Integrated Motor and Drive (IMD) for Traction Applications

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University of Wisconsin-Madison

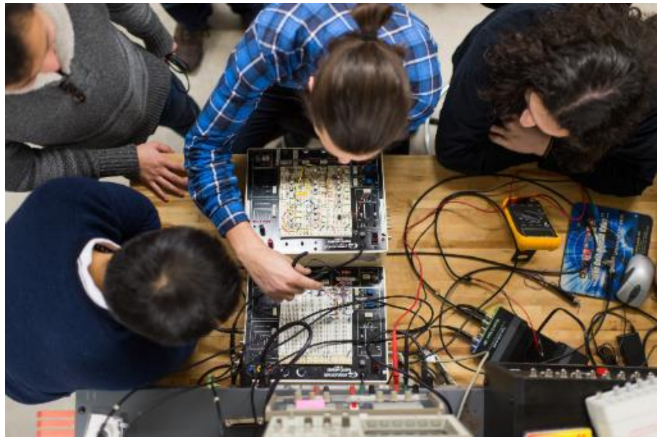
About WEMPEC (Wisconsin Electric Machine and Power Electronics Consortium)

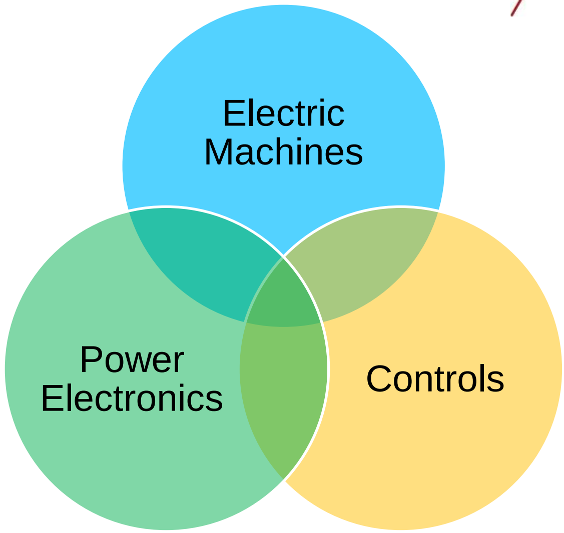
Founded in 1981
- Prof. Don Novotny
- Prof. Tom Lipo

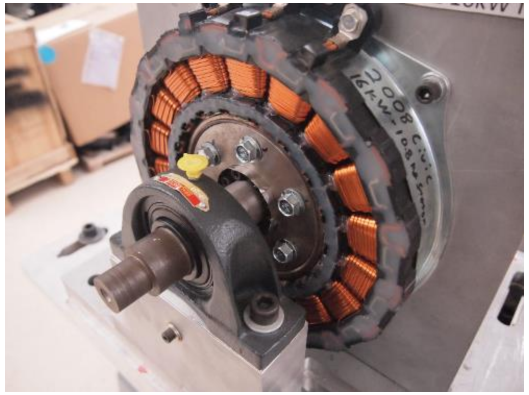
People
- 5 Faculty
- 7 Faculty Affiliates
- 1 Emeritus Faculty
- 3 Staff
- 21 PhD Students
- 16 MS-R Students
- 12 MS-P Students

700+ Degrees granted

55+ Active Members







WEMPEC Faculty

Prof. Giri Venkataramanan

DIRECTOR

- Power converter circuits, topologies, modeling, dynamics, design and control
- Power electronics in electric utilities
- Industrial drives
- Energy sustainability and technology access

Prof. Bulent Sarlioglu

DIRECTOR OF TECHNOLOGY AND COLLABORATION

- Power electronic converters using wide band-gap (WBG) devices
- Power dense motors for aerospace
- Vehicle electrification
- Industrial applications
- WBG current source inverters

Prof. Dan Ludois

DIRECTOR OF RESEARCH

- Electrostatic machines
- Wound rotor machines
- Low power medium voltage converters
- Capacitive wireless power transfer
- Passive component integration

WEMPEC Faculty

Prof. Jinia Roy

Associate Director

- Renewable energy systems
- Medical power conversion (MRI)
- Physical applications (plasmas)
- WBG based modular power electronic architectures
- Pulsed power applications.

Prof. Lei Zhou

Associate Director

- Precision Mechatronics
- Semiconductor manufacturing equipment
- Robotics
- Medical devices

Prof. Tom Jahns

Emeritus Professor

- Electric machines, especially PM machines
- Power conversion and control for distributed generation
- Microgrids
- Battery energy storage

WEMPEC Members

ABB Drives and Power Products Division
Aisin Corporation
Allied Motion
American Axle & Manufacturing
ANSYS Inc.
Arnold Magnetic Technologies
BAE Systems Controls
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POWERSYS Inc
Rockwell Automation Motion Controls
Rockwell Automation Standard Drives
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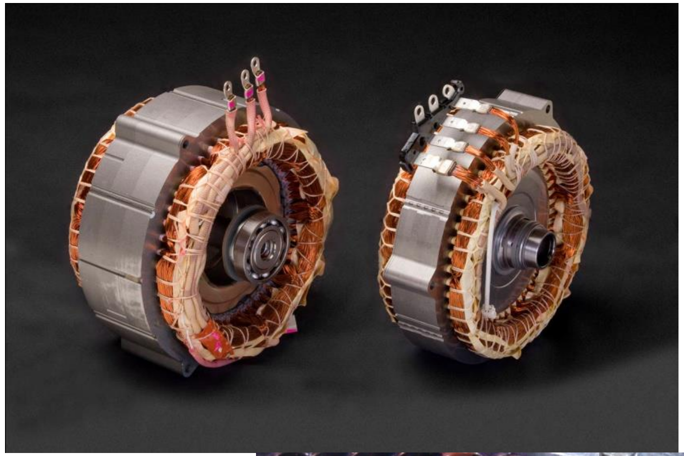
TECO – Westinghouse
Teledyne LeCroy
Trane Company
Typhoon-HIL, Inc.
Verdego Aero
Woodward Airframe Systems

