Advanced thermal management design boosts performance of silicon carbide inverters for heavy-duty vehicles

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Kevin Bennion, senior researcher and task leader on the silicon carbide inverter project, evaluates experimental thermal management technologies for electric drives. Credit: Dennis Schroeder, NREL

As electric vehicles (EVs) grow in popularity, innovative technologies must meet the rising energy demand by significantly increasing system efficiency. Although light-duty EVs have been the focus for many electrification initiatives, heavy-duty trucks make up 39% of greenhouse gas emissions in the transportation sector.

Electrification of heavy-duty EVs is integral to decarbonization efforts, but vehicle components must be designed to handle more power while continuing to regulate operating temperatures.

A state-of-the-art thermal management system developed by the National Renewable Energy Laboratory (NREL) in collaboration with John Deere promises to significantly increase the power density of silicon carbide (SiC) inverters within heavy-duty EV applications. Within heavy-duty applications, the power inverter is responsible for controlling the power flow between DC and AC electrical systems in order to run vehicle systems, accessories, and electric machines, such as motors and generators. A high-efficiency inverter is a critical component necessary for environmentally friendly vehicle alternatives that reduce greenhouse gas emissions such as hybrid, full electric, or fuel cell vehicles. Recent studies indicate that the improved inverter design boasts a 378% increase in power density over the previous silicon-only inverters.

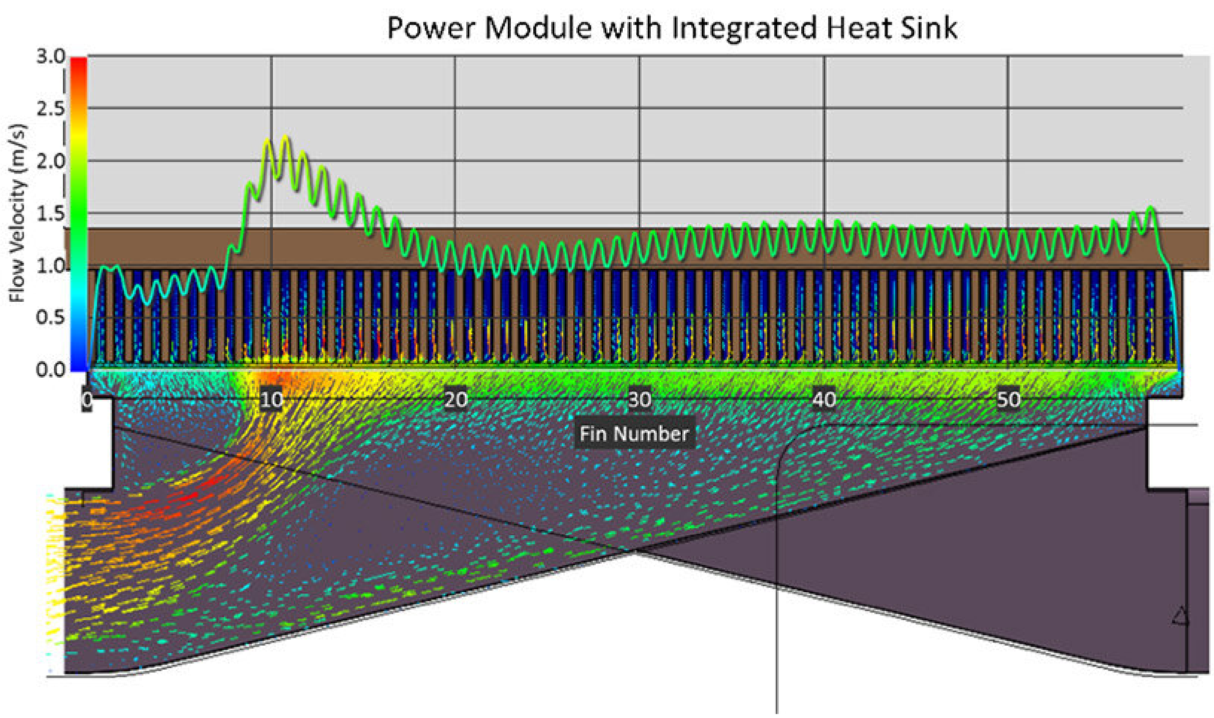
"The key to NREL's design innovations for SiC thermal management is to improve the heat transfer coefficient, which allows this system to cool itself efficiently and continuously during operation with the engine coolant," said Kevin Bennion, NREL senior researcher and thermal management expert. "This design facilitates an unmatched power density and keeps the system running safely and efficiently."

The SiC inverter thermal management system was tested in John Deere hybrid loaders, similar to the one pictured. Credit: John Deere

In general, heavy-duty vehicles demand more power and far higher torque during operation than the average light-duty sedan. NREL's leading research in wide-bandgap power module thermal management helped reduce component footprint, improve performance and efficiency, and support higher-frequency operation of SiC inverters for heavy-duty applications.

However, power outputs rely on the maximum temperature limits of the inverter's power module, which runs the risk of overheating and shutting down. As a result, NREL researchers developed a state-of-the-art thermal management system to optimize system efficiency while regulating operating temperatures of the SiC modules directly cooled with 115°C water-ethylene glycol coolant. The technology developed by the NREL team has been extensively evaluated by the John Deere engineering team led by Dr. Brij Singh.

"Starting in 2015, NREL's contributions have been extremely valuable in the successful execution and completion of impactful tasks in the DOE-funded PowerAmerica project with John Deere," Dr. Singh said. "This project has resulted in the in-vehicle demonstration of the high-temperature SiC inverter technology."



NREL's integrated thermal management system incorporates perpendicular jet flow to extract heat from the system. Credit: Emily Cousineau, NREL

A simplified solution to optimize heat transfer

A common strategy for the thermal management of EV inverters is to run a fluid coolant parallel over the component's surface to transfer heat and cool the system quickly. The advanced system designed at NREL incorporates perpendicular jet flow with mini-channel- and mini-manifold-based cooling systems to extract heat from the inverter and power module. This design enables an impressive heat-transfer coefficient—as high as 93,000 watts per square meter per degree Kelvin (W/[m^2-K]) which is over four times higher than current commercial systems.

In addition, the NREL design uses the existing diesel engine cooling system for a simplified engine-coolant-capable architecture. Conventional heavy-duty inverters require a separate coolant system to operate successfully while ensuring the inverters' durability. By eliminating the need for a separate cooling circuit, NREL's novel thermal and thermomechanical research contributed to the inverter achieving a staggering 43 kilowatts per liter power density. This is a 378% improvement over baseline silicon systems.

Real-world improvements in fuel efficiency

The thermal and mechanical innovations in the SiC design significantly reduced the inverter footprint, creating a smaller and lighter system. The lighter overall weight and improved performance have clear benefits to fuel efficiency and operating costs.

"The SiC inverter technology stands out among all competing technologies in terms of energy efficiency, fuel economy, performance, and system integration," Bennion said. "With the premium cost of the SiC power converter, the market adoption of this new technology will likely take place where those factors are more important than the initial cost. We believe this inverter will have significant impacts in heavy-duty machinery, aviation, and military applications."

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