Project ID: elt261

Award #: DE-EE0008806

2021 Vehicle Technologies Office Annual Merit Review

High Efficiency Powertrain for Heavy Duty Trucks using Silicon Carbide (SiC) Inverter

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Presenter: Steve Peelman, Chief Engineer

Ricardo Inc.

June 23, 2021

Overview

Timeline

- Start date: 10/1/2019
- End date: 06/31/2023
  - 45% complete by timing
  - 35% complete by funding

Budget

- Total project funding: $7,390,911
- DOE share: $4,605,398
  - FY 21 Funding: $1,711,263
  - FY 22 Funding: $2,540,338

Barriers and Technical Targets

- Inverter efficiency: target to achieve 98.5% at the end of the development phase and prove out during fleet service operation
- Power: demonstrate 250kW continuous output
- Power density: target to achieve > 50kW/l, demonstrated by power output and form factor
- Operation usage: achieve 250-mile daily usage during demonstration period

Partners

- Project Lead: Ricardo Inc.
- Subs:
  - North Carolina State University
  - Meritor Inc. (TransPower)

Relevance/Objectives

- Overall Objective
  - The objective of the High Efficiency Powertrain (HEP) project is to research, develop, and demonstrate the life cycle cost-effective Class 8 battery electric vehicles using a 250kW SiC high voltage inverter capable of commercial operations of ≥250 miles per day as well as increased efficiency and productivity when compared to baseline Peterbilt 579 diesel truck fleet performance
- Current Period Objective
  - Complete A-Sample inverter design, build and test to achieve >92.5% efficiency (objective met)
  - Complete B-sample inverter design and build, incorporating lessons learned from A-sample inverter development and inverter functional and performance testing, verifying 98.5% efficiency is achieved
  - Complete Class 8 Truck Battery Electric Vehicle (BEV) development and testing
  - Integrate the B-sample inverter to the BEV Class 8 Truck
  - Verify that 250kW continuous power operation is achievable with the Meritor 14Xe eAxle and BEV system
- Impact
  - Accelerate the US truck fleet electrification and reduction in the use of petroleum/diesel fuel and exhaust emission

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

Milestones

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Milestones FY2021	Type	Description
Complete B-sample SiC inverter hardware design and build	Technical	B-sample hardware design is complete, and software interface spec completed
Complete hardware/ software integration functional testing	Technical	B-sample inverter hardware/ software integration functional testing completed
Complete eAxle Vehicle Mechanical design and inverter integration	Technical	Production-sample eAxle with B-sample inverter mechanical design completed
Finalize the list of data to be collected and analyzed during the demonstration phase	Technical	Data to evaluate vehicle performance, cost, and usage characteristics submitted to DOE for approval
Production-Ready Design Validated to Achieve Performance Measures **April 2022**	**Go/No Go**	Assessment of the Production-ready design has been completed, verifying that 250kW continuous power operation is achievable on system and 98.5% inverter efficiency is achieved

Milestones FY2022	Type	Description
2 trucks in service and demonstrated in fleet operation	Technical	2 demonstration trucks entered into revenue service for daily driving cycle
Drive system performance and reliability demonstrated	Technical	Early evaluation of the drive system performance and reliability available
Drive system performance and reliability demonstrated	Technical	Evaluation of drive system performance, reliability and maintenance
Drive system performance and reliability demonstrated	Technical	Evaluation of drive system performance, reliability and maintenance complete; longer term improvements identified
Vehicle demonstration performance testing complete **June 2023**	**Go/No Go**	Vehicle performance has been demonstrated, 250kW continuous power operation on an eAxle integrated into a vehicle with actual in-field use

FY2021– SiC inverter 98.5% efficiency confirmation; FY20202 vehicle in-field service demonstration phase

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

Approach

- The Budget Period 1 approach was focused on the A-Sample SiC inverter development, comprised of
  - Initial requirements/specifications
  - Concept design
  - Simulation activities
  - Gate driver/control board development
  - Mechanical design development
  - Software development
  - Inverter build & test
  - Deliverable confirmation of >92.5% efficiency
- Meritor continued their 14Xe eAxle development as well as the vehicle electric system platform development
- Challenges overcome
  - Inverter efficiency: multidisciplinary team developed an A-Sample inverter that achieved >92.5% efficiency
  - Power density: confirmed feasibility to achieve > 50kW/l based on design and power output

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

Technical Accomplishments and Progress

- **Inverter System Requirements**
  - Inverter requirements
    - LV Battery 24VDC
    - HV Battery supply: 800 VDC
    - 250kW Continuous Power
    - 350kW Peak Power
  - Class 8 Truck HV Battery supply
    - 650 VDC (Demonstration Phase)
- **Software Requirements**
  - Motor Control Application SW Architecture and Design defined
  - Base SW Design defined
    - Power moding, Scheduler, HW Drivers, Test GUI
- **Mechanical Requirements**
  - Cooling, Vibration, Power density targets
- **Electrical Requirements**
  - SiC Power Modules selected
    - Switching frequency defined
    - Cooling requirements defined
  - Gate Drive design and components selected
  - Micro processor and power supply selected
- **Testing Complete**
  - Power Efficiency up to 125kW at 650VDC
  - Motor speed control up to 2000 RPM

