Oak Ridge National Laboratory

# High-Fidelity Multiphysics Material Models for Electric Motors (Keystone Project #2)

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# Overview

## Timeline

- Start Date: FY19
- End Date: FY21
- 25% Complete

## Budget

- Total project funding
  - DOE share – 100%
- Funding for FY19: $337K

## Barriers

- **Power Density**: Achieving 50 kW/L will require understanding and quantifying the physics of materials and their interactions under extreme power and temperature
- **Reliability**: Reaching 300,000 mile lifetime will require understanding non-ideal material behaviors to predict and mitigate failure modes due to – for example – higher bus voltages and higher temperature operation
- **Cost**: Reducing cost to $3.3/kW will require high fidelity virtual prototyping of new motor designs to minimize expensive materials while meeting power density and reliability targets

## Partners

- **Ames Laboratory**
- **National Renewable Energy Laboratory**
- **Sandia National Laboratories**
- **ORNL Team Members:** Randy Wiles, Emre Gurpinar, Jonathan Wilkins

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

# Relevance – Project Objectives

**Overall Objective**: Develop high-fidelity, high-performance computing (HPC) tools for electric motor design, optimization, and virtual prototyping

- Support innovations in electric motor designs by increasing optimization throughput by developing open-source, high-performance computing tools
- Develop new and improved material models to better predict electric motor behavior due to complex multi-physical interactions
- Use high-performance computing to address reliability concerns due to non-ideal component behavior including:
  - Voltage transients due to switching
  - Localized heating and demagnetization
  - Reduced rare-earth magnets

**FY 2019 Objectives**:

- Build a test fixture for accurate measurement of low rare-earth content magnets
- Develop fast uniaxial hysteresis characteristic modeling methods
- Evaluate vector hysteresis mathematical modeling strategies
- Characterize and model Neodymium-Iron-Boron (NdFeB) and Aluminum-Nickel-Cobalt (AlNiCo) magnets using new techniques

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# FY19 Milestones and Go/No-Go Decision

| Date | Milestones and Go/No-Go Decision | Status |
|---|---|---|
| Q1 | Milestone: Identify the most important physical phenomena limiting the accuracy of electric motor simulation software for high-speed electric machines | Complete |
| Q2 | Milestone: Complete fabrication of permanent magnet characterization fixture subcomponents | Complete |
| Q3 | Milestone: Prototype control strategy and data acquisition methods for permanent magnet characterization fixture | On Track |
| Q4 | Go/No-Go Decision: If vector magnetization model improves demagnetization prediction accuracy, add transverse DC bias capability to permanent magnet characterization fixture | On Track |

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# Approach

**Goal:** Support early stage research into high power density motors by developing a high fidelity HPC optimization tool

- Reduce modeling error to **<5%** without heuristic 'corrections'
- Increase optimization throughput by **10x**

**Impact and Uniqueness:**

- Focus on multiphysics interactions
  - Phenomena previously too complex to model and solve efficiently
  - New and existing materials
- Tool for pursuit of DOE ELT 2025+ goals
  - Open source software
  - Facilitate access to DOE HPC resources for high power density motor optimization

## ***OeRSTED*** *Development Process*

**O**ak **R**idge **S**imulation **T**oolkit for **E**lectromagnetic **D**evices

Identify Modeling Deficiency → Research Mathematical Descriptions → Develop Computational Techniques → Validate with Experiments → Incorporate into Simulation Tool → Improve Motor Design

