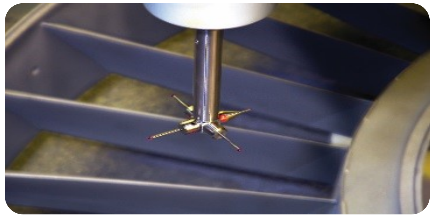


Cost Effective Rare-Earth-Free Flux Doubling, Torque Doubling, 8x Power Density Traction Motor with Near-Zero Open-Circuit Back-EMF and No Cogging Torque

Principal Investigator: Somasundaram Essakiappan

University of North Carolina at Charlotte

US DOE Vehicle Technologies Office Annual Merit Review 2020

Project ID: elt255

June 1-4, 2020

This presentation does not contain any proprietary, confidential, or otherwise restricted information

UNC CHARLOTTE

UK

QM POWER

Overview

Timeline

- Project Start Date: October 2019
- Project End Date: March 2022
- Percent completed: 20%

Budget

- Total Project Funding: $750,000
  - DOE Share: $600,000
  - Recipient Cost Share: $150,000
- Funding for FY 2019: $354,848
- Funding for FY 2020 (expected): $270,638

Barriers & Technical Targets Addressed

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

Partners

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

UNC CHARLOTTE

QM POWER

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

Relevance

- The EETT Roadmap identified key R&D targets for Electric Traction Drive Systems in the year 2025: (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
- To achieve the technical targets in power density and cost reduction, this project will develop:
  1. A high-speed Q-Mag motor with advanced cooling techniques: the positioning of magnets in the stator instead of rotor leads to simpler rotor manufacturing, high-speed and high-torque operation
  2. An efficient drive system using silicon-carbide (SiC) power electronic semiconductor devices, operating at dc voltages at or above 800V, to enable drive operation in motoring and regeneration mode
  3. This project will also perform a path-to-commercialization analysis with input and direction from industry partner(s)

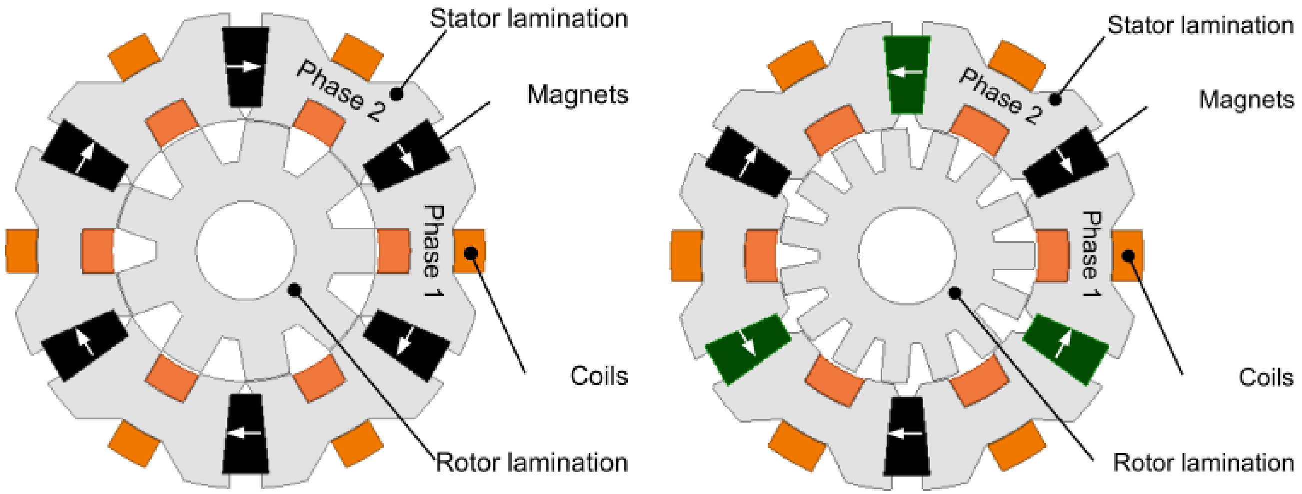
UNC CHARLOTTE

QM POWER

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 magnetically attracting manner (circumferentially vs radially) and inter-dispersed with control winding coils, enabling greater flexibility in flux path 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



QMag topology illustration, (left) type-C (all magnets are magnetized in the same direction), (right) type-A (adjacent magnets are magnetized in opposite directions to concentrate flux).