Technical Accomplishments and Progress

- **Budget Period 1 Challenges Overcome**
  - Evaluation of Power Modules led to selection of Danfoss solution
  - Simulation of switching frequency losses led to selection of 20kHz
  - Evaluation of HV DC Link compact capacitor options led to selection of PolyCharge solution
  - Semiconductor shortages were managed to complete successful build
  - Test facility limitations required alternate test plans for A-Sample testing

- **Budget Period 1 Successes**
  - Working inverters produced on first build with only minor component updates
  - Successfully brought up the inverter high voltage supply to 650 VDC in small incremental voltage steps on first try
  - Switching waveforms were as expected, with approximately 50V of overshoot
  - Exceeded efficiency goal for A-Sample
    - On a path to meet or exceed efficiency goals for final design

Technical Accomplishments and Progress

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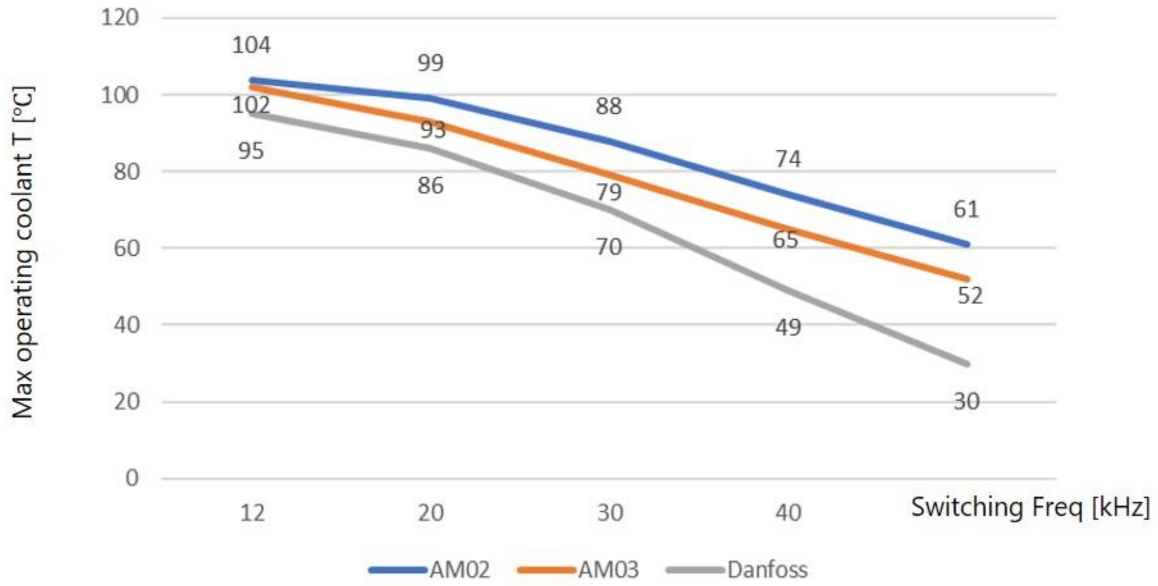
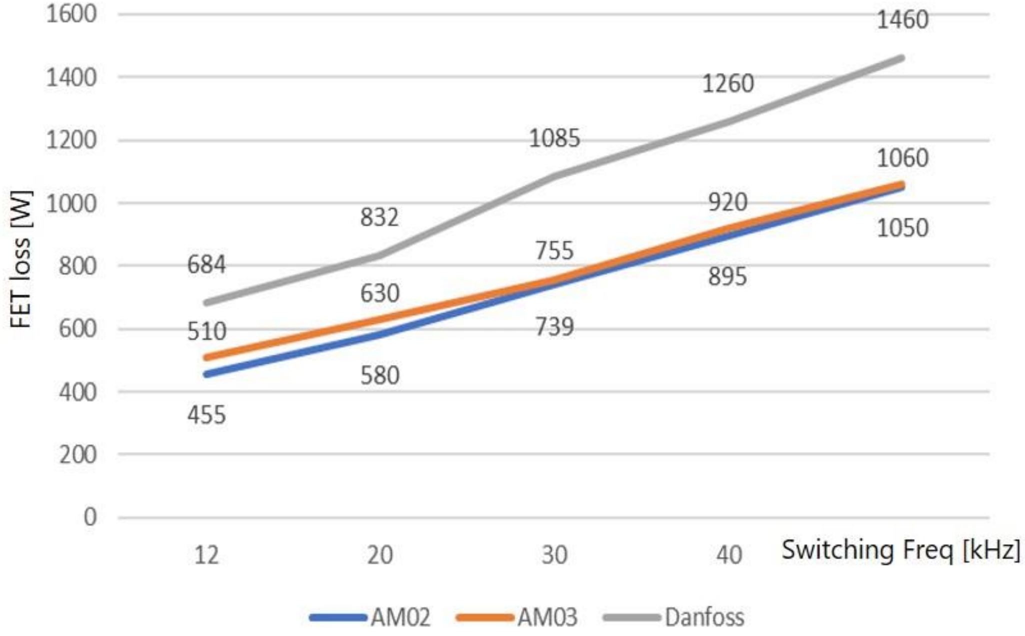
Motor Drive Thermal Simulation

