Project ID: elt248

Multi-Objective Design Optimization of 100-kW Non-Rare-Earth or Reduced-Rare-Earth Machines

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Overview

Timeline

- Project Start: May 2019
- Project End: May 2024
- Percent Complete: 20%

Budget

- Total DOE Project Funding
- $1.5M over 5 years
  - $300k per year

Barriers

- Electrical and Electronics Technical Team Roadmap October 2017
  - Non-rare-earth machines as insurance policy against rare-earth magnet price volatility
  - Improved materials (i.e. copper, steel) to cut costs in half and double reliability
  - Understanding of system-level trade-offs (i.e. cost/performance impact of material substitution)

Partners

- Oak Ridge National Lab
  - Burak Ozpineci, Jason Pries, Tsarafidy Raminosa
- Sandia National Labs
  - Bob Kaplar, Jason Neely, Lee Rashkin, Todd Monson
- University of Wisconsin
  - Thomas Jahns, Bulent Sarlioglu
- Illinois Institute of Technology
  - Ian Brown
- NC State University
  - Iqbal Husain

Relevance

Design Tools & Methods: Method of Moments (MoM)

- **To meet 2025 goals for enhanced peak power (100 kW), specific power (50 kW/L) and reduced cost requires the ability to:**
  - Establish system-level trade-offs (i.e. cost versus efficiency)
  - Rapidly explore the impact of new materials (i.e. Fe4N)
  - Quickly develop design models of new machine topologies (i.e. non-rare-earth machines)
  - Rigorously compare alternative machine topologies via Pareto-optimal fronts
- MoM is a numerical technique that can be used to model low frequency electromagnetic behavior. It holds promise as a tool to enhance the team's ability to perform these tasks. Specifically, in contrast to existing tools (finite element analysis), only active material in electric machinery (steel) is meshed. If the material is linear, only the surface of the active material is meshed.
- **The objective is to develop an open-source MoM toolbox for propulsion drives that can be used to support design efforts**

Relevance

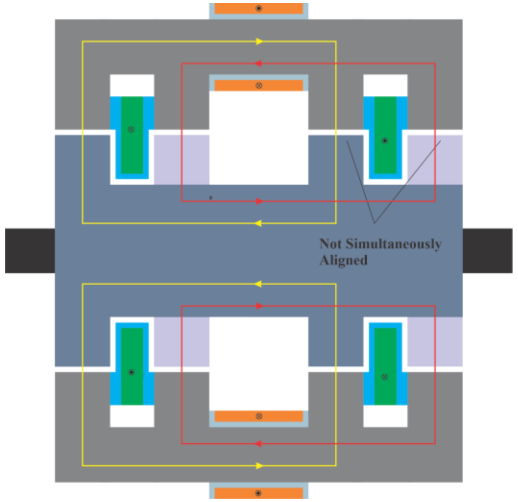
Design Tools & Methods: High Frequency Loss Modeling

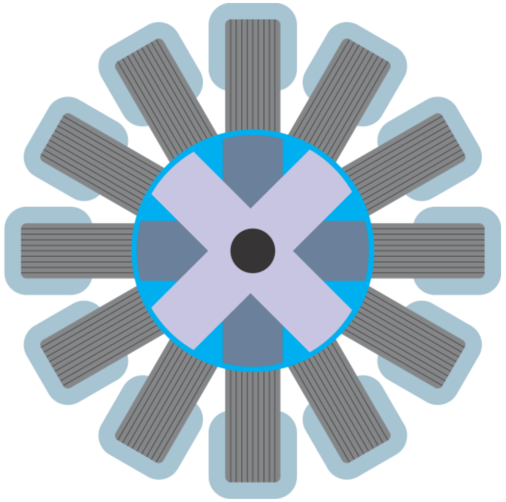
- Electric vehicle drives require high power density
- High power density leads to high-speed electric machines
- High-speed machines lead to high inverter switching frequency
- High switching frequency leads to need to co-design inverter aspects and machine
- Inverter/machine interaction best captured with time-domain simulation
  - Involves machine inductances, inverter and modulation parameters
- Normal simulations rather slow for poly-physics multi-objective optimization (PPMOO) based design (which can require 10 million design evaluations)
- Need way to combining machine and inverter design which will result in
  - Lower drive system losses
  - Higher drive system power density

Relevance

Novel Machines: Homopolar AC Machines

- Desire for electric vehicle drive cost to be both stable and low
  - Avoid machines with rare earth materials
  - Avoid machines with rotating windings
  - Support a large constant power speed range
  - Can be readily manufactured (even more easily than induction machines)
- One possibility: a homopolar ac machine (variant)





