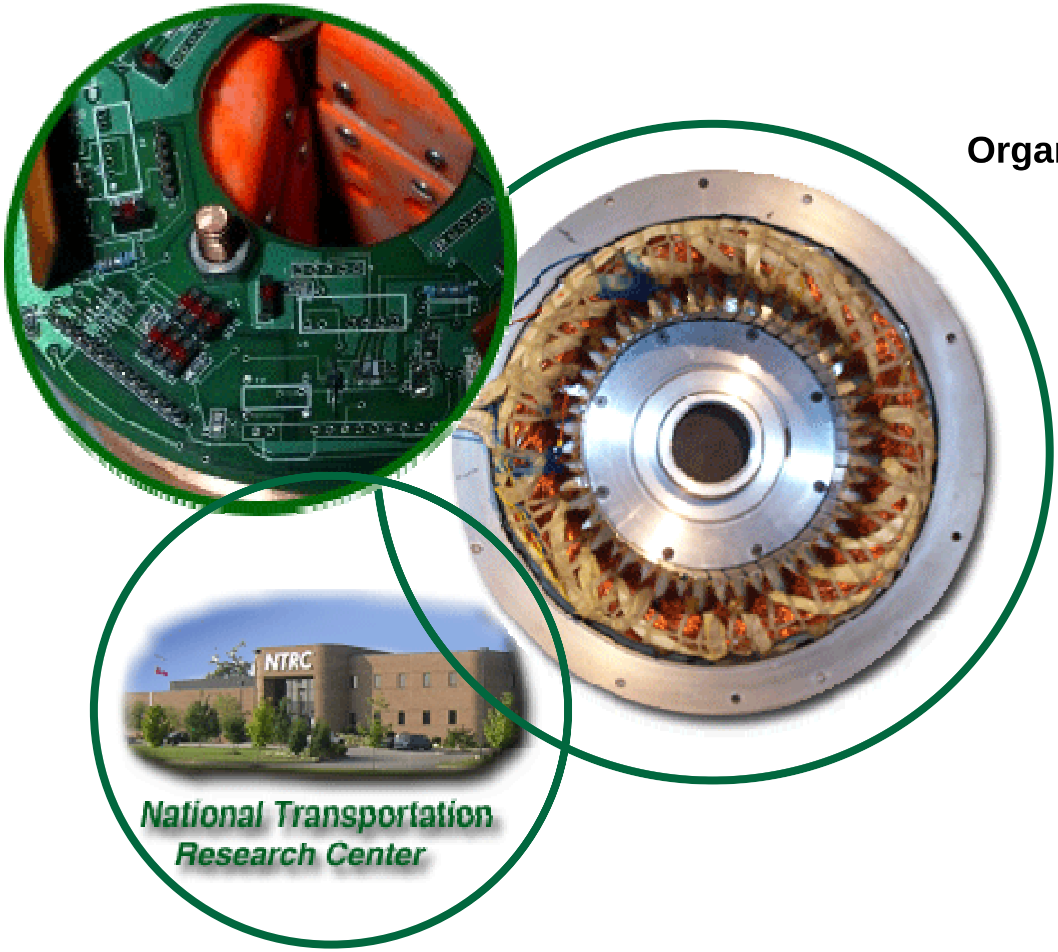
Electric Machine R&D

Laura Marlino

Email: marlinold@ornl.gov
Phone: 865-946-1245
Organization: Oak Ridge National Laboratory



DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
Bethesda, Maryland

February 28, 2008

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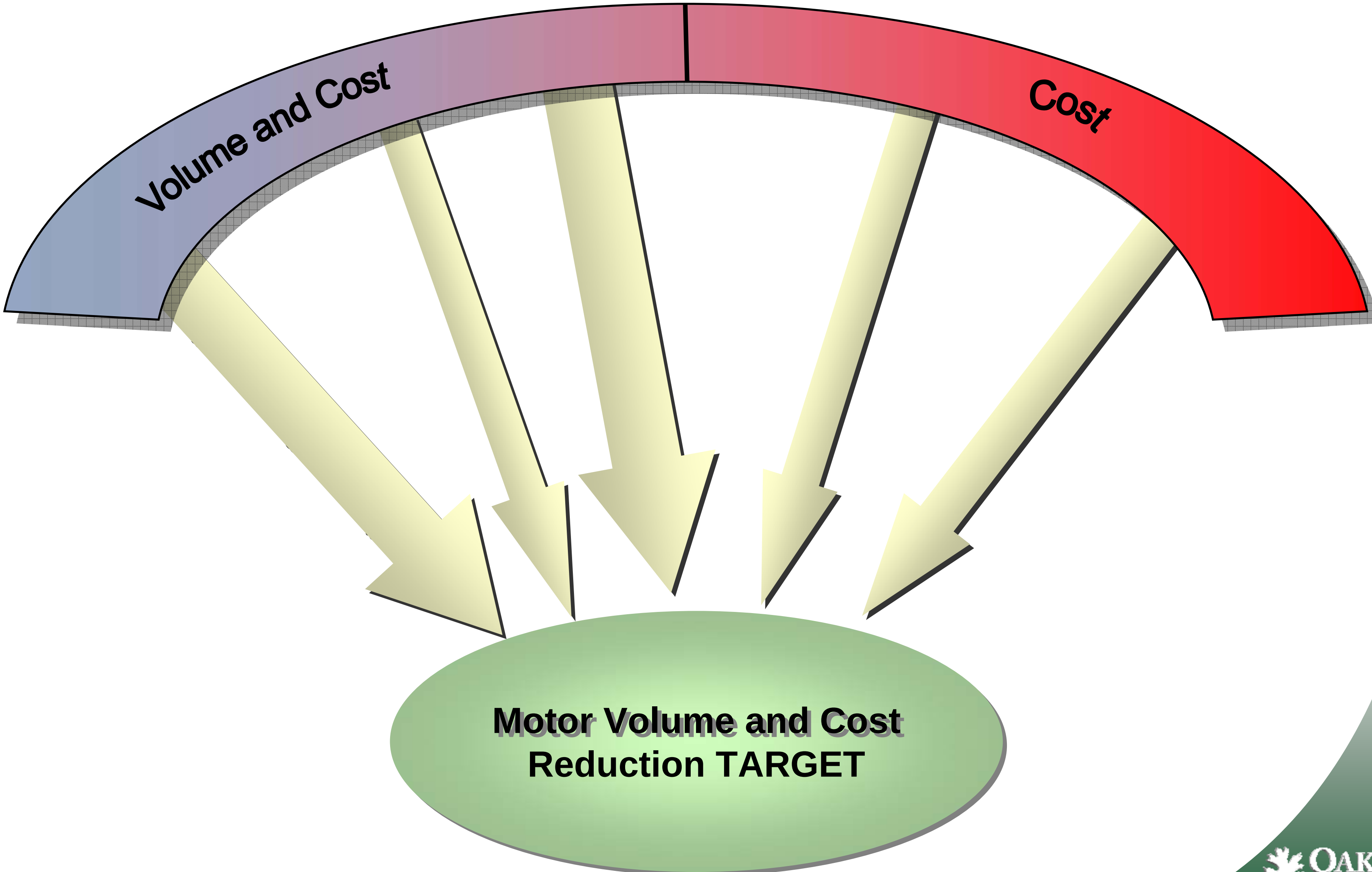
Multiple Pathways Pursued: Increase Potential for Success and Provide Portfolio of Options



