Design, Optimization, and Control of a 100-kW Electric Traction Motor Meeting or Exceeding DOE 2025 Targets

2021 DOE Annual Merit Review

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Project ID: elt250

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Overview

Timeline

- Start Date: 4/1/19
- End Date: 3/28/24
- Percent Complete: 40%

Budget

- Total project funding
  - DOE’s Share: $1,500,000
  - Partner’s Cost Share: $200,033
- BP1&2 DOE Funding: $600,000

Barriers

- Despite intensive research efforts the cost of electric traction motors has not fallen sufficiently
- The price of fundamental materials (i.e. steel, copper) is unlikely to substantially decrease
- Holistic approach is needed considering design, materials, cooling, and controls

Project Partners

- Illinois Institute of Technology
- EDT National Laboratories
- Nine Other Universities

Relevance

- USDRIVE set aggressive targets for electric traction motors

USDRIVE Electric Motor Targets			
Year	2020	2025	Change
Cost ($/kW)	4.7	3.3	30% cost reduction
Power Density (kW/l)	5.7	50	89% volume reduction

- The research proposed directly addresses cost and power density targets through
  - Higher speeds
  - Improved material utilization and design approaches
  - Increased slot fills
  - Aggressive cooling

- Multiple reduced scale prototypes and one full scale 100 kW prototype will demonstrate progress towards the USDRIVE targets

Milestones

BP2 Milestones (4/1/20 – 3/30/21)

Milestone	Type	Description	Status
Demonstration of core loss minimization through optimization	Technical	Rotor optimization tools extended to minimize stator core loss through rotor material distribution and flux shaping	Complete
Structural compliance integrated into dimensional optimization tool	Technical	Demonstrate combined electromagnetic, thermal, and structural compliance dimensional co-optimization	Complete
Dynamometer testing of BP1 reduced scale electric traction motor prototype	Technical	Dynamometer testing of BP1 reduced scale electric traction motor prototype matches finite element predicted torque within 15% to validate optimization tools	On-going
Design of BP2 reduced scale prototype	Technical	Design of BP2 reduced scale electric traction motor prototype complete to validate optimization tools developed in BP2 and previous BP	Complete
Design study for 2nd generation 100 kW electric traction motor	Go/No Go	Electromagnetic and structural finite element analysis of 100 kW electric traction motor design demonstrates a volumetric power density of 20 kW/l of active materials with winding (and/or magnet) temperatures remaining within material limits estimated by lumped parameter thermal modeling	Complete

BP3 Milestones (4/1/21 – 3/30/22)

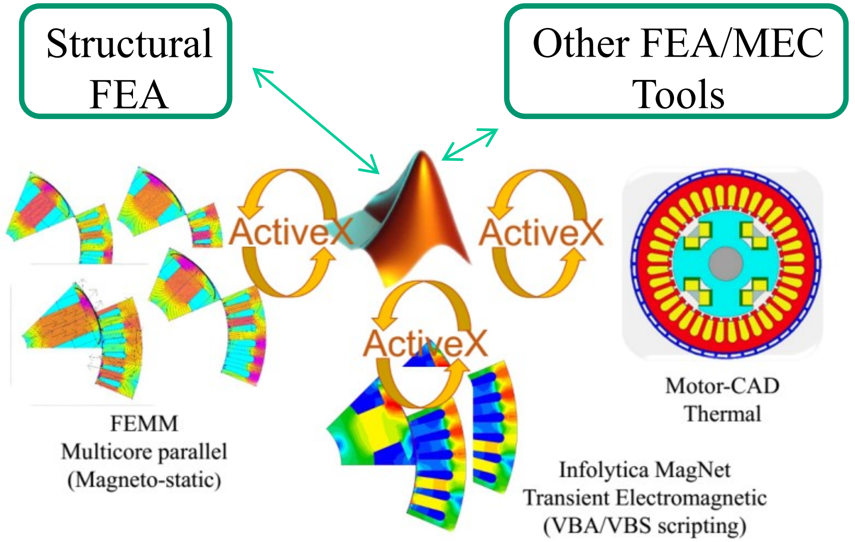
Milestone	Type	Description
Dimensional co-optimization including NVH	Technical	Combined electromagnetic, thermal, structural compliance and noise vibration and harshness (NVH) dimensional co-optimization tool demonstrated
High performance torque and flux regulation demonstration	Technical	High performance torque and flux regulation experimentally demonstrated on reduced scale prototype at high speed
Dynamometer testing of reduced scale electric traction motor prototype	Technical	Dynamometer testing of reduced scale electric traction motor prototype matches finite element predicted torque within 15% to validate optimization tools
Design of BP3 reduced scale prototype	Technical	Design of BP3 reduced scale electric traction motor prototype complete to validate optimization tools developed in BP3 and previous BPs
Design study for 3rd generation 100 kW electric traction motor	Go/No Go	Electromagnetic and structural finite element analysis of 100 kW electric traction motor design demonstrates a volumetric power density of 30 kW/l of active materials with winding (and/or magnet) temperatures remaining within material limits estimated by lumped parameter thermal modeling

