Integrated Electric Drive System (Keystone Project #3)

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Oak Ridge National Laboratory

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ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

Overview

Timeline

- Start – FY19
- End – FY21
- 25% complete

Barriers

- Integration of inverter and motor to achieve high power density electric drive
- Identification, evaluation, and integration of high energy density capacitor technology
- Meeting DOE ELT 2025 Integrated Drive power density target of 33kW/L

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY19: $300K

Partners

- National Renewable Energy Laboratory (NREL)
- Sandia National Laboratory (SNL)
- Ames Laboratory
- ORNL team members:

  Emre Gurpinar, Tsarafidy Raminosoa, Gui-Jia Su, Jon Wilkins, and Burak Ozpineci

Relevance – Project Objective

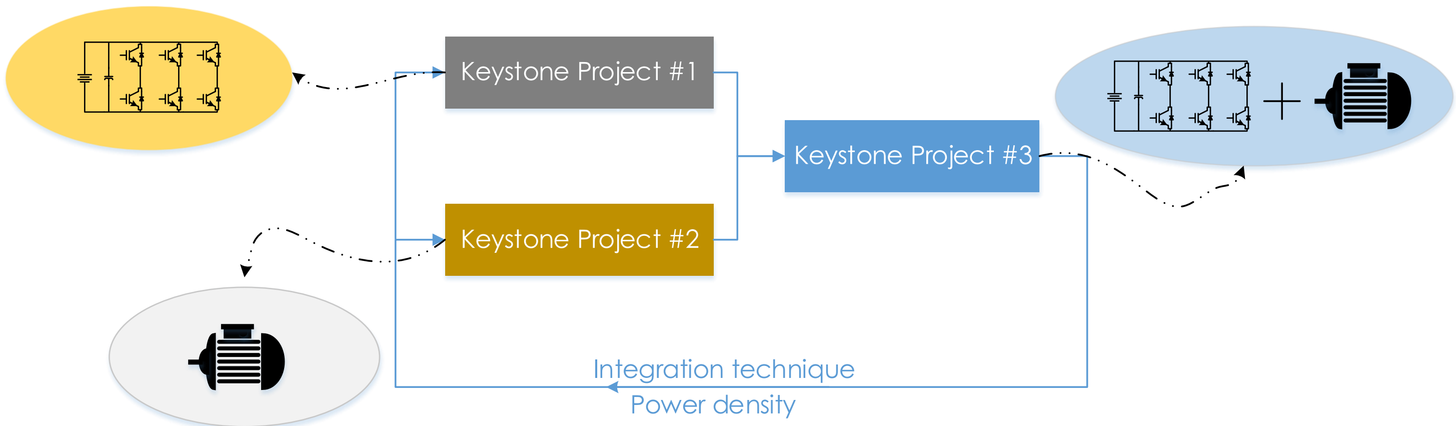
- **Overall Objective:**
  - The main objective of this project is to research technologies that will allow the integration of the inverter with the motor resulting in a high power density integrated traction drive.
  - The project results from Keystone Projects #1 and #2 will be fed into this project for an iterative approach.
- **FY19 Objectives:**
  - Identify the gaps and challenges in current integrated electric drive technologies for electric vehicle (EV) traction application
  - Evaluate various technologies to integrate an electric motor and an inverter
    - Compare advantages and disadvantages of different integration technologies
    - Build finite element (FE) models to analyze thermal effects in collaboration with NREL
  - Integrate direct current (DC) bus capacitor with the machine for better power density

Milestones

Date	Milestones and Go/No-Go Decision	Status
Q1	Milestone: Review state of the art in integrated drives and identify the challenges of integration	Complete
Q2	Milestone: Research different ways of integrating an inverter and a motor	Complete
Q3	Milestone: Co-design the inverter and electric motor with different approaches according to consortium target	On Track
Q4	Go/No-Go Decision: If the identified technologies results in a more compact, power dense solution to meet DOE targets then design the system for further analysis	On Track

