Scalable, Low-Cost, High Performance IPM Motor for Hybrid Vehicles
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DOE Peer Review Presentation

Ayman EL-Refaie, Project Manager & Principal Investigator
Frank Johnson, Materials Design Leader

GE Global Research
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This presentation does not contain any proprietary, confidential or otherwise restricted information
Team and stakeholders

Kelly Fletcher
Business Programs Manager
GE Energy

Margaret Blohm
Advanced Technology Leader
Nanotechnology

Ayman M. EL-Refaie
Program Manager
Principal Investigator

Francis Johnson
Materials Development Leader

GE Energy

Doug Hofmann
Motors and Controls

GE Global Research
Nanostructured Magnetic Materials and Advanced Motor Development

Prof. Thomas M. Johns
Grainger Professor of Power Electronics and Electrical Machines

Prototype Manufacturing

Patrick McCleer
President
## Overview

### Timeline

**Phase I:**
- Start: October 2007
- Finish: June 2009
- 100% complete

**Phase II:**
- Start: July 2009
- Finish: December 2011
- 75% complete

### Barriers

- Very challenging set of specs
  - High efficiency over a wide speed and load ranges
  - High power density and high coolant inlet temperature
  - Low cost targets based on 100,000 units/year
  - High speed poses mechanical challenges

### Partners

- GE Global Research (lead)
- GE Motors
- University of Wisconsin-Madison
- McCleer Power

### Budget

**Phase I:**
- $2.43M total budget
- $1.944M DOE share
- $486K GE cost share
  - Funding received (DoE+GE) in FY10 $1.6M
  - Planned Funding (DoE+GE) for FY11 $1.1M

**Phase II:**
- $3.37M total budget
- $1.618M DOE share
- $1.752M GE cost share

- Funding received (DoE+GE) for FY10 $1.6M
- Planned Funding (DoE+GE) for FY11 $1.1M
Purpose of work FY’10/FY’11
Design 55kWpk IPM motor to meet DOE specification and show scalability

Very challenging set of specs

Table 2. Motor Specifications

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum top speed (rpm)</td>
<td>14,000</td>
</tr>
<tr>
<td>Peak power output at 20% of maximum speed for 18 seconds and nominal voltage (kW)</td>
<td>55</td>
</tr>
<tr>
<td>Continuous power output at 20 to 100% of maximum speed and nominal voltage (kW)</td>
<td>30</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>≤35</td>
</tr>
<tr>
<td>Volume (l)</td>
<td>≤9.7</td>
</tr>
<tr>
<td>Unit cost in quantities of 100,000 ($)</td>
<td>≤275</td>
</tr>
<tr>
<td>Operating voltage (Vdc)</td>
<td>200 to 450; nominal 325</td>
</tr>
<tr>
<td>Maximum per phase current at motor (Arms)</td>
<td>400</td>
</tr>
<tr>
<td>Characteristic current (umag/Ld)</td>
<td>≤ Maximum current</td>
</tr>
<tr>
<td>Efficiency at 10 to 100% of maximum speed for 20% of rated torque (%)</td>
<td>&gt; 95</td>
</tr>
<tr>
<td>Back EMF at 100% of maximum speed, peak line-to-line voltage (V)</td>
<td>&lt; 600</td>
</tr>
<tr>
<td>Torque pulsations-not to exceed at any speed, percent of peak torque (%)</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

![Torque-Speed Specs](image)

Eff>95%
Relevance

Developing a low-cost, high-performance advanced traction motor is a key enabler to meeting the 2020 technical targets for the electric traction system.

