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

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Overview

Timeline

- Start Date: FY19
- End Date: FY24
- 30% Complete

Barriers

- **Power Density**: Achieving 50 kW/L will require understanding and quantifying the physics of materials and their interactions in extreme power density and high temperature operation
- **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

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY20: $334k

Partners

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

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

Relevance

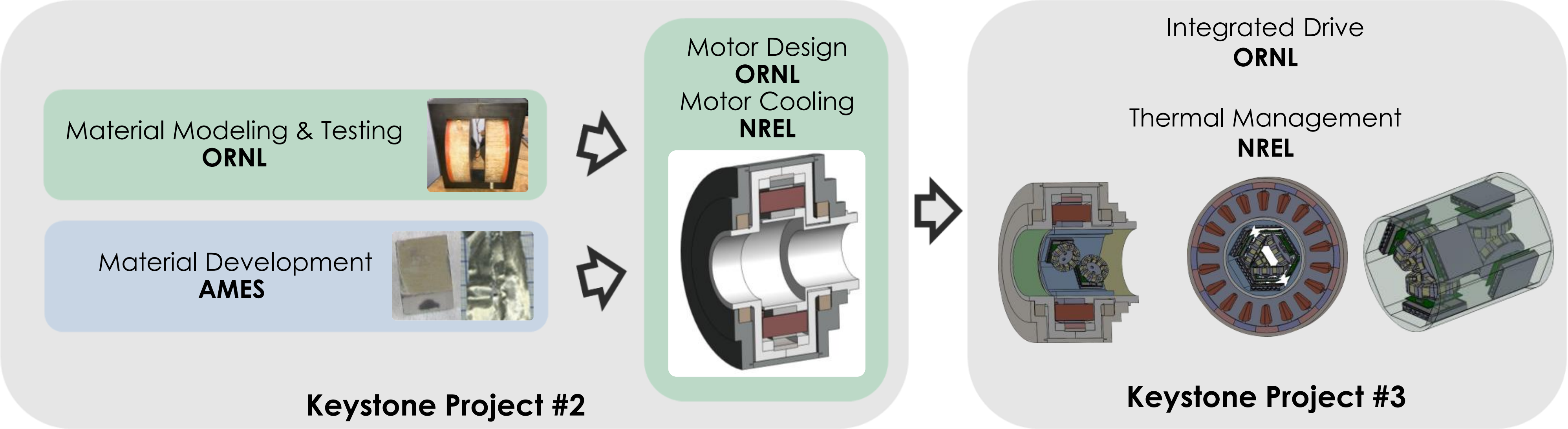
Magnetic Material Testing and Modeling

Electrical steel core losses

- Lower machine inductances lead to worse pulse-width modulation induced core losses
- Lower surface area to volume ratio makes accurate prediction of hot spot temperatures more important for cooling system analysis
- Vector hysteresis and eddy current losses exhibit different flux density magnitude dependency than uniaxial properties

Heavy rare-earth free permanent magnets

- Low coercivity leads to reliability issues from demagnetization
- Complex magnet arrangements lead to vector demagnetizing fields that are not well modeled with commercial finite-element analysis (FEA) software



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Approach

Magnetic Material Testing and Modeling

Heavy rare-earth free permanent magnets

- Measure first-order reversal curves and develop detailed demagnetization models
- Measure multi-axis permanent magnet first-order reversal curves and identify vector demagnetization models

Electrical steel core losses

- Test PWM losses of magnetic materials including DC-bias voltage and current
- Develop detailed loss post-processing for commercial software and direct simulation of core losses in custom developed ORNL software
- Implement computationally efficient algorithms for vector modeling of electrical steel hysteresis

Impact on other Consortium Projects (Selected)

- **ELT209, Su, ORNL**: Assess the impact of new modulation schemes on motor PWM core losses for the High-Voltage, High-Power Density Traction-Drive Inverter
- **ELT212, Raminosoa, ORNL**: Accurately predict efficiency, losses, and demagnetization robustness of non-heavy rare-earth high-speed motors
- **ELT214, Bennion, NREL**: Provide accurate loss distributions for electric motor thermal management
- **ELT215, Anderson, Ames**: Assess impact of new heavy rare-earth free magnets on motor performance
- **ELT216, Monson, SNL**: Assess PWM losses in isotropic iron-nitride based soft magnetic composites
- **ELT234, Kramer, Ames**: Determine efficiency impacts of newly developed soft magnetic materials

Role in Consortium: Testing and modeling of magnetic materials is driven by issues identified as part of the high-power density motor development process and the results feed into downstream modeling, design, and simulation efforts