UNC CHARLOTTE

QM POWER

[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

Technical Approach

The timeline to accomplish the project objectives is listed below:

Year 1: Computer Modeling, Analysis & Testbed Development:

1. Q-Mag Motor design, Finite Element Analysis modeling, and parametric optimization
2. Simulation modeling of SiC based power converter to drive the QMag motor
3. Design and construction of experimental test bed

Year 2: Prototypes Construction, Cooling Mechanism Design, Model Calibration and Verification:

1. Fabrication of prototypes for Q-Mag motor and SiC power electronic inverter
2. Cooling mechanism and optimization analysis for traction motor and drive
3. Refinement of simulation models using preliminary experimental results

Year 3: Testing, Optimization and Documentation:

1. Final testing and optimization
2. Documentation of system design, test results and performance characterization
3. Productization plan for Q-Mag architecture for traction application

UNC CHARLOTTE

QM POWER

Milestones

Milestone	Tasks	Deliverable Date
Milestone 1.1: Feasibility verification of Q-Mag motor and SiC drive for traction applications	1.1, 1.2	April 15, 2020 (Completed)
Milestone 1.2: Construction of a dyne system to test and demonstrate a 125kW Q-Mag motor-based traction system	1.5	July 15, 2020 (On track)
Milestone 1.3: Verification of test plan for Q-Mag motor-based traction system	1.6	September 1, 2020 (On track)
Go/No-go: Verification of flux doubling and power converter	1.1, 1.2, 1.3, 1.4, 1.6	September 20, 2020

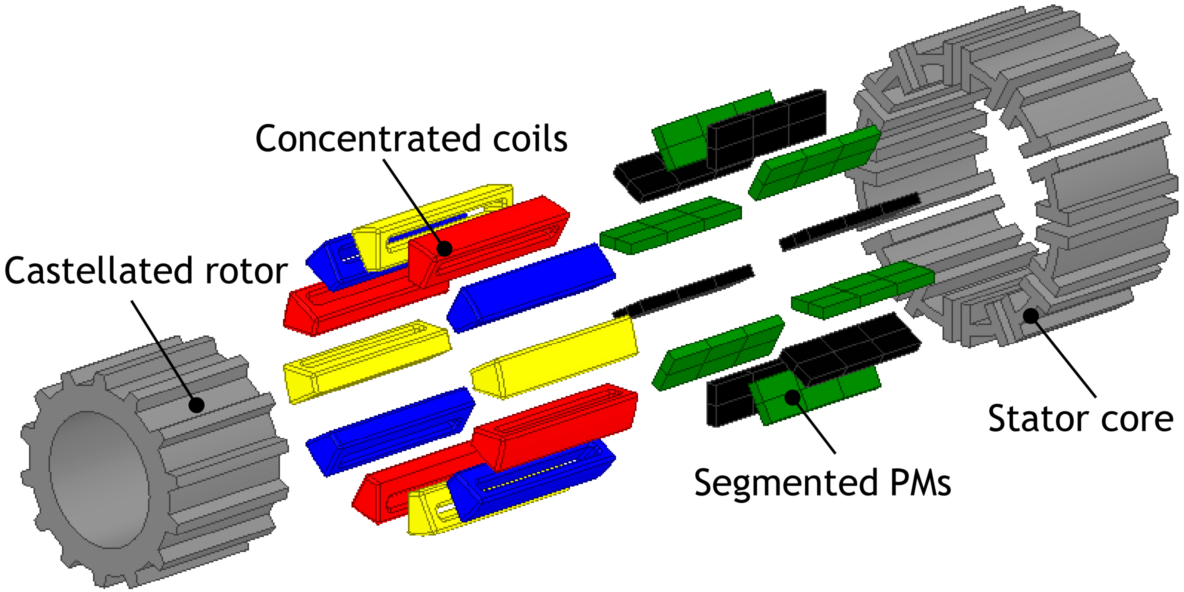
Task 1.1 – SiC based power converter modeling
Task 1.2 – Q-Mag motor parametric modeling
Task 1.3 – Thermal performance analysis of Q-Mag motor
Task 1.4 – Critical review of the model of Q-Mag motor
Task 1.5 – Experimental test plan development
Task 1.6 – Critical review of the test plan for Q-Mag motor-based traction system

