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

2020 DOE Annual Merit Review

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Illinois Institute of Technology

Project ID: elt250

Overview

Timeline

- Start Date: 4/1/19
- End Date:3/28/24
- Percent Complete: 20%

Budget

- Total project funding
  - DOE’s Share: $1,500,000
  - Partner’s Cost Share: $200,033
- BP1 DOE Funding: $300,000

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

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

Milestones

BP1 Milestones (4/1/19 – 3/30/20)

Milestone	Type	Description	Status
Initial electric traction motor topologies down selected	Technical	Down selection of topologies (e.g. radial flux V-IPMSM, transverse flux soft magnetic composite, etc.) for dimensional and topological optimization completed	Complete
Demonstration of combined electromagnetic and structural topological optimization	Technical	Combined electromagnetic and structural topological optimization demonstrated to optimally distribute rotor iron in high speed (>= 15,000 RPM) synchronous reluctance or interior permanent magnet synchronous machines	Complete
Space harmonic reduction in fractional slot concentrated windings	Technical	Example fractional slot concentrated windings with multiple subsets distribution for reduced space harmonic content demonstrated	Complete
Design of BP1 reduced scale prototypes	Technical	Design of BP1 reduced scale electric traction motor prototype complete to validate optimization tools developed in BP1	Complete
Design study for 1st 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 10 kW/l of active materials with winding (and/or magnet) temperatures remaining within material limits estimated by lumped parameter thermal modeling	Complete

BP2 Milestones (4/1/20 – 3/30/21)

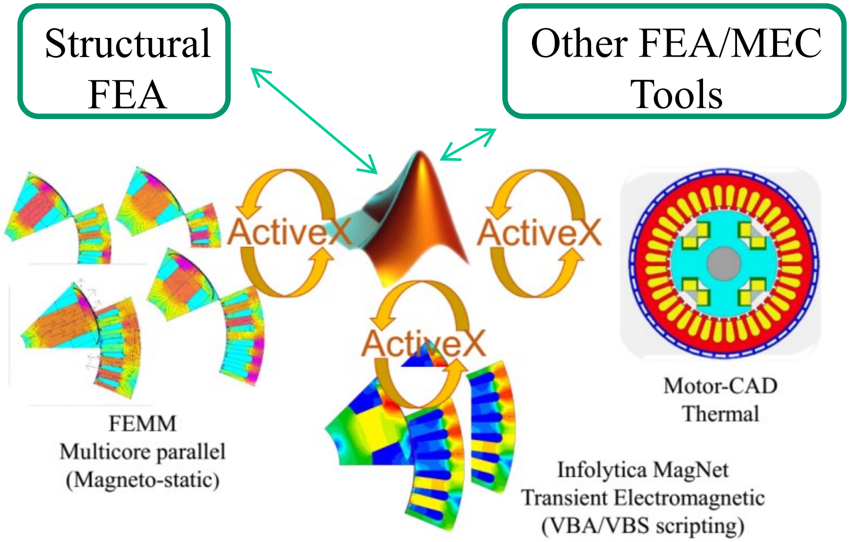
Milestone	Type	Description
Demonstration of core loss minimization through optimization	Technical	Rotor optimization tools extended to minimize stator core loss through rotor material distribution and flux shaping
Structural compliance integrated into dimensional optimization tool	Technical	Demonstrate combined electromagnetic, thermal, and structural compliance dimensional co-optimization
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
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
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

