

# Technical White Paper

## Design Priorities in EV Traction Inverters



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### ABSTRACT

This technical white paper explores key system trends, architectures, and technologies for traction inverters. The document covers individual devices used to enable traction inverters, including embedded processing, power management, gate drive, sensing, high-voltage domain and low-voltage domain technology. Finally, the document focuses on the system engineering concepts and Texas Instruments' reference designs to accelerate the design time of traction inverters.

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## 1 Introduction

The traction inverter is the heart of the drivetrain system of an electric vehicle (EV). As such, the inverter plays a vital role in increasing the adoption of EVs worldwide. The traction inverter provides torque and acceleration by converting DC power from the batteries or generator (in cases of hybrid vehicles) to AC power to power traction drive motors, such as permanent magnetic machines (PMSM), induction motors (IM), externally excited synchronous motors (EESM), and switched reluctance motors (SRM). A traction inverter also converts recuperation energy from the motor and recharges the battery while the vehicle is coasting or braking.

There are several key design priorities and trade-offs to consider when measuring the performance of the traction inverter:

- Functional safety and security – Functional safety designs typically follow ISO 26262 or an e-safety vehicle, intrusion-protected, applications process, which includes safety diagnostics, a system-level failure mode and effects analysis, and a hardware security module (HSM).
- Weight and power density – The key technologies enabling high-power density inverter designs are the wide band-gap switch and powertrain integration. According to the United States Department of Energy (DOE) and the Oak Ridge National Laboratory, the inverter power density target of 100kW/L for OEMs in the US market has been met by 2025. The use of SiC enables an 800+V DC bus, reduces the current rating, and simplifies the wiring harness.
- Efficiency – System efficiency includes traction inverter efficiency, motor efficiency, and inverter efficiency in regenerative braking mode.
- Performance and reliability – Performance of the inverter system is measured through motor torque control, which includes a current-sensing loop and the motor torque transient response. Reliability includes power module reliability, motor reliability and isolation, and so forth.
- System cost – Apart from the electric machine and wiring harness, the main components include:
  - Mechanics: Inverter housing and cooling, busbars
  - Power modules
  - EMI filter
  - DC link capacitor
  - MCU and control electronics
  - Gate drivers
  - Power conversion
  - Active discharge circuitry
  - Motor position sensor
  - Current and voltage sensors
  - Communication interfaces

## 2 Architectures and Trends

The architecture of a traction inverter varies with vehicle type. Plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have a three-phase voltage source traction inverter topology to drive the car, with power levels in the 100kW to 500kW range. While the single axle drive is the standard option here (front or rear), adding a second traction inverter + eMotor on the second axle is a popular option to create a so called dual-motor architecture. Additionally, in PHEVs, the integrated starter generator (ISG) used to start the combustion engine, or sometimes even to drive the car, features another inverter structure.

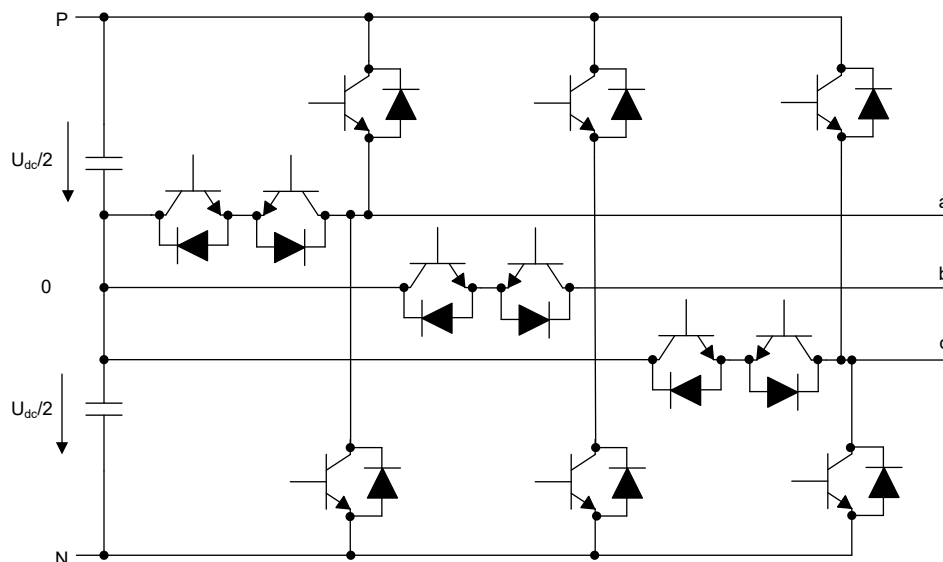
In between the battery pack and traction inverter, a DC link capacitor is placed to supply the inverter with a controlled DC voltage. The capacitor provides a low impedance path for high frequency currents while providing energy storage that maintains a low ripple voltage. This DC link capacitor must be discharged quickly in case of a shutdown, malfunction, or accident for first-responders to be able to handle the car safely, which leads to one of the central features of a traction inverter, the DC link active discharge.

In some cases, a DC-DC boost converter can be used to step up the battery voltage before leading into the DC link capacitor. This is the case for vehicles with low battery voltage levels, primarily in hybrid electric vehicles. Providing the power output for the traction inverter on such a low voltage (100+V) results in high currents through the wiring, which can be reduced by increasing the voltage level to 400+V at the output of the DC-DC boost converter. Additionally, a DC-DC boost converter stabilizes the DC link voltage and enables a scalable battery architecture. However, the converter can potentially add cost, size, and weight to the system and introduce conversion losses.

### 2.1 Two-Level and Three-Level Inverters

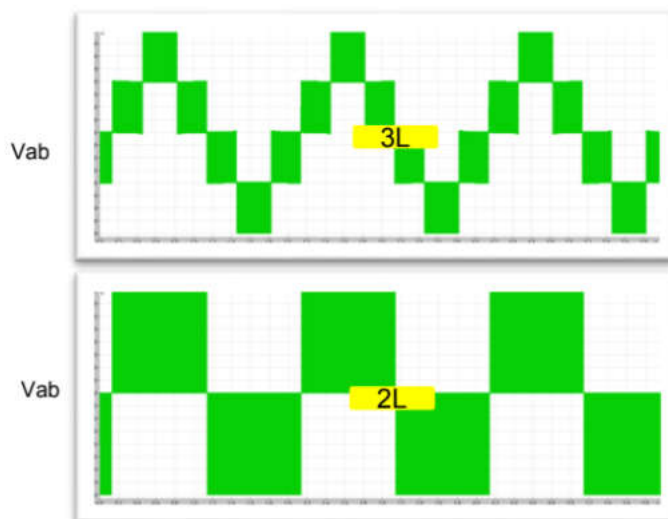
The two-level inverter is the most common traction inverter topology used in electrified vehicles and in the industry, with the power range of tens of kilowatts up to hundreds of kilowatts. The two-level inverter features two voltage levels, DC+ and DC−, and six individual switches producing an AC signal to energize the stator windings, as per the orientation of the phases. Typically, the switching frequency is in the range of 5kHz to 30kHz.

One possibility to improve on this design is the three-level inverter, which offers significantly higher efficiency and lower harmonic distortion and allows the use of a smaller electromagnetic interference (EMI) filter. In a three-level T-type inverter, the addition of another leg (T-leg) of switches in between the already existing ones allows the system to provide a third voltage level to the inverter stage, DC/2, see [Figure 2-1](#).



**Figure 2-1. Three-Level T-Type Traction Inverter With an Added T-Leg of Switches**

As shown in [Figure 2-2](#), the third voltage level provided to the three-level T-type inverter improves the output voltage sine wave form. The third voltage level also reduces third harmonic distortions (THD) significantly. Combined, this reduces motor power losses, which are the main losses in the system.



**Figure 2-2. Voltage Output Waveform of Three-Level (Top) Versus Two-Level Design (Bottom)**

To further improve the system cost-performance ratio, the three-level T-type inverter can be driven as a combination of two-level and three-level control under different load conditions. In this setting, the T-leg switches are only active in light load conditions, which allows for lower current ratings, and therefore potentially reducing the overall cost of the system. In high load conditions, the system works in two levels as usual.

## 2.2 E-Axles and X-in-1 Architecture

One example of improving system level integration is the implementation of E-Axles, which combine the power electronics, electric motor, and transmission into one housing. E-Axles improve motor performance by achieving higher torque and top speed, while improved cooling and a coil winding structure increase power density and motor efficiency. E-Axles are already common today and can be found on both front and rear axle drives, as well as in dual motor vehicles.

Integration can be extended to additional parts of the electric powertrain. This enables the rise of the X-in-1 system integration trend, which combines even more powertrain components to potentially improve size, cost, efficiency and weight. There is no standard combination for X-in-1 designs. In general, the components in [Table 2-1](#) can be combined up to a 12-in-1 level.

**Table 2-1. Different Levels of Component Integration in the Electric Powertrain**

Component	X-in-1 Design Name			
E-Motor	3-in-1 (E-Axle)	6-in-1	8-in-1	12-in-1
Inverter				
Gearbox				
Onboard Charger (OBC)				
HV DC-DC Converter				
Power Distribution Unit (PDU)				
Vehicle Control Unit (VCU)				
Battery Management System (BMS)				
Starter Generator				
Intelligent Boost Modules				
Thermal Management				
Positive Temperature Coefficient (PTC)				

For any of these X-in-1 levels, in general, three different strategies can be observed (see [Table 2-2](#)):

1. X-in-1 in the box: Combines different component boards into one box.

2. X-in-1 on the board: Combines functionalities onto one board.
3. X-in-1 in the device: Combines functionalities into one MCU.

