Project ID: elt261

Award #: DE-EE0008806

2020 Vehicle Technologies Office Annual Merit Review

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

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Ricardo Inc.

June 1-4, 2020

Overview

Timeline

- Start date: 10/1/2019
- End date: 12/31/2022
  - 15% complete

Budget

- Total project funding: $7,390,911
- DOE share: $4,605,398
  - FY 20 Funding: $1,711,263

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

Partners

- North Carolina State University- sub
- Transportation Power Inc. (Meritor Inc.)- sub

Relevance/Objectives

- Overall Objective
  - The objective of the High Efficiency Powertrain (HEP) project is to research, develop, and demonstrate life cycle cost-effective Class 8 battery electric vehicles utilizing a 250kW SiC 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 inverter and system simulations
  - Complete A-sample inverter design and build
  - Validate A-sample inverter drive system against simulation results to achieve >92.5% efficiency (A-sample target)
  - Vehicle packaging and system integration design

- Impact
  - Accelerate the US truck fleet electrification and reduction in the use of petroleum/diesel fuel

Relevance/Objectives

- The HEP project is split into 3 periods of performance
  - Year 1: A-sample SiC inverter development based on lower power Ricardo inverter design and vehicle packaging/integration design
  - Year 2: B-sample SiC inverter development, functional and performance testing, subsystem testing and system controls development will be the focus of this phase with the aim of meeting the performance metrics of continuous power, power density and inverter efficiency
  - Year 3: Vehicle integration and builds as well as the 250 mile daily operational service demonstration of 2 Class 8 trucks over a 10 month period to evaluate drive system performance and reliability is expected during the final project phase
- 250 kW SiC inverter will be designed for high continuous power operation and developed by Ricardo with support by NC State University
  - Optimization of film capacitors in the DC link, DC bus bars and current sensor solutions are expected to reduce volume up to 30% while maintaining the reliability and lifetime of the components
  - The latest generation of SiC power modules from Wolfspeed will be used
- Meritor's innovative eAxle will be used, which eliminates the traditional gearbox and differential drive parts
  - This compact design will allow Meritor and TransPower to optimize the balance of parts integration

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

Milestones

Milestones Year 1	Type	Description
Mechanical design concept complete	Technical	Basic system architecture definition and key component selection completed, and all requirements understood
Mechanical Design piece part drawings completed	Technical	A-sample mechanical design completed and ready to build
Initial sample debug complete	Technical	A-sample debug completed
Preliminary design validation complete	Technical	A-sample design validation completed
Preliminary Design Validated to Achieve Performance Measures **Dec 2020**	Go/No Go	Assessment of the preliminary technology design has been completed, verifying that 250kW continuous power operation at greater than 92.5% efficiency

Milestones Year 2	Type	Description
B-sample hardware design complete	Technical	B-sample hardware design is complete, and software interface spec completed
Hardware/software integration functional testing	Technical	B-sample hardware/software integration functional testing completed
Mechanical design complete	Technical	Production-sample mechanical design completed
List of data to be collected and analyzed during the demonstration phase finalized	Technical	Data to evaluate vehicle performance, cost, and usage characteristics submitted to DOE for approval
Production-Ready Design Validated to Achieve Performance Measures **Dec 2021**	Go/No Go	Assessment of the Production-ready design has been completed, verifying that 250kW continuous power operation is achievable

Only Year 1 and Year 2 milestones are are presented; Year 3 is the demonstration phase

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

Approach

- **Year 1: Design and Prototype Testing with the aim to demonstrate >92.5% SiC inverter efficiency**
  - SiC inverter concept design (Ricardo with NCSU support)
    - Requirements/specifications development
    - Gate driver simulations with soft switching
    - Component architecture and device options investigation
    - Initial firmware development
  - Complete system simulation(Ricardo with NCSU support)
  - SiC inverter design (Ricardo with NCSU support)
    - Topology confirmation and thermal management development
    - Finalize block diagram, schematic and layout
    - Design release and component procurement
  - A-sample inverter testing and simulation verification→ go/no-go decision based on meeting 92.5% efficiency Dec 2020 (Ricardo)
  - Packaging and system component design and controls development (Transpower)
- **Year 2: Inverter B-sample Development and Drive System Component Development**
  - B-sample SiC inverter design and development→ go/no-go decision based on inverter design validation efficiency of 98.5% Dec 2021 (Ricardo with NCSU support)
  - Subsystem and system testing (Transpower with Ricardo support)
  - System integration development and vehicle build (Transpower)
- **Year 3: Vehicle Integration and Demonstration of 2 class 8 Trucks** (Transpower with Ricardo support)

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

Technical Accomplishments and Progress

SiC Inverter Technical Progress

- A-sample block diagram created
- Draft requirements document created and will be updated in parallel with design activities
- Inverter topology in development
- Investigating 656V nominal battery voltage effect on inverter continuous power target of 250kW

