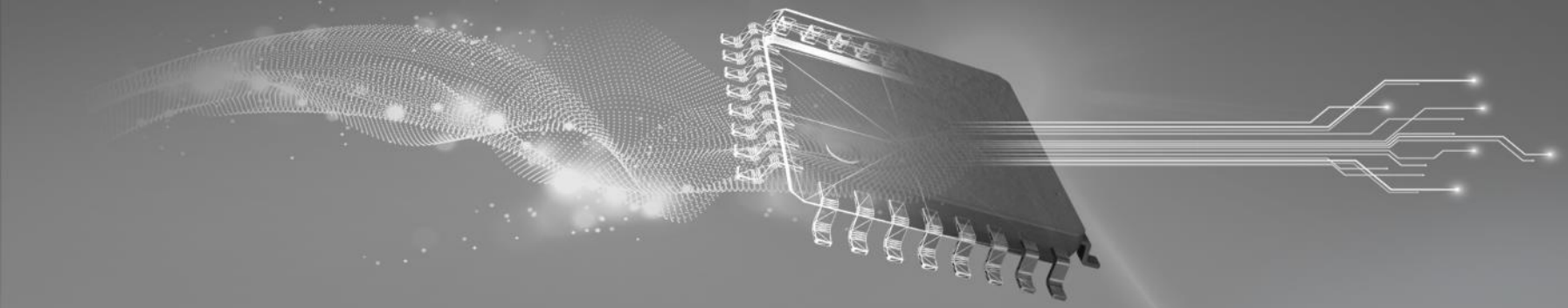
TI TECH DAYS



Maximize density, power, and reliability with TI GaN and C2000™ real-time MCUs

GaN: Yichi Zhang

C2000: John Kim

Texas Instruments

Overview

- Introduction of GaN and C2000 real-time MCUs which enable efficient power conversion and fast control
- Example of TI GaN and C2000 real-time MCUs in wide variety of applications
  - Totem pole PFC
  - 900V bidirectional energy storage system with 99% efficiency
  - 1.25kW 3-phase inverter with 99% efficiency

GaN + C2000: Efficient power and control

- Both LMG341x GaN & C2000 enable high MHz operation, for high power density
  - GaN FETs have inherently lower switching and conduction losses, to switch at high frequencies and increase power density
  - C2000 MCUs offer precision sensing, powerful processing and premium actuation capabilities engineered specifically for high frequency power control applications
- TI GaN with integrated gate drive and protection. Enables fastest GaN switching in the market, for high efficiency and reliability .
- C2000 is a platform of scalable, ultra-low latency, real-time controllers designed power electronics that demand high power density, high switching frequencies, perfectly paired with GaN and SiC technologies

TI GaN + C2000: Delivering efficient power solution

1MHz CrM PFC
with 99% Efficiency

TI-GAN

- Integrated driver delivers 2X switching speed and half the losses of discrete GaN
- Built-in protection designed for operation under extreme conditions
- Simple interface signal for closed loop connection with C2000 real-time MCUs

Power Density: 250 W/in^3 (15.2 W/cm^3)
Versus
Silicon: 55 W/in^3 (3.4 W/cm^3)

C2000 real-time MCUs

- 12-/16-bit ADCs with up to 3.5MSPS for high speed and accurate voltage and current sensing
- Powerful 32-bit Floating point DSP enabling multi-phase and multi-level control topologies
- Highly flexible, High resolution 150ps PWM enables high frequency converter design

Applications for GaN & C2000 real-time MCUs

Energy Delivery

Solar Power

Charging Infrastructure

Wind Power

Digital Power

Telecom / Server
AC/DC Rectifiers

Uninterruptable
Power Supplies

DC/DC
Converters

Motor Control

Appliance

E-bike

Pumps

Industrial Drives

Robotics

Automation

Servo Drive

AC Drives

C2000™
32-bit MCUs
Texas Instruments

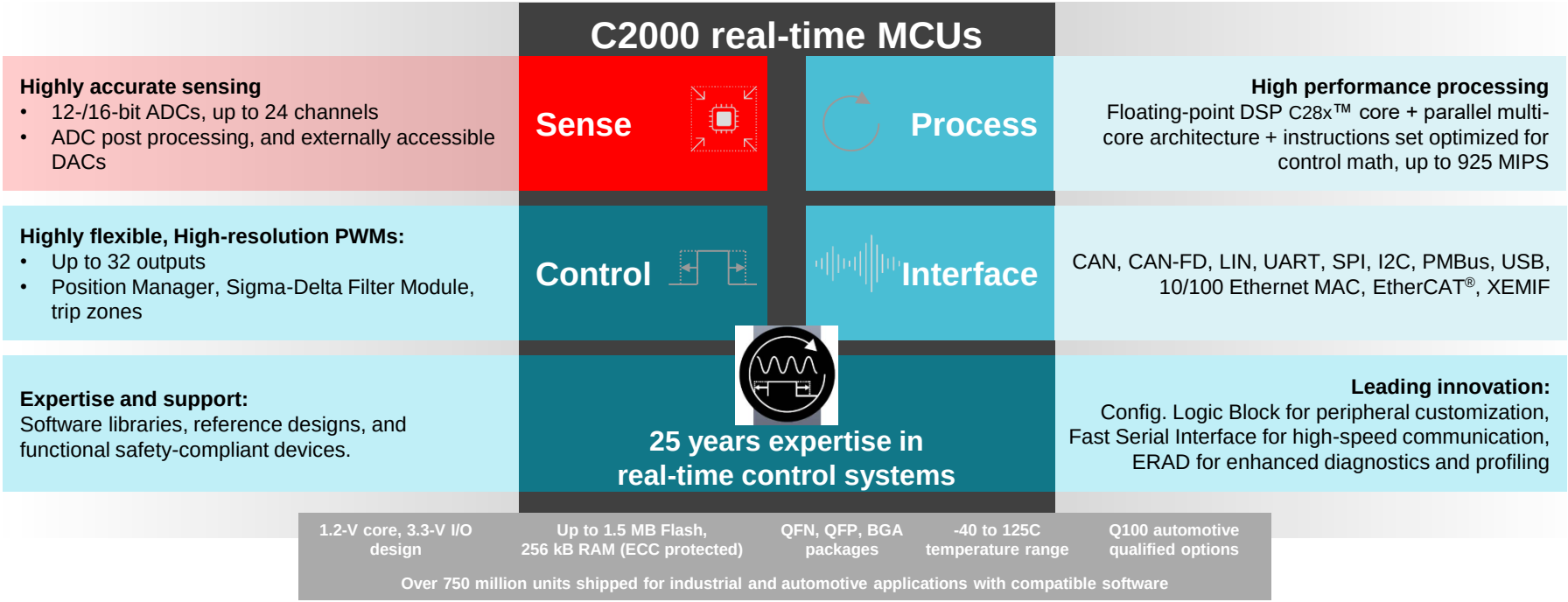
On-Board Charging
(OBC)

DC-DC

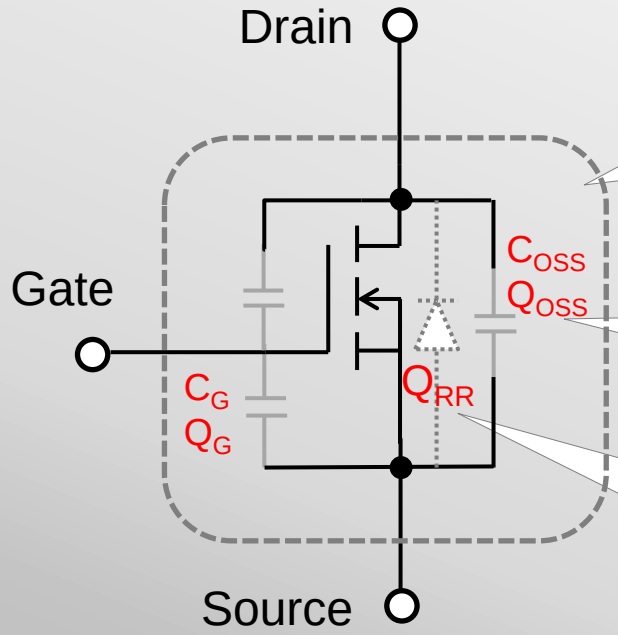
Automotive & EV/HEV

C2000™ real-time MCUs overview

Scalable, **ultra-low latency**, **real-time controller** platform designed for efficiency in power electronics, such as high power density, high switching frequencies, GaN and SiC technologies



