Non-Rare Earth Electric Motors

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Overview

Timeline

- Start: FY18
- End: FY20
- 17% complete

Barriers

- Magnet cost and rare-earth element price volatility
- Power density and efficiency of non-rare-earth motors
- 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 received in FY17: $0K
- Funding for FY18: $648K

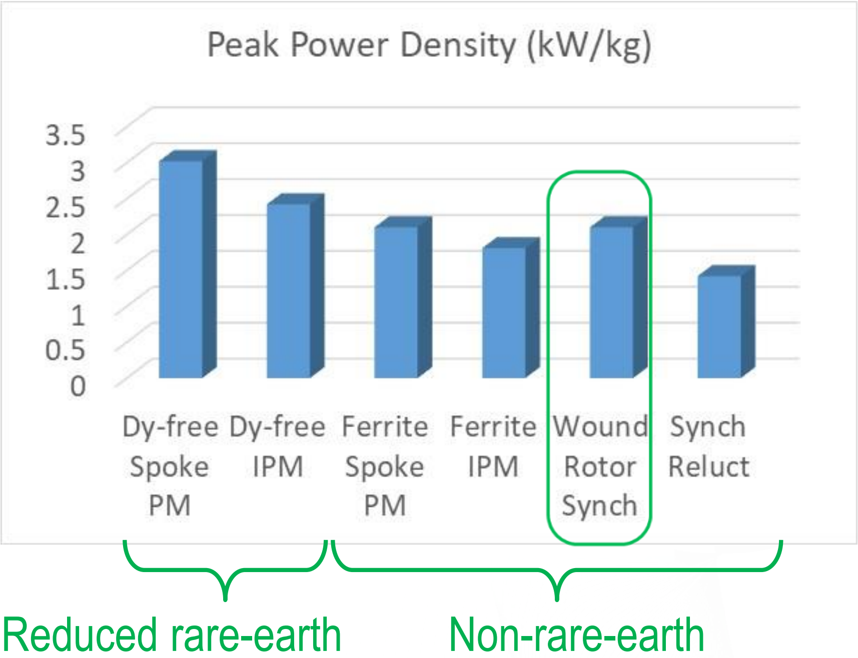
Partners

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

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

Project Objective and Relevance

- **Overall Objective**
  - Enable the use of non-rare-earth traction motors
  - Analyze the impact of new advanced materials for non-rare-earth electric motors



- **FY18 Objective**
  - Evaluate a rotary transformer for contact-less power transfer to rotor excitation of wound rotor synchronous motors (WRSM)
  - Investigate impact of ultraconducting copper winding on the power density and efficiency of traction motors
  - Design an electric motor that uses the best properties of AlNiCo permanent magnets (PM) developed by Ames Laboratory

(*) 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

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Milestones

Date	Milestones and Go/No-Go Decisions	Status
Dec 17	Milestone: Downselect rotary transformer technology.	Completed
Mar 18	Go/No-Go decision: If the combined power density of motor and rotary transformer indicates potential to meet the DOE ELT 2025 targets, proceed with designing and building prototype.	Completed
Jun 18	Milestone: Complete the build of rotary transformer prototype to evaluate power capability, efficiency and size.	On track
Sep 18	Milestone: Complete annual report including evaluation results.	On track

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Approach/Strategy

- **Enable adoption of the non-rare-earth electric motors for traction to achieve the DOE ELT 2025 targets:**
  - WRSM:
    - Non-permanent magnet option; thus, very cost effective and can help achieve the 30% cost reduction DOE ELT target for 2025.
    - Its high reliability will contribute to the achievement of the DOE ELT 2025 life expectancy target of 300,000 miles.
  - Non-rare-earth AlNiCo PM motor:
    - AlNiCo magnet is a low cost alternative and can help achieve the DOE ELT 2025 $3.30/kW cost target.
    - AlNiCo has the best high temperature resistance among PM materials. This can help improve the reliability of traction electric motors to achieve the DOE ELT 2025 300,000 mile lifetime target.
- **Improve power density and performance of non-rare-earth traction electric motors by using ultra-conducting copper winding:**
  - 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.

