art PEEM systems at end-of-life**
- **Develop traction drive system meeting 2010 targets**

FY10 Approach

- **Benchmark end-of-life Prius, Accord, and Camry systems and determine performance degradation**
- **Incorporate PE, EM, and thermal management advances into traction drive system design**
- **Initiating advanced PEEM system development addressing 2015 targets**

APEEM Program Structure

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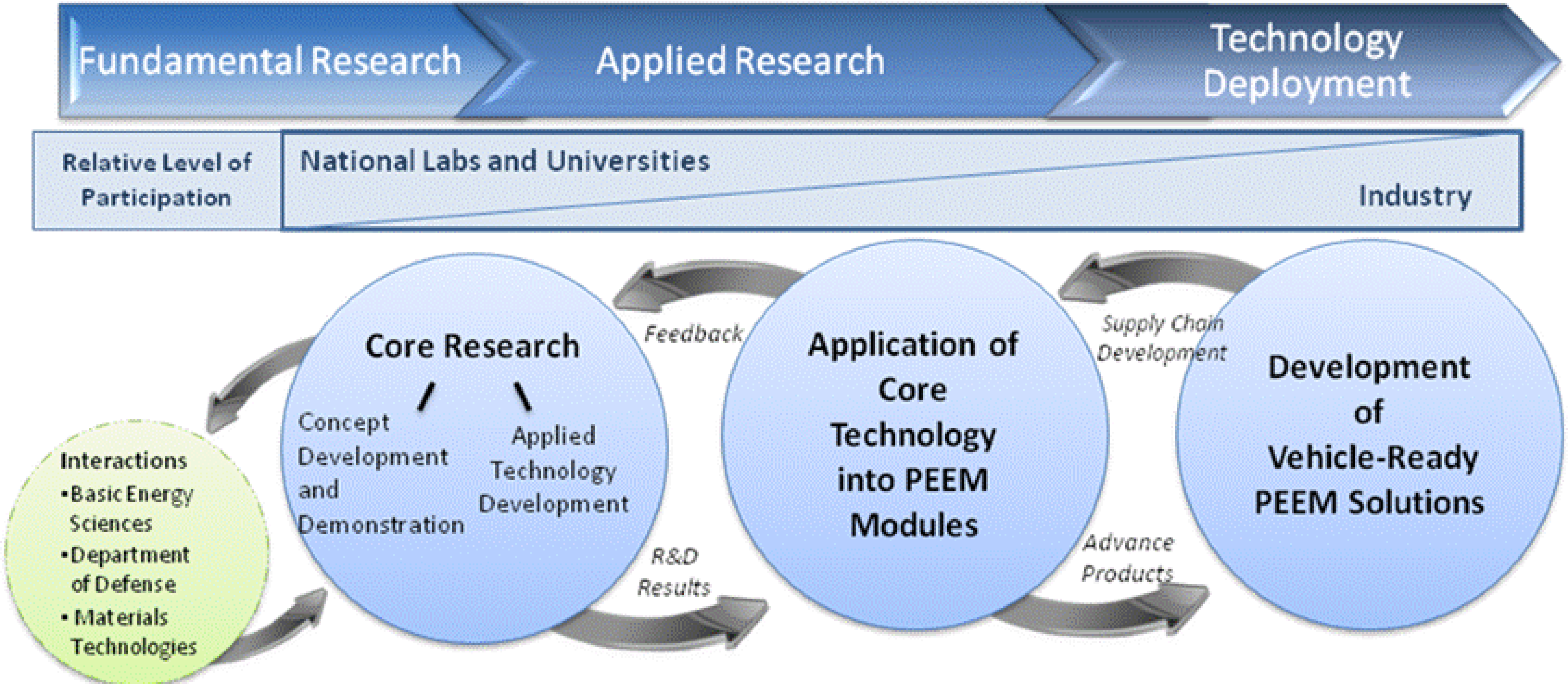

- Develop technology that enables module/system advances

- Integrate core "technologies" into PEEM modules (inverters, converters, etc.)
- Address manufacturing aspects of core technologies
- Facilitate commercialization
- Create industrial champions
- Develop supply chain insertion mechanism

- Develop practical methods for producing inverters, motors, converters, or traction systems that incorporate advanced technologies

Program Flow Advances APEEM Technologies to the Marketplace

Technical Target Input	Technology Development	Module Development
EE Tech Team	*National Laboratories*	*Industry*

Interactions with Others (e.g., IAPG, Office of Science, Solar, Wind)

- **DOE**
- **Chrysler**
- **Ford**
- **General Motors**

FreedomCAR & Fuel Partnership

- **Ames Laboratory**
- **Argonne National Laboratory**
- **Oak Ridge National Laboratory**
- **Sandia National Laboratory**
- **National Renewable Energy Laboratory**
- **NASA**
- **NIST**

- **General Motors**
- **Delphi Automotive Systems**
- **Virginia Tech University**
- **U.S. Hybrid**
- **GE Global Research**

Advancing Power Electronics and Electric Machines

More Fuel Efficient Vehicles on the Road

APEEM Technology Portfolio

- **Entire project portfolio applicable to HEV, PHEV, or FCV/BEV applications; scalability is critical**
- **Cost is most significant gap in electric motors and power electronics**
- **Increasing emphasis on integration, packaging, heat transfer, topologies, reliability, and non-rare earth magnet solutions**

PEEM ARRA Efforts ($500M DOE)

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Company - Location	Manufacturing Focus: (total funding)
Remy, Inc. - Indiana & North Dakota	Hybrid Electric Motors & Controls ($146M)
General Motors Corp. – Maryland & Michigan	Global Rear Wheel Drive Electric (GRE) Drive Units ($278M)
Ford Motor Co. - Michigan	HEV & PHEV Transaxles ($125M)
Magna E-Car Systems of America, Inc. - Indiana & Michigan	Electric Drive Systems ($130M)
Delphi Automotive Systems. LLC - Indiana	Electric Drive Power Electronics ($219M)
Allison Transmission, Inc. - Indiana	Commercial-duty Hybrid Systems ($183M)
UQM Technologies - Colorado	Drive Electronics & Electric Motor/Generator ($90M)
KEMET Corp. - South Carolina	DC Bus Capacitors ($37M)
SBE, Inc. - Vermont	DC Bus Capacitors ($18M)
Powerex, Inc. – Pennsylvania	Semiconductor Devices ($12M)