GaN: Key advantages over silicon FET



Low C_G,Q_G gate capacitance/charge (1 nC-Ω vs Si 4 nC-Ω)

- ✓ faster turn-on and turn-off, higher switching speed
- ✓ reduced gate drive losses

Low C_{OSS},Q_{OSS} output capacitance/charge (5 nC-Ω vs Si 25 nC-Ω)

- ✓ faster switching, high switching frequencies
- ✓ reduced switching losses

Low R_{DSON} (5 mΩ-cm^2 vs Si >10 mΩ-cm^2)

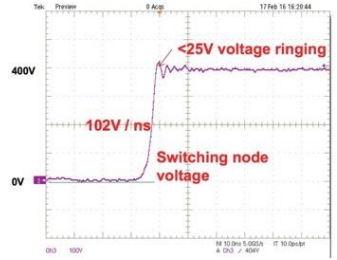
- ✓ lower conduction losses

Zero Q_{RR} No ‘body diode’

- ✓ No reverse recovery losses
- ✓ Reduces ringing on switch node and EMI

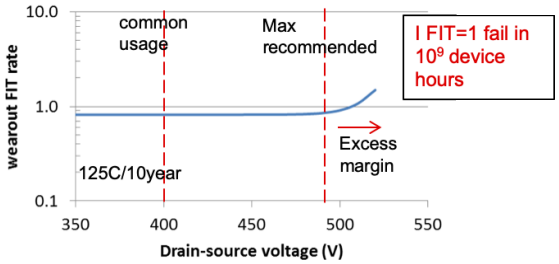
TI GaN: Efficient and reliable GaN

Twice the Speed, Half the Losses



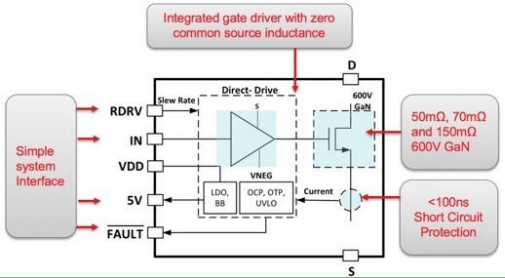
Highest switching speed in the industry enabling 50% lower losses in 65W to >10kW applications

Lifetime Reliability



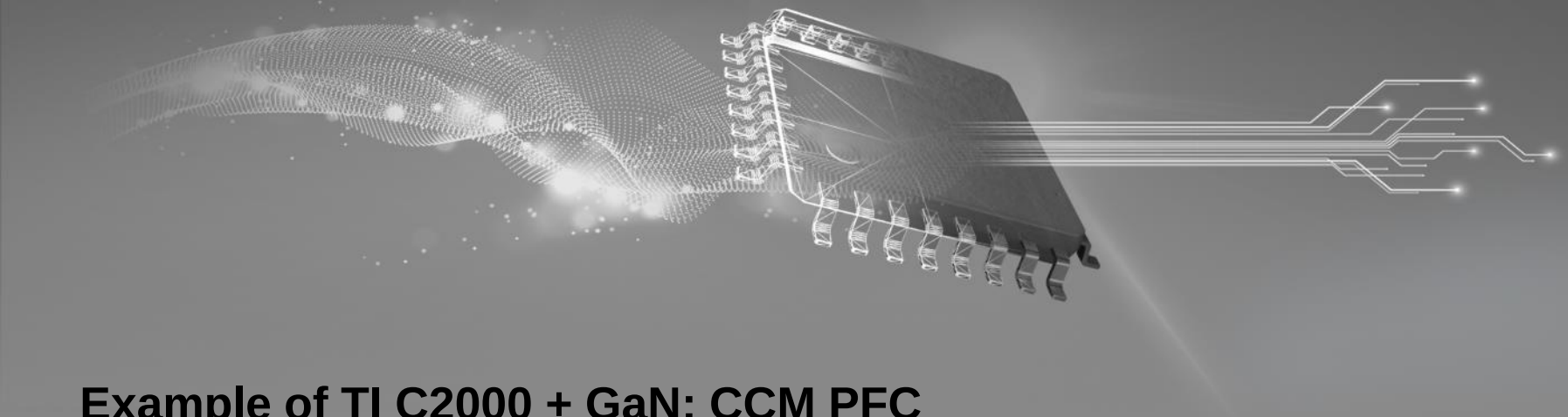
Robust self-protected solutions with >30M device reliability hours and >3GWHr of power conversion to date

Low Cost and Integrated



TI Owned process and manufacturing of GaN FET with integrated driver and protection in a low inductance package

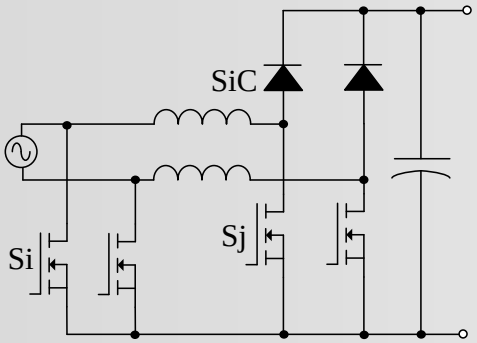
TI TECH DAYS



Example of TI C2000 + GaN: CCM PFC

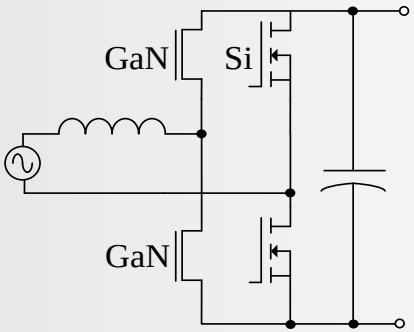
CCM PFC: topologies

Dual-boost PFC



- Good EMI performance
- Distributed heat
- Moderate efficiency
- Low power density
- Requires 6 power switches and 2 inductors

Totem-pole PFC

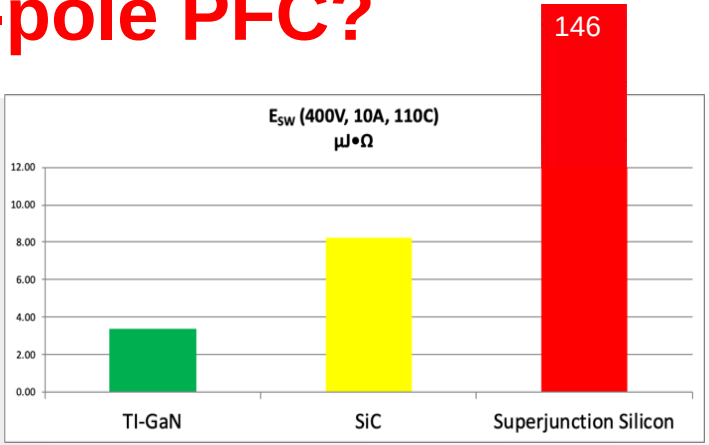


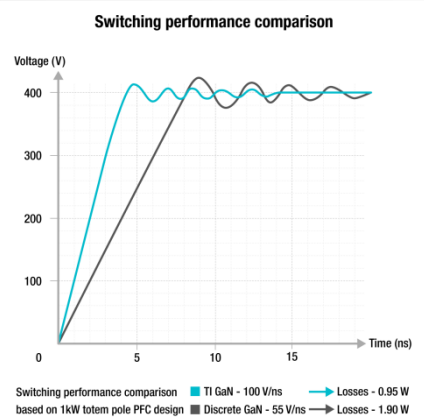
- High power density
- High efficiency
- Distributed heat
- Requires 4 power switches and 1 inductor

