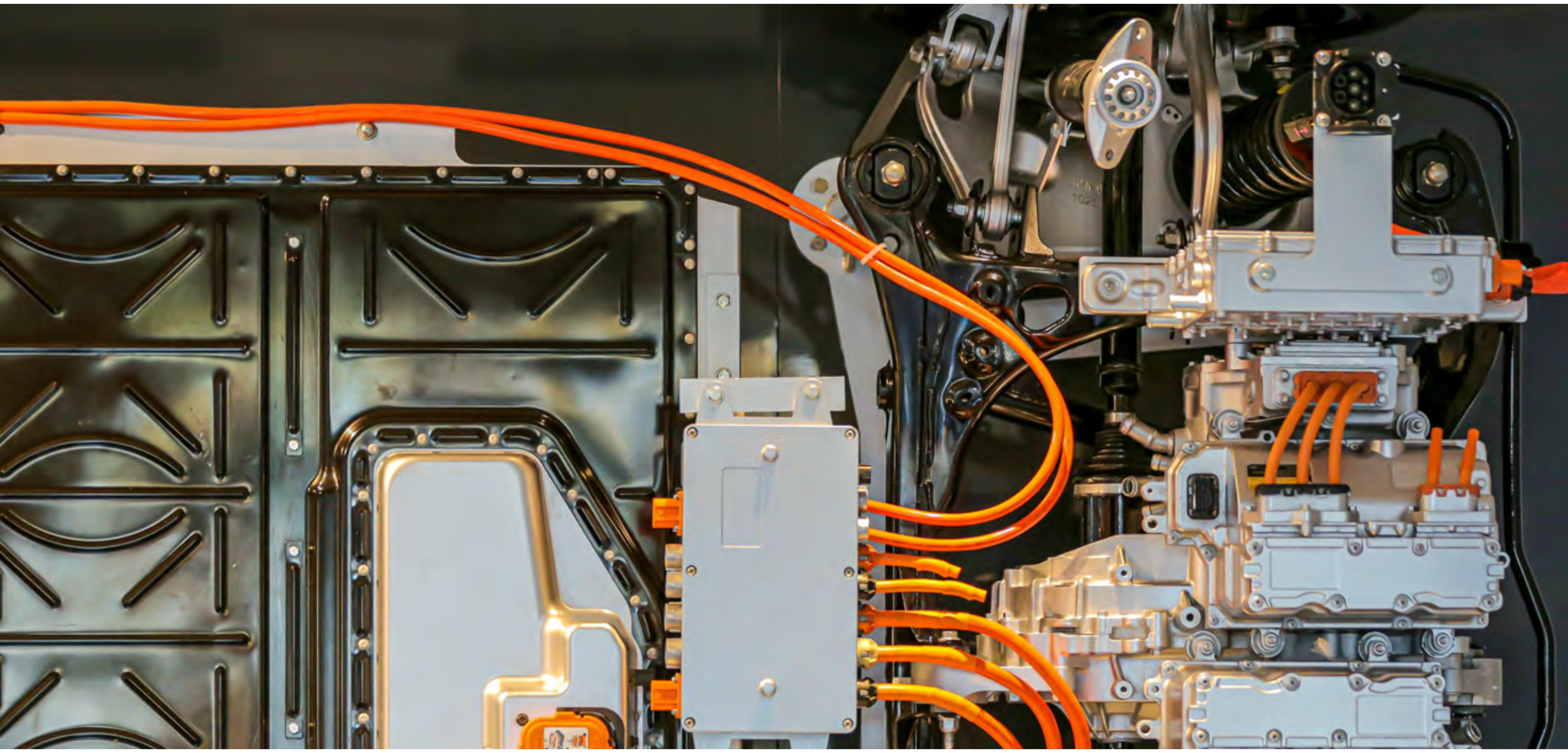
Maximizing Power Density in Automotive DC/DC Converters

Advanced Current Sensors and Isolated Gate Driver Solutions



Executive Summary

Automotive power electronics face space constraints requiring 3.6 kW/L power densities.[1] Current commercial systems average only 1.2 kW/L, creating a significant performance gap.[2] This challenge intensifies with wide-bandgap semiconductors (SiC and GaN), which demand sub-500 nanosecond (ns) response times and MHz-level bandwidth capabilities. Traditional current sensing and gate driving approaches cannot meet these requirements because of technology limitations and uncoordinated approach between current sensors and gate drivers.