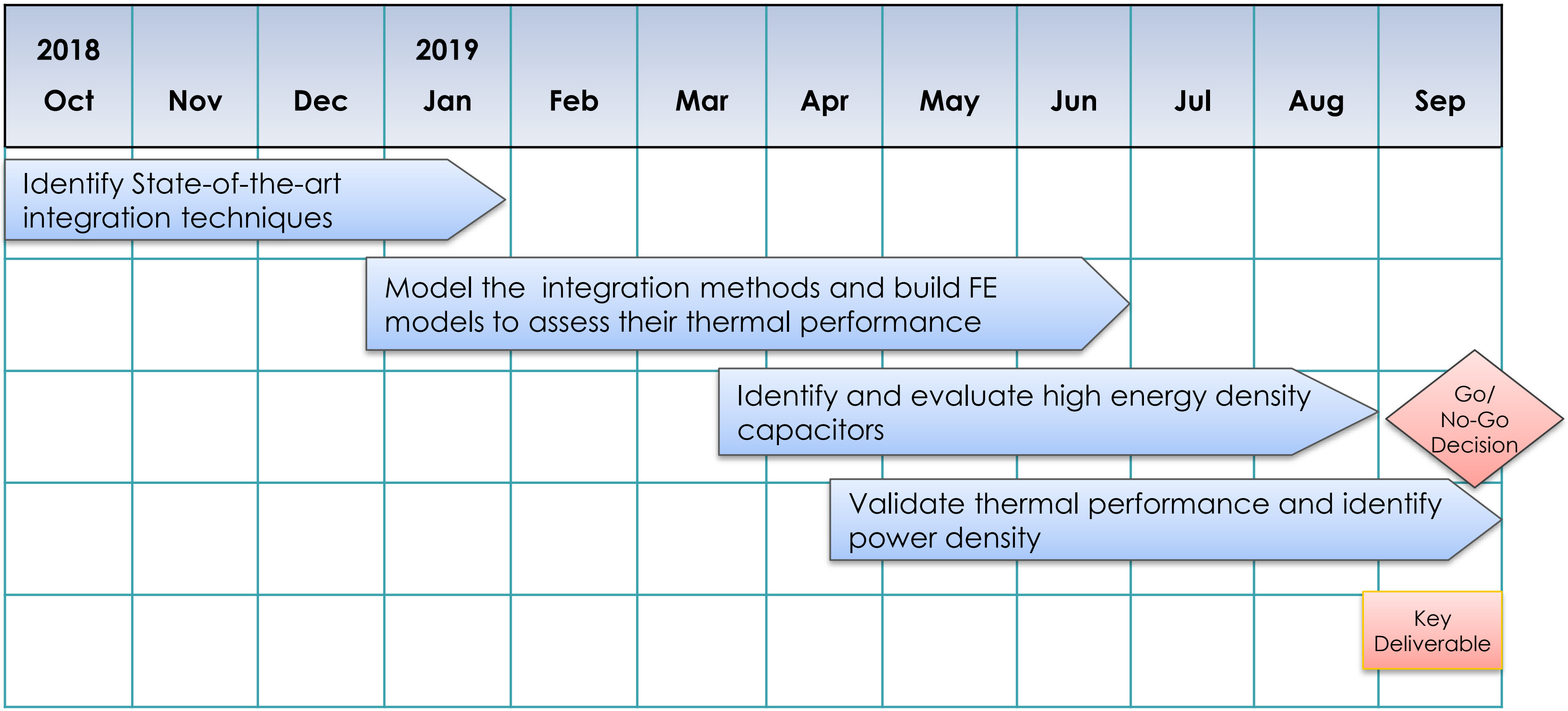
Approach/Strategy

- Review ORNL traction drive reports and existing literature to understand current integration techniques as well as to identify challenges for tight integration of motor and inverter.
- Find all the possible integration methods and assess their thermal performances using Finite Element (FE) platform.
- Identify and evaluate high energy density capacitors as well as alternate space to integrate passive components.
- Propose an integration method to increase power density of the traction drive system.
- Validate the selected system by simulation and prototyping.



Project dependencies

Approach FY19 Timeline



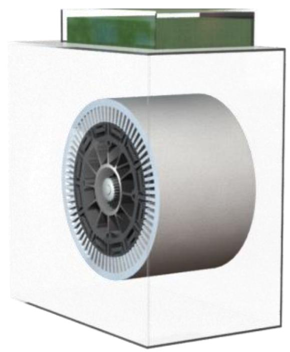
Go/No-Go Decision: If the selected integration technique(s) results in a more compact, power dense solution to meet DOE ELT 2025 target, then start making more accurate models for further analysis.

Key Deliverable: Selection of an integration method to achieve DOE 2025 target based on simulation results.

