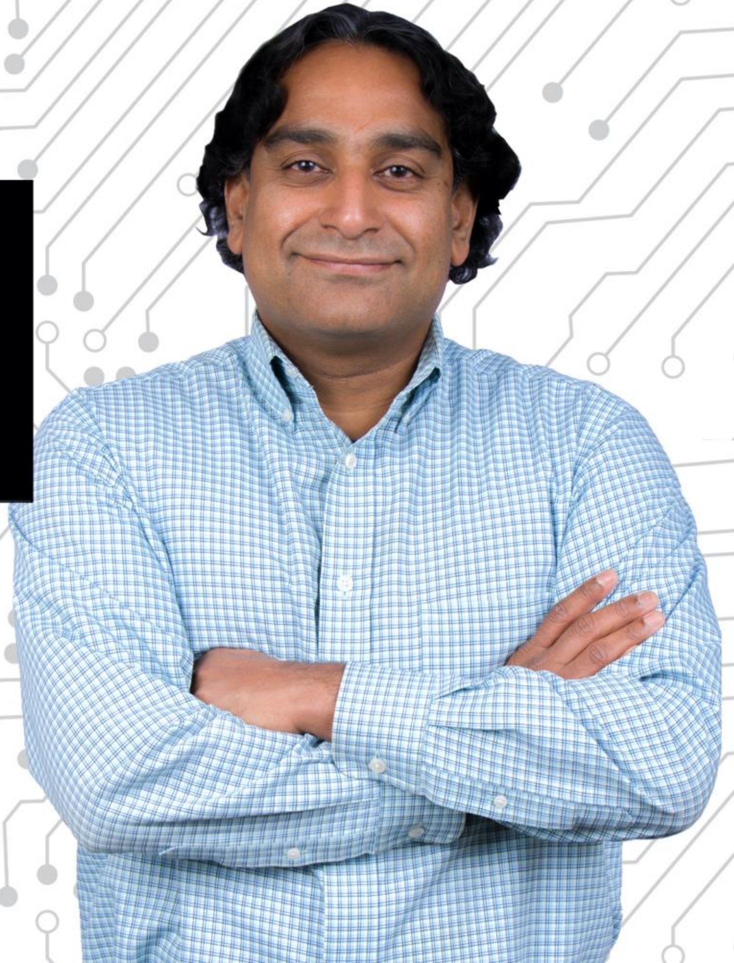
HIGH VOLTAGE SEMINAR

RAMANAN NATARAJAN
GALLIUM NITRIDE

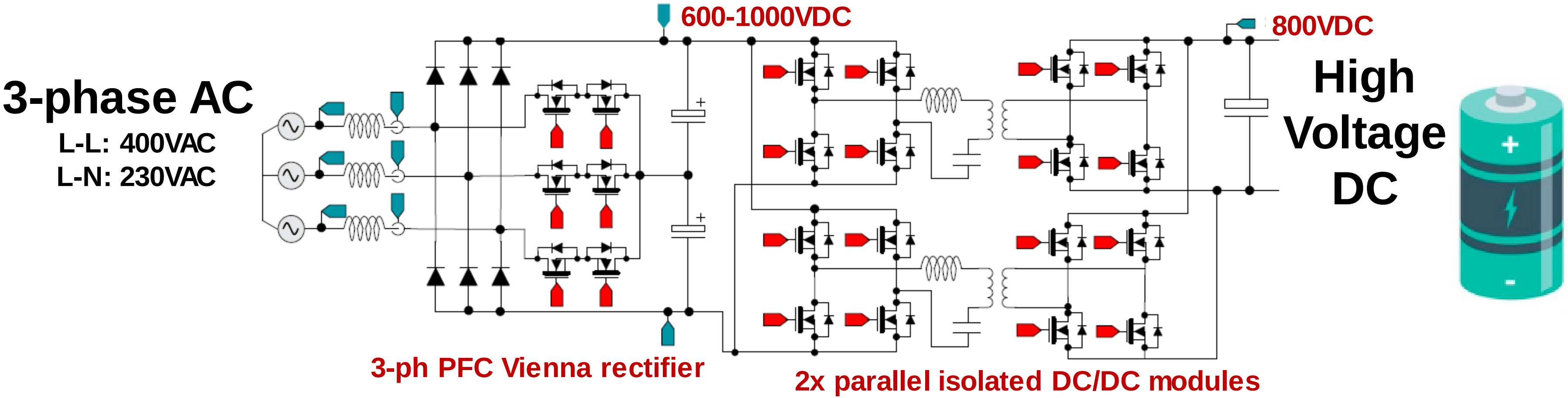
THE BENEFITS OF 650-V GaN FETS FOR 800-V POWER CONVERTERS



Agenda

- Applications driving >800-V DC-link voltages & trends
- The case for 650-V GaN switches
  - Figure-of-merit for switching energy
- Power topologies enabling use of 650-V switches in 800-V converters
  - Stacked half-bridge arrangements
  - Multi-level power converters
- Conclusion

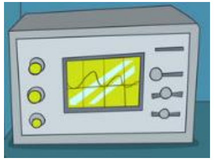
Multi-kilowatt applications with 800-V DC-link



AC/DC battery chargers for energy storage

DC/AC grid tie inverters

Test & measurement equipment (eg. AC sources)



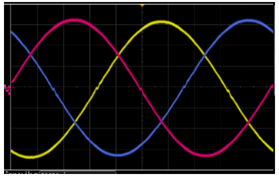
AC/DC onboard chargers, DC/AC vehicle-2-grid inverters, charging stations

Trend for higher operating frequency

- *Shrink the passives* i.e. inductors, transformers, storage capacitors to:
  - Reduce component cost
  - Reduce weight, height for better shock & vibration performance
  - Enable smaller PCB foot-prints
  - Create air-flow pathways for better cooling and higher efficiency
  - Better wave-shaping, lower distortion
  - Allow surface mount technology (SMT) components for automated assembly
- **Lower switching power loss & higher efficiency a pre-requisite for this**


Electric vehicle onboard chargers

- *power 6.6/7.2-kW to 11/22-kW with little-to-no increase in size*
- *density <2-kW/liter to >4-kW/liter*

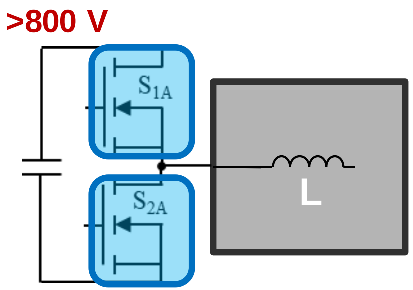
Photovoltaic or battery inverter

- *<1% harmonic distortion*

Do 650-V devices make sense with 800-V DC link?

