Navigating the Thermal Frontier

Allegro's Role in Next-Generation Data Center Cooling

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Introduction

The rapid expansion of artificial intelligence (AI) and high-performance computing (HPC) is creating an urgent and critical challenge for modern data centers: unprecedented power densities that push traditional cooling systems beyond their limits. As the heat generated by next-generation processors escalates, thermal management has shifted from a secondary concern to a primary limiting factor for performance, scalability, and efficiency. This paper explores why the future of large-scale computing now depends on pioneering new cooling technologies and how innovative motor control solutions are essential to addressing this power-density problem.

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The AI Power-Density Problem

When Thermal Management Becomes the Limiting Factor for Data Center Performance and Scalability

The explosive growth of artificial intelligence (AI), machine learning (ML), and high-performance computing (HPC) is driving unprecedented power densities within modern data centers, presenting significant thermal management challenges. This surge in computational demand has led to significant thermal management challenges. As GPU and CPU power consumption escalates, with single chips dissipating up to 1-2 kilowatts, traditional cooling methodologies are being pushed to their limits. The challenge of effectively removing this heat has become one of the defining engineering problems in today's infrastructure.

As workloads intensify, thermal design is no longer a background consideration but a primary factor in data center architecture. The ability to maintain temperature stability directly determines system performance, energy efficiency, and operational cost. In large-scale deployments, even small gains in thermal performance can have considerable economic and environmental impacts. The industry has reached a critical inflection point: the future scalability of AI and HPC workloads depends on innovative new approaches to cooling.

The Cooling Conundrum: Air, Hybrid, or Liquid systems?

Data centers historically relied on air cooling as the primary method for thermal management. Fans, heat sinks, and optimized airflow patterns have kept server rooms running efficiently and economically. This method's lower maintenance requirements and mature ecosystem have made it the default choice for most computing infrastructure. However, the equation has changed. As chip power densities surge, the amount of heat that must be dissipated per unit of rack space has grown dramatically. Air simply cannot transfer heat fast enough to maintain acceptable operating temperatures in these high-density environments without consuming excessive power or requiring impractically large air-handling systems. This is due to air's inherent properties of having lower heat capacity and higher thermal resistance in comparison to liquid cooling. Furthermore, the significant amount of valuable floor space consumed by air cooling methods like alternating hot and cold aisles is a major drawback for AI data centers. This can directly limit the number of server racks that can be deployed, capping the facility's total computing power and hindering their ability to scale efficiently.

The emerging trend toward liquid cooling technologies is gaining momentum. Liquids have a much higher specific heat capacity than air, allowing them to carry significantly more thermal energy within the same volume. This superior heat transfer capability enables liquid cooling to manage the thermal output of next-generation processors more effectively, improving both system performance and energy efficiency. The transition, however, comes with its challenges. Engineers must design systems that prevent coolant leaks, ensure long-term pump reliability, and integrate fluid delivery networks into existing rack architectures.

To mitigate these challenges, hybrid cooling solutions are emerging which blend the best aspects of both approaches. In-Row Heat Exchanger (IRHX) systems, for example, incorporate self-contained units with pumps and fan coils that circulate coolant through cold plates mounted directly on processors. This approach enables targeted liquid cooling with minimal changes to the facility's infrastructure. It comprises a water distribution cabinet, a pumping unit, and fan coils. In this system, cool liquid is circulated to the servers, distributed through a cold plate (often a co-innovation between hardware providers), and then the warmed liquid is returned to the In-Row Heat Exchanger to be cooled by fans before recirculation.

Another hybrid cooling method is the Rear Door Heat Exchanger (RDHX), shown in Figure 1, which is an advanced thermal management solution that operates as a liquid-to-air cooling system. Integrated into the rear door of a server rack, the RDHX draws in hot air from the servers and passes it over coils containing a cool circulating liquid.

The heat from the air is transferred to the liquid, and the now-cooled air is returned to the data center aisle, neutralizing heat directly at the rack level.

Direct-to-chip cooling, shown in Figure 1, is an emerging architecture in which coolant flows directly through a plate mounted on the chip. This approach provides exceptional thermal transfer efficiency, making it ideal for the most demanding workloads.

