

# **Alnico and Ferrite Hybrid Excitation Electric**

**John M. Miller**  
**Oak Ridge National Laboratory**  
**May 16, 2012**

**Project ID: APE043**

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

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# Overview

## Timeline

- **Start – Oct. 2011**
- **Finish – Sept. 2014**
- **20% complete**

## Budget

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

## Barriers

Permanent magnet electric machines possess the highest specific power and lowest operating cost compared to any competing technology. However, the high cost of RE permanent magnet materials, a supply susceptible to interruptions and embargo's all demand taking a close look at lower energy permanent magnet materials, substitution materials, and novel structures.

- **Vehicle Technologies Program targets**
  - 2020 targets: \$4.7/kW, 1.6 kW/kg, 5.7 kW/l
  - Performance comparator is baseline IPM

## Partner/Collaborators

- **ORNL Team Members:** Curt Ayers, Tim Burress, Chester Coomer, Randy Wiles (ESTD)
- **Balasubramaniam Radhakrishnan (CSMD)**  
(lamination materials and processing)
- **Collaborators:** Andy Wereszczak, HT Lin (MSTD)  
(PM material micrograph evaluations)
- **Advisory:** Michael Brady, David Parker (CSMD)
- **Ames Lab:** Iver Anderson & William McCallum

# Objectives

- Overall
  - Develop electric machines that minimize or eliminate the need for RE magnet materials, and
  - Have potential to match the baseline IPM performance metrics using low cost non-RE magnets
- FY12
  - Explore permanent magnet material choices suitable for use in hybrid excitation 55kW PEV traction motor
  - Explore novel flux switching machine architectures and operating modes with potential to match baseline IPM performance levels.

# Milestones

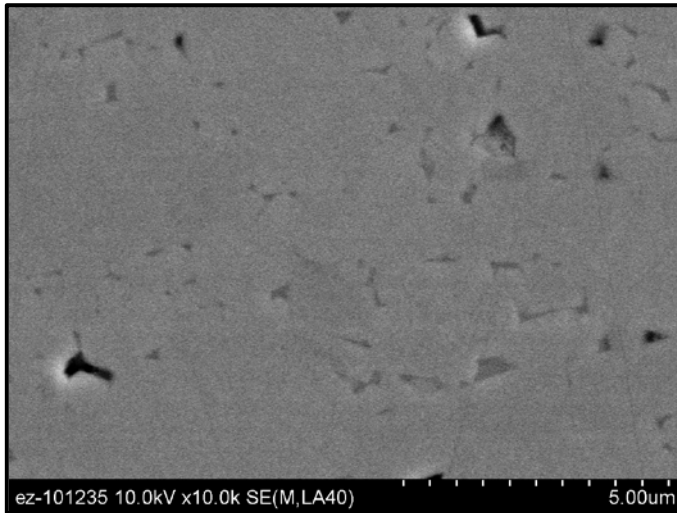
Month/Year	Milestone or Go/No-Go Decision
Sept-2012	<p><b><u>Milestone</u></b>: Completed magnetic and electrical design of flux switching machine and desired mechanical structure</p> <p><b><u>Milestone</u></b>: Initiate modeling of candidate machine and develop list of parameters</p> <p><b><u>Go/No-Go Decision</u></b>: Conceptual design within 20% of baseline machine metrics</p>
Sept-2013	<p><b><u>Milestone</u></b>: Completed simulation of refined candidate machine and comparison to baseline machine</p> <p><b><u>Go/No-Go Decision</u></b>: Conceptual design on par with baseline machine – go forward with prototype</p>
Sept-2014	<p><b><u>Milestone</u></b>: Complete fabrication of a 55 kW traction drive motor utilizing selected architecture, non-RE magnet materials, low loss electrical steel, and appropriate winding designs.</p> <p><b><u>Go/No-Go Decision</u></b>: dyno validation and compare to baseline</p>