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Approach

Period	Date	Milestone and Go/No-Go Decisions	Status
FY20	Q1	Milestone: Analyze mapping of demagnetizing fields between circular Halbach and linear Halbach PM arrangements	Complete
	Q2	Go/No-Go Decision: If significant transverse demagnetizing fields exist in the Halbach Outer Rotor Permanent Magnet Machine, determine if vector demagnetizing fields can be reliably mapped onto a linear motorette	Complete
	Q3	Milestone: Complete development of automated PWM loss testing software for ring core samples with DC-bias voltage and DC-bias current	On-Track
	Q4	Milestone: Develop post processing method for estimating PWM losses from FEA results	On-Track
FY21	Q1	Milestone: Compare PWM losses simulated by existing FEA coupled scalar Preisach hysteresis model to measured test data	On-Track
	Q2	Milestone: Gather second order magnetization reversal curve data from electrical steel toroid test article	On-Track
	Q3	Milestone: Gather second order vector magnetization reversal curve data from permanent magnet testing apparatus	On-Track
	Q4	Go/No-Go Decision: If accuracy of either first- or second-order Preisach hysteresis models is adequate for capturing PWM losses, finalize hysteresis model identification and proceed to 2D FEA integration	On-Track

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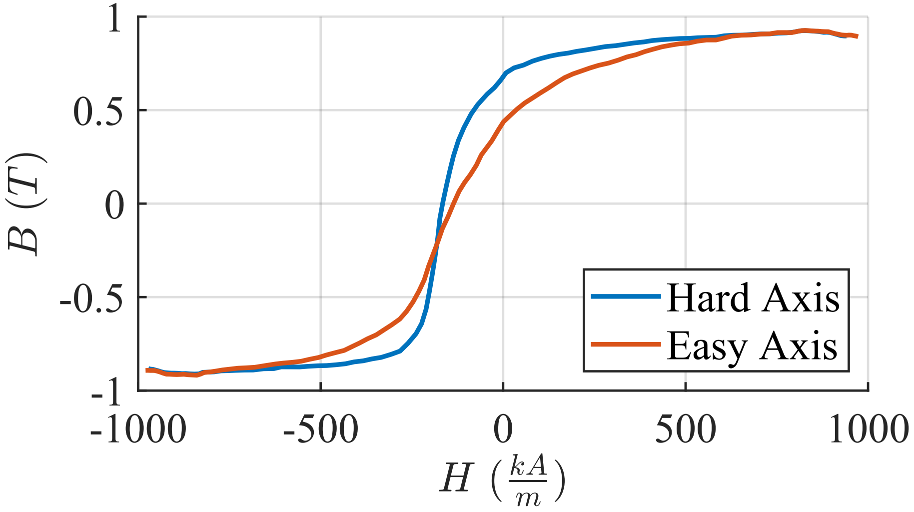
Technical Accomplishments and Progress (FY19)

Characterized Vector Demagnetization

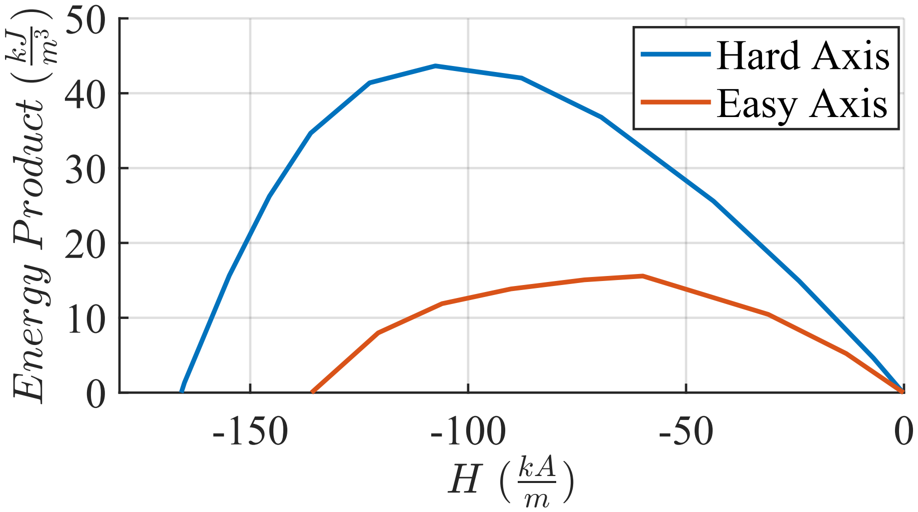
- Developed permanent magnet test fixture and methodology for examining demagnetization curves for easy axes and hard axes
- Performed initial characterization of AlNiCo 9 sample

	Hard Axis	Easy Axis
Remanence (B_r)	0.68 T	0.43 T
Coercivity (H_{ci})	166 kA/m	136 kA/m
Energy Product (BH_{max})	44 kJ/m^3	16k J/m^3