Coordinated power management integrates high-bandwidth current sensors with optimized gate drivers to enable real-time feedback control. This approach allows current sensors to provide instantaneous feedback to gate drivers, enabling adaptive switching control that maximizes efficiency while maintaining protection. The coordination eliminates traditional trade-offs between size, performance, and complexity across multiple voltage domains.

Automotive manufacturers implementing coordinated solutions mentioned in this white paper gain decisive competitive advantages: reduced weight and energy consumption extend vehicle range through improved efficiency, while higher power densities enable next-generation autonomous vehicle systems requiring 5+ kW auxiliary power.[2] Early adopters will lead the transition to higher-performance EV architectures.

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Why Power Density Matters in EV Power Electronics

Range anxiety remains the primary barrier to EV adoption, driving demand for maximum energy efficiency within strict weight and space constraints. EV auxiliary power requirements are expected to increase beyond the current 2-3 kW to 5 kW and more for autonomous vehicle sensors, cameras, and actuating motors.[2] This growth occurs within space constraints:

- Limited available volume for power electronics within the vehicle chassis creates an urgent demand for maximum power-to-size ratios
- High current ratings exceeding 500 A on low voltage (LV) rails[2]

However, a performance gap exists between research capabilities and commercial reality. Research demonstrates that up to 5 kW/L is achievable, with the Fraunhofer IISB, Germany, successfully developing high voltage (HV) to LV conversion systems at this density.[3] Commercial systems lag behind:

Current commercial automotive DC/DC converter systems average only 1.2 kW/L across leading automotive suppliers

Industry targets require a minimum 97% efficiency and at least 2.5 kW/kg specific power density for next-generation automotive DC/DC converter systems[2]

The HV to LV conversion architecture illustrated in Figure 1 shows how a single battery pack must supply multiple low-voltage rails through the automotive DC/DC converter system. It highlights the complex integration challenges facing next-generation EVs.

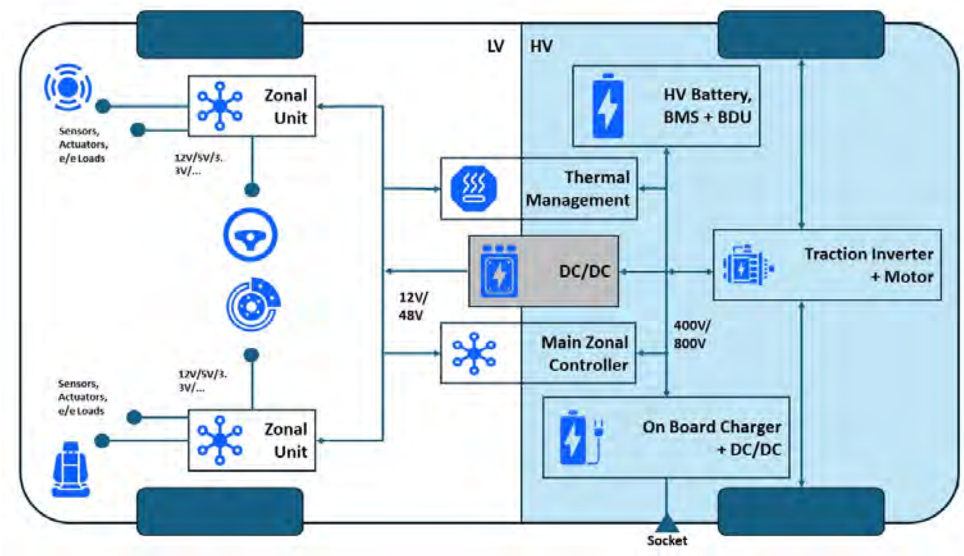

Figure 1. HV to LV conversion architecture consisting of a battery pack feeding multiple low-voltage rails through automotive DC/DC converter system.

Achieving these performance levels requires coordinated advances in both current sensing and gate driving technologies. Existing approaches treat these as separate subsystems, while modern automotive DC/DC converters need integrated power management where high-bandwidth current feedback enables optimal gate driver control in real-time.

Challenges of Traditional Current Sensing Technologies in DC/DC Converters

Current sensing forms the foundation of all DC/DC converter systems, providing necessary feedback for control loops, protection functions, and efficiency optimization. In automotive applications, converters operate across multiple voltage domains (800 V input, 48 V/12 V output) with different current sensing requirements for each side.