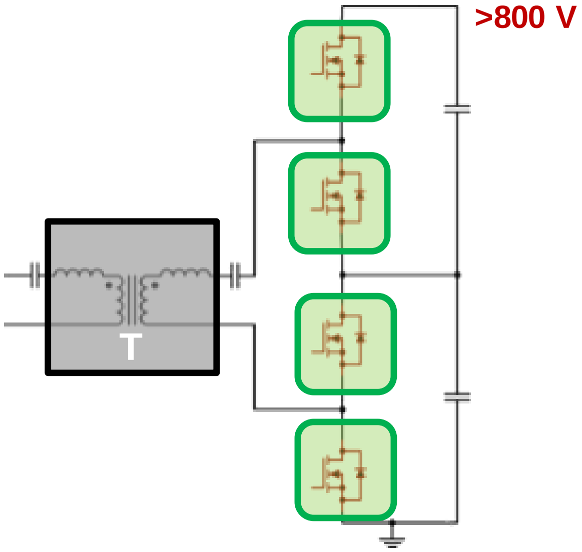
Conventional wisdom

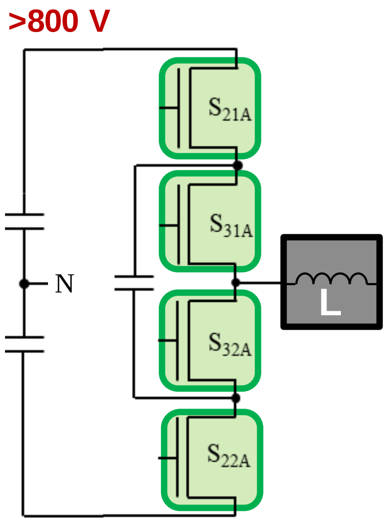
2-level converter



Opportunities to differentiate

stacked 1/2-bridges, multi-level converters

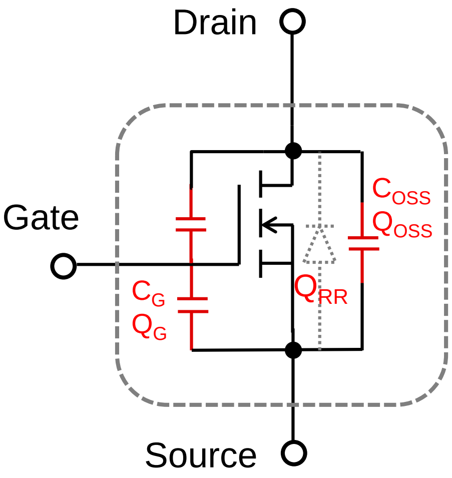




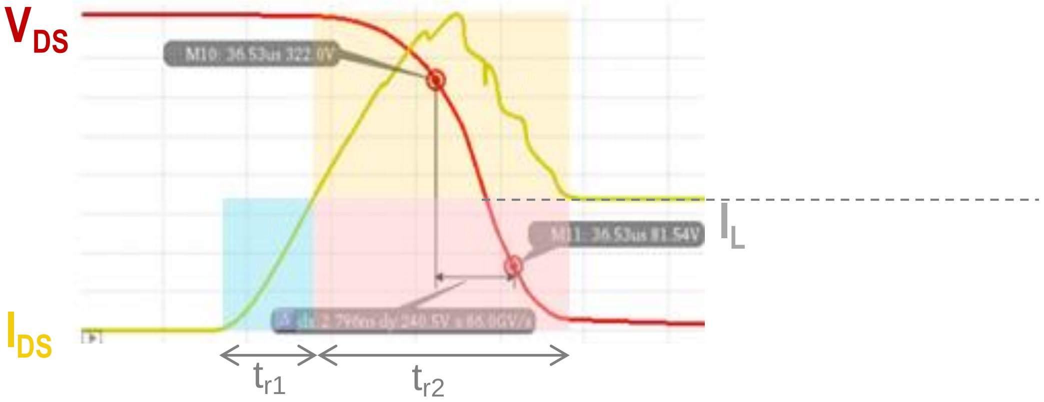
1200-V switches

650-V devices

Power switch attributes influencing switching loss



Energy loss during hard-switching turn-on and turn-off

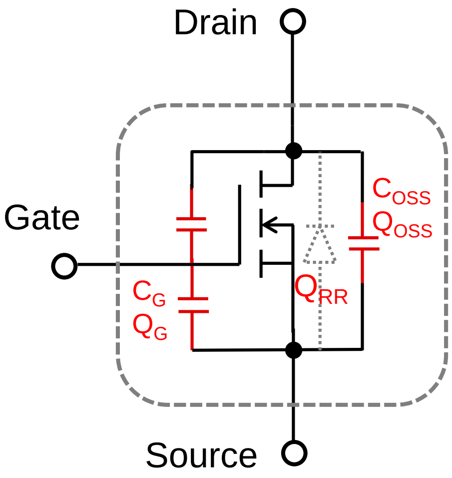


Turn-on dI_{DS}/dt loss $\approx V_{ds} * I_L /2 * t_{r1}$

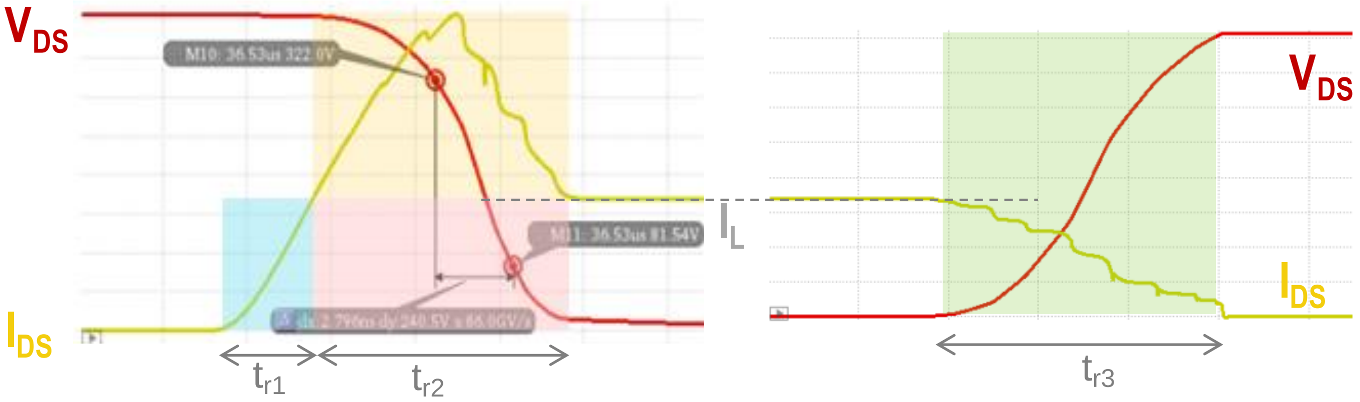
Turn-on dV_{DS}/dt loss $\approx V_{ds}/2 * I_L * t_{r2}$

Turn-on Q_{RR}, C_{OSS} loss $= Q_{OSS*}V_{ds} + Q_{RR} * V_{bus}$

Power switch attributes influencing switching loss



Energy loss during hard-switching turn-on and turn-off



- Overlap losses influenced by *gate-source, gate-drain charge* & gate driver capability

Turn-on dI_{DS}/dt loss $\approx V_{ds} * I_L /2 * t_{r1}$

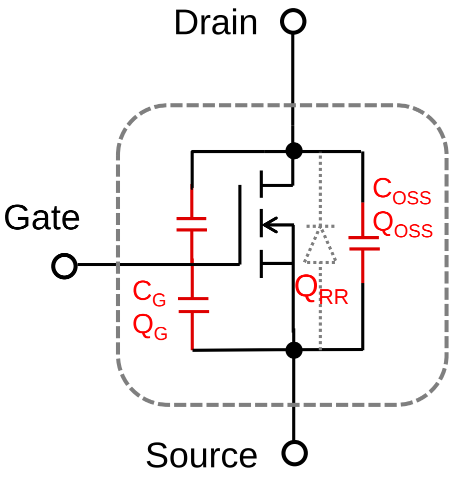
Turn-on dV_{DS}/dt loss $\approx V_{ds}/2 * I_L * t_{r2}$

Turn-on Q_{RR}, C_{OSS} loss $= Q_{OSS} * V_{ds} + Q_{RR} * V_{bus}$

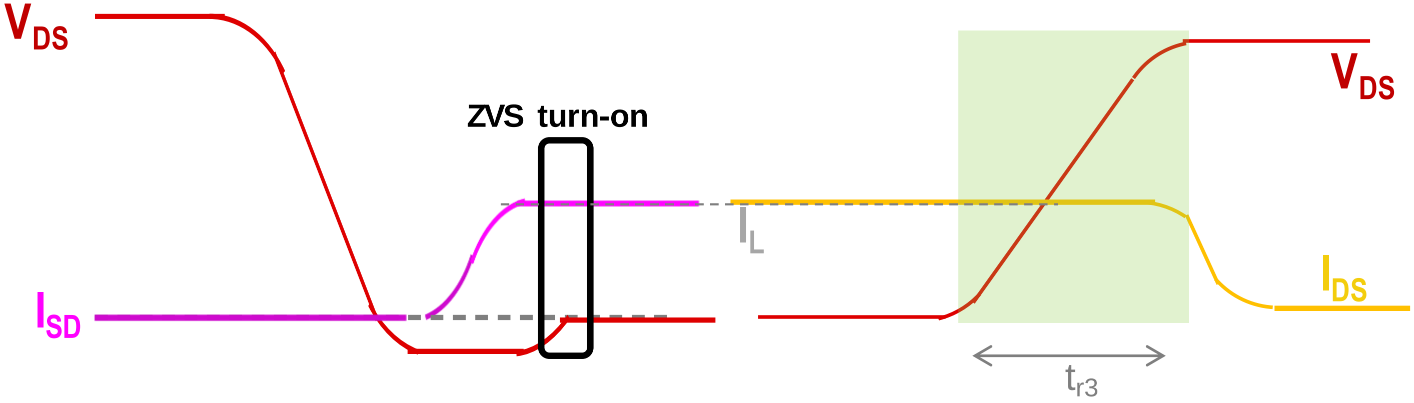
Turn-off $d(I_{DS},V_{DS})/dt$ loss $\approx \int V_{DS}(t) * I_{DS}(t) * dt$

