Integrated Traction Drive Thermal Management

Keystone Project 3

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Overview

Timeline

- Project start date: October 1, 2018
- Project end date: September 30, 2024
- Percent complete: 90%

Budget

- Total project funding: $1,500,000
  - DOE share: $1,500,000
- Funding for FY 2023: $250,000
- Funding for FY 2024: $250,000

Barriers

- Barriers addressed:
  - Cost reduction
  - Power density of a traction drive/system
  - Reliability and lifetime.

Partners

- Interactions/collaborators
  - Oak Ridge National Laboratory (ORNL)
  - Ames Laboratory
  - University of Wisconsin-Madison
  - Georgia Institute of Technology (Georgia Tech)
- Project lead
  - National Renewable Energy Laboratory (NREL)

Relevance

Objectives:

- Research and evaluate motor-integrated power electronics packaging technologies and thermal management approaches.
- Develop a thermal management system and its subcomponents to enable integrated electric-drive DOE power density targets in collaboration with project partners.
- Explore novel materials and manufacturing options (3D printing with thermally enhanced polymers or ceramic materials) for key thermal management system components.
- Support activities of DOE's Electric Drive Technologies (EDT) consortium members' research teams in thermal management component design and thermal modeling of integrated traction drives.

Project Impact:

- Identify pathways enabling high-performance, compact, and reliable integrated electric drives.
- Help achieve DOE 2025 target of 33-kW/L system power density for an electric traction drive.

FY 2024 Milestones

Milestone Description	Criteria	End Date	Status
Evaluate performance of in-slot heat exchanger and cylindrical inverter housing for the outer-rotor electric drive using modeling, and if needed, select experimentation.	Modeling results must show that heat removal performance meets thermal loads of inverter power modules and the electric motor at the rated design power output.	06/30/2024	On Track