Milestones: Budget Period 1

Time	Type	Description of Milestone or Go/No-Go Decision	Status
BP1 Q1	Tech	A plan for the magnetic modeling of the proposed homopolar machine will be complete.	Met
BP1 Q2	Tech	A plan to incorporate switching loss effects into the machine design code.	Met
BP1 Q3	Tech	A FEA of a PMAC will be completed to serve as a test case for the MoM algorithm.	Met
BP1 Q4	Go / No-Go	The MoM analysis of an electric machine will be compared to that of FEA. The MoM prediction of average torque will be reasonably accurate compared to FEA code while the computation time will be significantly less.	Met

Milestones: Budget Period 2 (Revised)

Time	Type	Description of Milestone or Go/No-Go Decision	Status
BP2 Q1	Tech	A plan for the magnetic modeling of the two proposed HAM variants will be in place.	
BP2 Q2	Tech	An analytical method of calculating the relevant stresses and strains on an electric machine retention sleeve will be set forth.	
BP2 Q3	Tech	The Pareto-optimal front of the ICPM will be compared to that of a standard PMSM.	
BP2 Q4	Go / No-Go	The MoM method will be applied to the design of an asymmetrical reluctance machine. The time required on a high-end desktop machine will be such that this is a pragmatic way to design the machine.	

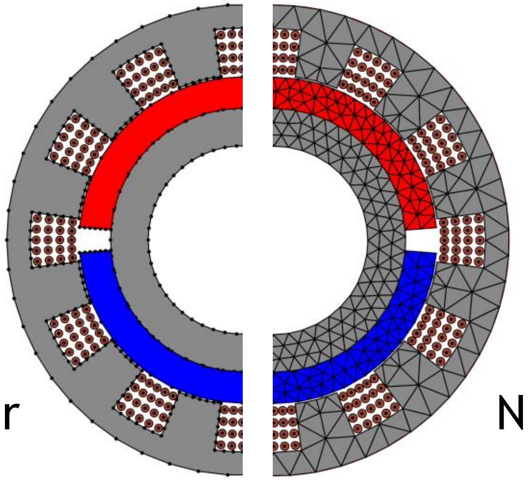
Approach

Method of Moments Toolbox

- Establish a Matlab-based toolbox for a permanent magnet synchronous machine (PMSM) to demonstrate utility of MoM to community
  - Derive techniques to compute machine performance using MoM (torque, loss, machine parameters)
  - Demonstrate effective use of MoM in multi-objective optimization
  - Create a user-friendly interface that facilitates adoption
  - Distribute beta-versions to community to obtain feedback for tool enhancement

MoM Mesh of PMSM

Linear



Nonlinear

MoM Model Structure

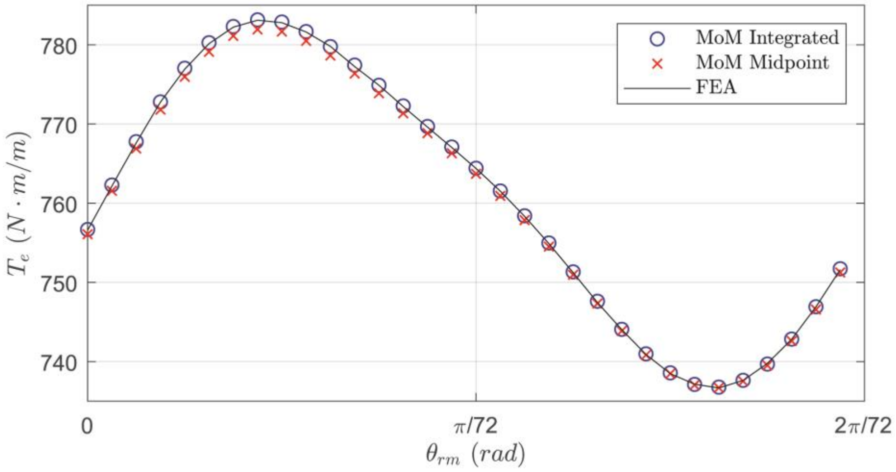
$$\underset{\substack{\uparrow \\ \text{Magnetization} \\ \text{(unknown)}}}{\mathbf{M}} = \overbrace{\left(\mathbf{f}_{\mathbf{BtotM}} - \mathbf{f}_{\mathbf{BM}}\right) \backslash \mathbf{f}_{\mathbf{BI}_f}}^{\text{Material and geometric properties}} \underset{\substack{\uparrow \\ \text{Free Current} \\ \text{(input)}}}{\mathbf{I}_f}$$