Technical Accomplishments – FY19

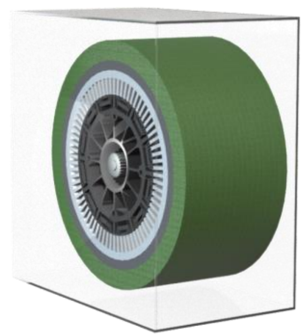
Identified Integration Techniques

Radial Housing Mount – Case #1



- Easy mounting
- Detachable for debugging
- Separate cold plate
- Separate casing
- Low power density due to the geometry

Radial Stator Mount – Case #2



- Shared cooling jacket
- Shared casing
- Debugging is difficult

Axial Endplate Mount – Case #3

- Easy mounting
- Detachable for debugging
- Separate casing and cold plate

Axial Stator Mount – Case #4

- Easy mounting
- Detachable for debugging
- Shared casing
- Can be shared or separate cold pate
- Cold plate can be used as thermal shield

Motor Power electronics

Technical Accomplishments – FY19

Identified Opportunities and Challenges

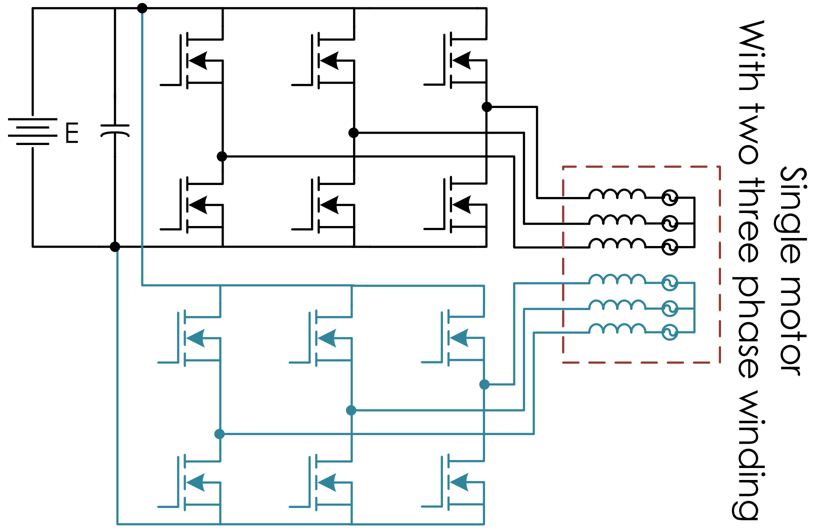
- **Packaging challenges**
  - Availability of high energy density capacitor
  - Symmetrical layout of the capacitor for equal current distribution
  - Low profile interconnect design
- **Thermal challenges**
  - Thermal shielding from stator winding to Inverter
  - Cooling down auxiliary circuitry of the inverter enclosed in a casing
    - I. Gate driver ICs - Can go up to 150°C
    - II. Power supplies - Off the shelf DC/DC converters can go up to 100°C
    - III. DC link capacitors - Film capacitors can go up to 125°C
- **Opportunities for integration**
  - Integrating various inverter components within the motor structure

Technical Accomplishments – FY19

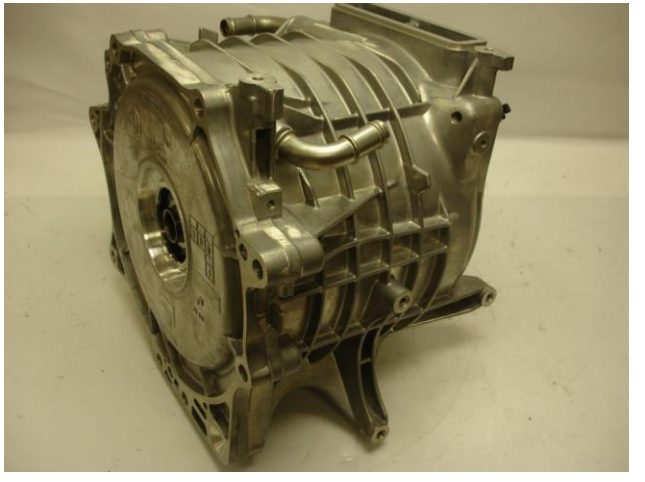
Selected a Motor and an Inverter Topology for Thermal Analysis

Thermal simulation to identify required thermal performance

- BMW i3 motor is chosen as traction motor due to its power rating being similar to 2025 ELT targets
- A segmented inverter is chosen due to its ability to reduce the DC link capacitor current stress and size
- A SiC-based MOSFET is selected as the device for inverter modeling