AlNiCo 9 permanent magnet array and sensor locating fixture



AlNiCo 9 intrinsic magnetization curves

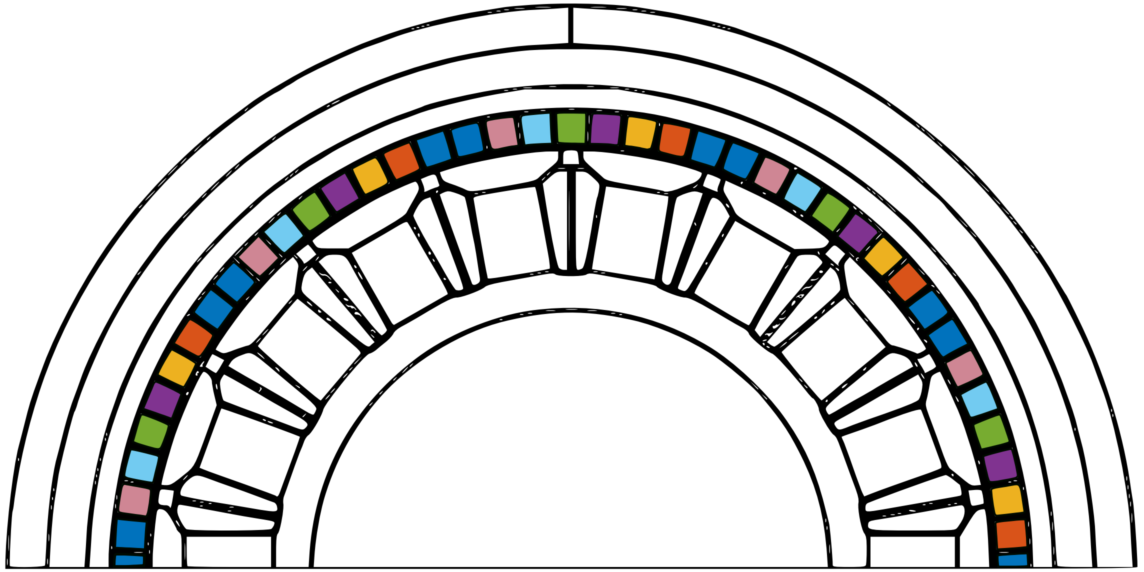


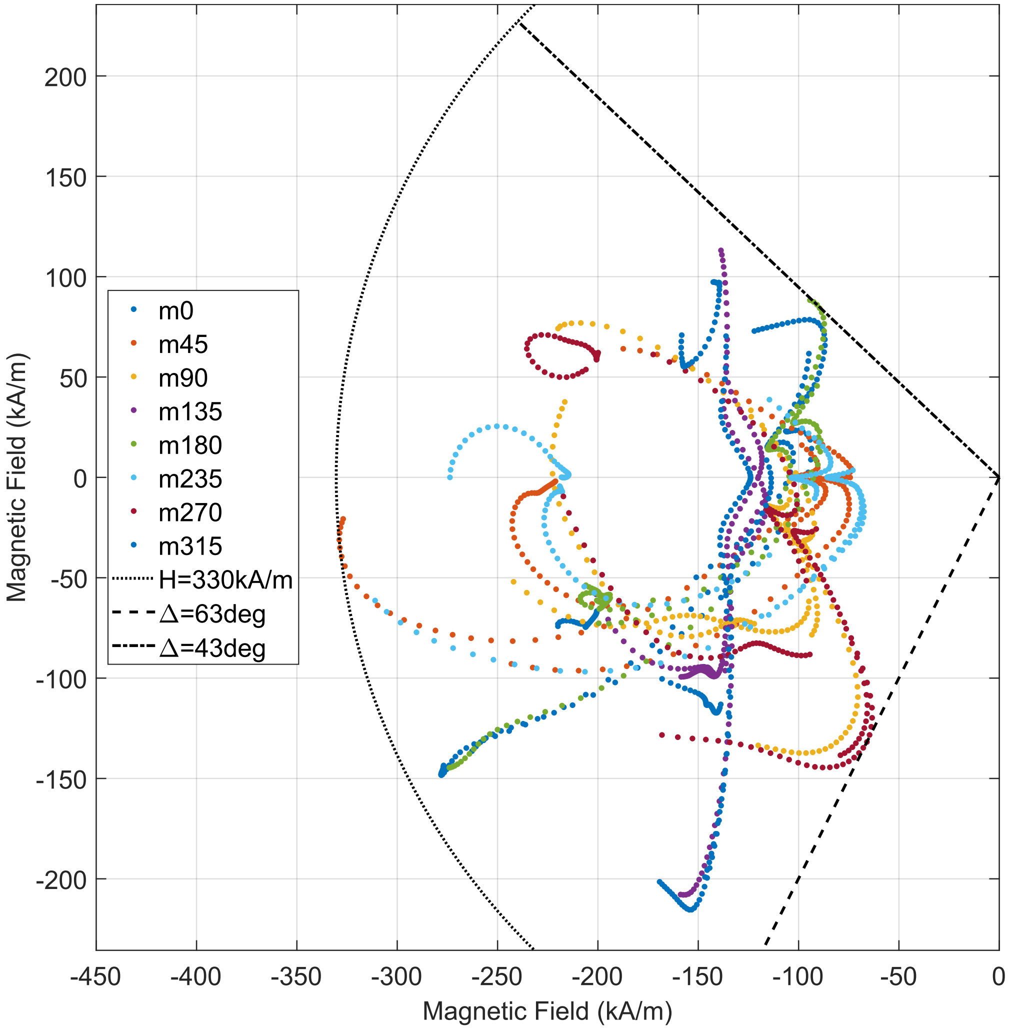
AlNiCo 9 second quadrant energy product curves