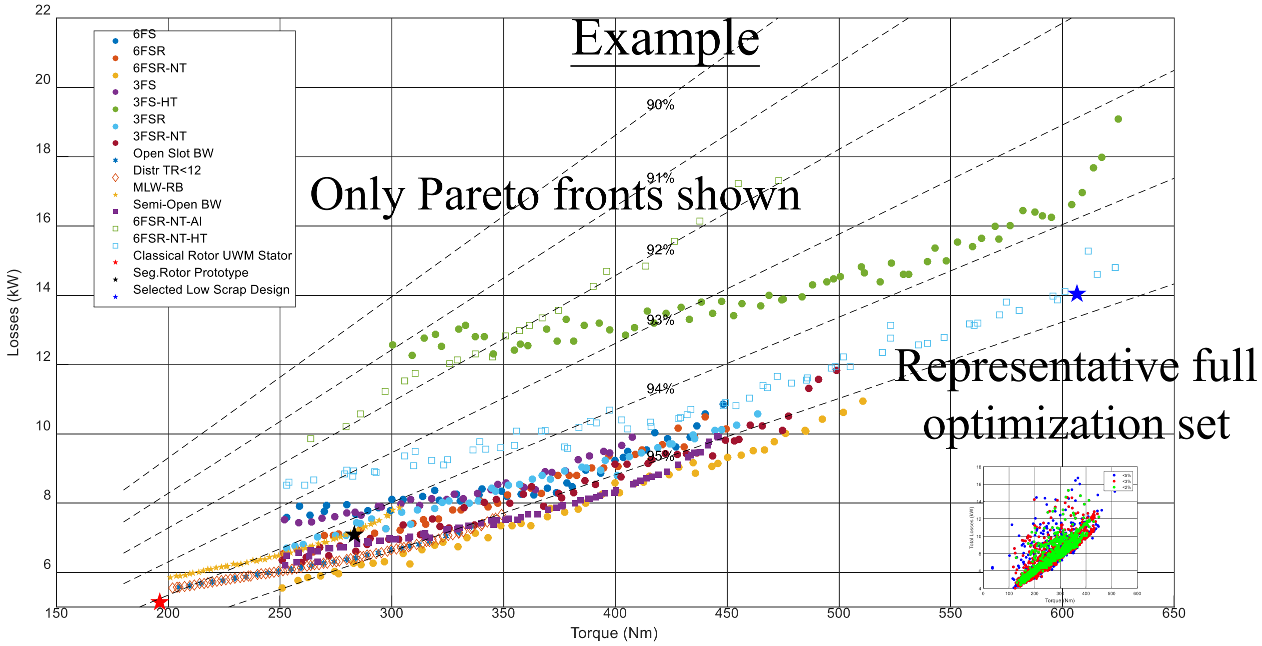
Approach – Major Overall Research Thrusts

- **Multiphysics design**
  - Improved dimensional or shape optimization tools
  - Topological optimization
- **High slot fill windings**
  - Die compressed windings
  - Bar/hairpin
  - Cast windings
- **Winding/MMF optimization and synthesis**
- **Support thermal management of electric traction motors**
- **Design, construction, and testing of prototype traction motors**
  - High speed IPMSM
  - Medium speed, high pole count, transverse flux machine or other exotic machines

Approach – Multiphysics Optimization

- Common approach: perform a purely electromagnetic optimization using a geometric template, down-select a design, and check the estimated drive cycle temperatures and structural integrity. If the design does not pass the temperature and integrity checks iterate, i.e. sequential optimization
- Dimensional optimization goal: Simultaneously address electromagnetic, structural, and thermal design in a computationally efficient manner using a geometric template
- Integrated FEA and lumped equivalent circuit solvers, geometric template engines, and optimizers
- Large scale design studies with Pareto front comparisons for design of initial prototype topologies

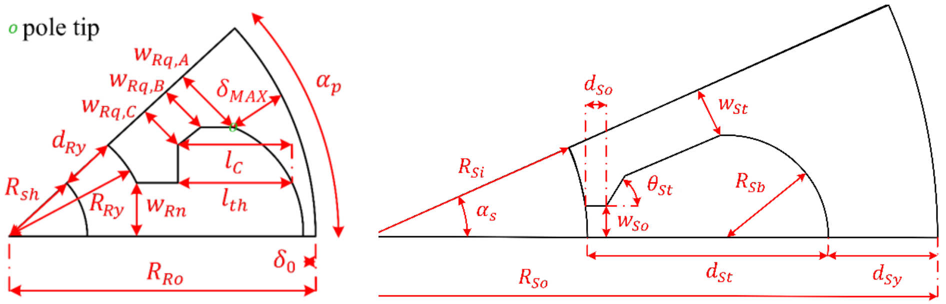


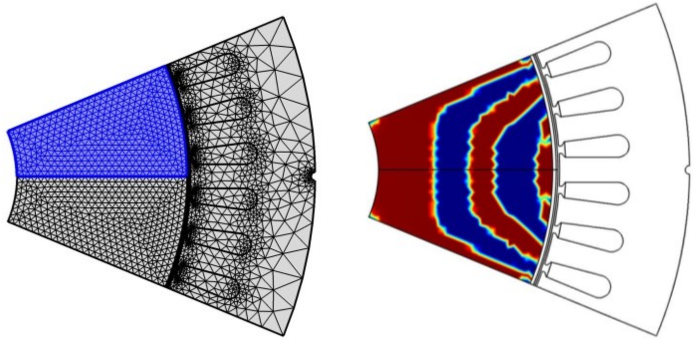


Approach – Multiphysics Optimization

- Design without geometric template or combined with dimensional optimization
- Optimally distribute materials in a design domain
- Small features difficult to build into a template
- Goals for topology optimization of electric motors:
  - Simultaneous structural and electromagnetic topological optimization
  - Develop combined topological optimization techniques for IPMs
    - Embedded magnets can move or change dimensions
    - Maintain rectangular profile for low cost
  - Create and shape flux barriers and iron for core loss reduction
  - Optimally shape thermal cooling channels
- Example: Electromagnetic topology optimization of synchronous reluctance machine rotor

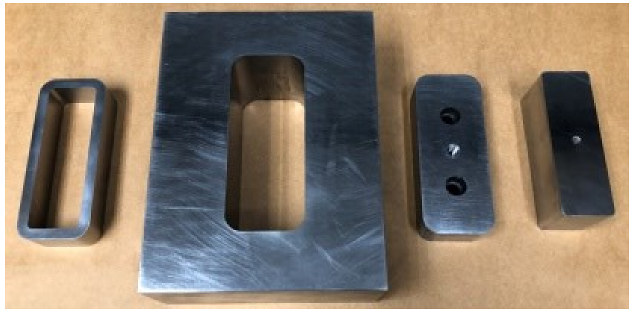
<u>Example Geometric Templates</u>





Approach – High Slot Fill Windings

- Increased current loading, A, or increased efficiency, η
- Die compressed windings
  - First introduced by A. G. Jack *et al.*, “Permanent magnet machines with powdered iron cores and pre-pressed windings,” in *Conference Record of the 1999 IEEE Industry Applications Conference*, 1999, pp. 97–103.
  - Currently require concentrated winding
  - Example from another past DOE project; field winding of wound field synchronous machine



