Novel Flux Coupling Machine without Permanent Magnets

John S. Hsu

Oak Ridge National Laboratory

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Overview

Timeline

- Start: October 2008
- End: September 2011
- 80% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY09
  - $881K
- Funding received in FY10
  - $928K
- Funding received in FY11
  - $540K

Barriers

- **Barriers addressed**
  - **High permanent magnet (PM) cost in PM motors.**
  - **Low permissible temperature of PMs.**

VT Program Targets addressed

- **DOE 2020 Motor Targets**
  - $4.7/kW
  - 1.6 kW/kg
  - 5.7 kW/l

Partners

- OEM and supplier interest expressed
- ORNL Team Members: Randy Wiles, Timothy Burress, Steven Campbell

Objectives

Produce a novel machine without permanent magnets (PMs) capable of meeting DOE 2020 motor targets of 1.6 kW/kg and 5.7 kW/L while significantly reducing the cost gap towards the DOE target.

Addresses potential supply disruption and cost increase issues associated with rare earth permanent magnets (PMs)

FY11 objectives

- **Complete the fabrication of a novel flux coupling prototype motor that has same volume as Camry but higher power rating**
- **Complete the tests of the prototype motor.**

Milestones

FY09

- Performed electromagnetic and mechanical Finite Element Analysis (FEA) simulations progressing toward a design suitable for a proof-of-concept prototype.
- Go / No-Go decision was favorable. The projected performance of the preliminary design was favorable for meeting the DOE motor objectives.

FY10

- Completed the FEA, electro-magnetic analysis and the engineering design of the novel machine prototype.
- Go / No-Go decision was favorable. The performance simulation of the optimized novel motor indicated that the DOE 2020 motor weight and volume targets and 2015 cost target could be met.

FY11

- Fabricate and test novel flux coupling prototype machine.

Approach/Strategy

Technical strategy:

- Use stationary electric coils to supply flux to rotor without brushes and without using PM materials.

Approach:

- Perform electromagnetic FEA simulations and compare the performance results to the Camry motor and to the DOE 2020 targets.
- Add a stationary field coil to provide an adjustable rotor flux, which eliminates the PMs.
- Develop a novel flux path to function like a PM machine, eliminating the need for brushes.
- Design a motor that enables a hybrid cooling system to utilize existing internal oil channels and water jackets in the motor housing.
- Design optimize field control to achieve higher power factor, efficiency, and torque. (FEA simulation study for determining the optimum field values at different operating points.)
- Fabricate and test novel flux coupling prototype.

Overall Technical Accomplishments

- Demonstrated performance optimization through the use of an excitation field.
- Developed an analytical MATLAB program to provide performance versus speed curves under the voltage and current constrains.
- Designed a transmission oil and water ethylene glycol (WEG) hybrid cooling system.
- Fabricated motor components. Several fabrication issues were overcome due to the complex nature of the design. The rotor and outer housing components are undergoing final machining to allow for better fit-up and assembly.