- Comprehensive system-level platform created in PSIM using SiC power device thermal parameters and target motor electrical specifications
- Closed-loop controller developed with Maximum Torque Per Amp (MTPA) and Field Weakening
- Thermal performance (device losses and junction temperature) captured under various Synchronous Permanent Magnetic (SPM) Machine Torque-Speed operating points for peak thermal stress determination under different coolant temperatures



Maximum operating coolant temperature (Operating Point: 1000 Nm @ 2000 rpm) for T_j (< $T_{j,max}$) vs Switching frequency



FET loss @ maximum operating coolant temperature (Operating Point: 1000 Nm @ 2000 rpm) vs Switching frequency

Technical Accomplishments and Progress

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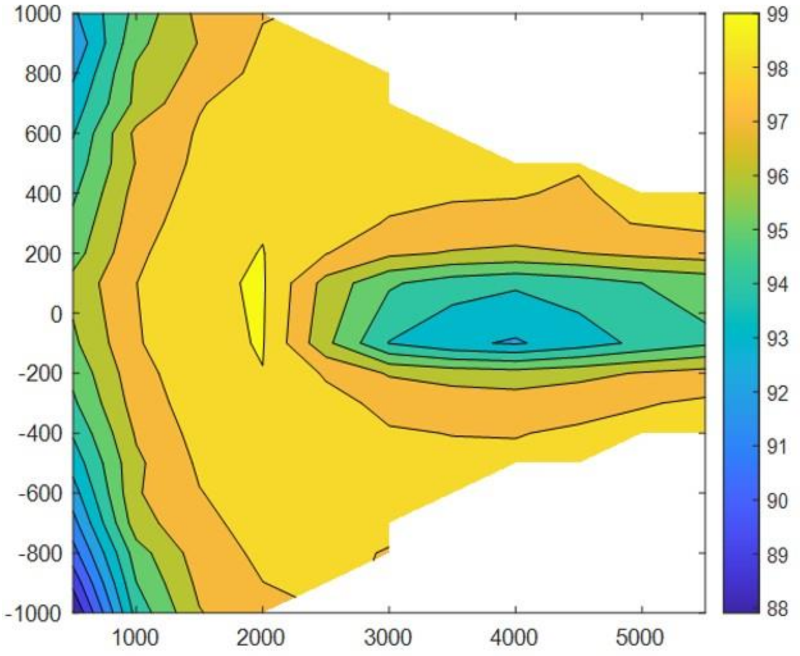
Inverter Efficiency Estimation using Class-8 Truck Drive Cycle

- Data generated for power module conduction and switching losses, and junction temperature
- Simulation condition:
  - Switching frequency = 20 kHz
  - DC bus voltage = 660 V
  - Coolant temperature = 55 °C
- Peak (inverter only) efficiency: 99.10% (100 N-m @ 2000 rpm)



	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500
1000	92.82	95.30	97.28	97.93							
900	92.18	95.75	97.05	98.13	98.33						
800	92.83	96.16	97.33	98.31	98.38	98.43					
700	93.43	96.24	97.94	98.45	98.19	98.47					
600	93.92	97.25	98.09	98.58	98.29	98.39	98.36				
500	94.40	97.05	98.25	98.70	98.57	98.36	98.28	98.27	98.09		
400	94.83	97.36	98.39	98.82	98.54	98.23	98.11	98.07	97.87	98.38	98.52
300	95.24	97.55	98.59	98.93	98.42	97.93	97.73	97.67	97.83	98.04	98.20
200	95.57	97.81	98.71	99.03	98.04	97.21	96.92	96.77	96.98	97.28	97.48
100	96.31	97.99	98.82	99.10	96.65	95.15	94.46	94.15	94.49	95.00	95.33
-100	95.80	97.91	98.74	99.06	96.25	93.96	93.19	92.89	93.50	94.24	94.83
-200	95.26	97.65	98.63	98.98	97.88	96.90	96.58	96.41	96.70	97.08	97.37
-300	94.82	97.45	98.50	98.88	98.32	97.75	97.55	97.49	97.69	97.93	98.15
-400	94.11	97.12	98.34	98.76	98.47	98.08	97.98	97.96	98.13	98.32	98.48
-500	93.39	96.80	98.15	98.65	98.50	98.25	98.18	98.18	98.33		
-600	92.55	96.90	97.96	98.51	98.45	98.30	98.28				
-700	91.63	96.58	97.76	98.36	98.38	98.28					
-800	90.59	95.53	97.51	98.19	98.27	97.93					
-900	89.27	94.98	97.24	97.99	98.21						
-1000	87.91	94.37	96.94	97.77							