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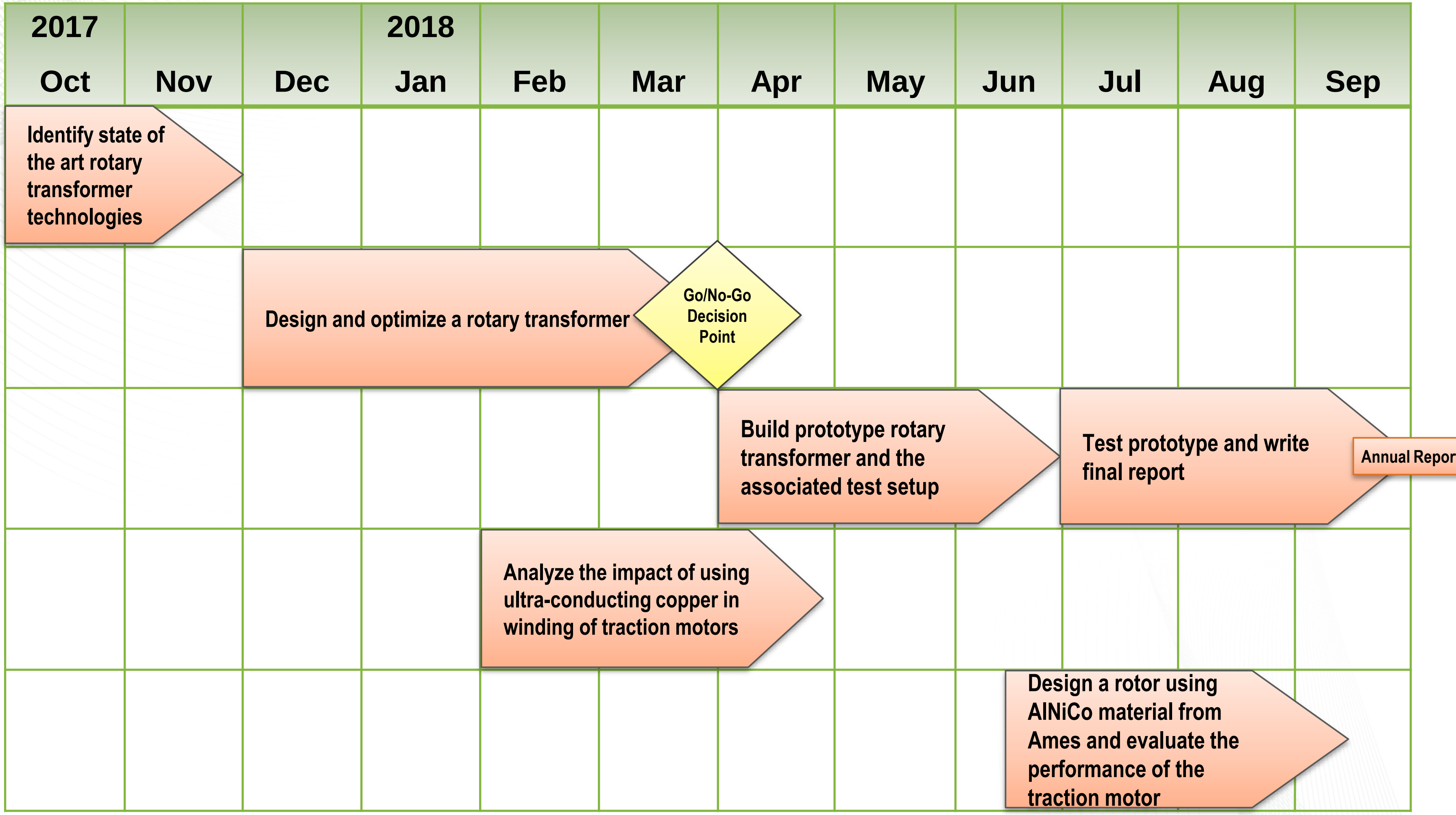
Approach FY18 Timeline



Go/No-Go Decision Point: If the combined power density of motor and rotary transformer indicates potential to meet the DOE ELT 2025 targets, proceed with designing and building prototype.

Key Deliverable: Proof of concept rotary transformer prototype and final report.

