2021 DOE Vehicle Technologies Office Annual Merit Review

Integrated Motor and Drive for Traction Applications

Project ID: elt243

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Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC)

University of Wisconsin-Madison

June 21-25, 2021

Overview

Timeline

- Project start date: 4/01/2019
- Project end date: 3/31/2024
- Percent Complete: 40%

Budget

- Total project funding
  - DOE's share: $ 1,500,000
- Funding for FY 2019: $ 300,000
- Funding for FY 2020: $ 300,000

Barriers and Technical Targets

- Multi-physics integration of power electronics with machine to enhance performance metrics
- High-temperature power electronics availability and cost
- High-performance machine materials availability and cost
- Advanced thermal management for machine & power electronics

Partners

- Oak Ridge National Laboratory (ORNL)
- National Renewable Energy Laboratory (NREL)
- Ames Laboratory

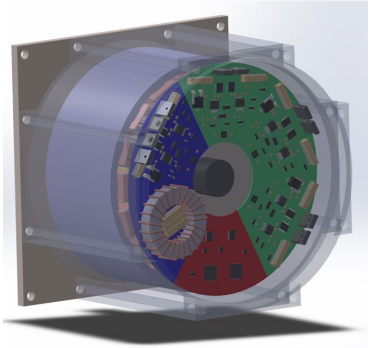
Relevance

Objective

- Pursue an aggressive research program to merge **high-torque-density traction machines** and **high-efficiency inverters** into state-of-the-art **integrated motor drives (IMDs)** packaged inside combined housings that will exceed existing traction drive performance metrics in several categories, as follows:

Electric Motor Requirements	
Metric	**Value**
Cost ($/kW)	≤ 3.3
Power Density (kW/L)	≥ 50
System Peak Power Rating (kW)	100

Power Electronics Requirements	
Metric	**Value**
Cost ($/kW)	≤ 2.7
Power Density (kW/L)	≥ 100
System Peak Power Rating (kW)	100



Impact of research

- Reduced overall mass and volume → Future EVs with higher power rating and efficiency
- Modular architecture → Reduced manufacturing cost and higher fault tolerance/reliability
- Co-packaged motor and drive → Higher power density with lower EMI emissions and reduced cost
- Shared thermal management system → Simplification leading to reduced coast and enhanced reliability

Our project aims to develop advanced IMD technology that will benefit Electric Vehicle manufacturers for achieving major performance improvements at lower cost

Milestones for Budget Period 2

April 2020 to March 2021

Milestone Title and Description	Completion Date	Description of Verification Method	Status
Motor electromagnetic design	07/30/2020	Perform the design of the electric machine and specify the machine parameters	Completed
PCB fabrication for benchtop prototype	09/30/2020	PCB for benchtop prototype is designed and fabricated for testing	Completed
Motor mechanical design	10/30/2020	Verify the mechanical design of the motor with ORNL and NREL, deliver the final design for prototyping	Completed
Performance analysis of benchtop prototype inverter	12/31/2020	Evaluate the performance of the benchtop prototype inverter	Completed
Go/No Go Decision: Preliminary IMD Design Completed	03/31/2021	Drawings, schematics are ready for making the prototype motor and benchtop inverter.	Completed

All planned tasks for Budget Period 2 successfully completed

Milestones for Budget Periods 3 and 4

Milestones for Budget Period 3 (April 2021 to March 2022)

Milestone	Type	Description
Detailed prototype machine and inverter design	Technical	Complete the detailed design of the prototype machine and inverter in preparation for fabrication
Fabricate prototype machine	Technical	Support fabrication of prototype machine
Fabricate prototype inverter	Technical	Complete the fabrication of the prototype inverter
Initial testing of prototype inverter and machine	Technical	Conduct inverter to verify their performance capabilities initial tests of prototype machine
Go/No Go Decision: Complete the fabrication of the prototype machine & inverter	Go/No Go	Complete fabrication of prototype machine and inverter including performance verification testing as components.

Milestones for Budget Period 4 (April 2022 to March 2023)

Milestone	Type	Description
Integrated system testing	Technical	Perform the testing of the integrated system of electric machine and power electronics
Performance analysis of IMD	Technical	Estimate losses, efficiency, EMI/EMC, and thermal performance
Fabrication of prototype IMD	Technical	Carry out the physical integration of the prototype machine and inverter into the same enclosure
Initial testing of prototype IMD	Technical	Debug prototype IMD and carry out initial tests to demonstrate basic functionality of the prototype IMD
Go/No Go Decision Title: Demonstrate prototype IMD functionality	Go/No Go	Complete fabrication of the prototype IMD and demonstrate functionality during initial testing. Alignment with Table A performance measures is demonstrated.

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Approach

Electric Machine Design

- – Design the electric machine using analytical and FEA software
- – Specify the machine parameters
- – Collaborate with ORNL and NREL for mechanical, structural, and thermal design
- – Transition the detailed design to the ORNL and NREL for machine built

Design of bench-top inverter prototype

- – Estimate losses, efficiency, and EMI/EMC for bench-top inverter prototype
- – Design gate drive, filter, and controller unit for the inverter
- – PCB layout for bench-top inverter prototype considering parasitic parameters and thermal performance
- – Fabricate the bench-top inverter prototypes for testing using testbed
- – Compare the performance of designed inverter with simulation

Technical Accomplishments and Progress

Achievements during Budget Period 2 (4/1/2020 to 3/31/2021)

Motor part

- Developed preliminary designs of surface permanent magnet (SPM) machines
- Mechanical design including critical speed analysis and carbon fiber sleeve analysis
- Designed and evaluated integrated cooling system including water jacket and air cooling

Inverter part

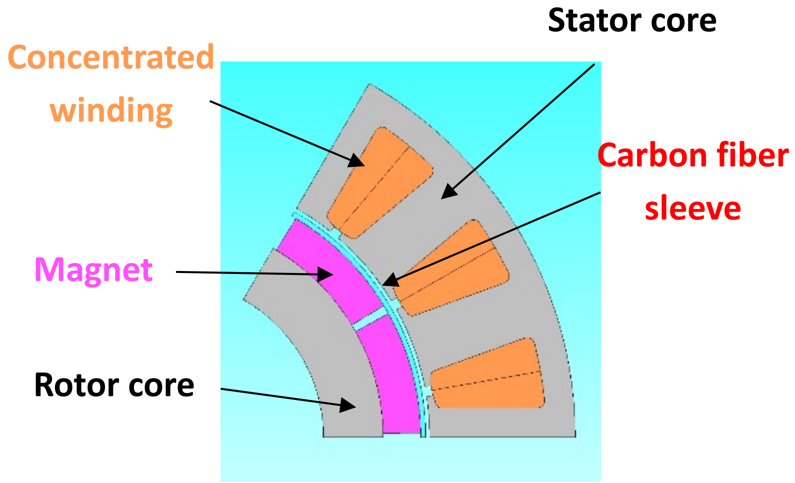
- Developed a CSI double pulse test to estimate the losses and efficiency of CSI
- Designed and optimized DC-link inductor for CSI benchtop
- Designed and fabricated PCB for benchtop prototype inverter with liquid cooling
- Evaluated the performance of the benchtop prototype inverter and compared to simulation results

