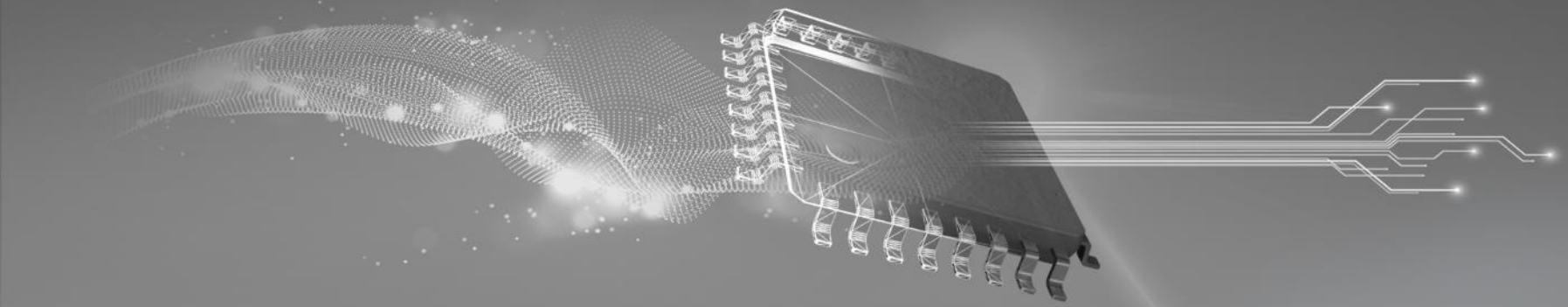
TI TECH DAYS



Gate drivers for an integrated powertrain system in HEV/EV

Nagarajan Sridhar
Automotive marketing lead – High Power Drivers Business, Texas Instruments

Will Hadden
Systems engineer – High Power Drivers Business, Texas Instruments

Texas Instruments

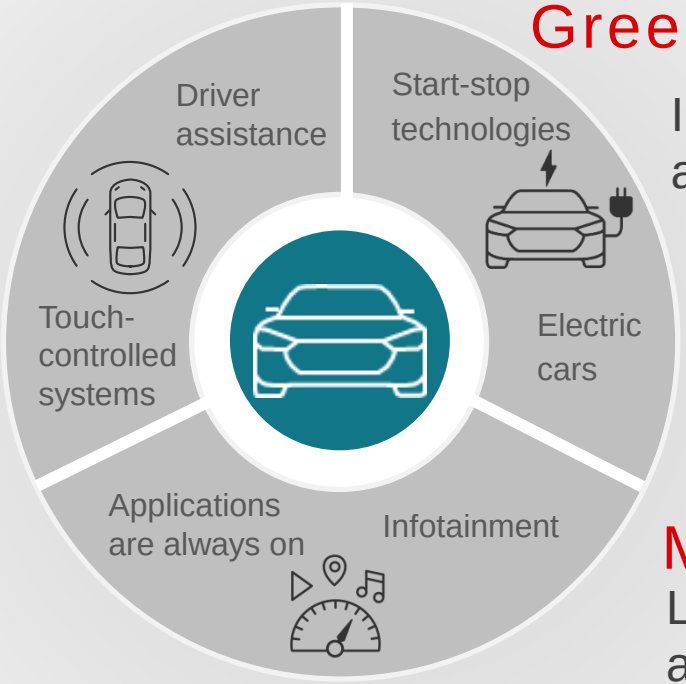
Outline

- Towards zero emissions
- Value of powertrain integration
- Power density at a system level
- Wide band-gap semiconductor devices: SiC and GaN
- Isolated Gate driver: key to powertrain integration
- Trend towards advanced diagnostics and protection

Automotive megatrends

Safer

From crash survival to crash avoidance

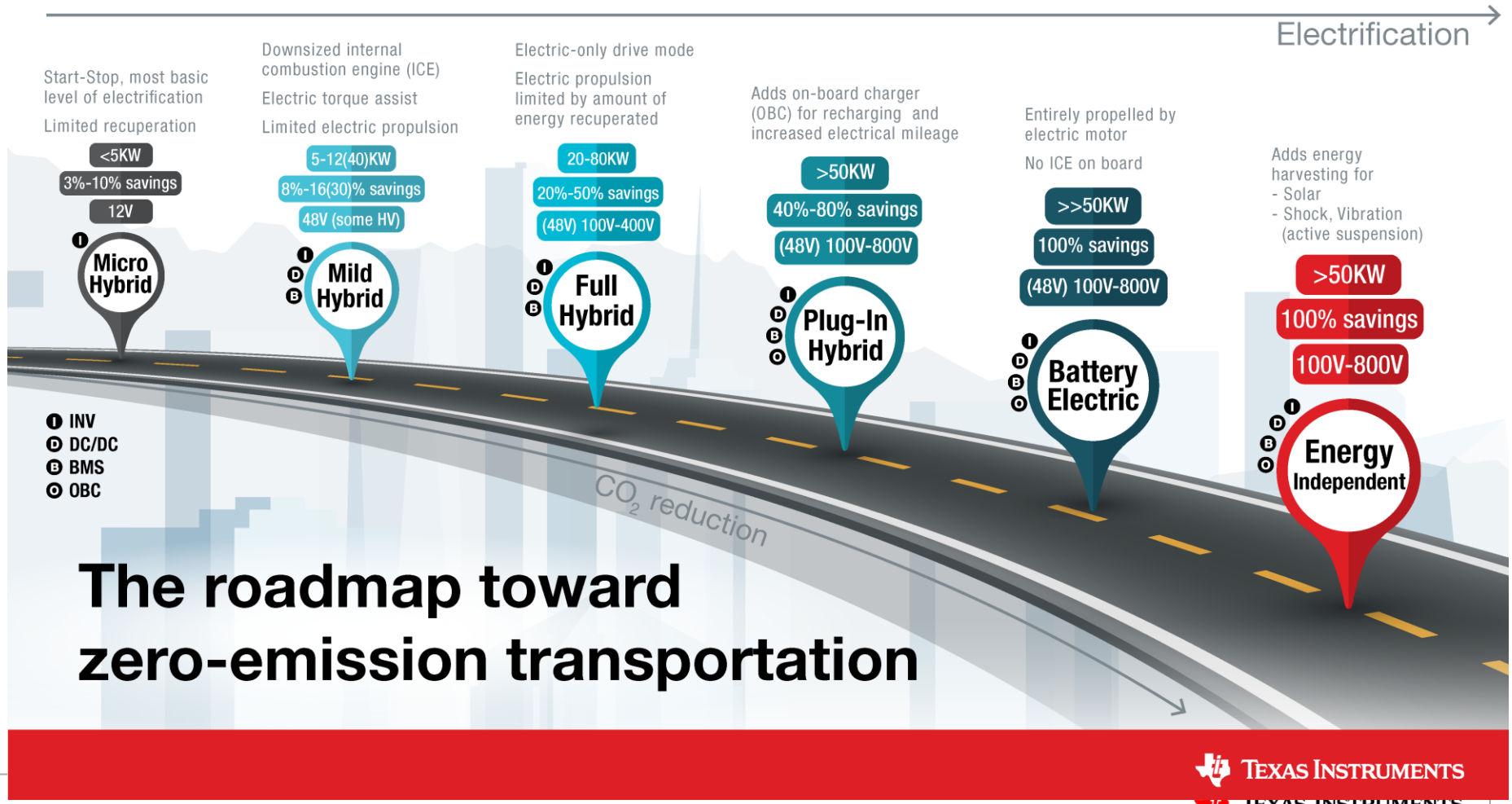


Greener

Improved fuel efficiency and lower emissions

More Fun

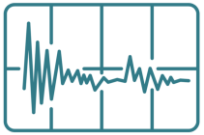
Less driver distraction and always-on connectivity


Electrification
Start-Stop, most basic level of electrification
Limited recuperation
<5KW
3%-10% savings
12V
Micro Hybrid
Downsized internal combustion engine (ICE)
Electric torque assist
Limited electric propulsion
5-12(40)KW
8%-16(30)% savings
48V (some HV)
Mild Hybrid
Electric-only drive mode
Electric propulsion limited by amount of energy recuperated
20-80KW
20%-50% savings
(48V) 100V-400V
Full Hybrid
Adds on-board charger (OBC) for recharging and increased electrical mileage
>50KW
40%-80% savings
(48V) 100V-800V
Plug-In Hybrid
Entirely propelled by electric motor
No ICE on board
>>50KW
100% savings
(48V) 100V-800V
Battery Electric
Adds energy harvesting for
- Solar
- Shock, Vibration (active suspension)
>50KW
100% savings
100V-800V
Energy Independent
I INV
D DC/DC
B BMS
O OBC
CO_2 reduction
The roadmap toward zero-emission transportation

