High Voltage Seminar

Designing Titanium-grade efficiency into GaN-based power supplies

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Agenda

- Introduction: server PSU and Titanium-grade efficiency
- GaN in AC/DC stage
  - Application landscape
  - Efficiency and cost comparison study
  - iTCM totem-pole PFC and ZVD
- GaN in auxiliary power
  - Application landscape
  - Efficiency and cost comparison study

Trends in data center power supply units

Energy efficiency

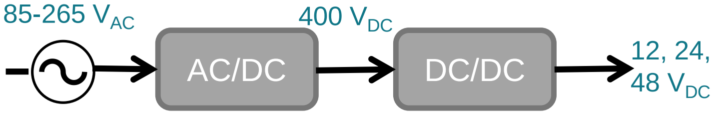
Beyond 80+ Titanium
@ 50% & 100% load

80 PLUS Certification	115V Internal Non-Redundant			230V Internal Redundant			
% of Rated Load	20%	50%	100%	10%	20%	50%	100%
80 PLUS	80%	80%	80%	N/A			
80 PLUS Bronze	82%	85%	82%	---	81%	85%	81%
80 PLUS Silver	85%	88%	85%	---	85%	89%	85%
80 PLUS Gold	87%	90%	87%	---	88%	92%	88%
80 PLUS Platinum	90%	92%	89%	---	90%	94%	91%
80 PLUS Titanium	---	---	---	90%	94%	96%	91%

80 PLUS | 80 PLUS BRONZE | 80 PLUS SILVER | 80 PLUS GOLD | 80 PLUS PLATINUM | 80 PLUS TITANIUM

- **<u>PSU system eff spec 2021:</u>**
  - ITE-level PSU >96.5%
  - Rack-level PSU peak efficiency > 97.5% @ 230 Vac

Trends

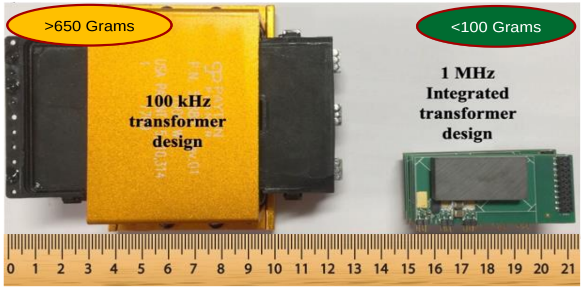


(Grid) AC → DC:
Power Factor Correction (PFC)

DC → DC:
Topology: LLC, PSFB

High power & power density

3 kW/4 kW/5 kW & >100 W/in³

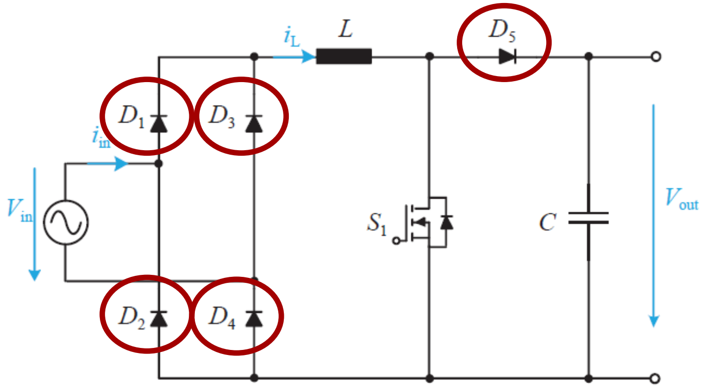


<u>ITE-level PSU</u> going up to 3 kW+ in same FF
- Power density: 80 W/in^3 in Y19-Y20 → 115 W/in^3 in Y23-Y24

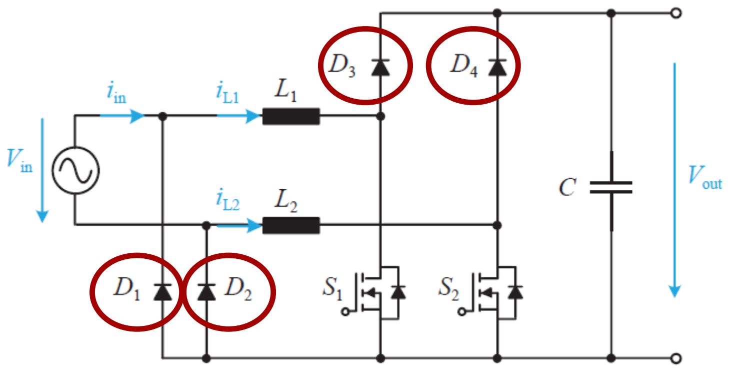
<u>Rack-level PSU</u> going up to 4 kW+ in same form factor
- Power density: >100 W/in^3 by Y23

Traditional power factor correction topologies

- Boost PFC with bridges
  - Why boost? Continuous input current



Boost PFC

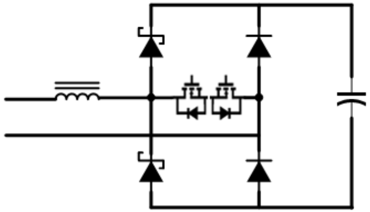
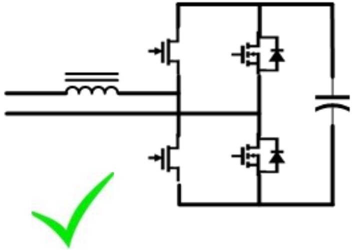
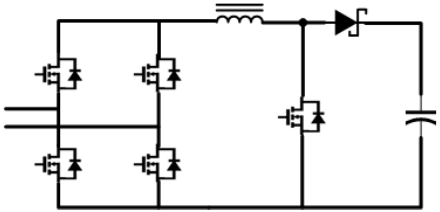


Semi-bridgeless dual-boost PFC

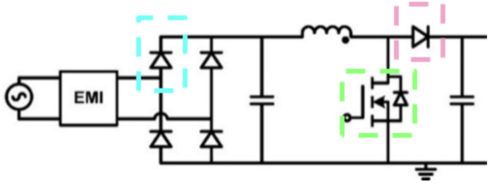
Issue: Conduction losses of diodes are huge.

Comparison: @10 A, Pdiode =10 A*1.3 V = 13 W; Pmos,on = 50 mΩ*10 A*10 A = 5 W

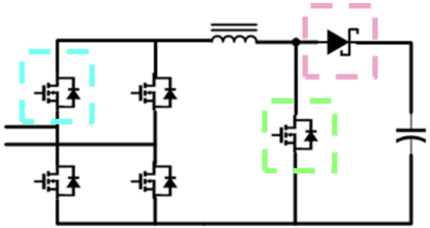
Full bridgeless high-efficiency PFC topologies

	AC switch PFC	Totem-pole PFC	Active bridge PFC
Block diagram			
Power components	2 slow diodes 2 MOSFETs 2 fast diodes	2 slow FETs 2 fast FETs	4 slow MOSFETs 1 fast FET 1 fast diode
Cost	Medium	Low	High
Conduction losses	On-time: 2 MOSFETs Off-time: 1 fast diode + 1 slow diode	On-time: 1 fast FET + 1 slow FET Off-time: 1 fast FET + 1 slow FET	On-time: 2 slow FETs + 1 fast FET Off-time: 2 slow FETs + 1 fast diode
Efficiency	~98.7%	~99.0%	~98.5%

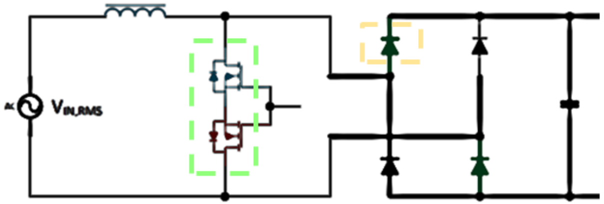
Commonly used topologies in PFC applications



