TEXAS INSTRUMENTS

TI *Live!* INDIA AUTOMOTIVE SEMINAR

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AEC-Q100 GaN: FUTURE FOR ON-BOARD CHARGING AND HIGH-VOLTAGE DC/DC

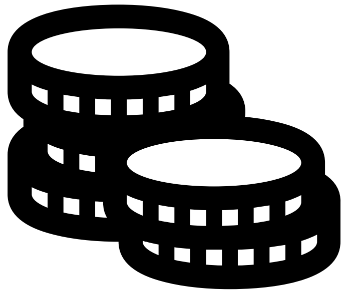
What will we cover?

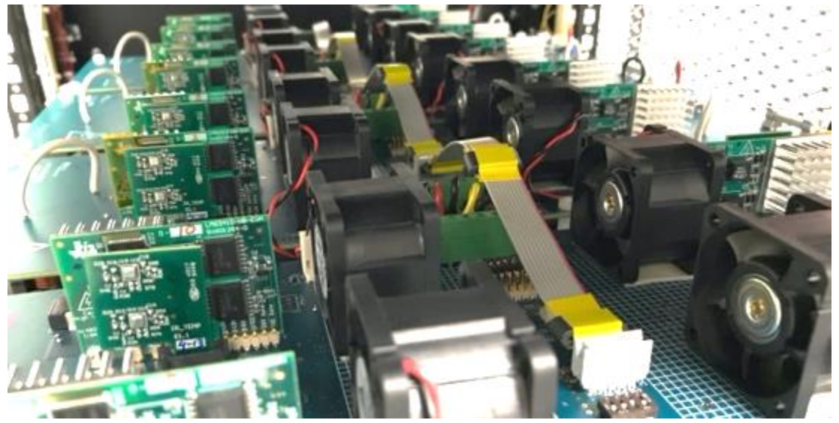
- GaN FET basics
- TI GaN devices
  - Direct drive architecture
  - Automotive qualification
  - Reliability and rigorous testing
- Design tools and reference solutions
  - Resources for top-side, cooled packages
  - 6.6-kW on-board charger (OBC) reference design
  - Design concepts for 22 kW and 800 V

HEV/EV trends OBC & high-voltage DC/DC

High power density	Lower cost	Fast time-to-market	Reliability

1-2 kW/Liter ➔ 3-5 kW/Liter





Higher operating frequencies → Smaller magnetics
Smaller magnetics → Size, cost, weight reductions

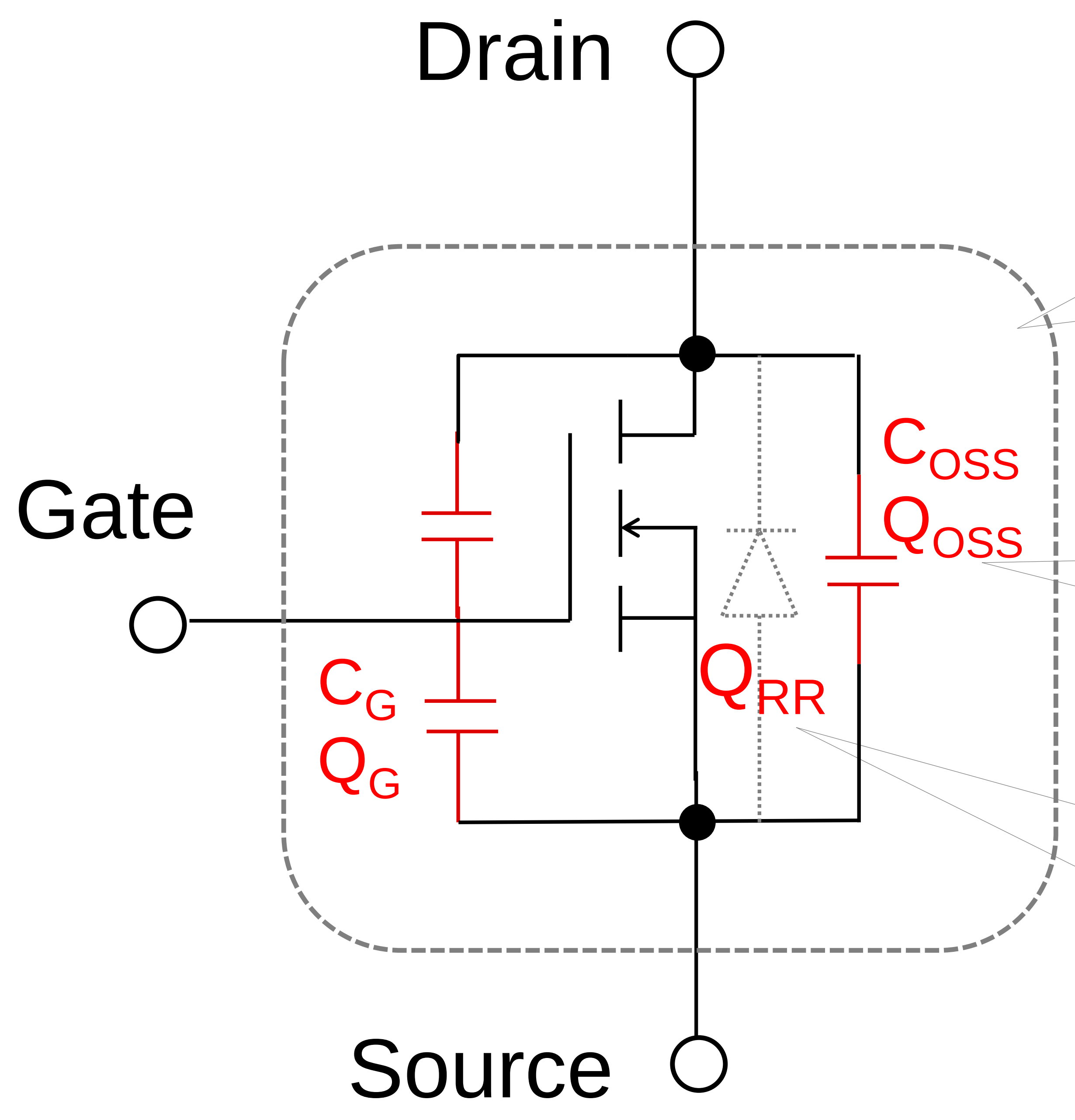
New challenges for system-level design

- **On-board charger:** Increasing power density, support bidirectional power flow for V2G/V2L, support 800V batteries
- **DC/DC:** Size and cost reductions, redundant designs for ASIL, active monitoring of system thermals and performance

- Solutions that easily scale from **3.3-22 kW, 400-800V** OBCs, while delivering on performance metrics
- Expertise in many different fields: control + power stage + magnetics

- Component level and power supply level reliability
- Confidence for adopting new wide band-gap technologies
- Robust components for higher system reliability

GaN FET basics



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

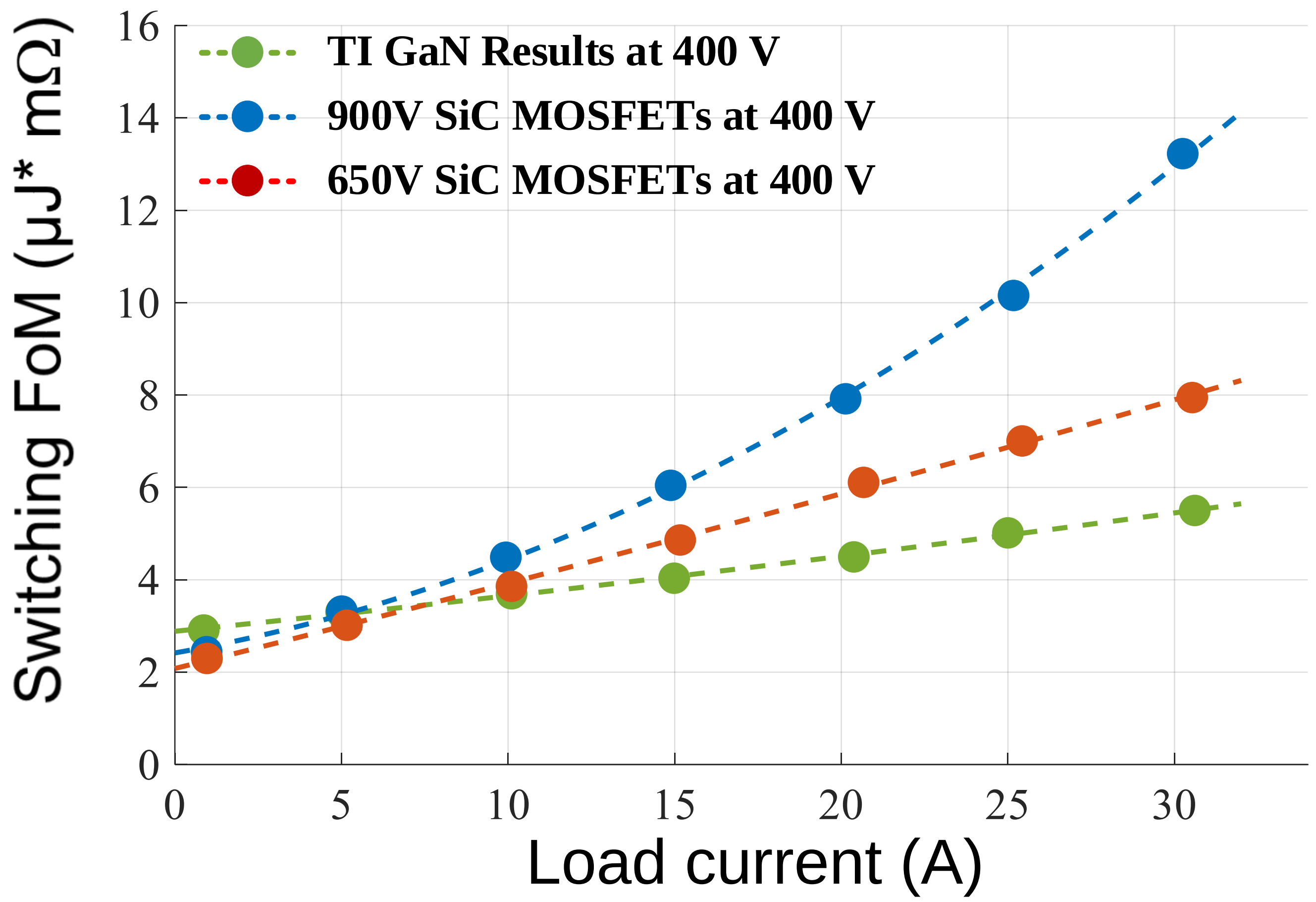
Zero Q_{RR} No ‘body diode’