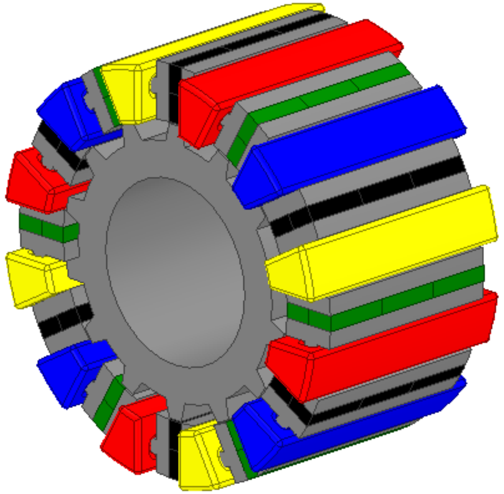
UNC CHARLOTTE

QM POWER

Technical Accomplishments and Progress

- The Q-Mag motor has been analyzed and shown to be feasible candidate for traction applications
- Developed parametric models following the principle of operation of Q-mag motors
- Performed a comparison of Q-mag motor topologies and established their relative merits and capabilities for high power density, high speed operation, simplified modular manufacturability, improved better cooling, etc.



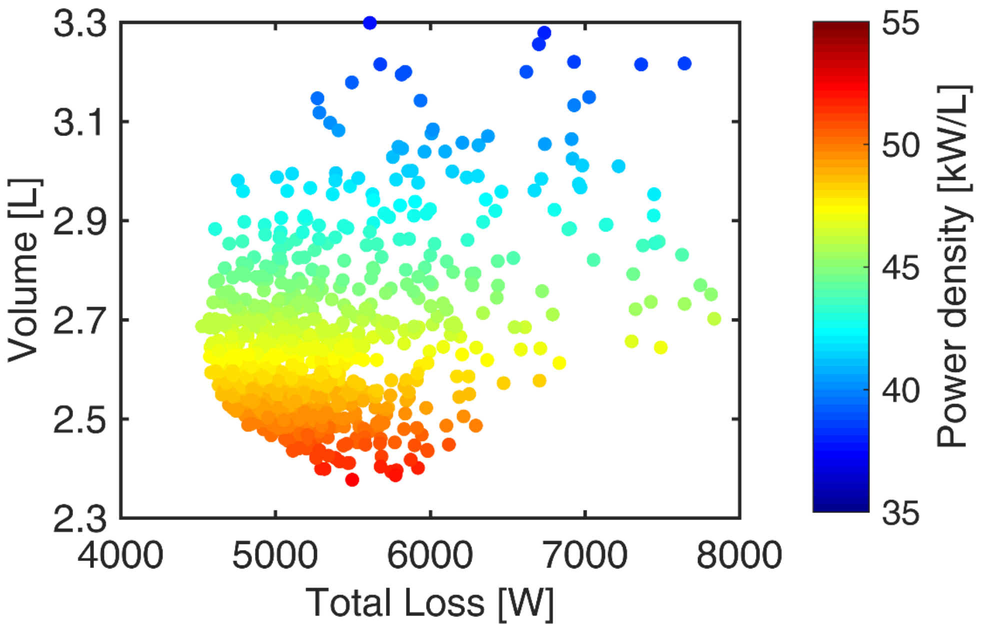


UNC CHARLOTTE

QM POWER

Technical Accomplishments and Progress

- Conducted the large scale design optimization of Q-mag motors for 50kW/L based on parametric modeling and heuristic algorithms, assuming an equivalent electric loading, i.e., the product of current density and slot fill factor, equal to 9.75A/mm^2 can be achieved by the cooling design and advanced winding technology
- The torque-speed and efficiency maps have been calculated based on 2D FEA, showing that the optimally designed motor can operate with constant power at up to 3X the base speed.