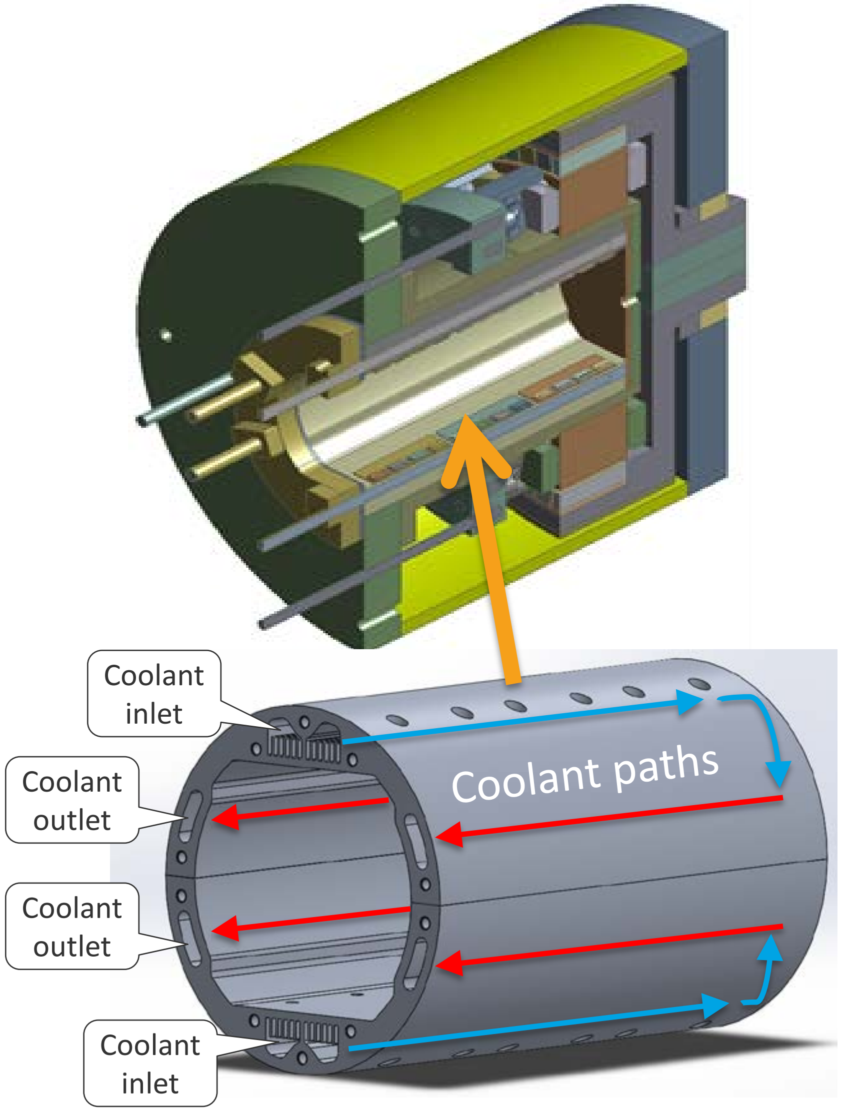
Approach

- Evaluate various cooling strategies for most efficient heat removal from integrated traction drive components:
  - Water-ethylene glycol flow in internal channels.
  - Automatic transmission fluid spraying and jet impingement on stator winding end-turns.
  - High-thermal-conductivity (low-thermal-resistance) component assemblies.
  - Direct cooling with dielectric fluids.
  - Preferably use a single fluid loop approach to enable a combined cooling system for electric motor and inverter cooling and increase overall system power density.
- Select appropriate materials for the cooling system components (i.e., heat exchangers for ORNL drive):
  - Transparent for electromagnetic field to minimize interference with electric motor operation.
  - Electrically isolating to avoid short-circuiting electrically sensitive parts.
  - Thermally conductive to improve heat removal from heat-generating components.
- Support design of a thermal management solution appropriate to each collaborating team’s selected integrated drive concept:
  - Design, model, and test thermal management system components to reduce thermal resistance of the motor and power electronics packaging stack-up to keep component temperatures within selected material operating temperature limits.
  - Employ thermal modeling tools: finite element analysis (FEA) and computational fluid dynamics (CFD) to inform efficient design solutions.

Technical Accomplishments and Progress

ORNL integrated traction drive

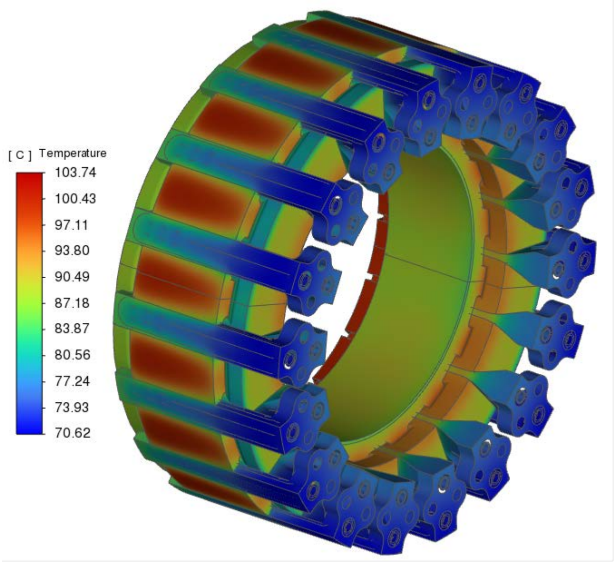
- Features redesigned by ORNL concept with cantilever outer-rotor suspension.
- Designed the **cylindrical housing for power electronics** integration into central cavity of the electric motor:
  - Inverter housing concept is based on two half-cylinders forming a cylindrical heat sink with internal channels in the walls.
  - Coolant flowing in these channels removes heat from the power electronics and the stator's internal surface.
  - Split-cylinder design simplifies 6-phase inverter integration/attachment to the heat sink.
  - The housing is currently being manufactured from aluminum.