**Table 2-2. Design Strategies for X-in-1 Integration**

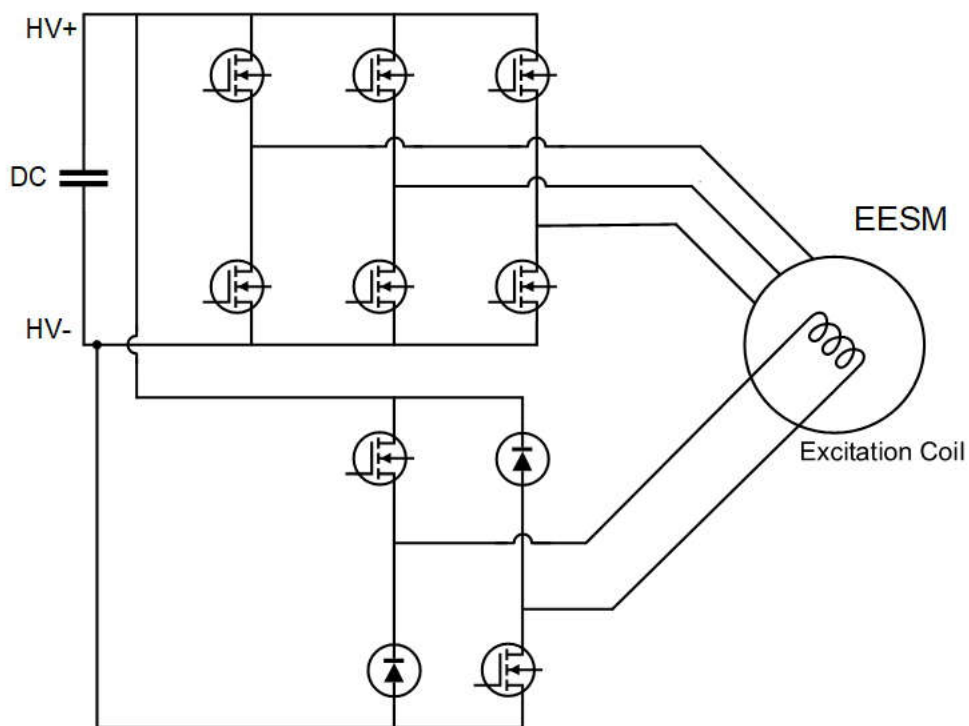
Integration Factor	One Box	One Board	One Chip
Scalability	High – each function has a specific PCB	Low scalability	
Load Sharing	Less loading – each MCU focuses on real-time tasks without overloading	Shared work across MCUs	High loading – MCU handles many real-time tasks at the same time
Safety	Must always be achieved		
Availability	Independently operating	Between one board and one chip design	No availability if fault in common component (MCU, PMIC, and so forth)
Layout	Easier to layout		Hard to layout, thermal and EMC concerns
Software	Less complexity		High complexity
Heat	Multiple spots distributing heat		Single heat spot can require active cooling
Resources	Scalable using different processor components		Needs cascaded design
Communication	Requires cables, connectors, PHYs	No cables, connectors, or PHYs needed	
Resource Expansion	No GPIO expander needed	Potentially requires GPIO expander	Fixed resources and pin count can require additional logic
Design Weight	High – due to multiple boards and wiring	Low	
Design Size	Highest volume (stacked boards)	Single board design for low height	

The 8-in-1 architecture dominated the market in 2025. Still, from 2030 onward, 12-in-1 integration is expected to take a significant amount of share alongside the lesser-advanced 6-in-1 integration version. As of today, integration is largely driven from China.

## 2.3 Other Trends in Traction Inverter Design

There are additional trends in traction inverter designs worth mentioning. Some of these trends include:

- Increasing power levels and automotive safety integrity levels (for example, 100kW to 500kW and ASIL C to ASIL D)
- Shifting toward 800+V technology with increased switching transient voltages (as of 2025, 900V cars are already available)
- Easily adjusting the gate-drive strength to reduce overshoot and improve efficiency
- Employing an inductive position-sensing technology, instead of a resolver, to potentially reduce costs
- Employing coreless current sensing alternatives, ranging from u-shield devices to multi-sensor coreless (TMCS2100-Q1) devices to simplify the complexity of the system
- Removing rare earth materials from the motor through the externally excited synchronous machine (EESM, see [Figure 2-3](#))
- Implementing Ethernet communication
- Other ways to improve integration on the IC level for potential lower cost and space:
  - Integrating active discharge into the gate driver
  - Integrating DC-DC controller into the gate driver
  - Integrating transformer into bias supply



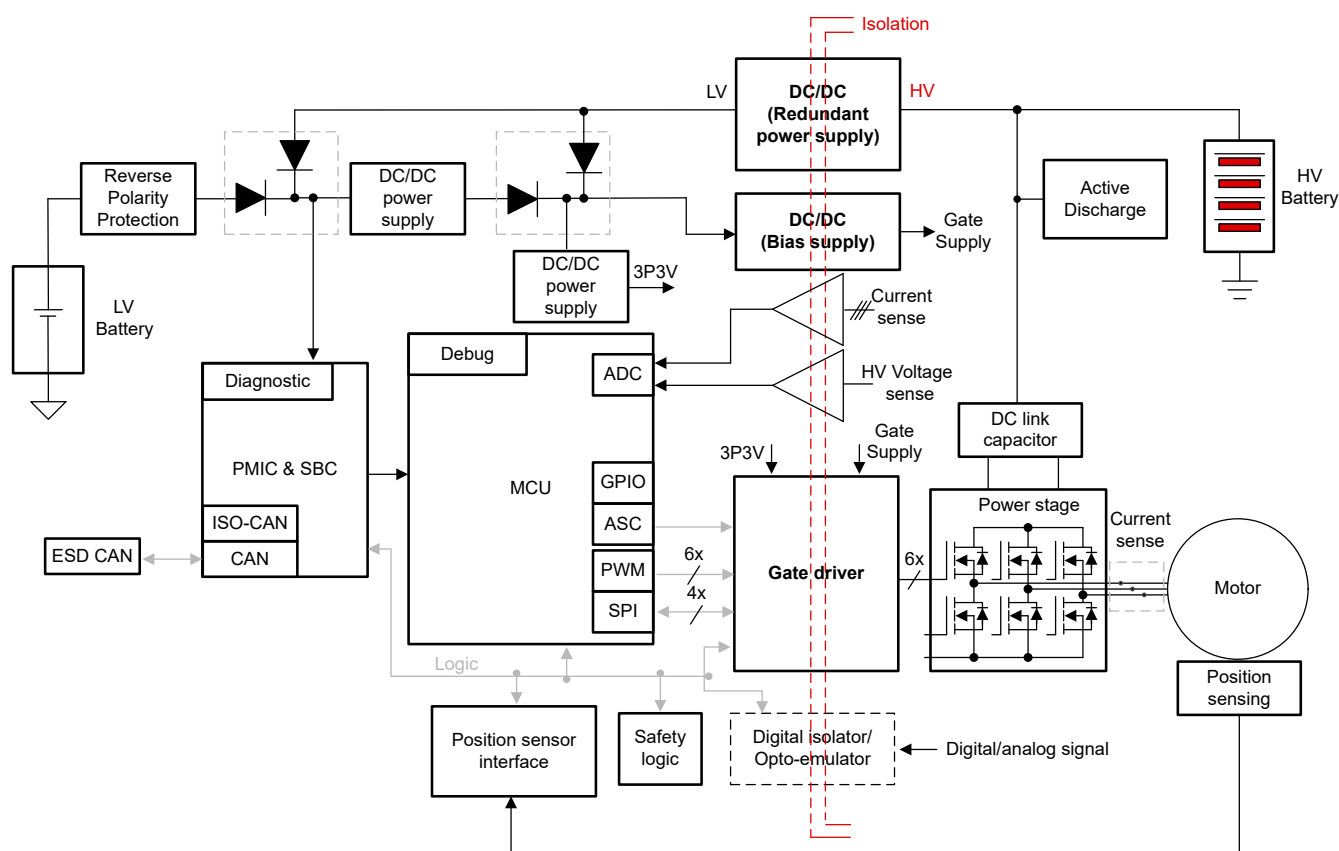
**Figure 2-3. EESM Traction Inverter System Diagram**

### 3 Key Technology to Enable Traction Inverters

A traction inverter combines functions on both the high voltage part of the powertrain architecture (HV battery side, 400V – 800+V) and the low voltage part (LV battery side, 12V – 48V). Thus, a traction inverter requires isolation in between devices on the low-voltage and high-voltage domain. TI's capacitive and inductive isolation techniques, found in isolated gate drivers, digital isolators, isolated modulators and amplifiers and solid-state relays, incorporates reinforced signal isolation in a capacitive circuit that uses silicon dioxide for the dielectric. [Figure 3-1](#) shows a block diagram of a traction inverter system. The isolation barrier (red dotted line) separates the low-voltage domain (LV battery side) and high-voltage domain (HV battery side).

In the low-voltage domain, a microcontroller (MCU) determines how to drive the power stages. The MCU sends pulse-width modulation (PWM) signals to the isolated gate drivers, which transfer the signals across an internal isolation barrier to the high-voltage side to drive the gates of the power stages. To amplify the signal to a strength necessary for the bulky power stages, the isolated gate driver requires a gate supply voltage from the isolated bias supply. The MCU runs the sensing and speed control in a closed loop and handles host functions to fulfill mandatory hardware and software security and safe code execution requirements. The MCU interfaces with the analog front end of the resolver or a Hall-effect sensor.

Implementing a safe power-tree keeps the MCU and critical power rails from losing power. A power-management integrated circuit (PMIC), connected to the LV car battery, powers the MCU. The LV battery voltage can be pre-regulated to a stable supply voltage before reaching the isolated bias supply. Additionally, for higher safety levels an HV to LV DC-DC supply can be added to provide voltage on the LV side by ORing, even when there is a failure on the LV battery or pre-regulation.



**Figure 3-1. Traction Inverter System Block Diagram**

Key functions in the high-voltage domain include:

- Power switches – Typically power modules based on silicon carbide (SiC) or an isolated gate bipolar transistor (IGBT), which are controlled by isolated gate drivers with protection and monitoring capabilities, such as internal temperature sensing and active short circuit (ASC) protection.



- Isolated gate driver – This IC takes a PWM signal input from the MCU on the LV side to drive the gates of the power modules with on the HV side. The isolated gate driver transfers this digital signal across the internal isolation barrier and uses the signal on the HV side to drive the gates of the power modules. At the same time, the isolated gate driver prevents hazardous DC or uncontrolled transient current flowing from the high-voltage domain.
- Isolated bias supply – A galvanically isolated power supply that takes the analog input from the LV side and transfers the input over to the HV side, providing the secondary supply to the gate driver. Here, the isolated gate driver combines the analog voltage with a PWM signal to drive the power stage gates.
- Isolated voltage and current sensing – To sense the DC link voltage and motor-phase current and maintain the correct torque applied to the motor, also used for the motor control loop.
- Position sensing – Vital for closed loop control meeting safety requirements. For position control, the sensors enables a known position and the positions throughout motion.
- Active discharge – To discharge the DC link capacitor voltage to a safe voltage. Active discharge is required for the type of motors that can generate back-electromotive force (EMF). United Nations regulation No. 94 of the Economic Commission for Europe of the United Nations requires that the voltage of the DC bus capacitor drops to a safe voltage (60V) in less than 5 seconds. Additionally, diagnostic circuitry is included to perform a self-tests on critical functions to prevent system failure.

The inverter control and safety schemes also vary with vehicle type. For example, a permanent magnet synchronous motor (PMSM) can be leveraged because the PMSM has high efficiency, low torque ripple, and a large speed range. PMSMs often use space vector PWM control, also known as field-oriented control. Other popular motor types in PHEVs and BEVs include induction motors, externally excited synchronous machines, and switched reluctance machines.

To reduce the potentially-costly, and geopolitically-precarious, rare earth materials used in a permanent magnet, the externally excited synchronous motors (EESM) are growing, not only for the secondary axle, but also for the primary. EESM machine types include conductive EESM and inductive EESM (iEESM). Commercial vehicles using EESM include the Toyota® Prius™, Chevrolet® Bolt EV™, Ford® Focus Electric™, VW® e-Golf™, BMW® iX3™, and so forth. In an EESM, the permanent magnet rotor is replaced with an electromagnet powered by a separate DC excitation current, for example in an H-bridge setup added to the traditional inverter structure. Additionally, this allows dynamic control of the rotor magnet flux, which is not possible with standard magnets.