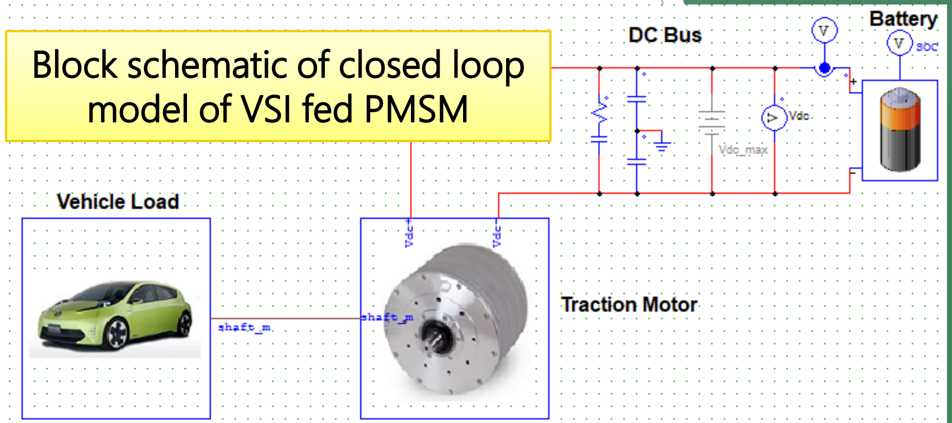


UNC CHARLOTTE

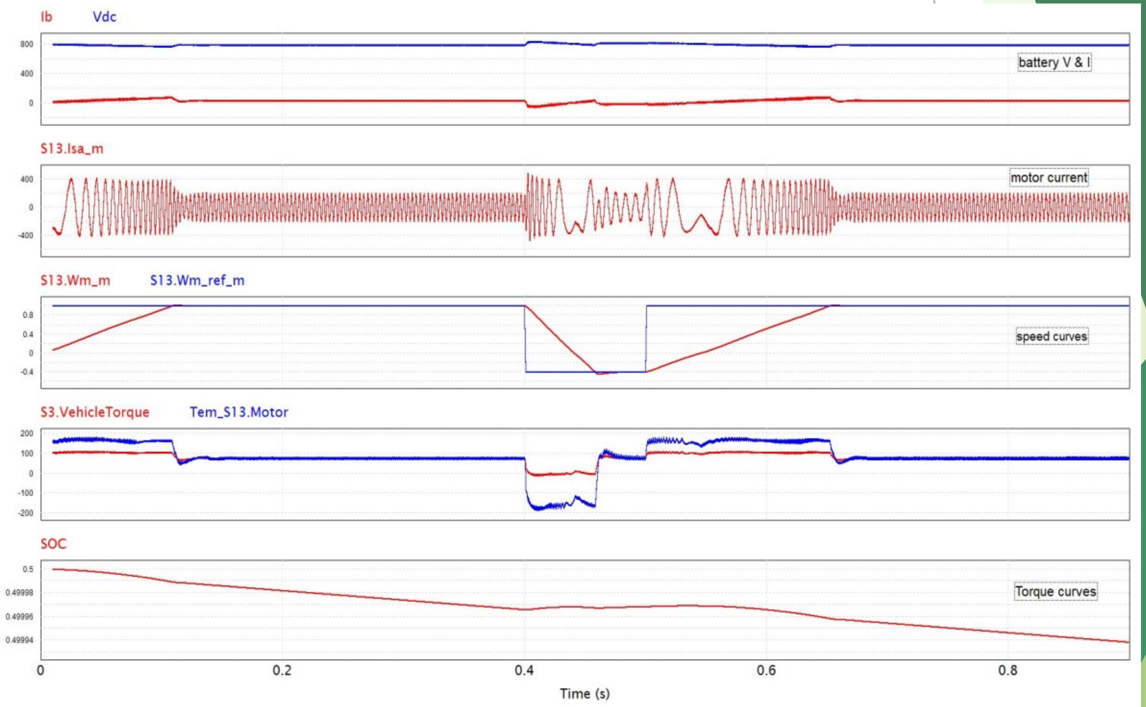
QM POWER

Technical Accomplishments and Progress

- The SiC three phase motor drive and controller were developed and evaluated in simulation at 125 kW, 800 Vdc.
- Power electronic stage utilizes non-ideal device model with on-state resistance, switching loss characteristics