Projects vs. Pathways

	Increase Motor Speed	Increase Efficiency	Use less Materials	Use Less Expensive Materials	Manufacturing Improvements
Uncluttered Rotor PM Machine			X	X	
Axially Excited Electro-Magnetic Synchronous Rotor Motor	X		X	X	X
Application of Concentrated Windings to Electric Machines	X	X	X		X
Amorphous Core Material Evaluation		X	X		X
Magnetic Material for PM Motors				X	X

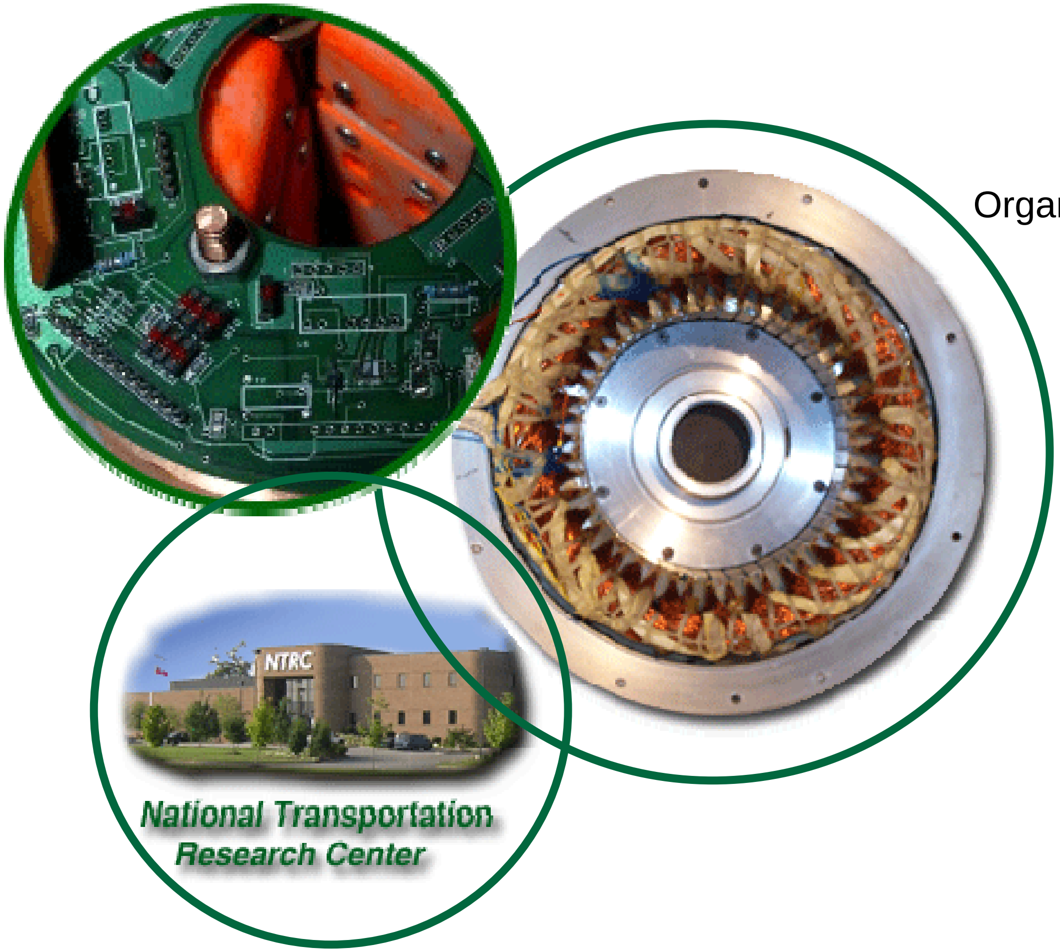
Uncluttered Rotor PM Machine for a CVT Design

Laura Marlino

Email: marlinold@ornl.gov
Phone: 865-946-1245
Organization: Oak Ridge National Laboratory

Principal Investigator: Don Adams
Agreement: 13272

Project Duration: FY06 to FY09
FY08 Funding: $707K



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Purpose of Work

- **The objective of this project is to develop a new machine that combines the motor and generator/motor into one unit and has the potential to be used as a continuously variable transmission (CVT) that requires two electric machines. The expected advantages of this new machine are:**
  - Additional torque coupling between the two rotors for producing more wheel torque.
  - The combination of a motor and generator into one machine with only a single permanent magnet rotor has the potential for a simpler and less costly CVT.
  - Output power of the uncluttered rotor to the wheel due to the reaction torque can be doubled through a gear set.

Responses to Reviewers' Comments

Comments:

"Very innovative, good approach for meeting goals"
"Interesting design idea; unconventional approach"

Comments:

"Want to see data on hardware"
"Needs validation data"

Action:

Prototype hardware being designed will be tested to obtain realistic performance metrics

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Barriers

VTP Related Challenges

- Program targets require higher machine power density, implying higher speeds and/or higher torque.
  - The mechanical strength, the critical speed of the rotor assembly, vibration, bearing life expectancy, gear losses, etc. become serious factors in limiting the maximum operational speed of the rotor.

Technology Related Challenges

- Flux transfer within a limited volume has shown progress but remains to be solved.

Technical Approach

- **The multi-year goal is to develop modeling tools to understand the characteristics of the machine, design a working prototype, then build and test the unit**

Technical Approach (cont'd)