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

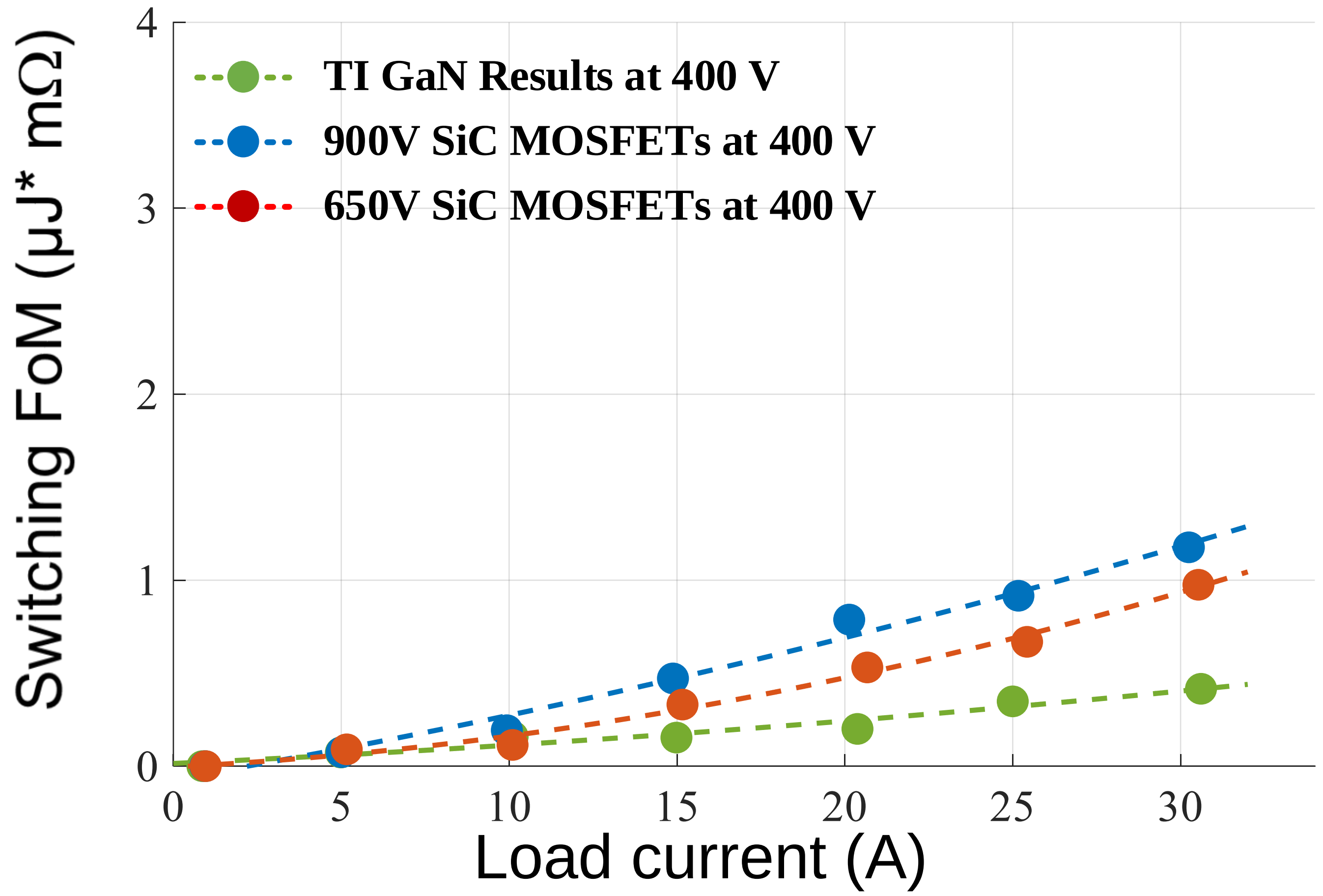
GaN vs SiC: Ideal switching comparison

Figure-of-merit = switching energy (μJ) * $R_{DS,ON}$@125°C (mΩ)

The smaller, the better!

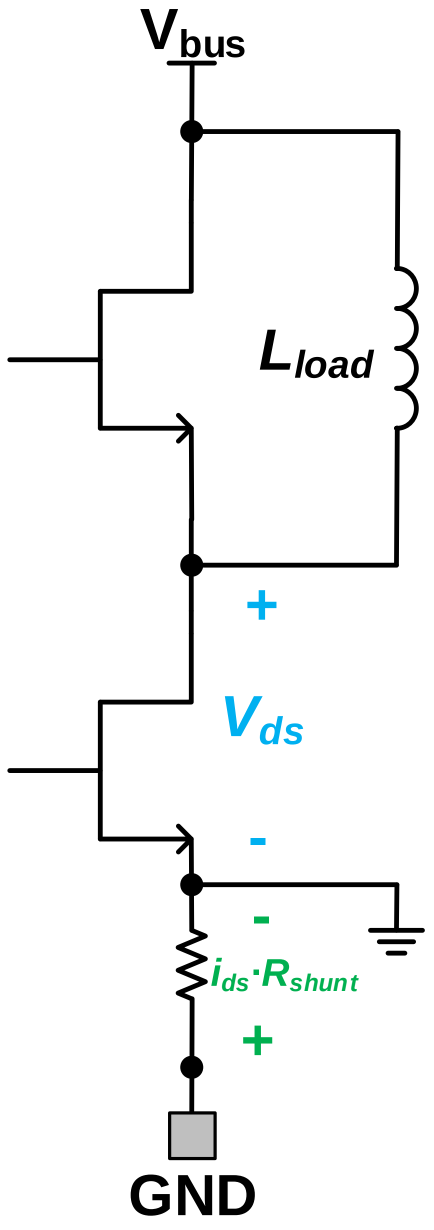


Hard-switching figure-of-merit *(turn-on and turn-off losses, plus Coss & QRR losses)*



Soft-switching figure-of-merit *(turn-off losses only; ZVS at turn-on)*

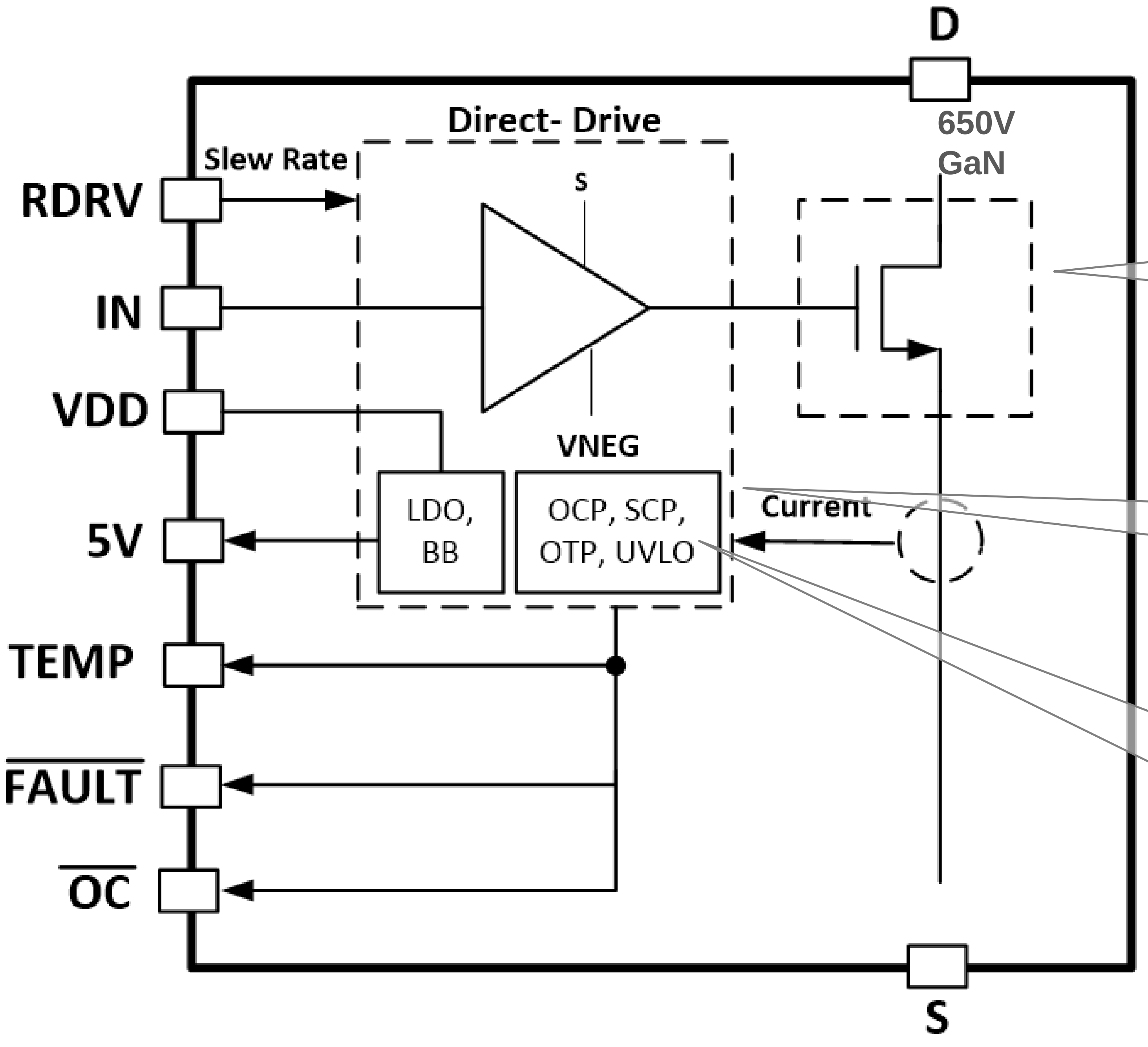
Double pulse test



TI's approach to GaN

Features and reliability

LMG352xR030-Q1 GaN FET with integrated driver, protection & reporting



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

650-V GaN FET **30mΩ**

Integrated **2.2-MHz** gate driver

- Minimizes parasitic inductances (<1nH common source; <4H gate-loop)
- Adjustable slew rate (30 -150 V/ns)