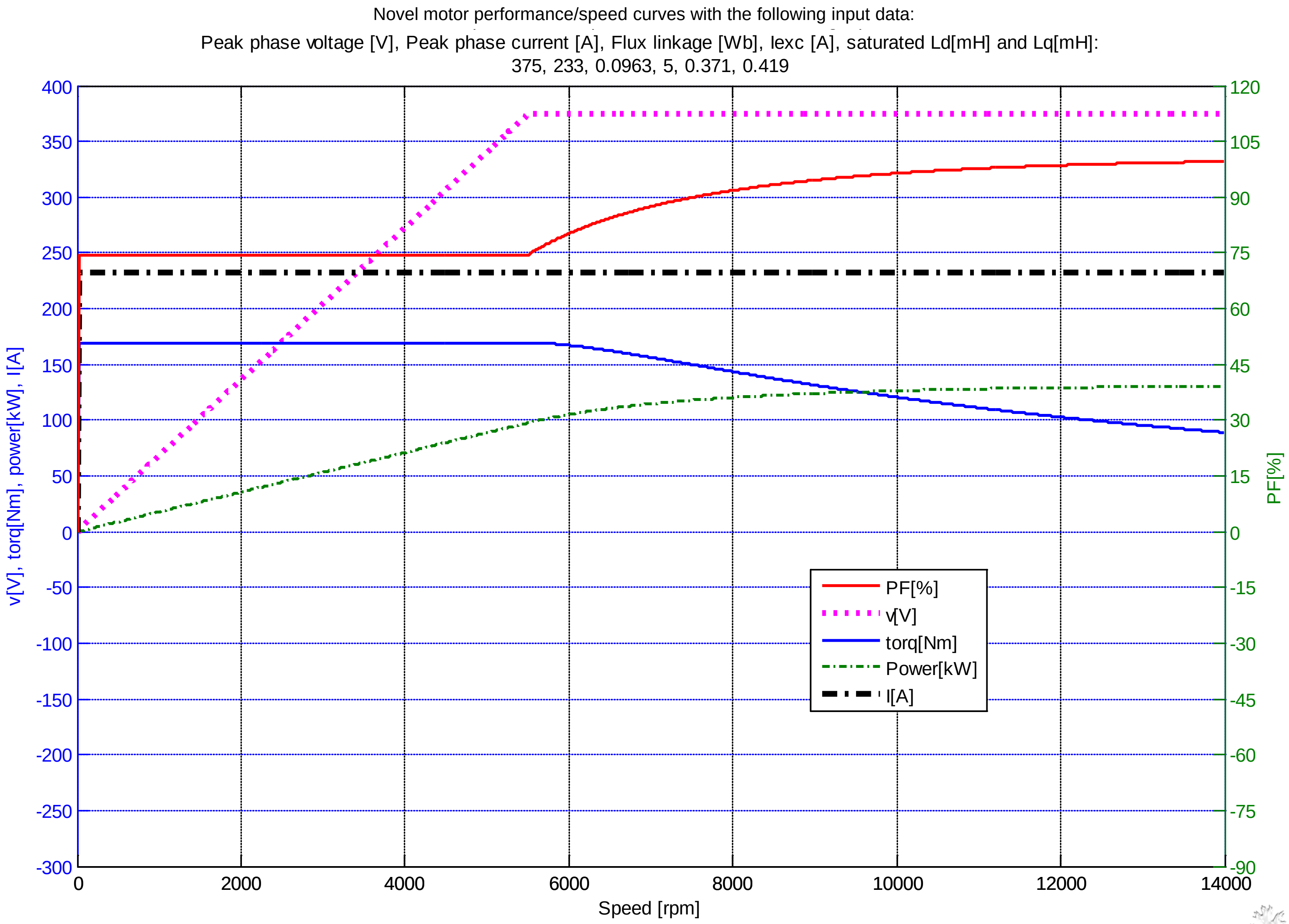
Additional idea generated in the project, but not incorporated in the design:

- Developed a conceptual method of a novel “Multilevel Winding” technique that improves the fill factor in the stator slots by 38% over the conventional mush wound motor.

