




Cost Effective Rare-Earth-Free Flux Doubling, Torque Doubling, 8x Power Density Traction Motor with Near-Zero Open-Circuit Back-EMF and No Cogging Torque

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US DOE Vehicle Technologies Office Annual Merit Review 2021

Project ID: elt255

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Overview

Timeline

- Project Start Date: October 2019
- Project End Date: March 2022
- Percent completed: 50%

Barriers & Technical Targets Addressed

- Targets from Electrical and Electronics Technical Team Roadmap[1]
- Electric motor power density 50 kW/*l*
- Power electronics power density 100 kW/*l*
- Cost reduction

Budget

- Total Project Funding: $750,000
  - DOE Share: $600,000
  - Recipient Cost Share: $150,000
- Funding for FY 2020: $270,638
- Funding for FY 2021 (expected): $124,514

Partners

- University of North Carolina at Charlotte (Prime Recipient)
- University of Kentucky
- QM Power Inc.

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[1] *https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20 Roadmap%2010-27-17.pdf*

Relevance

- The Vehicle Technologies Office 2025 R&D targets for Electric Traction Drive Systems are: (1) cost parity with ICE drivetrains (2) power density improvements for traction motors (50 kW/l) and power electronics (100 kW/l) (3) reliability improvements to 300,000 miles or 15 years and (4) reduction of reliance on rare-earth elements
- Based on the VTO targets, the proposed Q-Mag drivetrain project will include:
  - ➢ Permanent magnet Q-Mag machine with stator-mounted permanent magnets simplifying rotor construction, a base speed of 12,500 rpm (max speed = 3x) and rated torque 96 Nm, providing 125 kW power rating → *Increased power density achieving 50 kW/l through high-speed operation*
  - ➢ SiC power electronic converter using 1.2 kV devices fed from 800V dc bus, and an output current rating of 400 A
  - ➢ Direct in-slot cooling techniques, to enable high currents and therefore high torque
  - ➢ A productization / commercialization plan to create a roadmap for US manufacturing
- If validated, this architecture has the potential to substantially improve drivetrain packaging and operating efficiency, leading to reductions in cost

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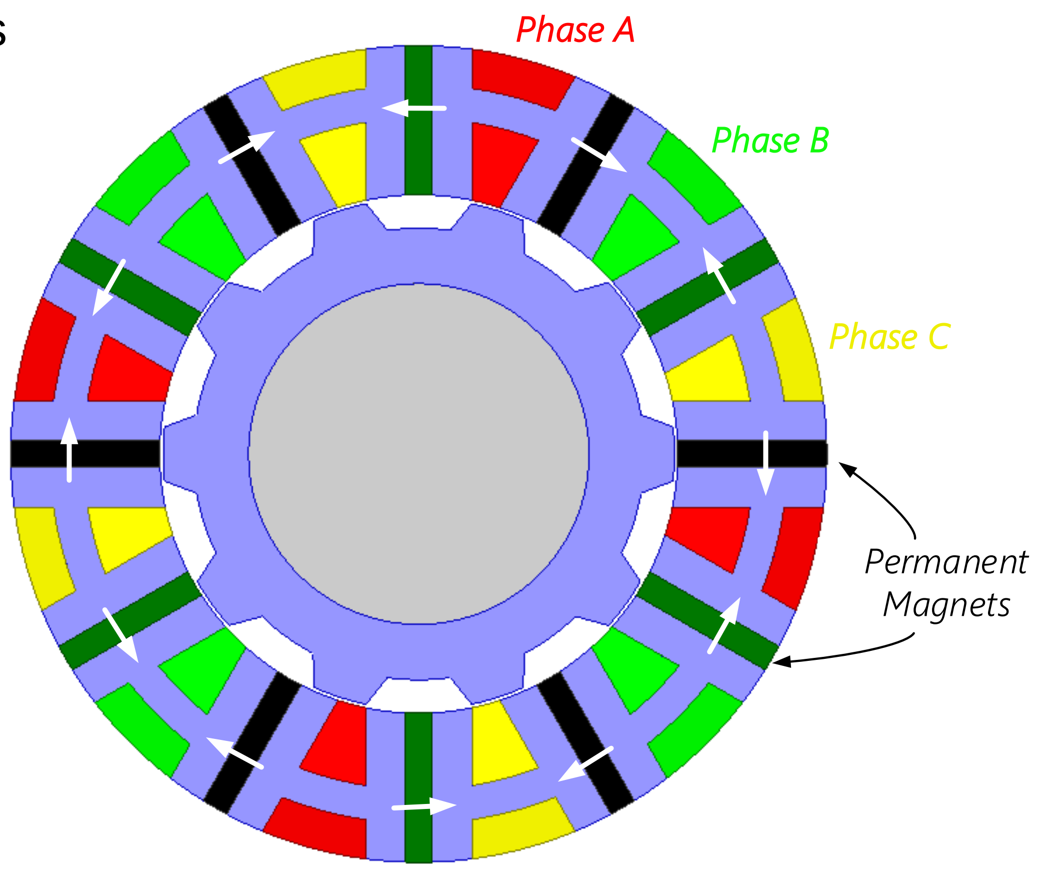
Technical Approach

