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ROBOTICS
Page 5

POWER ELECTRONICS
Page 22

PCIM
Page 28

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Editorial

Robotics is at a turning point. Humanoid robots are no longer considered a distant vision of the future, with market forecasts pointing to substantial growth in humanoid robotics over the coming decade. However, turning physical AI into systems ready for reliable real-world deployment requires more than advances in software and artificial intelligence. High-performance semiconductors, efficient drives, and intelligent energy concepts will be equally critical.

This issue focuses on robotics and explores the technologies that enable the transition from prototype to widespread adoption. The articles demonstrate how power semiconductors, modular architectures, and integrated drive solutions are advancing the next generation of humanoid and autonomous systems. In particular, they highlight how GaN technologies can enable more efficient, compact drive systems and support precise motor control.

Energy supply is becoming an increasingly important factor. New approaches to mobile power systems, inductive charging, and bidirectional switches based on GaN and SiC illustrate how future energy architectures can be made more efficient, flexible, and scalable.

Developments in adjacent application areas also offer valuable insights. The example of modular architectures for megawatt charging demonstrates the importance of power density, thermal management, and scalability for the next generation of electrical systems.

A look at the evolution of the PCIM highlights the close connection between technological innovation and international collaboration. From its origins to its expansion into China and India, its history reflects the dynamism of an industry that has been shaping technological progress for decades.

The articles in this issue make one thing clear: The future of robotics will not be determined by artificial intelligence alone. Innovative semiconductor technologies, intelligent energy management, and advanced power electronics will be essential to bringing autonomous systems into reliable real-world operation. Enjoy the read.

Best Regards



Lisette Hausser
Vice President PCIM

Contents









ROBOTICS

5 Physical AI in the Human World

6 Power Semiconductors as Performance Enablers for Humanoids

8 The Multi-Billion-Dollar Market for Humanoid Robots: Reaching $51 Billion in 10 Years

11 Empowering the Future of Humanoid Robotics

16 Future Robotics as a Growth Market for Power Electronics

19 GaN-Based Motor Drive Architecture for Robotics and UAV Applications

POWER ELECTRONICS

22 A 100 kW Bidirectional DC Fast Charger: Architecture, Design and Performance

26 In Search of the “Killer App” for Bidirectional GaN: Something Entirely New in Power Electronics

PCIM

28 From niche event to world-leading trade fair

PUBLISHING DETAILS

30 Imprint

Physical AI in the Human World

The use of humanoid robots is still in its early stages. Yet, within just 10 years, it could grow into a multi-billion-dollar business.

You are likely familiar with the Hollywood film “I, Robot.” In this movie, set in a not so distant Chicago in the year 2035, humanoid robots are ubiquitous artificial beings employed across many sectors of human life as workers and assistants. Where there are humans, there are also murders.

Detective Del Spooner haunted by recurring flashbacks of a traumatic experience involving humanoid robots is tasked with investigating a murder case in which humanoids also appear to be implicated. So goes this vision of the future, based on the novel “I, Robot” by Isaac Asimov.

In the reality projected by market researchers for the year 2035, it is estimated that approximately 2.1 million humanoid robots will be in use worldwide a relatively small number from today’s perspective. Current projections suggest that in developed nations, many people would be willing to purchase such a humanoid designed to assist with daily tasks if it were priced at around 25,000 dollars/euros. From the perspective of the electronics and semiconductor industry, a future with humanoid robots is, first and foremost, a multi-billion-dollar business.

For “physical AI” to operate in the human world independently of the cloud, it requires not only powerful central processing units but, crucially, sensory components, power semiconductors, and specialized control Ics all of which are essential for ensuring the mobility of a humanoid.

Semiconductor manufacturers currently estimate that, depending on the chosen architecture, each humanoid platform will incorporate between 500 and 600 dollars’ worth of semiconductor components.

While efforts are currently underway primarily in the United States and China to develop humanoid robots that are as high-performing as possible and designed to resemble humans, the medium- to long-term future will inevitably raise questions about how social interaction between humans and humanoids will take shape. It is no surprise that the prophets of the AI and robotics age paint these new possibilities in the most glowing terms. Yet, as seen recently in the lead-up to the U.S. midterm elections, the initially positive attitude Americans held toward AI data centers appears to be shifting. It remains to be seen how this will play out in the case of humanoid robots though, fortunately, things need not necessarily take a turn for the worst, as they did in *I, Robot*. eg



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Power Semiconductors as Performance Enablers for Humanoids

Depending on the architecture, semiconductors worth 500 to 600 dollars could go into humanoid robots in the future—a market from which specialists in power semiconductors also hope to benefit. Gallium nitride (GaN) could play a key role in this.

"If a humanoid robot incorporates, say, $300 worth of GaN technology, that's a great kind of 'hype' for us," says Dr. Alex Lidow, co-founder and CEO of Efficient Power Conversion (EPC), describing the appeal that the buzz surrounding "humanoid robotics" holds for a specialist in GaN power semiconductors like his company.

"Whether we're talking about household robots or humanoids used in manufacturing," Dr. Lidow explains, "extremely compact, high-performance electric motors play a critical role. And that is precisely where our GaN components and the ICs we've developed specifically for these applications come into play."

In his view, there are currently two primary areas where humanoid robots could be deployed. "For the elderly, in particular, a household robot would be incredibly valuable capable of doing laundry, washing dishes, vacuuming, and tidying up. I've already seen such robots in action; they aren't perfect, but they work quite well." He estimates that many people in developed nations would be willing to purchase a humanoid robot for $25,000 (or 25,000 euros).

Another major area of application he envisions is that of warehouse robots. He describes the requirements for such humanoid robots as follows: "They should weigh approximately 75 kg, operate for at least six hours on a single battery charge, and be capable of lifting up to 35 kg." While these humanoids would need to be able to identify and sort items, extreme precision in their positioning might not be required.

In the automotive industry, by contrast, humans perform tasks that demand highly precise positioning. "A humanoid would therefore need to be capable of this as well;



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in this field of application, the focus is primarily on hand-eye coordination," explains Dr. Lidow.

"Looking at current market analyses and publicly available architectures for humanoid robots," says Mirco Drews, Senior Manager of Strategic Business Development at Nexperia, "future systems could contain anywhere from 150 to 300 power switches. These would be distributed across motor drives, power conversion stages, battery management, as well as protection functions and power distribution."

For next-generation humanoid robots, GaN power semiconductors could therefore prove to be a key technology. "Their low switching losses enable motor drives with higher switching frequencies as well as compact DC/DC converters, while simultaneously improving the overall efficiency of the system."

In practical terms, their use would result in, among other things, smoother movements for humanoid robots, faster response times for their control systems, reduced cooling requirements, and longer battery life. In his view, particularly promising areas of application include 48V motor drives for robot joints and highly efficient DC/DC converters that supply the various voltage ranges required within the robot.

As Drews points out, however, developers of these next-generation humanoids will not rely solely on GaN power semiconductors. Robust low-voltage MOSFETs will still be necessary for implementing battery protection, power distribution, load switching, safety functions, and numerous essential auxiliary systems.

According to Luca Verre, Group Vice President and Head of Strategy for the MDRF Products Group at STMicroelectronics, a typical humanoid platform contains approximately $600 worth of addressable semiconductor content, depending on the chosen architecture. This $600 figure encompasses sensing, embedded intelligence, power management, motor control, and connectivity with these semiconductor components distributed throughout the entire humanoid robot.

A humanoid robot, Verre explains, "is not built around a single chip; it is built around a network of signals and decision-making processes. All of this must remain stable while the humanoid robot navigates the messy and unpredictable human environment." For this reason, "physical AI" relies on companies "that can help machines understand the world, react in real time, and do so reliably at scale."

Against the backdrop of a 2024 market assessment by Goldman Sachs Research which suggests there could be 300 million humanoid robots globally within 25 years, representing a revenue potential of $1.7 trillion by 2050 Infineon Technologies is also engaging intensively with the field of humanoid robotics, with a particular focus on silicon and GaN (gallium nitride) power semiconductors.

With projected semiconductor costs of approximately $500 per robot, Infineon is actively seeking collaborations with partners in this sector. Earlier this year, the company entered into a strategic partnership with the Vietnamese firm VinRobotics to develop humanoid robots. The objective of this agreement is to jointly develop and manufacture next-generation humanoid robots for use in industrial, service, and private environments.

In March of this year, Infineon announced the expansion of its collaboration with Nvidia. The goal of this partnership which builds upon a cooperation previously announced in August 2025 is to combine Infineon's strengths in motor control, microcontrollers, power systems, and security technology with Nvidia's established AI, robotics, and simulation platforms. Furthermore, Infineon has joined the Nvidia Halos AI Systems Inspection Lab to work on robust hardware and software safety foundations, ensuring that these systems can operate reliably in real-world environments. eg



Dr. Alex Lidow, EPC:
"Extremely small and high-performance electric motors play a crucial role in the realization of next-generation humanoid robots. This is where we come into play with our GaN components and ICs specifically developed for these applications."



Mirco Drews, Nexperia:
"Looking at current market analyses and publicly available architectures for humanoid robots, future humanoid robots could contain anywhere from 150 to 300 power switches. In this context, GaN could prove to be a key technology."



Lucca Verre, STMicroelectronics:
"A humanoid robot is not built around a single chip; it is built around a network for signals and decision-making. All of this must remain stable while the humanoid robot navigates through the messy and unpredictable human world."

The Multi-Billion-Dollar Market for Humanoid Robots: Reaching $51 Billion in 10 Years

At 8 percent, the semiconductor share of a humanoid robot's bill of materials (BOM) is lower than many might have expected. In terms of the BOM, the robot's dexterous hands and actuators are significantly more important. The market success of humanoid robots will likely hinge on their acceptance outside of industrial settings specifically, whether they become a natural, integrated part of the human environment.

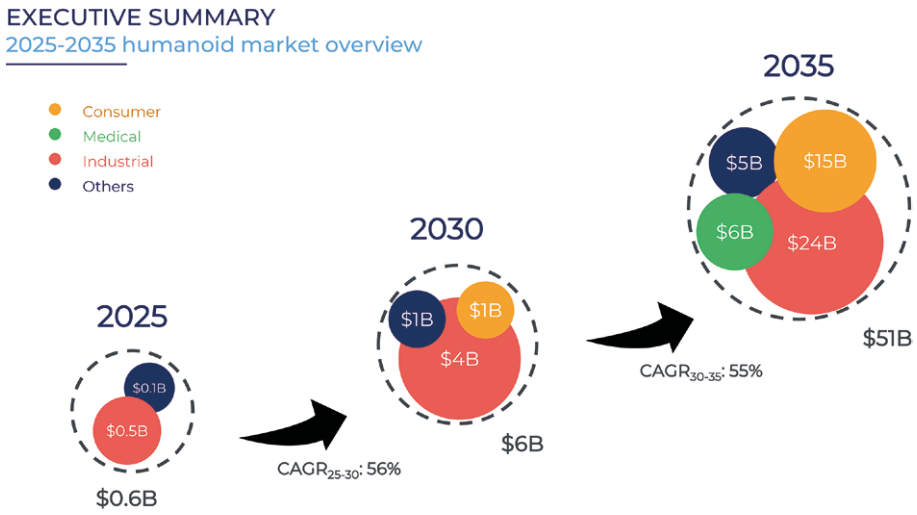
Although humanoid robots may currently be a niche product, they carry enormous revenue potential. When market researchers at the Yole Group investigated the actual size of this market, they estimated a revenue volume of $600 million for 2025. By 2030, they project a tenfold increase to approximately $6 billion an annual growth rate of 56 percent. In every sense, it is an exploding market.

Looking further ahead to 2035, market researchers at Yole project a revenue volume of $51 billion. Between 2030 and 2035, this would represent an annual growth rate of 55 percent a figure that remains substantial. In their current calculations, the researchers assume that humanoid robots are replaced every six years. Based on this, they estimate that approximately 8,000 robots entered the market in the previous year. Their forecast anticipates that 136,000 humanoid robots will enter the market annually by 2030, with that number reaching 2.1 million units by 2035.

Those who might expect the majority of the bill of materials (BOM) to consist of semiconductors such as power semiconductors would be mistaken. The market researchers point out that the BOM is dominated by mechanical components, dexterous hands, joint actuators, servomotors, and controllers. In contrast, they estimate that semiconductors account for only a small portion of the average selling price (ASP). For 2025, the researchers project that semiconductors will make up roughly 8 percent of the total. By 2035, they anticipate that due to economies of scale and higher levels of integration in processor units and silicon-based perception solutions this share of the BOM could decline to 5 percent.



Image: Taiba/stock.adobe.com



Starting from a relatively modest revenue of $600 million generated primarily through industrial applications the market for humanoid robots is expected to grow tenfold to $6 billion by 2030. By 2035, analysts project a revenue volume of $51 billion. Industrial applications will continue to account for the largest share of this revenue, at $24 billion, followed by the consumer and medical sectors. (Image: Yole Group)

In their assessment of the future development of the market for humanoid robots, market researchers at Yole anticipate that their market entry will occur in three distinct waves. The first wave which is already underway focuses primarily on applications in intralogistics and support for light final assembly tasks within existing (brownfield) facilities and large warehouses.

In these contexts, the return on investment is driven more by ergonomic relief and the filling of labor gaps than by a one-to-one replacement of human workstations. Examples include Apptronik's "Apollo" robot, which handles the delivery of transport containers at Mercedes-Benz, and Agility's "Digit," which is used for handling bulk materials.

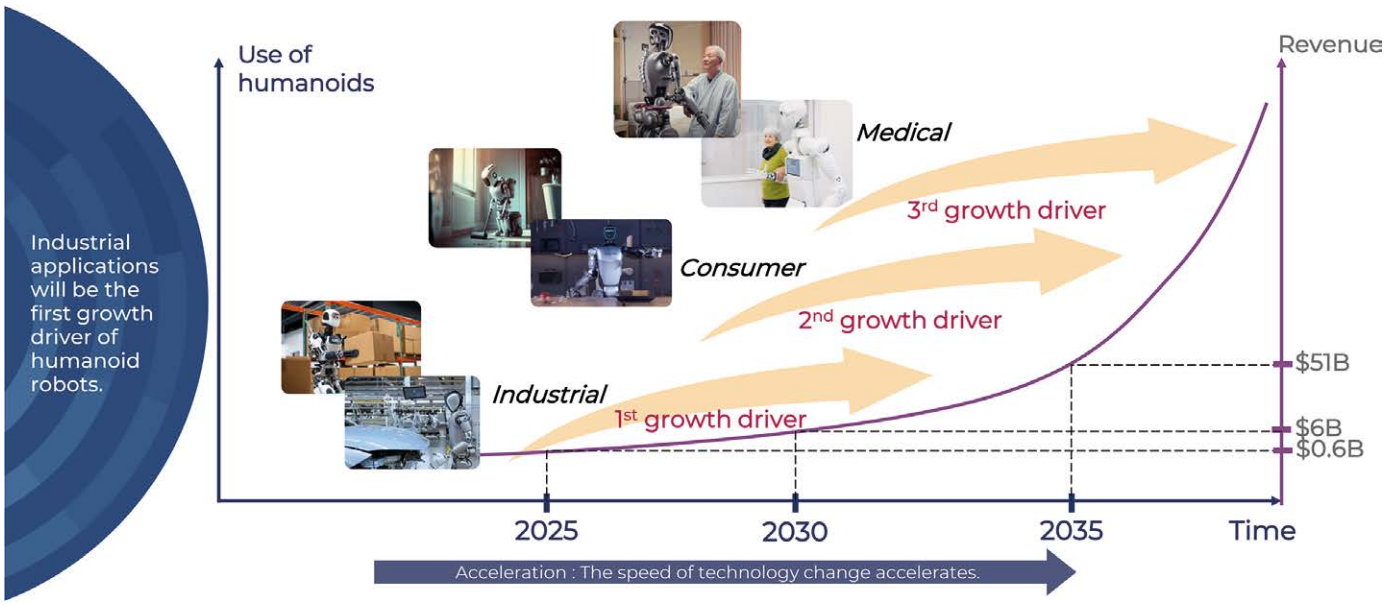
For the second wave, the market researchers expect that competition driven largely by Chinese OEMs will lead to the emergence of applications in the consumer sector. This includes humanoid robots such as the "R1" from Unitree, which reportedly has an average selling price of $5,600. Compared to their industrial counterparts, these "consumer" robots are characterized by more limited payload capacities, durability, and safety specifications.