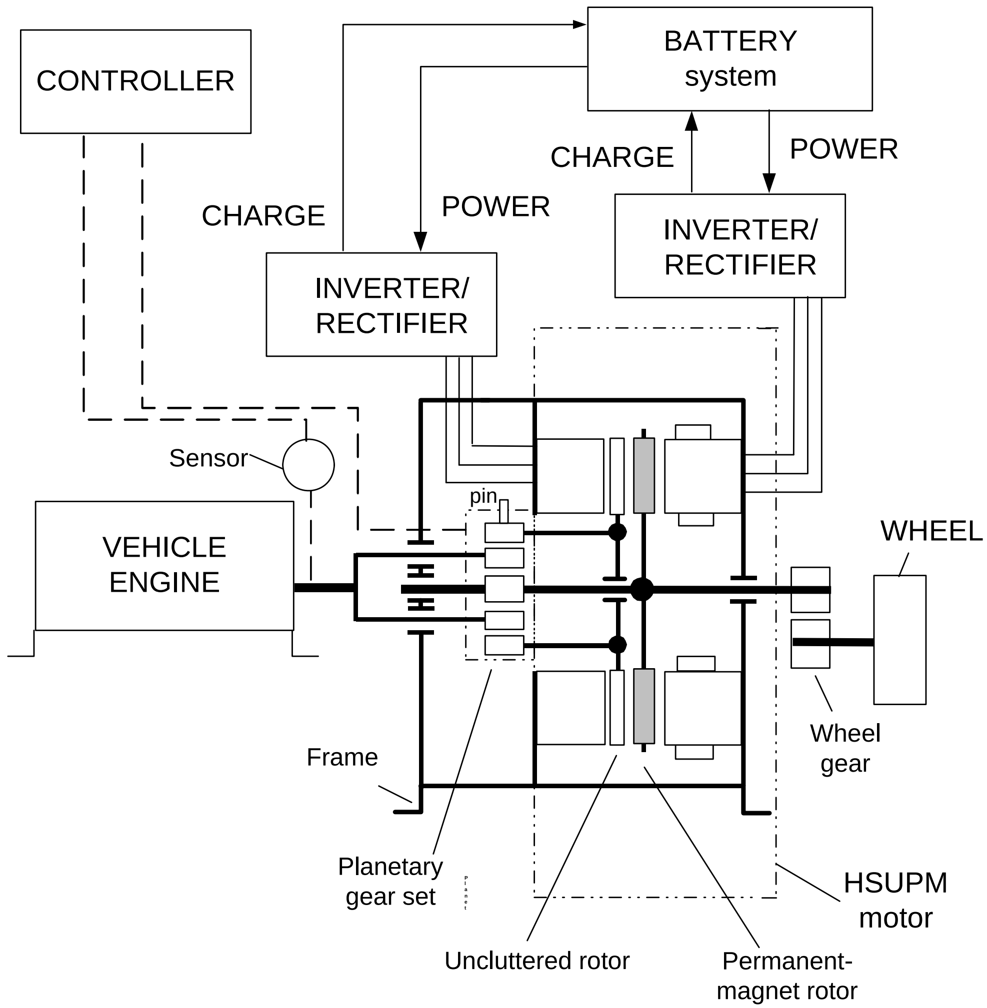


Figure 1. General layout of the CVT machine and its interface with the vehicle system

Axial gap embodiment as a CVT from U.S. Patent 7,270,203

Technical Approach for F08 (cont'd)

- **Task 1: Continue the design progress to understand basic tradeoffs**
- **Task 2: Evaluate the machines cost, size, weight, operational modes, and typical efficiency against targets to determine if the design should go to fabrication**
- **Task 3: Prepare a report on the simulation and design of an uncluttered-rotor CVT motor will be incorporated into the Annual Report**

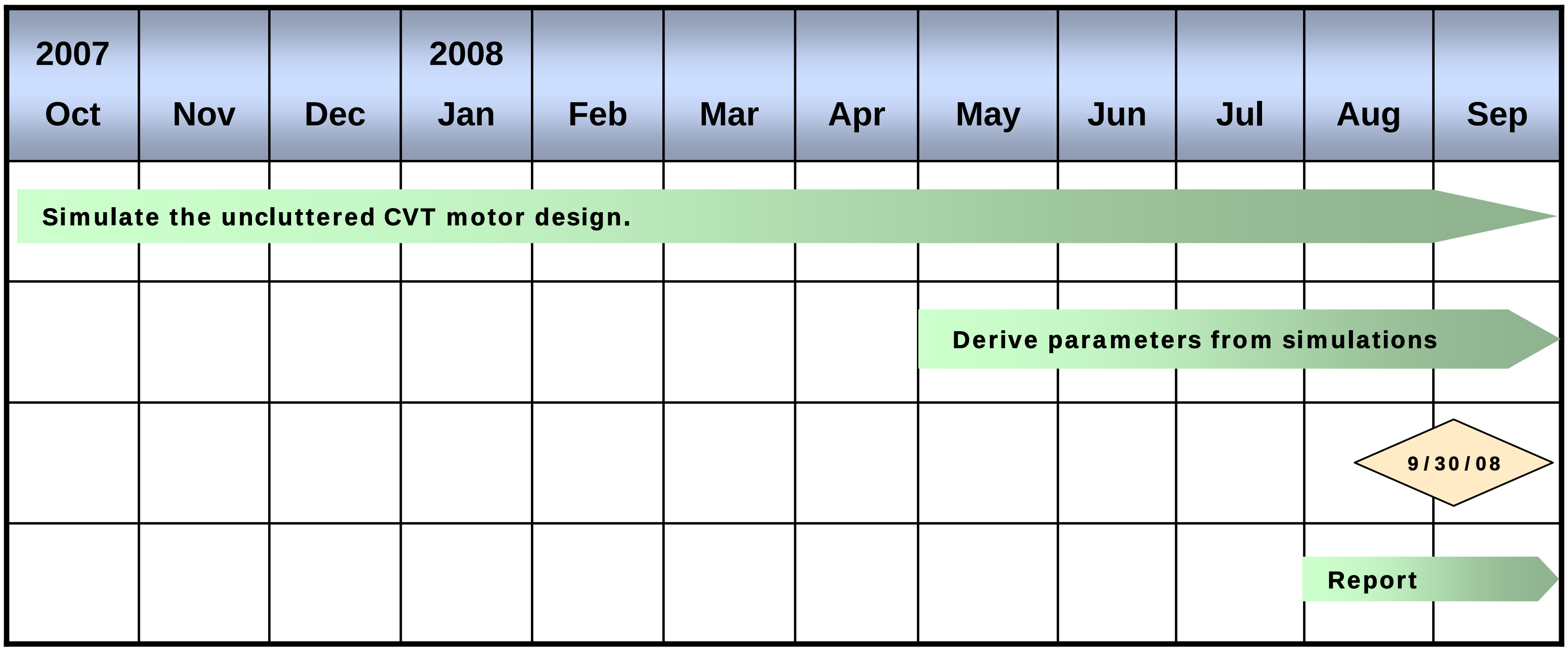
Technical Approach - Uniqueness

- **This machine provides a brushless arrangement of counter-rotating components**
- **The uncluttered CVT machine has two rotors; an uncluttered rotor and a permanent magnet rotor, and two stator wound cores that provides operational flexibility**
  - **Operate simultaneously as a motor and generator**
  - **Combine two machines to function as single motor with higher torque**
- **Because of the additional torque coupling between the two rotors and the combination of motor and generator in one machine with only a single permanent magnet rotor, the uncluttered rotor CVT has the potential to be less costly than conventional CVTs**

Technical Accomplishments Through FY07

- **In FY06 a proof-of-concept secondary rotor that had no rotating windings and a wound core stator for exciting the secondary rotor were fabricated and evaluated, and the concept was validated.**
- **In FY07 simulations were initially conducted for axial-gap and radial-gap approaches. The radial-gap machine was selected for detailed simulations. The simulation results further confirmed that the principle of this new type of machine is workable; the torque of the PM rotor can be transferred directly to that of the secondary rotor, the stationary excitation core of the secondary rotor sees no rotational torque, and the axial force can be practically eliminated by an axially symmetrical arrangement.**

Timeline for FY08



Decision point discussion: Data acquired from design and simulation results will be evaluated against targets to determine whether to fabricate a prototype.