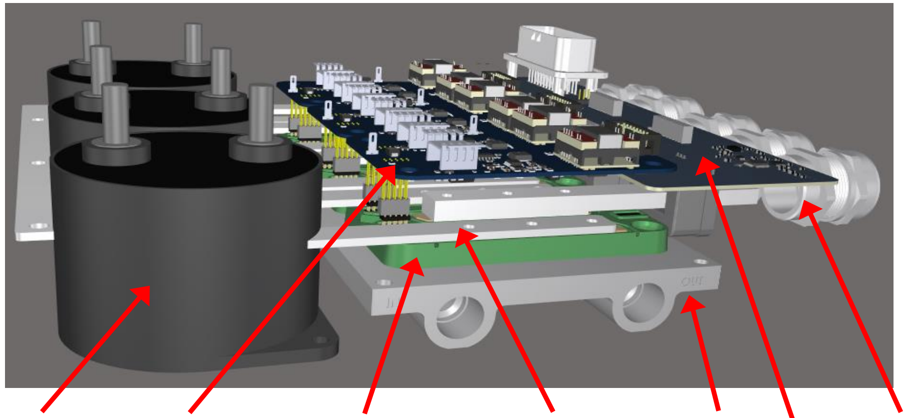


Fig. 1 Proof of Concept SiC inverter design

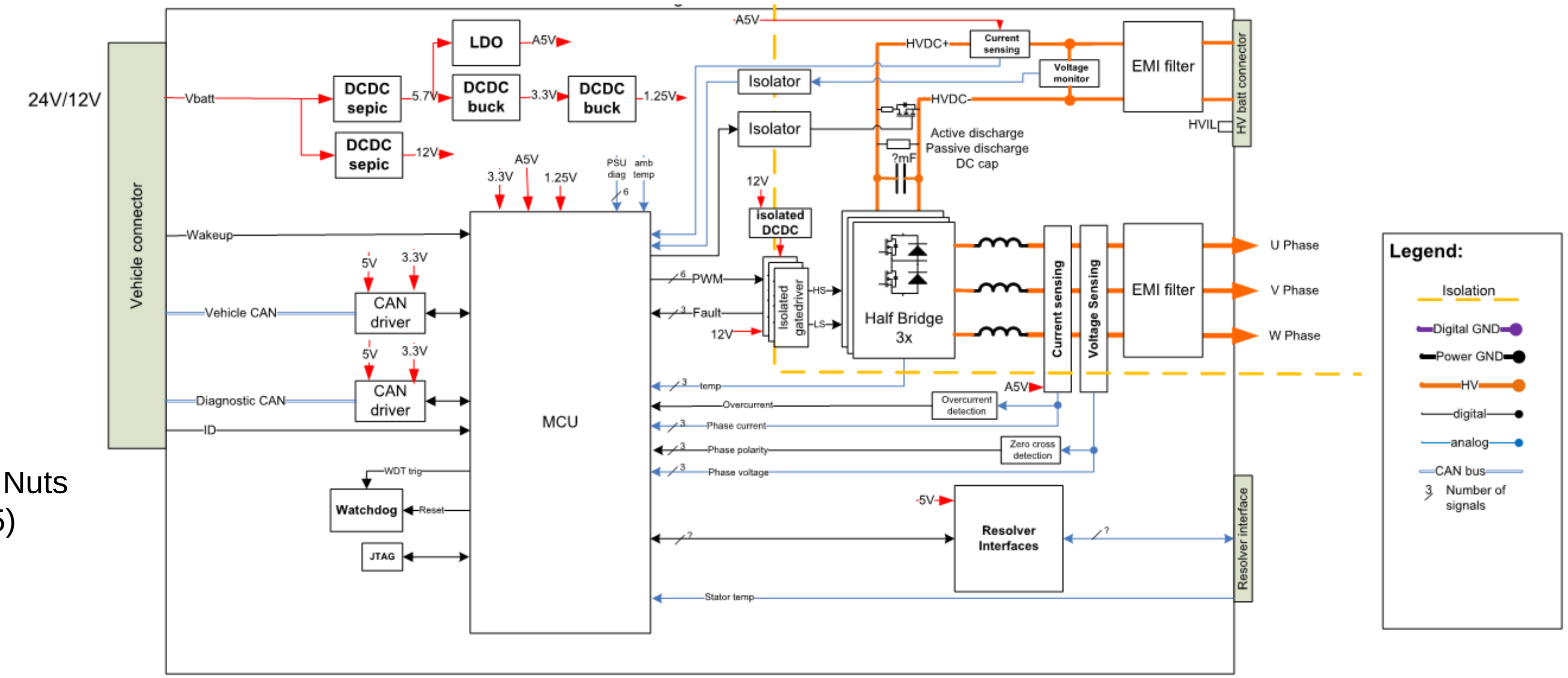


Fig. 2 SiC inverter first draft block diagram

Technical Accomplishments and Progress

250kW SiC Inverter S/W Development

- Microcontroller selection
  - Evaluation between TI, NXP and Infineon alternatives
- Software tools evaluation and selection
  - Software toolchain and modeling environment
  - Instrumentation tools and software
  - Simulation tools
- Software development plan elaboration
  - Tailoring of software processes and definition of development phases, milestones and objectives
- High-level software requirements elaboration
  - Based on system level requirements and features
- Evaluation of reference software designs and selection of control algorithm
  - Model-Based Development→ Field-Oriented Vector Control