The third wave would involve the deployment of humanoid robots in the medical sector. To date, however, regulations and liability concerns have hindered their use at the bedside. Nevertheless, there are political signals such as the guidelines issued by the Chinese State Council aimed at integrating humanoid robots into elderly care. There are also indications of potential applications in rehabilitation, mobility assistance, and hospital ward logistics, which will serve as precursors to their eventual use in direct patient care.

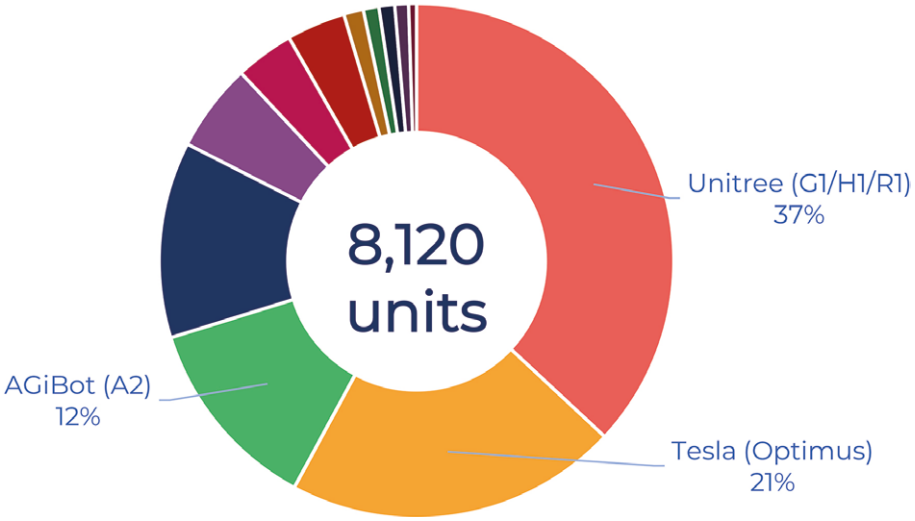
Regarding the necessary investments, market researchers at Yole conclude that developers of humanoid robots should focus primarily on creating dexterous hands; this would not only make the robots appear more human-like but also expand their potential utility within industrial settings.

In this context, they note that dexterous hands currently account for approximately 31 percent of the average bill of materials (BOM) for a humanoid robot, while actuators account for 42 percent. The next challenge lies in reducing the costs of humanoid robots to a level that makes them attractive for consumer purchase. Ultimately, meeting safety standards and complying with regulatory requirements will be the final steps needed to trigger this third wave.

In their market research, analysts at Yole identified approximately 60 companies worldwide actively engaged in the devel-



Over the coming years, humanoid robots will enter the market in three waves. The first wave already underway concerns the industrial sector. By 2030, consumer applications are expected to emerge. Market researchers anticipate that the use of these robots in care settings and directly at the bedside will not occur until the third wave, which is likely to begin in the next decade. (Image: Yole Group)



In its initial phase in 2025, with a sales volume of approximately 600 million dollars, the market for humanoid robots was essentially divided among four companies: Unitree, Tesla, AgiBot, and Ubtech. These four firms accounted for roughly 82 percent of the total market. (Image: Yole Group)

opment and manufacturing of humanoid robots. More than 50 percent of these firms are based in China, while 12 are located in the United States. In Europe, there are very few companies active in this sector; those identified by Yole analysts are primarily startups.

The market researchers conclude that, since 2017, roughly 10 billion dollars in financial investment has flowed into the development of humanoid robots globally with a significant portion concentrated in two companies: Ubtech and Figure AI. While both firms lead in terms of funding, they do not lead in terms of unit shipments. Regarding sales figures for 2025, Yole projects that 37 percent of all humanoid robots delivered will come from Unitree, followed by Tesla with a 21 percent market share, and AgiBot with 12 percent. Specifically, the Yole Group analysts estimate that four companies Unitree, Tesla, AgiBot, and Ubtech currently dominate approximately 82 percent of the humanoid robot market.

In this initial wave, on the demand side, leading humanoid robot manufacturers are forming partnerships with major corporations such as automotive and logistics companies to launch pilot programs. Such initiatives are being pursued by companies including Apptronik, Figure AI, Agility, Astribot, and Ubtech. Beyond industrial applications, Unitree has established itself as a strong provider within the sectors of research and development (R&D), education, and integration for early-stage adopters. Regarding the ecosystem necessary for the development of humanoid robots, Yole market researchers point to a plan implemented by China's Ministry of Industry and Information Technology (MIIT) between 2023 and 2025, which aimed to establish a comprehensive innovation environment for "HumanID" and secure the essential core components. While Nvidia remains the leader in the computing sector, Yole analysts note that local firms such as Horizon Robotics and Cambricon are gaining traction by following similar trends seen in automotive computing. For other critical components, including sensors, actuators, batteries, and encoders, the Chinese ecosystem is already sufficiently well-positioned to supply these parts in large volumes.

Given that companies like Fourier Intelligence and Agility Robotics currently sell humanoid robots for industrial use at prices reaching $100,000 or more, Yole market researchers anticipate that the average purchase price will drop from approximately $75,000 in 2025 to around $25,000 by 2035. Their forecast suggests that, regardless of whether a unit is a simple, basic, or top-tier model, the retail price in 2035 will likely fall within the $20,000 to $30,000 range.

An indicator for this forecast might be the price of the entry-level R1 robot unveiled by Unitree in July 2025 which has an average selling price of $6,000. Other companies, such as Apptronik, are taking a different approach: they aim to sell their humanoid robots at the price of a new car, according to Apptronik co-founder and CEO Jeff Cardenas. eg

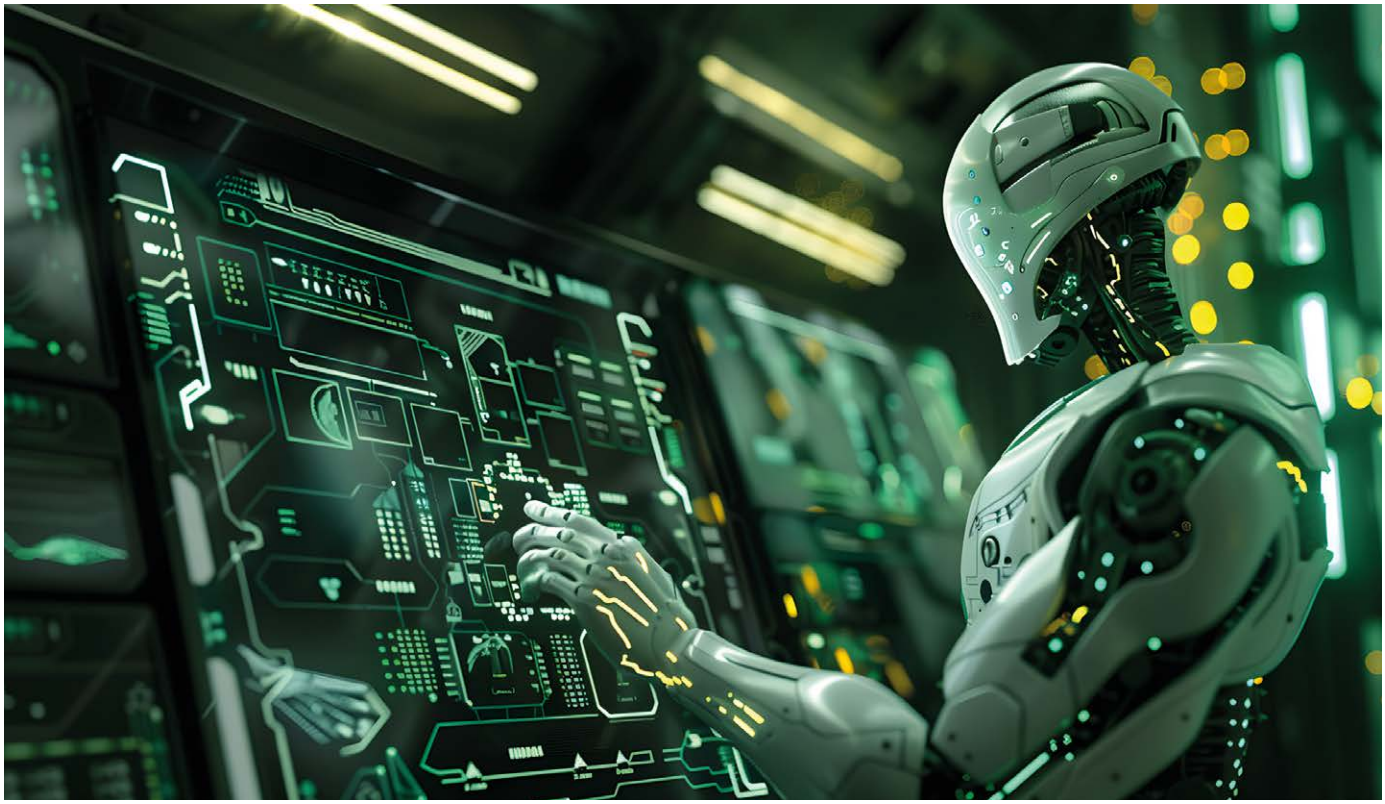


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Empowering the Future of Humanoid Robotics

Humanoid robots place demanding requirements on power electronics, motor control, sensing, and communication technologies. This article presents an ecosystem spanning reference designs, a modular development platform, robotic demonstrators, and a digital-twin workflow, illustrating the path from semiconductor innovation to complete humanoid robotic systems.

By Martin Schiestl, Patrick Haselwanter and Maurizio Incurvati, all at Infineon Technologies

Battery-powered applications equipped with electric drives are accelerating innovation in power electronics and motor control across a wide range of industries, where efficiency directly impacts system-level performance. In drones, every percentage point of efficiency can extend flight time, increase payload, or improve operational range. Similarly, e-bikes rely on highly efficient motor drives to extend operating range while balancing performance, weight, and cost. The same trend can be observed in cordless power tools, where compact size, high power density, and long operating time are critical differentiators.

Across all these applications, improving power conversion efficiency and motor control performance has become a key enabler for enhanced user experience and system capability. As battery-powered devices continue to proliferate, demands on semiconductor technologies, sensing solutions, and advanced control architectures continue to increase.

One application area that combines these challenges particularly well is robotics. The spectrum ranges from consumer products such as robotic vacuum cleaners and lawn mowers to commercial drones, autonomous mobile robots, collaborative robots, and, increasingly, humanoid robots. Many of these systems operate from batteries and therefore face the same constraints regarding efficiency, power density, thermal performance, size, weight, and runtime.

At the same time, the robotics market is experiencing remarkable growth. According to ABI Research and Goldman Sachs, global robot shipments could exceed 100 million units annually by 2030, with humanoid robots representing the fastest-growing segment and expected to grow by approximately 140% per year between 2025 and 2030. This momentum highlights the significant potential of humanoid robotics, a market that UBS estimates could reach up to USD 1.7 trillion by 2050.

The Challenge of Actuation in Humanoids

To enable human-like movement and dexterity, advanced humanoid robots may incorporate more than 70 actuated joints with up to 600 power switches distributed across the

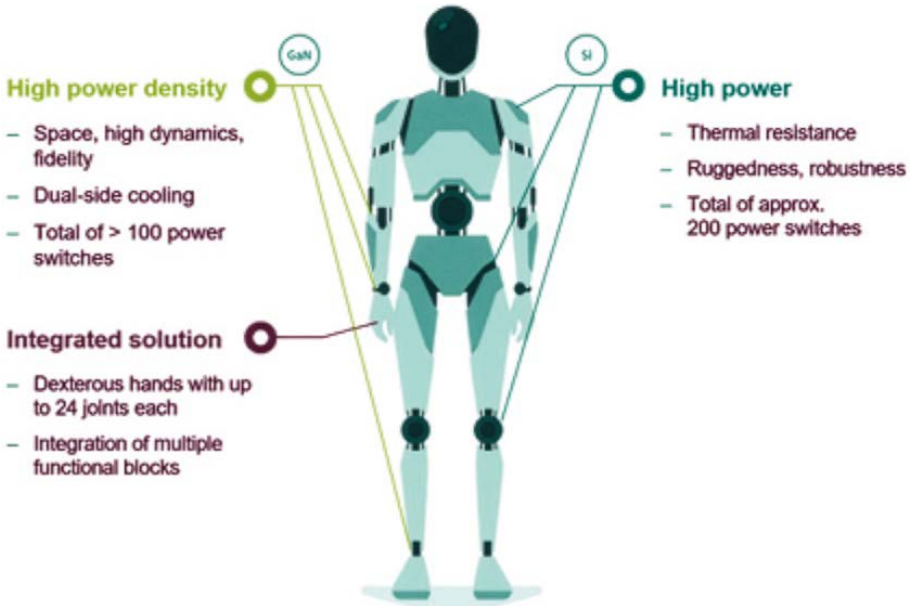


Figure 1: Humanoid robot: Choice of semiconductor technology and its level of integration (Image: Infineon Technologies)

fingers, hands, arms, torso, and legs, forming a tightly interconnected electromechanical system of considerable complexity. From a system-level perspective, the coordination of dozens of distributed actuators requires deterministic, high-bandwidth communication networks, such as EtherCAT or TSN-enabled Ethernet, alongside robust functional and operational safety mechanisms to ensure reliable operation in human-centric environments.

At the actuator level, requirements vary considerably across the robot, ranging from high-current and high-power drives for load-bearing joints to highly compact and integrated solutions for hand and finger actuation. Depending on the requirements, different semiconductor technologies, package types, and levels of integration may be selected, as indicated in Figure 1.

For space-constrained actuators where integration is key, GaN offers advantages that extend beyond transistor-level performance. It enables higher switching frequencies that reduce motor current ripple and associated magnetic and winding losses. Furthermore, GaN specifically allows for highly integrated power stages that combine power switches, gate drivers and protection logic within a compact footprint. Besides GaN technology, Si MOSFETs remain an attractive alternative, particularly for actuators where cost-effectiveness, design flexibility, and proven robustness are key considerations. Leveraging a mature ecosystem and broad portfolio availability, Si-based solutions continue to provide an excellent fit for joints where integration density is less critical and power capability is a primary requirement.

Bringing together power semiconductors, drivers, sensing, control, communication, and protection within a compact form factor is central to the design of humanoid robot actuators. As a practical realization of this approach, the REF_HUMA_MTR_48V_25A integrates the essential building blocks of humanoid motor control on a single board.

Mid-power Joint Solution for Humanoid Motor Control

The REF_HUMA_MTR_48V_25A is a humanoid-focused motor control reference design that integrates essential building blocks of a robotic actuator, including power stage, controller, sensing, communication, and auxiliary power circuitry, as shown in Figure 2.

Targeting mid-power robotic joints, it integrates a 48 V motor drive capable of supplying up to 25 A RMS continuous for power levels slightly exceeding 1 kW into a compact 66 mm diameter single-board solution. An overview of the system architecture is shown in Figure 3.

The design is centered around three CoolGaN Drive IGJ022H10SA2L integrated power stages, each combining a GaN half-bridge and gate drivers within a compact 4.5 mm × 7 mm RQFN package. Particular attention was paid to thermal management, with the design implemented on a 6-layer PCB featuring a 2 oz copper stack-up.