- Other losses related to *device output capacitance and stored reverse recovery charge*

Power switch attributes influencing switching loss



Energy loss during soft-switching turn-on (ZVS) and turn-off



- Overlap losses influenced by *gate-source, gate-drain charge* & gate driver capability

~~Turn-on dI_{DS}/dt loss ≈ V_{ds} * I_L /2 * t_{r1}~~

~~Turn-on dV_{DS}/dt loss ≈ $V_{ds}/2$ * I_L * t_{r2}~~

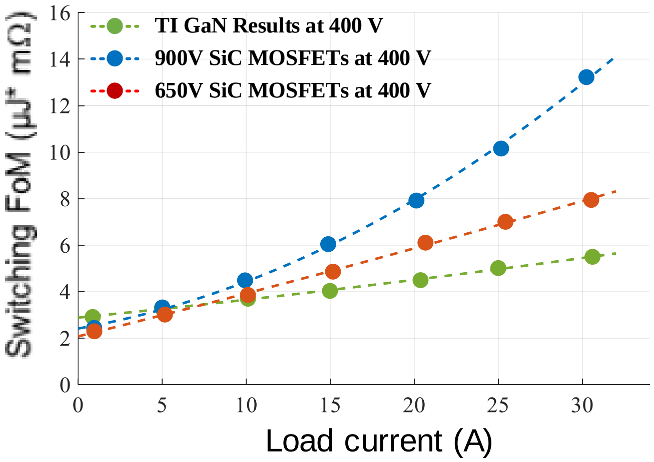
~~Turn-on Q_{RR}, C_{OSS} loss = Q_{OSS}*V_{ds} + Q_{RR} * V_{bus}~~

Turn-off $d(I_{DS},V_{DS})/dt$ loss ≈ $\int V_{DS}(t) * I_{DS}(t) * dt$

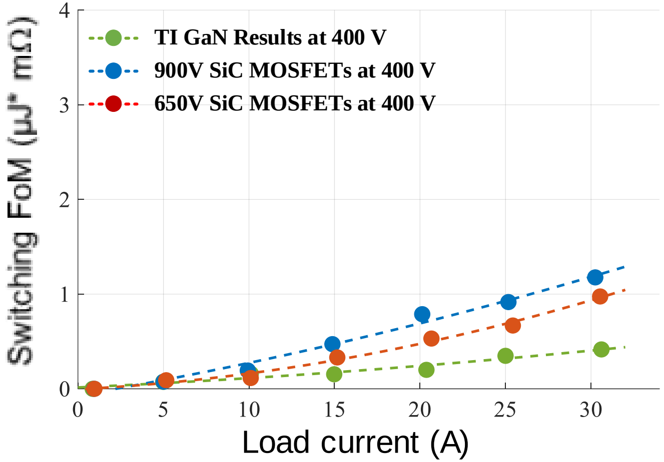
Figure-of-merit for switching energy: GaN excels!

Figure-of-Merit = Switching Energy (µJ) * $R_{DS,ON}$@125°C (mΩ)

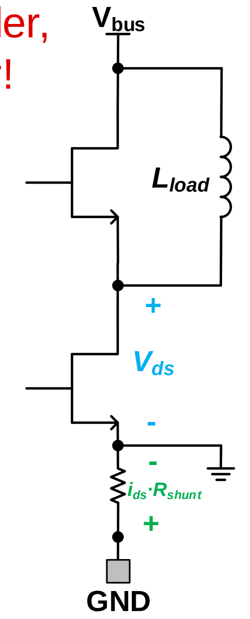
The smaller, the better!



Turn-on Figure-of-Merit *(turn-on and turn-off losses, plus Coss & QRR losses)*



Turn-off Figure-of-Merit *(turn-off losses only; ZVS at turn-on)*



Double Pulse Test

Switching energy loss increases with higher switch voltage rating as expected, since associated device capacitances increase

Figure-of-merit for switching energy: GaN excels!

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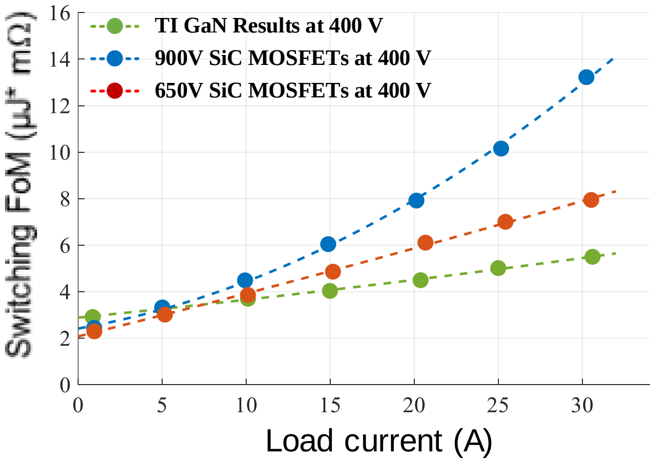
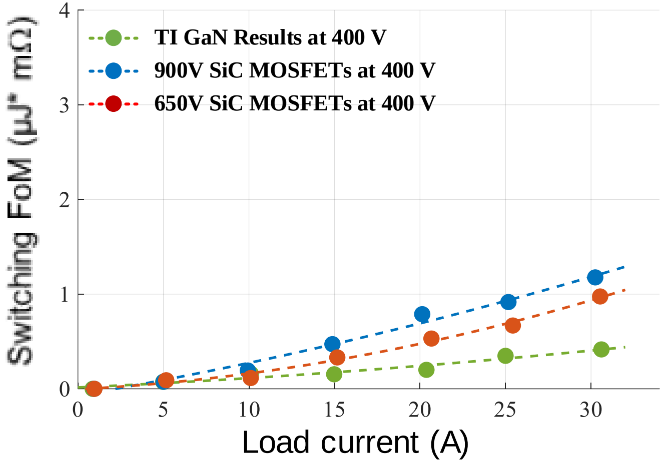
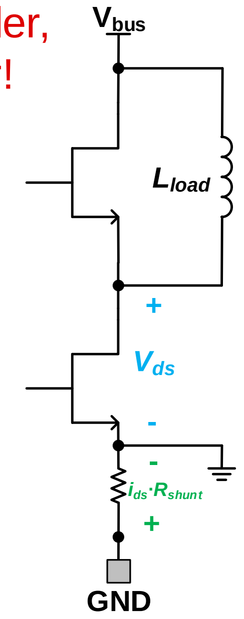


Turn-on Figure-of-Merit *(turn-on and turn-off losses, plus Coss & QRR losses)*



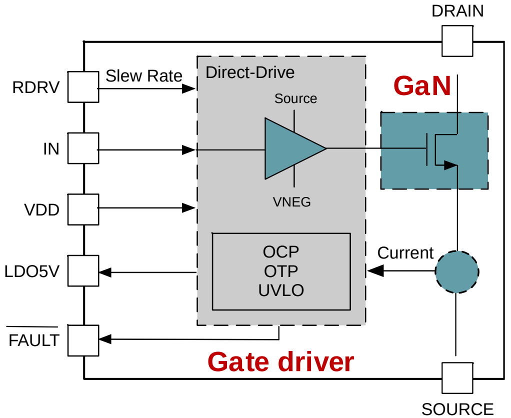
Turn-off Figure-of-Merit *(turn-off losses only; ZVS at turn-on)*

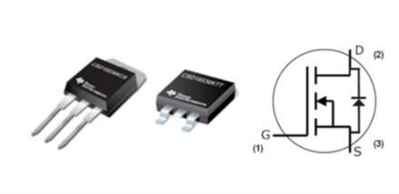
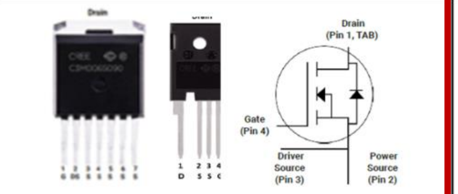
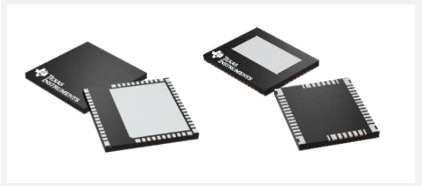


Double Pulse Test

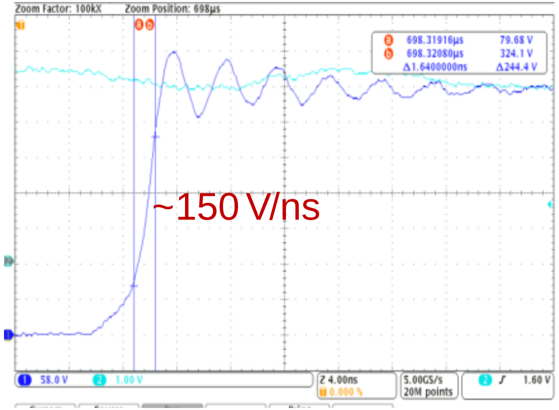
With lowest switching energy loss & zero reverse recovery, 650-V GaN offers the best opportunity for high-frequency operation!