Inverter Efficiency Map

Technical Accomplishments and Progress

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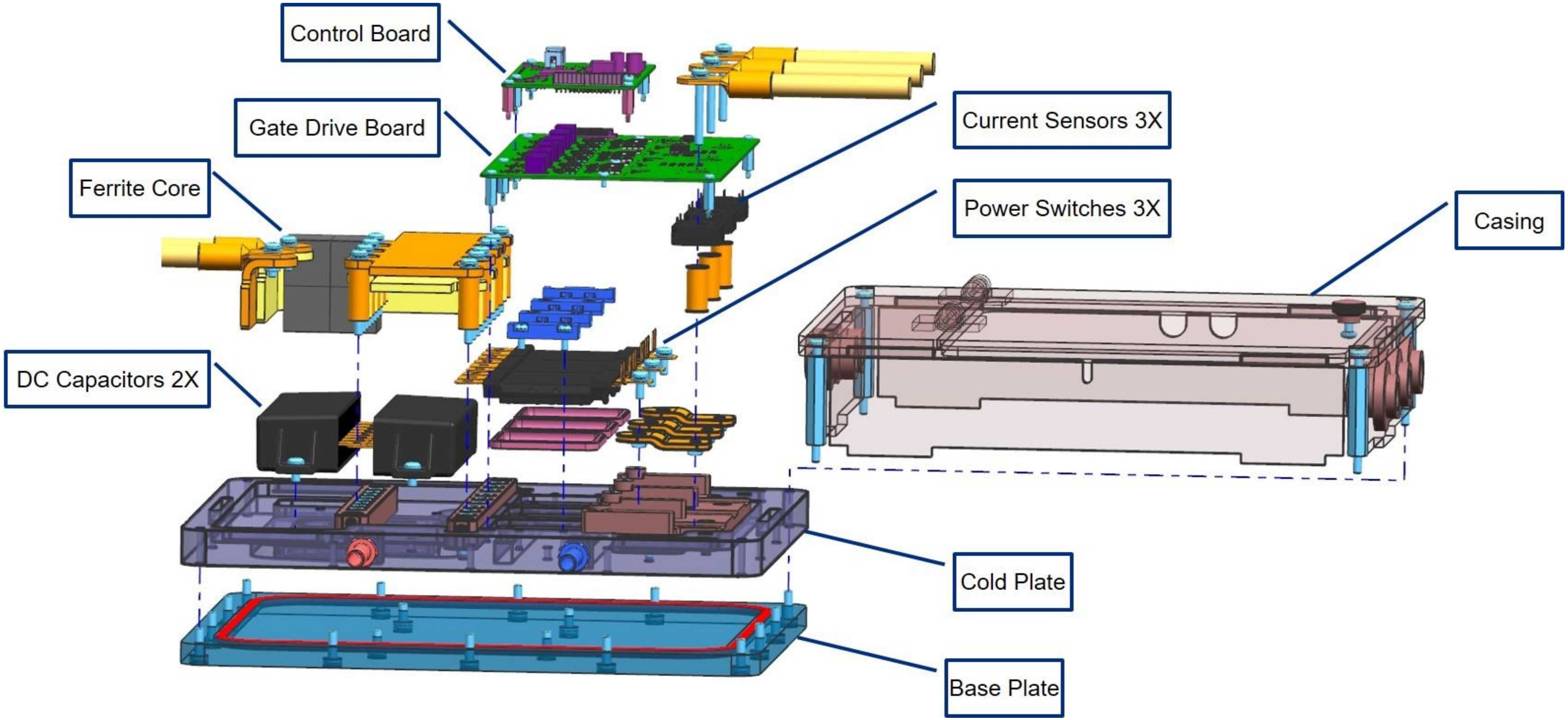
250kW SiC Inverter Development

- Created inverter concept design
- Completed HW components specification requirement
- Completed components evaluation and selection process based on requirement, form factor and simulation
- Created inverter control board and gate drive board PCB design
  - Schematic & Layout
- Built three A-sample prototype inverters for HW/SW development/testing
- First SiC inverter design worked successfully
- Implemented Base Software (BSW) features, low level peripheral interface development
- Implemented model-based Application Software (ASW) development for the inverter open loop control, torque control & speed control
- Software released for:
  - Board level debug test
  - Power switch double pulse test
  - Open loop R-L load efficiency test and initial motor test