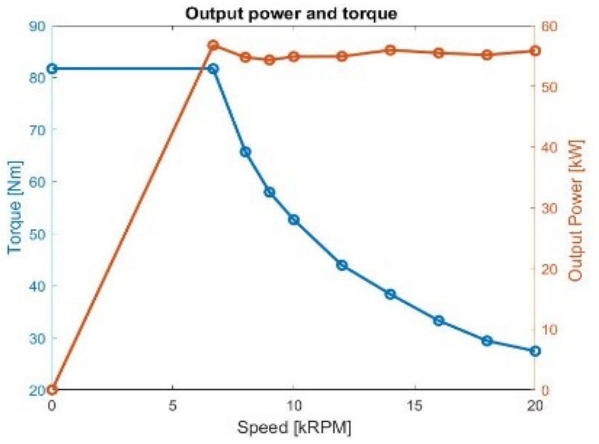
Focus throughout work to date has been on designing the motor and inverter and testing the benchtop prototype for the combined IMD system

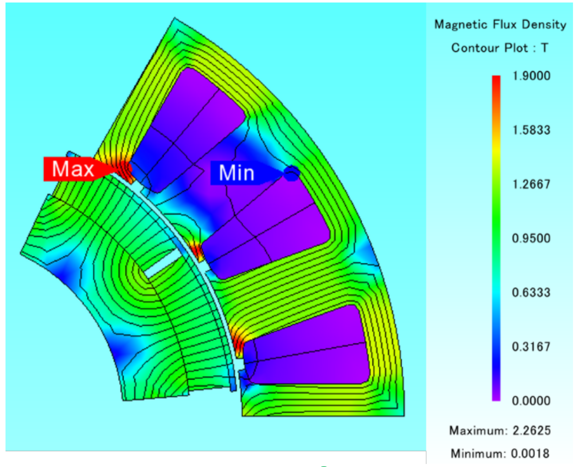
Technical Accomplishments and Progress

Electromagnetic Design

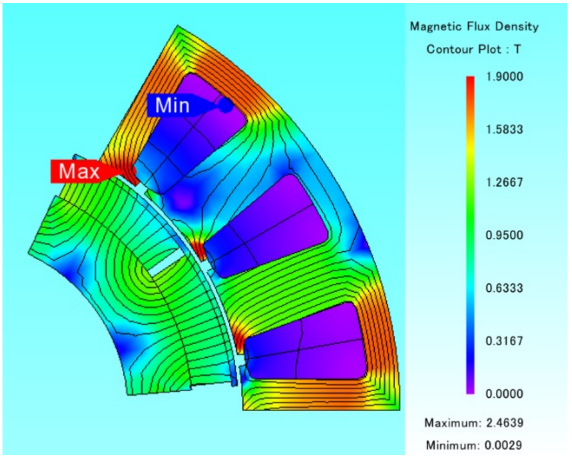
Machine parameters	Value
Magnet materials	NMX-S49F
Lamination materials	20JNEH1200
Number of stator slots	18
Number of rotor poles	12
Parallel circuit	6
Airgap length [mm]	1
Corner speed [rpm]	6,667
Max speed [rpm]	20,000
Stator OD [mm]	163.9
Stator ID [mm]	106
Rotor OD without sleeve [mm]	102.4
Rotor ID [mm]	63.8
Stack length [mm]	112
Magnet thickness [mm]	7.47
Sleeve thickness [mm]	1
Number of turns per coil	48
No-load flux linkage [Wb_{rms}]	0.344
Back-EMF L-N @ 6667 rpm [V_{rms}]	241
Phase winding resistance @ 120 °C [Ω]	0.056
d-axis inductance [mH]	0.362
q-axis inductance [mH]	0.394
Characteristics current [A_{rms}]	158.4 (2.0 pu)
Rated current @ 55 kW [A_{pk}]	115
Machine active volume [L]	2
Active power density [kW/L]	50.3







55 kW



100 kW

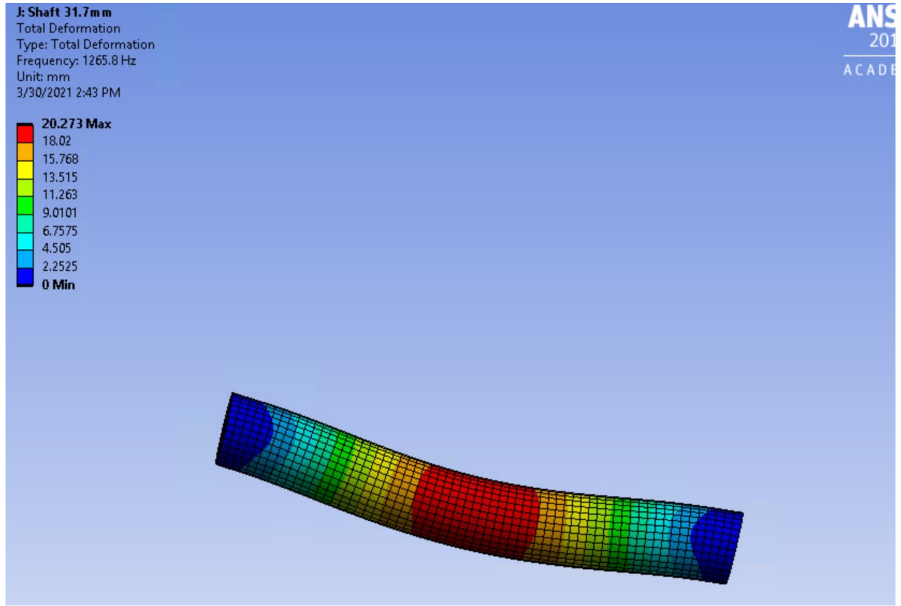
Active power density requirement has been met: 50.3 kW/L

Technical Accomplishments and Progress

Rotor Mechanical Design

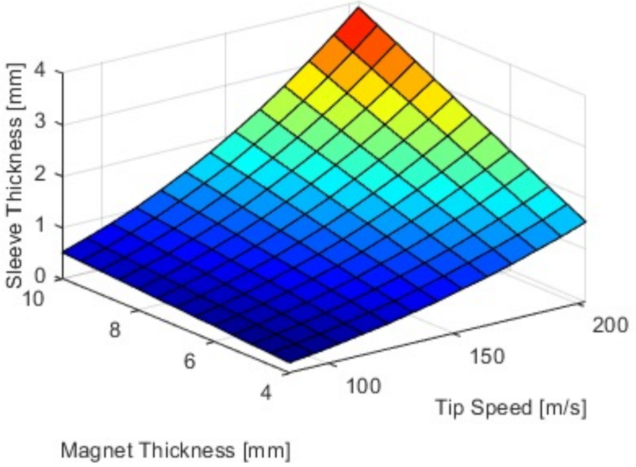
Critical speed analysis

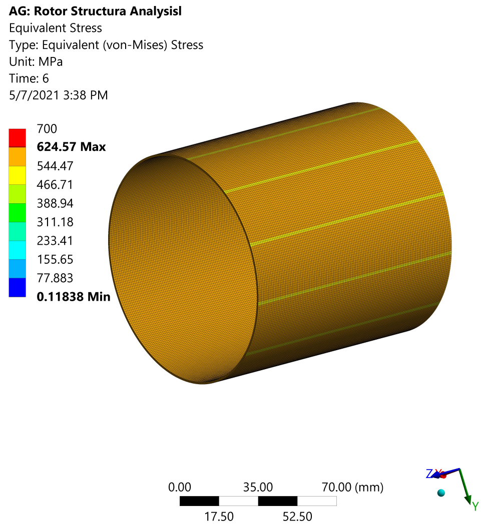
- Shaft diameter is calculated based on the torque requirement
- Maximum speed is 20,000 rpm of the machine



