Applications of Transphorm High Voltage GaN and its comparison with Si, SiC & other GaN

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Highest Performance, Highest Reliability GaN

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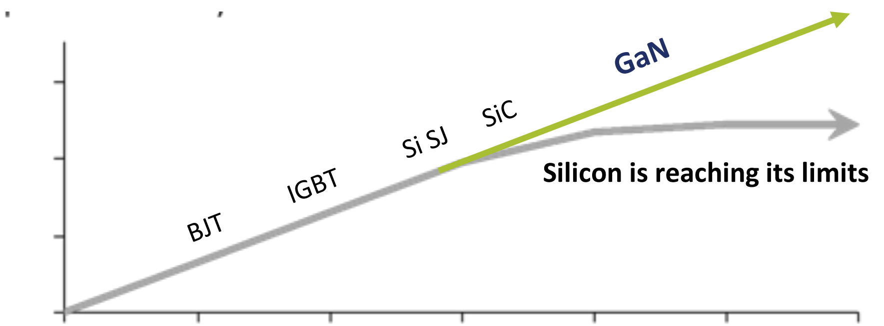
Agenda

- Introduction to GaN Application Space vis-à-vis other Power Technologies
- Comparison of Transphorm GaN vs. Si, e-GaN and SiC
- Applications of 650V GaN in 45W to 10+kW Power Levels
    a. Power range 45W to 65W – Adapters, LED Lighting
    b. Power range 100W to 150W – Adapters, Computer Supplies
    c. Power range 250W to 1kW – Computing, 2-wheeler (e-bikes, e-scooters)
    d. Power range 2.2kW to 10+kW – PV, UPS, Server Power, EV
- Few Cases Studied – Inverter and 2-wheeler OBC
- Benchmarking GaN vs. SiC and Si MOSFETs in Select Topologies

GaN is Best-in-Class in Relevant Voltage Range

“Moore’s Law” for Power Electronics

GaN Provides the Path to Continue to Scale Power Densities



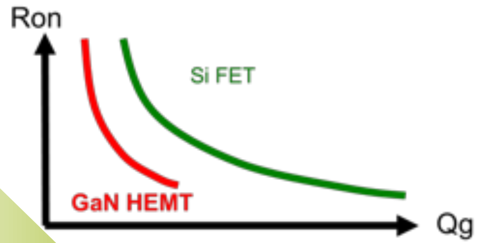
GaN vs. Silicon & Silicon Carbide

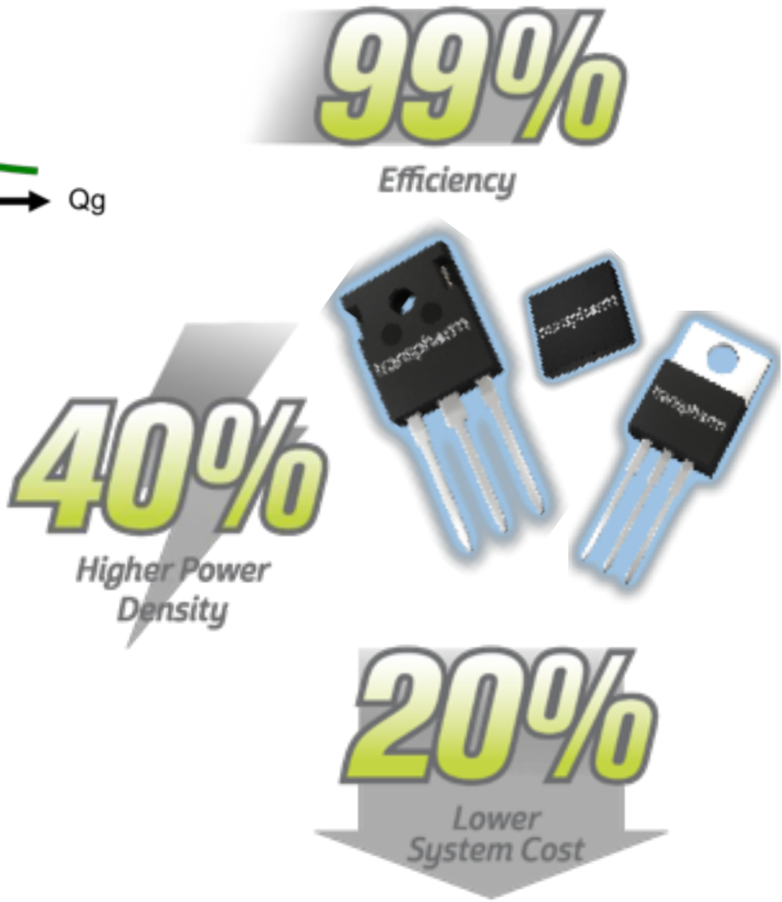
Intrinsic Performance Advantages

- GaN offers higher efficiencies with lower losses in power conversion at the relevant voltage range
- GaN can operate at much higher frequency than Si and SiC

Relative Cost Advantages

- GaN on Silicon less expensive than Silicon Carbide
- GaN offers lower system cost than Silicon in many applications
- Roadmap for GaN to approach cost parity with Silicon at device-level





Smaller, Lighter, and Cooler Power Systems Drives Increased Functional Value

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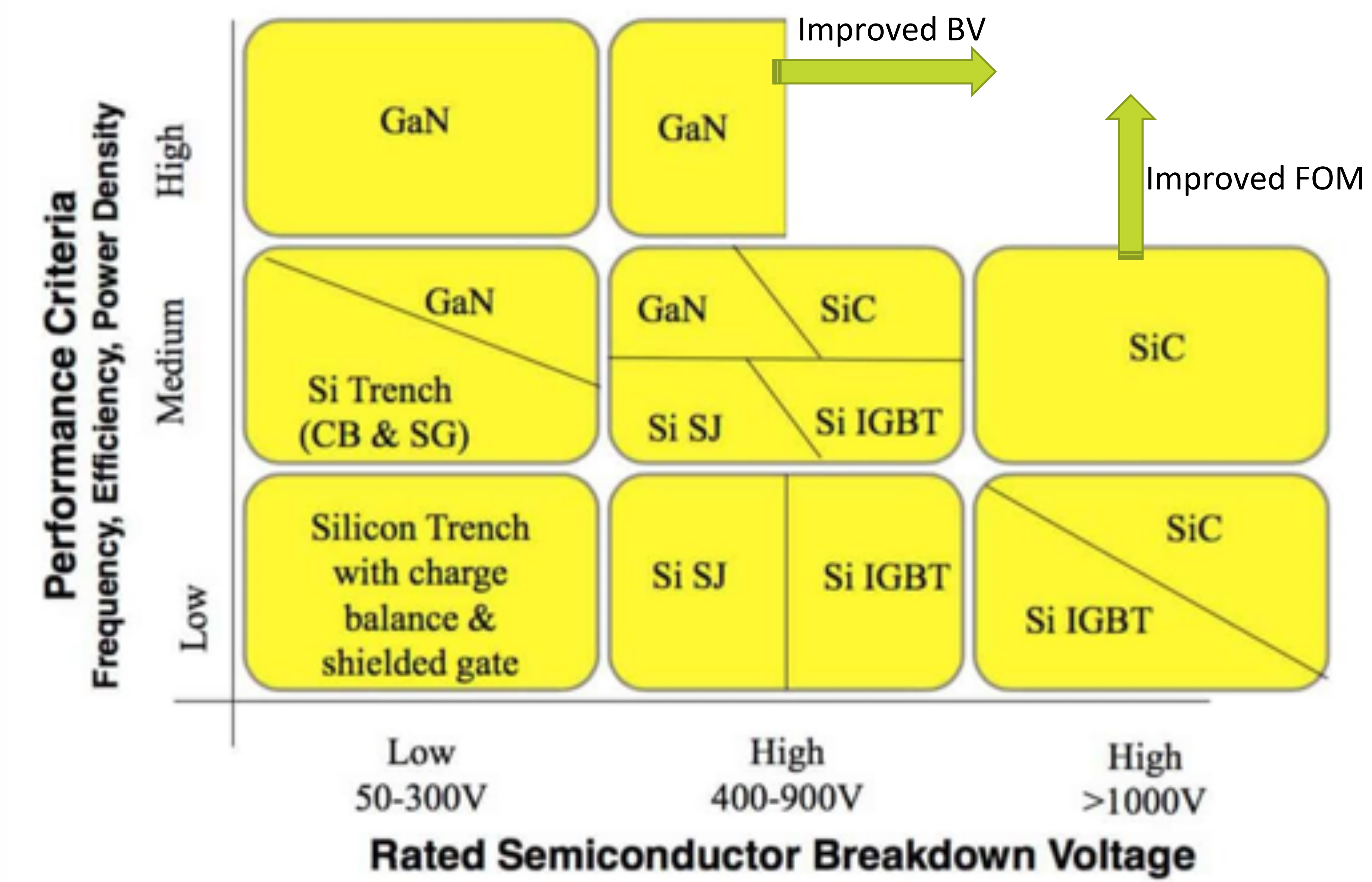
Device Comparison – Silicon, GaN and SiC



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GaN & SiC Companies & Key Markets

Product Portfolio

40V to 200V	400V to 750V	Up to 1700V
DC-DC supplies in Datacom, Notebooks, Telecom, Automotive	AC-DC Adapters, Computing, 5G, PV, Automotive, Motor Control	Automotive, Industrial, Motor Control & Infrastructure
EPC – Efficient Power Conversion GaN Systems Innoscience	transphorm GaN Systems Power Integrations Innoscience Navitas Infineon TI VisIC Technologies ST life.augmented	Wolfspeed Infineon ON Semiconductor ST life.augmented Panasonic UnitedSiC Microchip

VOLTAGE →

** Disclaimer: Some companies may have been missed; companies not shown in any order*

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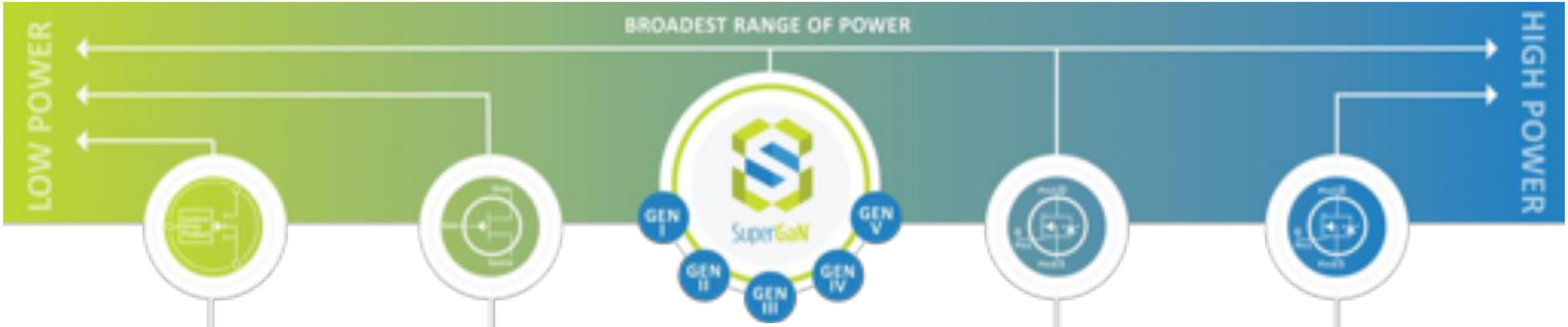
Competitive Landscape –TGAN FET, vs. Other GaN, SiC, Si



"IC" GaN

- Higher losses (Operating Temp)
- Only lower power offerings, no std. TO packages today
- Poor switching control[1]
- Field reliability based on low power[2]
- JEDEC qualified, 650V only
- Superior performance vs. Si

E-MODE GaN

- Higher losses (Operating Temp)
- Exposed GaN gate/input, no std. TO packages today
- Harder to design w/std. gate drivers
- Field reliability based on low power, e-mode gate weaker[2]
- JEDEC, AEC qualified, 650V only
- Superior Performance vs. Si

Transphorm GaN FET

- Superior performance – vs. other GaN, SiC and Silicon
- Best thermals – Robust Pkg
- Easy to design and use with std. gate drivers
- Most robust interface, Proven reliability in low/high power
- JEDEC + AEC-Q101 qualified,
- 650V | 900V | 1200V (R&D)

Si MOSFET

- Older technology
- Higher losses, Low power density
- Market incumbent

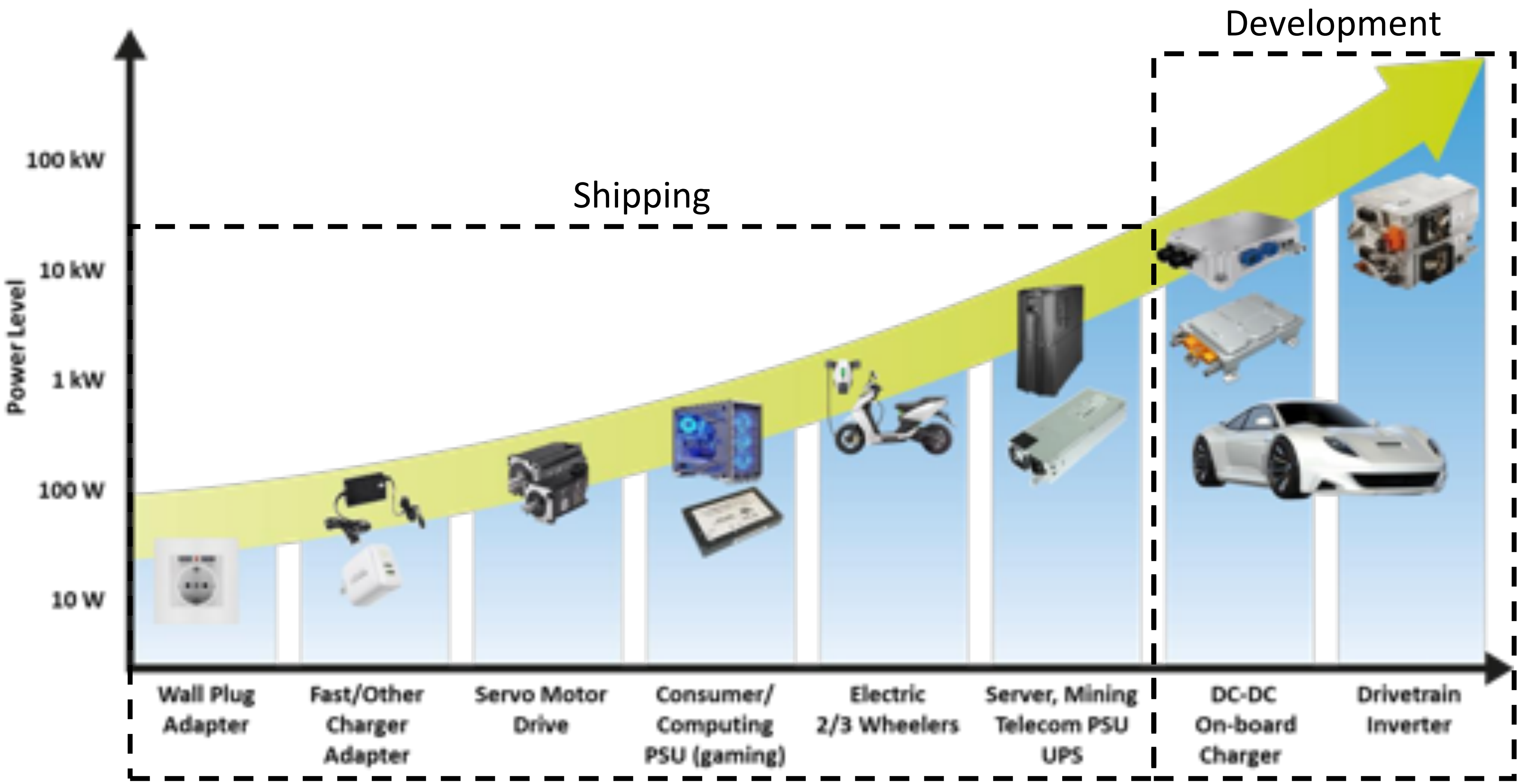
SiC FET/MOSFET

- Higher Power/Voltage
- Ramped in EV
- Substrate cost high, supply chain complex
- High switching losses

[1,] To provide additional device control, gate driver is sometimes removed making the "IC" a discrete solution
[2] Impact of OFF-state Gate Bias on Dynamic R,on of p-GaN Gate HEMT (33rd ISPSD, 2021), Currently available reliability statements based on lower power consumer applications for which failures are not typically reported.