For in-phase motor current measurement, the design integrates XENSIV TLE5571 coreless

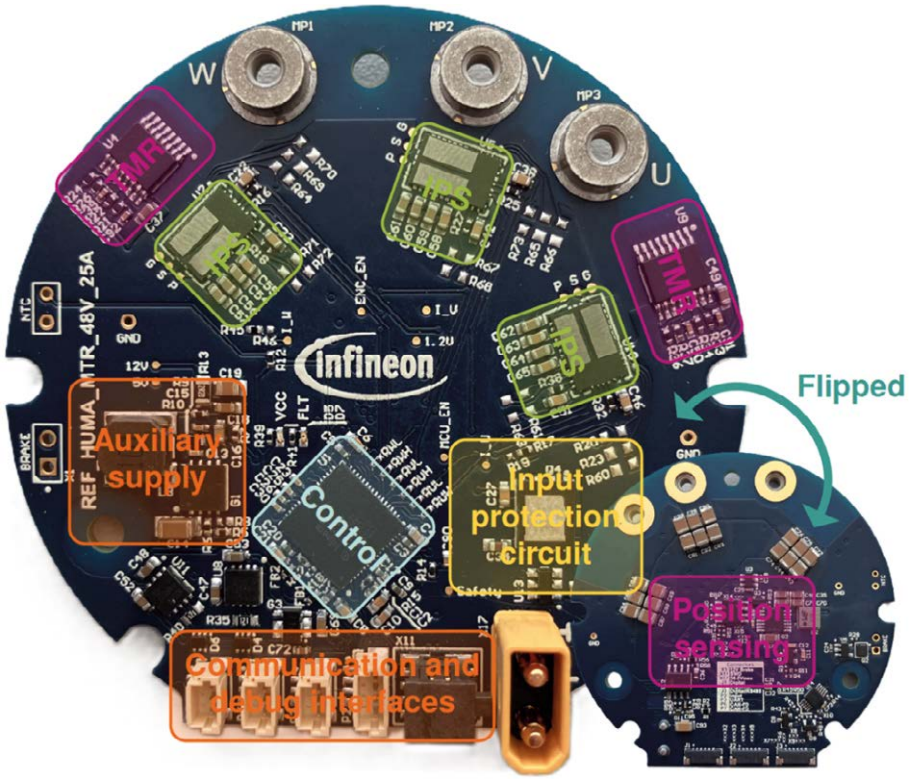


Figure 2: A single-board solution integrating all key functional blocks for a humanoid actuator (Image: Infineon Technologies)

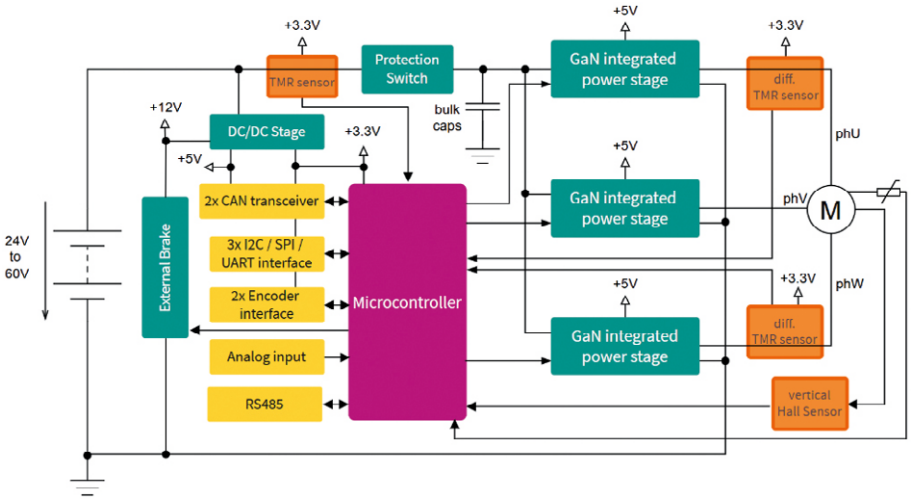


Figure 3: Building blocks of the REF_HUMA_MTR_48V_25A reference design (Image: Infineon Technologies)

current sensors, which use two integrated TMR bridges including a differential amplifier to provide galvanically isolated current sensing with high immunity to external stray magnetic fields. In the reference design, U-shaped conductors on the first and second inner PCB layers are employed to improve magnetic field coupling, thereby increasing sensor sensitivity. For input current monitoring and protection, the design further incorporates the XENSIV TLE5572 monocell TMR-based current sensor.

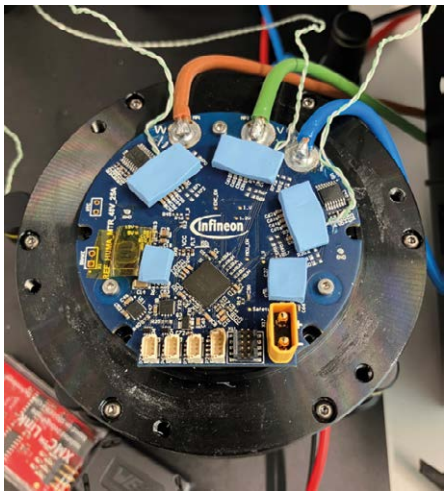


Figure 4: Thermal integration of the REF_HUMA_MTR_48V_25A into a CubeMars actuator. The thermal interface material connects the heat sources to the motor housing/heatsink (not depicted). (Image: Infineon Technologies)

Motor control is handled by a PSOC Control C3 microcontroller, featuring an Arm Cortex-M33 CPU operating at up to 180 MHz. The board also integrates two buck regulators to generate the required auxiliary supply rails for the MCU, sensing, and communication circuitry.

For motor position feedback, the design supports XENSIV TLE5012 and TLE49012 angle sensors, enabling precise acquisition of the rotor electrical angle, particularly important for achieving high torque at low speeds. In addition, a dedicated encoder interface allows connection of a second position sensor to support dual-encoder configurations. Such setups are commonly employed in humanoid robot joints utilizing mechanical reducers, where both motor-side and joint-side position information is required.

To facilitate integration into the overall humanoid control architecture, the platform further provides a comprehensive set of communication interfaces, including CAN-FD, I²C, SPI, and UART/RS485.

To validate the performance of the design, thermal measurements were conducted with the REF_HUMA_MTR_48V_25A mechanically integrated into a CubeMars AK10-9 V2.0 KV60 actuator housing serving as the heatsink. The measurements demonstrate continuous operation at up to 25 A RMS phase current, confirming the suitability of the design for mid-power humanoid robot joints. The thermal measurement setup and resulting steady-state thermal behavior are shown in Figure 4 and Figure 5, respectively.

Modular Design Platform

The REF_HUMA_MTR_48V_25A demonstrates how the key building blocks of a humanoid motor drive can be integrated within a compact single-board solution. However, while the fundamental functional blocks of humanoid actuators remain largely consistent, their implementation can vary considerably depending on requirements re-

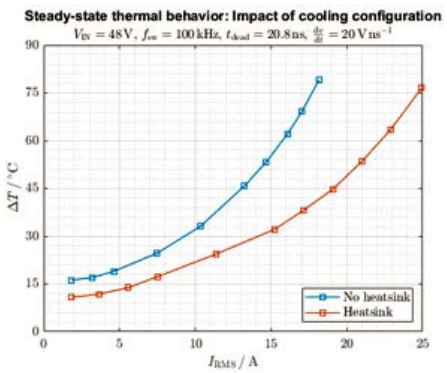


Figure 5: Steady-state thermal characterization of the REF_HUMA_MTR_48V_25A with and without heatsink. (Image: Infineon Technologies)

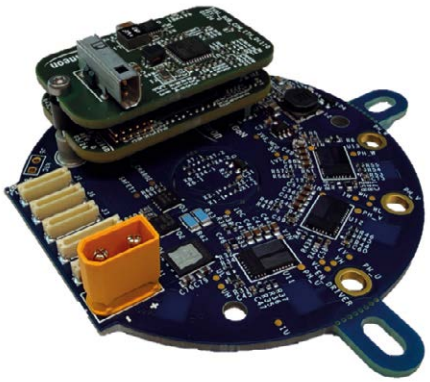


Figure 6: Modular design platform comprising stacked power, control, and communication modules. (Image: Infineon Technologies)

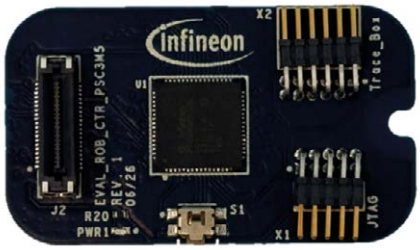


Figure 7: Interchangeable MCU board featuring a PSOC Control C3 microcontroller (Image: Infineon Technologies)

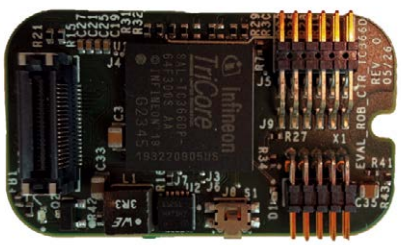


Figure 8: Interchangeable MCU board featuring an AURIX TC366DP dual-core microcontroller. (Image: Infineon Technologies)

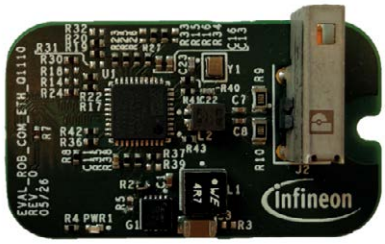


Figure 9: Communication module featuring a BRIGHTLANE™ single-pair Ethernet PHY for 100BASE-T1 connectivity. (Image: Infineon Technologies)

lated to performance, cost, communication interfaces, safety, semiconductor technology, and vendor-specific preferences. Moreover, computing, communication, and safety functions can to a large extent be decoupled from the power electronics, creating a strong case for a modular design approach.

This enables rapid technology iterations and supports objective performance comparison of different hardware and software solutions. To support this flexibility, the architecture is partitioned into three interchangeable functional domains:

- Base power module – integrates the power stage, current sensing, protection circuitry, and basic communication interfaces
- Interchangeable MCU board – hosts the controller and associated circuitry
- Optional communication module – provides hardware support for EtherCAT or Ethernet-based connectivity

By decoupling these functions, each domain can be modified independently, allowing straightforward evaluation of alternative semiconductor technologies, control platforms, and communication standards. Figure 6 shows the realization of the modular platform with stacked modules.

Among the possible power module implementations, the variant shown here employs three CoolGaN Drive IGJ022H10SA2L integrated power stages. In contrast to the single-board solution presented previously, this implementation utilizes the XENSIV TLE49781 high-bandwidth coreless current sensor. Combining Hall-effect and coil-based sensing elements, the device enables high-accuracy current measurement across a wide frequency range while maintaining galvanic isolation.

The module further supports both End-of-Shaft (EoS) and Out-of-Shaft (OoS) position-sensing schemes, enabling adaptation to different actuator and gearbox architectures. EoS sensing can be implemented using either the XENSIV TLE5012 or TLE49012 magnetic position sensor. For OoS sensing, two XENSIV TLE49012 devices are arranged with a 90° mechanical offset. This dual-sensor approach not only enables improved position measurement accuracy through sensor fusion, but also introduces redundancy.

Stacked onto the base power module are interchangeable MCU boards sharing a common electrical and mechanical interface. One implementation, shown in Figure 7, is based on a PSOC Control C3 microcontroller, providing a flexible all-round control solution with support for multiple communication interfaces. This combination makes it suitable for a wide range of actuator designs, ranging from cost-optimized systems to feature-rich robotic applications. For more demanding robotic systems, an alternative MCU board based on an AURIX TriCore TC366 is available, as shown in Figure 8.

Its multi-core architecture enables a clear separation between motor-control and communication tasks, resulting in improved determinism. The board additionally provides an RMII interface that can be combined with an external communication module to support Ethernet-based networking.

As humanoid robots evolve toward increasingly distributed sensing devices, the demand for high-bandwidth, low-latency, and deterministic real-time communication continues to grow. To address these needs, the platform supports dedicated communication modules that can be combined with the MCU board as required. Figure 9 shows a communication module based on the BRIGHTLANE 88Q1110 single pair Ethernet physical layer transceiver (PHY).

In combination with the RMII interface provided by the MCU module, this enables 100BASE-T1 communication and provides



Figure 10: Single-joint humanoid robotic arm demonstrator featuring the REF_HUMA_MTR_48V_25A reference design. (Image: Infineon Technologies)

a foundation for TSN-based networking, supporting deterministic real-time communication within humanoid robotic systems.

Humanoid Robotic Demonstrators

While the presented reference designs address the actuator level, humanoid robots ultimately rely on the coordinated operation of multiple drives. To demonstrate the suitability of the proposed designs in such systems, Infineon developed a series of humanoid demonstrators based directly on the presented hardware.

A first demonstrator implements a single-joint arm configuration, in which the elbow joint is actuated by a 48 V motor driven by the REF_HUMA_MTR_48V_25A, as shown in Figure 10.

The setup provides a representative environment for evaluating humanoid joint control and exercising the complete control stack, including sensored field-oriented control with cascaded current, speed, and position control. By executing predefined motion profiles under defined mechanical loading, it showcases the interaction between power semiconductors, sensing, control algorithms, and communication interfaces. This occurs under realistic operating conditions.

Building on the experience gained with this single-joint setup, Infineon further developed a fully integrated 7-degree-of-freedom (7-DoF) humanoid robotic arm, shown in Figure 11.

The system combines seven high-torque 48 V motors, each equipped with motor control electronics derived from the modular design platform. In doing so, it demonstrates how Infineon's semiconductor portfolio, ranging from PSOC motor-control MCUs and CoolGaN power devices to XENSIV magnetic sensing solutions and CAN/Ethernet connectivity, can be integrated to realize a complete humanoid robotic platform. Beyond showcasing individual technologies, the robotic arm provides a customer evaluation platform for exploring and benchmarking different combinations of power stages, sensing technologies, control architectures, and communication solutions. At the same time, it serves as a reusable foundation for future innovation, enabling rapid assessment of emerging semiconductor, sensing, safety, and communication technologies.

Building on the hardware platform, system-level functionality is evaluated through a ROS-based control framework. Real-time motion generation is performed on a NVIDIA Jetson Thor, which computes target trajectories and commands the seven joints. The resulting movement is simultaneously reflected in a digital twin running in NVIDIA Omniverse, with visualization provided by NVIDIA DGX Spark. This creates a seamless virtual-to-physical development environment, enabling robot motion to be observed and validated concurrently in the digital and physical domains, paving the way for AI-enabled humanoid robotic systems.

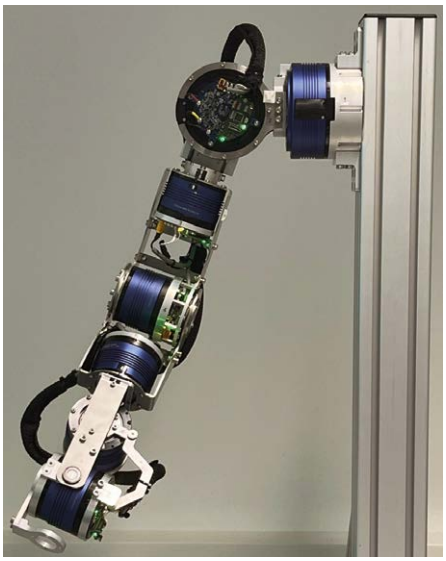


Figure 11: 7-DoF humanoid robotic arm demonstrator integrating motor control boards from the modular design platform. (Image: Infineon Technologies)

The Road Ahead

The convergence of cutting-edge semiconductors, advanced motor control, high-speed networking, AI computing, and digital-twin technologies is accelerating the evolution of humanoid robotics. From compact reference designs to fully integrated robotic demonstrators, the solutions presented in this article illustrate a scalable path from semiconductor innovation to complete robotic systems. st



Martin Schiestl joined Infineon in 2023 as a System Application Engineer, where he is currently leading the engineering team responsible for the humanoid motor drive system. Recently, he received the PCIM 2025 Young Engineer Award for his publication, »Compact Highly Integrated 1 kW Peak Motor Drive.«



Patrick Haselwanter is a System Application Engineer at Infineon Technologies, focusing on motor control solutions for humanoid robotics. He joined Infineon in 2025 after receiving his Master's degree in Mechatronics from Management Center Innsbruck.