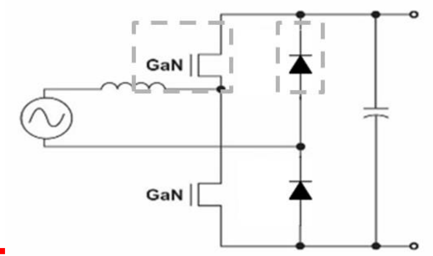
Classic boost with bridge rectifier



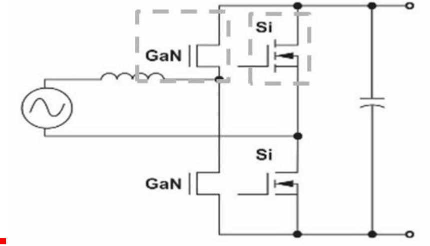
Classic boost with active bridge



AC switch PFC



Totem pole PFC with slow diode

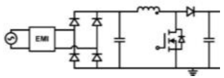
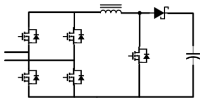
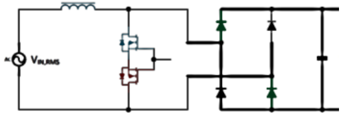
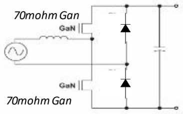
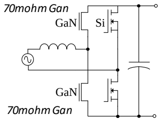


Totem pole PFC with slow MOS

$$P_{loss} = P_{cond} + P_{ov} + P_{Coss} + P_{Qrr}$$

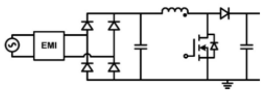
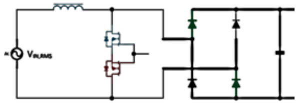
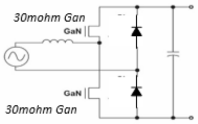
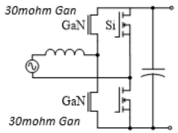
RMS current	Average current
$I_{rms} = \frac{P_o}{\sqrt{2}V_{rms\_in}}$	$I_{avg} = \frac{\sqrt{2}P_o}{\pi V_{rms\_in}}$
$I_{rms} = \frac{\sqrt{2}P_o}{V_{rms\_in}}\sqrt{\frac{1}{2} - \frac{4\sqrt{2}V_{rms\_in}}{3\pi V_o}}$	$I_{avg} = \frac{2\sqrt{2}P_o}{\pi V_{rms\_in}}\ (for\ P_{ov})$
$I_{rms} = \frac{\sqrt{2}P_o}{V_{rms\_in}}\sqrt{\frac{4\sqrt{2}V_{rms\_in}}{3\pi V_o}}$	$I_{avg} = I_o$
$I_{rms} = \frac{P_o}{V_{rms\_in}}\sqrt{\frac{4\sqrt{2}V_{rms\_in}}{3\pi V_o}}$	$I_{avg} = \frac{I_o}{2}$
$I_{rms} = \frac{P_o}{\sqrt{2}V_{rms\_in}}$	$I_{avg} = \frac{\sqrt{2}P_o}{\pi V_{rms\_in}}$

1400-W PFC system cost and efficiency comparison

FET technology	Si MOS	Si MOS	Si MOS	TI GaN FET with integrated gate driver	
	Diode Bridge + Classic Boost PFC (1-ph)	Active Bridge + Classic Boost PFC (1-ph)	AC switch bridgeless PFC	Totem pole Bridgeless PFC with Slow Si Diode	Totem pole Bridgeless PFC with Slow Si MOS
Topology					
Total System Cost (key components)	$	$$$$	$$	$$	$$$
"50% Load Efficiency" improvement vs. Classic Boost PFC with Diode rectifier	Baseline	0.54%	0.36%	0.37%	0.64%

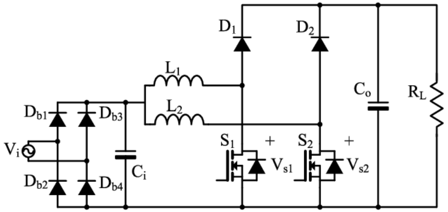
Key Components	Slow diode bridge (1)	Slow Si FETs (4)	Slow diode bridge (1)	Slow diode bridge (1)	Slow Si FET (2)
	Fast FET (1)	Active bridge control (1)	Fast FET (2)	Fast FET (2)	Fast FET (2)
	Fast diode (1)	Fast FET (1)	Fast diode (1)	Digital Isolator (1)	Digital Isolator (1)
	Low side gate driver (1)	Fast diode (1)	Iso gate driver (1)		High/Low gate driver (1)
		Low side gate driver (1)			

2800-W PFC system cost and efficiency comparison

FET technology	Si MOS	Si MOS	TI GaN FET with integrated gate driver	
	Classic Boost PFC (1-ph) w/- Diode bridge	AC Sw Bridgeless PFC with 2 Slow diodes	Totem pole Bridgeless PFC with Slow Si Diode	Totem pole Bridgeless PFC with Slow Si MOS
Topology				
Total System Cost (key components)	$	$$	$$	$$$
"50% Load Efficiency" improvement vs. Classic Boost PFC with Diode rectifier	**Baseline**	**0.46%**	**0.52%**	**0.81%**

- Comparing with AC switch topology, Totem pole PFC with active slow switch can achieve higher efficiency with higher device cost.
- Totem pole PFC with diodes can achieve comparable efficiency with comparable device cost.

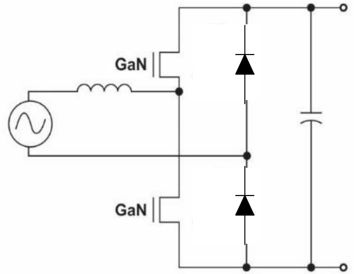
GaN enables data center energy savings, lowers Opex $



4 kW Interleaved PFC with Silicon MOSFETs

Efficiency

98.0% → **98.8%**



4 kW Bridgeless totem-pole PFC with GaN
($0.5 Cost adder per PSU)

Calculations	Total	Units
Datacenter power per year	100,000	kW
Energy in 1yr (computing + cooling), 24/7, 365	876,000,000	kWh
Energy for computing	438,000,000	kWh
Efficiency improvement using TP PFC	0.8	%
Energy savings in computing	3,504,000	kWh
Energy savings in computing + cooling	7,008,000	kWh
Electric energy unit cost	0.1	$/kWh
Savings/yr	700.8	$k
Savings over 10-yrs	**7,008**	**$k**

GaN based TP PFC:

Total of $6.2K cost adder in data center

$7M savings in a 100 MW data center over 10-yrs through +0.8% efficiency gain with GaN

How TI GaN enables very low switching energy

FET Switching Energy loss

- **Turn-on**
  - **C_{oss} loss**
  - **Overlap loss**
  - **Q_{rr} Loss**
- **Turn-off**
  - **Overlap loss**
- **Dead time loss**

C_{OSS} Loss
Very low in GaN due to much smaller parasitic capacitance

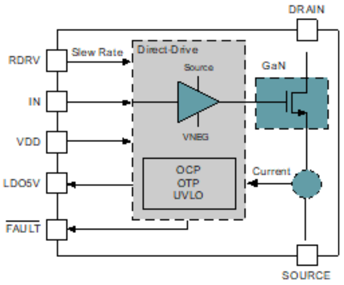
Minimal contributor at ~100ns dead-times, typical of high operating frequencies

Integrated gate driver and low package inductance enable up to **150V/ns dV_{DS}/dt**, resulting in very low turn-on overlap time

No body diode in 'Direct Drive' GaN (https://www.ti.com/lit/slpy008), hence zero reverse recovery loss

