TIDA-00961 – TRM/CRM/BCM TTPL PFC

(Transition Mode/Critical Conduction Mode/Boundary Condition Mode Totem-Pole PFC)

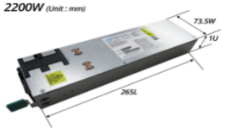
Agenda

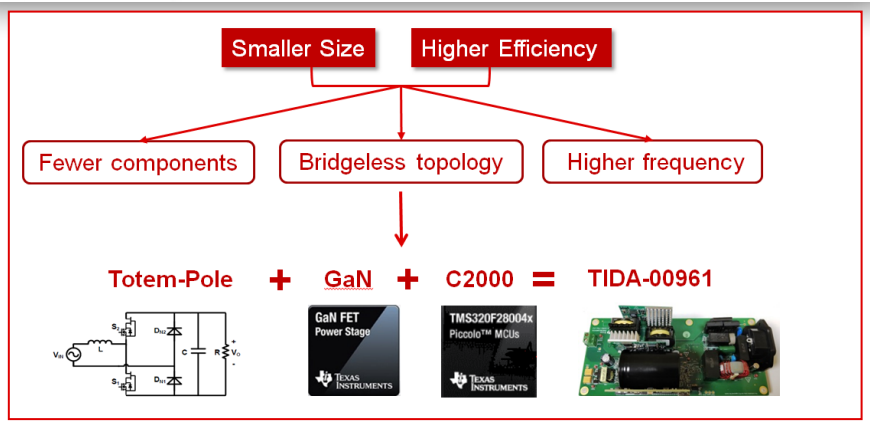
- Introduction
- Challenges & Solutions
- Implementation Details
- Experimental Results

System Introduction

Target Systems for the design

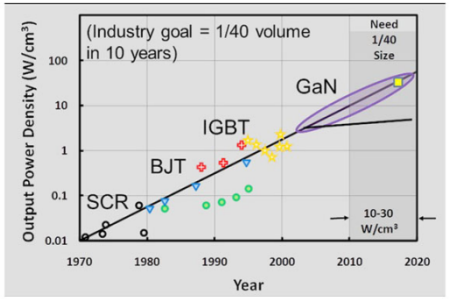
- **Network & Server Power Supply Unit (PSU)**
- **Telecom Rectifier**
- **Industrial Power Supply**
- **Automotive**





System Trends

- **Higher Energy Density**
  - Industry targets 1/6 reduction in vol in 10 yrs
  - Smaller size need Higher switching freq.
  - ~100/200 KHz today: expected 5 to 10 fold jump with GaN.

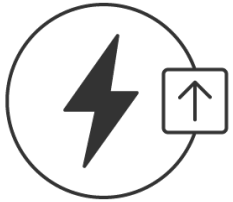


- **Higher Efficiency**
  - Regulatory standards
  - Thermal management
  - Complex topologies need digital control
  - Bridgeless topology in PFC, and hence GaN

80 Plus Performance Specification – Efficiency Requirements

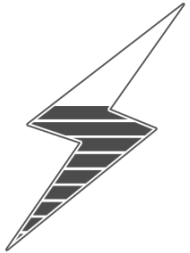
Load	80 PLUS	80 PLUS BRONZE	80 PLUS SILVER	80 PLUS GOLD	80 PLUS PLATINUM	80 PLUS TITANIUM
10%						90%
20%	80%	82%	85%	87%	90%	92%
50%	80%	85%	88%	90%	92%	94%
100%	80%	82%	85%	87%	89%	90%
PF	≥ 90 at 100%	≥ 90 at 50%	≥ 90 at 50%	≥ 90 at 50%	≥ 95 at 50%	> 95 at 20%

Benefits of the LMG341x GaN power stage



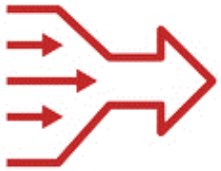
Maximum power density and efficiency

GaN power stage enables **double power density and 80% lower losses** than silicon MOSFET with high-speed, MHz switching frequency



Devices for every power level

Fully integrated driver, FET and protection in **50 mΩ, 70 mΩ and expanding portfolio** offer a single-chip solution for applications ranging from sub-100 W to 10 kW



Simplifies design

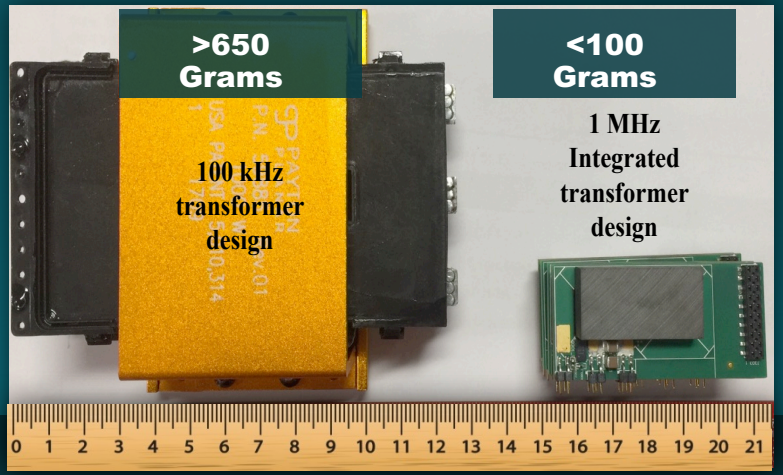
Comprehensive portfolio of designs for AC-DC, isolated DC-DC and inverter topologies enables ease of design and **faster time to market**

System reliability

Backed by **20 million device reliability hours** and features built-in intelligence for over-temperature, over-current and under voltage lockout protection

View the LMG3410R070 datasheet

Maximized efficiency + power density for industrial and telecom designs



Compared with a 100kHz silicon design, the GaN design is **6X** smaller

The **Highly Efficient, 1.6kW High Density GaN Based 1MHz CrM Totem-pole PFC Converter Reference Design** is a high density (165 x 84 x 40 mm) design that achieves 98.7% efficiency at full load and 230-V AC input for many space constrained applications such as server, telecom, and industrial power supplies.

- TIDA-00961 and tools folder
- Design guide

Highly Efficient, Compact, 1.6 kW Bridgeless ZVS Transition Mode GaN PFC Reference design for Server PSU /*TI Design: TIDA-00961*

TIDesigns

Features

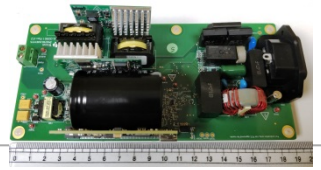
- TMS320F28004x controller based fully programmable solution
- Two phase interleaved operation
- Output Power: 1.6 KW, 4.1A @ 390V
- Efficiency: ~ 99% ; Power Factor : >0.99
- Switching frequency range from 200kHz to 1.2MHz
- Compact Form Factor (165 x 84 x 40 mm for the full board and 65 x 40 x 40 mm for the power stage)
- High Power Factor > 0.99 and low THD; Meets Current THD Regulations as per IEC 61000-3-2
- Wide input voltage range: 85 – 265 VAC