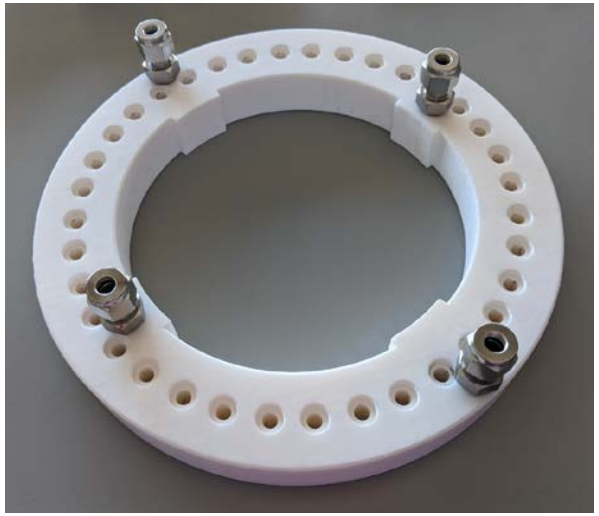
Design concept of a cylindrical housing for a six-phase inverter with cooling fluid channels in its walls. Figure by Bidzina Kekelia, NREL, and Jon Wilkins, ORNL

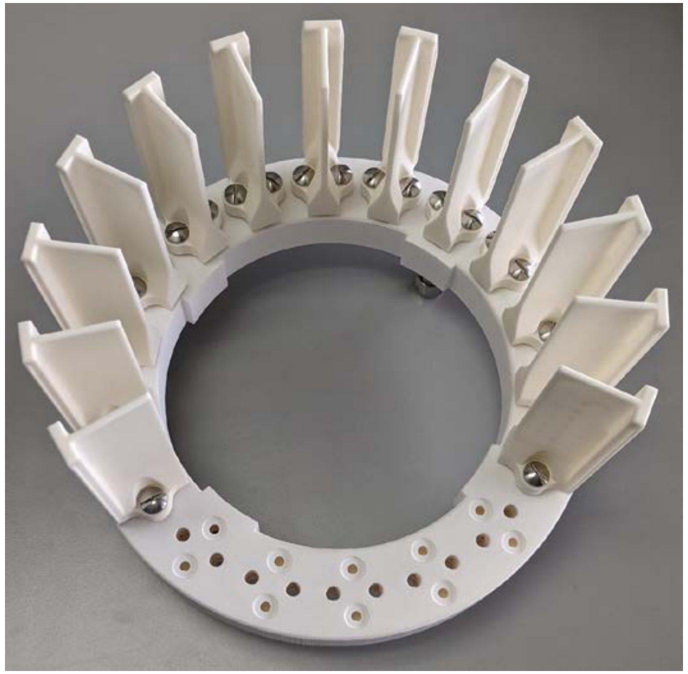
ORNL integrated traction drive (continued)

- Designed and manufactured **T-shape in-slot heat exchangers** (3D-printed from aluminum-oxide Al_2O_3) to be embedded between stator windings.
- Designed and manufactured **coolant distribution manifold disk** (3D-printed from Rigid 10K resin).

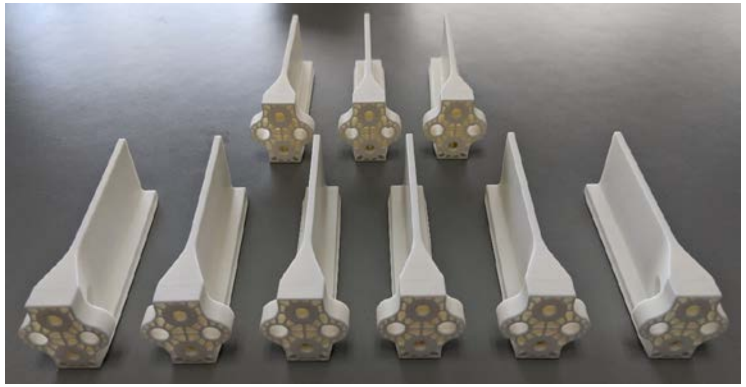


Conjugate heat transfer modeling results for 58-kW, 6,666-rpm steady-state conditions and 5-L/min coolant flow rate in the stator heat exchangers. Figure by Rajneesh Chaudhary, NREL