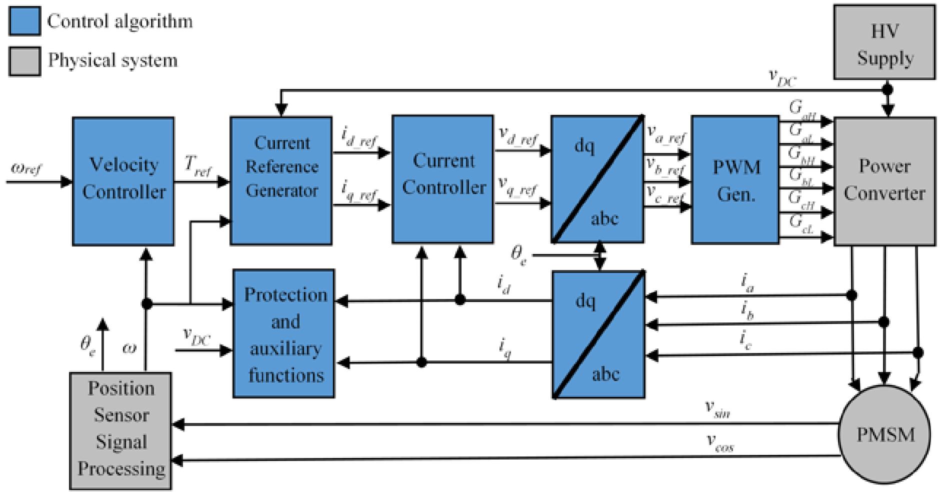


Fig. 3 Mock up of initial S/W development kit

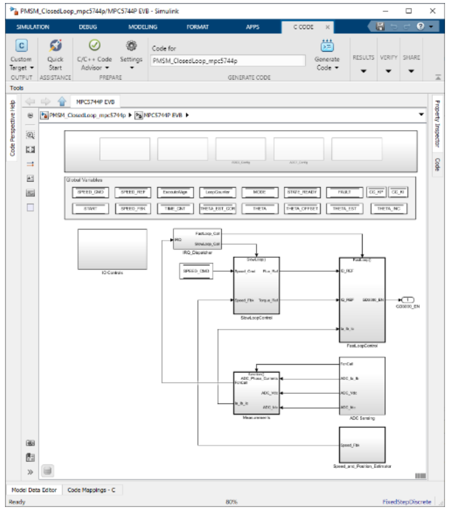


Fig. 4 Closed-loop NXP microcontroller Simulink model

250kW SiC Inverter Three Phase with ZVS Simulation using the PSIM tool

- Two control methods used in the inverter simulations performed by Ricardo: Sine-Triangle (S-T) Control and Space Vector Pulse Width Modulation (SVPWM) Control