Technical Accomplishments and Progress (FY20)

Analyzed Vector Demagnetization Requirements in Halbach Outer Rotor Surface Permanent Magnet Machine (Q1 Milestone)

- Halbach PM arrangements in permanent magnet electric machines lead to vector demagnetizing fields due to the hard-axis of some magnets not being aligned with the radial direction
- The magnitude and angle of the demagnetizing field needs to be assessed for each individual magnet



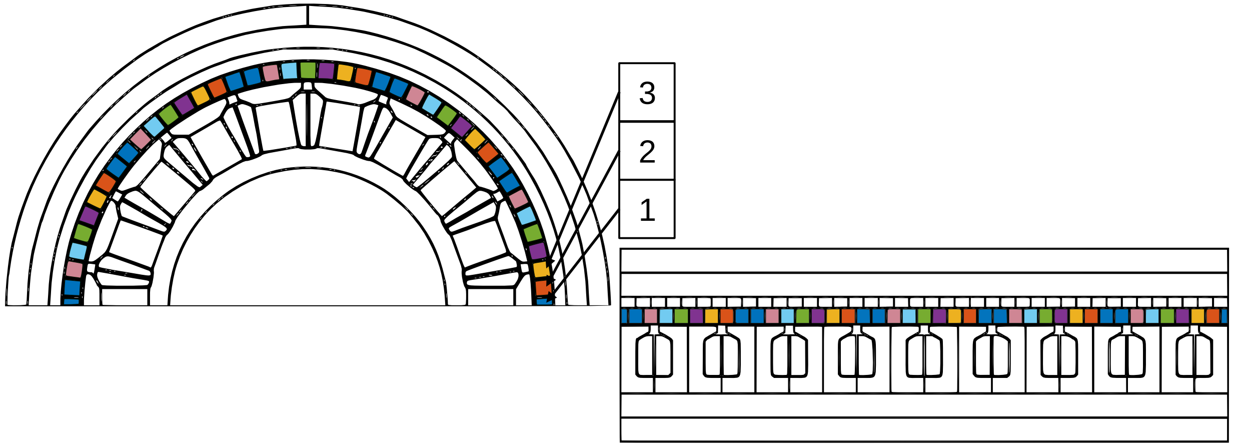


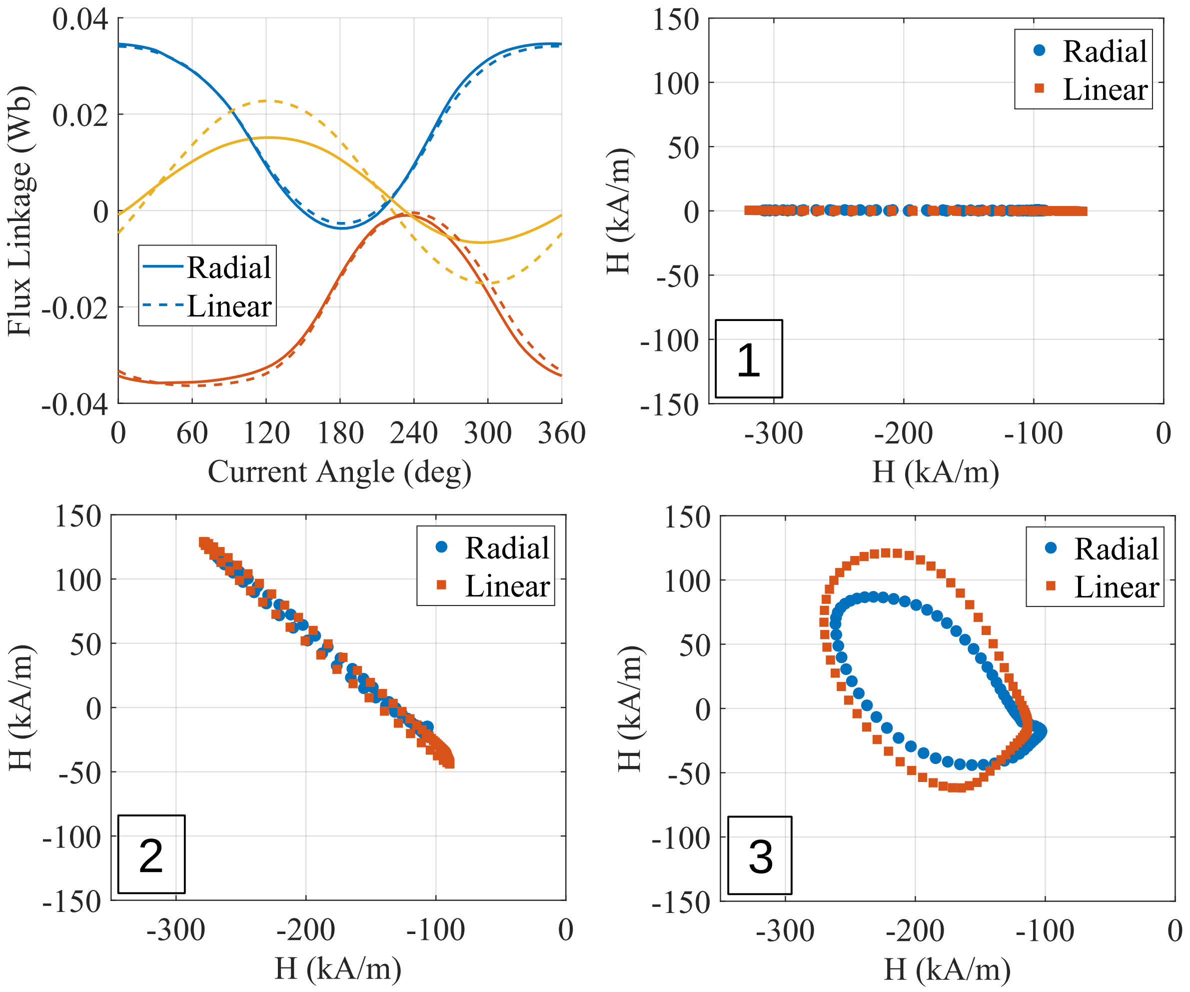
(Left) Radial-flux PM machine with Halbach array, (Top) Trajectories of demagnetization fields experienced by each magnet (grouped by angle of initial magnetization direction) as the current vector angle is varied

