Low-Cost Rare-Earth-Free Electric Drivetrain Enabled by Novel Permanent Magnets, Inverter, Integrated Design and Advanced Thermal Management

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Project ID # elt275

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

Overview

Timeline

- Project start date: October 2020
- Project end date: January 2024
- Percent complete ~1.5%

Budget

- Total project funding:$6,250,000
  - DOE share:$5,000,000
  - Contractor share: $1,250,000
- Funding for FY 2020:$1,443,209

Barriers and Technical Targets

- Barriers addressed
  - Develop a rare-earth free electric drivetrain while maintain motor performance and avoiding irreversible magnet demagnetization
  - Develop a low-cost electric drivetrain with systems cost $\leq \$7/\text{kilowatt}$
  - Develop an electric drivetrain with systems power density ≥ 12 kW/liter
  - Develop an electric drivetrain with DC bus voltage ≥ 700 V

Partners

- Marquette University (Lead)
- Niron Magnetics
- Virginia Tech
- NREL
- General Motors

Relevance

The objective of this project is to research, develop, and test a heavy rare-earth mineral free iron nitride (FeN) permanent magnet enabled electric drivetrain system for use in vehicle applications capable of the following:

Electric Traction Drive System Technical Targets [2]	
Parameter	**Target**
Cost [1]	$\leq$ \$7/kilowatt (kW)
Power Density [2]	$\geq$ 12 kW/liter
Operating Voltage	$\geq$ 700 V

Notes:

(1) Calculate cost based on 2020 equivalent dollars. The cost does not include cases, shielding, or external connectors/connections.

(2) Calculate based on peak power capability for a duration of at least 10 seconds with volume based on overall outer bounding dimensions. Volume does not include cases, shielding, or external connectors/connections.

The objective is to develop next generation low-cost rare-earth-free electric drivetrains

Milestones (BP1:Q1-Q5)

Milestone	Type	Description
Down select and develop preliminary motor designs	Technical	Developing preliminary motor designs that eliminate/reduce rare-earth material and that provide a path to meet system-level targets.
Demonstrate FeN packing factor	Technical	Achieve volumetric packing factor > 95% of theoretical density
SiC MOSFET selection	Technical	Select and test device switching performance and establish loss data and efficiency projection
Preliminary inverter design validated to achieve performance metrics	Go/No Go	SiC inverter system design passes the critical design review (CDR) against design matrix (30 kW/L power density, 98.5% efficiency), Final design Bill-of-materials (BOM) and cost analysis report is generated to meet the cost target. Sub-components are designed and tested.

The timeline will change due to various logistical delays

Milestones (BP1:Q6-Q9)

Milestone	Type	Description
Motorettes test results	Technical	Motorettes tested and results match predictions. Proposed thermal management (and material selection) can maintain a hot spot below 180^{o}C and no signs of irreversible demagnetization.
Heavy rare-earth-free motor test results	Technical	Sub-scale/Full-scale heavy rare-earth-free motor built and tested (Peak torque up to 360 Nm and motor power density >16 kW/L achieved with no signs of irreversible demagnetization)
Inverter assembly, test, and validation	Technical	Finish assembly and testing of 200 kW inverter unit at full power and confirm performance specifications.
Produce test coupon	Go/No Go	Produce 100 gram coupon with 36 MGOe energy product

The timeline will change due to various logistical delays

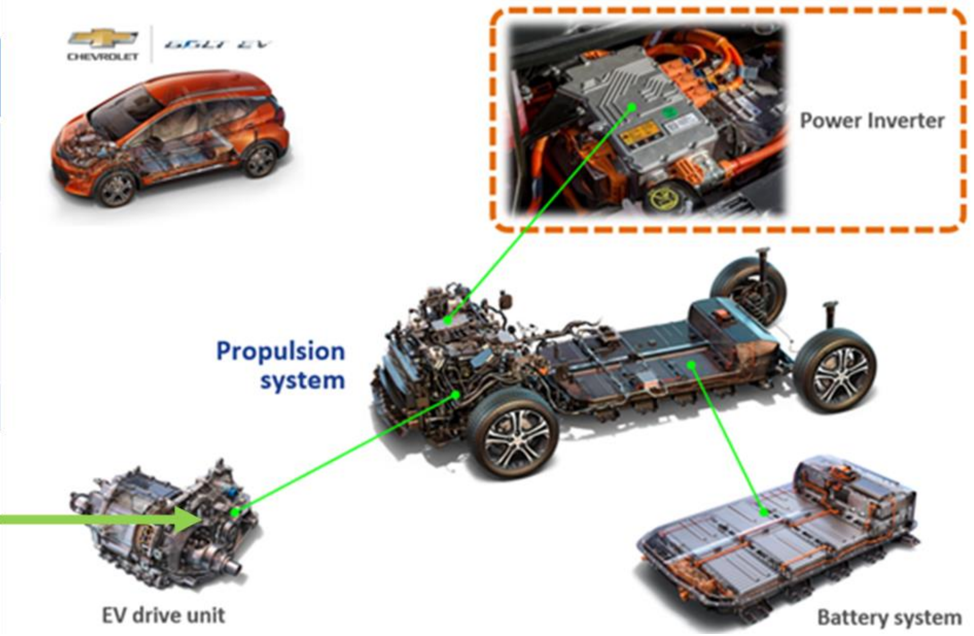
Milestones (BP1:Q10-Q13)