Value of powertrain integration

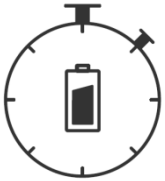
- Performance and reliability improvements: increasing system level power density with reduced discrete component reduction
- Wide band-gap semiconductor devices: a disruptive technology in the automotive market
- Impact on overall cost

Trends driving change in power management



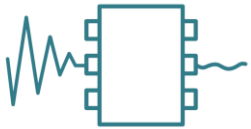
Low EMI –
Minimizing interference with other system components and simplify the engineer's design and qualification processes

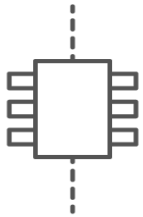
Power density –
Integrating active and passive components to safely and reliably achieve size-reduction goals



Low Iq –
Extending battery and shelf life enables more functionality, improved lifetime and reduced system cost

Low noise –
Reducing or shifting noise simplifies the power chain and improves reliability for precision analog applications





Isolation –
Enabling the highest working voltage and highest reliability in high-voltage and safety-critical applications

Power density at a system level

- The power efficiency and size of the powertrain system determines the performance of an HEV or EV
- Increase power density powertrain systems through integration – to achieve the highest efficiency in the most compact space
- Significant changes in topologies/architectures, integrated IC solutions and semiconductor power switches

Wide band-gap semiconductor devices: A disruptive technology

- High voltage operation
- High frequency operation
- Higher junction temperatures
- Lower power losses
- Increased heat dissipation
- SiC: Traction inverter and high power OBC
- GaN: OBC & DCDC
- Reduced system cost

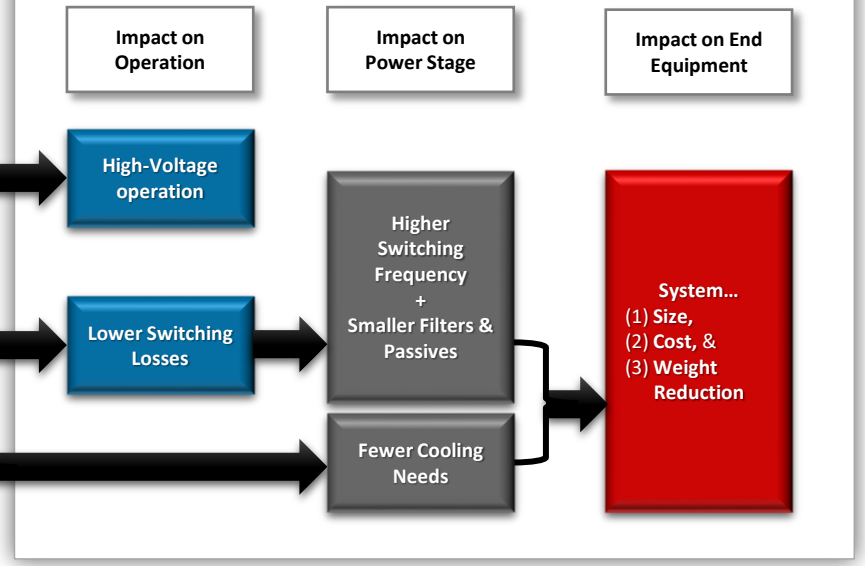
Why SiC?

SiC Material Properties + Power System Benefits

Intrinsic Material Properties

Property	Definition	Si	GaN	SiC – 4H
E_G (eV)	Bandgap Energy	1.12	3.4	**3.2**
E_{BR} (MV/cm)	Critical Field Breakdown Voltage	0.3	3.3	**3.5**
v_s (x10^7 cm/s)	Saturation Velocity	1.0	2.5	**2.2**
μ (cm^2/V.s)	Electron Mobility	1400	990-2000	**900**
λ (W/cm.K)	Thermal Conductivity	1.3	1.5	**4.5**

Properties leading to System Benefits



Isolated gate driver: Key solution to powertrain integration

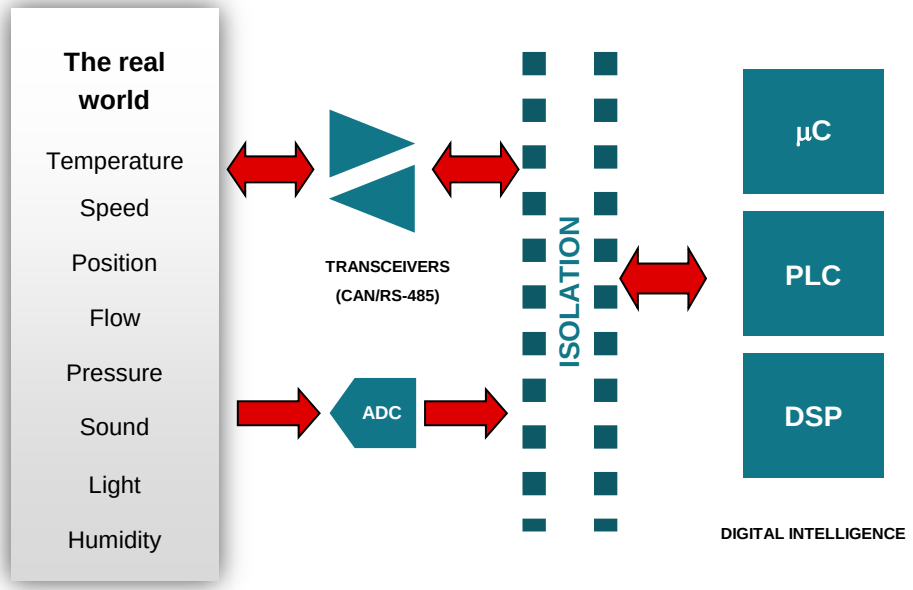
- At a powertrain system level, when viewed as a black box, there are three semiconductor components
  - Power semiconductor.
  - Isolated gate driver
  - Digital controller (microcontroller)

Need for isolation

Isolation is a means of preventing DC and unwanted AC between two parts of a system while still enabling data and power transfer between those two parts.

Isolation is used to:

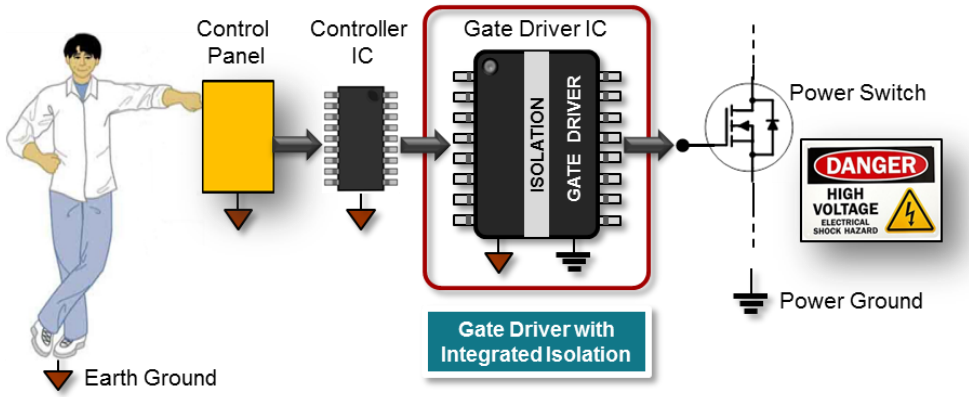
- Protect human operators and low-voltage circuitry from high voltages
- Handle ground potential differences between communicating subsystems
- Improve noise immunity



What is an isolated gate driver?

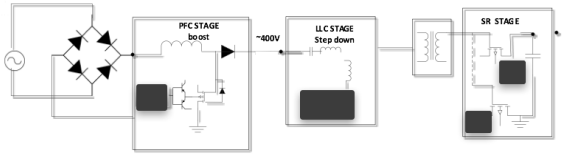
Isolated Gate Driver:

- **Drives Power Switch**
- **Isolates Controller from Power Switch**



Isolated Gate Drivers Application Topologies

AC/DC

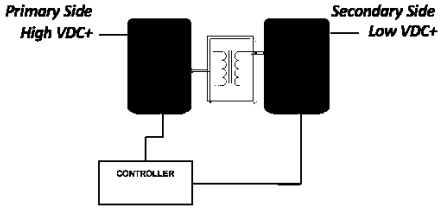


OBC: PFC (Power Factor Correction) Power Conditioning

Applications:

- Wall Charger & Adaptor
- 5G/Telecom Power Supply
- Merchant Network & Server PSU
- UPS
- **EV Charging Station**
- **EV On-board Charger**
- HVAC
- Appliances & Industrial Power Tools

DC/DC

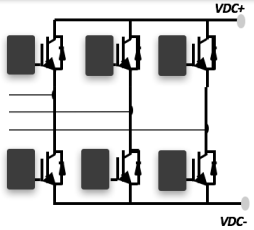


DC-to-DC Power Conversion Synchronous Rectification

Applications:

- 5G/Telecom Power Supply
- Merchant Network & Server PSU
- UPS
- EV Charging Station
- **EV On-board Charger & DC-DC**
- Solar MPPT Boost Stage
- Automotive Body Electronics
- HVDC & Grid Power Conditioner