Engineers need to understand the three traditional solutions in current sensing and analyze the challenges associated with them from the perspective of EVs across different voltage domains.

Shunt resistors create power loss problems that scale with the square of current (I^2R). In high-voltage applications, they lack inherent galvanic isolation, necessitating additional isolation measures, such as isolated amplifiers or modulators. These measures increase costs and reduce bandwidth, while power dissipation requires larger, more expensive high-wattage resistors with special thermal management.[4,5]

In low-voltage applications, I^2R losses become critical in high-current scenarios common to these systems. Low-side sensing configurations also create susceptibility to ground potential disturbances while being unable to detect short-circuit conditions from supply to ground.[4,5]

Current transformers face challenges in both voltage domains. In high-voltage applications, winding isolation and parasitic capacitance issues become pronounced due to significant common-mode voltage differences and fast voltage transients (dv/dt). In low-voltage applications, their inability to measure dc current, combined with size constraints, makes them impractical for space-constrained systems.

Magnetic sensors offer a better alternative, but they also have drawbacks. The hall-effect type exhibits inherent offset voltage and noise that limit accuracy, particularly when measuring small signals or low currents. The tunneling magnetoresistance (TMR) technology, on the other hand, has a higher signal-to-noise ratio and is suitable for high-frequency applications, but thermal gradients may cause offset drifts.

In high-voltage applications, these issues impede accuracy with weak magnetic field signals, while in low-voltage applications, the offset and noise become problematic for precision current measurement.

Therefore, power losses, isolation complexity, and bandwidth constraints from traditional current sensing approaches fundamentally limit the efficiency and responsiveness required for high power density automotive applications.

Table 1 illustrates the comprehensive trade-offs between different current sensing approaches, highlighting the limitations of traditional solutions across key automotive application parameters.

Table 1. Comparison of current sensing technologies for automotive DC/DC applications.

Solution	Non-Isolated Shunt	Module	Integrated Conductor (Hall, TMR)	Core-based (Hall, TMR)	Coreless (Hall, TMR)	Current Transformer
Operating Voltage	<100 V[1]	>1000 V	100-2000 V	>1000 V	>1000 V	>1000 V
Conductor/ Shunt Impedance	>ACS[2]	Medium	Medium	0	0	0
Overall Size	Medium[3]	Large	Small[4]	Large	Medium[5]	Large[6]
Design Complexity	High[7]	Low[8]	Low[9]	High[10]	High[11]	Medium[12]
DC Performance	High	Medium -High	High	High	High	No DC Component
AC Performance	Medium	Medium -High	High	High	High	High
Offset	Low	Medium	Medium[13]	Medium but programmable[13]	Low[13]	Low
Dynamic Range	Dependent on Shunt	0-1000 A	0-400 A (Hall) 0-100 A (TMR)	10-2000 A	100-5000 A	0-1000 A
System Bandwidth	Up to 100's of kHz[14]	Up to few MHz	Up to: 5 MHz (Hall) 10 MHz (TMR)	Up to 250 kHz[15]	Up to: 240 kHz (Hall) 1 MHz (TMR)	Up to 100's of MHz[16]
Cost	$-$$	$$$	$-$$	$$$	$-$$	$$[16]

Limitations of Traditional Gate Driver Technologies in DC/DC Converters

Gate drivers provide the precise switching signals required for power semiconductors in DC/DC converters. Traditional gate driver methods reveal significant limitations under modern automotive DC/DC converter demands, including high efficiency, fast switching frequencies, and reliable isolation across voltage domains.

Engineers should examine the three main challenges with conventional approaches in automotive DC/DC converters.

Bootstrap power supplies introduce complex circuitry with reliability concerns in automotive environments. Bootstrap capacitors require careful sizing and refresh timing to maintain adequate voltage levels. Temperature variations affect bootstrap performance and can lead to insufficient gate drive voltage during extended on-time periods.

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1 adding isolators increases value with complexity and cost, 2 typical value and depends on shunt, 3 with external circuitry, 4 single component, *5 considering the bus bar, 6 varies but generally tall, 7 must pick and design shunt/filtering usually required, 8 single package, additional features available, 9 single package w/added features: FAULT, Vref, 10 must pick a core with the right proportions and material + IC design, 11 must correctly dimension the bus bar/PCB track + orientation, 12 single package no added features, 13 TMR slightly higher than Hall but improving, 14 gain limited, 15 depending on the core material and shape, 16 depends on transformer size*

Discrete gate driver implementations require multiple components, including driver ICs, isolation transformers or optocouplers, bootstrap diodes, capacitors, and protection circuits. These components create current loops that generate EMI and parasitic effects while increasing system cost and reducing reliability through additional failure points.