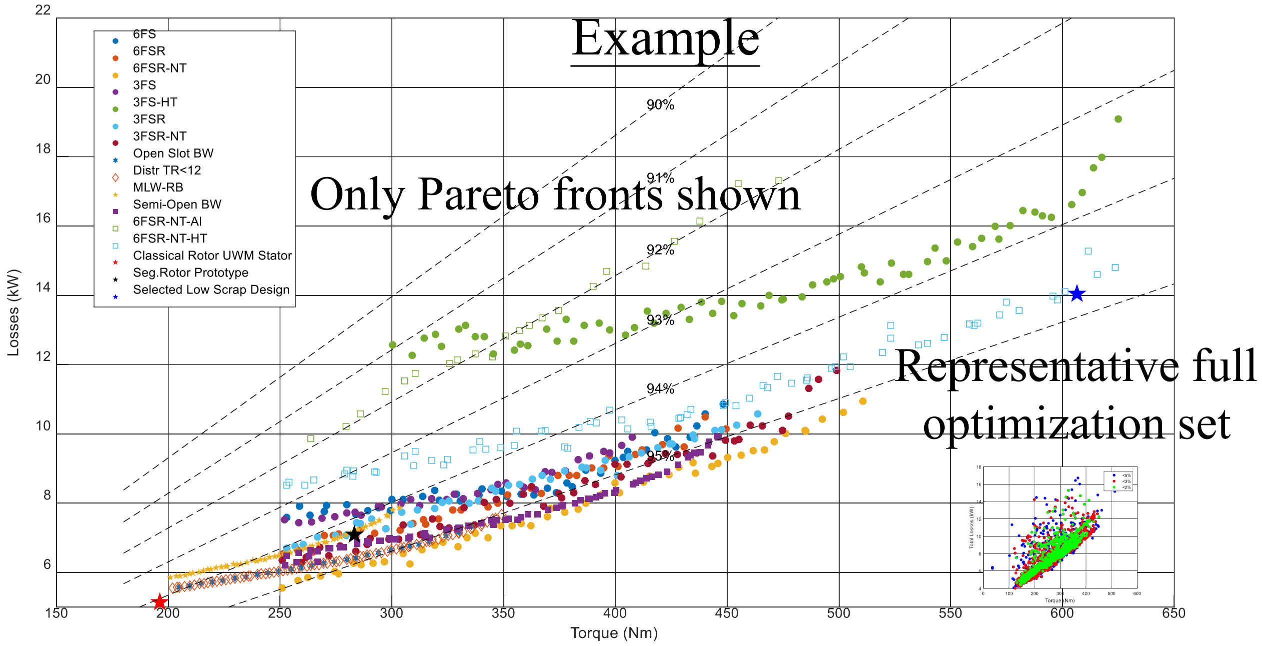
Approach – Major Research Thrusts

- **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

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

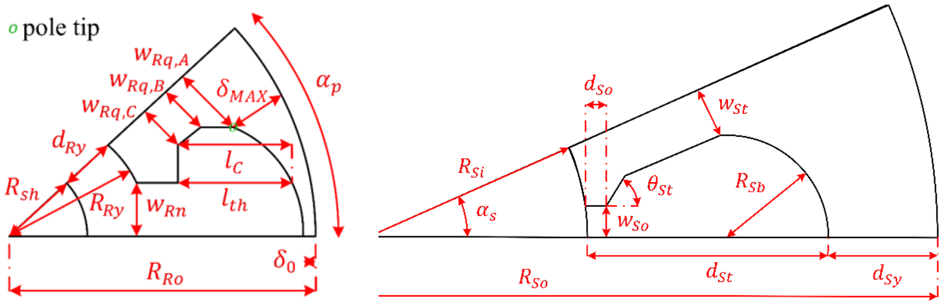


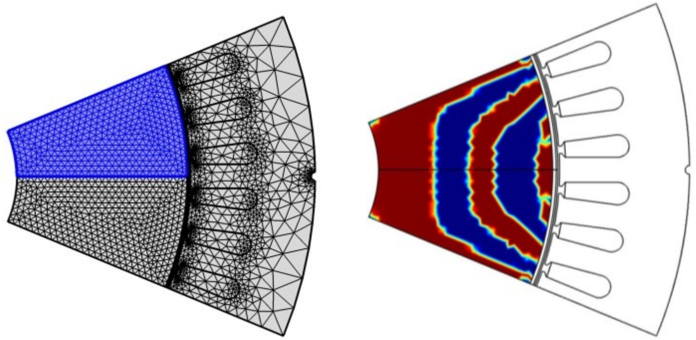


Approach – Multiphysics Optimization

- 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

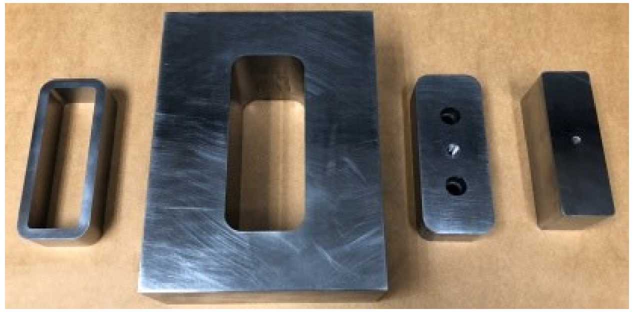
Example Geometric Templates





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

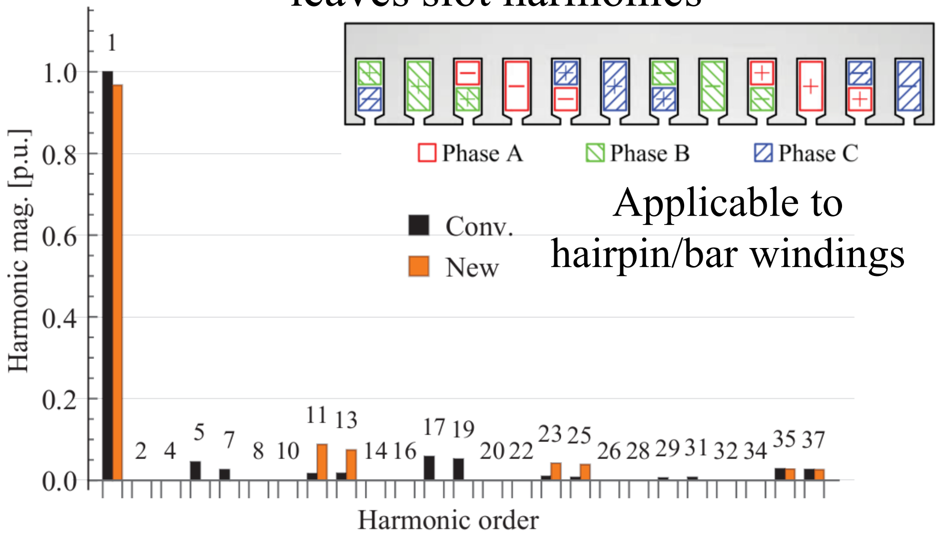


- Cast windings – Potentially low cost and able to tolerate high temperatures – potential for enhanced heat transfer surfaces
- Bar/hairpin windings with reduced skin and proximity losses

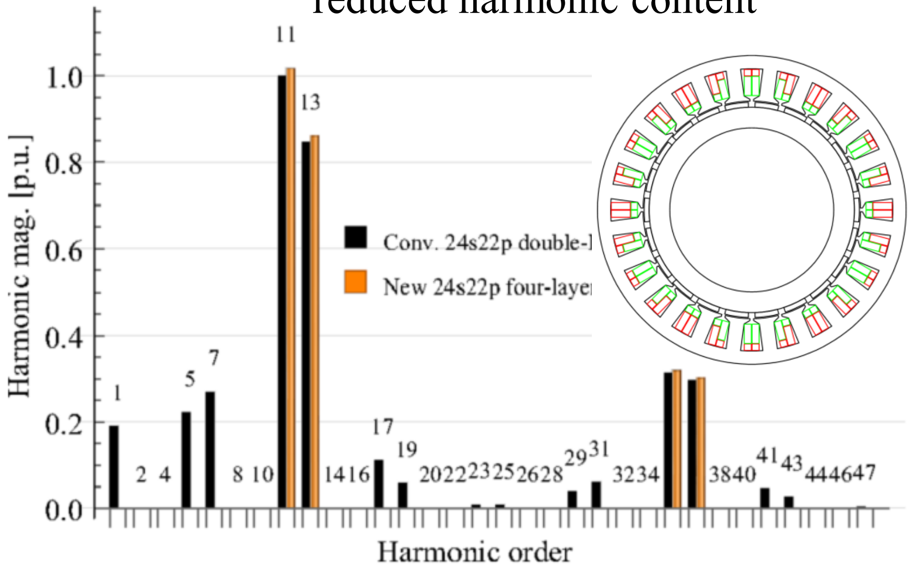
Approach – Winding/MMF Optimization and Synthesis

