OAK RIDGE National Laboratory

Non-Heavy Rare-Earth High-Speed Motors (Keystone Project #2)

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Oak Ridge National Laboratory

2020 DOE Vehicle Technologies Office Annual Merit Review

June 22nd, 2021 Project ID: ELT212

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

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Overview

Timeline

- Start: FY19
- End: FY24
- 53% complete

Barriers

- Magnet cost and heavy rare-earth element price volatility
- Non-heavy rare-earth electric motor performance
- Meeting DOE ELT 2025 targets for non-heavy rare-earth electric motor: $3.30/kW cost; 50kW/L power density and 300,000-mile lifetime

Budget

- Total project funding
  - DOE share – 100%
  - Funding for FY21: $765K

Partners

- National Renewable Energy Laboratory
- Ames Laboratory
- ORNL team members: Tsarafidy Raminosoa, Randy Wiles, Jon Wilkins, and Burak Ozpineci

Relevance - Project Objectives

Overall Objective

- Enable the adoption of high-speed and high-power density non-heavy rare-earth (HRE) traction motors
- Analyze the impact of new advanced materials for non-heavy rare-earth electric motors

FY21 Objective

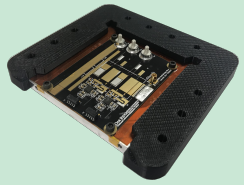
- Design a dual three phase non-heavy rare-earth permanent magnet high speed traction motor to meet the DOE ELT 2025 specifications
- Design the thermal management system and the mechanical assembly of the motor

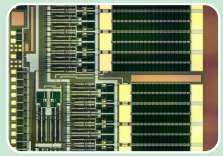
Project Scope within ELT Consortium

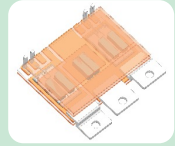
Keystone Project #1

Integrated Power Module
ORNL

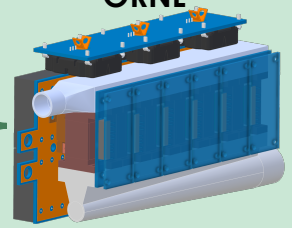
SiC and GaN Power Devices
SNL







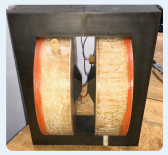
Inverter Design
ORNL



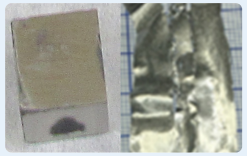
Power Module Packaging
University of Arkansas & Virginia Tech