Target Applications

- Telecom Rectifiers
- Server & Industrial supplies
- EV OBC

Tools & Resources

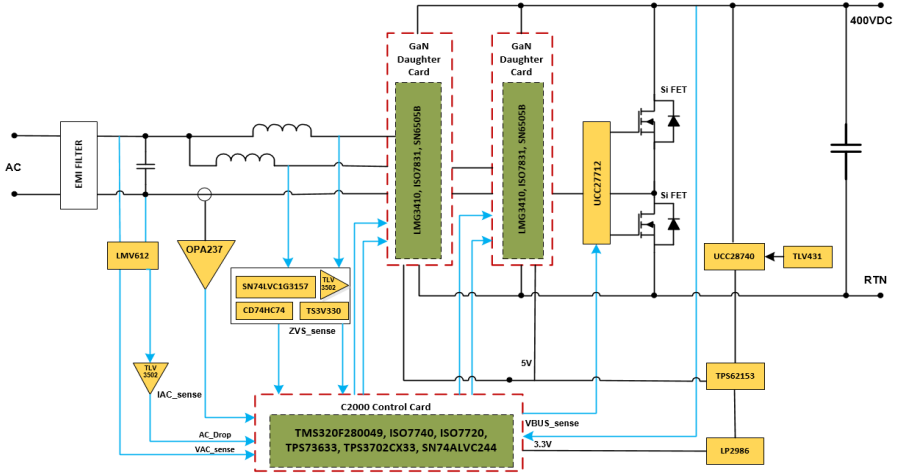
Board Image



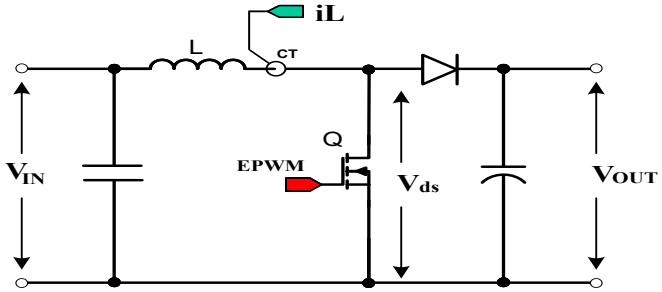
- **TIDA-00961 and Tools Folder**
- **Design Guide**
- **Design Files:** Schematics, BOM, Gerber
- **Device Datasheets:**
  - LMG3410, TMS320F280049, UCC27712, ISO7740, ISO7720, LMV612, OPA237, UCC28740, TPS62153

Benefits

- **Super High Efficiency** makes thermal design simpler
- **Extremely compact** solution with low component count
- Makes compliance with **80 Plus Titanium specs** easier
- Addresses universal AC input requirements
- Integrated GaN FET and driver eases layout constraints
- Provides a ready platform of GaN based transition mode totem pole PFC to address various power supplies up to 2 kW

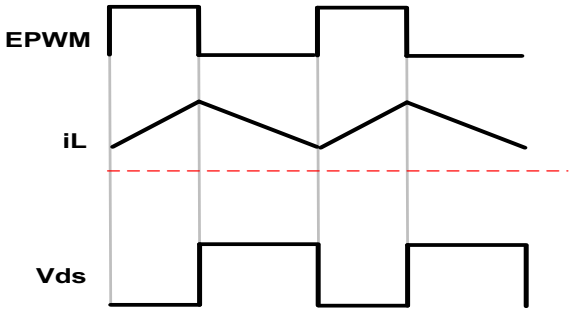


PFC Modes of Operation

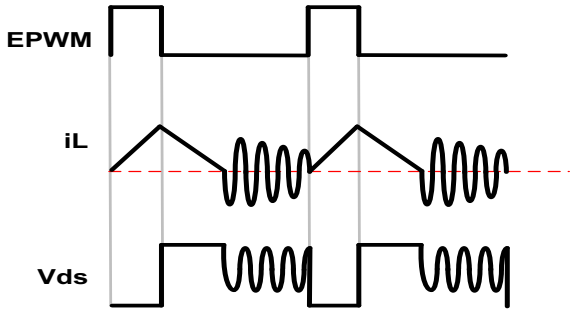


Variable Frequency Operation

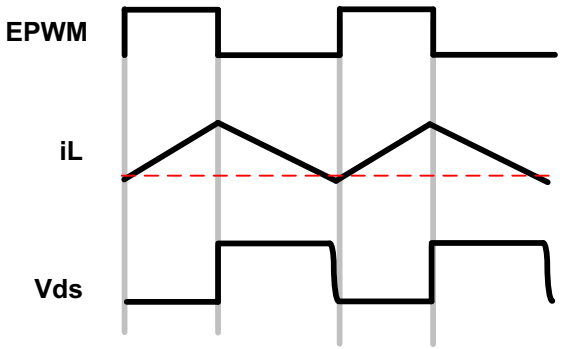
CCM Mode of operation



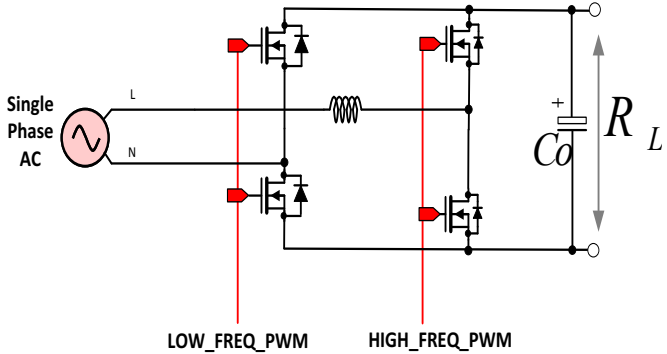
DCM Mode of operation



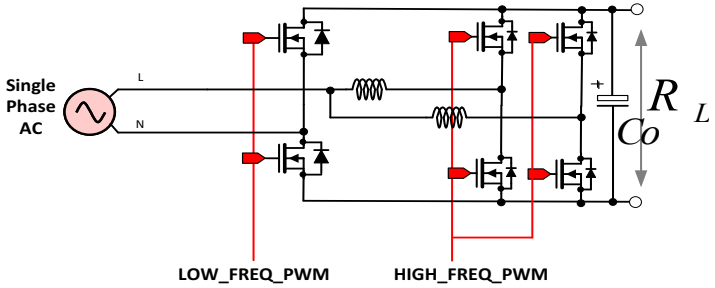
TRM/CRM Mode of operation



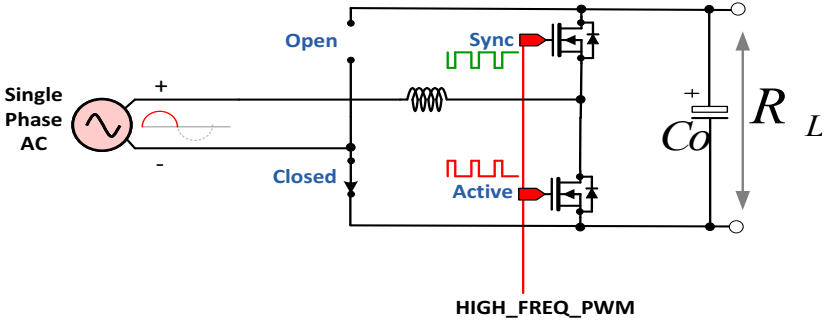
Totem-Pole PFC (CRM or TRM)



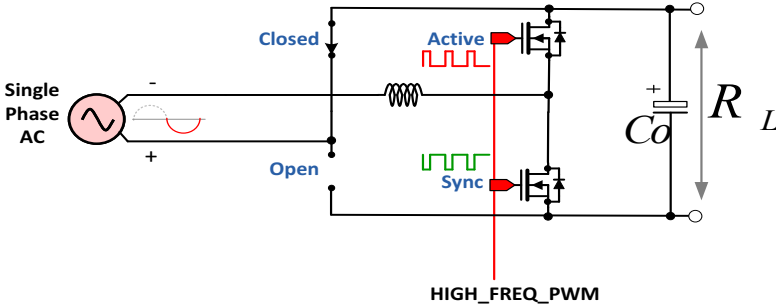
2 Ph IL TP PFC (CRM or TRM)