Carbon fiber sleeve analysis

- Carbon fiber sleeve thickness is calculated based on maximum speed
- Maximum yield stress of the carbon fiber is 2,000 MPa



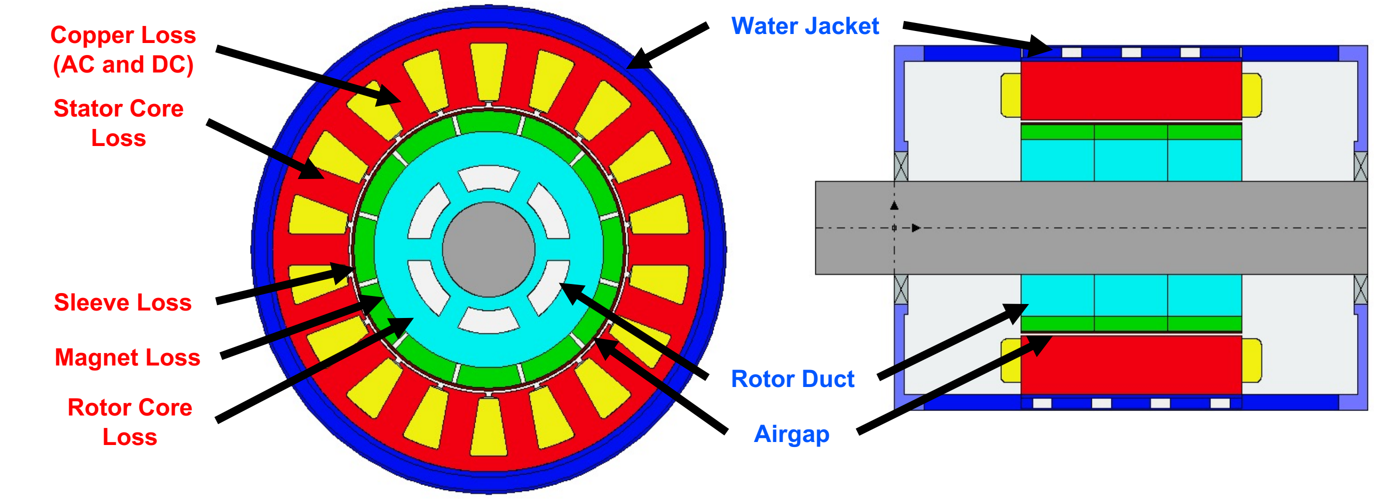


Critical speed is 75,948 rpm, which is three times higher than the maximum speed of the machine. Maximum stress on the sleeve is 625 MPa, which is smaller than yield stress of sleeve: 2 GPa

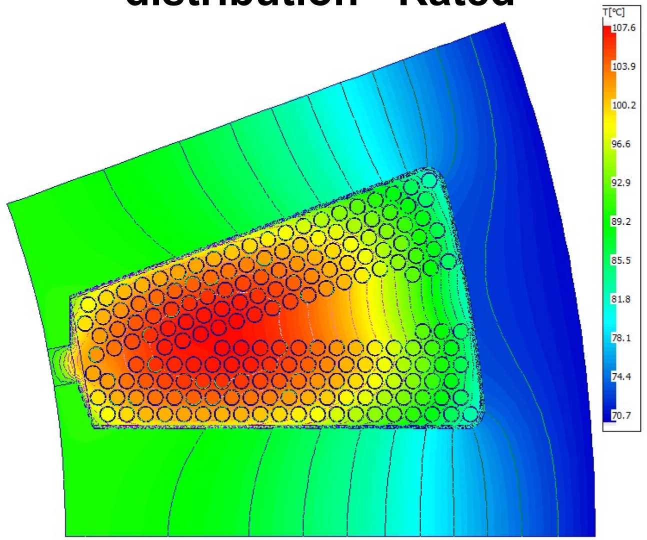
Technical Accomplishments and Progress

Thermal Design

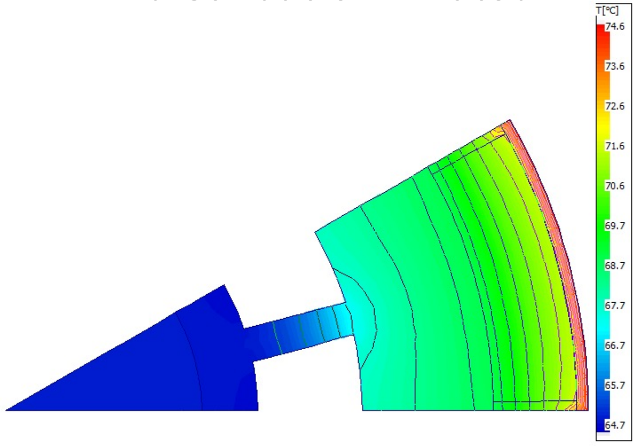
Thermal design includes both stator water jacket cooling and rotor air cooling



Stator temperature distribution - Rated



Rotor temperature distribution - Rated

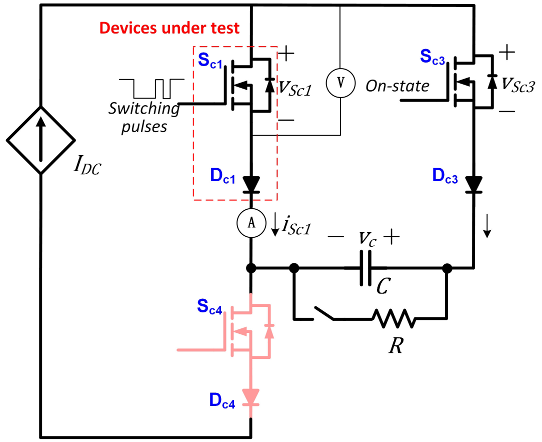


Temperature Distribution				Critical Temp.
Part	55 kW @ 6,667 rpm	55 kW @ 20,000 rpm	100 kW (30s transient) @ 6,667 rpm	
Housing [◦C]	70.3	72.8	72.7	-
Stator Lam. [◦C]	75.0	79.6	79.7	815
Stator Surface [◦C]	90.3	104.5	98.6	-
Rotor Surface [◦C]	74.6	116.0	76.3	-
Sleeve [◦C]	73.5	117.2	75.1	180
Magnet [◦C]	70.7	115.5	73.4	140
Rotor Lam. [◦C]	66.3	103.1	67.0	815
Shaft [◦C]	64.9	99.5	65.0	-
Fluid - WJ [◦C]	67.0	67.9	68.1	-
Fluid - Duct [◦C]	51.4	61.3	54.6	-
Fluid - Airgap [◦C]	81.5	108.3	86.5	-
Winding [◦C]	106.1	122.8	148.4	155
End Winding [◦C]	108.3	124.8	154.0	155