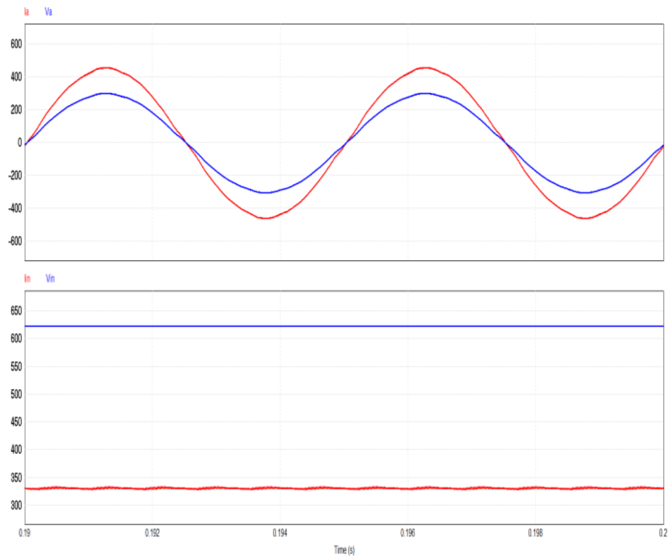


Fig. 5: S-T results

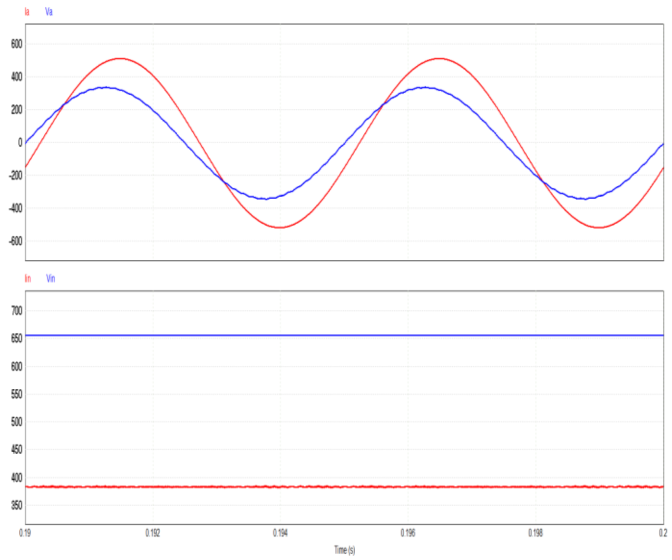


Fig. 6: SVPWM results

- S-T Control efficiency (Ra=0.66Ω/fo=200Hz/Vin=656V): **99.44%**
- SVPWM Control efficiency (Ra=0.63Ω/La=0.15mH/fo=200Hz/Vin=695V): **99.47%**
- Both control methods under R load and RL load situations provide satisfactory results
- Following completion of all simulation activities, the next step is to validate the results with actual hardware testing

Technical Accomplishments and Progress

Traction Inverter System Simulation and Design

- Inverter power-loss/efficiency evaluation platform developed using PSIM with device thermal model incorporating coolant temperature, heatsink thermal network model
- Simulation platform incorporated dynamic loss of the Wide Band Gap (WBG) power devices
- Device behavior under uneven die-to-die thermal impedance incorporated to aid in design/verification of heatsink and cooling loop
- Simulation platform used to evaluate and compare loss characteristics of different power devices to determine optimum module selection

	Wolfspeed CAB450M12XM3	**GE GE12047CCA3**	**Microsemi MSCMC120AM03CT6LIAG**
$R_{ds,on}^{*}$ [mΩ]	4.625	3.8	4.505
E_{sw} [mJ]	13	11.51	7
P_{cond} [W]	389	320	379
P_{sw} [W]	226	124	122
P_{loss} [W] (per switch)	615	444	501

Fig. 6: Power loss values for selected WBG power devices

Technical Accomplishments and Progress

Power Module Thermal Performance Evaluation

- Extensive thermal performance evaluation of WBG power module enables selection of commercially available SiC power modules with the most cost-effective use while operating within the associated Safe Operating Area (SOA) for peak power application
- Modeling of device, heatsink and associated thermal networks completed to perform optimization for system-level efficiency and power density maximization

Evaluation of Wolfspeed CAB450M12XM3 at 250 kW load

- With Tcoolant = 65°C:
  - Switching loss, Psw = 1450 W
  - Conduction loss, Pcond = 2100 W
  - Junction temperature, Tj = 167°C < 175 °C [within SOA]
  - Efficiency: 98.5%

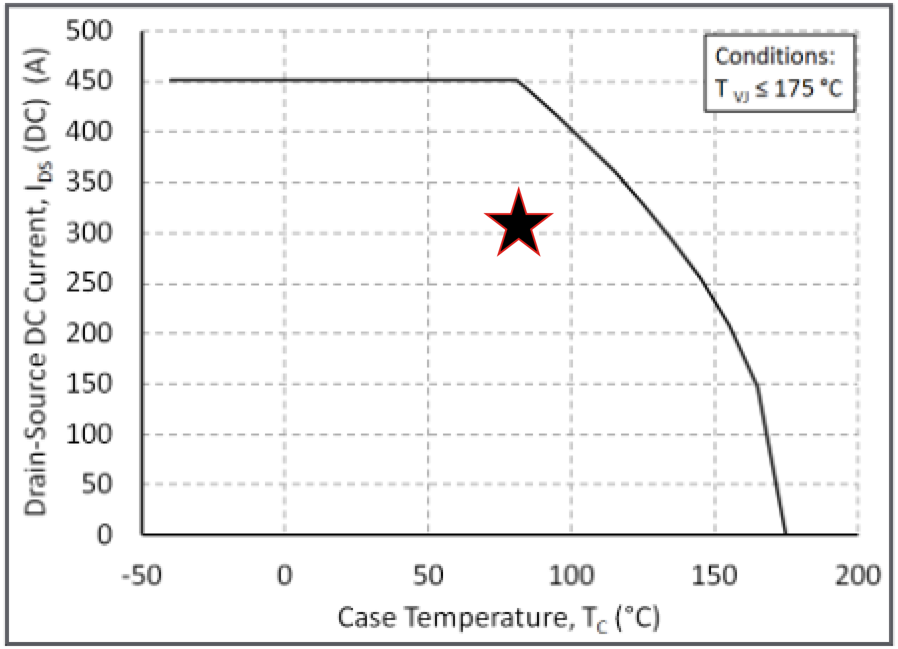


Figure 7 Continuous Drain Current Derating vs. Case Temperature

EMI and dv/dt Mitigation

- Inverter simulation platform being extended to analyze common-mode (CM) and differential-mode (DM) noise generated due to high switching transition associated with WBG devices
- System simulation platform to be used for:
  - Design evaluation of CM and DM filters based on parameters from motor, cabling and system layout
  - Machine dv/dt stress analysis
- Influence of DM filter in implementing Zero Voltage Switching (ZVS) of inverter switches being evaluated

