Highly Integrated Wide Bandgap Power Module for Next Generation Plug-In Vehicles

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Overview

Timeline

- Start – 1 January 2016
- Finish – 30 September 2020
- 80% Complete

Funding

- Project Budget $5.67 million
  - $3.79M Federal Share
  - $1.88M GM Cost Share
- 2019 funds received $454k
- 2020 funding planned $501k

Vehicle Technology Barriers

- Lower Cost Electric Drive Systems
- Higher Efficiency, long range EV
- Higher Performance and Lifetime
- Lower Mass and Volume

Project Team

- Lead:
  General Motors, LLC
- Subrecipients:
  Virginia Polytechnic Institute and State University
  Ohio State University
  Oak Ridge National Lab
  Monolith Semiconductor, Inc.
- Key Suppliers:
  Wolfspeed (Cree Power)
- Collaborations:
  PowerAmerica

Project Relevance

Research Focus Area: Traction Inverter

- Develop WBG semiconductor based power stage
- Technical development for key components needed for a WBG power stage: design compact gate drive, power module, high voltage capacitor, integrate commercial current sensor, use production ready GM control board, HV motor

Objective

- Automotive power module with SiC MOSFET dies
- Reduce traction inverter and electric motor losses over the drive cycle and quantify efficiency benefits
- Develop technology for long range BEV's with >600V battery
- Implement selected bonding, joining and thermal management solution (low Z_{th}, long lifetime and reliability)

Address DoE Targets

- Enable inverter to meet or exceed DOE 2020 targets:
- Power Density: 13.4kW/l; Specific power: 14.1kW/kg & $3.3/kW
- Efficiency >94% (10%-100% speed at 20% rated torque)

Uniqueness and Impacts

- Compact, high temperature, low inductance automotive package

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Milestones

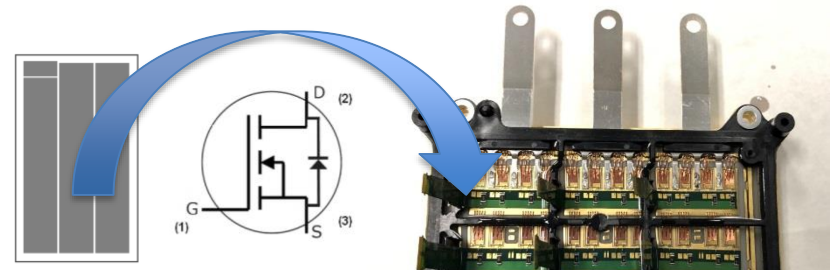
Date	2016-2018 Milestone or Go/No-Go Decisions	Status
June – 2018	Power Module Prototype Perf. – Phase 3 Go/No-Go	Completed
Oct – 2018	Prototype Performance Test Completed - Milestone	Completed
Nov – 2018	Power module and power stage fully characterized	Completed
Dec – 2018	Performed vehicle range study	Completed
Jan – 2020	**Rescoped phase III of the project to focus more on electric drive performance and development**	**Completed**
Jan – 2020	**Novel gate drive board tested**	**Completed**
Feb – 2020	**900V SiC Inverter Build Completed**	**Completed**
Sept – 2019 to Aug – 2020	**1200V Module Build**	**On-Track**
Sept – 2019 to Sept – 2020	**1200V Inverter Build and Performance Testing**	**On-Track**
Jan – 2020 to Sept – 2020	**HV Motor Insulation Study**	**On-Track**

WBG POWER MODULE APPLICATIONS

Features

- Low conduction and switching loss
- Ultra-low parasitic inductances
- High switching frequency operation
- Normally-off device operation
- High temperature operation $T_{j,max} = 175°C$
- High power high voltage power module