Milestone	Type	Description
Produce 2 kg fully dense magnets	Technical	Scale nanoparticle coating recipe to 2 kg capacity and produce 2 kg of magnets with 36 MGOE
Motor protype built	Technical	Rare-earth-free motor prototype built and ready for system integration
Inverter thermal-mechanical integration	Technical	One inverter unit is fully packaged and tested for full-power condition of 200 kW
System verification testing	Technical	Full system tested to verify performance targets of ≤ \$7/kW, ≥ 12 kW/l, and ≥ 700 V. System verification testing (torque-speed curve and efficiency map generated)

The timeline will change due to various logistical delays

Approach: Baseline System

	Chevy Bolt (Baseline)	Proposed
Max Torque [Nm]	360	360 or lower depending on speed
Max Power [kW]	150	200
Max Speed [rpm]	8810	up to 16,000 rpm
Max Motor Current [Arms]	400	<350
DC Bus Voltage [V]	<450	700-800



The Chevy Bolt system will be used as a baseline

Approach: Project Scope

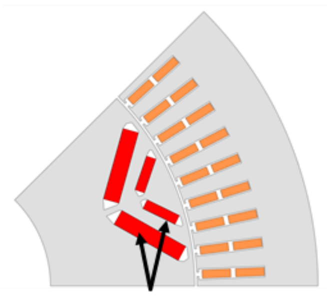
- Budget Period (BP) 1: [Concepts development and tradeoff studies]:
    - Develop concepts, performing tradeoff studies of the various concepts and down-selecting concepts.

- Budget Period 2: [Detailed design, sub-component/component testing and risk retirement]:
    - Develop a detailed design, conduct design optimization, and conduct sub-component/component testing.

- Budget Period 3: [System integration and verification testing]:
    - Procure components, conduct system integration, and perform verification testing.

The proposed approach will enable systematic concepts development and risk retirement

Traction Motor Development Approach



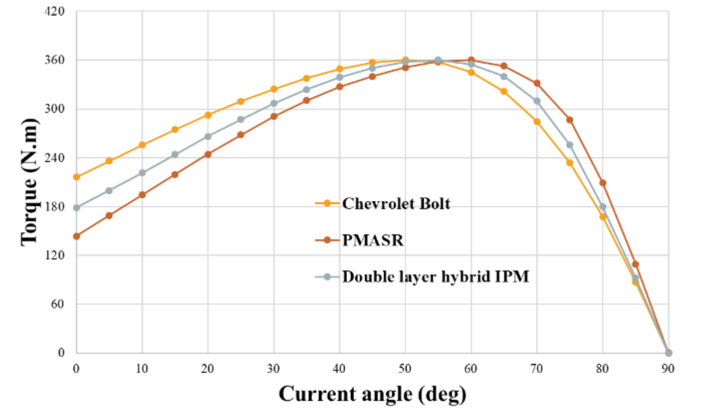
Chevy Bolt IPM motor

Rare-earth free Motor concept 1 Patent pending

Double-layer IPM with blended FeN and Ferrite magnets

Rare-earth free Motor concept 2 Patent pending

PM-assisted synchronous reluctance (PMASR) design with blended FeN and Ferrite magnets

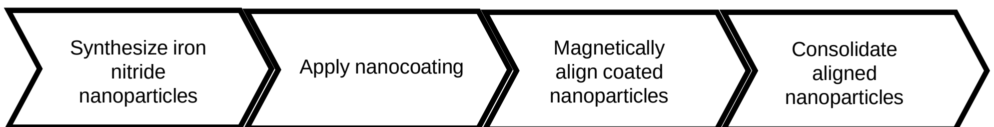


Comparison of torque curves of the three designs

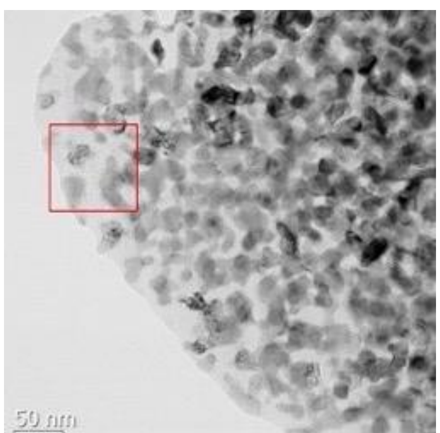
- *A family of designs ranging from elimination of heavy rare-earth material to complete elimination of rare-earth materials will be developed and design tradeoffs documented*
- *Preliminary designs indicate that torque producing capability of a baseline rare-earth IPM can be met with the proposed concepts*
- *The final design is expected to combine ferrites with FeN magnets*