Traction Motor: This project proposes to use the Q-Mag topology to design the traction motor, which is based on the Parallel Path Magnetic Technology[2]

- The Q-Mag topology features permanent magnets placed in the stator core with alternating polarities, and inter-dispersed with phase windings
- By modulating the phase currents, airgap flux densities at various rotor angles can be modulated enabling the shaping
- The rotor has simple salient poles (with no interior or surface magnets) offering high-speed operation, reliability and high power density to achieve DOE targets
- Direct winding cooling techniques boost current density capability, hence torque performance



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[2]Charles J. Flynn, "Parallel Magnetic Circuit Motor ", US Patent US 2011/0089775A1

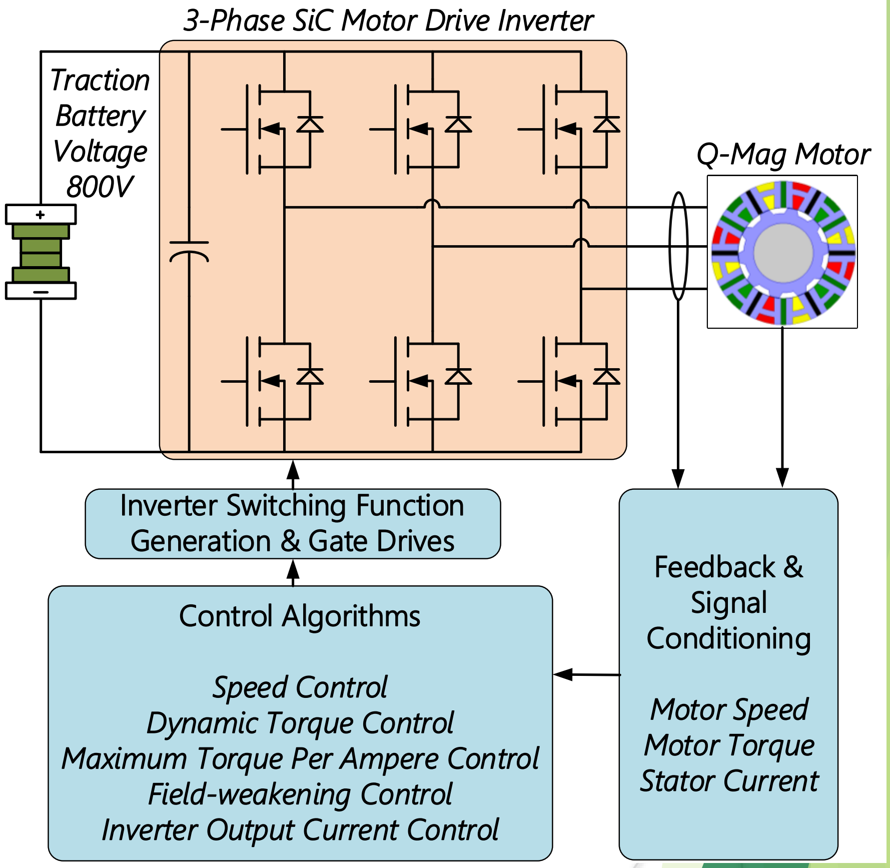
Technical Approach

Motor drive inverter: This project will use a silicon carbide (SiC) power modules-based drive inverter

- The inverter will operate at high switching frequencies thereby low distortion output current to drive the traction motor, reducing torque ripple
- SiC power modules optimized for reduced conduction losses will be strong candidates for the inverter, in order to handle high current drive requirements by the Q-Mag motor
- The switching frequency of the inverter will be optimized for all operating power ranges, high power quality, power density, and efficiency

Integration of traction motor and drive inverter:

- The traction motor and drive inverter are being designed concurrently, with frequent coordination of operating conditions and performance specifications
- Finite Element Analysis platforms (ANSYS) are being used to design, optimize and validate the traction motor; power electronic simulation platforms (Powersim, Matlab) are used to design the drive inverter – the integrated traction system will be validated using co-simulation methods
- Prototypes of traction motor and inverter drive will be integrated and tested on a dynamometer testbed



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Milestones

Milestone	Tasks	Deliverable Date
Milestone 2.1: Performance verification of optimized Q-Mag motor and SiC drive in terms of electromagnetic and thermal aspects	2.1, 2.2, 2.4, 2.7	September 1, 2021 (On track)
Milestone 2.2: Prototype construction of a Q-Mag prototype motor	2.1, 2.6	December 31, 2020 (Completed)
Milestone 1.3: Prototype construction of a SiC based power electronic drive system	2.2	June 30, 2021 (On track)
Go/No-go: Successful construction of a Q-Mag motor with a SiC based motor drive prototype	2.1, 2.2, 2.6	September 20, 2021