- 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

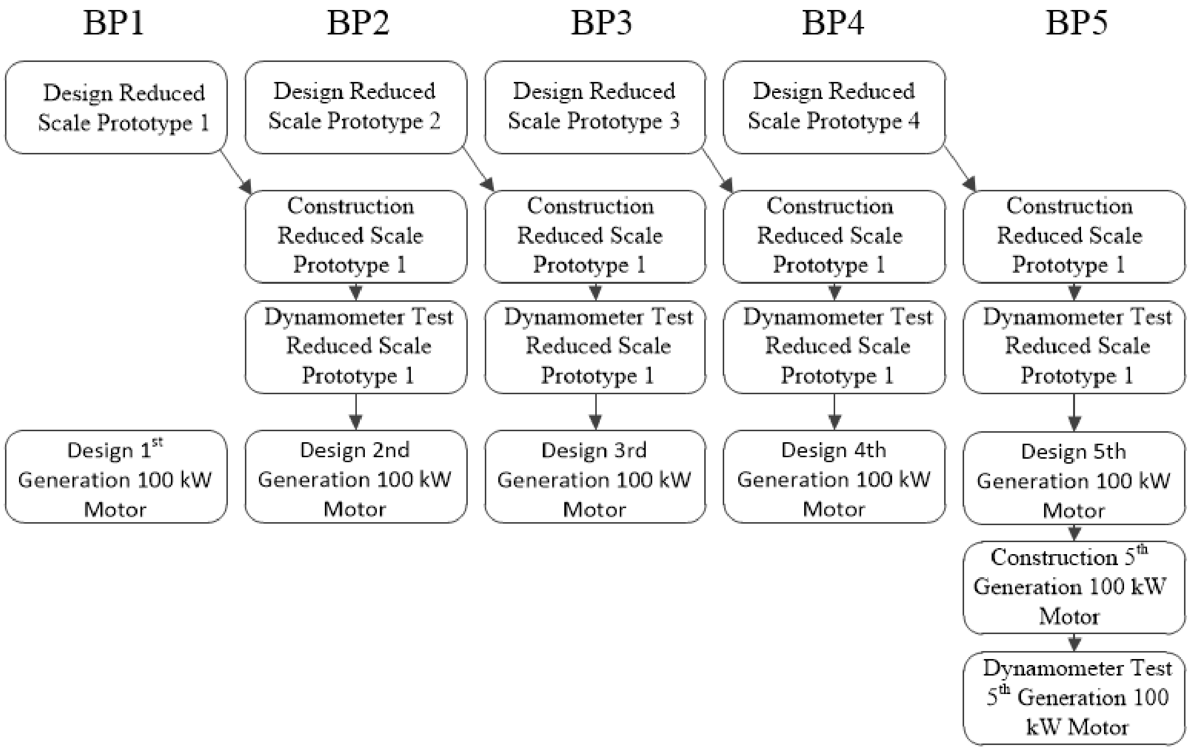


Approach – Support Thermal Management

- 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

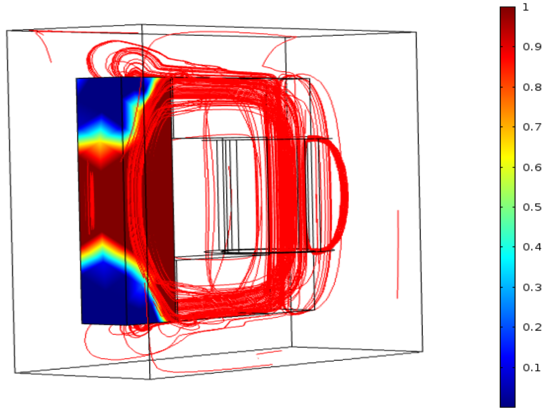
Approach – Design, Construction, and Testing of Prototype Traction Motors

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



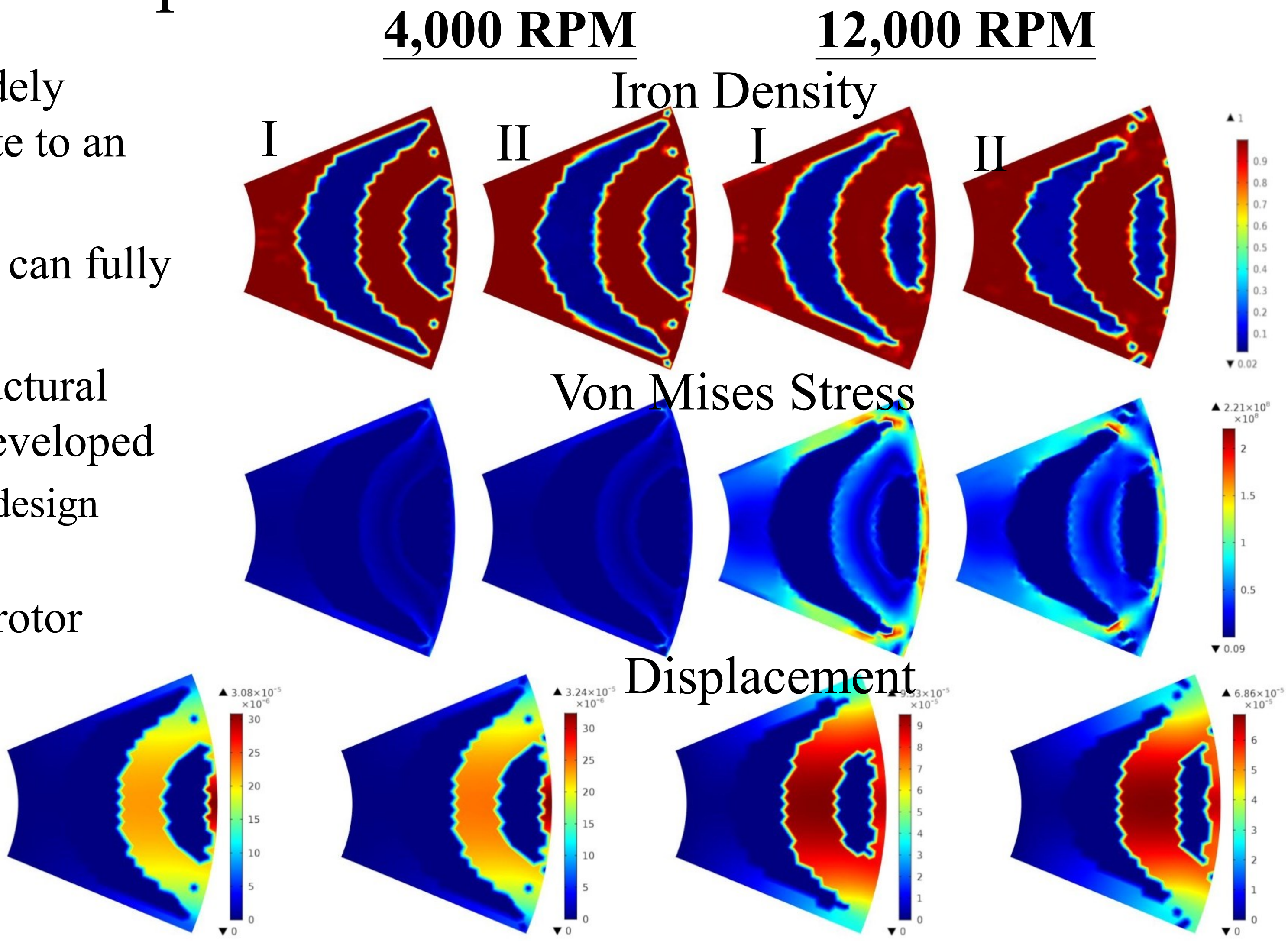
Approach – Initial Machine Configurations To Be Investigated