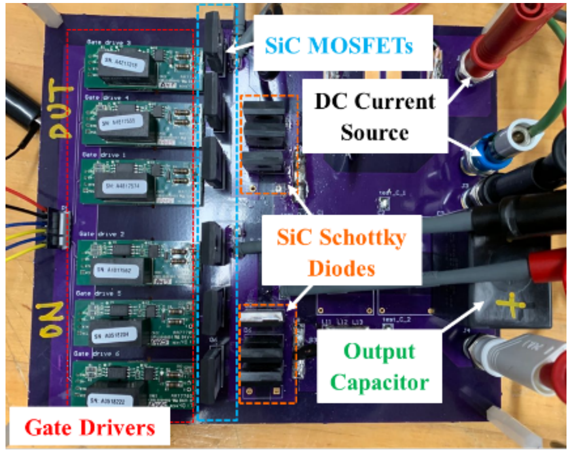
Temperatures of machine parts are kept below the critical temperature of corresponding materials

Technical Accomplishments and Progress

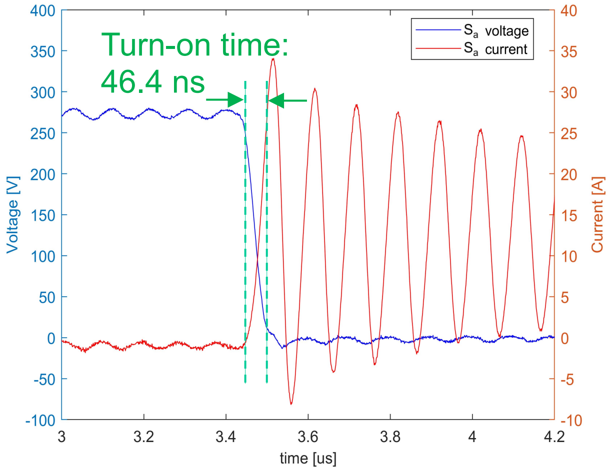
Power Losses and Efficiency Estimation for Power Electronic



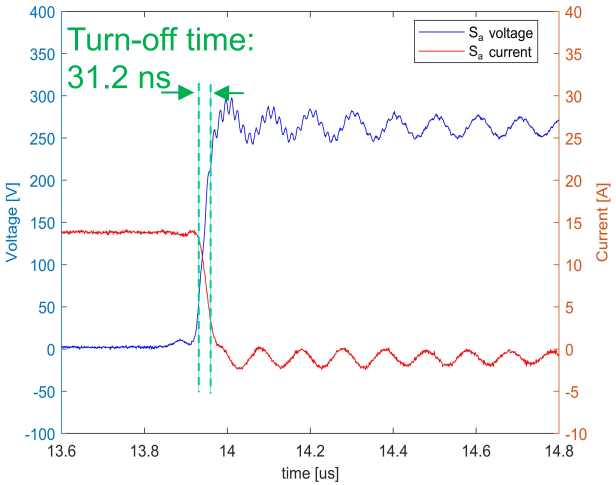
Current source inverter (CSI)-based double pulse test (DPT)



CSI DPT prototype



Turn-on waveform



Turn-off waveform

Power Loss Estimation based on DPT and datasheet

RPM	Output power (kW)	CSI loss (W)	DC-link inductor loss (W)	DC/DC converter loss (W)	Total Loss (W)	Efficiency (%)
6,667	55	684.6	412	293.9	1390.5	97.5
Operating condition: 55 kW output power, 50 kHz switching frequency, 650 Vdc						

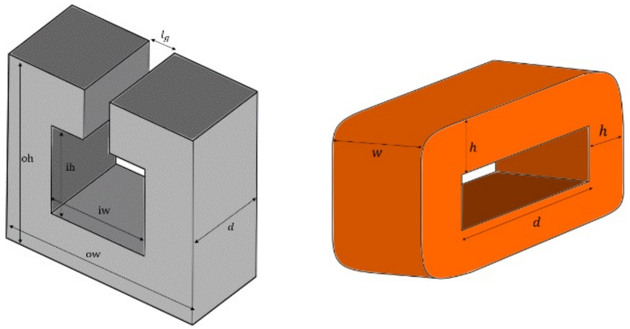
CSI DPT is used to better represent switching characteristics of CSI operation, and the power losses are estimated based on DPT and datasheet

Technical Accomplishments and Progress

Optimal Design of DC-Link Inductor

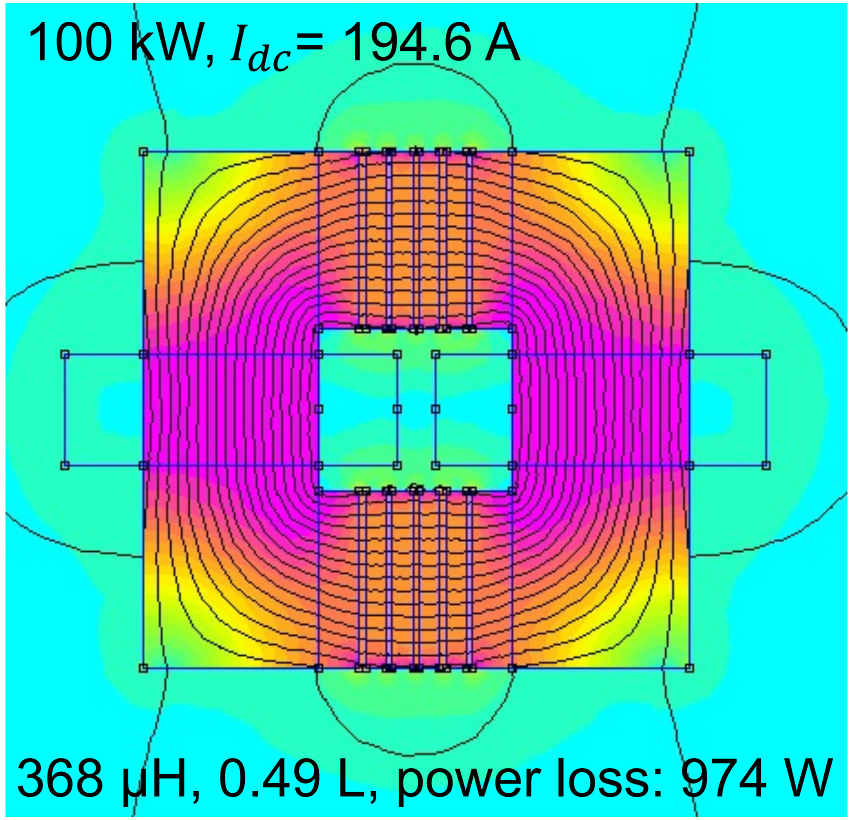
- ❑ **Nanocrystalline Core Inductor Design Challenges**
- ❑ Fringing flux ➔ Multiple airgap
- ❑ $p/4 < s$ design rule
- ❑ p: gap pitch, s: gap-conductor distance

- ❑ **Design Process**



Parameterized inductor geometry

MathWorks



Minimum volume of 0.49 L is achieved with multi-gapped nanocrystalline core inductor