In contrast, immersion cooling involves submerging servers or networking equipment directly into a non-conductive dielectric fluid. Figure 2 illustrates the Allegro motor driver sockets for this cooling method. In single-phase immersion cooling, the fluid is continuously circulated to a heat exchanger to remove absorbed heat. Dual-phase immersion cooling, on the other hand, uses a low boiling point fluid, where the highly efficient process of boiling and condensation transfers heat from components to a cooled surface.

Both approaches rely on precise motor control for pumps and fans, which must operate reliably under varying loads and conditions. Allegro Microsystem's plays a critical role in enabling these solutions, supporting the evolving needs of modern data center ecosystems.

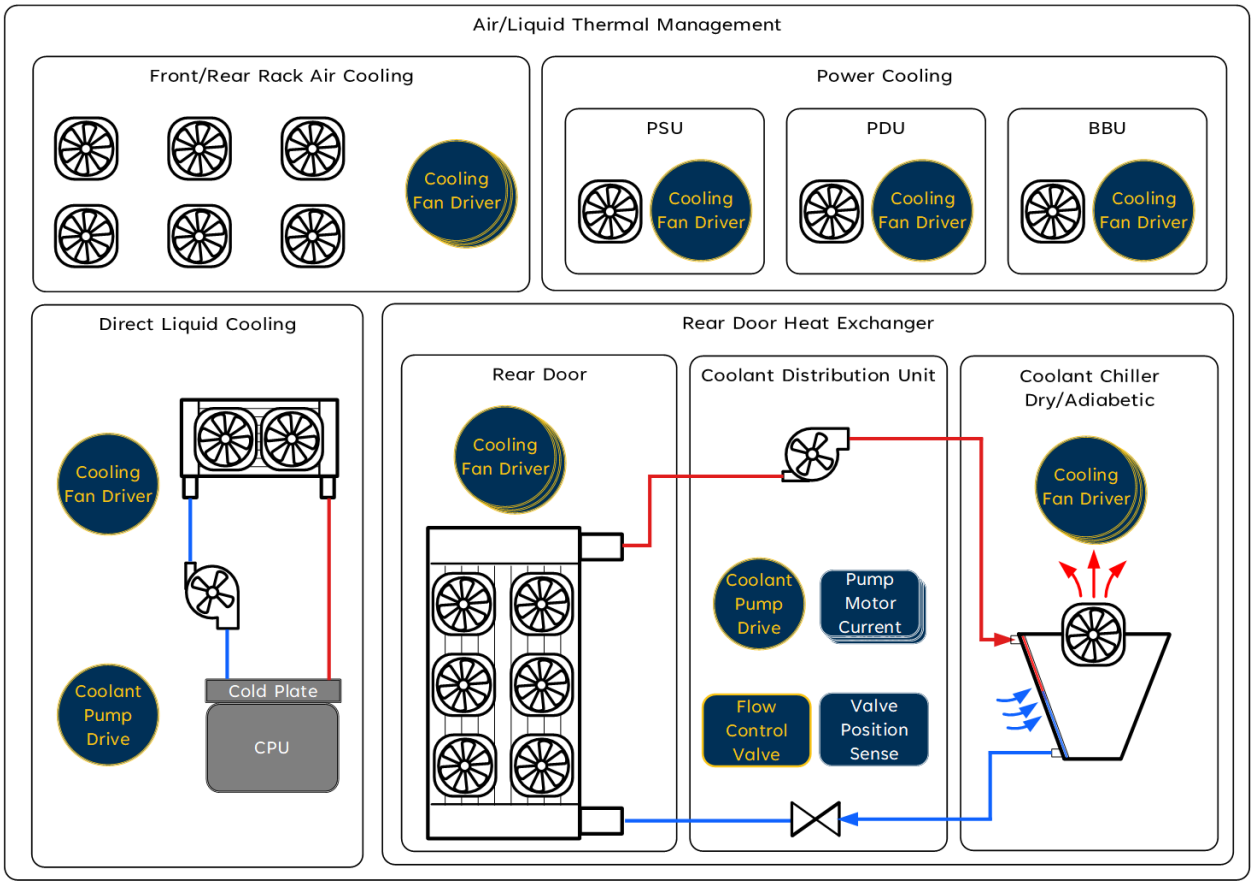


Figure 1: Thermal Management Block Diagram Showing Power-Level Cooling and Rear Door Heat Exchanger

