Achieve Power-Dense and Efficient Digital Power Systems by Combining TI GaN FETs and C2000™ Real-Time MCUs

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Designers in the power electronics industry need new technologies and methods to increase system performance. C2000 real-time MCUs and GaN FETs join forces to meet efficiency and power-density challenges.

At a glance

This white paper explains how the features of TI gallium nitride (GaN) field-effect transistors (FETs) with an integrated driver and TI C2000™ real-time microcontrollers (MCUs) work in harmony to solve issues that power electronics designers face when developing modern power-conversion systems.

1 GaN is revolutionizing the power electronics market

While you may consider GaN an emerging technology, TI's GaN technology addresses industry challenges and is ready for wide-scale deployment.

2 Choosing the right digital controller for GaN

The potential benefits of GaN are massive, but can only be fully realized when choosing the right digital controller.

3 Reducing system costs through high switching frequencies

GaN enables a reduction in power magnetics, fans and heat sinks because of its high switching frequency, while C2000 real-time MCUs address the intrinsic control challenges brought on by doing so.

4 Interfacing C2000 real-time MCUs with GaN devices

C2000 real-time MCUs enable control of and all feedback from TI GaN FETs without the need of external glue logic.

Server and telecom power supplies are examples of markets that can benefit from the use of GaN. The digital communications infrastructure market continues to grow, with some estimates projecting the rack server market to double in the next five years and hyperscale data centers to grow at a compound annual growth rate of nearly 20%.

Along with rapid growth come ever-increasing efficiency, power density and transient response requirements. GaN FETs drastically improve switching losses and high power density, advantages that can help solve the technical challenges as volumes scale up in these growing markets.

This white paper explores how the features of TI GaN FETs with an integrated driver and TI C2000 real-time MCUs are uniquely positioned to address the issues that power electronics designers face when developing modern power-conversion systems.

GaN is revolutionizing the power electronics market

While GaN technology has shown a lot of potential benefits, you may have some legitimate concerns about its practicality. Although there's a common perception that GaN FETs are a new technology, they have actually been around for over 20 years. Cost, protection and reliability have all been prohibiting factors for the adoption of GaN, and TI's family of GaN devices addresses each of these concerns.

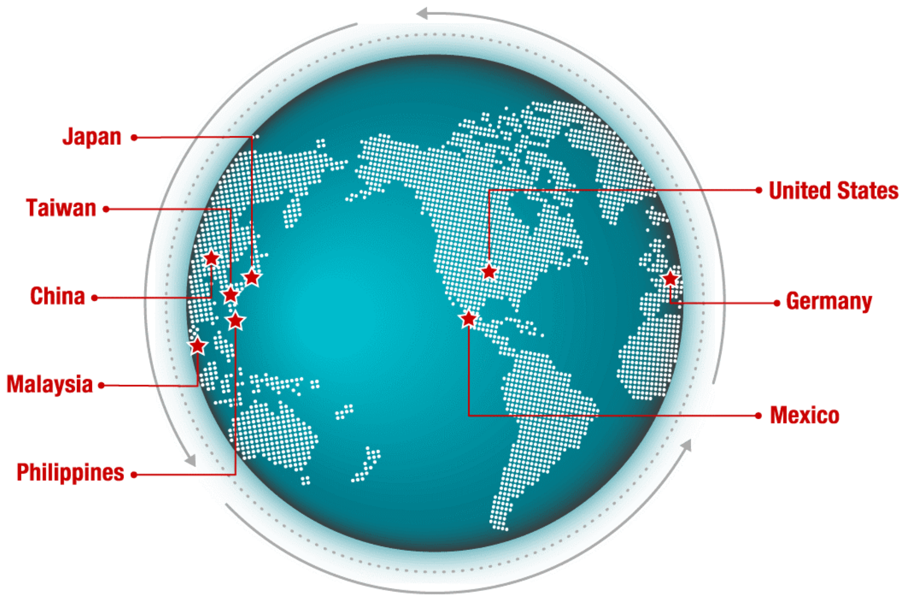

Figure 1. *Map of TI manufacturing operations.*

Cost

TI GaN FETs use a GaN-on-silicon process that leverages existing TI process technology nodes. Not only can we avoid expensive substrates like silicon carbide or sapphire, but we can also harness our years of expertise in working with silicon technologies. TI performs development, testing and packaging completely in house, shown in **Figure 1**, making GaN cost-competitive today and even cheaper tomorrow.