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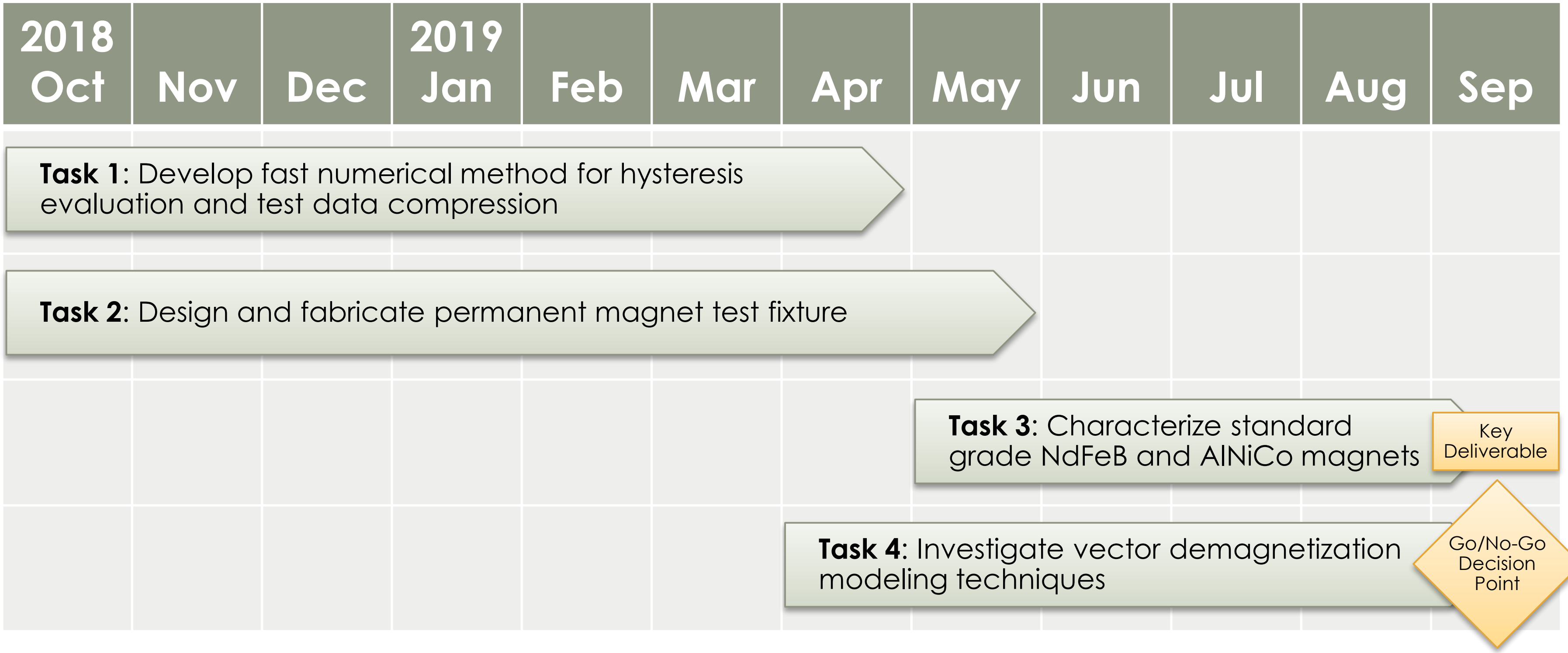
# FY19 Timeline




**Go/No-Go Decision Point:** If vector magnetization model improves demagnetization prediction accuracy, add transverse DC bias capability to permanent magnet characterization fixture

**Key Deliverable:** Test data and analysis of permanent magnet vector demagnetization characteristics

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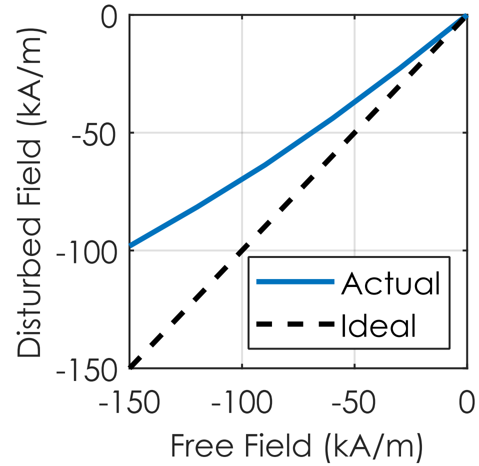
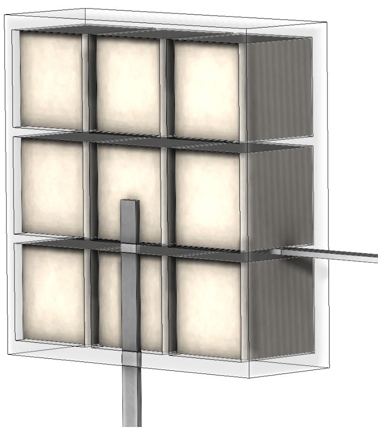
# Technical Accomplishments – FY19