45W to 10+ kW markets served by Transphorm GaN

Transphorm offers breadth of 650V, 900V JEDEC/AEC-Q101 Qualified Products
New developments include 1200V and FQS Platforms



Transphorm in Adapters & Chargers - 30W to 240W

30W → 240W

Wall plug – high efficiency, compact (35 W)

Ultra slim, light weight (65 W)

New 65 W 2C-1A)

Quick Charge-5, USB C PD (100 W)

Notebook – small size, 200 kHz (160 W)

Compact 30 W Power Bar

High-efficiency (65 W)

Compact Power Bar, 65 W 1A-1C

Compact 100 W 2C-1A

Multi out 150 W (2C-1A)

Compact USB-C (65 W)

New 65 W 2C-1A (Phihong)

New 120 W 2C-2A-Axial

Ultra compact 240 W

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Shipping GaN into Kilowatt-class Power Supplies

GaN Power for Data Center | Comms Infrastructure | Crypto-Mining Applications

GaN Offers Substantial Systems Cost Savings within Data Centers

- 40% of total operational costs come from energy to power and cool server racks
- GaN enables **~2x increase in power density, 98%+ efficiency**
- GaN enables 80+ Titanium class efficiency certification in a simpler manner

"Titanium" Server Power Supply Solutions

(1.5 kW to 3.2 kW), **Powered by TGAN**

Smaller

Faster

Cooler

5 MW Data Center Example

AC Line (208 Vac) to 400 Vdc to 48 Vdc

- \$103K saved / year[1]
- 397 tons reduced carbon footprint[2]

Regulation: The European Union's Ecodesign Directive[3] on *Jan 1, 2023* increases efficiency and power factor requirements

Near- and Intermediate-Term Market Drivers

Crypto-Mining Demand – building systems requiring Titanium efficiency

- Power hungry process – consumes ~120 TWHr, equivalent to small country[4]
- Power supply – component running 24/7 taking most stress in mining rig [5]
- Transphorm solutions can enable up to 1% higher efficiency at 230V AC

Highly Efficient

Highly Reliable

Notes:
1) Based on company estimates done for a 5MW data center.
2) Based on existing rectifiers with 92% efficiency | Source: EPA estimated one kWh produces 1.52 pounds of carbon dioxide (excl. line-losses).
3) European Union's Ecodesign Directive (Directive 2009/125/EC).
4) Cambridge University research | BBC News, "Bitcoin consumes 'more electricity than Argentina'"
5) tom's Hardware, "Best Power Supply Units for Cryptocurrency Mining"

Transphorm GaN Structure & Advantages

Highest Reliability, Simplest Driving, Higher efficiency & Easiest to Design

Low Power

Standard Controllers with integrated Driver

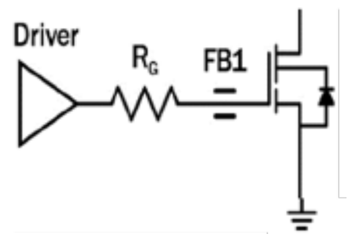
- On Semi, TI, NXP, ST
- Weltrend, Diodes
- Silanna, Infineon/Cypress

High Performance, High Reliability in Multiple Packages

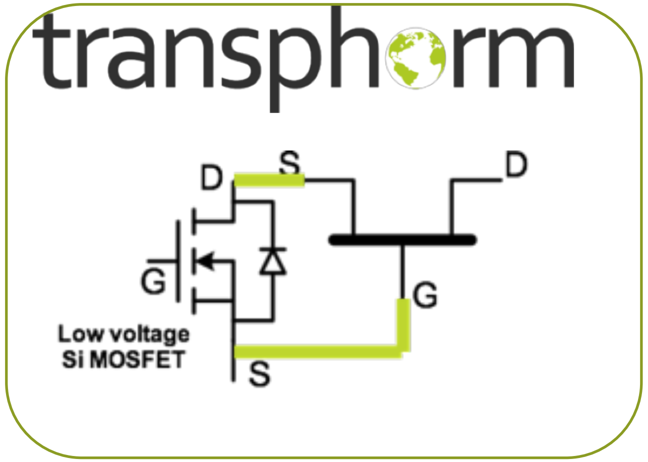
Hi Power

Standard Gate Driver

- Silicon Labs, MPS
- Analog Devices
- ON Semiconductor
- Texas Instruments



Simple to Drive GaN FET



Highest Efficiency

Field Reliability
> 85 B hours

Qual.
JEDEC
&
AEC-Q101

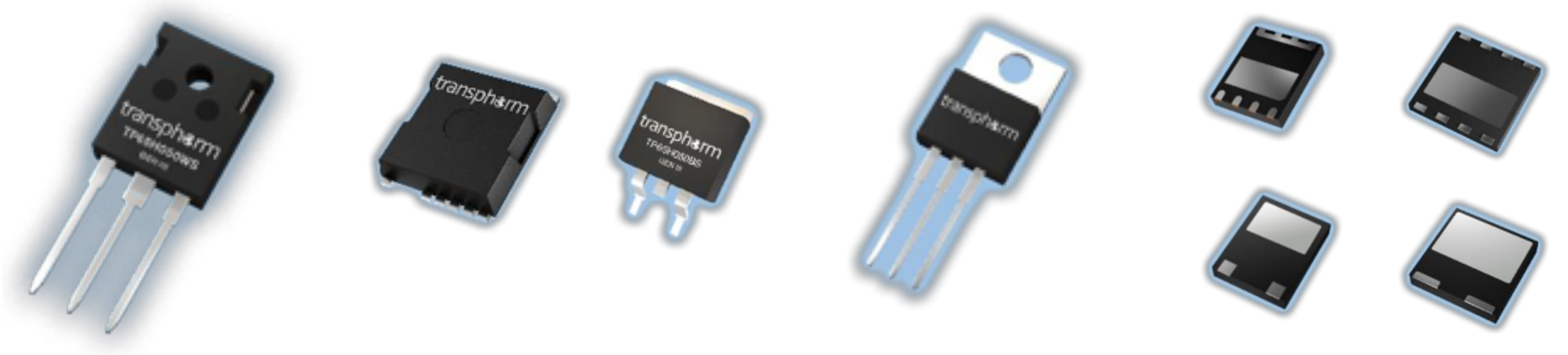
Early Life Failure
< 0.07 FIT

Volume Production
45W to 5kW

Transphorm 650 V Packaged Device Offerings

Widest GaN Package Offering in the Market

1 kW to 10 kW | 1 kW to 3 kW | 150W to 1 kW | 30 W to 250 W



TO-247	TOLL	D^{2}PAK	TO-220	PQFN56	PQFN88
50 mΩ[1]	50 mΩ[2,3]	50 mΩ	150 mΩ	480 mΩ	480 mΩ
35 mΩ[1]	35 mΩ[2,3]		70 mΩ	240 mΩ	240 mΩ
15 mΩ[2]				150 mΩ	150 mΩ
					70 mΩ

[1]JEDEC and Q101
[2]2023 Q101
[3]Samples 10/E 2022

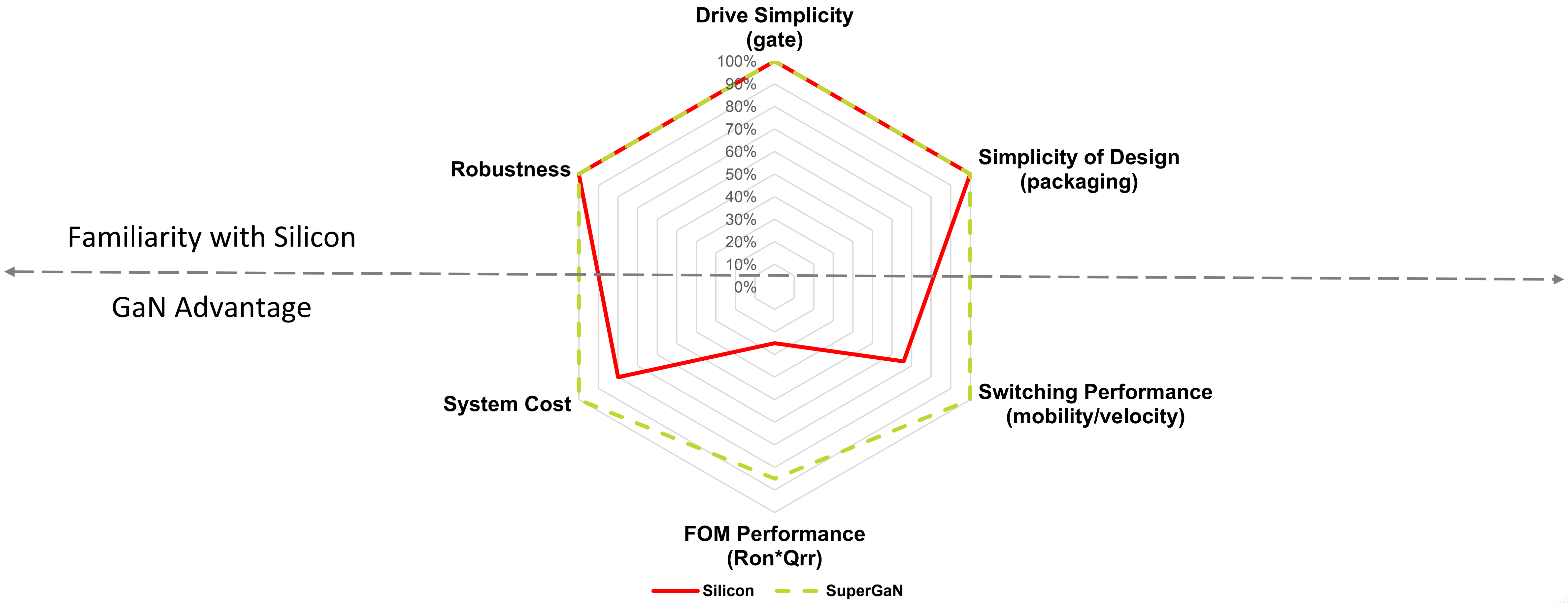
Comparison of a TPH GaN-HEMT & SJ-MOSFET

	Parameters	Cool MOS IPB65R150CFD	GaN-HEMT TP65H150G4LSG	
Static	V_{DS}	650V @ 25 °C	650V (spike rating 800V)	
	R_{DS} (25°C) **Rds (150°C)**	**0.135/0.15 ohm** **0.351 ohm**	**0.15/0.18 ohm** **0.307 ohm**	Conduction Loss
	Qg	86 nC	8 nC	Driving Loss
	Qgd	47 nC	2nC	
Dynamic	$C_{o(er)}$	50 pF [1]	43 pF [1]	Switching Loss
	$C_{o(tr)}$	512 pF [1]	85 pF [1]	
Reverse Operation	Qrr	700 nC [2]	40 nC [3]	Reverse Recovery Loss
	trr	140 ns [2]	31 ns [3]	

[1] V_{GS} = 0V, V_{DS} = 0 – 480V
[2] V_{DS} = 400V, I_{DS} = 11.3A, di/dt = 100A/µs
[3] V_{DS} = 480V, I_{DS} = 9A, di/dt = 450A/µs

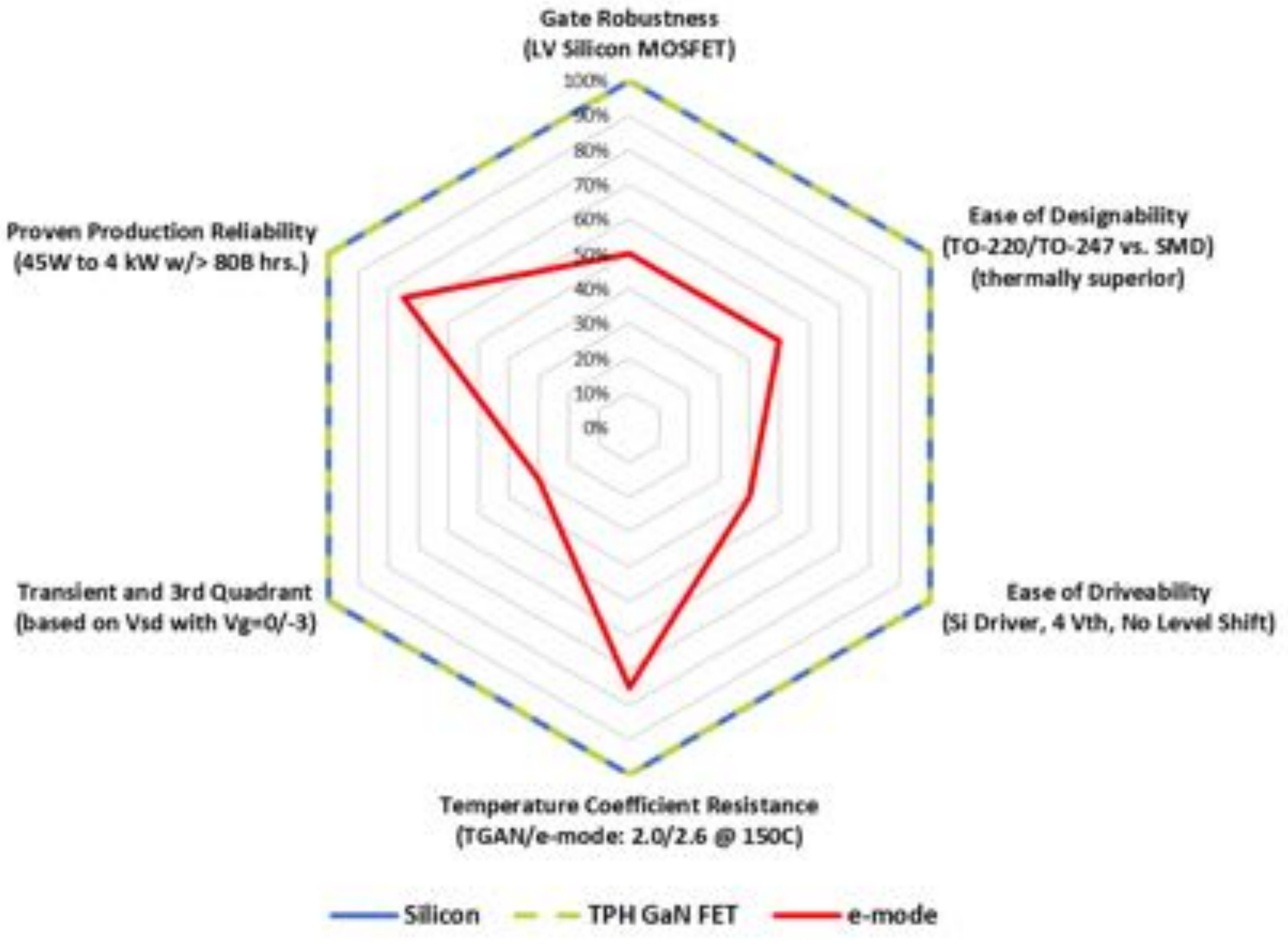
Transphorm GaN vs. SJ-MOSFET Comparison

SuperGaN Technology Offers Ease of use & Reliability of Silicon with Higher Performance



Transphorm GaN vs. e-mode Comparison

SuperGaN® Technology vs, e-mode GaN (Silicon as the Baseline), GaN IC uses e-mode



Transphorm GaN Technology vs. **SiC (650V)**

Simpler, more Efficient, Lower-cost and Robust Solutions

Key Factors	Transphorm GaN FET (650V Class)	SiC MOSFET and SiC CASCODE (750V – 1500V)
Leadership in Market Segment	33W to 10kW	5kW – 100kW
Gate Biasing	Simpler even compared to Si	Complex due to aux power supply
Gate Driver - Power Requirement	1x (0.4A)	Requires 20x more current (10A)
Cost & Availability of Gate Drivers	Up to 2A driver ok	Costly due to high current requirement
Peak Efficiency	High	Medium
Speed of operation (frequency)	Faster	Slower
Added BoM components (cost)	Lowest	High
Package (SMD/leaded/Module)	Both SMD & leaded	Leaded and Module
Reliability	Comparable	-
Leakage Current (IDSS) at 175C	30uA	150uA
Reverse Conduction Voltage Losses	1.8V	4
Total Cost	Lower (Si substrate)	Higher (SiC substrate)