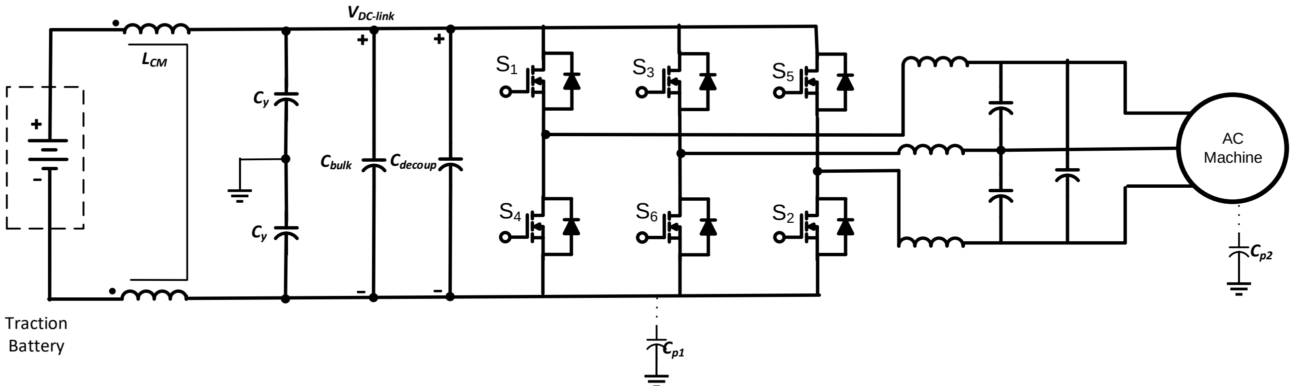


Fig. 8 Traction inverter system example

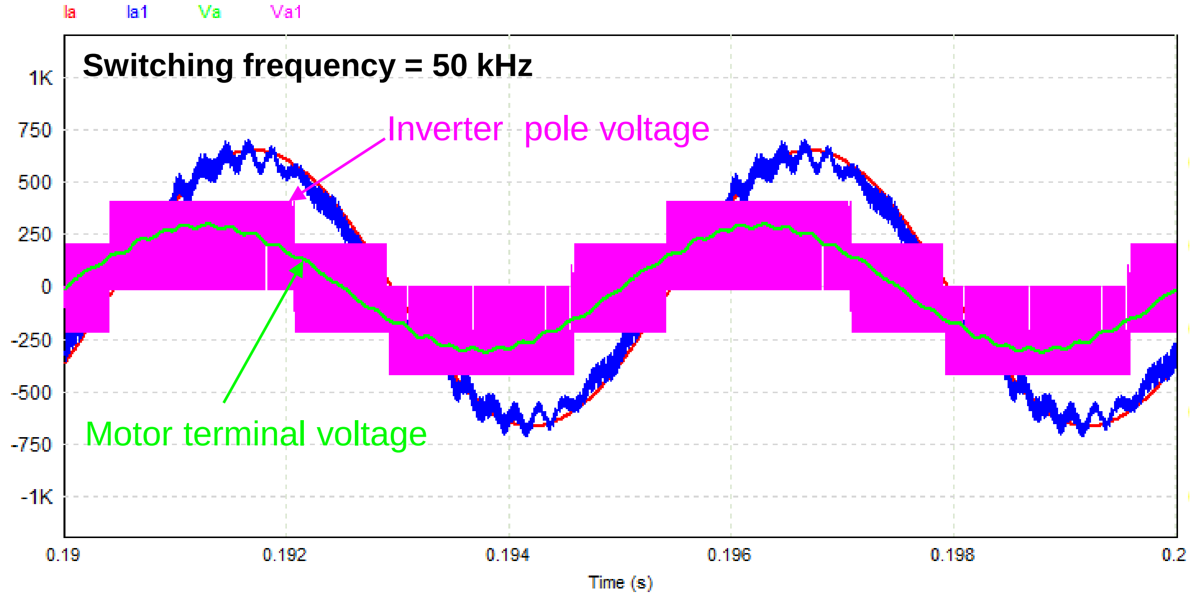


Fig. 9 Reduction of DM dv/dt stress using LC sine filter

Technical Accomplishments and Progress

Shunt-based Current Sensor Design

- For AC current sensing, shunt-based solution promises higher power density due to decreased size, while decreasing price compared to other solutions
- Key challenges such as noise immunity due to high dv/dt generated by WBG power devices and isolation requirements have been mitigated at the component level through the use of completely differential signal chain from shunt to the digital controller
- Different digitization/modulation techniques evaluated in a hardware testing platform