Conventional isolation approaches, like using discrete transformers, have bandwidth limitations that affect switching performance. These approaches suffer from aging effects and variable propagation delays that impact precision timing.

The abundance of discrete components and timing uncertainties in traditional gate driver architectures hinder the compact, coordinated control necessary to meet automotive power density objectives.

Figure 2 illustrates the complexity of conventional discrete implementations compared to modern integrated approaches that eliminate multiple discrete components. The research demonstrates the evolution toward integrated gate driver solutions that address these traditional limitations.[6]

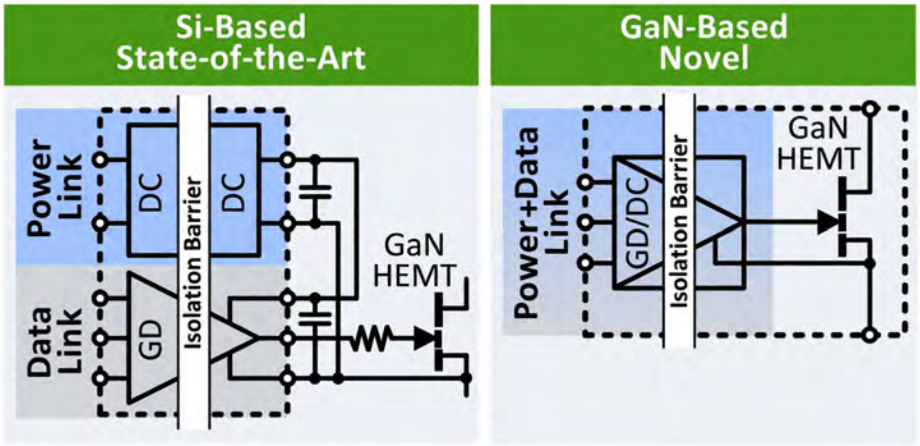

Figure 2. Evolution from traditional Si-based gate drivers to integrated GaN-based solutions. (Source: IEEE)

Wide-Bandgap Device Requirements for Current Sensing and Gate Driver

The automotive industry's switch to wide-bandgap (WBG) semiconductors like SiC and GaN for higher power densities puts pressure on supporting technologies. When these devices switch at MHz frequencies, the current sensing and gate driver limitations become obstacles. For ultra-fast switching, WBG semiconductors need response times under 500 ns. These ultra-fast response requirements for high power density automotive DC/DC converters are beyond traditional silicon device methods.

The high-frequency operation of WBG semiconductors exposes limitations of all traditional current sensing approaches. Shunt resistor solutions struggle with bandwidth limitations from external amplifiers. Current transformers cannot provide dc sensing capability required for battery applications and suffer from saturation at higher flux densities.[7] Hall-based magnetic current sensors reach bandwidth limitations, typically 500 kHz or less, which limits the for WBG semiconductor integration. However, it opens up research to combine with other technologies. For example, TMR sensing technology can boost the bandwidth to 10 MHz and thus achieve intrinsically higher bandwidth.

Gate drivers for WBG devices must have ultra-low coupling capacitance (<10 pF) and CMTI ratings with at least 100 V/ns to withstand high voltage transients. SiC and GaN applications require gate drivers with precise positive and negative gate voltages to optimize switching performance and prevent shoot-through. Failure to meet these strict requirements causes device damage, reduced efficiency, or system instability, negating WBG semiconductors' power density advantages.

The elevated operating temperatures of WBG devices (up to 150°C) compound these challenges by imposing additional requirements on both technologies. Current sensors must maintain accuracy specifications across extended temperature ranges without degradation, while gate drivers need robust isolation barriers that preserve signal integrity and timing precision in harsh thermal environments. These temperature demands eliminate many conventional solutions and favour integrated approaches designed specifically for automotive WBG applications.