Segmented inverter topology



BMW i3 traction motor

125kW peak power

Technical Accomplishments – FY19

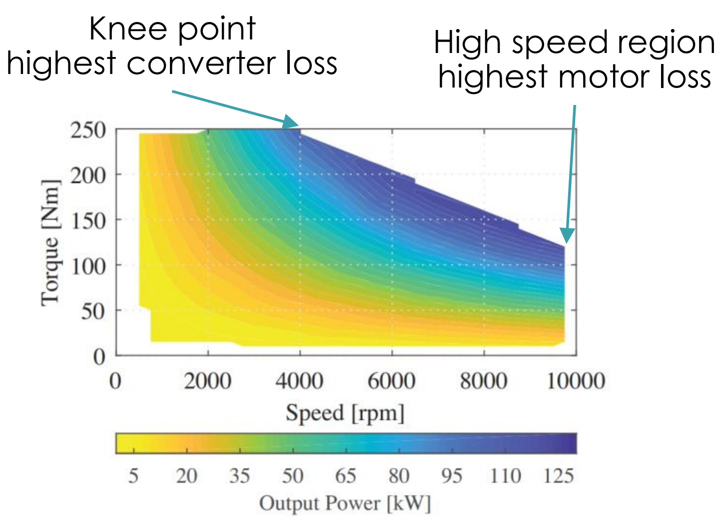
Estimated Inverter Loss

Inverter loss estimation

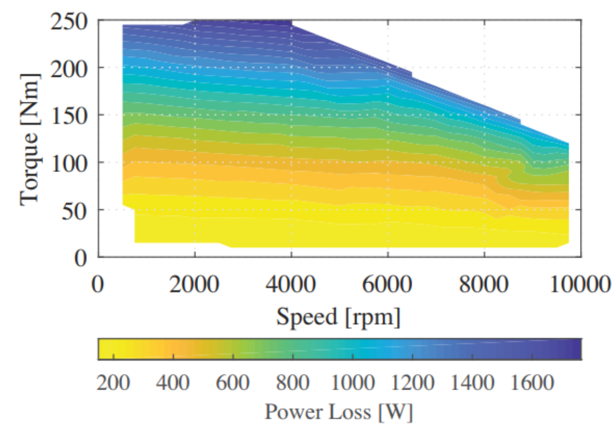
- Motor power map is utilized to identify phase currents to estimate inverter loss
- A SiC based die is selected and two of them are paralleled to achieve current requirement
- Datasheet values are considered for theoretical estimation of inverter losses

Selected SiC MOSFET die parameters
CREE - CPM3-0900-0010A

	Die	Unit
V_{DS}	900	V
R_{DS} @ 125°C	12	mΩ
I_{DS} @ 125°C	140	A
E_{ON} @ 125°C	1.35 @ I_{DS} = 100A	mJ
E_{OFF} @ 125°C	0.83 @ I_{DS} = 100A	mJ



Power map of BMW i3 traction dive



Inverter loss map

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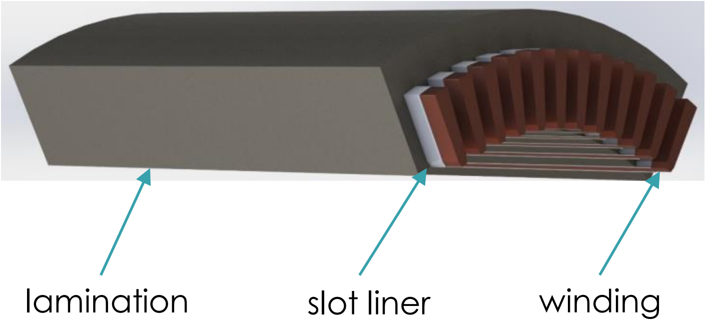
Technical Accomplishments – FY19