# Approach

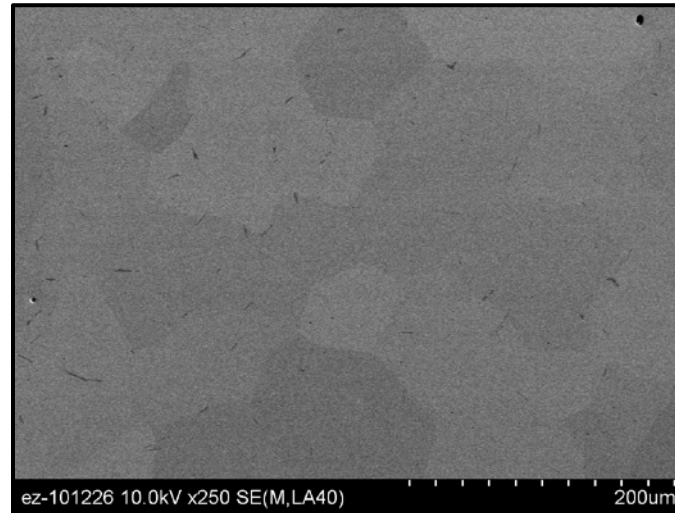
- **Renew investigation of ferrite and Alnico magnet machines**
  - Ceramic and Alnico magnets have excellent high temperature performance ( $>250^{\circ}\text{C}$ )
  - Research machine architectures capable of high performance with low energy PM's
  - Select flux switching design as candidate architecture suitable to accommodate Alnico or hard ferrite PM
  - Determine coercivity bounds of enhanced Alnico and modified ferrite magnets, in the right structure and architecture, needed to match or exceed baseline IPM performance, for future project work.
- **Characteristics of ferrite and Alnico magnets from  $-40^{\circ}\text{C}$  to  $+120^{\circ}\text{C}$ .**
  - Ferrites contain mixed domains, some in opposition to the magnetization, therefore a weaker magnet
  - Alnico has high remanence but low coercivity. However, Alnico can tolerate armature reaction aligned with to as much as transverse to the magnetization direction.

# Approach (contd.)

- Research into **higher speed electric machines**
  - Today's traction motors and automotive alternators (14,000 to 18,000 rpm)
  - Expand this out to 28,000 to 30,000 rpm *to match baseline IPM performance but with weak magnets*
  - Determine the point of equivalence between lower energy PM's and high energy RE PM's designs where performance requirements are met or exceeded



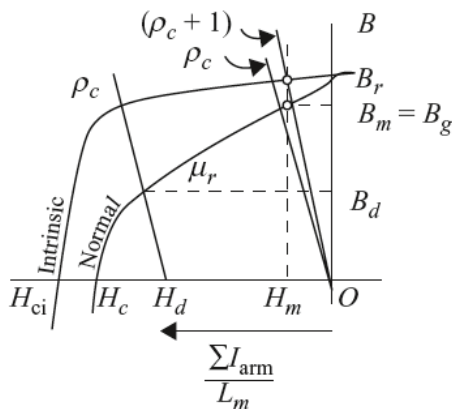
SrO-6Fe<sub>2</sub>O<sub>3</sub> Ferrite out of plane  
Courtesy Andy Wereszczak



Alnico8 out of plane  
Courtesy Andy Wereszczak

# Approach (contd.)

- Due to use of weaker magnets the candidate electric machine must rely on higher speed operation, on the order of 28,000 rpm and a gear reduction stage



$$B = B_i + \mu_0 H$$

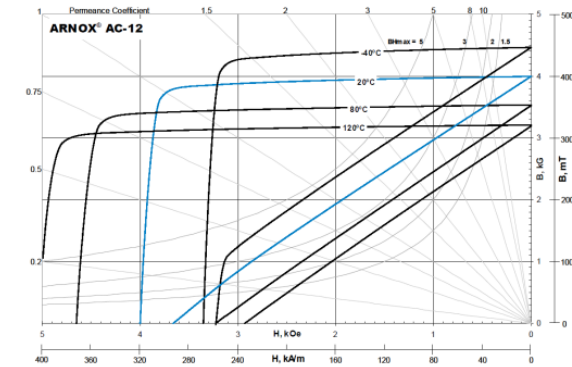
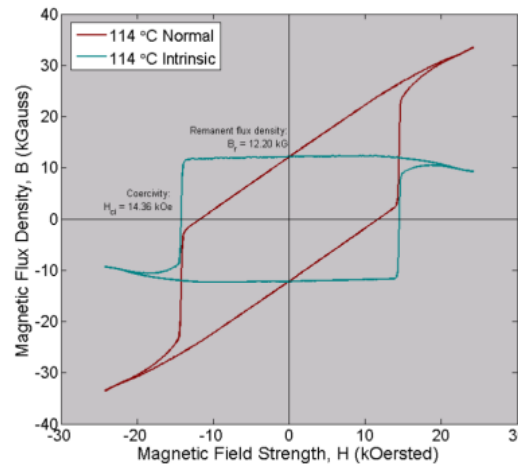
$$B_i = \mu_0 \chi H + B_r$$