- IPMSMs – BP1 & BP2
  - Heavy rare earth free permanent magnets
  - Magneto-structural topology optimization of rotor
  - Winding and rotor MMFs synthesized to maximize average torque, minimize core losses, torque ripple, etc.
  - High slot fill winding (bar/hairpin, die compressed, cast, needle wound)
- Transverse Flux Machine – BP2
  - High torque density through high electrical loading
  - High pole number traditionally led to low speed operation
    - Utilize new low core loss magnetic materials
    - WBG power converters can produce high frequency fundamental
  - Reduce armature reactance and increase power factor through 3D optimization



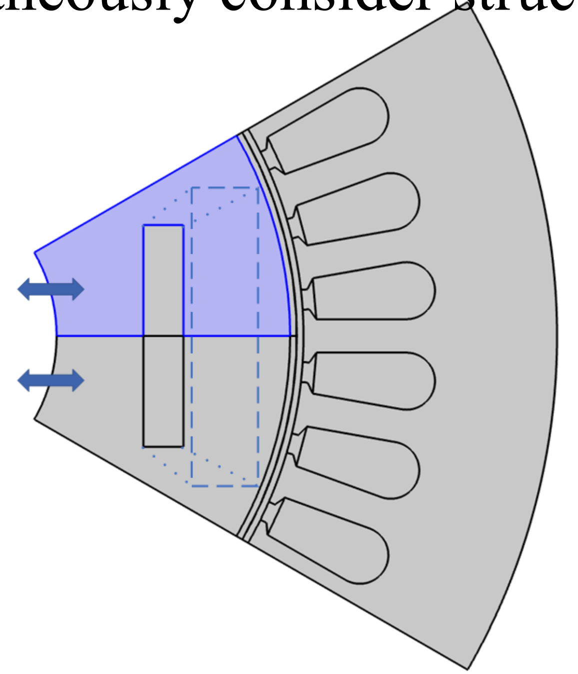
Technical Accomplishments – Combined Magneto-Structural Topology Rotor Optimization

- Magnetic and structural optimization is widely performed by coupling a geometric template to an optimization and FEA/MEC solver
- Creating robust geometric templates which can fully explore a design space is difficult
- A technique for simultaneous magneto-structural topology optimization of rotors has been developed
  - Optimum material distribution in the rotor design domain
- Example synchronous reluctance machine rotor magneto-structural topology optimization
  - Two optimization formulations I & II



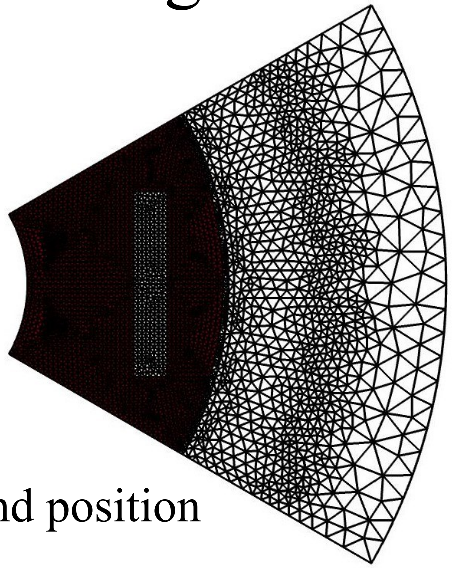
Technical Accomplishments – Combined Dimensional and Topology Optimization

- 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

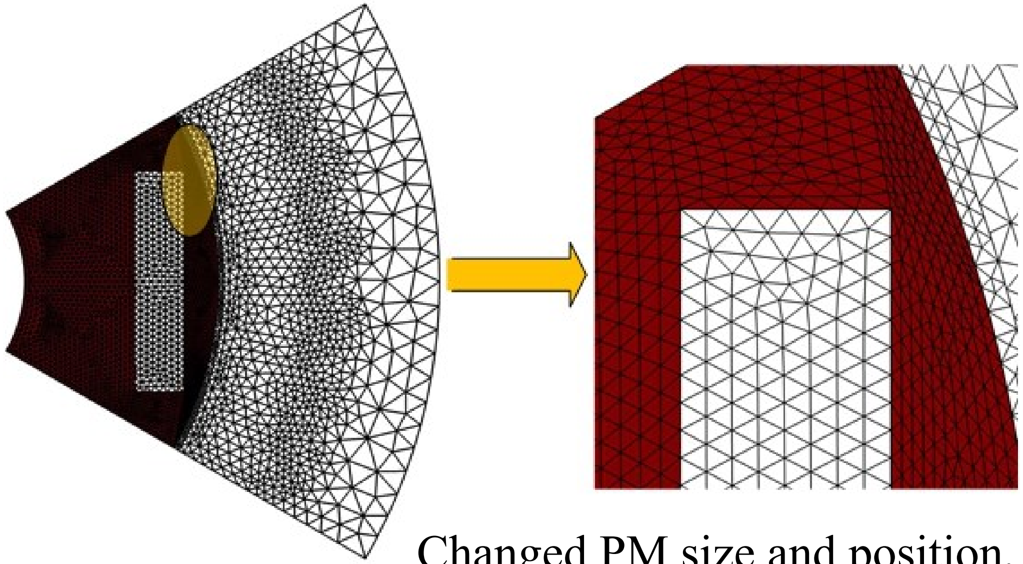


Technical Accomplishments – Mesh Deformation

- 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



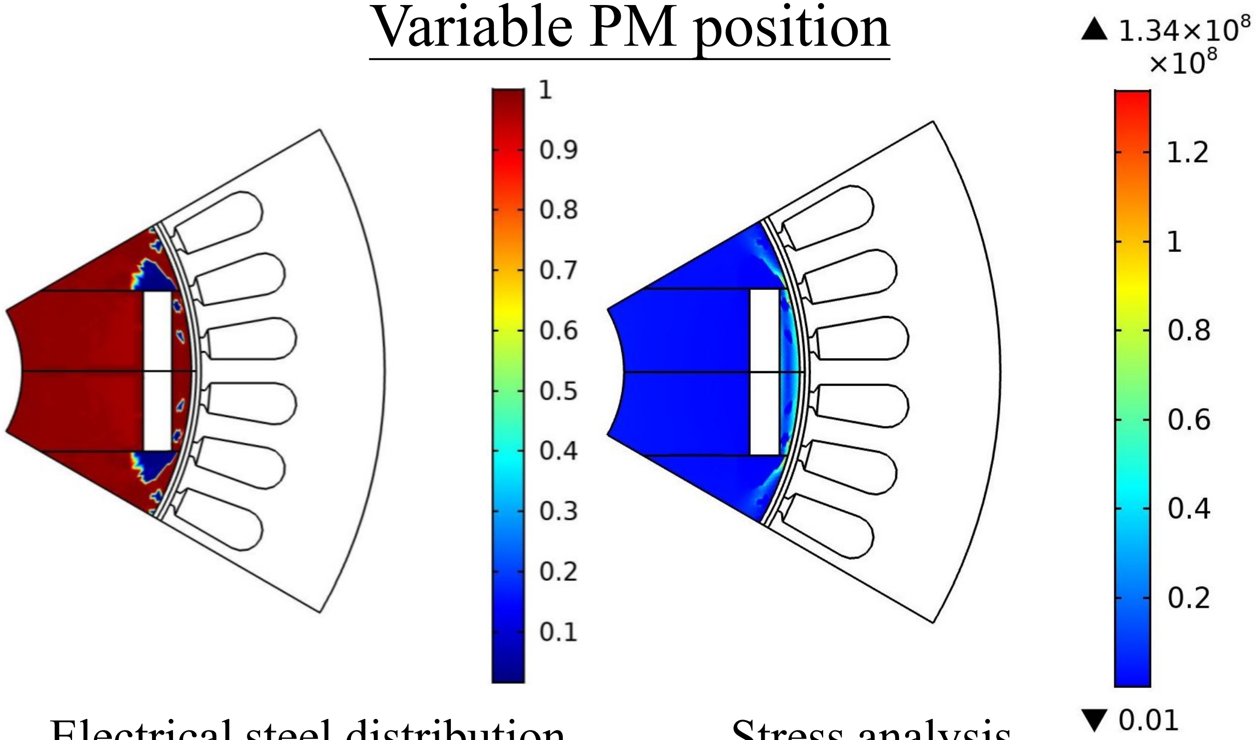
Changed PM size and position, deformed mesh