Task 2.1 – Procurement and fabrication of a Q-Mag prototype motor

Task 2.2 – Design and development of a SiC based power electronic drive system

Task 2.3 – Calibration of the simulation model with preliminary test results

Task 2.4 – Refinement of the optimization study based on the calibrated models

Task 2.5 – Review & guidance on test procedures required to optimized traction system

Task 2.6 – Prototype construction of 125kW Q-mag motor

Task 2.7 – Critical review of cooling methods and optimization techniques

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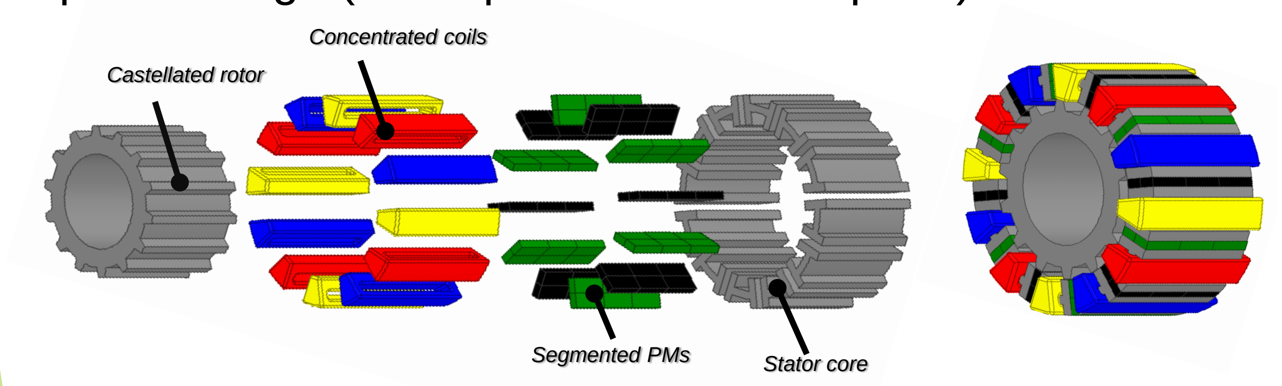
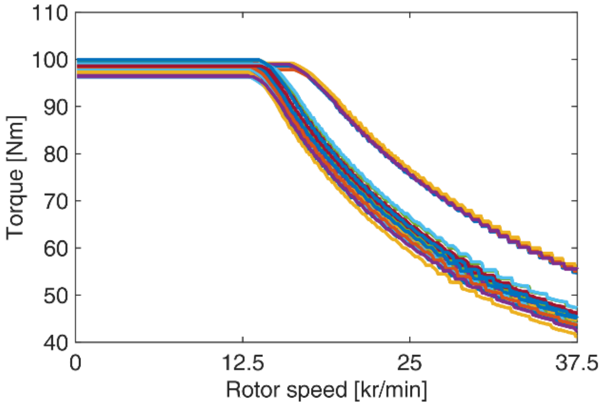
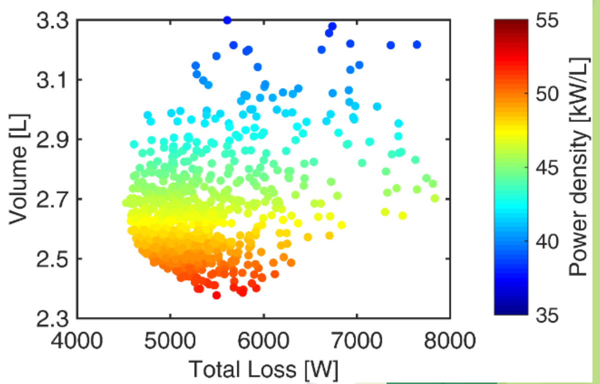
Technical Accomplishments and Progress (FY 2019)

- The Q-Mag motor was designed, and optimized using Finite Element Analysis on ANSYS Maxwell
- The motor design consists of a modular stator core, concentrated Gramme-wound coils and stator-mounted segmented permanent magnets
- Parametric models were developed and a large-scale multi-objective design optimization to (a) maximize power density (b) minimize losses and (c) maximize power factor was performed, assuming an equivalent electric loading (product of current density and slot fill factor) equal to 9.75A/mm^2 can be achieved by design of advanced winding and thermal management technologies
- Multiple design generations of the adopted heuristic optimization yielded a satisfactory Pareto front with a number of candidate designs yielding estimated power densities capable of meeting DOE targets
- 2D FEA torque-speed and efficiency map results show constant power 125 kW operation with a wide constant power range (max speed = 3x base speed)



"Exploded view" of Q-Mag motor components





*Q-Mag Large Scale Optimization Results showing designs capable of 12,500 rpm / 96 Nm performance and **50 kW/l power density**. The Pareto front presents a number of design candidates*