- SJ Mosfet has large reverse recovery loss
  - can't survive in a half bridge configuration
- GaN FET with 0 Qrr is ideal for totem pole PFC

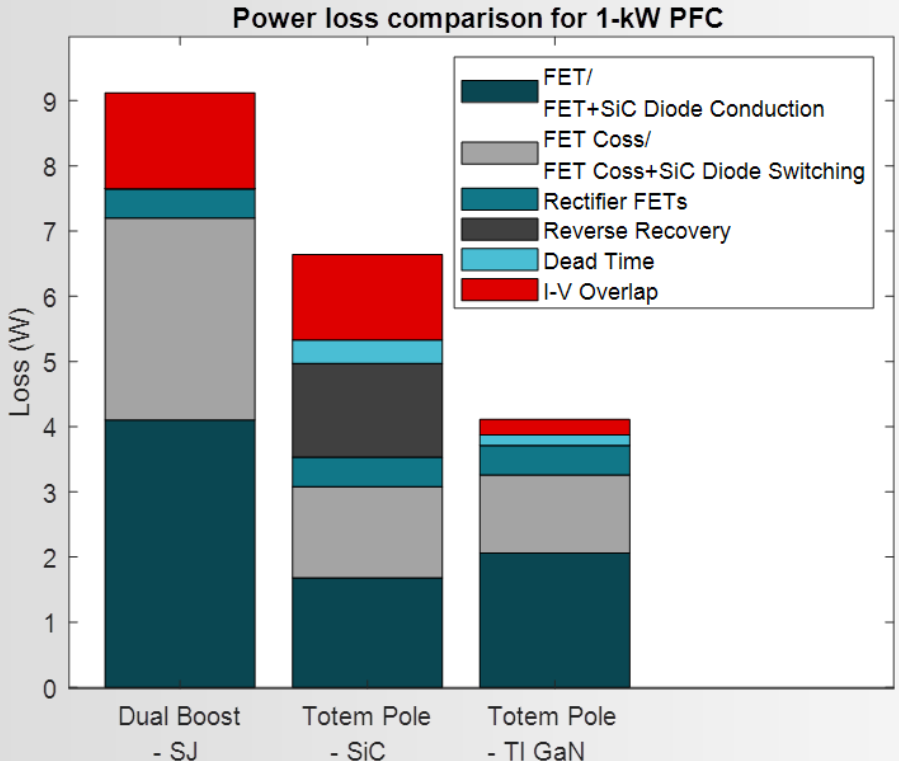
Why choose TI GaN in totem-pole PFC?

- GaN has **>50%** lower switching energy compared to SiC
- GaN has **zero** reverse recovery losses
- TI GaN switches at up to **100 V/ns** – resulting in **5.5x** reduction in losses compared to SiC and **2.7x** compared to discrete GaN
- TI GaN has the best cost parity to Si MOSFETs



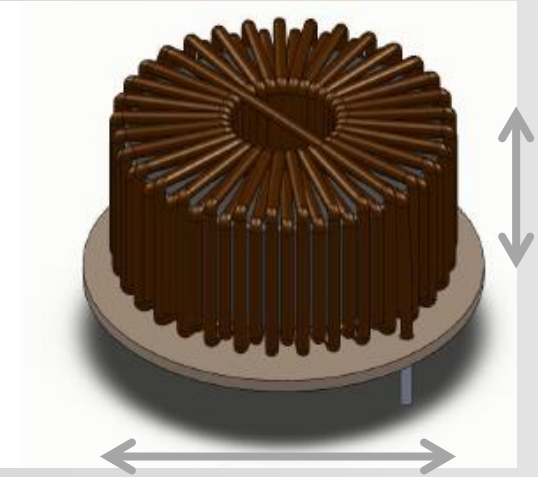


1-kW CCM PFC: power loss comparison



Higher switching frequency

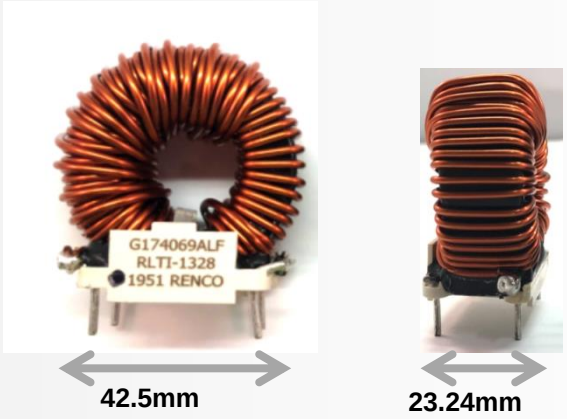
40-kHz CCM PFC inductor (1000 W)



Inductor volume 138915mm^3

3.2x reduction in inductor volume

100-kHz CCM PFC inductor (1000 W)

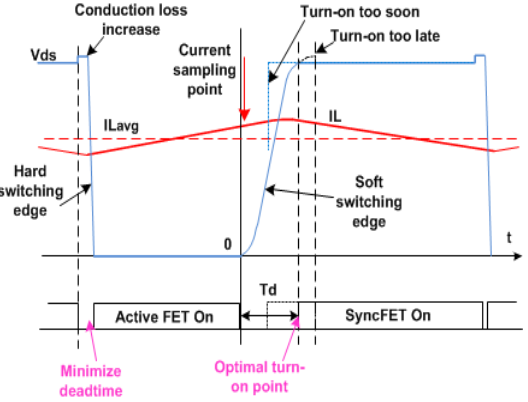


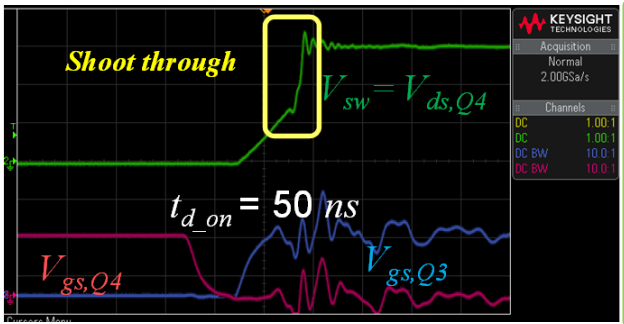
Inductor volume 43952mm^3

Path to 99% efficiency with GaN: control

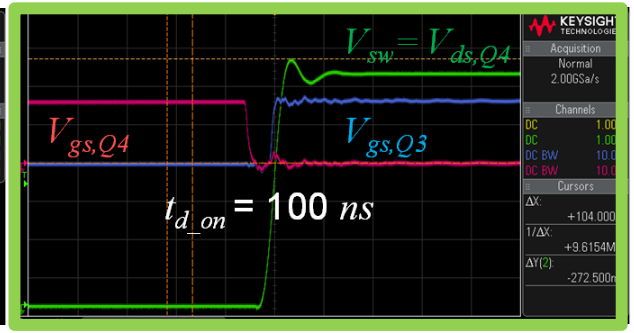
- Adaptive Dead Time (A.D.T)
  - Dead time calculated based on operating condition to minimize the third quadrant loss and improve efficiency
  - C2000 real-time MCUs with **Hi-res PWM deadband** and **compute power** can enable **adaptive dead time implementation**.