Technical Accomplishments FY08

- **Progress has been made in the evolution of the design through simulations**

Technology Transfer

- **The ‘flux slip ring’ concept that is key to this technology can revolutionize motor designs**
- **Technology transfer is pending prototype demonstration**

Future Work

- **FY09**
  - **Build and evaluate CVT prototype**

Summary

- **The objective of this project is to develop a new machine that combines the motor and generator/motor into one unit which has the potential to be used as a continuously variable transmission (CVT).**
- **Development of a detailed design continues to progress. Throughout this process, ideas have been stimulated for even more highly advanced machines.**
- **The machine will be built and evaluated in FY09 and subsequently made available for the marketplace.**

Publications, Presentation, Patents

- **<u>Publications</u>**
  - **J. Hsu, "Hybrid-Secondary Uncluttered Induction (HSUI) Machine," *IEEE Transactions on Energy Conversion* 16(2), ITCNE4, (ISSN 0885-8969), 192–197 (June 2001).**
  - **J. Perahia, "Discussion of Hybrid-Secondary-Uncluttered Induction (HSUI) Machine," *IEEE Transactions on Energy Conversion* 17(1), ITCNE4, (ISSN 0885-8969), 150 (March 2002).**
  - **J. Hsu, "Closure on Hybrid-Secondary-Uncluttered Induction (HSUI) Machine," *IEEE Transactions on Energy Conversion* 17(1), ITCNE4, (ISSN 0885-8969), 150 (March 2002).**
- **<u>Patents</u>**
  - **John Hsu, "Hybrid Secondary Uncluttered Induction Machine," U.S. Patent No. 6,310,417, October 30, 2001.**
  - **John Hsu, "Simplified Hybrid-Secondary Uncluttered Machine and Method," U.S. Patent 6,891,301, May 10, 2005.**
  - **John Hsu, "Hybrid-Secondary Uncluttered Permanent Magnet Machine and Method," U.S. Patent 6,977,454, December 20, 2005.**
  - **John Hsu, "Electric Machine for Hybrid Motor Vehicle," U.S. Patent 7,270,203, September 18, 2007.**
  - **John Hsu, "Radial Gap Hybrid Secondary Uncluttered Permanent Magnet Electric Machines," Invention Disclosure 1934, May 7, 2007.**

Questions

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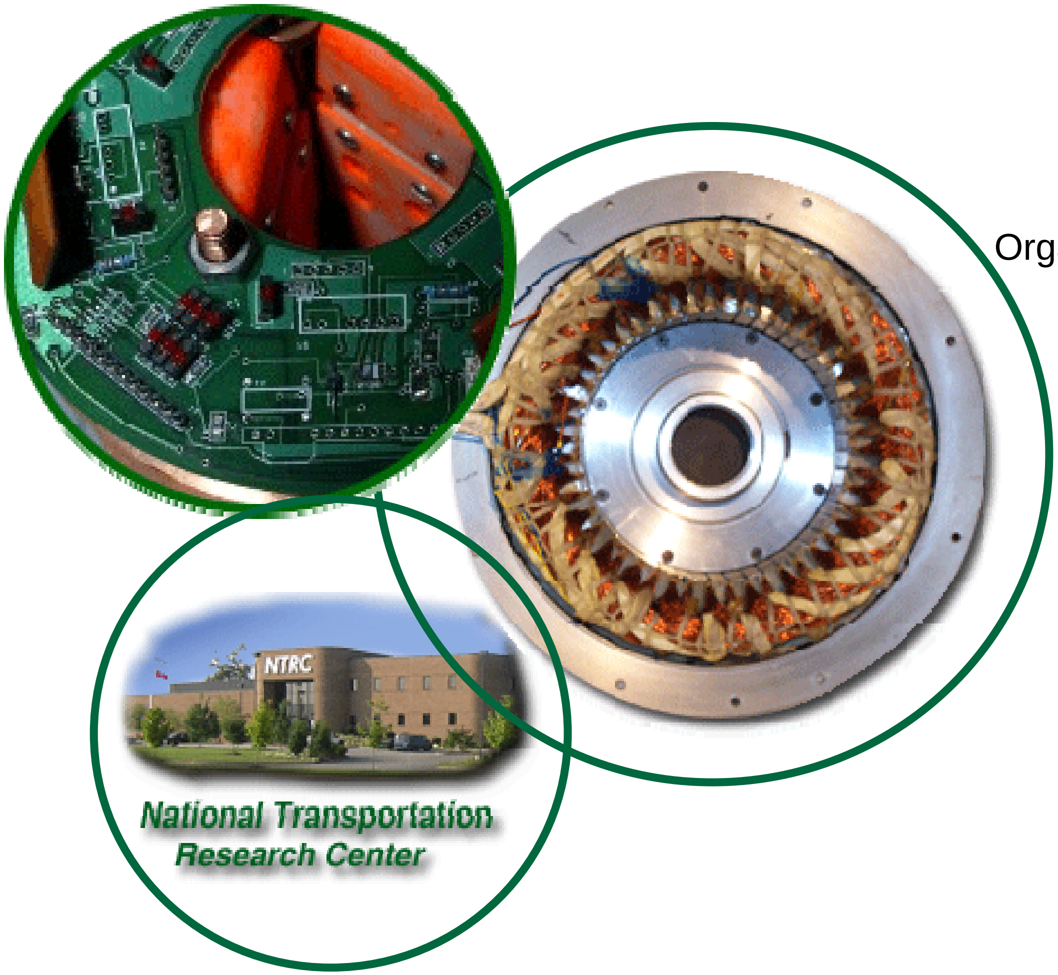
Axially Excited Electro-Magnetic Synchronous Motor

Laura Marlino

Email: marlinold@ornl.gov
Phone: 865-946-1245
Organization: Oak Ridge National Laboratory



Principal Investigator: Curt Ayers
Agreement: 13272

Project Duration: FY08 to FY10
FY08 Funding: $139K

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Purpose of Work

- **A new motor concept will be analyzed that utilizes an electromagnet rotor, *no permanent magnets* (reduce dependence on foreign/monopoly source of permanent magnet material in production US vehicles)**
- **The brushless rotor will be externally excited to produce magnetic poles - the rotor is anticipated to behave like a PM rotor, but with no need for a boost converter**

Desired Motor Characteristics:
Inexpensive materials
Low cost for manufacturing
High speed capability
Increased temperature operating range

Responses to Reviewers' Comments

- **This project is a new start in FY08**

Barriers

VTP Related Challenges

- Achieving an acceptable volume and weight tradeoff:
  - removal of PM, but
  - addition of rotor excitation components
  - eliminate cost, weight and volume of boost converter

Technology Related Challenges

- Robust magnetic flux path for excitation of rotor electromagnet poles
- Rotor design that can handle 20,000 rpm