SiC Power Module Package

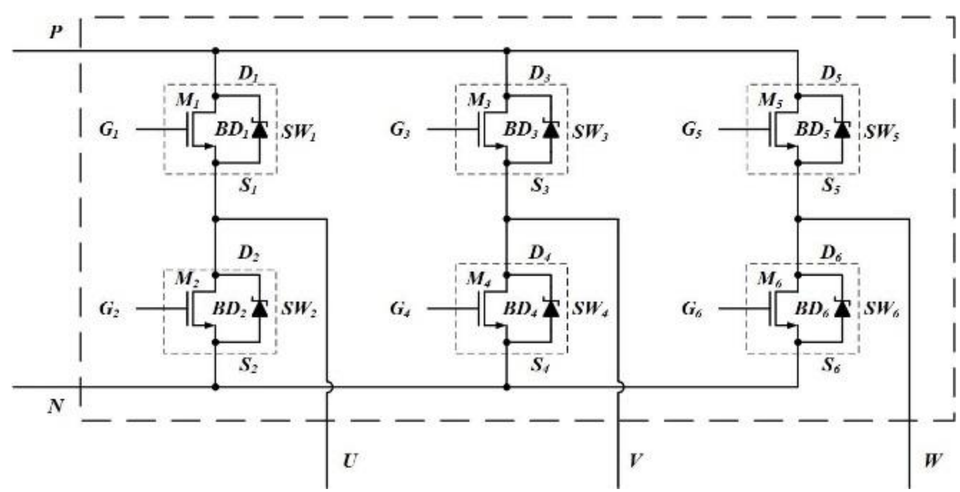


Wolfspeed SiC die
900V 10mΩ &
1200V 13mΩ

System benefits

- Reduced size and weight
- Compact design and inverter packaging
- High efficiency inverter
- Increased power density
- Improved thermal performance and packaging

Functional Circuit

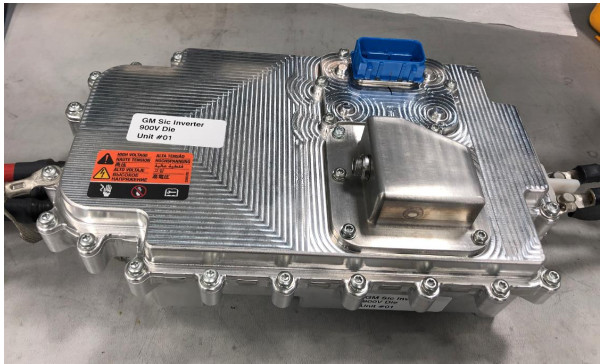


Potential applications

- High efficiency converters
  Such as dc/dc boost converter
- Traction power inverters

Technical Approach

- This program will develop a highly integrated wide band gap automotive power module with a smaller package, lower mass and higher efficiency
- Targets higher DC link bus voltage systems (e.g. 600-800V_{DC}) and maximum phase currents of 300-500A_{RMS}
- The high power density module utilizes SiC MOSFET die to enable high efficiency operation
- Higher power density will be further enabled through the removal of the external diode by using the third quadrant operational capability of the SiC MOSFET
- Design a package that has low stray inductance
  - Target below 10nH for the complete power stage
  - Design power module with stray inductance below 5nH
- Develop advanced current sensing methods
- Develop short circuit protection methods



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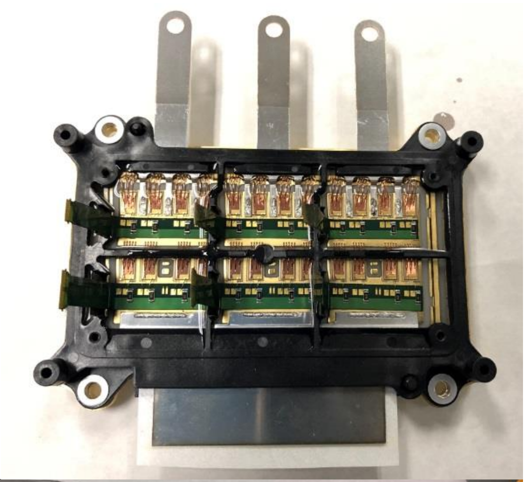
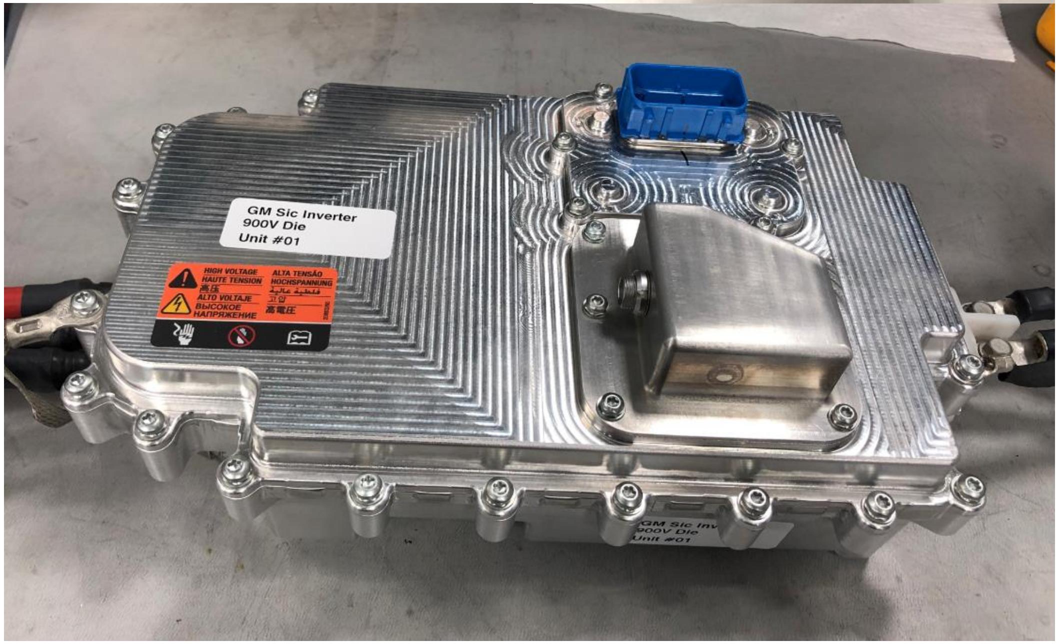
Accomplishments:
Inverter with 900V SiC Die Complete