## 4 Microcontroller and Power Management IC

With the inverter architecture and specifications defined, the next step is to select the MCU. TI offers a strong portfolio of microcontrollers for HEV and EV applications including the high-performance [C2000™ MCU family](#) with real-time control capability and fast control loop. Along with the MCU, a performance power management IC (PMIC) must be chosen to provide power and safety-relevant communication loops. Although the MCU and PMIC are typically considered partnered sockets, no intrinsic dependability exists, so TI offers evaluation of the PMIC independent of the MCU socket to increase the flexibility and design options of the system.

### 4.1 C2000™ Family

The [TI C2000™ MCU family](#) has been delivering leading, real-time, control performance in digital power and motor control applications for more than two decades. These MCUs integrate flash memory, analog-to-digital converter (ADC) modules for parallel measurements in time-critical applications, high resolution pulse width modulation (HRPWM), digital signal processor (DSP), and more. The applications of the C2000™ family range from standalone inverters up to full powertrain integration, including traction inverters, onboard chargers (OBC), high voltage DC-DC converters, heating ventilation and air conditioning (HVAC).

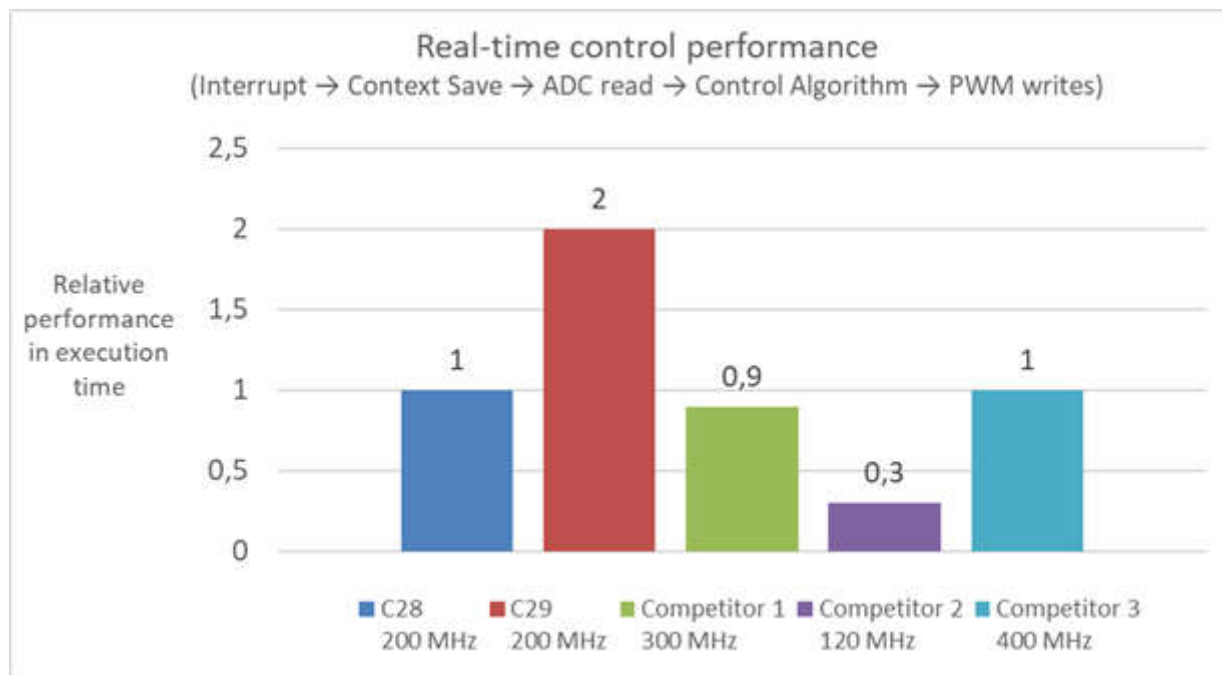
C2000™ MCUs include a TI proprietary 64-bit C29 CPU for real-time processing along with C2000™ control technology, which is a proven, flexible architecture for advanced control. The measured performance of the execution time of the C2000™ MCUs is outstanding among the competition, see [Figure 4-1](#). Specifically, the C2000™ MCUs included in the [F29H85x](#) family of devices offers the following competitive advantages:

- Functional safety compliant up to ASIL D
- 4MB of flash
- A hardware security module (HSM) and configurable logic block (CLB), which supports:
  - AUTOSAR
  - MCAL

- Third-party basic software modules (BSW)

TI's C2000™ MCUs include the following features to help accelerate control algorithms for traction inverters:

- A state machine-based 32-bit floating-point control law accelerator capable of independent code execution from the main DSP core field-oriented control
- Support for 32-bit floating point operations or 64-bit floating point in this family
- A trigonometric math unit (TMU) that provides intrinsic instructions to support common trigonometric math functions common in transforms and torque loop calculations.
- Reduced cycle counts for both Viterbi and cyclic redundancy check operations found in complex math equations



**Figure 4-1. Real-Time Control Performance of TI's C29 MCU Family Versus Competition**

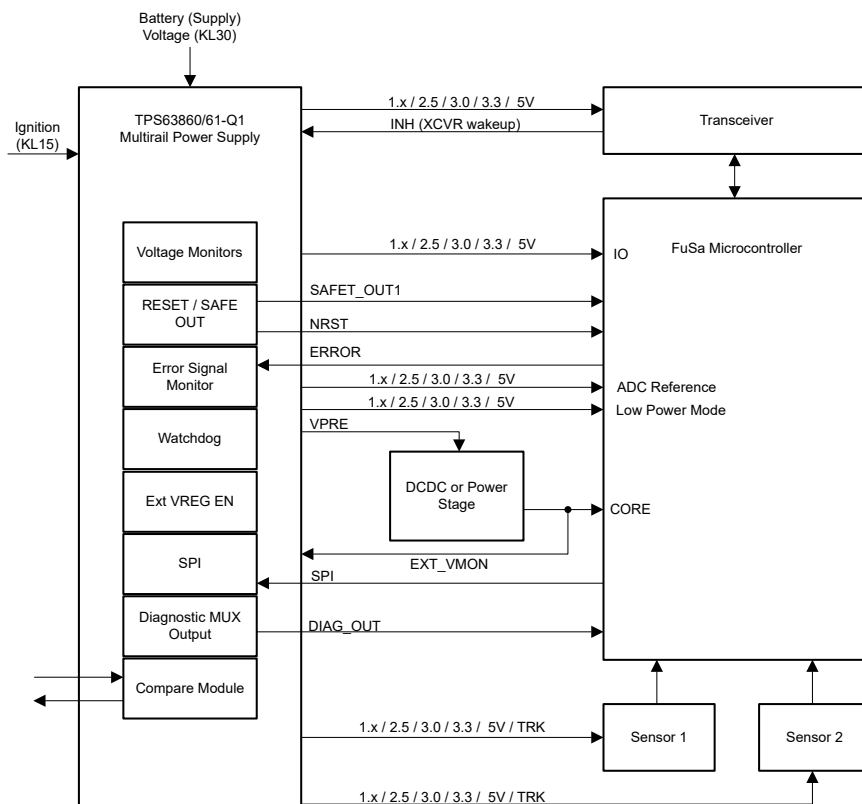
## 4.2 Power Management IC

The PMIC incorporates MCU monitoring functions, such as a watchdog (Q&A or trigger) timer, error signal monitoring, and diagnostics using SPI, GPIO, and I2C interfaces. The complexity of communication from the PMIC to the MCU often leads the designer of the traction inverter to select both sockets from a single vendor. However, TI has set up a range of safety PMICs that also support MCUs of competitors while enabling the required functional safety rating. This additional support increases the flexibility of a design.

For the traction inverter use-case, TI proposes the [TPS653860-Q1](#) and [TPS653861-Q1](#) PMIC devices featuring the following power outputs:

- Pre-regulator (buck-boost converter) with 6V, 5V, or 4.3V output at 1.5A (version 1) or 2.8A (version 0)
- Protected LDOs (PLDOs) 1 + 2 against shorts to VBAT and GND up to 200mA at 1.xV, 2.5V, 3V, 3.3V, and 5V
- LDOs 1 + 2 with a bypass mode for 600mA at 1.0V – 1.8V, 3.3V, and 5.0V
- LDOs 3 + 4 with a bypass mode for 200mA at 1.0V – 1.8V, 3.3V, and 5.0V at 1%

See [Figure 4-2](#) for a typical application diagram. With a maximum input voltage of 36V, a pre-regulator device is required in vehicles with a 48V battery. A setup like this is observed for multiple applications within the vehicle architecture dealing with the step to 48V.



**Figure 4-2. Typical Application Diagram for TPS65386x-Q1 PMIC**

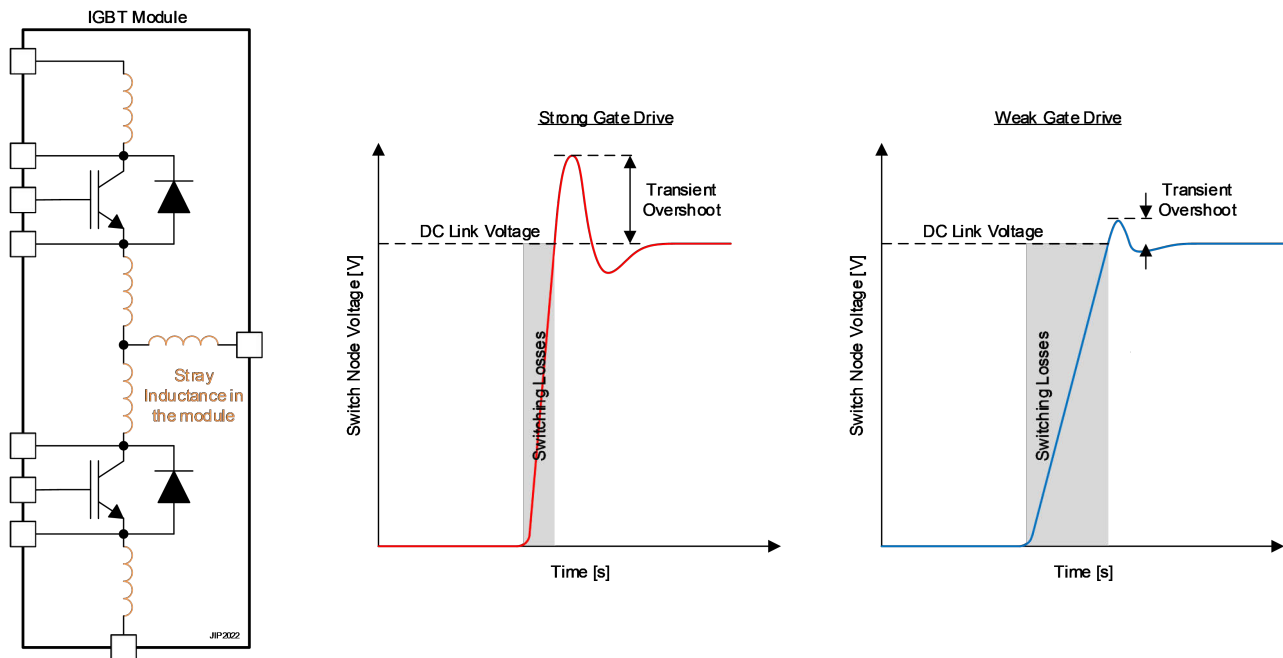
## 5 Isolated Gate Drivers

TI gate driver isolation—up to 5.7kVRMS—helps protect against electric shock while offering higher working voltages, and wider creepage and clearance for improved system reliability. There are two major isolated gate driver families:

- The protection gate driver [UCC2182xx-Q1](#)
- The programmable gate driver [UCC5881-Q1](#)

The [UCC2182xx-Q1](#) is an isolated gate driver with active protection and advanced safety features, such as multiple UVLO options (12V, 15V, and 17V) with reinforced isolation, desaturation (DESAT), and overcurrent (OC) protection, as well as overtemperature protection. Sink and source current is increased to 15A from legacy devices, while the 20-DFP package enables a 45 % smaller footprint. The device features a soft shutdown pin for fine-tuned current in shutdown, primary and secondary active short circuit (ASC) protection, and a built-in self-test during start-up to check comparators on the diagnostic features.