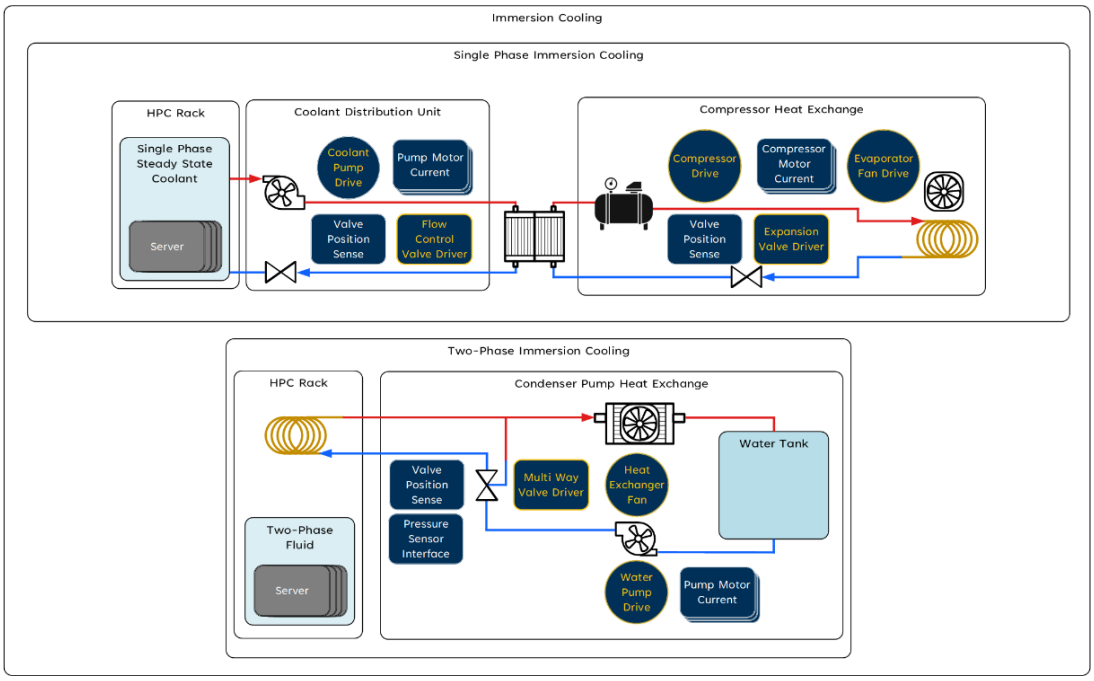


Figure 2: Block Diagrams of Allegro Motor Drive Solutions in Immersion Cooling

Allegro's Role in Thermal Innovation

Allegro MicroSystems stands at the intersection of power electronics, motion control, and thermal management. Allegro's robust portfolio of advanced motor driver technologies enables engineers to design the next generation of data center cooling systems in air, liquid, or hybrid configurations with higher efficiency, greater reliability, and simplified implementation. These motor drivers are optimized for both fans and pumps are built to handle the diverse operating conditions found in high-performance computing environments.

A central element of Allegro's technology lies in its implementation of Field-Oriented Control (FOC). FOC is an advanced method of controlling brushless DC (BLDC) motors that optimizes torque generation by continuously aligning the magnetic field vector of the motor with its rotor position. This is accomplished through Clarke and Park transforms, which convert the complex 3-phase AC currents into a simple DC reference frame, allowing for precise, independent control of the motor's torque and flux. FOC offers superior efficient motor commutation as well as quieter operation in comparison to sinusoidal and trapezoidal commutation. This is further enhanced through precise motor-driver pairing, where Allegro's advanced drivers are tuned to the specific parameters of a user's high-efficiency motor, such as one with more winding turns, to optimize the current control for the most efficient operation possible. In hyperscale data centers, where thousands of motors operate to manage heat, even small efficiency gains can accumulate rapidly. A seemingly modest one percent improvement in fan or pump efficiency can result in significant annual energy savings across an entire facility.

