A New Class of Switched Reluctance Motors Without Permanent Magnets

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Project ID: APE020

Overview

Timeline

- Start: FY09
- Finish: FY11
- 50% Complete

Budget

- Total project funding
  - DOE: 100%
- Funding Received in FY09: $569K
- Funding Received for FY10: $447K

Barriers

- Barriers
  - Maintaining 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

Objectives

- The purpose of this multi-year 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, low cost, and power density of the conventional SR machine

- Explore potential to remove boost converter or reduce battery voltage

- 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)

- FY10 Objectives
  - Develop and refine control scheme
  - Conduct acoustic and structural modeling
  - Perform dynamic simulations
  - Arrive at final optimized design

Milestones

Month/Year	Milestone or Go/No-Go Decision
September 2009	Milestone: Choose preferred design approach and associated preliminary control algorithm
September 2009	Go/No-Go decision: Determine if preferred design approach has the potential to address DOE targets based on preliminary studies
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

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 our 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

FY09 Technical Accomplishments (1)

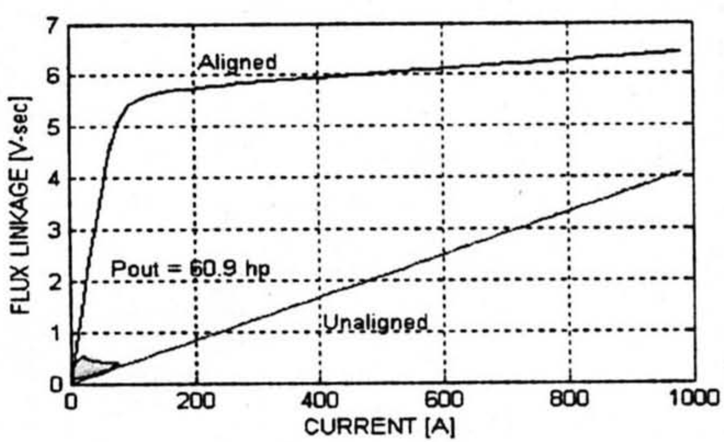
- **Completed FEA design studies of numerous approaches**
  - Feasibility of several unconventional designs verified through extensive FEA simulations with consideration of estimated capabilities
    - Manufacturing and material costs
    - Peak-torque
    - Torque-ripple
    - CPSR (constant power speed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

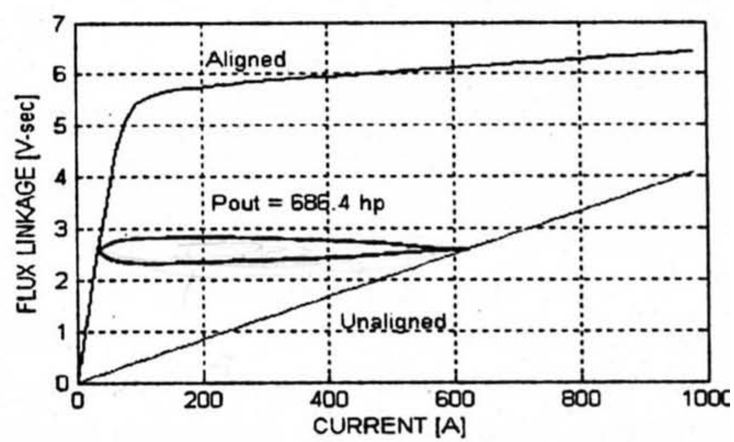
- **Two dynamic three-phase electromagnetic simulators developed (with consideration of mutual coupling)**
  - FEA-based
    - Most accurate
    - Good for design optimization
    - Not good for control optimization
  - Parametric
    - Still accurate
    - Can play role in parameterized optimization
    - Great for control optimization
  - Both FEA and parametric dynamic models are being developed and will have universal capabilities, regardless of the embodiment or motor type (SR, PM, induction, etc)

FY09 Technical Accomplishments (2)

- Verified that continuous conduction control can be utilized with preferred design approach
  - Continuous conduction (CC) control consists of a non-zero minimum current, contrary to that of conventional control
  - Much higher power capabilities are available since a higher flux linkage is attained prior to reaching the torque producing region
  - Creates potential to reach power levels up to 2 times that of a conventional control method