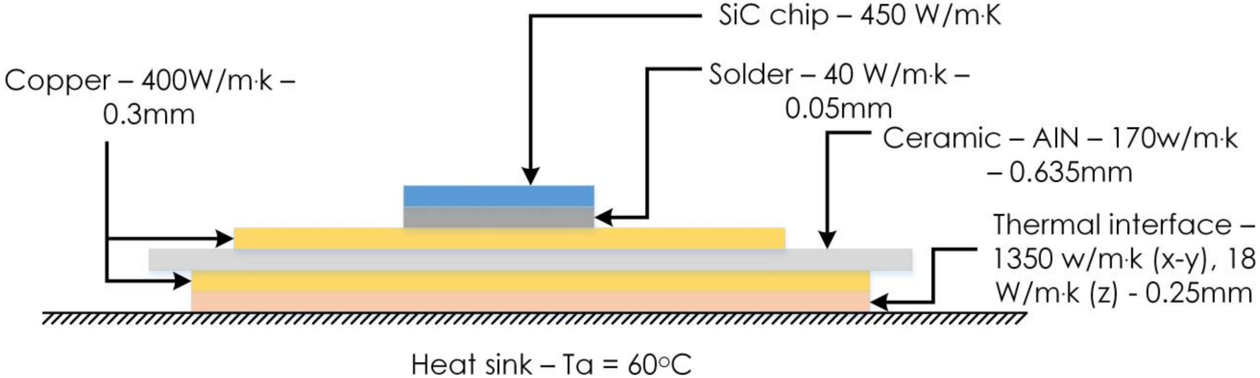
Created Models for Thermal Evaluation

Models for thermal analysis

- One sixth of the motor has been modeled with the assumption of one sixth of the total motor loss is going to be dissipated from this section
- Windings in each slot are modeled as copper bars with anisotropic thermal conductance
- One phase leg of the segmented inverter is modeled
- A conventional direct bonded copper (DBC) substrate is modeled for thermal evaluation

One sixth of BMW i3 stator





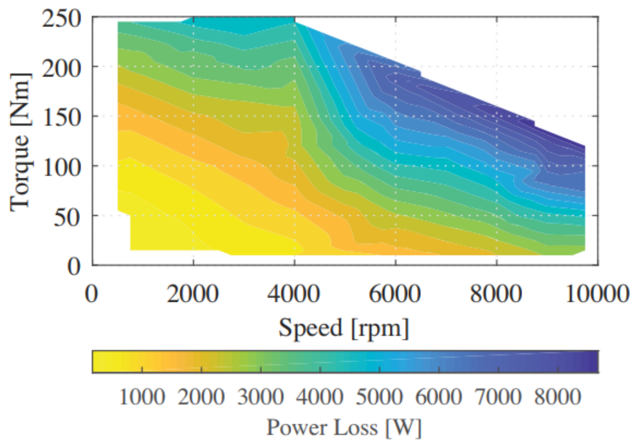
DBC structure for thermal simulation

Technical Accomplishments – FY19

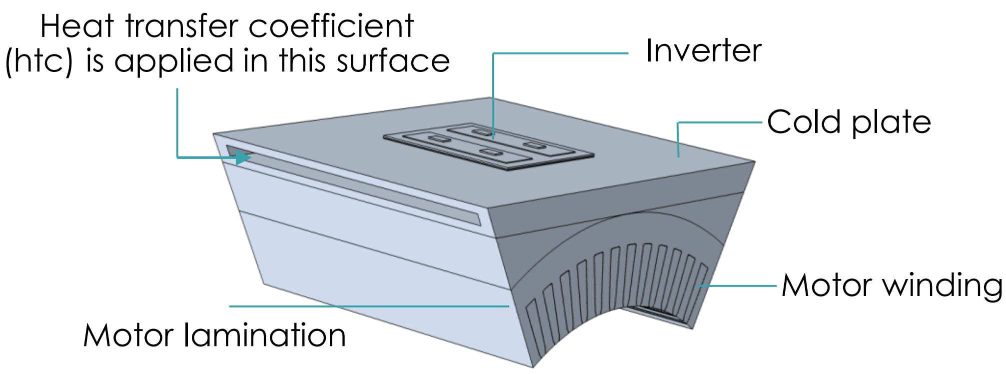
Designed Radial Mount Inverter System for Thermal Analysis

Simulation conditions

- Ambient temperature for the system is kept to 60°C
- Heat transfer coefficient (htc) is varied between 1000 – 10000 $W/m^2 \cdot K$ to identify winding and inverter operating temperature for varying operating conditions
- Total motor losses are identified from experimental result.
- Winding and core losses are evenly distributed within motor winding and in the motor laminations.



