U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

A New Class of Switched Reluctance Motors Without Permanent Magnets

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May 11, 2011

Project ID: APE020

2011 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting
Washington, D.C.

Overview

Timeline

- Start: FY09
- Finish: FY11
- 80% Complete

Budget

- Total project funding
  - DOE: 100%
- Funding Received for FY10: $447K
- Funding Received for FY11: $460K

Barriers

- Barriers
  - Increasing power density
  - Minimizing flux leakage
  - Reducing acoustic noise and torque ripple
- Targets
  - Motor power density:
    - 5 kW/L (2015 target)
  - Motor specific power:
    - 1.3 kW/kg (2015 target)
  - Motor cost:
    - Between $7/kW (2015 target) and $4.7/kW (2020 target)

Partners

- University of Tennessee
- MotorSolver LLC
- ORNL Team Members:
  - Curt Ayers
  - Randy Wiles

Objectives

- The purpose of this project is to design, develop, build, and test a novel SRM traction drive that has a higher power density and significantly lower torque ripple and acoustic noise than conventional SRMs while maintaining the simplicity, and low cost of the conventional SR machine

- Seek to provide initial quantitative results showing that estimated characteristics of the proposed design reach the following targets:
  - Power density: 5 kW/L (2015 DOE target)
  - Specific power: 1.3 kW/kg (2015 DOE target)
  - Motor cost between $7/kW and $4.7/kW (2015 and 2020 targets, respectively)

- FY11 Objectives
  - Construct prototype
  - Characterize prototype machine parameters
  - Develop and prepare drive/controller hardware and software
  - Conduct comprehensive motor testing in dynamomter test cell to determine performance, efficiency, torque ripple, and acoustic noise characteristics

Milestones

Month/Year	Milestone or Go/No-Go Decision
September 2010	Milestone: Parametrically optimize preferred design approach and control scheme
September 2010	Go/No-Go decision: Determine if finalized prototype design has the potential to address DOE targets based on detailed analyses
September 2011	Milestone: Complete dynamometer testing and summary report
September 2011	Project Completed

Programmatic Approach

- **Select preferred design approach of novel switched reluctance machine**
  - Analyze basic feasibility of various novel switched reluctance machine designs
  - Conduct finite element analysis (FEA) to obtain motor characteristics
  - Develop preliminary novel control schemes
  - Simulate final design(s) with basic dynamic model
    - Obtain estimated capabilities of torque and power as a function of speed
  - Choose preferred design approach based on preliminary cost assessments, FEA, and dynamic simulation results

- **Perform detailed design and simulation of selected design approach**
  - Conduct structural, thermal, and acoustic noise modeling
    - Adjust design approach as necessary
    - Investigate potential to apply air-gap enhancements
  - Carry out comprehensive dynamic simulations
    - Refine novel control algorithm and investigate potential to apply other novel control techniques
    - Obtain accurate capabilities of torque and power as a function of speed

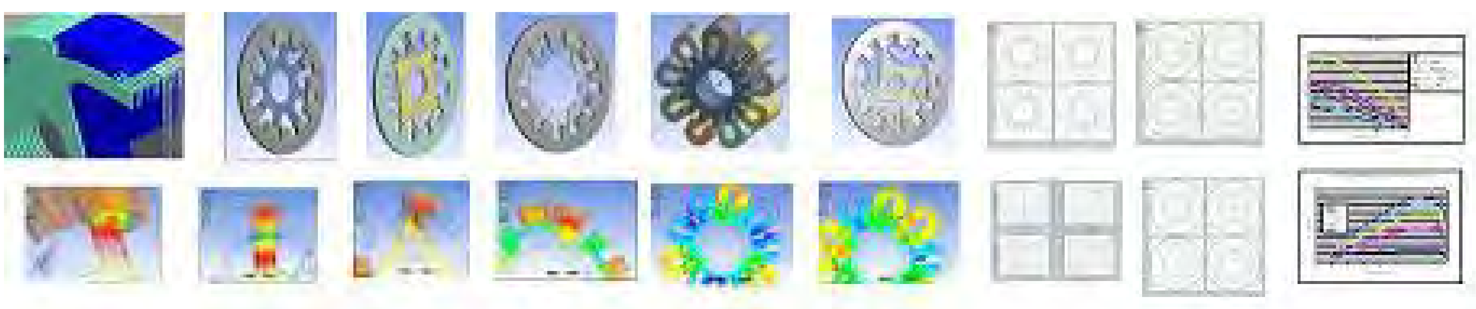
- **Build and test SR motor prototype and novel control technique**
  - Determine power density, specific power, and cost based on results from dynamometer tests

