Project ID: elt248

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

Scott Sudhoff and Steve Pekarek
Purdue University

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Overview

Timeline

- Project Start: May 2019
- Project End: May 2024
- Percent Complete: 40%

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 Laboratory
  - Burak Ozpineci, Jason Pries, Tsarafidy Raminosa
- Sandia National Laboratories
  - 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

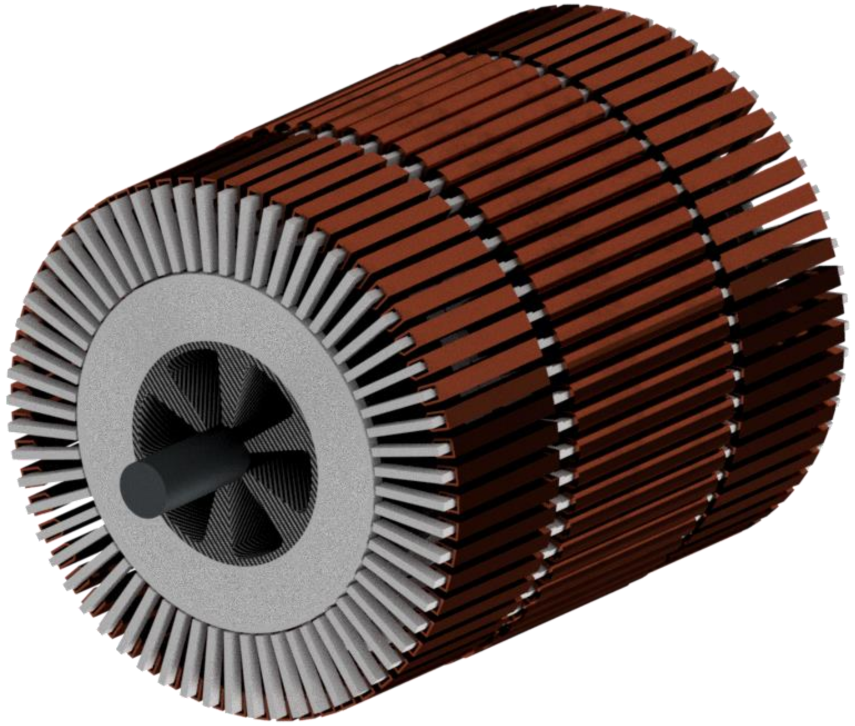
Design Tools and Methods

- **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
- **Magnetic Analysis: Developed Method of Moment Toolbox**
  - High-speed alternative to FEA
  - Open source - available to world! (delivered this year)
- **High-Frequency Loss Modeling (last year)**
- **Non-Axis Symmetric Sleeve Analysis (this year)**

Relevance

Novel Machines

- Desire for electric vehicle drive cost to be both stable and low
  - Avoid machines with certain problematic rare-earth materials
  - Avoid machines with rotating windings
  - Support a large constant power speed range
  - Can be readily manufactured
- Dual Field Homopolar AC Machine
  - Infinite constant power speed range
  - Field winding, if used, is stationary (PM free)
  - Magnets, if used, can be stationary
  - Stator is inherently segmented
- Inert Core Machines
  - Dual airgap for high torque density
- Rotationally Asymmetric Reluctance Machine
  - PM free; optimized for one rotational direction



Dual Field Homopolar AC Machine

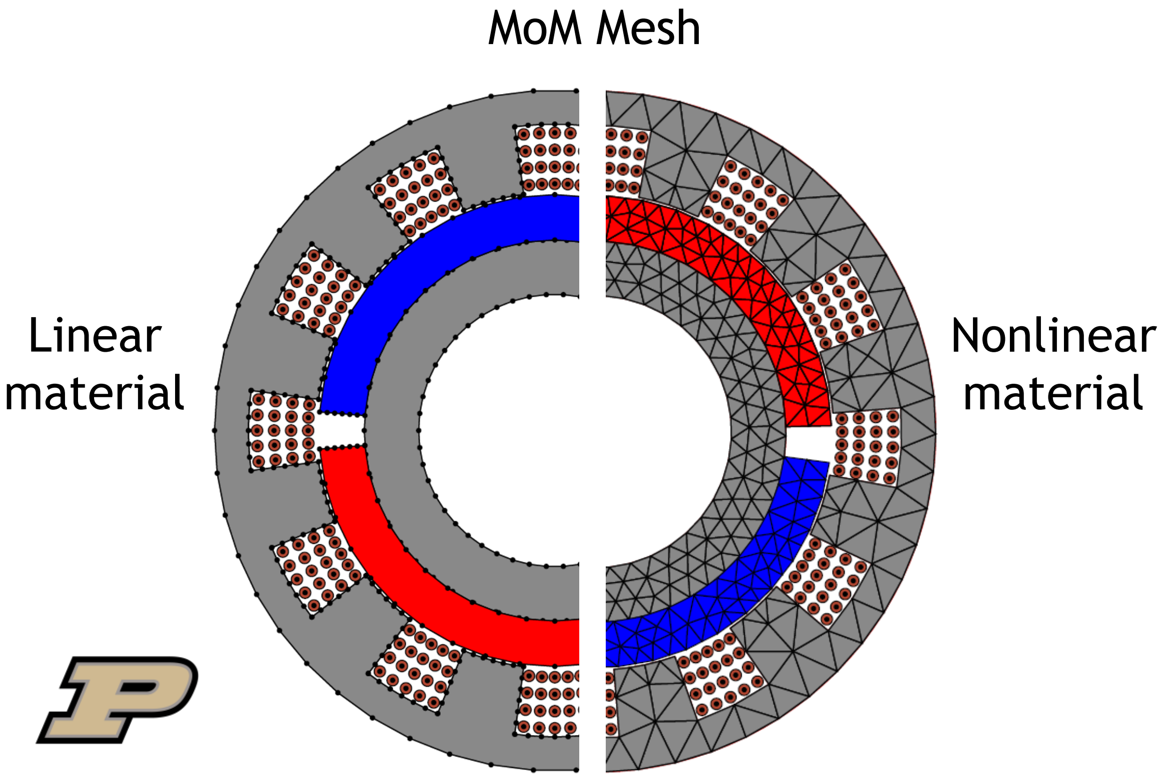
Milestones: Budget Period 2 (Revised)