Integrated gate driver and low package inductance enable up to **150V/ns dV_{DS}/dt**, resulting in very low turn-off overlap time

TI GaN
'Direct Drive' GaN FET with **integrated** driver, bias regulation, protection in multi-chip module



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Low inductance surface mount package

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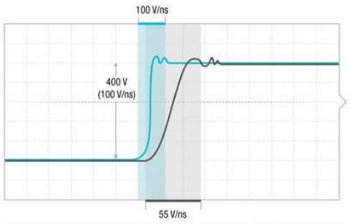
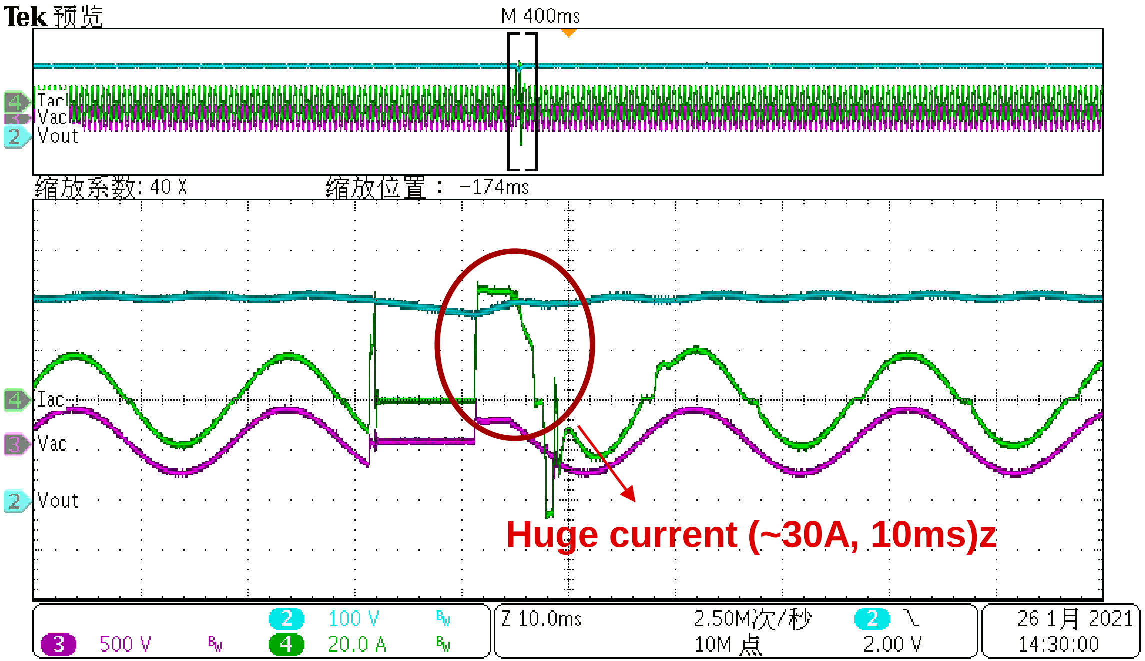


Design simplicity for high-frequency power converters

https://www.ti.com/product/LMG3522R030-Q1

Robustness highlight 1 | Over thermal shutdown – ideal diode mode in AC drop test for PFC

- **AC drop test** for PFC
  - AC line voltage loses half cycle
  - Recharge DC link will result in huge operation current for 10ms (half line cycle)
- Active switch: Cycle-by-cycle over current protection operation
- **Synchronized rectifier?**
  - Competitor devices failed this tests

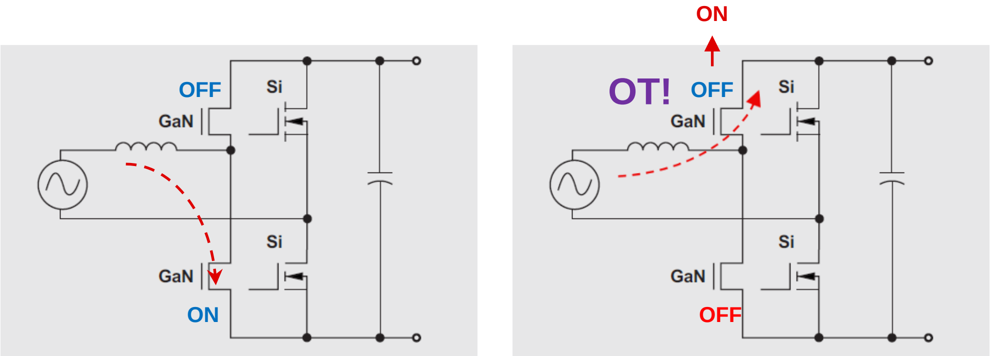


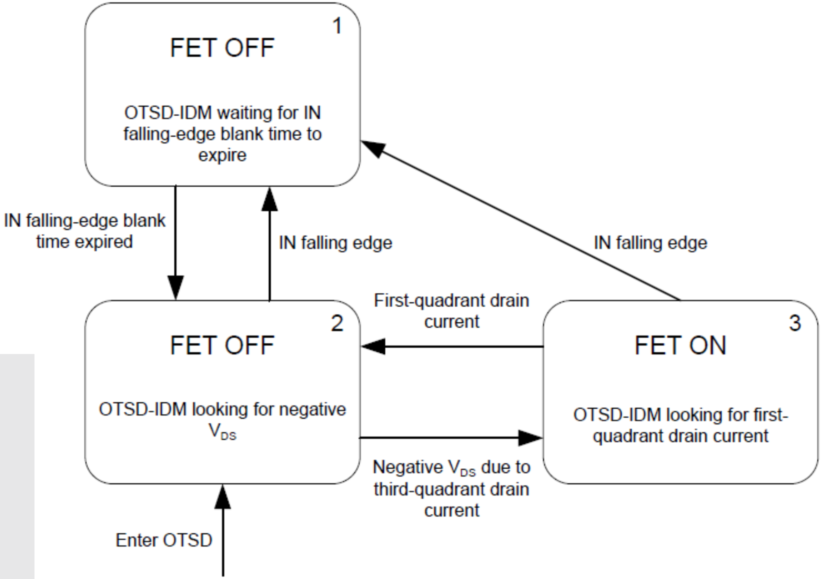
V_{SD}	Third-quadrant mode source-drain voltage	$I_S = 0.1$ A		3.8	V
		$I_S = 20$ A	3	5	V

Channels: MOSH, MOSL, VAC, IAC

Robustness highlight 1 | Over Thermal Shutdown – ideal diode mode in AC Drop test for PFC

- **OTSD-IDM**
  - When over thermal event is triggered: the FET will be automatically turn on when it detects the 3-rd quadrant current.