FY09 Technical Accomplishments

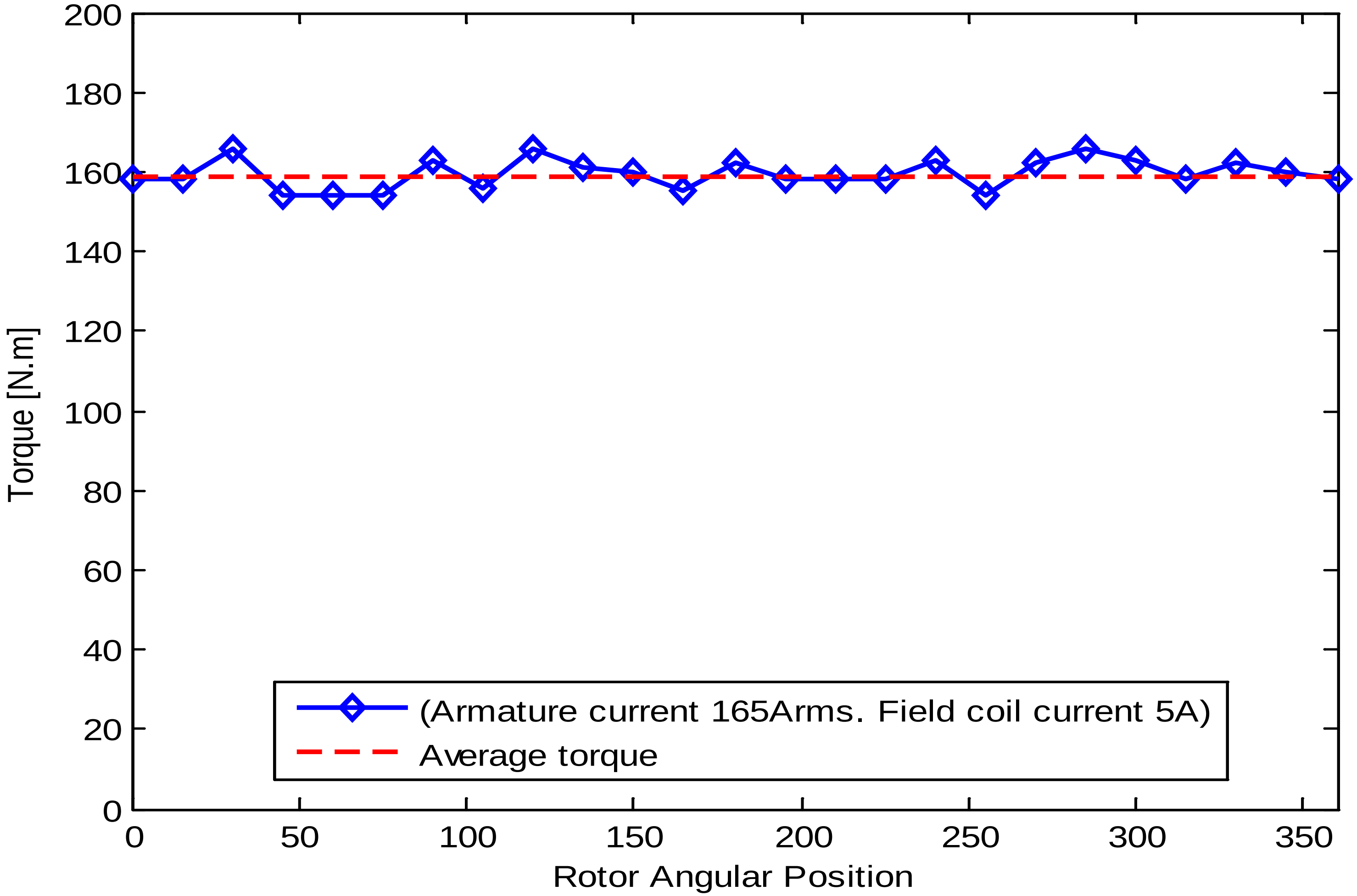
Motor Performance Vs. Speed

(Using saturated inductances at 375 V, 233A peak phase values and 0.0963Wb flux linkage)



FY10 Technical Accomplishments

Torque quality of prototype motor



FY10 Technical Accomplishments

Axial force at 10% axial gap unbalance

Questions concerning axial gap unbalance were raised and addressed:

- Under extremely high (8A) excitation, simulation results show an axial force of 763 Newton.
- The bearing rated axial load is 1625 Newton, which readily compensates for the axial force.

Conclusion: Standard bearings can be used.

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FY10 Technical Accomplishments

	Camry	**Novel Machine**	**2020 Target**
Max. power output	70 kW (tested)	115 kW (computed)	55 kW
kW/kg	**1.9** kW/kg	**2.1** kW/kg	**1.6** kW/kg
kW/l	**5.0** kW/l	**8.5** kW/l	**5.7** kw/l
Cost	**10.7 $/kW (**$749** for **70 kW**)	***6.1 $/kW (**$702** for **115 kW**)	4.7 $/kW (**$259** for **55 kW**)