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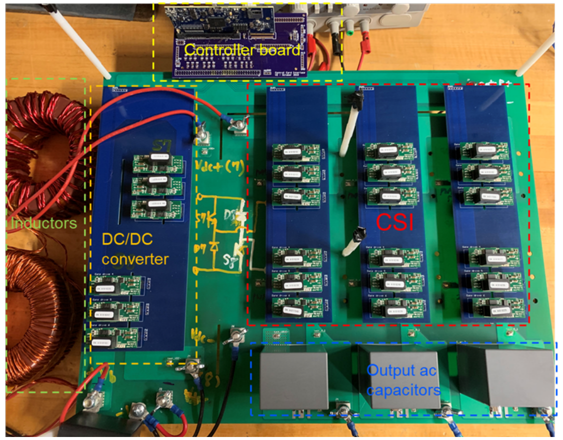
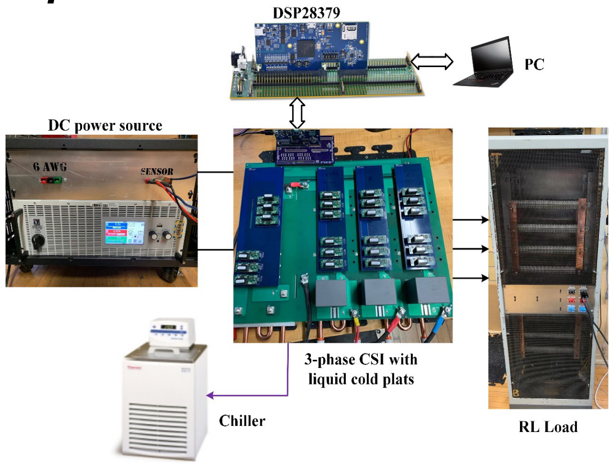
Technical Accomplishments and Progress

Bench-top Inverter Prototype

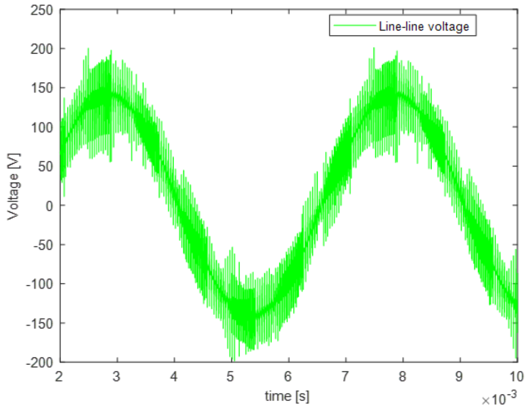


Benchtop CSI + dc/dc converter testbed PCB

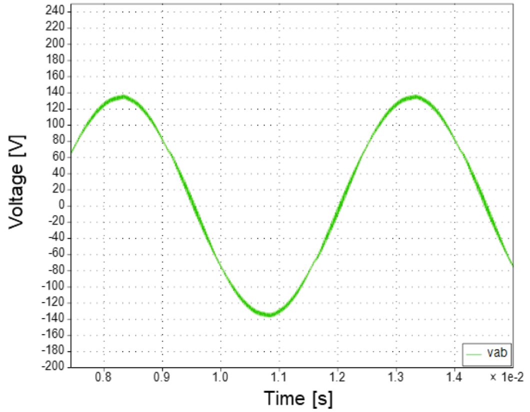


Block diagram of key testbed components of CSI with liquid cooling

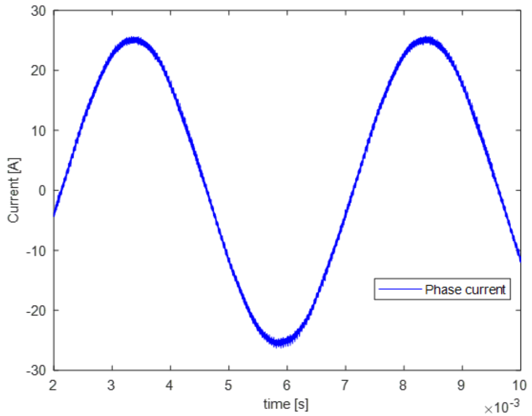
Experiment

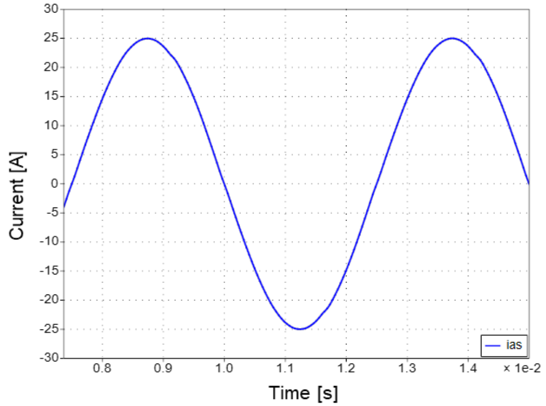


Simulation



line-line voltage comparison of CSI benchtop with RL load





phase current comparison of CSI benchtop with RL load

Measured voltage and current waveforms are highly sinusoidal as predicted by the simulation

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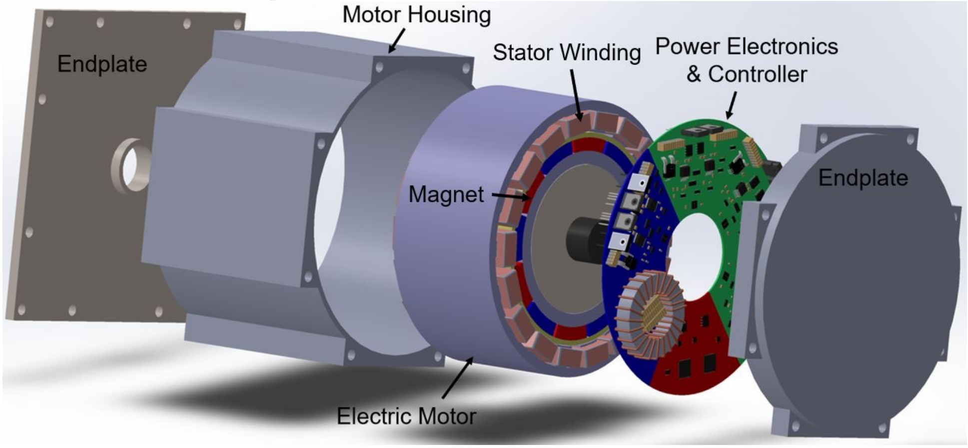
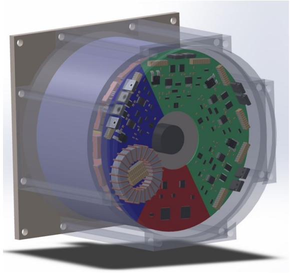
Technical Accomplishments and Progress