Accomplishments

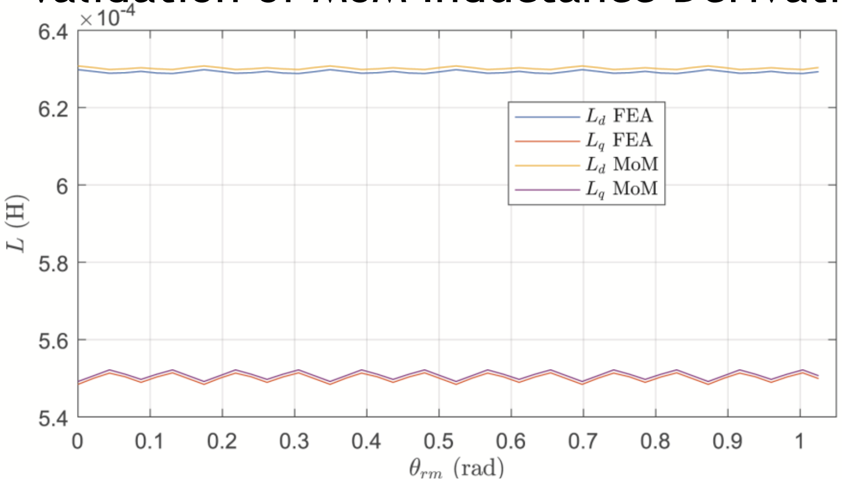
Developed Computational Engine of MoM Toolbox

- Derived fundamental expressions for efficient calculation of electromagnetic forces/torque
- Derived fundamental expressions to compute machine parameters (i.e. inductance, back-emf)
- Developed Discrete Body of Revolution-based method to reduce computation time of MoM models by exploiting periodicity of geometry/excitation
- Derived method to solve nonlinear MoM problems with relatively few iterations
- Created a GUI for the toolbox to facilitate use by the community

Validation of MoM Torque Derivation



Validation of MoM Inductance Derivation

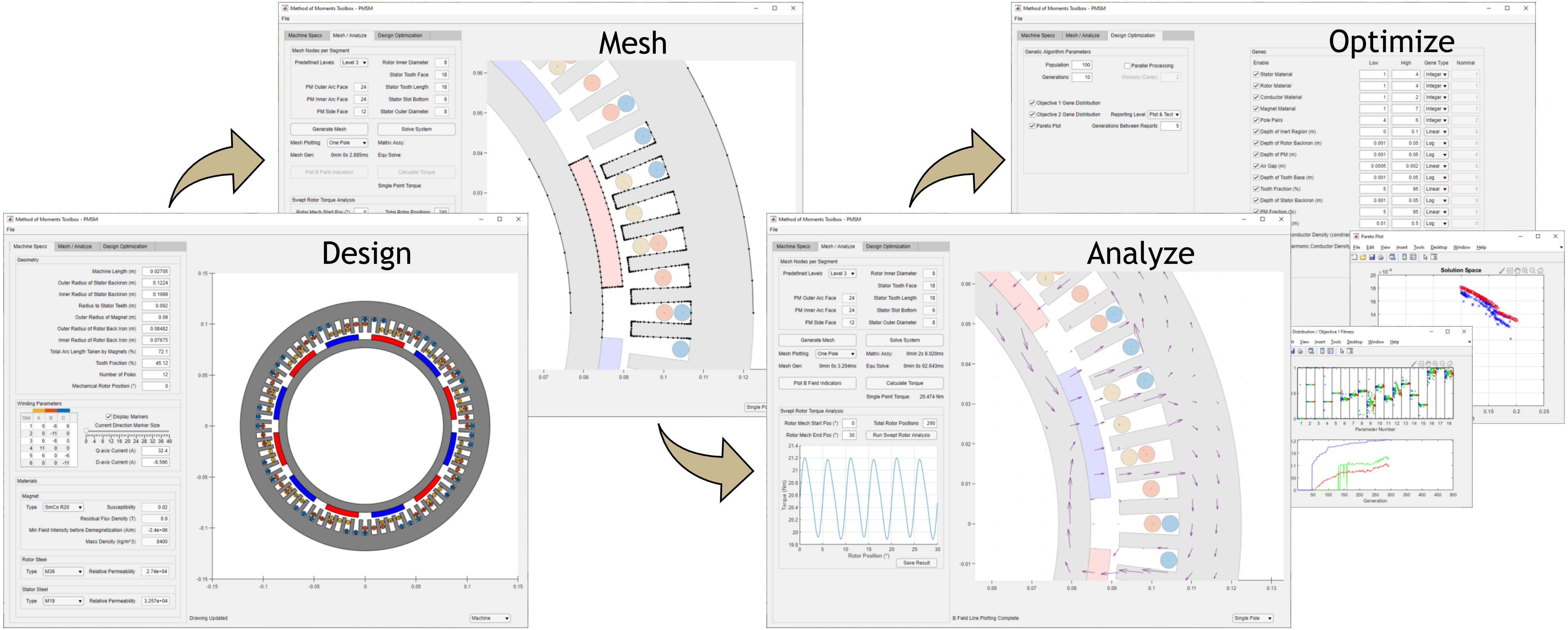


✔*Milestone:* Method of Moments - *BP1 - Q3 & Q4*

PMSM MoM model shows strong agreement with commercial FEA model while taking considerably less time (MoM: 1s, FEA: 120s)