### Technical Targets for Electric Traction System

<table>
<thead>
<tr>
<th></th>
<th>2010&lt;sup&gt;a&lt;/sup&gt;</th>
<th>2015&lt;sup&gt;b&lt;/sup&gt;</th>
<th>2020&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost, $/kW</td>
<td>&lt;19</td>
<td>&lt;12</td>
<td>&lt;8</td>
</tr>
<tr>
<td>Specific power, kW/kg</td>
<td>&gt;1.06</td>
<td>&gt;1.2</td>
<td>&gt;1.4</td>
</tr>
<tr>
<td>Power density, kW/L</td>
<td>&gt;2.6</td>
<td>&gt;3.5</td>
<td>&gt;4.0</td>
</tr>
<tr>
<td>Efficiency (10%-100% speed at 20% rated torque)</td>
<td>&gt;90%</td>
<td>&gt;93%</td>
<td>&gt;94%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based on a coolant with a maximum temperature of 90°C.

<sup>b</sup> Based on air or a coolant with a maximum temperature of 105°C.

<sup>c</sup> A cost target for an on-board charger will be developed and is expected to be available in 2010.
Objectives

• Investigate the design space in order to meet the DOE specifications
• Develop scalable thermal management schemes
• Develop advanced rotor concepts to meet the high-speed requirement
• Build proof-of-principle machines to verify the various developed concepts
• Build a 30kW/55kWpk machine that meets the specs
• Develop a cost model based on 100,000 units/year
• Show scalability by building a 65kW/120kWpk machine
• Novel sintered permanent magnet with 3X lower eddy current loss using co-sintered insulating phase
Barriers

• Heroic motor efficiency requirements over a wide speed and load range – must address every significant loss component
• Minimization of high-cost materials in the motor design - get maximum performance value from rare-earth PM materials
• High power-density thermal management – how to control temperature and extract heat in very compact motor and with high coolant inlet temperature
• Design rotor for mechanical integrity at high speed
• Scaling up high resistivity permanent to kg-scale needed for motors requires understanding sintering process parameters of permanent magnet and insulating phases.
• Eddy current reduction in permanent and permanent magnet stability must be maintained during scale up.
Milestones

Motor Development

Finish testing the second proof-of-principle machine

Finalize the final 33kW/55kW pk machine design and initiate build

Receive the final 33kW/55kW pk machine and initiate testing

Finalize the scale-up 65kW/120kW pk machine design and initiate build

Finish testing the final 33kW/55kW pk machine design and initiate build

Select compositions and processing routes

Material Development

100g-scale production of high resistivity PM

Kg-scale production of high resistivity PM
Approach

• Simplified stator windings will reduce end-turn length and losses, together with motor mass and volume and manufacturing cost.

• Advanced rotor concepts to achieve higher power density as well as meeting the high-speed requirement.

• Advanced scalable thermal management schemes for both the stator and the rotor to meet the required set of specifications.

• High resistivity permanent magnets
  • Screen alternate insulating phase materials
  • Measure insulating and magnet phase sintering parameters
  • Measure and verify resistivity and magnet stability
Accomplishments to Date

Motor design
- 2 rotor & 2 stator EM concepts developed & analyzed in detail
- Scalable rotor and stator cooling concepts selected to meet performance, simplicity and scalability requirements
- First proof-of-principle motor built and fully tested
- Second proof-of-principle machine (different rotor structure) is built and fully tested
- Third and final 30kW/55kWpk machine built and testing initiated
- Development of cost model is almost finalized (fine tuning is still needed)

High resistivity permanent magnets
- Permanent magnet microstructure with 3-4X effective resistivity enhancement demonstrated
- Alternate set of insulating materials identified
- Subscale (≈50 gram) magnets produced at GE and vendor
- Continuing trials of kg scale-production at vendor High resistivity permanent magnets

Patents and publications
- 12 US patent applications have been filed up-to-date with few others pending.
Motor Test Set Up

- Dynamometer
- Test Motor
- 3ph Inverter
- DC Power

Setup upgraded to meet the 105°C coolant inlet temp. requirement.
First Proof-of-Principle Machine

- Measurements match predictions very closely
- Machine meets and exceeds both peak and steady state power requirements
- Machine meets 95% efficiency target up to 9000 rpm. Efficiency progressively drops to ~88% at 14000 rpm (significantly better than the state of the art)
- Machine meets 105°C coolant inlet temperature up to 7500 rpm on stator side and 9000 rpm on rotor side. More work needed at higher speeds
Thermal Summary

• Calorimetric based loss measurements (temp. and flow rate measurement) and electrical input/mechanical output based loss measurements have reasonable agreement.
• Measurements match predictions. Within measurement uncertainty except for the highest speed.