Preliminary IMD Configuration

Option #1 Axial-mounted IMD

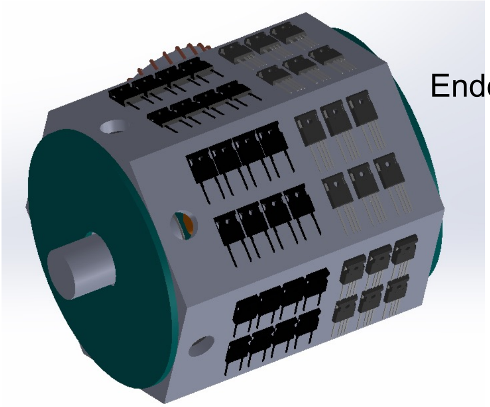


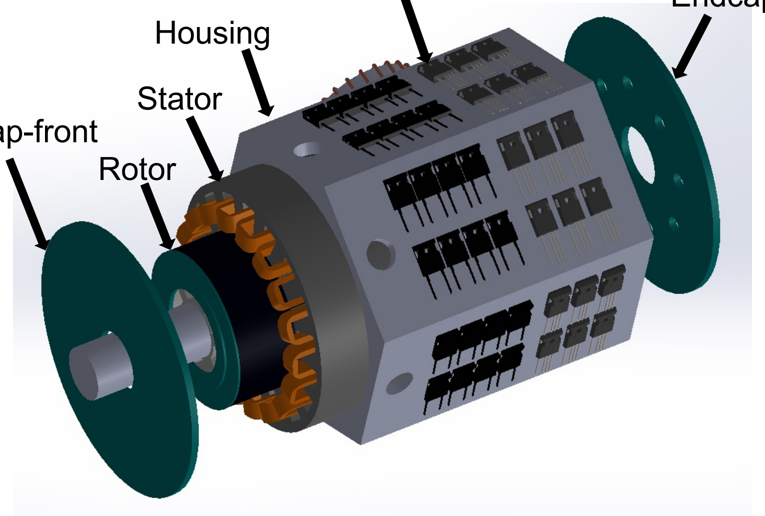


Notes:

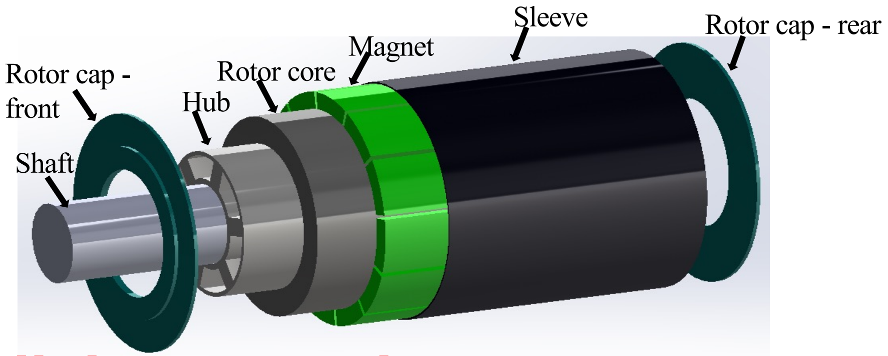
- *Cooling not shown*
- *Housing and structure for illustration purposes only*
- *Volume grows in axial direction*

Option #2 Radial-mounted IMD





Rotor Exploded view



- *Radial-mounted power converter and machine share the same water jacket*
- *Air is guided through machine by axial rotor ducts and airgap for rotor cooling*
- *Volume grows in radial direction*

Axial-mounted and radial-mounted power converters represent two promising topologies for IMD configuration

Responses to Previous Year Reviewer's Comments

Reviewer: 036

- Does the CSI efficiency number include the DC/DC converter?
  - Yes, the CSI efficiency number includes the DC/DC converter in 2020 AMR presentation, as well as in 2021 AMR review.
- Is the intent to cool the motor and PE with one coolant system?
  - Yes, the intent is to cool the stator of the motor and power electronics with one coolant system using liquid cooling. We are investigating the rotor cooling methods, i.e., air vs. liquid cooling.

Reviewer: 047

- Can you please comment on the robustness and fault tolerance of CSI vs. VSI for automotive traction drive applications?
  - The CSI is more robust for DC-link short-circuit faults than VSI. This is because of the reverse voltage blocking capability of the power switch configuration of CSI. In addition, the DC-link inductor in CSI can slow the current rise immediately following fault initiation.
  - CSI has less bearing current issue than VSI, because CSI has more sinusoidal output voltage waveform due to output filter than the PWM voltage of VSI.

Collaboration and Coordination with Other Institutions

- **Oak Ridge National Laboratory (ORNL)**
  - UW-Madison participates in biweekly telecon meetings with ORNL to discuss the mechanical, structural design
  - UW-Madison transit the detailed design to ORNL for machine built
- **National Renewable Energy Laboratory (NREL)**
  - UW-Madison and NREL had biweekly meetings to discuss the thermal design for motor and inverter
  - UW-Madison transit the detailed design to NREL for machine built
- **Ames Laboratory**
  - UW-Madison has biweekly meetings with Ames Laboratory to discuss the material selection for motor and inverter

Partnership collaboration with National Labs will continue during 3rd project year

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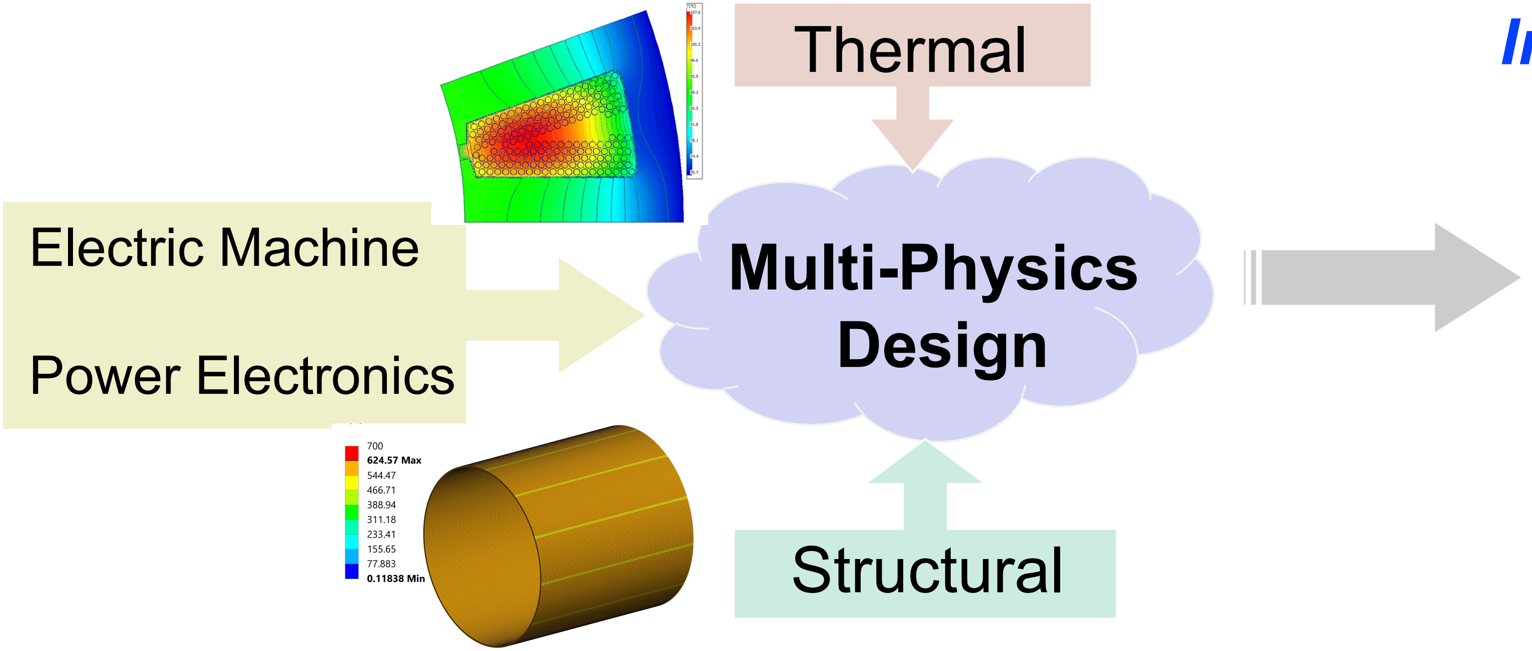
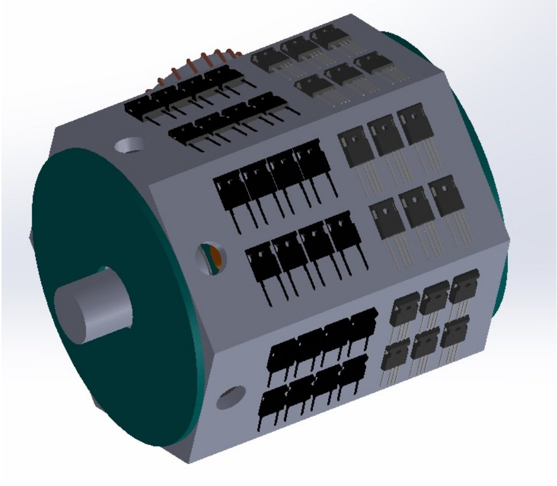
Remaining Challenges and Barriers