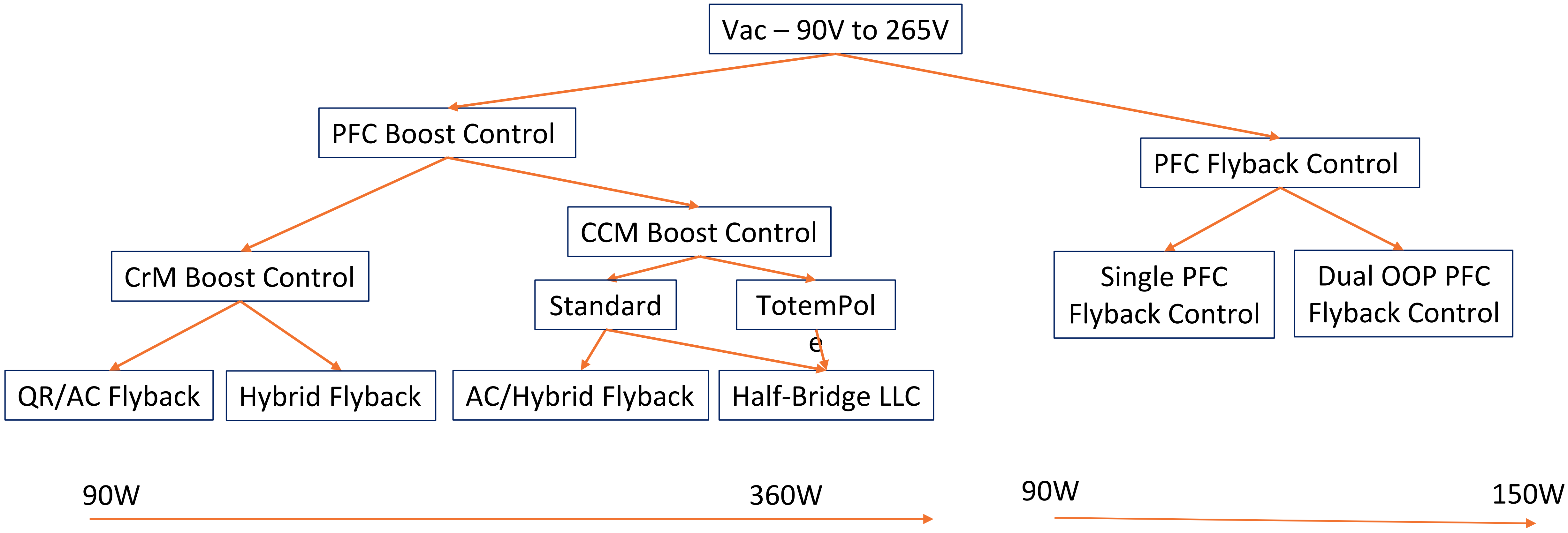
Considerations for 45W to **35**0W Power Supplies

Mobile Devices, Notebooks, Gaming Consoles, Power Tools, LED lighting, Medical Supplies

Variations of the Flyback and Two-stage Topologies

USB-C Adapters/Computer Supplies (70W to 360W)

Topology choices have expanded, just over the past year



Pros: Smaller bulk cap and PFC O/P Cap
Cons: Complex 2-stage design especially if multi-output

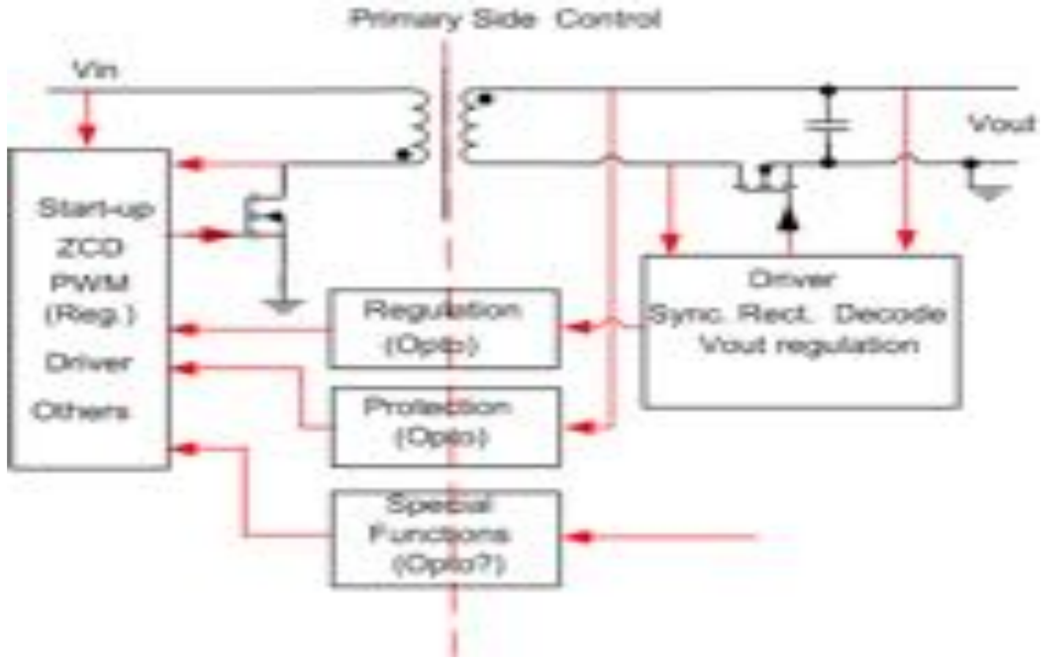
Pros: Lower Cost, great for multi-output
Cons: Larger PFC O/P Cap if single output

Transphorm GaN & Topologies for Power Adapters

Platform	Vout	Topology	Transphorm GaN Offering		
			Rds(on)	Package	Driver
45W	1C PD 3.0	QRF	240mΩ - 480mΩ	QFN5x6	Internal Gate Driver of Controller IC
65W	1C PD 3.0	QRF or ACF	240mΩ	QFN5x6	
65W	2C PD 3.0	QRF or ACF	240mΩ	QFN8x8 / 5x6	
100W	1C PD 3.0	PFC + ACF or PFC + QRF	150mΩ 240mΩ	QFN8x8 / 5x6 or TO-220	
118W	1C PD 3.1	PFC + ACF	150mΩ - PFC 150mΩ - ACF	QFN8x8 or TO-220	Internal
140W	1C PD 3.1	PFC + ACF	150mΩ - PFC 150mΩ - ACF	QFN8x8 or TO-220	Internal
250W	Fixed	PFC + HB-LLC	150mΩ - PFC 240mΩ * 2 – HB LLC	QFN8x8 or TO-220	Internal to Controller IC or Low-cost External
330W	Fixed	TTP PFC + HB-LLC	150mΩ * 2 - PFC 240mΩ * 2 – HB LLC	QFN8x8 or TO-220	
600W	Fixed	TTP PFC + HB-LLC	150mΩ * 2 - PFC 150mΩ * 2 – HB LLC	QFN8x8 or TO-220	

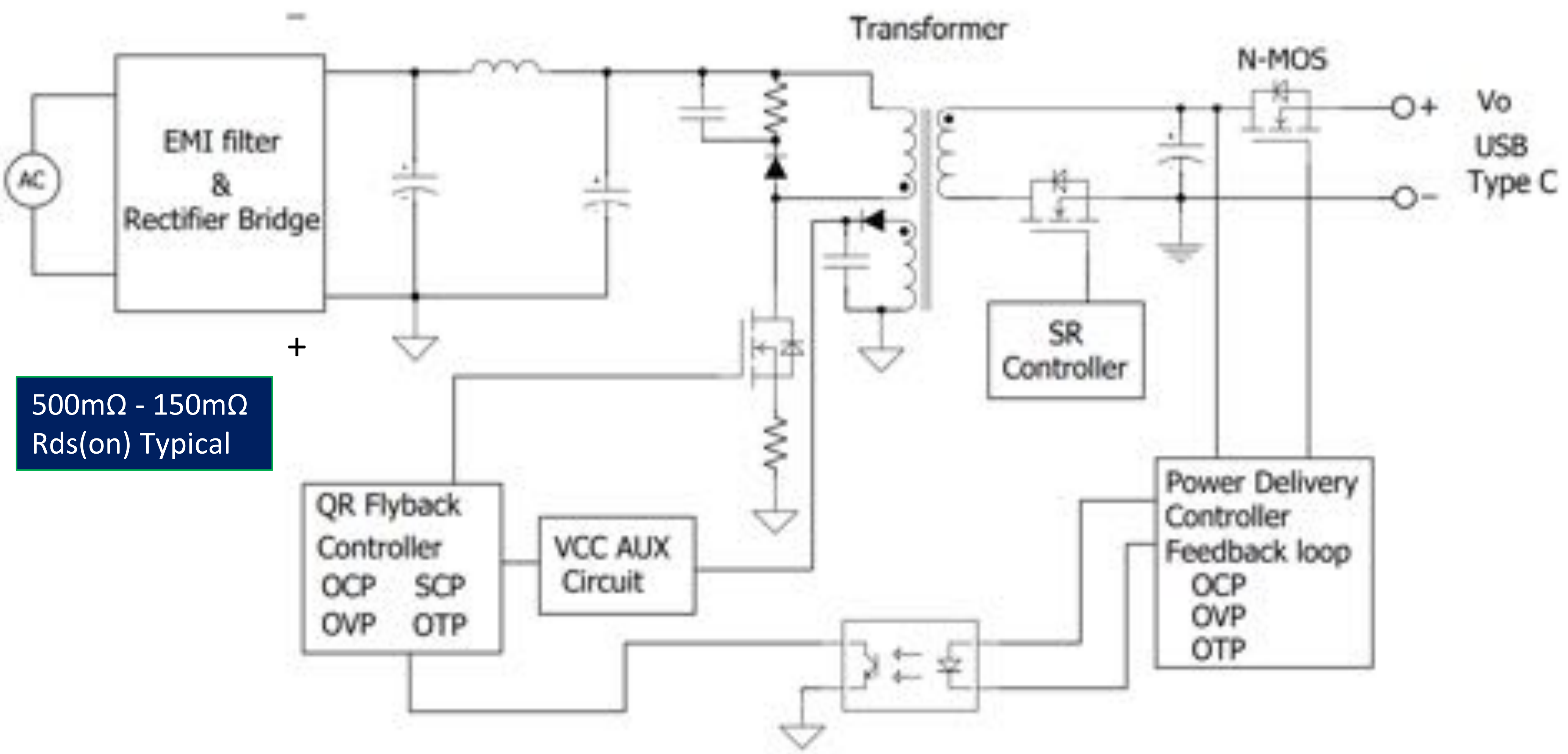
USB-C Adapters (<70W Considerations)

- Almost every power IC company has developed flyback controller ICs to address this market
  - Typical low-side flyback block diagram
  - Primary side controller and synchronous rectification (SR)
  - Simple and well understood implementation
  - Controller architecture, sensing of valleys, timing differs and gives the competitive advantage



30W-65W Adapter Block Diagram

(Using Quasi-resonant Flyback Topology)



500mΩ - 150mΩ
Rds(on) Typical

QR Flyback, ACF Designs from Transphorm

45W Single Board - QRF

Input	Iout	Eff %
90 Vac @ 50 Hz	2.25A	92.53%
115 Vac @ 60 Hz	2.25A	93.90%
230 Vac @ 50 Hz	2.25A	93.78%
265 Vac @ 50 Hz	2.25A	93.43%
Density 24W/in^3		

65W Single Board - QRF

Input	Iout	Eff %
90 Vac @ 50 Hz	3.25A	93.04%
115 Vac @ 60 Hz	3.25A	94.04%
230 Vac @ 50 Hz	3.25A	93.85%
265 Vac @ 50 Hz	3.25A	93.46%
Density 25.4W/in^3		

65W Multiple Boards - QRF

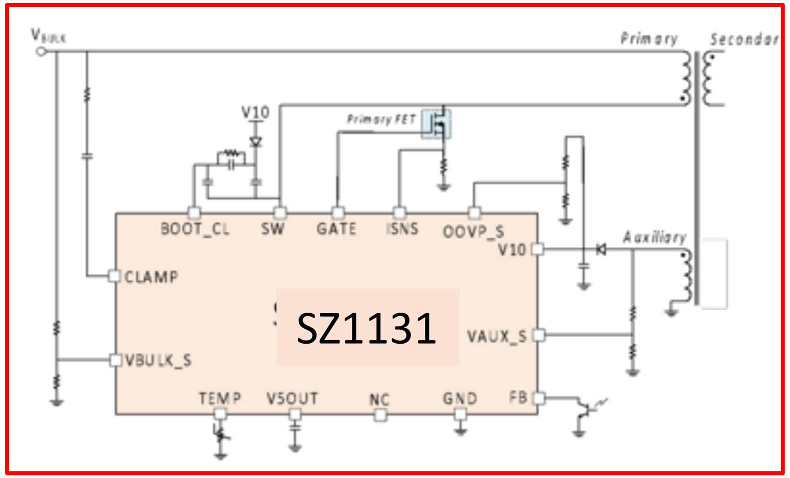
Vin	Iout	Efficiency (%)
90 Vac @ 50 Hz	3.25A	92.21%
115 Vac @ 60 Hz	3.25A	93.14%
230 Vac @ 50 Hz	3.25A	92.66%
265 Vac @ 50 Hz	3.25A	92.36%
Density 32W/in^3		

65W Multiple Boards - ACF

Input	Iout	Eff %
90 Vac @ 50 Hz	3.25A	93.05%
115 Vac @ 60 Hz	3.25A	94.06%
230 Vac @ 50 Hz	3.25A	94.53%
265 Vac @ 50 Hz	3.25A	94.36%
Density 29.8W/in^3		

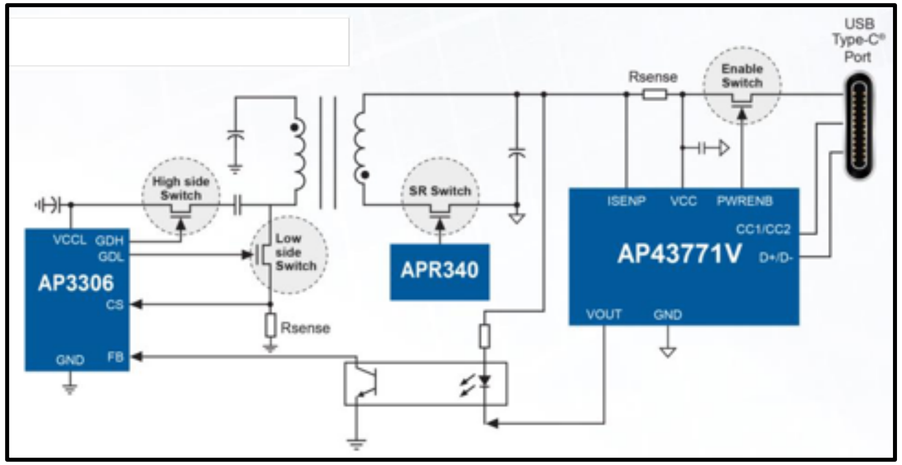
Best-in-Class Active Clamp Flyback Solutions

Silanna and Diodes Solutions deliver over 94% efficiency @ >30W/in³



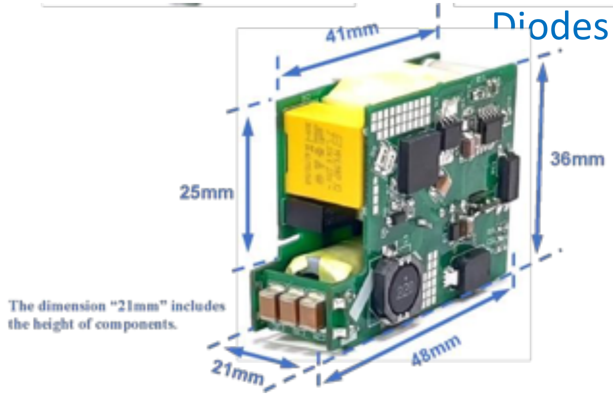
Most Integrated AC Flyback Controller
Improves efficiency, power density & EMI

