Electric Motor Thermal Management

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Overview

Timeline
Project Start Date: FY 2010
Project End Date: FY 2013
Percent Complete: 60%

Budget
Total Project Funding:
DOE Share: $1,275K (FY10-FY12)
Funding Received in FY11: $450K
Funding for FY12: $425K

Barriers and Targets
• Cost
• Weight
• Performance & Life

Partners
• Interactions / Collaborations
  – University of Wisconsin (UW) – Madison (Thomas M. Jahns)
  – Oak Ridge National Laboratory (ORNL)
  – Motor Industry Representatives

• Project Lead
  – National Renewable Energy Laboratory
The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems.

Thermal management is needed to reduce size and improve performance of electric motors.

- Meet/improve power capability within cost/efficiency constraints
- Reduce rare earth material costs (dysprosium)
Relevance/Objectives

The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems.

Objectives
- Quantify opportunities for improving cooling technologies for electric motors
- Link thermal improvements to their impact on Advanced Power Electronics and Electric Motors (APEEM) targets
- Increase publicly available information related to motor thermal management

Addresses Targets
- Translates cooling performance improvements into impacts on program targets
- Prioritizes motor thermal management efforts based on areas of most impact
## Milestones

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone or Go / No-Go Decision Point</th>
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| Oct. 2011  | Milestone report  
• Analytical and 3D finite element analysis (FEA) models for determining effective conductivity of composite materials as applied specifically to motor slot windings  
• Results of initial thermal property testing of motor lamination materials  
• Method of evaluating loss distributions within the electric motor for different operating conditions (in collaboration with University of Wisconsin – Madison)  
• Development of stator thermal model validated against published data  
• Parameter sensitivity study of thermal design factors for motor stator cooling |
| Jan. 2012  | Go/No-Go  
• Completed selected motor lamination material thermal property tests  
• Decided to not expand material tests at this time  
Milestone (intermediate)  
• Completed thermal sensitivity analysis for interior permanent magnet (IPM) motor stator and rotor utilizing test data provided by ORNL |
| Jul. 2012  | Go/No-Go  
• Thermal sensitivity analysis shows significant impact common to multiple motor configurations leading to future project proposals for specific cooling enhancements |
| Sept. 2012 | Milestone report  
• Lamination material thermal properties, motor thermal sensitivity analysis, and oil heat transfer experimental data |
Approach/Strategy

- Complete thermal FEA and lumped parameter thermal models for cooling parameter sensitivity analysis (UW, NREL)
- Complete material thermal property tests (NREL)

- Characterize fundamental oil-cooling heat transfer performance
- Initiate experiments to identify cooling limitations (durability)
Approach/Strategy

Motor thermal analysis is a challenge
- Complicated
- Many unknowns

Absolute results of analysis could change, but the goal is to identify trends for improvements in motors

Try to make intelligent choices to ensure quality:
- Results not focused on single motor design
- Assumptions and results compared to published literature
- Model results compared against test data
- Collaborations with motor designers
- Component testing

Challenges

- Variation in Motor Configuration
- Heat Generation Distribution and Variation
- Material Properties and Interfaces
- Identify challenges across motor configurations
- Evaluate Multiple Operating Conditions (low speed/high torque, high speed/low torque)
- Test data comparison
- Literature searches and in-house thermal characterization

Approach/Strategy

- Stator – Distributed Winding
- IPM – Distributed Winding
- IPM - Concentrated winding
- Collaborations
  - University of Wisconsin
  - Oak Ridge National Laboratory
Technical Accomplishments and Progress

Lamination Material Tests

Measured bulk thermal conductivity of lamination materials

- Tests performed with Xenon Flash equipment
- Four samples of each material tested
- General data for silicon steels lists the thermal conductivity to be between 20-30 W/m-K [1].

Lamination Material Tests

Measured specific heat of lamination materials

- Tests performed with differential scanning calorimeter
- Two samples of each material tested
- Provides data for specific heat over a range of temperatures
- Generally available data for silicon steels list the specific heat to be 0.49 J/(g-K) [1].

Technical Accomplishments and Progress

Additional specific heat measurements for sample materials

Data range from two samples of each material

**Specific Heat ARNON**

- Temperature (°C)
- Specific Heat (J/g-K)

**Specific Heat HF10**

- Temperature (°C)
- Specific Heat (J/g-K)
Technical Accomplishments and Progress

Quantified thermal contact resistance between laminations

- Tests performed with ASTM interface test stand
- Tested at multiple pressures and lamination layer counts
- Data used to approximate effective cross lamination thermal conductivity
- Data support modeling activities
- Expands publicly available data

Measure total thermal resistance of lamination stack

$R_{tot}^-$
Technical Accomplishments and Progress

Calculated contact resistance from measured bulk material properties and lamination stack resistance measurements.

- Contact resistance decreases with pressure.
Technical Accomplishments and Progress

Calculated effective conductivity from measured bulk material properties and lamination-to-lamination contact resistance

- Effective thermal conductivity increases with pressure
- Effective thermal conductivity levels off after the number of laminations increases beyond 50
Technical Accomplishments and Progress

Quantified thermal properties for slot windings

• Expanded on published analytical methods to include wire, filler material, and insulation material (3-component analytical model)
• Developed parametric FEA modeling capabilities to characterize multi-dimensional heat spreading effect across slot windings
• Supports motor thermal modeling activities

Technical Accomplishments and Progress

Completed thermal sensitivity analysis of surface permanent magnet motor stator

- Developed 3D thermal model
- Validated model against published data
- Confirmed thermal property (material/contact) and boundary condition assumptions

Technical Accomplishments and Progress

Cooling sensitivity analysis with different winding/core heat distributions at fixed heat exchanger performance

- Highlights critical thermal paths
- Cooling location and heat distribution impact results

![Graph showing the relative reduction in total thermal resistance for different configurations.]

