Motor Packaging with Consideration of Electromagnetic and Material Characteristics

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Project ID: APE035

2012 U.S. DOE HYDROGEN and FUEL CELLS PROGRAM and VEHICLE TECHNOLOGIES PROGRAM ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING

Overview

Timeline

- Start – Oct. 2010
- Finish – Sept. 2013
- 45% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received for FY11
  - $400K
- Funding received for FY12
  - $600K

Barriers

- Plug-in and battery electric vehicles, PEV's require substantial all electric range, AER. This need translates directly to the need for more efficient electric machines (1→3% greater) at same or reduced cost that motivates refocusing our efforts more on materials, their processing and machine structure.
- Vehicle Technologies Program targets
  - Improve efficiency over DOE 2020 target of 94%

Partner/Collaborators

- ORNL Team Members: Tim Burress, Curt Ayers, Randy Wiles
- ORNL Materials Science and Technology Division – epoxy matrix composites (funded by DOE VTP Materials Program)
- ORNL Computer Science and Mathematics Division – lamination steel processing
- ANL and NREL collaboration

Objectives

- Overall
  - Develop more efficient electric machines based on investigation of lower loss materials and their processing.
  - Improve the continuous power from 54% to >58% of peak based on same thermal management system.
- FY12
  - Develop technologies that can improve the efficiency of a 55 kW traction drive electric machine by at least 1.5% averaged over its (m,w) three to five most frequent operating points.
  - Employ thermal material and process innovations to realize program goal.

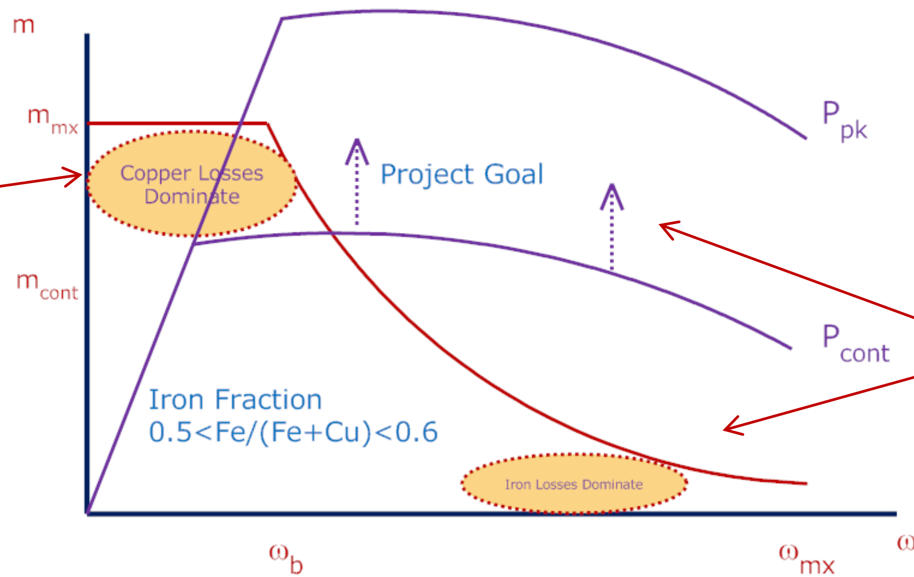
Milestones

Month/Year	Milestone or Go/No-Go Decision
Dec-2011	Milestone: Completed baseline/comparator machine model (March 2011) Milestone: Complete simulation study of epoxy matrix alumina thermal conducting materials (Dec 2011)
Sept-2012	Milestone: Complete loss survey of baseline machine and quantified major contribution sources (March 2012) as foundation for thermal material application. Go/No-Go Decision: Laboratory prototype temperature rise and uniformity at mapping point justifies continuation.
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 in 3-way comparison with baseline machine.