$$B = B_r + \mu_0 (1 + \chi) H = B_r + \mu_0 \mu_r H$$

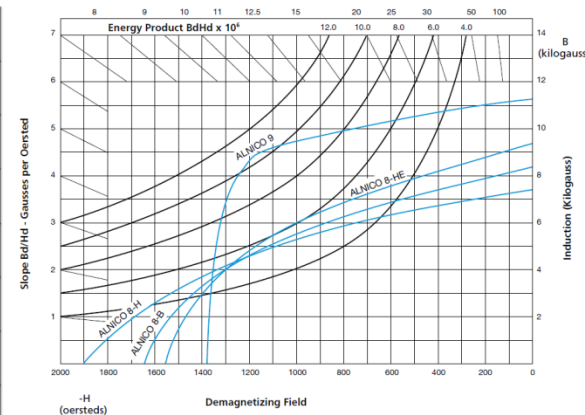
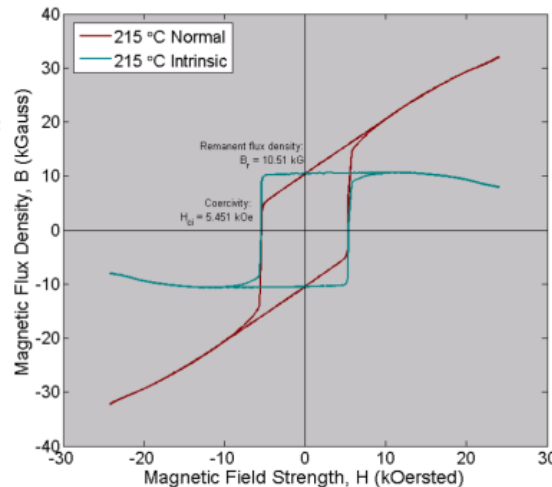
$$\chi = 0.05 \text{ RE}; = 0.3 \text{ Alnico9}; = 2.7 \text{ Alnico5}; = 0.05 \text{ Ferrite}$$

$$P_c = \frac{B_m - B_r}{\mu_r B_m} \approx \frac{L_m A_g}{g A_m} \cong \frac{L_m}{g}$$

$P_c$  = permeance coefficient of the PM design  
where,  $L_m$  = magnet length and  $g$  = gap



Hard ferrite magnet: Arnold Magnetics



Alnico magnet: Arnold Magnetics

Prius NEO magnet courtesy T. Burress

# Technical Accomplishments and Progress - Overall

- Dismissed the Transverse Flux Machine (TFM) as a candidate due to 3D geometry and need for low flux Soft Magnetic Composites (SMC).
- Maintain interest in heteropolar architectures as candidate for future investigation if very low loss electrical steels are available. This machine is typically very high frequency.
- Selected the permanent magnet biased flux switching machine as candidate for continued exploration because it admits ferrite and Alnico and because it can accommodate a field winding for hybrid excitation
- Maintain collaboration with ORNL MSTD on new magnet material developments (ARPA-E program) and with Ames Laboratory.