- Inverter with 900V SiC die successfully completed
- 900V SiC power modules successfully passed characterization and performance tests
- Successful leak test and high potential test (2200V)
- Package is the same as the 1200V SiC inverter that is currently under development



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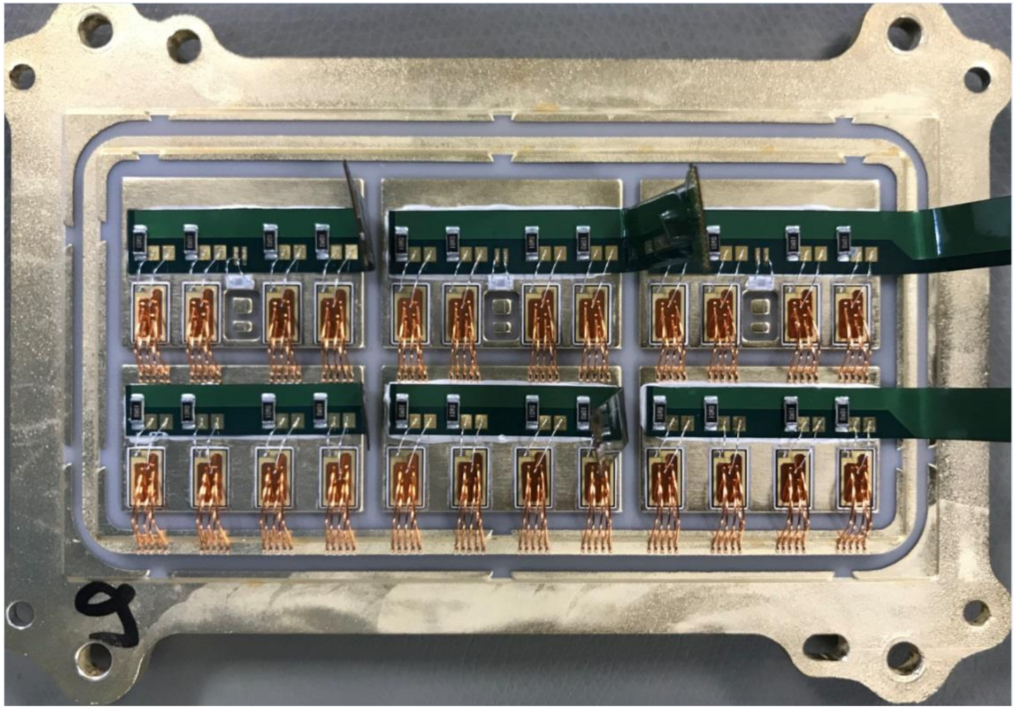
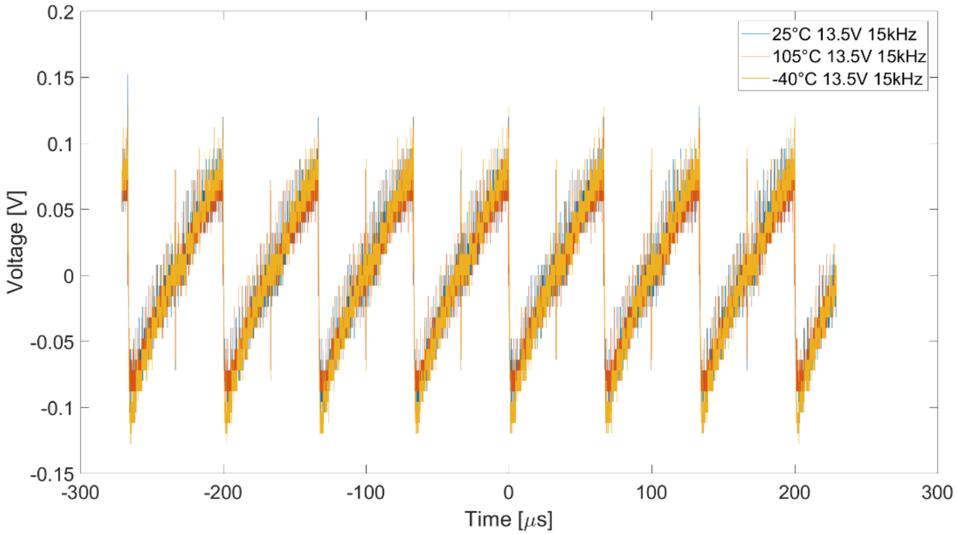
Accomplishments:
1200V SiC Die and Substrates