- Optimization of the power PCB for integration with IMD design
- Multi-physics integration of IMD to achieve optimal use of volume and cost
- Advanced thermal management for IMD to limit maximum temperatures of components of motor and power electronics
- Optimize integrated cooling system solution for both motor and power electronics
- Availability of high-temperature power electronics and high-performance machine materials at low cost



Integrated Motor Drive (IMD)



IMD concept requires aggressive multi-physics design to optimize motor drive system for volumetric power density and cost

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Proposed Future Research

Budget Period 3: Final IMD Design and Prototype IMD Component Construction

We plan to carry out following tasks:

Task 3.1 – Final Design of Prototype Machine and Inverter

- Based on results of preliminary design review, carry out more detailed design of prototype inverter and machine.
- Conduct analysis and simulations to verify that finals designs of prototype machine and inverter meet their performance targets.

Task 3.2 – Fabrication of Prototype Machine and Inverter

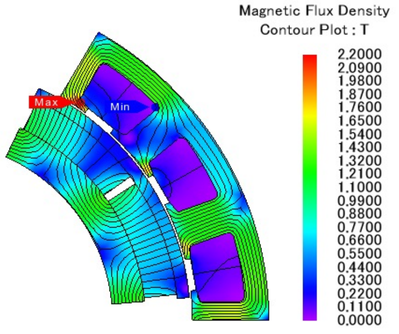
- Work with ORNL and NREL to support fabrication of the prototype motor and inverter

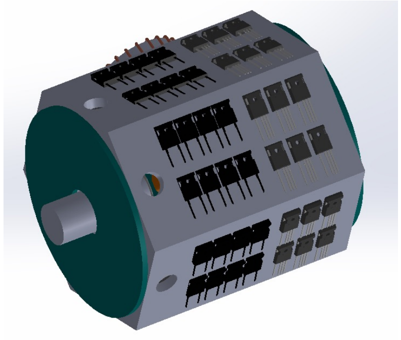
Task 3.3 – Testing of Prototype Machine

- No load testing of prototype machine, e.g., back emf, flux linkage, etc..
- Perform loaded tests for various speeds, torque, and power conditions.
- Investigate any discrepancies between experimental and analytical designs.

Task 3.4 – Preliminary testing of BPI and Inverter Design for IMD

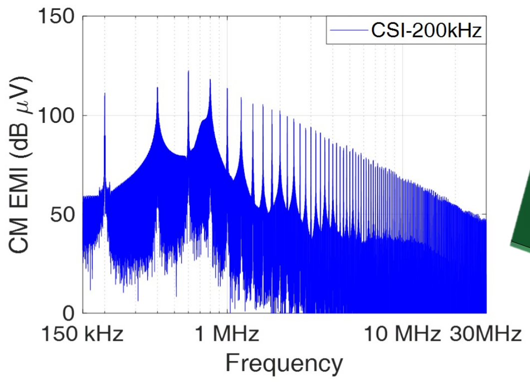
- Detailed performance and thermal analysis of benchtop prototype inverter (BPI) for inverter design for IMD.
- Design PCB for inverter design for IMD for integration and cooling system

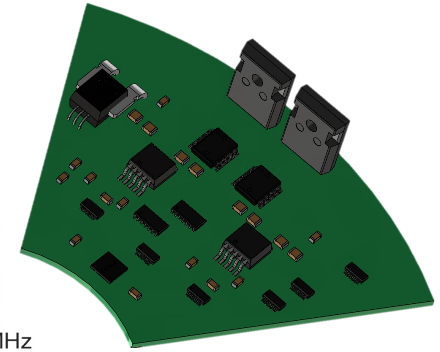




OAK RIDGE National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY





3rd year will focus on designing and prototyping machine and inverter for combined IMD approach

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

Summary

- Integration of power electronics inside machine represents one of the most promising approaches for making major progress to reach challenging DOE performance metrics
  - Demands systems-oriented, multi-physics-based approach to achieve success
  - Opens promising avenues to boost power density and lower cost, with valuable additional benefits in areas such as reliability/fault tolerance
- Second year of project has succeeded in electric machine design and benchtop inverter prototype design
  - Electrical machine is designed, and its subparts including electromagnetic design, rotor structural design and thermal design are evaluated.
  - The benchtop inverter prototype is designed and fabricated for testing, and the performance of the inverter is evaluated.
- 3rd year will focus on final IMD design and prototype IMD component construction
  - Prototype machine and inverter will be fabricated and tested
  - Inverter will be designed and tested for IMD for integration and cooling system