# Technical Accomplishments and Progress – FY12 (contd.)

- Magnetics design of flux switching machine underway
- FEA results to date are promising for hard ferrite magnet design
- Invention disclosure submitted protecting the concept (ORNL IP)

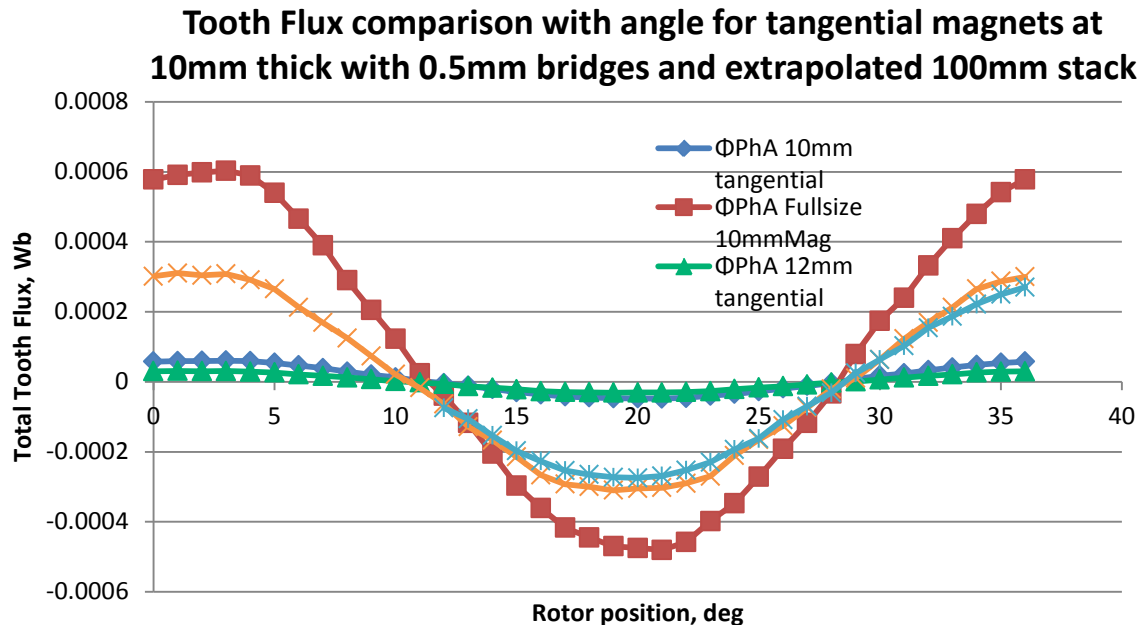


Illustration of one-phase magnetic performance of flux switching concept

# Technical Accomplishments and Progress – FY12 (contd.)

- Investigating applicability of ceramic magnet figure of merit, FOM, stating that residual induction  $B_r$  and a permeance derived value of field strength  $H_x$  have more merit than energy product.
  - FOM: total ceramic magnet volume is inversely proportional to  $B_r H_x$  to meet a specific motor performance objective
- Investigating the contention that energy product in Alnico magnets is in proportion to the volume of such magnets in an electric machine. The point here is that relaxation induction in Alnico after removal of current produced field is not substantially influenced by the field orientation so long as it lies within  $90^\circ$  of opposite to magnetization.
  - Require more understanding of how permeance coefficient influences this situation.

# Collaborations

- **Project dependent on technical contributions from:**
  - **ORNL Material Science and Technology Division for analysis of permanent magnets and for thermal conducting materials for stator potting**
  - **ORNL Computer Science and Mathematics Division for low loss steel and for advice on new developments in RE alternative magnets.**
  - **Ames Laboratory for advice and consulting on availability of modified ferrite and enhanced Alnico magnets.**

# Future Work

- **Reminder of FY12**

- Concept flux switching machine magnetic and electrical design capable of achieving 80% of baseline IPM performance
- Commence building model and definition of parameters

- **FY13**

- Prototype hybrid machine using hard ferrite only and compare performance against baseline IPM machine
- Validate simulation model based on prototype machine characterization

- **FY14**

- Refine prototype design to include low loss electrical steel and advancements in conductor and winding designs.
- Refinement to include available modified ferrite or enhanced Alnico as available.

**This project is supported by material investigation of APE035**

# Summary

- This project focuses on design and development of an electric machine architecture that will minimize or eliminate the need for RE magnet material
  - *EM structure that minimizes PM exposure to high demag field*
  - *Incorporates materials suited to high speed operation – high frequency of flux in the mild steel components*
- Impacts
  - Substantially reduce dependence on RE materials in the vehicle traction drive system
  - Machine architecture alternative to the dominant IPM that today is based almost exclusively on RE magnets
  - Opportunity to substantiate FOM for PM's in electric machines or to develop a more refined FOM