$$T_d = \frac{2 \times C_{sw} \times V_{out}}{I_{L\_peak}}$$

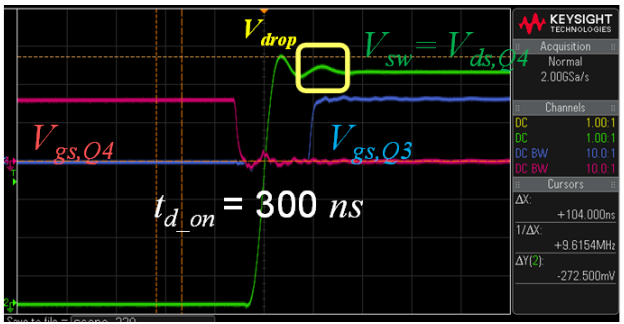




Turn-on too soon



Optimal T_d

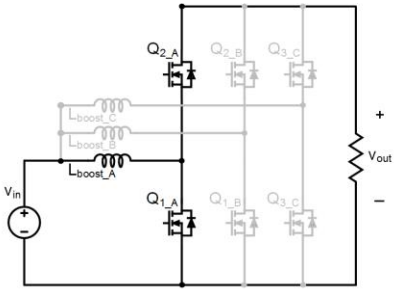


Turn-on too late

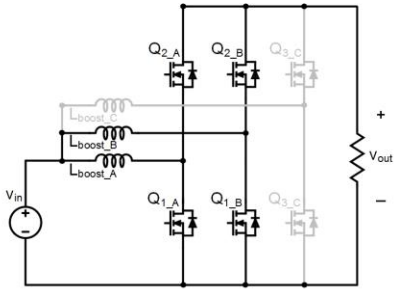
Path to 99% efficiency with GaN: control

- Phase shedding
  - Shed phase in lighter load application to reduce switching loss and improve efficiency
  - Phases need to be added/dropped quickly for safe operation and optimal efficiency
  - Decision based on current reference in voltage loop

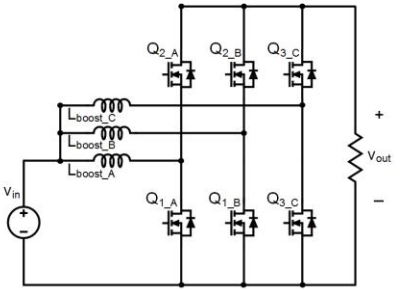
C2000™ Real-Time Controllers enable to implement flexible phase shedding



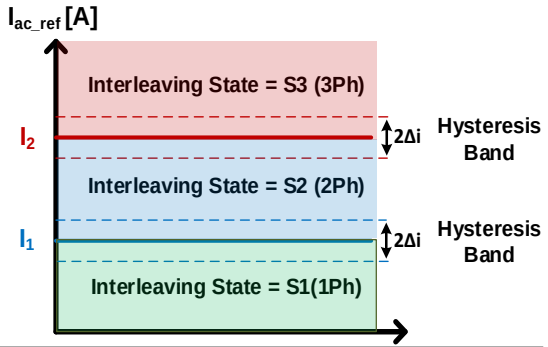
1Phase Operation
(For light load)



2 Phase Interleaving Operation
(For mid load)



3 Phase Interleaving Operation
(for heavy load)



Bi-Directional 3Ph Interleaved Totem-Pole CCM PFC/Inverter Reference Design TIDM-02008

Features

- GaN-based 3 phase interleaved totem pole bidirectional PFC
- Rated Power : 3.3 kW (at 230 V_{rms})
- Peak efficiency : 98.7 % (at 230 V_{rms})
- Total Harmonic Distortion (THD) < 2% (at low line)
- PWM switching frequency : 100 kHz
- PFC mode specification: 120/230 V_{ac_in}, 380 V_{dc_out}
- Inverter mode specification : 380 V_{dc_in}, 120/230 V_{ac_out}
- Soft starting for totem-pole bridge
- Phase shedding and adaptive dead time control for higher efficiency
- F28004x CPU + CLA (co-processor) support

Target Applications

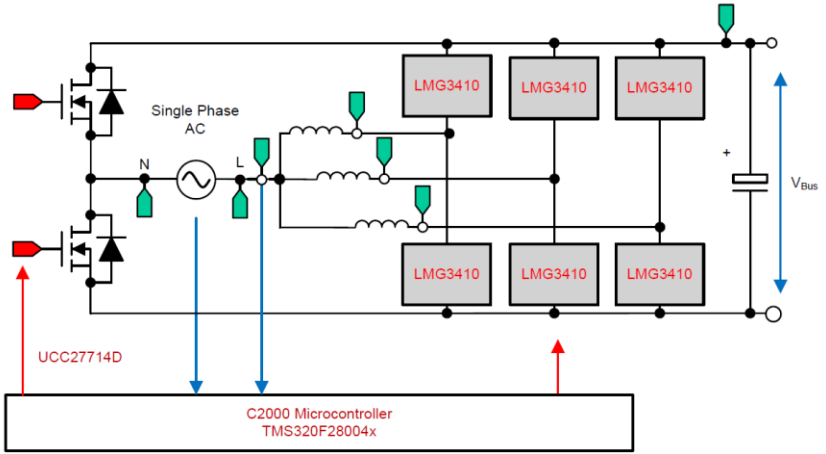
- Energy storage system
- Industrial power supply
- Onboard charger

Tools & Resources

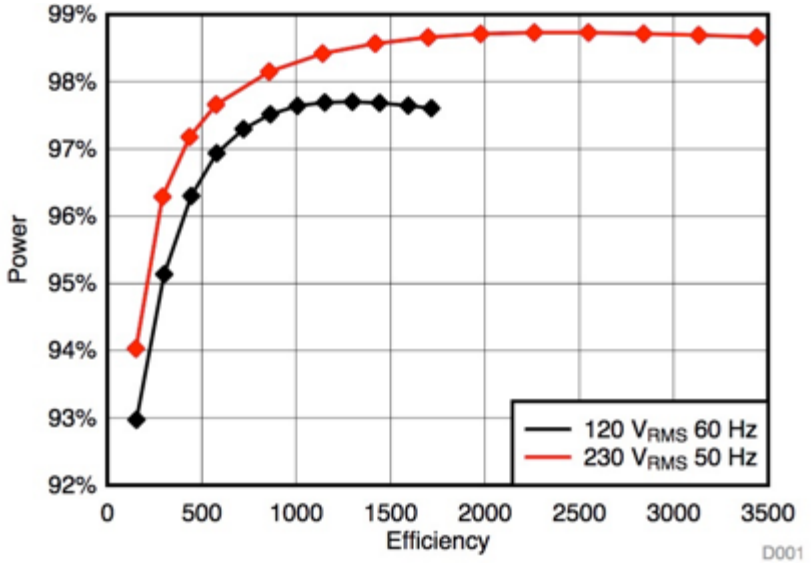
- **TIDM-02008 Tools Folder**
- **Test Data/Design Guide**
- **Design Files:** Schematics, BOM, Design Files
- **Key TI Devices:** TMS320F280049, TMS320F28075, LMG3410R070, UCC27714, OPA2376, SN74LVC1G3157, ISO7831, TLV713

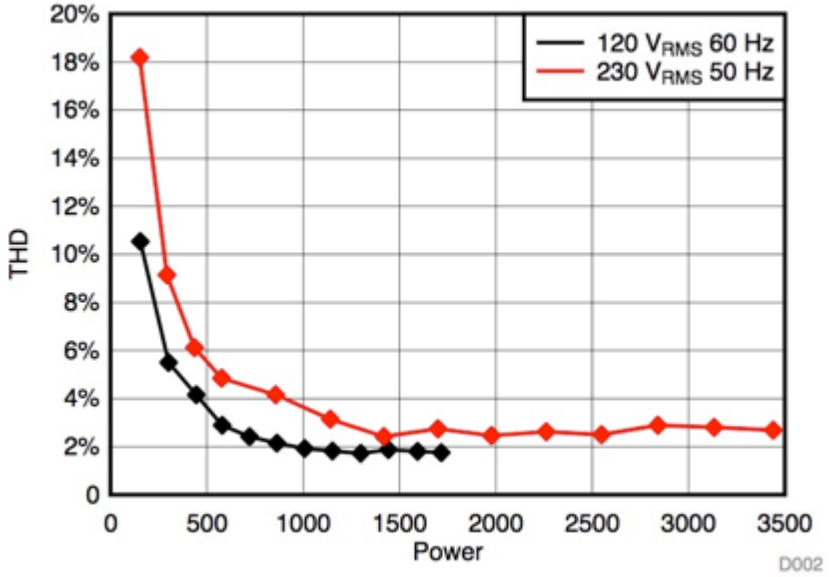
Benefits

- **High power density** design while maintaining OEM specified form factor
- Further **system integration** through latest TI-GaN gate drivers
- Enables **superior control and implementation of advanced control schemes** brought by high performance C2000 MCU
- Enables **simple adaptation of software** through powerSUITE™ support