## Developed Test Method for Multi-axis Permanent Magnet Characterization

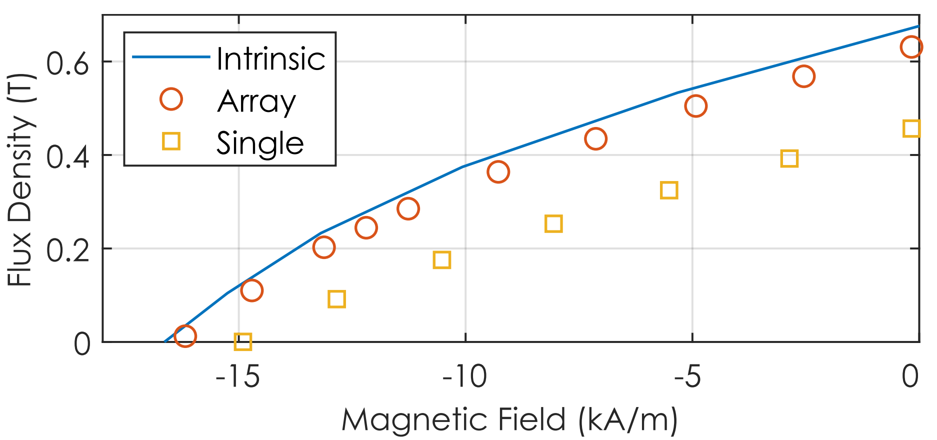
- **Goal**: Improve motor modeling fidelity
- **Challenge**: Standard magnet characterization methods are unsuitable for measurement of multi-axis hysteresis measurements and error prone when measuring $BH_{max}$ for low rare earth content magnets
- **Solution**: Developed a novel split magnet array measurement technique utilizing ultra-thin 3-axis hall effect probes
- **Impact**: Improved multi-axis measurement of permanent magnet demagnetization characteristics




*Field intensity applied to a high permeability magnet has a nonlinear relationship with the free field intensity*



*CAD schematic of the split magnet measurement technique showing magnetic field sensor placement*

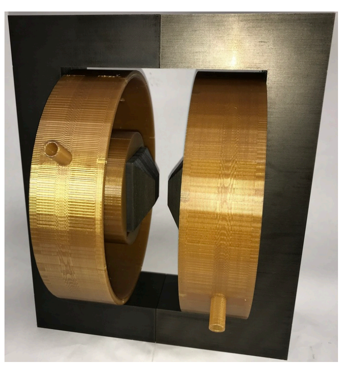



*Measuring the demagnetization characteristic on a single magnet results in significant errors compared to the split magnet array technique*