Technical Accomplishments and Progress

A-Sample Inverter Final Assembly Design

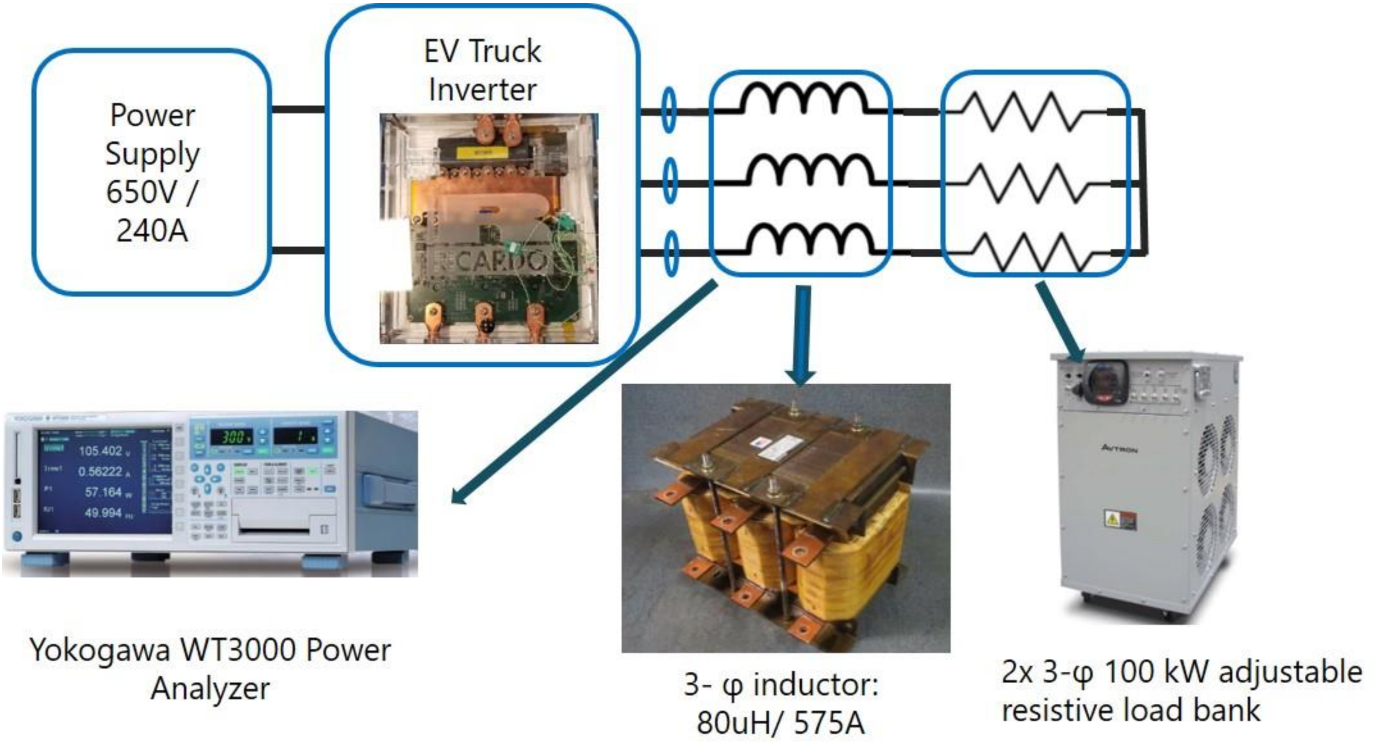
- SiC inverter volumetric power density: 50 kW/Liter



Technical Accomplishments and Progress

Test Development: Inverter Power Performance Efficiency Test

- Efficiency testing of A-sample conducted under nominal voltage (VDC = 650 V), with static R-L load
- Current sensing using 100 kHz LEM Ultrastab closed-loop high-precision fluxgate current transducer
- Coolant flow rate controlled at 11 L/min
- Power module case and busbar temperature measurement using embedded K-type thermocouple

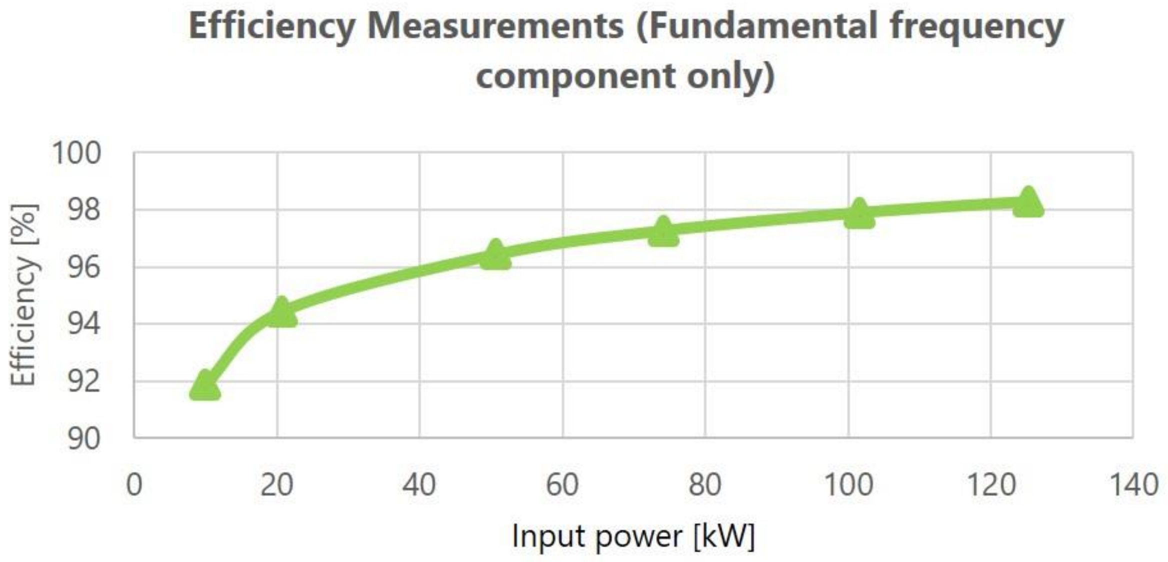


Test setup for efficiency measurement using static R-L load

Technical Accomplishments and Progress

Test Development: Inverter Power Performance Efficiency Test

- Efficiency data captured for 10 kW ~ 125 kW
- Measured efficiency comparable to simulation data from PSIM thermal model
- Peak efficiency: **98.3%** (@ 125 kW) – considering fundamental component only
  - In motor drive application, fundamental component of power will be converted to usable torque