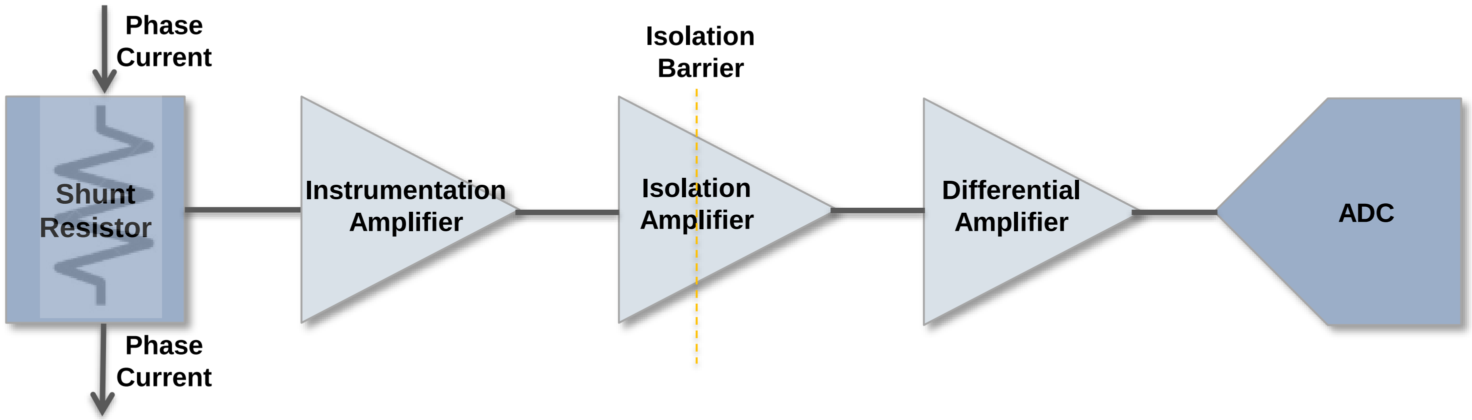


Fig. 10 Shunt-based current sensing scheme

Technical Accomplishments and Progress

Shunt-based Current Sensor Design

- Two different ADC sampling techniques, SAR and ∑-∆ modulator-based, evaluated in a hardware platform for current sensing performance in a high power application
- Phase-leg of a SiC-based converter used to emulate high dv/dt stress (up to 70 kV/µs) and high current (70 A) under 1 kV bus voltage
- Evaluation of SAR and ∑-∆ modulator-based sampling techniques in progress to determine the optimum design for 250kW, 400A inverter current sensing with respect to latency, bandwidth, and noise immunity

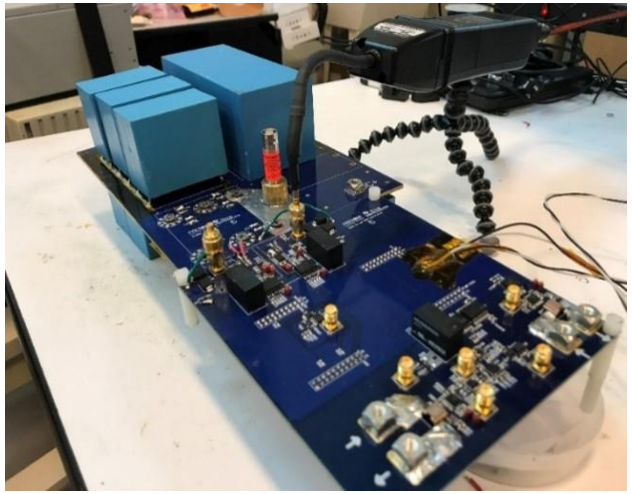
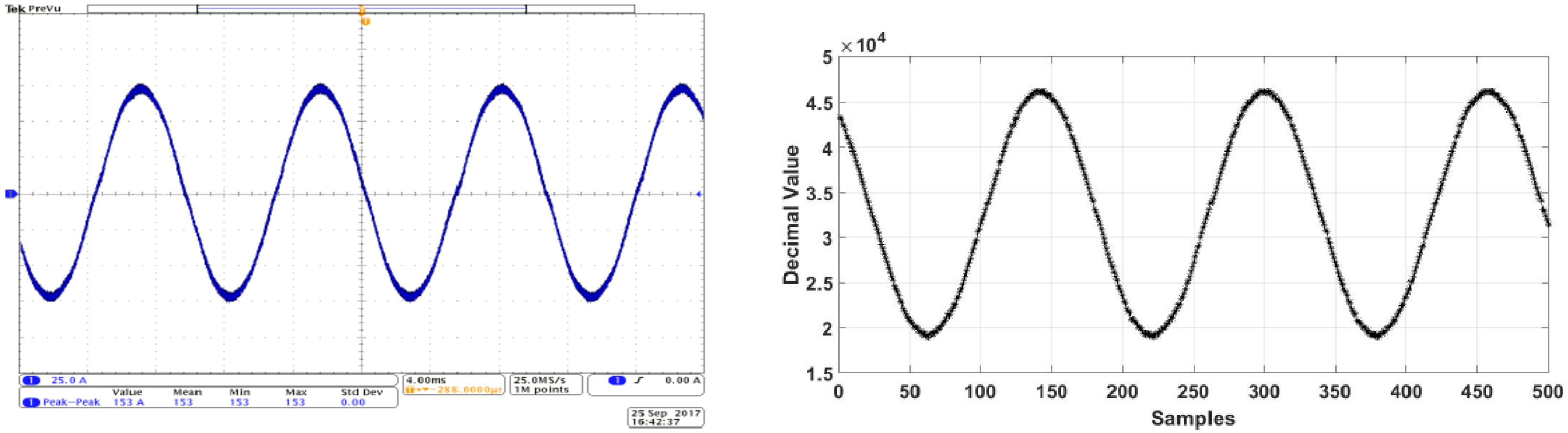