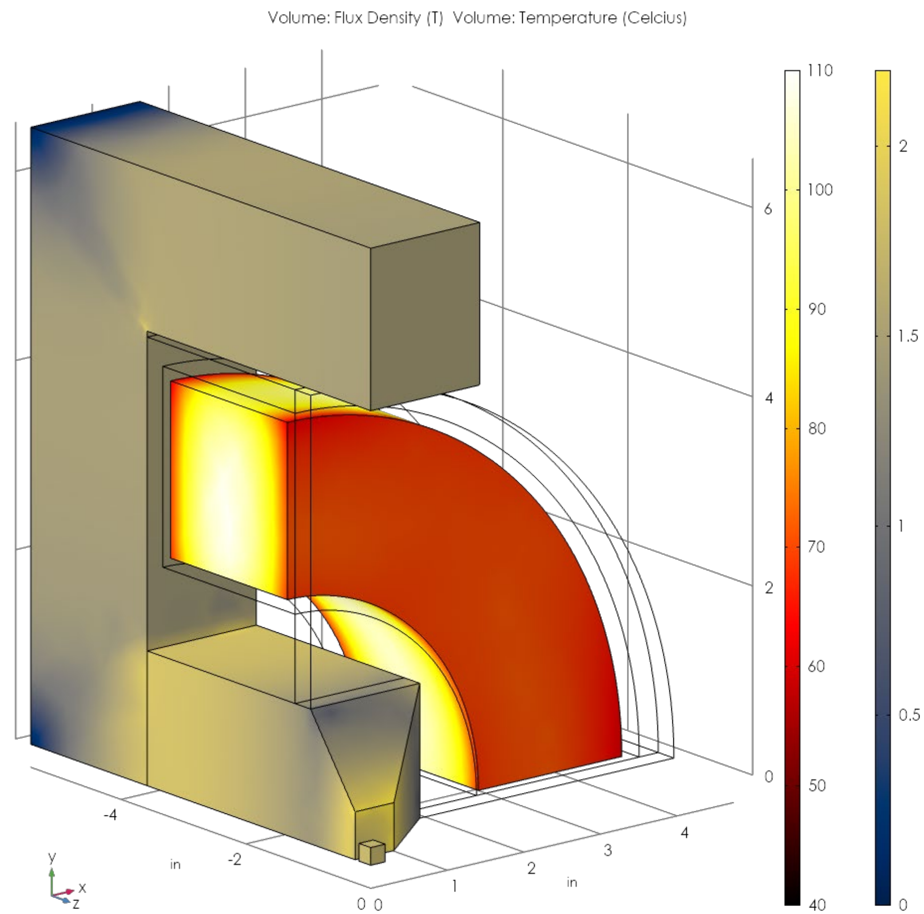
# Technical Accomplishments – FY19

## Designed a Permanent Magnet Characterization Fixture

- **Goal**: Improve motor modeling fidelity
- **Challenge**: Standard permanent magnet characterization equipment is not suitable for accurately testing demagnetization characteristics along 3 unique axes
- **Solution**: Developed a custom fixture for implementing an improved measurement technique on cube shaped magnets
- **Impact**: Improved understanding of vectoral characteristics of permanent magnets



*Magnetic core and Ultem winding housing*

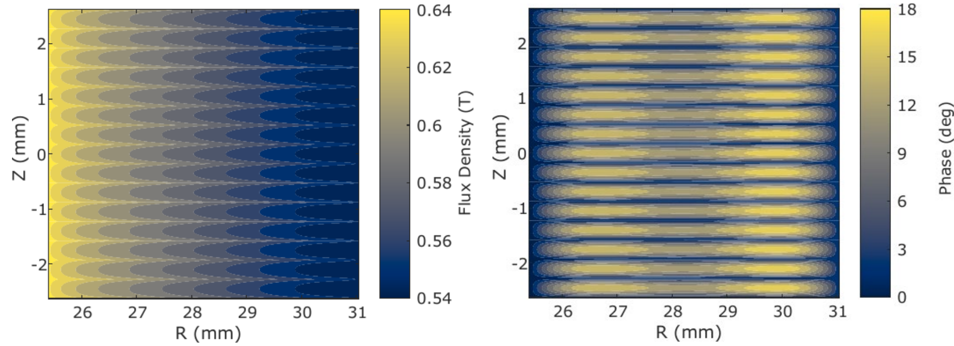



*Simulation of the permanent magnet test fixture demonstrating the ability to apply a constant 1.8T demagnetizing flux to a permanent magnet while maintaining peak winding temperature below 110C*