DC/AC (Inverter)



Traction Inverters

Applications:

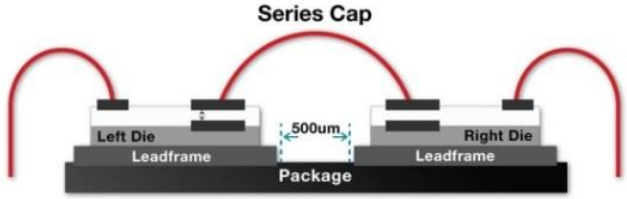
- **HEV/EV: Traction/Aux Motor Inverter**
- VF/Servo Drives & AC Inverter
- Solar String & Central Inverter
- Elevators & Conveyor Belts
- **Industrial Transport: Rail & Heavy EV**
- Grid Power Conditioner
- HVAC
- UPS

TI's Capacitive Signal Isolation Technology

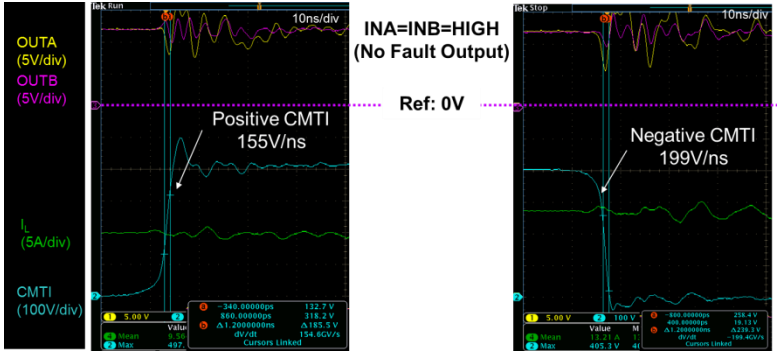
Increased System Robustness over Lifetime

[*Link to* ti.com/isolation]

- **Industry-leading Integrated Capacitive Isolation**
- **SiO_2 is the most stable dielectric over temperature & moisture**
- **Leverage advantages of TI's customized CMOS process:**
  - High precision
  - Tight part-to-part skew
  - No wear out mechanisms
  - Low defect levels
  - Highest lifetime in the industry: **>1.5 kV_{RMS} for 40 years**
  - Superior transient protection for harsh environments: **>12.8kV**



UCC21530 CMTI Results



[*NOTE:* CMTI = Common-Mode Transient Immunity]

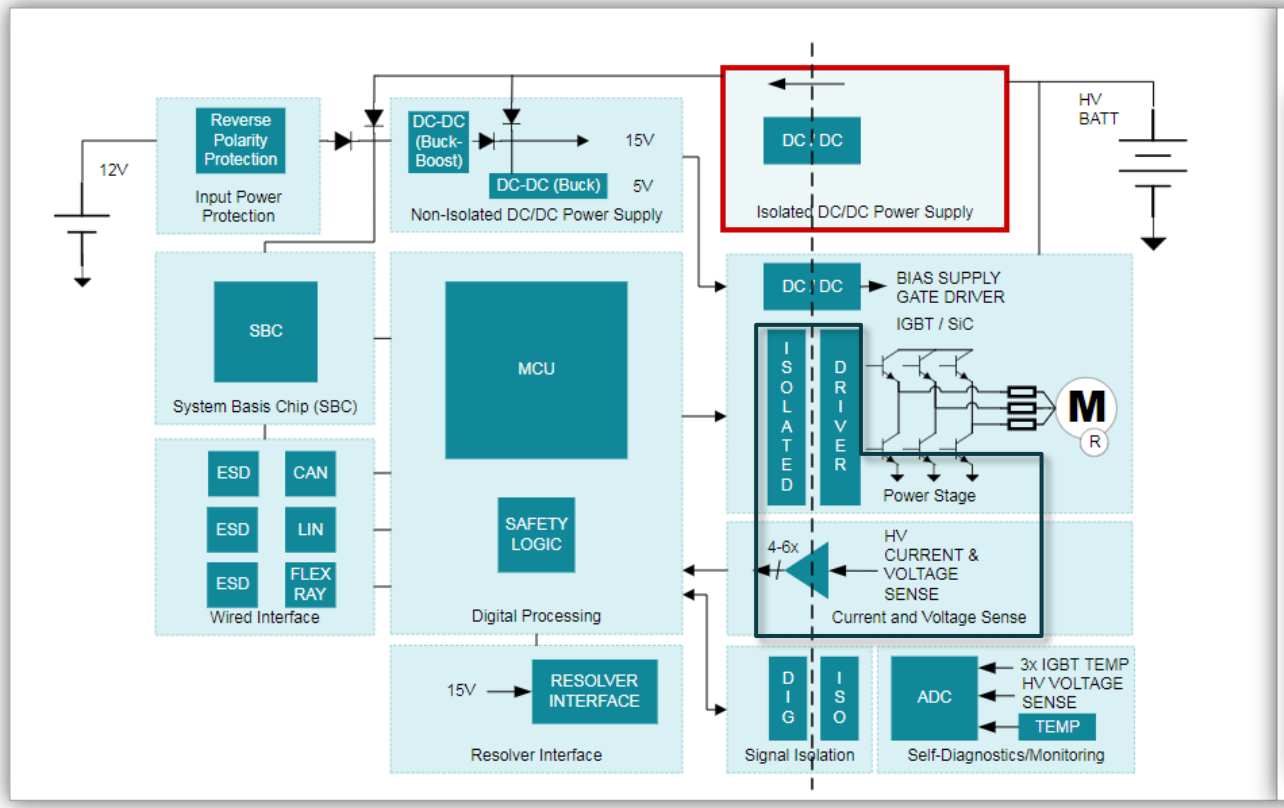
TI's Isolated Gate Drivers: Built for HEV/EV

HEV/EV Needs	Vehicle Implications	Power System Implications	TI's Isolated Gate Driver Products
			
Longer Range	Light Weight	▪ Efficiency ▪ Power Density ▪ Faster Switching ▪ Smaller Magnetics ▪ Lesser Cooling ▪ WBG Switches	▪ ±15A (Min) Integrated Drive current ▪ 100V/ns (Min) CMTI ▪ 10-bit Noise-immune Multi-channel ADC for sensing/diagnostics ▪ Fast accurate (50ns) short-circuit detection ▪ Programmable Active Short Circuit ▪ Switch Health/Lifetime Monitor ▪ Diagnostics & SPI Programmability
Faster Charging	Higher Power		
Affordable	Low Cost		
Passenger Safety	Safety Standards	ISO26262 Certification	SafeTI™: ISO26262 Compliance

Gate Driver Integration of advanced diagnostics & protection

- Achieve the lowest possible FIT rates
- Significantly reduces the number of components and PCB space
- Reduces the overall system cost

Traction Inverter: High Voltage



Gate Drivers

Isolated: Switch Protection + Diagnostics

ISO5852S-Q1
(IGBT / SiC) +2.5A/-5A, 8mm, 5.7kVrms, 30V output, Internal Miller Clamp, DESAT Detection, Isolated Fault Feedback & RESET, Power Good, Safe Shutdown (Soft Turn OFF)

UCC217XX-Q1
(IGBT / SiC) ±10A, 8mm, 5.7kVrms, 33V output, Internal/External Miller Clamp, DESAT/Over-Current Detection, Isolated Fault Feedback & RESET, Power Good, Isolated Analog Sensor , Safe Shutdown (Soft Turn OFF / 2-level Turn OFF), VEE UVLO Option

UCC5870-Q1
(IGBT / SiC) ISO26262-qualified for system-level ASIL-D functional safety certification, ±15A, 8mm, 3.75kVrms, 33V output, SPI-programmable, Internal Miller Clamp, DESAT Detection, Active Miller Clamping, 6-channel Isolated Analog Sensing based on 10-bit ADC for Switch Current & Temperature Sensing, Isolated Fault Feedback, Safe Shutdown (Soft Turn OFF / 2-level Turn OFF), High-level of SPI-programmability, Active Short-circuit Mode, Critical signal & isolation channel monitoring, …

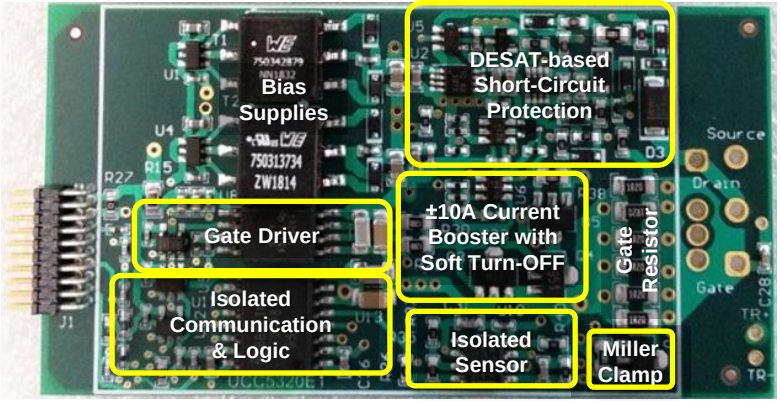
[*Link:* ti.com EE Reference Design & Products → Traction Inverter – High Voltage]

