Motor Packaging with Consideration of Electromagnetic and Material Characteristics

John M. Miller
Oak Ridge National Laboratory
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Overview

Timeline

- Start – Oct. 2010
- Finish – Sept. 2013
- 14% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received for FY11
  - $400K

Barriers

- Higher levels of vehicle electrification puts emphasis on electric machines having higher continuous power rating relative to peak. This need translates directly to more efficient electric machines at same or reduced cost that motivates refocusing our efforts more on materials, their processing and structure
- Vehicle Technologies Program targets
  - 2020 targets: $4.7/kW, 1.6 kW/kg, 5.7 kW/l
  - 95% or better efficiency at 2 best mapping points

Partner/Collaborators

- ORNL Team Members: John Hsu, Tim Burress
- ORNL Materials Science and Technology Division – epoxy matrix composites (funded by DOE VTP Materials Program)
- ORNL Computer Science and Mathematics Division – lamination steel processing

Objectives

- Overall
  - Develop more efficient electric machines that demonstrate increased continuous power rating.
  - Improve the continuous power from 54% to >58% of peak.

- FY11
  - Develop technologies that can improve the efficiency of a 55 kW traction drive electric machine by at least 1.5% over its best efficiency mapping points.
  - Employ material and process innovations to realize program goal.

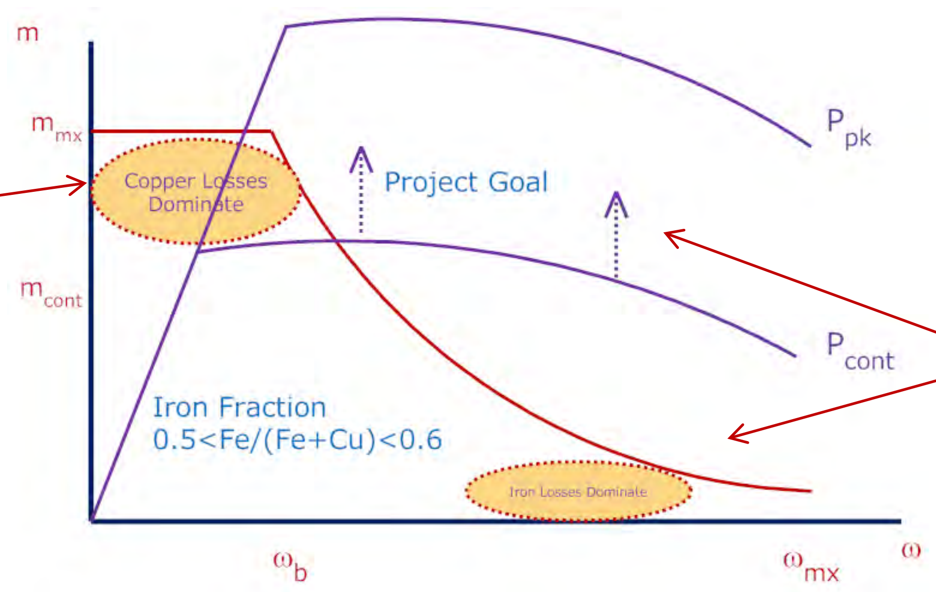
Milestones

Month/Year	Milestone or Go/No-Go Decision
Sept-2011	Milestone: Completed baseline/comparator machine model (March 2011) Milestone: Complete simulation study of silicon steel deformation sequences. Milestone: Complete simulation study of epoxy matrix alumina thermal conducting materials.
Sept-2012	Milestone: Complete z-axis nonlinear property model and simulation for functional prototype design. Go/No-Go Decision: Conceptual prototype meets efficiency and continuous power goals in simulation.
Sept-2013	Milestone: Complete fabrication of a 55 kW traction drive motor utilizing selected magnetic and thermal materials and experimentally demonstrate the efficiency and continuous power goals.

Approach

- The first efficiency improvement step is the development of a loss survey for the baseline machine that identifies which areas exhibit highest losses and under what circumstances, including control strategy