Approach

- **The first efficiency improvement step is the development of a loss survey for the baseline machine that quantifies losses and opportunity for reduction.**
  - **Requires agreement on what the 3 to 5 most frequent operating points are, and**
  - **What drive schedule is employed to determine these points**

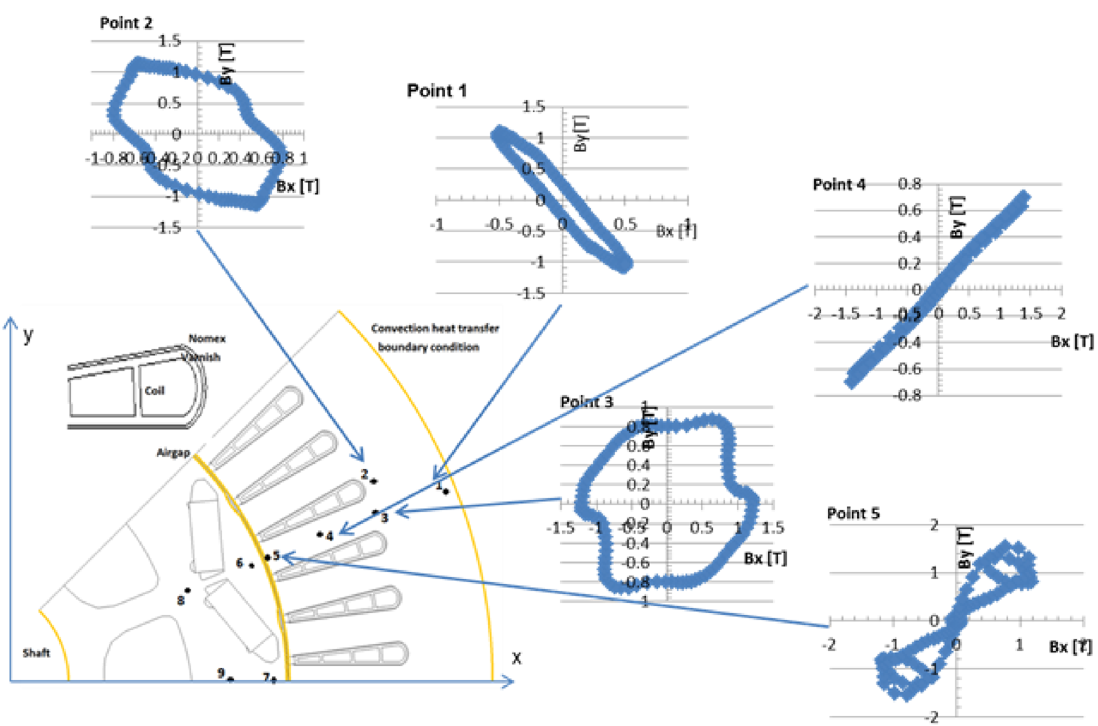
Material focus on:
- Electromagnetic design
- Conductor and winding design
- Stator potting material, EMC
- Uniformity of stator core and winding temperature.

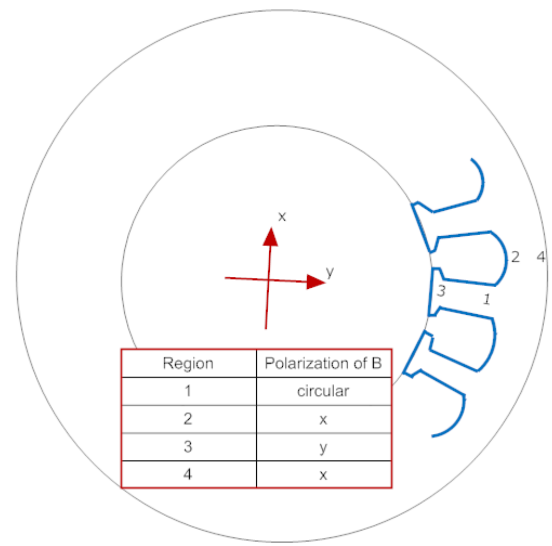


Material focus on:
- Electromagnetic design
- Magnetic steel – NO vs GOES loss at high frequencies
- Quantify opportunity for higher GOSS texture and/or higher silicon steels.

