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

GaN: Yichi Zhang
C2000: John Kim
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

### 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

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**Power Density:** 250 W/in³ (15.2 W/cm³)

*Versus*

Silicon: 55 W/in³ (3.4 W/cm³)
Applications for GaN & C2000 real-time MCUs

- Energy Delivery
  - Solar Power
  - Wind Power
- Motor Control
  - Appliance
  - E-bike
- Digital Power
  - Uninterruptable Power Supplies
  - DC/DC Converters
- Industrial Drives
  - Robotics
  - Automation
  - AC Drives
- Automotive & EV/HEV
  - On-Board Charging (OBC)
  - Servo Drive
  - DC-DC
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.

- **Highly accurate sensing**
  - 12-/16-bit ADCs, up to 24 channels
  - ADC post processing, and externally accessible DACs

- **Highly flexible, High-resolution PWMs:**
  - Up to 32 outputs
  - Position Manager, Sigma-Delta Filter Module, trip zones

- **Expertise and support:**

- **High performance processing**
  - Floating-point DSP C28x™ core + parallel multi-core architecture + instructions set optimized for control math, up to 925 MIPS

- **Interface**
  - CAN, CAN-FD, LIN, UART, SPI, I2C, PMBus, USB, 10/100 Ethernet MAC, EtherCAT®, XEMIF

- **Leading innovation:**
  - Config. Logic Block for peripheral customization, Fast Serial Interface for high-speed communication, ERAD for enhanced diagnostics and profiling

**25 years expertise in real-time control systems**

- 1.2-V core, 3.3-V I/O design
- Up to 1.5 MB Flash, 256 kB RAM (ECC protected)
- QFN, QFP, BGA packages
- -40 to 125°C temperature range
- Q100 automotive qualified options
- Over 750 million units shipped for industrial and automotive applications with compatible software
GaN: Key advantages over silicon FET

- Low $C_{G, QG}$ 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 $C_{OSS, QOSS}$ output capacitance/charge (5 nC-Ω vs Si 25 nC-Ω)
  - faster switching, high switching frequencies
  - reduced switching losses

- Low $R_{DSON}$ (5 mΩ-cm² vs Si >10 mΩ-cm²)
  - 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
Example of TI C2000 + GaN: CCM PFC
CCM PFC: topologies

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

- 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

Power loss comparison for 1-kW PFC

- Dual Boost - SJ
- Totem Pole - SiC
- Totem Pole - TI GaN

Loss (W)
Higher switching frequency

- 40-kHz CCM PFC inductor (1000 W)
  - Inductor volume: 138915 mm$^3$
  - Dimensions: 63 mm (width) x 35 mm (height)

- 100-kHz CCM PFC inductor (1000 W)
  - Inductor volume: 43952 mm$^3$
  - Dimensions: 42.5 mm (width) x 23.24 mm (height)

3.2x reduction in inductor volume
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.

\[ T_d = \frac{2 \times C_{sw} \times V_{out}}{I_{L, peak}} \]

Optimal turn-on point

- 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
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

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

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, UCC27714D, OPA2376, SN74LVC1G3157, ISO7831, TLV713

C2000 Microcontroller
TMS320F28004x
TIDM-02008: Measured efficiency and THD

![Graph showing efficiency and THD measurements.](image-url)
TIDM-02008 test results

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

<table>
<thead>
<tr>
<th></th>
<th>ISR1 (100 kHz)</th>
<th>ISR2 (10 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU utilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(*Advanced options: All Off)</td>
<td>53%</td>
<td>6 %</td>
</tr>
<tr>
<td>CPU utilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Advanced options: All On)</td>
<td>65%</td>
<td>9%</td>
</tr>
<tr>
<td>CLA utilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(*Advanced options: All Off)</td>
<td>57%</td>
<td>9 %</td>
</tr>
<tr>
<td>CLA utilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Advanced options: All On)</td>
<td>79%</td>
<td>12 %</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>20</th>
<th>100</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open frame Power Density (W/in³)</td>
<td>73</td>
<td>170</td>
<td>211</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>98.3</td>
<td>98.9</td>
<td>99.2</td>
</tr>
</tbody>
</table>

470 mm x 162 mm x 51 mm
Topology comparison at 99% efficiency

Inverter relative volume breakdown

- SiC HB
- SiC T type
- ANPC PWM3
- FC4L (TI-GaN)

Inverter relative cost breakdown

- SiC HB
- SiC T type
- ANPC PWM3
- FC4L (TI-GaN)
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
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
  - 50°C ambient conditions up to 1.25kW
  - 85°C 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

Manipulator

AC Motor 1 Angle Sensor 1

AC Motor 6 Angle Sensor 6 (Encoder, Resolver)

Power Interface Cable
Length of 10m+ for each motor!

High dv/dt

Encoder cable
(Length 10m and more)

Digital or analog communication (encoded angle) require high immunity against fast transient bursts, high-voltage surge and ESD.

Robot Controller Cabinet Multi-Axis Inverter

3-Phase Inverter 1
3-Phase Inverter 2
3-Phase Inverter 6

Position Interface 1
Position Interface 2
Position Interface 6
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%
Backup
# C2000 MCU ideal for high switching frequency control

<table>
<thead>
<tr>
<th>C2000 MCU DNA</th>
<th>Scalable MCU architecture from high to low end power stages with high frequency control &amp; processing capabilities</th>
<th>Ideal For WBG (GaN/SiC) Switching/control/system</th>
</tr>
</thead>
</table>
| 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/algorith 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 TI Designs/examples
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