WEMPEC

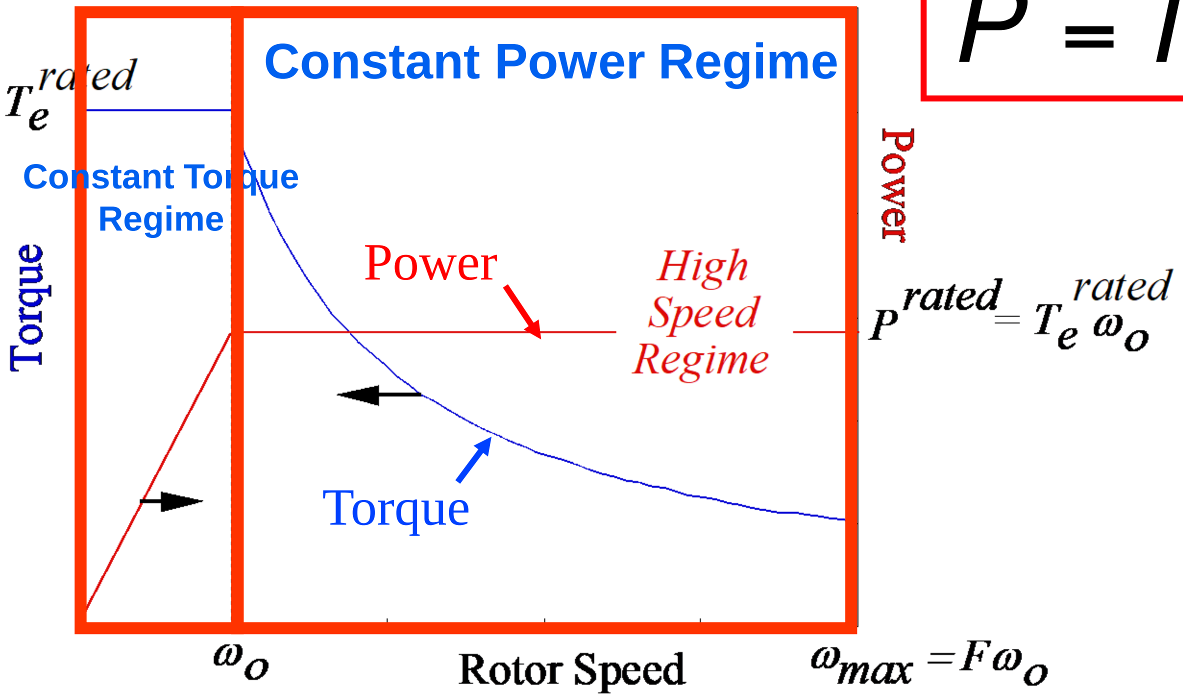
EV Electric Traction Machine Requirements

- High Efficiency
  - Smaller Battery
  - Longer Range
  - Less Cooling
- High Volumetric Power Density (kW/l)
  - More Passenger Space
- Low Cost
  - No heavy rare earth element
- High Mass Specific Power (kW/kg)
- High Peak Torque
- High Maximum Speed
- Wide Constant Power Speed Ratio
- High Maximum Operating Temperature
- High Reliability
- Low Ripple Torque



Torque/Power Operating Envelopes

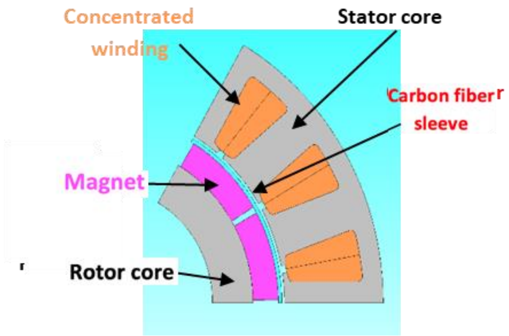
$$P = T_e * \omega_r$$



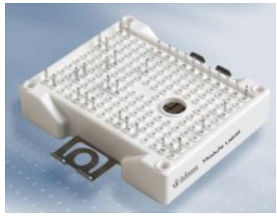
- Permanent Magnet (PM) machines are excellent for applications emphasizing operation in constant-torque regime (e.g., servos)
- PM machines often cause problems in applications requiring wide ranges of constant power (e.g., traction)

Integrated Motor and Drive for Traction Applications

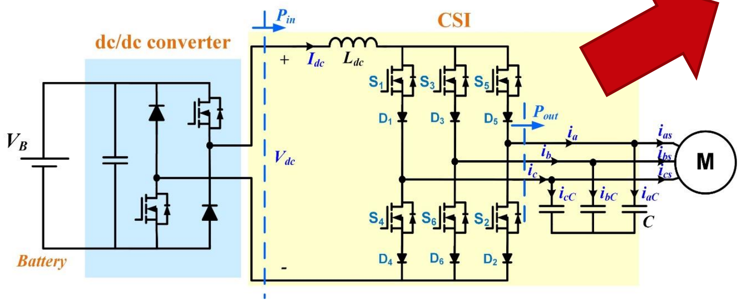
SPMSM



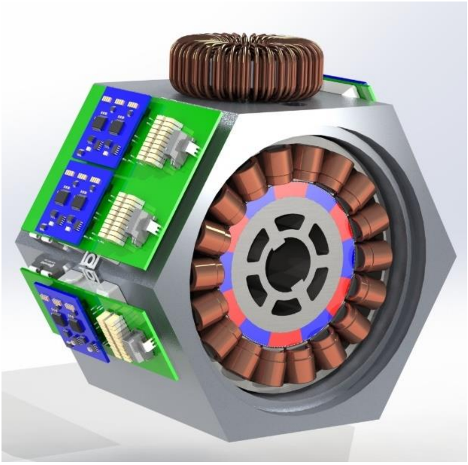
WBG Switches

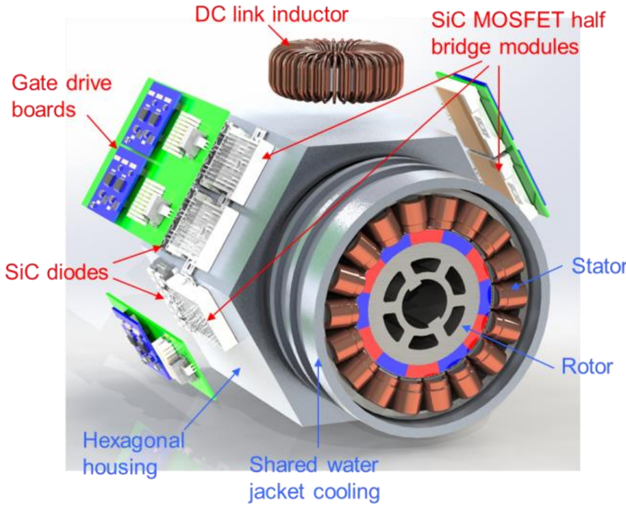


Current Source Inverter (CSI)



Integrated Motor Drive (IMD)





Project Objectives:

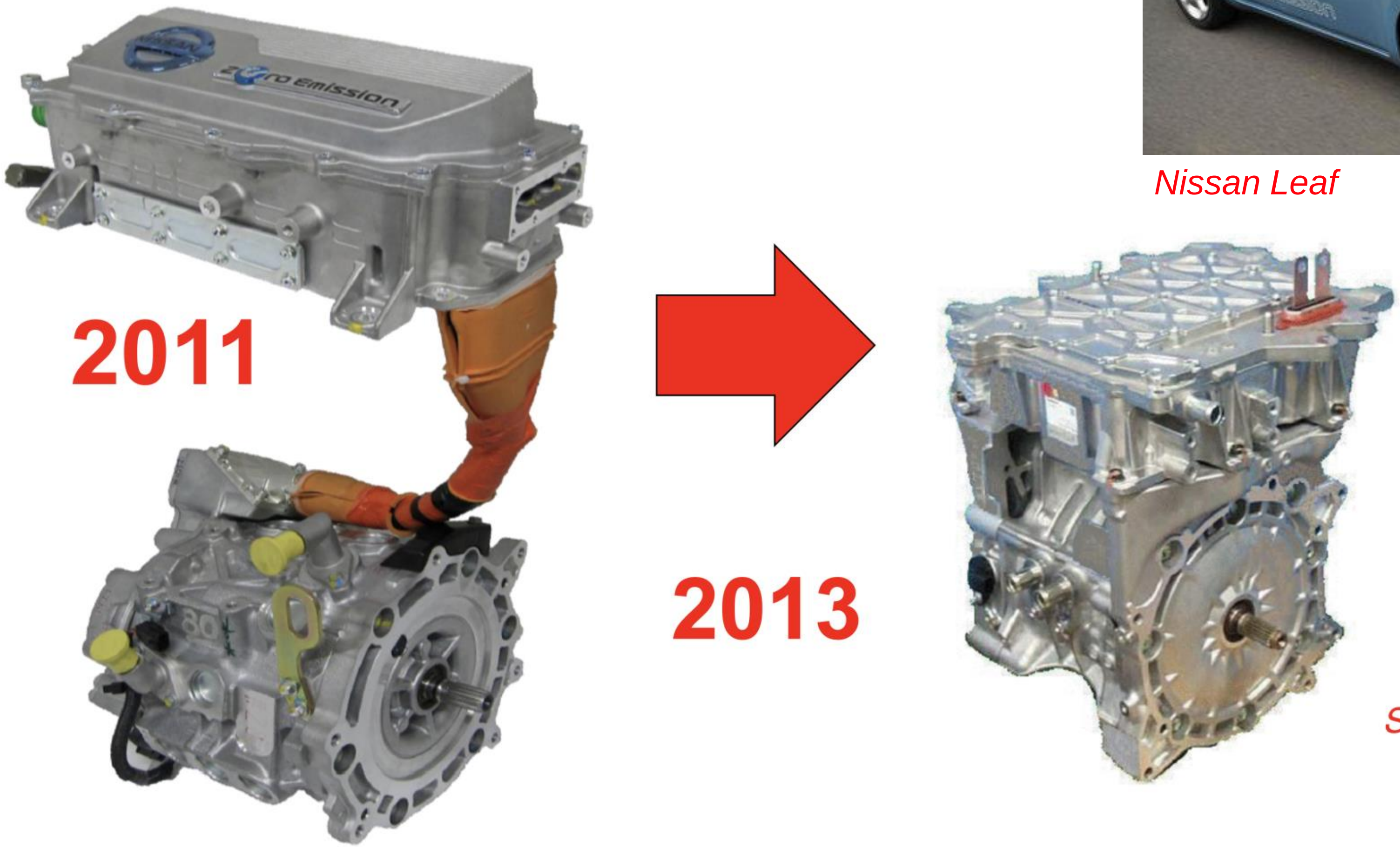
Pursue an aggressive research program to merge ***high-torque-density traction machines*** and ***high-efficiency inverters*** into state-of-the-art **integrated motor drive (IMD)** packaged inside combined housing that will exceed existing traction drive performance metrics in key categories, as follows:

Performance Metric Targets		
Metric	***Motor***	***Pwr Electr.***
Power Density (kW/L)	≥ 50	≥ 100
Cost ($/kW)	≤ 3.3	≤ 2.7
System Peak Power Rating (kW)	100	100

Our project aims to develop advanced IMD technology for achieving major performance improvements at lower cost

Electric Vehicle
Inverter-Motor Evolution

Nissan Leaf



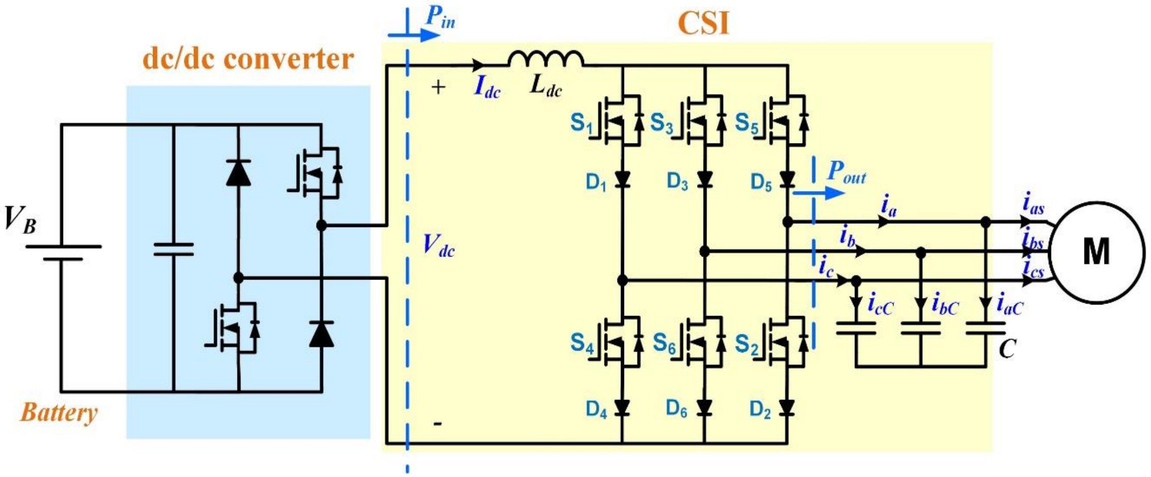
Shimizu et al,
SAE 2013 Congress

- Power cable elimination and mass reduction by 10%

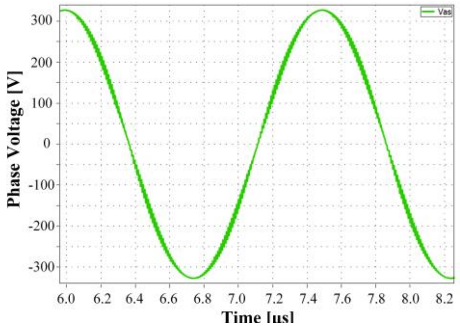
Feature #1
Use Current Source Inverter instead of Voltage Source Inverter (All Vehicles in the Market)