Technical Approach Background

- **Motor choice for HEVs has evolved from induction motors to PM designs**
  - **→ increase the power density**
- **PM motors are more costly and more difficult to manufacture, and depend on expensive rare earth PM material**
- **PM motors exhibit:**
  - **Rotor temperature limitations at ~ 180°C**
  - **Speed limitations (back EMF, etc.)**
- **Induction motors use inexpensive materials and manufacturing is cheap and simple, <u>but</u>:**
  - **Induction motors have relatively low power density**
  - **Exhibit low torque as compared to PM motors**

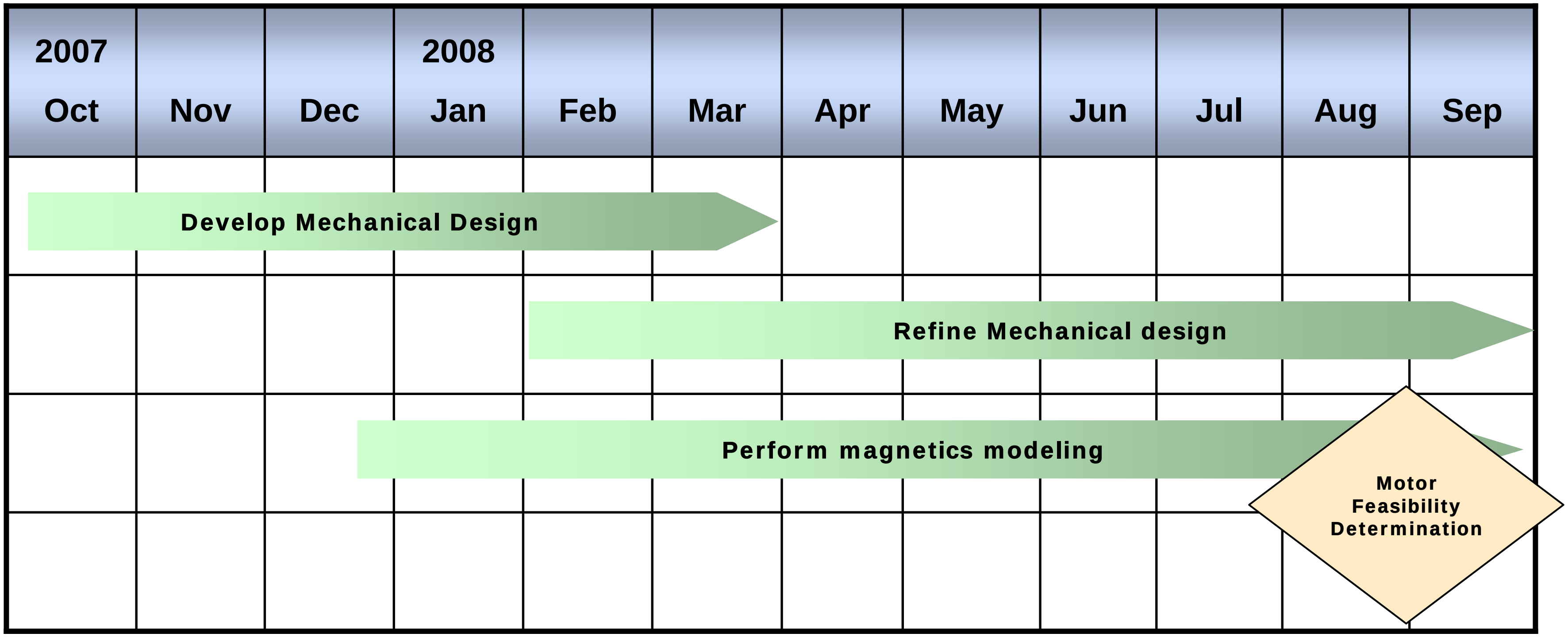
Technical Approach (cont'd)

- **Develop initial mechanical design**
  - **Rotor design to work with a conventionally wound stator**
  - **Produce enough detail to start electromagnetic modeling**
- **Perform initial electromagnetic modeling**
- **Iterate and refine mechanical design in conjunction with electromagnetic FEA results**

Technical Approach - Uniqueness

- **Unique rotor excitation method that removes need for PM in the rotor**
- **Rotor strength is inherently controlled, so the motor has built-in field control capability**
- **Allows simpler, more robust construction, leading to higher speed and temperature capability**
- **Removes expensive PM material, adds in less expensive copper and steel**
- **Removes need for a boost converter, adds in smaller amount of power electronics for rotor control**

Timeline for FY08



Decision point discussion: Feasibility to continue this project to the next year will be based on the design's ability to meet the torque and speed projections. Weight and cost studies will also be done to assess any increase in mass or core materials that decrease the feasibility of the concept.

Technical Accomplishments FY08

Initial Design Results

- **Initial design concept validated:**
  - **Need for boost converter eliminated**
  - **Eliminated PMs**
  - **Maintained mass and volume levels comparable to Camry**

Technology Transfer

- **Intent is to patent this motor technology, and license to industry partners**

Future Work

- **FY09**
  - **Build first generation prototype to validate mechanical and electromagnetic modeling results. Inverter/controller will be designed during this effort.**
- **FY10**
  - **Build next generation prototype that incorporates design lessons learned from FY09 build and test efforts. Inverter/controller will be modified as necessary for optimal performance results.**

Summary

- **First year feasibility study is progressing well and on schedule.**
- **Fundamental flux path required for this concept has been verified as feasible.**
- **Weight/steel/copper tradeoff looks promising, with benefit from increased speed and no PM requirement in the design (power density is acceptable).**
- **Mechanical design iterations in conjunction with electromagnetic FEA work are successfully moving forward.**
- **Concept success and ability to produce patent is expected near end of this FY.**