Protection

TI's GaN technology provides rich diagnostics and self-protection features. GaN FETs automatically detect and handle overcurrent, short-circuit, undervoltage and overtemperature conditions. Simultaneous reporting of these conditions to the MCU enables modifications to the control algorithm to prevent reoccurrence.

Reliability

TI has logged over 40 million device reliability hours for its GaN devices and a failure-in-time rate of <1 for 10-year lifetimes. In addition to intrinsic reliability tests, we subject our GaN devices to the harshest switching environments and have converted over 5-GW hours of in-application stress testing.

TI GaN devices address cost, protection and reliability concerns by combining the FET driver and GaN FET into one package. With a fast-switching, 2.2-MHz integrated gate driver, TI GaN FETs enable twice the power density compared to silicon while achieving 99% efficiency. This technology provides the lowest losses for the highest efficiency in AC/DC applications. Furthermore, integrated, high-speed protection and digital temperature reporting enable active power management and thermal monitoring for power supply units (PSUs). With all of these unique benefits, TI technology makes the adoption of GaN real.

Choosing the right digital controller for GaN

The higher switching frequencies enabled by GaN allow power supplies to be more efficient and reach higher power densities. These typically require more complex power topologies and control algorithms like zero voltage switching, zero current switching or inductor-inductor-capacitor (LLC)-resonant DC/DC with hybrid hysteresis control.

The adaptability of a digital controller only benefits these complex topologies. You need one that is capable of processing complex time-critical calculations, offers precise control and is scalable through software and peripheral compatibility. C2000 real-time MCUs directly address these considerations. **Figure 2** illustrates a C2000 real-time MCU and a GaN FET driver.

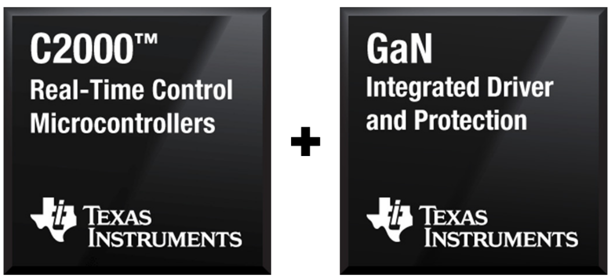

Figure 2. *C2000 MCUs and TI GaN devices work together to achieve the most efficient, reliable and power-dense digital power systems.*

C2000 real-time MCU efficiency of instructions

C2000 real-time MCUs have an advanced instruction set, which drastically reduces the number of cycles required for complex math calculations. This reduction in calculation time means that it is possible to increase the control-loop frequency without increasing the device's operating frequency. Many of these efficiency gains are seamless to the user and occur automatically. The code compiler, the central processing unit (CPU) pipeline and the instruction set are all designed in a way to get the maximum amount of computing power per instruction cycle.

More visible to users are the floating-point unit (FPU) and trigonometric math unit (TMU). Integrating these enhanced instructions closely into the C28x core allows the instructions to be pipelined and executed in parallel like normal CPU instructions, further increasing the efficiency of every clock cycle.

For example, the FPU yields a >2.5 times improvement in speed over standard fixed-point calculations. At the same time, the FPU also enables the C28x core to leverage model-based simulation and code-generation tools, which use floating-point math. This means that you will spend less time developing code and validating your system, and get your product to market faster.

The TMU complements the FPU and yields a similarly impressive 20 times improvement over the FPU alone. In the **Bidirectional High-Density GaN CCM Totem Pole PFC Using C2000 real-time MCU** reference design, the benefits become clear when trying to calculate control of pulse-width modulators (PWM) on time and the dead time, reducing these calculations from ~10 µs to less than 0.5 µs. This makes it possible to perform an adaptive dead-band calculation on a cycle-by-cycle basis, allowing for the most precise and efficient control of the GaN FET.

Meeting transient response requirements

Why are small cycle-by-cycle efficiencies important? Well, one reason is that these efficiencies enable you to meet faster transient response requirements.

Transient response requirements describe how quickly a power supply can react to changing loads. For example, due to the higher power requirements of modern processors used in servers, meeting transient response requirements has become more difficult. Historically, 1 A/µs was common; however, today's standards require 2.5 A/µs or higher. Increasing the frequency of your control loop directly helps by changing how fast you can sense and react to varying conditions. The unique processing abilities of C2000 real-time MCUs can help address these transient response requirements.