Silanna – SZ1131



High-side PFET based AC Flyback Controller, lowers cost & complexity

Diodes – AP3306



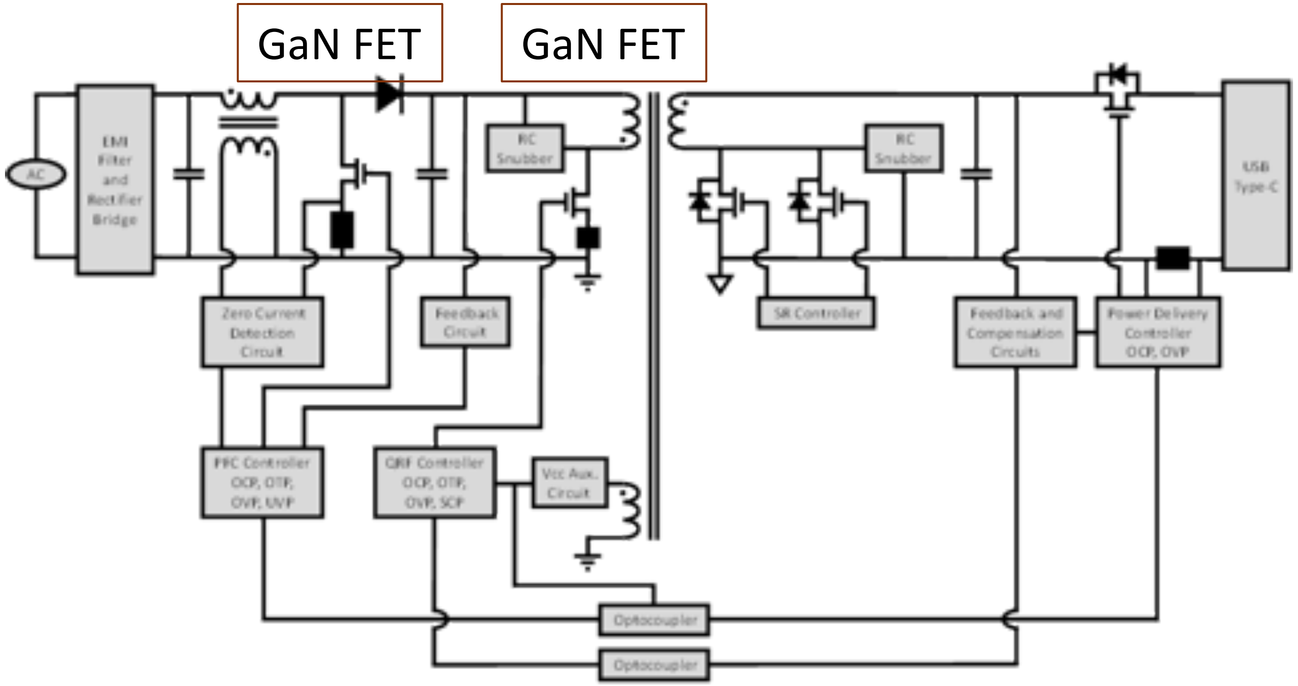
AP3306 – Flexible Active Clamp Flyback (ACF) Controller

65W 1C ACF + GaN Reference Design

- 94% peak efficiency
- < 30mW non-load power
- >31W/ inch3 (uncased) power density
- Full EMI compliant design

USB-C Adapters (>70W Considerations)

- Several different power levels 75W to 250W, especially with the new USB-C 3.1 extended range protocol
- IEC 61000-3-2 is mandatory (with exceptions)
- Only a single stage topology such as QR or AC Flyback used in <75W cannot be applied
- Two stage topology is most common as shown below – variations discussed later



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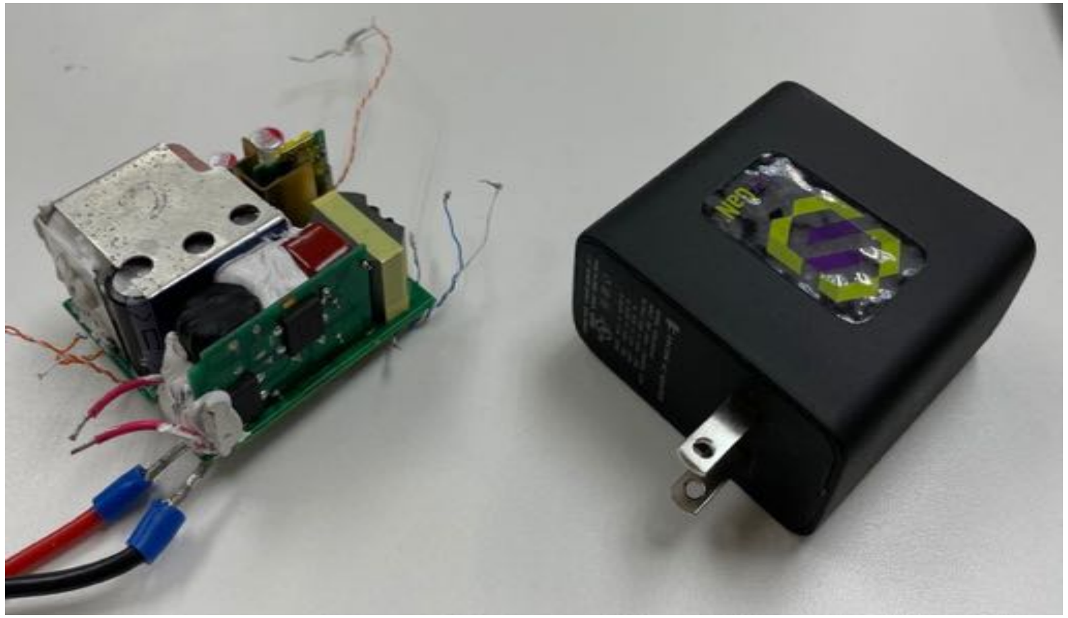
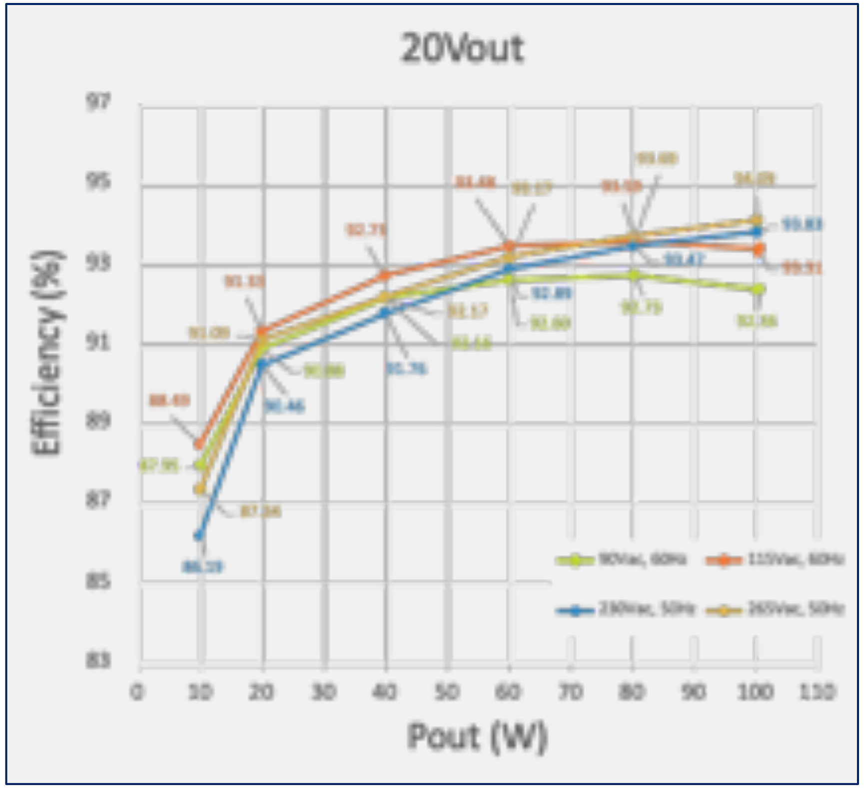
100W – Low-cost, High Efficiency Design

Using 150mΩ & 240mΩ TPH GaN – 16W/in^3

Highlights:

- Qualified to Qualcomm QC-5 fast charge standard
- CRM PFC Boost + QR Flyback Topology
- Passes conducted & Radiated EMI
- Can be modified for 1C + 1A or 2C…
- Turnkey design with case design

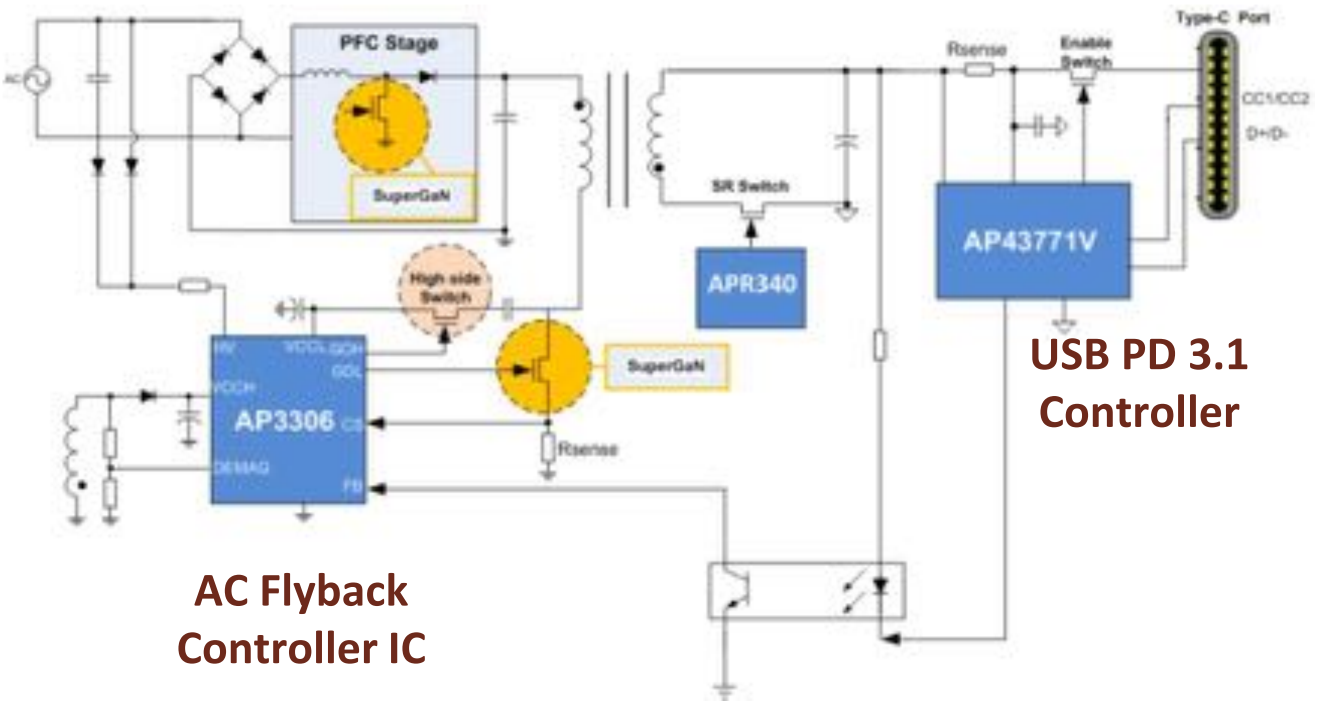




Excellent Efficiency vs. Line Voltage & Load
94% peak @ 265V & over 92% @ 90V

USB-C Adapters (90W to 150W Considerations)

- Active-clamp flyback following the PFC stage is preferred up to 140W, eg. shown below
- USB PD 3.1 pushes power to 140W and voltages to 28V max
- Allows wider voltage range adjustment compared to half-bridge LLC, especially with USB3.1
- This topology will be compared with an ultra-flexible digital control topology used in the Apple 140W USB-C adapter *(source: www.chargerlab.com)*



https://www.diodes.com/applications/ac-dc-chargers-and-adapters/quick-chargers/#accordion-second-item

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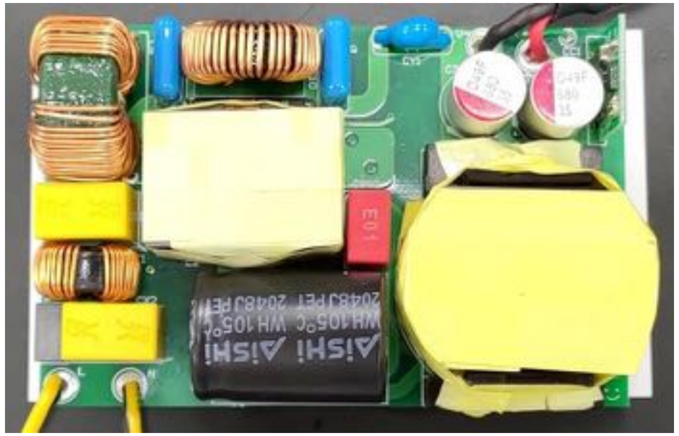
Transphorm 140W USB-PD 3.1 Design Performance



Diodes 140W 28V@5A Prototype Dimension:

- W:55mm, L: 87mm, H:29mm (139 C.C.) – PCB only
- W:59mm, L: 91mm, H:33mm (177 C.C.) – with Case (+2mm each side)

Diodes+TPH solution uses Bridge, can use SR MOSFET to improve low input line Efficiency

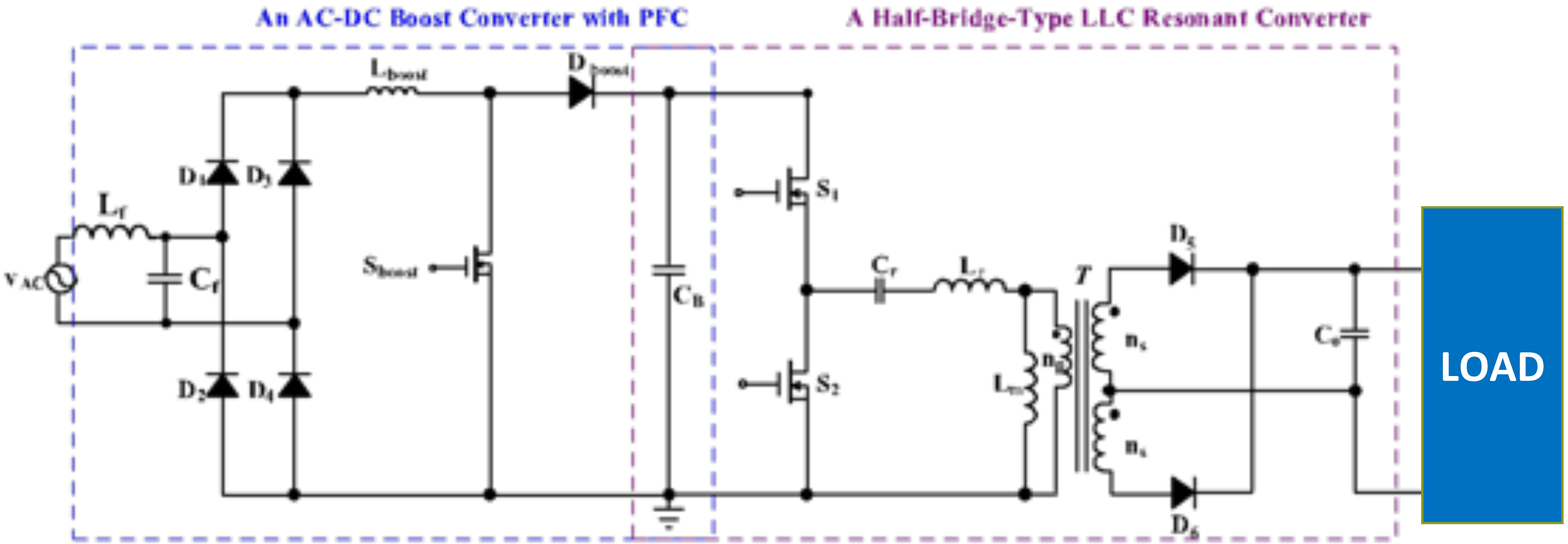
Vin (Vrms)	Input Freq. (Hz)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	Pd (W)	Effi. (%)	Avg. Effi. (%)
90Vac	60	154.21	28.74	5	143.69	10.525	93.17%	
115 Vac	60	152.42	28.69	5.000	143.47	8.955	94.12%	93.31%
		113.30	28.40	3.750	106.51	6.789	94.01%	
		75.56	28.21	2.500	70.52	5.046	93.32%	
		38.23	28.08	1.250	35.10	3.134	91.80%	
230 Vac	50	150.89	28.75	5.000	143.75	7.145	95.26%	94.27%
		112.24	28.49	3.750	106.84	5.403	95.19%	
		75.03	28.27	2.500	70.69	4.343	94.21%	
		37.94	28.05	1.250	35.06	2.881	92.41%	
264	60	150.09	28.64	5	143.18	6.915	95.39%	