** Requires 1 kg of high grade PMs at $90/kg.

*** Includes additional cost of 11kg steel and 3kg copper wire (+$40.00) but eliminates 1kg permanent magnets (-$90.00)

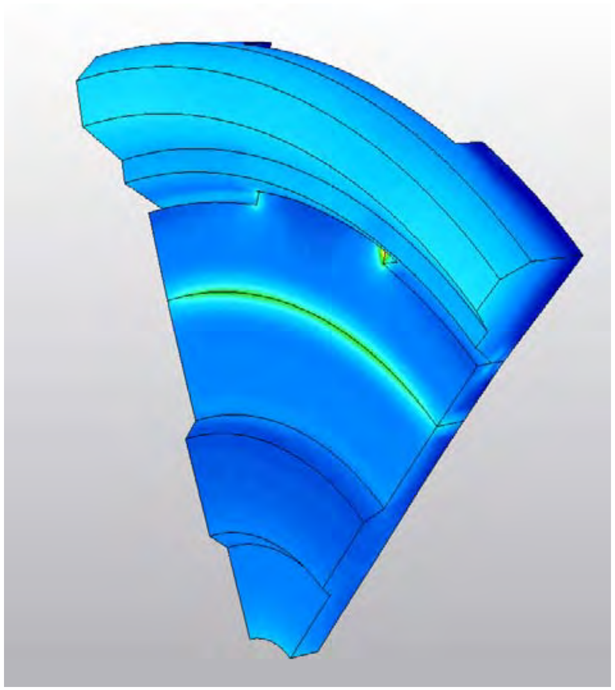
FY10 Technical Accomplishments

	Camry	**Novel Machine**
Max. power output	70 kW (tested)	115 kW (computed)
Weight	36.3 kg	55.7 kg
Volume	13.9 Liters	13.6 Liters*
Power factor	0.61 – 1.00	0.75 – 1.00

- Volume calculation of new machine based on maximum height, width, and depth of motor components only (i.e. stator core, winding extensions, and rotor excitation cores).

FY11 Technical Accomplishments

Rotor end plate simulation results demonstrate that rotor can withstand the stress and deformation at 14,000 RPM.

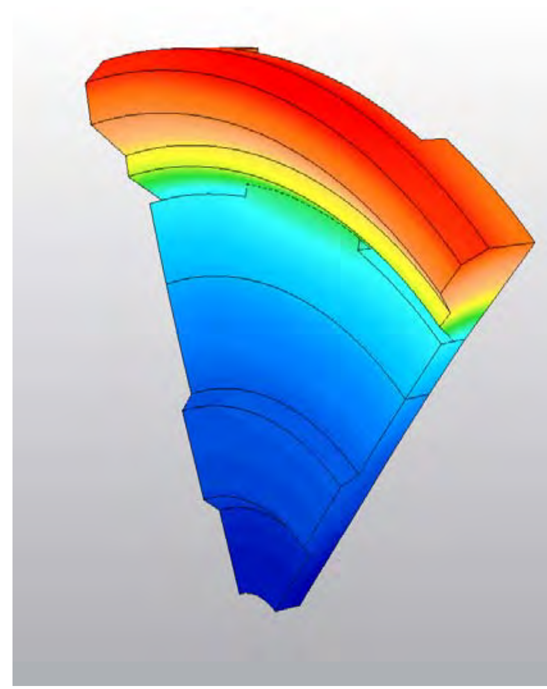


Simulated Stress - Maximum Rotor Assembly Stress at 14,000 RPM = 79,480 PSI.

(Permissible 85,000 PSI Tensile strength, mill annealed)

Simulated Displacement - Maximum Rotor Assembly Displacement at 14,000 RPM = 0.005 inches

(Radial gap 0.029 inches)



FY11 Technical Accomplishments

Prototype Fabrication

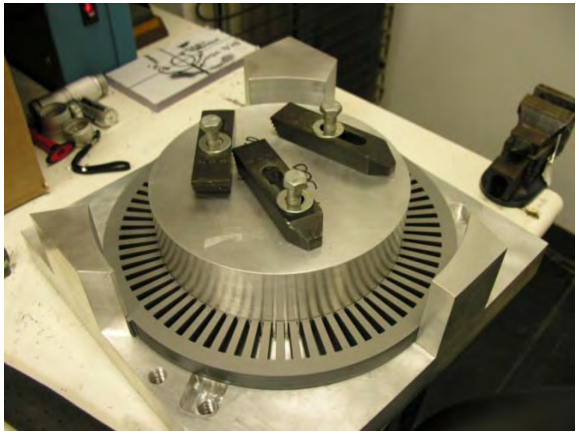
- **Rotor laminations and stator laminations have been laser cut.**
- **Shaft encoder for motor positioning feedback during testing has been identified and ordered.**
- **Excitation coils have been wound.**
- **Stator clamping fixture necessary for the alignment of the laminations was designed and fabricated.**
- **Stator laminations were welded and vacuum impregnated with motor varnish prior to winding.**
- **Stator assembly has been wound with high temperature magnet wire.**