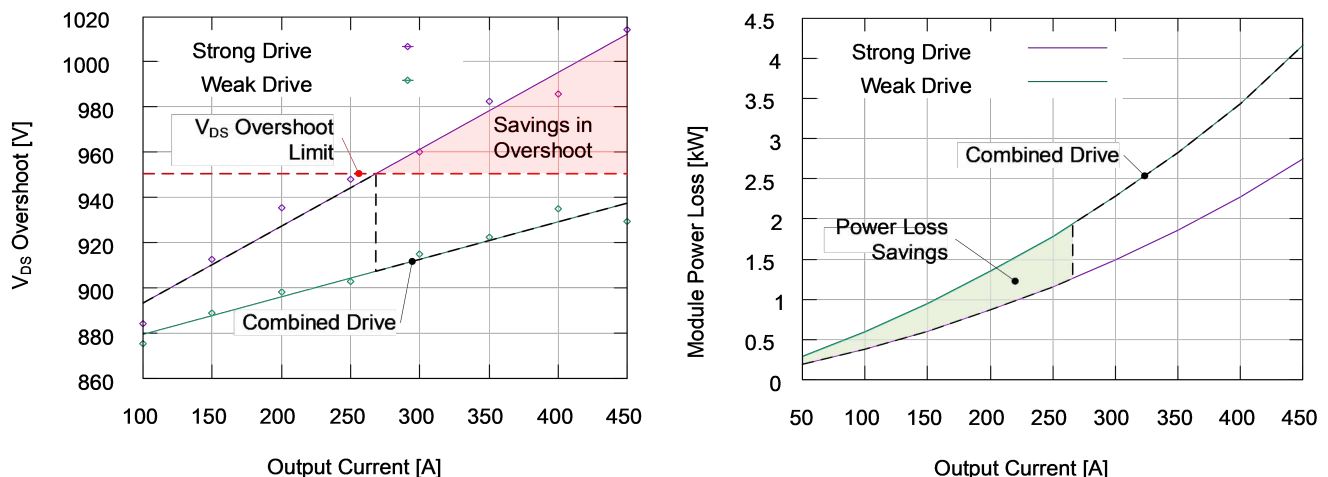
The programmable gate driver [UCC5881-Q1](#) is named for the programmable registers, which can be set to modify different parameters, such as UVLO or DESAT per the data sheet for the device. These registers can be addressed using SPI. In the latest generation of TI's programmable gate drivers, the user can also vary the gate drive strength. When driving the gate of a power stage, a strong drive signal leads to lower switching losses as a strong signal reduces the time the switch spends conducting current at a voltage drop. At the same time, strong drive signals create larger overshoot, which can come close to the voltage limit of the drain-source and damage the switch, especially at fully charged battery packs, where the headroom is the smallest. Weak drive signals lead to a lower overshoot and safer operation, but cause higher switching losses due to the lower slew rate, see [Figure 5-1](#).



**Figure 5-1. Weak Versus Strong Gate Drive and Effect on Losses and Overshoot**

Programmable gate drivers, such as the UCC5881-Q1, can utilize both weak and strong drive signals to create a combined drive. The current of the drive is inversely proportional to the voltage rise time of the switch node, so strong drive currents increase the slope of the switch node voltage. As the current reaches the DC link (target) voltage, the switch node voltage continues to increase for a short amount of time before falling back to the DC link (target) voltage. This additional increase is called overshoot. The stronger the current of the drive, the higher the slope, so the voltage levels can easily reach the voltage limit of the drain-source.

The strength of the programmable gate drive (the exact operation mode can be set on-the-fly through SPI or GPIOs) works on a strong drive, up until a certain output current where the drive switches into weak gate drive mode. This combined drive reduces the risk of overshoot damaging the switch (compared to only a strong gate drive) while enabling considerable savings in power losses (compared to only a weak gate drive), see [Figure 5-2](#).



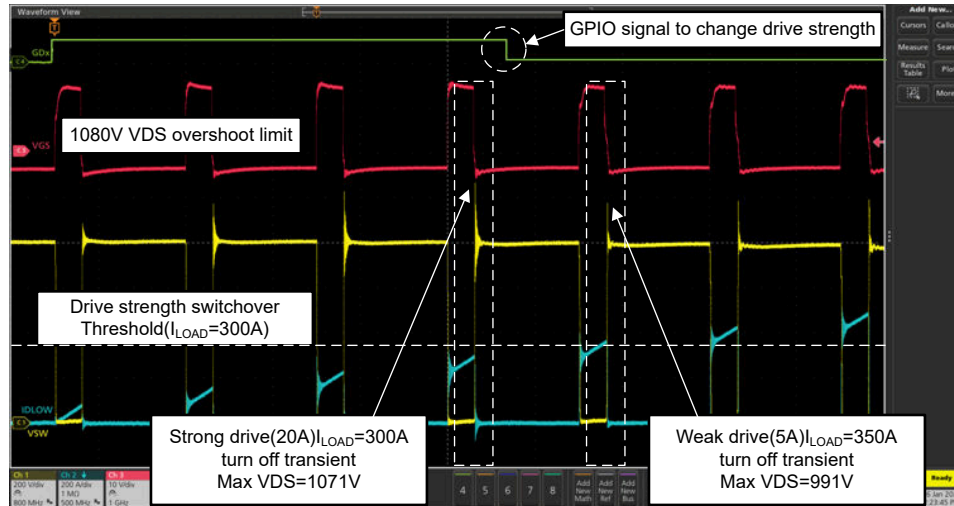
**Figure 5-2. Combined Drive Output of a Programmable Gate Driver**

Based on the CLTC drive cycle, the savings in power loss using a variable strength drive results in:

- More than a 2% improvement in inverter efficiency
- –140 dollars (U.S. currency) in battery cost

- +15.5km in operating range
- -9kg in weight
- -7.5l in battery volume (physical size)

Figure 5-3 shows an implementation of the strength feature of the programmable gate drive in real application. As the turn-off transient (yellow curve) approaches the 1080V VDS overshoot limit at ILOAD = 300A using the strong gate drive (20A), a change in the signal strength of the GPIO drive (green curve) turns on the weak drive mode (5A) and the transient voltage reduces to 991V in the following switching cycle.



**Figure 5-3. Programmable Drive Strength Application Example**

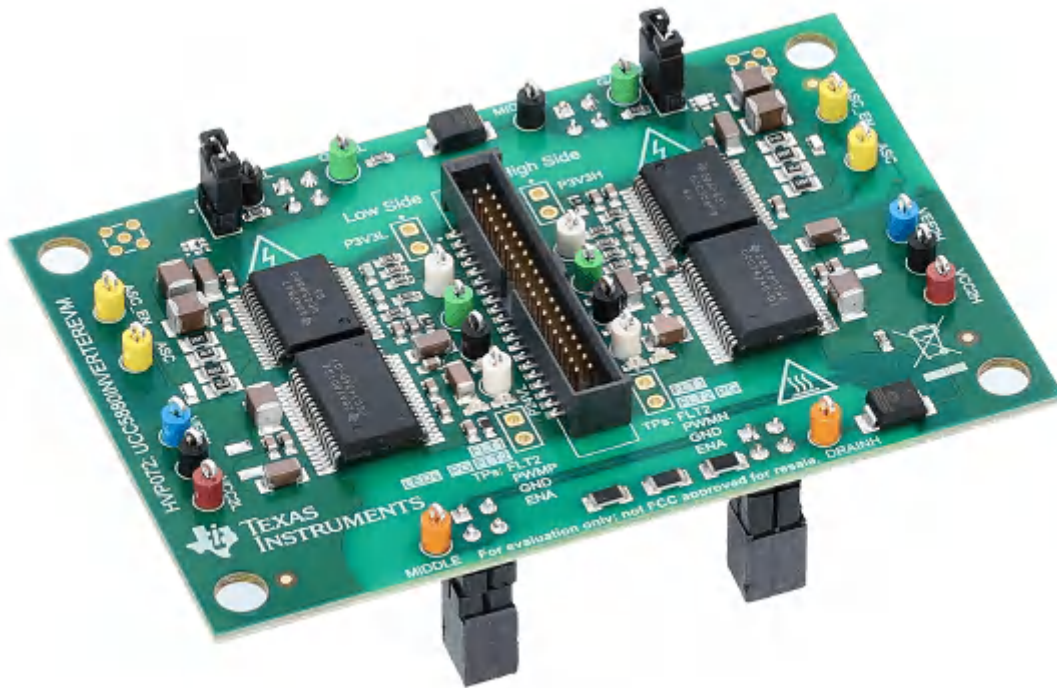
The UCC5881-Q1 driver family includes the following additional features:

- Primary and secondary side ASC protection, enabling increased design flexibility in the system
- Split output driver with dual output for an adjustable gate drive ( $\pm 15A$  and  $\pm 5A$  drive current) with an integrated 4A active Miller clamp or optional external drive for a Miller clamp transistor
- Interlock and shoot-through protection and programmable minimum pulse rejection
- Internal and external supply undervoltage and overvoltage protection
- Integrated diagnostics supporting ISO26262 functional safety requirements up to ASIL D, such as health monitoring (performing threshold voltage measurements over the lifetime of the system) and failure anticipation (provide power switch data to MCU to predict failures)
- Shunt resistor based overcurrent protection
- Overtemperature (PTC, NTC, or diode) and DESAT detection
- Extended temperature range from  $-40^{\circ}C$  to  $+125^{\circ}C$

The [UCC5880-Q1](#) inverter evaluation module (EVM) can be used standalone to test the gate driver with a 100nF capacitor load soldered on the board or to drive half-bridge power modules directly based on a Wolfspeed® XM3 SiC MOSFET for high power tests, see [Figure 5-4](#).

Two [UCC14241-Q1](#) isolated bias supplies are included on the board. The EVM is flexible to configure different SPI communication methods, including regular SPI, daisy-chain, and TI address-based. The EVM can interface with a Sitara™ and C2000™ real-time microcontroller control card for 3-phase inverter testing up to 300kW.