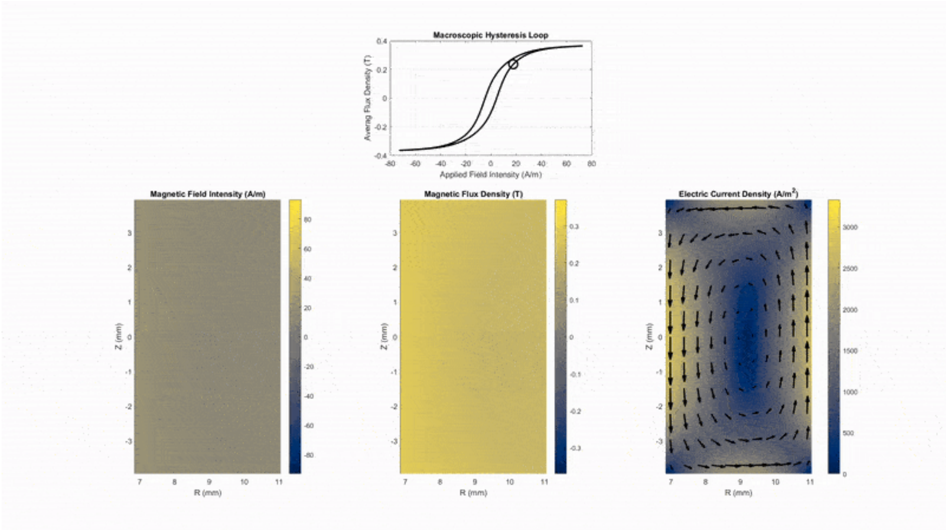
# Technical Accomplishments – FY19

## Implemented Visualization Methods for Coupled Eddy Current/Hysteresis Simulations

- **Goal**: Improve motor modeling fidelity
- **Challenge**: Designers must be able to develop some intuition about the coupling of eddy currents and magnetic hysteresis in order to effectively mitigate losses and control issues in high power density electric motors
- **Solution**: Develop software to inform machine designers using impactful visualizations of electromagnetic fields from dynamic simulations
- **Impact**: Improved understanding of the spatial phase shift distribution of magnetic fields in electrical laminations




*Eddy currents and hysteresis cause a non-uniform magnitude and phase distribution of the magnetic flux density in an M19 electrical steel core at 250Hz*



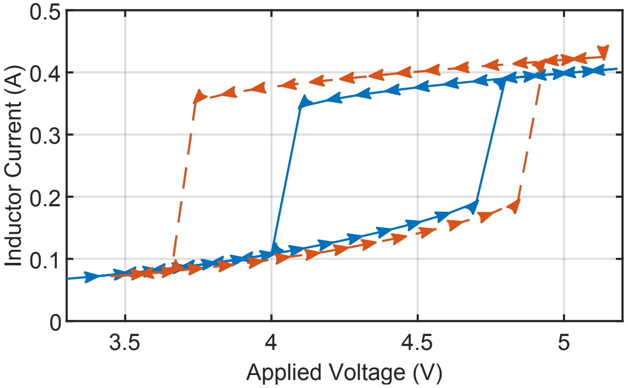

*Animation demonstrating the magnetic fields and eddy currents in a ferrite toroid simulated at 10kHz; these fields perturb the measured macroscopic hysteresis loop*

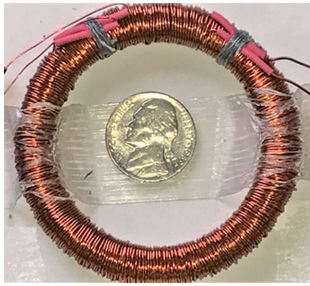
*J. Pries, E. Gurpinar, L. Tang, and T. Burress, "Continuum Modeling of Inductor Magnetic Hysteresis and Eddy Currents in Resonant Circuits," in IEEE Journal of Emerging and Selected Topics in Power Electronics, Oct. 2019.*

# Technical Accomplishments – FY19

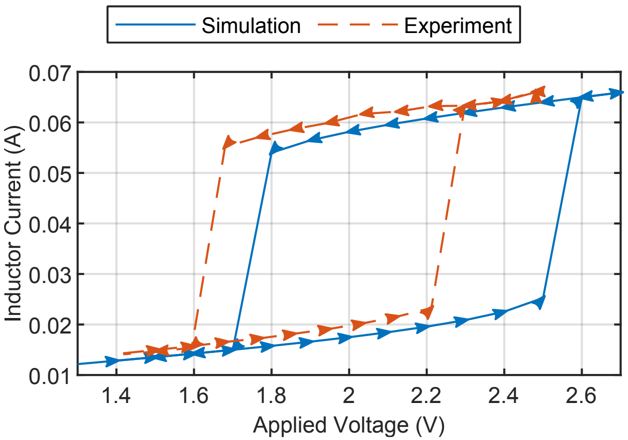
## Validated Scalar Magnetic Loss Modeling Approach Under Complex Test Conditions