Maurizio Incurvati is Lead Principal Engineer at Infineon Technologies, focusing on innovation in GaN-based motor drives in humanoid actuators. He has been teaching power electronics, drives, and control engineering at university level. He has coauthored numerous publications with industry and academia.

Future Robotics as a Growth Market for Power Electronics

Humanoid and legged robots are increasingly moving into industrial and commercial applications. Driven by advances in artificial intelligence, sensing technologies and electromechanical systems, the field is currently experiencing a level of investment comparable to the early stages of electric mobility.

By Dr. Maximilian Hofmann, Liu Xinjun, Dr Bernd Eckardt, all at Fraunhofer IISB

Recent market studies estimate the global humanoid robotics market at approximately USD 7.8 billion in 2025 and forecast growth to well above USD 200 billion within the next decade, corresponding to annual growth rates of around 35-40%. At the same time, major technology companies and robotics start-ups are investing billions of dollars into humanoid and highly mobile robotic platforms intended for manufacturing, logistics, healthcare and service applications. (I, II) While public attention is largely focused on artificial intelligence, the physical performance of future robotic systems will ultimately be determined by their hardware platform. Mobility, payload, operating time, efficiency and cost are fundamentally constrained by electric actuators, power electronics, energy storage systems and charging infrastructure. From a power electronics perspective, humanoid and quadruped robots represent an interesting emerging application domain. A single robotic platform may incorporate dozens of distributed electric actuators and local inverter stages combined with battery-based energy storage systems, AI processors and sensor networks.

System Architecture: The Case for a 48-V DC Backbone

Future humanoid and legged robots can be regarded as highly distributed electrical energy systems comprising multiple actuators, embedded computing hardware, sensor networks and energy storage systems. A promising architecture for such systems is based on a common 48-V DC backbone supplying decentralized power conversion stages for actuation, sensing and data processing. A conceptual design of such an architecture is shown in Figure 1.

While no universally accepted voltage level for future robots has yet emerged, 48 V represents an attractive compromise between efficiency, safety and system complexity. Compared to low-voltage architectures below 24 V, conductor currents can be reduced significantly, lowering cable losses, connector stresses and wiring mass. At the same time, 48-V systems avoid many of the insulation, safety and EMC challenges associated with high-voltage architectures. For example, supplying a 3 kW joint actuator requires approximately 125 A at 24 V, but only 62.5 A at 48 V. The resulting reduction in conduction losses and cable cross-section strongly motivates the use of a 48-V architecture.

The distributed nature of humanoid robots strongly favors local power conversion. Instead of a centralized inverter supplying multiple motors, each robotic joint can be equipped with a dedicated three-phase inverter located directly adjacent to the electric machine. Such an approach minimizes motor cable lengths, reduces electromagnetic emissions and enables highly modular actuator designs. Furthermore, local inverters allow individual control of torque, speed and regenerative operation at each degree of freedom. The architecture shown in Figure 1 therefore combines distributed actuator inverters

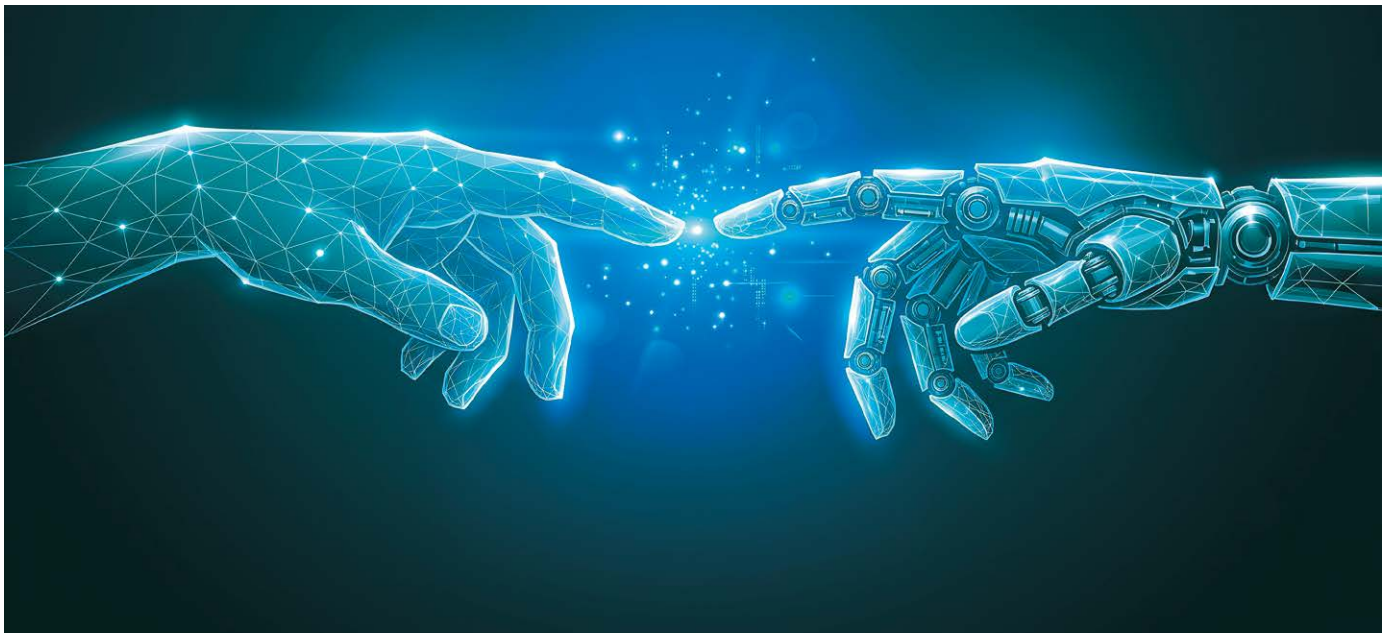


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with centralized energy storage connected through the common DC bus.

An important feature of this architecture is the coexistence of multiple voltage domains. Whereas electric actuators operate directly from the 48-V distribution level, sensors typically require supply voltages between 1 V and 5 V and AI accelerators or GPU-based computing units may operate at core voltages below 1 V. Consequently, several local DC/DC conversion stages are required to generate application-specific supply rails.

High-Power-Density Actuator Concepts for Future Robotic Systems

Unlike conventional industrial drive systems, robotic actuators increasingly follow a highly integrated design philosophy. Electric machine, power electronics, sensing, mechanical transmission and thermal management are combined within a single compact mechatronic module. Such integration reduces inactive mass, minimizes cable lengths and parasitic inductances, lowers electromagnetic interference, and enables a holistic optimization of the complete energy conversion chain. Rather than optimizing motor, inverter and mechanics independently, future robotic actuators are developed using an electric, electromagnetic, thermal and mechanical co-design approach. The actuator concepts of Fraunhofer IISB shown in Figure 2 illustrate two complementary approaches for future robotic systems: a highly integrated rotary joint actuator and a compact high-force linear actuator.

Rotary Joint Actuator

The rotary actuator is designed as a compact robotic joint drive with frameless electric machine for applications such as shoulder, elbow, hip or knee joints. Operating from a 48 V DC architecture, the current demonstrator delivers up to 250 Nm peak torque and 3.5 kW peak power for 10 s, while providing 30 Nm rated torque and 0.4 kW continuous power at a transmission ratio of 22. The resulting peak-to-rated power ratio highlights the strongly dynamic operating conditions encountered in robotic systems.

A key element of the concept is the electric machine design. The motor employs concentrated rectangular windings with short end-winding sections, improving copper utilization and reducing resistive losses compared to conventional distributed winding topologies. In addition, the rotor features a Halbach-array

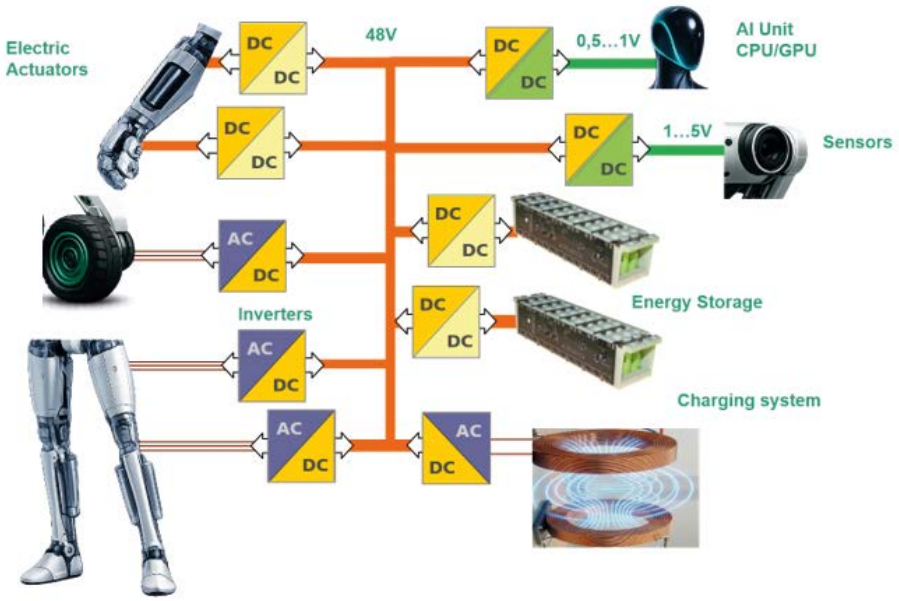


Figure 1: Conceptual 48-V robotic power architecture comprising distributed actuator inverters, point-of-load converters for AI and sensor systems, battery storage and wireless charging infrastructure (Image: Fraunhofer IISB)

design without heavy rare-earth materials, which reduces torque ripple and cogging torque and thus enables smoother output performance. PCB-based phase interconnections further reduce electrical resistance and parasitic inductance while supporting a compact and reproducible assembly process. The inverter is integrated directly into actuator and can employ GaN or Si-MOSFET devices depending on the operating requirements. GaN devices, however, offer significant advantages when power density and integration become the primary design objectives. Compared to silicon MOSFETs, GaN transistors exhibit substantially lower gate charge and output capacitance, enabling switching frequencies above 100 kHz. Increasing the switching frequency from typical silicon values of 20–50 kHz to more than 100 kHz reduces motor current ripple, allows significant reductions in DC-link capacitance and magnetic component volume, and reduces additional losses in the motor system. Since passive components frequently occupy more space than the semiconductor devices themselves, this directly increases volumetric power density at actuator level.

The current actuator therefore serves not only as a compact high-performance joint drive, but also as a technological platform for future quasi-direct and direct-drive robotic actuators with reduced dependence on mechanical transmission.

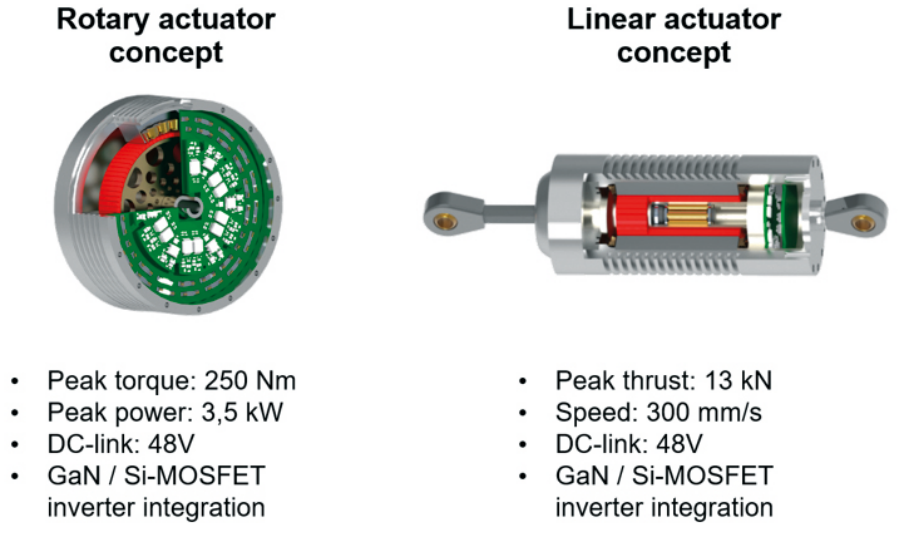


Figure 2: Highly integrated rotary and linear actuator concepts for future robotic systems (Image: Fraunhofer IISB)

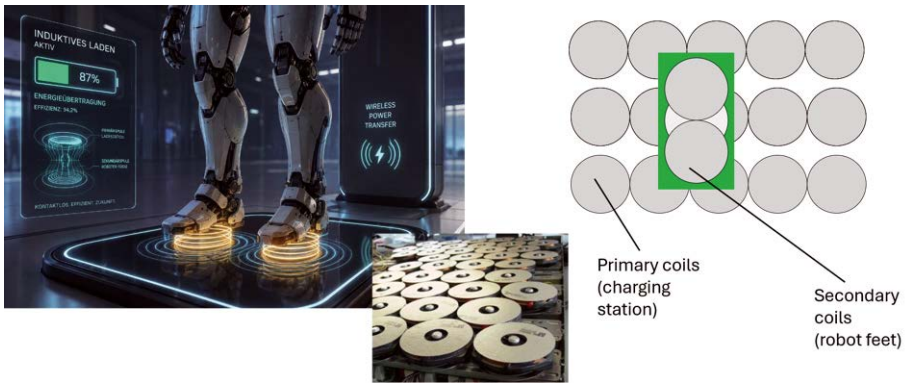


Figure 3. Conceptual implementation of highly position-tolerant inductive charging for humanoid robots based on foot-integrated receiver coils and contactless energy transfer infrastructure. (Image: Fraunhofer IISB)

Linear Force Actuator

While rotary actuators dominate many robotic joints, linear actuators become attractive whenever compact force generation and short mechanical load paths are required. The presented actuator integrates a high-speed electric motor with an inverted planetary roller screw into a compact coaxial architecture capable of delivering up to 13 kN dynamic thrust at linear velocities of 300 mm/s. The complete actuator occupies a diameter of only 70 mm and a total length of 285 mm.

The use of an inverted planetary roller screw enables efficient conversion of rotary into linear motion while maintaining high load capability and stiffness. Compared with conventional ball-screw systems, the concept provides a more compact force path and improved suitability for highly loaded robotic joints operating under dynamic conditions. These characteristics make the actuator particularly attractive for humanoid leg applications, where compactness, robustness and high axial force capability are critical.

Beyond its current implementation, the concept provides a development platform for future robotic force actuators in which mechanical conversion stages can be progressively reduced and force generation can move closer to the electromagnetic actuator itself.

Inductive Charging as an Enabler for Robotic Infrastructure

The energy supply infrastructure will play a decisive role in the large-scale deployment of humanoid and mobile robotic systems. While significant attention is currently devoted to actuator technology and artificial intelligence, operational availability is ultimately determined by how energy is replenished during operation. Conventional conductive charging systems are mature and highly efficient, but introduce contact wear, contamination risks and positioning requirements that become increasingly challenging in fully autonomous environments. Battery-swapping concepts can reduce charging downtime but require complex mechanics, additional battery inventory and a high degree of standardization.