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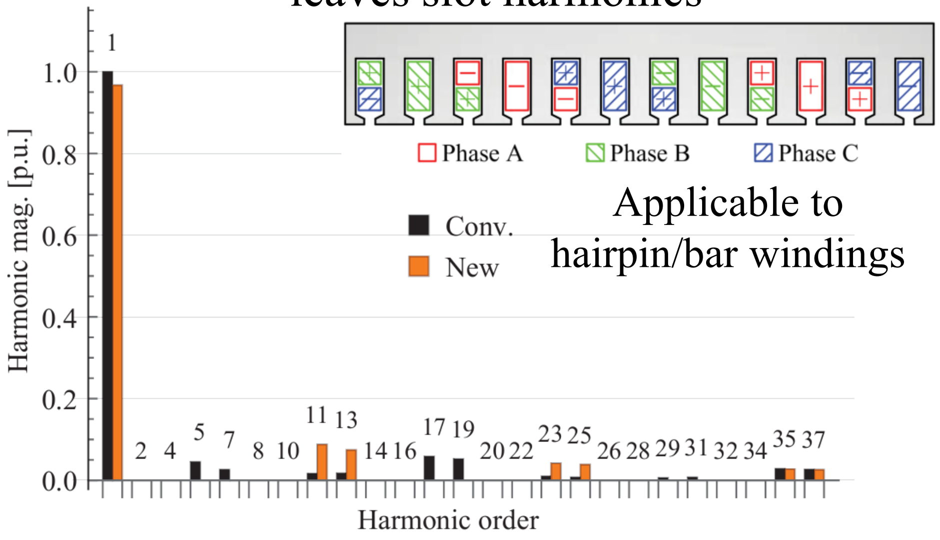
- Cast windings – Potentially low cost and able to tolerate high temperatures – potential for very high slot fills
- Bar/hairpin windings with reduced skin and proximity losses

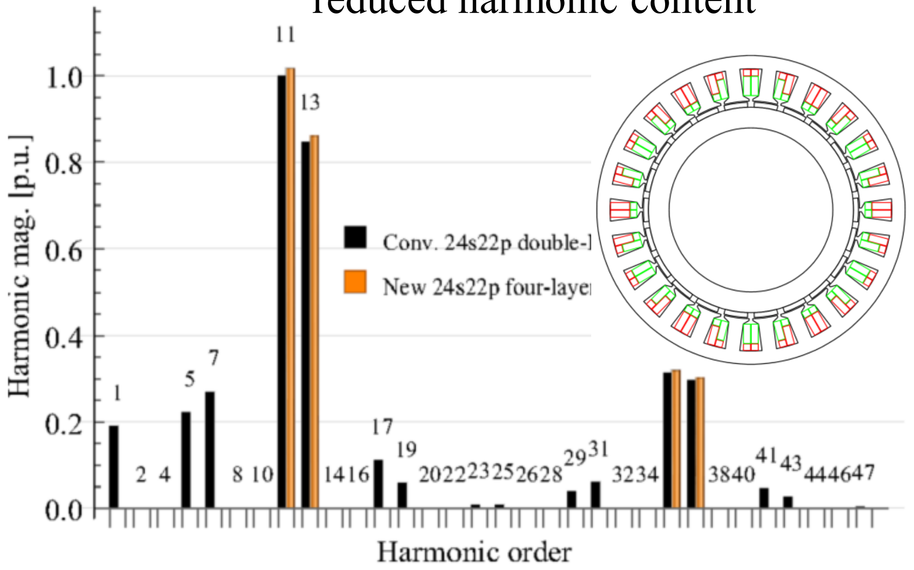
Approach – Winding/MMF Optimization and Synthesis

- Average torque production, eddy current losses **(η),** torque ripple, and NVH depend on the winding/MMF harmonics
- Optimize windings/IPM rotors to reduce or eliminate certain unwanted space harmonics
- Ideally synthesize a feasible winding from a harmonic spectrum

Example mixed layer winding which only leaves slot harmonics



Example 24-slot, 22-pole, 4 layer FSCW with reduced harmonic content

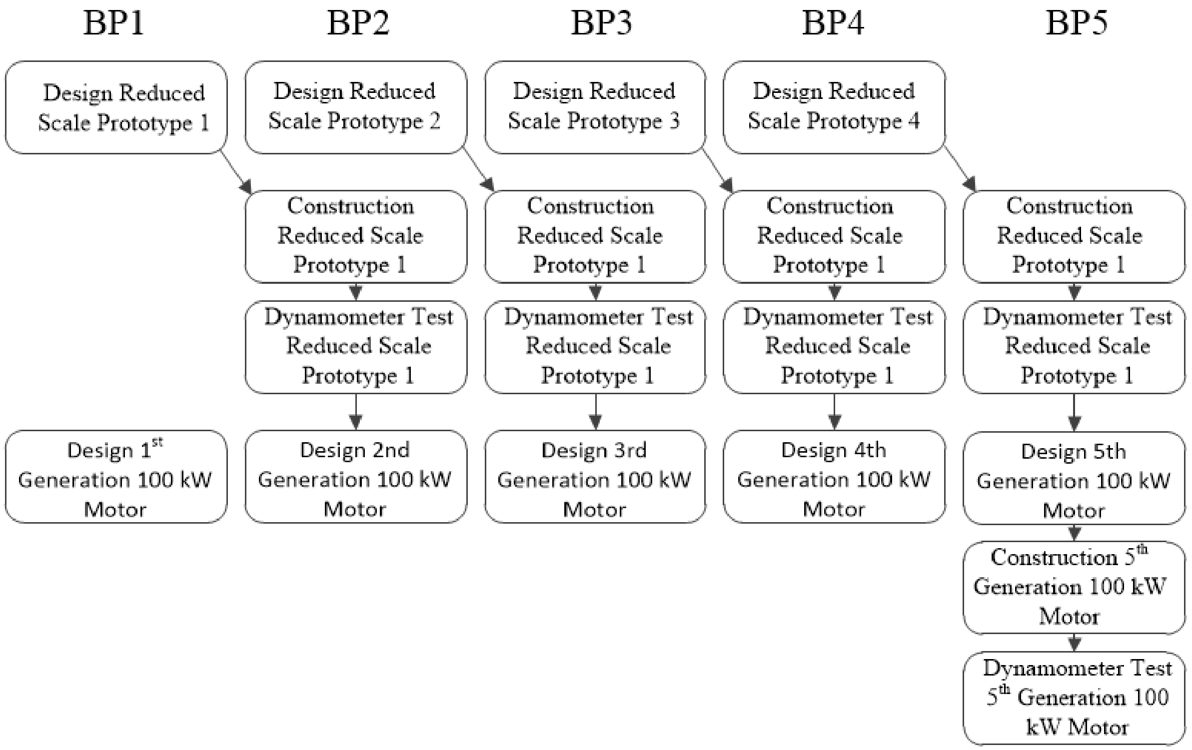


Approach – Support Thermal Management

- Calibration of thermal models, including oil spray cooling in prototype reduced scale motors
- Investigate high slot fill windings with through conductor cooling
- Investigate topological optimization of cooling channels in laminations/shell (e.g. heat transfer and pressure drop)
- System identification of machine thermal equivalent circuit networks from limited temperature sensors
  - Useful for loss minimizing and electro-thermal control
- Investigate aggressive cooling strategies for windings and magnets, e.g. pool boiling