FeN Magnets Development Approach

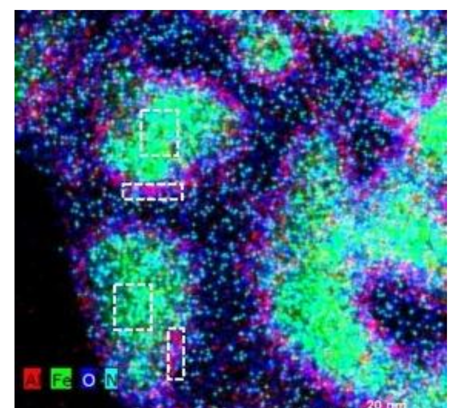
- Niron is manufacturing iron nitride permanent magnets from coated nanocrystalline powders
- Niron is developing low-temperature alignment and consolidation routes to produce high energy product (36 MGOe) iron nitride permanent magnets



Iron nitride magnet manufacturing process



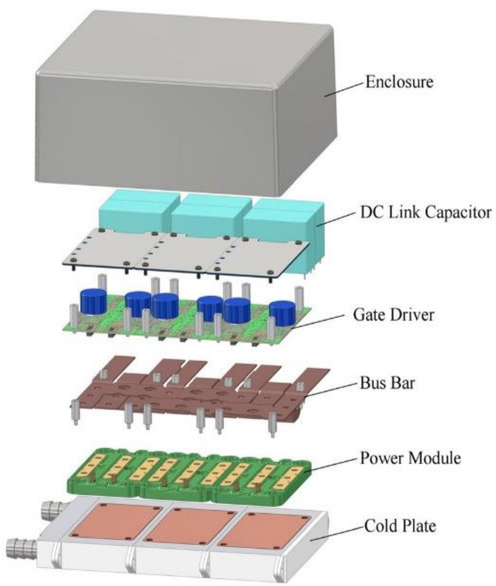
Iron-based nanoparticle precursors

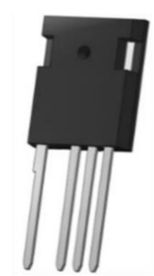


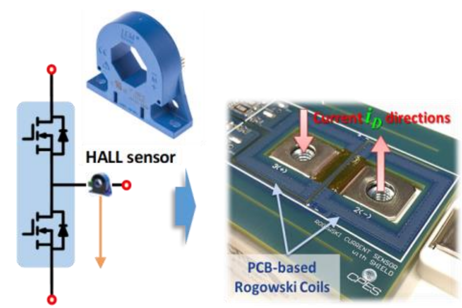
Coated iron nitride nanpoarticles

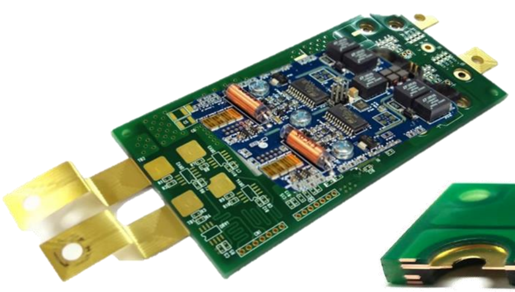
Inverter Development Approach

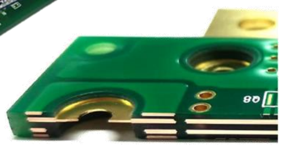
- Cost-out Approach: **Improve power density (>30kW/L) and efficiency (>98.5%)**
- Higher dc-link voltage **800V** to reduce ampere ratings for lower conduction loss and copper usage.
- Low-cost 1.2 kV Discrete SiC MOSFET for high efficiency
- High switching-frequency for smaller dc-link capacitor
- PCB Integration Technology: Embedded current sensor + gate-driver + heavy-copper PCB bus + PCB copper-inlay cooling



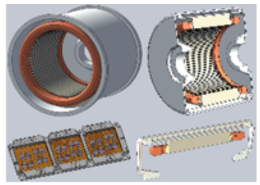




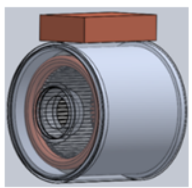
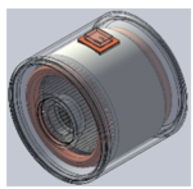
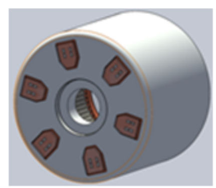