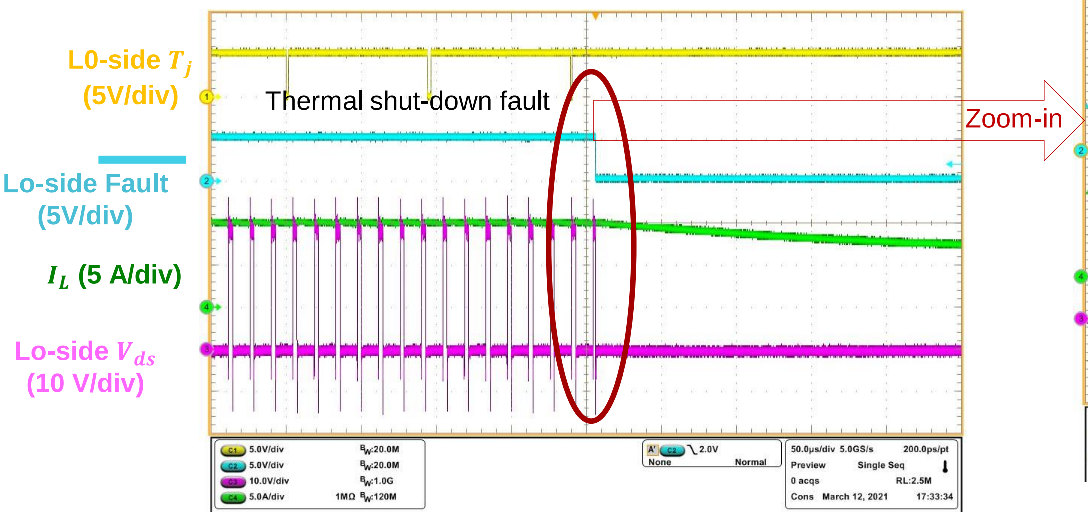


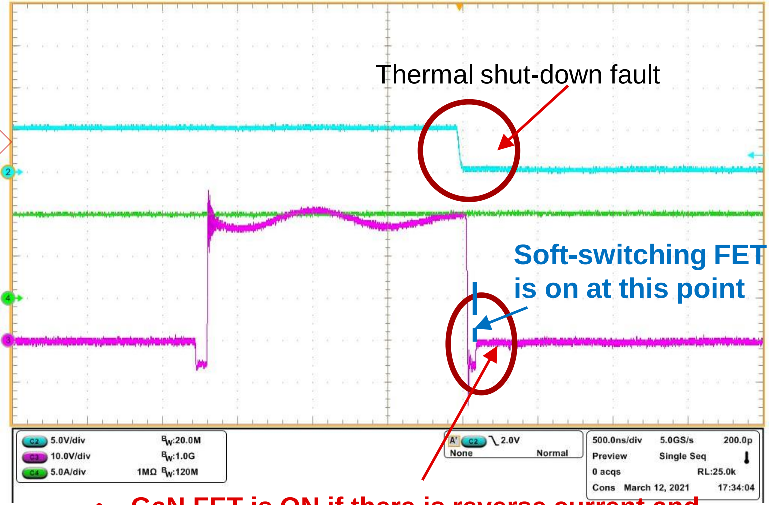
https://www.ti.com/lit/gpn/lmg3422r030
(page 25 – overtemperature shut-down ideal diode mode)

Robustness highlight 1 | Over thermal shutdown – ideal diode mode in AC Drop test for PFC

- LMG342X/352XR0X0 is turned **ON** when a reverse current is flowing from source to drain and thermal shut-down is encountered
- This behavior mitigates risk for thermal run-away and device failure

Test Result when GaN FET >160°C





- **GaN FET is ON if there is reverse current and thermal shut-down fault encountered**
- **Voltage drop reduced to = I_{SD}*30mΩ**

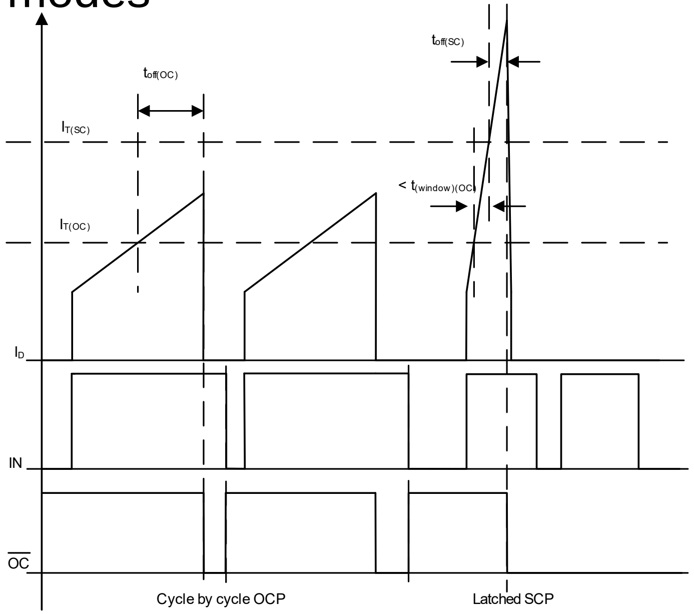
Robustness highlight 2 | Short Circuit Protection (SCP)

- Abnormal short circuit conditions are latched off for system intervention
- dI/dt used to differentiate between OCP & SCP modes

LMG342x/352x	50 mΩ	30 mΩ	Action
Over-current protection*	50 A	70 A	Cycle-by-cycle
Short-circuit protection*	**75 A**	**95 A**	**Latched-off**

* Typical Values

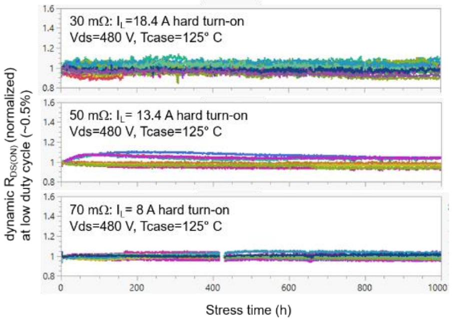
[schedule, specs, features & pinouts subject to change without prior notice.]



Over-current detection vs. Short-circuit detection

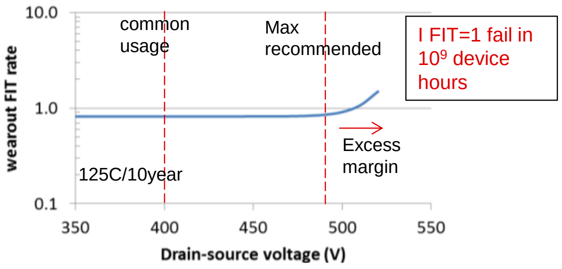
Robustness highlight 3 | TI GaN qualification & reliability summary

Reliable in power supply



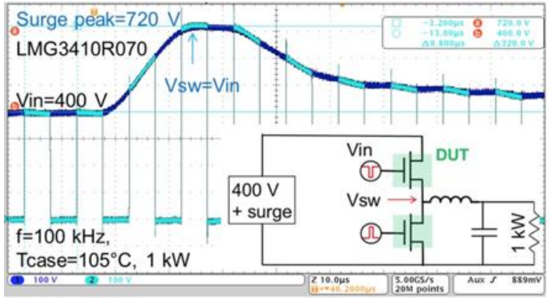
- JESD47/AECQ100 device qualification
- Every GaN product qualified inside power supply running at high voltage/current/temp against *charge trapping*

Intrinsically reliable GaN



- <1 FIT over 10-years at 125C, from 1.8Mhours of reliability test data for *time dependent breakdown*
- Over 1 billion years switching lifetime under hard-switching against *hot-electron wear-out*

Robust by design



- Designed to withstand 720V voltage surge
- Integrated over-current and over-temperature protection for every GaN FET

PMP23069 3.6-kW CCM TTPL PFC

Features

- GaN based Totem Pole 1PH using LMG3522 & controlled using C2000 MCU
- Power Spec
    - Input: 85-264 Vac , 50/60Hz
    - Output: 380V DC
    - Power: 3.6kW at 230Vrms & 1.8KW at 120Vrms
    - Efficiency : > 98.7% peak efficiency
    - Power density > 180W/in^3
- Low total harmonic distortion (THDi) < 2% @230V_{AC} input
- Reverse current protection
- Integrated baby boost circuit
- Inrush and protection from relay FET