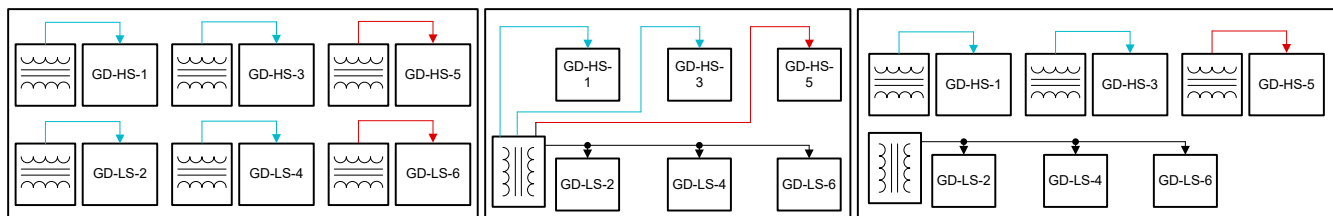


**Figure 5-4. UCC5880-Q1 Evaluation Module for a Variable Isolated Gate Drive in Traction Inverters**

## 6 Low Voltage Isolated Bias Supply

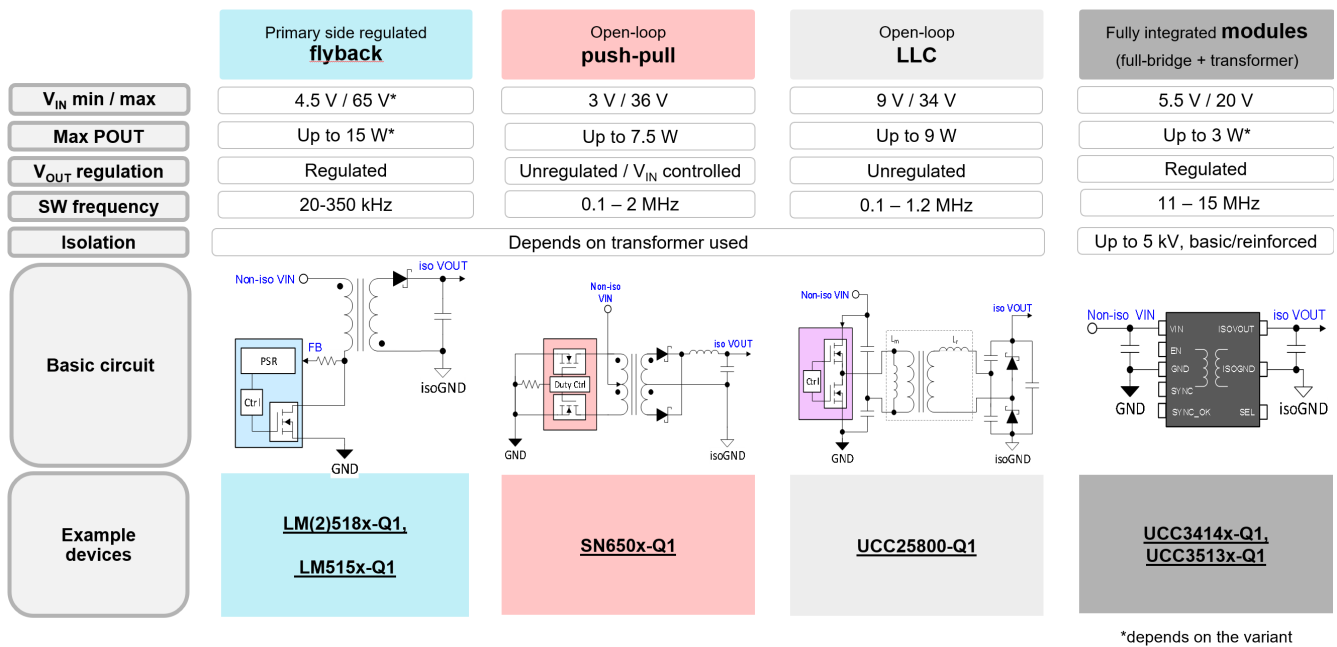
In traction inverters, the low-voltage isolated bias supply connects to a low-voltage source, such as a 12V or 48V battery, to provide a bias supply on the secondary side for the gate driver. There are three main low-voltage isolated bias supply architectures, see [Figure 6-1](#):

- Fully distributed: each gate driver connects to an individual bias supply. This system enables the easiest PCB routing and is the most fault tolerant, but is potentially more expensive.
- Centralized: A single converter with multiple outputs supplies all the gate drivers. Each gate driver can receive an individual isolated supply (demanding a 1:6 transformer). However, there is also the option for a single 1:4 transformer to supply the high side individually and the low side together. The PWM driver module remains the central IC in the supply controlling the transformer. This system potentially costs less but requires a larger transformer and complicates meeting the functional safety classification requirements due to the single-point failure.
- Semi-distributed: This is the trade-off between cost and fault redundancy. The low side gate drivers share a single bias supply, either from a 1:3 or a 1:1 transformer, while the high side gate drivers each get individual bias supplies.



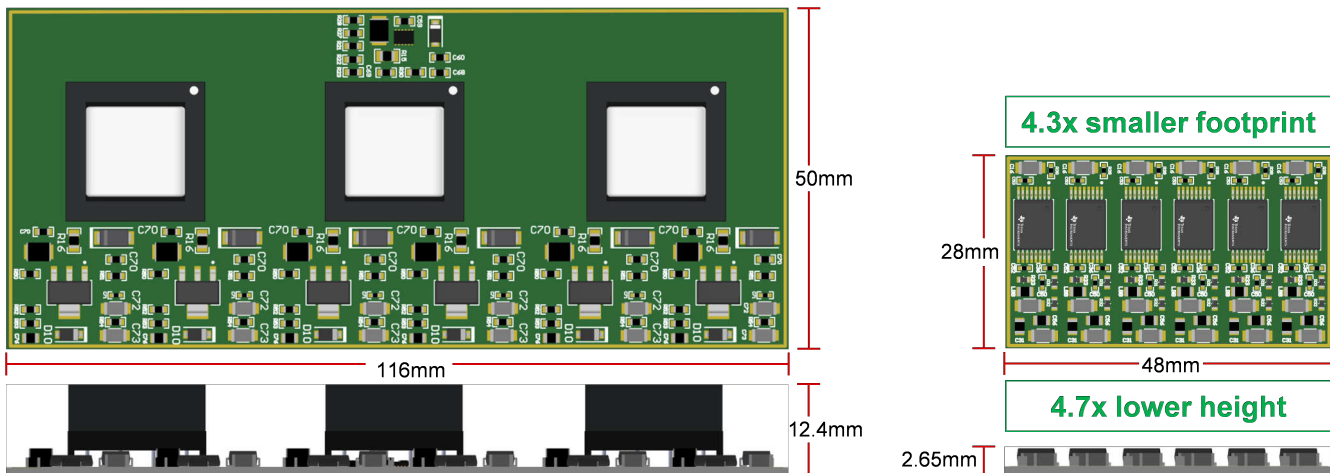
**Figure 6-1. Low Voltage Bias Supply Architectures**

TI provides various designs for the four most common topologies for isolated bias supplies. These include primary side regulated flyback converters, open-loop push-pull converters, open-loop inductor-inductor-capacitor (LLC) resonant converters, and fully integrated modules, see [Figure 6-2](#). Controller options with both external field-effect transistor (FET) and external magnetics are also available instead of the converters.



**Figure 6-2. Common Topologies for Isolated Bias Supplies**

The UCC34xxx-Q1 and UCC35xxx-Q1 family of isolated DC-DC converter modules features a wide input voltage range (5.5V – 28V). With the transformer integrated, a smaller BOM footprint can be enabled, which has potentially smaller costs than other designs. For a full inverter design, the UCC34xxx-Q1 device shrinks the system footprint by 77% and the number of components by 20% when compared to a semi-distributed flyback design, see Figure 6-3. The UCC34xxx-Q1 family of devices reaches an output power of 1.5W with an output voltage accuracy  $\leq 1.5\%$ , whereas the new generation of the UCC35xxx-Q1 family provides 2W of power.



**Components reduction 113 → 90    Footprint shrink 5800 mm<sup>2</sup> → 1344mm<sup>2</sup>**

**Figure 6-3. Size Comparison Between a Converter Module (Fully Distributed) Versus Flyback (Semi-Distributed) System Design**

The **UCC25800-Q1** device is an inductor-inductor-capacitor (LLC) resonant converter with ultra-low EMI emission. This device allows the design to utilize a transformer with higher leakage inductance but much smaller parasitic primary-to-secondary capacitance, and protection features such as adjustable overcurrent protection, input overvoltage protection, overtemperature protection, and protection from pin faults.

The [SN6507-Q1](#) device is a high-frequency push-pull transformer driver with integrated MOSFETs and duty cycle control, which enables a wide input voltage range. The device integrates a controller and two 0.5A NMOS power switches that switch out of phase. This device also includes a programmable soft start, spread spectrum clocking, and pin-configurable slew rate control.

The [LM2518x-Q1](#) family of devices are primary-side regulated (PSR) flyback converters with integrated power switches and the ability to operate over a wide input voltage range of 4.5V to 42V. The isolated output voltage is sampled from the primary-side flyback voltage, eliminating the need for an optocoupler, voltage reference, or third winding from the transformer for output voltage regulation. Boundary conduction mode (BCM) switching enables a compact magnetic design and better than  $\pm 1.5\%$  load and line regulation performance.

## 7 High Voltage Isolated Bias Supply

To increase system-level safety, a traction inverter often includes a high-voltage isolated power supply, which converts power from the high-voltage (HV) battery and connects to the low-voltage side, creating a redundant power path. Thus, in the event of device failure in the low-power supply path, the system can be supplied from the HV battery. This supply is required for ASC, where either the HS or LS power stages must be powered to bring the system to the safe state.

This high-voltage isolated power supply can be required to start up when the input voltage is as low as 30V, and must also be able to operate as high as 1kV for an 800V battery to include load-dump scenarios and account for the state of charge (SOC). A low start-up voltage can occur after a vehicle crash or if a traction inverter malfunction results in a separation of the high-voltage battery. The motor starts rotating and acts like a generator, which induces a non-controlled voltage into the DC bus. To control the voltage so that the voltage does not exceed 50V (touch safe), the auxiliary power supply must turn on and power up the safety-relevant circuits that can discharge the DC link caps (active discharge) or actively short circuit the motor. As in the low voltage isolated bias supply, the devices can be a DC-DC controller, converters, or integrated modules.

TI offers various reference designs to fulfill this requirement:

- [UCC28C56EVM-066](#) – Evaluation module for a primary-side controlled flyback regulator, 40V – 1kV input, 15V<sub>out</sub>, 40W PSR flyback
- [TIDA-01505](#) – Automotive 40V to 1kV input flyback reference design supporting regenerative braking test
- [PMP22288](#) – 15W flyback reference design for automotive inverter power
- [PMP10200](#) – Ultra-wide input voltage range PSR flyback converter reference design

At the device level, Texas Instruments supports multiple topologies for high-voltage isolated bias supplies, see [Table 7-1](#).