• Temperature rise behavior in the various machine locations are reasonably as expected.
• However, the thermal resistance between the cooling jacket and stator is higher than expected. 2nd machine attempts to improve thermal conductance in this area.
Second Proof-of-Principle Machine

- Machine first tested with unmagnetized magnets to separate mechanical losses
- Based on the test results, more modifications are planned to reduce mechanical losses at 14000 rpm by ~35%
Second Proof-of-Principle Machine

- Measurements match predictions very closely
- Machine **meets and exceeds both peak and steady state power requirements**
- Machine **meets 95% efficiency target up to 9000 rpm. Efficiency progressively drops to ~88% at 14000 rpm (significantly better than the state of the art)**
- Machine **meets 105°C coolant inlet temperature up to 7500 rpm on stator side and 9000 rpm on rotor side. More work needed at higher speeds**
Thermal Summary

- Calorimetric based loss measurements (temp. and flow rate measurement) and electrical input/mechanical output based loss measurements have reasonable agreement.
- Measurements match predictions. Within measurement uncertainty.

- Temperature rise behavior in the various machine locations are reasonably as expected.
- Thermal contact between the cooling jacket and the stator improved significantly, although thermal resistance still higher than expected.
Third and Final 30kW/55kWpk Machine

- Machine back emf at 100°C and 1000 rpm closely matches predictions
- Third machine optimized to meet the 35kg mass requirement as well as the 105°C coolant inlet temperatures
- Machine is currently mounted on the test setup and testing initiated
High Resistivity Permanent magnets

Phase I Conclusions
• Demonstrated sintered NdFeB multilayer composite permanent magnet with effective resistivity 3X baseline NdFeB and 5-10 % reduction in energy product (effectively the same reduction as in the case of axially-segmented magnets)

Phase II plans
• Improve reproducibility of composite microstructure and resistivity
• Scale production process to be capable of supporting prototype motor (>1 kg)
• Demonstrate cost advantage relative to conventional materials (bonded, segmented)
Collaboration with Other Institutions

- University of Wisconsin-Madison: Collaboration on developing design tools, exploring the design space, designing the second proof-of-principle machine
- McCleer Power (Industry): Collaboration on building prototypes and developing manufacturing processes
- University of Dayton: Collaboration on high-resistivity material development
- Electron Energy Corporation (Industry): Collaboration on high-resistivity magnet scale-up
High-performance, low-cost IPM FY11 timeline

- **2010**
  - Oct: Build third (final) 55kWpk/30kW machine
  - Nov: Test third (final) 55kWpk/30kW machine
  - Dec: Design first 120kWpk/65kW machine

- **2011**
  - Jan: Finalize cost model
  - Feb: Build first 120kWpk/65kW machine
  - Mar: Test results of third 55kWpk/30kW machine
  - Apr: Kg-scale production of high resistivity PM
  - May: 1 kg-scale composite magnet
  - Jun: Scale to kg-scale production of high resistivity PM
  - Jul: 100g-scale production of high resistivity PM
  - Aug: Test witnessed by DoE
  - Sep: 120kWpk/65 kW machine
Future Work for FY11

• Finish testing of the final 55kWpk/30kW machine
• Design and build the scale-up 120kWpk/65kW machines
• High resistivity permanent magnet
  - Refine sintering process conditions
  - Scale to kg-scale production at vendor (EEC)
Beyond FY11 FY12

• Test 120 kWpk/ 65 kW machine
• Finalize cost model
• Write final report
Summary