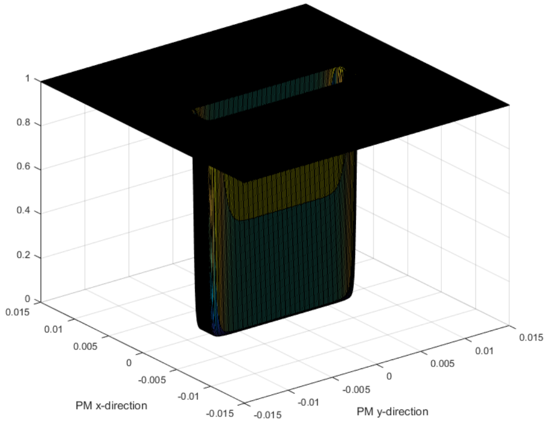
Approach – Design, Construction, and Testing of Prototype Traction Motors

- Apply new technologies, concepts, materials, and learnings in reduced order prototypes
- Incremental planned prototype building and testing schedule

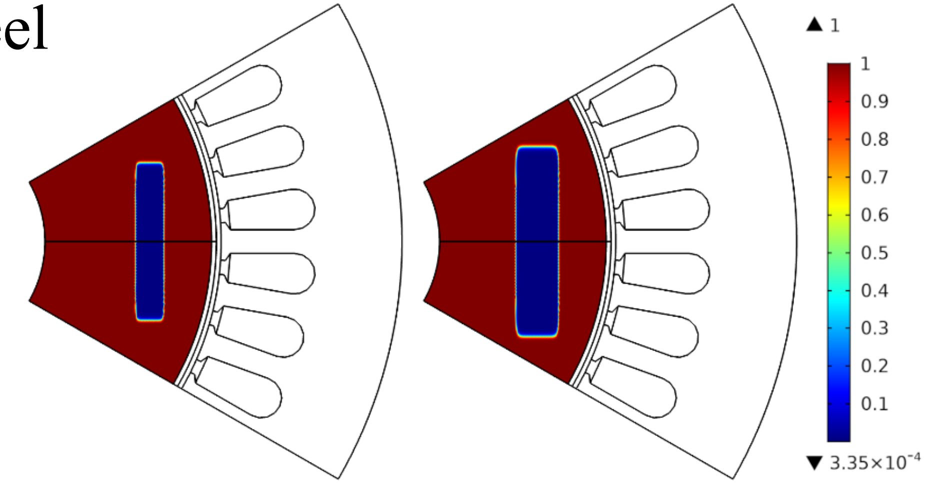


Technical Accomplishments – New Magneto-Structural Combined Dimensional and Topology Optimization Method

- Previously developed magneto-structural combined dimensional and topology optimization method used mesh deformation to displace or change size the dimensional optimization regions, i.e. block magnets
- New method projects or interpolates PM from a function onto the mesh
- PM can move or change size without deforming the mesh while topology optimization proceeds in the surrounding electrical steel



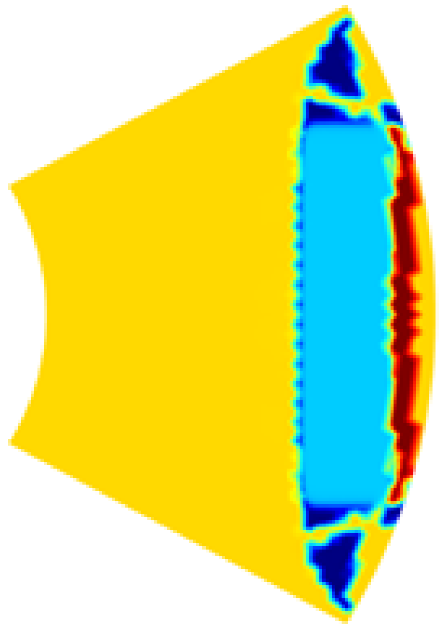
Smoothed Heaviside PM function



Projected PM onto mesh with a size change to the PM

Technical Accomplishments – New Magneto-Structural Combined Dimensional and Topology Optimization Method

- PM structural loads are mapped as pressures to the first layer of iron elements



Electrical steel (yellow), PM (light blue), and electrical steel elements with pressure loads (red) distributions.