- **Goal**: Improve magnet component design for power converters in electric vehicles
- **Challenge**: Magnetic components are difficult to model when pushed out of their linear regime and often yield results which are difficult to explain
- **Solution**: Utilize advanced modeling tools developed for electric motors to aide in magnetic component design for converters
- **Impact**: Validation of magnetic loss modeling techniques to predict complex phenomena in out-of-sample tests conditions



*Hysteresis and eddy currents interact to produce two stable resonant modes in an RLC circuit operating at 250Hz utilizing M19 electrical steel toroid*



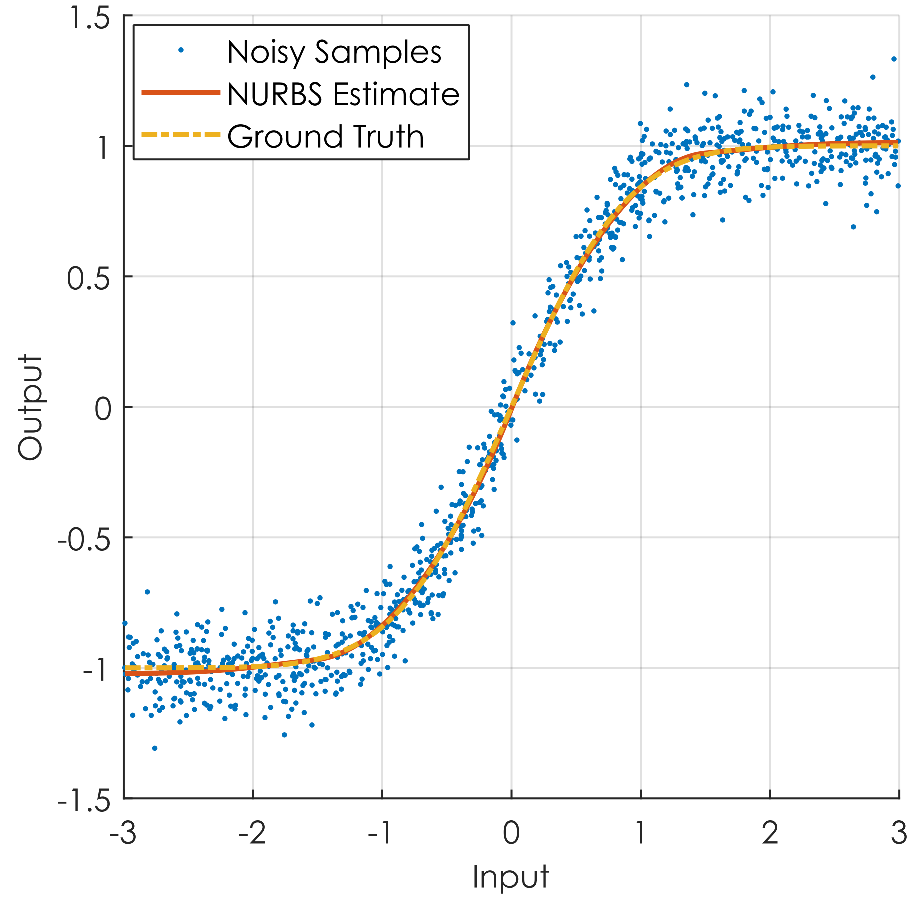

*Hysteresis and eddy currents interact to produce two stable resonant modes in an RLC circuit operating at 10.7kHz utilizing T38 ferrite toroid*

*J. Pries, E. Gurpinar, L. Tang, and T. Burress, "Continuum Modeling of Inductor Magnetic Hysteresis and Eddy Currents in Resonant Circuits," in IEEE Journal of Emerging and Selected Topics in Power Electronics, Oct. 2019.*