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:

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

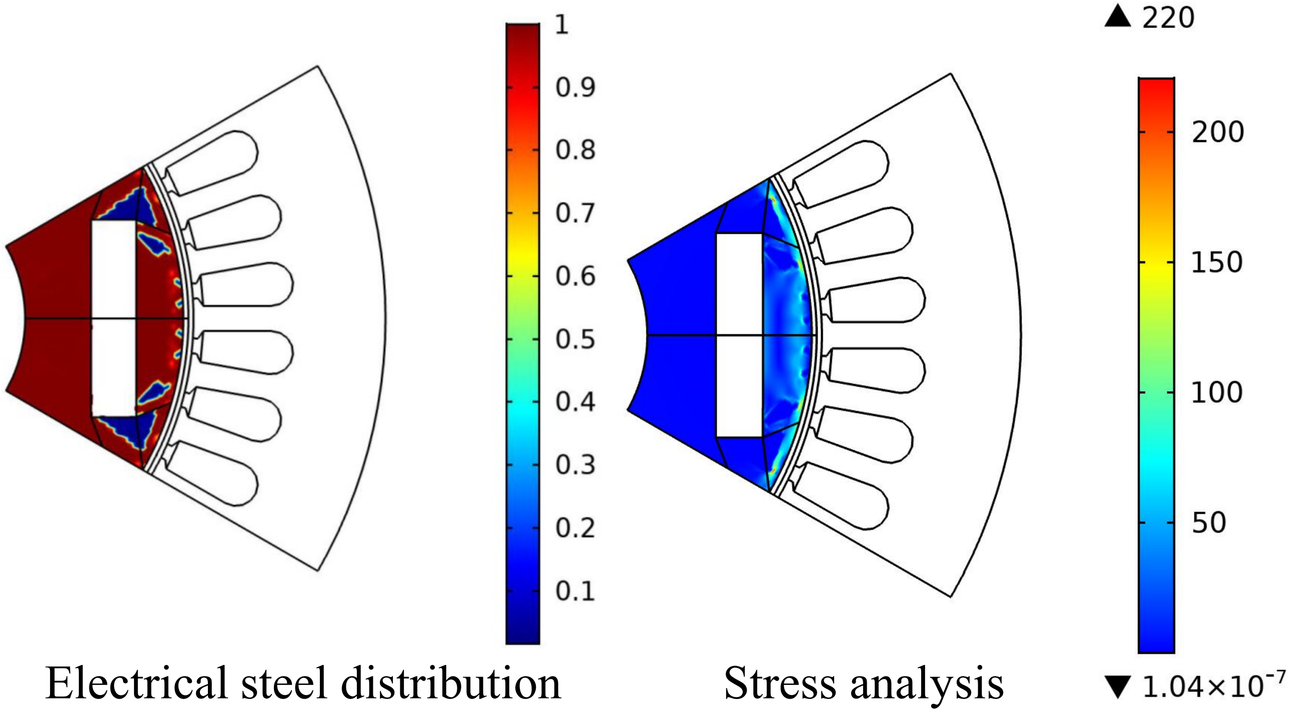
Variable PM position



Electrical steel distribution

Stress analysis

Variable PM position and size



Electrical steel distribution

Stress analysis

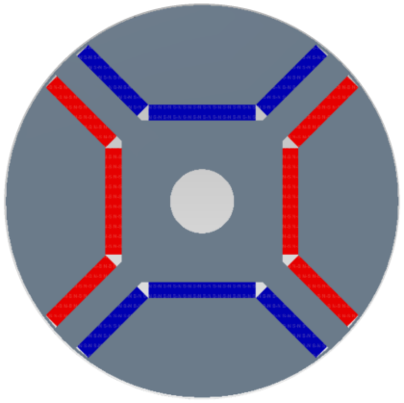
Technical Accomplishments – Multi-Layer IPM Rotor Synthesis Tool Based on Desired Airgap Flux Density Harmonics

Features:

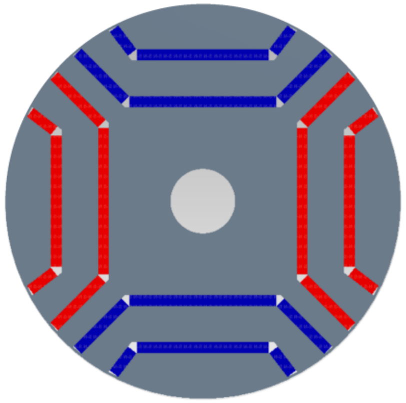
- Direct shaping of airgap magnetic field produced by the rotor, degrees of freedom = 2 × number of layers
- Variable number of poles and great dimensional flexibility: 9 parameters per layer, and each layer varies independently
- Excel VBA for interactively loading design parameters and organizing simulation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

Benefits:

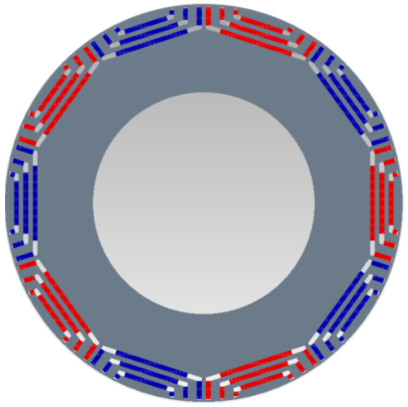
- Rotor magnetic field profiled in coordination with stator winding to minimize unwanted harmonic interaction and reduce power losses
- Less torque ripple and smoother power output
- Higher airgap flux density and better resistance to demagnetization



