Integrated Motor and Drive (IMD) for Traction Applications

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Department of Electrical and Computer Engineering
University of Wisconsin-Madison

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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

Electric Machines
Power Electronics
Controls
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
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<td>ABB Drives and Power Products Division</td>
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<td>Aisin Corporation</td>
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<td>Allied Motion</td>
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<td>American Axle &amp; Manufacturing</td>
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<td>ANSYS Inc.</td>
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<td>Arnold Magnetic Technologies</td>
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<td>Woodward Airframe Systems</td>
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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
Permanenent 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

**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:

<table>
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<th>Performance Metric Targets</th>
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<tr>
<td>Metric</td>
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<tr>
<td>Power Density (kW/L)</td>
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<tr>
<td>Cost ($/kW)</td>
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<td>System Peak Power Rating (kW)</td>
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Our project aims to develop advanced IMD technology for achieving major performance improvements at lower cost.
Electric Vehicle Inverter-Motor Evolution

- Power cable elimination and mass reduction by 10%

Nissan Leaf

Shimizu et al, SAE 2013 Congress
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

Output Voltage of VSI

Low-THD sinusoidal voltage and current waveforms

High dv/dt, creating motor insulation stress

Required Performance

- CSI replaces thermally-limited dc-link capacitor (<150°C) in VSI with a compact high-temperature inductor (> 200°C)
- 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

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

VSI

- **Topology**: Cbus
- **DC Link**: Fragile and temperature-limited
- **Output Voltage**: High dv/dt, creating motor insulation stress
- **Common-Mode EMI**: High Common Mode (CM) EMI and bearing current risk

CSI

- **Topology**: Lbus, Cf
- **DC Link**: Rugged and capable of high temperature
- **Output Voltage**: Low-THD sinusoidal voltage and current waveforms
- **Common-Mode EMI**: 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]

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<th>RE</th>
<th>Ce</th>
<th>La</th>
<th>Pr</th>
<th>Nd</th>
<th>Sm</th>
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<tbody>
<tr>
<td>HRE</td>
<td>Eu</td>
<td>Gd</td>
<td>Tb</td>
<td>Dy</td>
<td>Ho</td>
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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

Chevy Volt electrical machine rare earth material usage

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

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*
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).

Combination of water jacket and forced air is an effective thermal management configuration for the integrated motor drive.
The maximum temperatures reached in all of the key components at 100 kW power are acceptable.
Permanent Magnet Machine Fabrication I: IMD Housing

**Inner 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

**Outer Housing**
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, **1MWhr battery**
Example photos below of ‘office pod’ wireless control center, charging connections

Acknowledgements

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AND

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Award Number
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