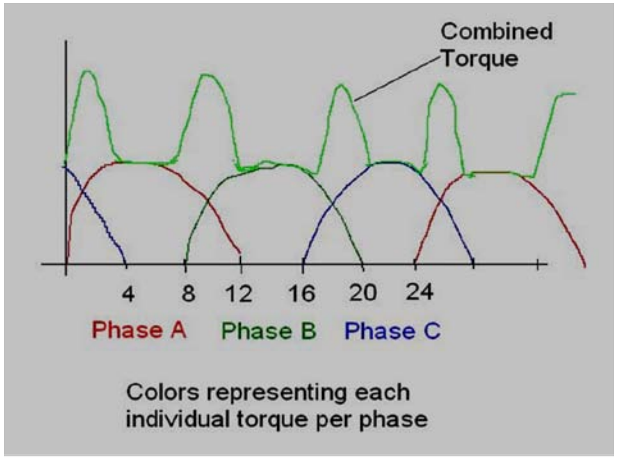
- Originated integration of hardware and software solutions



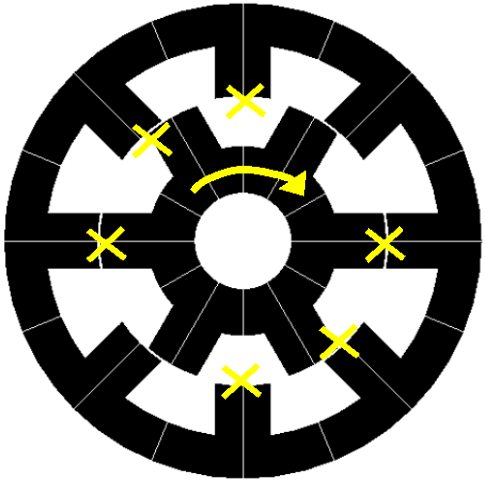


FY10 Technical Accomplishments (1)

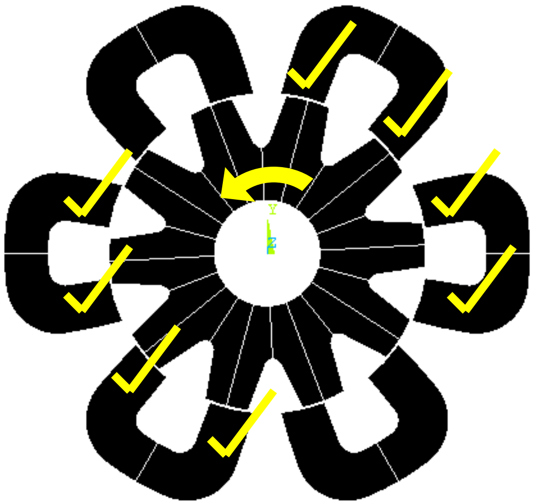
- Novel design and control techniques provide opportunity to significantly reduce torque ripple and acoustic noise
  - Average number of instantaneous active teeth increased
  - Proper control allows increase of utilized air-gap area without sustaining substantial leakage
- No positions associated with “near zero” or “approaching zero” locked rotor torque



Exemplary sketch of locked rotor torque profile



Conventional 8/6 (4-phase)