Internal buck-boost and LDO

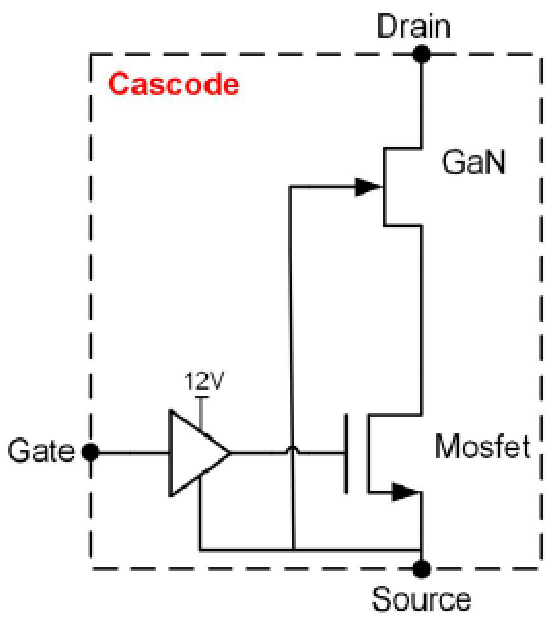
- Support for 7.5-18-V unregulated supply
- 5-V regulated output **for powering digital isolator and peripherals**

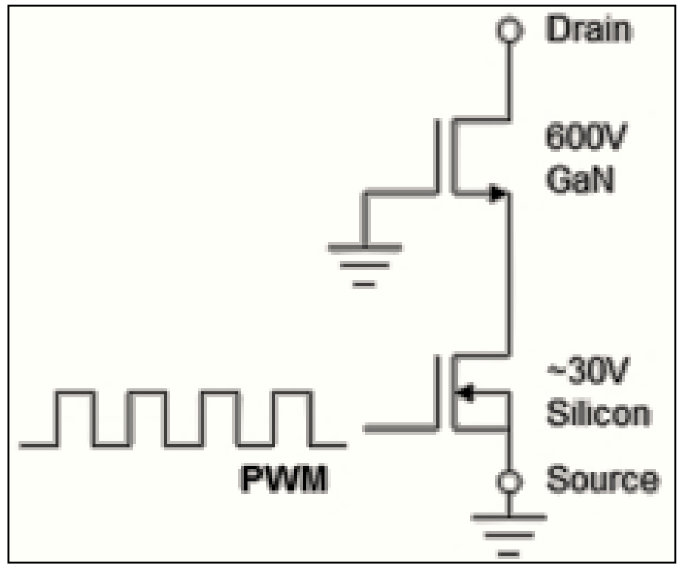
Integrated protection features:

- GaN FET temperature **digital PWM reporting** for active power management
- Over-current (OCP), over-temperature(OTP) and short-circuit protections (SCP)

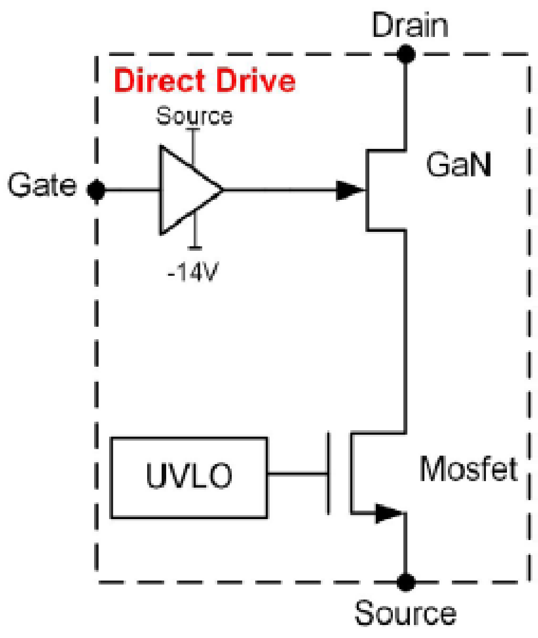
What is direct drive?

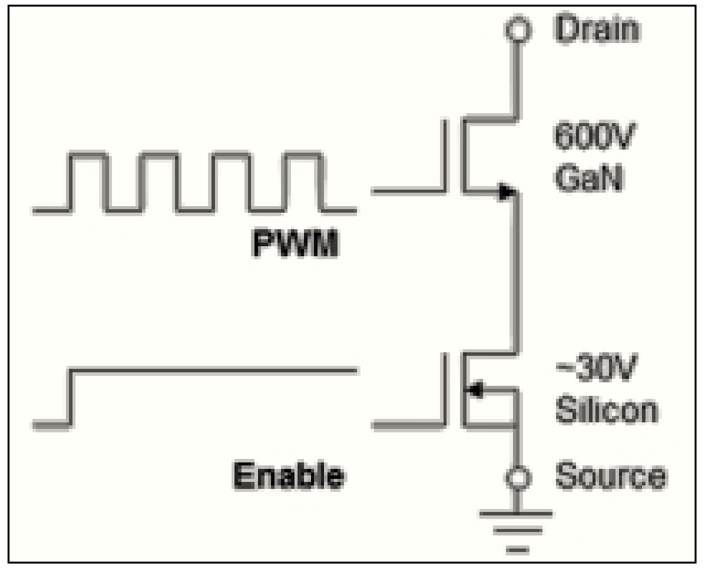
Typical cascode dMode GaN





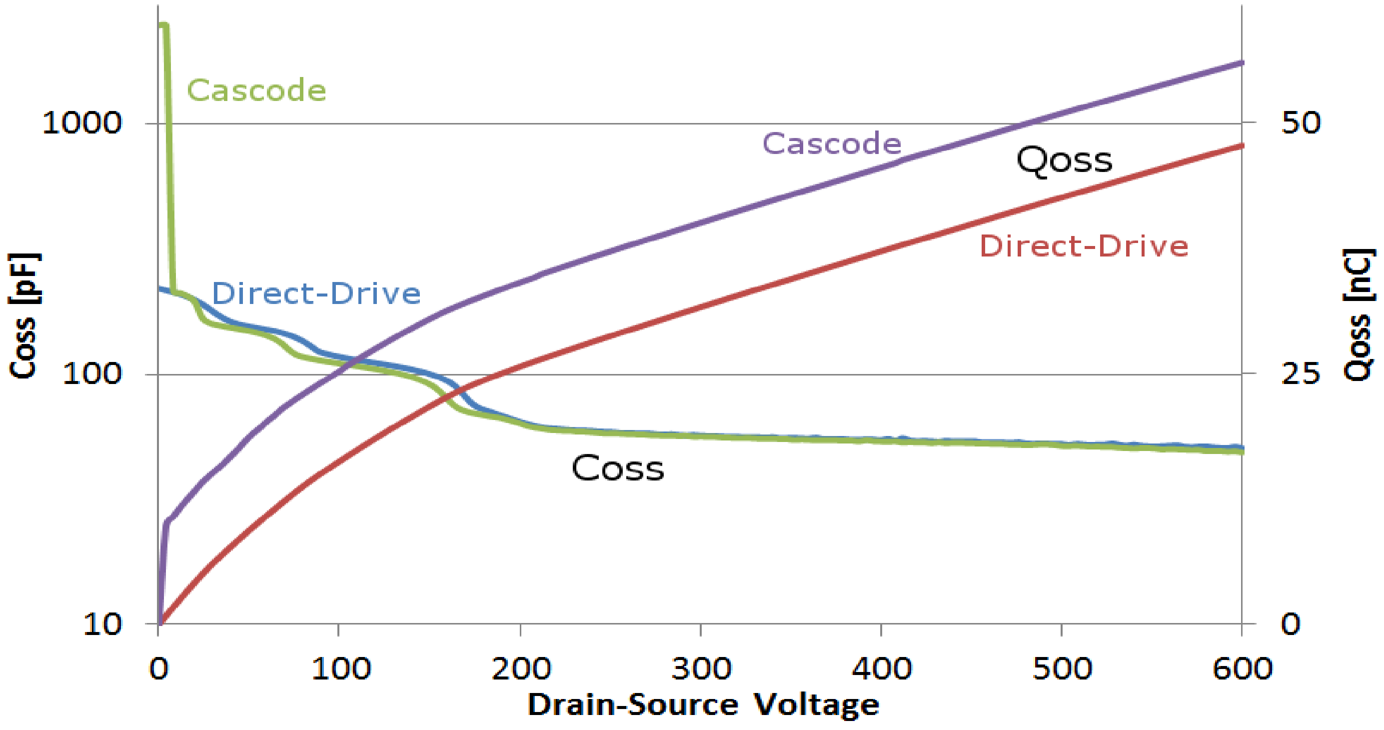
TI direct drive





Cascode **C$_{OSS}$** is sum of **C$_{OSS}$** of silicon FET and **C$_{GS}$** of GaN FET