Positive Half Cycle



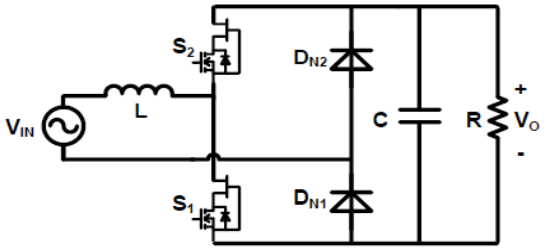
Negative Half Cycle



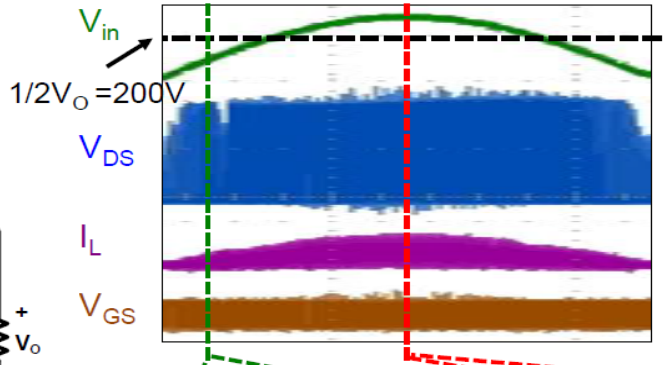
Key Challenges & Solutions

#1 Achieving ZVS across line-load and over full AC cycle

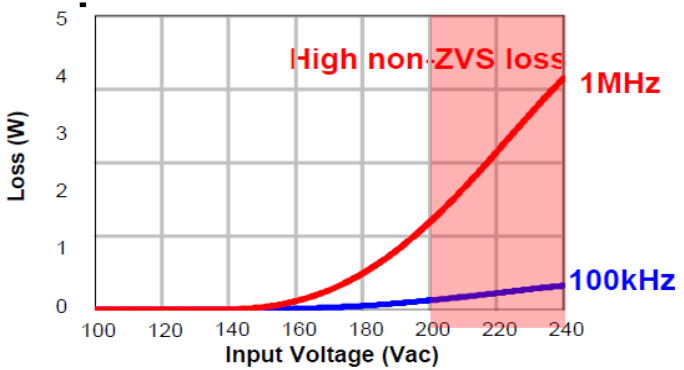
Totem-pole PFC

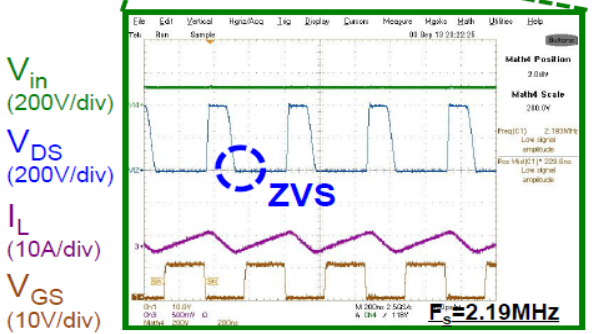


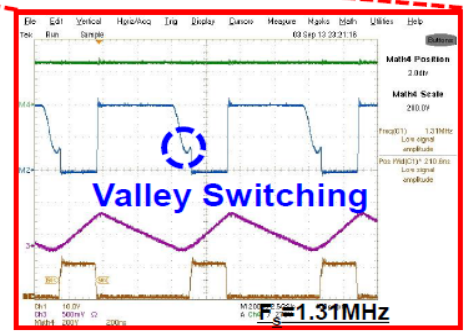
V_{IN_RMS}=230V, V_O=400V, Full Load, F_S=1-3MHz



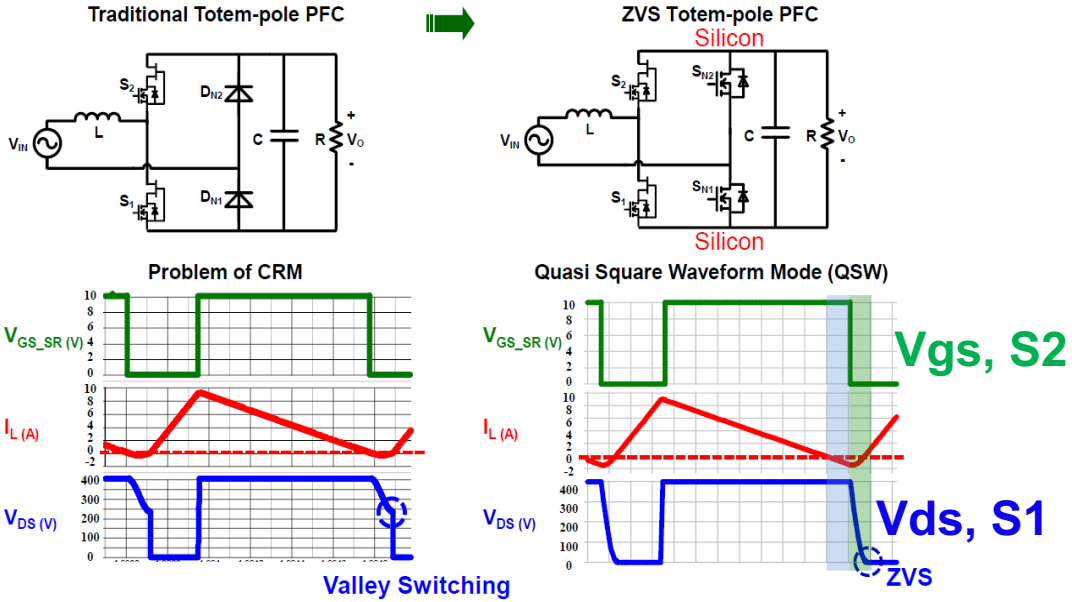
Line-cycle Averaged Non-ZVS







ZVS Extension – Inductor Current Sensing



* Bin Su, Junming Zhang, and Zhengyu Lu, "Totem-Pole Boost Bridgeless PFC Rectifier With Simple Zero-Current Detection and Full-Range ZVS Operating at the Boundary of DCM/CCM", IEEE Transactions on Power Electronics, Vol. 26, No. 2, pp. 427 – 435, Feb 2011

* Christoph Marxgut, Florian Krismer, Dominik Bortis, and Johann W. Kolar, "Ultraflat Interleaved Triangular Current Mode (TCM) Single-Phase PFC Rectifier", in IEEE Transactions on Power Electronics, Vol. 29, No. 2, pp. 873 – 882, Feb 2014

* Source: CPES, Virginia Tech

Conventional Solution

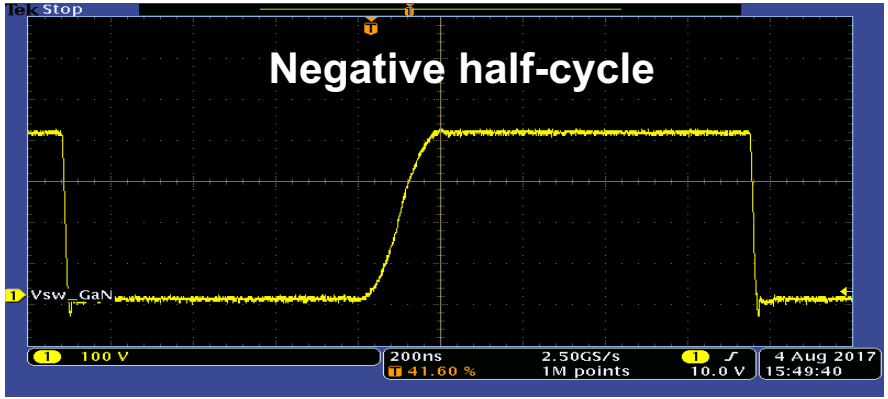
- Inductor current zero crossing sensing

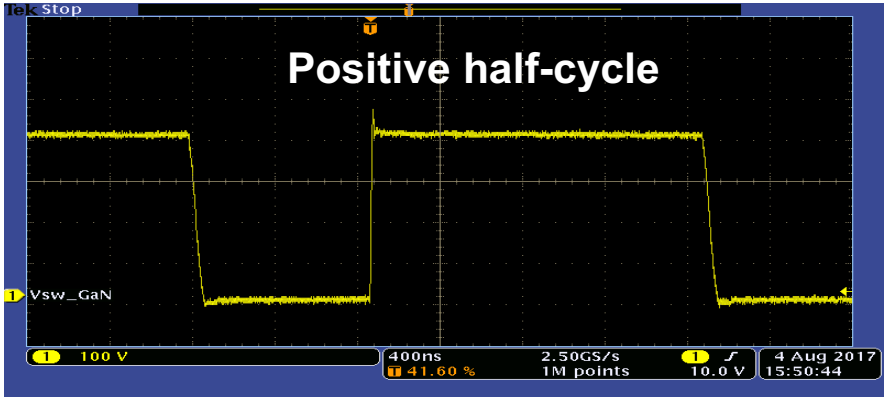
- Low SNR
- Worse under high-line low-load