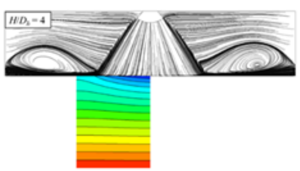
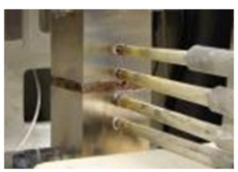
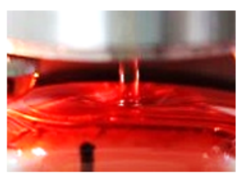
Thermal Management Development Approach



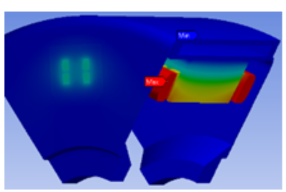
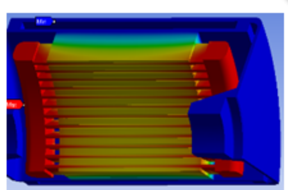
Develop Component Designs and Technologies for Motor and Power Electronics

Evaluate Integration approaches

Research and characterize thermal management improvements for active and passive heat transfer technologies

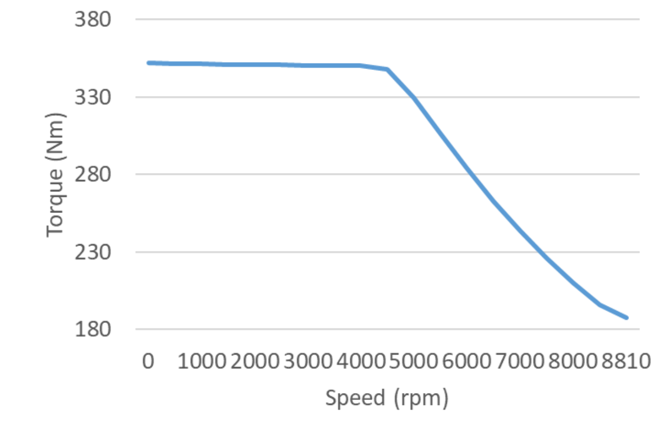
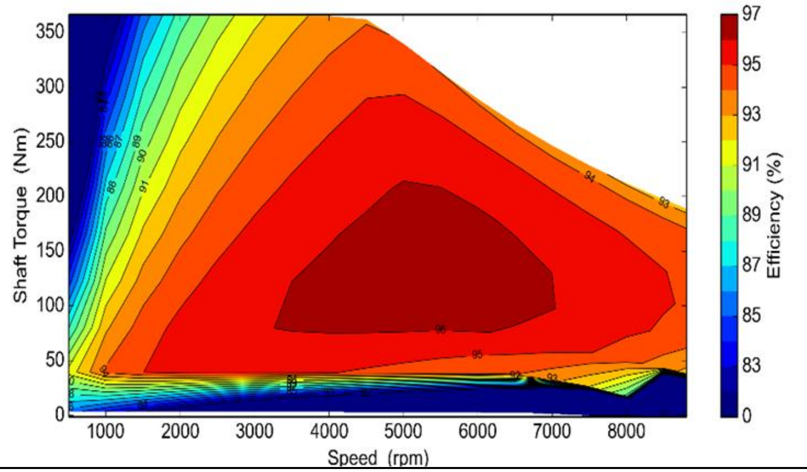



Evaluate cooling solutions with numerical modeling

- Establish performance targets
- Support design tradeoff studies

Image sources: Emily Cousineau, Xuhui Feng, Bidzina Kekelia of NREL

Technical Accomplishments Benchmarking of Bolt Motor

	
Chevy Bolt traction motor torque-speed curve	Chevy Bolt traction motor efficiency map

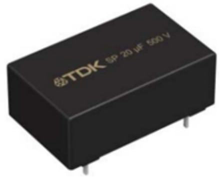
- *Parametric FEA models developed and used to benchmark/analyze the the Chevy Bolt traction motor*
- *Preliminary designs that reduce rare-earth content have been developed and currently being evaluated*

Technical Accomplishments Iron Nitride Magnets

- Literature review completed
- Nanoparticle coating chemistry selected
- First coated iron nitride nanoparticles produced
- Consolidation method selected