Technical Accomplishments and Progress

Test Development: Inverter/Motor Open Loop Speed Control, No Load Test

Test Objective

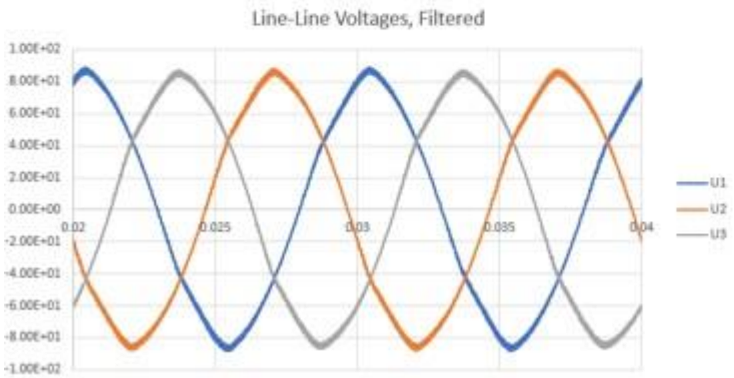
Verify inverter / motor system operation with a representative traction motor

- Verify capability of inverter to operate motor over a range of speeds
- Collect data to be used in calibration of analog to digital conversion values used by software

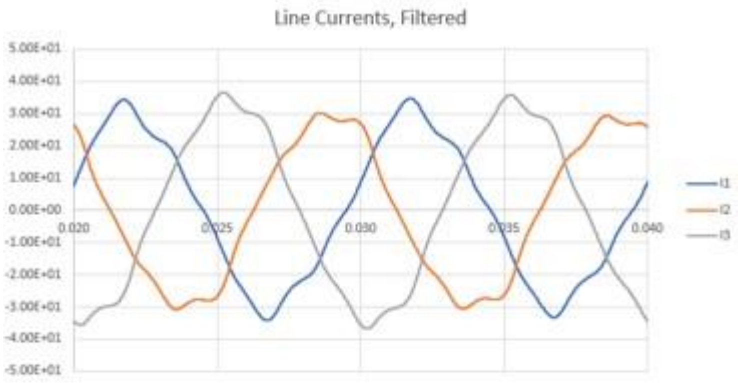
Results

- Controlled motor up to 2000 RPM
  - Speed verified using hall-effect sensor and tachometer
  - Line-Line voltage amplitude and frequency match commanded values and control motor as expected

Voltage and Current Waveforms at 500 RPM



Voltage and Current Waveforms at 2000 RPM

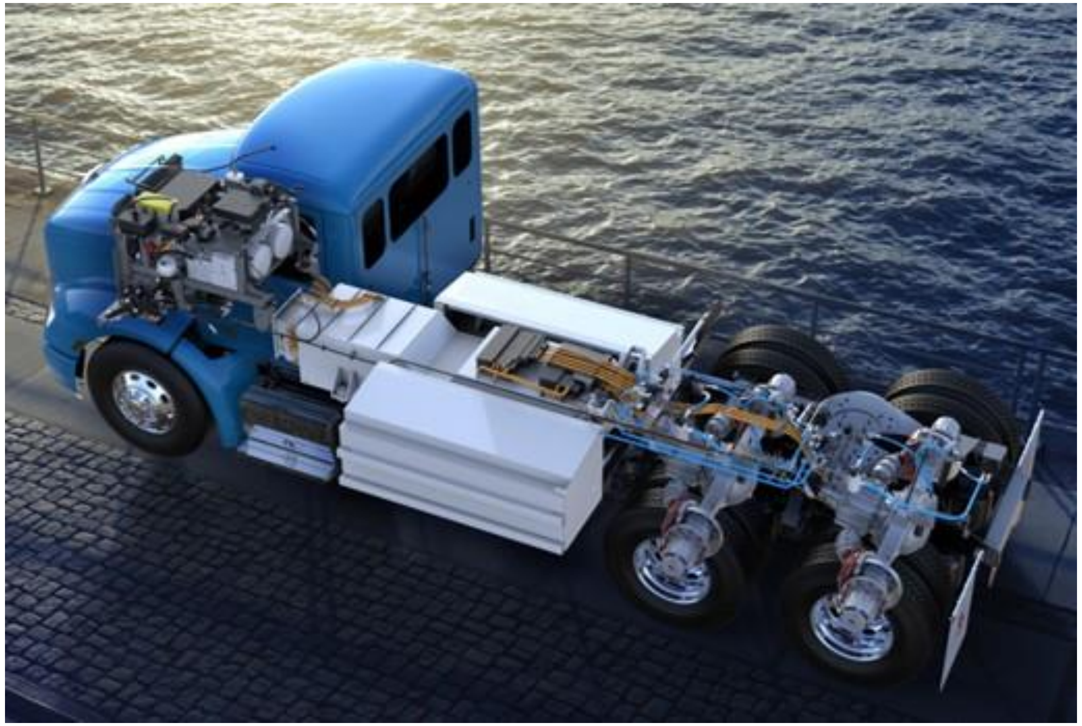


Technical Accomplishments and Progress

Meritor (TransPower) Heavy Duty Vehicle Development

Electric Drive System & eAxle

- Finalized the Electric Drive System design on the Peterbilt Class 8 chassis
- Performed CAD packaging under hood, under frame rails, maintain 12” ground clearance
- Performed FEA analysis of drive system
- Completed DFMEA Risk Analysis for all battery electric systems
- Performed 14Xe 3-speed eAxle GEN 4 eCarrier packaging