**Table 7-1. TI Devices That Support Topologies for High-Voltage Isolated Bias Supplies**

Device	UCC28C5x-Q1	UCC28700-Q1	UCC28730-Q1	UCC28740-Q1	UCC28781-Q1
<b>Switching Type</b>	Hard-switched	Valley switching	Valley switching	Valley switching	Zero-voltage switching (ZVS)
<b>Feedback Regulation</b>	Primary, Secondary (Optocoupler)	Primary	Primary	Secondary (Optocoupler)	Secondary (Optocoupler)
<b>Typical Power Levels</b>	20W – 100W	2W – 50W	2W – 50W	2W – 50W	50W – 150W

## 8 DC Link Active Discharge

Every EV traction inverter requires a DC link active discharge as a safety-critical function. The discharge circuit is required to discharge the energy in the DC link capacitor under the following conditions and requirements:

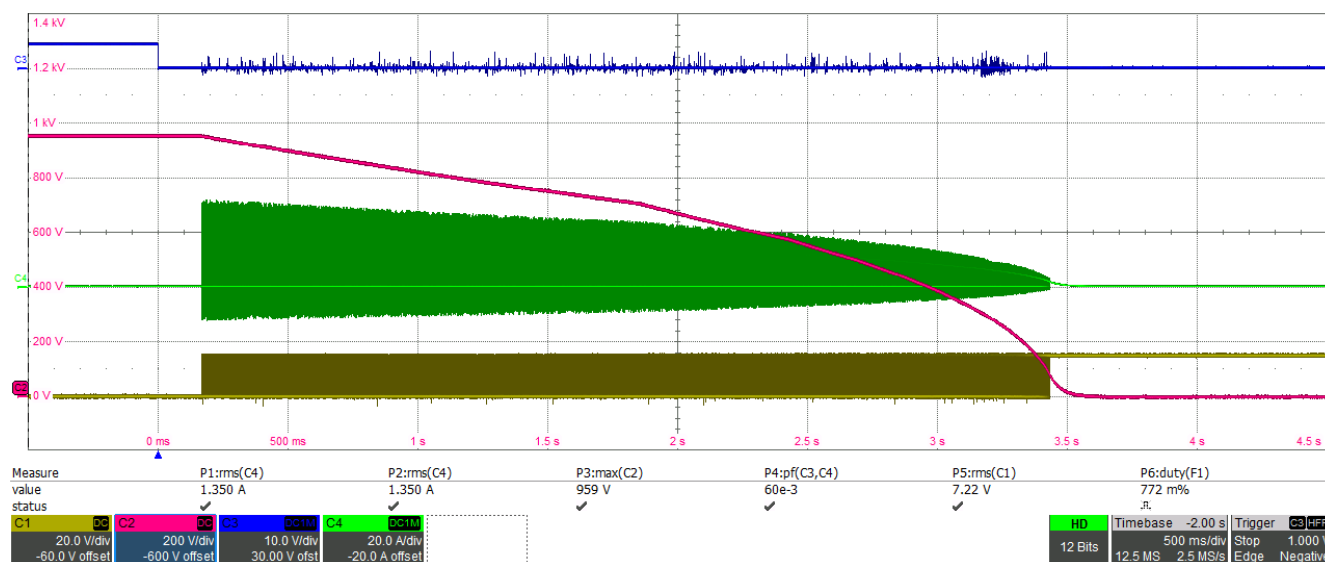
- In an emergency situation or during repairs, the voltage in the system must be safe to touch in less than 2-5s. The emergency situation response must run without an MCU and locally, for example, inside the traction inverter.
- At vehicle key-off, where all systems remain operational, the discharge happens within minutes.
- System-level safety requirements of ASIL D



TI has several active discharge designs targeted for different system-level requirements. In general, the active discharge dissipation method can be separated into three categories; resistive discharge, discharge through the power stages, or discharge through the motor windings.

In resistive discharge, a bleeding resistor can potentially work but draws current at all times and is potentially too slow. Therefore, a switched resistor can be used. Using a switched resistor, both ON or OFF control and PWM switching control, can be realized as:

- Power transistor on or off control using the [TPSI3100-Q1](#) device. The TPSI3100-Q1 reinforced isolated switch driver has an integrated 17V gate supply that can drive the discharge power switches without requiring a secondary bias supply, as the device integrates a secondary bias supply from power received on the primary bias supply. When combined with an external power switch, the device forms a complete isolated solid-state relay configuration. Internal, dual, high-speed comparators enable a communication back-channel with multiple diagnostic features.
- Controlled PWM using the [AFE539F1-Q1](#) device. The AFE539F1-Q1 smart AFE device has built-in non-volatile memory for PWM and custom waveform generators. The device has added programming ability and logic to enable operation without an MCU. [Figure 8-1](#) shows a scope shot of a DC link discharge using the AFE539F1-Q1 device. Channel 1 (yellow) is the AFE359F1-Q1 output, channel 2 (pink) shows the voltage drop from 950V to 0V. Channel 3 (blue) shows the EN signal input at the gate driver, which initiates active discharge, and channel 4 (green) is the SiC FET drain-to-source current.



**Figure 8-1. DC Link Active Discharge Based on the Smart AFE (Left) and Testing Waveforms (Right)**

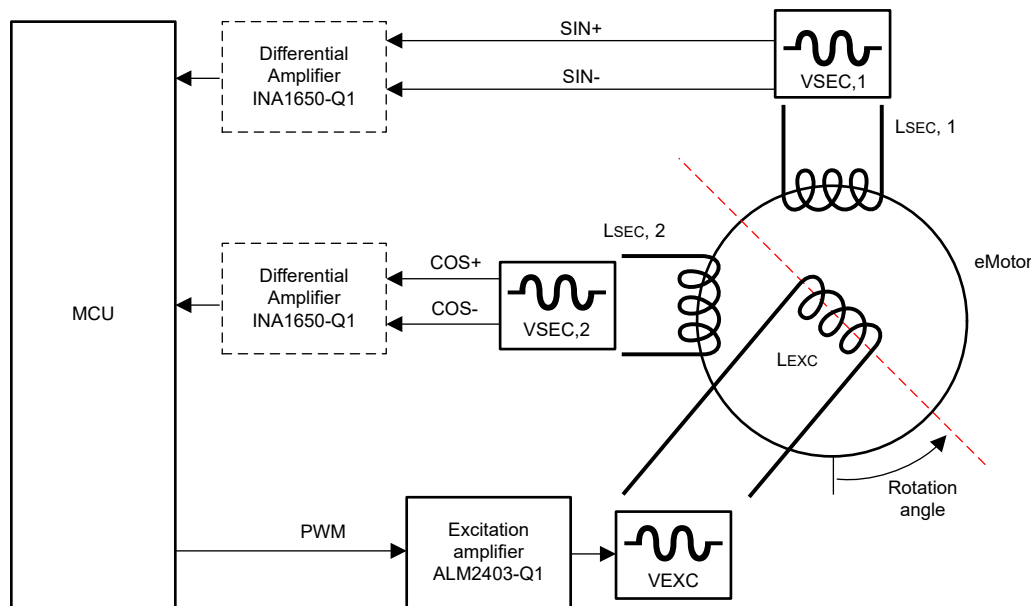
Energy can be discharged through the motor windings. Dividing a winding-based discharge into multiple stages is possible. These stages include a rapid discharge stage or a bus voltage regulation stage. Generating large negative d-axis current quickly reduces the DC link energy, while the q-axis current must be at zero. Fast loop control from TI's Sitara™ or C2000™ MCUs and safety isolated gate driver include serial peripheral interface (SPI) programming ability, while six ADC channels provide a reliable and smoothly controlled discharge. Although this design is potentially cost-efficient, the design requires a fully functional system, from the MCU to the bias supply and gate drivers.

A coming trend in traction inverter designs is discharge through the power stages. Here, a pulsed operation mode of the power stages enables discharge through the linear region of the MOSFET, where the MOSFET behaves as a resistor. For this to work, the gate driver requires very precise gate control and a high frequency pulsed operation to not overstress the MOSFET. Alternatively, the gate driver can drive a pulsed short circuit operation mode to discharge a DC link voltage.

## 9 Motor Position Sensing

A motor rotor position sensor measures the angular position of the rotor shaft. Motor position sensors are vital for a closed-control loop control meeting safety requirements. For position control, the sensors enable a known position and the positions throughout motion. In general, two options can be explored, a resolver structure or inductive sensing, which simplifies the system design.

The resolver approach implements the principle of a rotating transformer, see [Figure 9-1](#). The transformer has a single primary winding and two secondary windings positioned at a right angle. Applying an excitation voltage ( $V_{EXC}$ ) to the primary winding using a PWM signal from the MCU, generated through an excitation amplifier such as TI's [ALM2403-Q1](#) device, results in a current that generates magnetic flux. The flux distributes through the secondary windings with respect to the rotor rotation angle and induces  $V_{SIN}$  and  $V_{COS}$ . The feedback signals are mostly single-ended, but can also be converted from differential signals to a single-ended output. A safety MCU recaptures the rotor angle from the voltage ratio on the resolver secondary windings.



**Figure 9-1. Resolver Structure Featuring Excitation Coil  $L_{EXC}$  and Secondary Coils  $L_{SEC1/2}$  to Retrieve Motor Rotation Angle**

For inductive position sensing, TI's [LCD5072-Q1](#) inductive position sensor front end (see [Figure 9-2](#)) is paired with an excitation coil (black) and sensing coils (colored) to cover a conductive target fixed to the rotor. An LC oscillator is integrated in the LDC5072-Q1 device for generating an excitation current from 2.4MHz to 5MHz into the excitation coil. This elevates the simplicity of the system by eliminating the need for the external excitation structure. The target (made from Al or Cu) and PCB coils are placed parallel to each other, and there is an eddy current in the target excited by the excitation current, which also generates an induced sine and cosine envelope voltage into the sensing coils. The amplitude of the induced voltages is determined by the motor angle position. Then, the sensing signals are demodulated by the LDC5072-Q1 device and the outputs of the sine and cosine signals to the MCU for angle calculation.