Technical Approach

- Utilize unconventional machine design and configuration to mitigate torque ripple and acoustic noise issues with switch reluctance motors
- Develop control algorithms that leverage unconventional hardware design advantages
- Implement solutions with the consideration of reducing manufacturing costs

FY09 Technical Accomplishments (1)

- **Completed FEA design studies of numerous approaches**
  - Feasibility of several unconventional designs verified through extensive FEA simulations with consideration of estimated capabilities
    - Manufacturing and material costs
    - Peak-torque
    - Torque-ripple
    - CPSR (constant power speed ratio)
    - Mass and volume
  - Most plausible design approach selected based on terms of cost, complexity, performance, torque ripple, and acoustic noise

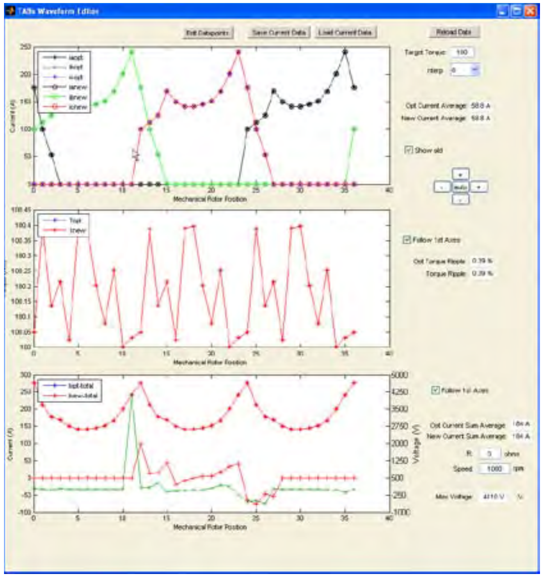


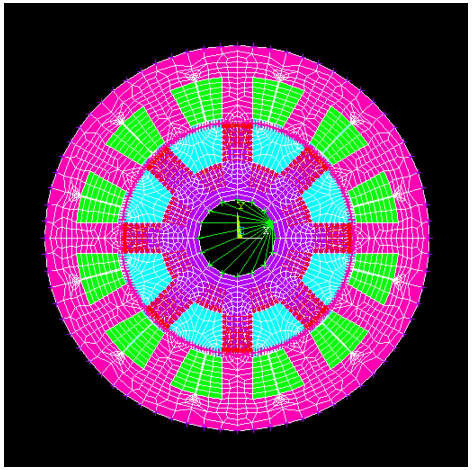
FY09 Technical Accomplishments (2)

- **Two dynamic three-phase electromagnetic simulators developed (with consideration of mutual coupling)**
  - FEA-based
    - Most accurate
    - Good for design optimization
    - Facilitates multi-physics approach
  - Parametric
    - Computationally efficient
    - Easily modified
    - Can play role in parameterized optimization
    - Great for control optimization
  - Both FEA and parametric dynamic models have universal capabilities, regardless of the embodiment or motor type (SR, PM, induction, etc)

FY10 Technical Accomplishments (1)

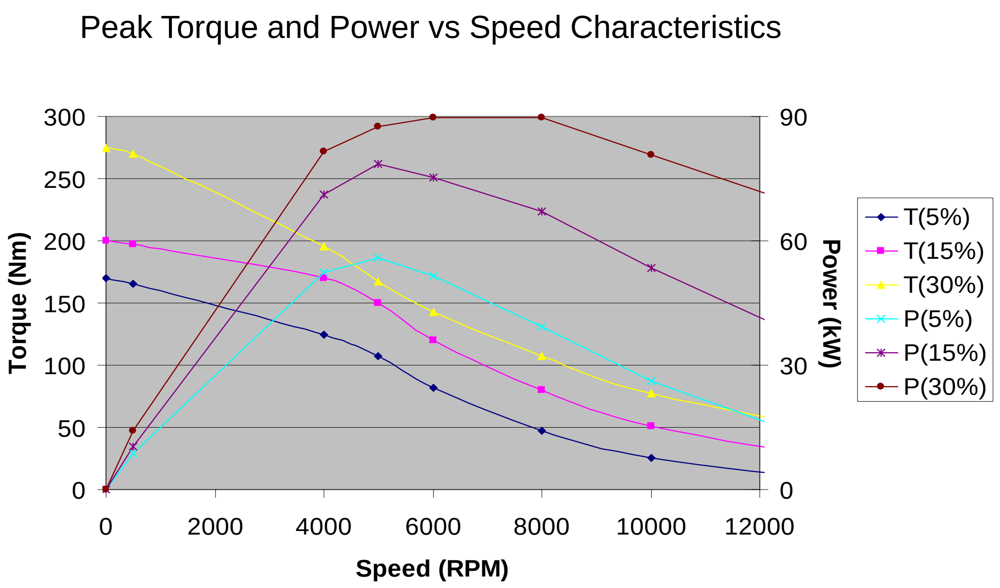
- **Design and control tools developed**
  - Automated geometric optimization
  - FEA-based multi-physics dynamic simulator
    - Integrates electromagnetic, structural, thermal FEA optimization into one package
    - Facilitates design-wide optimization with respect to constraints/objectives in various areas
    - Not primary objective, still underway
  - Complex multiple-variable, multiple-objective optimization of control waveforms as a function of speed and torque
    - Near-zero torque ripple achieved for low and moderate torque levels (up to 150 Nm)





