Oak Ridge National Laboratory

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

Tsarafidy Raminosoa
Email: raminosoat@ornl.gov
Phone: 865-341-1265

Oak Ridge National Laboratory

2019 DOE Vehicle Technologies Office Annual Merit Review

June 11th, 2019 Project ID: ELT212

U.S. DEPARTMENT OF ENERGY

Overview

Timeline

- Start: FY19
- End: FY21
- 25% complete

Budget

- Total project funding
  - –DOE share – 100%
    - Funding for FY19: $397K

Barriers

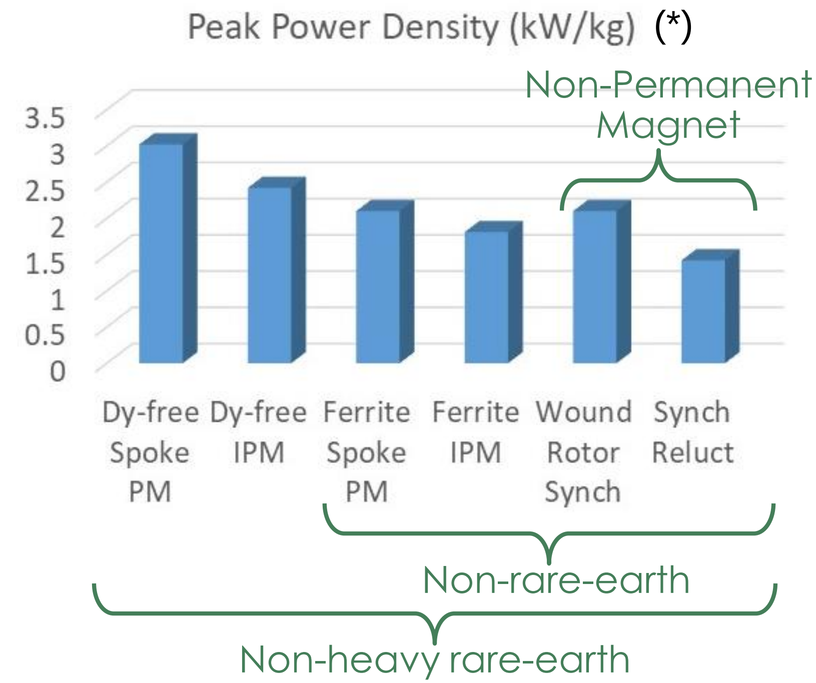
- Magnet cost and rare-earth element price volatility
- Non-heavy rare-earth electric motor performance
- Meeting DOE ELT 2025 targets for non-heavy rare-earth electric motor: $3.30/kW cost; 50kW/L power density and 300,000 mile lifetime

Partners

- National Renewable Energy Laboratory
- Ames Laboratory
- ORNL team members: Tsarafidy Raminosoa, Randy Wiles, Jason Pries, Tolga Aytug 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



- FY19 Objective
  - Evaluate the power density of non-heavy rare-earth traction motors and their ability to operate under a wide speed range and a top speed of 20,000 rpm
  - Investigate the impact of the conductivity of ultra-conducting copper (UCC) winding on the power density and efficiency of traction motors

(*) Ayman El-Refaie *et. al.*, "Comparison of traction motors that reduce or eliminate rare-earth materials," IET Electrical Systems in Transportation, 2017, Volume 7, Issue 3, Pages 207-214

FY19 Milestones

Date	Milestones and Go/No-Go Decision	Status
Dec 2018	Milestone: Identify key high-speed motor topology candidates that can achieve the 2025 DOE ELT targets.	Completed
Mar 2019	Go/No-Go Decision: If a high-speed motor topology candidate can yield a significant improvement in power density, proceed with the mechanical and thermal design of this candidate.	On track
Jun 2019	Milestone: Complete the analysis of the impact of the conductivity of UCC winding on the power density and efficiency of traction motors.	On track
Sep 2019	Milestone: Complete mechanical and thermal design of the selected motor candidate.	On track

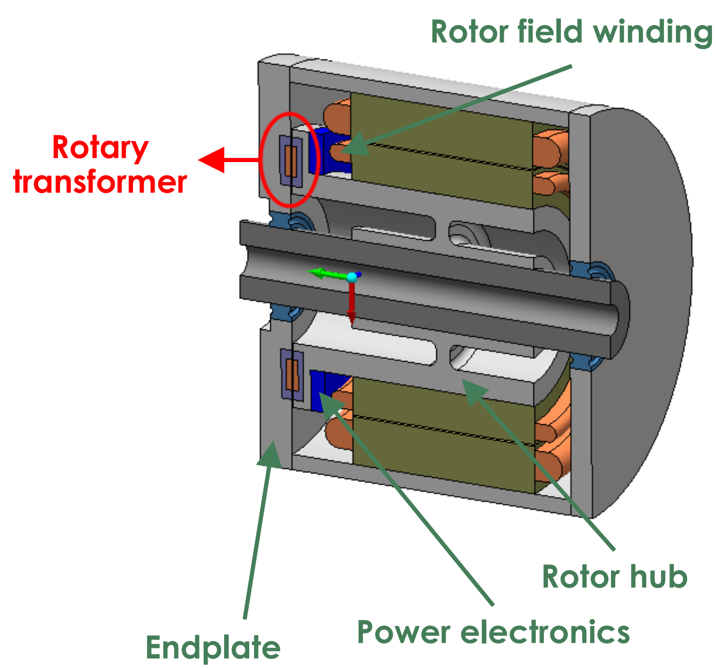
Any proposed future work is subject to change based on funding levels

Approach/Strategy

✓ Enable adoption of non-heavy rare-earth electric motors for traction to achieve the DOE ELT 2025 targets:

- **Option 1: Heavy rare-earth-free permanent magnet (PM) motors:**
  - HRE-free permanent magnets are promising compromise between energy density, cost and supply reliability.
  - Non-HRE PM motors are designed to be resistant to demagnetization in spite of the lower coercivity of HRE-free PMs compared to regular ones.