Publications, Presentation, Patents

- **None**

Questions

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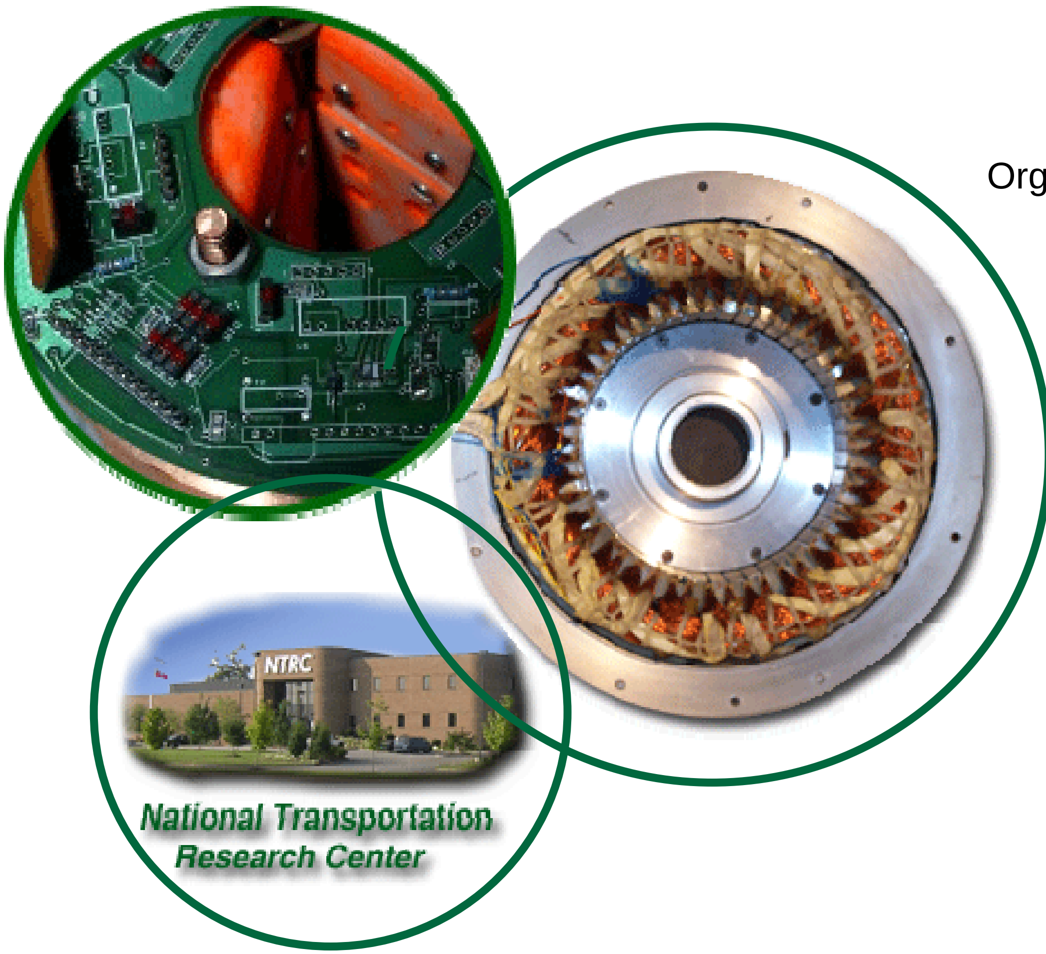
Application of Concentrated Windings to Electric Motors without Surface Mounted PMs



Laura Marlino

Email: marlinold@ornl.gov
Phone: 865-946-1245
Organization: Oak Ridge National Laboratory

Principal Investigator: John McKeever
Agreement: 13272

Project Duration: FY08 to FY09
FY08 Funding: $383K

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Purpose of Work

Reduce motor fabrication cost, size, and weight and increase efficiency through the use of concentrated winding bobbin cores

Responses to Reviewers' Comments

This is a new start in FY08; no previous review has been conducted

Barriers

VTP Related Challenges

- Reduce manufacturing cost of motors and increase efficiency

Technology Related Challenges

- Accurately modeling eddy current and hysteresis losses and modeling the effect of saturation on performance

Technical Approach Background

- **Application of fractional-slot concentrated windings (FSCWs) supports increased power density, specific power, efficiency, and reliability and decreased cost**
- **FSCWs have been applied mainly to surface mounted permanent magnet (SPM) motors**
- **This research will extend FSCWs to two types of internal permanent magnet (IPM) motors**
  - **Interior PM motors**
  - **Embedded PM motors**
- **Fractional-slot concentrated windings potentially offer significant advantages**
  - **Larger inductance for increased low speed traction and high speed fault tolerance**
  - **More effective use of copper – wound on bobbin, no end windings – reduced I^2R losses and reduced size**
  - **Manufacturing advantages – stator segments (old cut-core technology)**

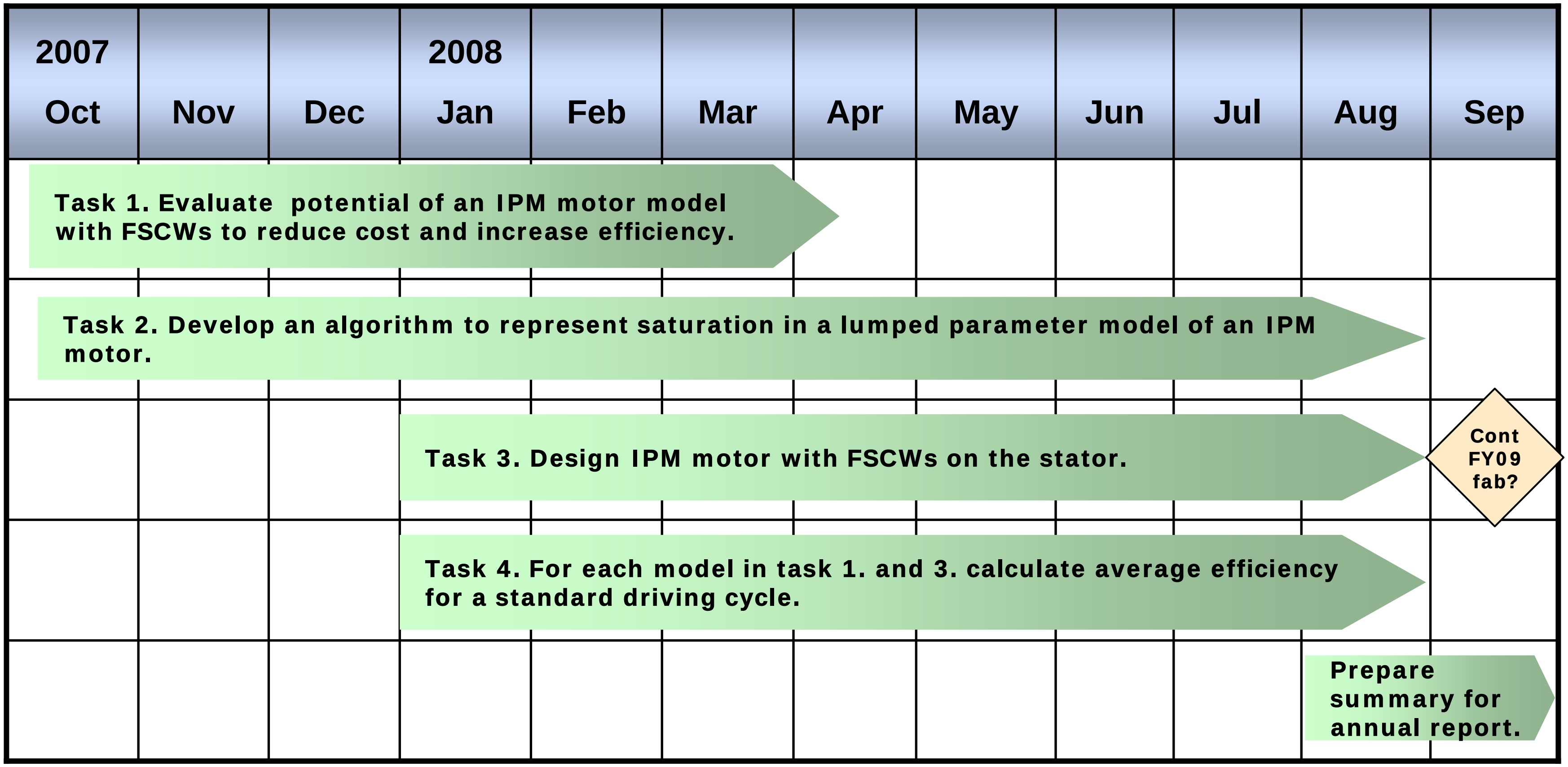
Technical Approach FY08

- **Model baseline IPM with integral-slot distributed windings and compare to motor with fractional-slot concentrated windings to evaluate potential for**
  - improving performance
  - reducing cost
  - increasing efficiency
- **Develop an algorithm that will simulate behavior of saturation for use in a lumped model of an IPM motor.**
- **Optimize design of an IPM motor using FSCWs.**

Technical Approach - Uniqueness

- **Eliminate end turns common to integral slot motors which**
  - **reduces wire resistance by as much as 36%**
  - **increase efficiency by 2 percentage points.**
- **May enable the use of weaker cheaper magnets because improved slot utilization allows more copper to be used in the windings.**
  - **cost of active materials can be significantly reduced.**

Timeline for FY08



Decision point discussion: Have the research results justified fabricating and testing an IPM with FSCWs on the stator in FY09?