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.	Met
BP2-Q2	Tech	An analytical method of calculating the relevant stresses and strains on an electric machine retention sleeve will be set forth.	Met
BP2-Q3	Tech	The Pareto-optimal front of the ICPM will be compared to that of a standard PMSM.	Met
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.	Met

Approach – Design Tools and Methods

Method of Moments Toolbox

- Establish Matlab-based toolboxes to support design of variety of electric machinery
  - Distributed to community to help promote rigorous multi-objective optimization of machines
  - Extended to new types of machinery (inert-core, asymmetric reluctance) to enable comparison of wide range of options



MoM Model Structure

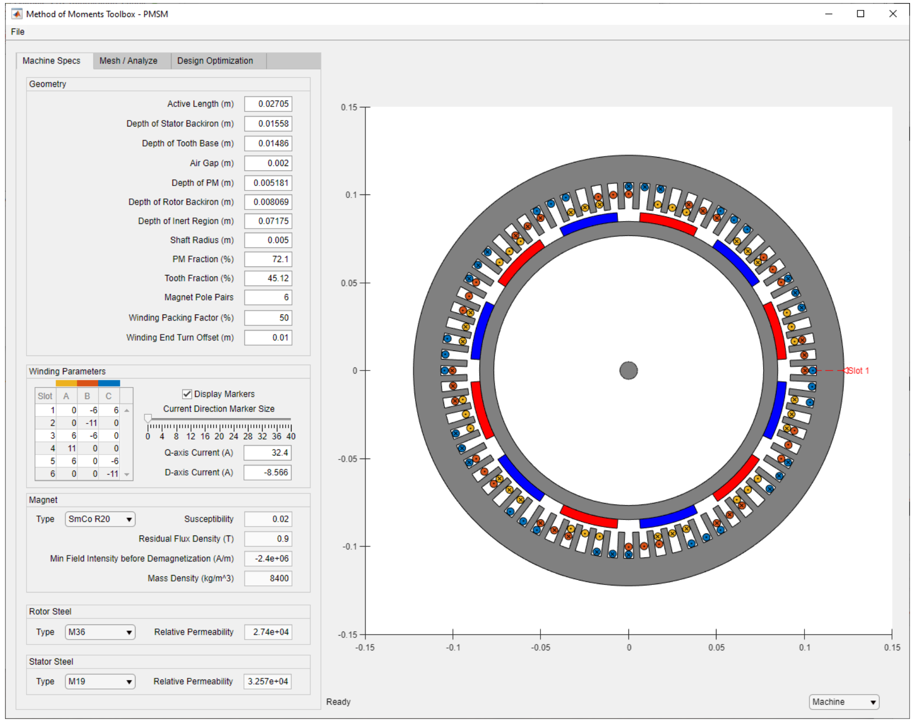
$$\underset{\substack{\uparrow \\ \text{Magnetization (unknown)}}}{\mathbf{M}} = \overbrace{\left(\mathbf{f}_{\mathbf{BtotM}} - \mathbf{f}_{\mathbf{BM}}\right) \backslash \mathbf{f}_{\mathbf{BI}_f}}^{\text{Material and geometric properties}} \underset{\substack{\uparrow \\ \text{Free Current (input)}}}{\mathbf{I}_f}$$

Accomplishments - Design Tools and Methods

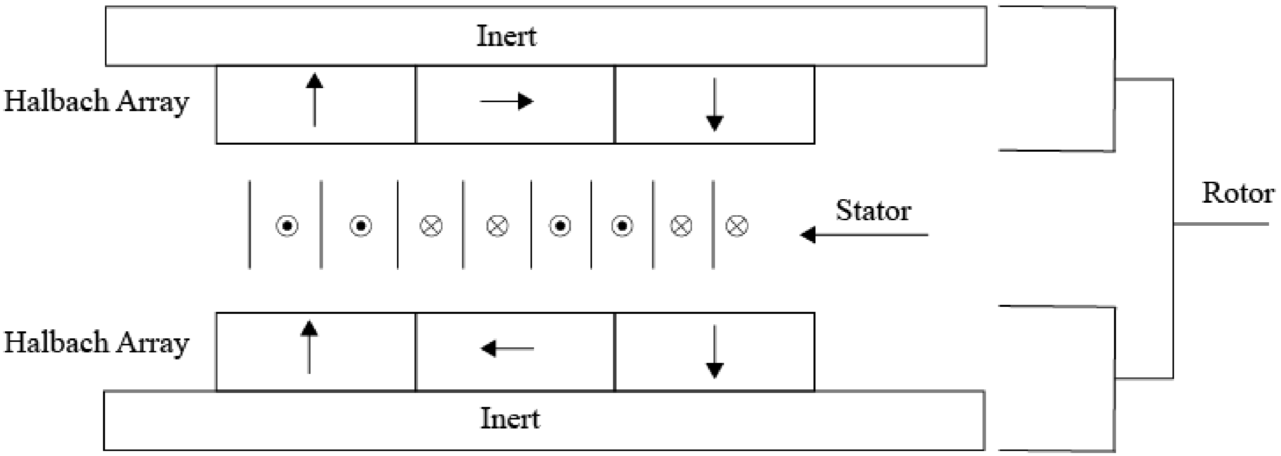
Developed Computational Engine of MoM Toolbox