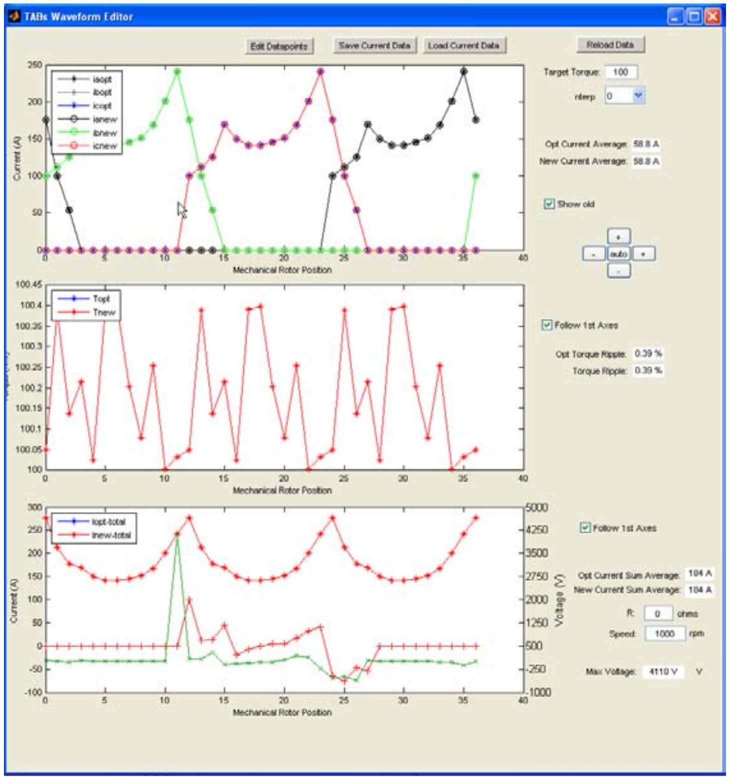
12/10 prior to optimization

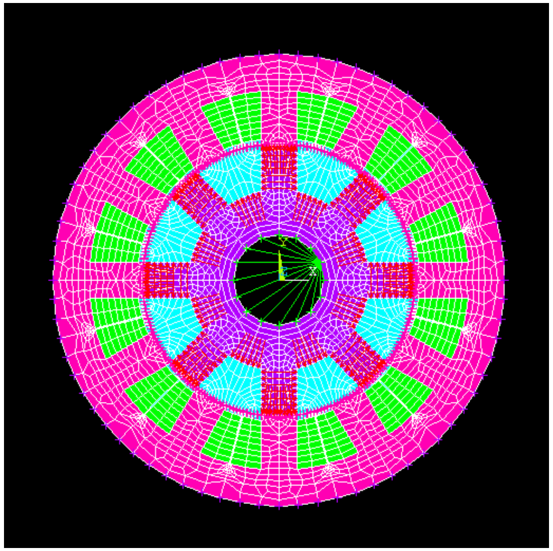
FY10 Technical Accomplishments (2)

- Achieved higher amount of ampere-turns (and thus torque capability) within same volume of a conventional SR
  - Increased winding area
  - Enhanced heat transfer capabilities
  - Improved manufacturability by winding coil prior to assembly
- Established that the design is capable of very high speed operation
  - Same simple rotor design as conventional SR
- Verified the following advantages of using separate stator pieces
  - Reduced modal tendencies of stator
    - Dampening composite could be used to attenuate vibration
      - Could also serve as thermal conductor
    - Noise and vibration can be greatly reduced
      - Further improving upon impact of reduced torque ripple
  - Decreased core/eddy current losses due to short flux paths

FY10 Technical Accomplishments (3)

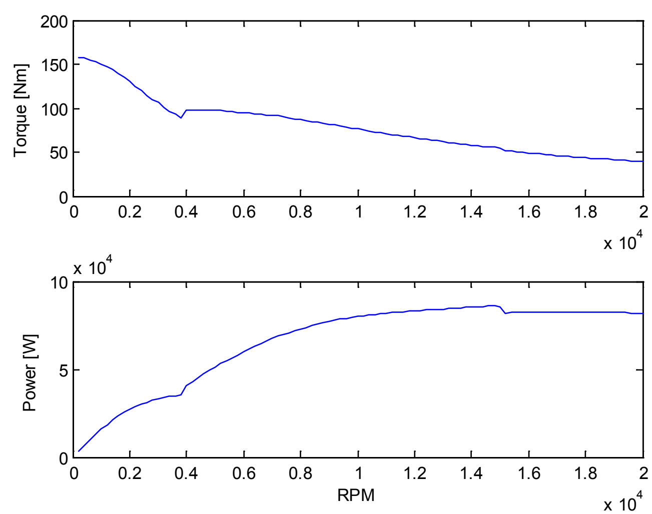
- EMAG, thermal, structural, acoustic FEA capabilities being combined in one package
  - Allows seamless and efficient comprehensive motor design studies
  - Not commercially available