- **Option 2: Non-permanent-magnet motor:**
  - WRSM is a non-permanent magnet option; thus, very cost effective and can help achieve the 30% cost reduction DOE ELT target for 2025.
  - An integrated contact-less excitation system can enable high speed operation at 20,000 rpm, and contribute to the achievement of the DOE ELT 2025 power density target of 50kW/L and life expectancy target of 300,000 miles.



Approach/Strategy

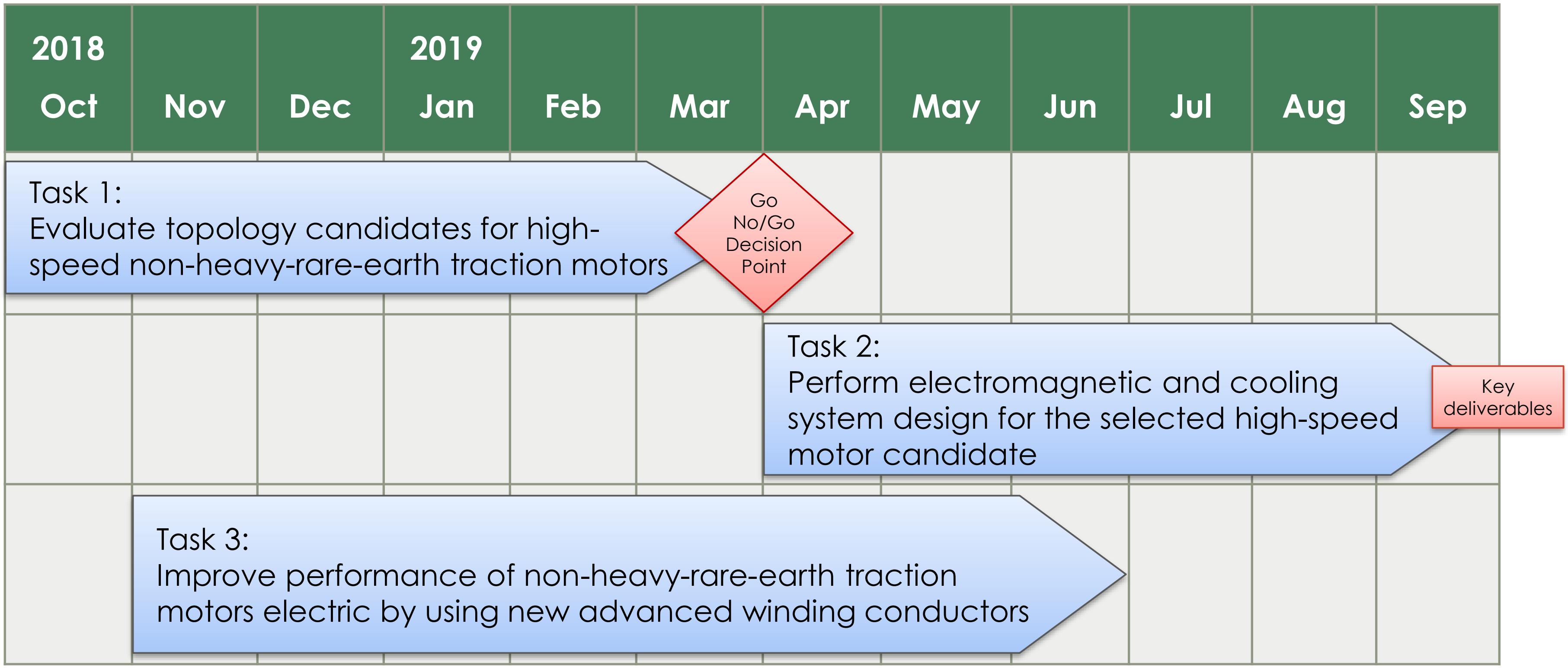
✓ Improve power density and performance of non-rare-earth traction electric motors with new advanced conductors and magnetic materials:

- High electrical conductivity composite conductor based on carbon nanotube (CNT) and copper can help reduce the winding loss, improve the motor efficiency and increase the power density to meet the DOE ELT target of 50kW/L.
- New advanced heavy rare-earth-free soft and hard magnetic materials can contribute to cost reduction and performance improvement.

Cu tape with CNT coating

Please refer to project ELT220

Approach FY19 Timeline



Go/No-Go Decision Point: If a high-speed motor topology candidate can yield a significant improvement in power density, proceed with the mechanical and thermal design of this candidate.

Key Deliverables: Design information for the selected motor candidate and annual report.