Meritor Electric Drive System Design

Transmission matrix and 3-speed eAxle timing

Responses to Previous Year Reviewer's Comments

- **Question 1: Approach to performing the work**
  - To deliver the inverter performance metrics, the team defined the system requirements, created the inverter concept, analyzed and managed the risks through simulation, and executed the test plan to validate the simulation and design.
- **Question 2 Technical Accomplishments and Progress toward overall project goals**
  - The team has achieved the BP 1 goal of 92.5% inverter efficiency, reaching **98.3% at 125kW** with the A-Sample design. B-Sample development design optimizations are expected to improve on this, allowing the inverter to meet the 98.5% efficiency deliverable for BP 2.
- **Question 3: Collaboration and Coordination across project team**
  - Ricardo, NCSU, and Meritor are collaborating well together. NCSU support for simulation and inductive/resistive load testing is excellent. Definition of the vehicle integration is progressing ahead of BP 2 start.
- **Question 4: Proposed Future Research**
  - Budget Period 1 activities followed the detailed project plan to design, build and test the A-sample inverter and achieve the expected deliverable, collaborating with NCSU and Meritor
- **Question 5: Relevance**
  - The SiC based inverter vehicle demonstration will extend the operating range over traditional powertrains and current battery electric technologies to accelerate the US truck fleet electrification and reduction in the use of petroleum/diesel fuel and exhaust emission
- **Question 6: Resources**
  - Project resources are sufficient to deliver against the milestones and are actively managed; BP1 efficiency goal exceeded

Collaboration and Coordination

North Carolina State University FREEDM Systems Center (Dr. Iqbal Husain): Sub

- Inverter and system simulation, thermal design, inverter design support, testing

Meritor Inc. (Tavin Tyler): Sub

- eAxle development and supply, balance of system development and testing, vehicle build and demonstration management

Ricardo Inc. (Steve Peelman & Elton Rohrer): Prime

- SiC inverter design and development, component and subsystem testing and overall project management

Research Challenges & Barriers

Challenge	Resolution Plans
Long lead items for inverter B-sample timing, including semiconductor shortage	Placed some long lead components on order, working through B-Sample BOM & monitoring situation
Motor data availability	Planning motor testing options with Meritor
250kW continuous power inverter testing	Finalize test plan with Meritor; early testing and/or simulation to include datapoint for inverter B-sample development
Cable connection length between inverter/motor creating additional stray inductance	Optimize system design and calibration
250 mile per day demonstration (planning for BP 3)	Fast charging availability and system optimization

Proposed Future Research

- Complete detailed inverter hardware and software requirements
- Complete inverter-vehicle interface requirements
- Design and develop the B-Sample hardware and software, considering lessons learned from A-sample development
- Build the B-sample prototypes and perform functional and performance tests
- Validate actual efficiency vs. simulation data
- Finalize the BEV component system architecture, complete system design and battery electric system integration of two Class 8 gliders including energy storage system and electrical accessories
- Develop and validate 3-speed eAxle hardware and shift control software
- Complete inverter and vehicle software control development
- Perform system validation testing and initial vehicle commissioning
- Confirm inverter efficiency of **98.5%**
- Complete vehicle integration builds
- Demonstrate High Efficiency Powertrain meets performance metrics in fleet operation service (approximately 10-month demonstration)

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

Summary

- Relevance: This project will develop highly efficient electric powertrain to allow the acceleration of US truck fleet electrification

- Approach: The project mission is to design and develop a class leading high power density, highly efficient 250kW continuous SiC inverter, utilize Meritor’s electrified axle with integrated 3-speed gearbox, integrate these to their drive system and demonstrate it during Budget Period 3 on 2 class 8 trucks in operational fleet service

- Collaborations: The experienced project team consists of Ricardo Inc. as the prime and leading the SiC inverter development, North Carolina State University providing simulation, design and test expertise support and Meritor Inc., as a leader in developing and supplying eAxles, integrated drive systems and full electric truck solutions

- Technical Accomplishments: Successfully developed the A-sample inverter that exceeded the target efficiency of 92.5%; eAxle and electric drive system development met internal milestones