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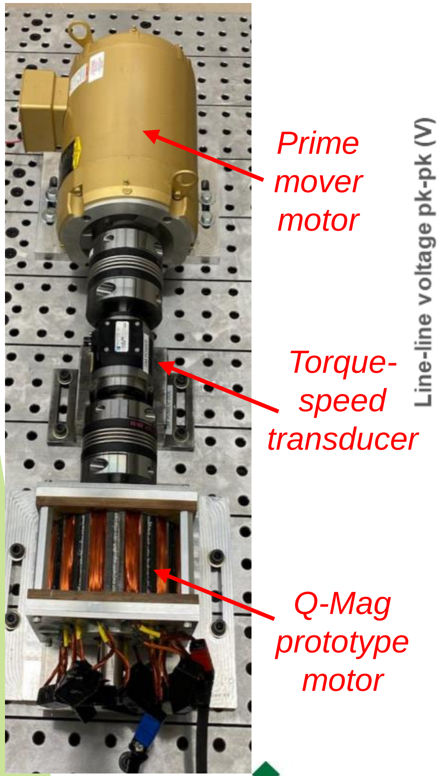
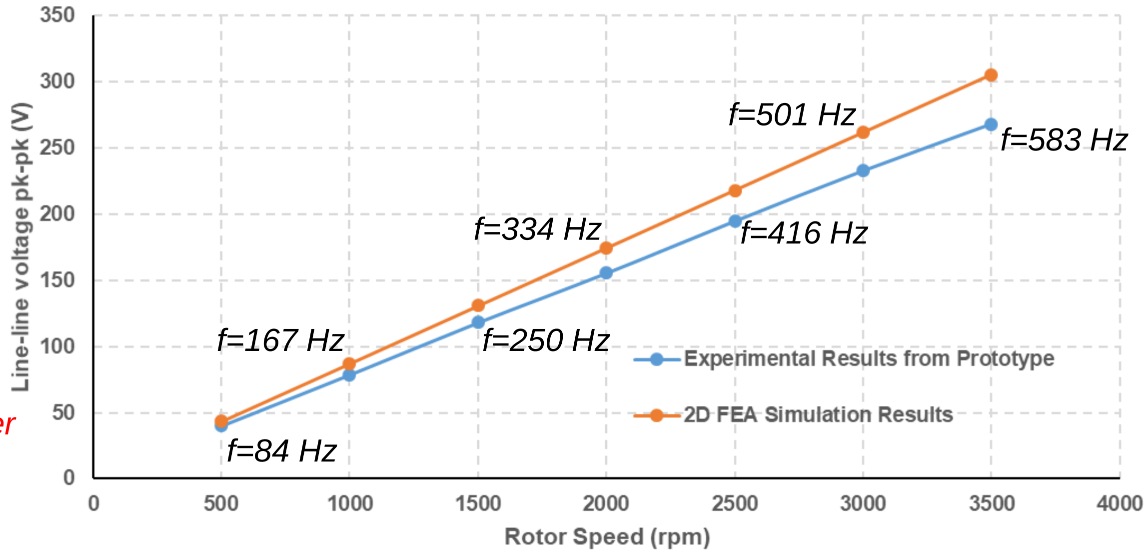
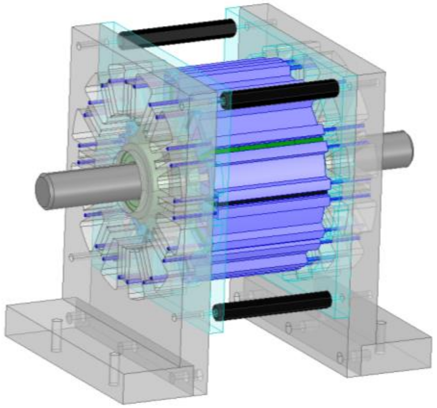
Technical Accomplishments and Progress (FY 2020)

- Based on the optimization results, a 10 rotor protrusions design was chosen and a design for manufacturing was performed, to fabricate an initial lower power prototype (21 kW, 40 Nm torque, 5,000 rpm base speed, no liquid cooling)
- A back emf test was performed up to 3,500 rpm (limited by prime mover ratings). Observed stator line-line voltage at 3,500 rpm shown, with highly sinusoidal waveform of fundamental frequency 583 Hz, in agreement with simulation results