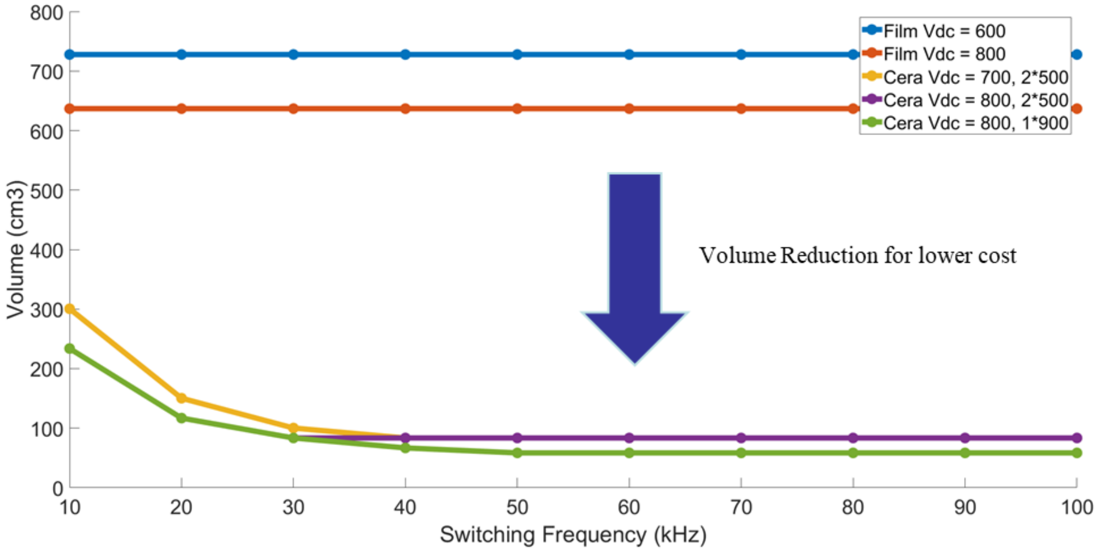
Technical Accomplishments
Traction Inverter

- ✓ Model: C4AQNEW5330M3CJ Film
- ✓ Rated Voltage: 1000 (V)
- ✓ Rated Current: 26.4 (Arms) @ 80 °C
- ✓ Capacitance: 33 (μF)
- ✓ Dimensions: 3.8*4.2*5.7 (cm)
- ✓ ESR: 2.5 ($m\Omega$) @ 80 °C
- ✓ R_{th}: 11 ($^{\circ C}/_{W}$)



- ✓ Model: CeraLink SP Series
- ✓ Rated Voltage: **500 (V)**
- ✓ Rated Current: 41 (Arms) @ 85 °C
- ✓ Capacitance: 20 (μF)
- ✓ Dimensions: 3.3*2.2*1.15 (cm^3)
- ✓ ESR: 3 ($m\Omega$) @ 80 °C

✓ Film capacitor is basically limited by the capacitor current stress



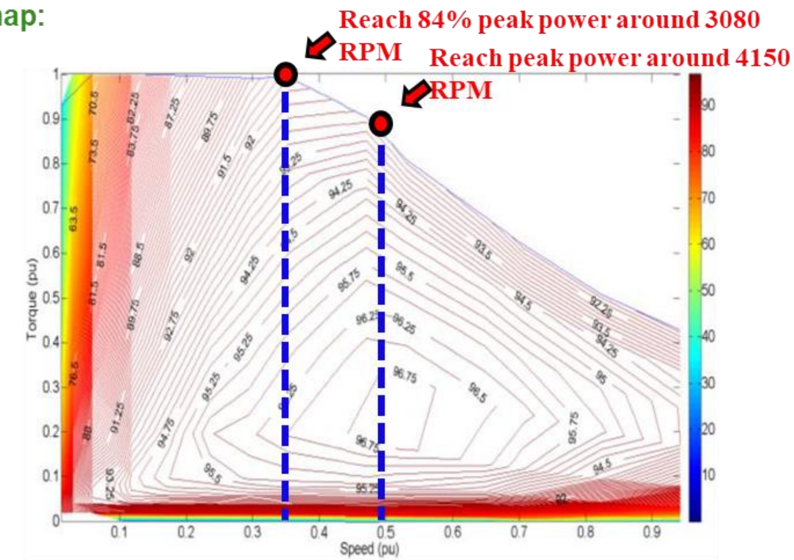
- *Two film capacitor candidates down-selected for further evaluation*