To meet the most extreme transient response requirements of 5 A/µs or higher, C2000 real-time MCUs leverage their integrated analog, which PWM signals entirely through hardware, without the use of external components. This control is achieved by using the integrated analog comparator to compare the feedback signals with a fixed setpoint or ramp generator, implemented through the internal 12-bit digital-to-analog converter (DAC). This technique adds the unique speed benefits of an entirely hardware-based control loop while maintaining the flexibility of a digital controller. During execution, the PWM trip points are continually monitored and adjusted by tweaking the DAC's output inside of the software control loop entirely independently from the tripping of the PWM. Ultimately, this means that C2000 real-time MCUs can offer the fastest response time to varying load conditions while maintaining the flexibility to meet efficiency standards.

Enable precise and safe system control

Shoot-through and the potential of third-quadrant conduction in GaN FETs require high-precision control. The high-resolution PWM in a C2000 real-time MCU enables 150-ps resolution for the PWM's period, duty cycle, phase and dead band. While the trip-zone submodule — along with built-in analog comparators — safely handles error conditions, these operate entirely asynchronously and provide the ability to shut down the PWM's output in just 25 ns without CPU intervention.

Multiphase systems done the easy way

Expanding the scope beyond single-phase designs, C2000 real-time MCUs also address issues with multiphase designs, where all phases must remain in sync in order to prevent system failure. You must consider modifying the frequency, duty cycle or dead band of the PWM. Sequential updates to these values are common today, but sequential updates require intricate knowledge of the hardware as well as all possible permutations of the code – something that's especially difficult in interrupt-based embedded systems.

The C2000 real-time MCU's global-load mechanism addresses PWM updates by allowing the updating of all required PWM registers in one instruction cycle, entirely without CPU intervention. This innovation enables control of high-frequency interleaved LLC topologies while simultaneously eliminating bugs, which commonly appear as intermittent nonrepeatable errors introduced by sequential updates. Use of the global-load mechanism not only results in a more robust and safer system, but also reduces system validation efforts.

Scalability of the C2000 real-time MCU portfolio

A low-cost C2000 real-time MCU such as the F280025C extends the C2000 portfolio of real-time MCUs, shown in **Figure 3** on the following page, to a cost point that fits in small server power designs, while still offering unique processing and control features. As system requirements change, the C2000 platform enables the scaling of real-time MCU features (analog-to-digital converter (ADC) inputs, computation power, PWM channels, packages) up or down while maintaining software investments to achieve a faster time to market.

Reducing system costs through high switching frequencies

Now that the individual benefits of TI GaN and C2000 have been discussed, let's address the system-level benefits. FET switching losses have traditionally limited the maximum speed at which you can efficiently switch a converter to a few hundreds of kilohertz. The switching frequency then places minimum size requirements on magnetics, which negatively impact power density and system cost requirements.

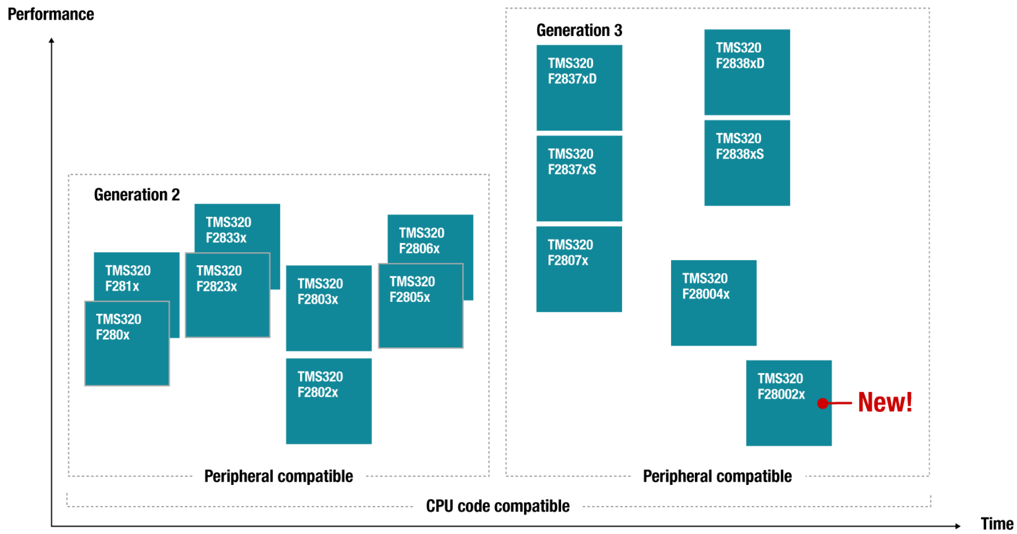

Figure 3. *The C2000 real-time MCU portfolio that supports TI GaN devices.*

As mentioned, the integrated driver in TI GaN devices enables switching frequencies of up to 2.2 MHz, with switching speeds greater than

150 V/ns, resulting in twice the speed and half the losses compared to discrete GaN FETs. This integration, combined with low-inductance packaging, delivers clean switching and minimal ringing. These efficiencies enable a reduction in the size of the magnetics used in power systems and ultimately reduce system costs by eliminating the need for fans or heat sinks while increasing power density.