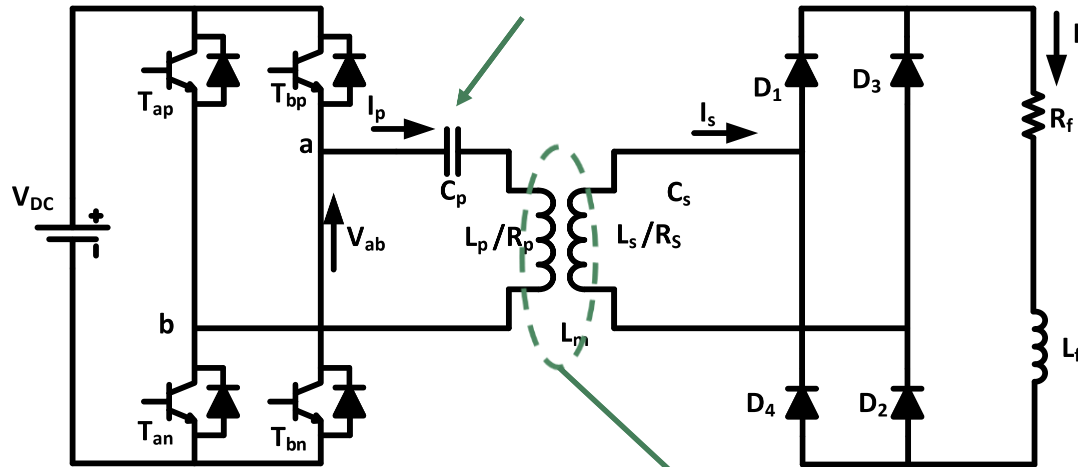
Any proposed future work is subject to change based on funding levels

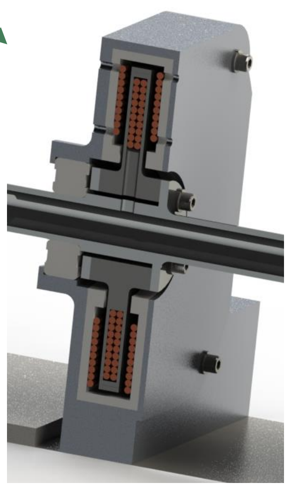
Technical Accomplishments – FY19

Demonstrated the stability of the open-loop control of the proposed contact-less excitation system for WRSM

- With open-loop control, no current measurement on the rotating part is needed.
- Primary series capacitor compensation is found to be sufficient. Addition of capacitor on the rotating secondary can be avoided without compromising power transfer capability and stability.
- The condition of stability of the open-loop control of excitation system was theoretically established ($R_f > \frac{16}{\pi^2}\,\omega L_s$).

Series resonant compensation on primary side only

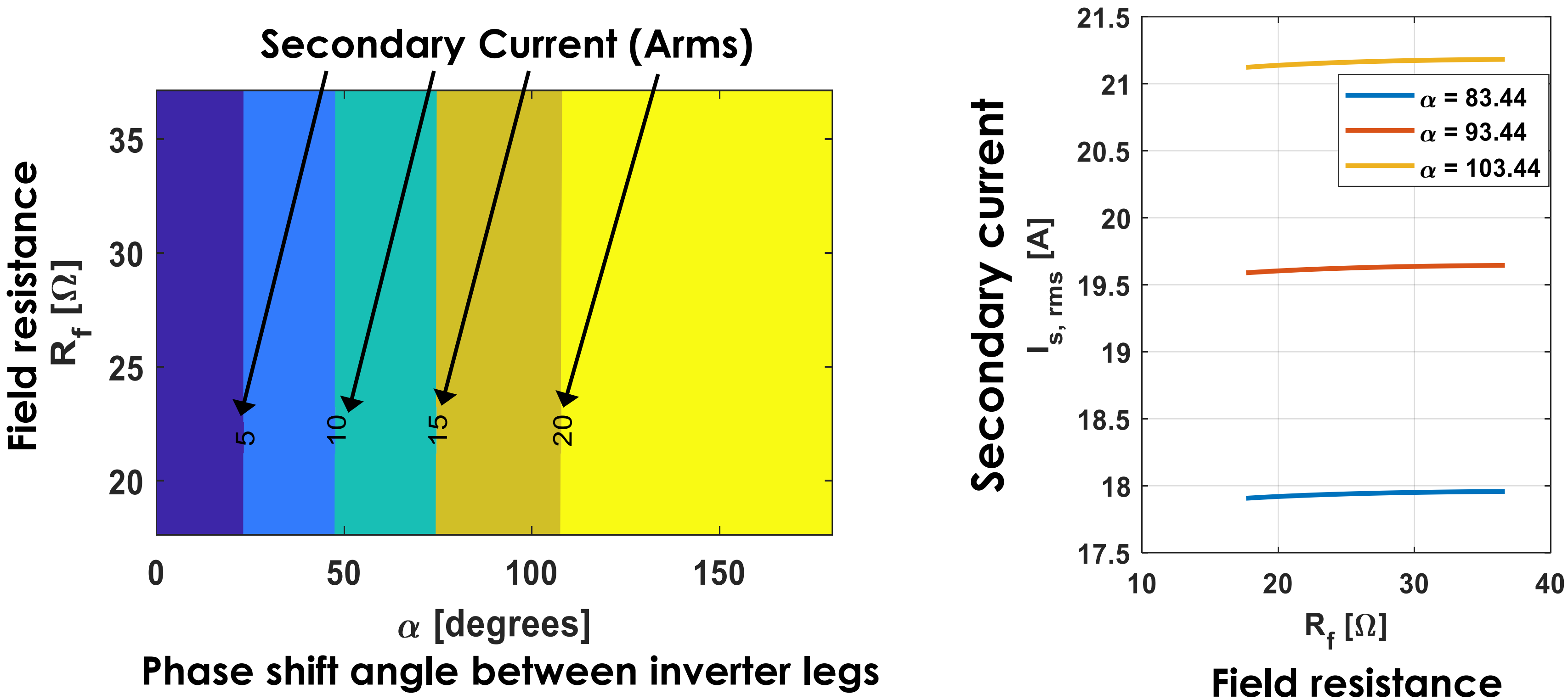




If the condition of stability is verified, the stability of the zero dynamics is independent of the value of the field winding resistance.