Coordinated Power Management: The Solution Approach

Coordinated current sensing and gate driving technologies offer key benefits for the entire system, enabling higher power density in automotive DC/DC converters. Table 2 concisely analyzes how these technologies work together across key features:

Table 2. Coordinated current sensing and gate driver technologies in achieving design goals for enhanced power density in automotive DC/DC converters

Design Goal	Key Current Sensor Specs	Key Gate Driver Specs
Enable higher switching frequency	**High bandwidth (1 to 5 MHz):** Provide real-time feedback required for stable, high frequency current loops. **Ultra-fast response time (< 500 ns):** Ensures the control loop receives current data with minimal phase lag for stable operation.	**Ultra-low coupling capacitance (< 3 pF):** Minimize EMI and parasitic loops. This improves signal integrity, avoids ringing, and is a primary enabler for stable, high-frequency switching.
Minimize power loss	**Ultra-low primary resistance (1 mΩ or less):** Replace lossy shunt resistors and dramatically cut I^2R conduction losses.	**Optimized drive voltage (Positive/Negative):** Provides precise V_{GS} needed for full SiC/GaN enhancement, minimizing conduction and switching losses.
Reduce system footprint & component count	**Compact, integrated packages (e.g., 4x4 mm QFN):** Replaces multiple components (shunt, isolated amplifier) with a single, small-footprint IC. **Contactless sensing:** Frees up valuable PCB real estate in the main power path.	**Integration of isolated bias supply:** Eliminates the entire external bias supply, bootstrap capacitors, and associated transformers, saving significant PCB area and BoM cost.
Ensure robust, optimized design	**Fast, integrated fault detection (500 ns and less):** Provides a microsecond-level hardware interrupt to the controller, protecting WBG devices from short-circuit events. **Robust basic isolation (> 1400 V_{DC}):** Provides robust electrical separation in a compact footprint, ensuring system safety and reliability.	**High common-mode transient immunity (> 100 V/ns):** Ensures the driver's state (on/off) is not corrupted by the extreme dv/dt noise from fast-switching WBG FETs.

This coordinated approach reduces traditional trade-offs between performance, size, and integration complexity. This approach enables reduced weight and lower energy consumption in existing vehicle architectures and higher power density for next-generation automotive DC/DC converter applications.

Implementation in Automotive DC/DC Converter Systems

Coordinated power management proves essential for automotive DC/DC converters handling multiple voltage domains (400-800 V input, 12 V/24 V/48 V output). Automotive DC/DC converter systems represent a primary application area where single converters serve multiple output rails simultaneously. The following examples demonstrate coordinated technology implementations.

HV To LV Conversion: The Primary Automotive DC/DC Application

HV to LV conversion represents the dominant application driving automotive DC/DC development, where automotive OEMs seek a single DC/DC converter providing multiple output voltage options from a single high-voltage battery pack.

HV Side Current Sensing (800 V Input) for Automotive DC/DC Converters

Automotive DC/DC converter systems require precision high-voltage input monitoring to optimize power distribution across multiple low-voltage output rails. Current sensors like the ACS37035 deliver the WBG-compatible performance required for 800 V input sensing:

- Meets WBG protection requirements with 500 ns overcurrent fault response
- Provides 1 MHz bandwidth for coordinated control with high-frequency WBG switching
- Reduces power losses with typical 1 mΩ resistance (versus 20 mΩ traditional shunts)
- Ensures 800 V EV system safety compliance with 1414 VDC basic isolation
- Operates reliably across automotive temperature ranges (-40°C to 125°C)

LV Side Current Sensing (48V/12V Outputs) for Automotive DC/DC Converters

Automotive DC/DC converter architectures demand individual current monitoring for each low-voltage output rail to enable independent control and protection of 48 V and 12 V domains. The ACS37220 provides WBG-compatible performance for low-voltage rail monitoring:

- Enables ultra-compact integration in 4×4 mm QFN package for space-constrained designs
- Meets WBG thermal requirements with operation up to 150°C across automotive temperature ranges
- Provides 150 kHz bandwidth sufficient for coordinated control of low-voltage output channels
- Minimizes power losses with <100 μΩ resistance for high-current 48 V/12 V applications

Figure 3 demonstrates the advancement from traditional discrete current sensing approaches to Allegro MicroSystems' integrated sensor solutions. These integrated solutions provide superior integration and performance benefits that enable coordinated power management in automotive DC/DC converters.