Technical Accomplishments and Progress (FY20)

Analyzed Feasibility of Mapping Vector Demagnetization from Radial to Linear Motor Topology (Q2 Go/No-Go Decision)

- Due to curved geometry, measurement of magnetic properties in radial flux electric machines is difficult
- Constructing scaled motor sections from a linearized design is simpler for material modeling validation purposes
- Linearized model will only provide useful feedback on radial flux motor if the demagnetizing field vectors are similar



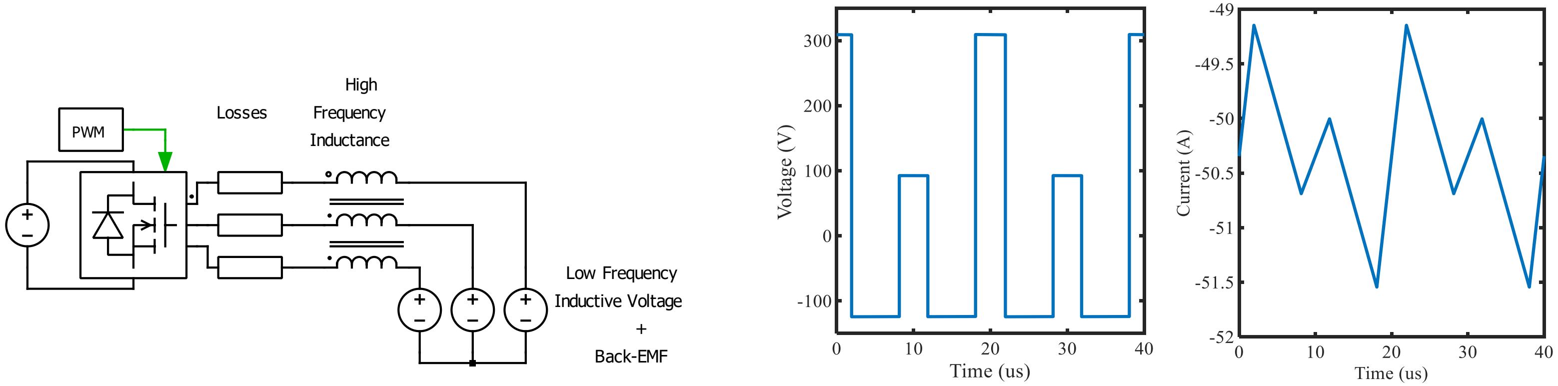


(Left) Radial-flux PM machine with Halbach array and an unfolded linear version of the same design (Top) Comparison of three-phase flux linkages and demagnetizing fields for 3 selected magnets in the two Halbach array motor designsn