Technical Accomplishments – FY19

Demonstrated the stability of the open-loop control of the proposed contact-less excitation system for WRSM

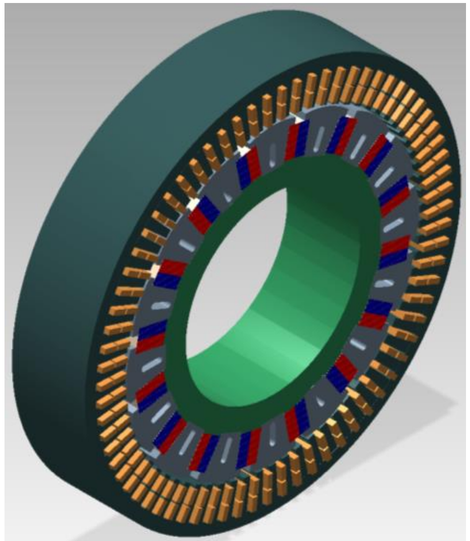


- The field winding current can be controlled with the inverter phase shift angle.
- The field winding current is not affected by the variation of field winding resistance due to temperature (for a temperature swing from -50°C to 150°C).

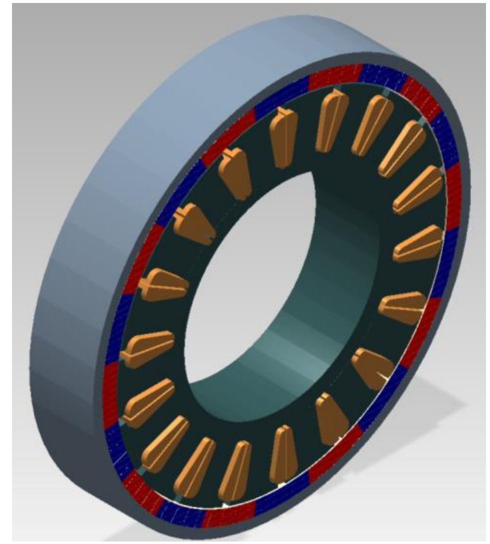
Technical Accomplishments – FY19

Completed design of heavy rare-earth-free permanent magnet motors

Spoke Internal Permanent Magnet (IPM) 72 slots, 16 poles, Distributed winding



- Reluctance torque helps maximize torque density
- Low exposure of the lower coercivity heavy rare-earth-free PMs to demagnetizing armature field
- Fractional 1.5 slot per pole per phase and rotor pole shaping to reduce torque ripple (No skewing)



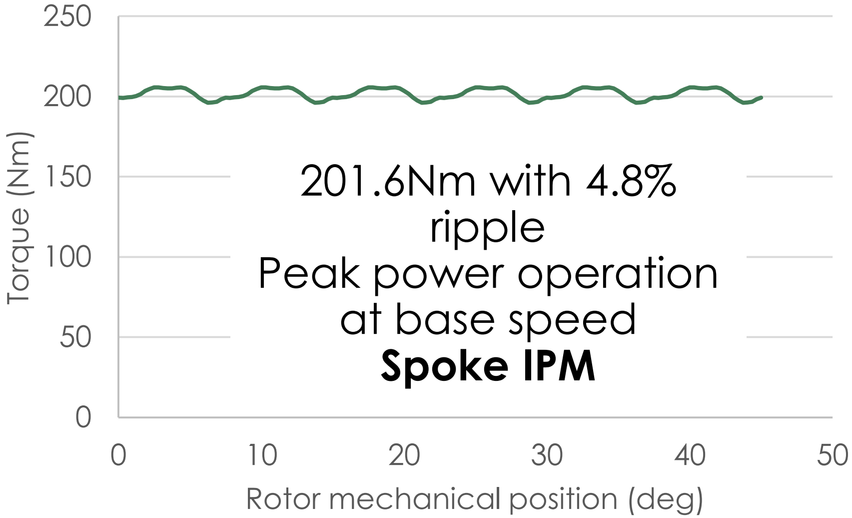
Outer rotor Surface Permanent Magnet (SPM) 18 slots, 20 poles, Concentrated tooth winding

- Rotor yoke is retaining the magnets
- Airgap radius is at the outermost possible, to maximize the torque density
- Tooth winding: high direct inductance for flux weakening and low torque ripple
- Halbach magnet arrangement:
  - Maximize airgap flux density
  - Reinforce demagnetization resistance