Technical Accomplishments
Traction Inverter

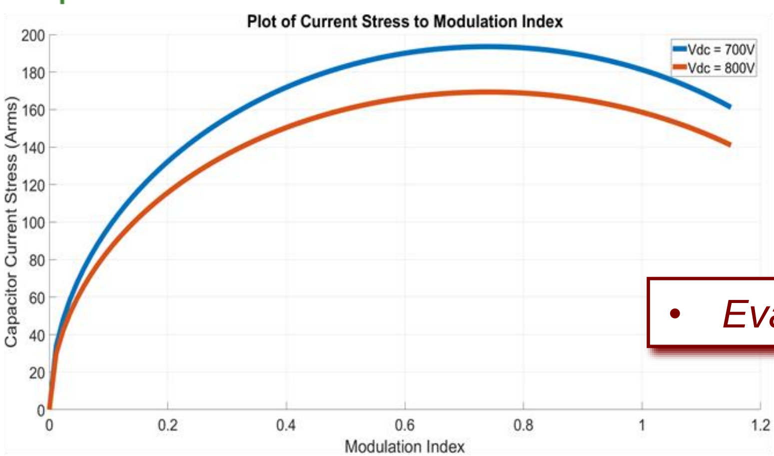
- Motor required maximum phase current during constant-torque region
- Power factor $cos\phi$=0.65~0.7 in constant-torque region, angle typically around 50°
- Boost dc-link voltage from 400~ 500 V to 700~800 V will reduce both ac current and dc-link capacitor current ratings, leading to high efficiency

$cos\phi = 0.7$		
V_{DC} (V)	$_{pn,rms}$ $(Arms)$	$_{rms,max}$ $(Arms$
700	352	194
800	308	170

Chevy BOLT Motor (150 kW) torque-speed-efficiency map:



Capacitor Current Stress:



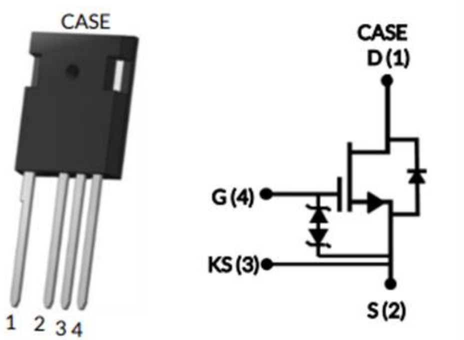
- *Evaluation of capacitor current stress is ongoing*

Technical Accomplishments
Traction Inverter

- ❑ Discrete 1.2 kV SiC MOSFETs will offer lower cost and flexibility for high-density integration
- ❑ Comparison has been performed and device option is narrowed to three candidates

UnitedSiC

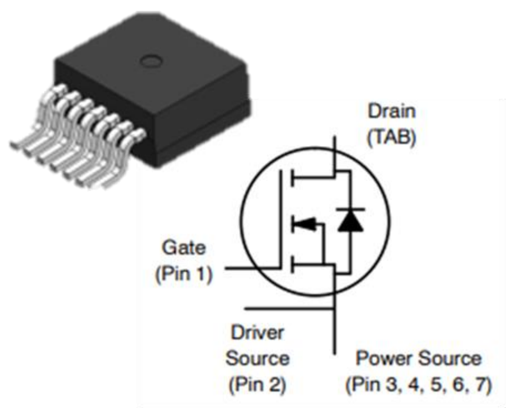
UF3SC120009K4S



1200V-8.6mΩ SiC FET

ON Semiconductor®

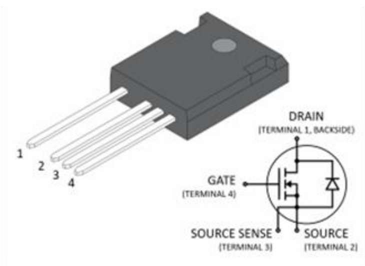
MOSFET - Power, Silicon Carbide, Single N-Channel
D2PAK7L, 1200 V, 98 A, 20 mOhm



Microsemi
a MICROCHIP company

MSC017SMA120B4

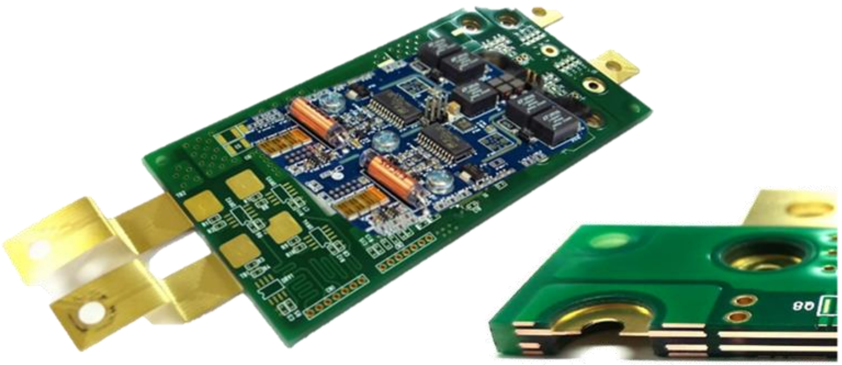
1200 V, 17 mΩ SiC MOSFET



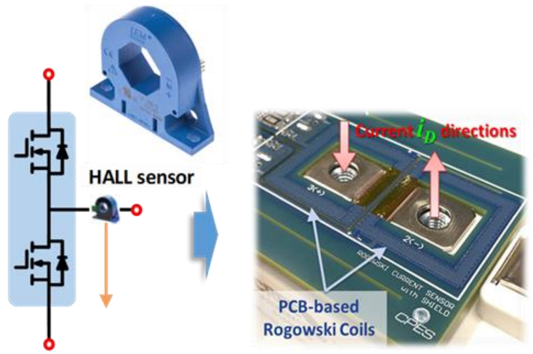
- *Three devices down-selected for further evaluation*

