Overview of the VTO Electric Drive Technologies Program

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Steven Boyd – Technology Manager
Susan Rogers – Technology Manager
The focus of the Electric Drive Technologies R&D activity is to develop technologies and designs to reduce the cost, improve the performance, and increase the reliability of power electronics, electric motors, and other electric propulsion components.

**FY 2015 Budget Allocation**

<table>
<thead>
<tr>
<th></th>
<th>FOAs 45%</th>
<th>Electric Motors 25%</th>
<th>Power Electronics 25%</th>
<th>Testing and Analysis 5%</th>
</tr>
</thead>
</table>

**R&D emphasis accelerates:**
- Adoption of wide bandgap (WBG) semiconductors
- Reduction or elimination of rare earth magnets

**FY15 Funding Opportunity Announcement (FOA) Topics:**
- Vehicle Technologies Incubator
- WBG Power Module Development

<table>
<thead>
<tr>
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<th>FY 2014</th>
<th>FY 2015</th>
<th>FY 2016 Request</th>
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<tbody>
<tr>
<td><strong>$</strong></td>
<td>$ 24 M</td>
<td>$ 21 M</td>
<td>$ 39 M</td>
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EV Everywhere Grand Challenge

A DOE Clean Energy Grand Challenge with the goal of enabling U.S. companies to produce plug-in electric vehicles that are as affordable and convenient for the average American family as today’s gasoline-powered vehicles within the next 10 years (by 2022).
Meeting EV Everywhere Targets Will Significantly Lower PEV 5-year Cost of Ownership (vehicle cost plus fuel)\(^1\)

\(^1\)2022 vehicle cost, plus 5-year fuel (EIA AEO 2013 Reference Cost) expressed in 2012 dollars
Vehicle Weight Reduction
Reduce vehicle weight by nearly 30%
(Includes body, chassis, interior, electric drive components, and compounding weight reductions)

Electric Drive System
Reduce cost from $30/kW in 2012 to $8/kW
(1.4 kW/kg, 4 kW/L, 94% efficiency)

Battery
Reduce cost from $500/kWh in 2012 to $125/kWh
(250 Wh/kg, 400 Wh/L, 2 kW/kg)
Detailed EV Everywhere Targets for Electric Drive System

2012 Electric Drive System
$30/kW, 1.1 kW/kg, 2.6 kW/L
90% system efficiency
(on-road status)
- Discrete Components
- Silicon Semiconductors
- Rare Earth Motor Magnets

2015 Electric Drive System
$12/kW
(R&D status)

2022 Electric Drive System
$8/kW, 1.4 kW/kg, 4.0 kW/L
94% system efficiency
(R&D status)
- Fully Integrated Components
- Wide Bandgap Semiconductors
- Non-rare Earth Motors

4X Cost Reduction
35% Size Reduction
40% Weight Reduction
40% Loss Reduction
Research Partnerships Accelerate Implementation of Innovation

- Integrates innovations
- Commercializes technology
- Creates American jobs
- Reduces emissions
- Saves energy

NATIONAL LABORATORIES
- Engineered materials
- Novel integrated topologies
- Packaging technologies & concepts
- Emerging electronic devices
- Additive manufacturing
- Supercomputing

INDUSTRY
R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

- Reduced energy “costs”
  - Increased efficiency
  - Less losses, heat, size
- Higher power density (smaller volume)
  - Higher switching frequencies
  - Higher temperatures
  - Less cooling needed
- Higher switching frequency
  - Smaller passives
  - Associated decrease in weight, volume, cost
- Lower system cost
  - Higher device cost
  - Lower system cost
  - Potential for future cost reduction in WBG semiconductors

Cost-effectiveness of SiC transistors over IGBTs for HEV inverters based on the entire value chain [1]

R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

Generator provides battery charge during engine-on conditions and is utilized as the engine starter.

Engine delivered torque under acceleration & steady state conditions above 62 mph when battery charge is not required.

Generator provides battery charge during engine-on conditions and is utilized as the engine starter.

Motor delivered torque under silent driving conditions up to 62 mph and provides incremental power driving acceleration.

Motor also provides battery charge during regenerative braking.