- Provided a MoM Toolbox for PMSMs to community (https://engineering.purdue.edu/ECE/Research/Areas/PES/Software/Method-of-Moments-Toolbox)
- Extended MoM to develop toolboxes for design of inert-core PMSM and asymmetric reluctance machines

Method of Moments Toolbox



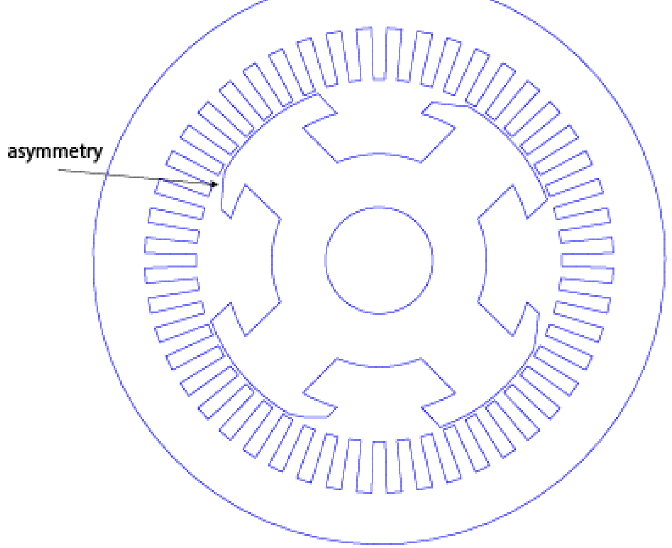
Inert-core PMSM



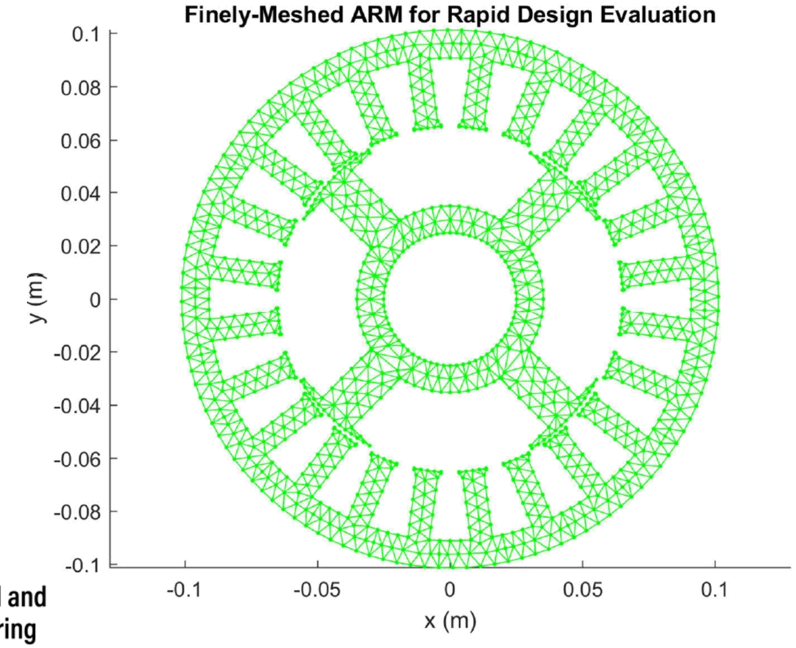
Asymmetric Reluctance Machine (ARM)

- Asymmetry included in rotor to enhance torque density
- No permanent magnets
- Requires MoM evaluation that includes magnetic saturation (volume mesh)
- Established MoM Galerkin nonlinear solver and evaluated mesh density/solve times
- Finalizing toolbox for multi-objective optimization of ARM

ARM



Volume Mesh



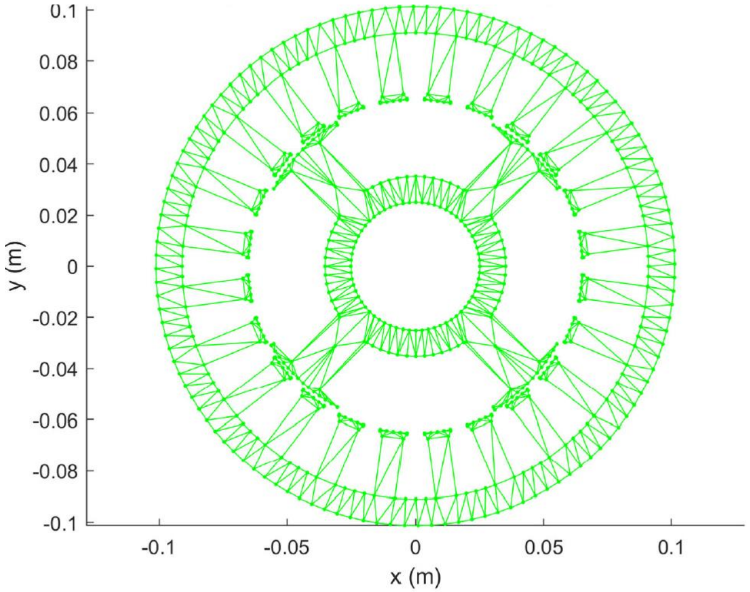
MoM Galerkin Structure

$$\mathbf{M} = \left(\mathbf{f}_{\mathbf{BtotM}} - \mathbf{f}_{\mathbf{BM}}\right) \backslash \mathbf{f}_{\mathbf{BI}_f} \mathbf{I}_f$$