Keystone Project #2

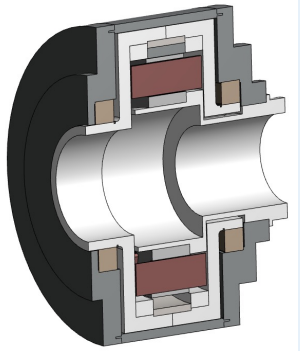
Material modeling and testing
ORNL



Magnetic material development
Ames



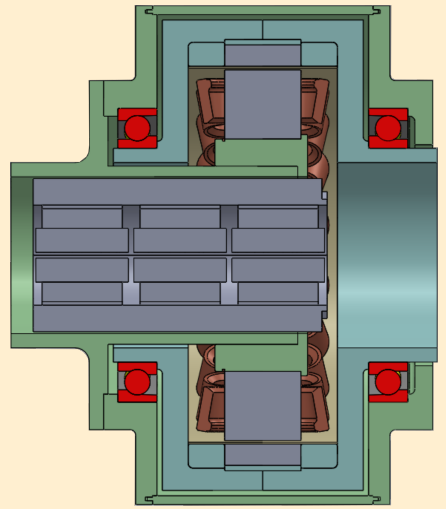
Motor Design
ORNL



Thermal management
NREL

Keystone Project #3

Integrated drive
ORNL

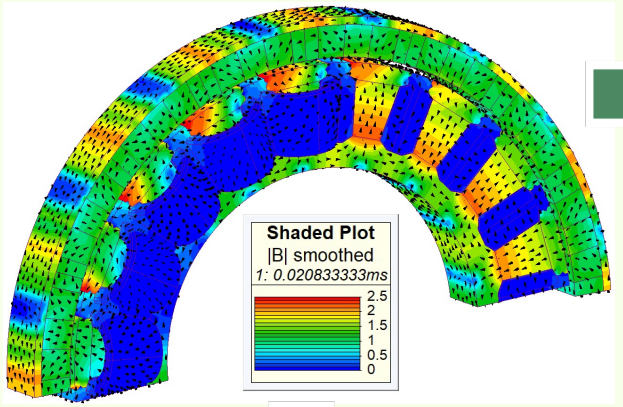


Thermal management
NREL

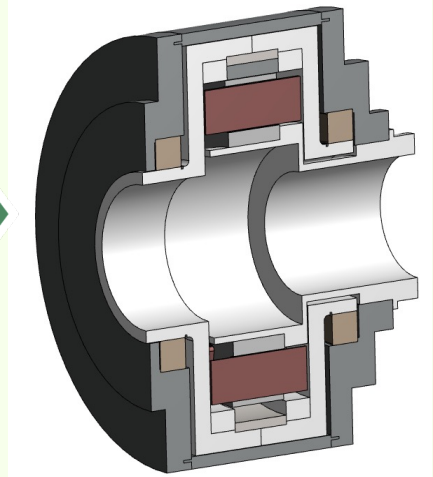
Relevance - Project Objectives

ELT212 ORNL

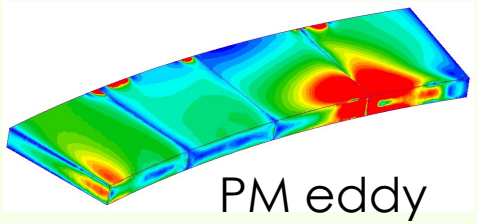
Electromagnetic design



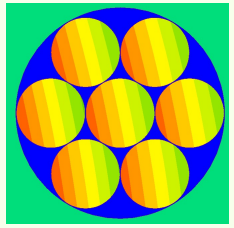
Mechanical assembly design



Loss evaluation



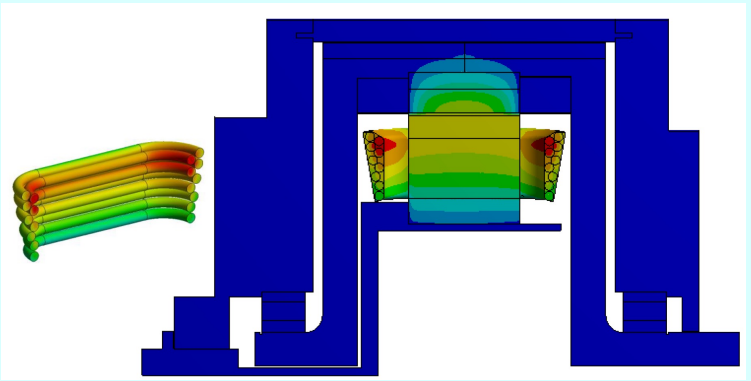
PM eddy current loss



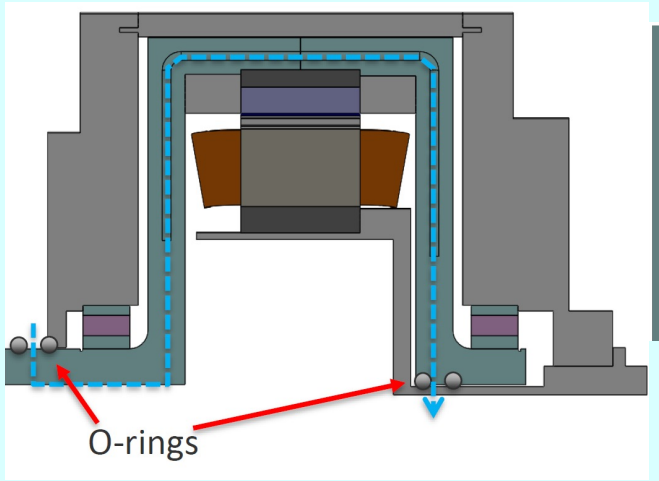
AC loss in Litz wire winding

ELT214 NREL

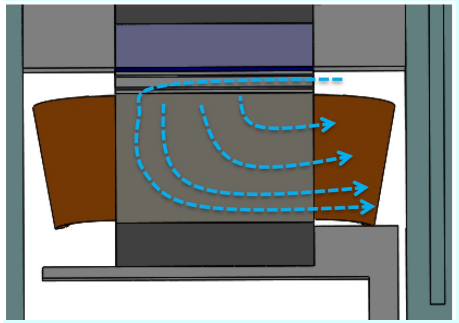
Thermal modeling



Cooling design



Rotor cooling



Slot heat exchanger

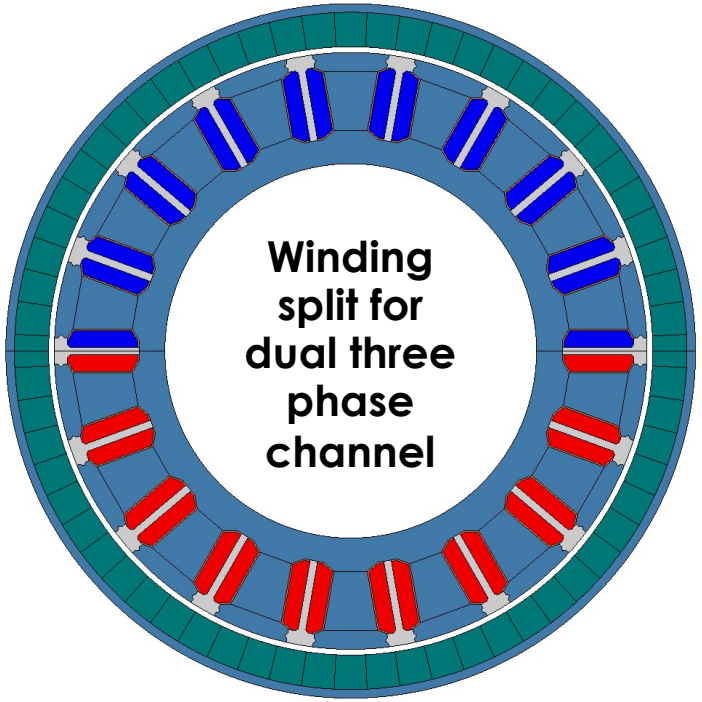
FY21 and FY22 Milestones and Go/No-Go Decision