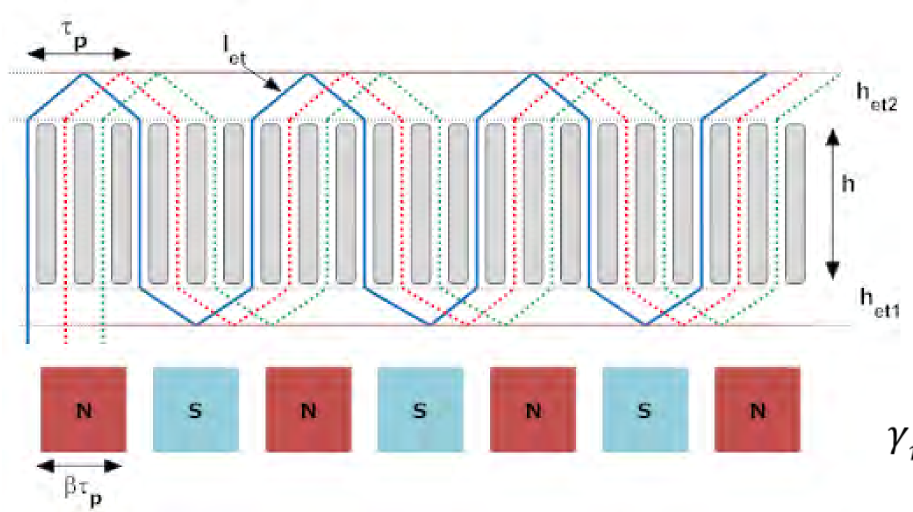
Material focus on:
- **Electromagnetic design**
- **Conductor and slot design**
- **Alternative winding configurations**
- **Conductor heat transfer**



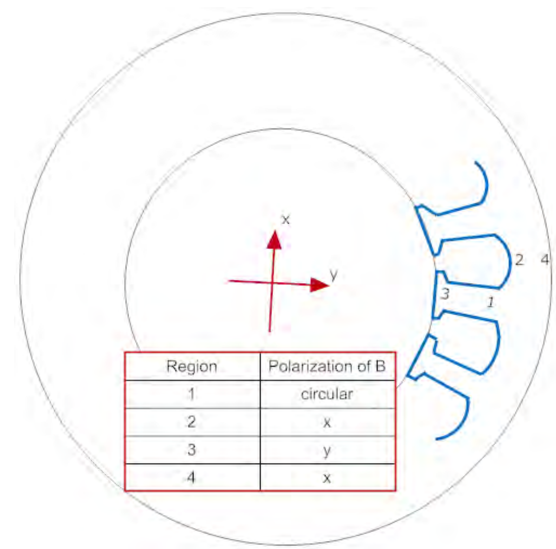
Material focus on:
- **Electromagnetic design**
- **Magnetic steel – shear rolled process**
- **Alternative winding designs**
- **Conductor heat transfer**

Approach (contd.)

- A second efficiency improvement step is to perform a loss survey in the context of machine aspect ratio with close attention given to the loss mechanisms of rotational flux within lamination steel
  - Develop materials understanding of how Goss oriented silicon steel would benefit stator laminations, and
  - The best areas to apply epoxy matrix composites for heat removal



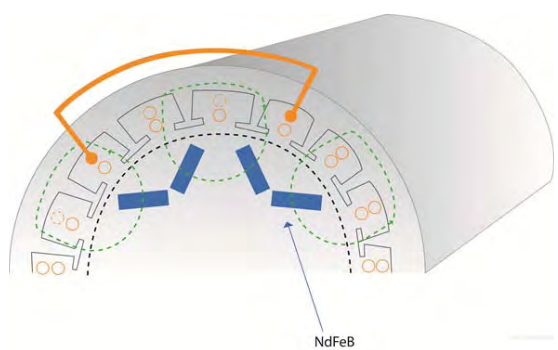
$$\gamma_r = \frac{h}{\tau_p}$$

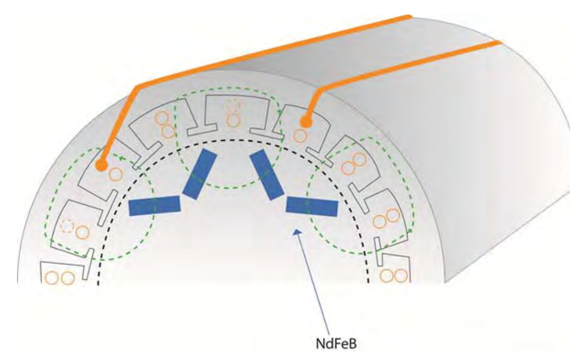


Note: The loss survey will benefit from use of dual chamber calorimeter to accurately quantify machine no-load spin and magnetic drag loss components.

Approach (contd.)

- The project proceeds from the launch point of the baseline benchmarked electric machine:
  - 2010 Prius interior permanent magnet (IPM) motor rated 60 kW, 13,500 rpm that has best efficiency of 96% at rated voltage (650 Vdc) and room temperature in the neighborhood of 5000 rpm and 60 Nm (31 kW) mapping point.
  - The baseline electric machine consists of a buried permanent magnet rotor having chevron shaped magnet pockets, full pitched lap winding, and an aspect ratio of 0.8.
- Project subtask: Alternative winding configurations and conductor material, construction and placement.
  - Simulate machine performance using alternative winding and conductor geometry.





Approach (contd.)