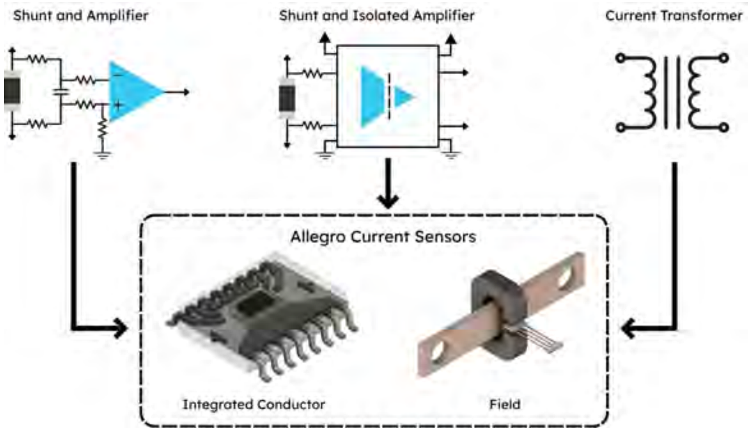

Figure 3. Evolution from traditional current sensing to integrated Allegro MicroSystems solutions.

Gate Driver Solutions for SiC Applications

For higher-power conversion systems, the AHV85311 delivers WBG-optimized SiC gate driving:

- Enables high-power SiC device control with 130 nC drive capability and adjustable positive/negative voltages
- Integrated Power-Thru bias supply eliminates need for external bias supply components like bootstraps or DC/DCs
- Provides ultra-low coupling capacitance <3 pF (well under the 10 pF WBG requirement)
- Enables fast switching by reducing EMI while offering WBG transient immunity requirements with CMTI of 100 V/ns dv/dt
- Delivers fast switching with 50 ns propagation delay for precise timing control

Isolated DC/DC Converter Topologies

High performance levels are necessary for isolated DC/DC converter topologies for safety-related applications. This calls for current sensing capabilities that guarantee galvanic isolation and give soft-switching resonant converters accurate feedback. These applications require ultra-high-frequency control loop capability that matches the advanced switching characteristics of WBG semiconductors.

Contactless Isolated Sensing

For applications requiring complete electrical isolation, the **CT455** TMR current sensor delivers WBG-compatible contactless sensing:

- Provides 1 MHz bandwidth for high-frequency WBG switching control using tunnel magnetoresistance technology
- Eliminates coupling capacitance concerns entirely with contactless design for immunity to extreme dv/dt transients
- Exceeds WBG protection requirements with <300 ns response time (well under the 500 ns requirement)
- Achieves near lossless operation with typical zero insertion resistance for maximum efficiency
- Provides inherent galvanic isolation ideal for safety-critical isolated converter applications

HV Side Isolated Current Sensing

The ACS37030 provides superior performance for isolated converters operating at MHz-level switching frequencies:

- Surpasses WBG protection requirements with 40 ns response time (12x faster than the 500 ns requirement)

- Ensures robust electrical separation with a 1414 V_{DC} working voltage for basic isolation
- Operates reliably in WBG thermal environments across -40°C to 150°C automotive temperature ranges
- Exceeds WBG bandwidth requirements with DC to 5 MHz capability (matching the upper WBG specification)
- Minimizes power losses with 0.6-0.9 mΩ resistance depending on package variant

Gate Driver Solutions for GaN Applications

The AHV85110 delivers optimized WBG performance for isolated GaN applications:

- Exceeds WBG coupling requirements with ultra-low 1.1 pF barrier capacitance (10x better than the 10 pF requirement)
- Optimizes GaN device performance with integrated Power-Thru bias supply
- Eliminates need for external bias supply components like bootstraps or DC/DCs
- Operates reliably in WBG thermal environments across -40°C to 150°C junction temperature range
- Meets WBG timing requirements with 50 ns propagation delay for precise switching control and 5 kV_{RMS} isolation

Figure 4 illustrates the AHV85110 in a typical half-bridge topology as high and low side driver. The Power-Thru technology enables both power and signal transfer across a single integrated transformer.

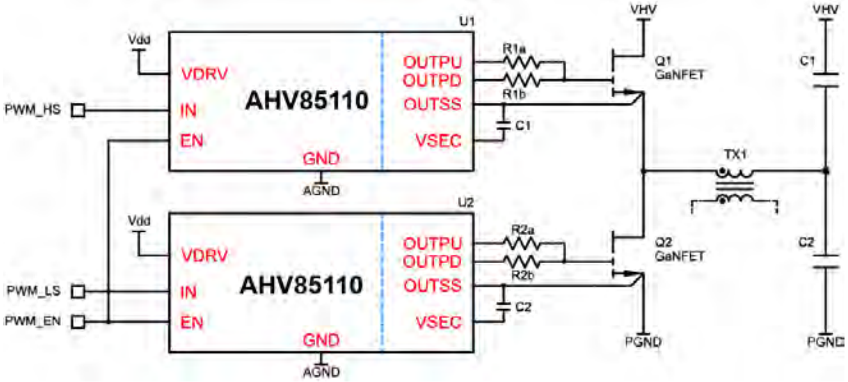

Figure 4. Typical AHV85110 half-bridge application – eliminates high-side bootstrap. (Source: Allegro MicroSystems)