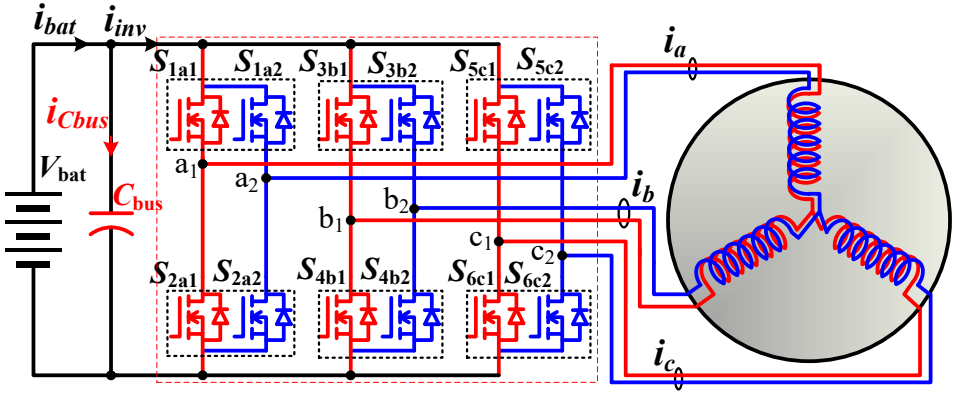
Date	Milestones and Go/No-Go Decision	Status
	FY21	
Dec 2020	Milestone: Finalize winding design to align with power devices current rating and selected DC link voltage.	Completed
Mar 2021	Go/No-Go decision: If thermal analysis confirms winding and magnet temperatures are below 150°C, proceed with detailed design of the overall integrated motor/drive and shared cooling system assembly.	Completed
Sep 2021	Milestone: Generate final drawings for full prototype fabrication.	On track
Sep 2021	Milestone: Manufacturing trials on key subassemblies and annual report.	On track
	FY22	
Dec 2021	Milestone: Analyze the dynamics of the rotor assembly.	On track
Mar 2022	Milestone: Complete manufacturability trials of winding and insertion of slot heat exchangers.	On track
Jun 2022	Go/No-Go decision: If manufacturability trials are successful, continue with the build of the prototype.	On track
Sep 2022	Milestone: Build a prototype of the non-heavy rare-earth motor.	On track

Any proposed future work is subject to change based on funding levels

Approach/Strategy

- ✓ Permanent magnet traction motors using non-HRE magnet materials are evaluated.
- ✓ Dual channel three phase winding configuration is proposed. This way, the motor can be powered by:
  - A conventional three phase drive with the two channels connected in parallel;
  - Or a dual three phase segmented drive (separate inverter for each channel) developed at ORNL (Refer to ELT209) to reduce current ripple and the DC Link capacitor.
- ✓ Dual channel configuration also reduces the back-EMF on each set of winding by half. This eases the voltage limitation constraint at high speed and eliminates uncontrolled regeneration.
- ✓ Dual channel configuration features fault tolerance which improves reliability.



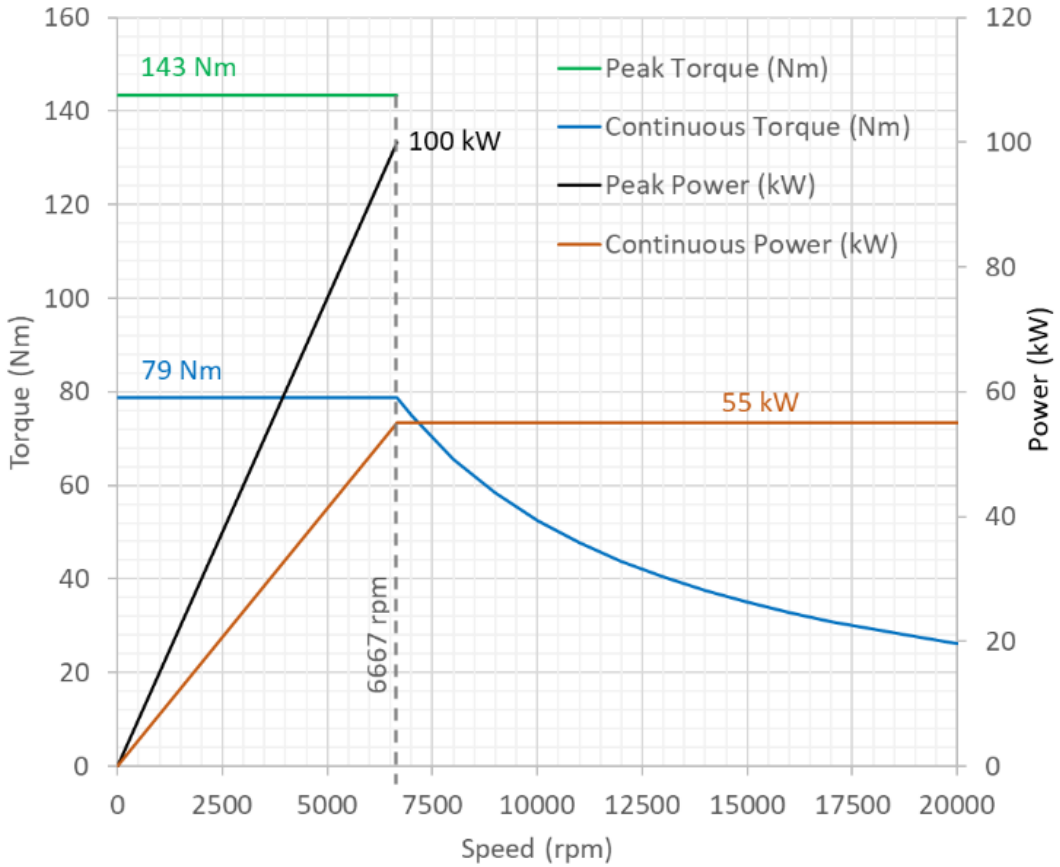


Segmented 3-phase inverter

Reduction of capacitor ripple current with interleaved switching
Refer to ELT209 by Gui-Jia Su

Technical Accomplishments – FY21

Completed Electromagnetic Design of Heavy Rare-Earth-Free Dual Three-Phase Outer Rotor Permanent Magnet Traction Motor