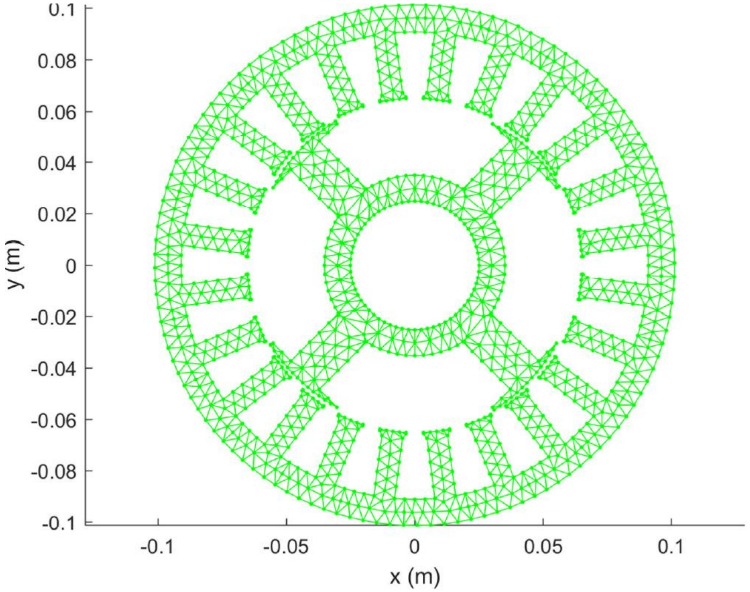
Tangent magnetization as unknown (as opposed to x- and y-component)

Accomplishments – Design Tools and Methods

Coarsely Meshed Arm



Finely Meshed Arm



Evaluation of MoM computational performance

	Coarse Mesh	Fine Mesh
Triangles	214	414
Elements	642	1242
System Matrix	642x642	1242x1242
Mesh	0.404 s	0.390 s
Matrix Fill	1.702 s	9.684 s
Solve	0.906 s	1.598 s
Observation	0.377 s	0.652 s
Torque	0.346 s	1.728 s
Total Comp Time	3.75 s	14.052 s

Rotor Position	Iteration Count Coarse Mesh	Iteration Count Fine Mesh
1	8	5
2	16	7
3	19	5
4	22	5
5	16	6
6	12	4

- Less than 2% difference in average torque using coarse mesh
- MoM enables rigorous multi-objective optimization (MOO)

✓ *Go/No Go Milestone: MoM computation enables MOO – BP2-Q4*

Approach - Design Tools and Methods

Retention Sleeve Analysis

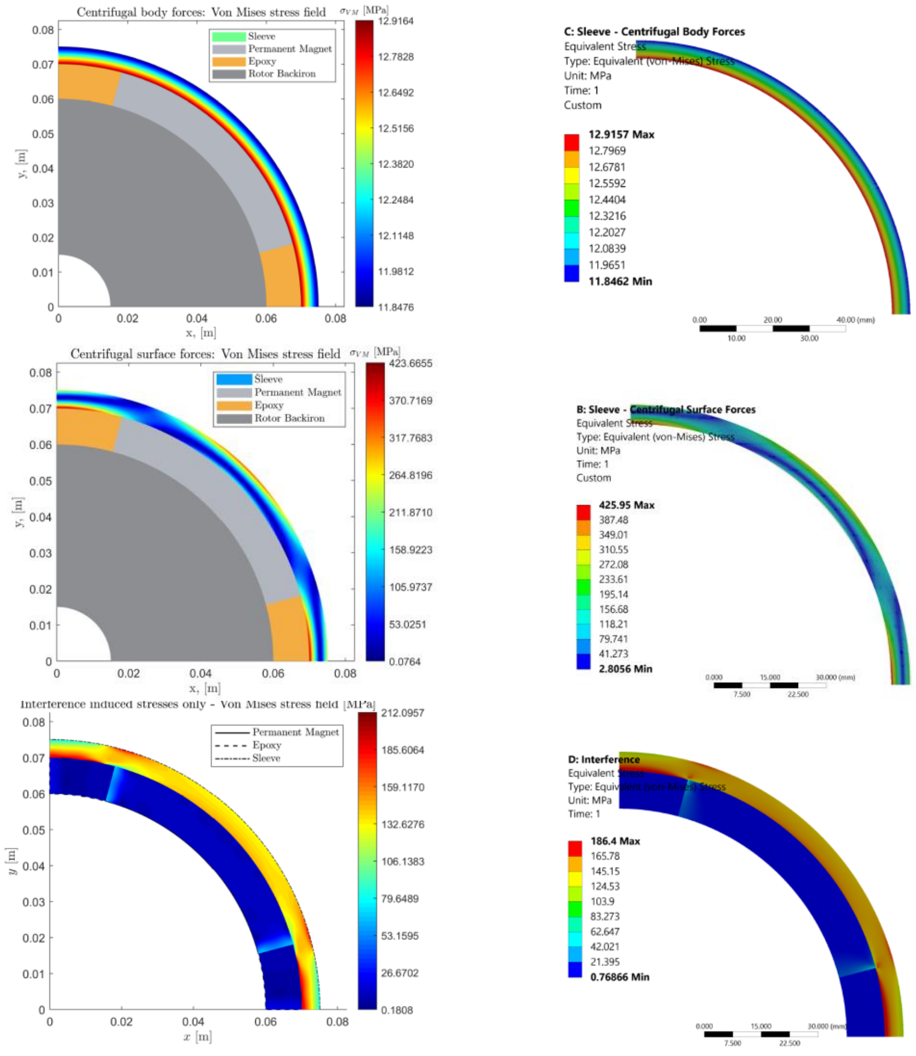
- *Technical Approach*:
  - Create a <u>computationally efficient means</u> to determine magnet and sleeve stresses based on body forces, sleeve forces, and interference induced forces
  - Key difficulty: address non-axisymmetric geometries
- *Project Integration*
  - Created combined optimization of machine with sleeve
- ✓ *Milestone: Full Report with Design Comparison – BP2-Q2*
  - Full report and numerically validated approach delivered with BP2-Q2 Quarterly Report

Goal: Integrate the sleeve design process into the machine design process.