Technical Accomplishments FY08

- **Simulated the performance of IPM motors using integral slot distributed windings and FSCW**
  - **deliver up to 55 kW for short bursts and 30 kW continuously**
- **Simulated power delivered at base speed for two FSCW-modified cases**
  - **above 80 kW achieved 97 and 93% efficiencies**
- **Assessment shows that a 9-slot stator configuration is not symmetric, which causes flux variations much larger than normal in the rotor, resulting in high eddy current losses**

Technology Transfer

- **No activity to date (too early)**

Future Work

- **FY09**
  - **Fabricate and test an IPM motor with FSCWs on the stator.**
- **FY10**
  - **Study the impact of other winding configurations on IPM motors.**

Summary

- **Performance simulations of IPMs whose stators have FSCWs, which have potential to reduce motor costs and increase specific power, appear to generate excellent power levels (80 kW) with reasonable efficiencies (93-97%).**
- **Initial assessments comparing power delivery and efficiency of commercial IPMs with FSCW IPM has begun. Further configurations will be assessed.**

Publications, Presentation, Patents

- **None**

Questions

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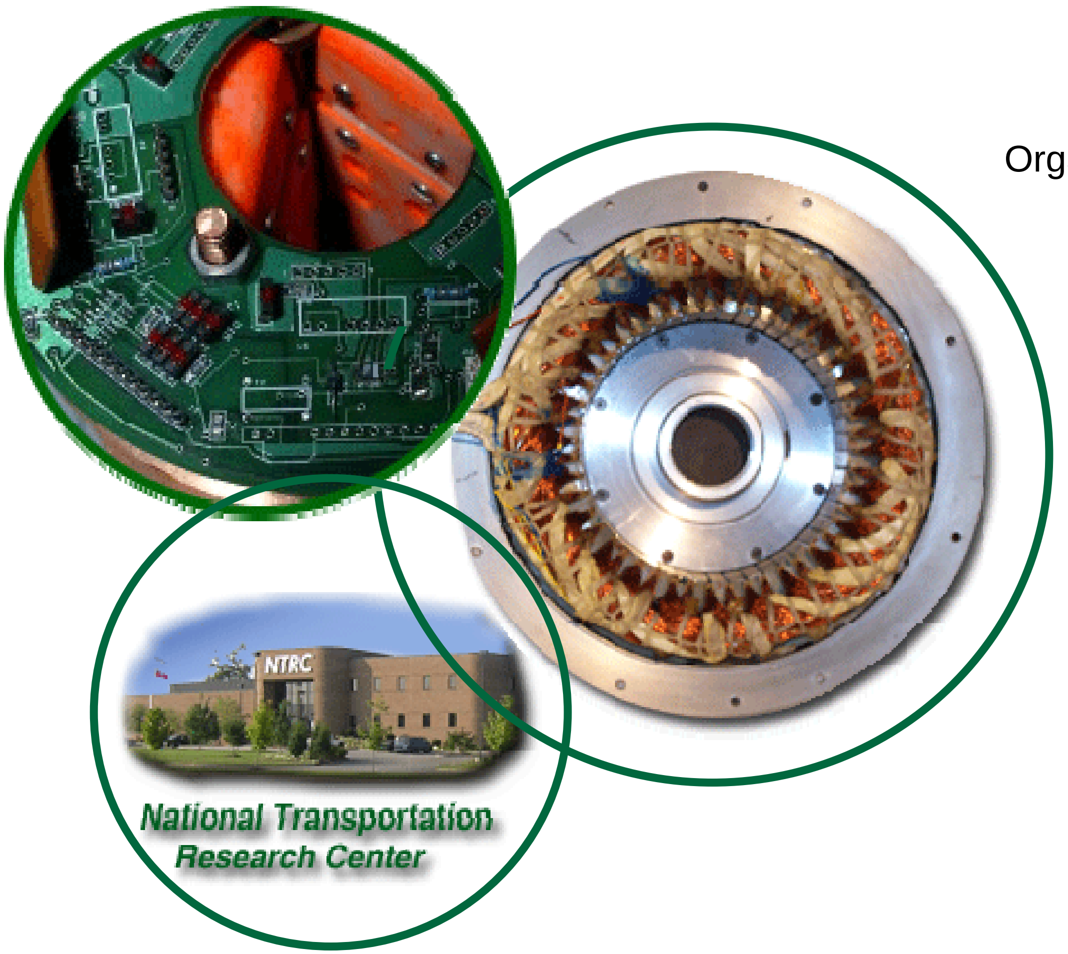
Amorphous and Nanocrystalline Core Material Evaluation

Laura Marlino

Email: marlinold@ornl.gov
Phone: 865-946-1245
Organization: Oak Ridge National Laboratory



Principal Investigator: John McKeever
Agreement: 13272

Project Duration: FY08 to FY09
FY08 Funding: $105K

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Purpose of Work

The purpose of this work is to reduce motor losses through the use of magnetically soft amorphous or nano-crystalline core material

Responses to Reviewers' Comments

This is a new start in FY08; no previous review has been conducted

Barriers

VTP Related Challenges

- **Motor loss reductions are needed.**

Technology Related Challenges

- **Amorphous and nanocrystalline core material is difficult to produce in bulk form that may be used to fabricate radial-gap rotor and stator cores.**

Technical Approach Background

- **Eddy current losses may be reduced by increasing the core material's resistivity; hysteresis losses may be lowered by reducing the area under of the hysteresis loop in the B-H curve.**
- **Conventional approach to increase resistivity is to laminate material and coat with non-conducting material with two disadvantages:**
  - loss of remanence
  - lower magnetic saturation
- **Evaluate new soft amorphous core material, Finemet, by Hitachi (formerly Metglass)**
  - **Advantages**
    - Higher resistivity (115 $\mu\Omega$cm) than silicon steel (52 $\mu\Omega$cm)
    - 90% reduction in total (hysteresis + eddy current) losses compared to conventional silicon steel alloy
    - Saturation comparable to Si steel
  - **Disadvantage**
    - Increased cost