Introduction to CSI-Based Motor Drive System

CSI-based Motor Drive System using WBG Devices

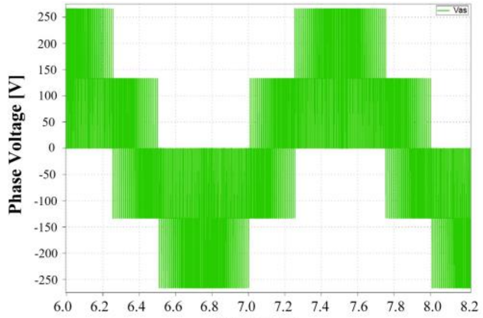


Output Voltage of CSI



Low-THD sinusoidal voltage and current waveforms

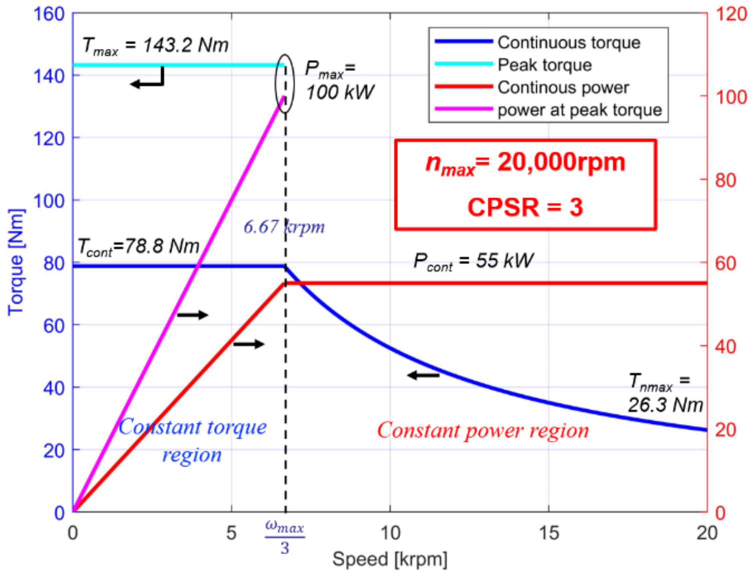
Output Voltage of VSI



High dv/dt, creating motor insulation stress

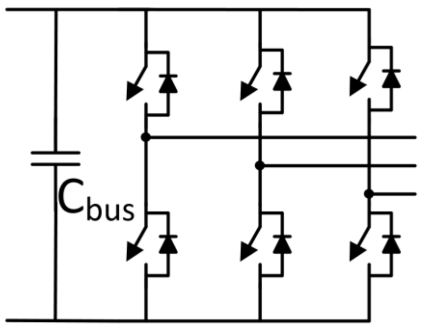
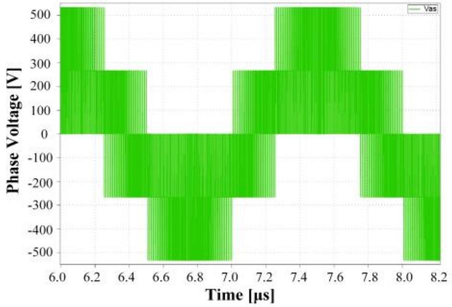
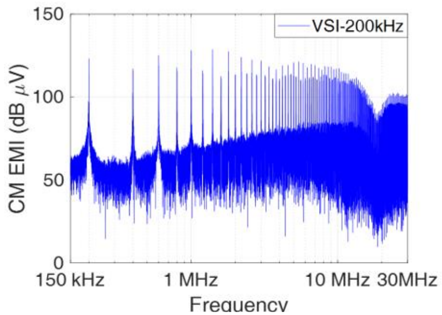
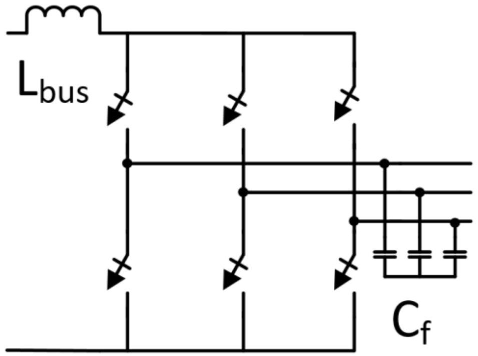
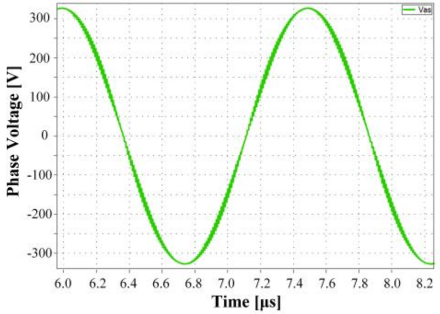
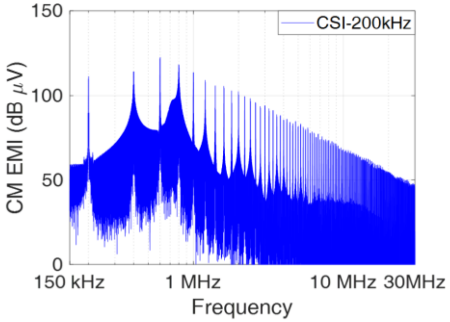
- CSI replaces thermally-limited dc-link ***capacitor*** (<150ºC) in VSI with a compact **high-temperature** ***inductor*** (> 200ºC)
- CSI has much more ***sinusoidal output voltage*** waveforms compared to VSI
- CSI requires reverse-voltage blocking switch configuration that can block voltage in both polarities

Required Performance



WBG-based CSI overcomes many of VSI limitations by significantly lowering output dv/dt stress, CM EMI, and temperature limitations

Appealing Features of CSIs vs. VSIs

	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

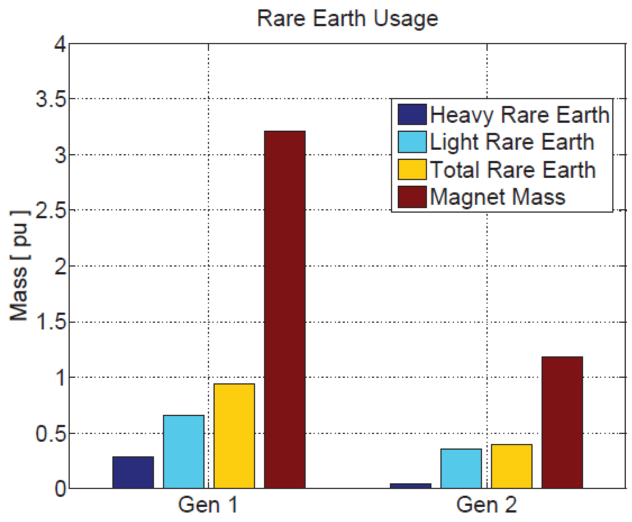
Feature #2

No Heavy Rare Earth Magnets
”No Dysprosium”