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



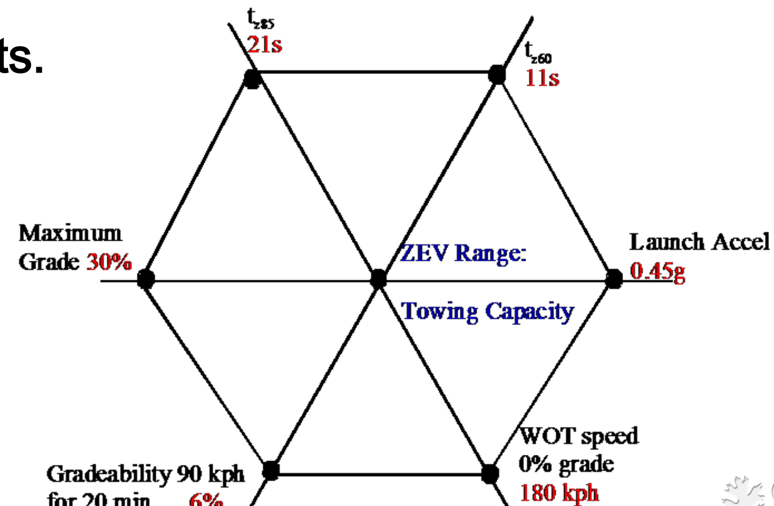


Region	Polarization of B
1	circular
2	x
3	y
4	x

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 (close to road load point of 90 kph on 6% grade).
- Lack of standard PEV drive cycle limits us in this area, so we will opt for the following points:
  - Maximum grade hold (30% grade). Applies to crawl out of ditch requirement.
  - WOT on level grade, no headwind, case.
  - Mapping point (60Nm, 5000 rpm) correlates to DOE continuous operation of about 30 kW operation.
  - Two continuous duty operating points.

$$P(V) = M_v V\dot{V} + gM_v[C_{rr}\cos\alpha + \sin\alpha]V + 0.5\rho C_d A_f\{V + V_w\}^3$$