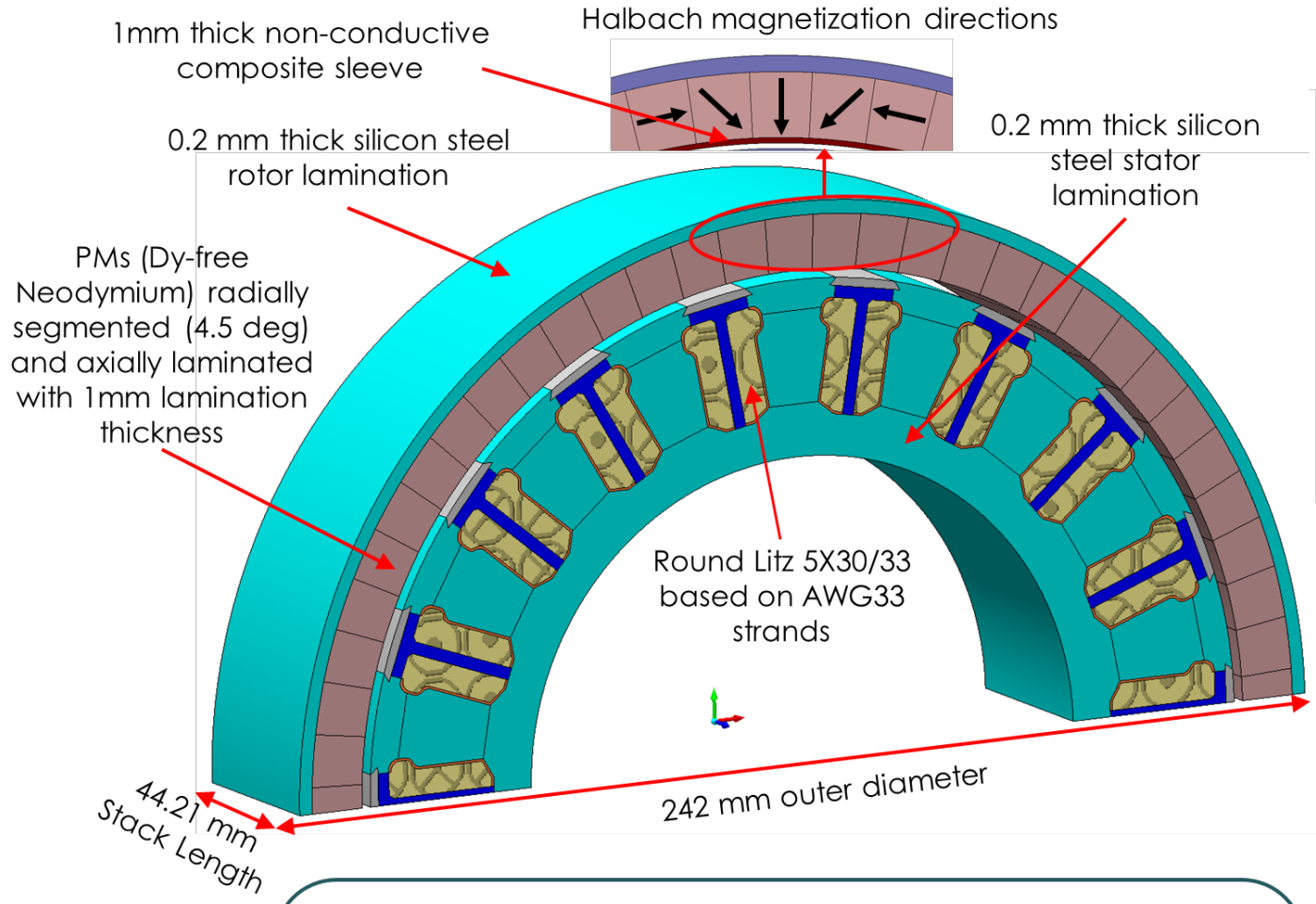


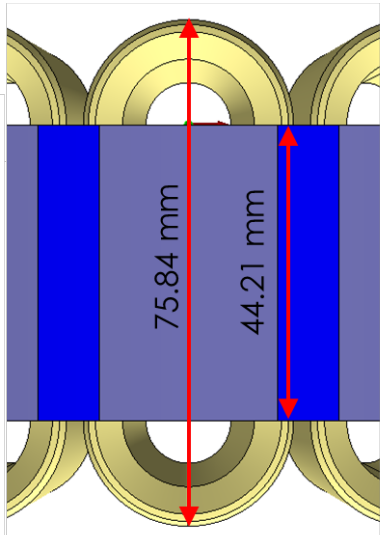
Peak power (kW)	100
Continuous power (kW)	55
Maximum speed (rpm)	≤20,000
Power factor	> 0.8
Maximum current (A)	600
Maximum efficiency (%)	> 97
Torque ripple (%)	5
Volume (@50 kW/l)	2L
Mass (@5kW/kg)	20kg

Summary of Specifications created by Profs. Tom Jahns and Bulent Sarlioglu, University of Wisconsin

Technical Accomplishments – FY21

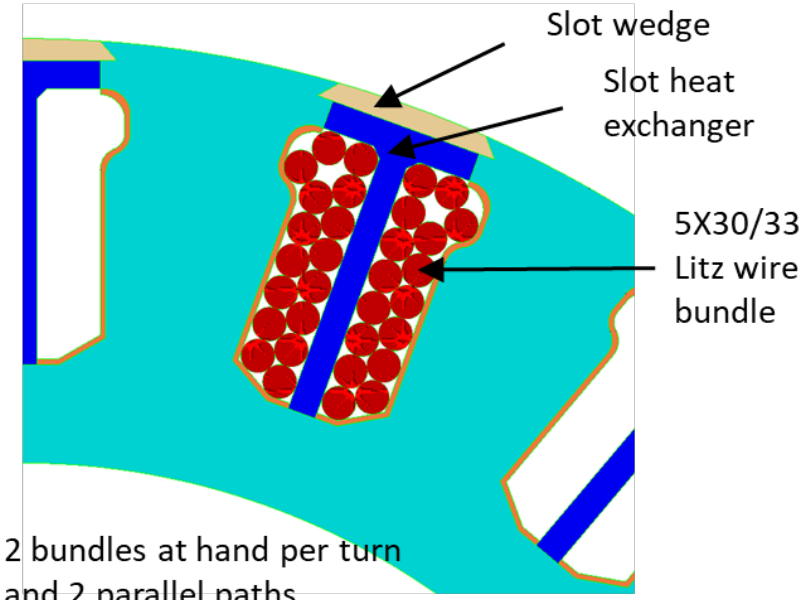
Completed Electromagnetic Design of Heavy Rare-Earth-Free Dual Three-Phase Outer Rotor Permanent Magnet Traction Motor