High **C$_{OSS}$** when **V$_{DS}$** < 10V; high losses if ZVS is not achieved

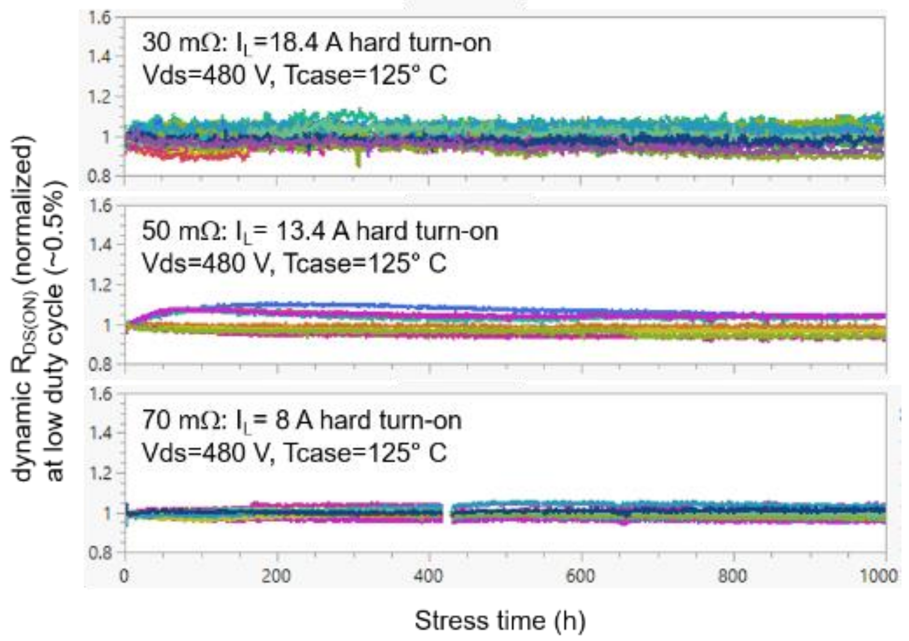


Direct-Drive reduces **Q$_{OSS}$** by at least 20% at 400V operation

Allows **<100ns** dead-time

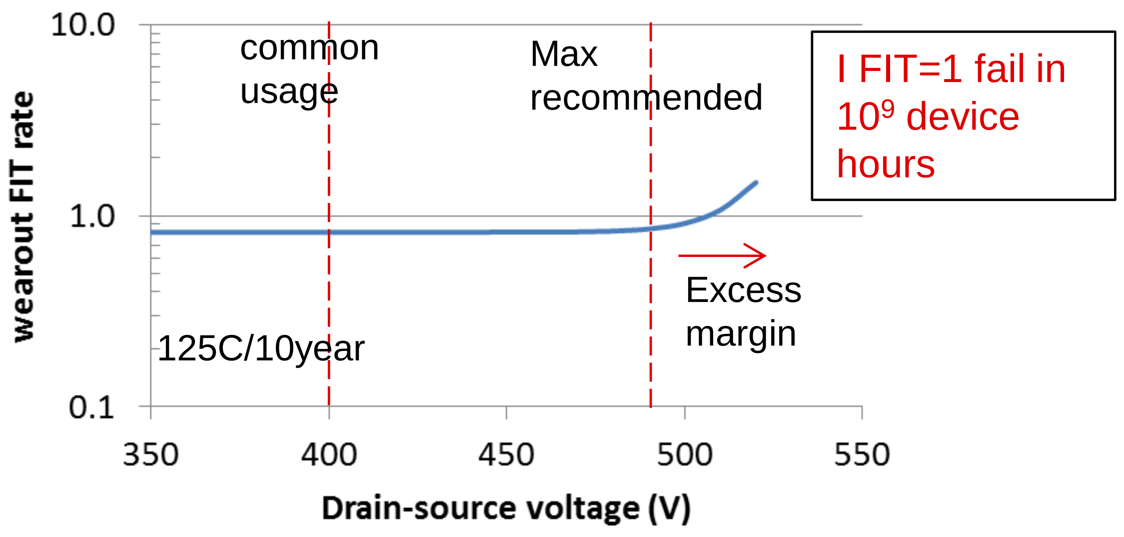
TI GaN qualification & reliability summary

Reliable in power supply



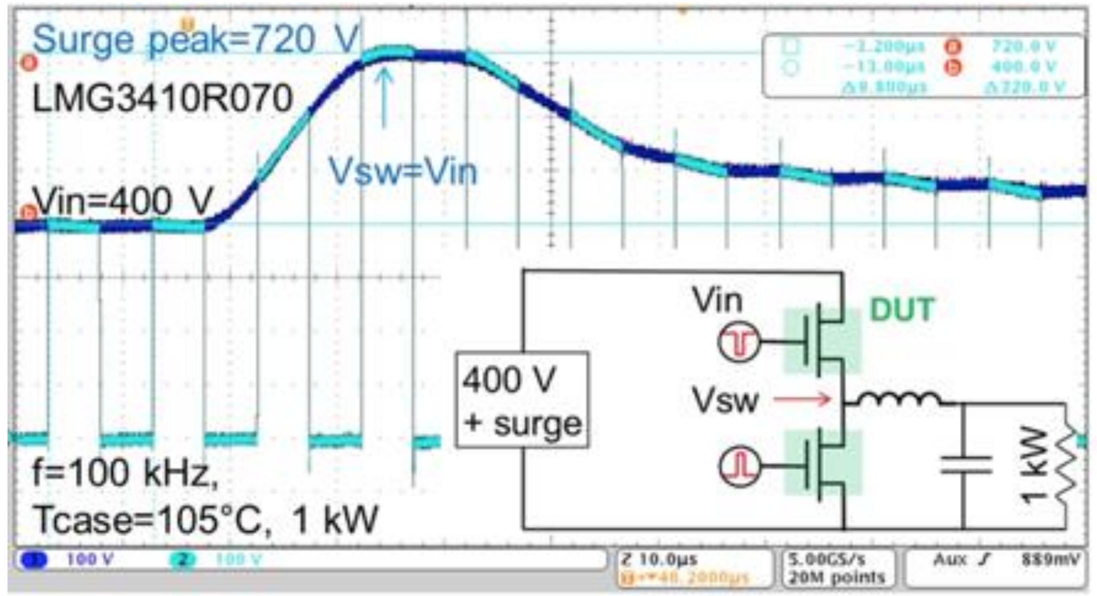
- JESD47, JEP-180 and AEC-Q100 Grade 1 qualification
- Every GaN product qualified inside power supply running at high voltage/current/temp against *charge trapping*

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

LMG352xR030-Q1 automotive qualification strategy

Why AEC-Q100 instead of AEC-Q101?

1. AEC-Q100 Grade 1 qualification for core device function, integrated driver and features
   - i. Leverage TI's expertise with power management ICs with an integrated switch
   - ii. Coverage of early life failure rate (ELFR), latch-up (LU) and NVM power cycling that would otherwise not be included in Q101 qualification

2. Additional testing based on AEC's power MOS qualifications
   - i. HTOL and HAST testing with Vds at recommended max operating voltage
   - ii. Additional testing to max specs of the integrated gate driver on the GaN gate

3. Additional testing at power supply level, based on emerging GaN standards and failure modes
   - i. Dynamic RDS_{on} stability and dynamic HTOL
   - ii. Board-level reliability testing

Designing with GaN

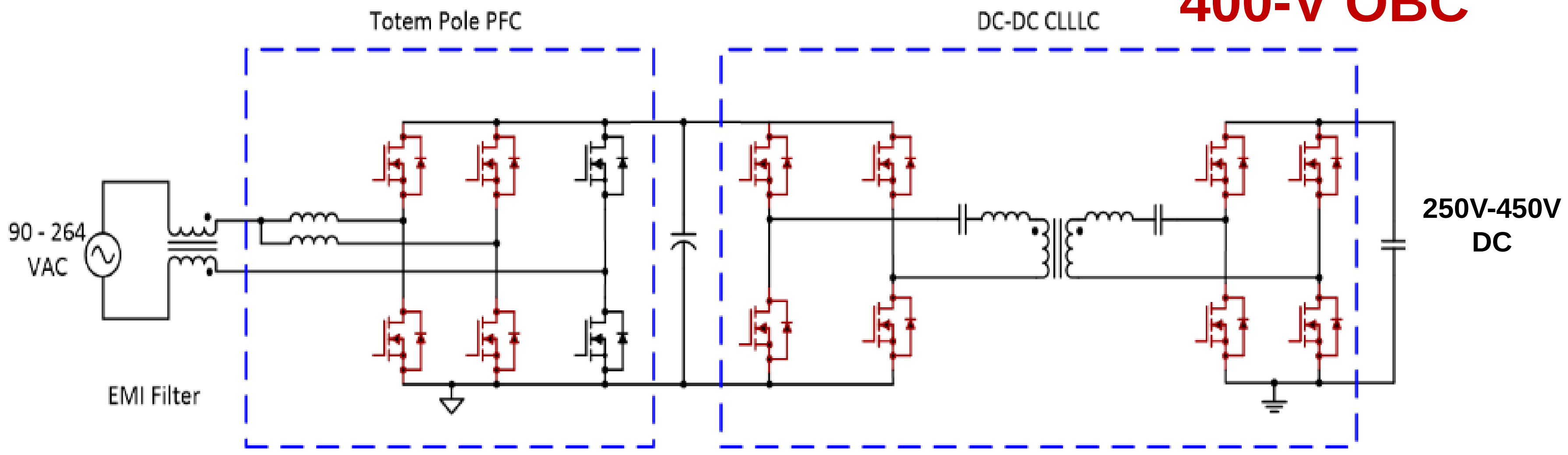
Benefits and reference designs

TI GaN: 6.6-kW, 400-V bi-directional on-board charger

Design Features

- 2-ph interleave PFC + CLLLC with **bi-directional power flow**
- **Single DSP control** for both stages using C2000
- **Multi-mode control algorithm for DC/DC** enables high operating frequency in DC/DC – frequency/phase modulation/burst mode
- **Resonant inductor integrated in transformer** reduces BoM count
- **Coupled inductor** for 2-ph interleave PFC reduces BoM count
- Concept **scalable to 800-V battery OBCs**