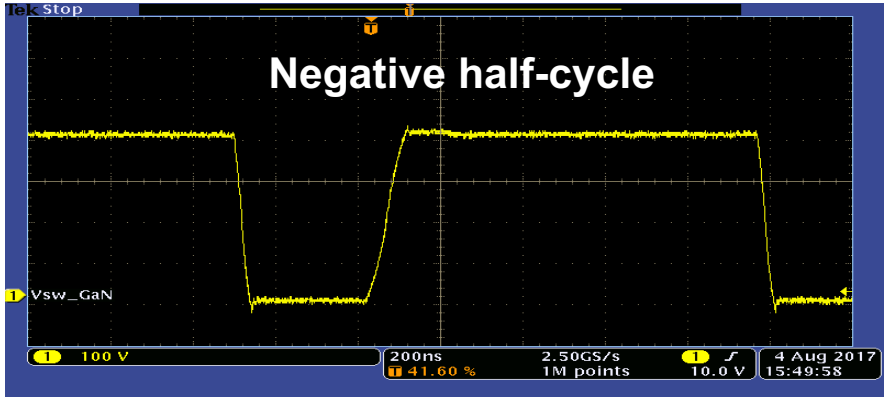
C2000 Solution

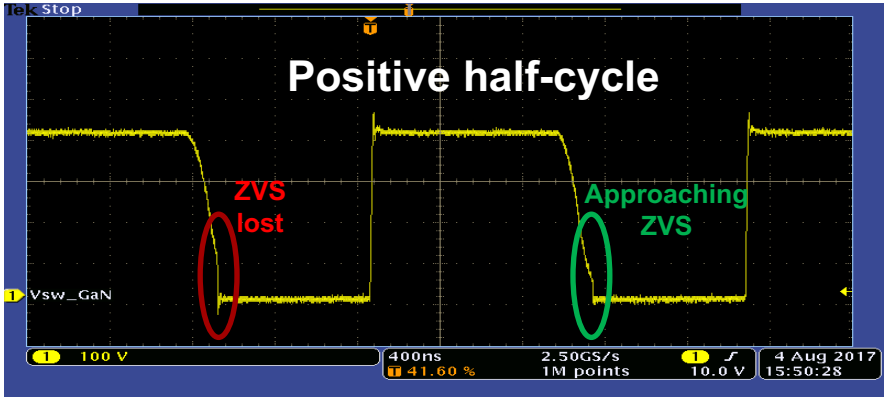
- Sensing voltage across the inductor
- On-chip CMPSS and type-4 PWM features on C2000 are used to solve this

ZVS with AC Input









#2 Cycle Intensive Calculations

- Calculating correct turn-on and turn-off durations at every switching/control instant

Solution

- C2000's TMU helps reduce the MIPS requirements considerably
  Example: From possible > 10us calculation time to <0.5us calculation time

Ton Calculations

$$f_1(T_{on}) = \frac{V_{in}V_o}{(V_o - V_{in})L} \cdot \frac{T_{on}^2}{2I_{ref}\sqrt{2LC_{oss}}} - \frac{T_{on}}{\sqrt{2LC_{oss}}} - \sqrt{\frac{V_{in}^2}{(V_o - V_{in})^2}\left(1 + \frac{T_{on}^2}{2LC_{oss}}\right) - 1}$$

$$f_2(T_{on}) = \frac{(V_o - V_{in})T_{on} + \sqrt{V_{in}^2 T_{on}^2 + 2LC_{oss}(2V_{in}V_o - V_o^2)}}{(V_o - V_{in})\sqrt{2LC_{oss}} - (V_o - V_{in})T_{on}\sqrt{V_{in}^2 T_{on}^2 + 2LC_{oss}(2V_{in}V_o - V_o^2)}}$$

$$C = \frac{V_o^2(2V_{in} - V_o)}{V_{in}(V_o - V_{in})} \cdot \frac{1}{2I_{ref}}\sqrt{\frac{2C_{oss}}{L}} - 2\pi - \frac{\sqrt{V_o^2 - 2V_{in}V_o}}{V_{in}} + tan^{-1}\frac{\sqrt{V_o^2 - 2V_{in}V_o}}{V_{in}}$$

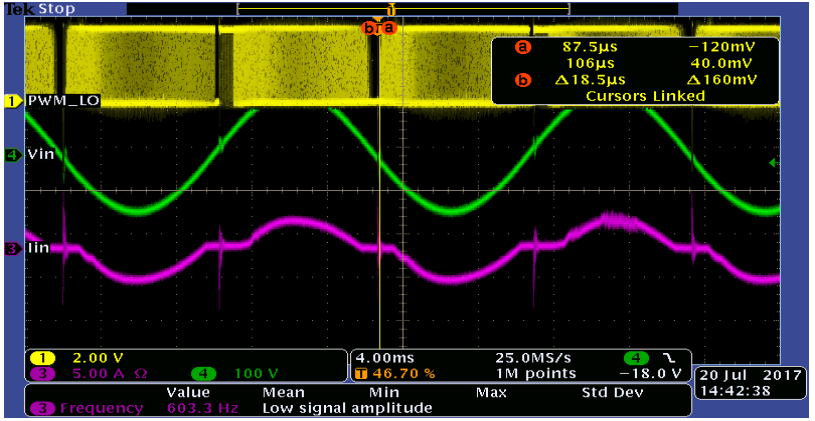
Dead-time Calculations

$$t := \sqrt{Lo \cdot 2 \cdot Coss} \cdot \left[3.14159 - atan\left[\frac{\sqrt{(2Vin - Vo) \cdot Vo}}{Vo - Vin}\right]\right]$$

- Possibility of negative current/current spikes
- Body diode losses

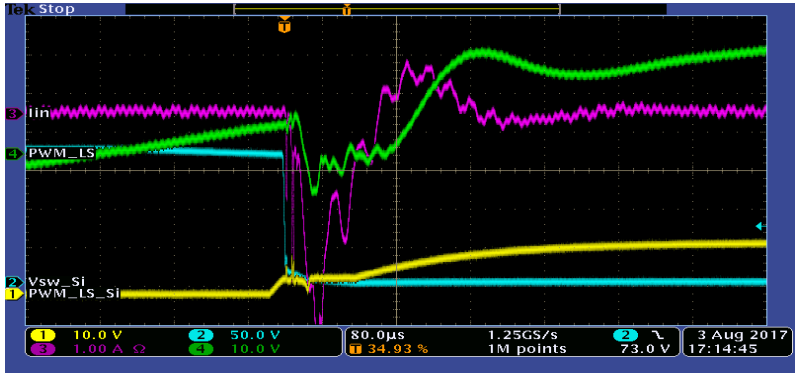
#3 Clean cross-over transitions

- TRM/CRM PFC uses a small PFC inductance
- Current goes discontinuous
- As a result any voltage that builds-up across silicon FET, discharges at a very high rate the moment silicon FET and/or the GaN sync FET are turned ON
- This can cause huge current spikes around the zero crossing point