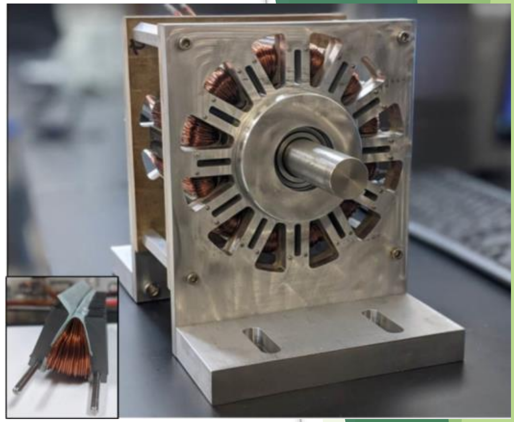




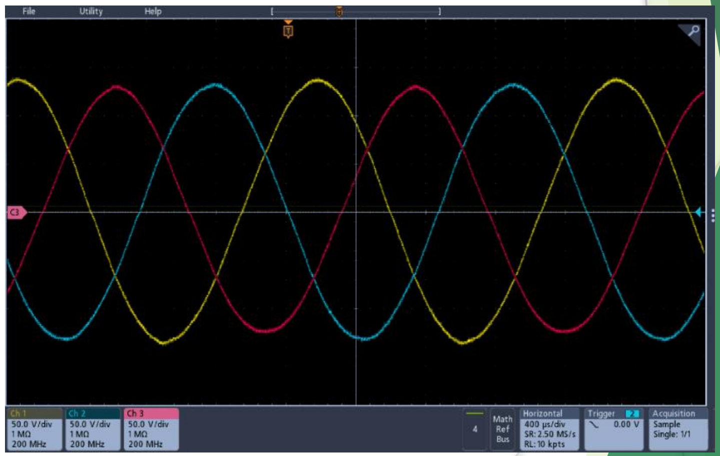
Line-line back EMF voltages (peak-peak) and fundamental frequencies. A difference of approximately 12% is noted between 2D FEA and measured values from prototype.



Mechanical design diagram for low power initial prototype



Prototype fabricated at QM Power laboratory.
<u>Inset image:</u> one phase coil wound on modular core segment



Sinusoidal open circuit back EMF line-line voltage at 3,500 rpm

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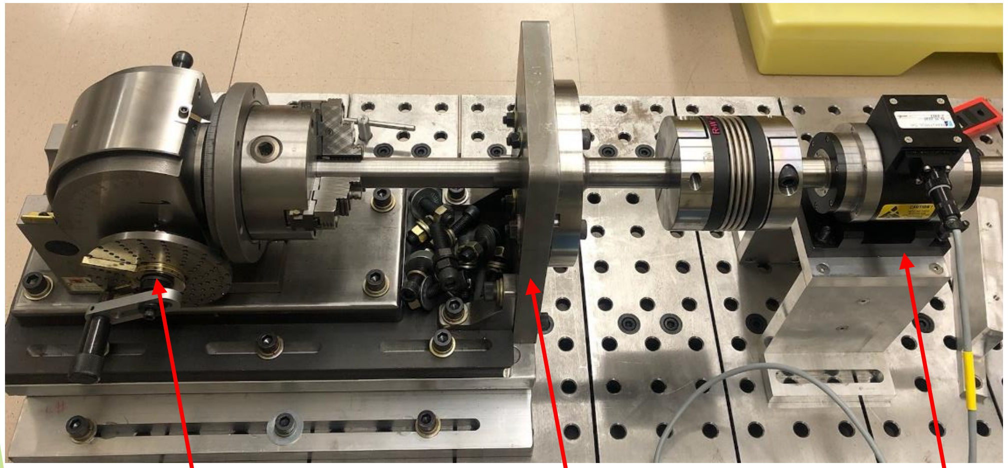
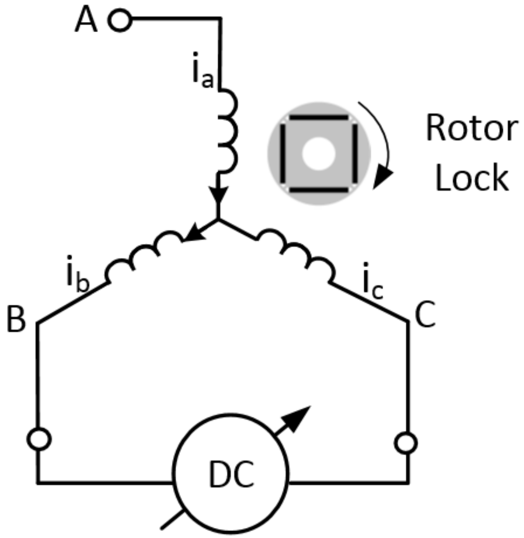
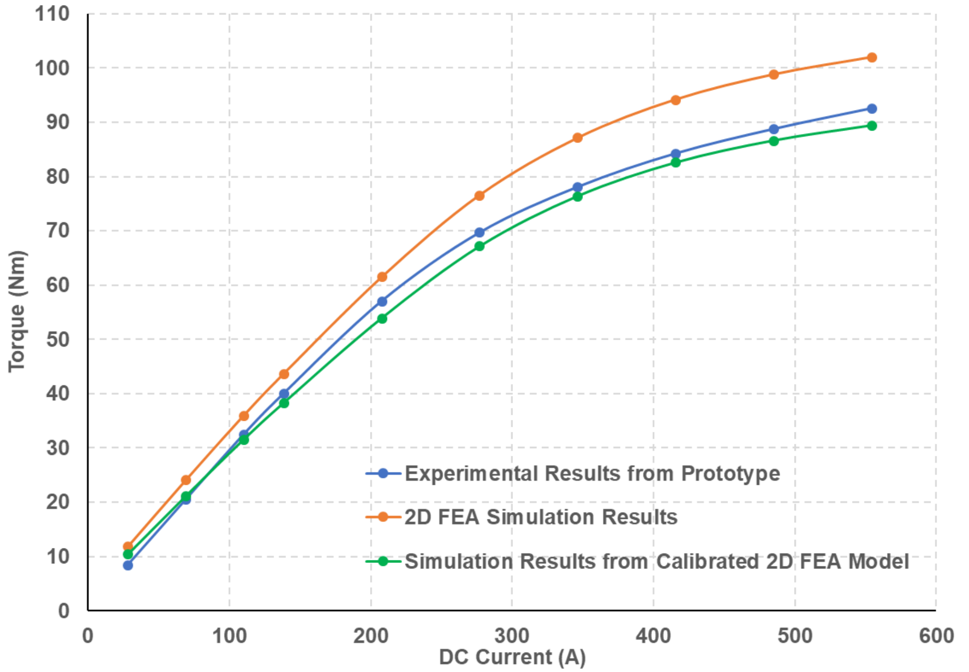
Technical Accomplishments and Progress (FY 2020)