Overcoming the challenges inherent to higher switching frequencies

TI GaN devices can drive system switching frequencies higher, enabling the magnetics to be reduce to one-fifth their previous size overall enabling a three times higher power density over similar silicon power-factor correction (PFC) application. The benefits are not just realized in PFC stages, but in all power electronic systems.

So what's the catch? Well, as with all good things, increasing switching frequencies adds drawbacks and design challenges. For example, in a totem-pole PFC, reducing the size of the inductor can cause additional control challenges, such as increasing dead-band-induced third-quadrant losses.The unique feature set in C2000 real-time MCUs addresses this with the following features:

- C2000 real-time MCUs offer a 150-ps high-resolution dead band, enabling finer edge placement and reducing unnecessary third-quadrant losses. Learn more about third-quadrant operation of TI GaN in the application report, "Does GaN Have a Body Diode? – Understanding the Third Quadrant Operation of GaN."
- The TMU enables adaptive dead-band control schemes, as discussed previously, further reducing losses by enabling faster calculations.

See these features in action in a 3.3kW Bidirectional interleaved CCM Totem Pole PFC reference design with 98.75% peak efficiency and less than 2% THD.

Reducing the input inductor in a totem-pole PFC can cause an increased current spike at the zero-crossing point, negatively impacting total harmonic distortion. The increased current spike occurs when the input waveform switches between its positive and negative half, causing inrush current as the synchronous and active FETs are reversed.

The inrush current is largely due to a buildup of voltage across the inductor as well as any output capacitance of the FETs and diodes. C2000 real-time MCUs address these issues through a sophisticated shadow loading scheme that enables the MCU to implement a soft-starting algorithm with minimal CPU overhead.

Finally, the speed and parallelism of integrated analog is fundamental to increasing the control-loop frequency in a digital microcontroller. Without this, it is not possible to realize the full benefits of TI GaN devices with integrated driver. The F28002x series has up to 16 individual analog channels which connect to 2 independent Analog to Digital Converters, each offering great performance with an integral nonliearity (INL) of 2 Least Significant Bits (LSB), Differential non linearity (DNL) of 1 LSB, and an Effective Number of Bits (ENOB) of 11 bits at a rate of up to 3.45 Mega Samples Per Second (MSPS). The implementation of multiple ADCs specifications enable the sampling of multiple sources of feedback simultaneously because of the flexible start of conversion triggers, which are closely coupled with the PWM unit and allow adjustments for the best real-time control strategy. For example, you could measure the AC grid's line and neutral voltages simultaneously to enable the control loop to run faster and provide more system accuracy.

As GaN drives the ability to reach higher efficiency standards and power density requirements new challenges have been presented. C2000 real-time microcontrollers are uniquely designed to address the intrinsic control problems introduced when reducing magnetics and increasing your system frequency.

Interfacing C2000 real-time MCUs with TI GaN devices

The interface between C2000 real-time MCUs and the GaN device includes a digital isolator, such as the ISO7741-Q1 shown in **Figure 4** below. This isolation device helps suppress transient noise and protects the C2000 real-time MCU. The microcontroller, isolation and GaN devices are all that are necessary for the interface.

TI digital isolators featuring high isolation ratings up to 5.7 kVrms and supporting speeds up to 150 Mbps are a good fit as an isolation barrier between the C2000 real-time MCU and the GaN FET. They provide the speed and low latency required to establish precise control and feedback paths between the devices