Inductive power transfer (IPT) offers an attractive alternative. The technology combines contactless operation with high flexibility, robustness and interoperability between different robotic platforms. In contrast to charging stations with exposed electrical contacts, wireless charging enables fully automated energy replenishment without mechanical wear and can be seamlessly integrated into the robot itself. The concepts investigated by Fraunhofer IISB target charging powers from 200 W up to 7.2 kW per foot of a robot with DC-to-DC efficiencies of up to 97 %, making wireless power transfer a viable option even for highly mobile robotic systems.

The envisioned application scenario is illustrated in the conceptual depiction of a humanoid robot charging through coils integrated into its feet in figure 3. The receiver coils are embedded directly into the robotic structure and transfer energy from floor-integrated primary coils without requiring dedicated charging connectors. This approach not only simplifies autonomous operation but also enables highly position-tolerant charging processes suitable for real production and logistics environments.

The underlying charging concept is based on a modular receiver architecture integrated into the robot feet. A single receiver with 12 cm diameter can transfer up to 3.6 kW, while the available charging power scales with the number of active receiver coils. Configurations with two and four coils provide charging powers of approximately 7.2 kW and more than 14 kW, respectively, while maintaining high overall efficiency.

From a power-electronics perspective, maintaining high efficiency despite unavoidable air gaps and positioning tolerances represents the primary challenge. The achievable transfer efficiency is determined by the magnetic coupling coefficient k, the resonator quality factors Q1 and Q2, and the losses of the semiconductors. High-performance IPT systems therefore require simultaneous optimization of coil geometry, resonant compensation networks and converter topology.

To address this challenge, the charging infrastructure can be implemented as a segmented field of individually controllable

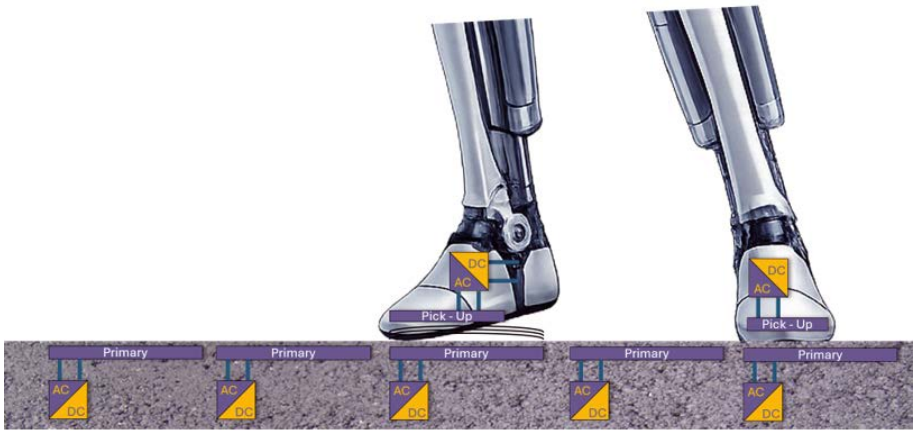


Figure 4. Distributed inductive charging infrastructure with segmented primary coil fields. Individual coil segments are activated according to robot position, enabling stationary as well as dynamic charging based on technologies developed within the Fraunhofer IISB E|Road program. (Image: Fraunhofer IISB)

primary coils embedded in the factory floor. Depending on the robot position, only the required coil segments are activated, enabling highly localized energy transfer while minimizing standby losses and stray magnetic fields. As the robot moves through the environment, the active charging zone effectively follows the robot by sequentially energizing neighboring coil segments.

This concept directly builds on the extensive activities of Fraunhofer IISB in the field of dynamic wireless power transfer. Within the E|Road Center, technologies for stationary and dynamic charging of electric vehicles are being developed and industrialized. The same principles can be transferred to robotic systems, allowing energy to be supplied not only while robots are stationary, but also while moving through production facilities or logistics environments.

Such an infrastructure fundamentally changes the system-level optimization of robotic platforms. Instead of periodically interrupting operation for charging, robots can continuously replenish energy while standing at workstations, waiting for tasks or moving along frequently used transportation routes. If part of the required energy is supplied dynamically by the environment, onboard battery capacity can be reduced, resulting in lower system mass, lower actuator loading and improved overall efficiency. Particularly for humanoid robots, where battery weight directly impacts locomotion energy demand and actuator sizing, infrastructure-supported charging may become a key enabling technology for future large-scale robotic deployment. st

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ABOUT FRAUNHOFER IISB

Fraunhofer IISB is one of Europe's leading research institutes in power electronics, spanning the entire innovation chain from semiconductor technologies and power devices to electric drives, energy systems and application-oriented power-electronic solutions. The institute combines expertise in power semiconductor technologies, converter systems, electric machines, battery systems, wireless power transfer and reliability engineering within a single research environment.

In the field of robotics, Fraunhofer IISB focuses on the development of the physical components required for future highly mobile robotic systems like high-power-density actuator systems, integrated power electronics for robotic joints, low-voltage GaN- and Si-based converter technologies, wireless charging infrastructure and the electro-thermal-mechanical co-design of highly integrated mechatronic subsystems. st

GaN-Based Motor Drive Architecture for Robotics and UAV Applications

Robotics and drones demand compact, efficient motor drives with high power density. Using an integrated GaN power module, EPC demonstrates a three-phase inverter designed for high-frequency operation in space-constrained robotic joints and drone propulsion systems.

By Maurizio Di Paolo Emilio, Director of Global Marketing Communications at Efficient Power Conversion (EPC)

The proliferation of small electric motors in robotics and unmanned aerial systems is creating demand for highly integrated and efficient motor-drive electronics. In the context of humanoid robot joints, robotic hands, and lightweight drone propulsion systems, we require power converters that have a high current density in very limited mechanical space. The motors are usually characterized by low phase inductance and low winding resistance, so that the inverter switching performance is particularly important. Higher switching frequencies can enhance current regulation bandwidth and dynamic response and improve overall efficiency while reducing the size of passive components under these operating conditions.

For these applications, GaN power devices are considered more and more, due to their capability of fast switching and reduced switching losses as compared to conventional silicon MOSFETs. GaN technology allows PWM operation way above 100 kHz enabling higher power density and more compact inverter architectures.

At the same time, the trend toward miniaturization is pushing the integration of semiconductors to the limit. Reducing the number of external components and simplifying PCB layout are becoming critical design objectives in compact motion systems. The monolithic integration of power devices, gate drivers, and auxiliary circuitry can greatly facilitate the system and improve the overall electrical performance.

The experimental system described in this article is based on the EPC91132 reference de-

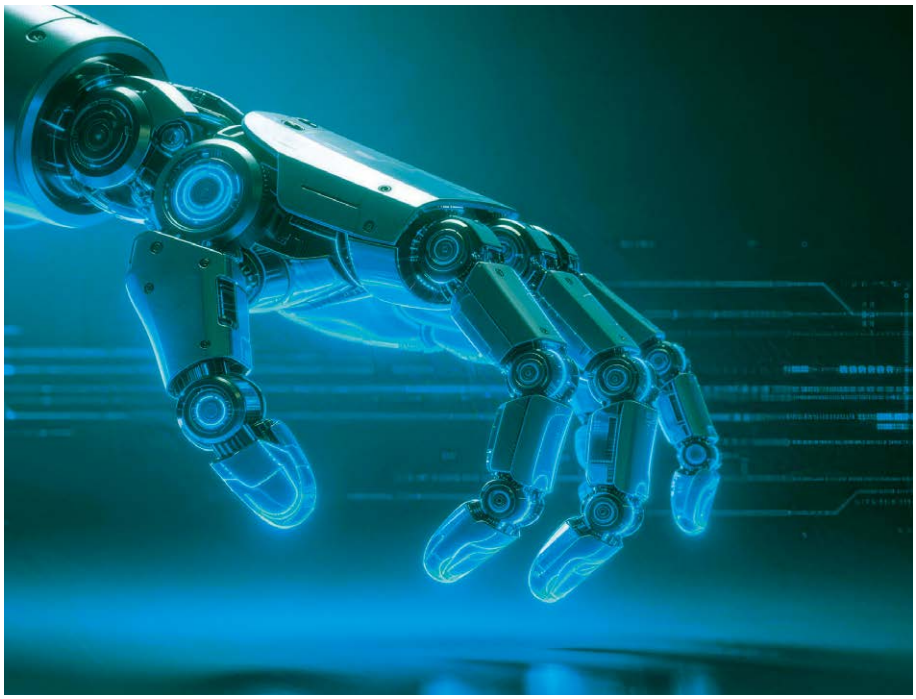


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sign developed by Efficient Power Conversion (EPC) and employs the EPC33110 integrated GaN power module.

Compact Three-Phase Inverter Architecture

To explore the advantages of highly integrated GaN technology in miniature motor-drive applications, a compact three-phase inverter platform was developed. The system is designed to operate in a DC bus voltage range from 10 V to 60 V and integrates the main functions needed for closed-loop motor control.

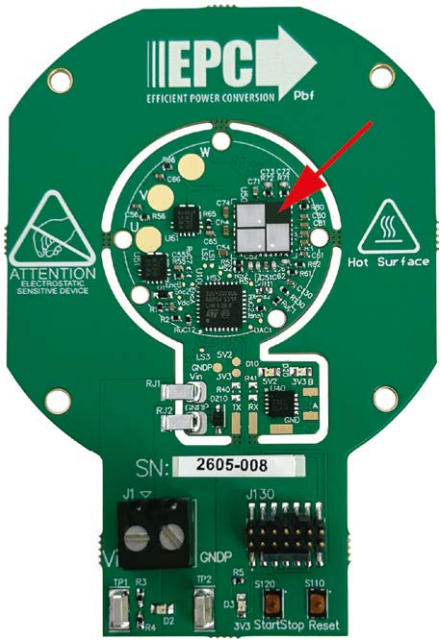


Figure 1: Overview of EPC91132 board – three-phase inverter for drones and humanoid motor joints. The red arrow indicates the EPC33110 module.(Images: EPC)

The inverter has integrated control electronics, auxiliary regulated power supplies, current sensing circuitry with overcurrent protection, monitoring of the DC bus voltage, and a magnetic encoder interface for rotor position feedback. A dedicated serial interface allows communication and real-time operation.

The platform mechanical structure was optimized to support multiple motor formats with the same core power stage. The inverter can be adapted for robotic joint actuators, or for compact drone propulsion systems, by changing the external PCB structure without changing the main electronic architecture (Figure 1).

Integrated GaN Power Module

The power stage is implemented using a highly integrated three-phase GaN module based on three monolithic half-bridges in a compact QFN package. The GaN power transistors, gate drivers, bootstrap circuits and level-shifting circuitry are all integrated into each half-bridge (Figure 2).

The lateral device structure of GaN technology allows the integration of logic and power devices on the same substrate, thus facilitating implementation of monolithic half-bridge architectures. The integration of the gate-driving functions in the module reduces PCB parasitics, layout complexity and the number of required external components.The compact packaging also helps to achieve a high power density while allowing effective thermal dissipation through exposed top side cooling surfaces. The module supports operation up to 80 V from a single 5 V supply and is compatible with both 3.3 V and 5 V logic interfaces. The combination of high-frequency operation, compact dimensions, and integrated gate-driving functionality makes the platform suitable for miniature motion-control systems such as humanoid robot joints and lightweight drone propulsion systems.

Evaluation in Robotic Joint Applications

The inverter platform was tested in a robotic joint motor application with a 48-VDC bus. Experimental characterization was carried out on a dynamometric test bench, under continuous load conditions up to 11 ARMS phase current.

The inverter was operated at PWM frequencies of 60, 80, and 100 kHz with a dead time of 20 ns. In steady-state conditions, continuous operation at 11 ARMS resulted in a temperature increase of approximately 70 °C without the use of forced-air cooling.

Thermal measurements were performed with and without the motor enclosure acting as a passive heatsink for the inverter assembly. After about ten minutes of operation the system had reached equilibrium. The motor was tested in the low rotational speed, high torque conditions typical of robotic joint applications.

The temperature was monitored using thermocouples located above the power module and through infrared thermal imaging measurements.

While in the case of humanoid robot joints, natural convection cooling is the only option, in drone applications, the propellers generate strong airflow, providing thrust and effective cooling for the entire system, thereby increasing the inverter's current capability.

Evaluation in Drone Propulsion Applications

Similarly the same inverter architecture was tested in a drone propulsion configuration using a compact outrunner motor coupled to a 12 inch propeller and powered from a 24 V

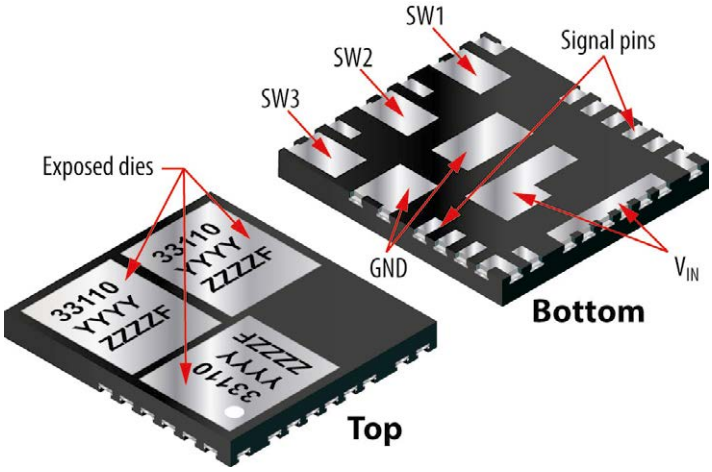


Figure 2: The EPC33110 integrates three GaN half-bridges together with gate drivers, bootstrap circuitry, and level shifters within a 6 mm × 6.5 mm QFN package

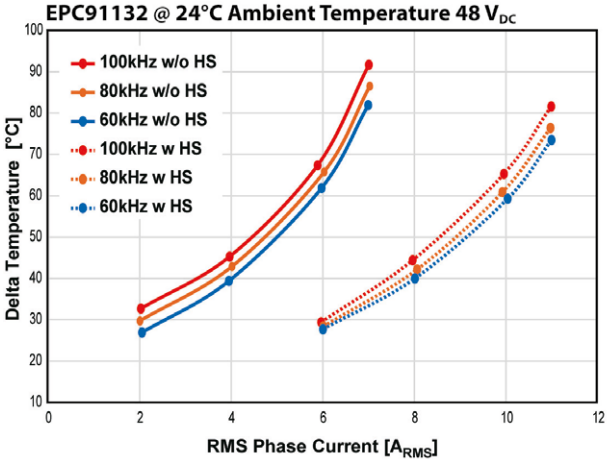


Figure 3: Output current capabilities of EPC33110 operated at 100 kHz PWM in a humanoid robot joint. DcBus = 48 V, PWM frequency = 60, 80, 100 kHz. Without (left) and with (right) the motor case as heatsink for the module

DC source. The motor was tested in a speed range of approximately 1000 RPM to 3400 RPM with the inverter running at a continuous PWM frequency of 100 kHz and a dead time of 20 ns.

For each speed, the device temperature was measured by attaching a thermocouple to the top of the EPC33110 module and waiting approximately 10 minutes until thermal equilibrium was reached. The average input power required at each speed was measured (Figure 4).

The drone motor was driven at a switching frequency of 100 kHz with a 20 ns dead time.

In this configuration the airflow produced by the propellers was effective to cool the motor and inverter assembly. Experimental measurements indicated a small increase in temperature above ambient during continuous operation. The inverter behavior under realistic propulsion loading conditions was characterized by measuring the input current, input power and propeller torque over the range of operation.

EMI Reduction and Guidelines for PCB Design

High dv/dt and di/dt transitions in high-speed GaN switching can generate ringing and radiated emissions making it difficult to meet the electromagnetic interference (EMI) requirements especially in small motor drives for humanoid robots and drones. Mitigation begins with the reduction of parasitic inductance at package and PCB level.