Technical Accomplishments
Traction Inverter

- Heavy Copper PCB and Copper-inlay PCB will be considered for system integration



Heavy Copper PCB for device and bus integration

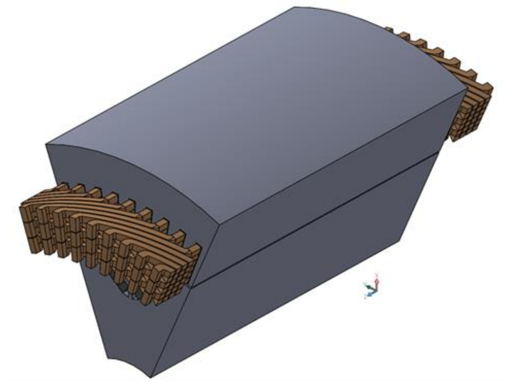


PCB-embedded rogowski current sensor

- *Discussions ongoing with multiple vendors*

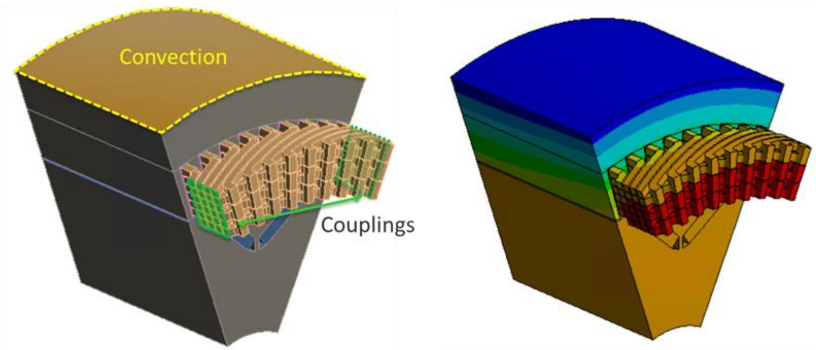
Copper-inlay PCB for vertical cooling

Technical Accomplishments Motor Thermal Management

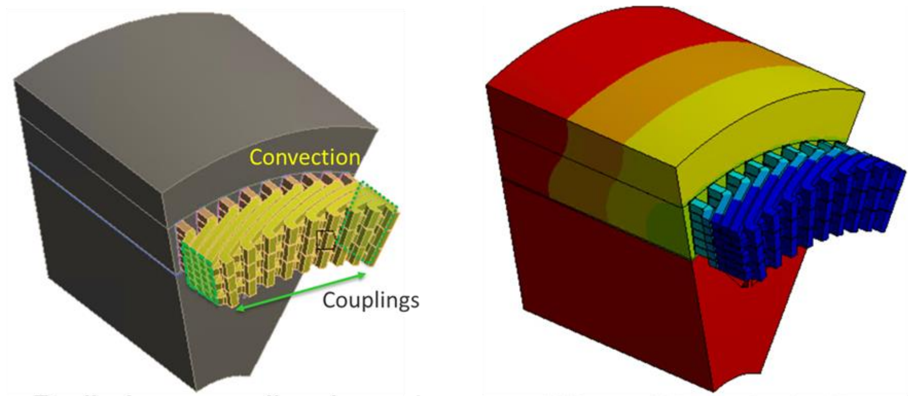


Motor section with ending windings full end winding geometry

- NREL developed models for baseline motor thermal comparisons.
  - Developed model with full geometry of bar end windings to capture impacts of oil cooling over full end winding surfaces
  - Refining cooling boundary conditions and material properties
  - Initiating work to validate model against available data.
  - Initiating work to quantify impacts of alternative cooling approaches

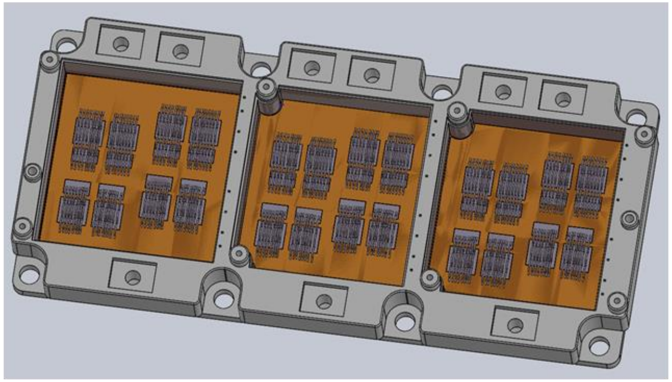


Preliminary cooling boundary condition with case cooling and coupled end winding for accurate heat flow and resulting temperature profile.