Why Outer Rotor SPM?

- Opportunity for integrating power electronics in the inner hollow volume.
- Robust continuous rotor construction (as opposed to segmented rotor construction for Spoke IPM). Magnet retention against centrifugal force naturally provided by rotor laminations and rotor support structure.
- Has the highest power density among the candidates analyzed.

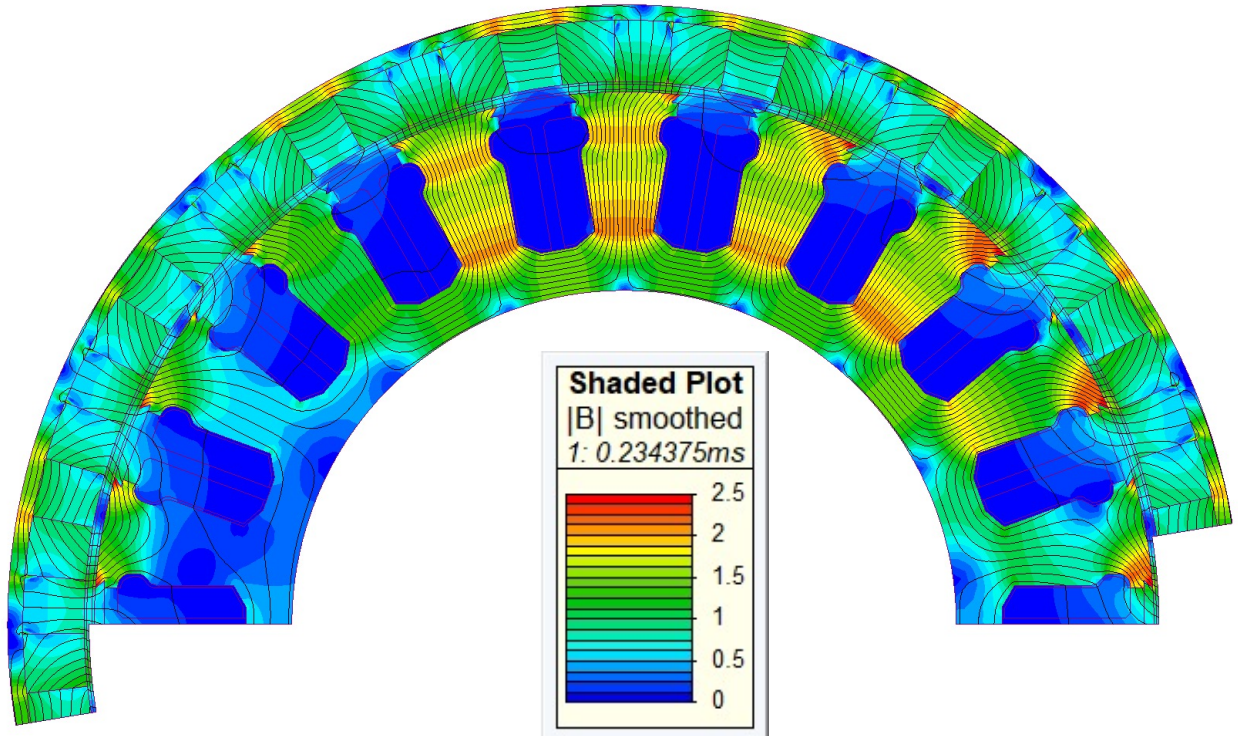


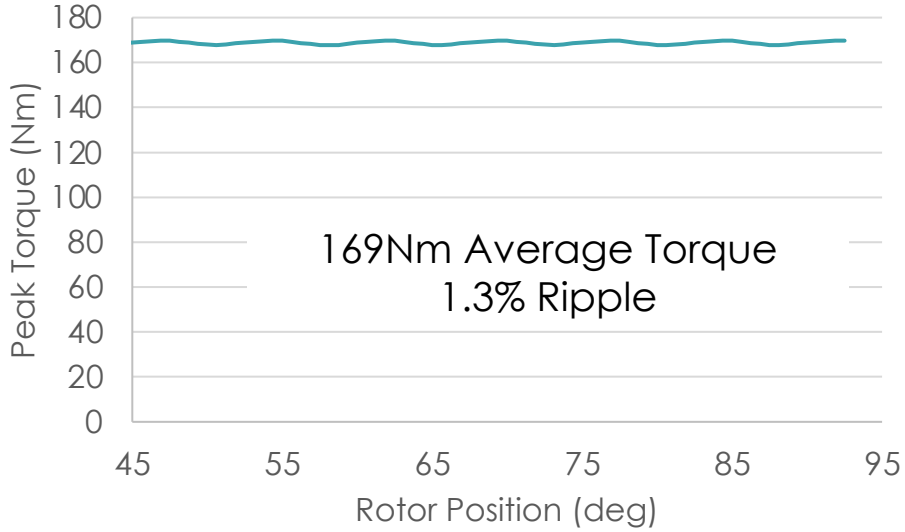
Active volume 2.48 L
(includes end winding but excludes inner hollow space for power electronics)