- A locked rotor test setup was designed and fabricated by the project team, consisting of an indexing head and a locking block. The rotor position was moved in 1° (mechanical) increments, over a total span of 36°
- Motor stator phases B & C were connected to a common terminal and in series with phase A. DC current was injected up to 500 A
- Torque performance up to 90 Nm measured, compared to 96 Nm in simulation results, with the difference potentially explained by material tolerances, deviation in physical properties between simulation components and real-world materials, and lack of liquid cooling (further analysis is in progress)





Simplified circuit diagram for locked rotor test



Maximum torque generated vs stator current (locked rotor). A difference of approximately 14% is noted between 2D FEA and measured values from prototype.

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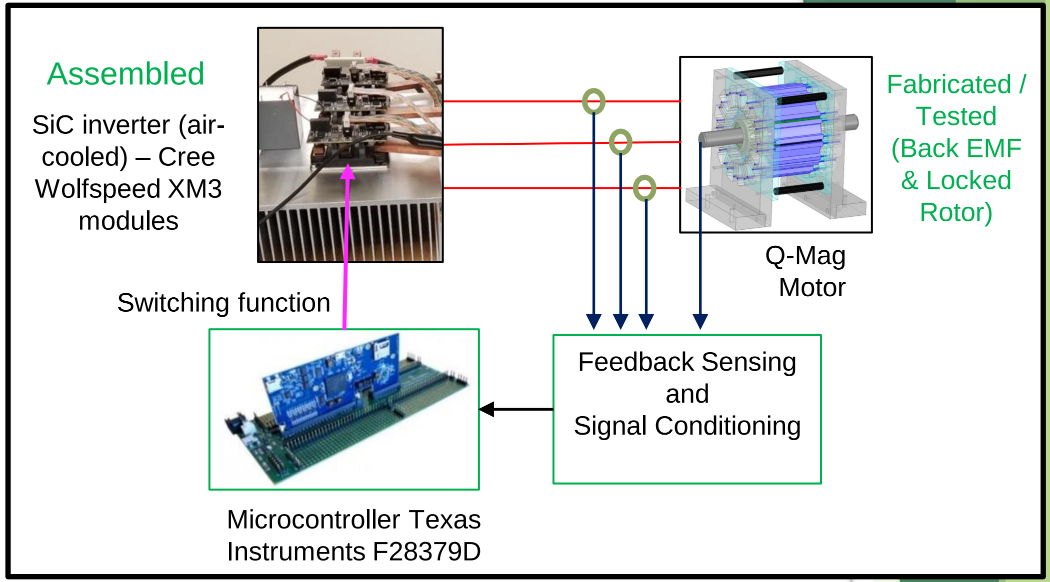
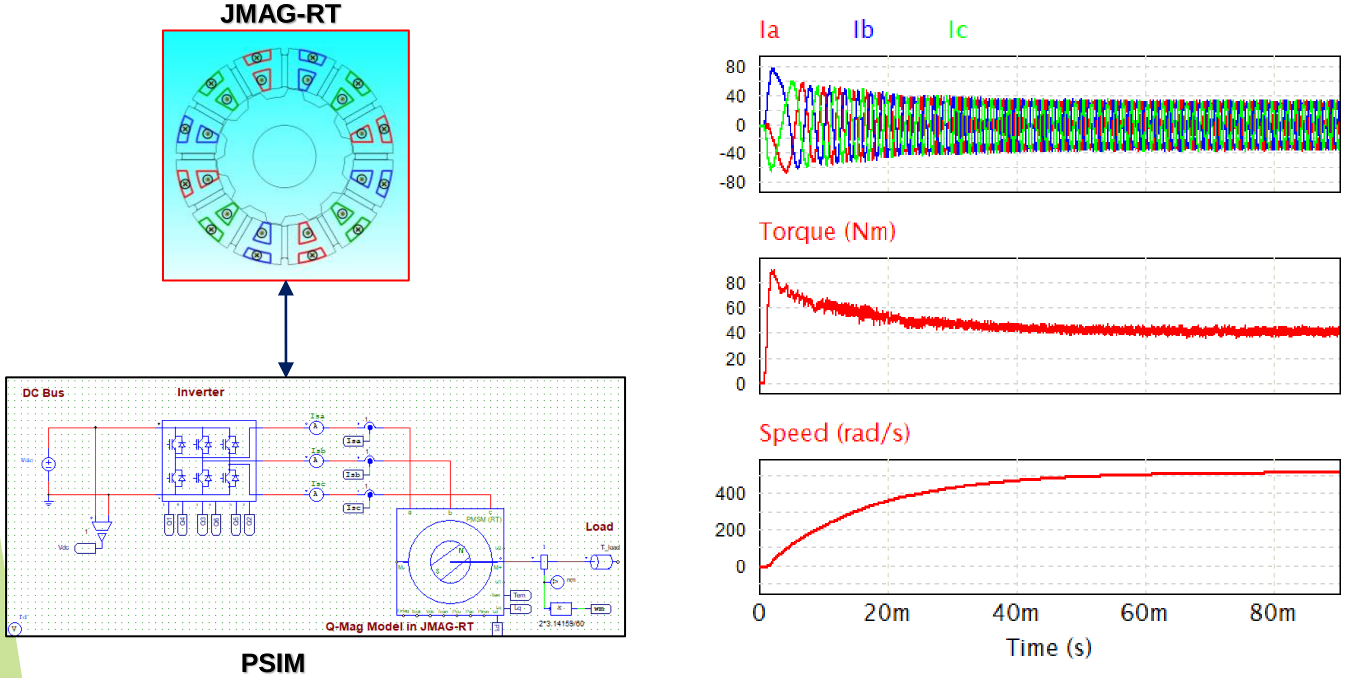
Technical Accomplishments and Progress