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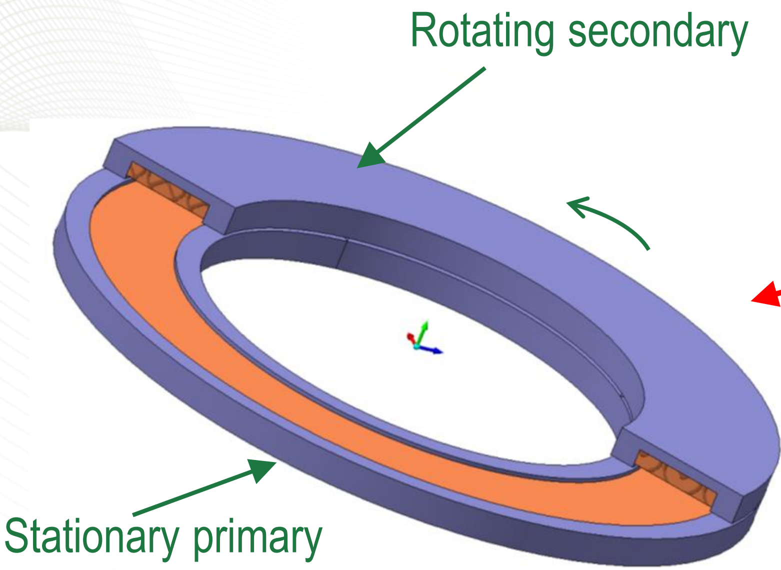
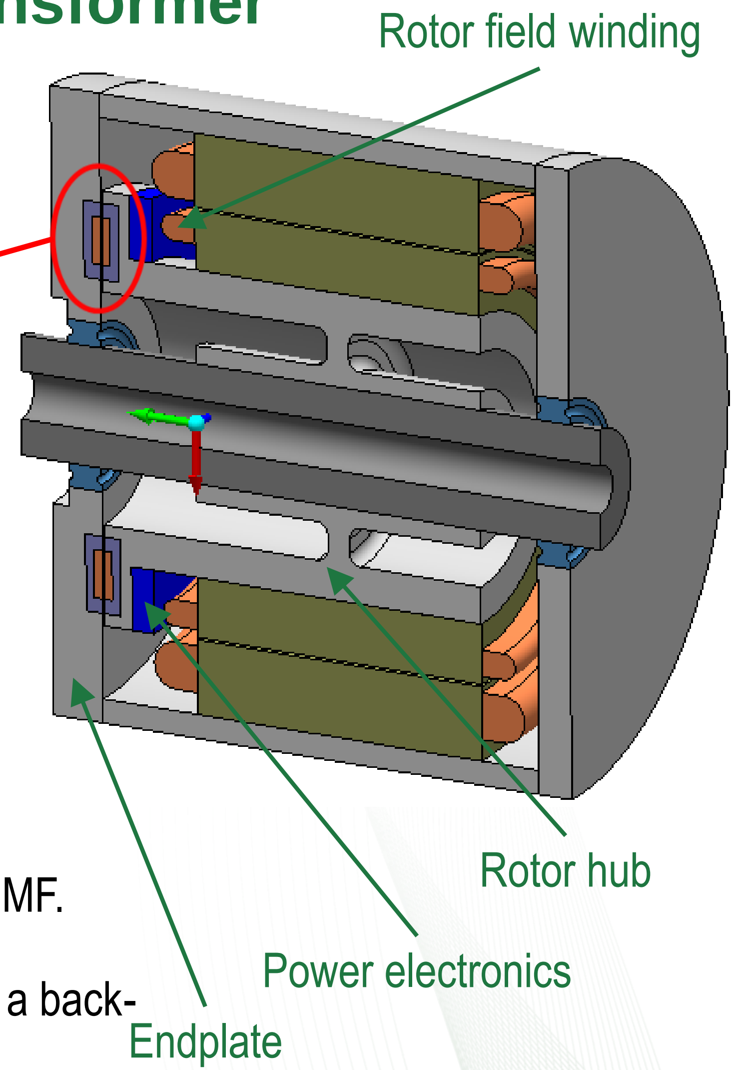
Technical Accomplishments – FY18
Principle of operation of a rotary transformer