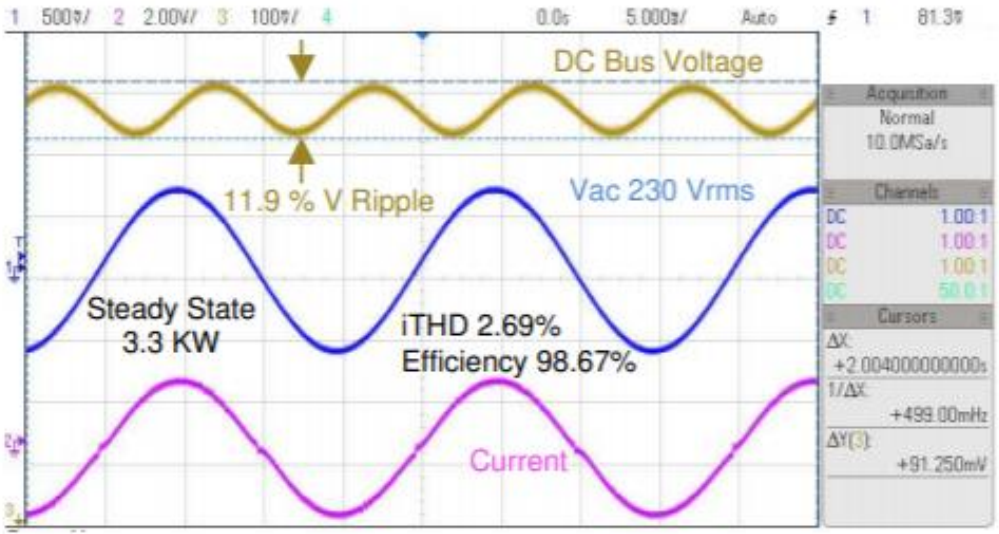


TIDM-02008: Measured efficiency and THD





TIDM-02008 test results



Steady State 230-Vac IN, 380V DC OUT, 3.3kW, iTHD 2.69%

TIDM-02008 CPU/CLA utilization

- The maximum ISR loading numbers were captured
  - ISR1 : Inner current loop, grid synchronization (PLL), etc
  - ISR2 : Outer voltage loop, relay on/off, OVP,UVP,OCP, etc

	ISR1 (100 kHz)	ISR2 (10 kHz)
CPU utilization (*Advanced options: All Off)	53%	6 %
CPU utilization (Advanced options: All On)	65%	9%

	ISR1 (100 kHz)	ISR2 (10 kHz)
CLA utilization (Advanced options: All Off)	57 %	9 %
CLA utilization (Advanced options: All On)	79%	12 %

*Advanced options : A.D.T, Phase Shedding, NL voltage loop, SFRA

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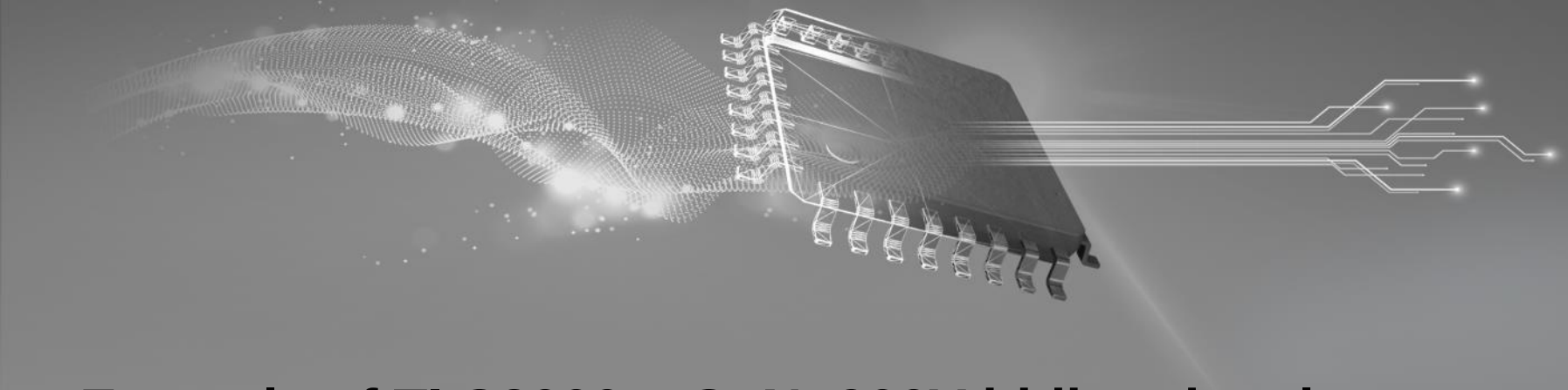


Example of TI C2000 + GaN: 900V bidirectional energy storage system with 99% efficiency

900V-5kW bidirectional ACDC converter with TI-GaN

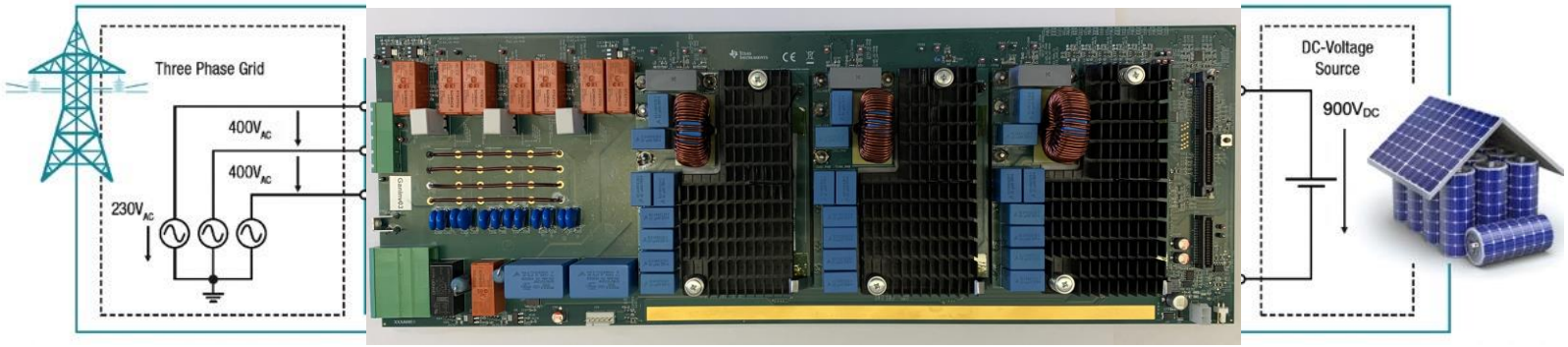
Design Features

- DC voltage up to **1400V**, AC voltage up to 480V L-L
- Peak efficiency of **99.2%**
- **Convection cooled** with no fan
- Scalable **multi-level** solution for >**5kW**
- Total harmonic distortion **(THD) < 3%**
- **Surface-mount devices** to reduce manufacturing cost
- **LMG3410R050**, 600V, 50mΩ GaN FET with integrated Driver & Protection
- **Leverages TI C2000** controller: **TMS320F28379D**