400-V OBC



Design Benefits

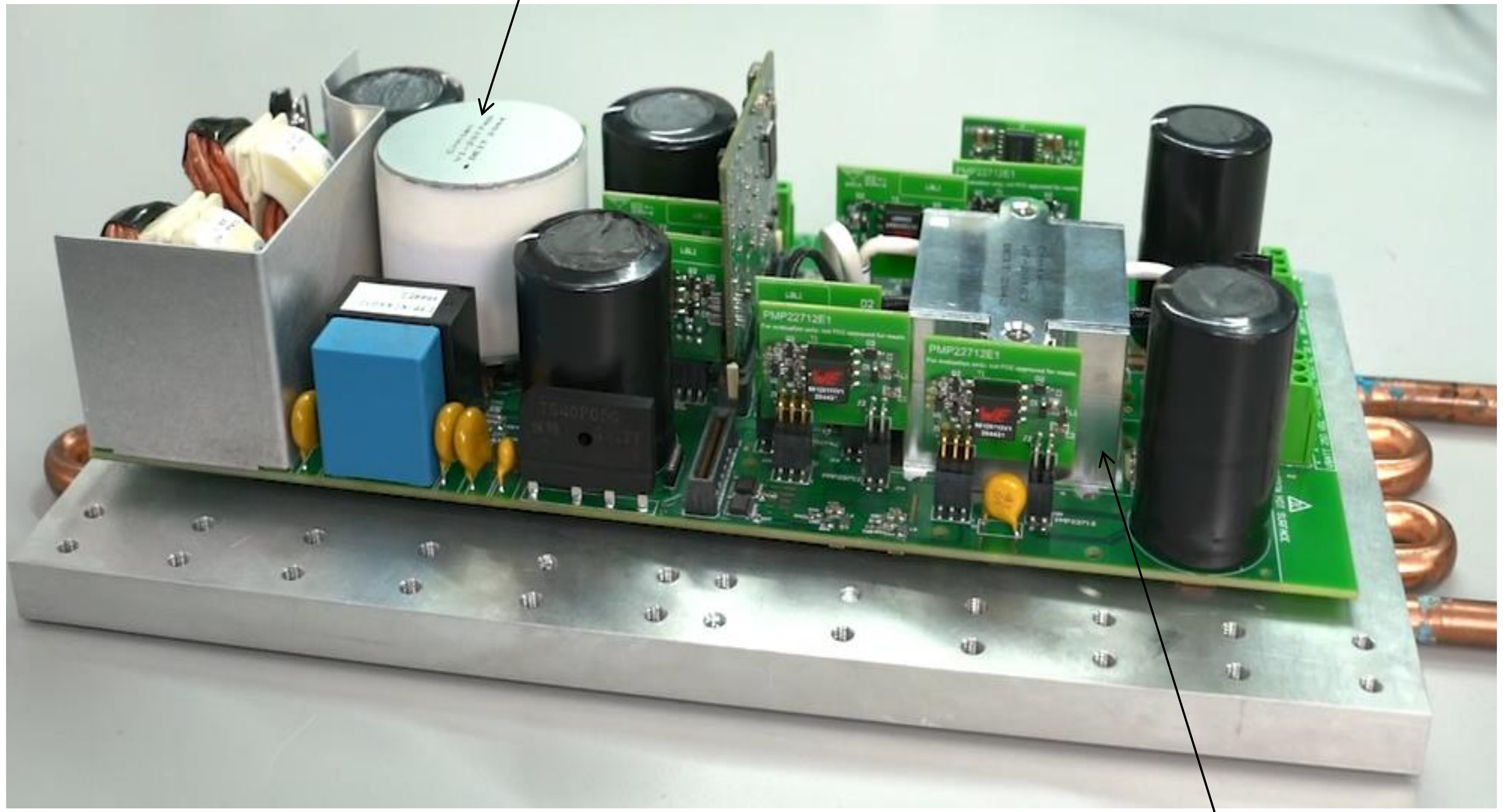
- **59% smaller DC/DC magnetics** offering lower cost vs SiC
- Higher power density vs SiC

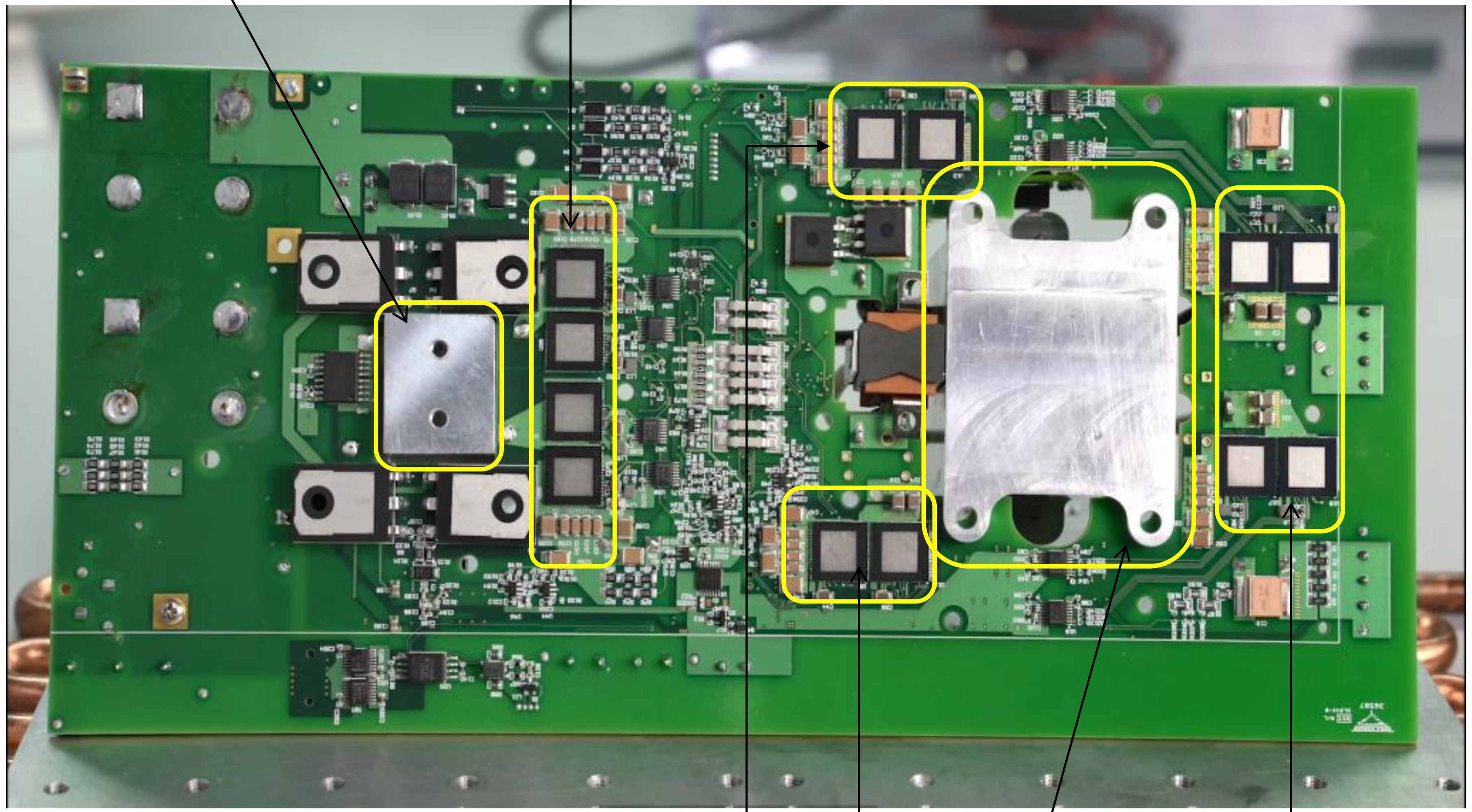
Typical operating conditions		SiC	TI-GaN
PFC switching frequency (kHz)		67	**125**
DC/DC switching frequency (kHz)		148-300	**250-800**
Open frame power density	**(W/in³)**	54	**62.5**
	(kW/liter)	3.3	**3.8**
Efficiency (%)		96.5	**97+**