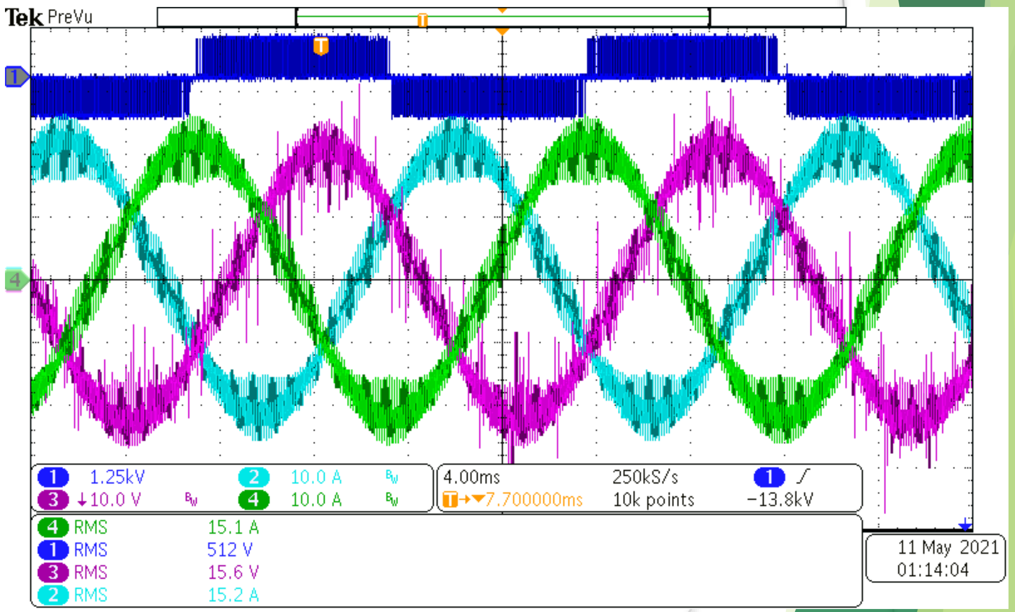
- The SiC three phase motor drive and controller were developed and evaluated in power electronics simulation at 125 kW, 800 Vdc, along with closed loop control for constant torque range and constant speed (FY 2019)
- A co-simulation model of power electronic drive and FEA model of the low power prototype was created and the operation of the closed loop control of the motor drive was verified (FY 2020)
- A forced air-cooled hardware prototype to drive the low power Q-Mag motor prototype was constructed and tested at 800 Vdc and up to 21 kW.