MacBook PRO 140W using two SR MOSEFT in Bridge to improve low input line Efficiency

Vin (Vrms)	Input Freq. (Hz)	Pin (W)	Vout (V)	Iout (A)	Pout (W)	Pd (W)	Effi. (%)	Avg. Effi. (%)
90Vac	60	149.15	27.99	5	139.94	9.210	93.83%	
115 Vac	60	148.10	27.99	5.000	139.94	8.160	94.49%	93.66%
		111.15	28.02	3.750	105.07	6.083	94.53%	
		74.55	28.05	2.500	70.12	4.427	94.06%	
		38.34	28.08	1.250	35.10	3.241	91.55%	
230 Vac	50	147.14	27.99	5.000	139.96	7.185	95.12%	93.47%
		110.83	28.02	3.750	105.09	5.744	94.82%	
		74.80	28.05	2.500	70.14	4.665	93.76%	
		38.92	28.08	1.250	35.10	3.816	90.19%	
264Vac	50	147.32	27.99	5	139.95	7.370	95.00%	

Computer, Display Power Supplies & LED Drivers

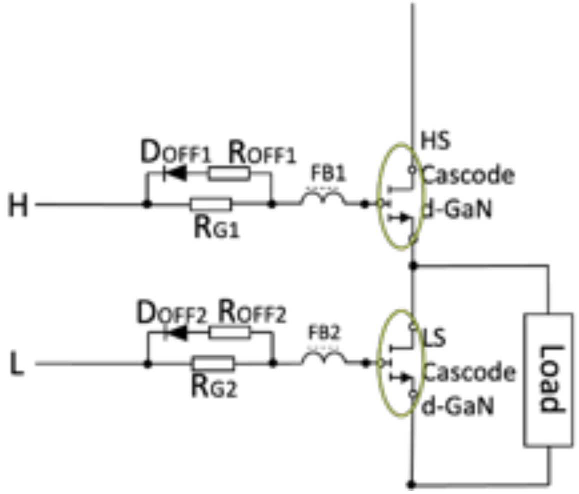
- For >150W (or even lower levels) up to 1kW (or higher), power factor correction followed by a half-bridge resonant topology is implemented
- Advantages of LLC resonant topology include:
  - ZVS, which produces high efficiency and allows shrinking transformer
  - Limits dv/dt and di/dt, which reduces ringing, spikes and radiated EMI problems

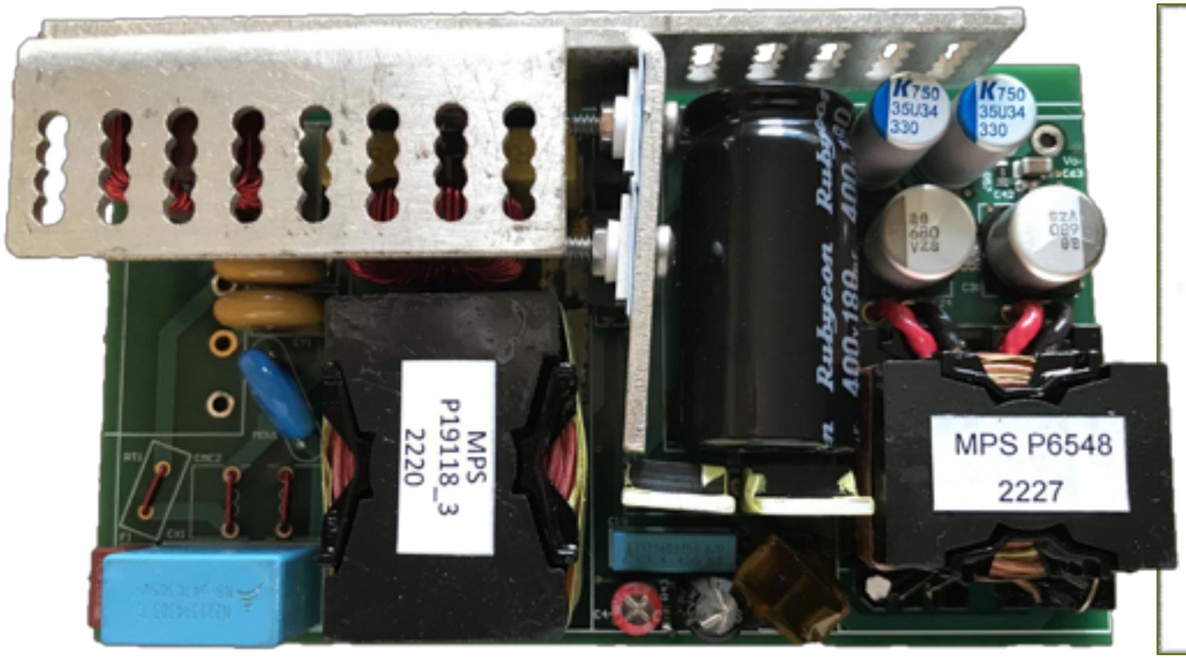


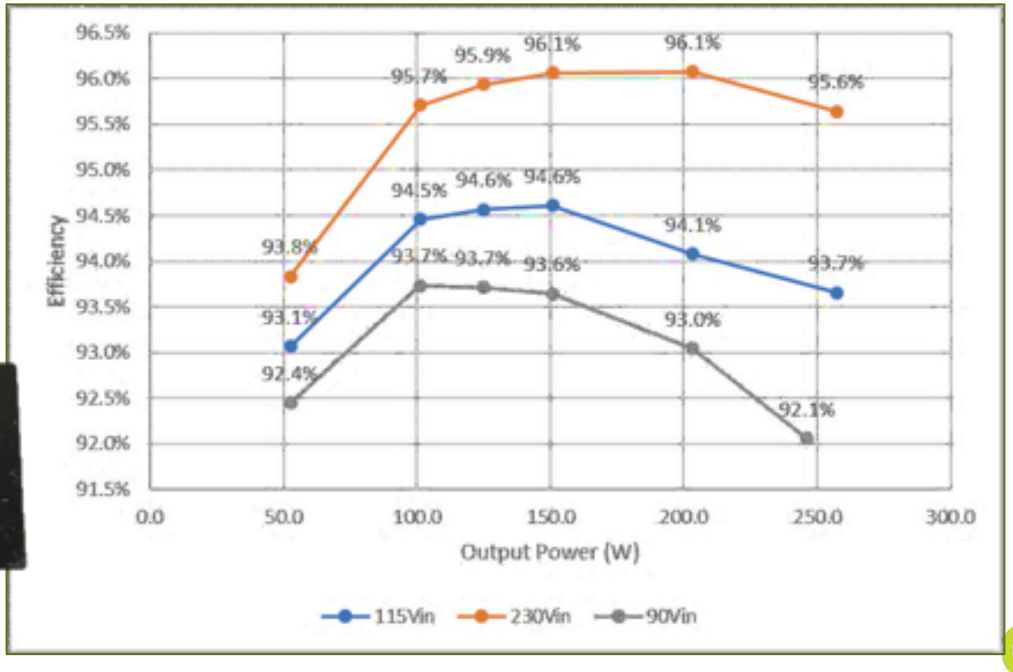
250W Solution & d-GaN Drive Considerations

Works with any controller with Si Gate Drivers

- Vin = 90 – 265Vac, Vo = 24V, Po = 250W
- Switching frequency: 133kHz(PFC), 172-180kHz(LLC)
- Board dimensions: 110mm*60mm*25mm (4.3” x 2.35” x 1”)
- High Power density: 24.8W/in^3 – significantly higher than silicon
- Over 96% total system peak efficiency at 230V AC input



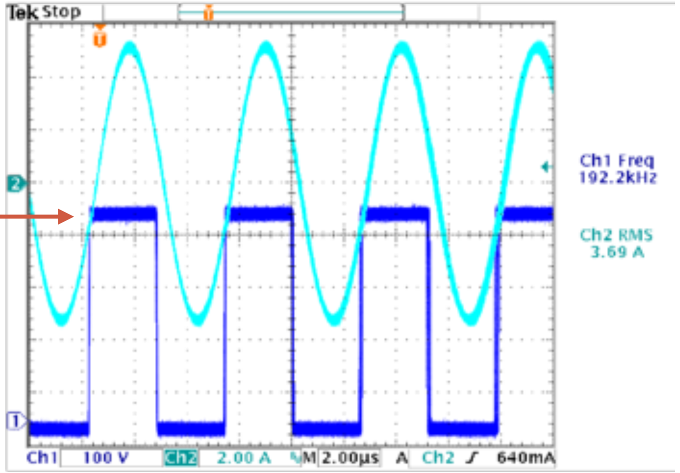


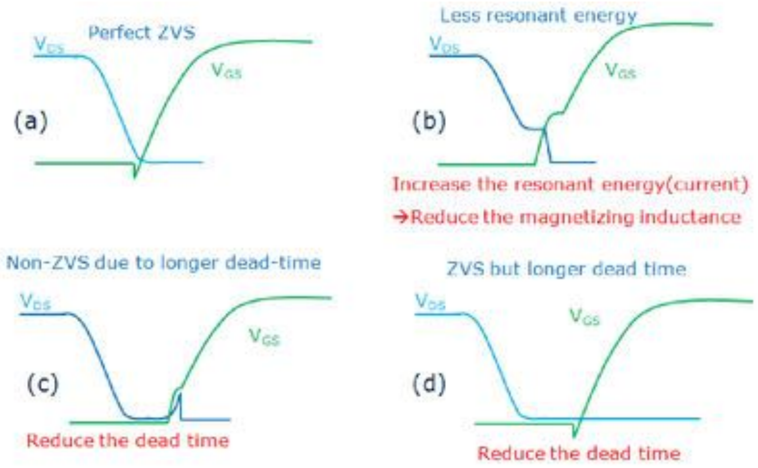


Notes & Results for a Half-Bridge LLC using GaN

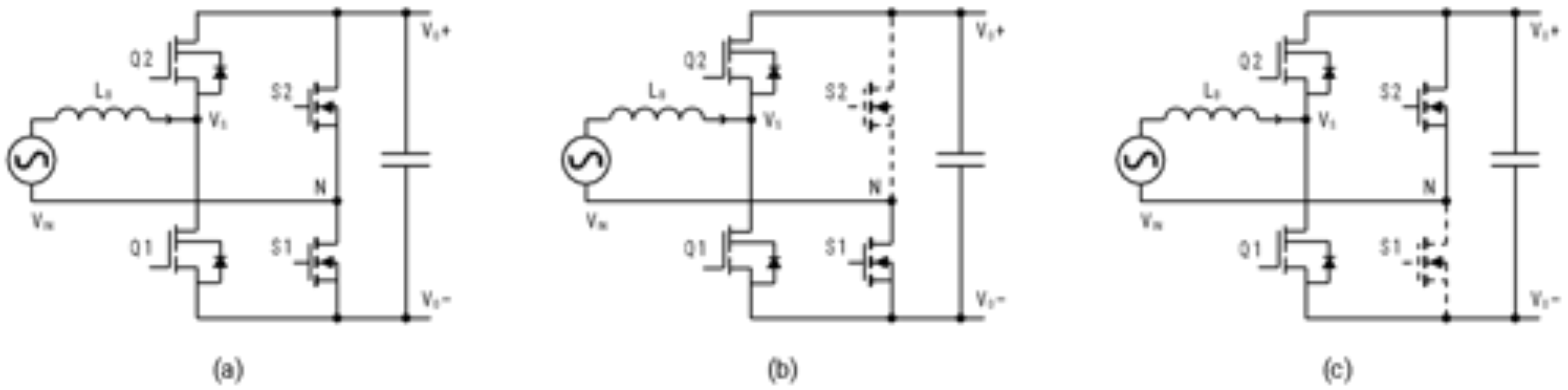
- Keeps stress on the bridge switches below 500V, compared to QR flyback and ACF flyback, thus making it is ideal for GaN
- Achieves ZVS switching, which begs the question, why is GaN preferred over Super Junction MOSFETs
- Both efficiency and size can be optimized by taking advantage of the superior reverse recovery Qrr and Coss of the GaN devices

Vds - 500V





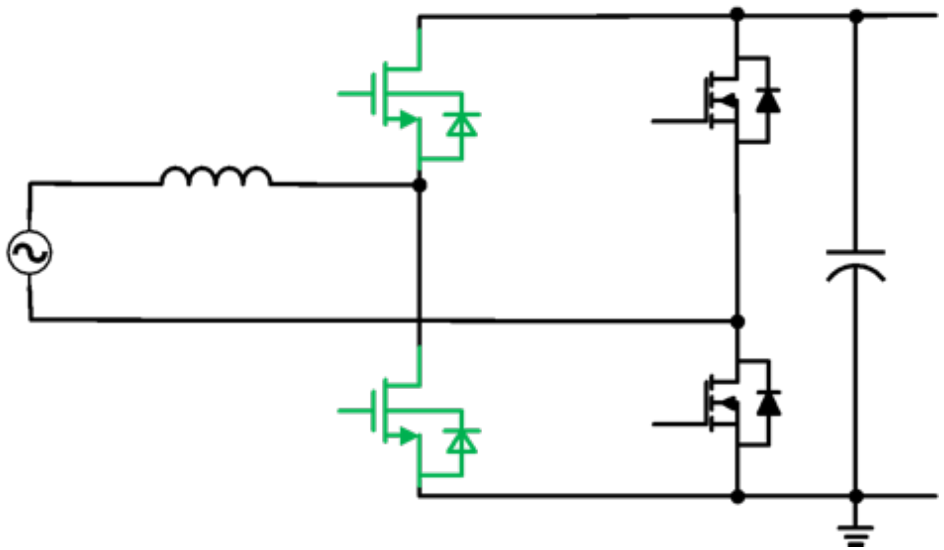
GaN Totem Pole Bridgeless Boost PFC Notes

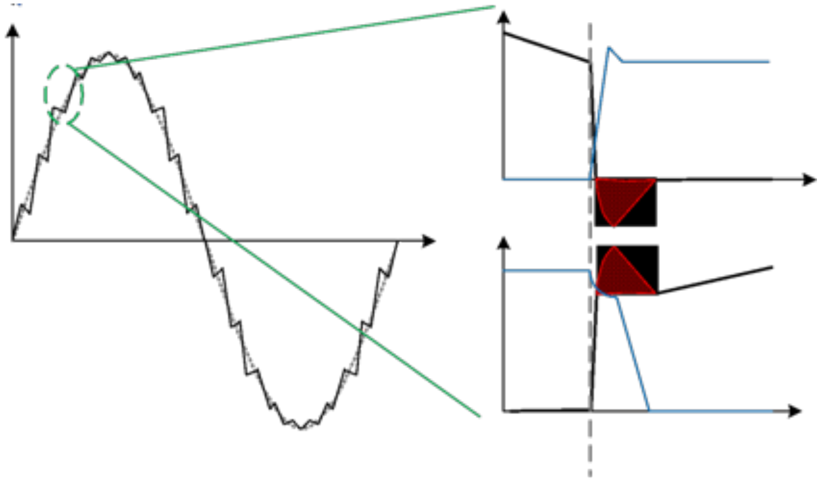


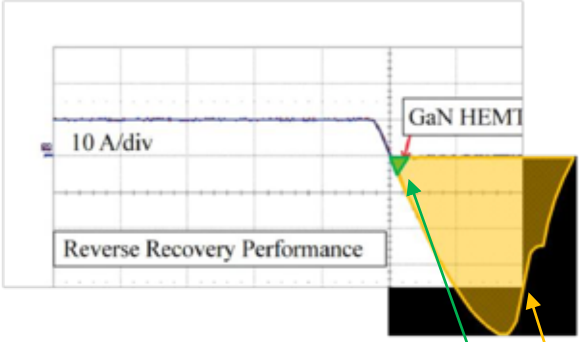
https://www.transphormusa.com/en/document/tdttp2500p100-kit-user-guide/

- Q1 & Q2 are two fast switching GaN FETs, operating at high PWM frequency
- S1 & S2 are low resistance MOSFETs operating at a slower line frequency
- The GaN Devices form a **synchronous boost converter** with one device acting as master to allow energy intake from the inductor and another to release energy to the DC output
- The roles of the GaN devices interchanges when AC polarity reverses
- Low Qrr of GaN and body diode of D-mode Cascode devices allows for CCM operation and avoids abnormal spikes, instability and high losses of Silicon MOSFETs.