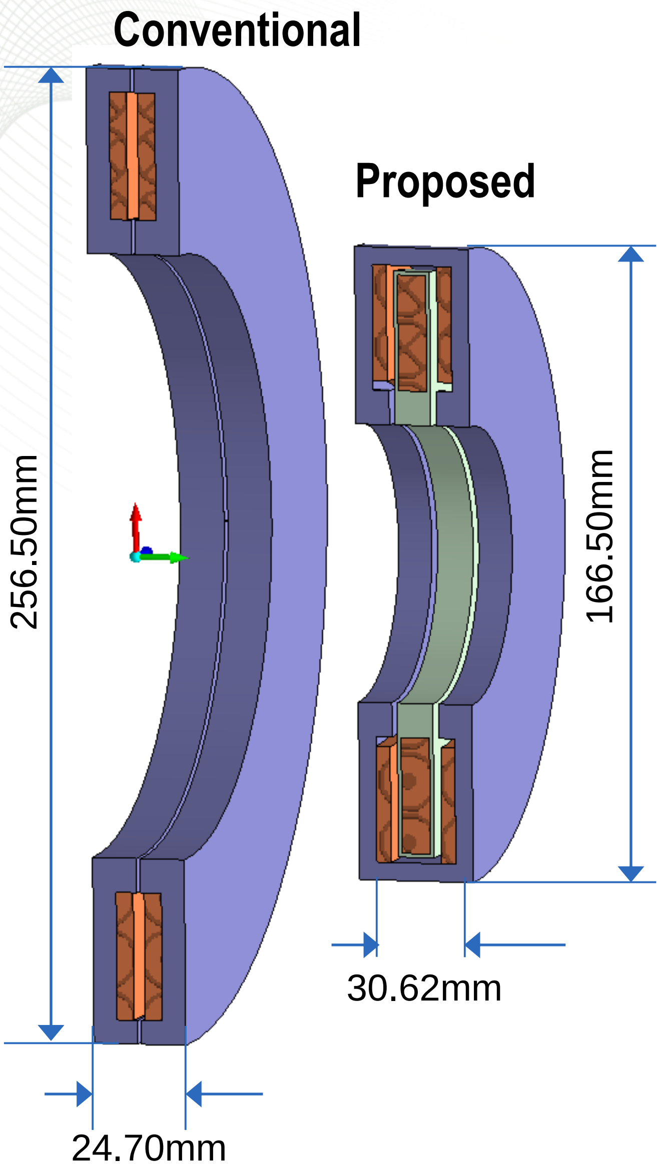


The rotation on the secondary coil does not change the flux it links from the primary coil.

⇩

- The rotation of the secondary does not create back-EMF.
- Only the time variation of the primary current induces a back-EMF in the secondary coil.
- This induced back-EMF is independent of the rotational speed of the secondary.

Technical Accomplishments – FY18
Proposed Novel Rotary Transformer Topology



Only small amount of power covering the ohmic loss in the rotor field winding is transferred through the rotary transformer.

10kW designs	Conventional	Proposed
Airgap	• Small (1 mm) • Requires tight control of airgap tolerance (precision manufacturing)	• Large (1.5 mm) • Eliminates airgap tolerance constraints and allow high speed operation
Rotor material	• Ferrite • Heavy and brittle. • High centrifugal stress and retention issue at high speed • Core loss in rotor	• Composite • Lightweight and mechanically strong • Low centrifugal stress at high speed • Non-conductive, thus no core loss in rotor
Volume (dm^3)	**1.28**	**0.67**

- 1.9X lower volume.
- Non-conductive and non-magnetic composite rotor support to avoid core loss and minimize centrifugal stress.

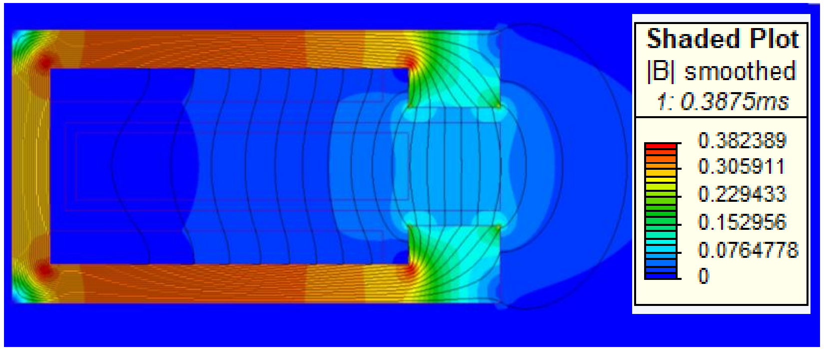
Technical Accomplishments – FY18
Implemented a parameterized computational code for geometry optimization

To best explore the design space, a computational program code that models the rotary transformer system for any combination of geometry parameters and any operating conditions is indispensable.

The program uses a coupled transient electromagnetic finite element model and electrical circuit model including resonant compensation circuits and rectifier.