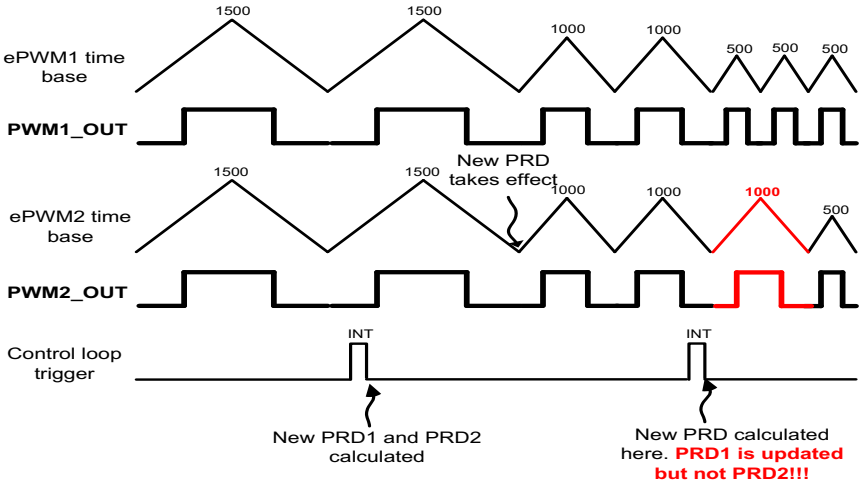


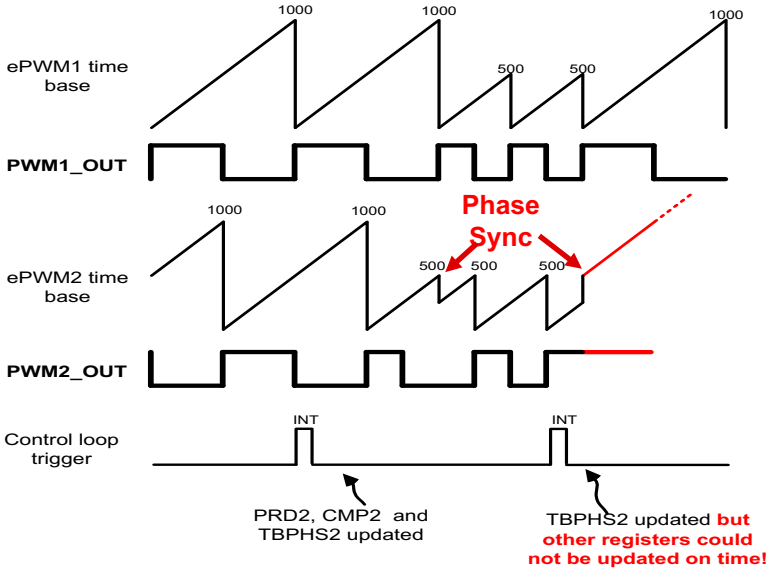
Solution

- Soft-start for active FETs
- Proper turn-on sequence
- These are implemented using a software state-machine



#4 Correct PWM waveform generation with HRDB

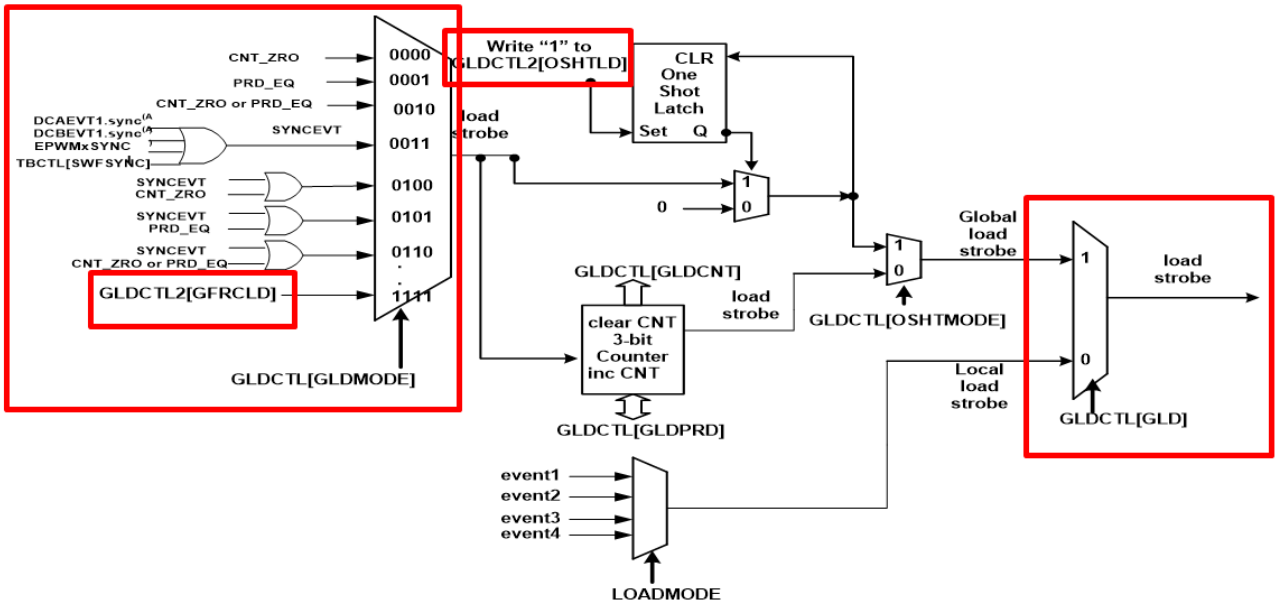




What is missing?

- A clean and easy way to update multiple registers in a PWM module
- A clean and easy way to update registers in multiple PWM modules

Solution: One Shot & Global Reload (Type-4 PWMs)



One shot reload usage

Initialization

- Enable global reload
- Link GLDCTL2 registers

Run Time

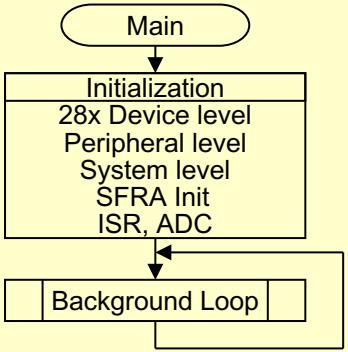
- Update all registers
- Write '1' to GLDCTL2[OSHTLD]
- Write '1' to GLDCTL2[GFRCLD], if desired

TRM PFC operating at high switching frequencies also requires **hi-res dead-band (HRDB)** between the turn-off of the active FET and the turn-on of the sync FET

Software Flowchart

C Environment

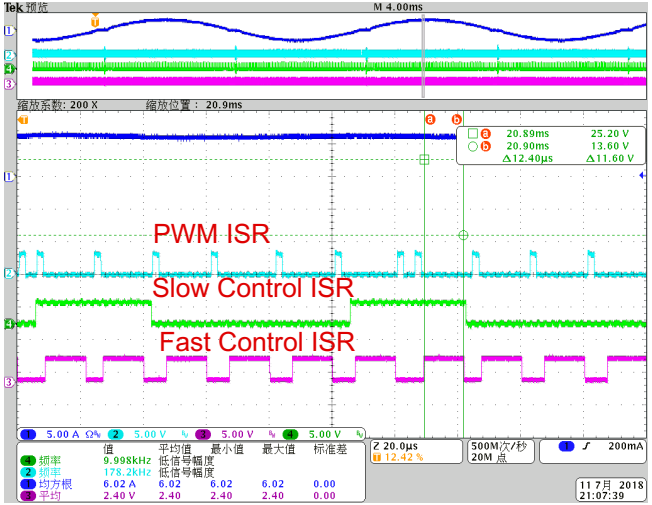
System Level Management



Processor Resource Utilization

- **CPU Bandwidth**

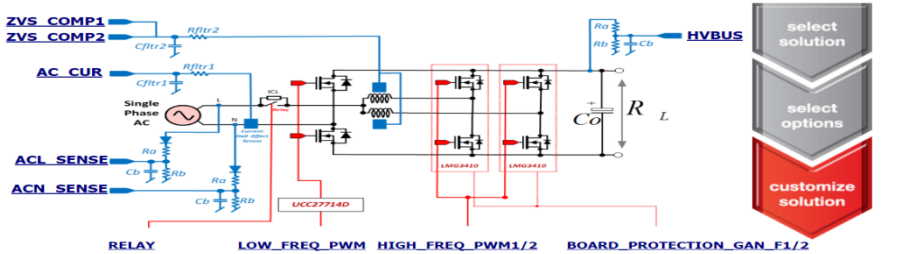
	Execution time	Description
Slow Control ISR	20.8us	10 kHz, voltage loop, phase shedding
Fast Control ISR	12.4us	50 kHz current loop, AC cycle state machine, phase re-enable, PLL
PWM ISR	2.04us	f_{sw} /3 ZVS loop, phase shifting



- **F280049 Peripheral Usage**
  - 4 PWM Modules, 2 CMPSS for OCP&ZVS, 4 ADC channels
- **Memory Usage**
  - FLASH: 14KW, RAM: 7KW (for F280049,128 KW Flash, 50KW RAM in total)