TI GaN: 6.6-kW, 400-V, bi-directional on-board charger

Coupled inductor
for 2-ph interleave PFC

Totem-pole PFC
GaN FETs



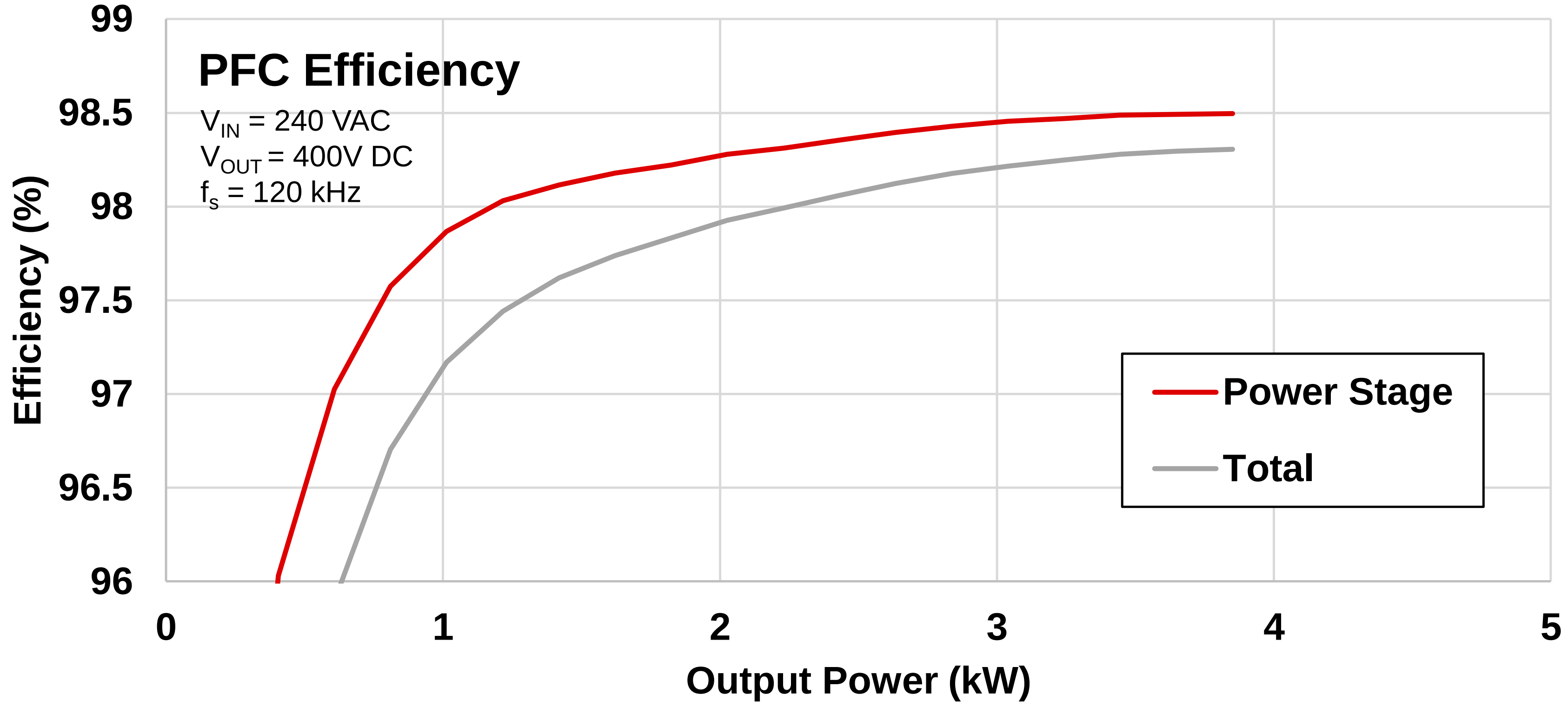


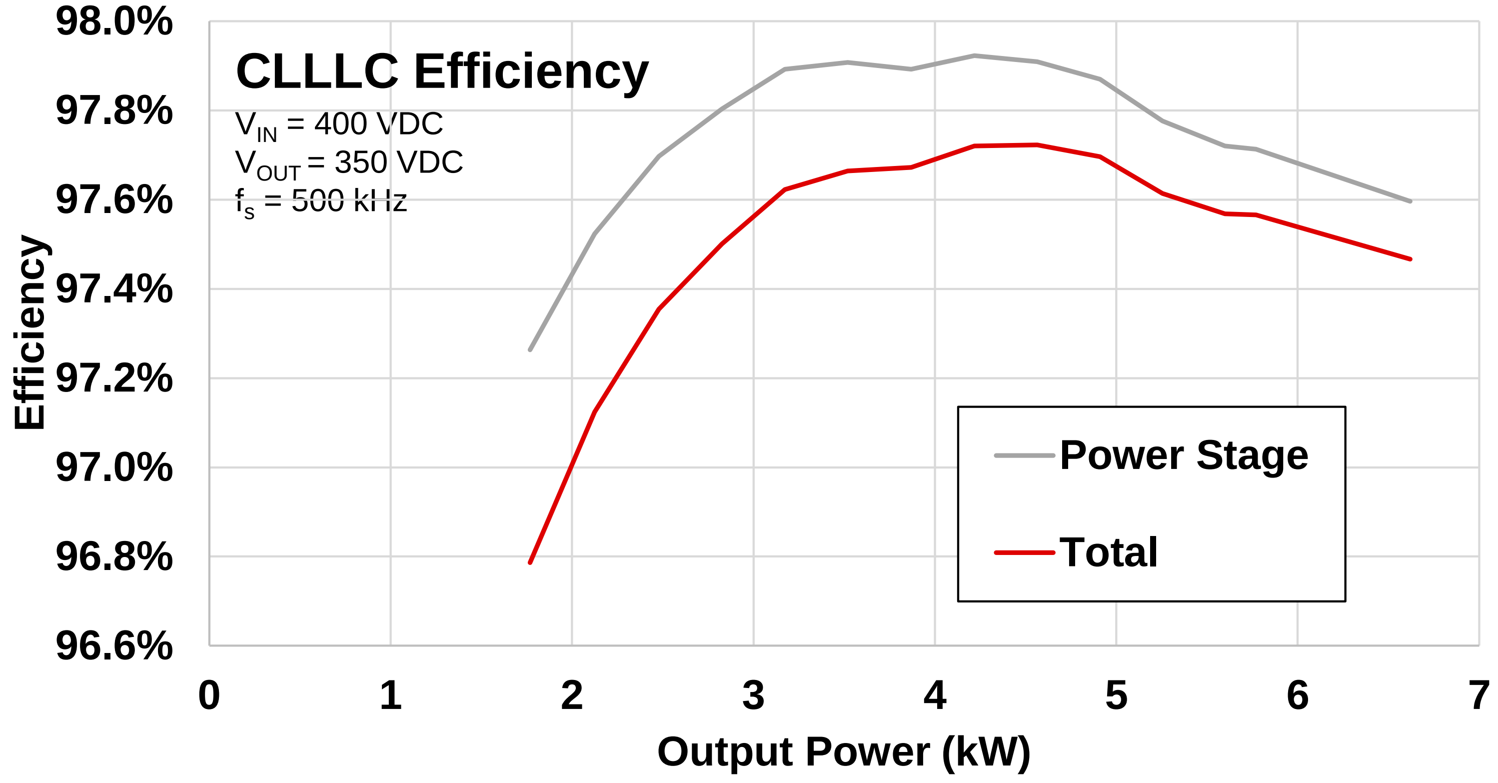
CLLLC GaN FETs (pri)

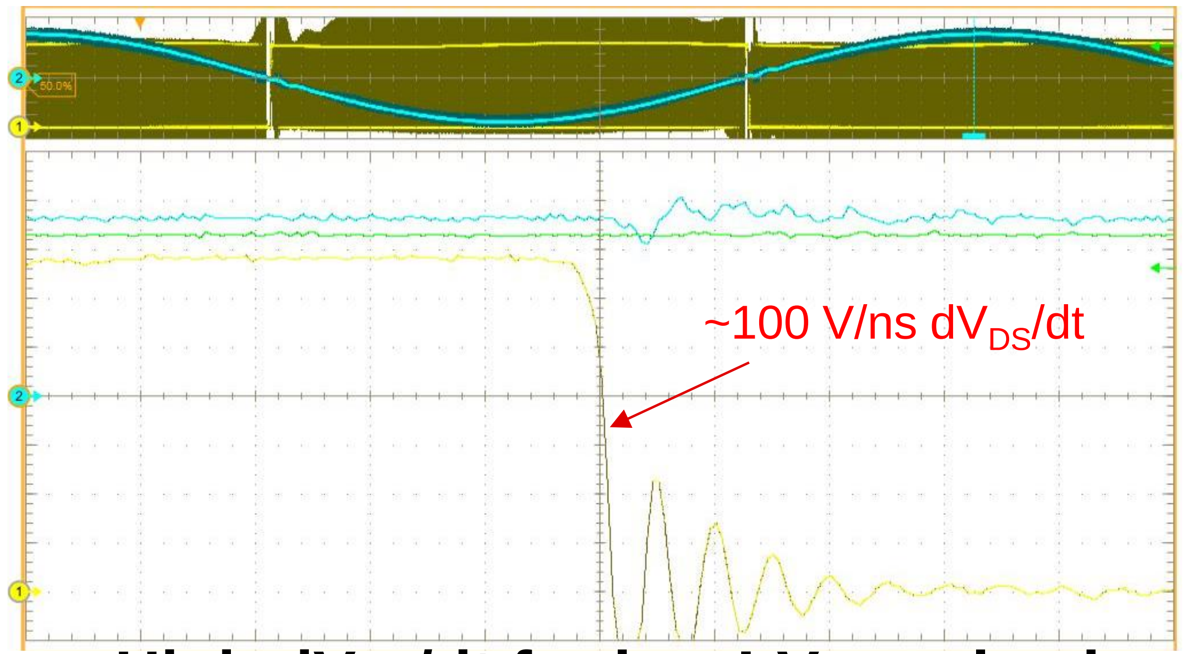
500-kHz CLLLC transformer
with heatsink

CLLLC GaN
FETs (sec)