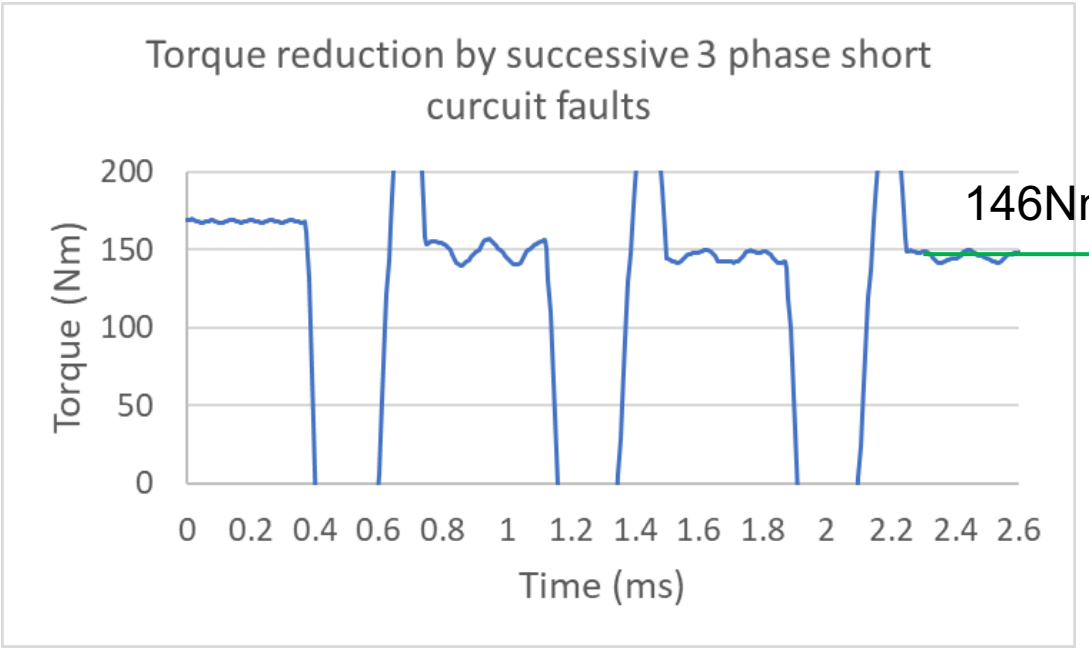
Technical Accomplishments – FY21

Completed Electromagnetic Design of Heavy Rare-Earth-Free Dual Three-Phase Outer Rotor Permanent Magnet Traction Motor

Flux Density Map at Peak Torque Condition



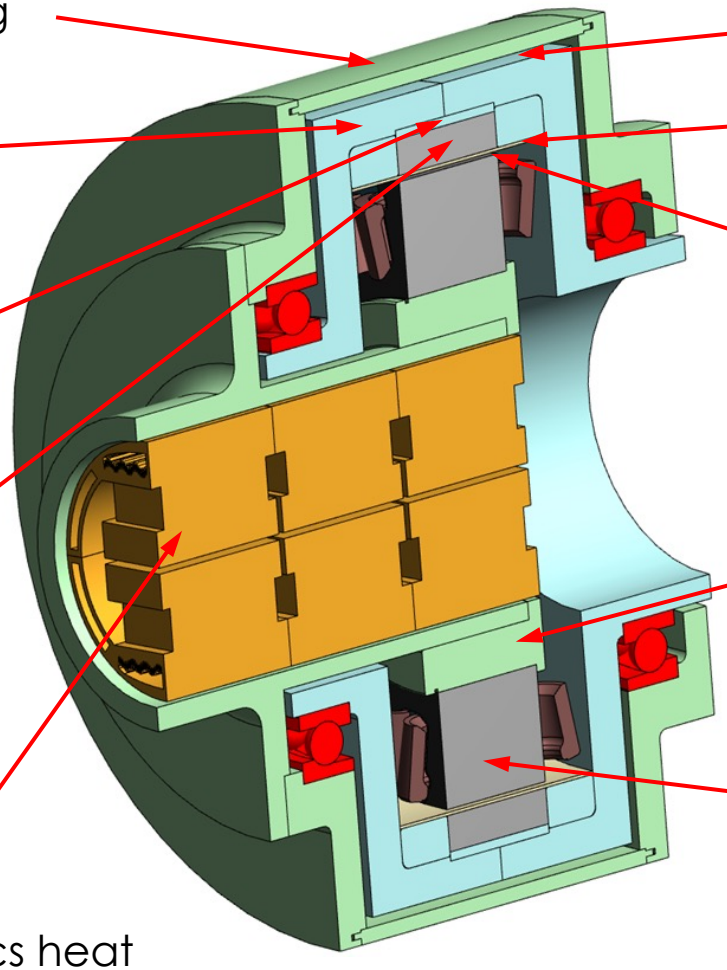




- Meets peak power and torque ripple requirement
- Robust against demagnetization