Design Benefits

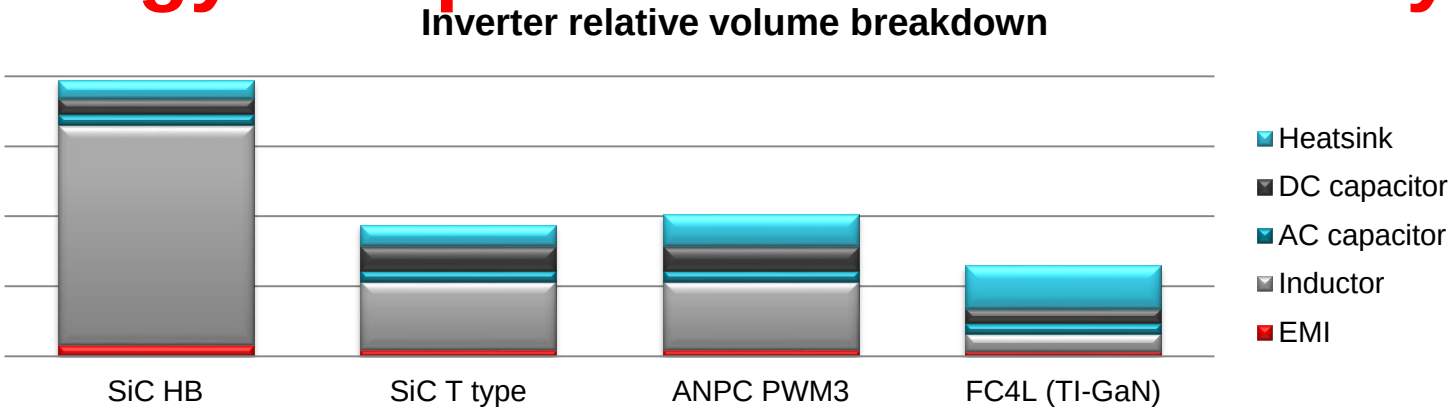
- **3X power density improvement over IGBT** and 1.25X over SiC

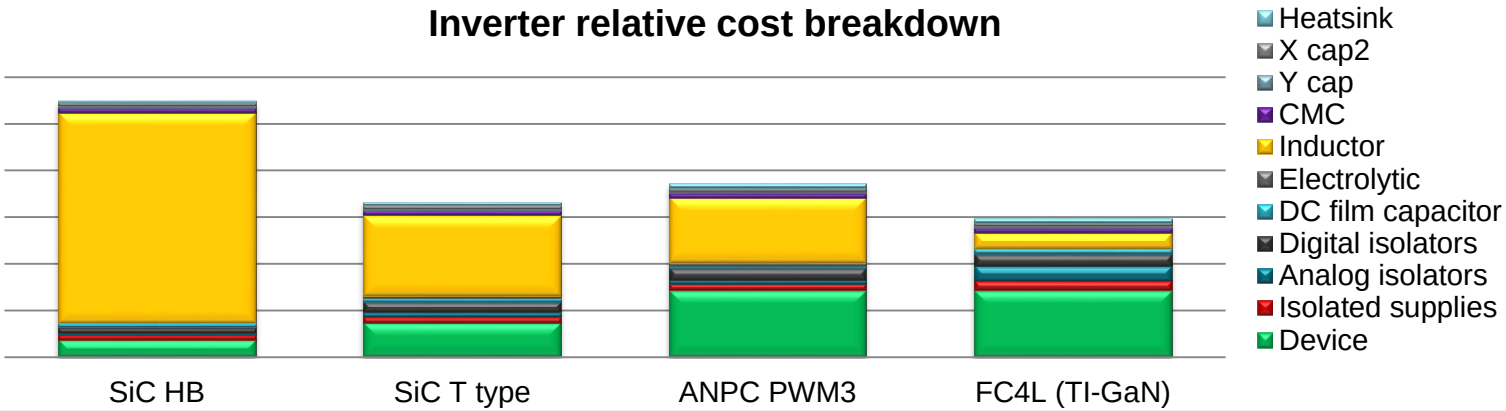
Frequency (kHz)	20	100	**140**
Open frame Power Density (W/in³)	73	170	**211**
Efficiency (%)	98.3	98.9	**99.2**



470 mm x 162 mm x 51 mm

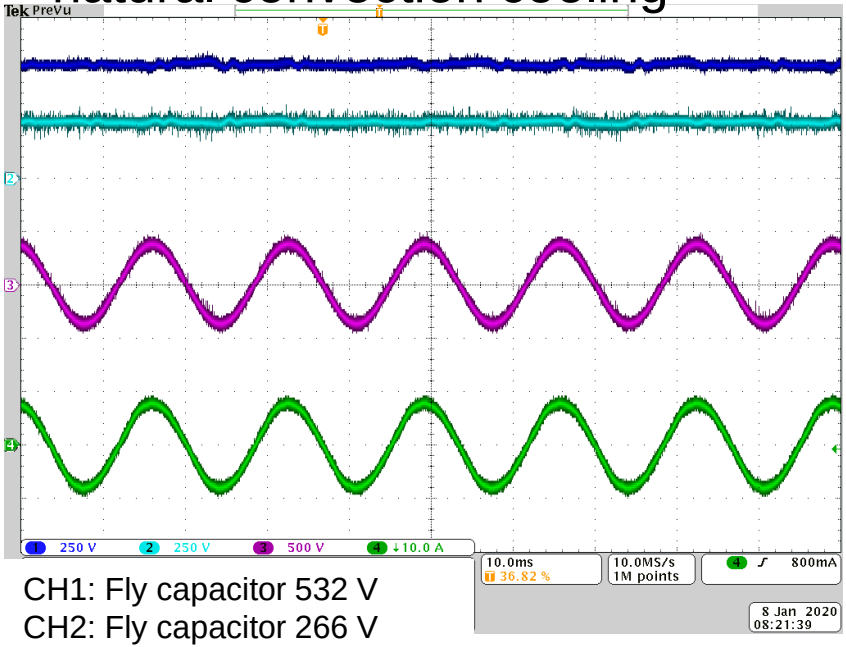
Topology comparison at 99% efficiency





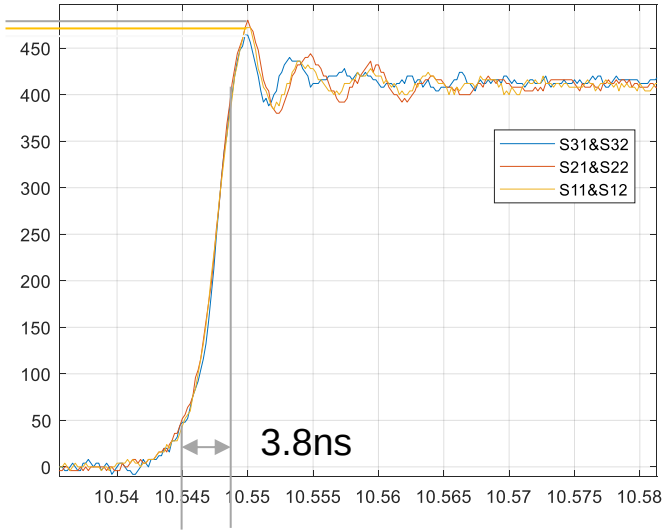
Results

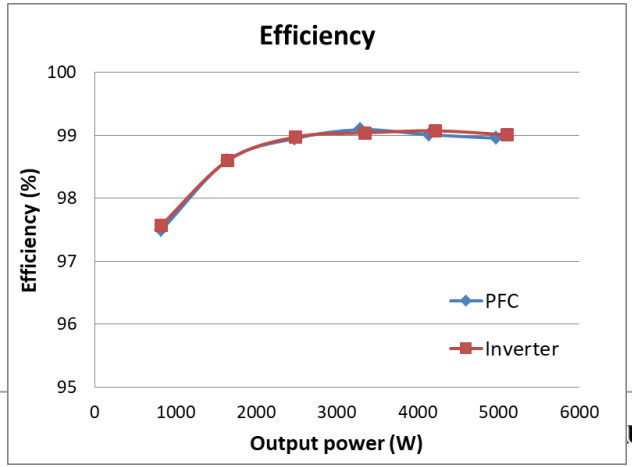
- 99 % efficiency 3 kW to 5 kW natural convection cooling