- 12 prototype substrates built with 1200V SiC Die
- 4 substrates fully functional without any problems
- Redesigned die top system (DTS) to account for new die layout
- Aluminum wirebond size increased and attachment points adjusted
- Thermistor added to the 1200V SiC modules

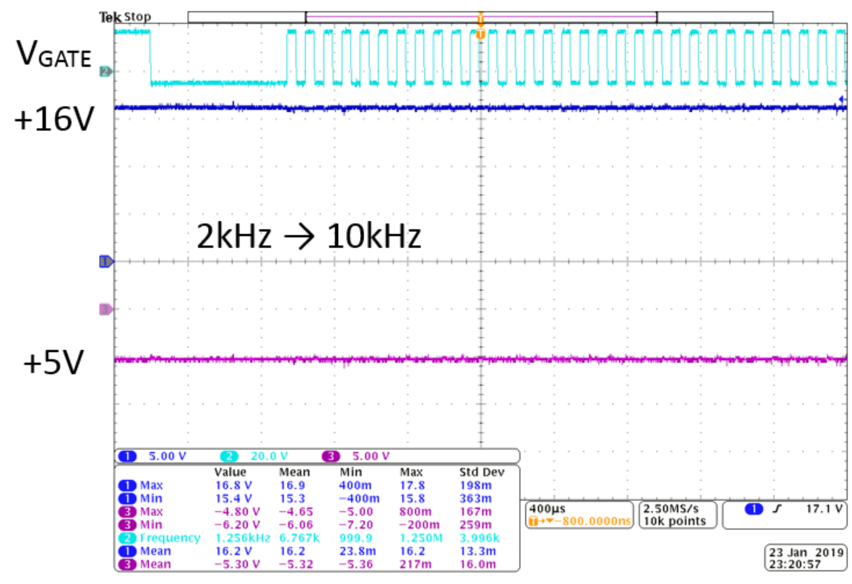


- New tool developed for flexible PCB cable assembly process to increase yield
- Next steps are to complete the power module builds and assemble full inverters

Accomplishments:
Novel, Compact Gate Drive Board with Very Tight Voltage Regulation



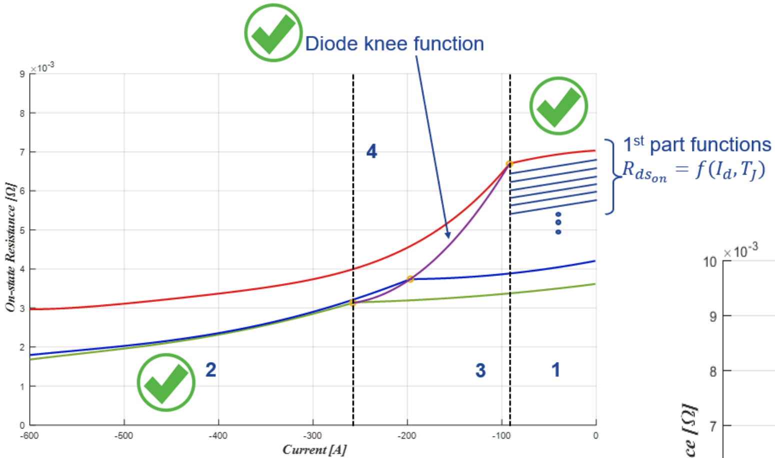
- The gate bias supply is designed to provide a very reliable gate voltage (+/-150mV) across all temperatures from -40 to 150°C
- This tight voltage regulation enables the selection of precise gate bias voltages, improving performance and efficiency