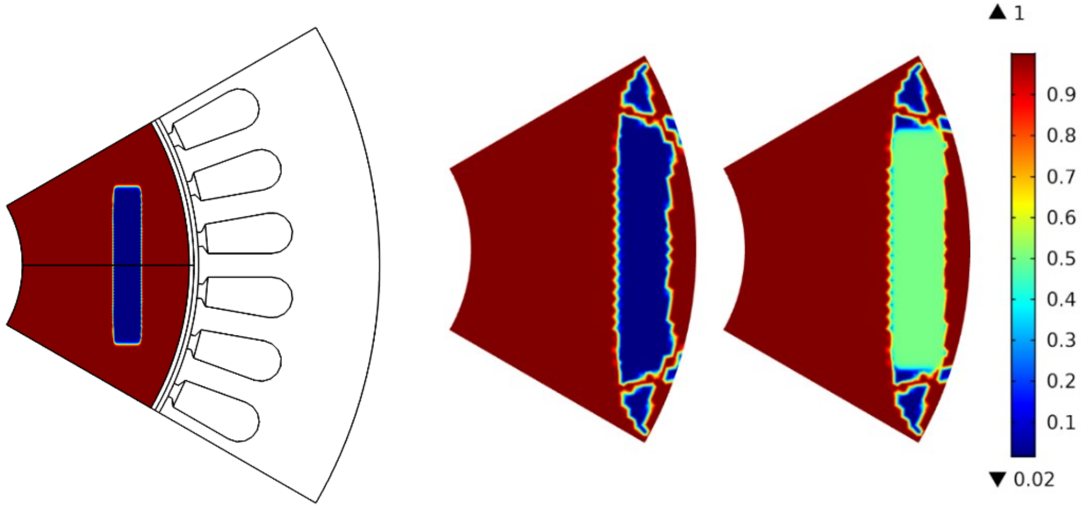
- Example optimization

$$\min \ f = -T_{avg}$$

$$s.t. \quad g_1 = T_{ripple} = T_{\max} - T_{\min} \leq 10\% T_{avg}$$

$$g_2 = Compliance \leq C_0$$

$$g_3 = Agg.\,Von\ Mises\ Stress,\ \sigma_{PN} \leq 80\%\ \sigma_{yield}$$

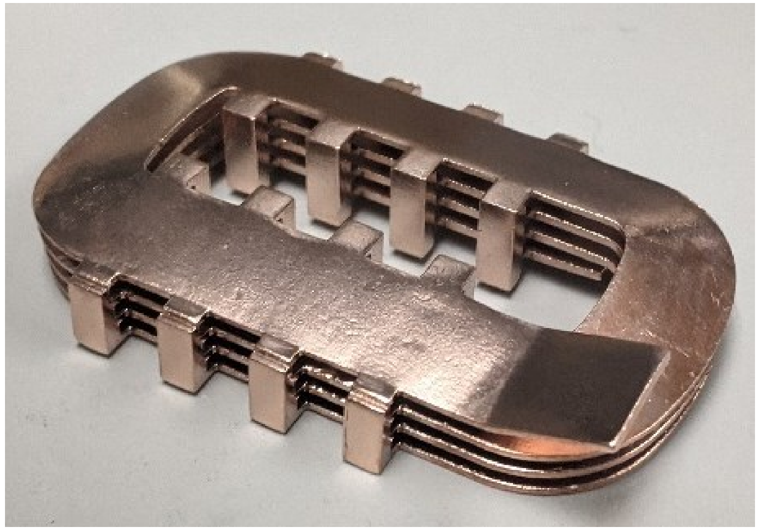


Initial PM size, location, and solid iron distribution

Optimized PM size, location, and iron distribution

Technical Accomplishments – Cast & Additively Manufactured Copper Coils

- Cast or additively manufactured copper coils for increased slot fills – target 80% or greater slot fill
- Lost wax casting process; along with other casting processes should be compatible with high volume manufacturing
- Binder jet additive manufacturing may become cost competitive