FOC commutation can also significantly reduce torque ripples, acoustic noise, and mechanical vibration, which are imperative considerations where quiet and stable operation are essential. The waveform is exemplified by Figure 3. The result is a cooling system that not only runs more efficiently but also operates with greater precision and stability, enhancing overall reliability.

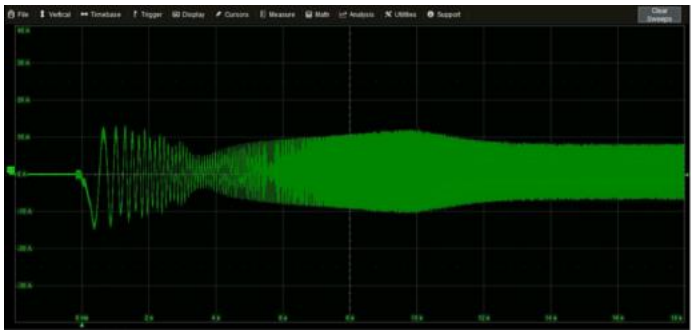
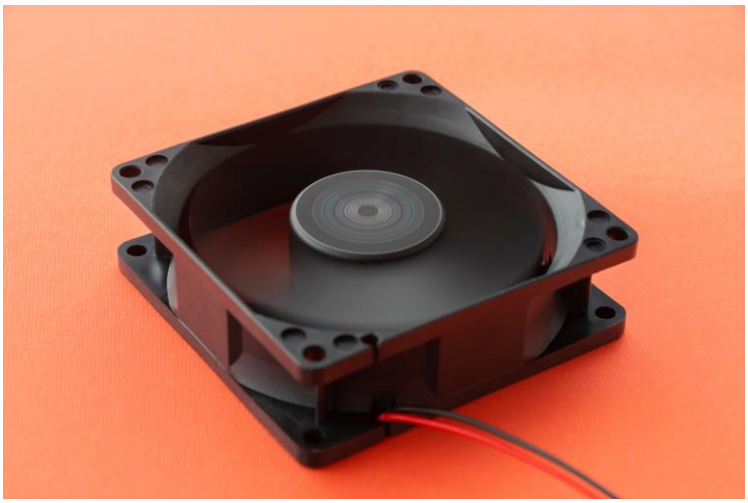


Figure 3: Waveform illustrating Field Oriented Control Commutation

Simplifying Design and Accelerating Development

As thermal management architecture becomes increasingly complex, ease of design has emerged as a key differentiator for engineers tasked with scaling new data center deployments. Allegro's highly integrated "code-free" motor driver architecture streamlines sophisticated motor control without requiring extensive firmware development, as illustrated in Figure 4. Products such as the A5931/32 and A89331/89332 integrate speed loop control and EEPROM storage for configuration data, enabling designers to fine-tune system behavior through simple logic-level interfaces. In addition, these devices utilize sinusoidal commutation. Sinusoidal commutation is best optimized for low audible noise, higher efficiency, and lower torque ripple in comparison to trapezoidal commutation. This is illustrated by the waveform shown in Figure 5. These devices feature I^2C communication shared with motor control pins (FG and PWM), allowing for in-circuit motor configuration and control data updates.



Allegro's portfolio of highly integrated motor drivers translates to fewer external components, simplifying board layout and reducing the overall footprint—an especially valuable attribute in space-constrained server and pump modules. These devices are available in compact QFN packages, making them ideal for dense rack environments where every millimeter of space counts.

A prime example of Allegro's expertise in integration and reliability is the A89333 motor driver. This motor driver is designed for 48-volt systems and is robust enough to withstand transients up to 90 volts while incorporating a fully integrated single-shunt FOC controller and onboard buck regulator. These features reduce system level cost and board complexity while improving robustness under demanding operating conditions. Functions such as windmill startup and nonreverse fast startup ensure continuous cooling during power fluctuations or rare restart events. These features are vital for mission-critical data center applications.