Integrated GaN power stages integrate power devices and gate drivers into low-inductance packages to reduce parasitics. At the PCB level, the critical commutation loops should be routed as short, wide copper paths with tightly coupled return currents on adjacent layers. This reduces loop inductance, stored transient energy and the effective antenna area that contributes to radiated EMI. High frequency decoupling capacitors have to be placed very close to the switching half bridges to suppress voltage overshoot and ringing. GaN devices are also free from reverse-recovery charge (QRR) and do not have the high energy transient oscillations usually associated with the commutation of silicon MOSFETs.

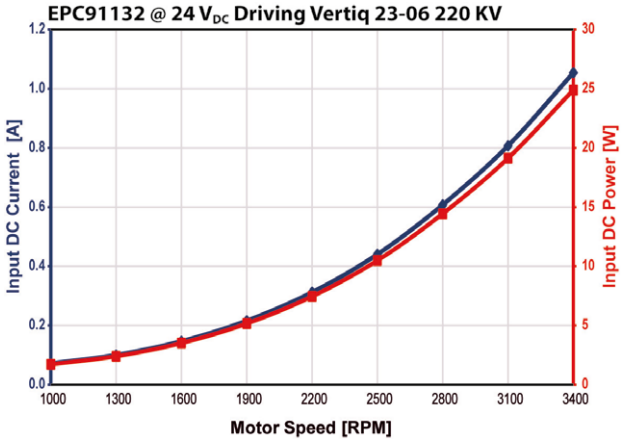


Figure 4: Input DC current and power required by the motor to sustain the torque generated by the propeller vs. motor speed

Conclusion

The growing use of compact motors in robotics and UAV systems is pushing the transition towards highly integrated GaN-based motor-drive architectures. Experimental tests in robotic joints and drone propulsion platforms show that the compact GaN inverters are capable of withstanding demanding operating conditions with acceptable thermal performance and manageable EMI behaviour, suitable for next generation robotic and aerial mobility applications. st

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A 100 kW Bidirectional DC Fast Charger: Architecture, Design and Performance

How can power electronics for megawatt charging be designed modularly? This paper presents a multiport concept from Oak Ridge National Laboratory (ORNL) for the system architecture, and a 100 kW bidirectional demonstrator from onsemi featuring a silicon carbide (SiC) T-NPC stage and two dual-active bridge (DAB) converters for the practical implementation, including the thermal and control-related limitations.

By Peter Gergely and Andrej Kanovsky, onsemi Slovakia

Megawatt charging systems are designed to transfer large amounts of energy in short periods whilst supporting different vehicle and battery voltages. Modular architectures are well suited to this purpose, with the grid-side AC/DC conversion and the vehicle-side DC/DC conversion being functionally separated. The AC/DC stage generates a regulated DC intermediate circuit voltage, while subsequent DC/DC converters adapt this voltage to the respective vehicle battery.

Multiport architecture for megawatt charging

The Oak Ridge National Laboratory (ORNL) has proposed a multiport concept that illustrates such an architecture for megawatt charging. It connects multiple charging points, stationary energy storage systems, and photovoltaic installations via a shared electrical infrastructure. The entire charging station has a capacity of 10 to 15 MW; individual multiport units are designed to transmit power outputs of between 1 and 5 MW. A converter for heavy-duty electric vehicles has a rating of 1.2 MW and can supply either a single charging point with the full power or three charging points, each with 400 kW.

The concept provides a DC/DC stage in a dual-active-bridge topology for each charging point. A DAB consists of two actively controlled full bridges which are coupled to one another via a high-frequency transformer. The primary-side bridge generates a high-frequency AC voltage from the DC link voltage. Following galvanic isolation, the second bridge performs active rectification and provides a DC voltage on the vehicle side. Since both sides have active power switches, energy can, in principle, be transferred in both directions. This means that a DAB can charge a vehicle battery and also transfer energy from a vehicle or stationary battery back into the shared DC system. Actively controlled semiconductors also enable synchronous rectification. During this process, the transistors perform the function of passive rectifier

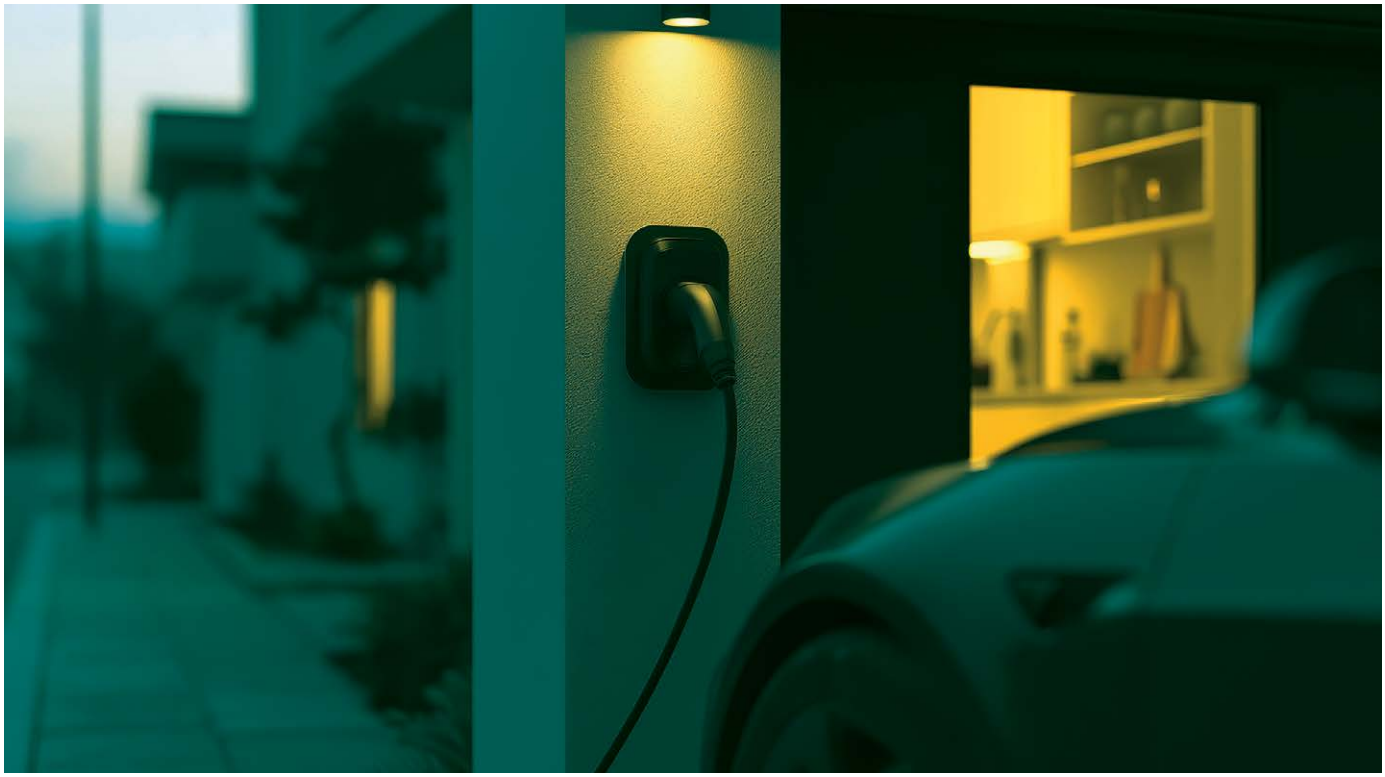
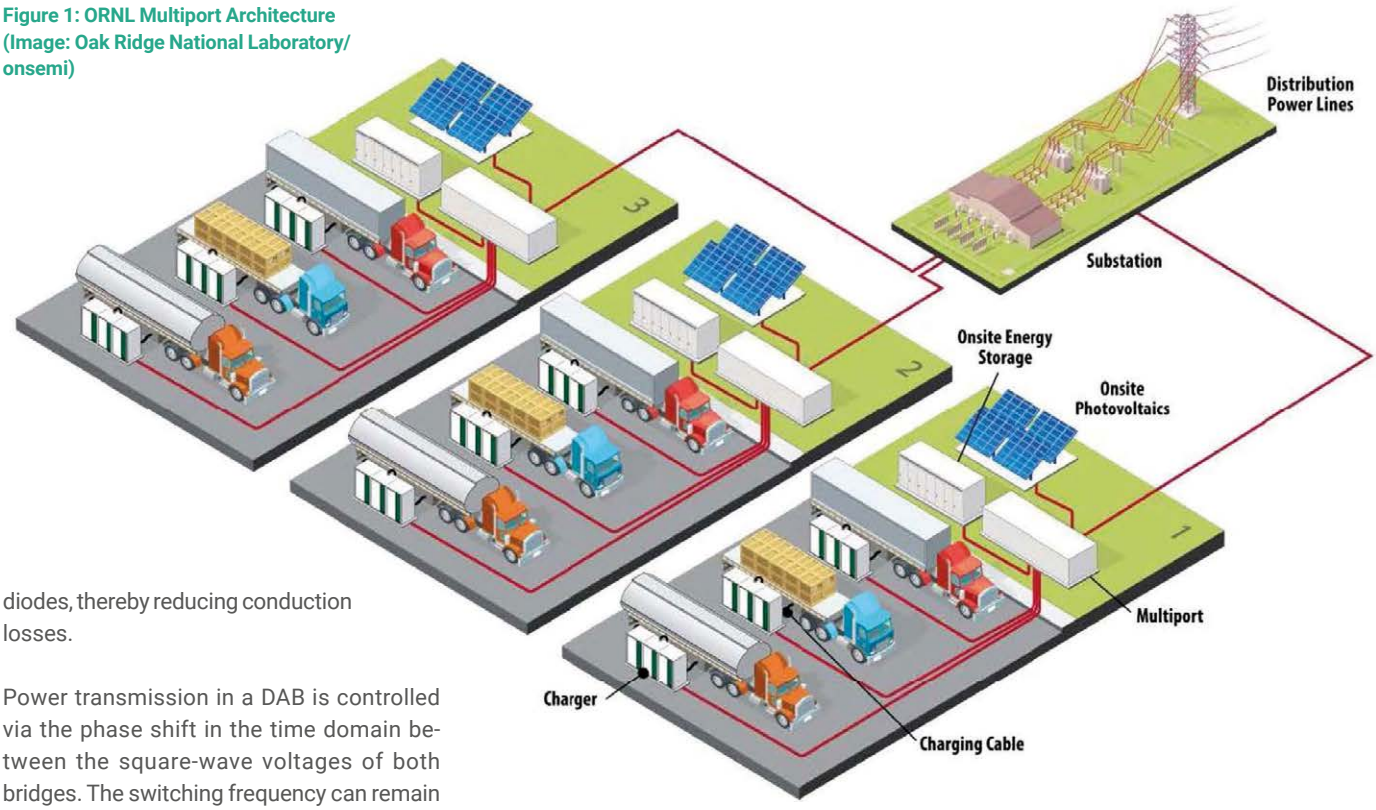


Image: Yulia/stock.adobe.com

Figure 1: ORNL Multiport Architecture (Image: Oak Ridge National Laboratory/ onsemi)



diodes, thereby reducing conduction losses.

Power transmission in a DAB is controlled via the phase shift in the time domain between the square-wave voltages of both bridges. The switching frequency can remain constant. This simplifies the design of the high-frequency transformer and the filters, as the main switching and interference components occur within defined frequency ranges. This control structure can also accommodate operation under varying loads.

From the three-phase mains supply to the DC intermediate circuit

On the mains side, an active three-phase power factor correction (PFC) stage handles the AC/DC conversion. This stage regulates the currents of the three mains phases, making them as sinusoidal and in phase with the respective voltages as possible.

This improves the power factor while reducing the harmonic content of the input current. At the same time, the PFC stage stabilizes the DC bus voltage for the downstream DC/DC converters.

A T-type neutral-point-clamped topology is ideal for this active mains stage. This three-point circuit can connect a phase terminal to three different voltage potentials. Compared with a two-stage circuit, this results in smaller voltage steps. This reduces current ripple and facilitates filtering. Depending on their position within the circuit, individual semiconductors only need to switch a portion of the total intermediate circuit voltage.

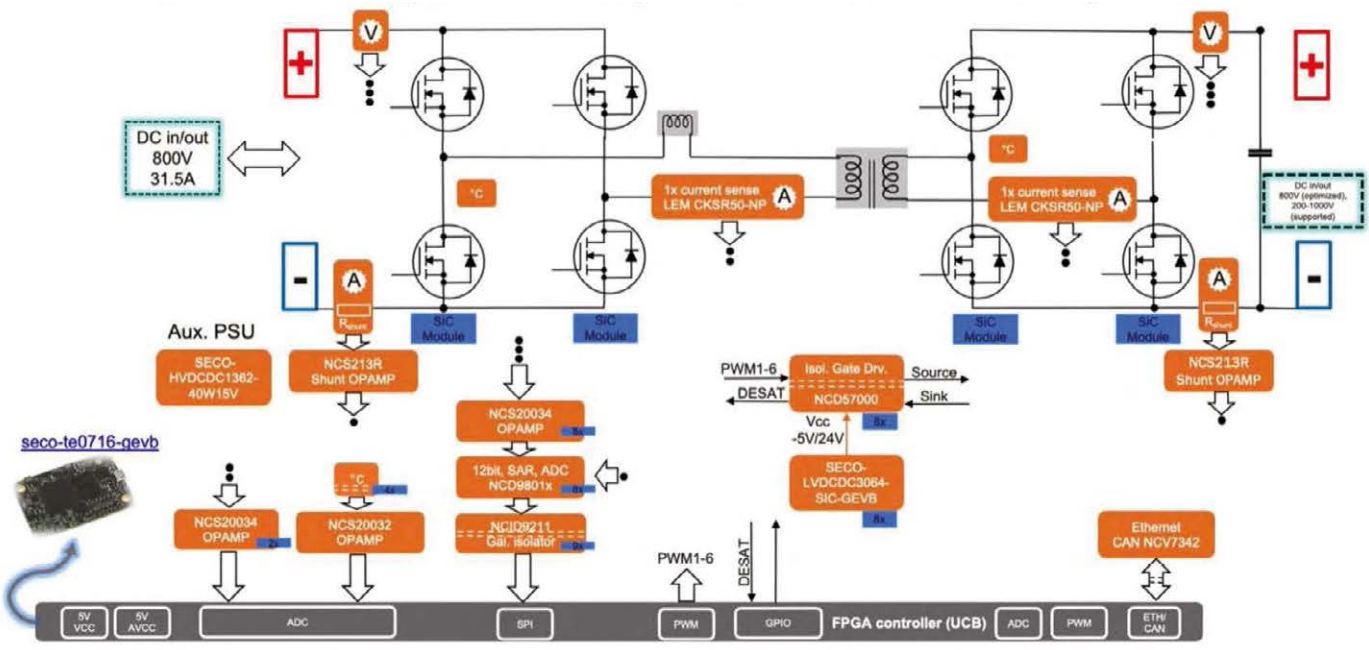


Figure 2: DAB Block Diagram (Image: onsemi)

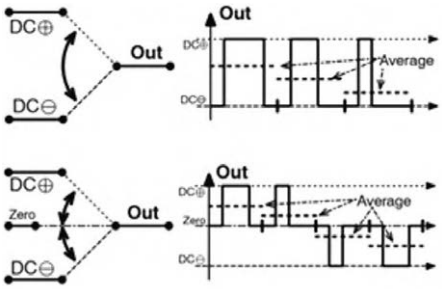


Figure 3: Unlike a two-stage converter, a three-point topology can also produce a zero state. The smaller voltage steps reduce current ripple and make filtering easier. (Image: onsemi)

As charging power increases, integrated silicon carbide (SiC) power modules are becoming increasingly important. These modules combine several power switches of a given topology within a single package, enabling short electrical connections between the semiconductors. At the same time, their substrates establish a defined thermal link to the heat sink. This integration reduces parasitic inductances and aids the dissipation of heat generated by the semiconductors.