Technical Approach

- **Determine if simulated estimates of motor efficiency for IPM motors are commensurate with loss reductions expected for this material.**
  - Simulate efficiency increase for rated currents and 30 kW continuous power.
  - Check expected efficiency increase of about 3 percentage points.
- **Using vendor estimates of future cost reductions, compare the tradeoff between improved performance and motor cost impacts.**

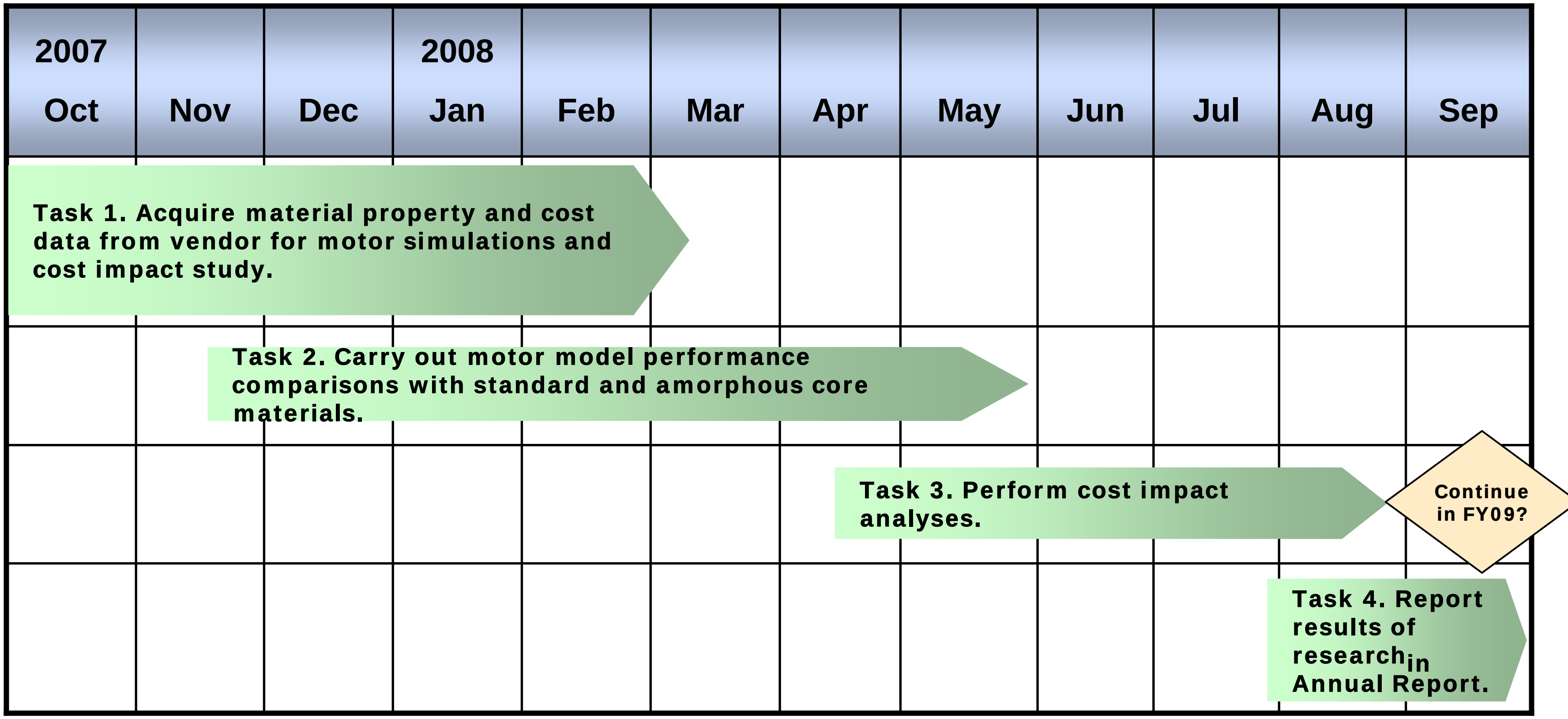
Technical Approach (cont'd)

- **Obtain material constants to simulate eddy and hysteresis losses in the motor models.**
- **Select and model a baseline IPM motor and calculate its efficiency when delivering 30 kW at rated current (230 A) using conventional core material and when using amorphous core material.**
- **Perform a <u>preliminary</u> analysis to determine the impact of amorphous core material on**
  - Core material cost
  - Other material cost
  - Manufacturing cost
  - Efficiency
  - Reliability
- **Perform a preliminary analysis to examine tradeoffs between efficiency improvement and amorphous material cost.**

Technical Approach - Uniqueness

- **The technology innovation is the amorphous or nanocrystalline structure of the new material which gives it higher resistivity (factor of 2X) and high permeance.**
  - When laminated rotor and stator cores are constructed from this material, core energy losses will be reduced up to 90% over conventional silicon steel core material.
  - Cost of new material currently exceeds that of standard laminated core material.

Timeline for FY08



Decision point discussion: The decision to continue in FY09 with refinements of the cost impact analyses and performance comparisons will be based on the promise shown by the rough order of magnitude estimates made in FY08.

Technical Accomplishments FY08

- **Contact with Magnetec**
  - To their knowledge, no one has ever produced laminations of NANOPERM or similar alloys because they are too brittle to be punched at a reasonable cost.
- **Contact with Hitachi**
  - Nanocrystalline material (Nanoperm) is too brittle to handle and magnetic saturation is too low ~1.2 T
  - Amorphous Fe-based alloys are ductile with saturation of ~1.6 T and a resistivity of 140 $\mu\Omega$cm

Technical Accomplishments FY08 (cont'd)

Assessment of previous efforts indicates:

- **To accommodate material limitations axial gap design was used**
- **Allows core elements to be made of amorphous metal ribbon**

Design Implications

- **Learned limitations amorphous core metal ribbon material places on motor design**
- **Insights gained regarding manufacture of material in bulk form for use on complex motors**

Technical Accomplishments FY08 (cont'd)

- **Performed eddy current loss calculations**
  - **Insulated laminations required to reduce eddy current losses even though the material has higher resistivity (115 μΩcm) than conventional Si steel (52 μΩcm).**
  - **No monolithic cores!**

Technology Transfer

- **No activity to date (too early)**

Future Work

- **FY09**
  - Determine if bulk laminations from 25 μm thick tape can be fashioned into motor rotors and stators.
  - Conduct a detailed study of the impact on overall motor cost of the amorphous core material through
    - Core material cost
    - Improved efficiency
    - Manufacturing process (solid core)
    - Other material cost
    - Extended operating temperature (reliability)
- **FY10**
  - Build amorphous core material prototype motor.

Summary

- **Amorphous and nanocrystalline materials are difficult to form into shapes large enough to be used in radial-gap rotor and stator cores.**
- **Conventional eddy current loss calculations indicate that bulk material will have to be laminated to produce desired efficiency gains.**
- **Assessment shows that significant manufacturing issues are involved with producing radial-gap bulk material.**

Publications, Presentation, Patents

- **None**

Questions

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