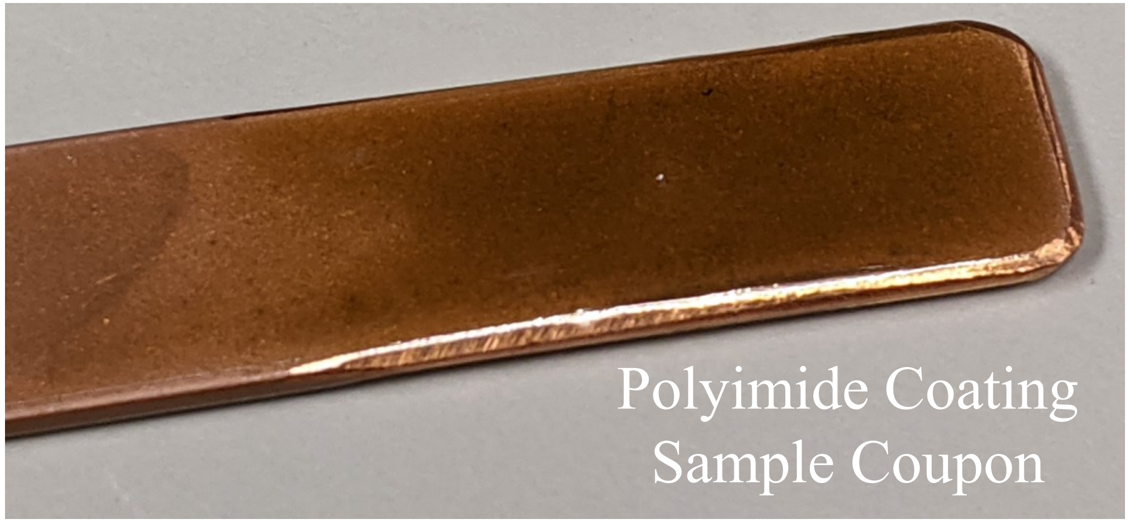
Cast coil with casting features

Cast coil prior to insulation

Additively manufactured coil prior to insulation

Technical Accomplishments – Insulating Cast Coils

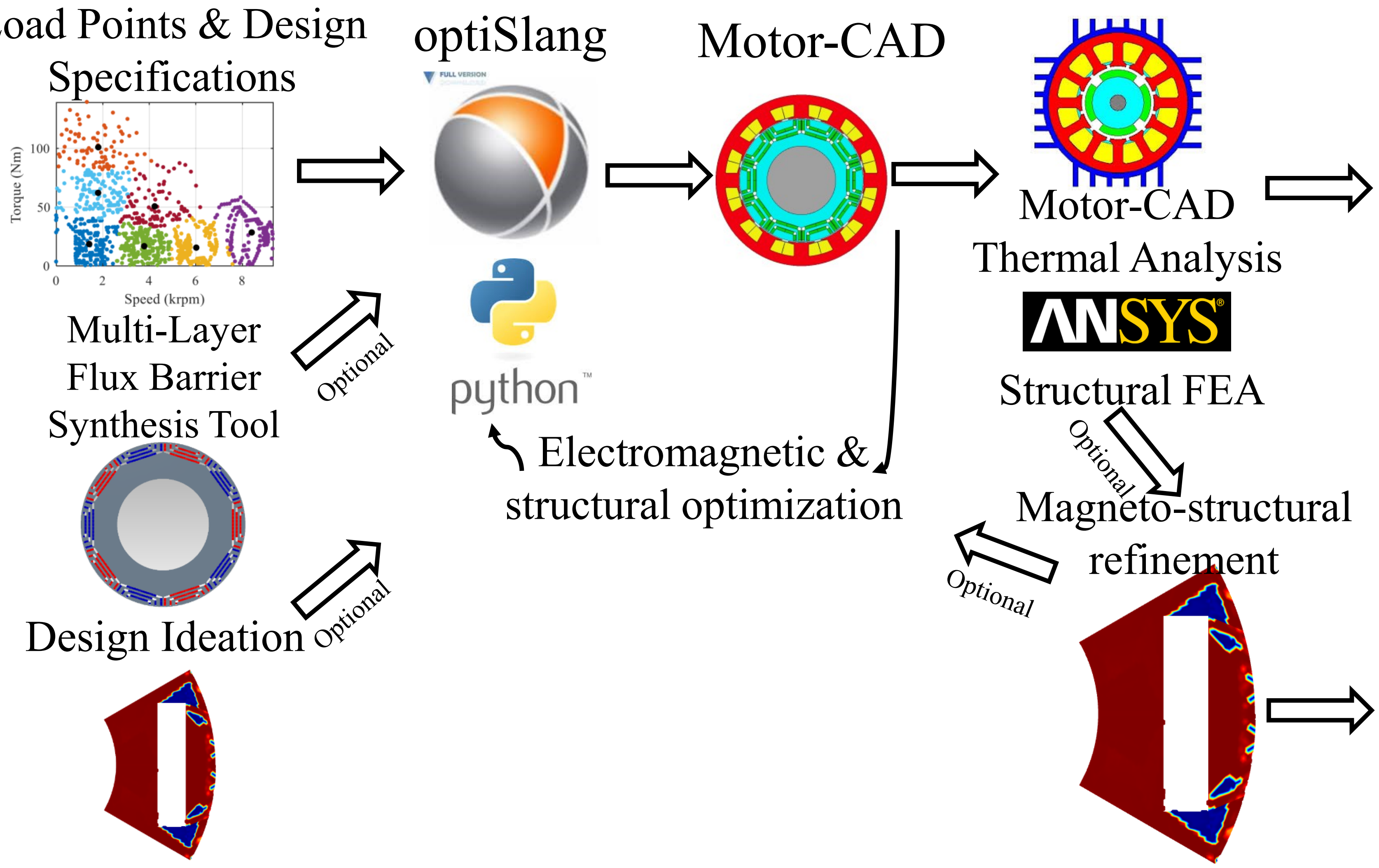
- The cast or additively manufactured coils require turn to turn insulation
- Depositing a thin even polyimide film on all surfaces using a dipping process
  - Polyimide film is high temperature (~+260 Deg. C.) and high dielectric strength
- Challenging to get even coverage on the edges
- Different solvent dilution levels, drying, and imidization temperature and time profiles
- Homemade oven with dual axis rotation to try to avoid pooling
- Additives to improve edge coverage with minimal impact on desirable temperature and dielectric properties



Polyimide Coating
Sample Coupon

Technical Accomplishments – Multiphysics Design Optimization

- Multiphysics design tool flow expanded for drive cycle optimization



Collaboration and Coordination with Other Institutions

- Regular monthly teleconference with EDT electric traction motor teams organized by ORNL
- Discussions with Sandia National labs regarding soft magnetic materials and additive manufacturing of them

Proposed Future Research

- Continue work on high slot fill windings including low AC loss versions
- Further incorporate magneto-structural combined dimensional and topology optimization into overall drive cycle optimization
- Incorporate NVH minimization into the optimization flow
- Investigate novel thermal management technologies
- Dynamometer testing of reduced power prototypes

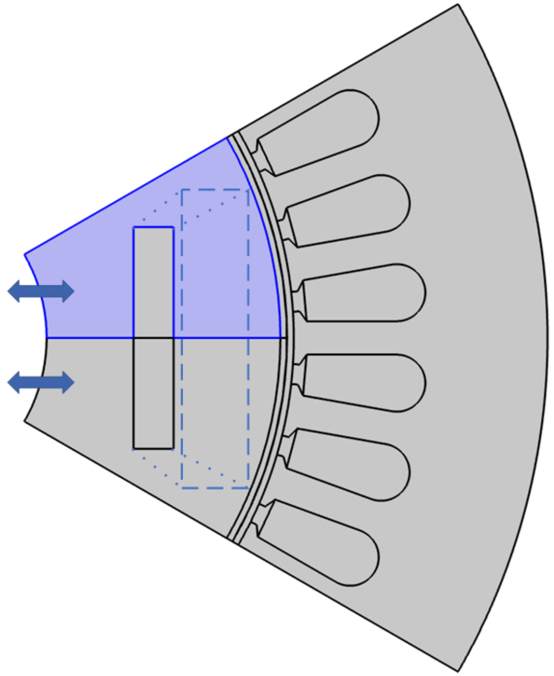
Summary

- Relevance
  - Cost of electric traction motors has not fallen sufficiently
  - Holistic approach is needed considering design, materials, cooling, and controls
- Approach
  - Multiphysics design including combined topology and dimensional optimization
  - High slot fill windings
  - Winding/MMF optimization and synthesis
  - Support thermal management
  - Design, construction, and testing of prototype traction motors
- Technical Accomplishments
  - Combined magneto-structural dimensional and topology optimization of IPMSM rotors without mesh deformation
  - Cast winding with polyimide insulation coatings
- Future Work
  - Extend the work on high slot fill winding to reduce AC losses
  - Further extend optimization tools to include NVH
  - Build and test reduced scale prototype incorporating research from BP2

Technical Back-Up Slides

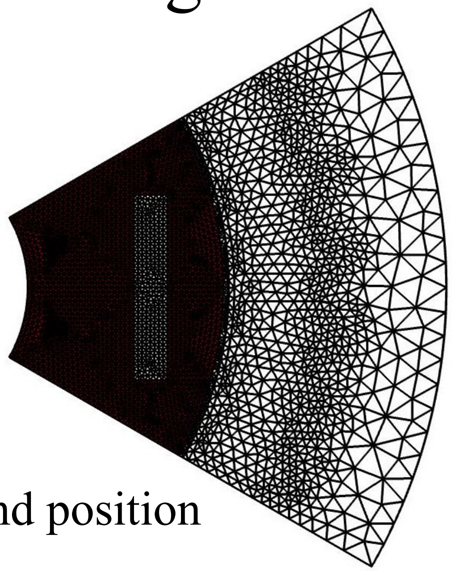
Previous Technical Accomplishments – Combined Dimensional and Topology Optimization