Applications

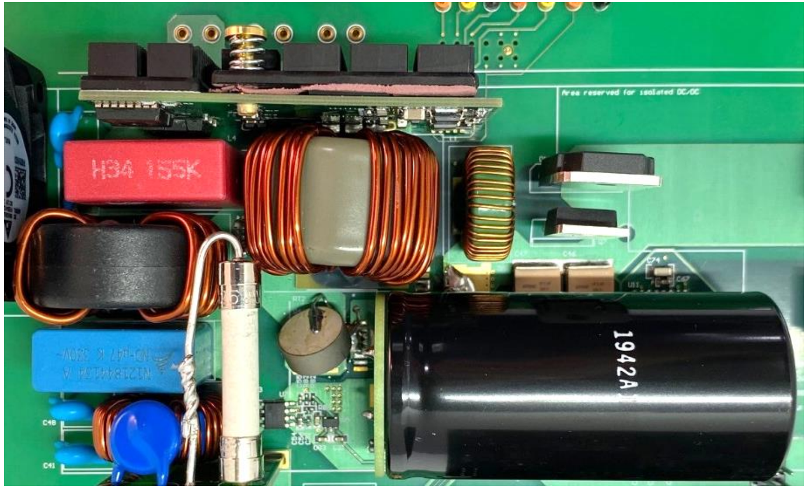
- Server power supply
- Merchant network and server PSU
- Merchant telecom rectifiers

Tools & Resources

- **Key TI Devices:** TMS320F28002x, LMG3522R030, UCC27712, UCC21220, UCC27511, TMCS1100A1

Benefits

- High power density design, with form factor matching OEM specifications
- Using latest TI-GaN with integrated gate drivers offering greater integration for the customers.
- High performance C2000 controller enables superior control and enables advanced control scheme to be implemented
- CLA support enables better integration options



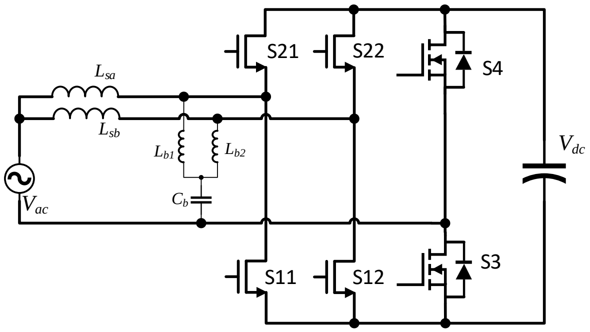
Texas Instruments

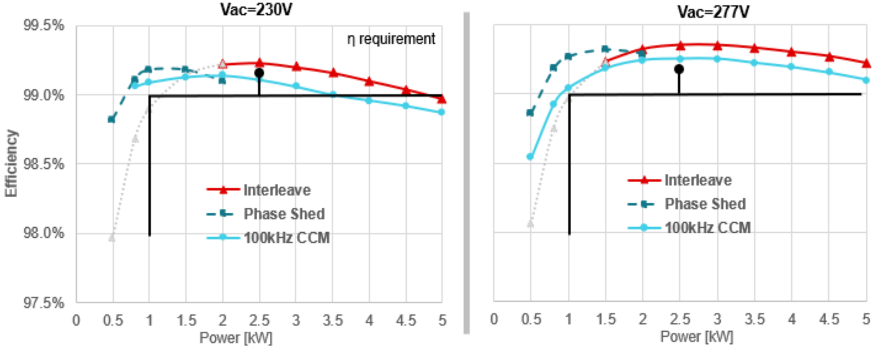
PMP40988: 5-kW iTCM TTPL PFC

Topologies:

- 2 phase Interleaved **Totem-pole** PFC with **GaN**
- Variable Frequency **iTCM** control with ZVS

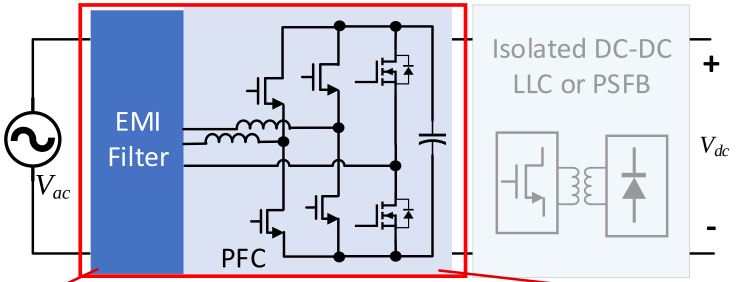
Parameters	Value
AC Input	180Vac ~ 305Vac (Thermal)
Nominal AC Input	230Vac – 277Vac (EMI)
DC Output Voltage	475Vdc ±5V
Maximum Power	5kW, 20ms hold-up
Efficiency w/o Fan	>=99.2% @ 50% load >=99% @ 20%~90% load
iTHD	Follow OCP v3 standard
EMI standard	EN55022 Class A
Internal Dimensions (PFC+control+fan+EMI+Ecap +MOV+Inrush+fuse+bleeder)	38mm x 65mm x 263mm
Power Density	120W/in^3, 180W/in^3 (excl. Cap)





System Efficiency Estimation

Improving efficiency / density trade-off with iTCM

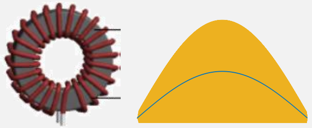


Totem-pole PFC + WBG Devices

CCM PFC

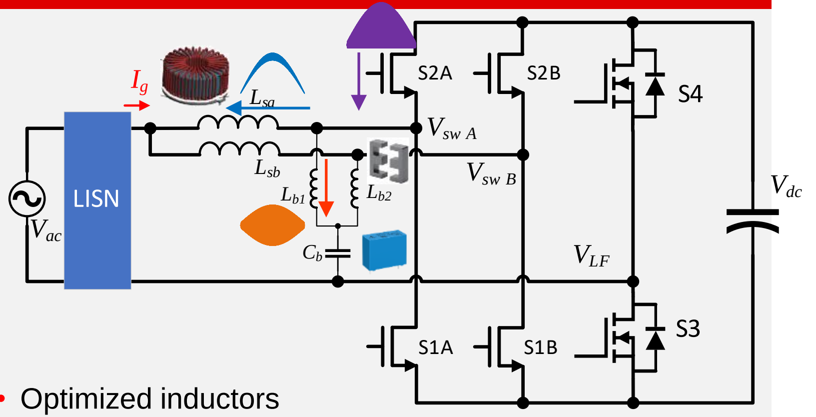
- Hard switching
- Larger passive component
- Power density / loss trade-off
- Frequency limited
- Requires WBG devices

TCM/CRM PFC



- Soft switching
- Higher density **or** efficiency
- Large ripple, high peak current and larger DM EMI
- Complexed control / higher THD