2010 Prius parameters:

M_v=1458kg, C_{rr}~0.008, C_d~0.33, A_f~2.36

ρ=1.225 @ T=25°C and sea level

α=0 and V_w=0

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

2010 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.**

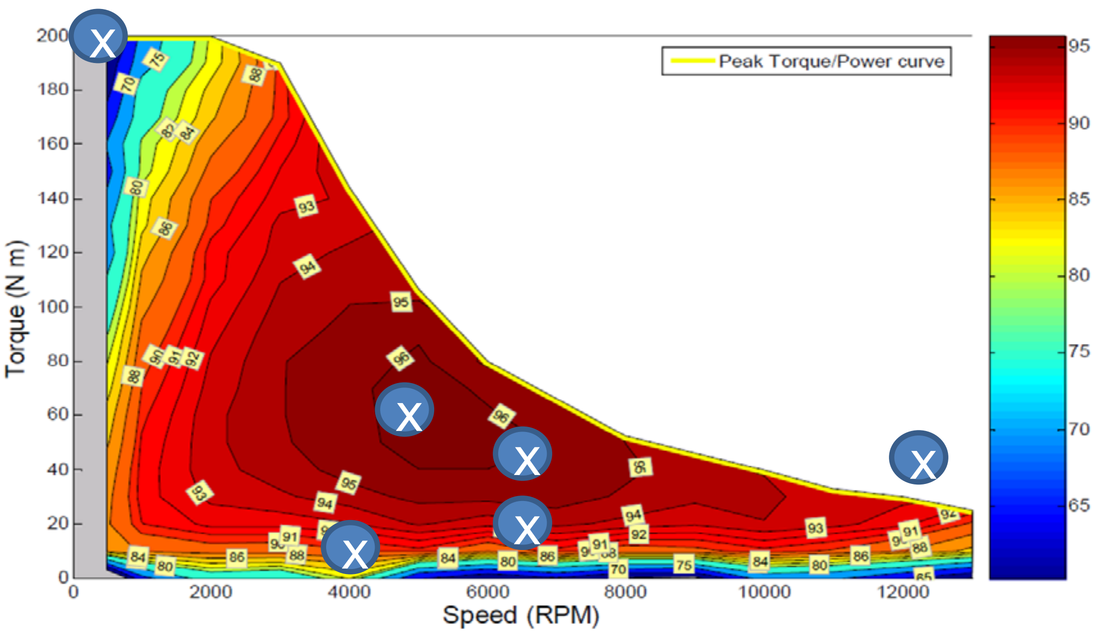


Fig. 3.11. 2010 Prius motor efficiency contours for 650 Vdc.

2010 Prius on 6% grade, driver only, P(V)=31kW
m_MG=48.7 Nm
n_MG=6,385 rpm
Close to the map point used.

On 0% grade V=55 mph
m_MG=15.6 Nm
n_MG=6,385 rpm

Urban cruise, 0% grade and V=35 mph
m_MG=8.95 Nm
n_MG=4,063 rpm

WOT performance, V=105
m_MG=45 Nm
n_MG=12,190 rpm

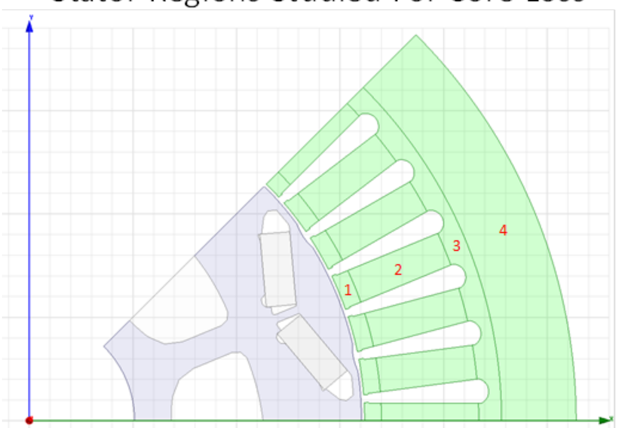
Technical Accomplishments and Progress - Overall

- **Completed assessment of machine loss**
  - Applied FEA to investigate the core loss in stator regions that have distinctive flux vector patterns
  - Compiled the loss survey map as guideline for continued research
- **Continued investigation of thermal materials that help in heat removal and flattening of stator thermal gradients**
  - Working with Solepoxy on EMC-epoxy molded compounds
  - Develop application concepts that facilitate heat removal
- **Using the machine loss findings to define the type of lamination steel most suited to high speed machines that minimize or eliminate need for RE magnets**
  - In contact with steel manufacturers

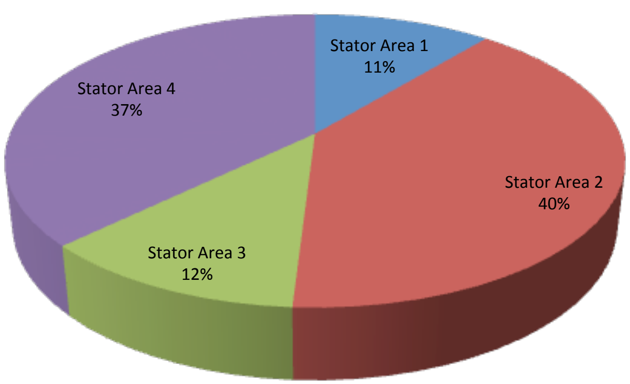
Technical Accomplishments and Progress – FY12 (contd.)