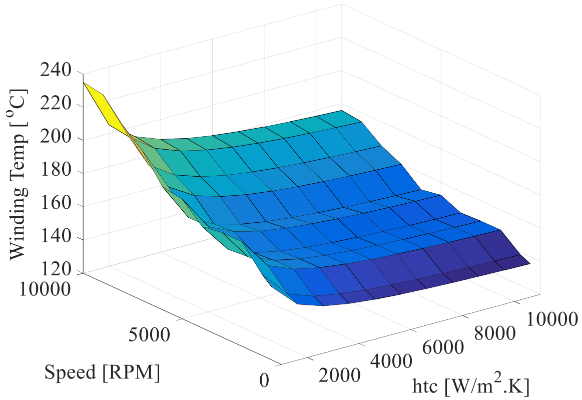
Experimental motor loss map



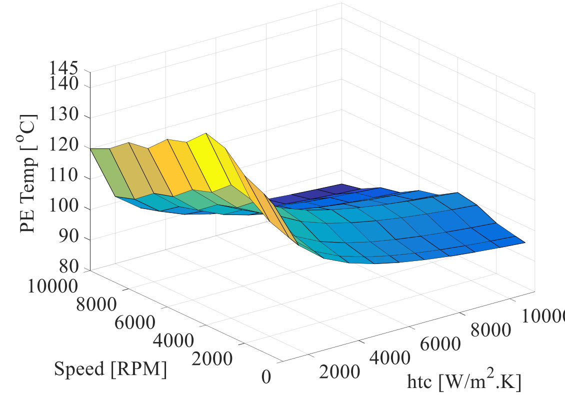
Detailed model of radial mount inverter

Technical Accomplishments – FY19

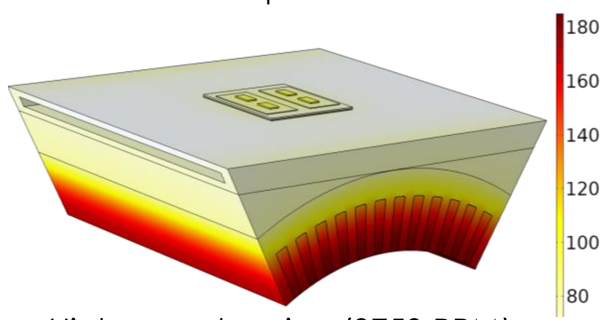
Evaluated Radial Mount Inverter



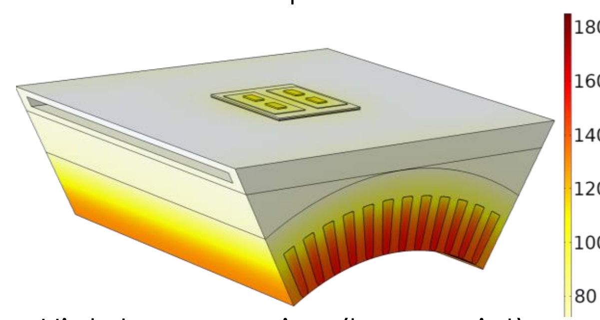
Winding temperature as a function of speed and htc



Inverter junction temperature as a function of speed and htc



High speed region (9750 RPM)
htc = 6000 W/m^2·K
Winding temperature = 181 °C
Inverter chip temperature = 95 °C



High torque region (knee point)
htc = 6000 W/m^2·K
Winding temperature = 156 °C
Inverter chip temperature = 114 °C

Motor and converter temperatures will remain within the limit for all operating conditions if the htc of the cooling surface can be designed at 6000 W/m^2·K

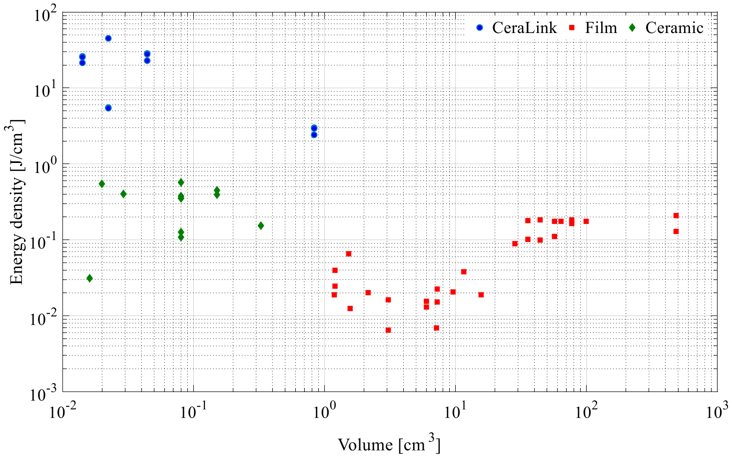
* These are illustrative samples of the approach, more detailed simulations are planned as more information on integrated solutions become available through interaction with the partners