UCC217XX: Solving YOUR system challenges…

New Features in UCC217XX	Key System Challenge Solved …		System Benefits
	IGBT	SiC	
±10A peak drive strength (throughout drive voltage range)	>10kW systems use discrete buffers (e.g., NPN+PNP) to increase drive strength: Reliability, drive supply & cost challenges		▪ Higher System Reliability + Higher Efficiency ▪ Lower System Cost + Smaller PCB Area
>150V/ns CMTI (Min)	(Typically <50V/ns)	SiC switches fast to reduce switching loss	▪ Enhanced System Robustness ▪ Higher System Efficiency
200ns Over-Current Detection + 650ns Isolated Fault Reporting	Programmable DESAT threshold voltage	SiC has <3µs short-circuit capability	▪ Fast System Protection ▪ Enhanced System Robustness
2-Level Turn OFF (Option)	Significantly reduced V_{CE} / V_{DS} Overshoot during System Shutdown		▪ Safe System Shutdown ▪ Enhanced System Robustness ▪ Improved Switch Lifetime
Integrated Isolated Accurate Analog-to-PWM Sensor	Eliminate all discrete components used for bus voltage sensing / switch temperature sensing / sec-to-primary feedback / isolated alarm / …		▪ Lower System Cost ▪ Smaller PCB Area
VEE UVLO (Option)	Eliminate discrete circuitry for VEE monitoring (voltage sensor + isolator)		▪ Lower System Cost ▪ Smaller PCB Area
External Miller Clamp (Option)	More effective technique than internal miller clamp for high-power switch modules		▪ Enhanced System Robustness ▪ Lower System Noise (Ringing + EM)
Standard SOIC-16 DW Package	Small package size, 1mm pad pitch, pin-to-pin compatibility with better specs		▪ Lower System Cost ▪ Smaller PCB Area

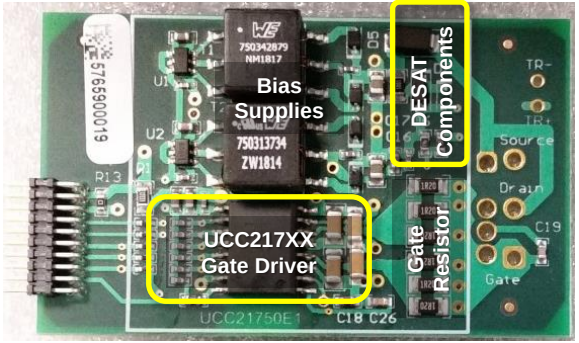
UCC217XX: Benefits of Integration

Power Stage using Simple Isolated Driver



UCC217XX Feature (Discrete)	Price Increase (1ku)	Area Increase
Discrete Current Booster	+ $0.90	+ 370 mm²
Discrete Short-Circuit Protection	+ $9.20	+ 215 mm²
Discrete Miller Clamp	+ $2.80	+ 30 mm²
Discrete Isolated Sensor	+ $4.50	+ 515 mm²
Total – Discretes	+ $17.40	+ 1130 mm²