Accomplishments

Method of Moments Toolbox Demonstration - PMSM



A graphical toolbox helps demonstrate the advantages that Method of Moments has to offer and how it can be easily integrated into existing design workflows.

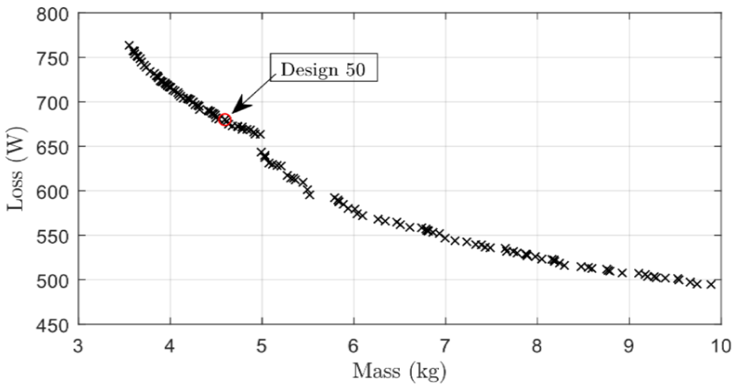
Accomplishments

Demonstrated Utility of MoM

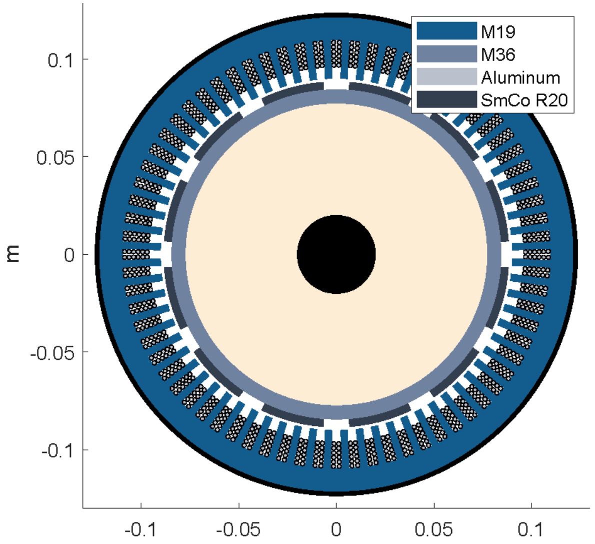
- Performed multi-objective design of a permanent magnet synchronous machine drive
  - Evaluated 250,000 machines in 11.4 hours using desktop computer
    - Intel Xeon E5-2687Wv2 processor operating at 3.4 GHz with 32 GB RAM

- Objectives: minimize mass and loss
- Specifications:
  - Voltage of dc bus
  - Torque at given speed(s)
- 18 Degrees of freedom (design variables)
- 17 Design constraints
- 4 rotor positions