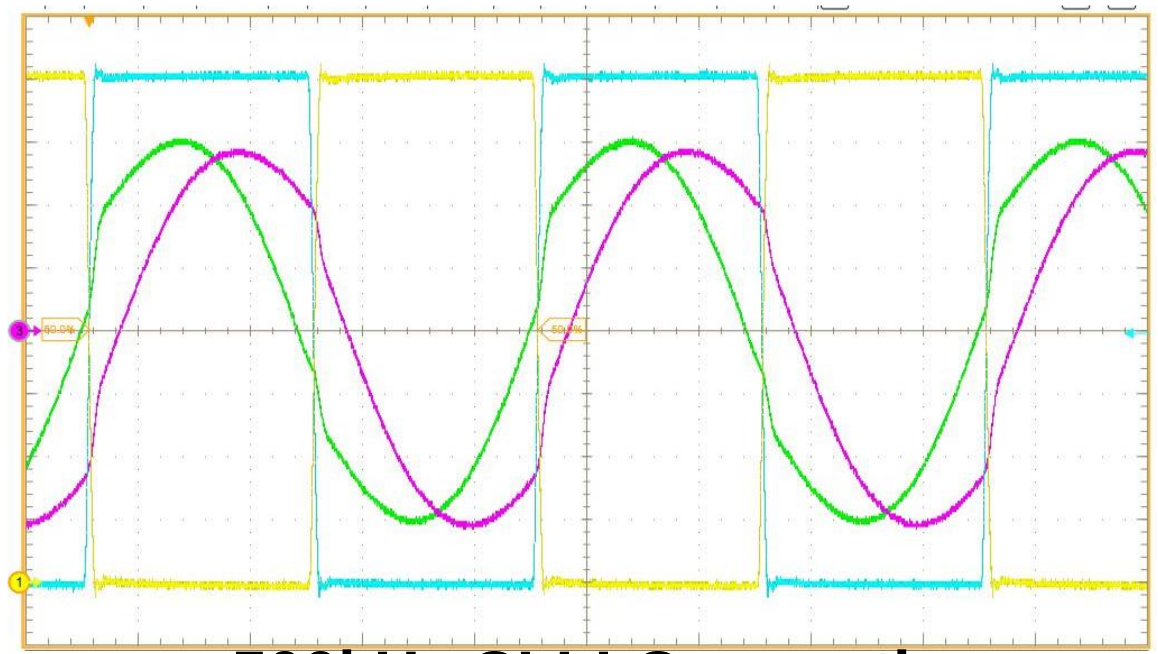
6.6-kW OBC: Test results



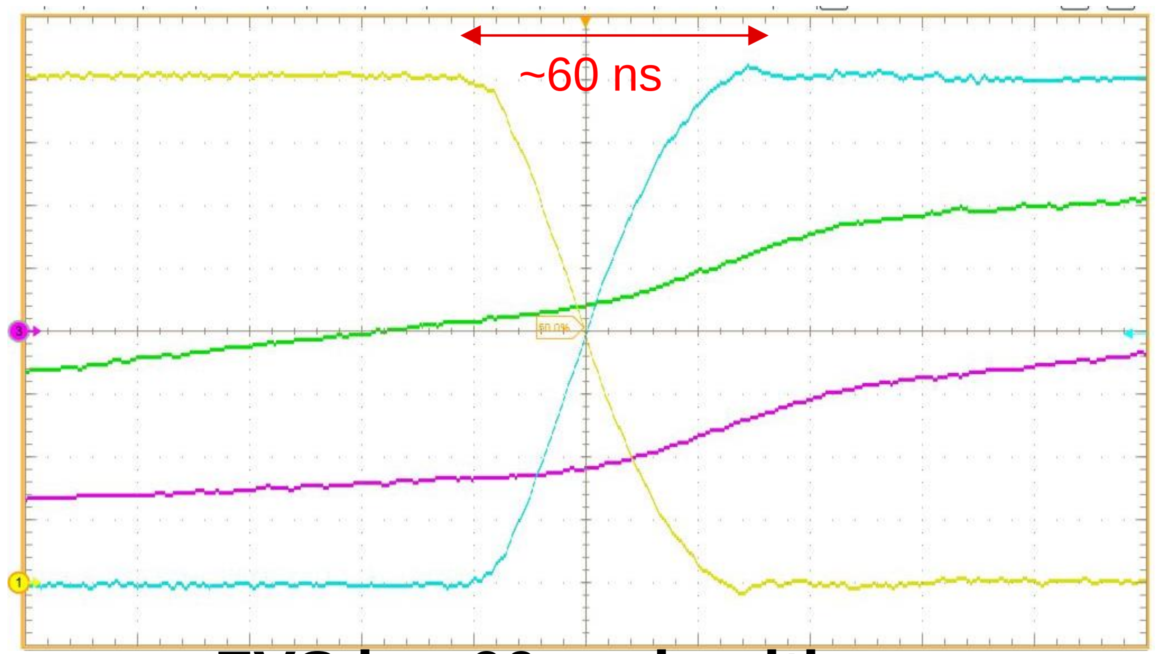




High dV_{DS}/dt for low I-V overlap loss



500kHz CLLLC operation



ZVS in <60ns deadtime

6.6-kW OBC: Test results

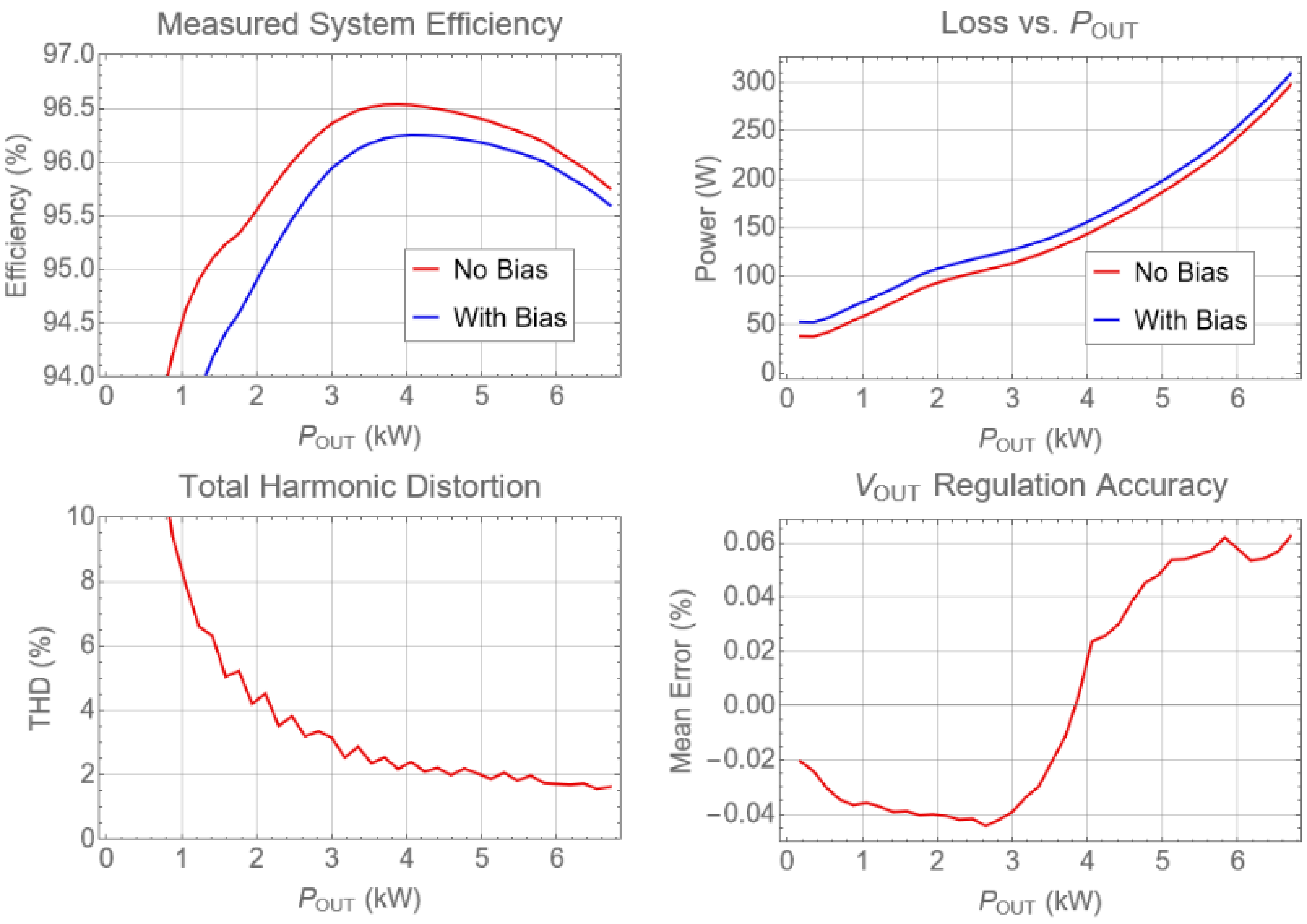


Figure 3-4. System Performance

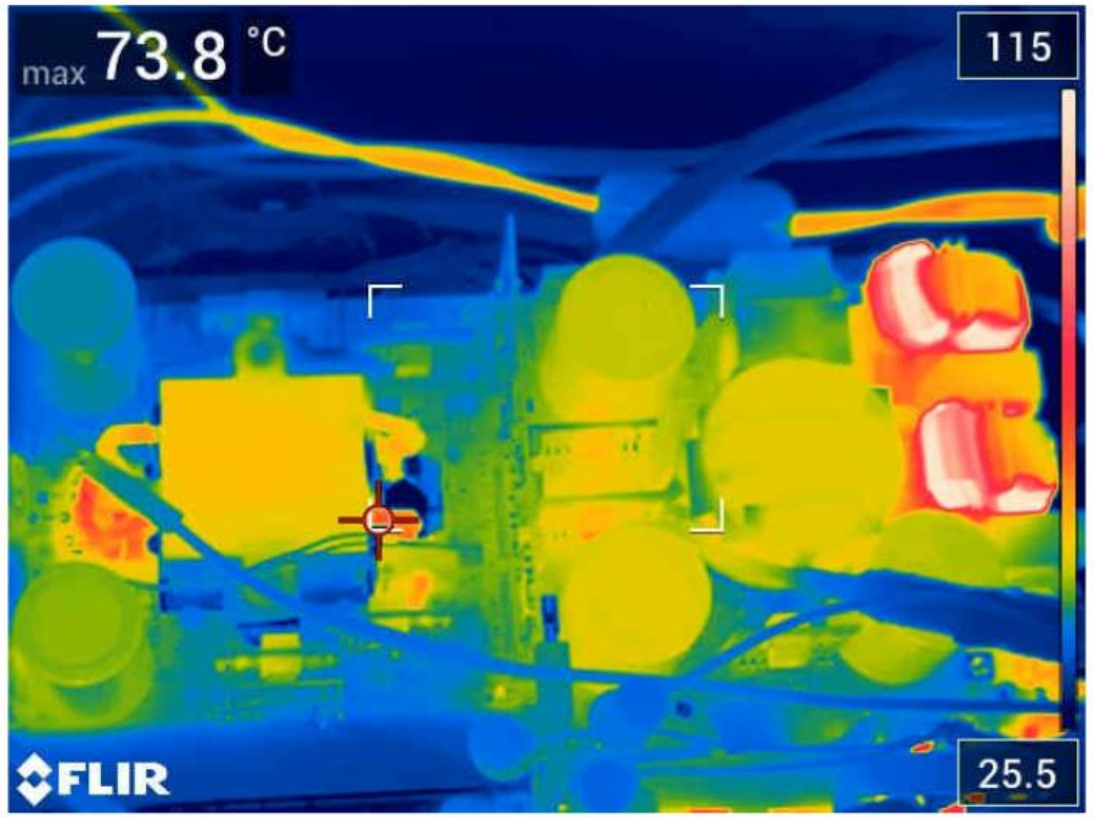


Figure 3-7. Top Side Thermal Image

Search PMP22560 on TI.com for the full test results

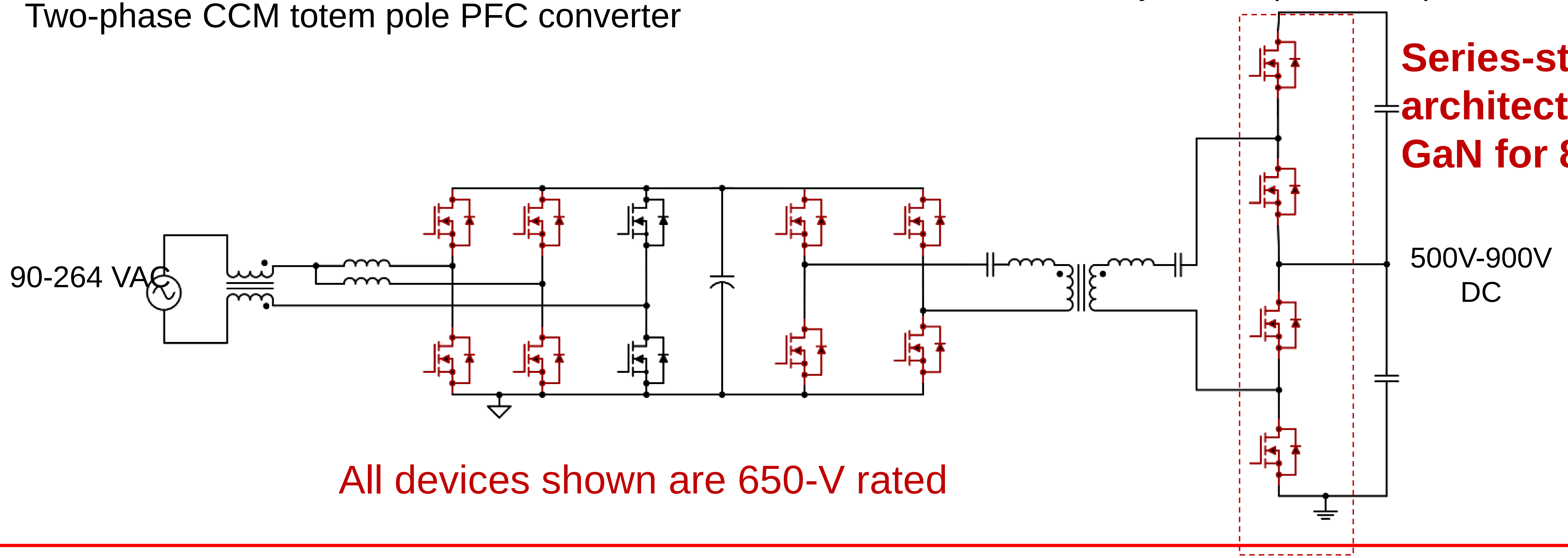
TI GaN: 6.6-kW, 800-V, bi-directional on-board charger

Design features

- Supports **800-V battery** using LMG3522R030-Q1 650-V/30-mΩ GaN FET with integrated driver & protection
- 6.6-kW from single phase AC input
- Utilize **series stack of GaN FETs** on secondary side of CLLLC DC/DC Converter
  - Concept scalable to three-phase AC input 11-kW/22-kW modular OBCs
- Two-phase CCM totem pole PFC converter

Design benefits

- High power density, low solution cost due to high switching frequency