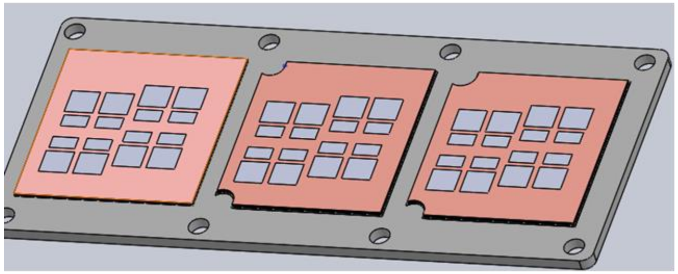
Preliminary cooling boundary condition with end-winding cooling and coupled end winding for accurate heat flow and resulting temperature profile

Technical Accomplishments Inverter Thermal Management

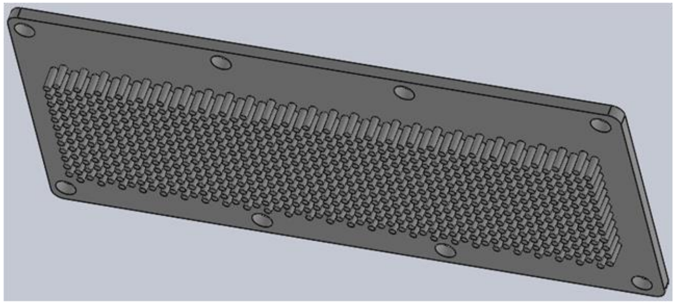


Baseline inverter power module for thermal comparisons

- NREL performed literature search in collaboration with project partners for baseline inverter thermal comparison
  - Identified representative power module for thermal comparisons
  - Gathered power module information, geometry data, and material data
  - Initiated work to develop thermal models and baseline heat loads
  - Initiated work to model baseline integrated heat exchanger
  - Initiated work of validate model against available baseline power module information



Preliminary model for baseline power module thermal analysis



Preliminary model for baseline heat exchanger performance comparisons

Responses to Previous Year Reviewers' Comments

- New project and was not reviewed last year

Collaboration and Coordination with Other Institutions

Principal Investigator
Dr. Ayman EL-Refaie
Marquette University

Marquette University
Electrical Machine Design
- Dr. Ayman EL-Refaie
- Dr. Qingqing Ma

Niron Magnetics
FeN PM Development
- Dr. Frank Johnsn
- Dr. John Larson

Virginia Tech
Low-cost Inverter
- Dr. Dong Dong
- Dr. Rolando Burgos

NREL – National Renewable Energy Lab
TMS Development
- Mr. Kevin Bennion
- Dr. Sreekant Narumanchi
- Dr. Bidzina Kekelia
- Ms. Emily Cousineau

General Motors
System integration and testing
- Dr. Alireza Fatemi
- Dr. Muhammad Alvi

- *A diverse and experienced team will develop various aspects of the electric drivetrain system*
- *Regular team meetings are taking place to discuss progress made and next steps*

Remaining Challenges and Barriers

- The project is still at a very early stage, but the key challenges include:
  - Being able to develop FeN permanent magnets with the target properties
  - Being able to develop a traction motor that completely eliminates rare-earth material without significantly compromising performance
  - Being able to meet the cost and power density targets for the inverter
  - Being able to develop an effective and fully integrated thermal management system

Proposed Future Research

- Consolidation of coated iron nitride nanoparticles to reach iron nitride volume fraction of 95% (BP1 Milestone)
- Development of magnetic alignment methods needed to enable energy product of 36 MGOe (BP2 Milestone)
- Develop and evaluate a wide range of traction motor design starting from reducing the rare-earth content all the way to complete elimination and quantifying the performance tradeoffs
- Finalize selection of the traction inverter components and proceed towards the complete inverter design
- Continue to evaluate thermal management schemes and develop motor/inverter integration concepts with shared thermal management

Summary Slide

- The project provides a comprehensive approach to meet the demanding DOE systems requirements in terms of cost, power density, higher DC bus voltage and eliminating rare-earth materials
- Several novel technologies and approaches are proposed and are expected to significantly advance the state of the art
- The project is still at an early stage and even though there have been significant logistical delays, the team continued making progress. We expect more progress in coming months