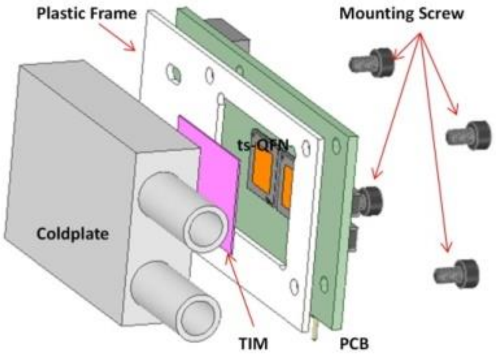
GaN FET engineered for high-frequency, high-power



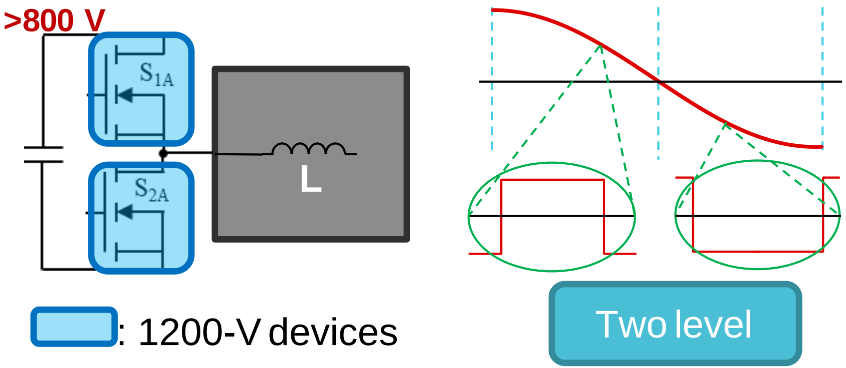
Standard Power Package	Kelvin Source Power Package	TI: GaN FET + Gate driver
		
Common Source: 2nH -10nH	Common Source: <1nH	Common Source: <1nH
Gate loop: 5nH – 20nH	Gate loop: 5nH – 20nH	Gate loop: 1nH – 4nH

- Integrated gate driver offering up to 150-V/ns dV_{DS}/dt
- 12x12mm QFN with lowest common source inductance
- Top-side thermal pad enables 1.6-2°C/W (>30W/package)
- Integrated protections



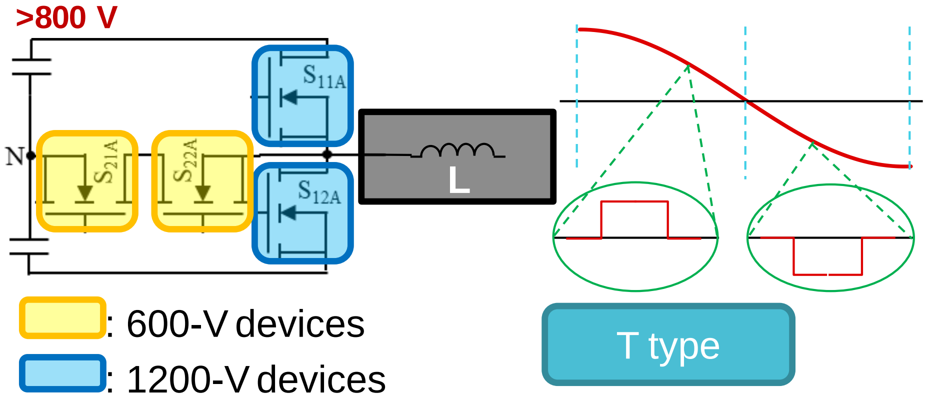


Power topologies for 1200-V devices



Pros:
- Lowest device cost, fewest # of switches
- Well understood analysis and modulation

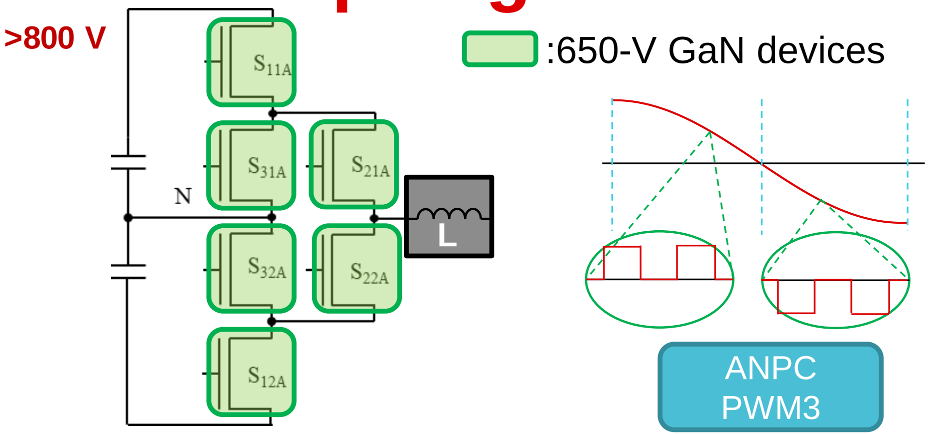
Cons:
- 1200-V devices needed, higher losses
- 100% of bus voltage on switch resulting in high voltage stress & switching losses
- Highest Volt-sec on inductor resulting in large magnetics



Pros:
- 50% Volt-sec on inductor (assuming same frequency) allows smaller magnetics
- Higher efficiency with same frequency
- Lower voltage distortion due to 3-level

Cons:
- 1200-V devices needed, higher losses
- Increased bus capacitance & # of switches
- Uneven loss distribution, more heatsink area

Power topologies for 650-V devices (multi-level)

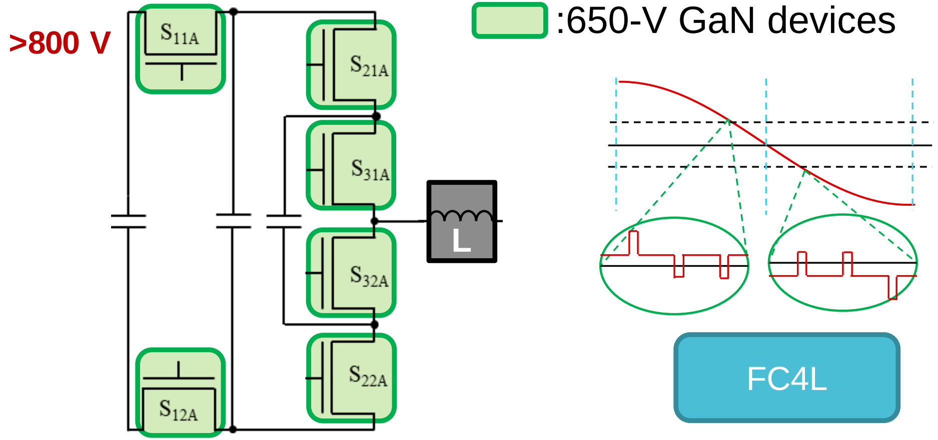


Pros:

- 50% of bus voltage on FET allows for efficient 650-V devices
- Low Volt-sec due to 2X equivalent frequency at 50% bus voltage enables smaller inductor with simplified isolation
- Lower voltage distortion due to 3-level