Both motors have potential to meet the DOE ELT 50kW/L power density target

Technical Accomplishments – FY19

Completed design of heavy rare-earth-free permanent magnet motors

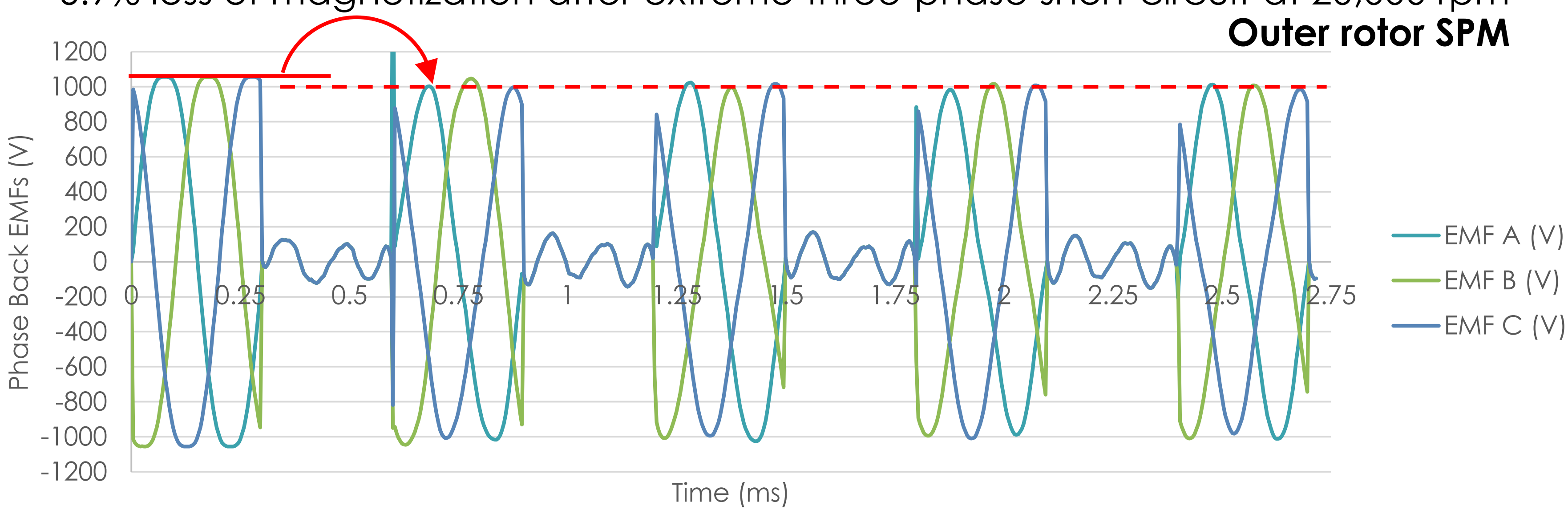


Both motors

- meet peak torque and torque ripple requirement
- resistant to demagnetization even under extreme three-phase short-circuit fault at top speed

6.9% loss of magnetization after extreme three-phase short-circuit at 20,000 rpm

Outer rotor SPM



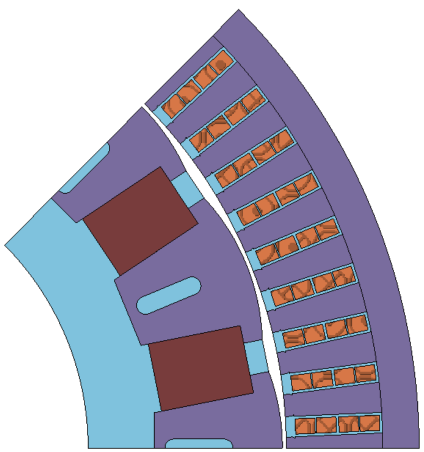
Technical Accomplishments – FY19

Evaluated the Impact of UCC winding conductivity on traction motors performance

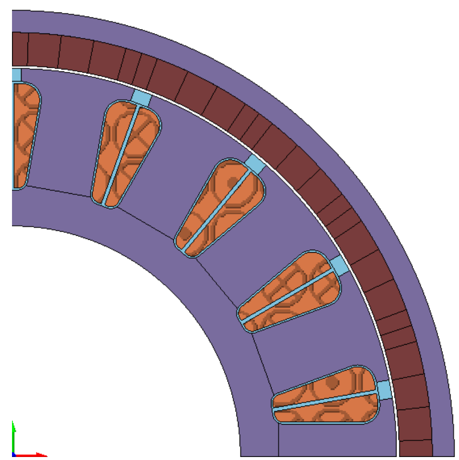
- Three topologies of heavy rare-earth-free permanent magnet (PM) motors are analyzed.
- The motors have the same outer diameter of 242mm and designed for 100kW peak power.
- The conductivity of the winding is varied up to 2X the copper's.
- The heat load in the slots are kept constant.