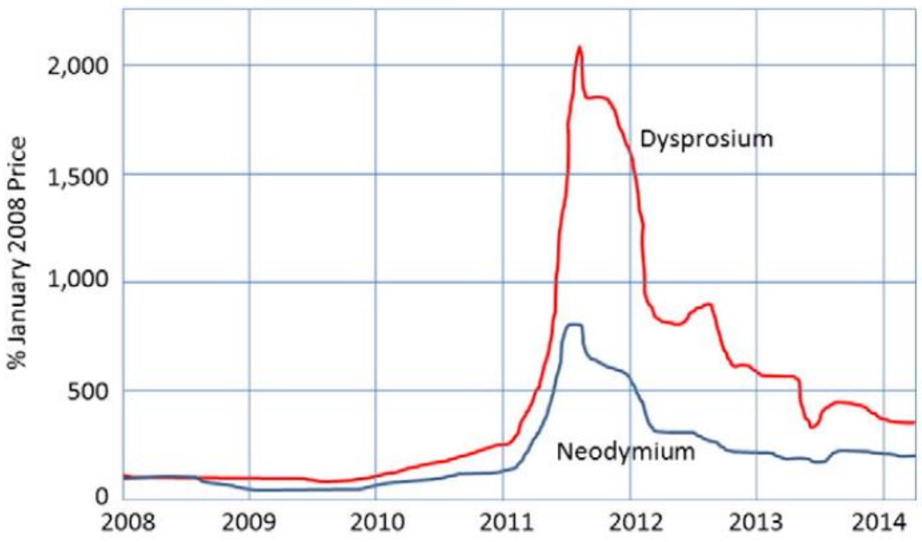
Surface Permanent Magnet Machine

PM Machine Design without Heavy Rare Earth Material

Definition of Rare Earth (RE) and Heavy Rare Earth (HRE) Material [44]									
RE	Ce	La	Pr	*Nd*	Sm				
HRE	Eu	Gd	Tb	***Dy***	Ho	Er	Tm	Yb	Lt



Chevy Volt electrical machine rare earth material usage



Price change for dysprosium and neodymium [45]

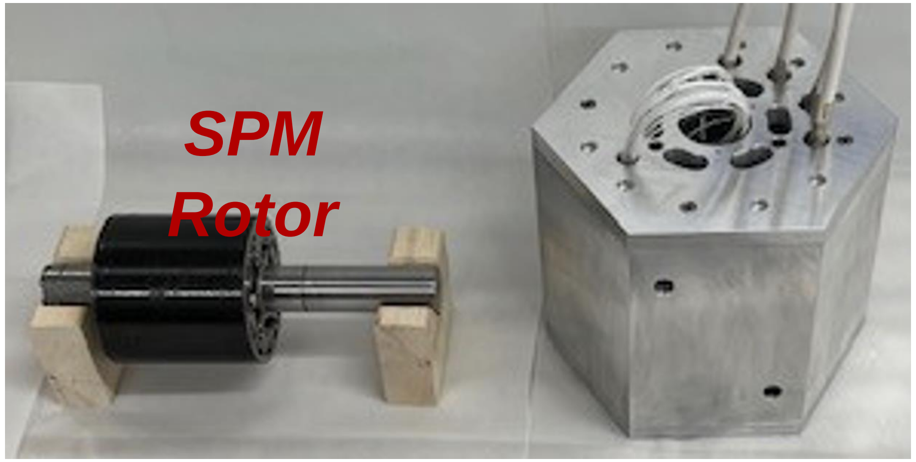
- No heavy rare earth material
  - **Reduce** machine cost
  - **Higher** demanganization
  - **Lower** temperature rating

There is high demand and research opportunity of PM machine design without HRE

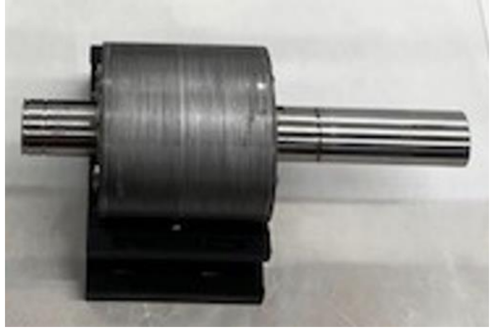
J.D. Widmer, R. Martin, M. Kimiabeigi, Electric vehicle traction motors without rare earth magnets, Sustain. Mater. Technol. 3 (2015) 7–13, https://doi.org/ 10.1016/j.susmat.2015.02.001.

Permanent Magnet Machine Fabrication
Stator and Rotors (SPM and SIPM)

Stator



SPM Rotor



SIPM Rotor

Electrical machine components have been fabricated, including stator with winding and RTDs, housing, and two permanent magnet rotors

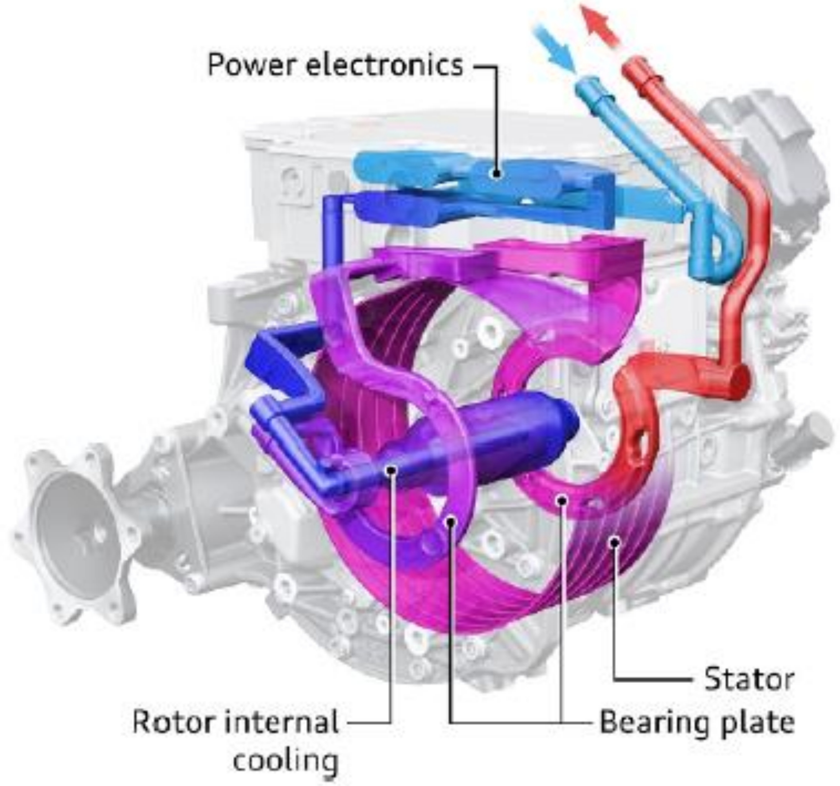
Feature # 3

Use air cooling for rotor by

Keep rotor losses very low

- Laminated Magnets
- Low loss steel

Internal Rotor Oil Cooling - Audi E-Tron Cooling System



“Audi e-tron Electrical Components (Technical Animation)”
https://www.youtube.com/watch?v=sicWHkG6g8c&t=30s

Cooling of the power electronics

- Semiconductors can dictate maximum permissible cooling water temperature instead of motor

Rotor internal cooling

- Used convection cooling by discharging heat occurring in rotor directly to coolant
- Equalize the inner and outer bearing temperature which benefits acoustic and bearing robustness
- Uses non wearing silicon carbide sealing rings to prevent coolant leakage

Stator cooling

- Uses conventional cooling on outer surface of stator core
- Coolant is routed through circulating cooling channels between stator core and housing