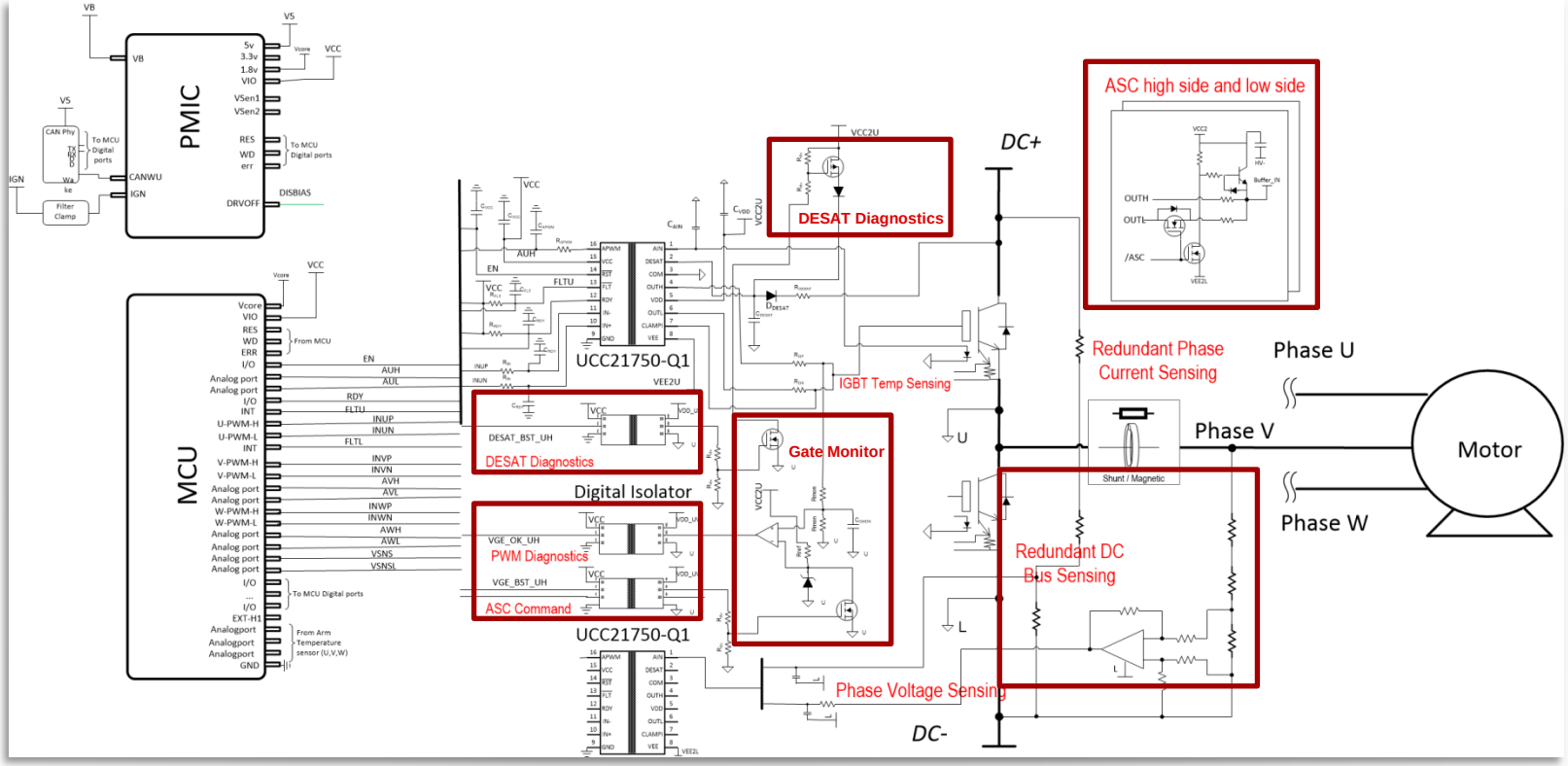
Power Stage using UCC217XX



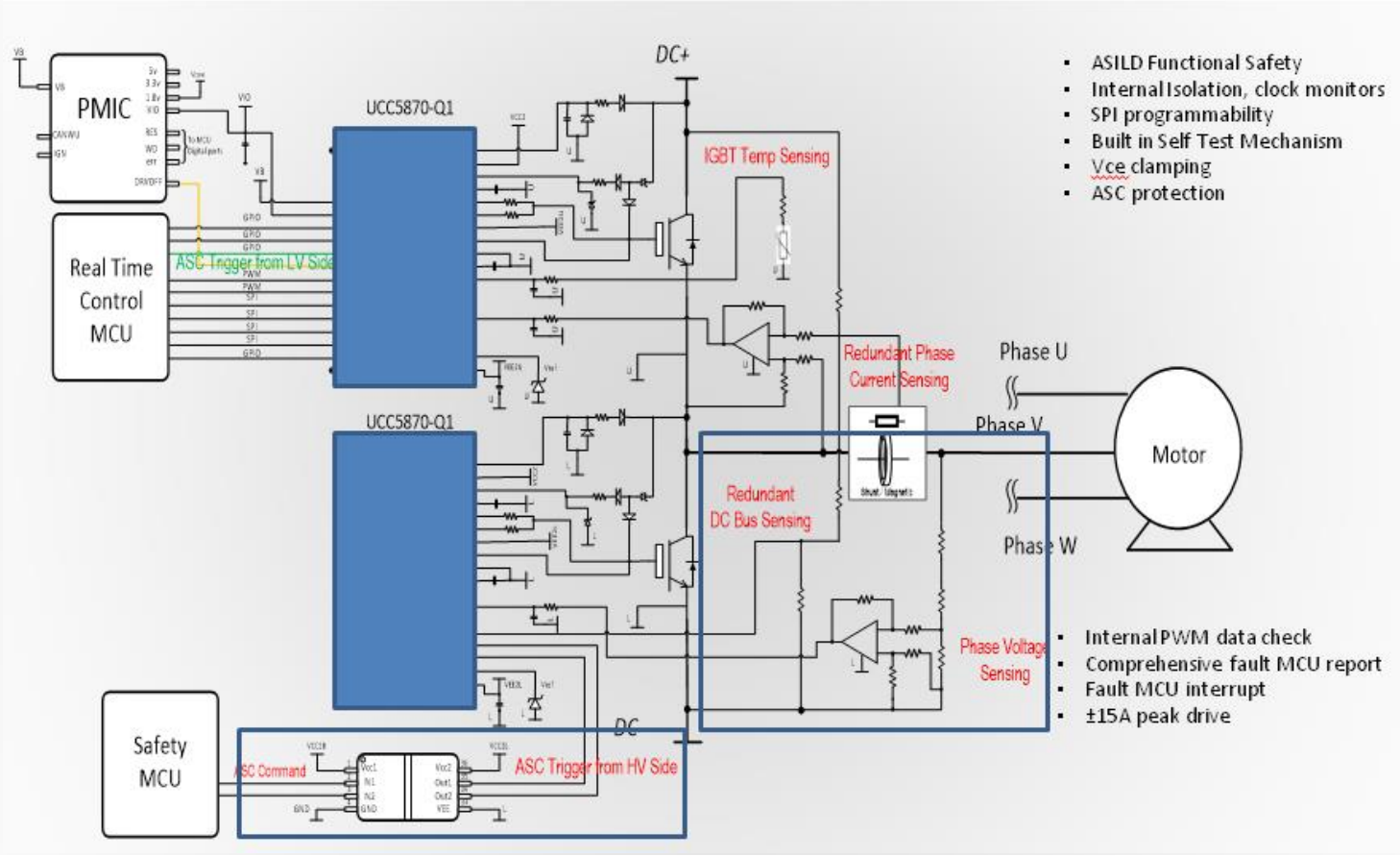
Integrated Features of UCC217XX enables

- ✓ Significant System Cost Reduction
- ✓ 2X PCB Area Reduction

Power Stage Safety Architecture Using UCC21750-Q1

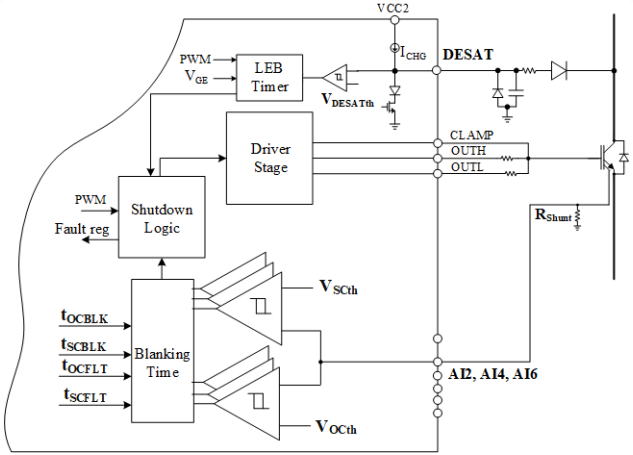


Power Stage Safety Architecture Using UCC5870-Q1



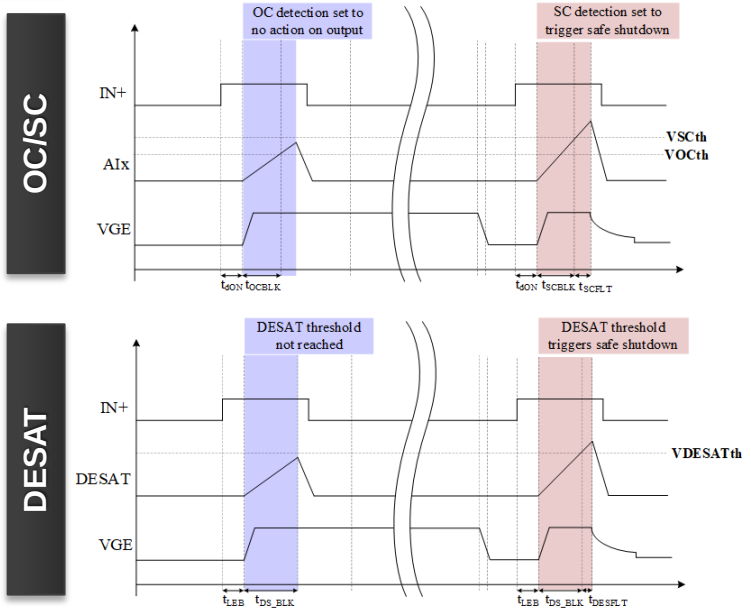
Short-circuit protection: flexibility, reliability

System benefits



- ✓ **Fast and noise immunity:** Initiates protection within **100ns** and is immune to noise with internal **deglitch filtering**
- ✓ **System flexibility across power module technologies:** Choice of **DESAT** and/or **OC protection** and **programmable thresholds, timing,** and **deglitch filtering**
- ✓ **Reliable shutdown mechanism:** Enables fast and safe shut-down of IGBTs or SiC MOSFETs using **soft** and/or **two-level turn-off**
- ✓ **Built-in reliability**: **Self-tests** built into protection circuitry

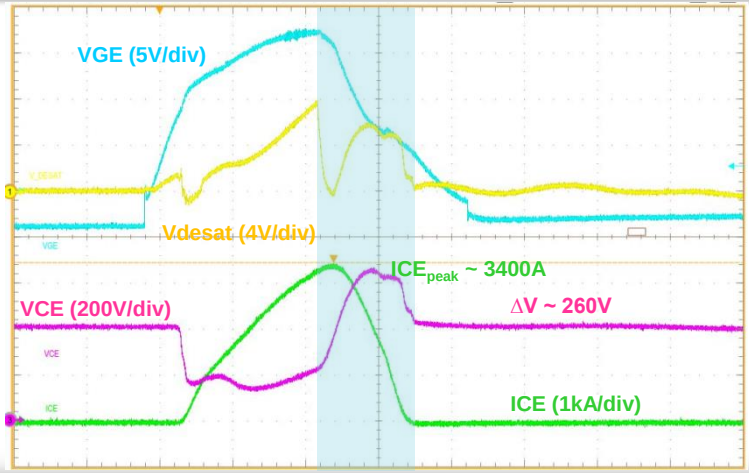
Measurements & specifications



Any combination of STO or 2LTO with OC, SC or DESAT faults available using SPI programming!

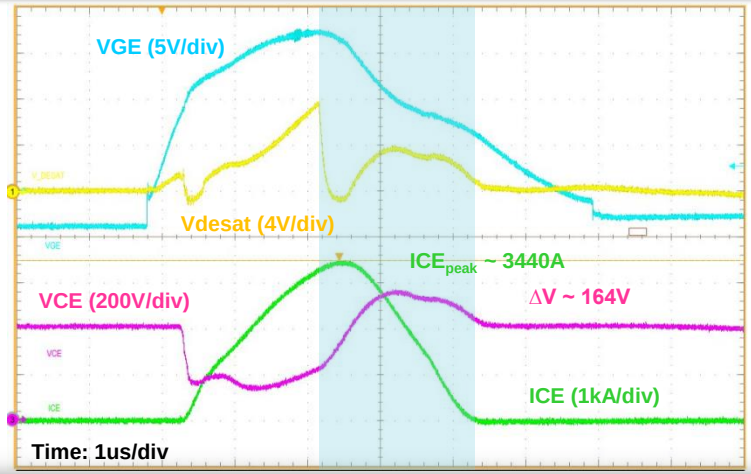
IGBT short circuit with safe shutdown: STO

Soft turn-off (STO): I_{STO}=0.6A



PARAMETER	MEASURED VALUE
Shutdown energy	1.0J
V_{CE} overshoot	260V

Soft turn-off (STO): I_{STO}=0.3A

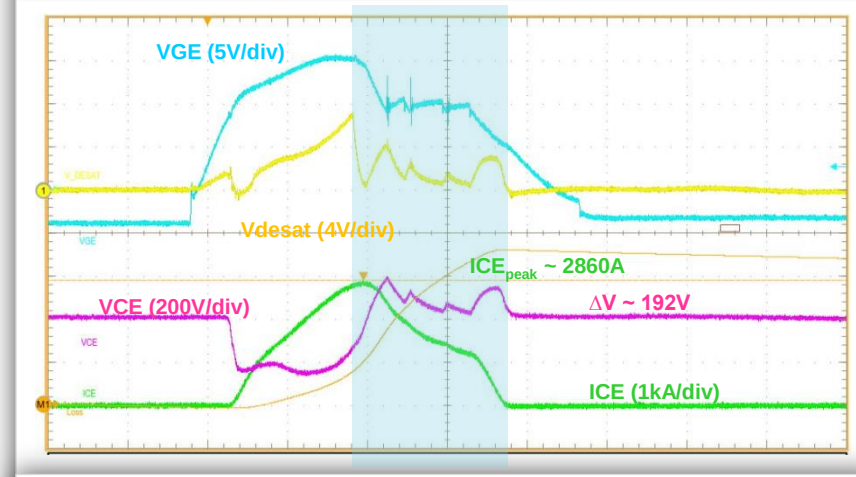


PARAMETER	MEASURED VALUE
Shutdown energy	2.0J
V_{CE} overshoot	164V

Programmable I_{STO} optimizes for the trade-off between shutdown energy and V_{CE} overshoot for IGBTs/MOSFETs