Reference designs with copper winding

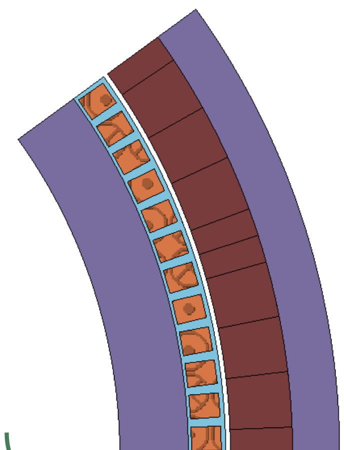
Inner Rotor Spoke IPM



Outer Rotor SPM motor



Outer Rotor Slotless SPM

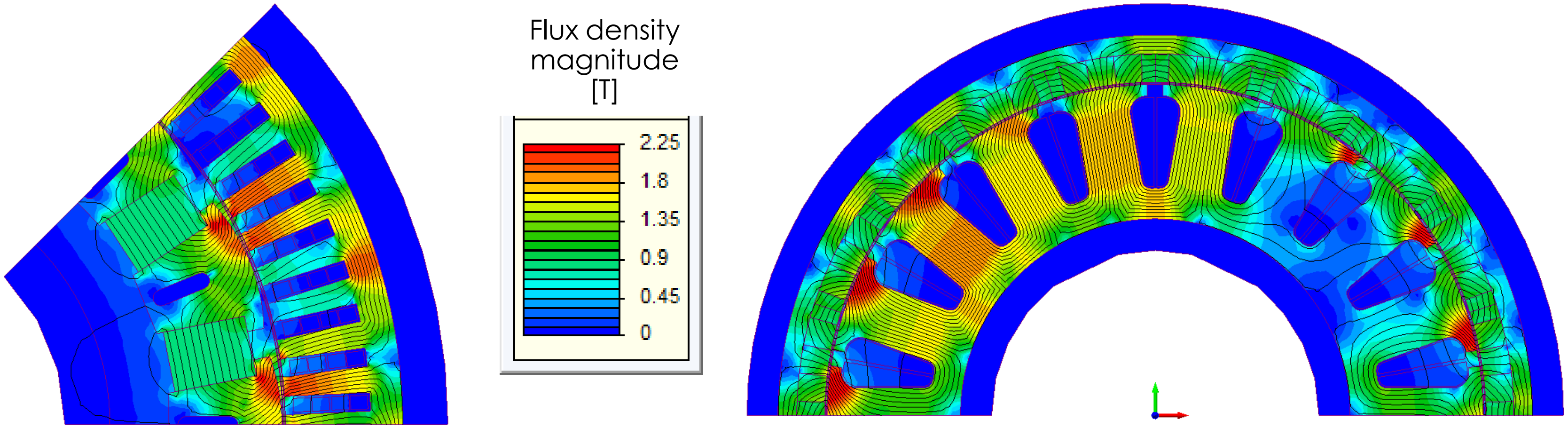


Same motors presented above
Affected by magnetic saturation

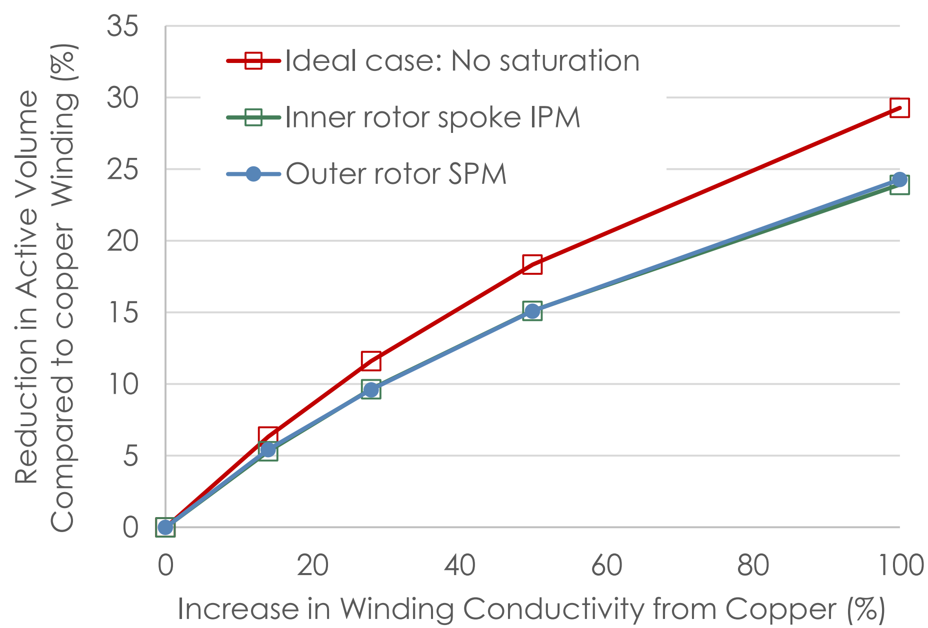
No magnetic saturation

Technical Accomplishments – FY19

Evaluated the Impact of UCC winding conductivity on traction motors performance – Spoke IPM and outer rotor SPM