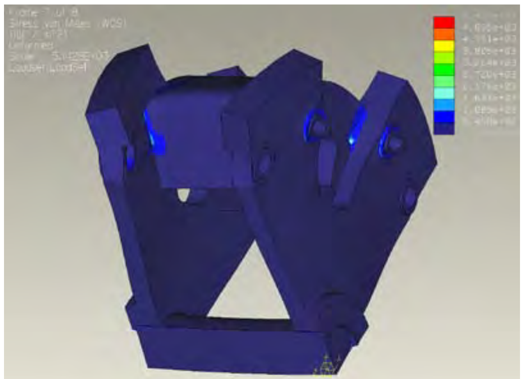
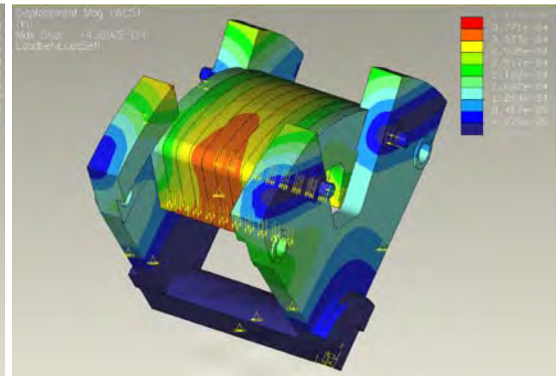
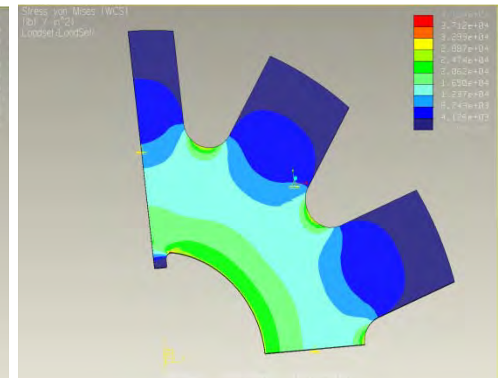
FY10 Technical Accomplishments (2)

- **Detailed dynamic simulations reveal that the design meets DOE targets with 5% torque ripple (125 Nm at 4,000 rpm → 52.4 kW)**
  - 5.6 kW/L vs 2015 target of 5 kW/L and 2020 target of 5.7 kW/L
  - 1.45 kW/kg vs 2015 target of 1.3 kW/kg and 2020 target of 1.6 kW/kg
  - Efficiency: 93% for 124.4 Nm at 4,000 rpm
- **75 kW at 8,000 rpm with 20% torque ripple**
- **90 kW at 8,000 rpm with 30% torque ripple**

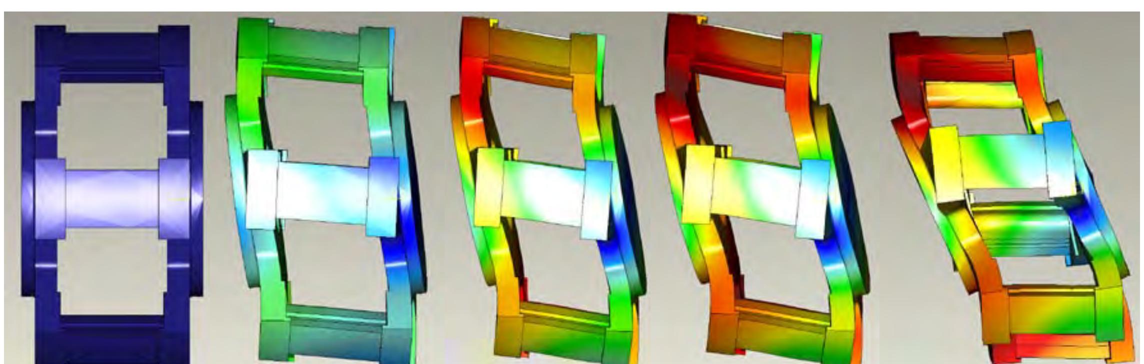


FY10 Technical Accomplishments (3)