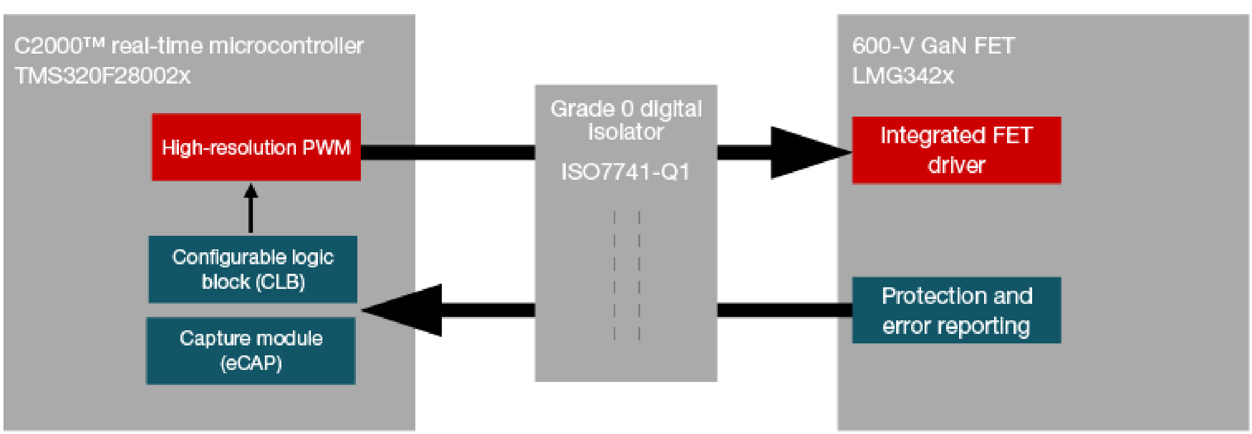

Figure 4. *The only components needed to interface a C2000 MCU with a TI GaN device.*

Control

Control of the GaN FET is achieved by using the high-resolution PWM module, which provides 150-ps resolution control on the PWM's period, duty cycle, phase and dead band. The PWM output has an integrated trip-zone submodule that can respond to feedback, without CPU intervention, in 25 ns.

Feedback

C2000 real-time microcontrollers integrate a unique peripheral set to sample the feedback signals from TI GaN devices, including the recently launched LMG3425R030, without the need of additional discrete components. Feedback comes in from two major sources:

- **Fault reporting.** The LMG3425R030 encodes its fault information. Decoding this information in software can be hazardous given the delays associated with processing the faults in software. For a quicker response, you can combine the fault signals externally to the device, but this requires the use of discrete components. The C2000 real-time MCU uses its configurable logic block (CLB) to read, process and respond to the fault conditions generated by the GaN device without the use of software and with no external components, optimizing performance and reducing system costs.
- **Temperature monitoring.** The temperature monitoring output from the LMG3425R030 device comes out as a fixed-frequency variable duty-cycle signal. Common implementations require the use of an external filter to implement a PWM-based DAC that would need to be sampled by an ADC. The C2000 real-time MCU's enhanced capture module completely eliminates these external components while capturing the temperature information with no CPU overhead, thus further optimizing costs and saving board space.

Conclusion

In modern digital power systems, efficiency and power-density standards present a big set of challenges. TI GaN devices deliver reliable and affordable technology while enabling increased power density and higher efficiency. The ISO7741-Q1 provides a cost-effective interface while C2000 real-time MCUs address difficulties associated with today's complex control schemes. These devices work in harmony to provide a flexible yet simple solution for modern digital power systems, while still providing cutting-edge features that enable the safest, most power-dense and efficient digital power systems.

Developers can now jump into a new era of power efficiency and power density. To make this journey easier, TI combines 25 years of experience in real-time digital power control, power electronics, hardware and software in fully tested and documented reference designs.

Additional resources

- Reference designs
  - Bidirectional High-Density GaN CCM Totem Pole PFC Using C2000 real-time MCU reference design
  - Highly Efficient, 1.6-kW High-Density GaN-Based 1-MHz CrM Totem-Pole PFC Converter Reference Design
  - High Efficiency GaN CCM Totem Pole Bridgeless PFC Reference Design
  - Vienna Rectifier-Based Three Phase Power Factor Correction Reference Design Using C2000 real-time MCU
- Papers
  - A New Approach to Validate GaN FET Reliability to Power-line Surges Under Use-conditions

- How to reduce current spikes at AC zero-crossing for totem-pole PFC
- Training
  - C2000 Digital Power Training Series
  - CLB Training Series
- Evaluation kits
  - TMS320F28002x controlCARD evaluation module: https://www.ti.com/tool/TMDSCNCD280025C
  - LMG3422R030 600-V 30-mΩ half-bridge daughter card: https://www.ti.com/tool/LMG3422EVM-043
  - ISO7741-Q1 evaluation module: https://www.ti.com/tool/ISO7741EVM
- Software tools
  - C2000Ware MATLAB® VisSim Embedded Coder

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