Technical Accomplishments and Progress (FY20)

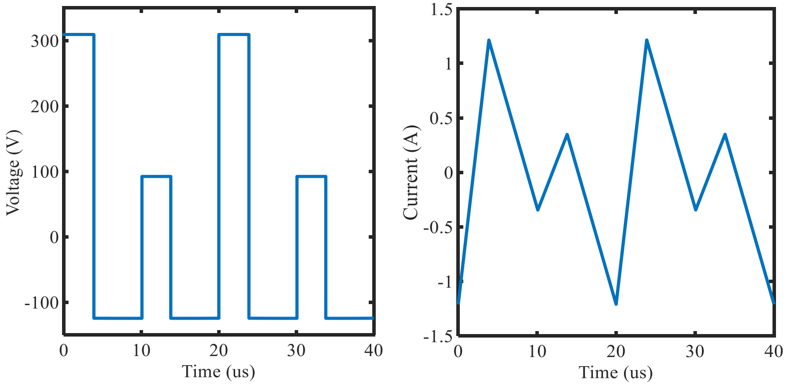
Developed Method for Including Bias Voltage and Bias Current in PWM Core Loss Measurements (Q3 Milestone)

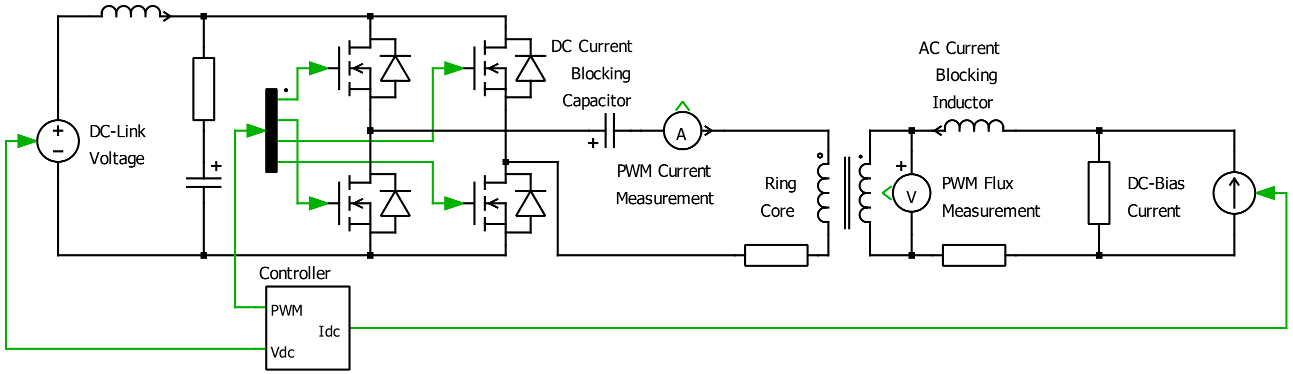
- On the time scale of the switching frequency, phase current and phase voltage due to back-EMF and inductance (Ldi/dt) appear constant
- DC-bias voltage impacts shape of PWM ripple current
- DC-bias current impacts differential inductance seen at PWM frequency
- Both DC-bias effects must be included in PWM testing to accurately estimate losses



PWM excitation of a three-phase electric motor over two switching periods (f_s=50kHz): (Left) Circuit model, (Middle) phase voltage waveform, (Right) phase current waveform

Emulation of PWM excitation of a three-phase electric motor in a two-winding test article using a single-phase inverter and passive components: (Bottom) Circuit model, (Right) simulated waveforms from PWM emulation circuit equivalent to the three-phase motor operating condition above.