Sleeve Body Forces

Sleeve Surface Forces

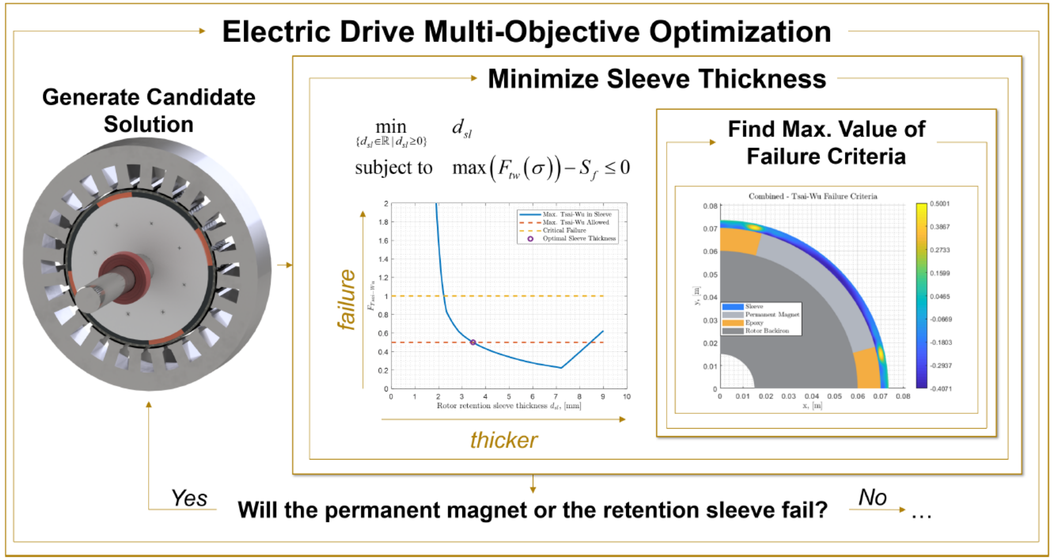
Sleeve Interference Forces



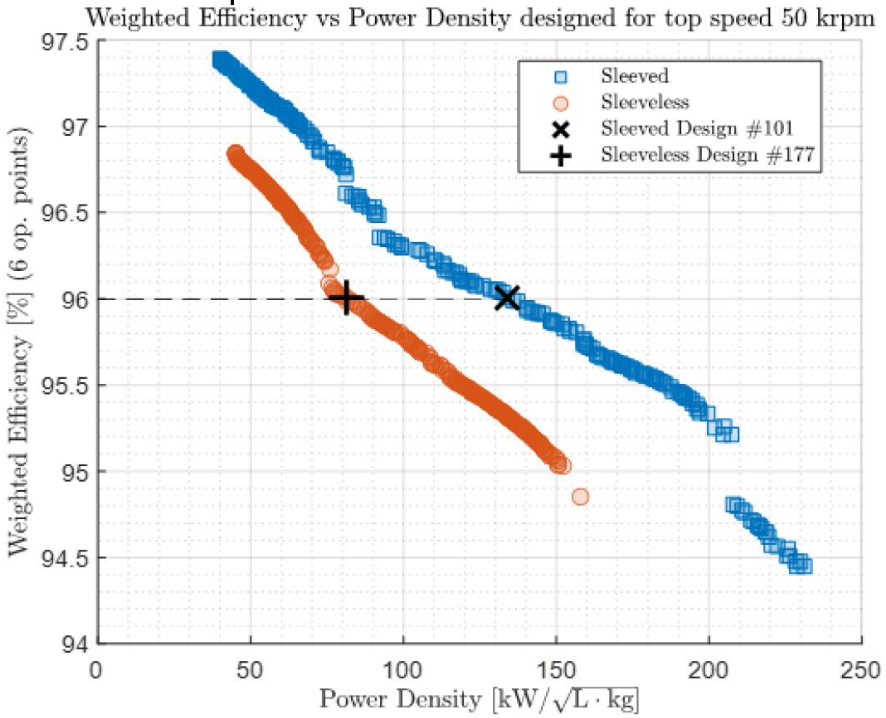
(a) Analytical Solution (b) FEA Solution

Retention Sleeve Analysis

- Integration of sleeve design into machine deign
  - Based on an optimization within an optimization approach
  - Given a candidate rotor design, an algorithm to choose an appropriate sleeve thickness is executed, based on Tsai-Wu failure criteria
  - Sleeved and sleeveless approaches can then be compared