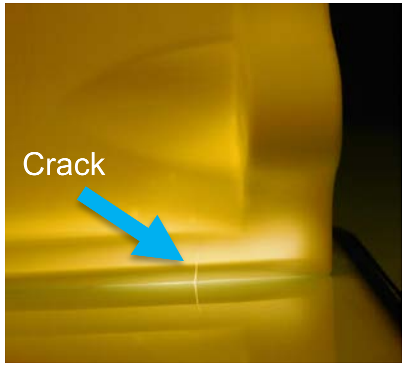
Coolant distribution manifold with inlet-outlet fittings (back) and attached T-shape in-slot heat exchangers (front). Photos by Bidzina Kekelia, NREL



T-shape in-slot heat exchangers 3D-printed by Lithoz. Photo by Bidzina Kekelia, NREL

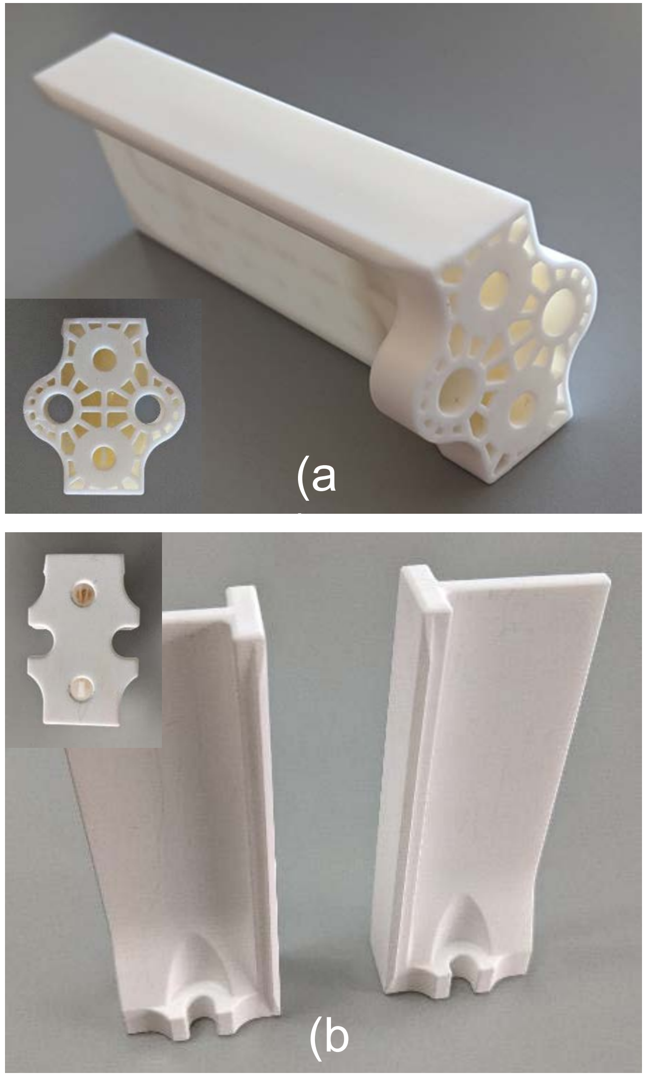
ORNL integrated traction drive (continued)

- Challenges encountered during 3D-printing ceramic heat exchangers:
  - Cracking during thermal post-processing due to uneven (transient) sintering/hardening and shrinkage of material with different wall thicknesses.
  - Areas with bulk material (manifold attachment area) were hollowed out, leaving interconnections with uniform wall thicknesses to remedy the cracking.