Pareto-Front of Loss versus Mass



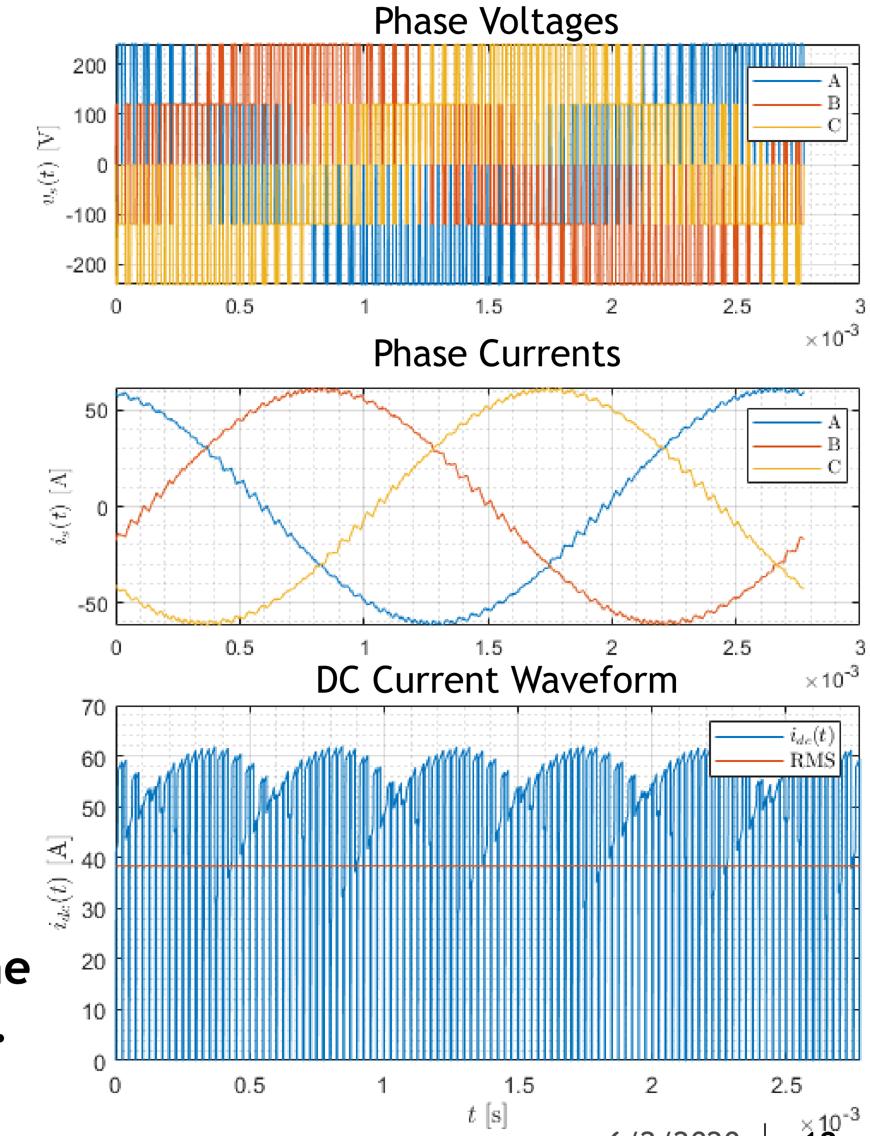
Cross Section of Design 50



Approach

High Frequency Loss Modeling

- *Technical Approach*:
  - Create a computationally efficient time domain simulation to determine current harmonic content and switching events
  - From simulation results, compute: semiconductor switching and conduction losses, winding skin effect and proximity losses, capacitor bank design and losses, torque ripple due to time harmonics
- *Project Integration*: Proposed combined optimization informs the selected switching modulation
  - Inverter loss and mass is correlated to the machine parameters
  - Optimizing the motor by itself does not imply the best system design
    - Balance machine inductance with switching frequency, or torque ripple to modulation strategy
- ✓ *Milestone*: Switching Loss Estimation Plan - *BP1-Q2*
  - A plan to incorporate switching loss effects into the machine design



Goal: Incorporate the effects of the inverter switched operation in the machine design, enabling simultaneous inverter/motor optimization.