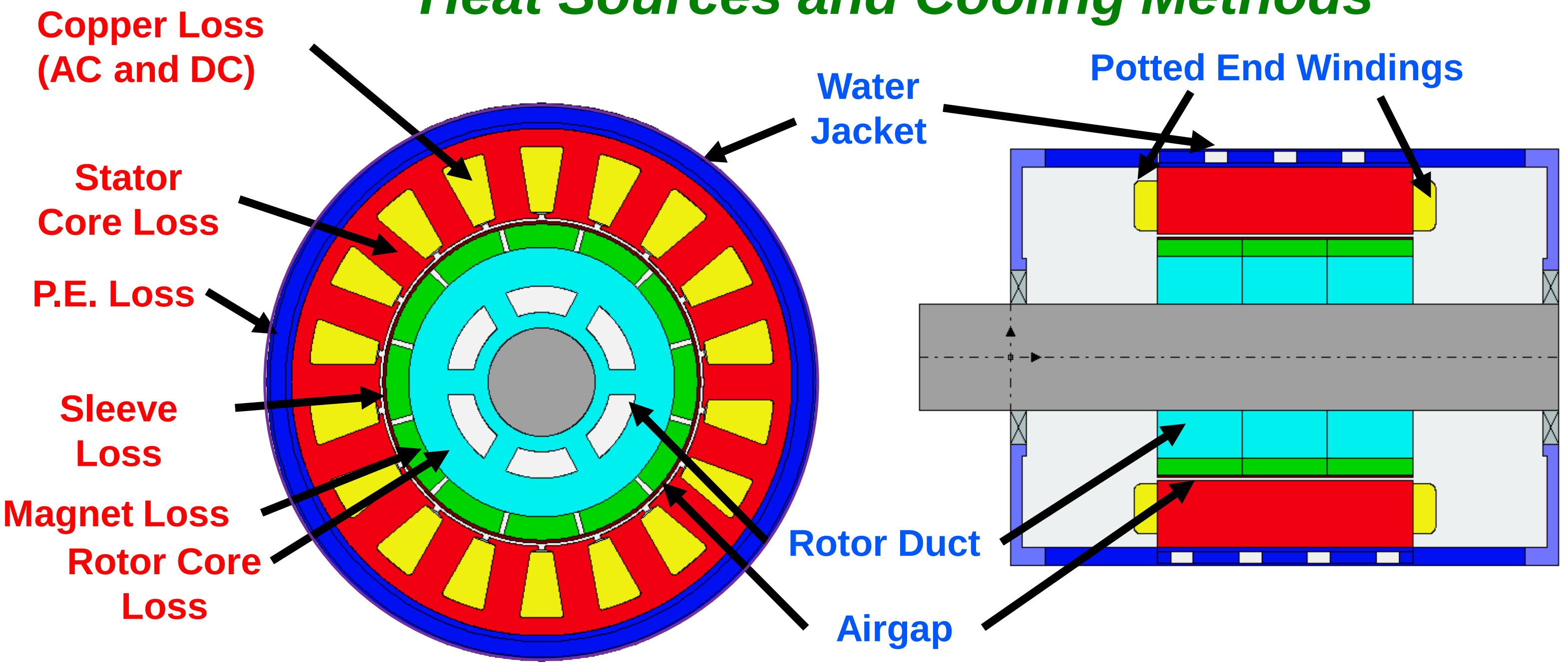
Bearing plate cooling

- Reduce both temperature of rotor bearings and temperature of wall separating machine from gear

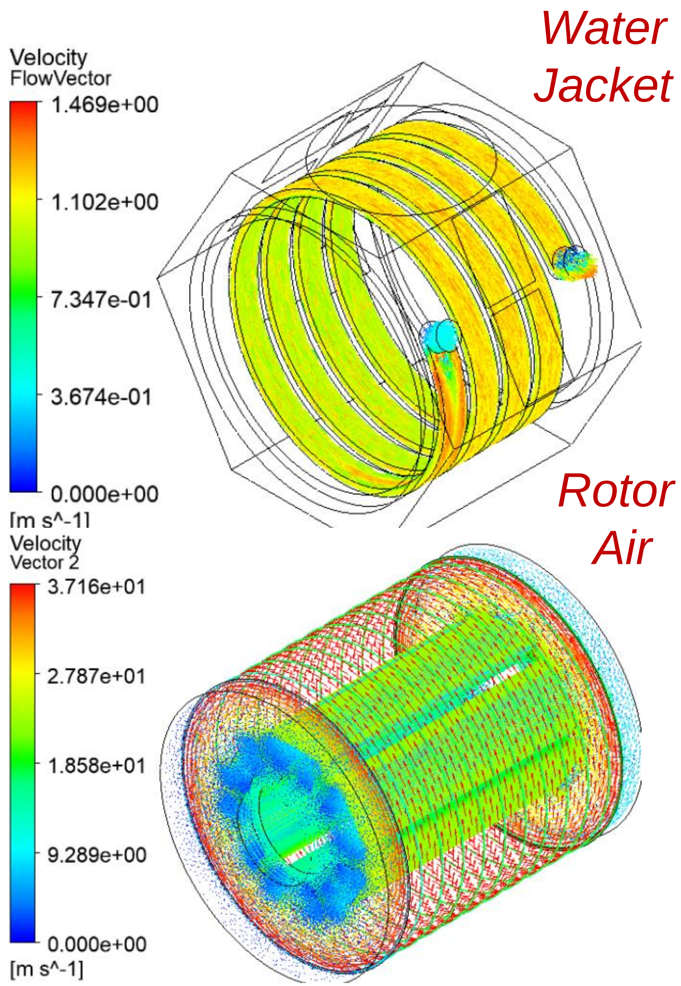
An integrated application of cooling system for both motor and drive in one water loop

Simpler IMD Cooling Approach

Heat Sources and Cooling Methods



Coolant Flow Path



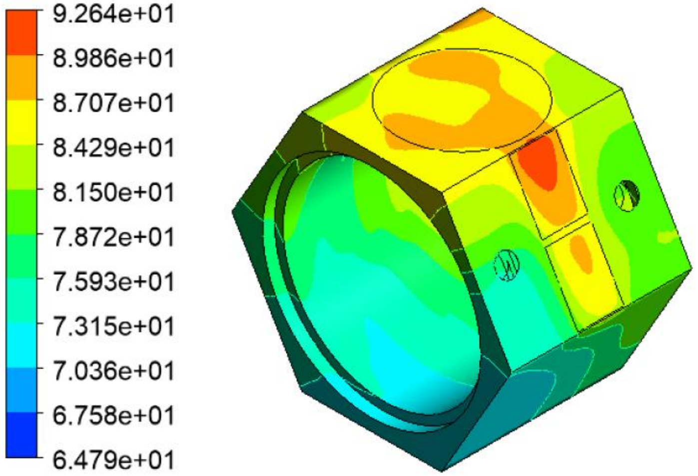
- The integrated cooling system consists of shared water jacket and forced air cooling
  - ➢ Shared water jacket dissipates heat from power electronics and machine stator through conduction
  - ➢ Forced air cooling dissipates heat from machine rotor and stator end winding through convection
- The pressure and flow requirements for both the water and air fall within achievable ranges for cooling the integrated motor drive
  - ➢ Water (6 L/min with 10 psi pressure drop), Air (0.01 m^3/s with 2.1 psi pressure drop)

Ken Chen, Wenda Feng, Feida Chen, Sangwhee Lee, Justin Paddock, Thomas M. Jahns, Bulent Sarlioglu, "Thermal Analysis of Liquid and Air Cooling of High-Power Density Integrated Motor Drives," in *Proc. IEEE Energy Conversion Congress & Expo. (ECCE)*, 2023.