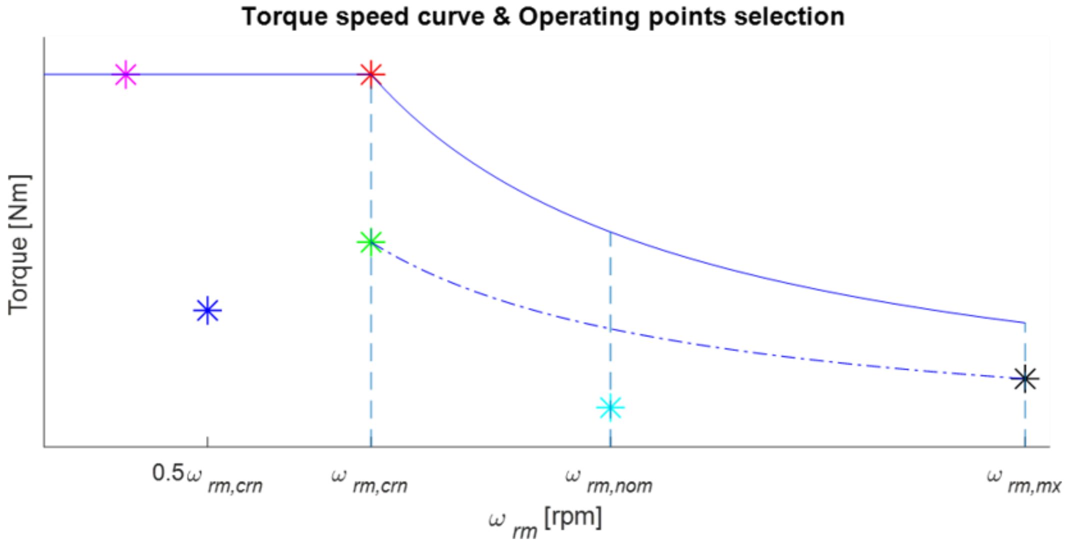
Comparison of Sleeved & Sleeveless



A means of integrating sleeve analysis for non- axisymmetric sleeve design into the machine design process has been achieved (the axisymmetric case is straightforward).

Approach - Novel Machines

Basis of Machine Comparisons



Rating	Value
α_{CPSR}	3
$P_{\mathrm{mx},pk}$ (kW)	100
$P_{\mathrm{mx},ct}$ (kW)	55
$P_{\mathrm{nom},ct}$ (kW)	27.5
$\omega_{rm,mx}$ (rpm)	20,000
$\omega_{rm,crn}$ (rpm)	$\omega_{rm,mx}/\alpha_{CPSR}$
$\omega_{rm,nom}$ (rpm)	$\sqrt{\omega_{rm,crn}\omega_{rm,mx}}$

	Op1	Op2	Op3	Op4	Op5	Op6
Speed	$\omega_{rm,crn}$	$\omega_{rm,crn}$	$\omega_{rm,mx}$	$\omega_{rm,crn}/2$	$\omega_{rm,nom}$	$\omega_{rm,nom}/4$
Power	$P_{mx,pk}$	$P_{mx,ct}$	$P_{mx,ct}$	$P_{mx,ct}/3$	$P_{mx,ct}/3$	$P_{mx,ct}/4$
Weight	5%	15%	5%	20%	40%	15%

Minimize weighted loss and size for each machine topology.

Compare machines in terms of Pareto-optimal fronts

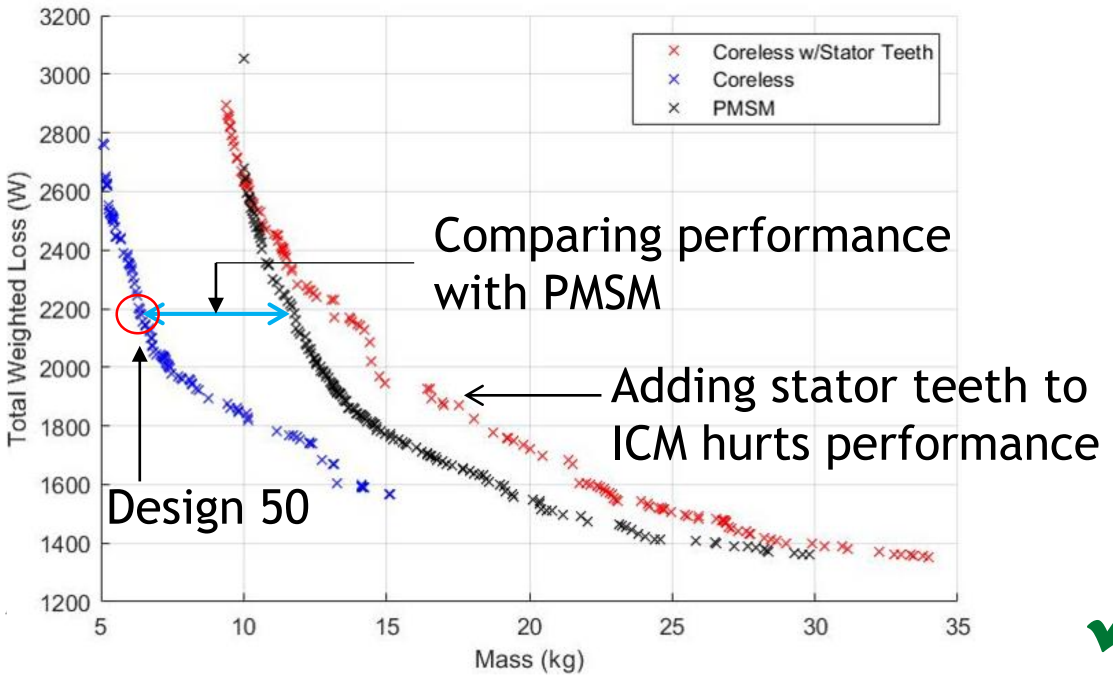
* Comparisons based on specifications agreed upon by ORNL led machine group (ORNL, Sandia, Purdue, IIT, NC State, Wisconsin)