- ORNL benchmarking showed that the 60 kW IPM motor could hold 25 kW operation given 50°C coolant temperature and 90°C stator temperature limit (i.e., 40°C over ambient) for short periods:

Tamb (°C)	Tstator limit (°C)	Del-T (°C)	Speed (rpm)	Time (min)
50	90	40	3000	<4
50	90	40	5000	15
50	90	40	7000	10

PRIUS IPM Motor Data: Tim Burress, "Benchmarking of Competitive Technologies," EETT meeting, Dec. 9, 2010

- This data is insufficient to determine what the continuous power rating is. The project will provide more detail on development of appropriate continuous power ratings for electric drive vehicles.
  - Machine design aspect ratio plays a key role in peak power capability

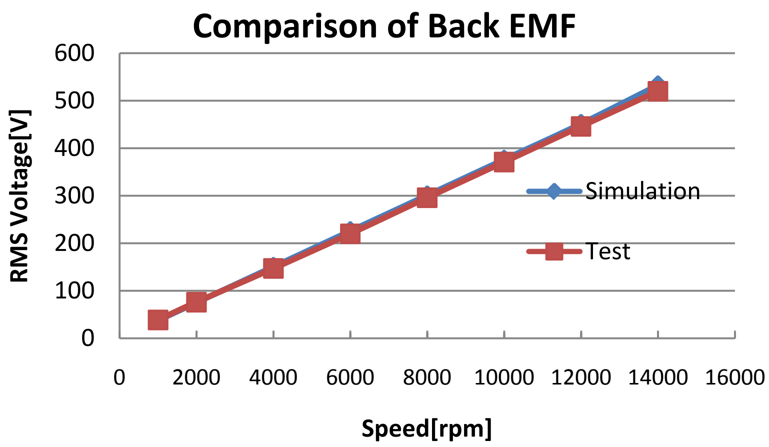
Motor	OD stator	OD rotor	Stack	Power	Aspect
Baseline	264	162	50.8	60kW	0.80
Comparator	~285	~200	50	~80kW	0.95

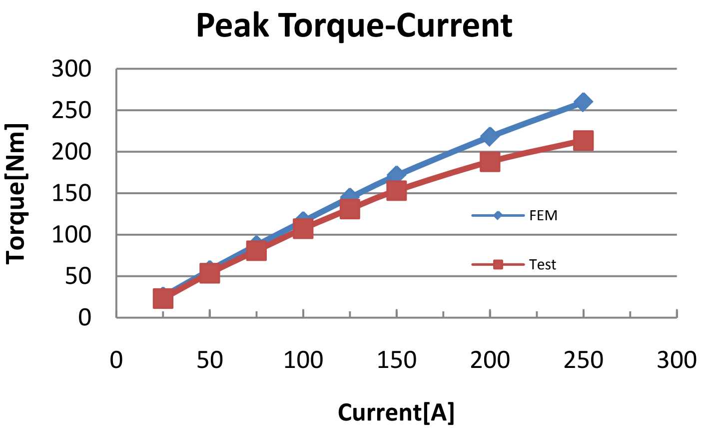
Technical Accomplishments and Progress - Overall

- Completed for baseline model:
  - IPM motor bemf validated by analysis and with laboratory tests.
  - Peak torque vs. current versus laboratory test data. Error at high currents with simulation over-estimating actual.
  - Airgap flux density versus angle including effects of rotor notching for peak and mean flux density showing very good agreement with test data.
  - Effects of rotor notching on torque vs. angle showing good agreement with lab data
- Commenced evaluation of end turn leakage inductance on baseline IPM motor for comparison to future alternative winding designs.
- Rotor magnet flux loss computed as 29% of total representing $26/rotor of ineffective rare earth material usage in baseline IPM electric machine (penalty to ensure rotor mechanical integrity)

Technical Accomplishments and Progress – FY11 (contd.)

- Baseline IPM motor bemf validated
  - One NdFeB magnet is the equivalent of a 9000 At field winding
- Peak torque vs. current versus laboratory test data. Error at high currents with simulation over-estimating actual
  - Attributed to magnet leakage flux at short stack end faces



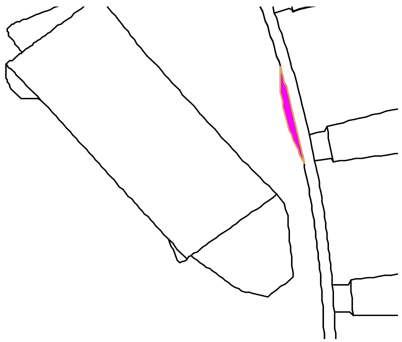


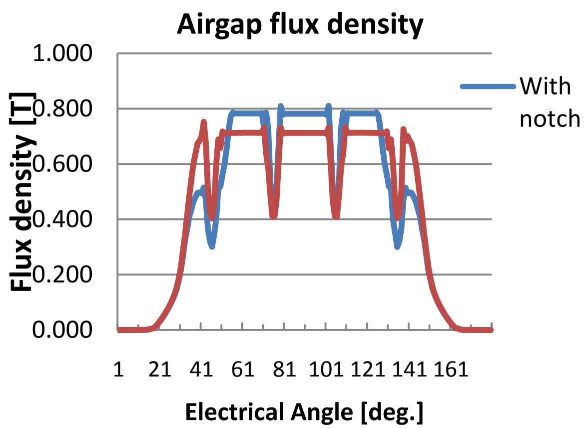
PRIUS Data: Tim Burress, "Benchmarking of Competitive Technologies," EETT meeting, 9 Dec 2010
Simulation results: Pan-Seok Shin using Flux2D