Block schematic of closed loop model of VSI driven Q-Mag



Co-simulation schematic and results of JMAG-RT FEA model of Q-Mag motor and power electronic inverter in PSIM



Forced air-cooled SiC traction inverter testing with a 13.3 kVA passive load (V_{dc} = 800V, $V_{ac\text{-}rms}$ = 512V, $I_{ac\text{-}rms}$ = 15A, f = 60 Hz)

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Responses to Previous Year Reviewers' Comments

Reviewer A: It was unclear to the reviewer not only if the proposed motor topology is novel or building upon previously developed technology but also why the proposed motor topology can achieve significant improvement in power density. The proposed topology has some analogy to flux-switching machines and seem to be a high reluctance topology, so it is difficult to see from where the power density improvement is coming.

Response: The concept of the Q-Mag machine is an extension of the PPMT technology (US Patent US 2011/0089775A1) combined with advanced technology development to achieve VTO project targets with multi-phase high speed and high voltage operation. The power density performance is achieved by innovative conceptual development, designed for a higher base speed of 12,500 rpm. A multi-objective large scale design optimization with one of the objectives being maximizing power density, advanced winding technology and direct winding / magnets cooling. FEA results show that the power density targets can be achieved using this method and provide the desired performance. The project team is looking forward to validating the power density performance, upon the construction and operation of the high power prototype.

Reviewer B: The project may showcase a motor-inverter system capable of delivering certain torque and power. However, is it really going to have the power density improvement and cost reduction? A baseline has to be established when a claim like this is made. Without simulation and dynamometer test results, and comparison with state-of-the-art IPM machine having the same dimensions, voltage constraints, current constraints and cooling strategy, it is hard to prove that the target metrics have been met.

Response: The project team has used a state-of-the-art commercially available IPM machine as baseline for our analysis. The results presented on the Q-Mag multi-objective optimization analysis are based on 2D FEA simulations performed during year 1 of the project, and the results show that there are several designs capable of meeting DOE's record-high power density targets. The assembled prototype developed in year 2 has been shown to be capable of up to 90 Nm torque performance, largely in line with simulation results. The prototype is currently undergoing dynamometer evaluation at lower power ratings in order to validate the drive system operation. A cooling system design to be incorporated into the machine will allow the motor to reach higher power levels for dynamometer testing.

Collaborations & Coordination

University of North Carolina at Charlotte, Prime recipient: Design, analysis and development of SiC motor drive inverter and controller, testing the integrated traction drive system (Q-Mag motor + inverter), project management

University of Kentucky, Subrecipient: Design, optimization and analysis of Q-Mag motor topology

QM Power Inc, Subrecipient: Construction of Q-Mag motor prototype, motor design and experimental testbed review and guidance

Key Vendors:

Wolfspeed (SiC power modules and gate drives)

Texas Instruments (Microcontroller platform)

ANSYS, JMAG-RT (Magnetics Finite Element Analysis platforms)

Powersim (Power electronics design and simulation platform)

TyphoonHIL (Digital Real Time Simulator platform)

Yokogawa (Metrology solution for electrical and mechanical performance measurement)

Proposed Future Research (FY 2020, FY 2021)

- Completion of dynamometer tests on prototype motor driven by SiC drive inverter up to 40 Nm, 5,000 rpm (low power prototype with forced-air cooling)
- Efficiency analysis of prototype motor and comparison with expectations based on simulation results, including loss breakdown analysis (core losses, copper losses, PM losses, windage and friction losses) and recalibration of motor design
- Investigation, analysis and design of thermal management system for the Q-Mag motor
- Development and construction of high power (125 kW, 12,500 rpm, 96 Nm) Q-Mag prototype
- Ramp up operating power of liquid-cooled, SiC motor drive inverter to 125 kW and develop embedded controller for closed loop motor control – constant torque and constant power speed ranges
- Economic analysis (cost, packaging, operating efficiency) of Q-Mag powertrain and development of productization roadmap

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

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Summary

- The proposed Q-Mag architecture based electric drivetrain system includes a high-speed motor and SiC motor drive inverter to meet DOE targets for power density and performance, at 50 kW/*l* for motor and 100 kW/*l* for power electronics
- The design based on the Parallel Path Magnetic Technology, placement of magnets in stator, reluctance type rotor design leading to reduced manufacturing complexity, capability for high-speed rotor operation, and direct in-slot cooling for the windings – all factors combine to provide excellent high power density performance
- Using Finite Element Analysis and a multi-objective design optimization, a 10 rotor protrusion-design was developed, and an initial prototype motor was constructed, rated at 21 kW
- Back EMF tests reveal close agreement of line voltage waveforms with those from simulation results, and satisfactory locked rotor torque measurement performance up to 90 Nm
- A SiC motor drive inverter was constructed and a forced-air version was tested, which will drive the initial prototype motor
- Dynamometer testing of the initial prototype motor is in progress according to schedule

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