Cons:

- Increased bus capacitance, control complexity to balance neutral point
- Uneven loss distribution



Pros:

- 3X equivalent frequency on inductor at 33% bus voltage allows smallest inductors (4-level)
- 33% of DC bus voltage on each switch
- Even loss distribution, lower distortion

Cons:

- Increased conduction loss
- Increased control complexity

800-V/6.6-kW 3-phase bi-directional ANPC 3-level converter

Features

- Power stage for three phase DC-AC inverter & AC-DC power factor correction converter
- Uses 650-V GaN FETs switches in 800-V system due to 3-level operation
- Shunt based current sense (high accuracy & linearity over temp.)
- Bidirectional operation with <1ms direction changeover
- C2000 DSP control

Benefits

- **High power density** due to
  - high switching frequency (100kHz)
  - high efficiency (>98% at full load)
- **Low component stress** helps to improve system reliability
- **Optimized control scheme** needs 6 PWMs vs. 9 PWMs
- **Reduced cost** only 4 high-frequency FETs (out of 6) per leg

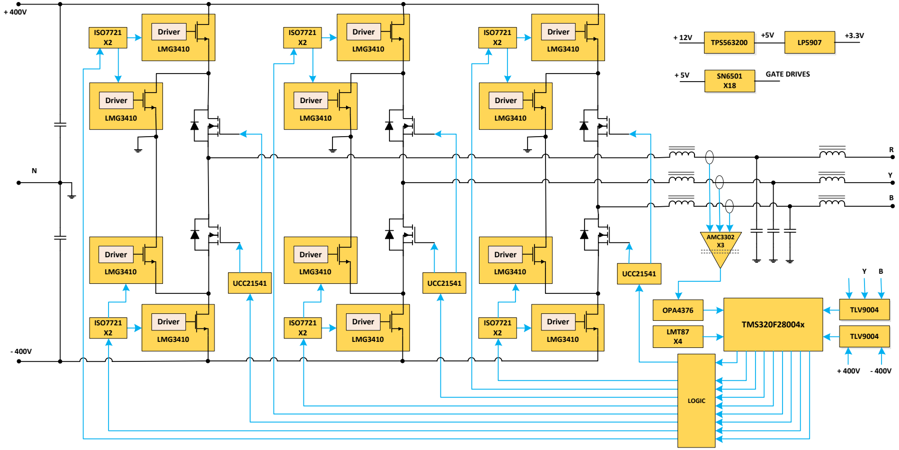
Target Applications

- Energy Storage Systems (Storage Ready Inverters)
- Bi-directional EV Charging Stations

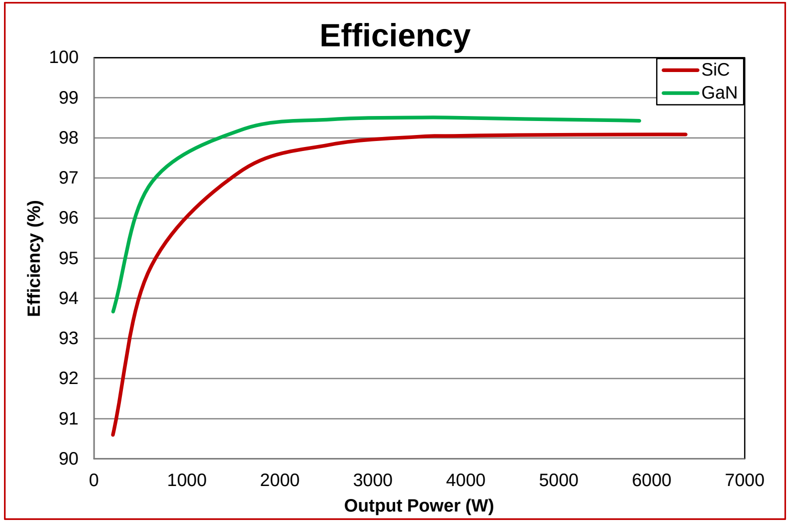
Tools & Resources

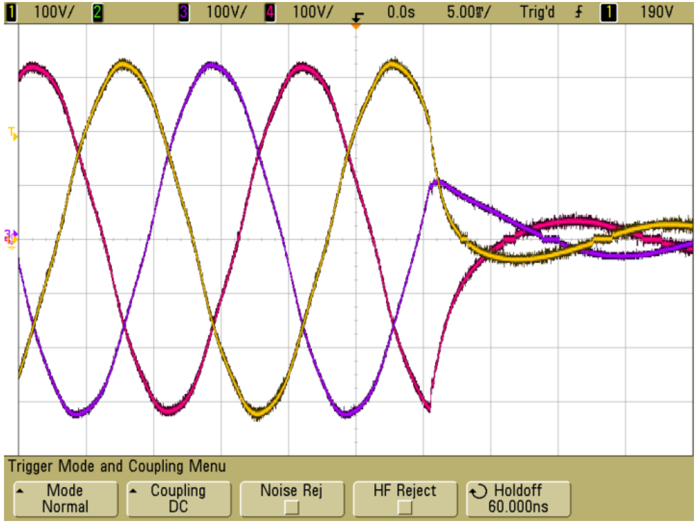
Devices used:

- UCC21530
- AMC3302
- UCC21541
- LMT87
- TLV9004
- TPS563200
- LP5907
- SN6501
- OPA4376
- TMS320F28004x



800-V/6.6-kW 3-phase bi-directional ANPC 3-level converter



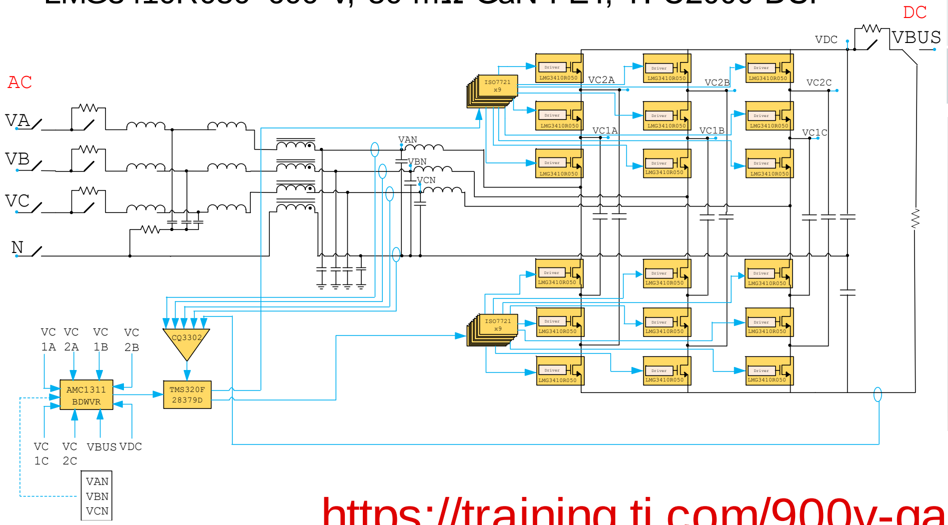


- ~98.5% efficiency above 1.5 kW with >90% efficiency at 200-W light load
  - GaN vs SiC efficiency improvement: 0.5% @ full load, 2-3% at light loads
- Clean sinusoidal voltage waveforms with <3% THD (total harmonic distortion)
- Stable transient response, settling time ~5ms
- 80º phase margin and 18dB gain margin with around 200Hz loop bandwidth

900-V/5-kW 3-phase bi-directional 4-level converter

Features

- AC voltage up to 480 V L-L, DC voltage up to 1400 V
- Peak efficiency of 99.2%
- Convection cooled with no fan
- Scalable 4-level flying capacitor multi-level solution
- Total harmonic distortion (THD) < 3%
- LMG3410R050 600-V, 50-mΩ GaN FET, TI C2000 DSP