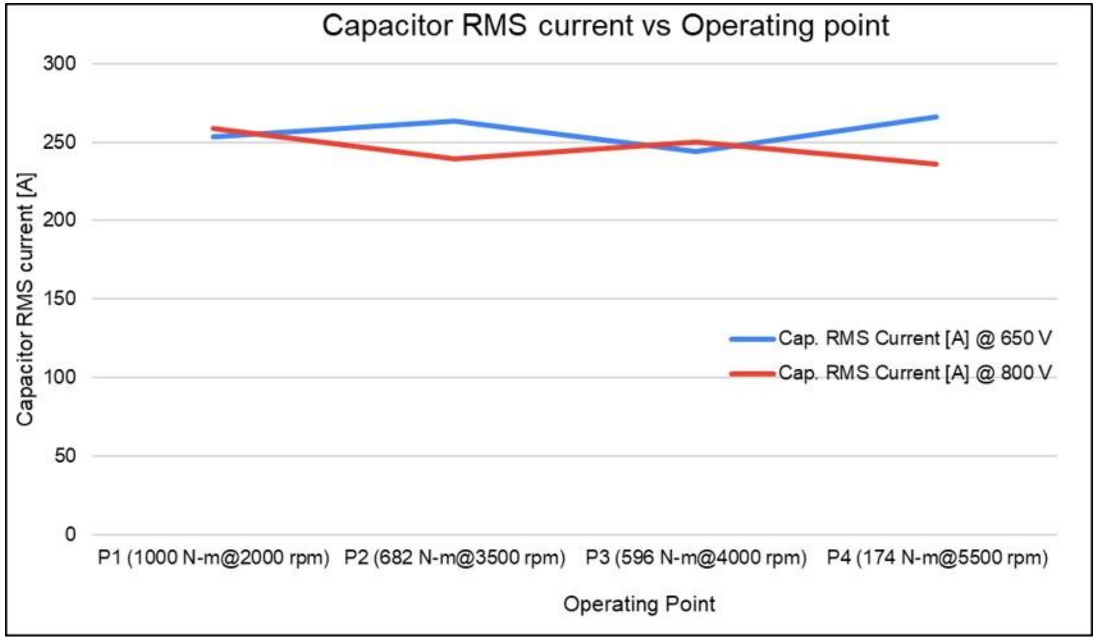
- Future Work: Future project activities will be focused on the optimization of the 250kW SiC inverter to achieve 98.5% efficiency and the system level integration and testing to allow the demonstration of 2 class 8 trucks operating for 250 miles daily

Technical Back Up Slides

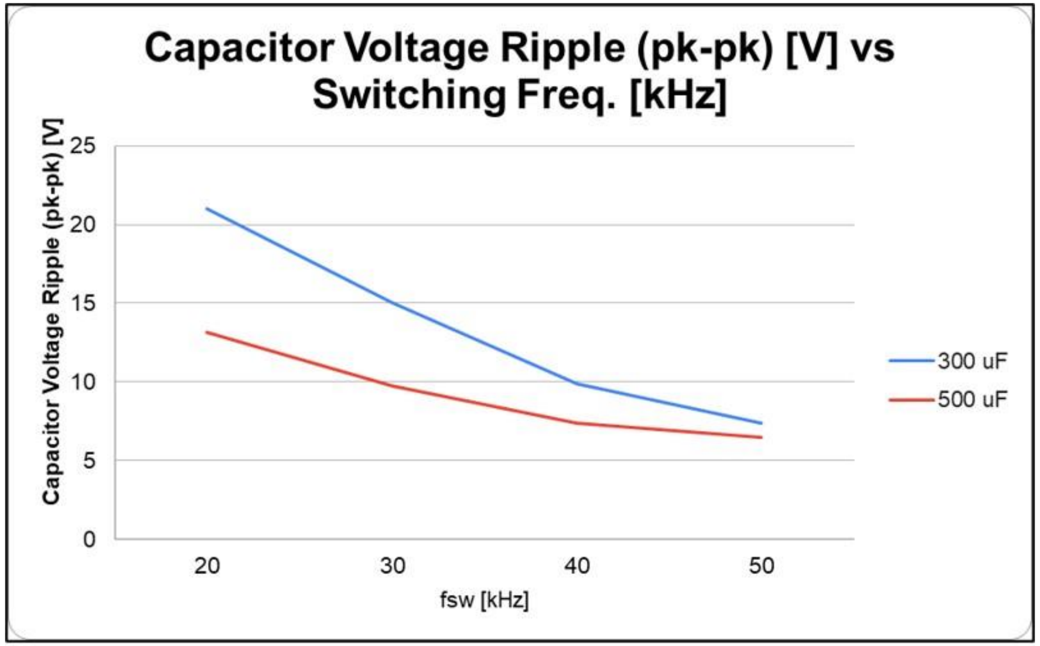
Technical Accomplishments and Progress

DC Link Capacitor Sizing Selection

- DC-link capacitor requirement evaluated based on inverter ripple current requirement and switching frequency with SVPWM modulation scheme
- Capacitor RMS current is independent of switching frequency and capacitance
- Depends on motor current, power factor and modulation index, i.e., operating point
- Increasing switching frequency and capacitance lowers peak-to-peak voltage ripple at the expense of power density



Capacitor RMS current for 650 V and 800 V DC-link voltage



Voltage ripple for 300 μF and 500 μF capacitance