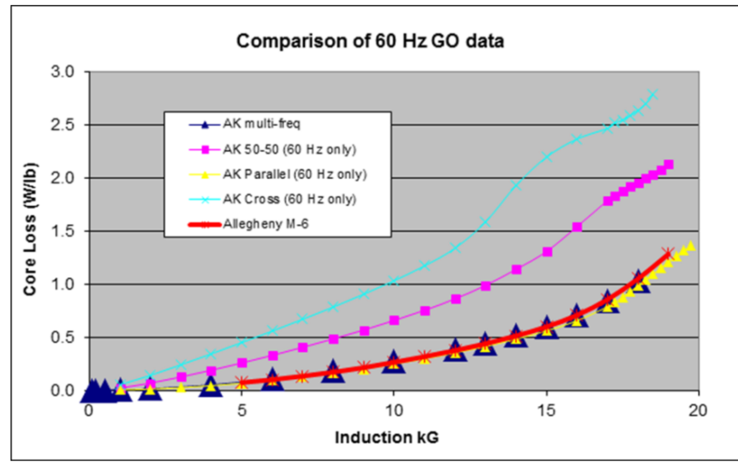
- Completed assessment of machine loss
  - *Proposed materials and processes will address improvement in core loss that covers 77% of the total loss*

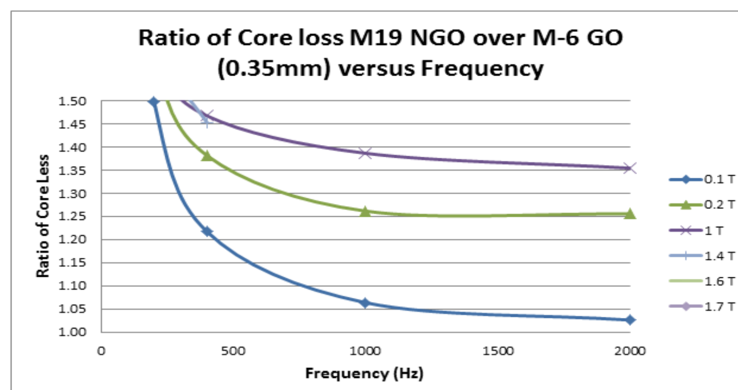
Stator Regions Studied For Core Loss



Core Loss In Various Stator Regions



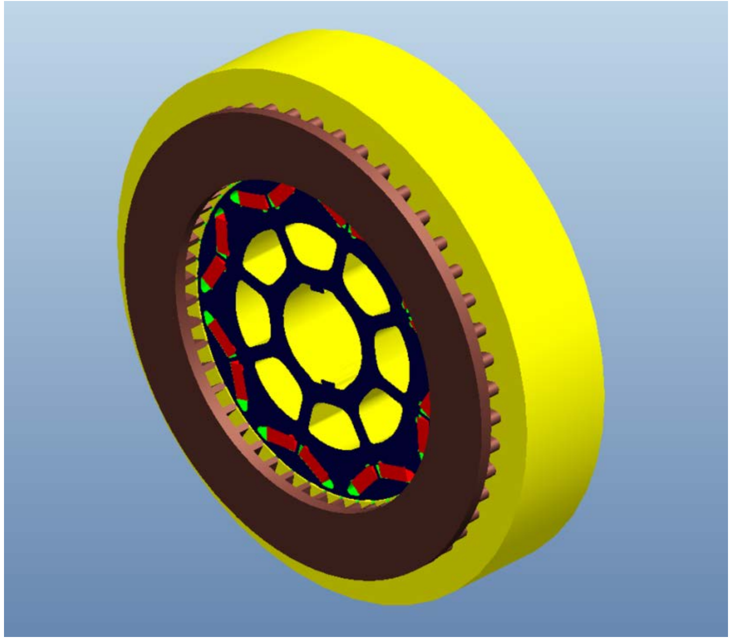


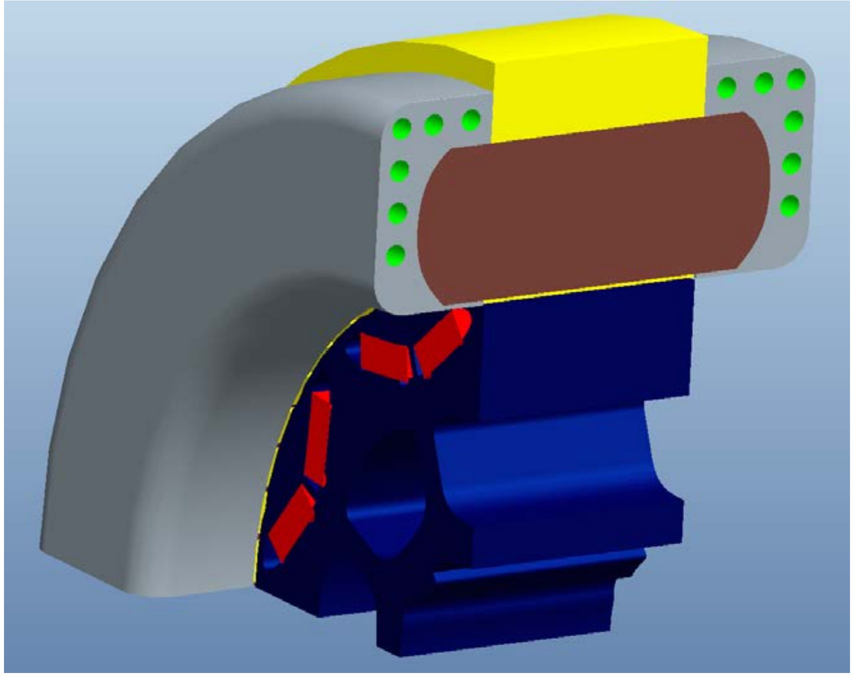


Graphic courtesy T. Burress

Technical Accomplishments and Progress – FY12 (contd.)

- **Continued investigation of thermal materials that help in heat removal and flattening of stator thermal gradients**
  - Materials work aims to lower heat generation
  - Thermal design aims to improve heat removal – new concept
  - Novel application of Epoxy/Ceramic Molding composites (EMC)
  - Earlier proposals of winding designs still apply and will be pursued if time/budget permits.