Fig. 12 Current sensing evaluation hardware testbed



(a)

(b)

Fig. 11 Phase current (left) and sampled data (right) show excellent noise immunity with 150 $A_{pk\text{-}pk}$ and 1 kV bus voltage using Σ-∆ modulator

Technical Accomplishments and Progress

RICARDO

TransPower/Meritor Heavy Duty Vehicle Development

Vehicle

- Actively engaged with heavy-duty suppliers on battery electric requirements
- Defining mechanical and electrical interfaces

Electric Drive System

- Identified preferred battery system with necessary energy capacity and preparing High Voltage system architecture
- Performing CAD packaging studies for complete Electric Drive System installed on rolling chassis including mass balance loading
- DFMEA and DVP drafted and under internal team review

eAxle

- Evaluating 14Xe eAxle packaging in vehicle with various suspensions to ensure clearance in the full jounce and rebound conditions

SPECIFICATIONS

Continuous Power Range	130*, 150, 180 and 200 kW
Peak Power	250 kW
GAWR Range per Axle	13,600 – 26,000 lbs. (6.8T – 12T)**
Applications	**Class 6-7:** Pickup and Delivery, School Bus **Class 8:** Refuse, Linehaul **8m, 9m, 10m and 12m:** Transit Bus **Other:** Terminal Tractors, EU Trucks
High Voltage Range	450 – 750V
Functional Safety Rating	ISO-26262 / ASIL-C
Ingress Protection	IP6K6K, IP6K8 and IP6K9K

* Future release
** Customizable GAWR could be investigated

- Increased efficiency
- 2-speed
  - 2.8:1 / 1.4:1
  - 5.6:1 / 2.8:1
- 3-speed
  - 5.6:1 / 2.8:1 / 1.4:1

Fig. 12 Meritor eAxle specification

Technical Accomplishments and Progress

Meritor eAxle Features & Progress

Design activities ongoing to meet Product Features:

- Can be used in a variety of vocations and vehicle applications
- Maintain existing axle housing interface hardware
- Suitable for electric, parallel hybrid, series hybrid, and plug-in hybrid configurations
- Accommodates parking brakes
- Regenerative brakes part of electric drivetrain
- Gearing optimized for regenerative braking
- Mobile and PTO capability
- Two-speed and Three-speed transmission capability
- Optional wheel end reduction
- Unsprung weight is marginally higher than a conventional mechanical axle- offset by power dense eCarrier design to mitigate ride and handling impact