Benefits

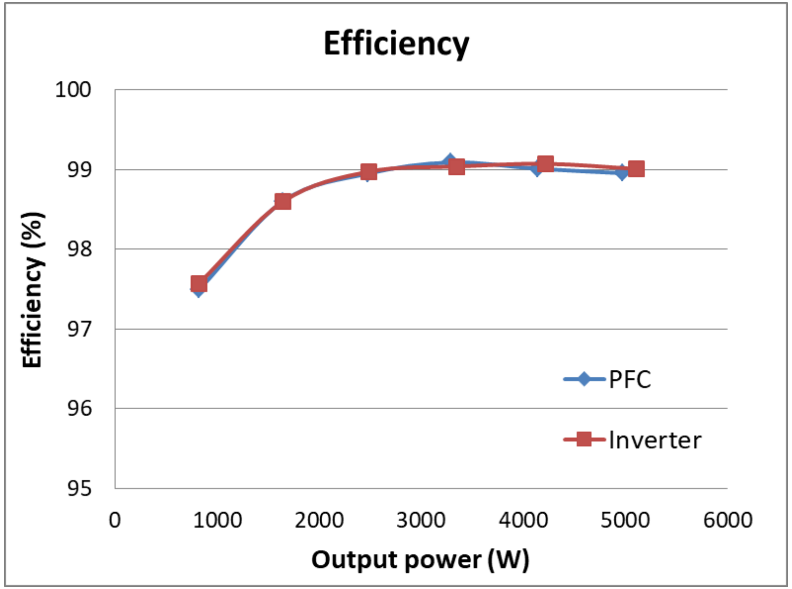
- **3X power density improvement over IGBT** and 1.25X over SiC

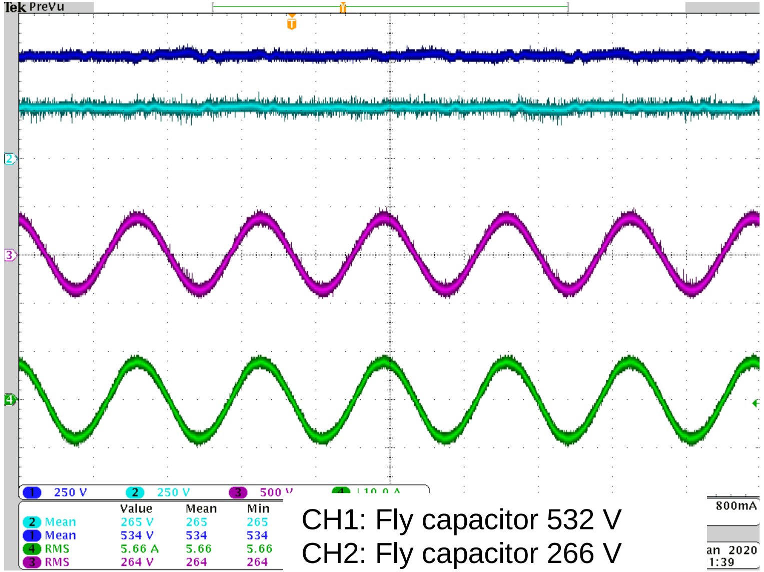
Typical Operating conditions	IGBT	SiC	TI-GaN
Frequency (kHz)	20	100	**140**
Open-frame power density (W/in³)	73	170	**211**
Efficiency (%)	98.3	98.9	**99.2**

470 mm x 162 mm x 51 mm

https://training.ti.com/900v-gan-solution-grid-and-beyond

900-V/5-kW 3-phase bi-directional 4-level converter



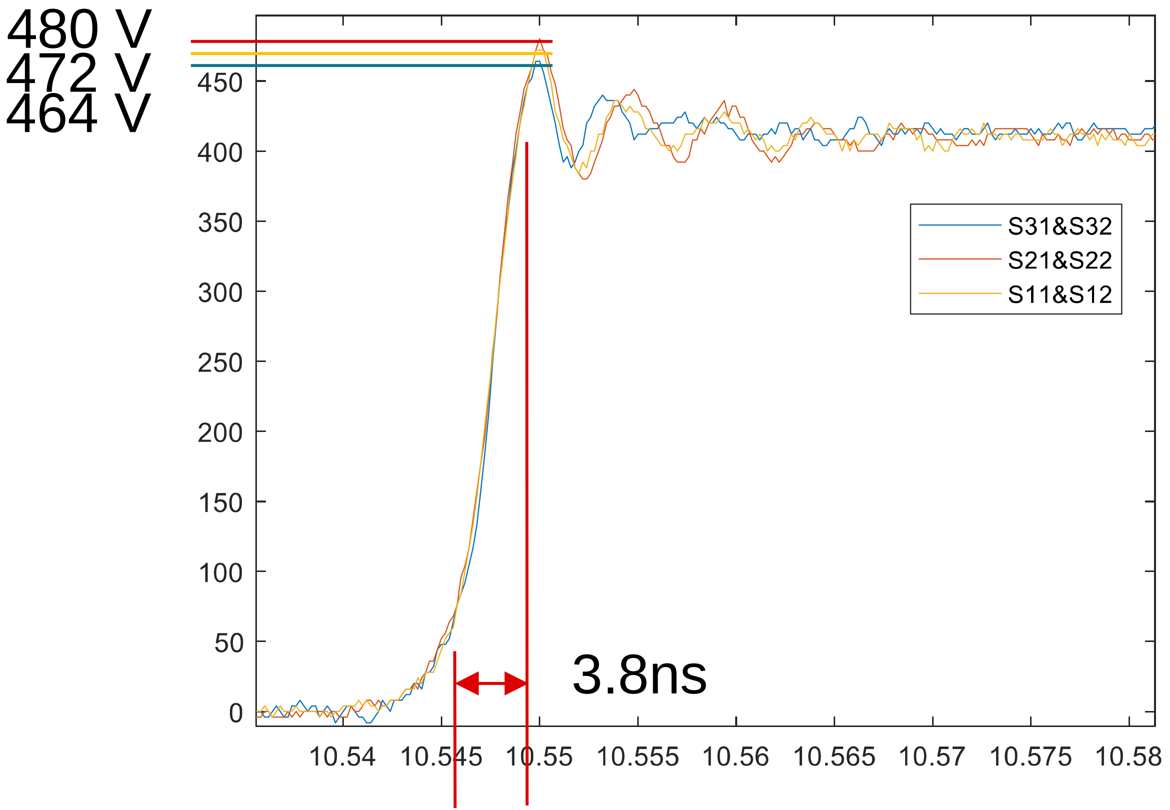


CH1: Fly capacitor 532 V
CH2: Fly capacitor 266 V
CH3: Grid voltage 270 V
CH4: Grid current 6 A

- Peak efficiency of 99.2%
- Total harmonic distortion (THD) < 3%

Texas Instruments

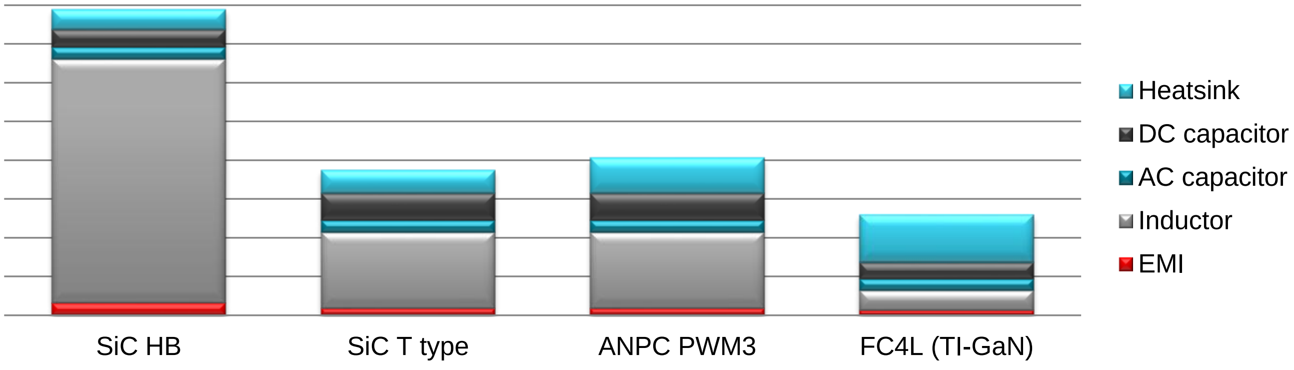
900-V/5-kW 3-phase bi-directional 4-level converter