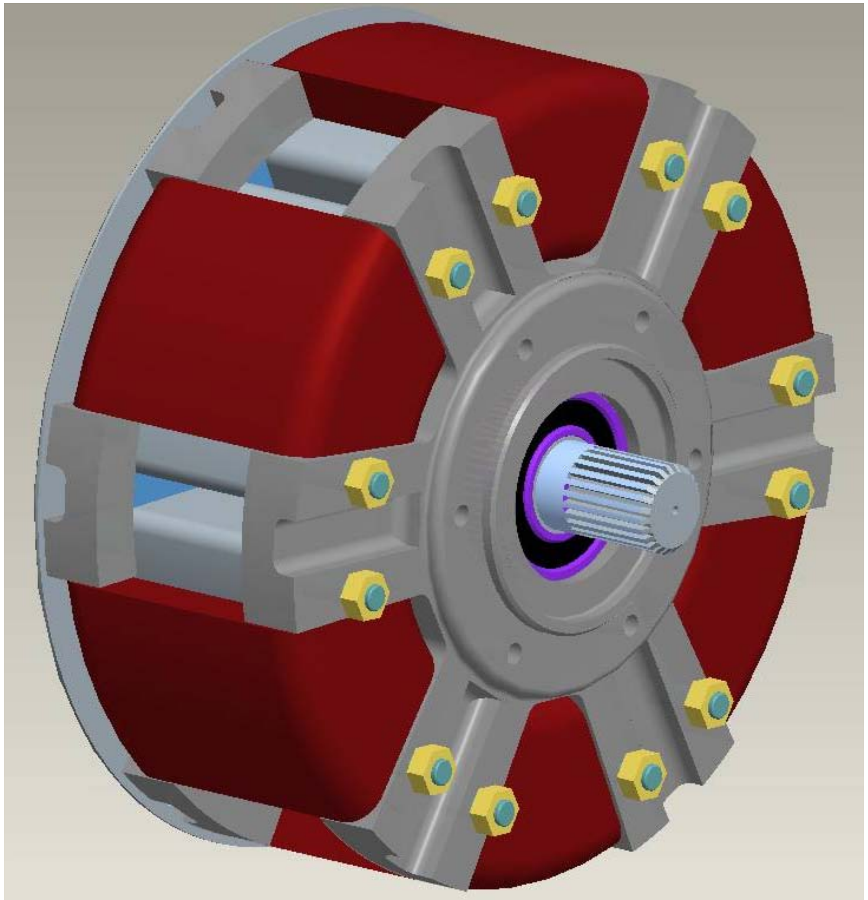
FY10 Technical Accomplishments (4)

- Preliminary non-optimized studies at 100 Nm and 2,000 rpm (20 kW) with less than 1% torque ripple
  - Note: optimization was conducted at this arbitrary point and is not maximum torque or power level
- Detailed dynamic simulations using continuous conduction reveal that a 90 kW power level can be obtained with a preliminary design having dimensions and system parameters (voltage, current, etc) similar that of the Prius
  - Assuming similar mass and volume as Prius motor
    - 5.8 kW/L vs 2015 target of 5 kW/L and 2020 target of 5.7 kW/L
    - 2 kW/kg vs 2015 target of 1.3 kW/kg and 2020 target of 1.6 kW/kg
  - Further design refinements to be made
    - Reduce power level and increase torque capability



FY10 Technical Accomplishments (5)

- Investigating tradeoffs between the use of firm structural support versus malleable dampening material
  - Dampening composite provides great benefit for the reduction of noise/vibration
- Preliminary design efforts have already resulted in feasible design options with consideration of cost, complexity, and manufacturing



Collaborations

- University of Tennessee
  - Provides feedback regarding fundamental machine design principals, assists with the development of modeling tools, and analyzes operational characteristics of operating in continuous conduction
- MotorSolver LLC
  - Provided feedback regarding fundamental machine design principals

Future Work

- FY10
  - Continue development of control algorithm
  - Continue comprehensive dynamic, acoustic, and structural modeling
  - Finalize design

- FY11
  - Incorporate control scheme onto DSP
  - Build and test SR motor prototype and test with novel control technique

Summary

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

- Improvements upon conventional SR technology
  - Significant reduction of torque ripple and acoustic noise
    - By utilizing greater percentage of air gap than that of a traditional SR motor
    - Less than 5% torque ripple for low and moderate torque and speed operation points
  - Localized flux paths yielding lower core losses
  - Increased winding area → more ampere-turns per motor size