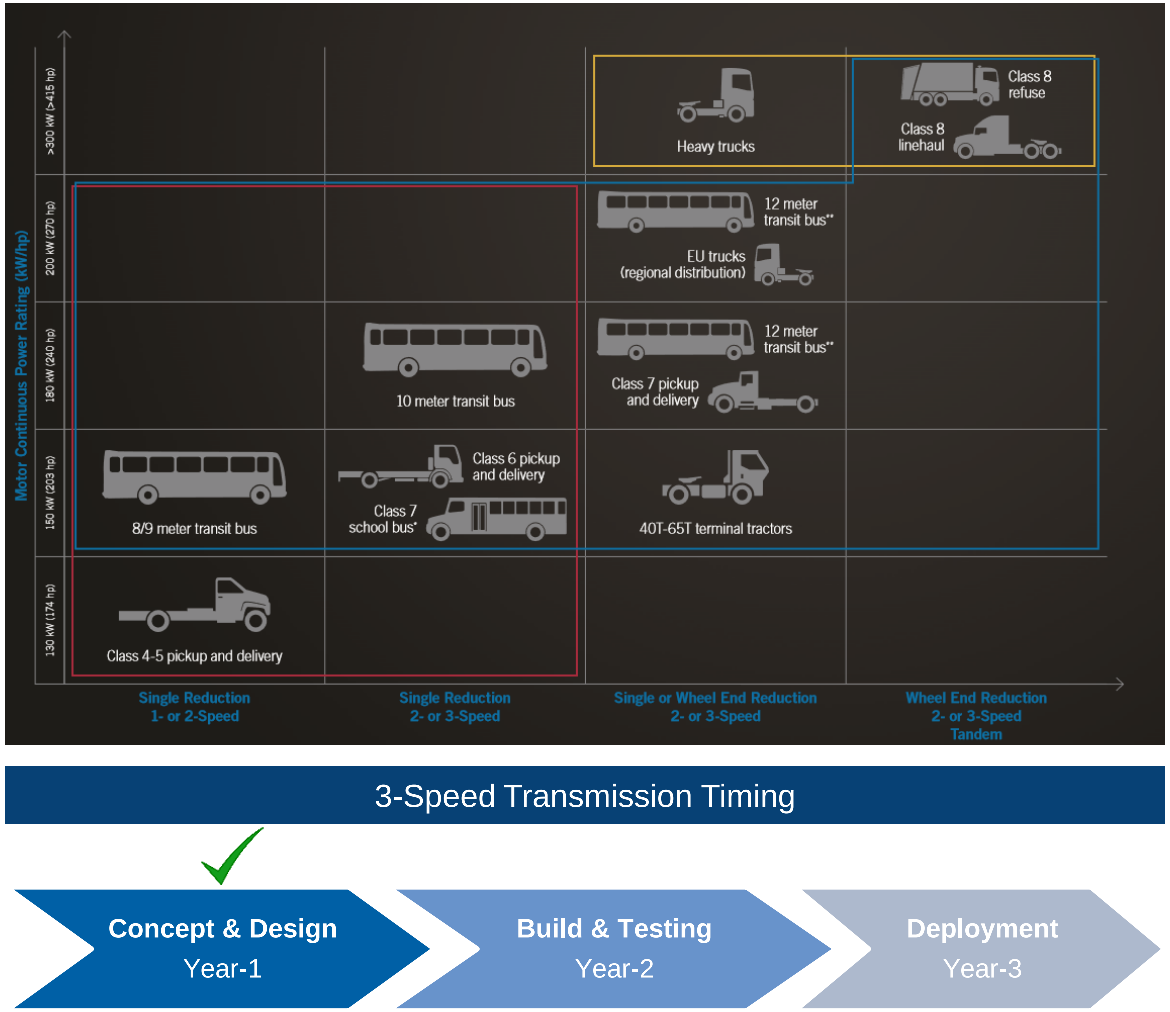


Fig. 13 Transmission matrix and 3-speed eAxle timing

Responses to Previous Year Reviewer’s Comments

- This is the first year review of the project

Collaboration and Coordination

North Carolina State University Freedm Systems Center (Iqbal Husain)- Sub

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

TransPower/Meritor Inc. (Tavin Tyler & Pedro Garcia)- Sub

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

Ricardo Inc. (Ben Marquart & Elton Rohrer)- Prime

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

Research Challenges & Barriers

- The main challenge to the project team of reaching 250kW continuous power output stems from the battery pack supply voltage, which is a nominal 656V and cannot be changed for the project. Initial simulations are positive and the approach to overcome this challenge is ongoing further simulations to account for all system parameters followed by initial physical testing.
- Another challenge facing the team is to optimize inverter packaging within the chassis to maximize efficiency. In addition to confirming a physical location for the inverter, noise generated from cable length will need to be filtered. The team will use the PSIM simulation tool to optimize the required filter for cable length as well as from motor and system layout parameters. The team expects to achieve 98.5% inverter efficiency at the end of the development phase (end of year 2).
- Device option reviews and inverter component design is focused on minimizing the inverter volume to maximize power density. These activities will run in parallel with the power output and efficiency activities to achieve the power density target of > 50kW/l.
- 250 mile daily range is dependent on duty cycle, auxiliary loads and overall battery pack sizing. Possible axle loading and packaging limitations on vehicle may restrict total battery pack size. Vehicle simulation over various drive cycles, mitigation activities with auxiliary loads and possibility for opportunity charging to be evaluated to maximize daily range.

Proposed Future Research

- Complete detailed inverter software requirements and software architecture
- Create and complete software test plans
- Prepare and execute a software features plan inline with the concept design and A-sample H/W milestones
- Design and develop inverter A-sample (gate driver, current sensor, DC link capacitors and bus bar), including thermal management considerations as well as DFMEA and DVP
- Build the A-sample prototypes and perform functional tests
- Validate actual efficiency vs. simulation data
- Design and develop the B-sample inverter using the design activities and results learnings from year 1
- Finalize the 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 eAxle shift control software
- Perform design validation testing and vehicle commissioning
- Complete vehicle integration builds
- Demonstrate High Efficiency Powertrain meets performance metrics in fleet operation service

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 TransPower’s drive system and demonstrate achieving the performance parameters during year 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 and design expertise support and TransPower Inc., a wholly owned subsidiary of Meritor Inc, as a leader in developing and supplying integrated drive systems and full electric truck solutions

- Technical Accomplishments: Proof of concept inverter design started and several different simulation scenarios have been completed

- Future Work: Future project activities will be focused on the development 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 Back Up Slide

- No technical back up slides