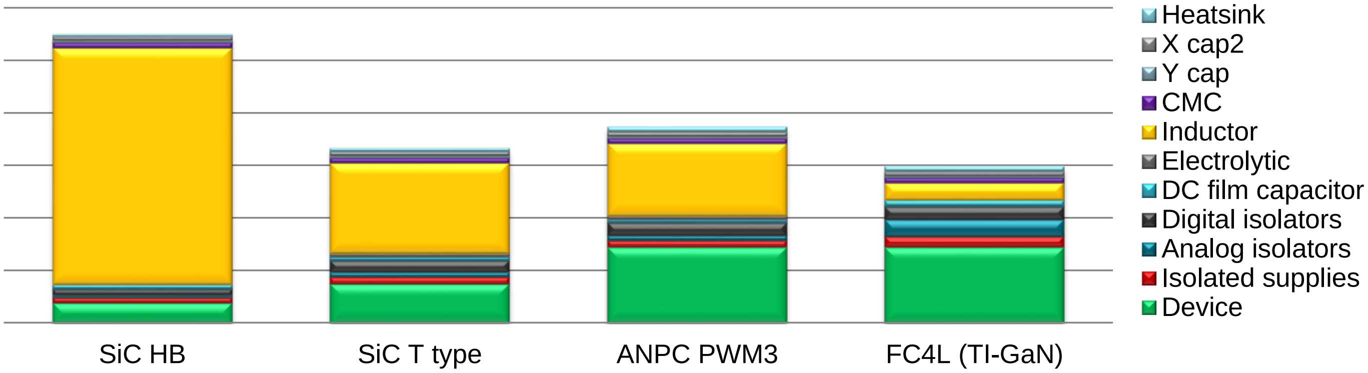
- 100V/ns dV_{DS}/dt of GaN FET contributes to low I-V overlap losses during switching enabling 10kHz operating frequency
- Low-inductance package mitigates voltage spikes during fast-switching transients

900-V/5-kW 3-phase bi-directional 4-level converter

Inverter relative volume breakdown

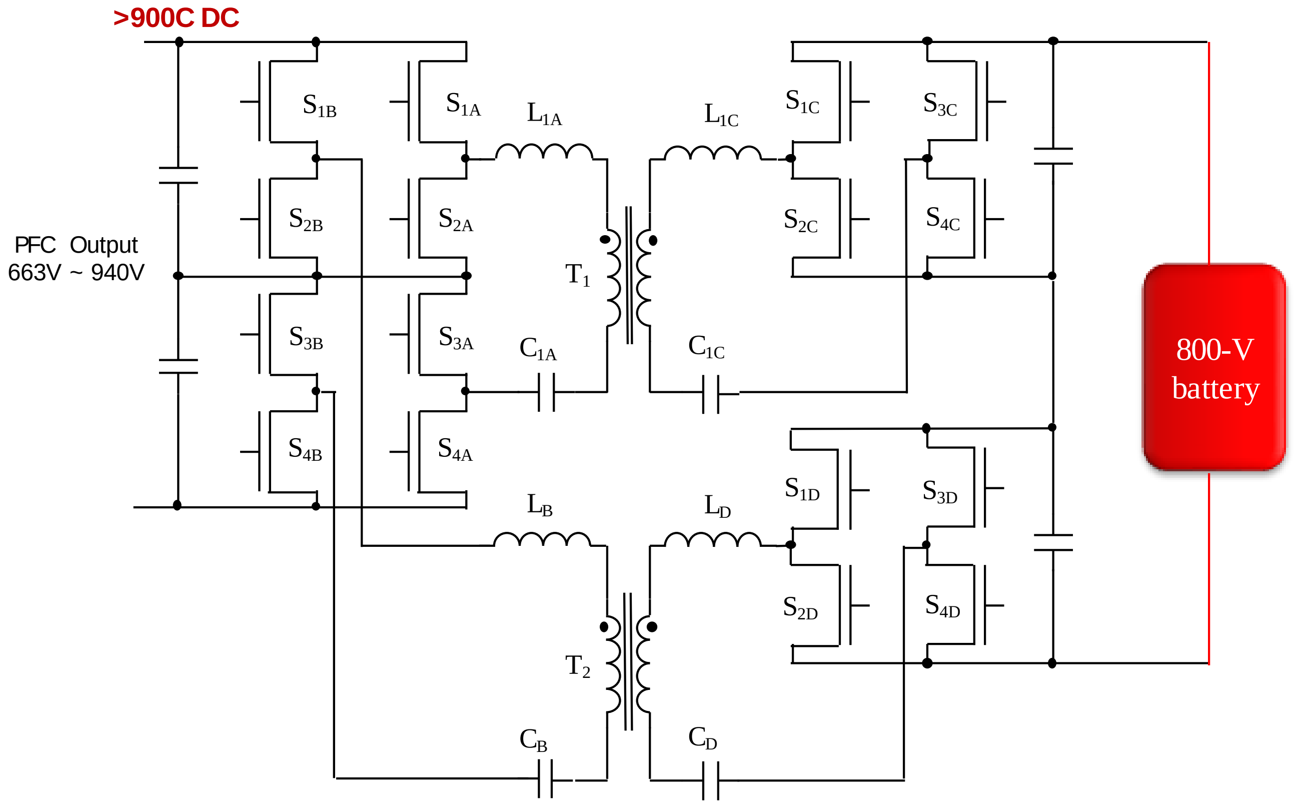


Inverter relative cost breakdown



- Lowest system cost for 4-level solution, despite higher semiconductor cost

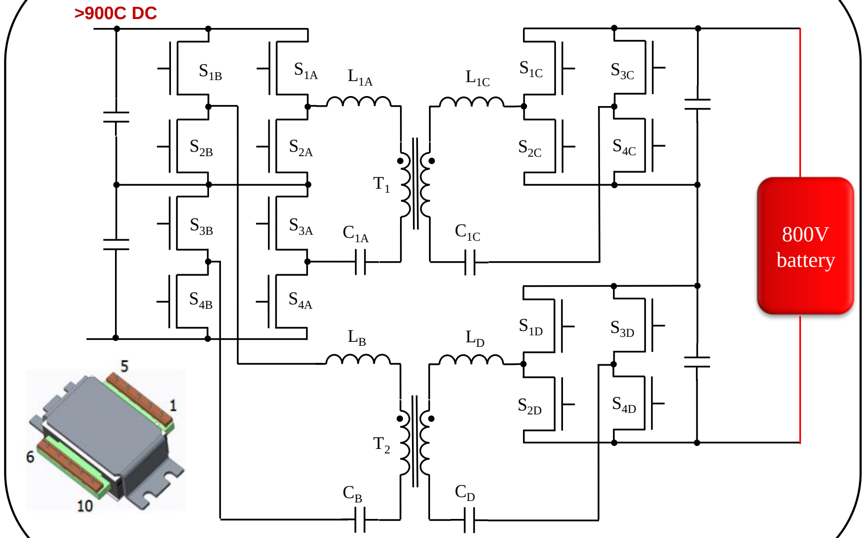
Power topologies for 650-V devices (stacked ½-br)



- Split DC bus capacitors enables series stacked ½-bridge arrangement of 650-V GaN-FETs
- Output connection re-configurable for series or parallel operation (800-V or 400-V batteries)

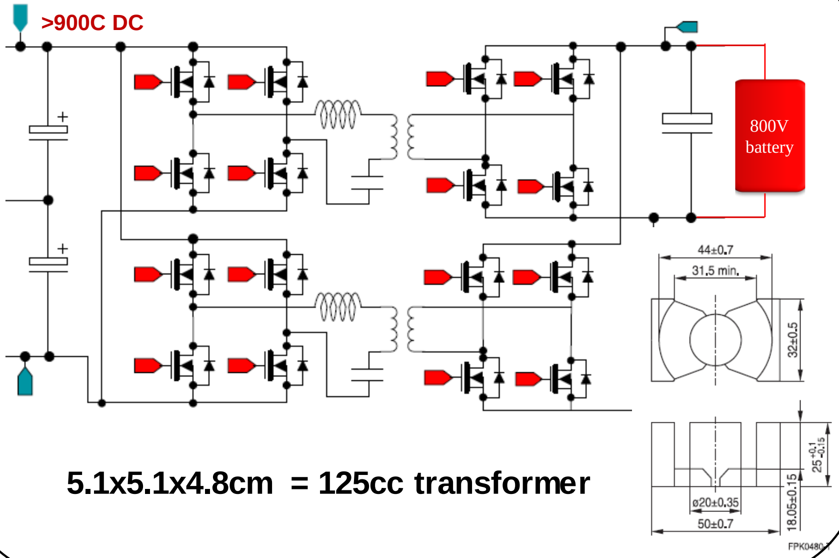
11-kW onboard charger: 650-V GaN vs. 1200-V SiC