Technical Accomplishments – FY19

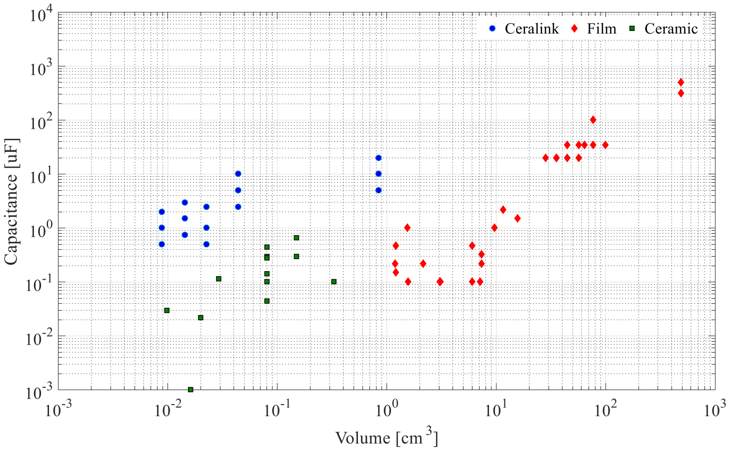
Evaluated Advanced Capacitor Technologies

- Selection of capacitor technology – CeraLink (TDK)
  - Can increase power density of an inverter since they have high energy densities: 50 - 60% DC Link capacitor volume reduction is possible
  - Can operate at 150°C
- Capacitor volume will be 110 cm^3 for BMW i3 traction drive if the segmented inverter is utilized

Comparison of off-the-shelf capacitors



Energy Density



Capacitance Density

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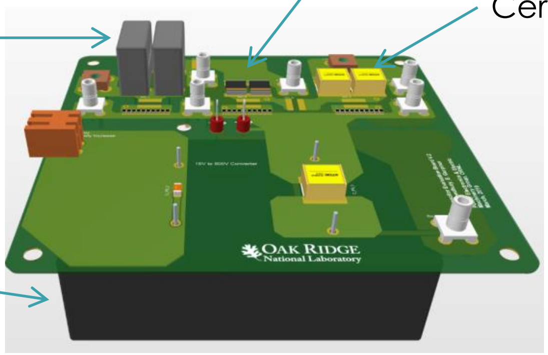
Technical Accomplishments – FY19

Evaluated Advanced Capacitor Technologies

Three capacitors are selected for characterization

	Rated Voltage [V]	Rated Current [A]	Capacitance Bias – 0(400) V	ESR @ 1MHz	ESL	Max Temp	Volume
Film	450	*	1μF (1μF)	*	*	105 °C	1509 mm^3
Ceramic	450	*	1μF (0.3μF)	*	*	125 °C	71.25 mm^3
Ceralink (TDK)	500	11	0.3μF (1μF)	12 mΩ	3 nH	150 °C	224 mm^3



Capacitor characterization PCB

** Not defined in datasheet*

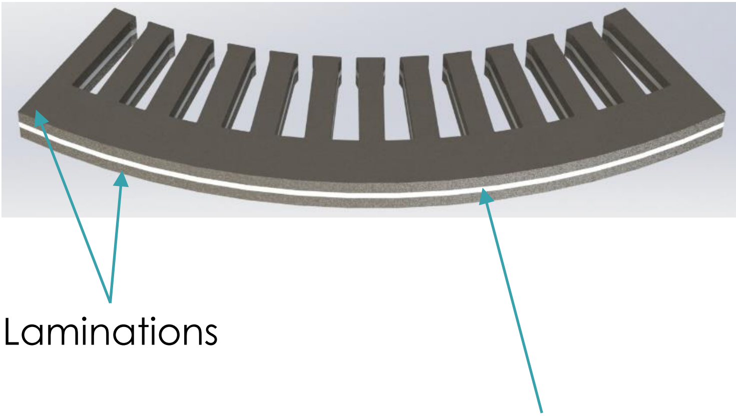
Technical Accomplishments – FY19

Alternate space for DC capacitor – Stator Lamination

Stator lamination as a capacitor – BMW-i3 & 2017 Prius

	Prius 2017	BMW i3
Lamination thickness	0.2 [mm]	0.2 [mm]
Laminations	295	650
Teeth	48	72
Total surface area with teeth	13756 [mm^2]	13077 [mm^2]
Total capacitance (considering back iron and tooth area)	46 pF	18 pF