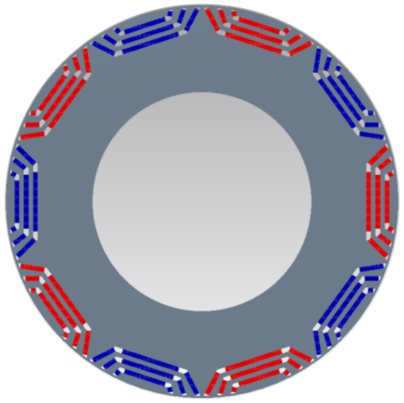
4-pole, 1-layer



4-pole, 2-layer



10-pole, 3-layer
parallel side pieces

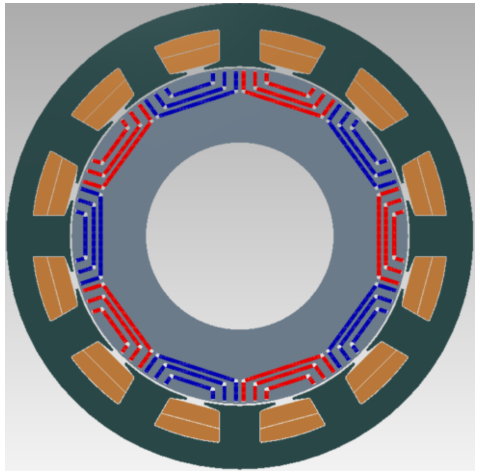


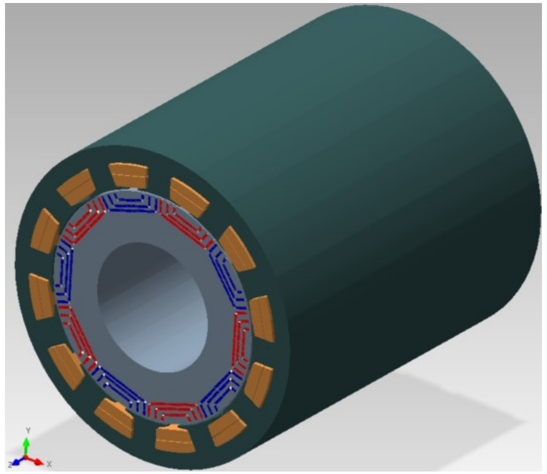
10-pole, 3-layer
skewed side pieces

Technical Accomplishments – Prototype With 3-Layer IPM Rotor

- 12-slot 10-pole configuration with tooth concentrated coils and 3-layer IPM rotor
- Dimensioned to balance active volume utilization rate and cooling: aspect ratio = 1.2, stack volume = 1.612 liters (80.6% of the total 2 liters)
- Strong rotor magnetic field designed for high power/torque output, low torque ripple, improved power factor, and easier cooling
- Benefits of a high slot fill: reduced copper loss, lower current density, and improved efficiency

Views of the machine geometry


Cross sectional


Isometric

Performance Data at Different Operating Points (Conventional 3-Phase Winding)

Speed (rpm)	Power (kW)	Torque (Nm)	Efficiency (%)	Power factor
6600	55.06	79.66	97.18	0.9625
6600	100.1	144.8	95.37	0.7928
13200*	120.3	87.04	93.47	0.9548
20000*	118.4	56.52	89.42	0.9442

*Depends on the flux weakening strategy. Here it assumes that the current and voltage limits determined by the peak power operation at base speed are fully utilized. The power and torque outputs are maximum, but the efficiency and power factor are not the best using this strategy.

Technical Accomplishments – 100 kW Machine Design Study

- IPMSM design was selected for the BP1 100 kW reference design study

Peak Operation Targets

Quantity	Value
Peak Power (kW)	100
Peak Power Corner/Base Speed (RPM)	8000
Peak Power Torque [Minimum] (Nm)	119.37
Peak Power Constant Power Maximum Speed (RPM)	24,000

*Design study carried out before new corner speed and max speed targets adopted

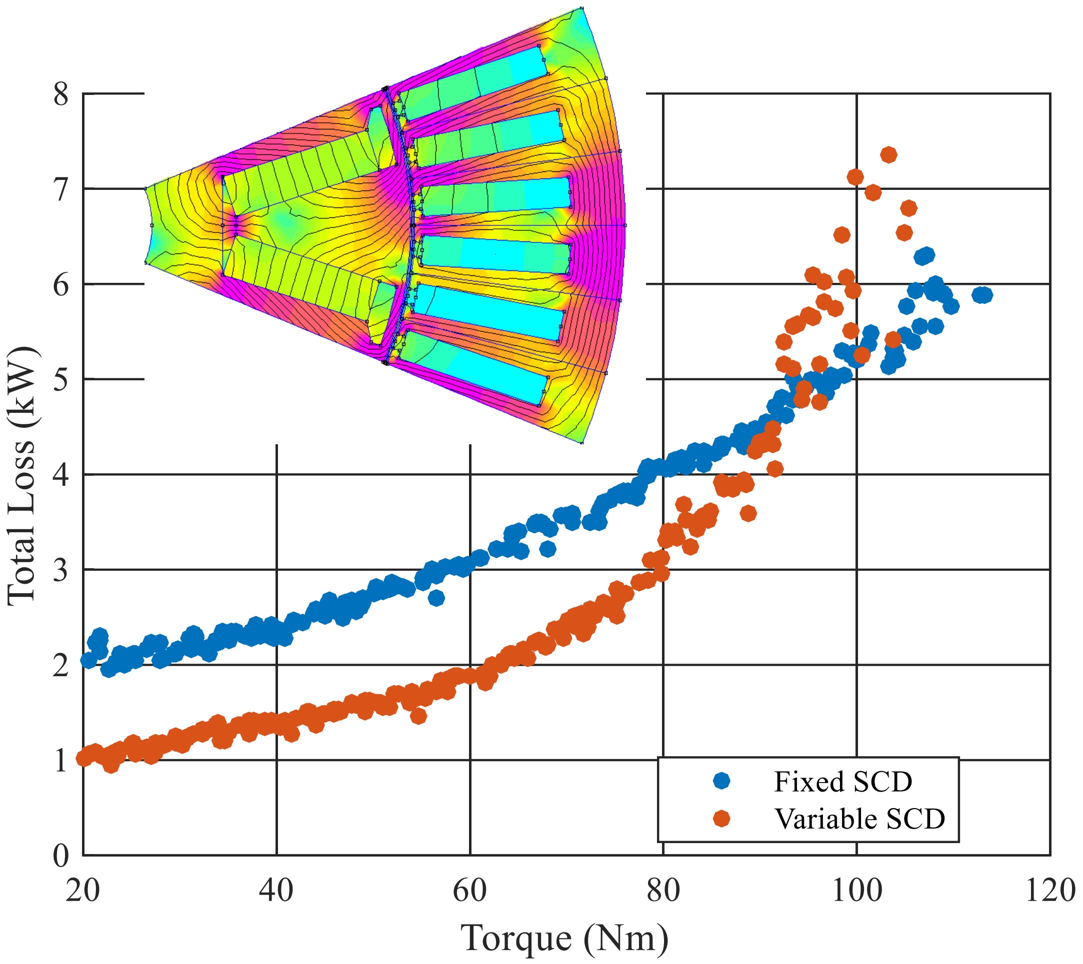
- Number of large scale optimizations carried out with various topologies and materials
  - Final optimization studies with V shape IPM
    - 48 slot, 8 pole with distributed bar/hairpin winding
    - 12 slot, 10 pole, 2 layer, star-delta connection
  - Materials: Heavy rare earth free Hitachi Neomax NMX S49F, M250-35a, and POSCO 35PNT650Y