R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

Just 1-2% improvement (halving losses) at inverters and boost could improve roundtrip efficiency 3-6%
R&D Focus Area: Wide Bandgap Semiconductors (WBGs)

Materials and processes: WBG packaging, capacitors

100A/1200V all-SiC Phase-leg Module

6.6 kW SiC bidirectional converter

System development and simulation for WBG applications

Inverter efficiency at 325V, 1750 RPM, 20 kHz switching

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Efficiency (%)</th>
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<tbody>
<tr>
<td>5</td>
<td>96.4</td>
</tr>
<tr>
<td>10</td>
<td>97.8</td>
</tr>
<tr>
<td>20</td>
<td>98.5</td>
</tr>
<tr>
<td>30</td>
<td>99.2</td>
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</table>

Component testing and demonstration using WBGs
R&D Focus Area: Non-Rare Earth Motors

- Currently, the vast majority of electric drive vehicles use Rare Earth (RE) Permanent Magnet (PM) motors due to their high efficiency and power density.
- Current RE Neodymium-base PMs need Dysprosium (Dy) to achieve high operating temperatures, and Dy cost can be half of total magnet material cost.
- RE elements have increased uncertainty in cost, reduced import quotas, and an eventual looming shortage, especially Dy.
- DOE started the Critical Materials Institute to focus on improving the supply, substitutes, use, and forecasting for RE materials, including Neodymium and Dysprosium.
- Many OEMs have recently released new vehicles with motors that use less RE materials, especially Dy.
R&D Focus Area: Non-Rare Earth Motors

Research motor design concepts that *reduce* rare earth content

Research motor design concepts that *eliminate* rare-earth magnets – IM, SRM, etc.

Flux-Switching Dy-Free PM Motor Prototype

Proof-of-Principle Synchronous Reluctance Motor on ORNL Dynamometer

Develop and refine less expensive magnets – AlNiCo or ferrite
# EDT Research Leads to Innovations

## National Laboratory Expertise and Unique Capabilities

<table>
<thead>
<tr>
<th>Oak Ridge National Laboratory (ORNL)</th>
<th>National Renewable Energy Laboratory (NREL)</th>
<th>Ames Laboratory</th>
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<tbody>
<tr>
<td>• Power electronics</td>
<td>• Thermal management &amp; reliability</td>
<td>• Magnetic materials</td>
</tr>
<tr>
<td>• Packaging</td>
<td></td>
<td>Alnico 9</td>
</tr>
<tr>
<td>• Wide Bandgaps (WBG)</td>
<td></td>
<td></td>
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<tr>
<td>• Electric motors</td>
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### Device
- Cu or Al base plate
- Substrate
- Jet Nozzle

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### Ames Laboratory
- Alnico 9
- Cu
- $\alpha_1$
- $\alpha_2$
- Fe
- Ti
- 100nm
EDT Research Accomplishments

• Additive Manufacturing Reduces the Size and Weight of Vehicle Power Electronics (ORNL)
  – The first-of-its-kind, all-silicon carbide (SiC) traction drive inverter features 50% printed parts and incorporates wide bandgap materials to enable high-temperature operation.
  – The inverter was successfully operated at 20 kW with 98.7% efficiency. Its projected power density is expected to surpass DOE EDT technical targets.
  – First use of additive manufacturing to accelerate power electronics prototyping.

• Plastic Heat Exchanger Improves Heat Transfer Efficiency and Reduces Inverter Weight (NREL)
  – A plastic manifold incorporating jet impingement and surface enhancements increased the heat transfer efficiency by 17% and reduced the traction drive inverter weight by 19%.
EDT Research Accomplishments

- **Next Generation Wide Bandgap Packaging Improves Inverter Efficiency (ORNL)**
  - Advanced, 3-dimensional (3D) planar-interconnected all-SiC power module features innovative packaging; offers comprehensive improvements in performance, efficiency, density, and cost of electronic systems.
  - SiC 100 A/1,200 V single phase-leg power module using an innovative, planar-bond-all (PBA) packaging technology.
  - Latest industrial SiC power devices and a 3D planar interconnection with double-sided direct cooling (both forced air and liquid).