As charging power increases, cooling also becomes a key aspect of the system design. In addition to the power modules, active cooling of the cables and connectors may be necessary for very high charging currents. To facilitate this, a closed-loop liquid circuit pumps coolant through pipes running parallel to the power cables and on to the connector. The heat absorbed there is transported back to the charging station and transferred to the cooling system.

These requirements result in a two-stage, modular design. An active T-NPC stage connects the system to the three-phase mains supply and generates a regulated DC link voltage. Galvanically isolated DAB converters adapt this voltage for the vehicle battery and enable bidirectional energy flow. SiC power modules and liquid cooling help manage electrical and thermal loads.

Simulation of a separate 50 kW T-NPC input stage with a SiC power module yields an efficiency of 98.96 per cent at an input voltage of 400 V AC, an output voltage of 800 V DC, and a switching frequency of 20 kHz. At a heat sink temperature of 90 °C, the junction temperature reaches a maximum of 125.34 °C, with losses of 523.9 W reported for the module. It should be noted that these values are derived from a simulation and are different from the measurements on the 100 kW demonstrator described below.

The Bidirectional 100 kW Demonstrator

onsemi's 100 kW DC fast-charging demonstrator brings the above-described circuit concepts to life in a practical power unit. Designed as a bidirectional system, it supports the flow of energy from the grid to the vehicle and back again. Galvanic isolation between the grid and vehicle sides is an essential part of the safety concept for DC charging systems. A target peak efficiency of over 97 per cent has been specified.

The grid connection is three-phase with a protective earth conductor. The input voltage range extends from 400 to 600 V AC at frequencies between 40 and 70 Hz. The maximum phase current is specified as approximately 170 A_(eff). The overall specification states a voltage range of 680 to 1,500 V DC for the output.

For the input current, total harmonic distortion of no more than 5 per cent is specified at an output power of between 50 and 100 per cent. The specified power factor is at least 0.9 at 25–50% output power, at least 0.98 at 50–100% output power and at least 0.99 at rated power, rated input voltage and rated frequency.

The maximum switching frequency of the AC/DC stage is 70 kHz. The second harmonic should remain below 150 kHz when selecting the frequency; this is a specified design target in accordance with EN 55011 Class A and FCC Part 15 Class A. The DC/DC stage operates at 100 kHz.

Power electronics and thermal design

The system consists of a PFC stage and two DC/DC converters. The PFC stage uses three T-NPC SiC modules with 2 kV chips and a specified turn-on resistance of 8 mΩ. The two DAB units are each rated at 50 kW. Each unit contains four 1200 V SiC modules of the NXH003P120M3F2PTNG type with a specified on-resistance of 3 mΩ.

The power electronics are distributed across two circuit boards. The primary-side power board comprises the PFC stage and the primary sides of the two DAB converters. The secondary-side power circuit board houses the secondary sides of the DAB converters.

The power modules are liquid-cooled. A flow rate of 10 l/min and a maximum pressure drop of 120 mbar are specified for the heat sinks at a coolant temperature of 55 °C. The modules are connected to a standard cold plate via thermal interface material.

Assembly and commissioning

Testing of the 100 kW power unit begins with an initial prototype test of the individual circuit boards. This involves checking the component values and the quality of the solder joints, among other things. This is followed by commissioning tests to verify the functionality of the circuit boards.

When commissioning the PFC stage, the necessary components are installed first and the laboratory equipment is prepared. Testing then takes place in both rectifier and inverter

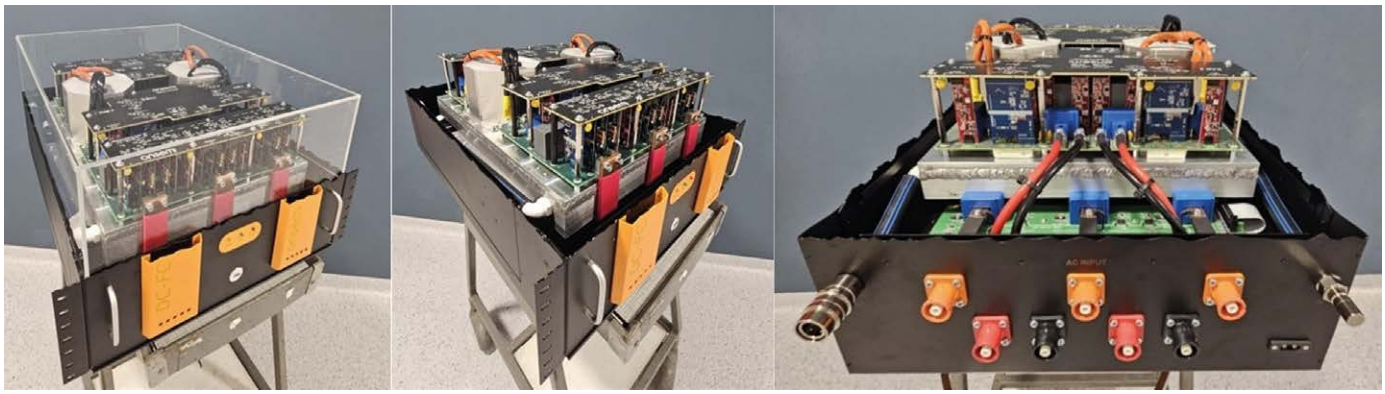


Figure 4: Final Assembled System of the Demonstrator (Image: onsemi)

modes. During this process, operational behaviour and efficiency are recorded. The DAB stages undergo a similar commissioning process.

The test plan comprises mechanical and visual inspections; commissioning of the individual circuit boards; testing of the mains input and AC/DC stage; commissioning of the DAB converters; and examination of the integrated system. It includes step-by-step load changes, variations in voltage and frequency, efficiency measurements and testing of fault and protection functions. These include overcurrent, overvoltage, undervoltage, and thermal overload. The system is controlled using an external real-time controller of the OPAL-RT OP4512 type.

PFC stage measurements

Power dissipation and efficiency were measured at the PFC stage. However, the intended output power of 100 kW could not be achieved for all combinations of input and output voltages. The junction temperature of the transistors was a limiting factor.

At an input voltage of 600 V AC, the minimum required output voltage increased to 860 V to keep the PFC stage in boost mode. Due to a limitation of the power analyzer used, the maximum output voltage was reduced from 1500 V to 1495 V for the measurements.

Measurements of the DAB stages

The power dissipation and efficiency of the two DAB stages were also determined. Initially, both converters were measured separately, with each achieving a maximum output power of 50 kW.

In order to cover a wide battery voltage range, the two DAB converters can be connected in parallel or in series on the vehicle side. They operate in parallel at battery voltages of 425 to 750 V. A series connection is provided for voltages between 850 and 1,500 V, and a transition range between 750 and 850 V exists where both connection configurations are possible in principle. However, the DAB stages operate outside their ideal voltage ratio of 1:1 within this range. In this cases the more favorable configuration should be determined based on efficiency rating.

Thus the description of the operating modes extends down to 425 V on the battery side, hence the overarching specification states an output voltage range of 680 to 1,500 V DC. The documentation does not explain these differing figures in detail. There are four operating modes:

- Charging the battery with DAB stages connected in series;
- Charging the battery with DAB stages connected in parallel;
- Inverter operation with DAB stages connected in series;
- Inverter operation with DAB stages connected in parallel.

In inverter mode, the operating points could not be measured at battery voltages of 800 V and 850 V. Above 750 V, the centre point of the DC intermediate circuit became unbalanced. Summary efficiency measurements of the complete system were carried out at a transmitted power of 50 kW and a three-phase mains voltage of 480 V, and at most of the investigated operating points, the measured efficiency was above the specified minimum value. Reducing the gate resistances of the SiC modules in the PFC and DAB stages is suggested as a way of improving efficiency further. This adjustment is planned to optimize the system further.

Further development required

The 100 kW power unit incorporates SiC power modules alongside measurement, control and protection functions within a bidirectional configuration. Connecting the two DAB converters in series or parallel enables operation across a wide battery voltage range.

Further development is required in terms of the thermal behavior of the SiC modules in the PFC stage and the transformers in the DAB converters. The stability of the control algorithms also needs to be improved further. Mechanical optimization could reduce the size and weight of the assembly by 25–30%. Further work is planned to determine how the system can be revised to fully achieve the intended performance targets. st

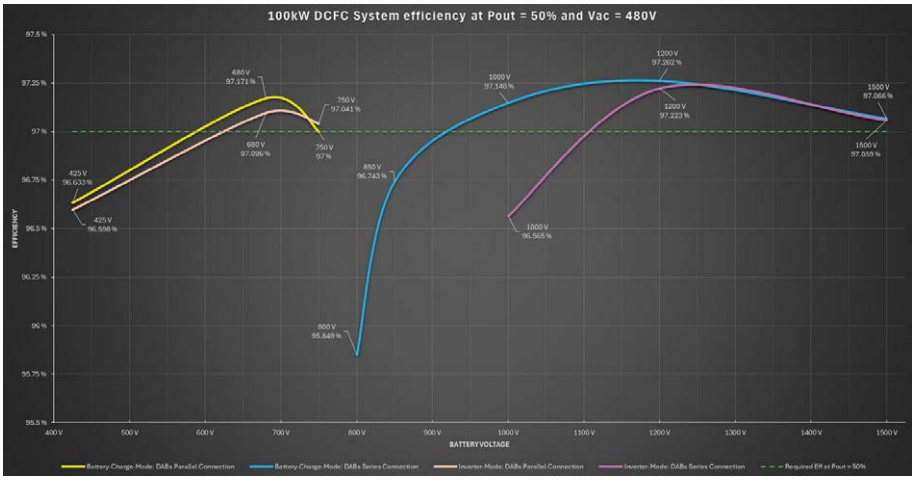


Figure 5: 100 kW DC Fast Charger Total System Efficiency at 50% Power and Vac 480 V (Image: onsemi)



Peter Gergely is a Systems Engineering professional at onsemi specializing in automotive power electronics, advanced packaging technologies, and semiconductor integration. His expertise spans power module development, SiC-based systems, thermal and reliability engineering, advanced manufacturing processes, and cross-functional technology leadership. He actively contributes to next-generation power electronics development and European semiconductor innovation initiatives.



Andrej Kanovsky holds an M.Sc. in Telecommunications and a Ph.D. in Power Electronics from the University of Žilina. He spent four years designing SMPS at Bel Power Solutions and twelve years in NPI and R&D at Delta Electronics. Since 2021, he has been a Principal Application Engineer at onsemi.

In Search of the “Killer App” for Bidirectional GaN: Something Entirely New in Power Electronics

The introduction of bidirectional power semiconductors based on GaN and SiC could be described as a step into a brand-new era. Instead of having to rely on multilevel topologies, bidirectional designs can now be implemented much more easily. That said, the number of current applications remains quite limited.

Improving what already exists this has been the guiding principle for the mainstream of electronics development, including in the semiconductor sector. Higher efficiency, lower losses, and increased power density have essentially been the “holy trinity” of power electronics over the last few decades. While new semiconductor technologies like SiC and GaN have provided an additional boost to these efforts, the underlying system architectures of power electronics have remained largely unchanged.

For this reason, it drew significant attention when, at PCIM 2025, three prominent power semiconductor manufacturers introduced something entirely new in the 650 V range: bidirectional GaN switches. Unlike conventional approaches, these new offerings did not merely represent an incremental improvement over existing silicon-based solutions. Instead, they provided engineers with the opportunity to fundamentally rethink how electrical energy is routed, controlled, stored, and converted within an entire power supply system.

Their ability to control current flow in both directions switching positive and negative half-cycles directly eliminates the need for additional anti-parallel diodes or extra FETs. This makes bidirectional power semiconductors, such as the 650 V GaN switches unveiled by Infineon Technologies, Renesas, and Navitas, ideal for applications like AC/DC converters, solid-state switches, and bidirectional power supplies, without requiring the use of multi-level topologies. Furthermore, employing these bidirectional switches not only reduces the required chip area on the board but also lowers conduction losses, as there is only a single, shared depletion region.

Creating a bidirectional flow of current was already possible, but it previously required significantly more components than are needed with today’s highly integrated GaN solutions. “The true value of this technology extends far beyond performance at the component level,” argues Mirco Drews, Senior Manager of Strategic Business Development at Nexperia. “The greatest impact of these components will be felt at the system level, where they will enable entirely new power architectures in the future.”

While energy was traditionally routed from source to load along a fixed path, this process will become significantly more dynamic in the future. It is expected that future systems will essentially exist in a constant state of balancing a continuous redistribution between energy storage and energy reuse, depending on specific operating conditions. Bidirectional GaN switches are set to play a key role in these future applications.

On the board, the use of bidirectional GaN power semiconductors not only saves chip area but also reduces conduction losses, as there is only a single shared depletion zone. Consequently, their implementation lowers both the potential design costs for an application and the number of components required for its realization which, in turn, impacts inventory requirements. For this reason, it was already clear by 2025 that 650V bidirectional GaN power semiconductors would help achieve significant cost savings at the system level.

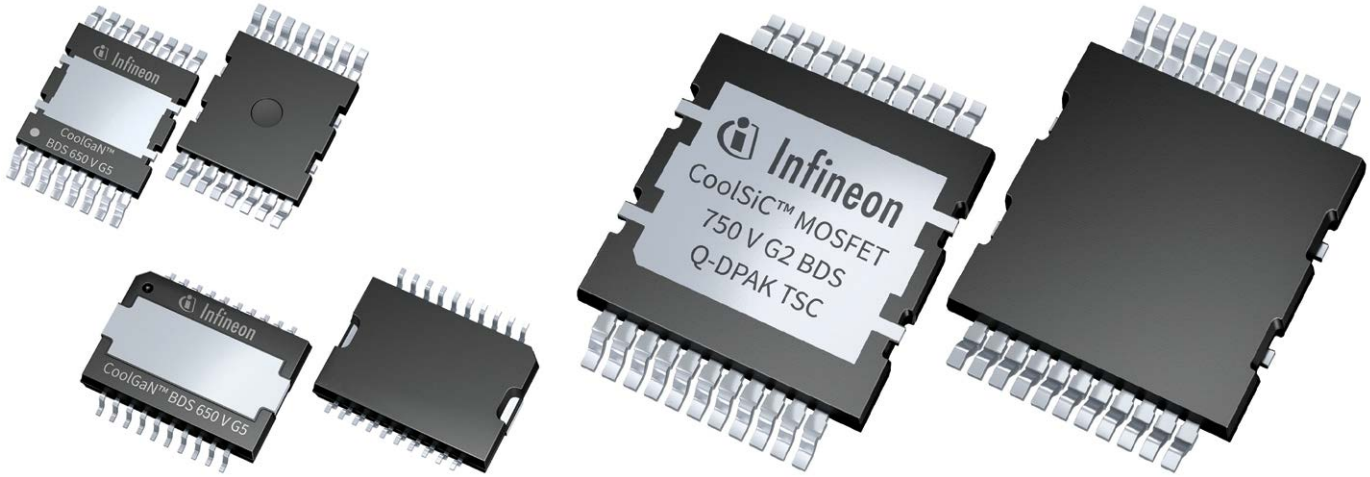
While bidirectional GaN power semiconductors did exist previously, they were limited to low-voltage versions. According to Dr. Gerald Deboy, a Fellow at Infineon Technologies



Mirco Drews, Nexperia:
“The true value of bidirectional power semiconductors extends far beyond conventional solutions; these new components will have their greatest impact at the system level, where they will enable the realization of entirely new power architectures in the future.”