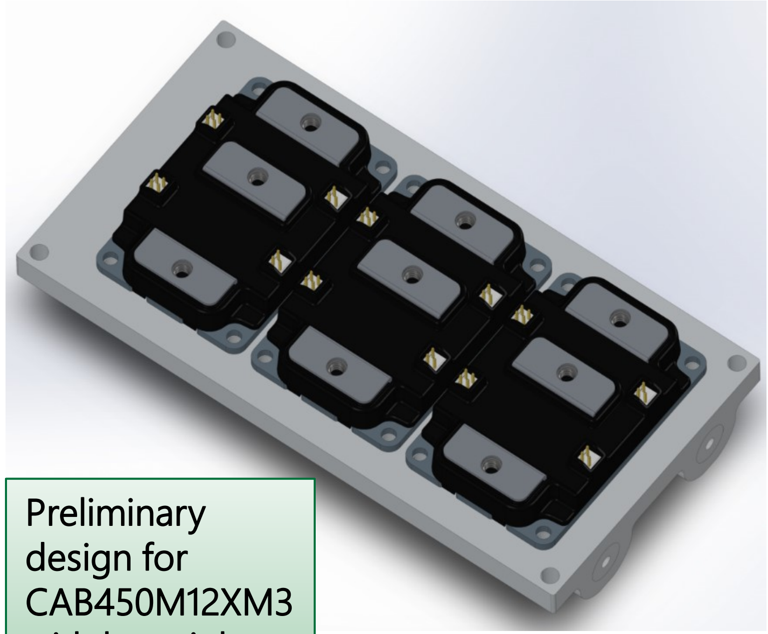
- Control algorithm includes speed and torque control loops to regulate inverter output (motor stator) currents in both motoring and regenerative braking modes – positive and negative torques application
- Inverter switching frequencies in the range 20 – 50 kHz provides low output current distortion <3% (THDi)



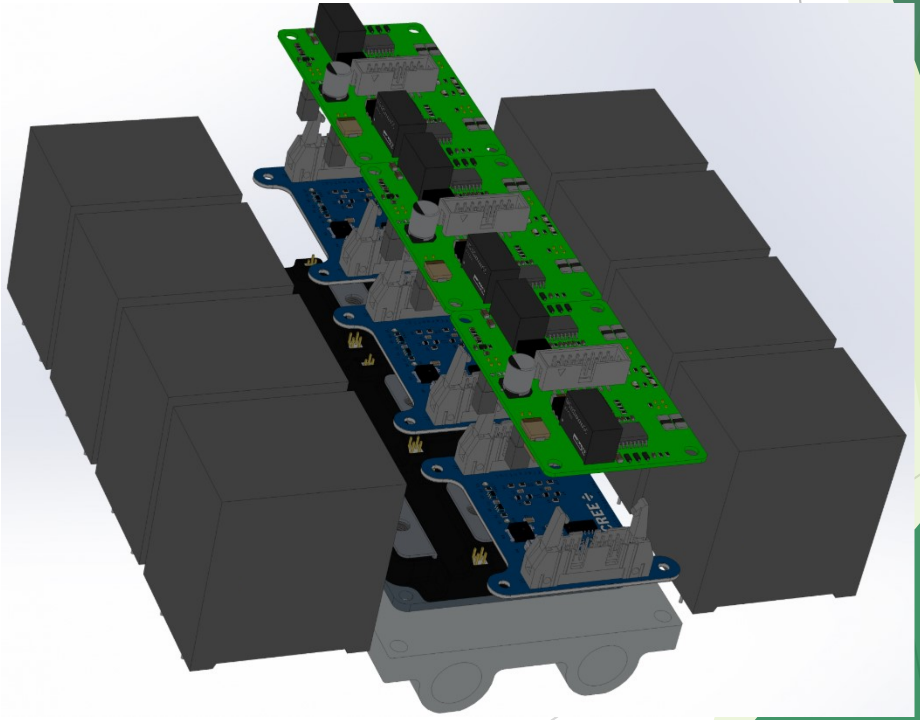
Battery V & I; motor currents; speed; torque; battery SoC in motoring and braking modes