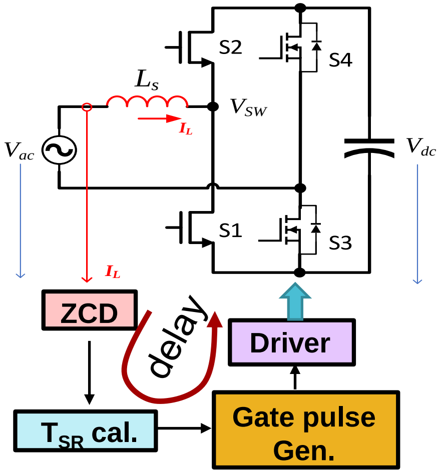
iTCM* Totem-Pole PFC

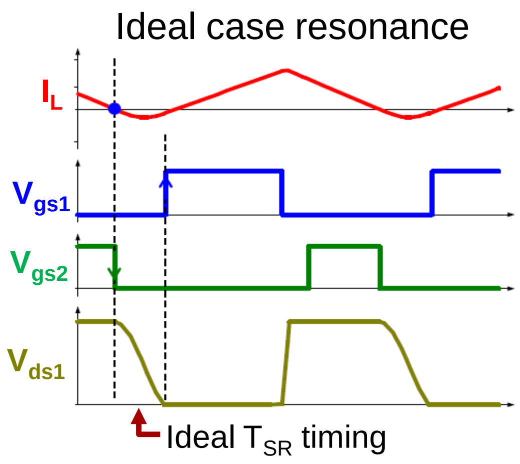


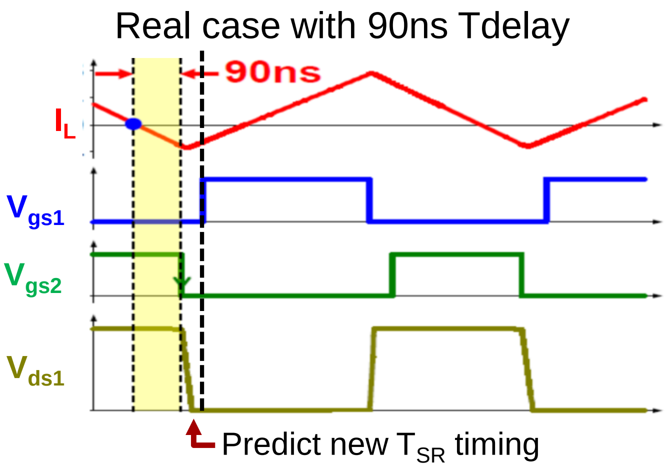
- Optimized inductors
  - HF inductor (ferrite) - no high peak currents
  - LF inductor (powder iron) - no large ripple
- Lowest DM EMI as HF ripple bypasses LISN
  - Reduces EMI filter size, Ls forms part of DM filter
- Increased magnetics component count, but each component smaller and easier to fit in 1U design
- Cb need to be X-cap rated and is rms current limited

*10kV SiC-based bidirectional soft-switching single-phase AC/DC converter concept for medium-voltage Solid-State Transformers https://ieeexplore.ieee.org/document/7972488

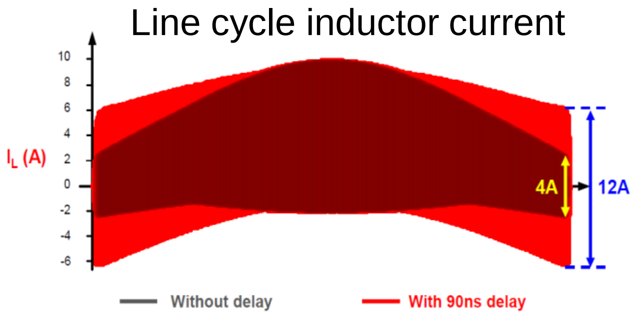
Traditional control method | Zero current detection







- Need to accurately determine zero current crossing event
  - Requires high bandwidth, low delay current sensor
- Sensor, micro controller and driver **delays** all limit minimum response time
- Requires additional computation to compensate for T_{SR} timing
- Results in increased THD and unnecessary conduction loss



Texas Instruments

LMG3526R030 650-V 30-mOhm GaN power stage with zero voltage detection

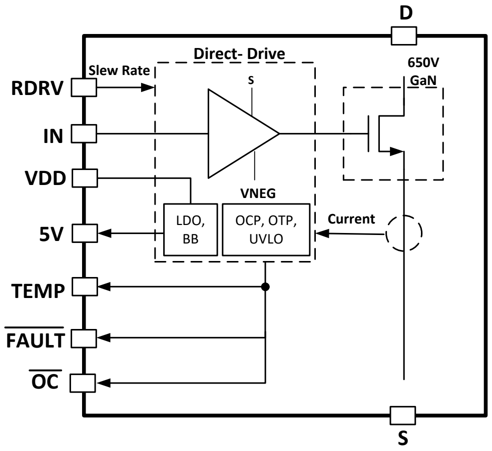
Features

- 30mΩ $R_{DS(on)}$ Drain to Source
- Integrated GaN Gate Driver
  - TI Direct-Driver technology switches the GaN directly
  - >200V/ns CMTI and 2.2MHz switching frequency
  - Internal buck-boost generates negative drive voltage
  - Only single 7.5-19V unregulated supply needed
- External resistor sets drive strength (RDRV pin)
  - 30 V/ns to 150 V/ns adjustability
  - No compromise in gate-drive inductance
- Fault monitoring and protection
  - <100ns Over-current protection @65A
  - <100ns Short circuit protection @85A
  - Over-temperature protection
  - UVLO protection
- Advanced features
  - Variable duty cycle PWM output report GaN die temperature
  - Sync FET mode reduces 3rd quadrant conduction loss
  - **Zero-voltage detection function**
- Package
  - 12x12mm Top-cooled QFN (pad is connected to source)

Applications

- High efficiency and high density power supplies
  - 2-5kW PSU for server, data center, telecom, industrial
- Targeted for 2.5kW-4kW per leg of AC/DC PFC stage
- 400 to 12/48V DC/DC converters of 3-10kW

Functional block diagram & package



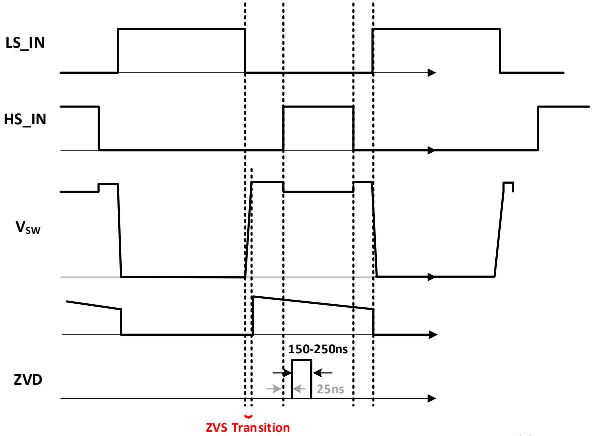
12x12mm Top-Cooled QFN

[schedule, specs, features & pinouts subject to change without prior notice.]

Zero-voltage detection

- **ZVD:** 150-250 ns pulse output **when zero-voltage switching (ZVS)** is achieved.
  - The drain voltage can be monitored through voltage sensing circuit. In combination with the gate signal, the OC pin can be configured to different digital outputs:
  - For CrM/TcM PFC, the feature can simplify control to achieve ZVS and **eliminate the sensing circuits** (e.g. shunt or CT).
  - For synchronous rectification in DC/DC converters, the feature can provide feedback for proper SR control **without additional sensors** (e.g. Rogowski).

Solution	System BOM and Cost	Losses	Delay Consistency
ZVD	Low: integrated in TI GaN	No	good
Rogowski	High: coil, op-amp, comparator	No	requires tuning
Shunt	High: shunt, op-amp, comparator	Yes	good



Test results for ZVD pulse

- ZVD output when zero-voltage switching is detected
  - At 500 kHz switching frequency, the device can achieve ZVS. The OC pin outputs a digital pulse, and the rising edge of the pulse occurs shortly after the IN pin signal change.
  - When the switching frequency is increased to 1.3 MHz, the device lost ZVS, and there is no digital pulse output.