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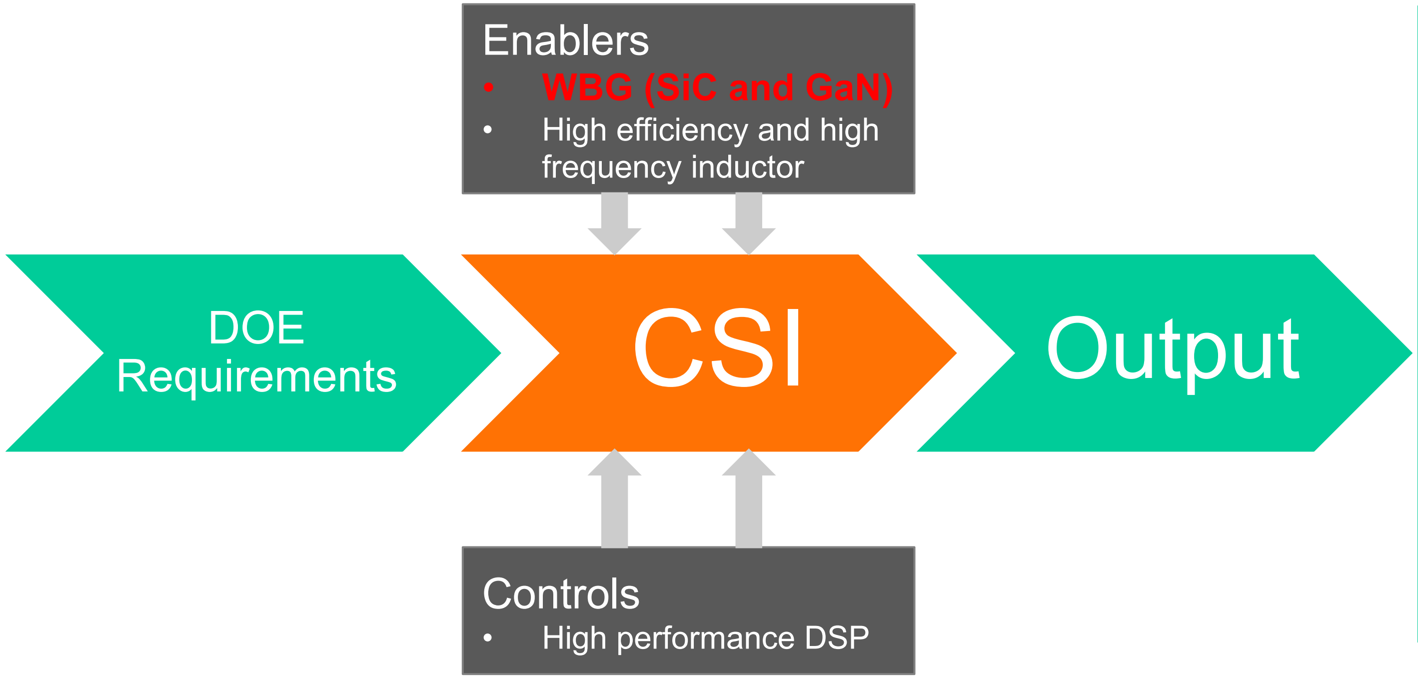
Technical Backup Slides

Technical Accomplishments and Progress

Current Source Inverter with WBG devices



High power density

High efficiency

Good EMI/EMC performance

- Output voltage almost sinusoidal

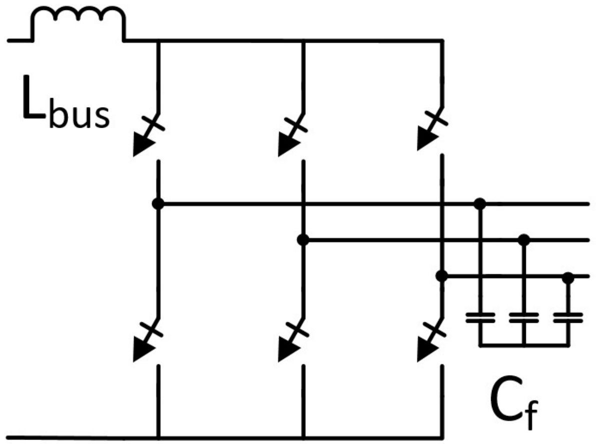
Low PWM harmonics

Good field weakening capability

- Output voltage boost function

High temperature capability

- No DC Link capacitor



CSI configuration

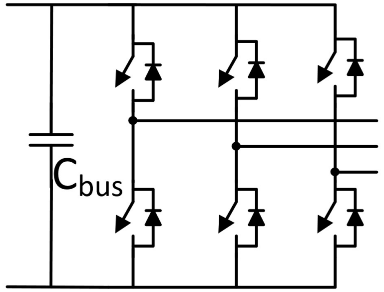
- Current source inverter (CSI) is a ***dual topology*** of traditional VSI
- The dc-link capacitor in the VSI is replaced by the ***dc-link inductor***, and three small capacitors are added at CSI's output terminals
- The dc-link inductor of CSI can be dramatically reduced in mass and volume because of ***high switching frequency*** values of WBG
- The ***high-frequency WBG*** switches is the enabler for CSI to come back
- The CSI has less EMI issue than VSI because of filtering effect of output capacitors for the output voltage.

Technical Accomplishments and Progress

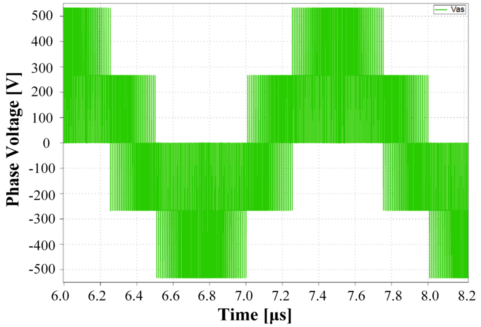
VSI vs. CSI Overview Comparison

	Topology	DC Link	Output Voltage	Common-Mode EMI

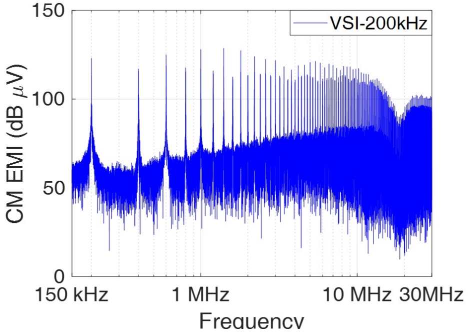
VSI



Fragile and temperature-limited

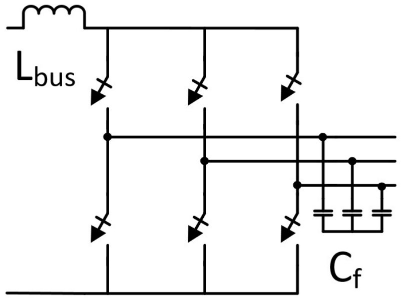


High dv/dt, creating motor insulation stress

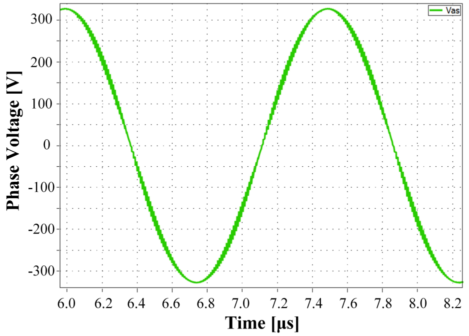


High Common Mode (CM) EMI and bearing current risk

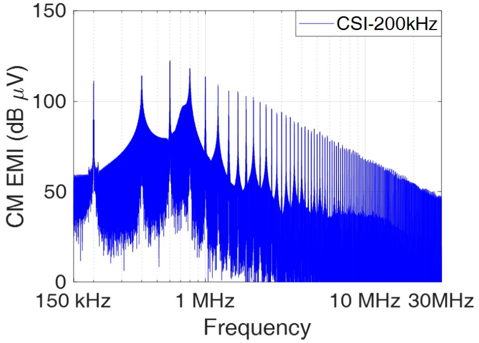
CSI



Rugged and capable of high temperature



Low-THD sinusoidal voltage and current waveforms



Integral LC filter provides appealing EMI roll-off

WBG-based Current-Source Inverter (CSI) overcomes many of the VSI limitations by significantly lowering output dv/dt stress, CM EMI emissions, bearing current risks, and temperature limitations