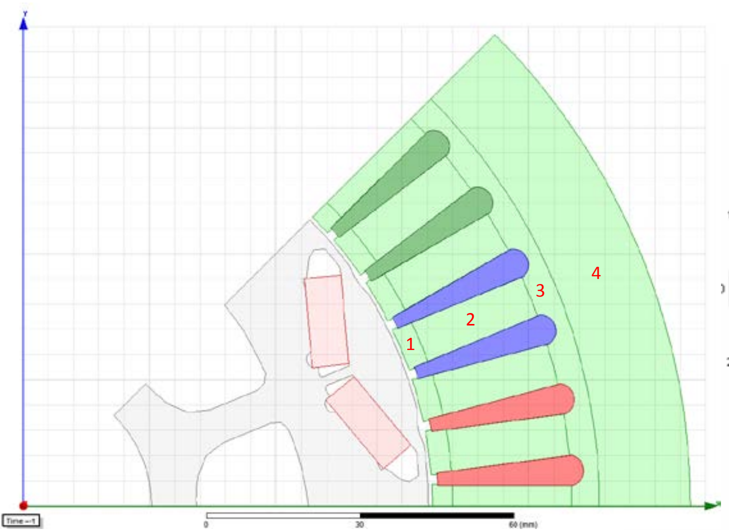


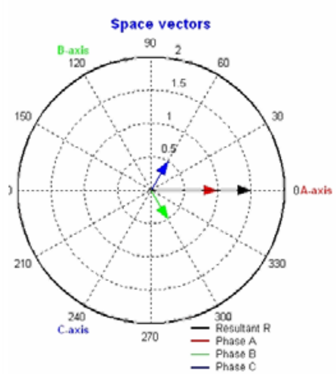


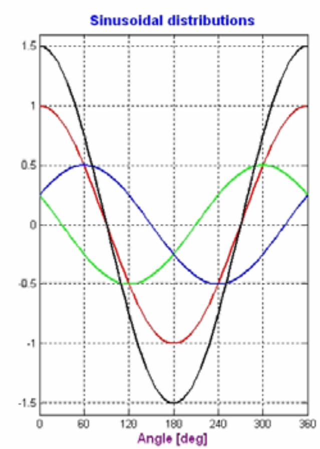
Graphics courtesy R. Wiles ORNL

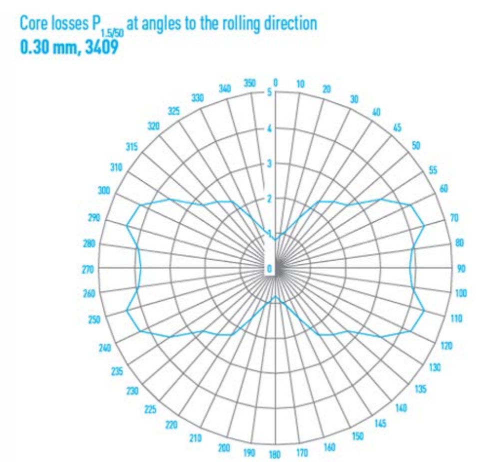
Technical Accomplishments and Progress – FY12 (contd.)

- **Using the machine loss findings to define the type of lamination steel most suited to high speed machines that minimize or eliminate need for RE magnets**
  - Investigation into electrical steel materials for application into high speed electric machines (e.g., 2x present designs)
  - Magnetic materials must be developed that efficiently contain flux at high frequency
  - Illustration: 3 phase currents applied to stator generate a rotating magnetic field. Phases are A-red, B-blue and C-green as shown.





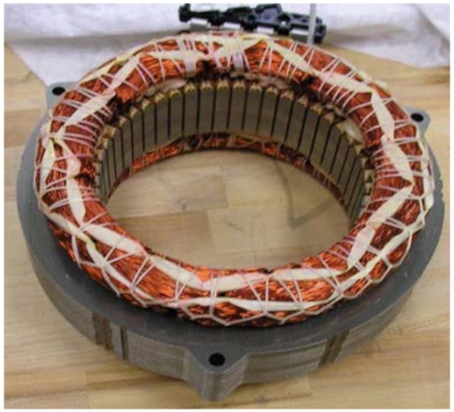


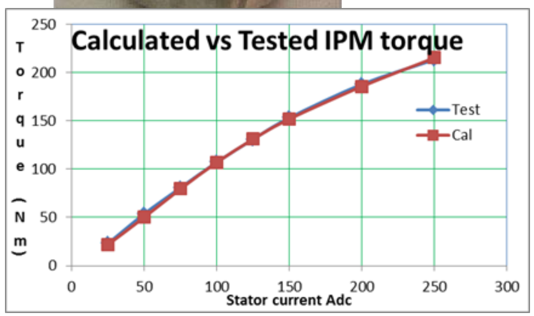


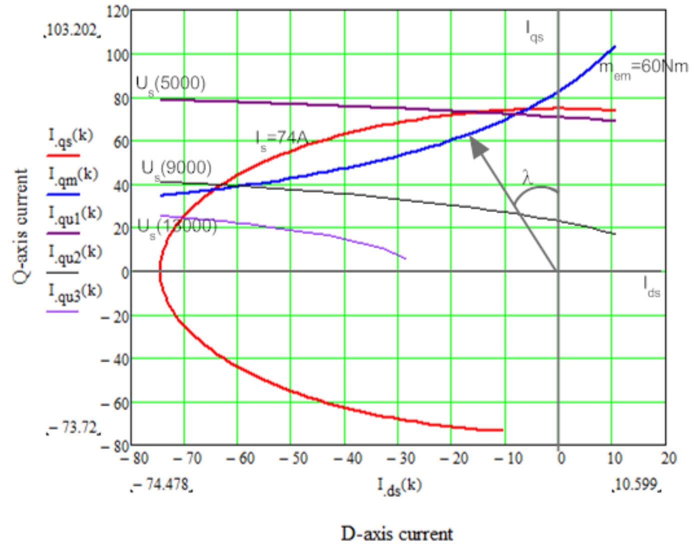
Graphic animation courtesy N. Mohan, UMN
IPM 900Hz wave means V4=163m/s (363 mph)