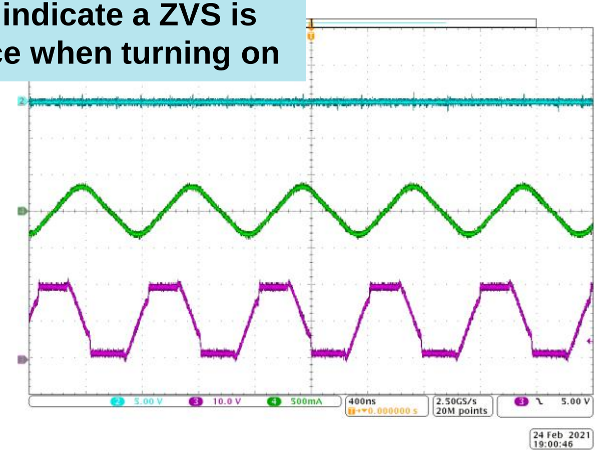
ZVS pulse: used to indicate a ZVS is achieved in the device when turning on

Low-Side Option1 Pulse Signal (5V/div)

I_L (1 A/div)

V_{ds} (10 V/div)

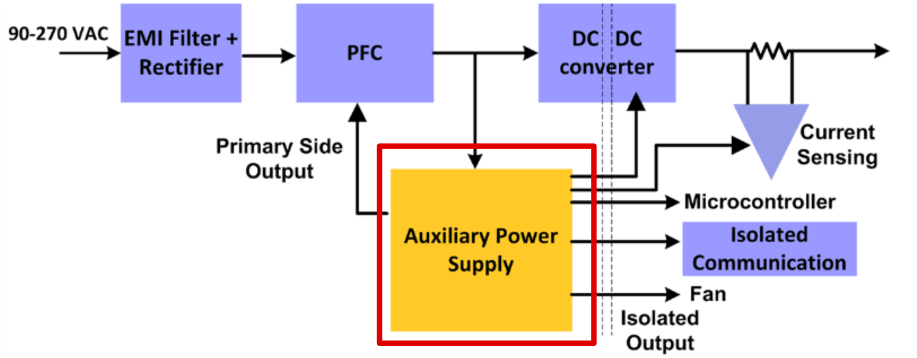
20 V and 500 kHz



20 V and 1.3 MHz

Server auxiliary application

- Power level: 5 W – 60 W
- Input voltage: PFC bus 390 V – 400 V
- Output voltage: 12 V – 20 V
- Function: Provide isolated power for control electronics, voltage and sensing electronics, fans, and additional bias supplies.
- Priority – Cost, efficiency + power density



Texas Instruments

Why we should care about auxiliary power supply

- All kW-server PSUs have an auxiliary power supply

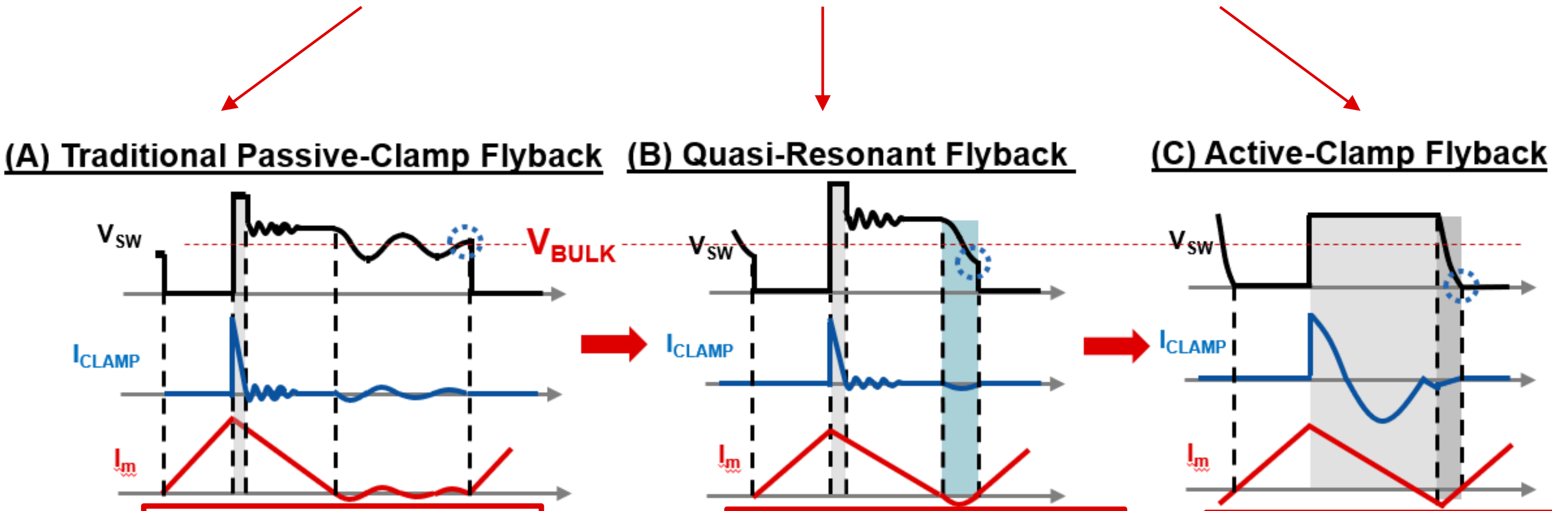
- Energy savings are critical in Titanium Grade (> 96.2%) server PSUs

- Small-form-factors required in CRPS server PSUs

- Existing solutions mostly use Silicon FET, diode, operate with fixed frequency
  - Currently achieve ~ 85-88% efficiency
  - For 45 W Aux PSU- > up to **3 Watts power saving** for 93% efficiency improvement

Seven solutions analyzed in this comparison study

45-W, 12-V DC/DC flyback converter



1. Si + Diode
2. Si + SR FET

3. Si + Diode
4. Si + SR FET
5. GaN + Diode
6. GaN + SR FET

7. GaN + SR FET

Specifications used in a comparison study

Application parameters:

- $P = 45\ W$
- $V_{in} = 400\ V$
- $V_{out} = 12\ V$

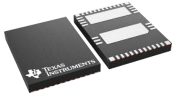
Design parameters:

- $N_{PS} = 8$
- $f_{sw} = 150\ kHz$
- $L_M = 250\ \mu H$

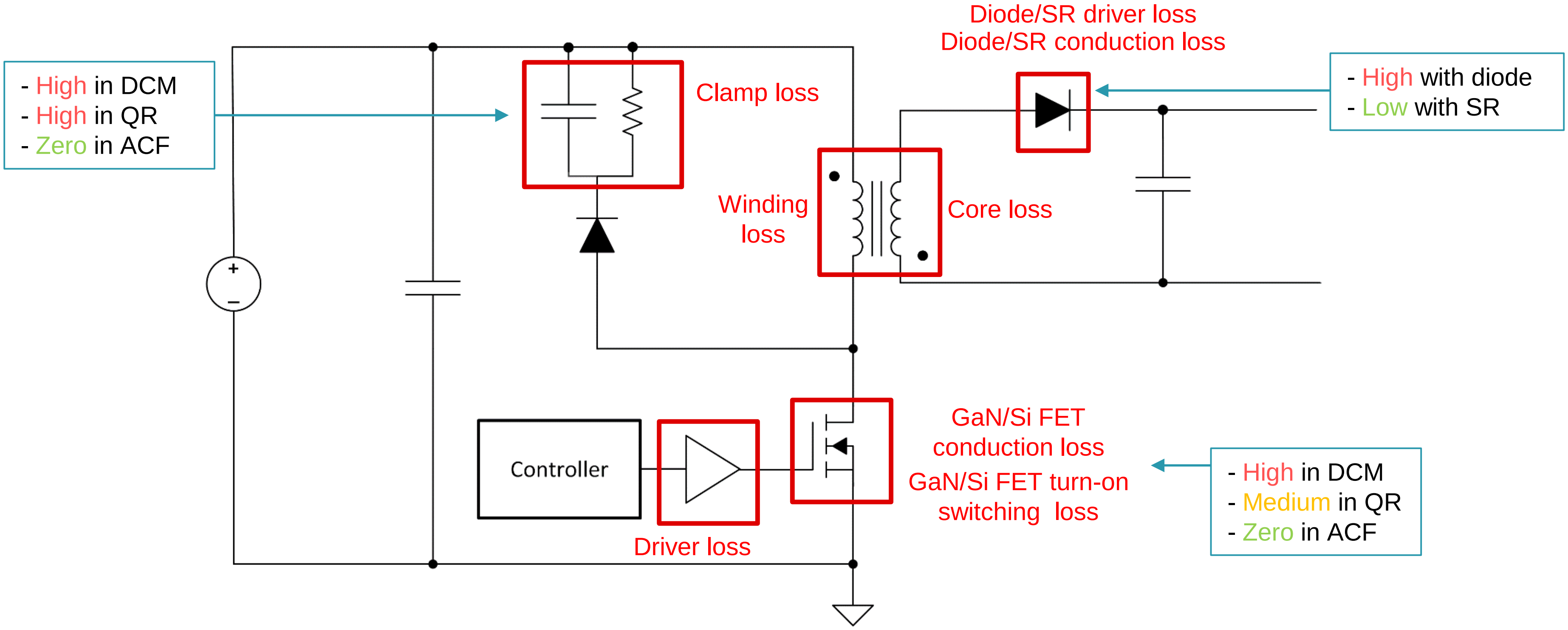
Pri FET: < 520V plateau
SR/Diode: < 100 V