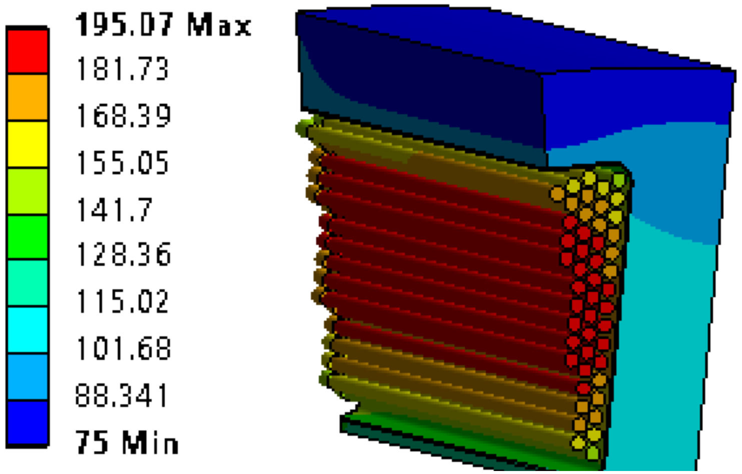
Combination of water jacket and forced air is an effective thermal management configuration for the integrated motor drive

Thermal FEA Simulation at Peak Power (100kW)

Water Jacket

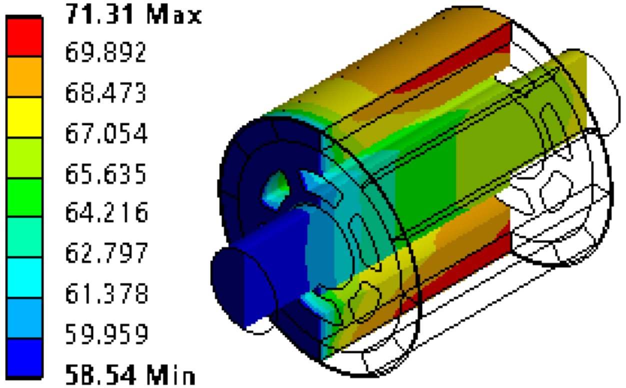


Stator Winding



End windings immersed in thermally-conductive potting material

Rotor



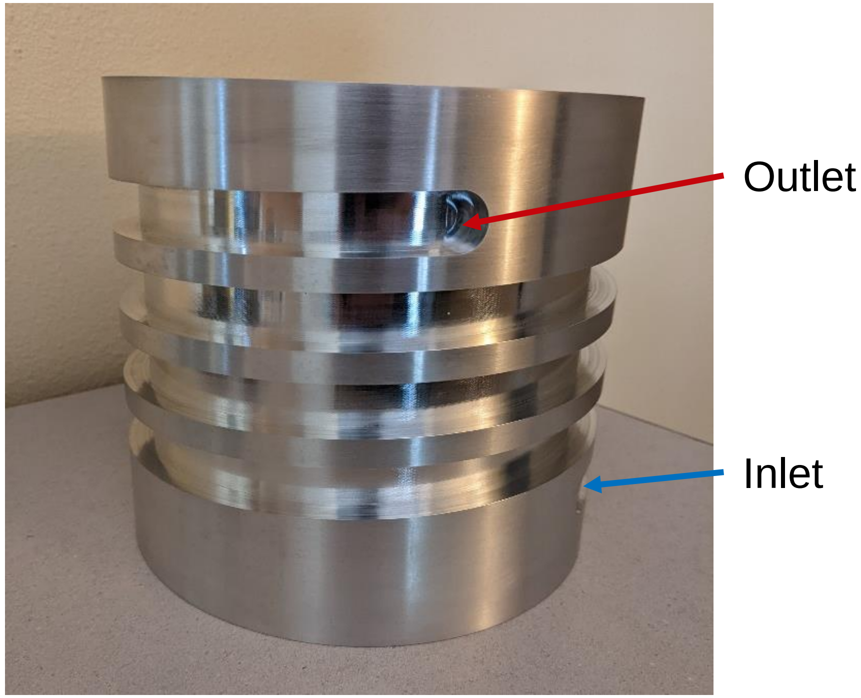
Temperature Distribution				Critical Temp.
Part	55 kW @ 6,667 rpm	55 kW @ 20,000 rpm	100 kW (30s transient) @ 6,667 rpm	
Stator Lam. [◦C]	91.4	104.1	100.4	740
Winding [◦C]	120.3	146.9	195.0	220
End Winding [◦C]	122.3	142.0	175.1	220
Sleeve [◦C]	61.8	71.3	63.5	180
Magnet [◦C]	61.2	70.8	62.9	85

The maximum temperatures reached in all of the key components at 100 kW power are acceptable

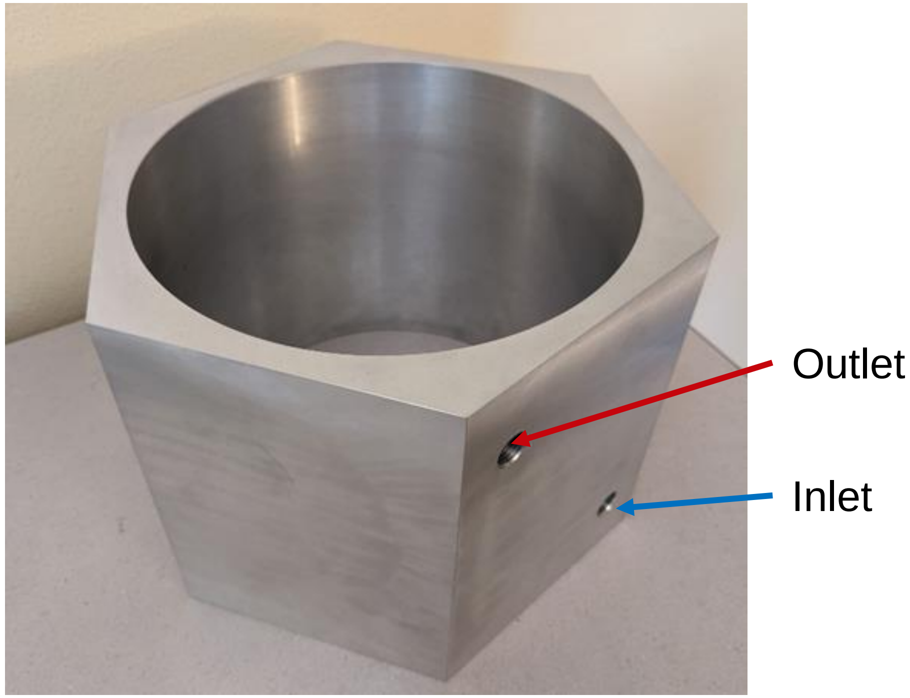
Ken Chen, Wenda Feng, Feida Chen, Sangwhee Lee, Justin Paddock, Thomas M. Jahns, Bulent Sarlioglu, "Thermal Analysis of Liquid and Air Cooling of High-Power Density Integrated Motor Drives," in *Proc. IEEE Energy Conversion Congress & Expo. (ECCE)*, 2023.