PowerSUITE – Interleaved TRM TP PFC

2-PH Interleaved TRM Totem Pole PFC using F28004x



Project Options

INCR_BUILD: 1: Open Loop | Input: AC | Control Running on: C28x

Phase Shedding: Enabled | Non-linear loop: Disabled | Auto run: Disabled

Control Loop Design

Tuning: None | Comp Number: - | Comp Style: -

COMPENSATION DESIGNER | SFRA

SFRA: Current | Current Loop Frequency: Current Loop ISR runs at Fsw | Voltage Loop Frequency: Voltage Loop runs at 10KHz

Power Stage Parameters

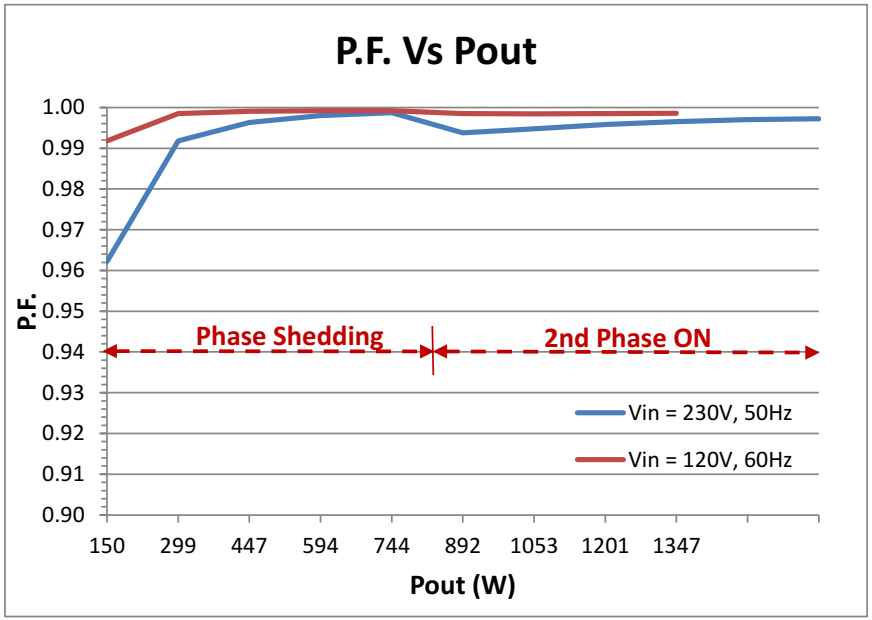
PWM :	Min. Switching Freq (Fsw in kHz)	200	Max. Switching Freq (Fsw in kHz)	1000	
Nominal Voltage :	Output Vbus (V)	390.0			
	Min. Input VL-L(Vrms)	90.0	Max Input VL-L(Vrms)	245.0	
Power :	Rated (W)	1600.0	Operating (W)	768.0	
Inductor (Li):	Inductance (uH)	0.481			
Output Cap (Co):	Capacitance (uF)	1410.0	ESR (Ohm)	0.365	

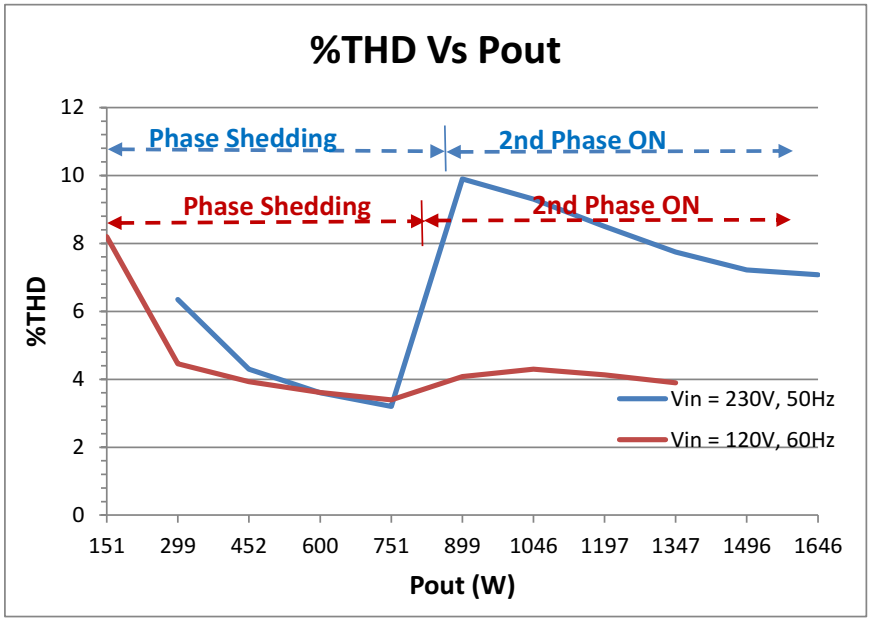
Voltage And Current Sensing Parameters

Refer to calculations.xlsx file located in the install package for more detials

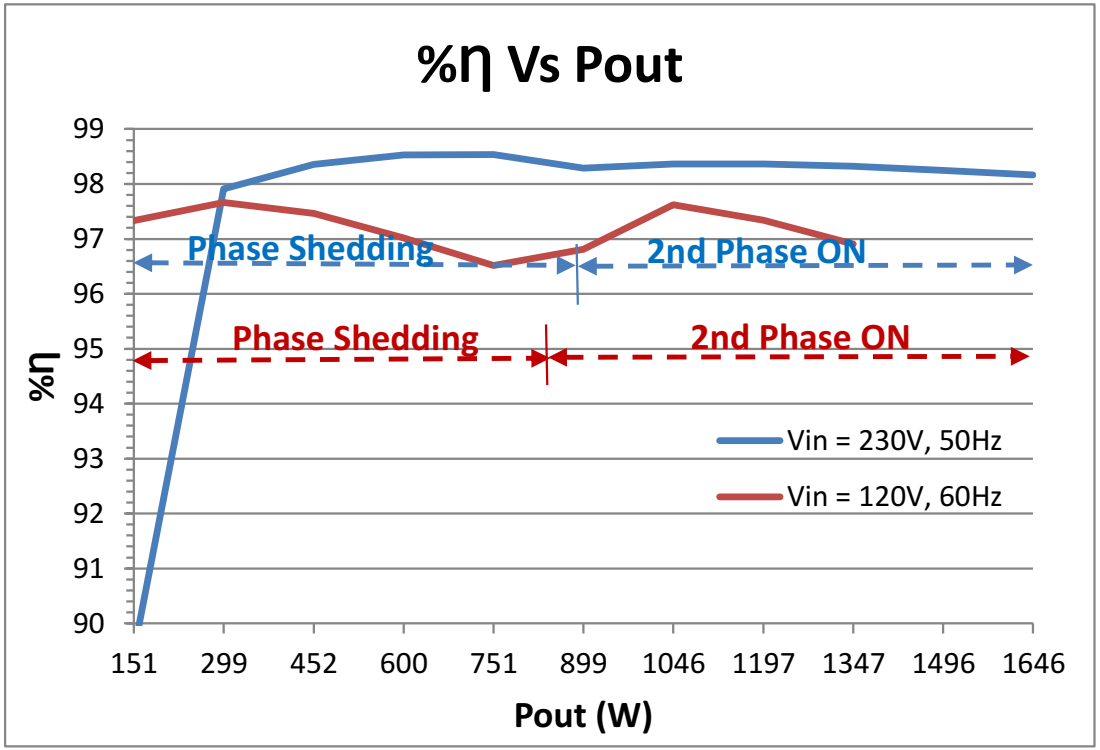
Voltage Sense :	Max Vbus (V)	536.85	Max Vin (+-V)	677.51
Current Sense :	Max (+-Amp)	22.295	Trip Set (+-Amp)	15.0
Sense Filter:	Rfltr (Ohm)	47.0	Cfltr (uF)	0.047
	Cut-off Freq (kHz)	72.085		

Input Current THD & Power Factor (2 Phase Interleaved)