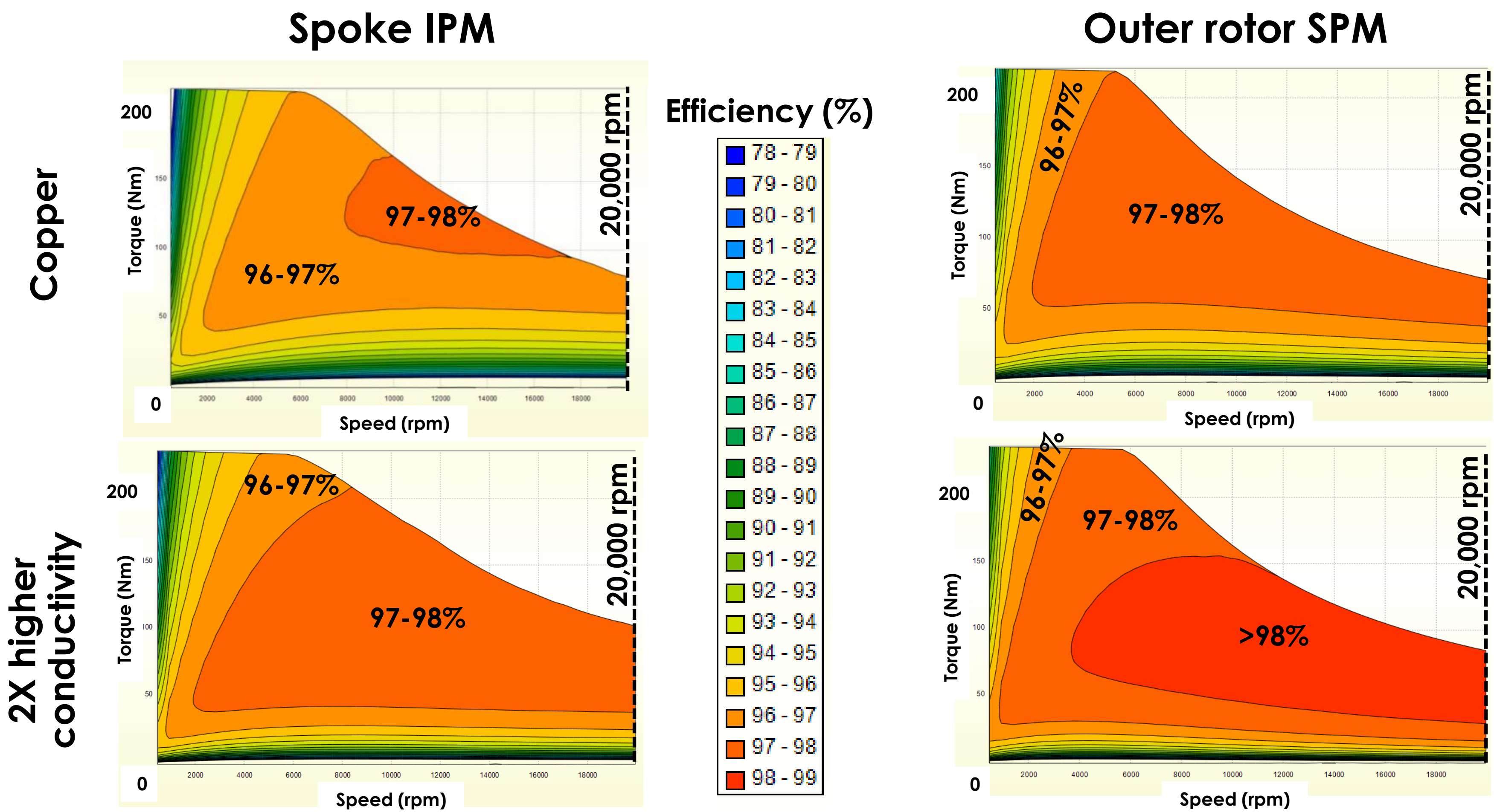


- The volume reduction is lower than the ideal forecast because of the magnetic saturation effect in the steel.
- 10% reduction in active volume for 30% improvement in UCC conductivity.
- UCC can help reduce the motor volume to meet the power density target.



Technical Accomplishments – FY19

Evaluated the Impact of UCC winding conductivity on traction motors performance – Spoke IPM and outer rotor SPM

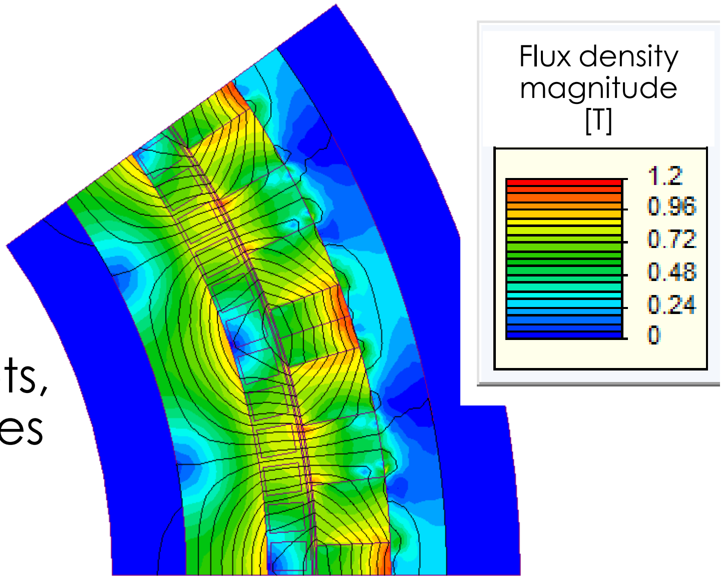


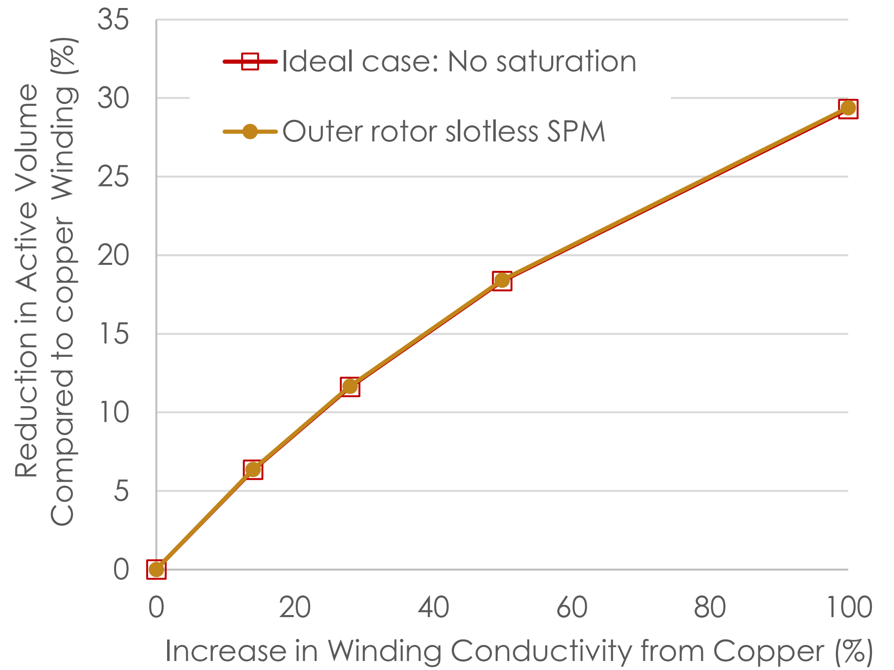
As the winding conductivity increases, the high efficiency operating area (≥ 97%) is enlarged toward the light load as well as high speeds

Technical Accomplishments – FY19

Evaluated the Impact of UCC winding conductivity on traction motors performance – Outer rotor slotless SPM