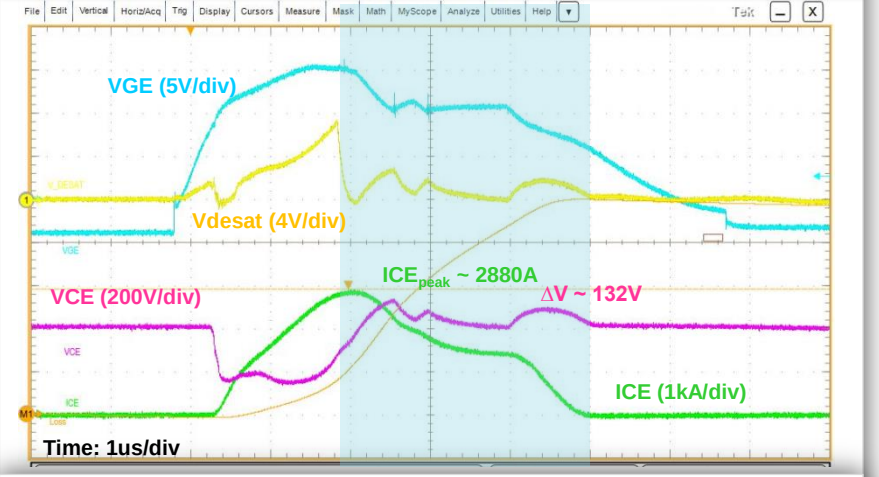
IGBT short circuit with safe shutdown: 2LTO

Soft turn-off (STO): I_{STO}=0.6A, V_{2LOFF}=9V



PARAMETER	MEASURED VALUE
Shutdown energy	1.4J
V_{CE} overshoot	192V

Soft turn-off (STO): I_{STO}=0.3A, V_{2LOFF}=10V

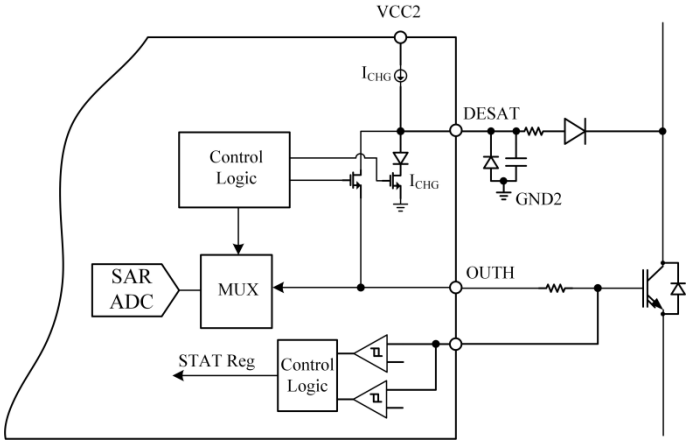


PARAMETER	MEASURED VALUE
Soft turn off current	2.1J
V_{CE} overshoot	132V

Programmable I_{STO} optimizes for the trade-off between shutdown energy and V_{CE} overshoot for IGBTs/MOSFETs

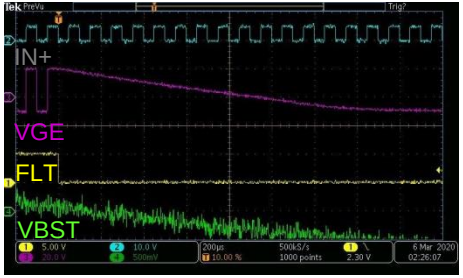
Gate voltage monitoring: flexibility, protection

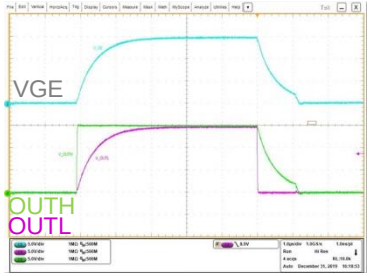
System benefits



- ✓ **Enhanced system safety:** Ensure output follows the driver input as high or low to **detect a system failure** such as open resistor at gate or gate short
- ✓ **Real-time fault monitoring:** **Dedicated fault output** to feed information back to MCU
- ✓ **Size reduction:** **Removes external components** to monitor driver output voltage

Measurements & specifications



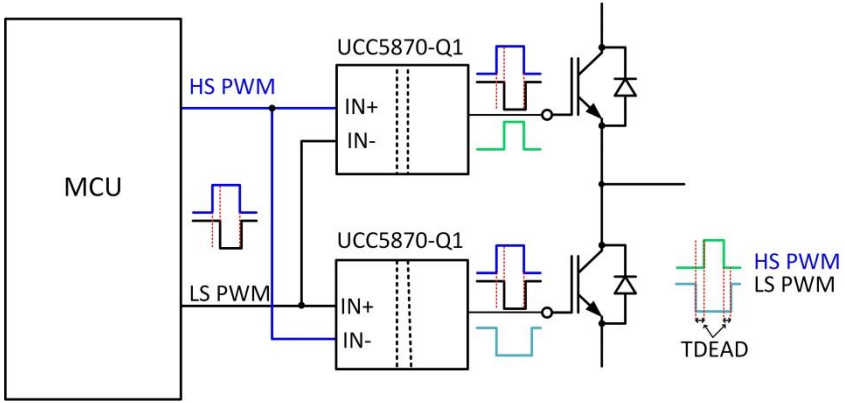


- ✓ VBST voltage drop triggers Gate Voltage Monitor Fault
- ✓ When Gate Voltage Monitor Fault is detected, the output is turned off

UCC5870-Q1 gate voltage monitor characteristics	Typ. value
Gate voltage monitor threshold value (reference to V_{CC2})	-3 V
Gate voltage monitor threshold value (reference to V_{EE2})	3 V
Blanking time (programmable)	500-4000 ns
Deglitch time	250 ns
Fault can be reported to nFLT1 or nFLT2, or report to state to nFLT2	

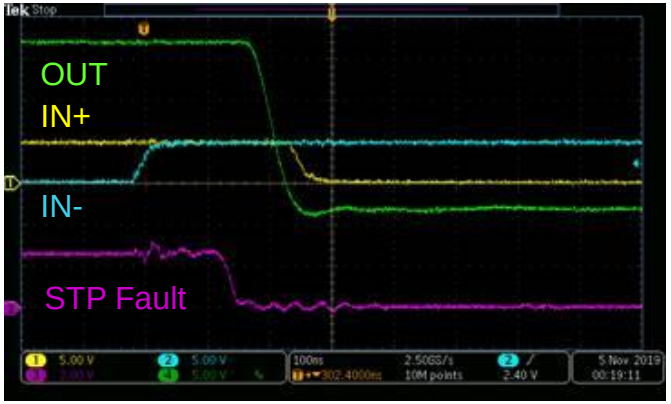
Motor controller interface: flexibility, protection

System benefits



- ✓ **System flexibility:** Supports **100% duty cycle** operation (min 250ns input pulse, 30 kHz max frequency with ADC)
- ✓ **Shoot-through protection:** Interlocking with two drivers prevents shoot-through with **programmable dead time** and **fault reporting**
- ✓ **Noise immunity:** Minimum **pulse width rejection** on IN+ and IN-

Measurements & specifications

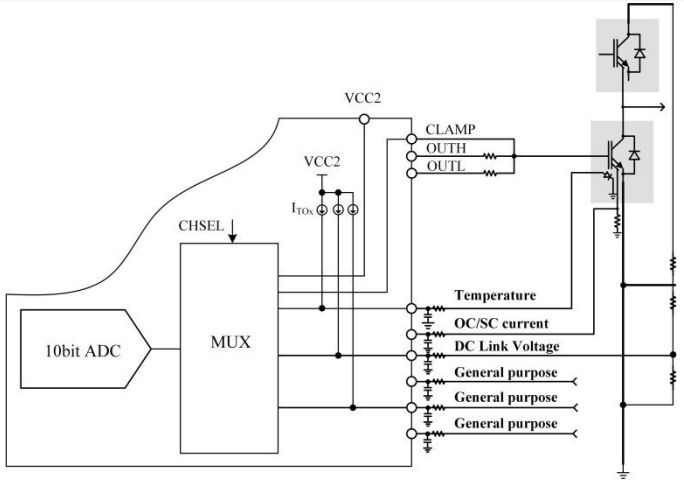


Shoot-through prevented and STP Fault triggered

- ✓ **100% duty cycle** possible with integrated charge pump
- ✓ **Programmable dead time**: 0ns, 105ns, 175ns…up to 4445ns in increments of 70ns
- ✓ **Noise rejection** chosen based on programming input pulse width rejection ranging from **0ns** to **210ns**