FY11 Technical Accomplishments

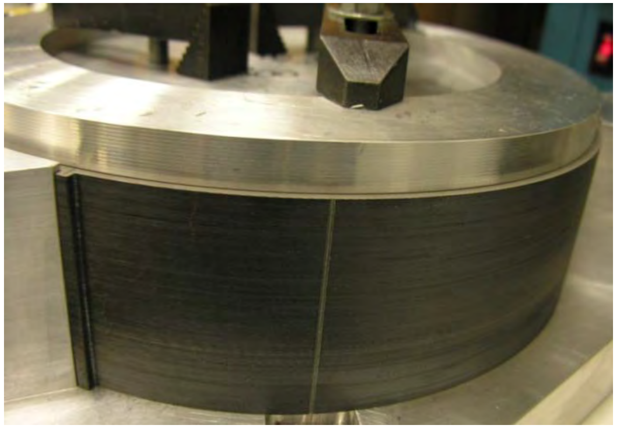
Prototype Fabrication (continued)

- **All motor components have been fabricated.**
  - **The rotor hub and the outer housings containing the hybrid coolant channels were sent to the fabrication vendor for additional machining to accommodate the stator.**
- **Fabrication challenges were overcome when the flux distribution ring warped during the welding process. The flux equalizer ring was successfully redesigned to eliminate the warping condition while maintaining the magnetic performance of the motor.**

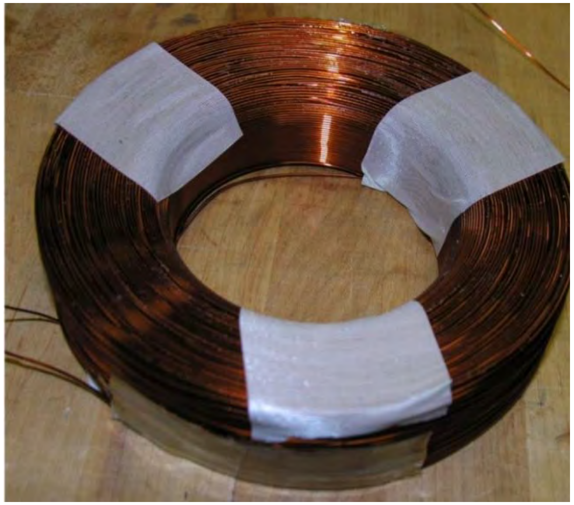
FY11 Technical Accomplishments
Parts Fabrication of Prototype Motor



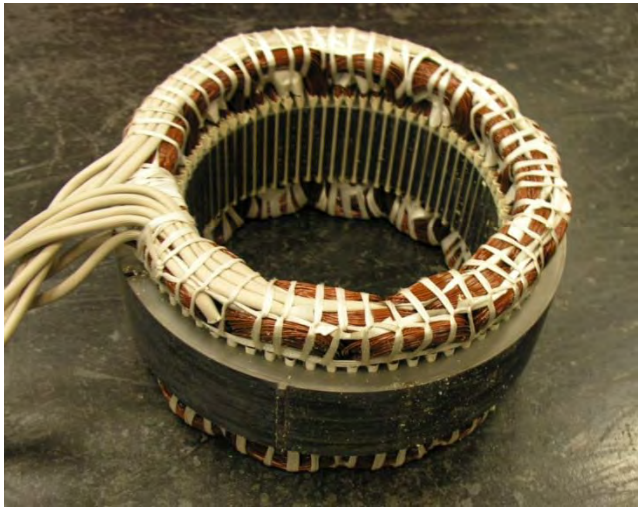
Lamination stacking fixture



Fixture for welding stator core OD



Stationary excitation coil



Wound stator core

Collaborations with Industry

OEMs and suppliers have expressed interest.

Future Work

FY 11

•Complete fabrication of prototype motor
•Complete testing of prototype motor
•Document performance results

FY12

•Pursue multi-level winding concept (increase slot fill by 38%) in ORNL packaging project

Summary

Based upon the simulation results it appears:

- **The novel flux coupling motor without PMs improves upon current IPM motor specific power and power density and potentially reduces cost per kW by 75%.**
- **Motor performance can be improved by utilizing brushless adjustable field excitation.**
- **Higher temperature operation can be achieved because PM limitation has been removed.**
- **Feasible to meet the FreedomCAR 2020 motor targets for weight and volume and FreedomCAR 2015 motor cost target.**