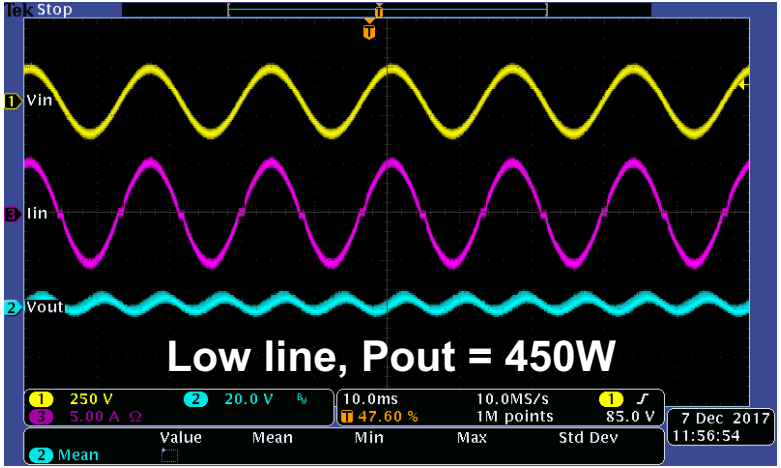


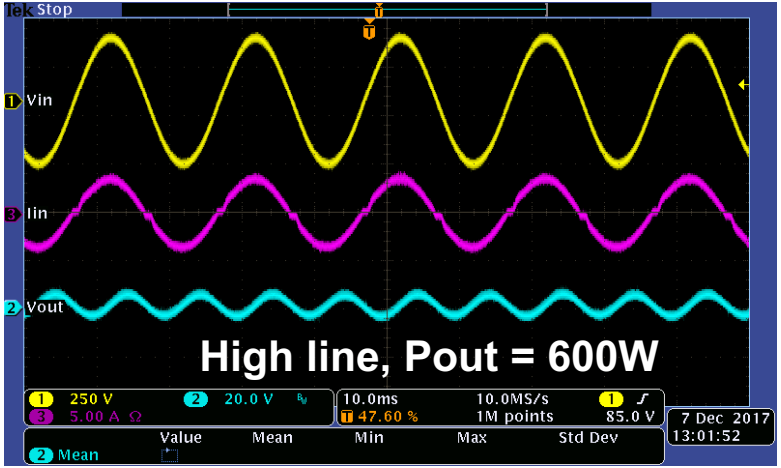


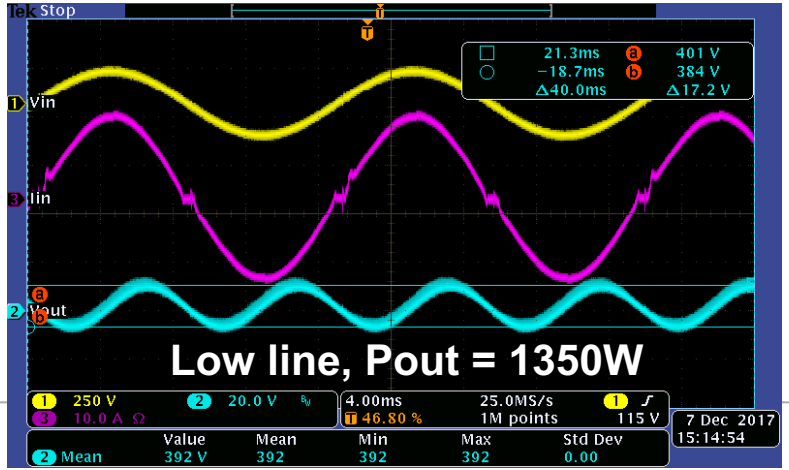
PFC Efficiency (2 Phase Interleaved)