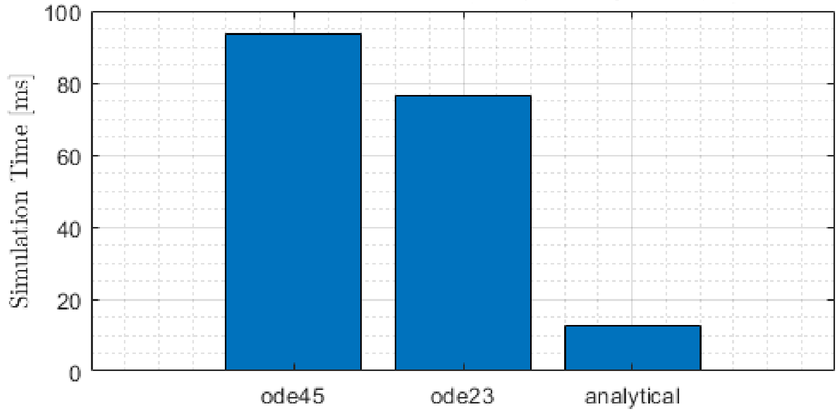
Accomplishments

High Frequency Loss Modeling

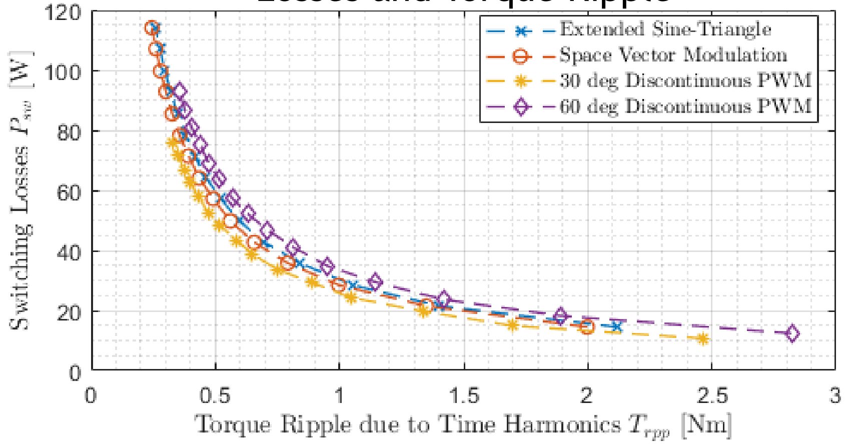
- A computationally efficient event-oriented time domain simulation model set forth
  - Analytical solution of system's differential equations permits simulations in milliseconds
  - Enables the simulation in a machine design fitness function
- The time domain simulation allows the evaluation under various modulation strategies
  - Extended Sine-Triangle, Overmodulation, Space Vector, Discontinuous PWM (30°, 60°, and 120°).
  - Account for implications in the electric drive in switching and conduction losses, torque ripple due to time harmonics, DC bus voltage ripple, capacitor losses, AC winding losses.

A computationally efficient time domain analysis enables the machine design optimization to include inverter capacitance, switching frequency, and modulation strategy as design variables.

Time to Simulate One Fundamental Cycle at 10 kHz Switching Frequency



Modulation Strategies Effects on Switching Losses and Torque Ripple



Approach

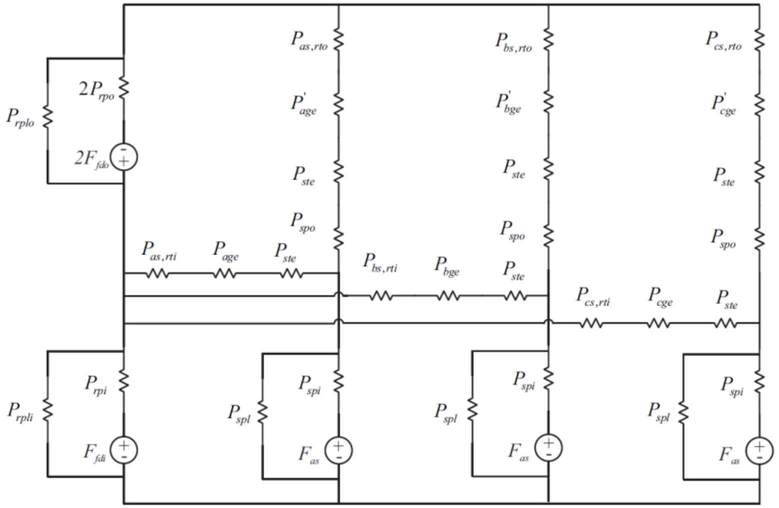
Homopolar AC Machine (HAM)

- *Technical Approach*:
  - Originate novel Homopolar Machine topologies to <u>reduce</u> or <u>eliminate</u> rare-earth material usages.
  - Derive magnetic modeling of the proposed electric machine to facilitate the development of other key elements such as winding bundle placement, excitation strategies, and detailed rotor geometry.
  - From the acquired magnetic model, <u>generate optimal designs</u> based on a rigorous multi-objective optimization.
- *Project Integration*: The design study evaluates the proposed topologies in terms of power density and cost effectiveness.

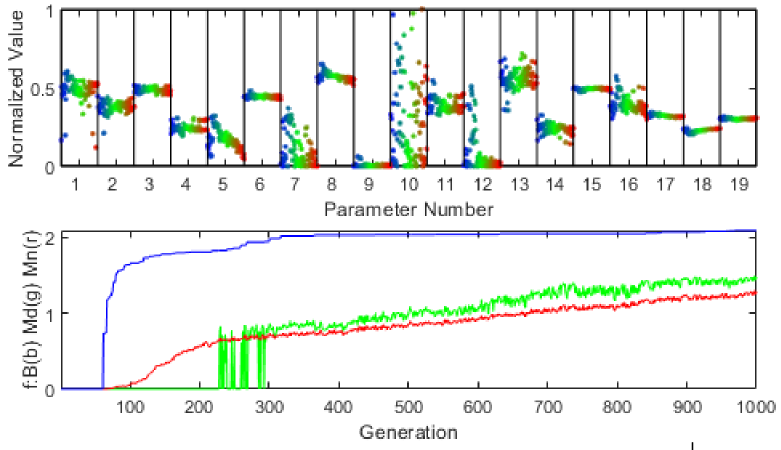
✓ *Milestone*: Proposed Homopolar Machine - *BP1-Q1*
A plan for the magnetic modeling of the proposed homopolar machine will be complete.