Crack in 3D printed ceramic in-slot heat exchanger. Photo by Lithoz

T-shape in-slot heat exchanger 3D-printed from Rigid 10K resin at NREL. Photo by Bidzina Kekelia, NREL

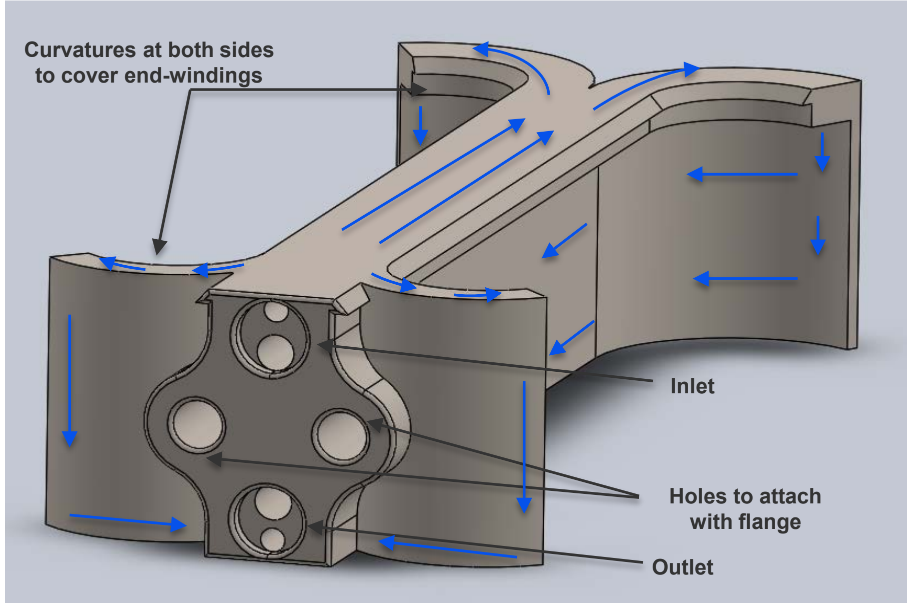


T-shape in-slot heat exchangers 3D-printed by (a) Lithoz and (b) Kyocera. Photos by Bidzina Kekelia, NREL

Technical Accomplishments and Progress

Georgia Tech

- A concept for motor winding cooling has been co-developed by NREL and Georgia Tech, aiming to directly cool both sides of the motor's end-windings.
- Besides significantly reducing the temperature of end-windings, this cooling approach is anticipated to yield a similar temperature distribution on both sides of the end-winding, thereby preventing any likely occurrence of substantial temperature gradients.
- The concept can be adapted for integration into existing electric motor designs.



Proposed geometry of the heat exchanger for motor winding cooling (including end-turns). Image by Georgia Tech

University of Wisconsin

- NREL is continuing to provide support to the University of Wisconsin's integrated traction drive team:
  - Evaluating the thermal testing data of the manufactured drive.
  - Reviewing team's presentations (publications) related to thermal management system of the drive.

Collaboration and Coordination

- Collaborating with ORNL’s integrated drive team through regular meetings and exchange of design data, thermal modeling results, and relevant information. Co-designing and manufacturing key thermal management system components and assemblies for ORNL’s outer-rotor traction drive.
- Supporting University of Wisconsin’s integrated drive team through regular meetings, providing technical advice on design, thermal modeling, and component material data. Discussions and technical exchanges are held between ORNL, University of Wisconsin, Ames Lab, and NREL researchers.
- Supporting Georgia Tech team through regular meetings, providing technical advice on design, thermal modeling, and component material data.