Standardize size and switching frequency

Power devices used in the comparison

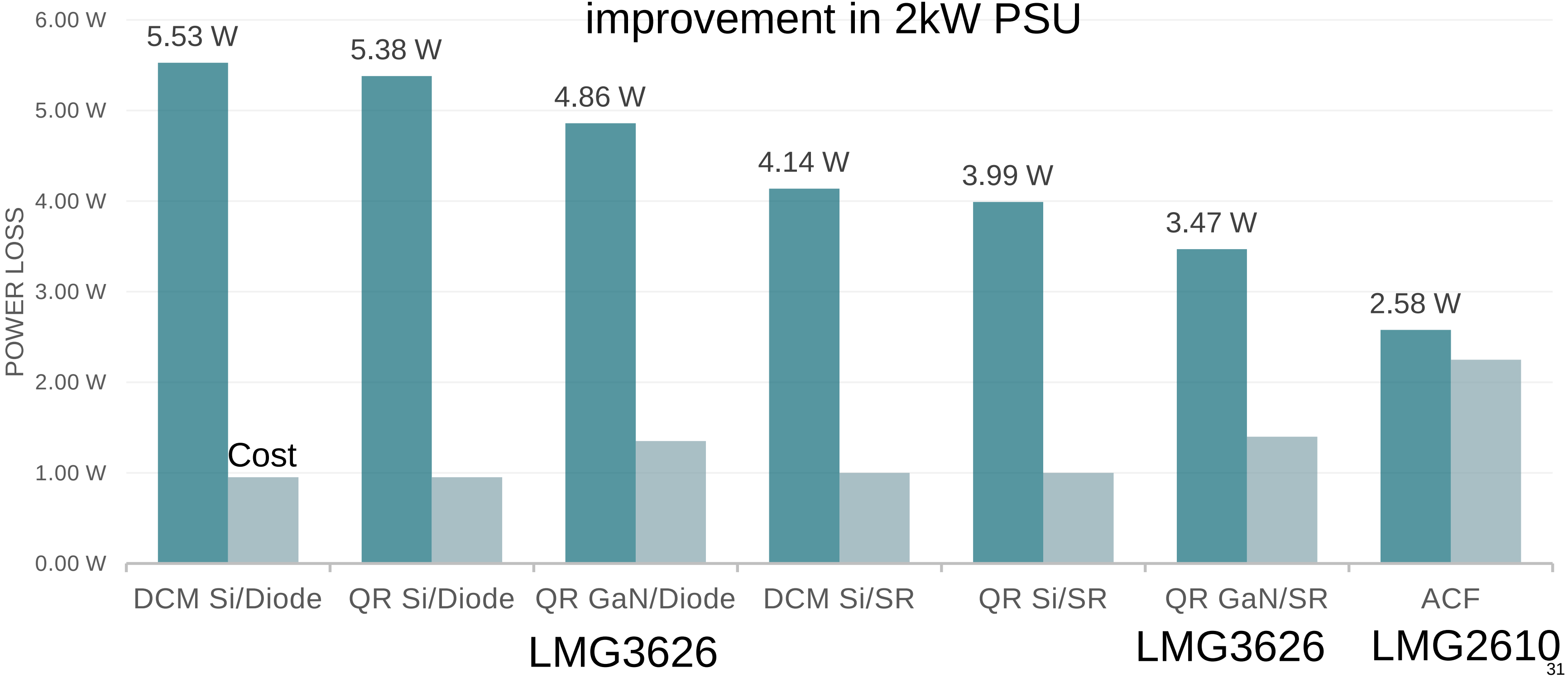
	Traditional DCM	QR	ACF
Pri. FET (Si or GaN)	450mΩ Si CoolMOS 	450mΩ Si CoolMOS  vs. TI GaN LMG3626 	TI GaN LMG2610 
Sec. Rectifier (Diode or SR)	Si Schottky Diode  vs. TI 15mΩ Si FET 	Si Schottky Diode  vs. TI 15mΩ Si FET 	TI 15mΩ Si FET 

Main sources of loss in the DC/DC flyback converter



Power loss and cost comparison

1 W of power loss savings -> 0.1% Half-load efficiency improvement in 2kW PSU



Value of LMG3626 and LMG2610

- **LMG3626** QR Flyback vs. Si/Diode DCM Flyback:

QR GaN/SR	
$\Delta P_{loss,tot}$	- 2.07 W
ΔEff	+ 3.80 %
$\Delta P_{loss,turn-on}$	- 0.52 W
$\Delta Cost$	+ $

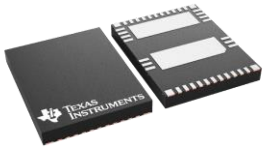
→

QR **GaN**/SR	
$\Delta P_{loss,tot}$	- 2.07 W
ΔEff	+ 3.80 %
$\Delta P_{loss,turn-on}$	- 0.52 W
$\Delta Cost$	+ $

If f_{sw} increased to 300 kHz:

→ $\Delta P_{loss,turn-on}$ = -1.02 W

- **LMG2610** ACF vs. Si/Diode DCM Flyback



→

ACF **GaN**/SR	
ΔP_{loss}	- 2.95 W
ΔEff	+ 5.50 %
$\Delta P_{loss,turn-on}$	- 0.74 W
$\Delta Cost$	+ $$

If f_{sw} increased to 300 kHz:

→ $\Delta P_{loss,turn-on}$ = -1.48 W

PMP23146 45-W server auxiliary power GaN ACF reference design

Features

- Maximum output Power: 45W/12V (400VDCin)
- **Power Density:** $60\ \mathbf{W/in^3}$
- **Peak Efficiency: > 92%**
- EQ20/I planar transformer
- Active Clamp Flyback(ACF) with LMG2610, UCC28782
- Single auxiliary output
- Operating frequency: **400KHz**
- Current sense emulation
- Form factor: 30mm x 35mm x 12mm

Target Applications

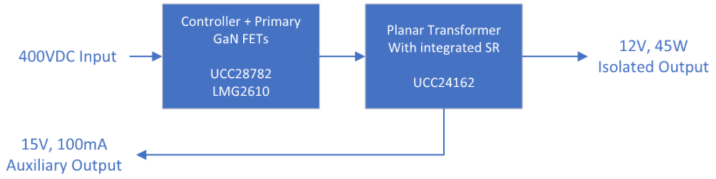
- Auxilary server power for Server PSU and Telecom rectifiers

Tools & Resources

- **Design Files:** Schematics, BOM, Gerber
- **Device Datasheets:**
  – UCC28782 , LMG2610

Benefits

- BOM count reduction through integration of half-bridge, bootstrap diode, and level shifter
- Current sense emulation: reduces conduction losses in shunt resistor
- Highest power density and efficiency with capability for switching frequency up to 1 MHz
- High power density enabled by GaN switching using a planar transformer



Please join our live Q&A