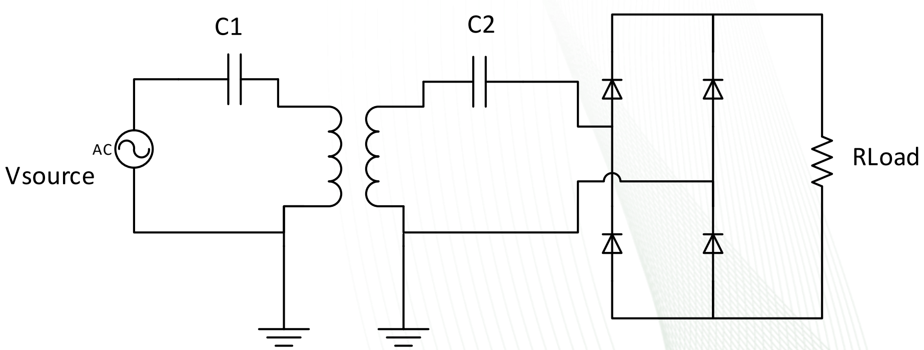
Implemented parameterized computational codes for modeling and optimization:

- **Input:** rotary transformer geometry parameters and operating conditions
- **Output:** mutual, self and leakage inductances, coupling factor, compensation capacitors, output power, loss, and efficiency



Electromagnetic Finite Element Model

Electrical Circuit Model



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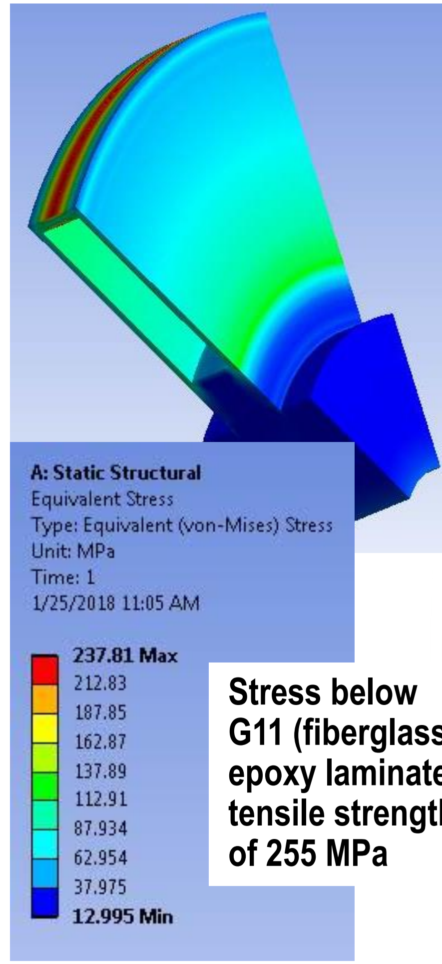
Technical Accomplishments – FY18
Validated mechanical integrity of the composite rotor design at high rotational speed

It is **critical** to make sure that:

- The rotor does not fly apart due to centrifugal forces at high rotational speed.
- The composite rotor support material (G11) does not break due to centrifugal stress at high speed.
- Any deformation due to centrifugal stress is extremely small compared to the airgap not to cause rub between rotor and stator.

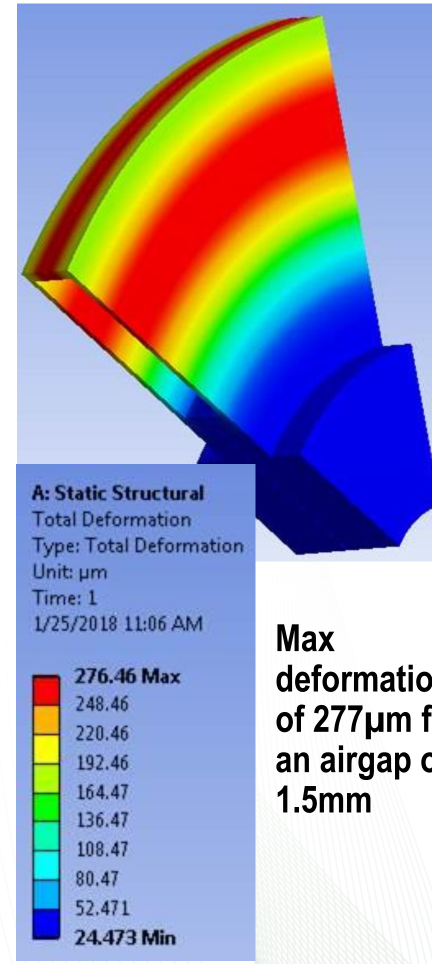
Rotor stress is low enough at top speed to make the rotor design using composite material viable