- Determining what can be done with standard materials

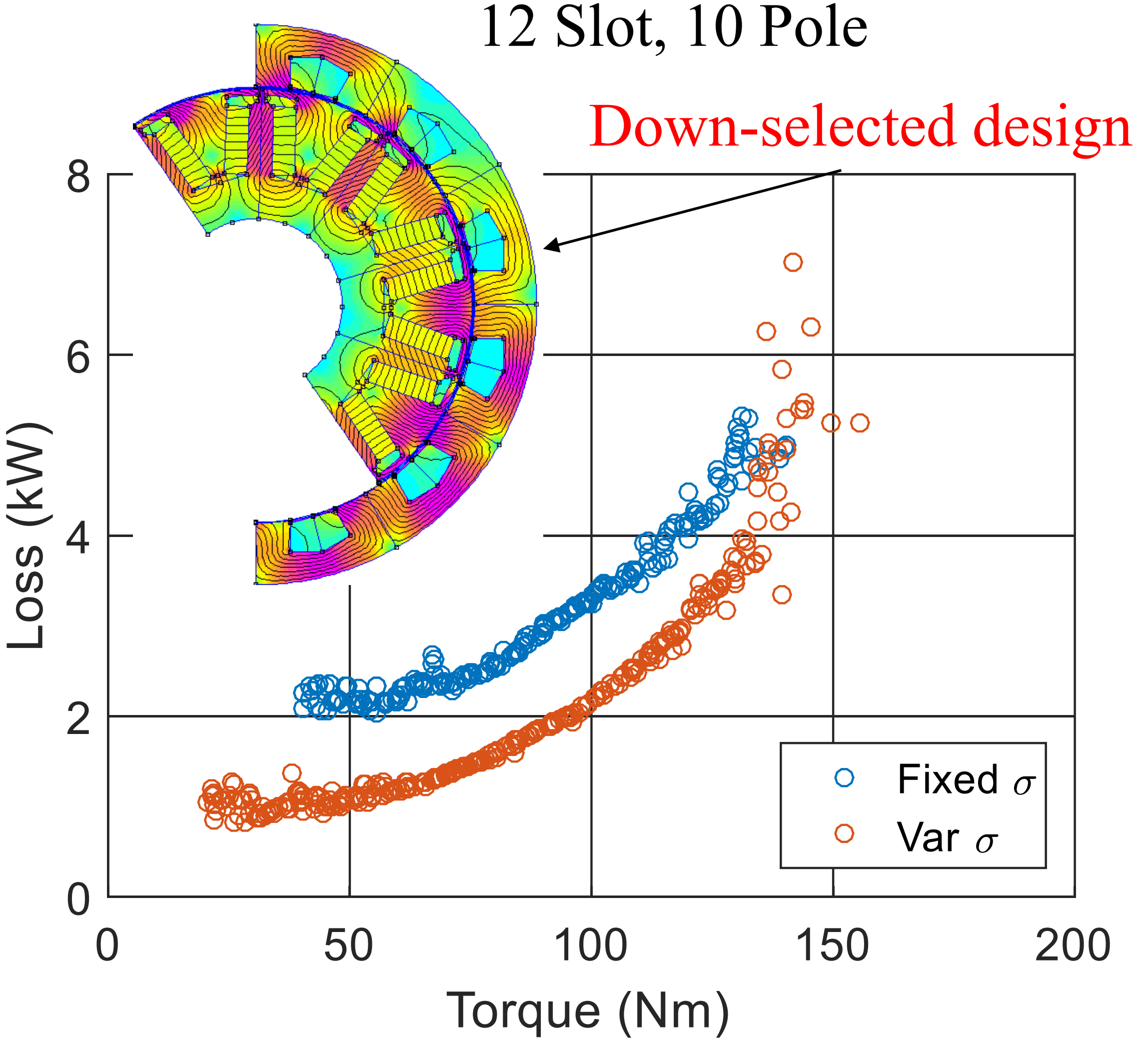
Technical Accomplishments – 100 kW Machine Design Study

- Optimization Pareto fronts for current densities up to 42 A_{peak}/mm^2

48 Slot, 8 Pole



12 Slot, 10 Pole



Technical Accomplishments – 100 kW Machine Design Study

- Down-selected 12 slot, 10 pole, 2 layer, star-delta predicted peak electromagnetic performance and separation of losses at corner speed of 8,000 RPM