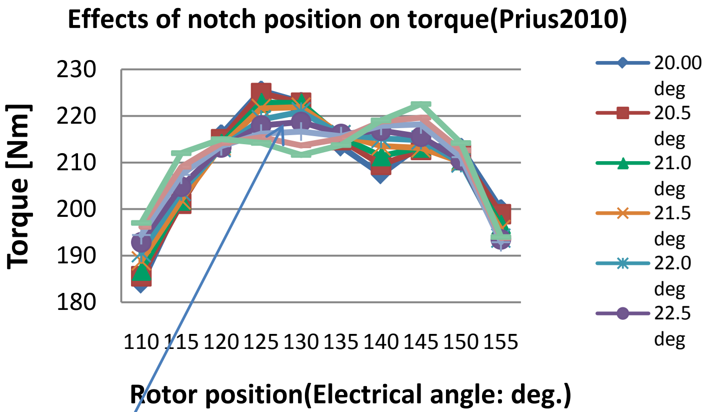
* Model includes m(I) correction

Technical Accomplishments and Progress – FY11 (contd.)

- Developed understanding of IPM rotor notching and influence on torque production
- Better understanding of flux leakage factor in rotor magnet pockets







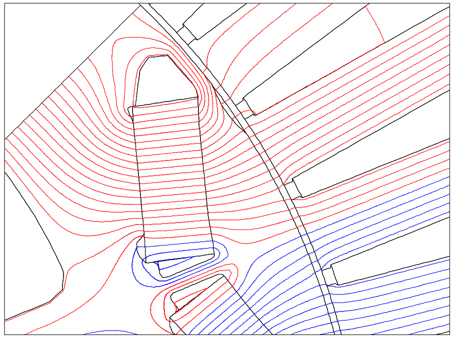
Airgap flux density distribution (peak/mean value: with notch = 0.782/0.430 T, vs. round surface= 0.712/0.435T)

PRIUS Data: Tim Burress, "Benchmarking of Competitive Technologies," EETT meeting, 9 Dec 2010
Simulation results: Pan-Seok Shin using Flux2D

* Rotor notch pitch necessary to smoothen m(θ) when θ=22.5

Technical Accomplishments and Progress – FY11 (contd.)

- Permanent magnet detail: baseline machine
  - Designed to support highest possible air gap flux density
  - With coercivity to withstand highest stator demagnetization fields at highest rotor operating temperature
  - Smoothest torque production with angle



Verification of flux leakage:
F=1-(22-6)/22 = 0.27

Calculated as 0.29

Baseline IPM: 0.78kg NdFeB @29% ineffective @$90/kg=$26 per rotor consumed saturating iron bridge and posts.

Simulation results: Pan-Seok Shin using Flux2D
NdFeB magnets (Br=1.24T, Hc=16.9kOe) and are approximately 50MGOe

Collaborations

- Project dependent on technical contributions from:
  - ORNL Material Science and Technology Division for thermal conducting materials for motor packaging
  - ORNL Computer Science and Mathematics Division for shear-rolled steel processing
  - NREL collaboration on thermal performance and exchange of new heat transfer material technologies

Future Work

- Reminder of FY11
  - Develop understanding of baseline machine leakage inductance
  - Commence alternative winding configuration studies
  - Start magnetic and thermal materials work
  - Apply to non-RE machine structures
- FY12
  - A major thrust of this project is the application of materials that possess fast flux (magnetic, thermal) response needed to meet efficiency target at higher operating frequency at high machine angular speeds
- FY13
  - Fabricate and test functional IPM prototype having material innovations and non-RE alternative if possible

Summary

- This project will demonstrate technologies that can improve the efficiency of a 55 kW traction drive electric machine by at least 1.5% over its best efficiency mapping points through use of:
  - *Advanced core materials*
  - *Alternative winding designs*
  - *Improved cooling materials and methods*

- Impacts
  - Improve machine operating efficiency over broad torque-speed region
  - Substantially improve traction drive motor continuous power rating

- FY11 simulation results of baseline motor provide comparator data needed for evaluation of materials and process innovations.
  - Substantial understanding of permanent magnet performance, leakage flux effects and torque production