Technical Accomplishments – FY21

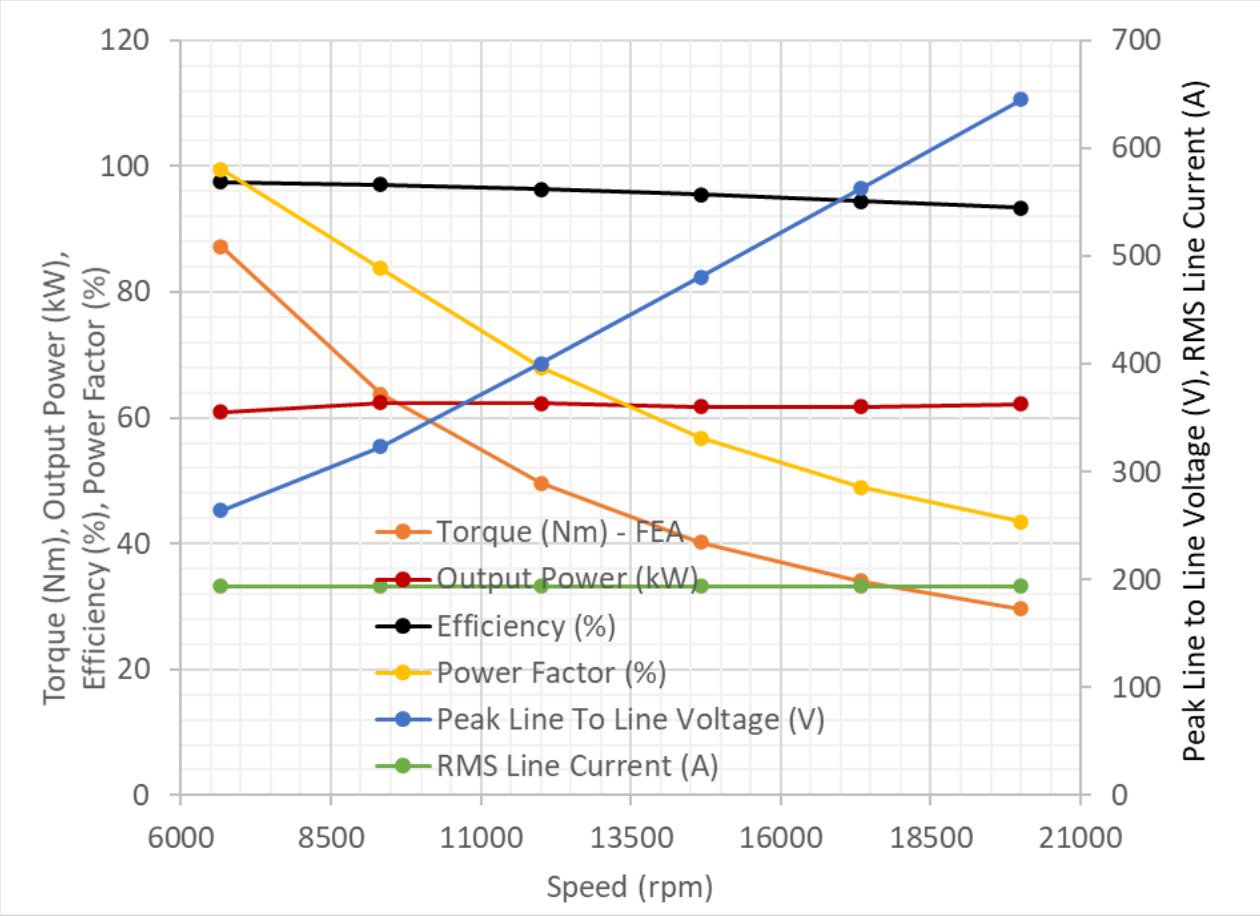
Assembly Design Enabling Integration of Power Electronics and a Shared Cooling System