# Technical Accomplishments – FY19

## Develop Fast Numerical Method for Hysteresis Evaluation and Test Data Compression

- **Goal**: Improve motor modeling fidelity
- **Challenge**: Magnetic hysteresis characteristics are non-linear and history dependent and require large datasets to accurately identify; typical evaluation methods are too slow to combine with high-throughput optimization methods
- **Solution**: Develop a data compression and filtering method utilizing a rational-spline curve fitting technique
- **Impact**: Improved speed of hysteresis characteristic evaluation for magnetic field simulations; high dimensionality reduction from test data to model




*J. Pries, "Identification of the Stress Dependent Magnetic Hysteresis Preisach Density Function of Electrical Steels using Non-uniform Rational Bezier Splines," in preparation for IEEE Transactions on Magnetics.*

*Non-uniform Rational Bezier Spline (NURBS) can be used to accurately reconstruct sigmoid functions in the presence of significant noise. Hysteresis loop branches are typically sigmoid shaped. This figure shows the error function, samples with additive gaussian noise, and a NURBS reconstruction using only 12 parameters.*

# Response to Previous Year Reviewers' Comments

**This project is a new start**

# Collaboration and Coordination with Other Institutions

## Ames National Laboratory

- Fabricating test samples of hard and soft magnetic materials for detailed characterization and incorporation into high-fidelity models

## National Renewable Energy Laboratory

- Testing electrical and thermal properties of spatially inhomogeneous magnetic materials and providing data for incorporation into high-fidelity models

## Sandia National Laboratories

- Fabricating samples of magnetic composite material for detailed magnetic characterization and incorporation into high-fidelity models

## Big River Steel and CG Cantemir (OSU)

- Evaluating magnetic properties of BRS electrical steel samples with high mechanical strength for possible use as electric motor rotor material

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

# Remaining Challenges and Barriers

- Mechanical retainment of permanent magnets against large magnetic forces must be guaranteed for safety and to avoid damage of sensitive magnetic field sensors

- Magnet temperature should be held constant throughout testing despite inherent loss generation during four-quadrant testing

- Certain requirements (e.g. monotonicity with respect to applied field) must be met by the compressed hysteresis surface-splines to avoid non-physical numerical results

- Data compression methodology must be extended to vector hysteresis characteristics in order to realize an efficient computational method

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# Proposed Future Research

- **FY 2019**
  - **Milestone**: Implement control software and data acquisition methods for the permanent magnet characterization fixture
  - **Key Deliverable**: Characterize NdFeB and AlNiCo magnets
  - **Task**: Investigate vector demagnetization modeling techniques
    - **Go/No-Go Decision**: If vector magnetization model improves demagnetization prediction accuracy, add transverse DC bias capability to permanent magnet characterization fixture

- **FY 2020**
  - Test permanent magnets under transverse DC bias field
  - Investigate local demagnetization modeling accuracy with vector hysteresis characteristics
  - Identify test methodologies for vector hysteresis characterization of soft magnetic materials

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# Summary

- **Relevance**: Increased motor modeling fidelity and optimization throughput will accelerate improvements in electric motor designs to achieve the ELT 2025 targets of 50kW/L, 6$/kW, and 300,000 mile lifetime
- **Approach**: Research sources of modeling discrepancies, develop new numerical methods, and implement motor optimization tools on DOE HPC systems
- **Technical Accomplishments**:
  - Developed test method for multi-axis permanent magnet characterization
  - Designed a permanent magnet characterization fixture
  - Implemented visualization methods for coupled eddy current/hysteresis simulations
  - Validated magnetic hysteresis modeling approach in complex test conditions
  - Developed a fast hysteresis characteristic evaluation method
- **Collaborations and Coordination with Other Institutions**:
  - **Ames**: Providing magnetic material samples for detailed characterization
  - **NREL**: Testing electrical and thermal properties of spatially inhomogeneous magnetic materials
  - **Sandia:** Providing magnetic material samples for detailed characterization
  - **Big River Steel/OSU**: Provided high strength electrical steel samples to evaluate for use as rotor material
- **Future Work**:
  - Complete implementation of control software for permanent magnet testing fixture and testing of permanent magnet samples
  - Test permanent magnets under transverse DC bias field
  - Investigate local demagnetization modeling accuracy with vector hysteresis characteristics
  - Identify test methodologies for vector hysteresis characterization of soft magnetic materials

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