- **New System for Materials Characterization (ORNL)**
  - Custom characterization system provides a deeper understanding of magnetization and loss mechanisms in electrical steel; provides information needed for high fidelity electric motor modeling.
  - Excitation coils can apply a magnetic field to a single sheet sample as the local magnetic field on the surface of the sample is measured.
EDT Research Accomplishments

• Manufacturability of Affordable Non-Rare Earth Magnets (Ames Laboratory)
  – Compression molding of gas atomized aluminum–nickel–cobalt (AlNiCo) was identified as the preferred method for producing rare earth free magnets that will reduce the cost of electric traction drive motors.

• Motor Thermal Management Enables New Motor Designs (NREL)
  – Motor thermal management expertise enabled more accurate measurements of thermal properties related to lamination stacks and automatic transmission oil cooling.
  – This effort resulted in first-ever detailed motor component thermal data in the open literature, which will enable motor developers to improve motor models and designs.
New Hybrid Technologies, LLC, licensed new power conversion technology developed by ORNL. The patented current source inverter* takes direct current voltage and converts it into a multi-phase alternating current for powering electric traction motors.

This technology:
- Increases inverter and motor durability
- Increases motor efficiency
- Increases constant-power speed range in a smaller package
- Enables reduced battery cost and size
- Enables SiC-based current source inverters to operate in elevated temperature environments
- Lowers inverter cost and weight
- Increases vehicle fuel economy

Technology Highlights
- 5X lower total capacitance
- Up to 3.5X higher voltage boost ratio
- 7X to 100X (depending on voltage) lower output voltage total harmonic distortion factor

*US Pat No. 8,110,948; funded by EDT Research
EDT Development Accomplishments - GM Inverter

**High Power Density**
- Manufacturability vs. volume tradeoff: High power density could lead to high cost
- “Next Gen Inverter” pushes for even higher volumetric power density
  - Smaller: Easier to package in vehicle
  - Smaller: Less materials and less expensive
  - Inverter level optimization: All components must be optimized for the chosen inverter architecture
  - Manufacturability must be improved simultaneously

**Integrated Power Stage**
- Integrated power stage: Eliminate boundaries and empty spaces; new partitioning of functionality
- Vertically integrated process: Power stage manufacturing integrated into inverter assembly
- Manufacturability: Unidirectional (bottom to top) assembly process; reduced assembly steps
Alloy and process for producing motor laminates with locally patterned low µ regions have been developed and are being scaled up for prototype demo.

Motor accomplishments:
Continue to evaluate more motor topologies (more than 10 evaluated so far)
Down-selected the first 4 topologies: Reduced rare earth (RE) content, non-RE magnets, no magnets, and dual-phase magnetic material
- First prototype has reduced rare-earth content (built and fully tested)
- Second prototype has non-rare earth magnets (built and fully tested)
- Third prototype has no magnets and includes one of the advanced materials (built and currently being tested)
- Fourth prototype is a scaled-down version that includes the dual-phase magnetic material; it is currently being built
UQM recently patented a new design for electric vehicle motors that uses non-rare earth (RE) magnets.

The new motor design performs comparably to rare-earth motors, and is designed to meet the same goals as permanent magnet-based motors.

Utilization of AlNiCo magnets will hedge the volatile pricing of NdFeB and other rare earth constituents.

UQM’s project strategy is to use and refine a magnetic circuit that avoids demagnetization: high permeance coefficient and low armature reaction fields experienced at the magnets.
Accomplishment: Delphi Inverter R&D Transitions to Volt

2008 Start

Delphi Project Targets [1]
• Improved packaging provides greater than 30% reduction in thermal resistance junction to coolant vs. commercially available
• Advanced Si devices provide conduction losses ~17% lower than target
• Improved packaging and lower device losses allows for use of less silicon, reducing package size, weight, and improving manufacturability – gives lower cost

Volt Traction Power Inverter Module [2]
“In the second-generation unit, better power flow between the inverters, better efficiency and thermal robustness enabled an average electric drive system FTP city efficiency improvement of 6%, a projected charge sustaining (CS) label fuel economy increase of 10%”

“GM selected Delphi’s novel dual-side cooled Viper as the power device for the TPIM. Viper... enabled the reduction of the silicon footprint, allowing for greater layout flexibility and reduced cost.”

[3] © General Motors
Information Sources

FY 2014 Electric Drive Technologies Annual Progress Report


Electrical and Electronics Technical Team Roadmap


EV Everywhere Blueprint


Vehicle Technologies Multi-Year Program Plan 2011-2015

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