CH1: Fly capacitor 532 V
CH2: Fly capacitor 266 V
CH3: Grid voltage 270 V
CH4: Grid current 6 A

480 V
472 V
464 V





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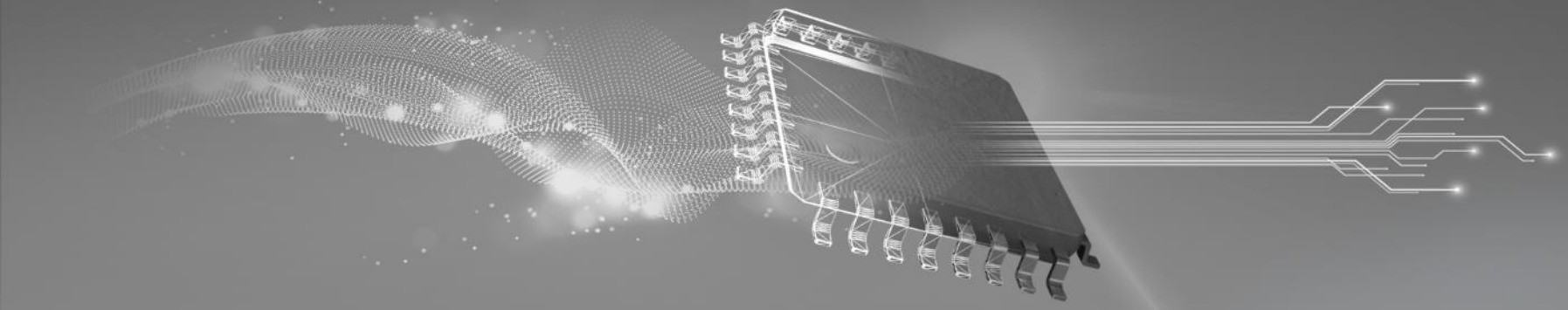


Example of TI C2000 + GaN:
1.25kW 3-phase inverter with 99% efficiency

TIDA-00915: 1.2kW 3Φ integrated drive

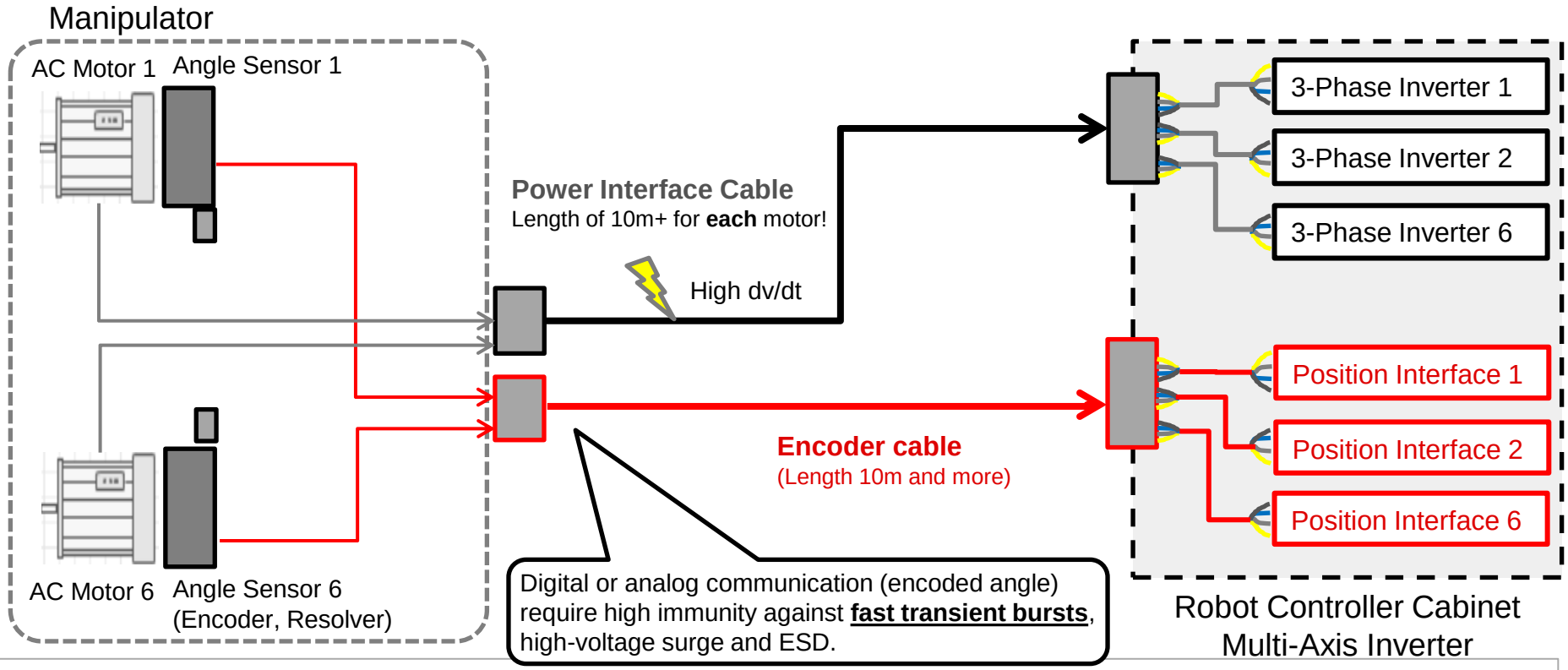
Solution Features

- Ultra-small form factor with power density of 150W/in3
  - 50ºC ambient conditions up to 1.25kW
  - 85ºC ambient conditions up to 550W
- Peak efficiency > 99%
- Natural convection cooling with 10mm heatsink
- Built-in short-circuit and over temperature protection
- 450V Max DC Operation

Applications

- Integrated motor drives
- Robotics
- Servo drivers

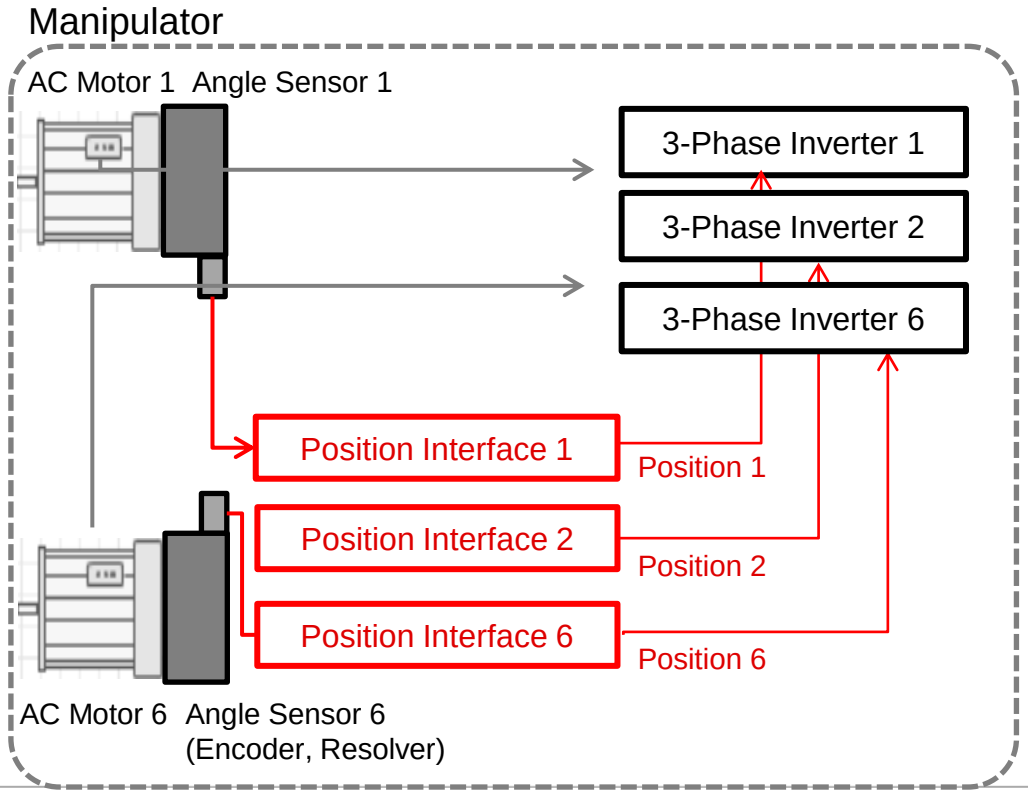
Traditional external drive systems with silicon