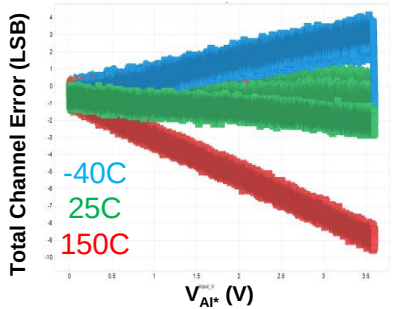
6-Channel ADC: accuracy, integration, low noise

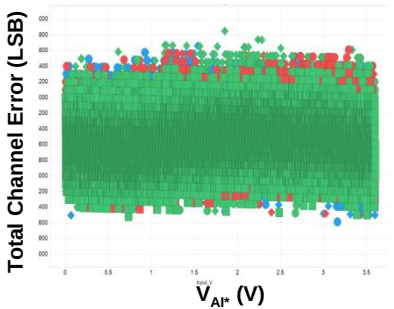
System benefits



- ✓ **System flexibility:** Variety of configurations to measure **temperature, current, or voltage**
- ✓ **Higher accuracy:** Integrated **10-bit** ADC and internal OR external **VREF**
- ✓ **System cost/size reduction:** Save **~$0.37** per channel by eliminating external ADC

Measurements & specifications



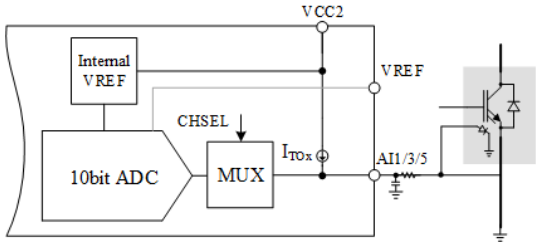


Precision reference can measure AI to within +1/-2 LSB (+3.5/-7 mV)*

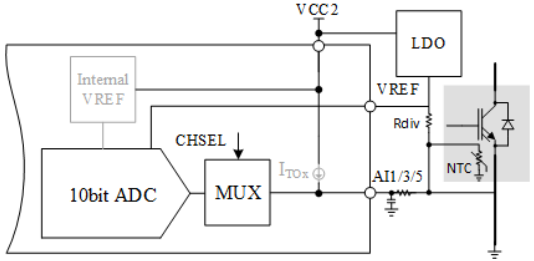
ADC	MIN	TYP	MAX
Input voltage range (A1 to A6)	0V	3.6V	3.636V
VREF (V)		4	
INL (LSB)	-1		1
DNL (LSB)	-0.5		0.5
External ADC reference turn-on delay (us)	10		
Pull-up current on AI2, 4, 6 Pins (uA)	5	10	15

6-Channel ADC: use cases

Isolated switch temperature sensing: NTC/PTC/Diode



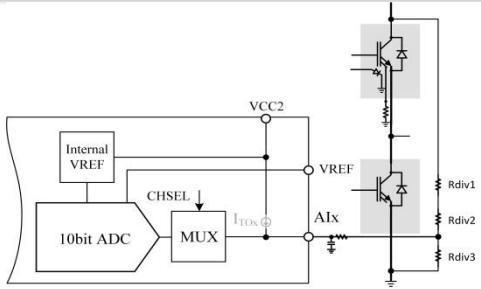
Example using thermal diode + internal VREF



Example using thermal diode + external VREF

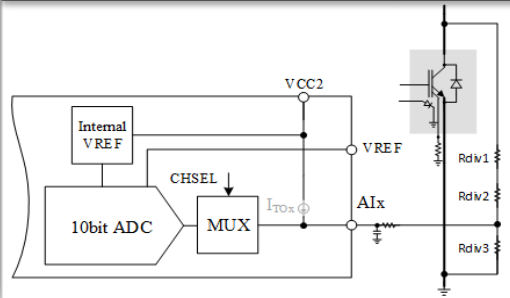
- Power switch junction temperature monitoring
- Power switch over-temperature configurable warning and shut-down
- Option for internal or external VREF to improve accuracy

Redundant bus voltage measurement



- HV bus sensing
- Monitor DC link voltage
- Referenced to low-side driver common

VCE voltage measurement

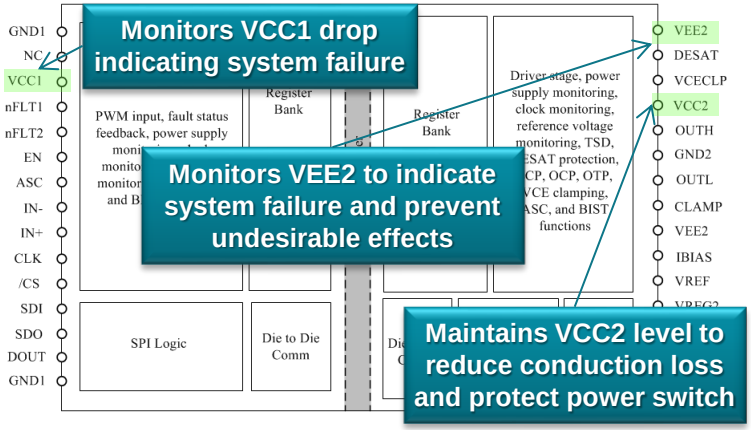


- HV VCE sensing
- Monitor if phase open or closed
- Option to reference to high-side or low-side common

[*Disclaimer:* Specs, features & pinouts subject to change without prior notice.]

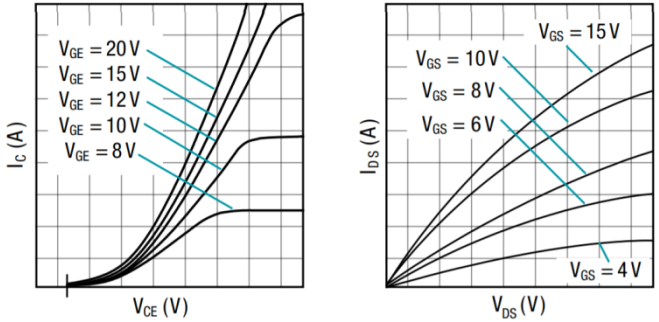
Over and under voltage lockout: adjustability

System benefits



- ✓ **Flexible supply monitoring across platforms** : **Programmable OVLO and UVLO** thresholds for primary and secondary supplies
- ✓ **Adjustable to fit power switch requirements**: Monitor supply voltage to **protect IGBT and SiC MOSFETs** from undue stress
- ✓ **Gather important feedback**: **Configurable fault outputs** nFLT1 and nFLT2 to report various faults and warnings

Measurements & specifications



IGBT vs. SiC MOSFET I-V characteristics vary with respect to gate drive voltage (VCC2) and conduction loss

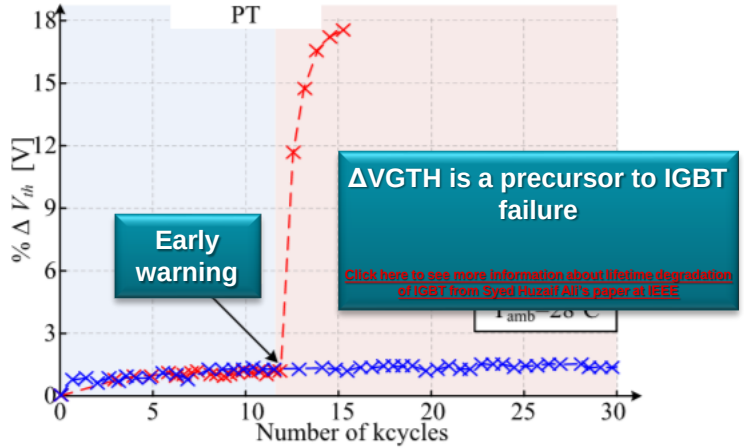
Supply	UVLO options	OVLO options
VCC1	3.3V, 5V	3.3V, 5V
VCC2	16V, 14V, 12V, 10V	23V, 21V, 19V, 17V
VEE2	-3V, -5V, -8V, -10V	-5V, -7V, -10V, -12V

Thresholds can be optimized based on gate voltage of power switch!