- >500kHz operation enabled by **superior switching capability of 650-V GaN** (vs 1200-V FETs)
  - Better switching figure-of-merit ($C_{OSS(TR)}$*R_{DS})
  - Zero reverse recovery for GaN FETs
- **Integrated fault protection/reporting for every GaN FET** offers redundancy and simplifies compliance



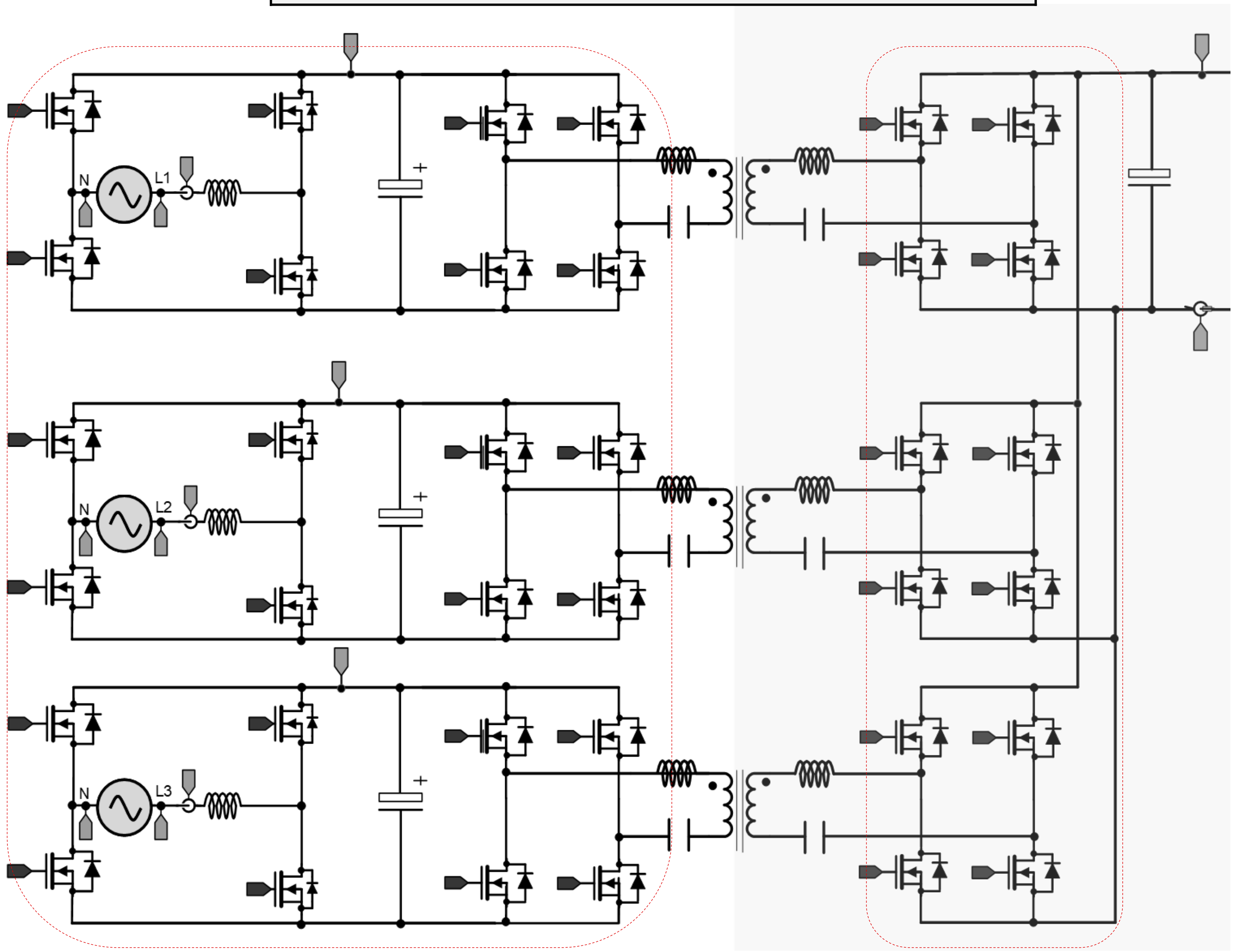
Series-stacked FET architecture using 650-V GaN for 800-V battery

All devices shown are 650-V rated

Building toward three-phase AC, 11/22-kW OBC

Modular OBC

DC Bus voltage / PFC & primary FET
400-450-V DC bus / 650-V FET



PFC & primary side FETs

Secondary side FETs

3x 3.6-kW in parallel = 11-kW OBC

3x 7.2-kW in parallel = 22-kW OBC

Benefits

- Reusable components and effort across one and three-phase designs
- Better light load efficiency by only enabling one 'module' when connected to one-phase AC sources
- Balanced approach for managing transformer thermals and system cost

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