Dr. Gerald Deboy, Infineon Technologies:
“In the high-voltage version of bidirectional GaN power semiconductors, substrate stabilization is of critical importance. It helps to improve isolation between components and increase the breakdown voltage. Highly insulating materials, such as SiC or sapphire, are well-suited for this purpose.”



Since PCIM 2026, Infineon Technologies has been pursuing a dual-track strategy regarding bidirectional power semiconductors. In addition to the 650 V CoolGaN Bidirectional Switch (BDS) (left)—which was introduced the previous year the company unveiled the SiC variants of its 750 V CoolSiC BDS series (right) at this year's PCIM. (Images: Infineon Technologies)

Austria, the key difference in the now-available high-voltage versions lies in substrate stabilization: "This helps improve isolation between the components and increases the breakdown voltage. Highly insulating materials, such as SiC or sapphire, can be used for this purpose."

More than a year ago, Infineon Technologies introduced its 650 V bidirectional GaN power semiconductors, featuring a common-drain design and a dual-gate structure. These components leverage the company's robust gate-injection transistor technology to provide a monolithic bidirectional switch capable of actively blocking both voltage and current in either direction. There is no doubt that such switches could enable innovative battery architectures for instance, in electric vehicles. They would, for example, allow for the dynamic control of individual battery modules based on their "state of health" and specific operating conditions. This advancement would make it possible to improve battery utilization while simultaneously enhancing the robustness of the overall system.

While the primary focus for future applications might have been on the automotive sector a year and a half ago, a growing number of promising use cases in data centers are now coming to the fore. Beyond the question of where all the AI processors for these planned data centers will actually come from, another issue is becoming increasingly pressing: how can the enormous energy costs of these data centers be brought under control? Here, too, bidirectional GaN power semiconductors offer excellent potential across the entire power supply chain. They provide the means to implement power distribution architectures capable of handling increasingly dynamic, bidirectional energy flows while simultaneously minimizing conversion losses.

According to Nexperia executive Drews, the true value of bidirectional GaN power semiconductors lies in shifting the focus of innovation moving away from optimizing individual power stages toward redesigning the entire system architecture. "Instead of simply continuing to shrink existing converters and make them more efficient, engineers can use these new bidirectional components to explore entirely fresh approaches to energy management, protection schemes, power distribution, and power conversion." Are these possibilities actually being embraced by developers? If you ask one of the three innovators, Navitas Semiconductor, they point out that their bidirectional 650 V GaN power semiconductors are currently being used in solar microinverters from Enphase Energy though they were already being used there last year. When the market potential for these products is discussed, the aforementioned applications are frequently cited, yet no one explicitly confirms that they are actively pursuing this approach. As of today, no other suppliers of such solutions have entered the market, even though several prominent power semiconductor manufacturers had previously indicated that they were working on similar products. Perhaps not enough time has passed for developers to truly explore the new possibilities offered by bidirectional GaN power semiconductors?

Of course, bidirectional power semiconductors can be implemented using materials other than GaN for instance, SiC. Infineon Technologies has taken this route, unveiling the industry's first SiC bidirectional switches at this year's PCIM exhibition. These are based on the company's 750 V CoolSiC G2 technology, which combines a vertically integrated dual-die design featuring a common-drain configuration into a single component housed in a top-side cooled Q-DPAK package.

According to the manufacturer, these components offer excellent RDS(on) x Qfr and RDS(on) x QOSS figures, as well as a low Qg. Consequently, switching and conduction losses are reduced, enabling ultra-fast and efficient switching.

Infineon states that a typical VGS(th) of 4.5 V at +25 °C, combined with a very low QGD-to-QGS ratio, increases immunity against parasitic turn-on. Meanwhile, an extended gate-bias tolerance ranging from -11 V to 25 V enhances design flexibility and the compatibility of these power semiconductors. With a voltage rating of 200 V/ns, these devices support high-frequency designs without requiring any compromises in terms of longevity.

As for potential applications, these bidirectional components are particularly well-suited for automotive use specifically in on-board chargers, EV charging systems, eFuse circuits, and pre-charge circuits. For instance, when paired with a CoolSiC H-DPAK half-bridge, they facilitate a seamless transition to single-stage, SiC-based on-board chargers, enabling designs that offer exceptionally high power density while remaining space- and cost-efficient. eg

From niche event to world-leading trade fair

Since its foundation in 1979, PCIM has evolved from a small specialist conference into the world's leading platform for power electronics. Furthermore, the subject is becoming increasingly important thanks to electrification, energy efficiency, e-mobility, and AI applications.

When PCIM first opened its doors at the Sheraton Hotel in Munich, no one could have imagined that it would one day become the world's most important event for power electronics. The conference was initiated by Gerd Zieroth of ZM Communications. From the outset, he prioritised integrating the specialist conference with the accompanying exhibition, a concept that remains at the core of PCIM to this day. Supported by a dedicated Advisory Board, including renowned experts such as Leo Lorenz, PCIM established a strong technical foundation, with the Advisory Board playing a key role in defining and ensuring the consistently high quality of the conference programme. With just a handful of exhibitors, including Siemens, AEG, Brown Boveri and International Rectifier, and around 200 conference participants, the first event was relatively small-scale. However, it still attracted an international audience, with representatives from France, the UK, Italy, the USA and Japan. Topics covered included power conversion and intelligent drive technology (Intelligent Motion). As well as grid and voltage quality (power quality). However, from the outset, power semiconductor technology and the associated components also played a central role. As well as the power semiconductors themselves, innovative drive concepts also came into focus. Renowned experts in electric drives and motion control such as Dan Jones and Ted Hopper epitomised the spirit of technological innovation of that era.

Move to Nuremberg

PCIM moved from Munich to Nuremberg in 1991. Ten years after the first PCIM, there were 83 exhibitors and 1,354 visitors, while 642 people attended the conference itself. Today, PCIM occupies six exhibition halls and attracts 685 exhibitors, as well as over 16,500 visitors from around the globe. Therefore, from today's perspective, it can be said that growth has been almost continuous over several decades, with the exception of the years affected by the pandemic.



In 2002, PCIM was taken over by Mesago, whilst retaining its fundamental concept. Lisette Hausser, PCIM's Vice President, explains: »The combination of a trade fair, a conference and seminars has proved to be a decisive factor in its success. We see the close link between science and industry as PCIM's unique selling point. This is where developers, researchers, component manufacturers and system providers come together directly, enabling innovations to reach the market more quickly.«

Drivers of growth

The event's growth was primarily driven by the development of power electronics. What was once a specialised field for drives and industrial applications has evolved over time into a key technology for many industries. Electric mobility, renewable energies, industrial automation, railway technology, aviation, and increasingly, data centres, would be unthinkable without high-performance power electronics. »PCIM has benefited from its consistent focus on this field, as well as from linking technology, system aspects and applications at an early stage,« Lisette continues.

Of course, PCIM was not immune to crises either. During the financial and economic crisis of 2008/2009, the event's growth initially stagnated as the automotive sector and industry were severely affected by a slump in demand. However, two new growth markets emerged at that time: photovoltaics and electromobility. The greatest challenge for PCIM, as for all other trade fairs, was the pandemic. No in-person events could take place at that time, so everything had to be converted to digital formats at short notice. Lisette continues: »Despite this, the power electronics market remained stable or even grew in certain sectors, such as data centres and renewable energy.«

Supply chain issues, the semiconductor shortage, and geopolitical tensions in 2022 and 2023 also had an enormous impact on various sectors, as is well known. However, Lisette explains that »this crisis has reinforced rather than weakened the importance of PCIM. It demonstrated that exchange is vital. In an environment characterised by rapid technological and market changes, a trade fair like PCIM is an especially important platform for exchange and networking.«

Internationalisation

PCIM Asia was established as the first PCIM event abroad as early as 2002 – a risky undertaking, as it involved entering an immature market. The market was highly fragmented technologically, there were few standards, and semiconductor expertise in China was

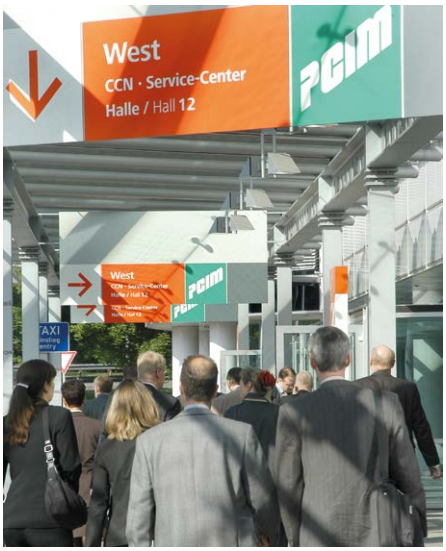


Lisette Hausser, Mesago:
»The history of PCIM is also the story of the rise of power electronics as a vital key technology in today's world.«

still very limited. However, demand for power electronics was also growing rapidly here. Consequently, during its formative phase in China between 2002 and around 2010, PCIM was heavily dominated by international players, with Chinese firms rarely represented in high-end technologies. Lisette: »Back then, PCIM Asia was essentially a channel for technology transfer from West to East.«

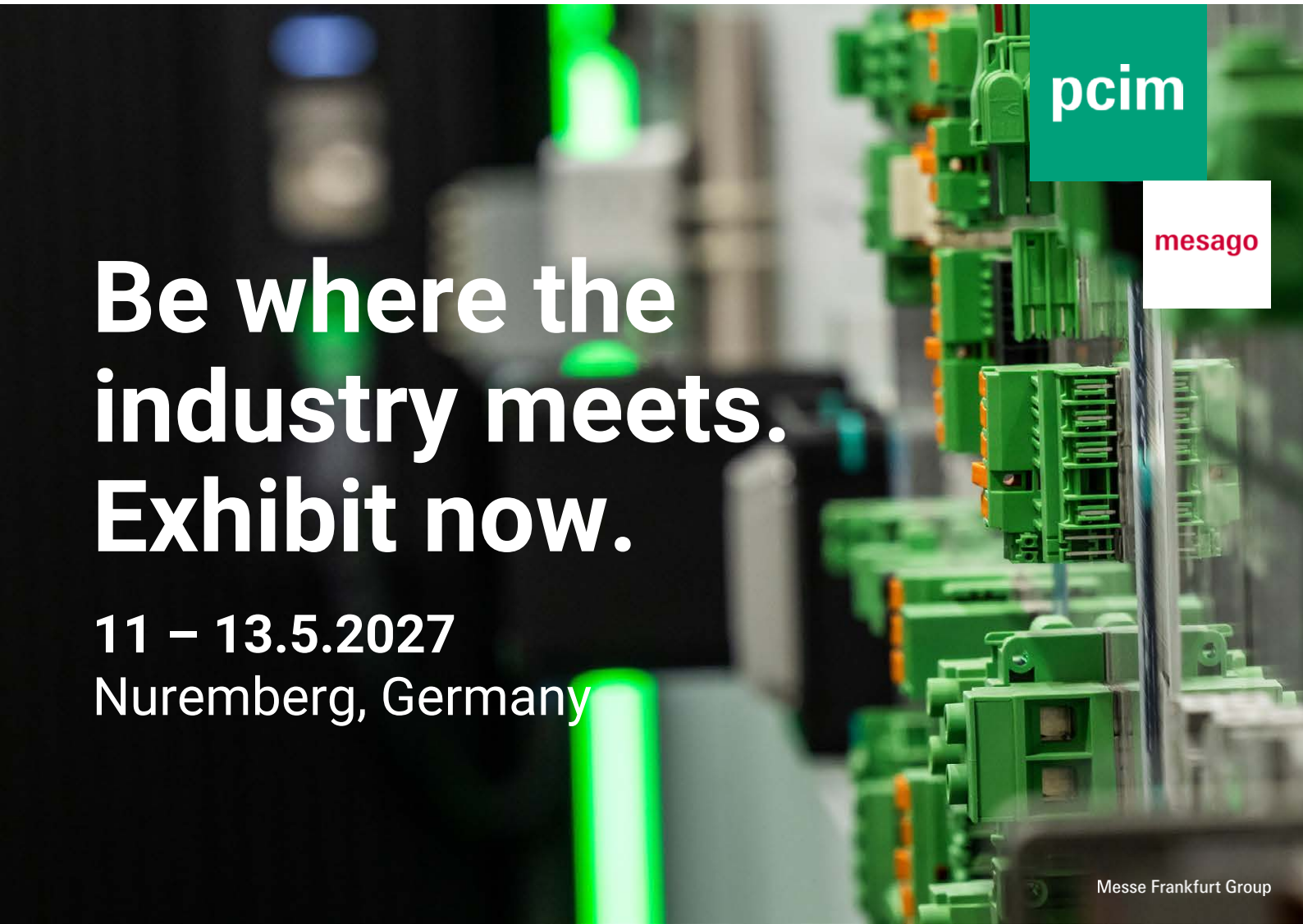
Between 2010 and 2018, PCIM Asia benefited greatly from the rapid growth of the Chinese market. Originally geared primarily towards international companies, it increasingly developed into a platform for the Chinese power electronics industry itself. Lisette continues: »This trend continued between 2018 and 2020. The trade fair evolved from a technology transfer and import channel purely for Western companies to an independent marketplace for Chinese and Asian companies.« Today, PCIM Asia comprises around 25,000 square metres of exhibition space, with 265 exhibitors and almost 17,000 visitors.

PCIM has also had a presence in India since 2025. Lisette adds: »With PCIM Asia New Delhi, we are tapping into one of the most dynamic growth markets for power electronics at present. Driven by government support programmes, increasing industrialisation,



PCIM has consistently reflected the latest developments in power electronics and power semiconductors.(Images: Mesago)

and rising demand for electrification and energy technologies, India offers attractive prospects for international companies." Following the successful launch of the PCIM Asia New Delhi Conference in 2025, which featured



40 exhibitors, 100 speakers, and 550 participants, plans are in place to further expand the event. We see the conference as a catalyst for the Indian power electronics sector, as well as a platform for innovation, knowledge transfer and international networking.«

The global meeting place for power electronics

From Lisette's perspective, PCIM has become a focal point for the global power electronics industry. »It is the largest and most important community gathering for the sector. All the key players come together in one place to discuss innovations,« she continued. This is where new technologies are discussed, market trends emerge and contacts are established across the entire value chain. The close link between the trade fair and the conference has ensured continuous knowledge exchange for decades.

Looking ahead

Lisette is convinced that, in the coming years, PCIM will continue to be the central hub of power electronics, thanks to its combination of exhibition and conference. She continues: »However, we want to support the industry not only during the trade fair days, but also to provide opportunities for knowledge exchange, professional development and networking throughout the year.«She believes that electrification and the energy transition will continue to be the key drivers of power electronics. At the same time, however, new, rapidly growing fields of application are emerging in the form of artificial intelligence and modern data centres. Lisette: »The rising demand for computing power requires enormous amounts of energy, high power densities and maximum efficiency in power supply. This makes power electronics a key technology for the digital infrastructure of the future.«

PCIM will keep pace with these developments, bringing together an ever-growing number of stakeholders from the energy supply, information technology, and infrastructure sectors. Lisette concluded: »It is important for us to maintain our focus on our core themes so as not to dilute the event.« st

THREE TURNING POINTS?

When asked about the three most significant events in the history of PCIM, Mesago cites the following:

- PCIM was founded in 1979 with the deliberate intention of being a focused, specialised platform, integrating trade fair and conference elements from the outset to give it credibility and technical depth.
- In the 2000s and 2010s, power electronics became a key technology, enabling PCIM to evolve into an international benchmark platform as the market grew.
- Through internationalisation, particularly via the launch of PCIM Asia in 2002, PCIM evolved from a European event into a globally networked ecosystem with regional focal points. This ecosystem is now complemented by India.



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