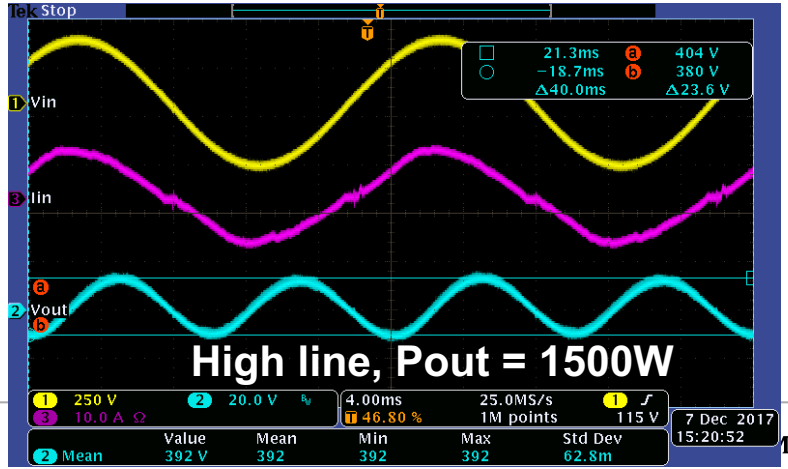


Input Voltage, Current and Output Ripple

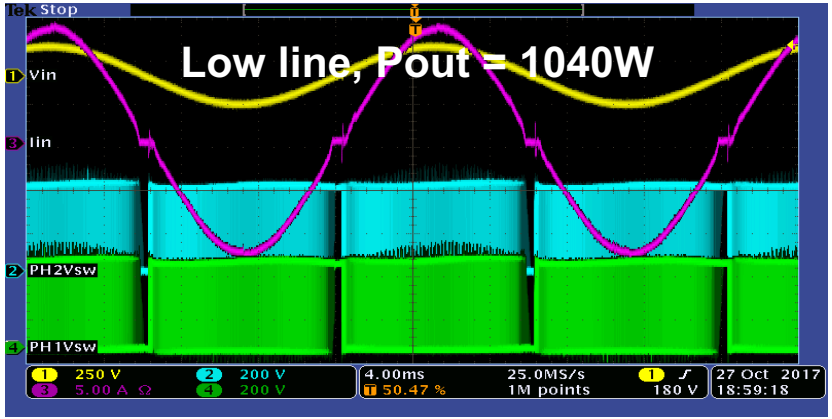


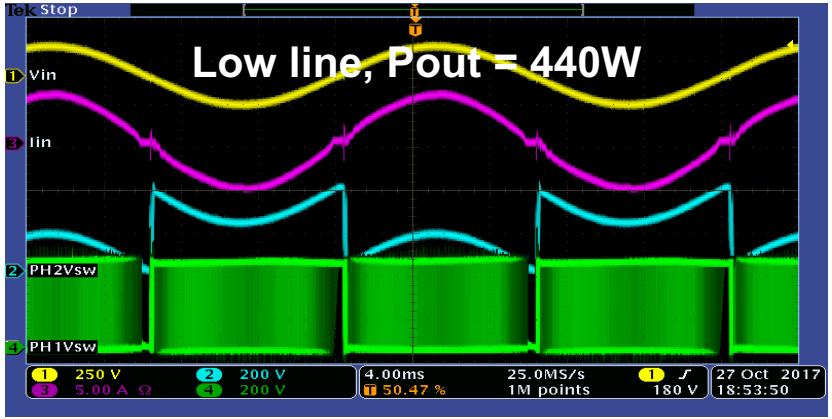


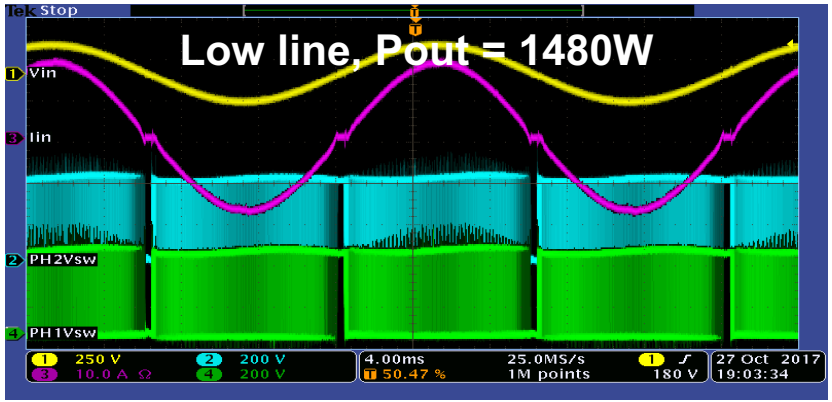


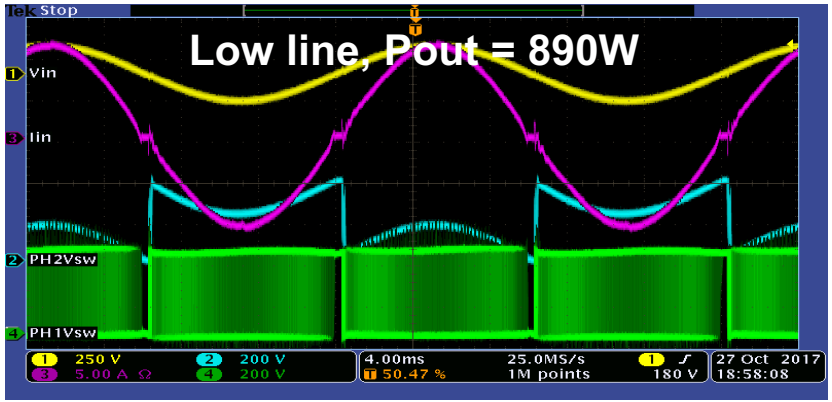


Phase Shedding – Low Line





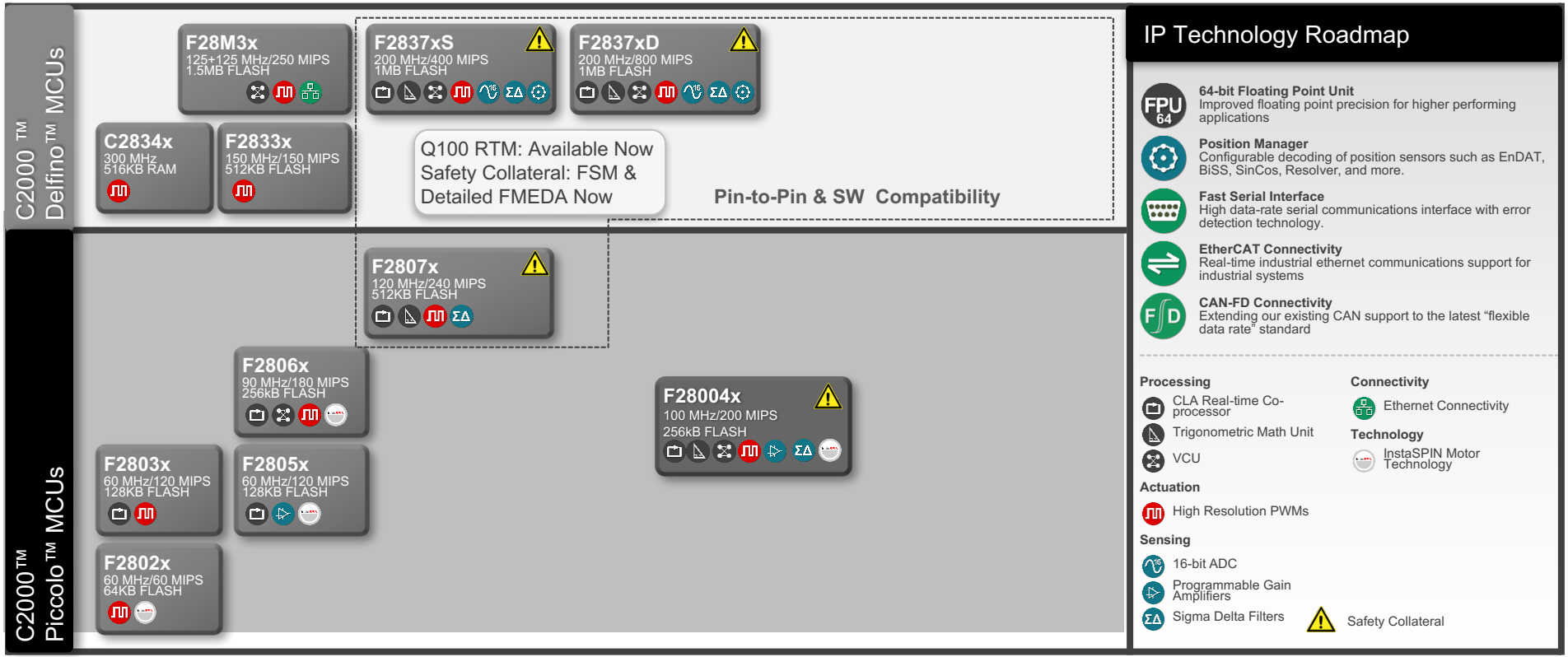




Two Phase Interleaved

Phase-2 OFF

C2000 Product Roadmap



IP Technology Roadmap

64-bit Floating Point Unit
Improved floating point precision for higher performing applications

Position Manager
Configurable decoding of position sensors such as EnDAT, BiSS, SinCos, Resolver, and more.

Fast Serial Interface
High data-rate serial communications interface with error detection technology.

EtherCAT Connectivity
Real-time industrial ethernet communications support for industrial systems

CAN-FD Connectivity
Extending our existing CAN support to the latest "flexible data rate" standard

Processing
- CLA Real-time Co-processor
- Trigonometric Math Unit
- VCU

Actuation
- High Resolution PWMs

Sensing
- 16-bit ADC
- Programmable Gain Amplifiers
- Sigma Delta Filters

Connectivity
- Ethernet Connectivity

Technology
- InstaSPIN Motor Technology

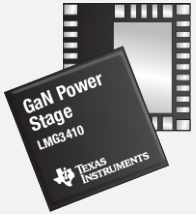
Safety Collateral

Production | Sampling | Development | Concept

LMG3410R070

Integrated 600-V GaN FET power stage in compact 8x8mm split-pad QFN package

Features



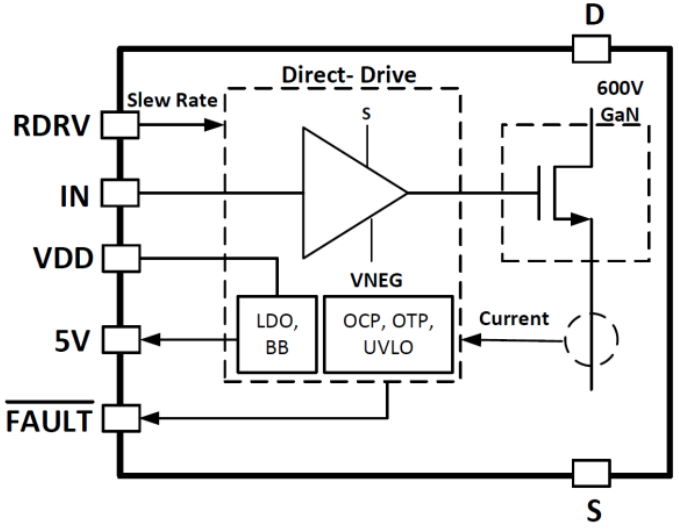
- 70-mΩ typical $RDS_{(ON)}$
- 20-ns typical propagation delay
- Integrated over-temperature, over-current protection and UVLO
- High edge-rate tolerance
- Externally-adjustable drive strength for switching
- Performance and EMI control: supports 30 to 100 V/ns
- Targeted towards high-speed operation: up to 1-MHz steady-state operation

Applications

- Watts to Kilowatts solution for every application:
  - Personal electronics
  - Motor drives and robotics
  - Telecom and network power
  - Grid infrastructure

Benefits

- Integrated direct gate driver with zero common source inductance
- Built-in 5V LDO to power external digital Isolator
- Integrated bias supply – only +12V unregulated supply needed
- High speed over current protection with <100ns response time



Summary

- TIDA-00961 is a fully programmable two phase interleaved TRM PFC solution
- Innovative ZVS scheme provides good ZVS performance across line and load
- C2000 controller features and TI GaN devices allow a switching frequency range from 200kHz to 1.2MHz
- Compact design – about **80W/in^3** power density
- Phase shedding for performance improvements under low load operation
- Released TI design - http://www.ti.com/tool/TIDA-00961
- E2echina: 基于 GaN 的高效率 1.6kW CrM 图腾柱PFC参考设计 TIDA-00961 FAQ

Thank you!

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