Goal: Develop novel high-speed propulsion motor with high power density and low cost.

Magnetic Equivalent Circuit of Proposed HAM



Multi-Objective Optimization

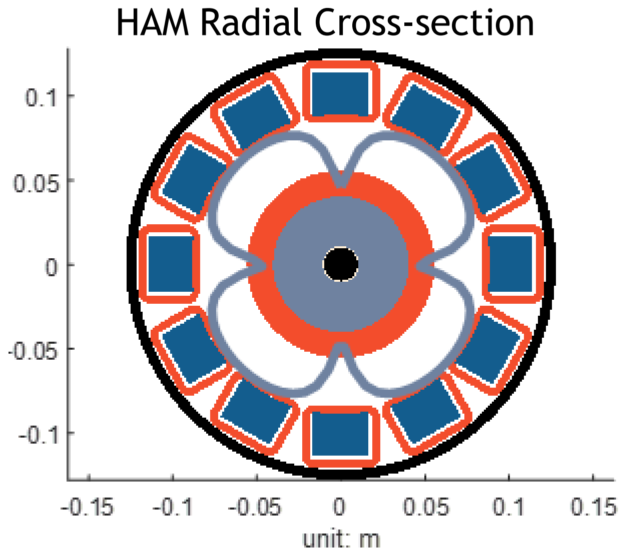


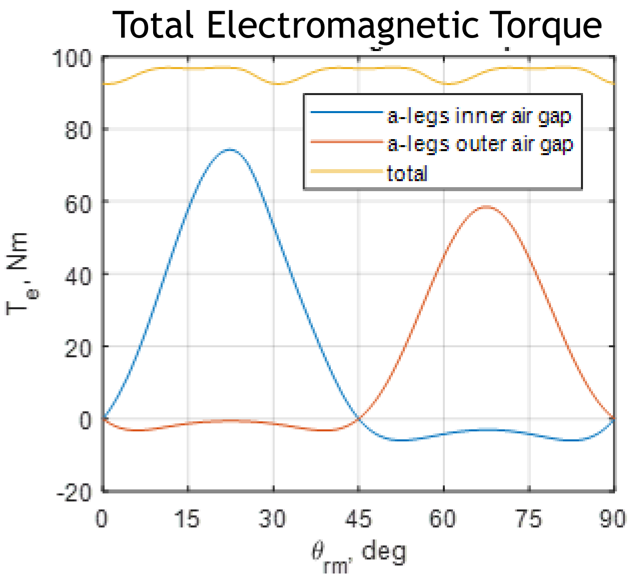
Accomplishments

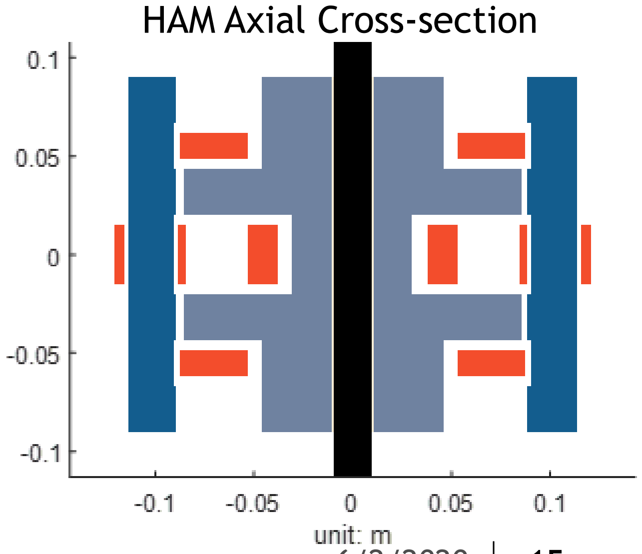
Homopolar AC Machine (HAM)

- Completed a plan for the magnetic modeling
- Implemented the magnetic model to predict HAM performance such as torque, power density, etc.
- Multiple HAM variants and their associated control strategies were set forth: an example torque plot demonstrates the torque ripple performance.
- Computationally efficient design paradigm allows quick turn around for any future design studies of topology improvements.