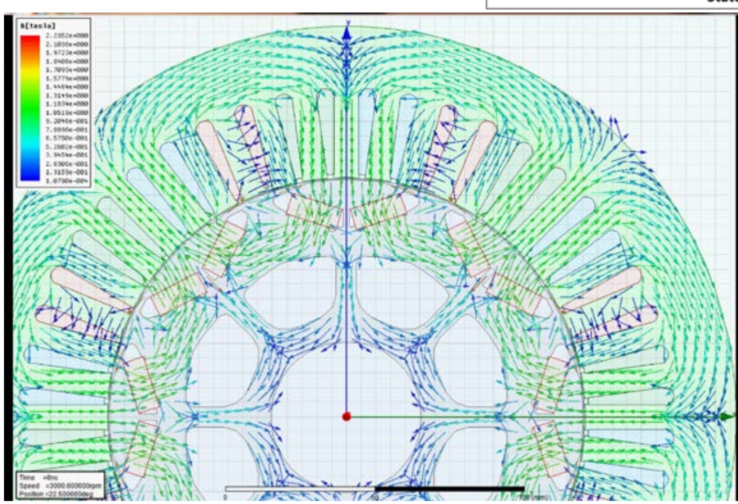
Technical Accomplishments and Progress – FY12 (contd.)

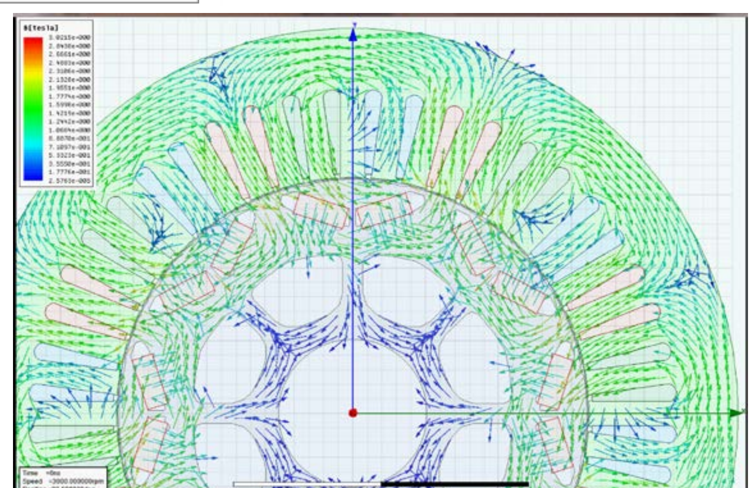
- **Deep understanding of machine flux essential to concepts leading to reduction of core (and copper) losses**











Left: 3000rpm Is=0; Right: 3000rpm, Is=170A at 0 deg
FEA courtesy Tim Burress ORNL

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 alternative steel processing opportunities
  - Supplied ANL the baseline IPM machine parameter characterization and modeling documents for use in Autonomie
  - NREL collaboration on thermal performance and idea exchange

Future Work

- **Reminder of FY12**

  Project intent is 3 year commencing FY11 to span analytical work leading to functional prototypes, 2 for thermal materials, possibly 1 for graded silicon steel stator.

  Core casting and shear rolling no longer under consideration.

- **FY13**
  - Continue development of thermal materials for heat removal,
  - Investigate novel processing of stator laminations, and
  - Fabrication of prototypes based on new materials and their processing

- **FY14**
  - Pursue novel lamination processing techniques and develop in support of higher speed electric machines and application to non-RE traction motors.

This project supports, and by start of FY15 feeds into, the hybrid excitation project.

Summary

- **This project aims to 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 and their processing***
  - ***Improved cooling materials and methods, and***
  - ***Potentially focus on conductor and winding designs if funding permits***
- **Impacts**
  - **Improve machine operating efficiency over broad torque-speed region**
  - **Substantially improve traction drive motor continuous power rating**
  - **Findings feed directly into SAE J2907 motor rating task force**
- **Findings to date indicate that lamination steels for higher speed electric machines are currently unacceptable**
  - **Investment is required for the advancement of novel surface and bulk treatments that reduce hysteresis and eddy current losses.**