Note: Axial direction is along the length of the motor.
Technical Accomplishments and Progress

Change in available power output versus relative change in effective thermal conductivity for case-cooled configuration

Significant potential for improvement before effects diminish

![Graph showing change in available power output versus relative change in effective thermal conductivity for case-cooled configuration.](image)
Technical Accomplishments and Progress

Convection coefficients, shown in yellow, applied to the (a) case, (b) rotor face, and (c) & (d) end windings.

Completed thermal sensitivity analysis for interior permanent magnet motor application (stator and rotor)
- Developed 3D thermal model of permanent magnet motor stator and rotor
- Validated model against test data provided by ORNL
- Dataset with longest run time selected for estimation of boundary conditions
- Remaining data sets used for model validation

<table>
<thead>
<tr>
<th>Operating Point</th>
<th>Loss Distribution</th>
</tr>
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<tbody>
<tr>
<td>Dataset</td>
<td>Power</td>
</tr>
<tr>
<td>[W]</td>
<td>[RPM]</td>
</tr>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
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<tr>
<td>7</td>
<td>50,000</td>
</tr>
<tr>
<td>8</td>
<td>50,000</td>
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</tbody>
</table>

• Builds on previous stator model parameter assumptions and validation
• Expands analysis to include rotor
Technical Accomplishments and Progress

Model comparison to experimental data

- Model performance is comparable to test data
- Shorter duration tests show less agreement in case temperature because steady-state temperatures have not been reached

![Graphs showing deviation in FEA temperature from measured temperature over time for End Winding and Case Temperatures]
Technical Accomplishments and Progress

Peak heat rejection versus cooling performance

Improved cooling methods can increase power by increasing heat exchanger cooling performance.
Technical Accomplishments and Progress

Sensitivity in power output capability for 20% increase in material thermal conductivity

- For high-speed, low-torque situations, the motor sees a primary benefit from improvements in the thermal conductivity of the rotor
- Convection cooling performance impacts results

Note: “Nominal h” refers to the baseline cooling performance, “High h” represents an aggressive cooling condition
Technical Accomplishments and Progress

Sensitivity in power output capability for 20% increase in material thermal conductivity

- For low-speed, high-torque situations, the motor benefits from thermal conductivity improvements in the slot winding, stator core, and case contact
- Convection cooling performance impacts results

Note: “Nominal h” refers to the baseline cooling performance, “High h” represents an aggressive cooling condition
Collaboration and Coordination

- **University**
  - UW – Madison (Thomas M. Jahns)
    - Support with electric motor expertise

- **Industry**
  - Motor industry suppliers, end users, and researchers
    - Input on research and test plans

- **Other Government Laboratories**
  - ORNL
    - Support from benchmarking activities
    - Ensure thermal design space is appropriate and modeling assumptions are consistent with other aspects of APEEM research
  - Other VTP areas
    - Collaborate with VTP cross-cut effort for combined cooling loops
Proposed Future Work

Package Mechanical Design

Thermal Design Targets

Cooling Technology Selection

Cooling Technology Selection
• Characterize oil-cooling heat transfer coefficients
• Initiate cooling durability tests (winding insulation)
• Go/No-Go for FY13
  – If improvement in cooling performance shows impact on total thermal performance, pursue efforts to characterize improved oil-cooling approaches
  – Continue cooling durability tests

![Graph showing cooling performance](image)
Proposed Future Work

Package Mechanical Design

• Complete thermal sensitivity analysis and model validation for concentrated winding motor with University of Wisconsin (FEA and lumped parameter thermal analysis)

• Quick look at methods to enhance internal heat spreading

• Go/No-Go for FY13
  – If motor cooling sensitivity analysis shows common areas for thermal improvement, initiate R&D on critical factors
**Summary**

**Relevance**
- Impacts the transition to more electrically dominant propulsion systems with higher continuous power requirements
- Enables improved performance of non-rare earth motors
- Supports lower cost through reduction of rare earth materials used to meet temperature requirements (dysprosium)
- Applies experimental and analytical capabilities to quantify and optimize the selection and design of effective motor cooling approaches

**Approach/Strategy**
Developed process to meet challenges of motor thermal management
- Identify thermal improvements across a range of motor configurations
- Evaluate multiple operating conditions (loss distributions)
- Engage in collaborations with motor design experts
- Perform in-house characterization of material and interface thermal properties
Summary

Technical Accomplishments

- Measured bulk thermal conductivity of lamination materials
- Measured specific heat of lamination materials
- Quantified thermal contact resistance between laminations
- Quantified thermal properties for slot windings
- Completed thermal sensitivity analysis for surface permanent magnet motor stator
- Completed thermal sensitivity analysis for interior permanent magnet motor application (stator and rotor)

Collaborations

- Collaborations established with research and development partners
  - University of Wisconsin – Madison
  - Oak Ridge National Laboratory
  - Motor industry representatives: Manufacturers, researchers, and end users (light duty and heavy duty)
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