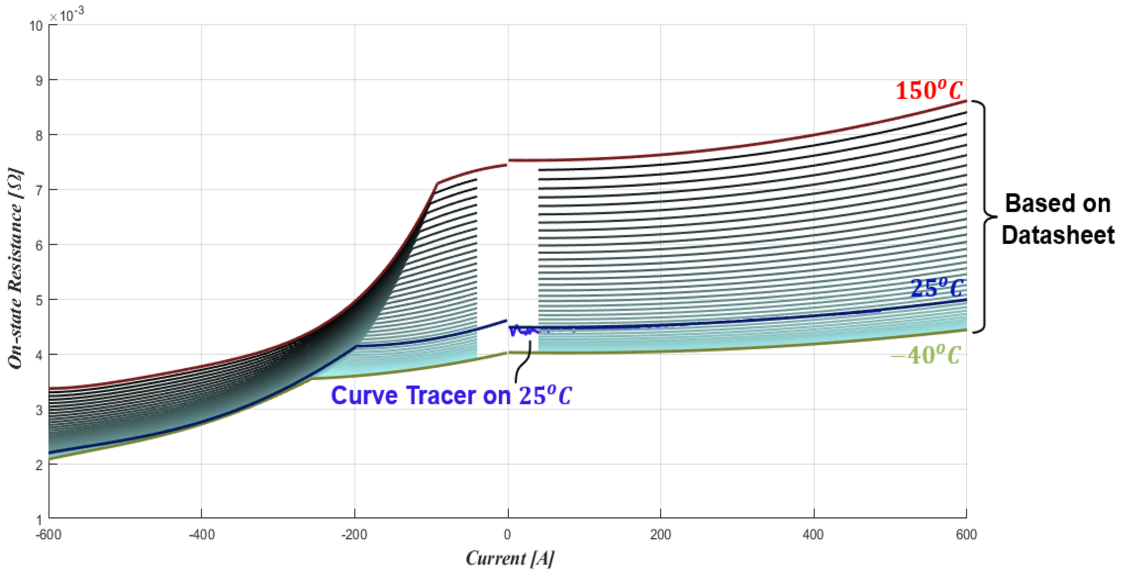
- The gate bias supply is designed to remain extremely stable under quickly changing load conditions, showing almost no voltage change transitioning from 2kHz to 10kHz switching

Accomplishments:
$R_{ds,on}$-Based T_j Estimation

- Developed an algorithm and physical method to calculate individual device junction temperature, T_j, based on $R_{ds,on}$ measured during device operation



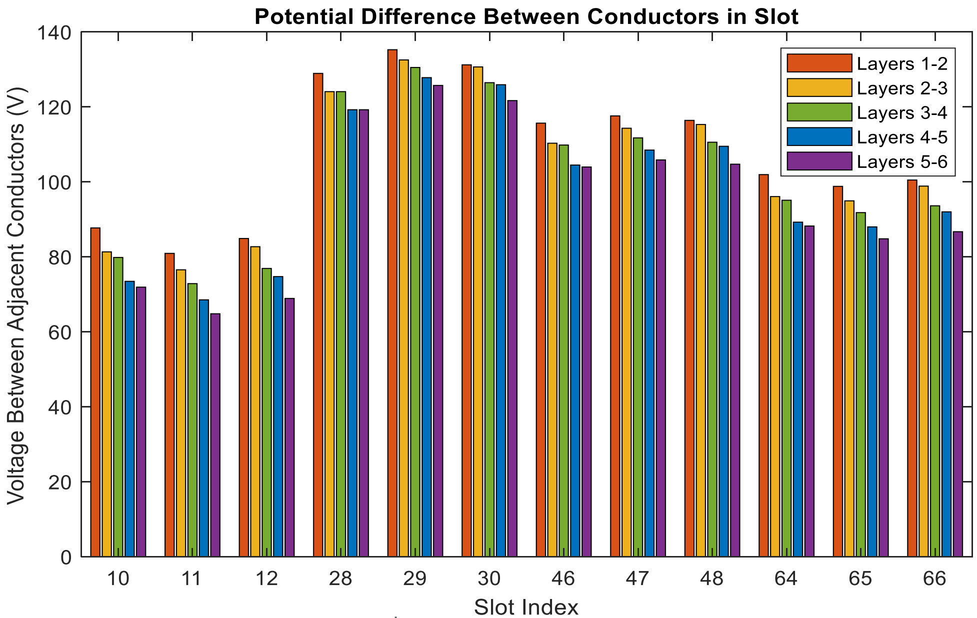
- Calculation completed using minimal inputs