11-kW 650-V GaN bi-directional OBC



5.6x5.6x2.1cm = 65cc transformer

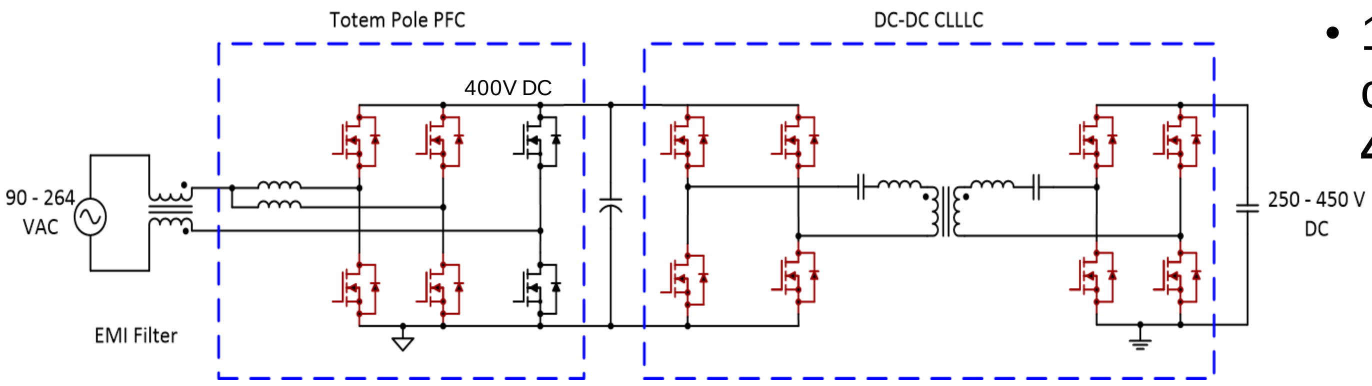
11-kW 1200-V SiC bi-directional OBC



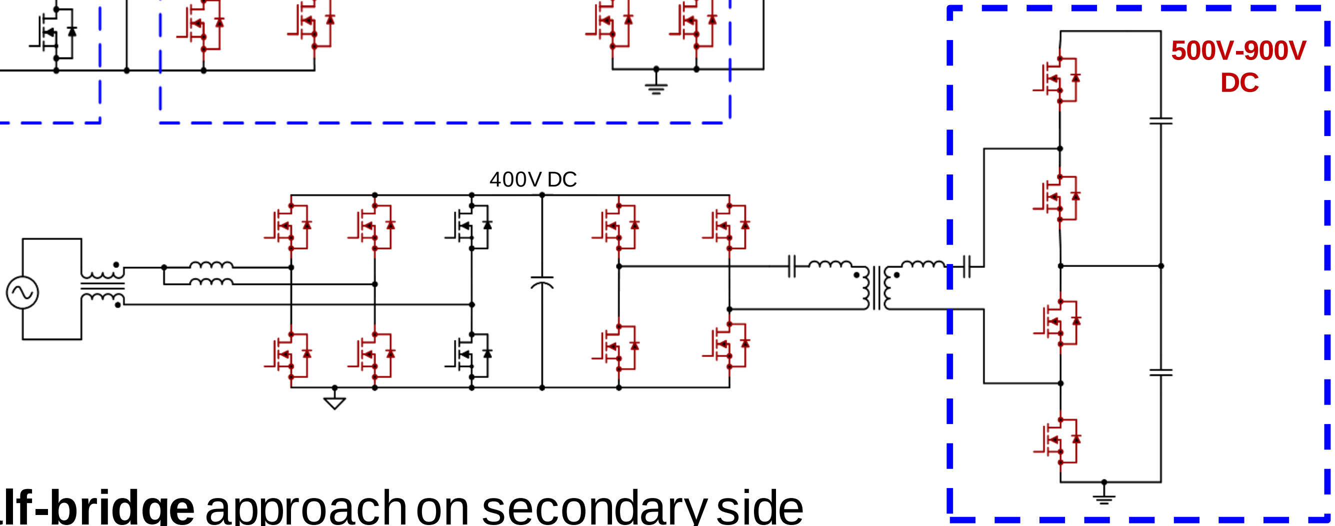
5.1x5.1x4.8cm = 125cc transformer

- 2X 5.5-kW modules comprising equal number of transformers (2X) and switches (16X)
- **Series stacked half-bridge** approach with GaN FETs; lower $R_{DS,ON}$ for minimizing conduction losses due to higher current
- >3x frequency (~750kHz) enables **50% smaller planar transformers with GaN**

Power topologies for 650-V devices (stacked ½-br)



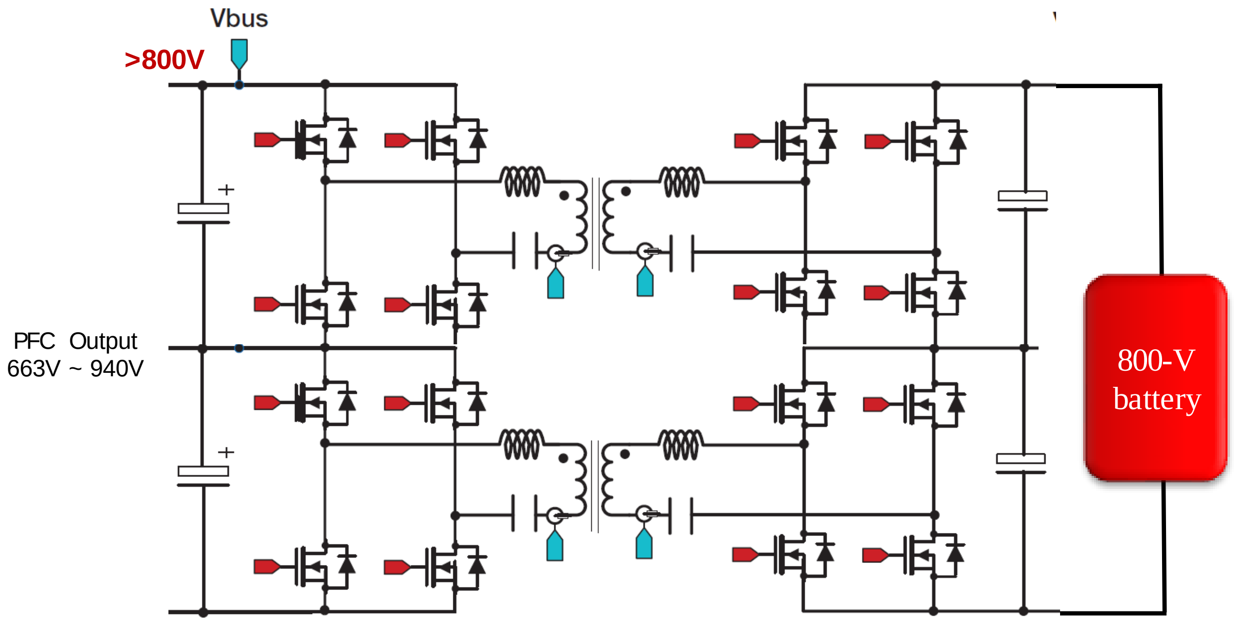
- 1-phase AC, 6.6-kW onboard charger for **400-V** battery



- 1-phase AC, 6.6-kW onboard charger for **800-V** battery

- **Series stacked half-bridge** approach on secondary side

Power topologies for 650-V devices (stacked ½-br)



- Variant of series stacked half-bridge, with a completely symmetrical structure
- DC bus capacitor balancing needed simultaneously on both primary and secondary sides

Conclusions

- Superior switching performance of 650-V GaN FETs provide an exciting opportunity to increase converter operating frequency
  - Challenge conventional approach to use 2-level converters with 1200-V IGBTs and SiC MOSFETs
  - 650-V GaN bring merits to both hard-switching and soft-switching converters

- Clever manipulation of power topologies easily enables use of 650-V FETs in converters with very high DC-link voltages (>800-V)
  - Fairly well-understood power topologies and related control algorithms
  - Mature eco-system of DSP control solutions, isolation products (isolators, bias power supplies) and total reference designs becoming available