120 slots,
20 poles

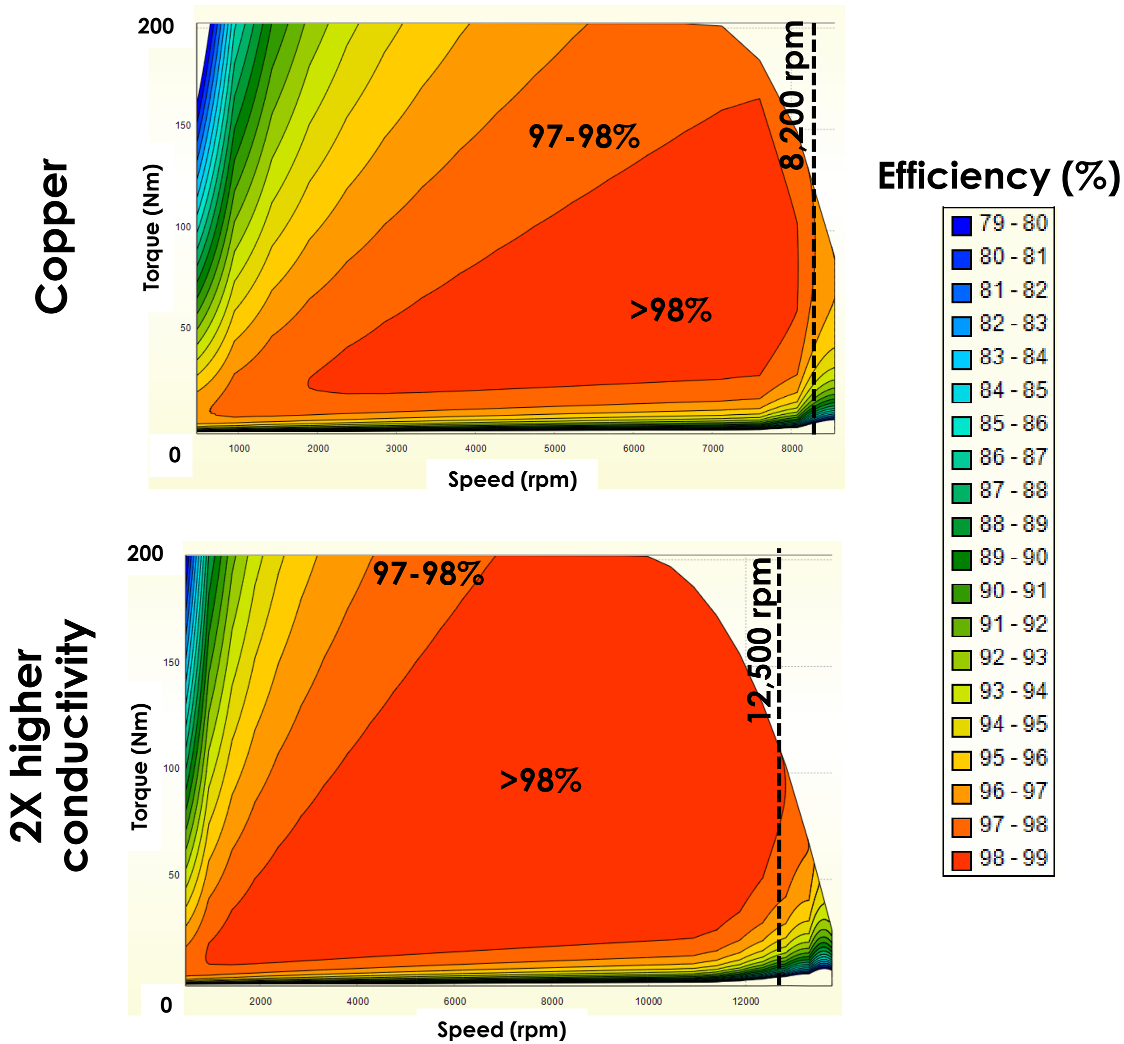




- Low magnetic loading because of long magnetic airgap:
  - Power density is lower than the conventional motor,
  - **Not affected by magnetic saturation**: the impact of the winding conductivity reaches the theoretical expectation.
- 12% reduction in active volume for 30% improvement in UCC conductivity.

Technical Accomplishments – FY19

Evaluated the Impact of UCC winding conductivity on traction motors performance – Outer rotor slotless SPM



- Slotless SPM cannot achieve a constant power operation up to 20,000 rpm because of low inductance
- As winding conductivity increases, efficiency is improved toward high speed area and speed range is increased

Responses to Previous Year Reviewers' Comments

This project is a new start.

Collaboration and Coordination with Other Institutions

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

Remaining Challenges and Barriers for FY19

- Robustness of the mechanical assembly for the selected high-speed non-heavy rare-earth traction motor
- Thermal viability of the selected high power density non-heavy rare earth traction motor

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

Proposed Future Research

- **Remainder of FY19**
  - Perform mechanical assembly and cooling system design on the selected non-heavy rare-earth motor candidate to ensure effective cooling and mechanical viability at 20,000 rpm
- **FY20**
  - Validate the performance of the selected non-heavy rare-earth motor experimentally
  - Design an integrated rotary transformer-based excitation system for a wound rotor synchronous traction motor

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 PM to enable high power density and reduce cost of non-heavy rare-earth PM motors
  - Use PM motor technologies that are resistant to demagnetization
  - Integrate contact-less excitation system into WRSM to enable the adoption of this low-cost non-PM motor for vehicle traction
- **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:**
  - Established the stability of the contactless rotary transformer-based excitation system
  - Designed two non-heavy rare-earth high-speed traction motors that can meet the DOE ELT 2025 power density target of 50kW/L
  - Investigated the impact of UCC winding conductivity on the power density and performance of several traction motor topologies
- **Future work:**
  - Validate the performance of the selected non-heavy rare-earth motor experimentally
  - Design an integrated rotary transformer-based excitation system for a wound rotor synchronous traction motor

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