Technical Accomplishments and Progress

- Loss budget analyses using estimated drive voltage and current requirements at rated power, junction temperatures, and switching frequencies were performed for candidate SiC modules
- Based on the heat extraction needs, heat plate candidates were identified, and inverter prototypes were visualized – a preliminary design for candidate module Wolfspeed CAB450M12XM3 is shown below, with power densities capable of meeting DOE targets (100 - 150 kW/litre, based on enclosure and ancillary component sizing)



Preliminary design for CAB450M12XM3 with heatsink



Preliminary design for drive inverter prototype with power modules and drives, heatsink, and dc capacitors

UNC CHARLOTTE

QM POWER

Responses to Previous Year Reviewers' Comments

- This is the first year that this project is being reviewed

UNC CHARLOTTE

QM POWER

Collaborations & Coordination

UNC CHARLOTTE

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 and subcontracting administration

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

QM POWER

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

Key Vendors:

Wolfspeed, ROHM, Infineon (SiC power modules and gate drives)

Texas Instruments (Microcontroller platform)

Powersim (Power electronics design and simulation platform)

Ansys (Magnetics Finite Element Analysis platform)

Yokogawa (Metrology solution for electrical and mechanical performance)

UNC CHARLOTTE

QM POWER

Remaining Challenges & Barriers

- Q-Mag motor prototyping:
  - ➢ Design of cooling system for machine and identification of coolant / pump system – insufficient heat extraction may lead to underperformance challenges for motor current and power capabilities
  - ➢ Manufacturing process for Q-Mag motor prototype – unique motor architecture may present challenges in assembly of laminations, windings, and magnets on the stator; high speed operation may require high precision for rotor construction
- SiC drive inverter prototyping:
  - ➢ Construction and operation of inverter at high dc voltages (at and above 800V) may present challenges in system integration, noise mitigation and ground loop currents, leading to impacts on power density performance
  - ➢ The integrated testbed requirements need to be fully identified and there may be challenges with dyno load motor selection and integration

UNC CHARLOTTE

QM POWER

Proposed Future Research

- Continue motor and inverter optimization
- Develop motor and inverter cooling strategies and identify mechanical subsystems for fluid management
- Develop prototyping plan for motor components – windings, laminations and magnets – and assembly
- Complete identification of experimental dynamometer testbed and assemble including metrology
- Analyze run-time control strategies for power quality and efficiency improvement in integrated drive system, over light-to-rated power operating ranges
- Test inverter module candidate(s) operation at rated voltage and current levels
- Translate control algorithm into microcontroller program

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

UNC CHARLOTTE UK QM POWER

Summary

- The proposed Q-Mag architecture based electric drivetrain system under development promises to meet DOE EETT targets for power density improvement, cost reduction, and magnetics utilization
- The design based on the Parallel Path Magnetic Technology, placement of magnets in stator, and simple rotor design could lead to reduced manufacturing complexity for high speed rotor operation
- Finite Element Analysis, design and optimization of motor topology show power density capabilities at or above 50 kW/litre operating at 125 kW in preliminary designs
  - ➢ Continued optimization of motor topology in progress
  - ➢ Manufacturing process development for prototype to be undertaken
- SiC inverter simulation, control algorithm development, and loss analysis show operation in motoring and braking modes, and preliminary designs show power densities at 100 – 150 kW/litre, meeting DOE targets

UNC CHARLOTTE UK QM POWER