- Combined dimensional and topology optimization of IPMSM
  - To keep PM in a block shape that is easy for manufacturing but vary its size and position
  - Topology optimization on the rest of the rotor to find optimal electrical steel layout
  - Magneto-structural topology optimization to simultaneously consider structural aspects
- Introduce four global control variables:
  - PM position in x-direction
  - x-axis dimension of PM
  - y-axis dimension of PM
  - Shaft dimension

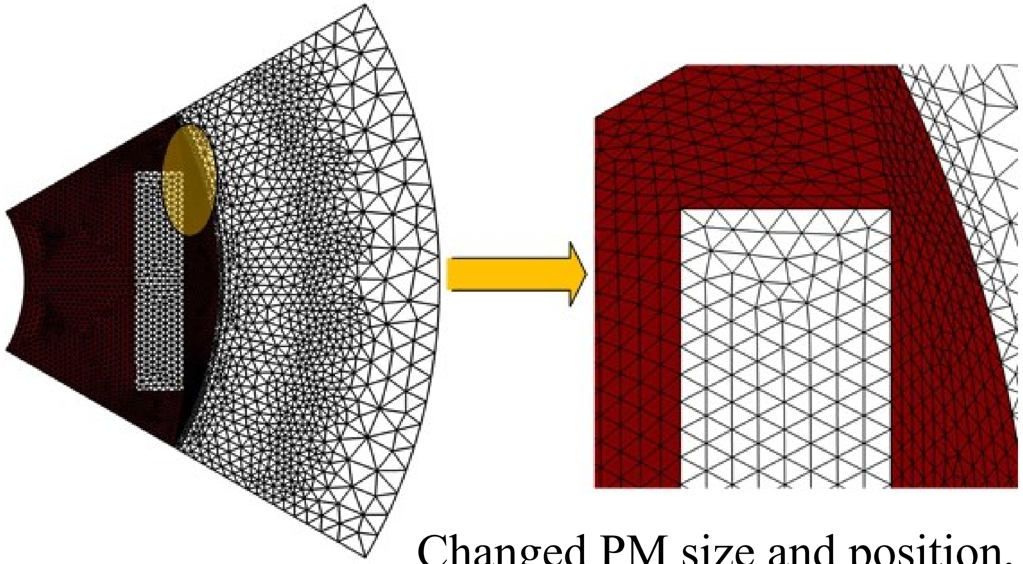


Previous Technical Accomplishments – Mesh Deformation

- The shape of design domain is deformed when PM size/position changed
- To incorporate dimensional optimization with density-based topology optimization, mesh deformation technique is adopted to keep the number of mesh elements and numbering consistent
- Laplace's smoothing technique is used in sub-domains to enhance mesh deformation for greater dimensional variation



Original PM size and position



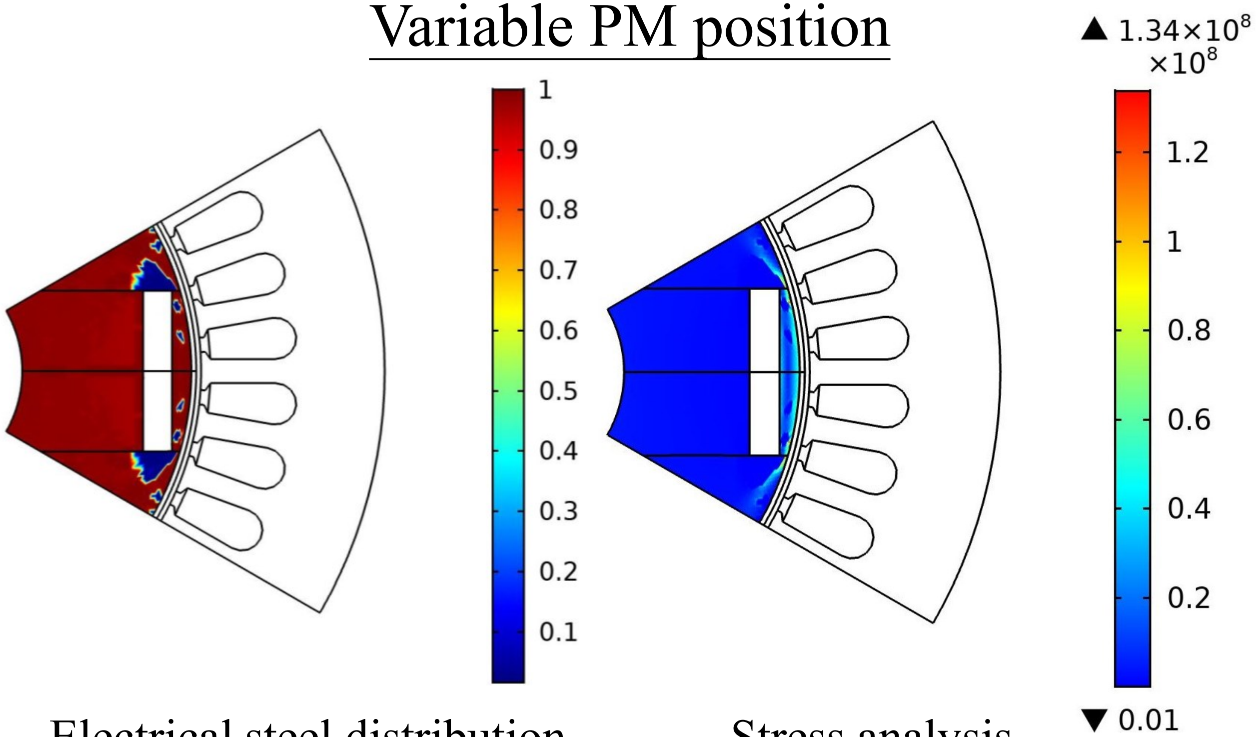
Changed PM size and position, deformed mesh

Previous Technical Accomplishments – Magneto-Structural Combined Dimensional and Topology Optimization of IPMSM Rotors

- Combined dimensional and magneto-structural topology optimization of IPMSM is working with flat bar magnets:

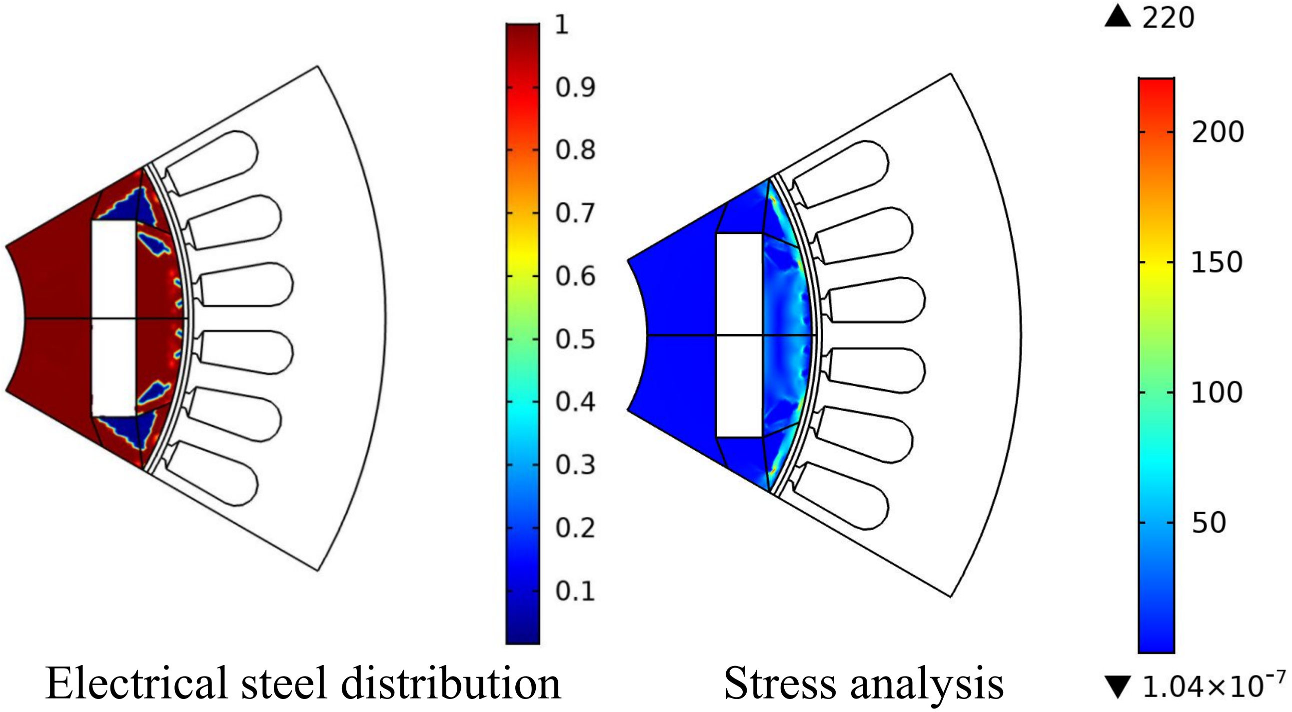
$$\text{min. f} = -T_{avg} = -\frac{1}{N}\sum_{\theta=0}^{N} T_\theta \ \text{ s.t. } g_1 = T_{ripple} < 10\%\, T_{avg},\ g_2 = \mathrm{C} < C_0,\ g_3 = \sigma_{PN} < k_{sf}\sigma_{yield}$$

Variable PM position



Electrical steel distribution Stress analysis

Variable PM position and size



Electrical steel distribution Stress analysis

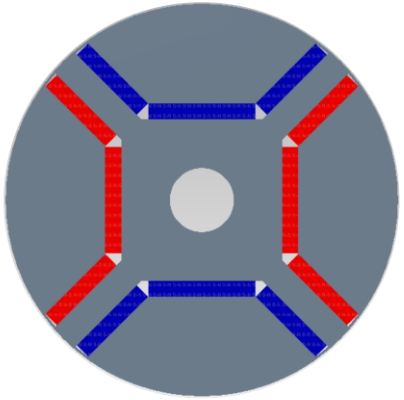
Previous Technical Accomplishments – Multi-Layer IPM Rotor Synthesis Tool Based on Desired Airgap Flux Density Harmonics

Features:

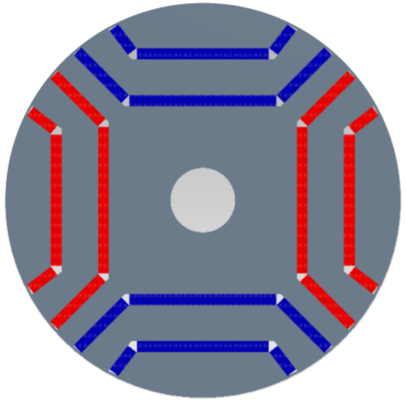
- Direct shaping of airgap magnetic field produced by the rotor, degrees of freedom = 2 × number of layers
- Variable number of poles and great dimensional flexibility: 9 parameters per layer, and each layer varies independently
- Excel VBA for interactively loading design parameters and organizing simulation results

Benefits:

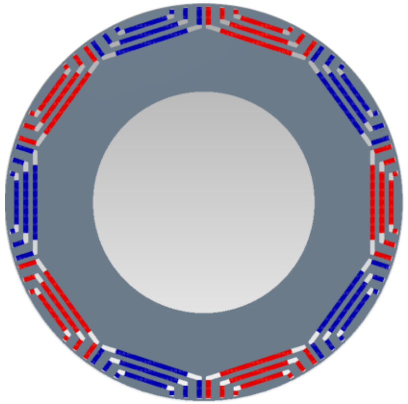
- Rotor magnetic field profiled in coordination with stator winding to minimize unwanted harmonic interaction and reduce power losses
- Less torque ripple and smoother power output
- Higher airgap flux density and better resistance to demagnetization



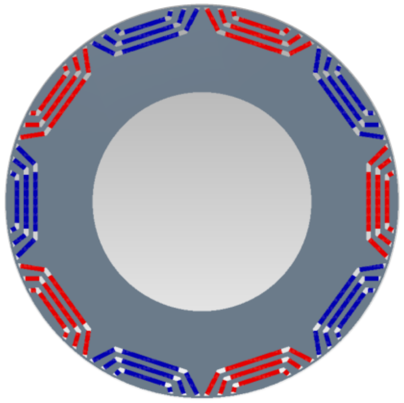
4-pole, 1-layer



4-pole, 2-layer



10-pole, 3-layer
parallel side pieces



10-pole, 3-layer
skewed side pieces