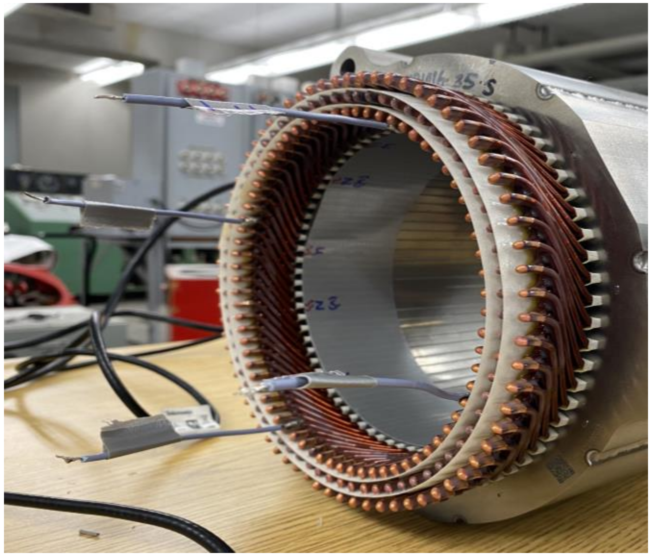


Performed by subrecipient: Virginia Polytechnic Institute and State University

Accomplishments:
24-Turn HV Motor Simulation & Test

- Developed a two dimensional simulation of a 24 turn motor
- Calculated the voltage differences between conductors in different slots





- Simulation results verified by real motor testing
- Next steps are to understand dv/dt and insulation impacts of the HV motor

Performed by subrecipient: Ohio State University

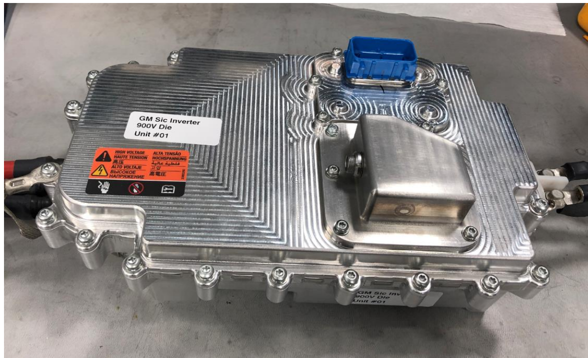
Remaining Challenges, Barriers & Future Plans

Challenges & Potential Barriers

- Power module yield during prototype construction
- HV capacitor availability due to COVID-19 impact
- Development of high bandwidth low cost current sensing
- Gate drive improvements: design reliable and fast short circuit protection that is integrated and faster than standard "de-sat" protection
- EMI noise generation due to the high dv/dt switching
- Electric motor insulation (increased dv/dt)
- Inverter cost is increased due to the high cost of SiC die

Future Plans (FY2020)

- Construction and testing of power module with 1200V SiC die
- Test electric drive system on dyne
- HV motor study



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

Summary

- Complete inverter successfully built and passed leak and high potential (2200V) tests (SiC MOSFETs 900V, 2.5mOhm)
- Gate drive solution completed and built
- HV capacitor developed
- Complete power stage package is about 60% of the standard Si power stage
- T_j estimation algorithm has been developed based on limited inputs
- HV motor study has commenced and preliminary simulation results align with HV motor lab testing
- Project is in final budget period – fabrication & inverter level testing on dyne (new substrates with 1200V, 13mOhm die have been successfully manufactured)