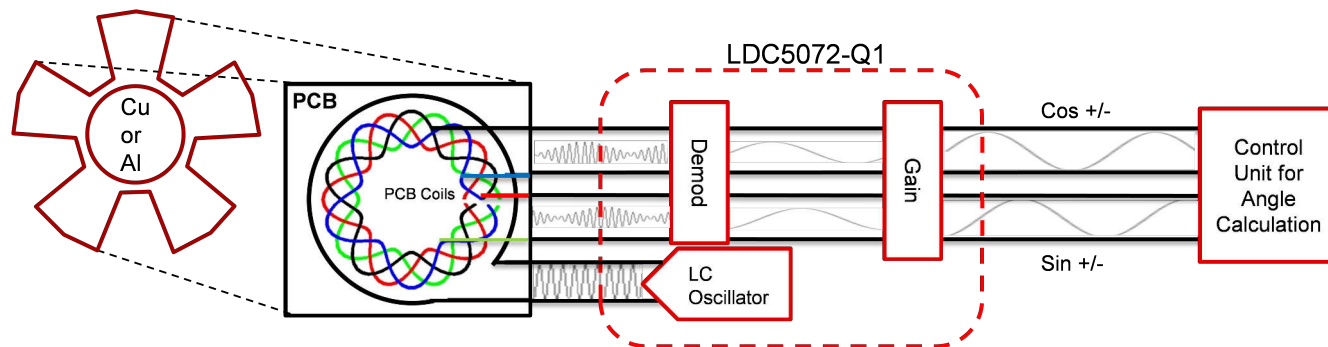


Figure 9-2. Inductive Sensing Diagram Using LDC5072-Q1

The LDC5072-Q1 device supports very high rotation speeds with an angular accuracy  $< 1^\circ$  at target speeds up to 480,000rpm. The device is designed in accordance to ISO26262 for functional safety requirements. The [TLC5072Q1EVM](#) evaluation module helps evaluate the operation and performance of the sensor front end in a quick and easy setup.

## 10 Isolated Voltage and Current Sensing

Traction inverter systems use isolated sensors for voltage and current measurements, such as DC link voltage and motor phase currents. TI offers designs for both isolated voltage and current measurement to help achieve functional safety requirement levels in traction inverter designs. This includes both digital modulators (digital output) and digital amplifiers (analog output) as well as Hall-effect sensing. Digital output isolators offer better signal fidelity, while the analog output isolators can ease the system design from the perspective of a hardware designer.

### 10.1 Isolated Current Sensing

Hall-effect current sensing works by picking up a magnetic field radiated from electrical current through a wire or busbar. This magnetic field induces a Hall voltage in the sensor, which can then be used to calculate the initial current through the wire. This method is contactless to the individual wire and high currents do not run through the sensor, but the method is susceptible to magnetic stray-fields.

To improve the measurement, most Hall-effect sensors utilize so-called C-core structures. These structures are ring-shaped ferromagnets which channel the magnetic field on the sensor. This method is reliable and not vulnerable to displacement errors, but needs significant space for the C-cores, which potentially adds to the BOM cost and weight of the overall system. Therefore, designers have been evaluating other current sense methods as well, all of which introduce either shields or busbar modifications to the system.

TI's [TMCS2100-Q1](#) Hall-effect sensor avoids the C-cores or any other major modifications completely, providing a multi-sensor coreless design. The TMCS2100-Q1 device is a programmable, precision, coreless, Hall-effect current sensor for ultra-high currents from 1A to  $>1\text{kA}$  peak with configurable overcurrent detection. The device supports any busbar mechanical configuration and completely eliminates the need for custom busbar designs, such as notches and shields, see [Figure 10-1](#).

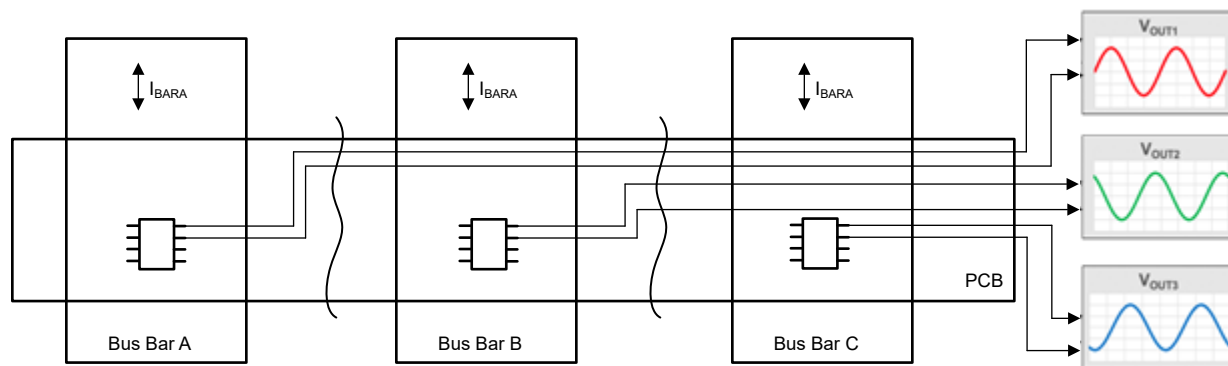


Figure 10-1. TMCS2100-Q1 Physical Setup

Busbar spacing can be as low as 5mm, while crosstalk influence is mitigated. The displacement error at 1mm is kept to 3.7% while achieving outstanding accuracy over different lifetime parameters. Comparing the main Hall-effect-based current sense design in traction inverters underlines the strength of the multi-sensor coreless design.

**Table 10-1. Different Methods of Current Sensing in Traction Inverters**

Key System Needs		C-Core	U-Shield	Differential Coreless	TMCS2100-Q1 Multi-Sensor Coreless
Ease of Manufacturing		Buy or build	Size or busbar mod	Busbar mod	IC only
Phase Cross Talk Rejection		<1% with core design	<1% with shield	>1.8% with sensor spacing of 2.6mm	<1% with customer calibration
Stray Field Rejection		Core design	Shield	Differential	Differential
Displacement Error		N/A	1mm → ca. 3.5%	1mm → 42%	1mm → 3.7%
Phase Delay (at 1kHz)		<4°	<3°	>4°	<2°
IC Power per Phase		25+mA	10mA-15mA	16-25mA	50mA
Accuracy	Overtemperature	3% + core	2%	4%	1%
	Linearity	3%	1%	1%	0.1%
	Across Frequency	3% + core	<5%	>5%	1%
	Over Lifetime	>5%	>7.5%	>3%	1%
Height (above busbar)		15mm	>14mm	<2mm	>3mm
System Complexity		IC + core + housing + fixture	IC + shield + busbar mod + fixture	IC + busbar mod + fixture	IC + fixture

TI also offers regular Hall-effect current sensors, such as the [TMCS1123-Q1](#) or [TMCS1126-Q1](#) devices, which include ambient field rejection and configurable overcurrent protection at a reinforced isolation of 5kV and a 1100V reinforced working voltage. TI recommends the TMCS1123-Q1 and TMCS1126-Q1 devices are used in the excitation circuit of an EESM motor system due to current rating limits.

While current sensing in all three output phases is the norm, another option is to sense only two of the three phases and recalculate the third value, as the three currents are meant to add up to zero. However, as the traction inverter is part of the EV powertrains, which are highly safety critical, this option comes with added design risks.

## 10.2 Isolated Voltage Sensing

Similar to the isolated gate drivers, isolated voltage sensors require power supply both on the HV and the LV side to transfer a signal from the DC link (HV side) to the MCU (LV side) across the isolation barrier. This can be achieved using a transformer plus driver combination, such as the [UCC28700-Q1](#) device, to provide both sides with a supply voltage, but TI also offers isolated voltage sensors with an integrated power supply.

Here, the AMC33xx-Q1 family of devices (for example, the [AMC3330-Q1](#) device) significantly reduces the complexity of the system using an internal isolated DC-DC converter, which allows single-supply isolation from the low-side of the device. At the input,  $\pm 1V$  can be applied for voltage measurements with high input impedance, such as resistor-divider networks to sense high-voltage signals. This device features an analog output.

To sense voltage in HV systems, a resistor ladder must be placed at the input of the voltage sense device to reduce the voltage at the input to a scale that is acceptable for the voltage sense IC. This resistor-divider network adds space and potentially costs to the system and must be finely trimmed to achieve the wanted output voltages. TI offers a matched resistor divider with 12.5M $\Omega$  of fixed input resistance and up to 1400VDC of input voltage—the [RES60A-Q1](#) device, features high ratio matching precision within  $\pm 0.1\%$  of the nominal.

The AMC038x-Q1 family of devices (for example, the [AMC038D-Q1](#) device) handles this problem by providing an integrated resistive divider, see [Figure 10-2](#). The resistive divider at the input scales down the voltage applied to the HVIN pin to a  $\pm 1V$  linear full-scale level. This signal is also available on the SNSP pin. The output of the device is a differential signal proportional to the input signal.

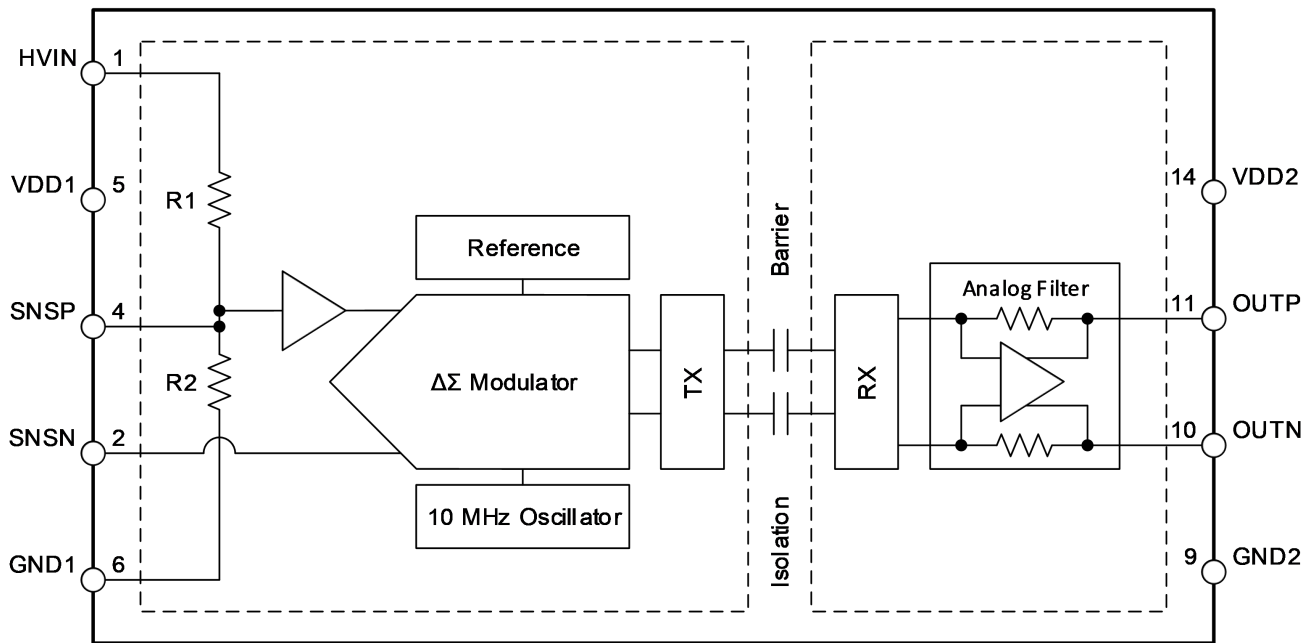


Figure 10-2. AMC0380D-Q1 Block Diagram

The integrated resistive divider enables significant board space savings, see Figure 10-3. Simultaneously, accuracy is improved due to the gain error being calibrated still at factory and very low temperature drift of the internal resistive divider. In general, better than 1% measurement accuracy is achievable even without calibration. The integrated resistor divider has a very low life-time drift and three different output options: delta-sigma modulator, single ended output, or differential output mode.