Emerging Bidirectional DC/DC Converter Applications

Emerging vehicle-to-everything (V2X) and advanced energy management systems require bidirectional power flow capability with WBG-compatible performance. These applications leverage the coordinated current sensing and gate driving technologies detailed in previous sections, with specific advantages for bidirectional operation.

The ACS37220 for LV side monitoring eliminates direction-dependent calibration with its differential sensing architecture. This makes it ideal for energy recovery phases on the lower voltage rails. The ACS37030 and ACS37035 for HV side monitoring provide high-frequency control and fast fault protection. These sensors handle changes in power flow direction on the higher voltage rails.

Both AHV85311 and AHV85110 gate drivers support bidirectional operation through integrated isolated bias that eliminates bootstrap limitations during reverse power flow. Their adjustable voltages and typical 50 ns timing help manage changes in power flow direction while keeping the very low coupling capacitance and high CMTI performance needed for WBG bidirectional applications.

Conclusion

Achieving 3.6+ kW/L power densities in automotive DC/DC converters requires current sensors that are smaller than shunts with less circuitry and compact isolated gate drivers with integrated bias supply. It further results in a reduced bill of material. Traditional approaches treating these as separate technologies cannot meet the demanding specifications of SiC and GaN devices: sub-500 ns response times, MHz-level bandwidth capabilities, ultra-low coupling capacitance, and extreme dv/dt immunity exceeding 100 V/ns.

Coordinated solutions that integrate high-bandwidth current sensing with optimized gate driving represent the most viable path to meeting these stringent requirements. The integration approach eliminates traditional trade-offs between performance, size, and complexity while enabling the real-time coordination necessary for optimal WBG device operation across multiple voltage domains.

Automotive manufacturers adopting coordinated power management approaches will gain decisive competitive advantages through reduced system weight and extended vehicle range via improved efficiency. Additionally, these approaches provide the power density necessary for next-generation autonomous vehicle sensor systems requiring 5+ kW auxiliary power. As the industry transitions toward higher-performance EV architectures, coordinated sensing and gate driving technologies will become essential enablers rather than optional enhancements.

Act Today

Allegro MicroSystems develops advanced sensing and power management solutions specifically designed for automotive applications. We help automotive engineers achieve higher power densities through our integrated current sensors and isolated gate drivers that enable coordinated power management in next-generation EV systems.

Your next step is evaluating coordinated power management for your specific automotive DC/DC converter requirements. The Allegro MicroSystems engineering team can help you implement the principles outlined in this white paper for your next-generation EV systems.

- Contact the Allegro MicroSystems automotive team to explore how coordinated power management can optimize your automotive DC/DC converter systems
- Schedule a consultation with our application engineers to discuss your specific power density requirements
- Download our technical specifications guide for automotive current sensors and gate drivers
- Request evaluation samples for your next DC/DC converter design

See the datasheet. ⟶

References

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Industrial Inverter Current Sensing With Three Shunt Resistors: Limitations and Solutions, IEEE

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Allegro MicroSystems’ resources

AEC-Q100 qualified ±707V Reinforced Isolation 1MHz Hall-Effect Current Sensor in SOICW-16 package - ACS37035, Allegro MicroSystems

DC to 5MHz, High-Accuracy Current Sensor with Reference or Fault Output - ACS37030, ACS37032, Allegro MicroSystems

1MHz Bandwidth Contactless XtremeSense™ TMR Current Sensor with Programmable Gain - CT455, Allegro MicroSystems

Self-Powered Isolated SiC Driver with Power-Thru Integrated Isolated Bias Supply - AHV85311, Allegro MicroSystems

Low-Resistance Current Sensor IC with Overcurrent Fault Protection - ACS37220, Allegro MicroSystems

Self-Powered Isolated GaN FET Driver with Integrated Bias Supply - AHV85110, Allegro MicroSystems