Stress



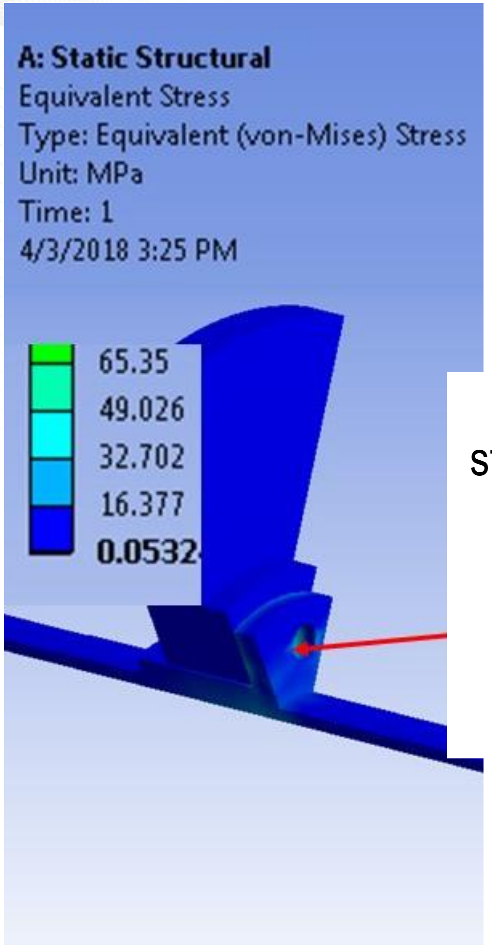
Stress below G11 (fiberglass epoxy laminate) tensile strength of 255 MPa

Deflection



Max deformation of 277µm for an airgap of 1.5mm

Technical Accomplishments – FY18
Validated mechanical integrity of shaft design at high rotational speed



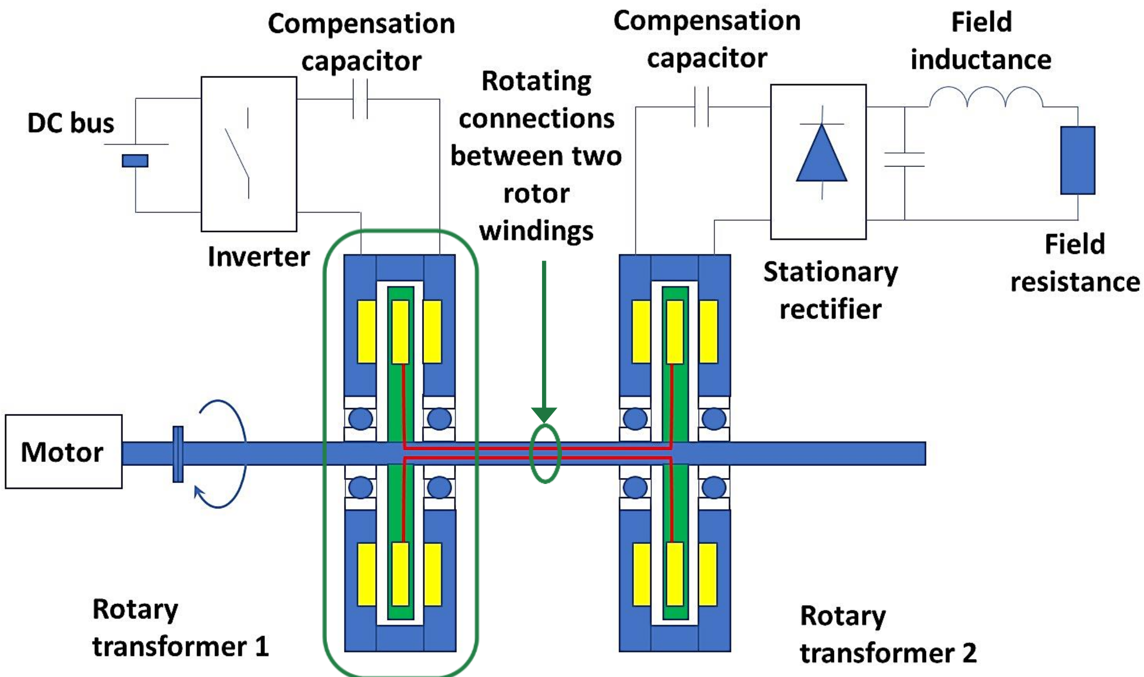
Stress in stainless steel shaft below 60MPa (Tensile strength of 215MPa)

It is critical to make sure the shaft does not break under the centrifugal stress applied by the rotor weight at high rotational speed.

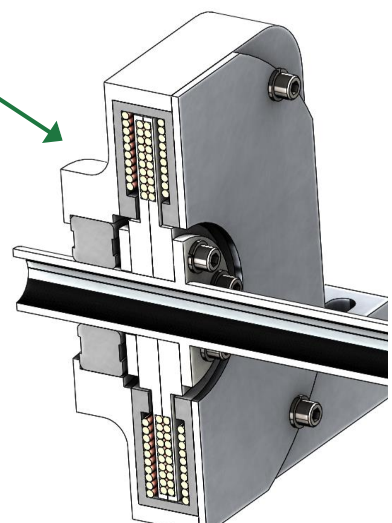
This verification is done by performing a mechanical stress analysis on the shaft with the rotors attached to it.