Permanent Magnet Machine Fabrication I: IMD Housing

Inner Housing



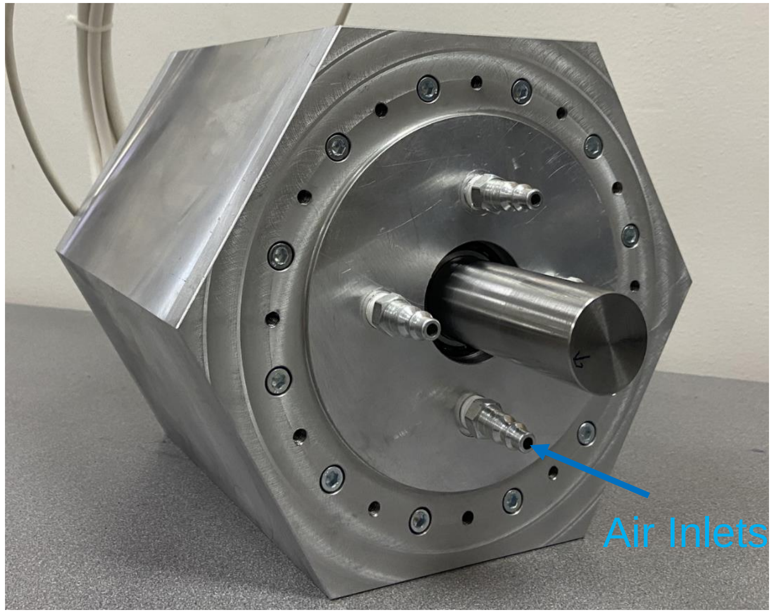
Outer Housing



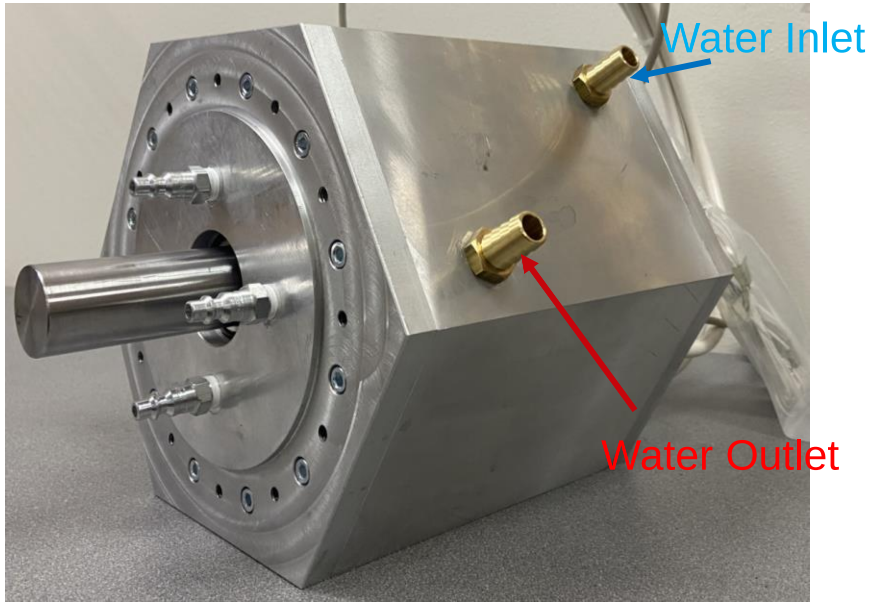
- Water cooling jacket is fabricated with inner housing and outer housing
- O-rings between the two housings (not shown) are used to reduce risk of leakage

Permanent Magnet Machine Fabrication III: Complete Machine and Housing

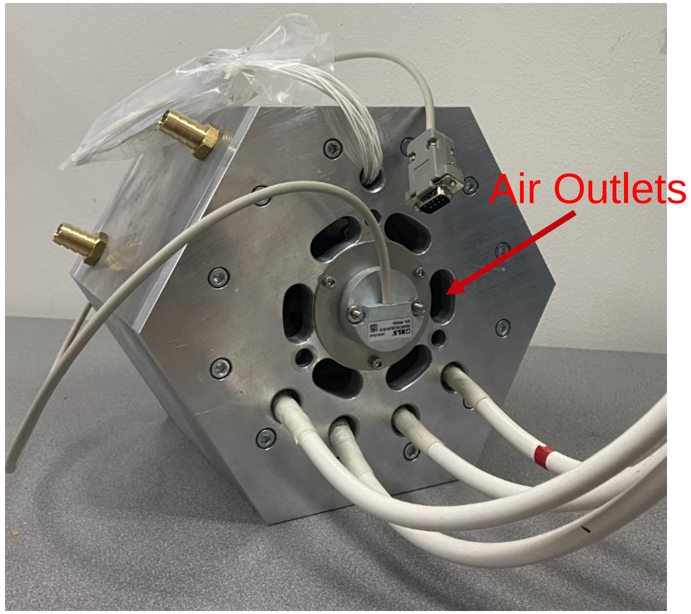
Drive End View showing Air Inlets



Side View showing Water In/Out



Non-Drive End View showing Electrical Leads



Three views highlight key electrical, water, and air interface details

Conclusion

- Efficiency of motor and power electronics is important
  - More range
  - Smaller battery
- No heavy rare earth motor design
  - Sustainable design
  - Cheaper
- Improved thermal design
  - Air cooling of rotor – cheaper and easier
  - Integrated cooling of power electronics and motor

Future Challenges

- Scaling up to ~1 MW motor and drives
  - SUVs and Minivans
  - High-Performance Vehicle
  - Busses
  - Trucks
  - Off-road vehicles

- Fault-tolerant drives
  - What happens if the motor or power electronics break down when driving?
  - Can we design better systems with multiple power drives in a vehicle
- EMI/EMC compliant Design
- Critical Materials considerations

Autonomous 1 MWhr Electric Tractor

John Deere (Europe) prototype/development autonomous electric tractor; 500kW drive system, **<u>1MWhr battery</u>**
Example photos below of ‘office pod’ wireless control center, charging connections
https://www.futurefarming.com/tech-in-focus/autonomous-semi-autosteering-systems/video-john-deere-shows-autonomous-electric-tractor/

Acknowledgements

Thank you
To Our Collaborators: NREL, ORNL, and Ames Lab

AND

DOE Vehicle Technologies Office
Award Number
DE-EE0008704