Allegro's A89332 driver is well-suited for powering pumps in single and two-phase immersion cooling, as it offers engineers significant design flexibility by supporting two distinct commutation methods. It features sinusoidal modulation, which minimizes torque ripple for quiet, smooth, and highly efficient operation. For applications requiring maximum power, it also offers a trapezoidal drive option, which provides the high starting torque needed to overcome fluid inertia and enables maximum motor speed for the highest possible coolant flow rates. The comparative waveforms are shown in Figure 5 demonstrating lower torque ripple and higher efficiency for sinusoidal drive.

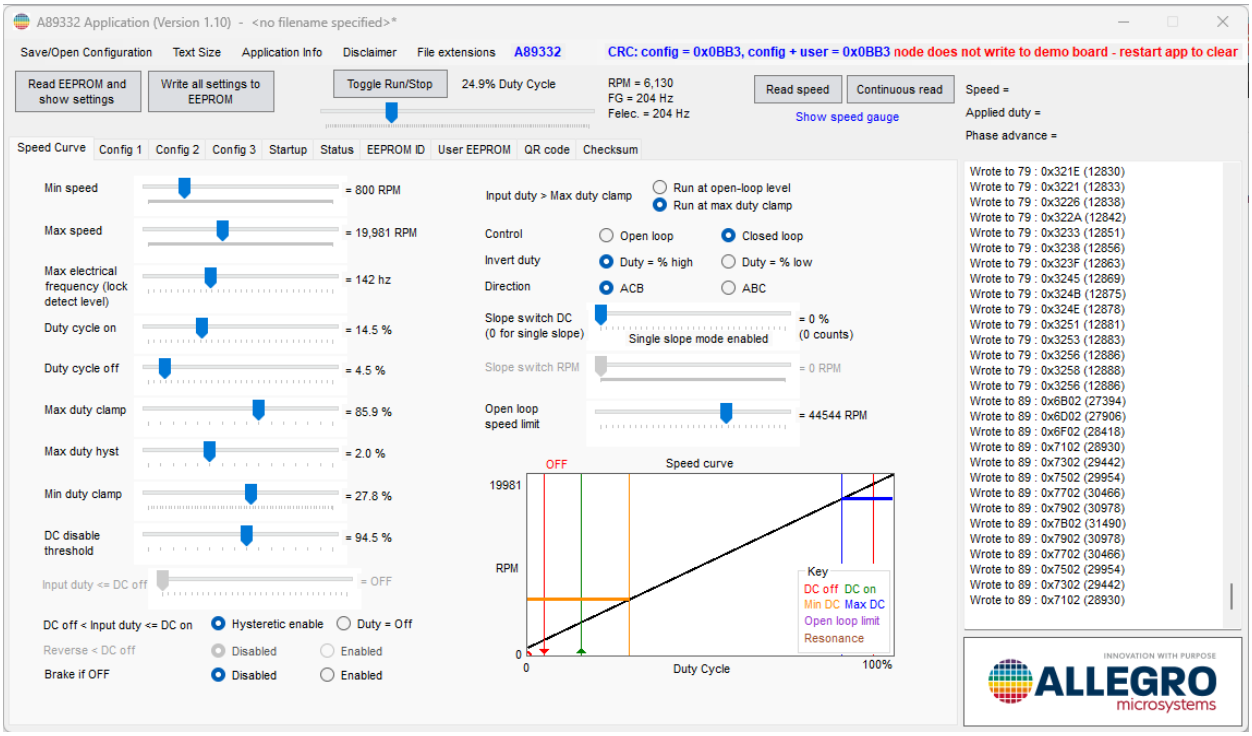


Figure 4: Graphical User Interface for A89332 Motor Driver

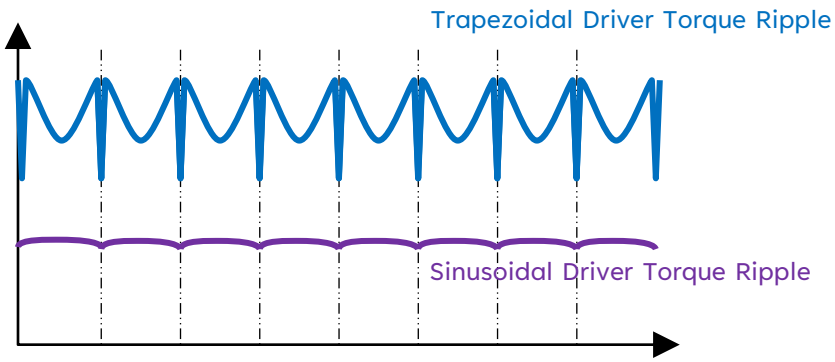


Figure 5: Comparison of Torque Ripple Waveforms for Trapezoidal and Sinusoidal Commutation

Robust Integrated Protections

Reliability is the cornerstone of any data center operation, where unplanned downtime can have immediate and costly consequences in real world applications. Allegro's motor driver portfolio entails protection features to ensure continuous, safe operation under a wide range of conditions. Safeguards such as over-current (OCP), over-temperature (OTP), and over-voltage protection (OVP) prevent system damage caused by electrical or thermal stress.

Beyond these protection features, Allegro's drivers incorporate advanced diagnostic and response features that support predictive maintenance and enhance system resilience. For example, power-loss brake functions prevent reverse fan rotation during faults, maintaining proper airflow and minimizing wasted energy. In addition, stall detection enhances system reliability by monitoring key parameters, including back EMF and frequency estimates, to identify stalled motors and enable protective actions that prevent damage. These intelligent protection mechanisms not only extend component lifespan but also improve the thermal and energy efficiency of the data center.

The robustness of these features reflects Allegro's deep expertise in mission-critical applications. Many of these design philosophies are derived from the company's long-standing leadership in the automotive and industrial sectors, where safety, reliability, and durability are paramount. By applying the same design rigor to the data center domain, Allegro ensures its products meet the highest standards for uptime and operational continuity.

48V Revolution and Compact Integration