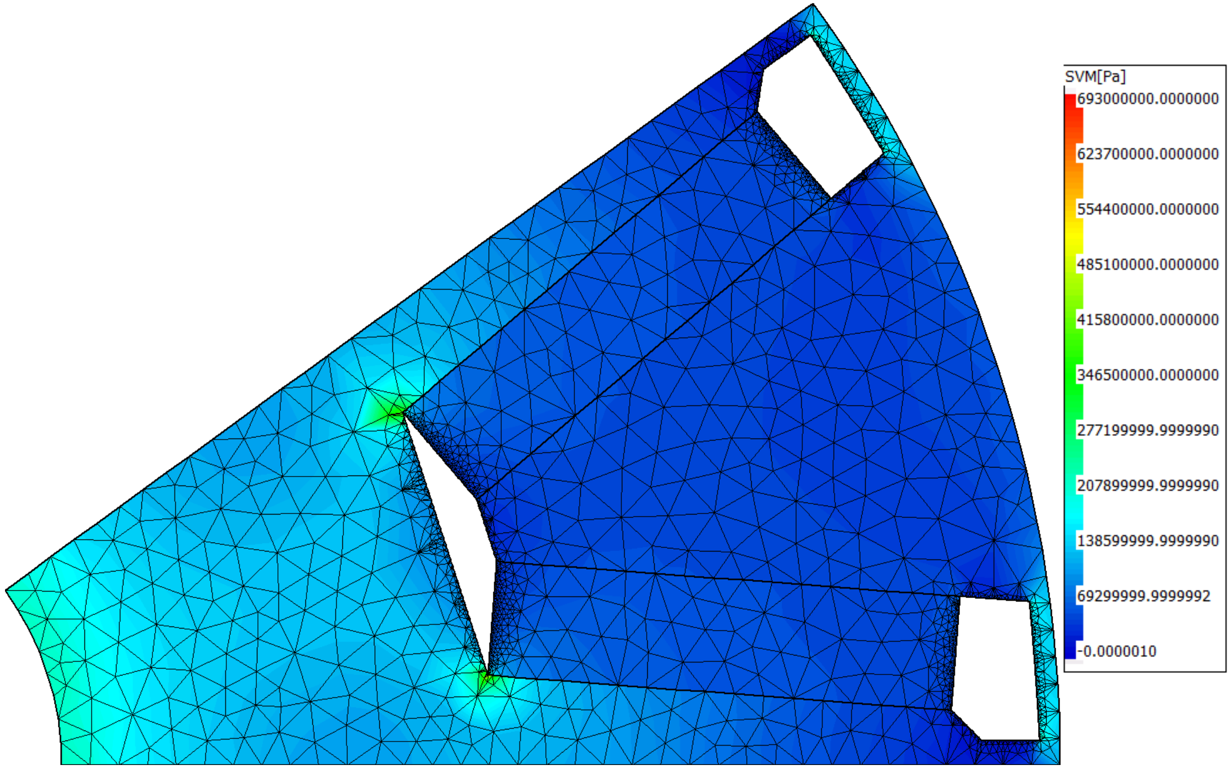
Parameter	Value
Stator Current Density (A_{RMS}/mm^2)	30
Peak Shaft Torque (Nm)	154.09
Torque Ripple (%)	7.666
Mechanical Speed (RPM)	8,000
Output Power (kW)	130.67
Total Losses (kW)	5.988
System Efficiency (%)	95.42
Armature DC Ohmic Loss at 120 ºC (kW)	4.485
Magnet Loss at 100 ºC (kW)	0.631
Stator Iron Loss [total] (kW)	0.633
Rotor Iron Loss [total] (kW)	0.229
Windage Loss (kW)	0.009

Parameter	Value
Stator Outer Diameter (mm)	196.567
Stator Stack Length (mm)	41.133
Active Machine Volume Not Including End Windings (l)*	1.179
Total Machine Volume Including End Windings (l)**	2.16
Peak Active Volumetric Power Density (kW/l)*	110.83
Peak Total Machine Volumetric Power Density (kW/l)**	60.495

* Active volume is the outer envelope of stator laminations, rotor laminations, and magnets.
** Total volume is the outer envelope of end turns, stator laminations, rotor laminations, and magnets.

Technical Accomplishments – 100 kW Machine Design Study

- Mechanical integrity of rotor at maximum speed of 24,000 RPM
- Adhesive between magnets and laminations is needed to avoid failure of the bridges even with high strength electrical steel grade



Parameter	Value
Average Rotor Lamination Stress (MPa)	89.34
Max. Rotor Lamination Stress (MPa)	484.7
Rotor Lamination Safety Factor	1.43
Average Rotor Lamination Displacement (mm)	0.02815
Max. Rotor Lamination Displacement (mm)	0.03663

Response to Previous Year Reviewer's Comments

- This project was not reviewed last year

Collaboration and Coordination with Other Institutions

- Regular contact with Vipin Gupta (Sandia National Lab)
- Plan to design high pole count machine in BP2 based on Sandia National Lab Iron Nitride material properties
- Regular bi-weekly teleconference with EDT electric traction motor teams organized by ORNL

Proposed Future Research

- Develop rotational variable in the combined dimensional and topology optimization of V-shaped IPMSM
- Extend combined dimensional and topology optimization to core loss minimization
- Compare candidate designs with different IPM rotor layers, considering the cost of various PM materials and available sizes
- Evaluate relative strength of stator and rotor to achieve optimal balance of PM cost, VA rating of power electronics, and power efficiency
- High slot fill cast windings with enhanced heat transfer
- Build and test reduced scale prototype incorporating research from BP1

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 flat bar IPMSM rotors
  - Design tool for the synthesis of multi-layer IPM rotors
- Future Work
  - Extend combined topology and dimensional optimization to V-IPMSM and core loss minimization
  - Cast windings with enhanced heat transfer surfaces
  - Build and test reduced scale prototype incorporating research from BP1

Technical Back-Up Slides

Technical Accomplishments – Prototype With 3-Layer IPM Rotor Winding With Subsets and Excitation Phase Shift

- Compared to the conventional 3-phase configuration, working harmonic is increased while half of the non-working harmonics are eliminated, further suppressing stator-rotor harmonic interaction
- Average torque can increase by 4% to 5% given the same magnitude of current excitation, with better power efficiency and even smoother torque output, especially at higher load levels
- Can be implemented as either three-phase wye-delta connection or dual-three-phase connection

Torque output (same magnitude of current excitation)

Performance Data of Different Windings (Same Magnitude of Current Excitation at 6600 RPM)

	Conv. 3-phase	With phase shift
Power (kW)	100.1	104.4
Toque (Nm)	144.8	151.1
Efficiency (%)	95.37	95.52
Power factor	0.7928	0.7783

Technical Accomplishments – 100 kW Machine Design Study

- Down-selected 12 slot, 10 pole, 2 layer, star-delta predicted continuous electromagnetic, spray cooling parameters, and temperatures at corner speed

Parameter	Value
Stator current density (A_{RMS}/mm^2)	11.5
Continuous shaft torque (Nm)	66.3
Torque ripple (%)	4.0
Mechanical speed (RPM)	8,000
Output power (kW)	55.5
Total Losses (kW)	1.4
System Efficiency (%)	97.6
Armature DC ohmic loss at 120 ºC (kW)	0.66
Magnet loss at 100 ºC (kW)	0.56
Stator iron loss [total] (kW)	0.50
Rotor iron loss [total] (kW)	0.13
Windage loss (kW)	0.01

Parameter	Value
Cooling fluid	ATF134
Ambient temperature (ºC)	50
Inlet temperature (ºC)	85
Inlet flow rate (l/m)	10
Nozzle diameter (mm)	1
Number of stator nozzles	24
Number of rotor nozzles	20

Component	Temp. ºC
Magnets	88
Rotor Lamination	91
Stator Tooth	125
Stator Winding Average	111.2
Stator Winding Maximum	123
Housing	106