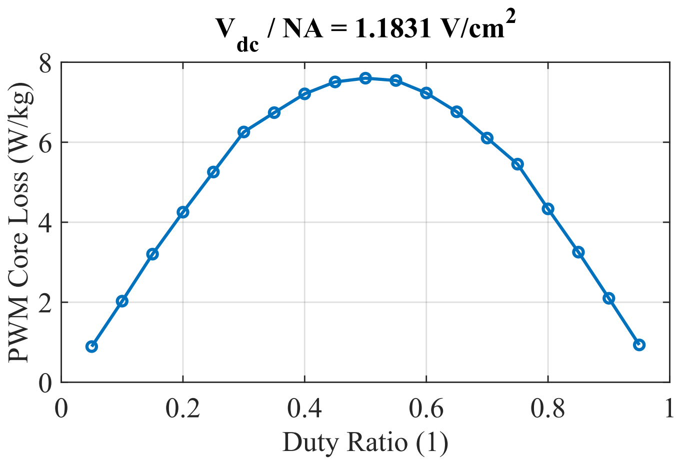


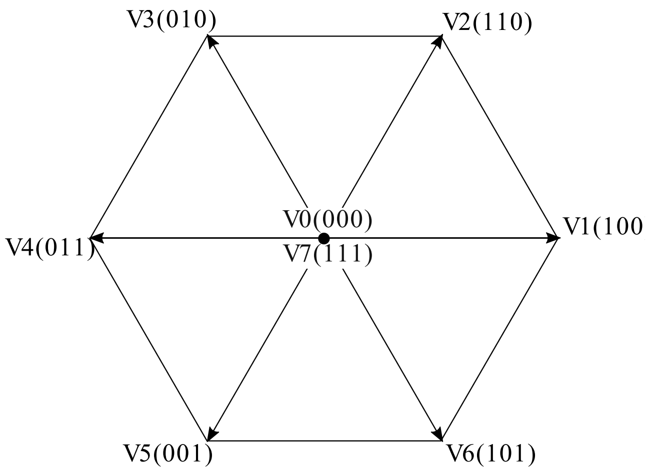


Technical Accomplishments and Progress (FY20)

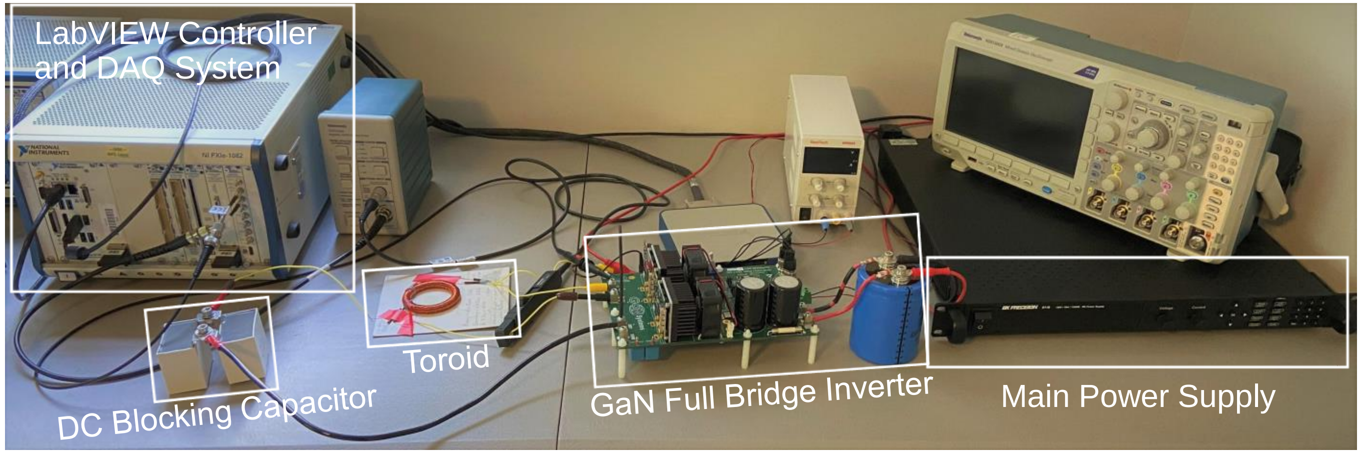
Performed Initial PWM Loss Measurement and Began Testing Software and Control Development (Q3 Milestone)

- Validated operation of full-bridge test circuit with DC-blocking capacitor and instrumentation bandwidth
- Custom ORNL developed automated PWM software for will provide high throughput and allow us to quickly compare the impact of different modulation schemes

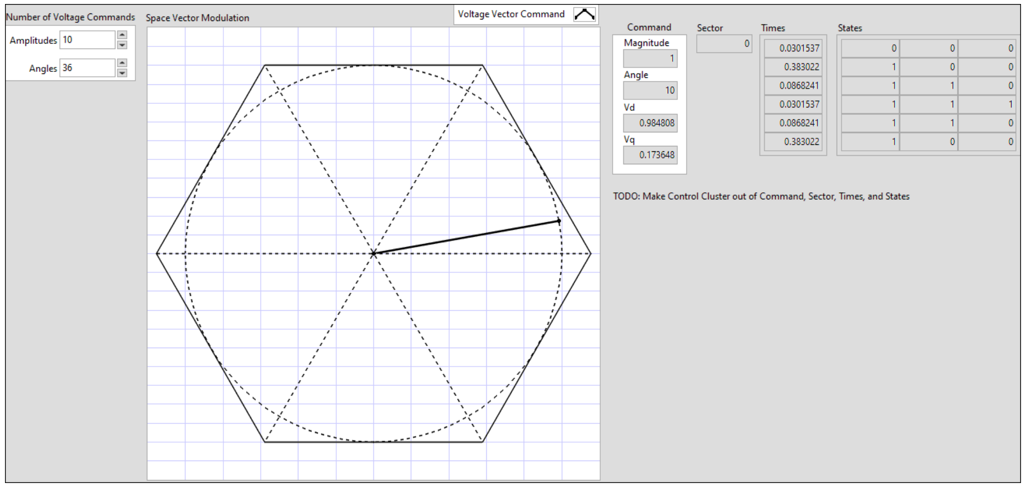




Core loss density from pulse width modulation harmonics for phase A as a function of duty ratio for a voltage vector command oriented along the machine α axis (V1 in the space vector hexagon). Core loss density peaks at a duty ratio of 0.5, which represents a voltage command of about half the DC-link voltage.