As the data center industry shifts toward 48-volt power architectures, the demand for compact and scalable electronic components has grown. Higher-voltage operation reduces current flow and allows for smaller conductor sizes, lowering resistive losses and improving overall energy efficiency. Allegro's expertise in developing automotive-grade 48-volt motor control solutions positions the company strongly in this emerging space.

Allegro's motor drivers are engineered to operate efficiently in both 12-volt and 48-volt systems, providing flexibility across various cooling platforms and configurations. Their compact QFN packages deliver high power density without compromising thermal performance, making them ideal for integration into confined pump assemblies or server fans.

Enabling the Future of Efficient Datacenters

Thermal management has become one of the most critical and complex challenges in modern data center design. The rapid growth of AI and high-performance computing workloads has elevated cooling from a supporting function to a core system requirement. As the industry moves from traditional air cooling toward hybrid and fully liquid-cooled architectures, the components that drive pumps and fans play a pivotal role in achieving performance, reliability, and sustainability objectives.

Allegro MicroSystems is uniquely positioned to steer this transition. Through innovations in field-oriented motor control, code-free programmability, integrated protections, and compact, scalable designs, Allegro delivers solutions that help engineers push the limits of current cooling technologies. Its motor drivers enable the development of thermal management systems that are efficient, reliable, and adaptable to evolving data center performance demands.

Conclusion

As the demands of artificial intelligence and high-performance computing continue to escalate, efficient thermal management has become paramount for the performance, scalability, and operational viability of modern data centers. The rising power densities are pushing legacy cooling systems to their breaking point, creating an urgent need for more advanced and reliable solutions. Allegro MicroSystems offers a comprehensive suite of innovative technologies designed to address the unique challenges of these next-generation cooling systems. By providing robust and responsive motor drivers and sensors, Allegro is enabling the critical infrastructure required to ensure that data center performance and longevity are not compromised by thermal constraints.

Allegro's robust portfolio of motor drivers empower engineers to create high-performance thermal management systems by delivering quiet, efficient, and reliable performance.