Power switch V_{GTH} monitor: system reliability

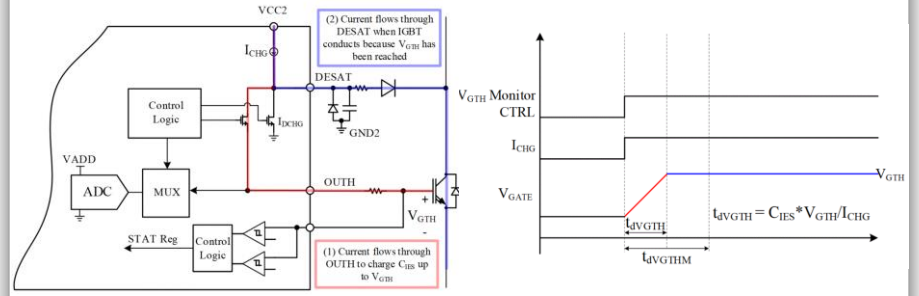
TI unique feature

System benefits

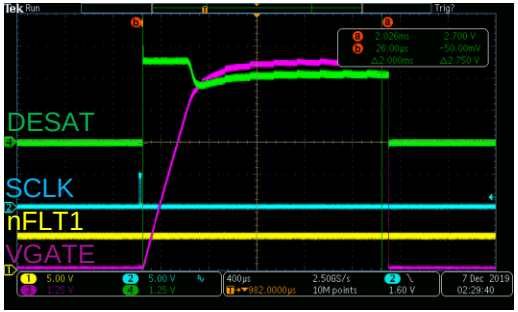


- ✓ **Integrated health monitor:** Gate driver used to perform **threshold voltage measurements** over system lifetime
- ✓ **Help system anticipate failure**: Works with MCU to provide **critical power switch data**

Measurements & specifications



Operation of VGTH monitor and timing diagram



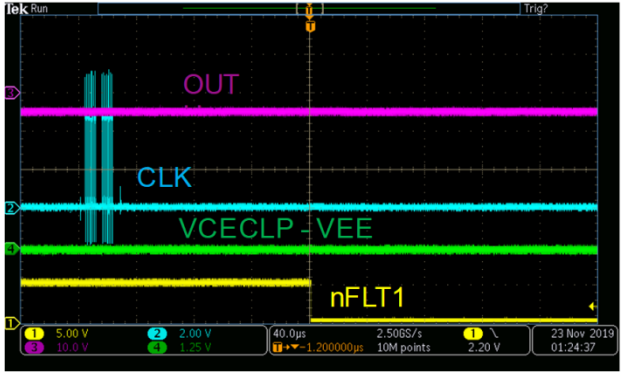
VGTH is accurate measure of health of external power switch

Test done with Cree SiC MOSFET C3M0065100K with voltage threshold of 1.8-3V

Built-in self-test (BIST): enhanced reliability

BIST (built-in self test) mechanisms	
UV/OV comparators of **internal regulator**	Automatic on power up (latent fail check)
UV/OV comparators **(VCC1, VCC2, VEE2)**	Automatic on power up (latent fail check)
Main **clock**	Automatic on power up (latent fail check)
Comparator for **thermal shutdown**	Automatic on power up (latent fail check)
DESAT diagnostic	On-demand (with SPI command)
OCP, SCP and OTP comparator diagnostics	On-demand (with SPI command)
VCE clamping detection diagnostics	On-demand (with SPI command)
Gate monitoring	On-demand (with SPI command)
CRC	On-demand (with SPI command)

Example & Benefits

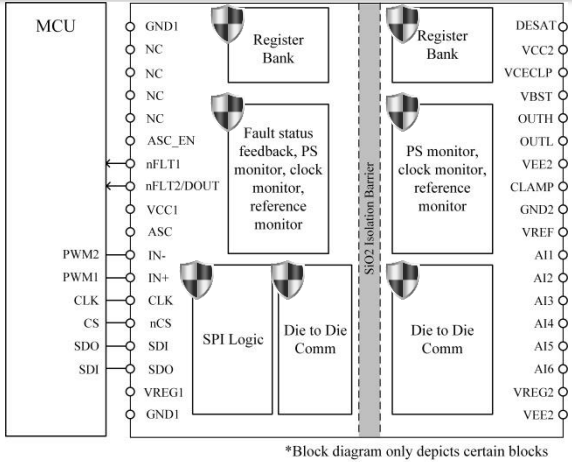


SPI command sent to check VCE Clamp and fault reported showing functioning detection mechanism

- ✓ **System and on-demand diagnostics:** Ensures operation of critical driver functions **at power up** and **on-demand** using SPI programming
- ✓ **Enables easier ASIL-D implementation**: Integrated diagnostics to **support system-level functional safety** requirements

Other diagnostics and protection: reliability and flexibility

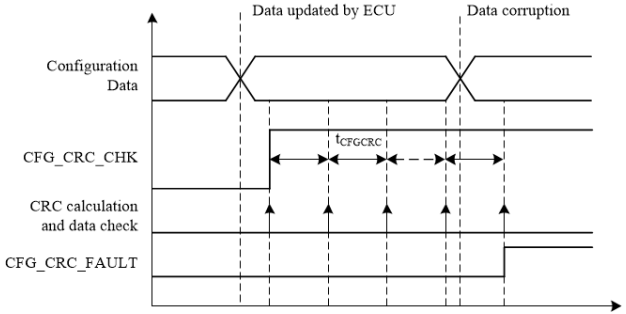
System benefits



*Block diagram only depicts certain blocks

- ✓ **Data protection:** **CRC (cyclic redundancy check)** protects various registers against faulty data transmission when in the Active State
- ✓ **Communication protection**: CRC checks for SPI transfer are **continuously updated** as SPI data is sent/received
- ✓ **Flexible feedback**: **Configurable fault outputs** nFLT1 and nFLT2 to report various faults and warnings

Measurements & specifications



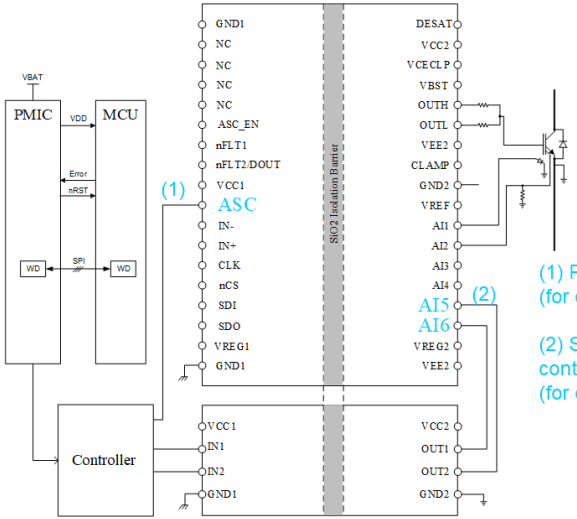
Configuration data CRC Check Timing

- ✓ When the driver is in the ACTIVE state, the configuration and control registers are protected by the CRC engine (this can be disabled)
- ✓ An error can be induced on the primary or secondary side
- ✓ CRC checks on SPI transfers are continuously updated as traffic is sent/received and is updated with every 16-bits that are received

See the datasheet detailed description section for more information

Active short-circuit (ASC): safe torque off

System benefits

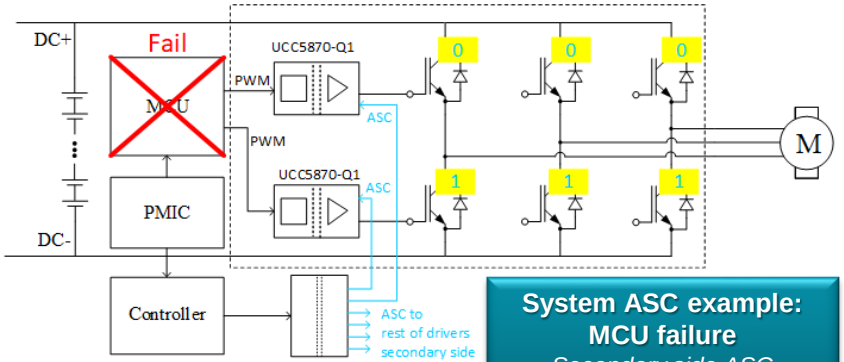


(1) Primary side ASC control (for controller failure)

(2) Secondary side ASC control (for controller + VCC1 failure)

- ✓ **System protection for multiple failure modes:** MCU failure, motor cable short, driver isolation failure, primary side power failure
- ✓ **System flexibility**: ASC input on **primary and secondary side**
- ✓ **SPI programmability:** Flexible **ASC State**
- ✓ **Fast ASC shut-down:** Driver-side ASC input (logic/PWM)

Measurements & specifications



System ASC example: MCU failure
Secondary side ASC control is used

Methods of ASC and configurable via SPI:

1. Primary side ASC trigger by ASC
2. Primary side ASC trigger by In+/-
3. Secondary side ASC trigger by pins AI5 and AI6

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale (www.ti.com/legal/termsofsale.html) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265