• Significant progress made since last year
• Two advanced proof-of-principle machines were built. Both were fully tested
• Major risks including spinning the novel rotor concept at 14000 rpm have been retired
• Test results closely match predictions. This provides confidence in design process
• Torque and power density requirements are met
• Efficiency requirements are met up to 9000 rpm. Achieved efficiency values at higher speeds exceed the state of the art.
• Alternate rotor materials identified to enhance thermal management and efficiency capabilities of the final 30kW/55kWpk machine
• Final 55kWpk/30kW machine designed and built and testing begun
• Novel high resistivity materials identified and scale-up begun
• 12 US patent applications filed to date
## Comparison to Required Specifications

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
<th>Units</th>
<th>PoP Machine1</th>
<th>PoP Machine2</th>
<th>Expected performance of Machine 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum top speed</td>
<td>14000</td>
<td>RPM</td>
<td>14000</td>
<td>14000</td>
<td>14000</td>
</tr>
<tr>
<td>Peak power output at 20% of maximum speed for 18 seconds and nominal voltage</td>
<td>55 @ 325 Vdc</td>
<td>kW</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Continuous power output at 20 to 100% of maximum speed and nominal voltage</td>
<td>30 @ 325 Vdc</td>
<td>kW</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt;= 35</td>
<td>kg</td>
<td>&lt;= 35 (22 Active)</td>
<td>&gt;35 (27 Active)</td>
<td>&lt;= 35 (22 Active)</td>
</tr>
<tr>
<td>Volume</td>
<td>&lt;= 9.7</td>
<td>liters</td>
<td>&lt;= 9.7</td>
<td>&gt;9.7</td>
<td>&lt;= 9.7</td>
</tr>
<tr>
<td>Operating voltage (Vdc)</td>
<td>200 to 450</td>
<td>Vdc</td>
<td>200 to 450</td>
<td>200 to 450</td>
<td>200 to 450</td>
</tr>
<tr>
<td>Nominal Operating voltage (Vdc-n)</td>
<td>325</td>
<td>Vdc</td>
<td>325</td>
<td>325</td>
<td>325</td>
</tr>
<tr>
<td>Maximum per phase current at motor</td>
<td>400</td>
<td>Arms</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Characteristic current</td>
<td>&lt; Max current</td>
<td>Arms</td>
<td>&lt; Max current</td>
<td>&lt; Max current</td>
<td>&lt; Max current</td>
</tr>
<tr>
<td>Efficiency at 10 to 100% of maximum speed for 20% of rated torque</td>
<td>&gt; 95</td>
<td>%</td>
<td>Refer to figs</td>
<td>Refer to figs</td>
<td>Similar to PoP Machines 1, and 2</td>
</tr>
<tr>
<td>Back EMF at 100% of maximum speed, peak line-line voltage</td>
<td>&lt; 600</td>
<td>Vdc</td>
<td>845</td>
<td>673</td>
<td>880</td>
</tr>
<tr>
<td>Torque pulsations - not to exceed at any speed, Percent of peak torque</td>
<td>&lt; 5</td>
<td>%</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Ambient (outside housing) operating temperature</td>
<td>-40 to 140</td>
<td>Deg C</td>
<td>-40 to 140</td>
<td>-40 to 140</td>
<td>-40 to 140</td>
</tr>
<tr>
<td>Coolant inlet temperature</td>
<td>105</td>
<td>Deg C</td>
<td>Rotor up to 9000 rpm Satator up to 7500 rpm</td>
<td>Rotor and stator up to 9000 rpm</td>
<td>Meets that requirment over the entire speed range</td>
</tr>
<tr>
<td>Maximum coolant flow rate</td>
<td>10</td>
<td>liters/min</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Maximum coolant pressure drop</td>
<td>2</td>
<td>psi</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum coolant inlet pressure</td>
<td>20</td>
<td>psi</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>