Illustration of stator laminations as capacitor



Assumptions

- Stator varnish thickness 10 µm
- Stator varnish dielectric constant 8.85×10^{-12} F/m
- All the laminations are stacked together forming series connected capacitors

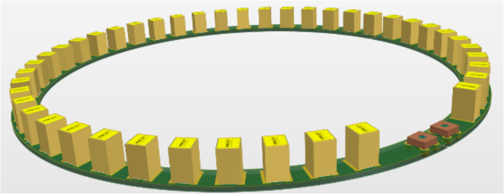
Capacitance is too low due to low dielectric constant and series connection of laminated capacitors !

Technical Accomplishments – FY19

Alternate space for DC capacitor

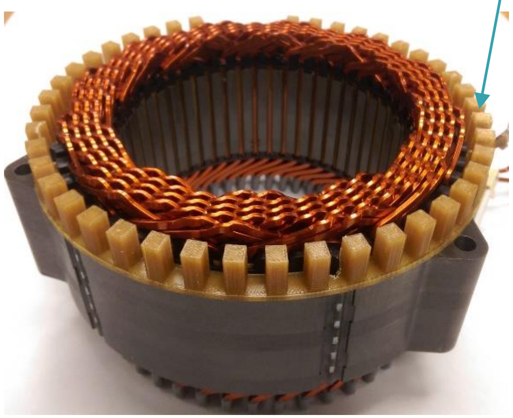
Stator end winding area

- Capacitors can be integrated inside the end winding area of the motor without affecting motor volume



Capacitors mounted on a ring PCB

3D printed dummy capacitor



Toyota Prius – 2017 motor stator with capacitors mounted inside end-winding area

- Off the shelf ceramic capacitors are used
- 168 μF capacitance can be installed in the end winding area (both side)
- Overall electric drives power density will increase
- More study is required to identify the effect of unequal current sharing and the ways to mitigate this issue.
- Each pillar in the figure consists of four parallel 0.5 μF capacitors

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Responses to Previous Year Reviewer's Comments

This project is a new start

Collaboration

Organization	Type of Collaboration
NREL NATIONAL RENEWABLE ENERGY LABORATORY	Thermal analysis of integrated electric drive systems
Sandia National Laboratories	Provide wide bandgap device models and samples
AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY	Provide properties of newly developed magnetic materials for traction motor drive.

Remaining Challenges and Barriers

- Impact on thermal design due to the integration of capacitors and various components of inverter inside motor structure.
- Better thermal management techniques to cool down the motor and the inverter using shared cooling

Proposed Future Work

- **Remainder of FY19**
  - Assess identified integration methods and analyze power density and thermal stress
  - Down select one of the integrated electric motor drive technologies
  - Evaluate feasibility of different component integration techniques
  - Characterize advanced capacitor technologies

- **Future work – FY20**
  - Apply identified integration methods to Keystone Project #1 and Keystone Project #2 and analyze the power density and thermal stress.
  - Identify effects on capacitors if integrated inside motor
    - Losses in the capacitor and effect on cooling system
    - Characterization of the capacitors

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

Summary

- **Relevance:** The core function of this project is to research technologies that will allow the integration of inverter with the motor to meet DOE ELT 2025 power density target of 33kW/L for a 100kW integrated electric drive.

- **Approach:** Review state of the art integrated drive technologies to identify challenges of integration. Propose a suitable integration technique to achieve a power dense electric drive.

- **Collaborations:** Interactions are ongoing with NREL, Sandia, and AMES.

- **Technical Accomplishments:**
  – Identified possible integration methods and their challenges to combine inverter with the motor for high power density integrated drive.
  – Identified an alternate location for bulk DC link capacitor to reduce volume of the overall integrated electric drive.

- **Future Work:**
  – Assess identified integration methods and analyze power density and thermal stress
  – Down select one of the integrated electric motor drive methods
  – Characterize advanced capacitor technologies
  – Complete analysis of the power dense integrated drive system utilizing the results from Keystone 1 and Keystone 2 projects.