Stress is significantly lower than tensile strength: shaft design is viable

Technical Accomplishments – FY18
Completed the preliminary proof of concept test bench design



Rotary transformer



The prototype is built to validate the operation of a rotary transformer exciting a high speed rotor without contact.

Power transfer capability and efficiency will be measured.

Controllability of the rotor current without direct current measurement will be evaluated.

Design highlights

- 1.5mm mechanical airgap
- Litz wire winding
- Composite rotors
- High speed test bench

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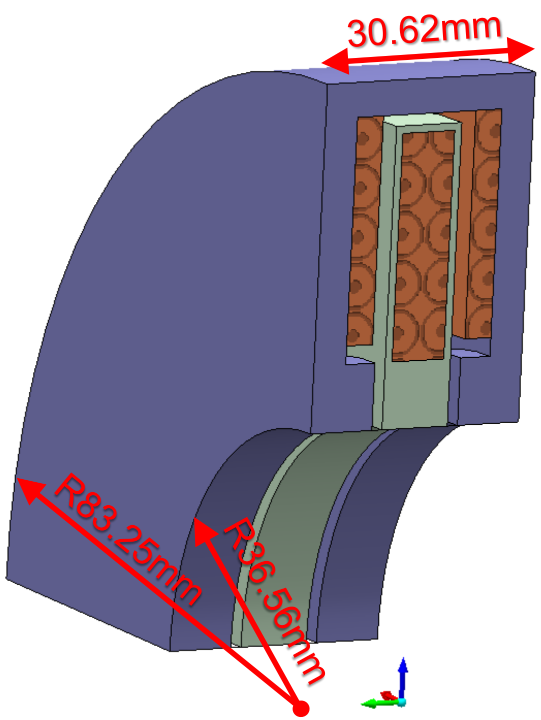
Technical Accomplishments – FY18
Completed optimization of a 10kW rotary transformer design

The parameterized computational code was used to optimize the geometry of the rotary transformer to achieve an output power of 10kW while minimizing the volume.

The magnetic loading of the ferrite core was constrained to be below 0.35T.



Optimized design

10kW output

98% efficient

Unity input power factor

Parameters	
Primary self inductance (mH)	0.070
Primary compensation capacitor (μF)	0.902
Secondary self inductance (mH)	0.064
Secondary compensation capacitor (μF)	0.997
Coupling factor	0.967
Mutual inductance (mH)	0.065
Total leakage inductance (μH)	4.576
Performance	
Freq	20000.00
Source voltage (Vrms)	162.63
Source current (Arms)	62.47
Input power (W)	10159.39
Average output power (W)	**10000.93**
Average load voltage (V)	449.64
Average load current (A)	17.99
Eff%	**98.23**

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Technical Accomplishments – FY18
Evaluated the impact of using ultraconducting copper in the winding of WRSM

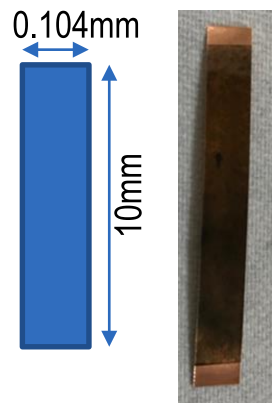
Initiated the evaluation of the impact of ultra-conducting copper on the performance of electric machines for traction.

Designed two wound rotor synchronous machines with foil windings in both rotor and stator:

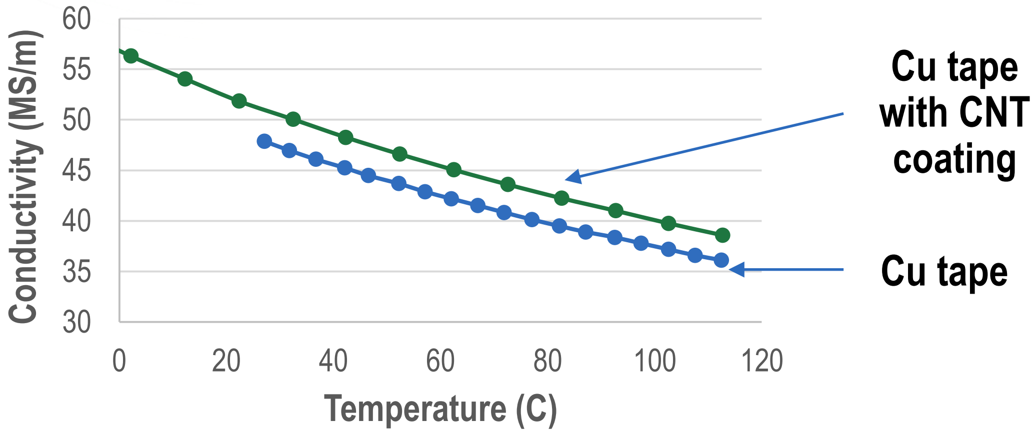
- The first design uses conventional copper foil and is used as a reference.
- The second design uses CNT coated copper foil.