Integrated motor drive with GaN + C2000 MCUs

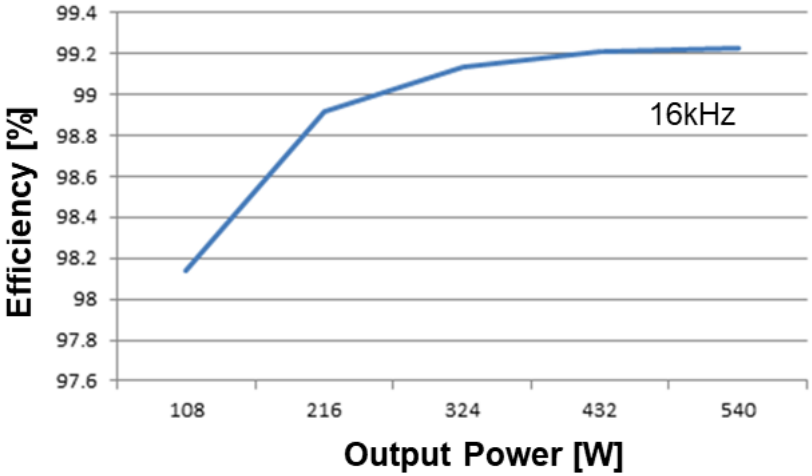
Cost savings:
- Reduce power and communication cabling
- Free up floor and cabinet space

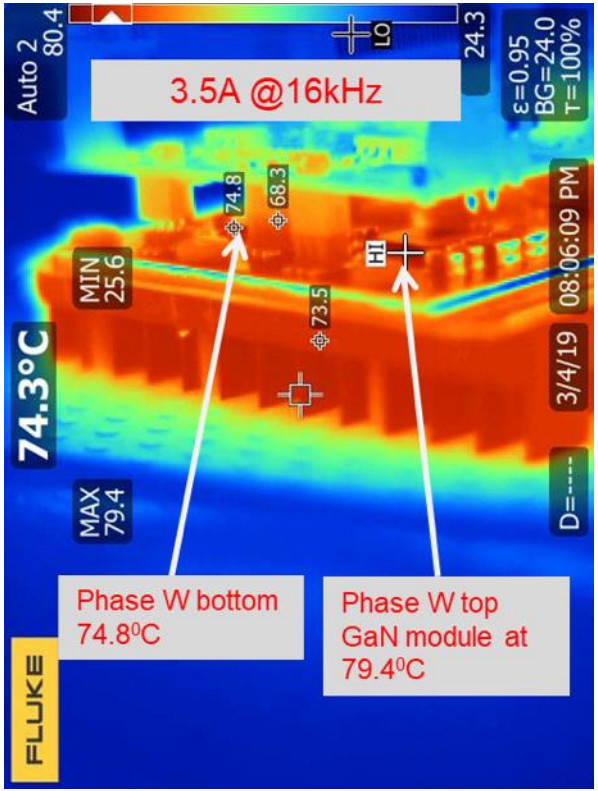
High Performance :
- Higher dv/dt, less switching power loss
- Improve EMC immunity on communication cables



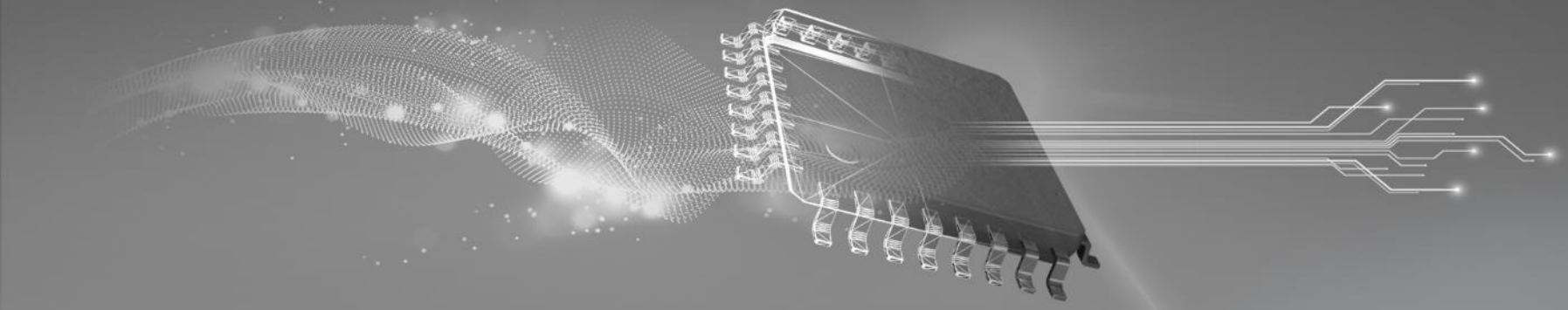
TIDA-00915: Natural convection cooling

Heatsink: 10mm fin height
Peak efficiency > 99.2%





TI TECH DAYS



Backup

C2000 MCU ideal for high switching frequency control

C2000 MCU DNA	Scalable MCU architecture from high to low end power stages with high frequency control & processing capabilities	Ideal For WBG (GaN/SiC) Switching/control/system
32-bit -28xCPU Up to 200MHz	• Industry's leading real time control CPU • Single/double floating point precision • Tightly integrated accelerators & control peripherals	• Efficient low latency, precision control algorithms • Widely adopted in Motor drive/Solar inverters/Automotive power stages
CLA/TMU/NLPID Up to 200MHz	• Industry's low latency event/algorithm processing engine • Executes in floating point precision and in parallel to the CPU • Fast trigonometric and non-linear algorithm processing engine	• Enabling multi-phase & multi-level control topologies • Ideal for low latency non-linear control
PWM/Capture engine	• Industry's proven best in class and flexible PWM generation • Up to 200/MHz PWM clock with protection • Up to 150ps pulse width resolution with high resolution dead band • Tightly integrated with the Analog sub-system	• Multi-phase & multi-level control topologies • Protects shoot-through/short circuit • Efficient switching of GaN/SiC power stage • Glueless interface to TI Gate Driver family
Analog sub-system	• Up to x4 high-precision, just-in time 12/16bit ADCs • Flexible Analog comparator & DAC subsystems • Pre-processing blocks to minimize latency in sensing	• Enables fast current/voltage sensing scheme • Enables customizable Peak-current mode control • Minimizes data analog preconditioning/latency
Delta Sigma- SDFM	• Up to 8 programmable Delta sigma filters, with digital comparators	• Enables isolated current/voltage sensing
CLB Configurable Logic	• Configurable logic to add customizable protection • Custom peripheral events using Analog and digital triggers	• Enables power stage protection • Develop advanced switching topologies
Fast Serial interface	• Supports low cost fast serial interface up to 200Mbps	• Enables isolated current sensing with low latency. • Allows distributed power stage architectures
Communication ports	• Connectivity ports 50MHz SPI, CAN/CANFD/Ethernet/Ethercat	• Enables External host links for monitoring/control

Red- Unique to C2000 MCU only Green – Showcased in TIDesigns/examples

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