- **Stress and modal analyses facilitated various structural design improvements and resulted in a final verification of mechanical integrity**

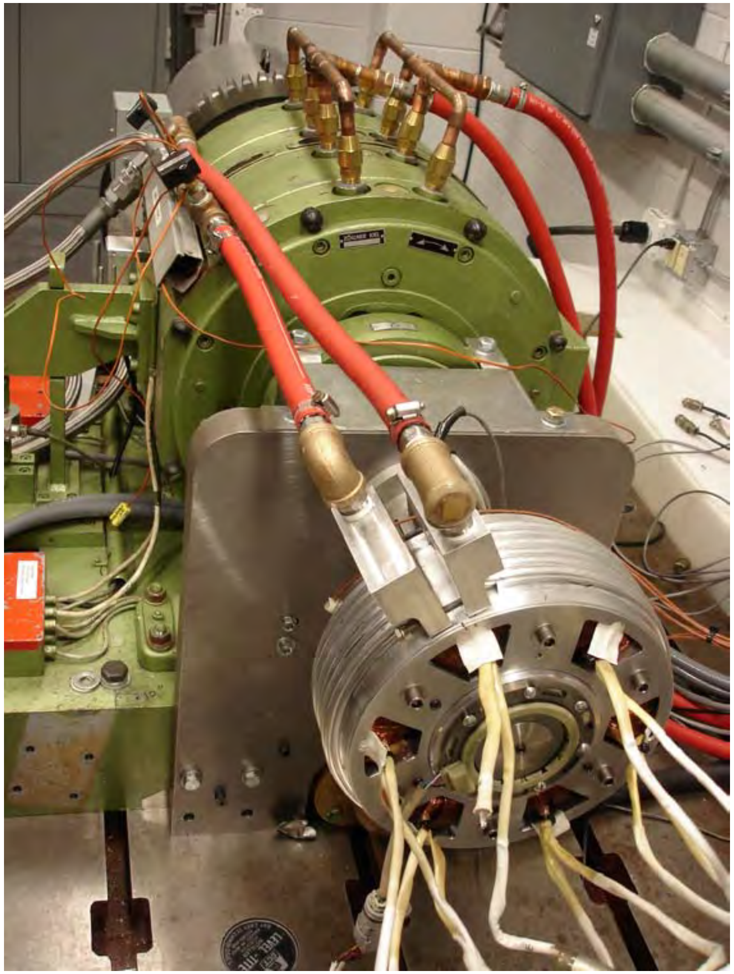
- **Modal analyses and qualitative acoustic assessments reveal that most problematic mode shapes occur beyond the maximum operation speed**



Mode shapes at 1600 Hz

FY11 Technical Accomplishments

- **Prototype testing in progress**
  - Parts received, assembly completed and installed
  - Inverter drive prepared and verified through static testing
  - Initial testing successful
    - Locked rotor tests
    - Current-regulation and position feedback verified



Collaborations

- University of Tennessee
  - Provided feedback regarding fundamental machine design principles, assisted with the development of modeling tools, and analyzed operational characteristics of operating in continuous conduction
- MotorSolver LLC
  - Provided feedback regarding fundamental machine design principles

Future Work

- FY11
  - Test SR motor prototype with proposed control technique

Summary

- **Verified in simulation and currently empirically verifying the following advantages of using separate stator pieces**
  - Reduced modal tendencies of stator
    - Damping composite can be used to attenuate vibration
      - Could also enhance heat conduction
    - Noise and vibration can be greatly reduced
      - Adds to noise/vibration improvement as a result of reduced torque ripple
  - Localized flux paths yielding lower core losses
  - Improved manufacturability and fill-factor by winding coil prior to assembly
  - Enhanced heat transfer capabilities

- **Design approach maintains the following conventional switched reluctance motor benefits:**
  - No permanent magnet material
    - Back-emf and demagnetization is not an issue
    - Permits operation at high temperatures
  - Low material and fabrication cost
  - Capable of high speeds (beyond 15,000 rpm)
  - Robust and reliable

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