Set forth an intricate magnetic modeling and design paradigm that enables the optimization of HAM topologies







Response to Prior AMR Comments

This is the first review of this project

Collaboration & Coordination

Collaborations in Power Converters, Materials, & Machines

- Biweekly meetings with the Oak Ridge Motor Team
  - Oak Ridge National Lab (Burak Ozpineci, Jason Pries, Tsarafidy Raminosa)
  - Sandia National Labs (Bob Kaplar, Jason Neely, Lee Rashkin, Todd Monson)
  - University of Wisconsin (Thomas Jahns, Bulent Sarlioglu)
  - Illinois Institute of Technology (Ian Brown)
  - NC State University (Iqbal Husain)
  - Purdue University (Scott Sudhoff, Steve Pekarek)
  - One present focus is uniform drive system targets (success achieved!)

- Biweekly meetings with Sandia National Labs
  - Jason Neely (inverters, elt223)
  - Lee Rashkin (inverters, elt223)
  - Todd Monson (materials, elt216)
  - Focus of meetings is
    - Machine/inverter interaction issues
    - Possibilities of new materials

- (Approximately) Quarterly coordination review (coordinated by Vipin Gupta, Sandia)
- All collaborations listed are within VTO
- All groups independently funded by DOE/VTO office

Remaining Challenges & Barriers

Design Tools & Methods

- Integration of high-speed time domain simulation into drive design fitness function. What is impact on system power density?
- Integration of structural analysis in fitness function. What is impact on system power density?
- Reducing nonlinear MoM solution time to facilitate optimization
- Reduce cost of electric drives
  - Utilize MoM to explore inert-core PMSMs (reducing steel, eliminating rare-earth PM materials)
  - Utilize MoM to explore asymmetric reluctance machines (increase torque density)

Novel Machines

- Homopolar AC Machine
  - Validation of rather complicated magnetic design model.
  - Performance evaluation at multiple operating points and comparison* to conventional machine topologies. Concern: torque density is modest. Opportunity: wide-constant power speed range.
- Asymmetrical Reluctance and Inert Core PM Machines
  - Need performance assessment and comparison* to conventional machine topologies.

* Comparisons based on specifications agreed upon by ORNL led machine group (ORNL, Sandia, Purdue, IIT, NC State, Wisconsin)

Proposed Future Research

Topics for 2020 & 2021

- Design Tools & Methods
  - Incorporate reported high-speed simulation method into poly-physics multi-objective optimization and demonstrate co-design of machine and inverter for VTO application (specifications based on ORNL VTO motor design group). This will lead to improved designs in which both motor and inverter are simultaneously considered.
  - Develop an analytical method of calculating the relevant stresses and strains on a retention sleeve for a non axisymmetric PMSM. Incorporate this into the poly-physics multi-objective optimization approach. Again, this will lead to improved designs which include structural issues from the beginning of the design process. *(<u>Milestone</u>: Retention Sleeve Analysis; BP2: Q3; Technical)*
- Novel Machines
  - Variants of the Homopolar AC Machine will be explored. In particular, work will focus on the dual-field Homopolar AC Machine. This machine is of interest because it utilizes a conventional inverter, is capable of a very wide constant power speed range, and has very low torque ripple. *(<u>Milestone</u>: Homopolar AC Machine Variants; BP2: Q1; Technical)*
- Design Tools & Methods applied to Novel Machines
  - Use Method of Moments developed in Year 1 for design of Inert Core Permanent Magnet Machine and compare to standard PMSM for VTO application. *(<u>Milestone</u>: ICPM Evaluation; BP2: Q3; Technical)*
  - Use Method of Moments to design Asymmetrical Reluctance Machine and compare to standard PMSM for VTO application *(<u>Milestone</u>: MoM Effectiveness Evaluation; BP2: Q4; Go/No-Go)*
- NOTE: Designs evaluated based on specifications of ORNL led machine design group: ORNL, Sandia, Purdue, IIT, Wisconsin, NC State
  - 20,000 rpm maximum speed, 100 kW peak power, 55 kW continuous power, 3-to-1 constant power speed range, 143 Nm peak torque

Proposed future work is subject to change based on funding levels.

Summary

Design Tools & Methods

- A MoM-based toolbox was created for analysis/design of electric machines. This included developing the underlying computational engine used to efficiently calculate torque, parameters, and loss. The utility of MoM in multi-objective design of machines was demonstrated using a PMSM design example. A GUI was developed to facilitate toolbox adoption.
- The new time domain simulation method of high frequency switching is much faster than traditional simulations and allows time-domain simulation of the drive to be used in a poly-physics multi-objective optimization-based drive design which co-designs the machine and key aspects of the inverter (capacitance, switching frequency, modulation strategy)

Novel Machines

- The new homopolar ac machine is still in its infancy as a new and most promising variant was developed in the BP1 Q4. However, the proposed topology shows promise, particularly in facilitating low cost and greater constant power speed range.