Totem Pole Bridgeless AC-DC PFC converter







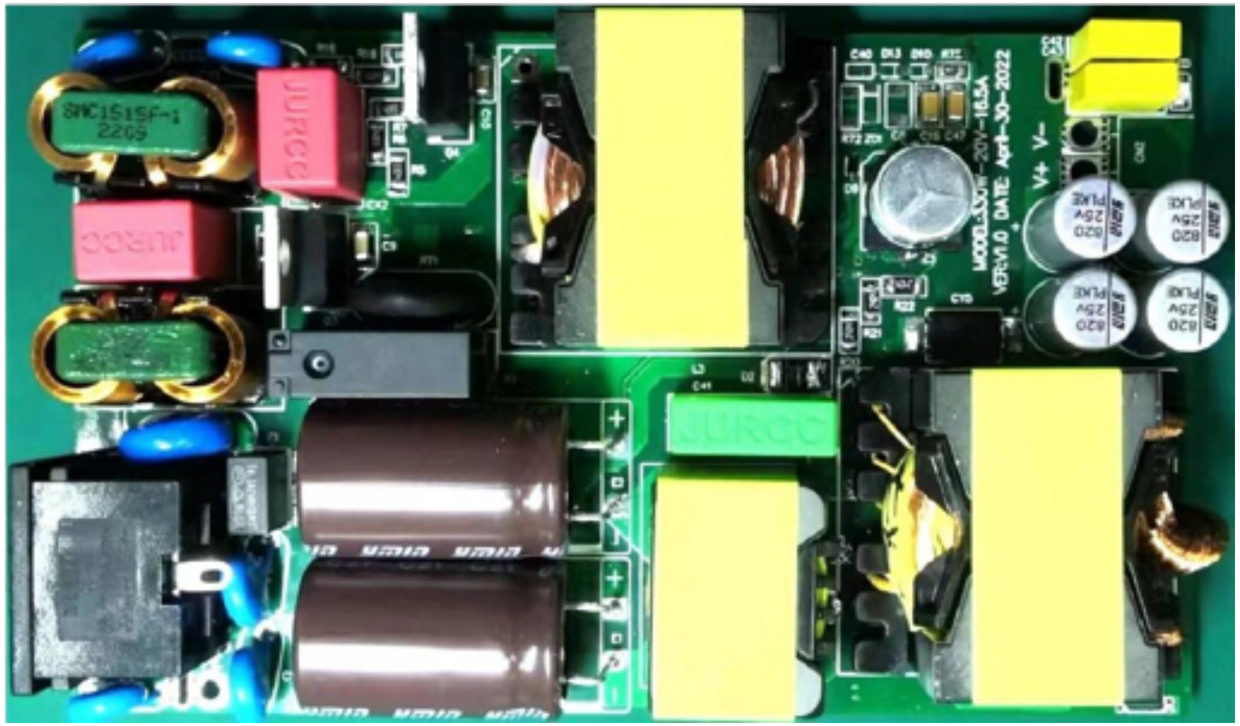
- Why Q1, Q2 must be GaN instead of SJ FETs?

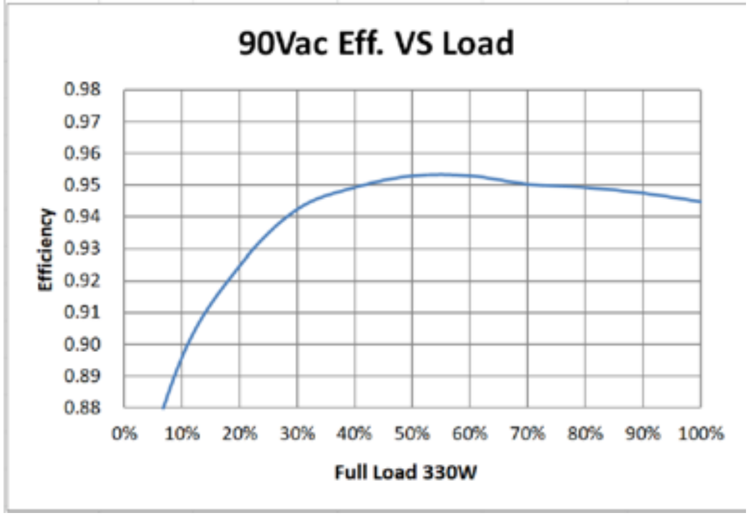
Because for CCM(continuous current mode) PFC, Q1 and Q2 will be hard switched turn-on, the Qrr related loss is huge for Si-MOSFET.

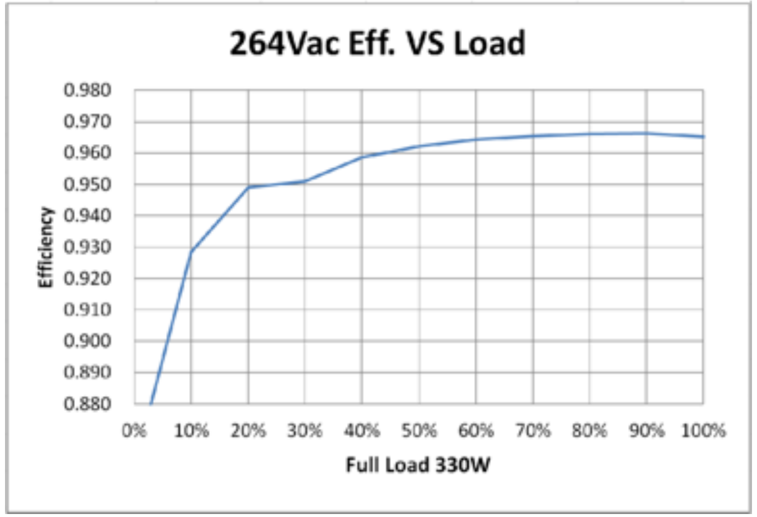
The Qrr in GaN HEMT is 20 times smaller than the state-of-the-art Si-MOSFETs, leading to much less power losses.

Q1, Q2	Rds(on)	Qrr	FOM(Rds*Qrr)
TP65H035G4WS	35 mΩ	150 Nc	1
IPW60R040C7	40 mΩ	9200 nC	70
IPW60R031CFD7	31 mΩ	960 nC	5.67

330W Platform using Totempole PFC







Power Density ~ 23.11W/in^3 (L=120mm, W=78mm, H=25mm;)

1) Small form-factor
2) Totem-Pole PFC and HB-LLC Topology
3) Over 96.5% peak efficiency
4) Improves efficiency at 90Vac by >1.5%

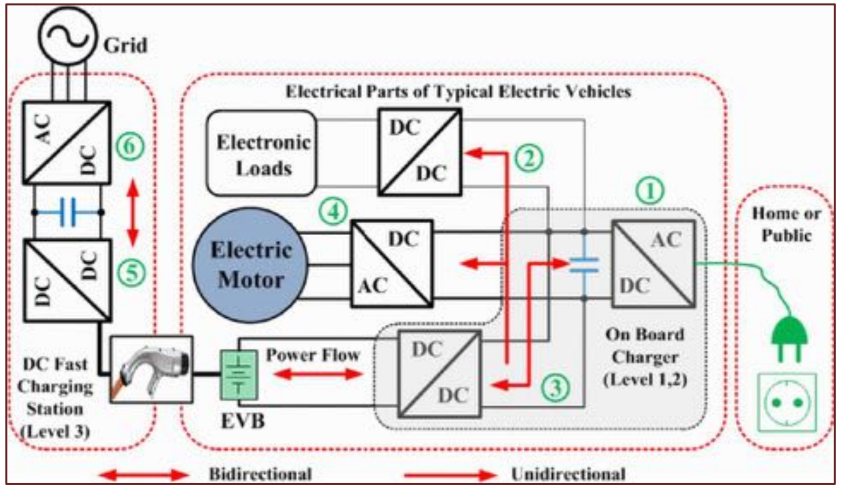
Solutions for 600W to 6.6kW Applications

Servers, LED lighting, Telecom, EV 2/3 Wheelers, UPS

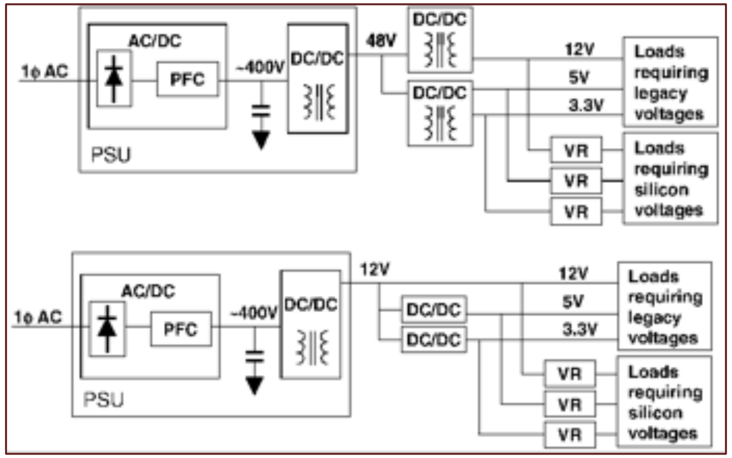
Variations of the PFC and Bridge Topologies

Powering Electric 2/3W, Servers and LED Lighting

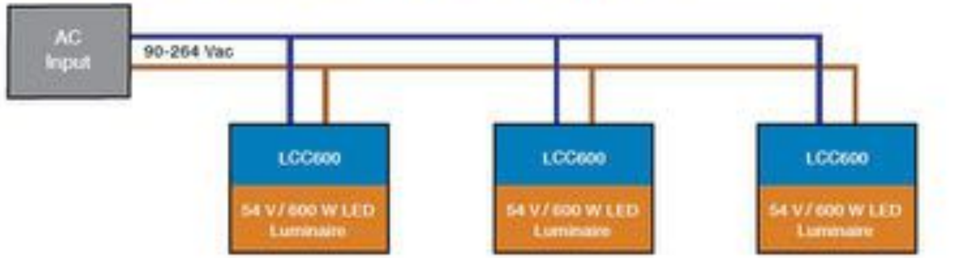
Electric 2/3W Power Architecture

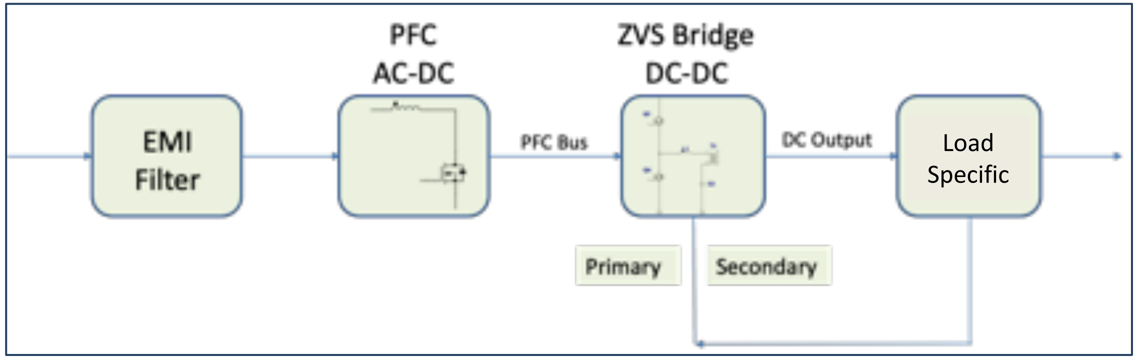


Datacom Server Power Architecture



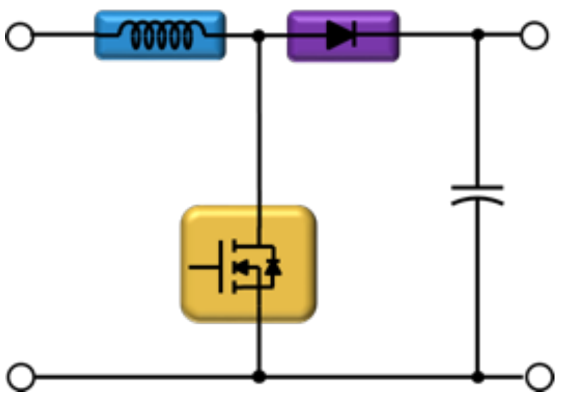
High Power LED Lighting – High Bay & Horticulture

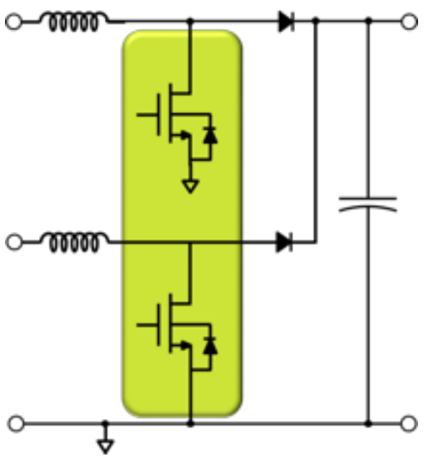


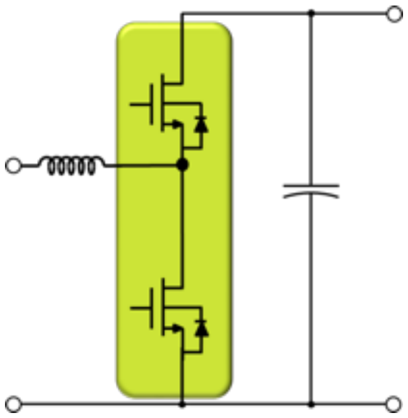


Strategies for Power Factor Correction

Standard Boost	CRM Interleaved	Synchronous Boost
Hard switching	Transition mode (soft switching)	Hard Switching (no diodes)
1 choke	2 chokes, FETs and diodes	1 choke
Requires SiC diode	Can use low-cost low Vf Si diodes	Uses hi-side syncFET as diode
Lower Efficiency	Higher Efficiency	Higher Efficiency
Lower Switching Frequency	Highest Switching Frequency	Higher Switching Frequency
Higher Output Ripple Current	Lower Output Ripple Current	Higher Output Ripple Current







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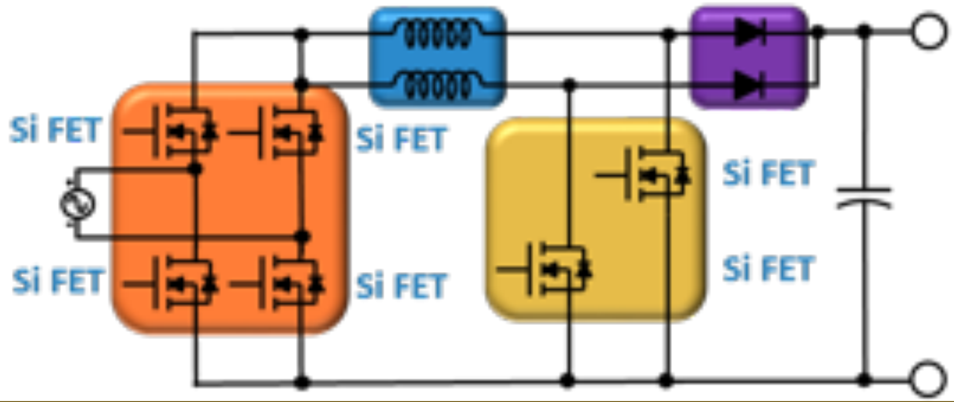
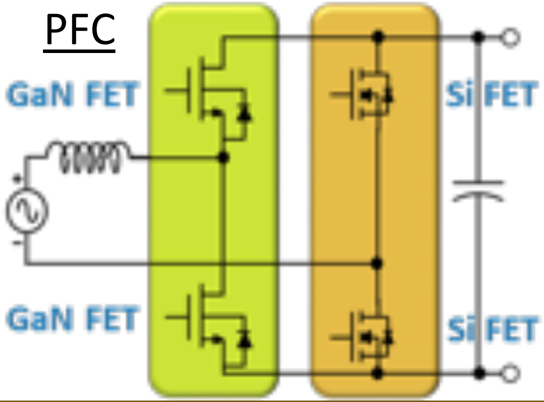
GaN Value Demonstration vs. Super Junction FETs