Experimental Setup (Excluding DC-Bias Current Components)



LabVIEW front-panel for automated PWM testing

Response to Previous Year Reviewers' Comments

- *Reviewer: A comparison of the improved demagnetization modeling/analysis to demagnetization analysis in commercially available packages should be included.*
- Response: We had done an internal investigation of the commercial software that is available to us (JMAG, COMSOL, MagNet) to confirm that the linear recoil model is used. Once complete first-order reversal curve data is available, we plan to assess the linear model versus the test results.
- *Reviewer: It is not clear that demagnetization analysis is the one that presents a high level of inaccuracy.*
- Response: It is difficult to make a definitive statement which encapsulates a comparison of all magnetic material modeling inaccuracies. For permanent magnets, it depends a great deal on the type of magnet. We agree that high-coercivity magnets – those with normal curve knees in the third-quadrant – can be modeled well with simple approaches for most applications. However for low-coercivity magnets – those with normal curve knee in the second-quadrant – determining the amount of demagnetization due to a fault, for example, is more complicated. The standard approach is to assume that the reversable part of the demagnetization below the knee is linear, but this is not true in practice. Also, if the demagnetizing field is not aligned with the hard-axis, the recoil line could be some combination of the hard and easy axis recoil lines, which is not considered in the standard approach.
- *Reviewer: Pulse-width modulation (PWM) losses and in general high frequency losses in the magnets should be evaluated. The highest level of inaccuracy is usually in the evaluation of core losses.*
- Response: We have taken this comment to heart and put a significant effort into development PWM testing capabilities this year to feed into the motor design efforts. Our initial investigations have indicated that PWM harmonics could be a significant barrier for achieving the program targets with certain motor topologies.

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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

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Remaining Challenges and Barriers

- It is unclear whether Preisach magnetization models utilizing only first order reversal curves will be sufficient for estimating PWM losses or if more complicated models using second or third order reversal curves will be necessary

- Methods for validating vector magnetization models for soft magnet materials need to be gleaned from existing literature and/or developed, and implemented

- Several numerical issues with existing vector magnetization models have been identified concerning the behavior when spatially orthogonal fields are applied in a sequence

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Proposed Future Research

Remainder of FY20

- Complete pulse-width modulation core loss testing of electrical steel test sample
- Complete development of core loss post processing tool for analysis of FEA simulation results

Planned for FY21

- Assess accuracy of PWM loss estimation from previously developed FEA code coupled with first-order Preisach hysteresis model for nonlinear electrical steel magnetic characteristics
- Test second order reversal curves of electrical steels to more accurately capture PWM losses in hysteresis models
- Test vector second order reversal curves in permanent magnets to more accurately capture losses due to slotting and pulse-width modulation, and demagnetization recoil
- Identify vector hysteresis models from test data

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Summary

- **Relevance:** Improving power density, reliability, and cost in heavy-rare earth free electric motors requires addressing magnetic core losses and permanent magnet demagnetization issue
- **Approach:** High volume testing with post processing tools can address immediate needs of the motor design process while also providing data for the long-term goal of developing high-fidelity magnetic material models
- **Technical Accomplishments:**
  - Tested vector demagnetization characteristics of AlNiCo 9 sample using new method
  - Analyzed vector demagnetization requirements of permanent magnets in Halbach outer rotor SPM
  - Analyzed feasibility of mapping vector demagnetization from radial to linear motor topology
  - Developed method for including bias voltage and bias current in PWM core loss measurements
  - Performed initial PWM loss measurements to validate approach and began testing software and control development
- **Response to Previous Years Comments:** Increased focus on PWM losses in addition to demagnetization
- **Collaboration and Coordination with Other Institutions:**
  - **Ames:** Detailed modeling of newly developed materials
  - **NREL:** Incorporation of measured thermal properties into material models
  - **SNL:** PWM Testing of FeN4 magnetic composites
- **Remaining Challenges and Barriers:** Numerical issues translating test data into models must be addressed
- **Proposed Future Research:**
  - Complete PWM testing of electrical steel and implement post processor for FEA simulation results
  - Second order reversal curve testing of electrical steel and permanent magnets

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