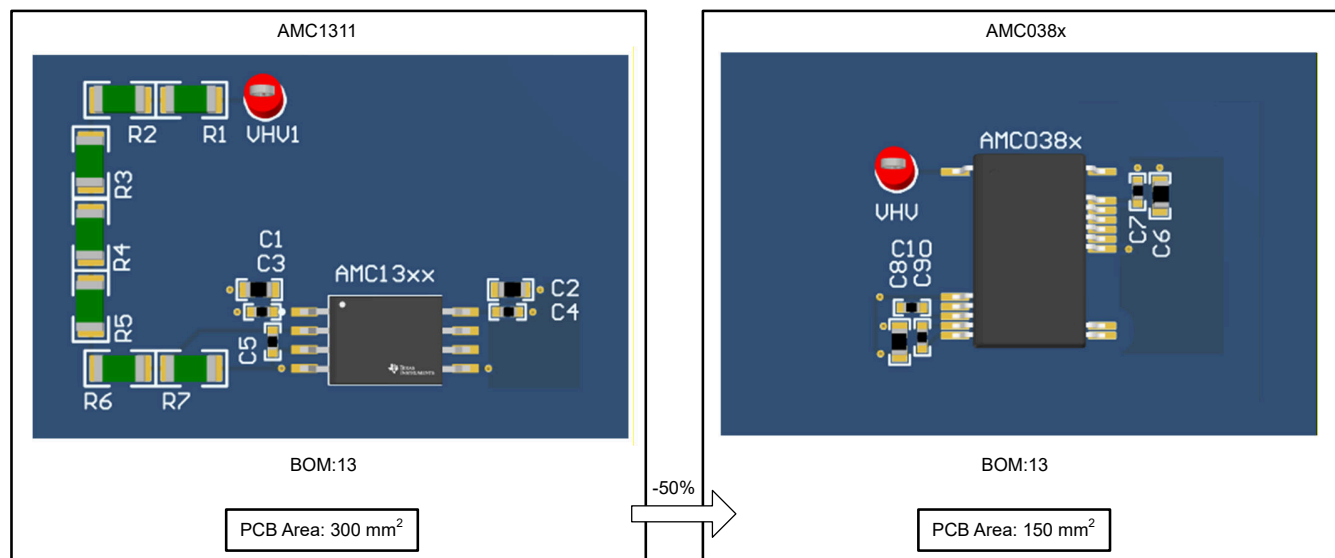


Figure 10-3. System Space Savings From Integrating the Resistive Divider into the TI AMC038x-Q1 Family

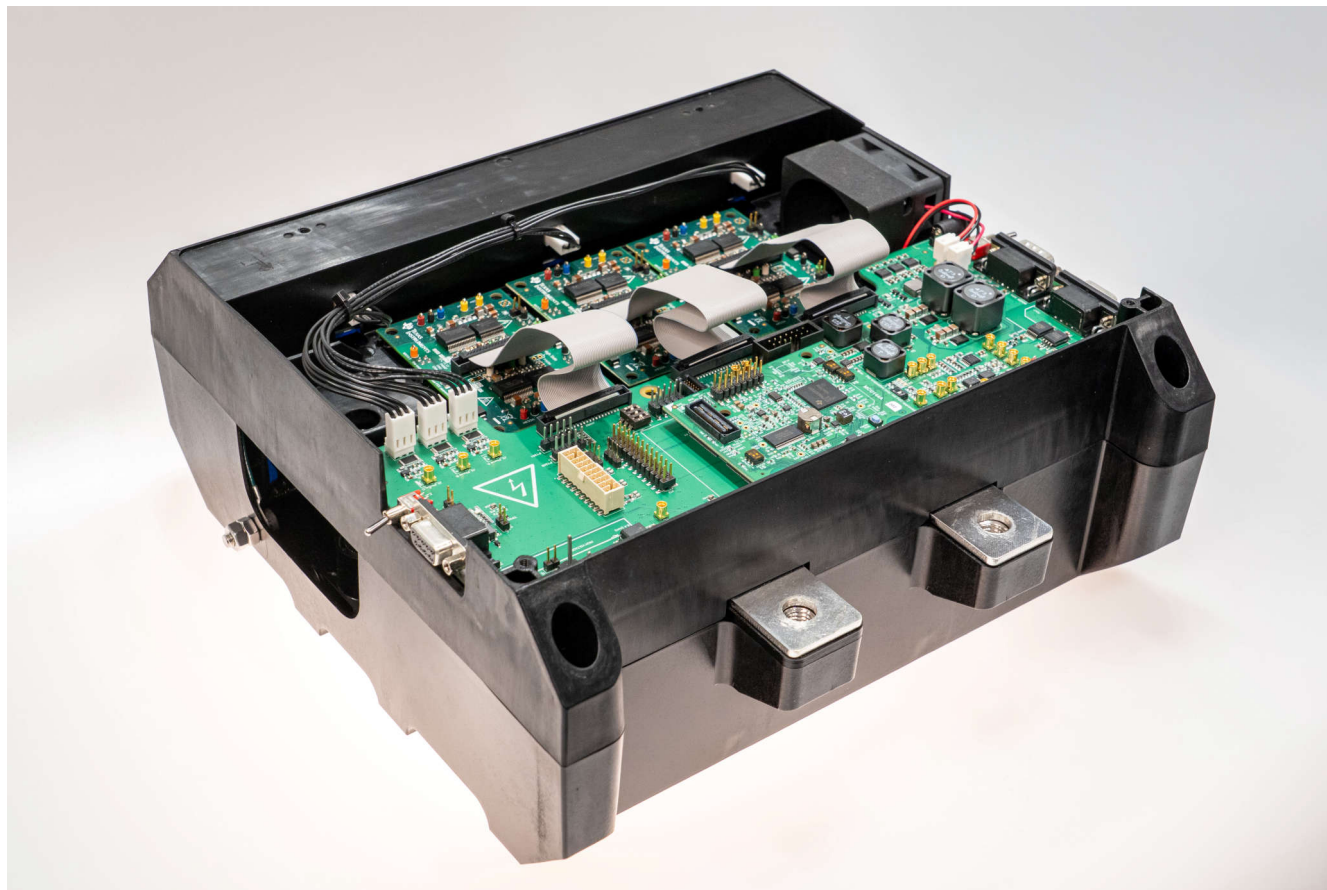
## 11 System Engineering and Reference Designs

TI's system engineering teams are dedicated to developing optimized system designs from TI's broad product portfolio. Thereby, helping customers accelerate the system design cycle. The following details some previously-developed reference designs:

- [TIDM-02014](#) SiC traction inverter reference design, see [Figure 11-1](#):



TIDM-02014 is an 800V, 300kW, SiC-based, traction inverter system reference design developed by Texas Instruments and Wolfspeed®. The design provides a foundation for OEMs and design engineers to create high-performance, high-efficiency traction inverter systems and reach market faster. This design demonstrates how traction inverter system technology from TI and Wolfspeed® improves the efficiency of the system by reducing overshoot in available voltages with a high-performance isolated gate driver and the real-time variable strength gate driver that drives the power module. The isolated gate driver, coupled with TI's isolated bias supply design, significantly reduces the PCB size, providing a PCB area that is more than two times smaller, less than 4mm in height, and eliminates 30+ discrete components, improving system power density. TI's high-control performance MCUs feature tightly-integrated, real-time peripherals, which enable effective traction motor control at speeds greater than 20,000rpm. The fast current loop implementation of the design helps minimize motor torque ripple and provides smooth speed-torque profiles. The mechanical and thermal designs of the system are provided by Wolfspeed®.



**Figure 11-1. TIDM-02014 Traction Inverter Reference Design**

- [UCC5880INVERTEREVM](#) gate driver evaluation module:

The UCC5880INVERTEREVM board can be used standalone to test the UCC5880-Q1 driver with 100nF capacitor load soldered on the board, or the EVM can be used to drive the half-bridge power modules directly based on the Wolfspeed® XM3 SiC MOSFETs for high-power tests. Two UCC14240-Q1 isolated bias supplies are included on the board. The EVM is flexible to configure different SPI communication methods, including regular SPI, daisy-chain, and TI address-based. The EVM can interface with a Sitara™ and C2000™ real-time microcontroller control card for 3-phase inverter testing up to 300kW.

- [TIDA-01527](#) discrete resolver reference design:

The TIDA-01527 is a discrete resolver front-end reference design with a C2000™ microcontroller and  $\pm 0.1^\circ$  accuracy. This reference design is an excitation amplifier and analog front end for resolver sensors. The design implements only discrete components and standard operational amplifiers on a 1-in-2 printed circuit

board (PCB). The provided algorithm and code example uses a C2000™ microcontroller (MCU) LaunchPad™ Development Kit with the TMS320F28069M MCU for signal processing and angle calculation. The reference design uses a remarkable, scattered-signal processing method. This method improves the system accuracy by 250% while potentially maintaining hardware costs and complexity to a reasonable level.

## 12 Conclusion

Automotive traction inverter technology is trending toward 800V, high-power density (toward larger than 50kW/L), high efficiency (> 99%), and high safety (ASIL D) requirements. In all relevant areas, TI's technology provides a technological edge with new devices and significant improvements.

In the **C2000™** MCU family, TI's new generation of C29 cores enable super-fast relative performance execution across the competition (specifically the F29H58x family of devices). The new generation of **TPS653860-Q1** and **TPS653861-Q1** PMICs enable adherence to full system safety requirements, with all the necessary control mechanisms, while simultaneously simplifying design efforts by cross-functioning with MCUs of competitors.

The new generation of **UCC5881-Q1** gate drivers enable increased motor control efficiency, with adjustable strength gate drives and system efficiency improvements of >2%, along with savings in space and potentially costs. The new **UCC34141-Q1** LV isolated bias module comes with an integrated transformer for massive reductions in the size of the system by up to 77%.

A completely new method of current sensing in the **TMCS2100-Q1** device eliminates the need for heavy and expensive C-core structures, elevating the traction inverter design. The device integrates resistive dividers or a DC-DC supply into the isolated voltage sense and shrinks the size of the BOM significantly. TI also enables inductive motor position sensing with the **LDC5072-Q1** AFE device to offer an alternative setup of the resolver, one without an exciter, simplifying the sensing setup from the perspective of the designer.

## 13 References

Owner	Reference	Document Type	Information Overview
Texas Instruments	<a href="#">Real-Time Benchmarks Showcasing C2000™ Control MCU's Optimized Signal Chain</a>	Application note	Information on the advantages that C2000™ brings to the real-time signal chain, including SW benchmarks.
Texas Instruments	<a href="#">Isolated Bias Power Supply Architecture for HEV and EV Traction Inverters</a>	Technical white paper	Information on the isolated bias supply on traction inverters.
Texas Instruments	<a href="#">What is a Smart DAC?</a>	Technical article	Information on smart AFE devices.
Texas Instruments	<a href="#">Addressing High-Voltage Design Challenges With Reliable and Affordable Isolation Technologies</a>	White paper	Overview of galvanic isolation, common isolation methods for high-voltage systems, and how isolation integrated circuits (ICs) can help designers.

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