- **3.3**kW power supply
- Competition: Superjunction (silicon)
- Result: Higher efficiency, lower BOM cost
  - Reduction in part count, magnetics, EMI filter

Active Bridge Interleaved PFC



Totem Pole Bridgeless PFC



Parameter Results	Interleaved PFC	Bridgeless Totem Pole PFC
Efficiency	98.5%	98.7%
Total cost	100%	60%

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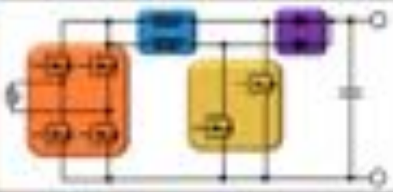
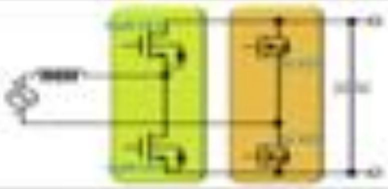
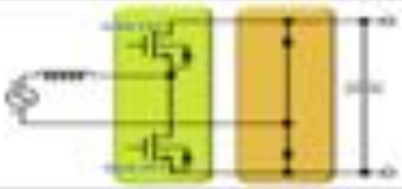
Cost and Performance Comparison (PFC)

3.3 kW AC to DC Power Factor Correction Silicon to GaN Comparison

PFC Components	Interleave PFC with Bridge	Totem pole PFC with Sync Rect	Totem Pole PFC w/Low Frequency Diodes
			
	Component Quantity	Component Quantity	Component Quantity
MCU	0	0	0
Control IC	1	0	0
DSP	0	1	1
SiC Diode	2	0	0
MOSFET Bridge (active)	4	2	0
MOSFET PFC	4	0	0
GaN FETs	0	2	2
PFC Boost Inductor	2	1	1
Current sense device	2	0	0
Current sensing	0	1	1
OP Amp	1	1	1
Gate driver PFC	2	1	1
Gate Driver Sync Rect	4	1	0
Total BOM Count	**22**	**10**	**7**
Total Cost	**0%**	**-13.1%**	**-32.5%**
Efficiency (Aux Power and EMI included)	**98.50%**	**99.10%**	**98.70%**

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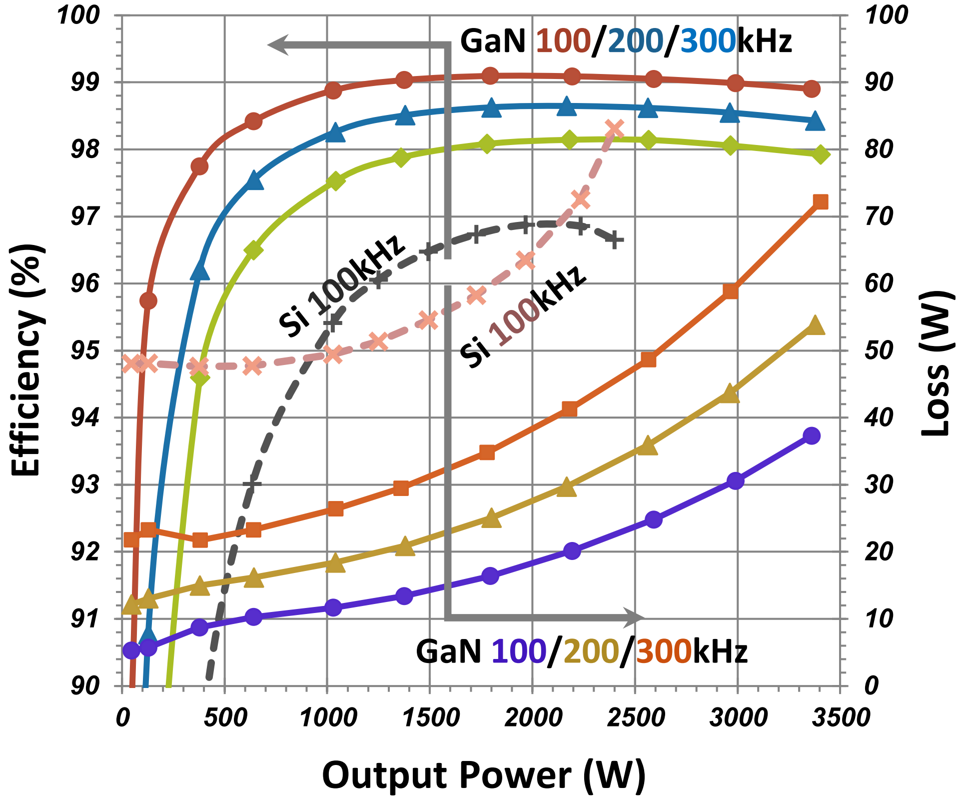
GaN vs. SuperJunction MOSFETs

(TPH 50mOhm vs. IPW65R041)

Half bridge boost converter, sync-rec, 240V:400V



2 device on 1 heat sink: R_{th}=1.27 C/W.
Inductor: L=268uH dcr=20mohm

- CFD Si CoolMOS IPW65R041 and GaN TPH 50mOhm used
- Peak Efficiency at 100kHz: Si: 96.9% vs. GaN 99.1%
- Converter Loss at 2kW: Si 65W vs. GaN 18W (device loss: 60W vs. 13W)
- Si devices reach Tj of 150 ^{o}C at 2.4kW, cannot deliver 3.3kW at 100kHz

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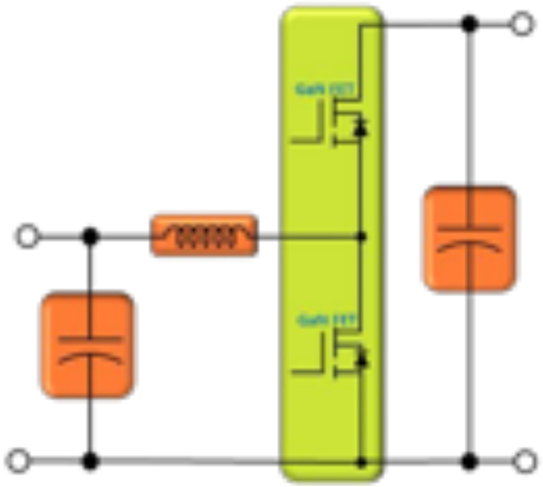
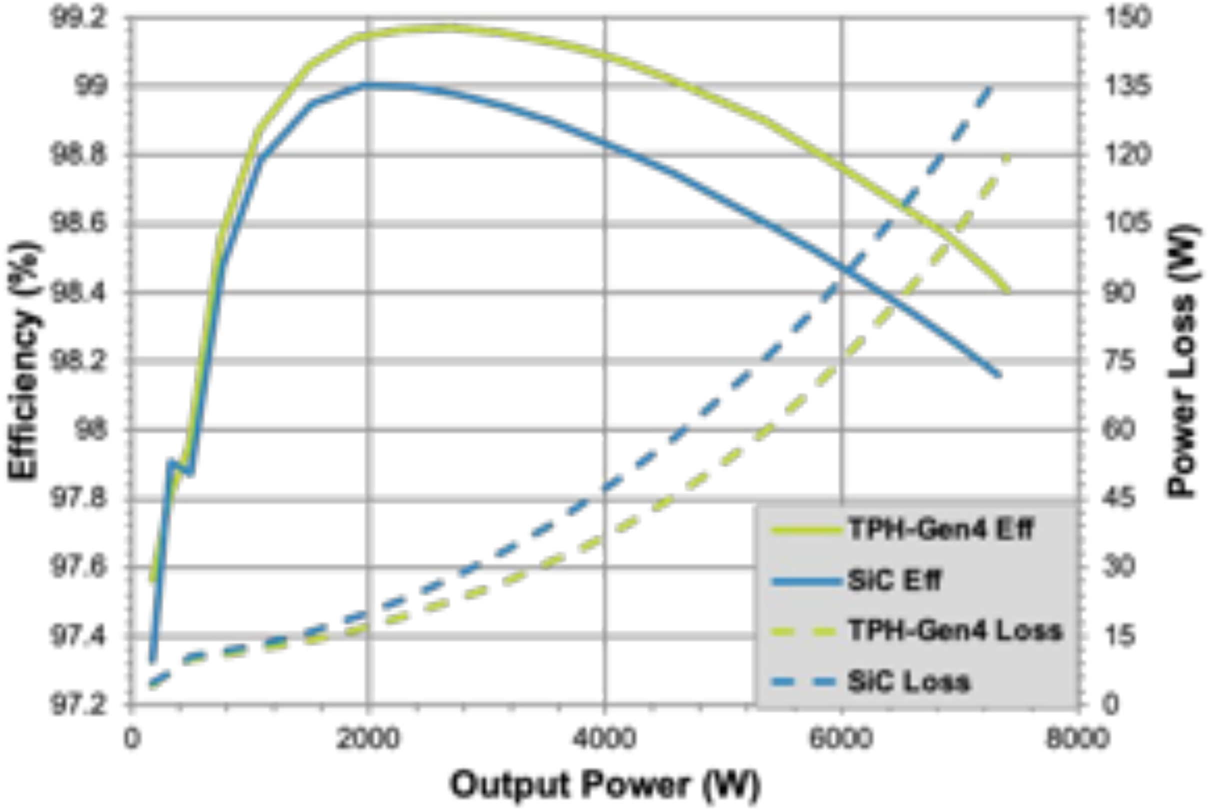
GaN vs. SiC MOSFET Comparison

GaN wins at 100 kHz: up to 20% reduction in power loss 3 kW to 7.2 kW

Half Bridge Synchronous Boost Converter		
Specification	GaN FET	SiC
On resistance @ 25°C	35 mΩ	30 mΩ
Input Voltage (V)	240	240
Output Voltage (V)	400	400
Operating Frequency (kHz)	100	100
Gate drive voltage	0 to 12 V	0 to 18 V
Gate drive resistor	30 Ω	0 Ω



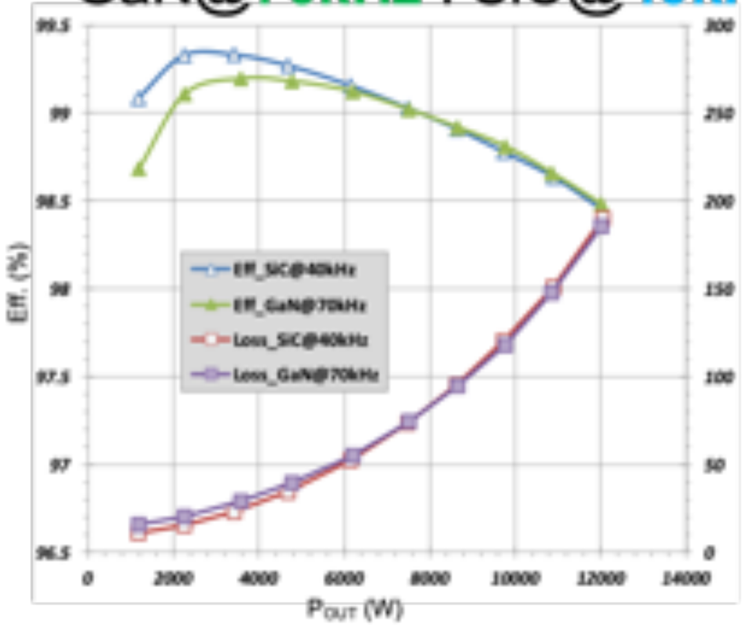


Comparable $R_{DS(ON)}$ devices at 25°C

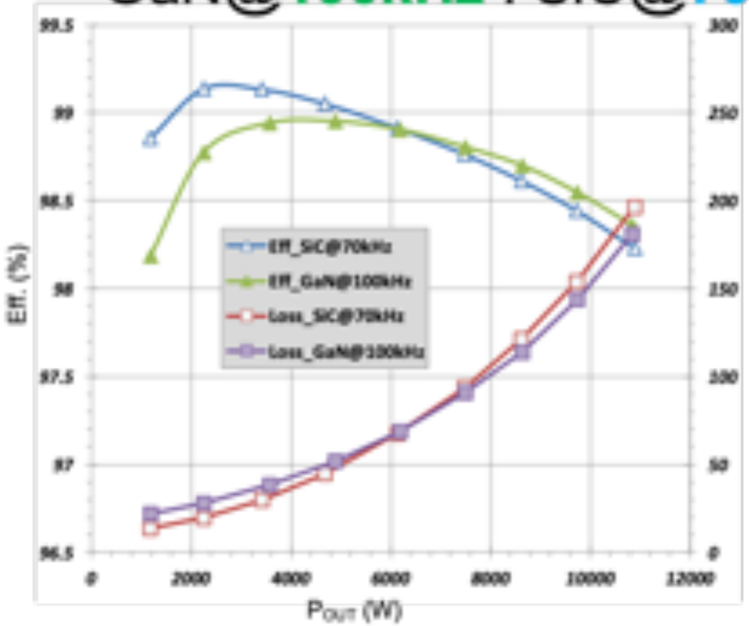
GaN vs. SiC at Various PWMs

Able to drive > 40% faster Switching and Achieve Similar Performance

GaN@70kHz : SiC@40kHz



GaN@100kHz : SiC@70kHz



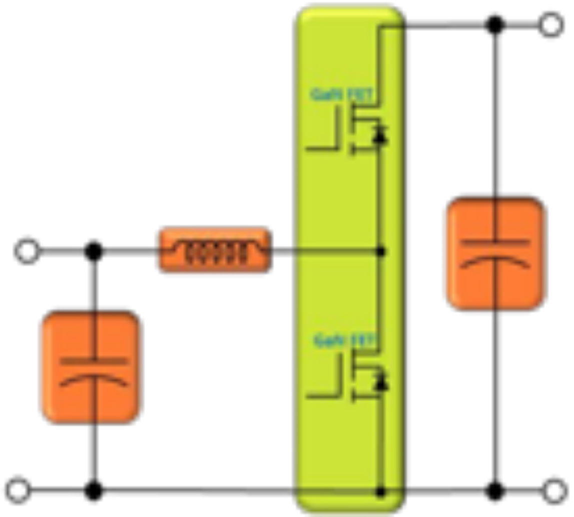
12 kW: V_{IN}:240 V, V_{OUT}: 400 V Half-bridge Synchronous Converter

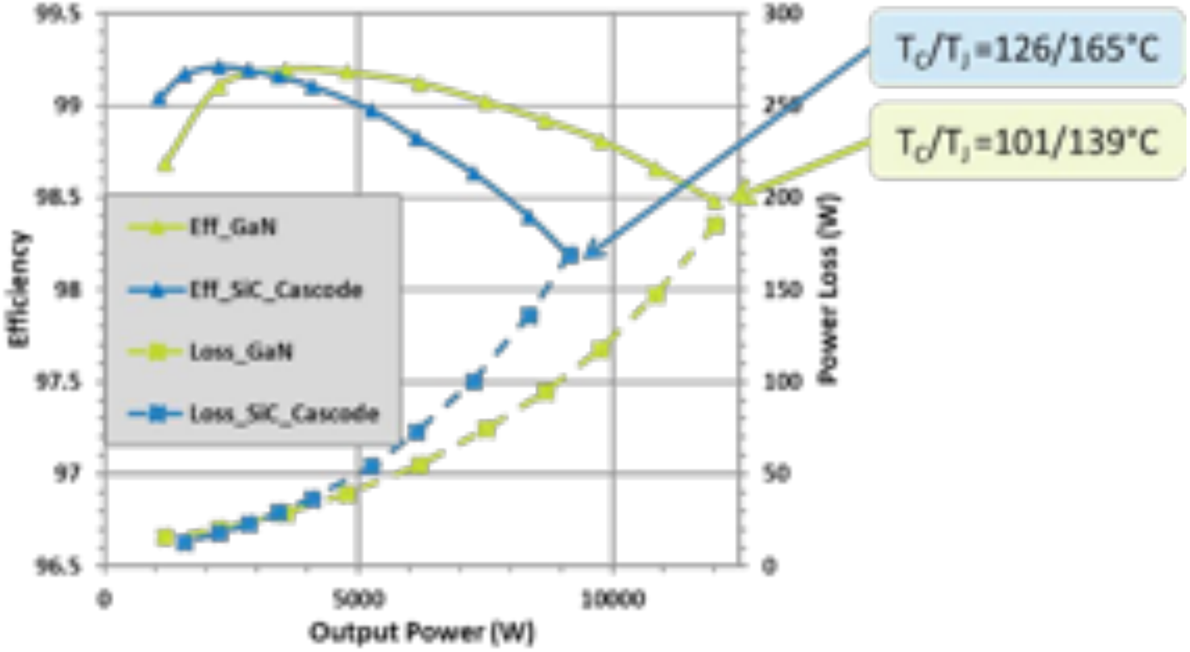
- GaN at 70kHz matches SiC at 40kHz at high power levels (75% higher frequency)
- GaN at 100kHz exceeds SiC at 70kHz at high power levels (43% higher frequency)