Accomplishments – Novel Machines

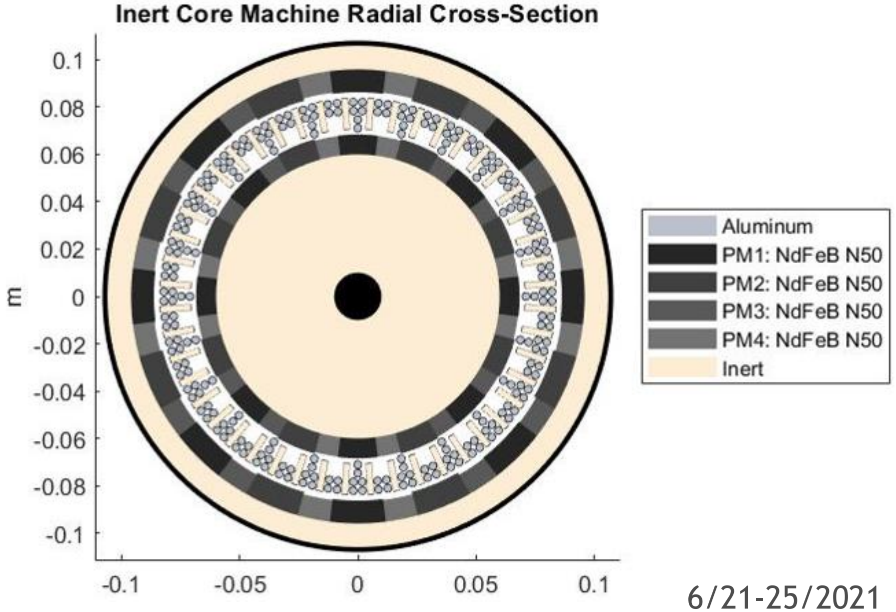
Inert-Core Machine (ICM)

- Halbach-based array on inner and outer rotors
- Eliminate (or greatly reduce) stator/rotor steel
- MoM-based design tool enables exploration of wide range of magnets materials/geometries
- Initial electromagnetic design indicates significant reduction in mass/volume compared to permanent magnet synchronous machine (PMSM)

Pareto-optimal fronts of ICM versus PMSM



Design 50 from Pareto-optimal front



✓*Milestone: Design comparison of ICM/PMSM – BP2-Q3*

Accomplishments – Novel Machines

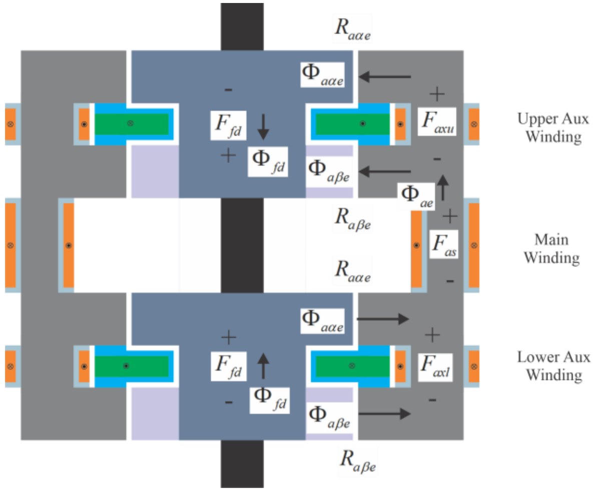
Dual Field Homopolar AC Machine (DHAM)

- *Technical Approach*:
  - Originate novel Homopolar Machine topologies to reduce or eliminate 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, generate optimal designs based on a rigorous multi-objective optimization.
- *Project Integration*: The design study evaluates the proposed topologies in terms of power density and cost effectiveness.

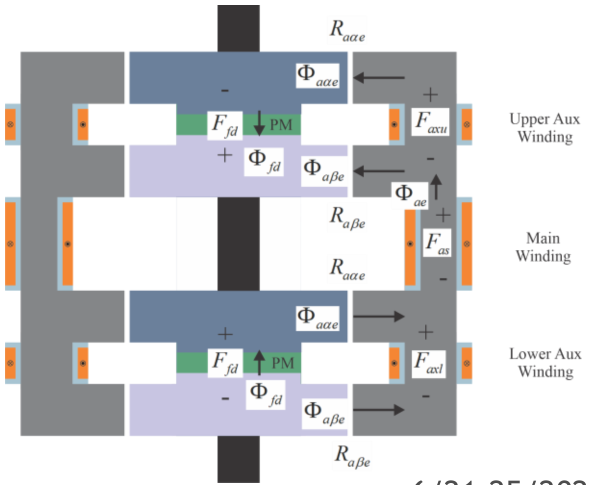
✓ *Milestone*: Proposed Homopolar Machine – *BP2-Q1*
A plan for the magnetic modeling of the proposed homopolar machine will be complete.