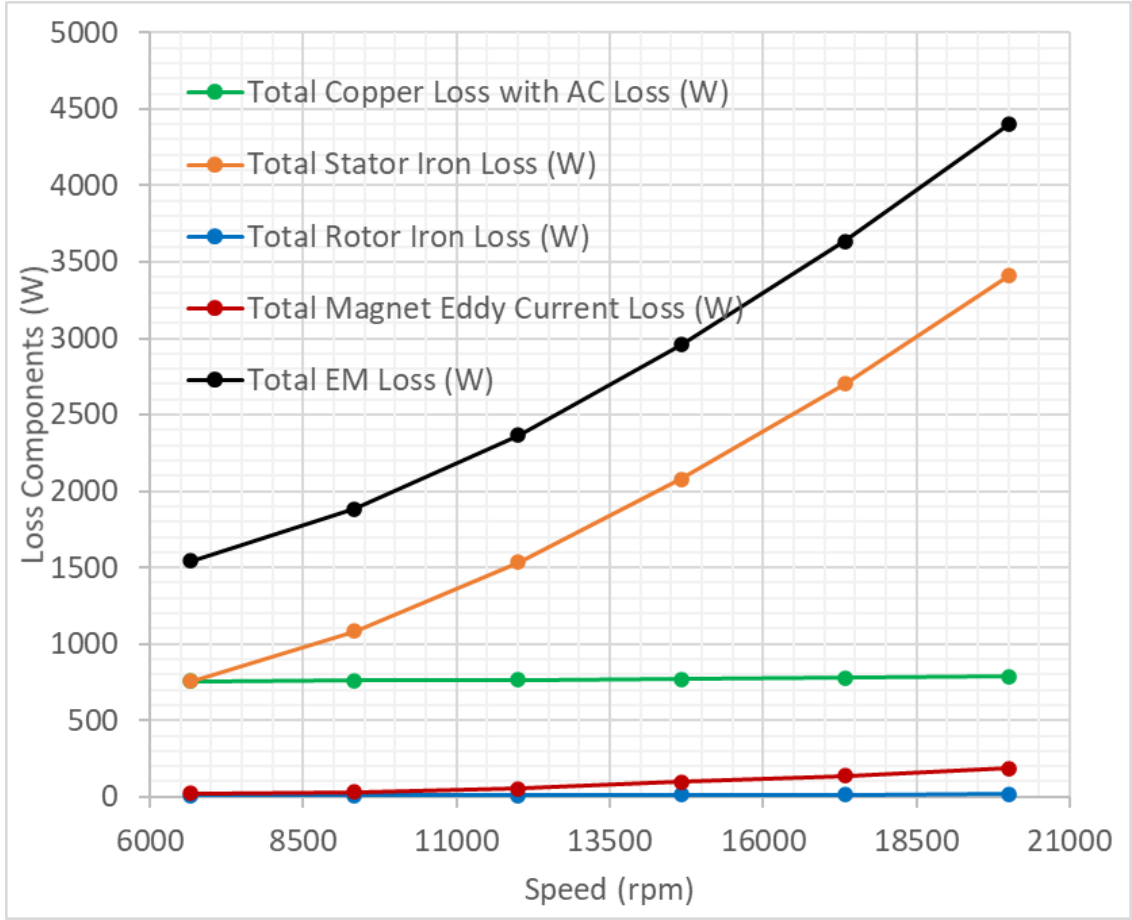


Refer to ELT221, ELT214, and ELT217 for more details on power electronics and shared cooling system integration

Technical Accomplishments – FY20

Evaluated loss for cooling design and thermal viability verification





Winding and magnet temperatures lower than 150°C are achievable without active liquid cooling of the rotor (Ref. ELT214 NREL)

Responses to Previous Year Reviewers' Comments

- ***Comment:*** High-density, non-rare earth (RE) permanent magnet (PM) machine design is of critical importance due to the high price of these magnets and control of these materials by a single country. However, outer-rotor PM machines have their own disadvantages. Stator cooling is an issue, and this can increase the copper (Cu) loss and core loss. Outer-rotor PM machines have very high centrifugal forces which can increase the high-speed mechanical loss and core loss. How do these losses affect the magnet temperature? How is the surface PM contained?

➢ ***Response*:** The design operates at high fundamental frequencies (16 pole, up to 20,000 rpm); hence iron loss is the dominant loss component. The stator is cooled through slot heat exchangers which are directly in contact with the winding conductors and the stator lamination. Thermal analyses have confirmed that the winding temperature is within the specifications. The PMs are naturally retained against centrifugal forces by the rotor lamination and the rotor support structure. An inner composite sleeve provide a volume containment for the PMs (non-structural). Thanks to the segmentation and the lamination, the induced eddy-current losses in the PMs are so low that they do not need any active cooling to keep their temperature below 150°C. This was confirmed by thermal analyses that took into account the mechanical losses at high speeds.

- ***Comment:*** *Even though some mechanical stress analysis has been performed on the outer rotor design, a more detailed rotor dynamics analysis taking into consideration the bearings selection should be performed. The slides show a Halbach array, which is an expensive option for the application. Some justification for such choice should be included.*

➢ ***Response*: T**he rotor dynamics aspect is critical and rotor dynamics analysis shall be included as part of future research. The cost of the Halbach array is offset by the significant cost reduction by avoiding Dysprosium in the permanent magnets.

- ***Comment:*** *Integration of the thermal management of the motor and inverter is a critical aspect of this project. How is this addressed? A plan for thermal management of motors has been outlined.*

➢ ***Response*:** Brainstorming sessions between ORNL and NREL have taken place and several multidisciplinary iterations between electromagnetic design, power device packaging, cooling, and overall mechanical assembly have been carried out and the team have converged to an integration concept. Please refer to projects ELT221[ORNL] and ELT214[NREL] for more details on the drive integration and the shared cooling system.

Collaboration and Coordination with Other Institutions

Organization	Role
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Investigates cooling methods for the selected advanced non-heavy rare-earth electric motors
AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY	Provides ORNL with the magnetic, electrical and mechanical properties of newly developed magnetic materials for traction motor design

Remaining Challenges and Barriers for FY21

- Manufacturability of the thermal management system:
  - *Challenge:* Insertion of ceramic based heat exchanger and its connection to manifold and power electronics' heat sink.
  - *Mitigation:* Rapid prototyping and trials on key subassemblies to evaluate manufacturability and leak-proof connections.
- Electrical connections:
  - *Challenge:* Electrical connection between inverters and motor windings shall enable separate testing of inverters and the motor.
  - *Mitigation:* Connection trials on 3D-printed subassembly.

Any proposed future work is subject to change based on funding levels

Proposed Future Research

- **Remainder of FY21**
  - Complete detailed design of cooling system and overall mechanical assembly.
  - Generate drawings and/or solid model files for prototype construction.
- **FY22**
  - Manufacturability trials of winding and insertion of slot heat exchangers.
  - Rotor dynamics analysis of the rotor assembly.
  - Build a prototype of the non-heavy rare-earth motor.
  - Experimentally validate motor performance.

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** Non-heavy rare-earth high-speed traction motors have potential to meet the DOE ELT 2025 targets of 50kW/L, $6/kW, and 300,000-mile lifetime
- **Approach:**
  - Non-Heavy Rare Earth PMs for high power density and reduced cost electric motors
  - PM motor technology resistant to demagnetization
  - Outer rotor motor topology or power electronic integration and electric drive power density improvement
  - Dual-channel three phase winding for use with the segmented drive to reduce current ripple and DC link capacitor
- **Collaboration:**
  - **NREL:** Exploring cooling methods for advanced non-heavy rare-earth electric motors
  - **AMES:** Providing magnetic, electrical and mechanical properties of newly developed magnetic materials
- **Technical accomplishment:**
  - Completed electromagnetic design of a non-heavy rare-earth outer rotor PM motor that meets most of the DOE ELT targets
  - Completed mechanical assembly design enabling integration of power electronics and a shared cooling system
- **Future work:**
  - Build motor prototype.
  - Experimentally verify prototype performance

Any proposed future work is subject to change based on funding levels