Remaining Challenges and Barriers

- Material selection for key thermal management system components and their interconnection is critical for the design of an effective and reliable cooling system:
  - Transparent for electromagnetic field to minimize interference with electric motor operation.
  - Electrically isolating to avoid short-circuiting electrically sensitive parts.
  - Thermally conductive to improve heat removal from heat-generating components of the drive.
- Coefficient of thermal expansion mismatch between components of cooling system poses a problem when electric-drive components undergo thermal cycling.
- Leak-free sealing of cooling system components inside electric machine cavity is challenging.
- Design of a single thermal management system for power electronics and electric motor would require cooling fluids with appropriate physical, thermal, and dielectric properties.

Proposed Future Research

Planned for FY 2024

- Finalize assembly of the coolant manifold disk and in-slot heat exchangers and leak-test it for final integration into the stator of ORNL's outer-rotor drive.
- Explore 3D printing of T-shape in-slot heat exchangers with thermally enhanced (with boron nitride) resin and experimentally evaluate their thermal resistance. In case of comparable performance to ceramic heat exchangers, this would provide a pathway to manufacturing cheaper and lighter integrated heat exchangers.
- Assist ORNL in finalizing the design and manufacturing of the cylindrical inverter housing for integration in the outer-rotor drive. Improve coolant inlet/outlets through optimization of channel routing in heat sink cap.

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

Summary

Relevance

- Effective thermal management is essential for high-performance, compact (power-dense), and reliable integrated electric traction drives to achieve the 2025 DOE system power density target of 33 kW/L.

Approach

- Use combination of various cooling strategies for most efficient heat removal from integrated traction drive components.
- Support design of a thermal management solution appropriate to collaborating EDT consortium member (ORNL, University of Wisconsin, and Georgia Tech) team's concepts.
- Select appropriate materials and explore alternative/novel combinations for the cooling system components (i.e., heat exchangers for ORNL drive).

Technical Accomplishments

- ORNL integrated traction drive:
  - Cylindrical inverter housing: completed several design revisions; the latest one is currently being manufactured by ORNL.
  - T-shape in-slot heat exchangers embedded between windings: completed several design and manufacturing iterations. The final batch of 3D-printed ceramic heat exchangers is expected to be delivered mid-April 2024.
  - Coolant distribution manifold-disk: completed several design revisions and was 3D-printed from high-temperature resin at NREL. Leak testing of the assembly is pending.
- University of Wisconsin integrated traction drive:
  - Supporting evaluation of the thermal test data of the manufactured/assembled integrated drive.
- Georgia Tech:
  - Supporting design concept of in-slot heat exchanger, which includes coverage of end-turn windings.
- Publications:
  - Abstract for a technical paper on thermal management system of ORNL's outer-rotor drive has been accepted by 2024 ASME InterPACK conference.

Collaborations

- Collaborating with ORNL's integrated drive team through regular meetings and exchange of design data and thermal modeling results.
- Supporting University of Wisconsin's integrated drive team. Discussions and technical exchanges are held between University of Wisconsin, ORNL, Ames Lab, and NREL researchers.
- Collaborating with Georgia Tech team on their concept of in-slot heat exchanger, which includes winding end-turn coverage.

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Thank You

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Publications and Presentations

Publications

- Bidzina Kekelia, J. Emily Cousineau, Rajneesh Chaudhary, Jeff Tomerlin, Sreekant Narumanchi, Vandana Rallabandi, Jon Wilkins, Shajjad Chowdhury, Himel Barua, Mostak Mohammad, and Burak Ozpineci. 2024. “Thermal management system of outer-rotor traction drive with integrated power electronics in its central cavity.” *Proceedings of the ASME 2024 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems*. San Jose, CA, 8–10 Oct. 2024 (abstract accepted).

Presentations

- Bidzina Kekelia and Xuhui Feng. 2023. “Tutorial: Electric Motor and Integrated Traction Drive Thermal Management.” Presented at the ASME 2023 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK 2023), San Diego, CA, 26 Oct. 2023.