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

Field-based DHAM



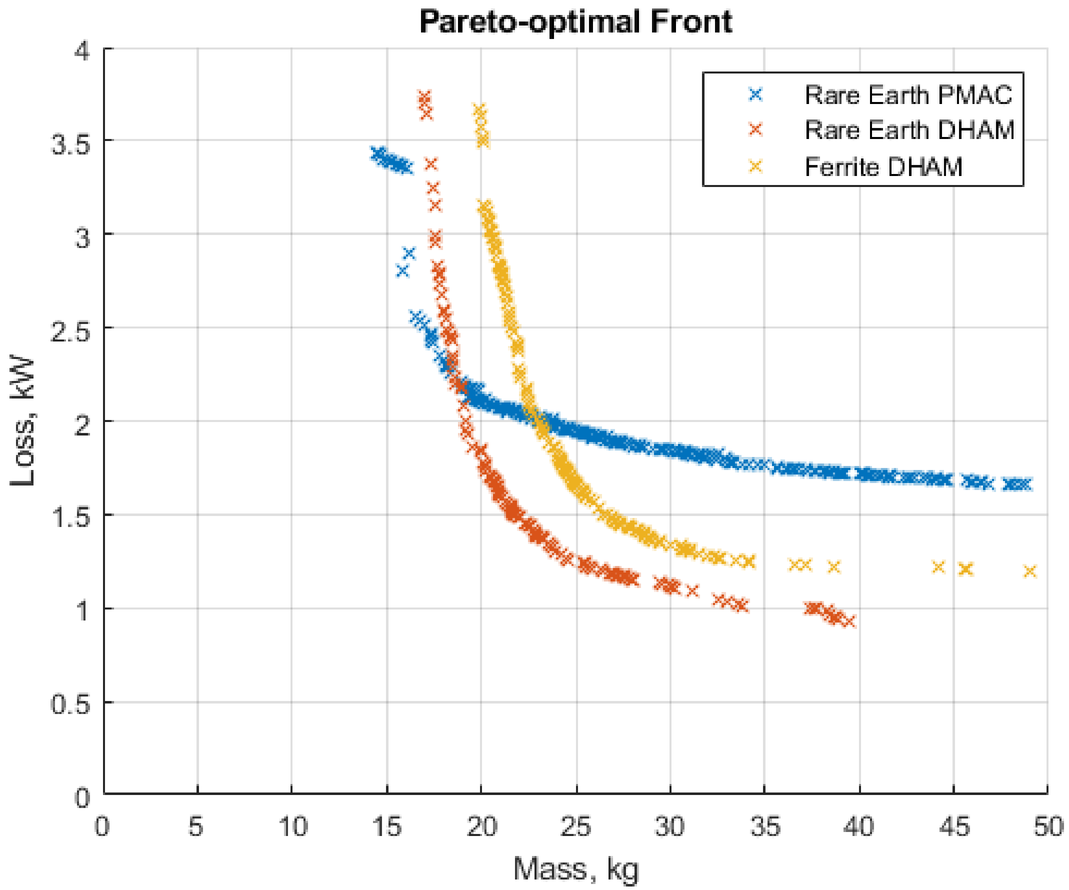
Magnet-based DHAM



Accomplishments - Novel Machines

Dual Field Homopolar AC Machine (DHAM)

- Auxiliary windings self-excite and do not need external excitation.
- Infinite constant power speed range, even when using magnets (electrically).
- Main windings have sinusoidal voltages and currents and produce constant torque (ideally)
- Can be built using field windings, rotating magnets, or stationary magnets
  - Stationary magnets can be readily cooled avoiding high-temp magnet operation.
- Inherent use of segmented stator for easy construction
- Simple and robust rotor
- Can house power electronics within internal structure



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Response to Prior AMR Comments

Approach to Performing the Work

- Chief Criticism: Homopolar topology may not meet DOE requirements
- Response: A breakthrough will likely require a consideration of non-conventional topologies. With regard to the homopolar machine, a new variant of the homopolar machine developed this year (the Dual Field Homopolar AC Machine) looks very promising.

Collaboration & Coordination

Collaborations in Power Converters, Materials, & Machines

- Biweekly meetings with the Oak Ridge Motor Team
  - Oak Ridge National Lab (Burak Ozpineci, 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

- Adding thermal/structural models to inert-core and asymmetric reluctance machines

Novel Machines

- Dual Field Homopolar AC Machine
  - Magnetic model needs to be improved
  - Inverter losses needed to be added
  - Rotor shaping algorithm is not completely satisfactory
  - Comparison to conventional machine topologies
  - Concern: torque density is modest - however, the power electronics can be placed inside of the machine.
- Asymmetrical Reluctance and Inert-Core PM Machines
  - Following thermal/structural model development compare to conventional machine topologies
  - Concern: cooling inert-core machine may be a challenge due to lack of stator iron
  - Concern: asymmetric reluctance machine may not meet volume/mass of PM-based machines, likely much lower cost

Proposed Future Research

Topics for 2021 and 2022

- Design Tools & Methods
  - Thermal/structural models added to MoM-based design toolboxes
- Using the work of the first two years, following machines will be rigorously compared through comparison of Pareto-optimal fronts
  - Surface mounted permanent magnet ac machine
  - Dual field homopolar ac machine
  - Inert core permanent magnet ac machine
  - Asymmetrical reluctance machine
- 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
  - Designs will satisfy the design criteria above and will be compared in terms of their Pareto-optimal fronts of aggregate loss versus size

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

Proposed Future Research

Time	Type	Description of Milestone or Go/No-Go Decision	Status
BP3-Q1	Tech	Comparison of the Pareto optimal fronts of Homopolar and PMAC machines will be completed.	Pending
BP3-Q2	Tech	Design code for an ICPM including structural and thermal analysis will be completed.	Pending
BP3-Q3	Tech	Design code for an Asymmetric Reluctance Machine structural and thermal analysis will be completed.	Pending
BP3-Q4	Go / No-Go	Pareto optimal fronts will be demonstrated to have converged.	Pending

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

Summary

Design Tools & Methods

- A MoM-based toolbox for PMSMs was finalized and made publicly available at no charge. The MoM approach was then extended to develop design tools for alternative machine topologies.
- An analytical method of computing sleeve stress for non axis-symmetric PMAC machines was developed and integrated into a PMAC design code.

Novel Machines

- A Dual field homopolar ac machine concept has been invented and appears promising. It is a machine with sinusoidal voltages and currents, constant torque, and has an infinite constant power speed range. It can be constructed with a field winding, a rotating permanent magnet, or a stationary permanent magnet for a field.
- Design codes for inert-core permanent-magnet ac machines and a rotationally asymmetric reluctance machine have been developed. These machines also appear promising.