Wire and bar winding designs using conventional and ultra-conducting copper will be analyzed too.

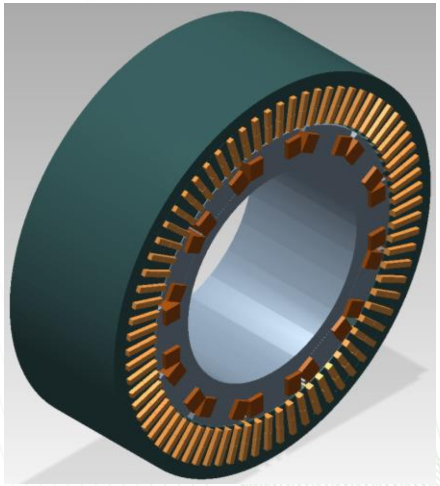
Cu tape with CNT coating



Please refer to project ELT071



WRSM with foil windings in both stator and rotor



Temperature (°C)	Reference Copper Conductivity (MS/m)	CNT/Cu Conductivity (MS/m)
150	32.60	34.89

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Technical Accomplishments – FY18
Evaluated the impact of using ultra-conducting copper winding in WRSM

	Reference Copper	CNT/Cu
Outer diameter (mm)	242.00	242.00
Stack length (mm)	85.62	79.67
Total mass (kg)	22.07	20.71
Windings		
Stator slot fill factor (%)	56.00	56.00
Rotor slot fill factor (%)	66.93	66.93
Performance under continuous rated power		
Torque (N·m)	201.04	201.04
Output power (kW)	100.00	100.00
Efficiency (%)	92.97	92.99

For the same power, the current ultra-conducting copper samples enable

6% reduction in mass

7% reduction in volume

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 rotor and rotary transformer cooling methods • Measure longitudinal and transversal thermal conductivity of Ultra-conducting copper samples from ORNL.
AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY	• Provide ORNL with AlNiCo magnet material with their magnetic, electrical and mechanical properties (for traction motor design).

Remaining Challenges and Barriers for FY18

- Precision of compensation components (capacitors) to get the resonant frequency.
- Designing a traction PM motor using Ames' AlNiCo magnets while minimizing demagnetization risk during construction and operation.
- Getting wire or bar conductors from ultra-conducting copper foils.

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

Proposed Future Work

- **Remainder of FY18**
  - Evaluate the prototype for efficiency and power transfer capability
  - Design and characterize a traction PM motor using Ames' AlNiCo magnet

- **FY19**
  - Integrate the rotary transformer and rotating rectifier into a WRSM.
  - Experimentally validate the wound rotor synchronous traction motor with an integrated rotary transformer and rectifier

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

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Summary

- **Relevance:** Proposed a rotor excitation technology that enables low cost WRSM to achieve the DOE ELT 2025 targets of 50kW/L, $6/kW, and 300,000 mile lifetime.
- **Approach:**
  - Use contactless rotor excitation to enable the adoption of the low cost non-permanent magnet WRSM in vehicle traction.
  - Use newly developed materials (AlNiCo and ultra-conducting copper) to enhance performance of non-rare-earth traction motors.
- **Collaborations:**
  - **NREL:** Thermal modeling analysis to verify the thermal viability of the rotary transformer design.
  - **AMES:** Providing characteristics of high performance AlNiCo to be used in traction motor design.
- **Technical Accomplishments:**
  - Proposed novel rotary transformer topology.
  - Implemented a parameterized computational code for geometry optimization.
  - Validated mechanical integrity of the composite rotor design at high rotational speed.
  - Completed the preliminary proof of concept test bench design.
  - Completed optimization of a 10kW rotary transformer design.
  - Evaluated the impact of ultra-conducting copper based winding in traction motors.
- **Future Work:** Integrate rotary transformer and rotating rectifier into an actual wound rotor synchronous traction machine.

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