GaN vs. SiC Cascode FET

GaN shows up to 30% reduction in power loss at 9.2 kW

Half Bridge Synchronous Boost Converter		
Specification	GaN FET	SiC
On resistance @ 25°C	15 mΩ	18 mΩ
Input Voltage (V)	240	240
Output Voltage (V)	400	400
Operating Frequency (kHz)	70	70
Gate drive voltage	0 to 12 V	0 to 15 V
Gate drive resistor	15 Ω	0/50 Ω

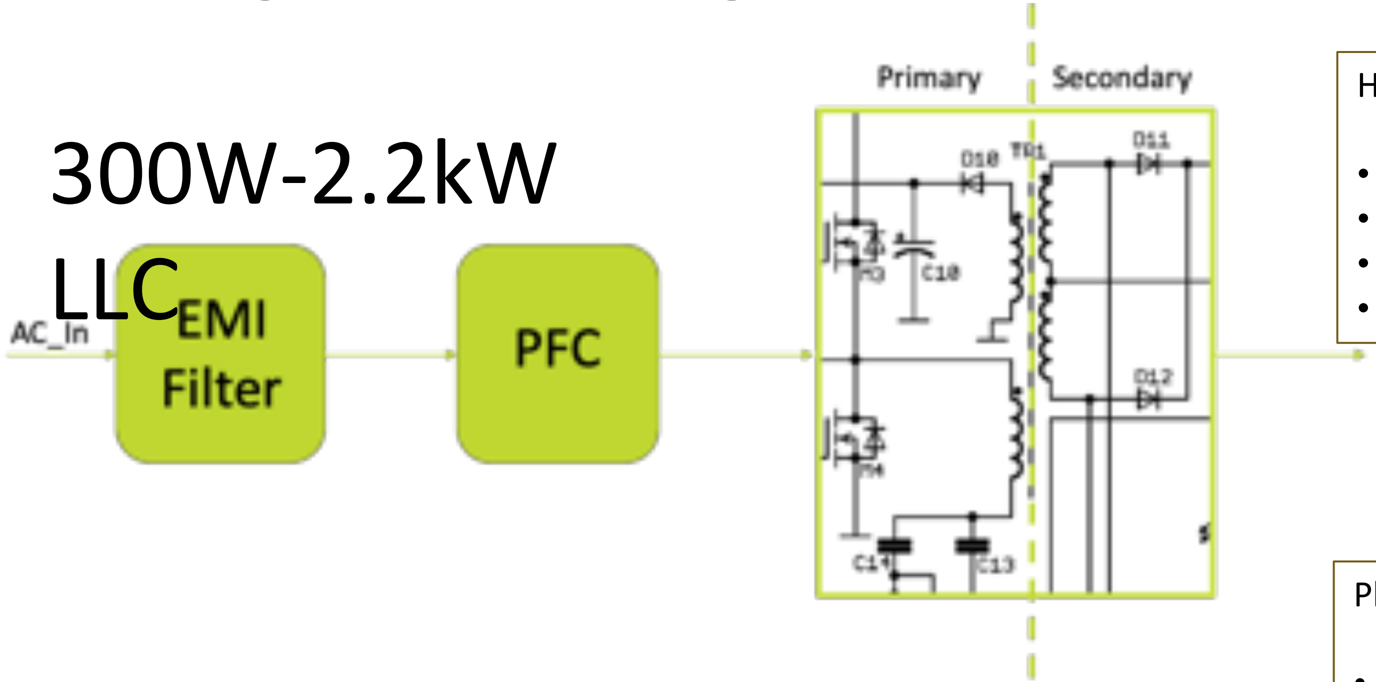




Device Power Loss Comparison at *9.2 kW
(*Limited due to SiC device junction temperature)

Strategies for Bridge Controllers in DC-DC

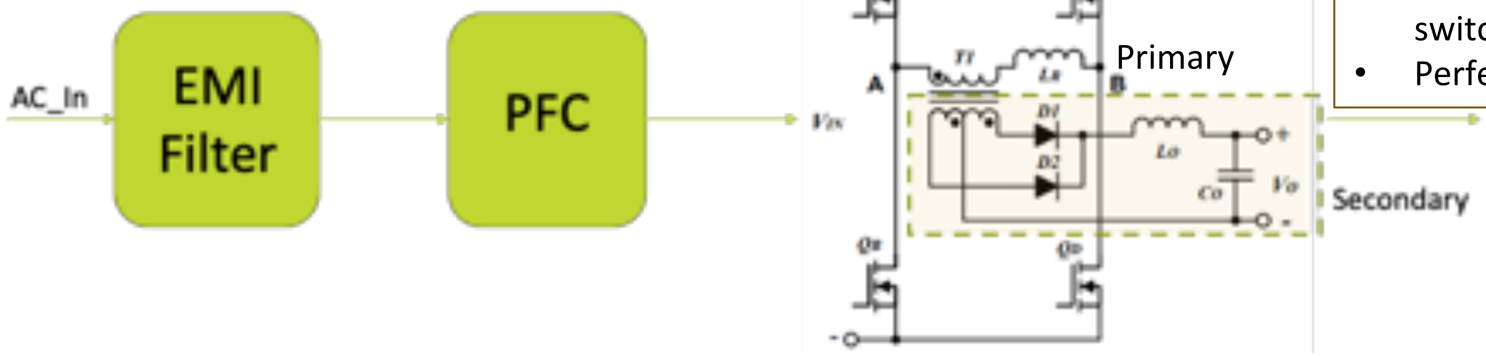
300W-2.2kW LLC



Half-bridge LLC

- Relatively Fixed O/P with fixed duty ratio
- Highest efficiency, resonant & ZVS
- Can be paralleled to do multiphase
- Another variant is resonant full-bridge

600W-6.6kW PSFB



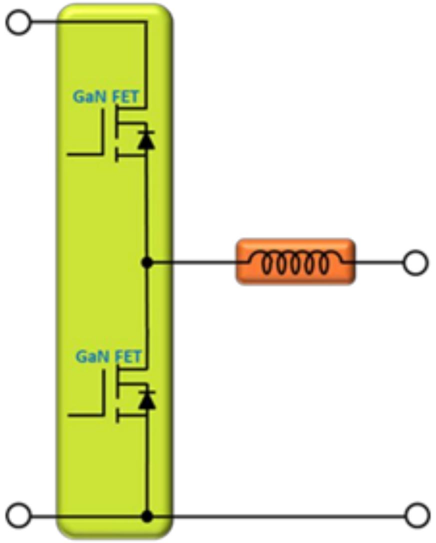
Phase-shifted Full-Bridge

- Works for wider O/P voltages
- High efficiency, due to natural ZVS
- Soft-switching at higher loads but hard switching at low loads
- Perfect for GaN!

GaN allows higher performance

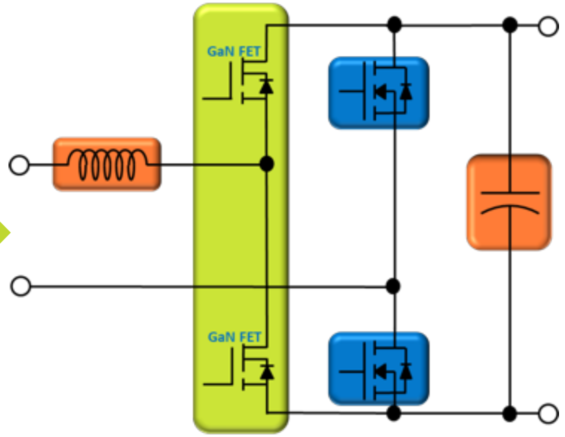
Half Bridge & Full Bridge Topologies

Basic building block to using GaN



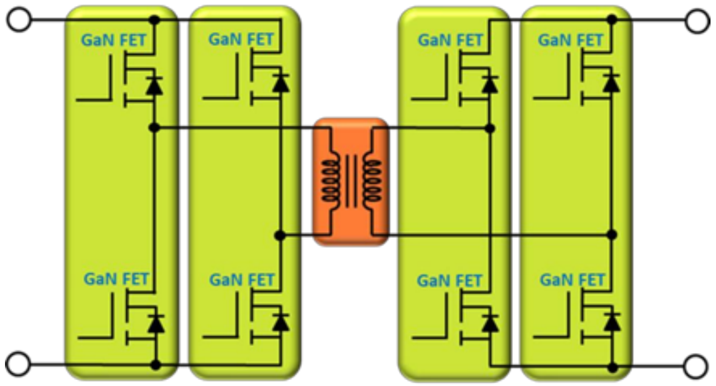
Hard Switched Standard Half Bridge

FOM
Ron * Q_{RR}
&
Ron * Q_{oss}

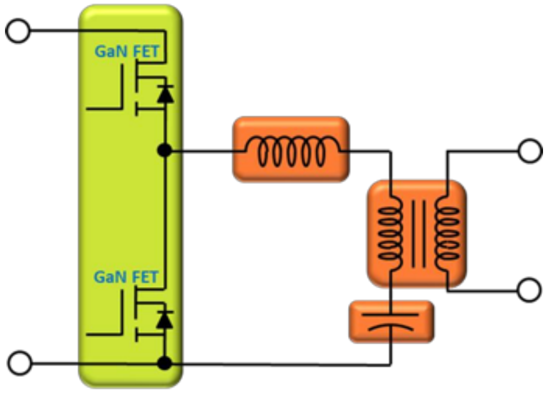


Bridgeless Totem-pole PFC (hard switched)

FOM
Ron * Q_{oss}
Bi-directional
Adv



Isolated Phase Shifted Full Bridge (PSFB)



Half Bridge (LLC)

- Half-bridge requires reverse conduction
- IGBT has no reverse conduction capability, hence needs external parallel diode
- Si MOSFET has internal body diode but has high Qrr
- GaN FETs can reverse conduct and has low Qrr: Enables diode-free H bridge

High Voltage DC-DC Output Converter

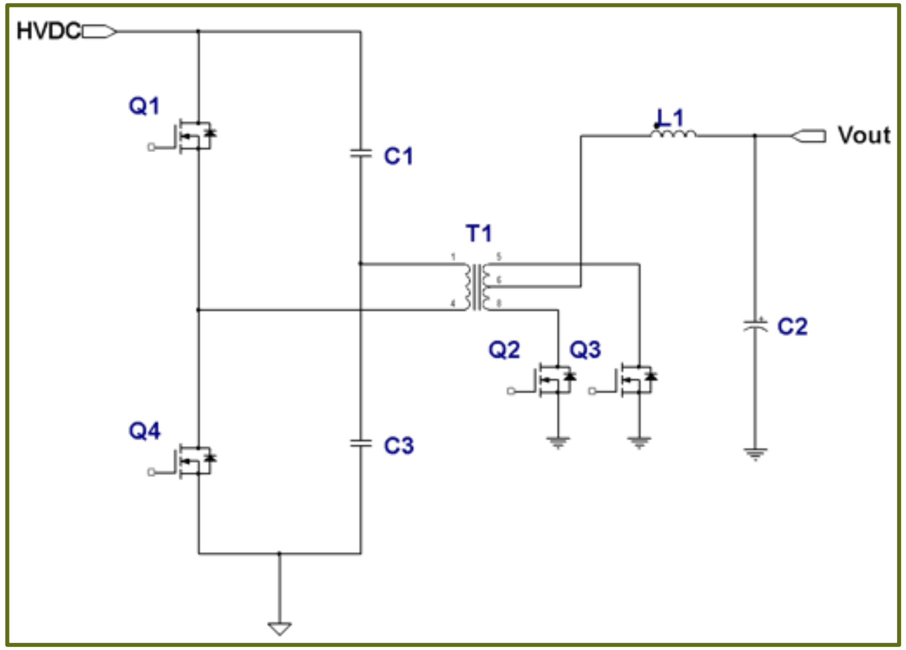
(Rdson Max for Each Topology)

Topology (By Wattage)	Pros	Cons
Resonant Half Bridge LLC (300W to 2.2kW)	ZV Switching Fewer Power Devices (2) High Efficiency	Narrow input and output voltage range Higher stress on passive components Standby power is challenging
Phase Shifted Full Bridge (600W to 12kW)	ZV Switching Highest Power Density Lower Stress on Passive components Wider input and output voltage range High Efficiency	4 Power Devices
Resonant Full Bridge LLC (600W to 10kW)	ZV Switching Higher Power Density than Resonant Half Bridge High Efficiency	4 Power Devices Narrow input and output voltage range Higher stress on passive components Standby power is challenging

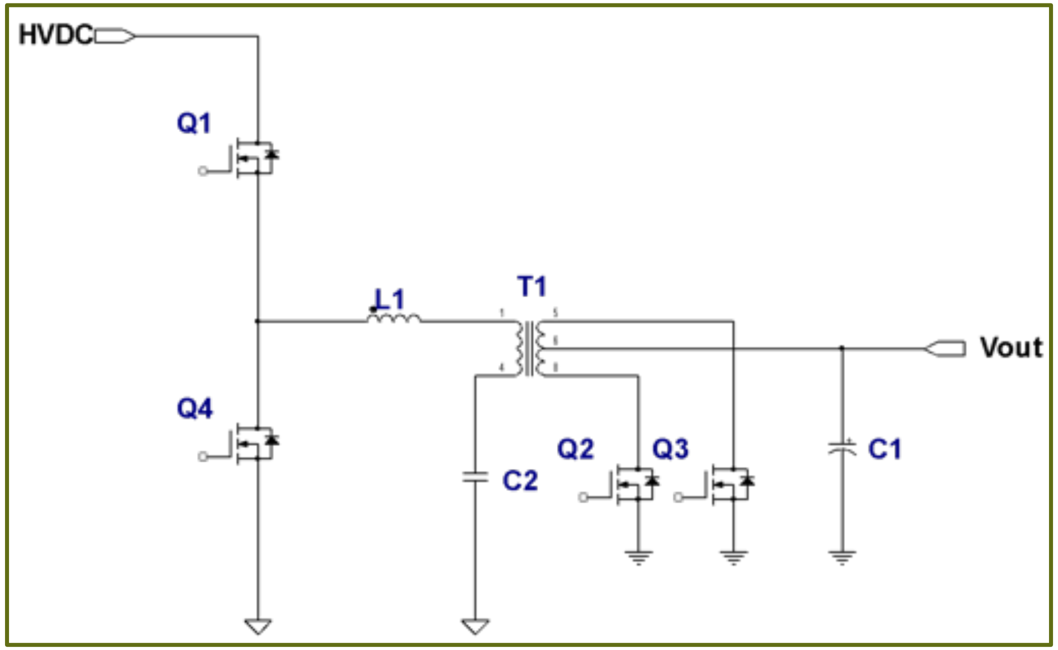
Rdson (mΩ) Max.	Half Bridge LLC Max Power	Full Bridge LLC Max Power	Phase-Shifted Full Bridge Max Power	Representative Part Number from Transphorm*
240	250W	500W	600W	TP65H300xxx
150	400W	800W	900W	TP65H150xxx
70	800W	1,600W	1,800W	TP65H070xxx
50	1,200W	2,400W	2,500W	TP65H050xxx
35	2,000W	4,400W	5,000W	TP65H035xxx
15	4,000W	8,000W	9,000W	TP65H015xxx

** GaN devices from various manufacturers are available as well*

Half-Bridge (Hard-switching & Soft-switching LLC)

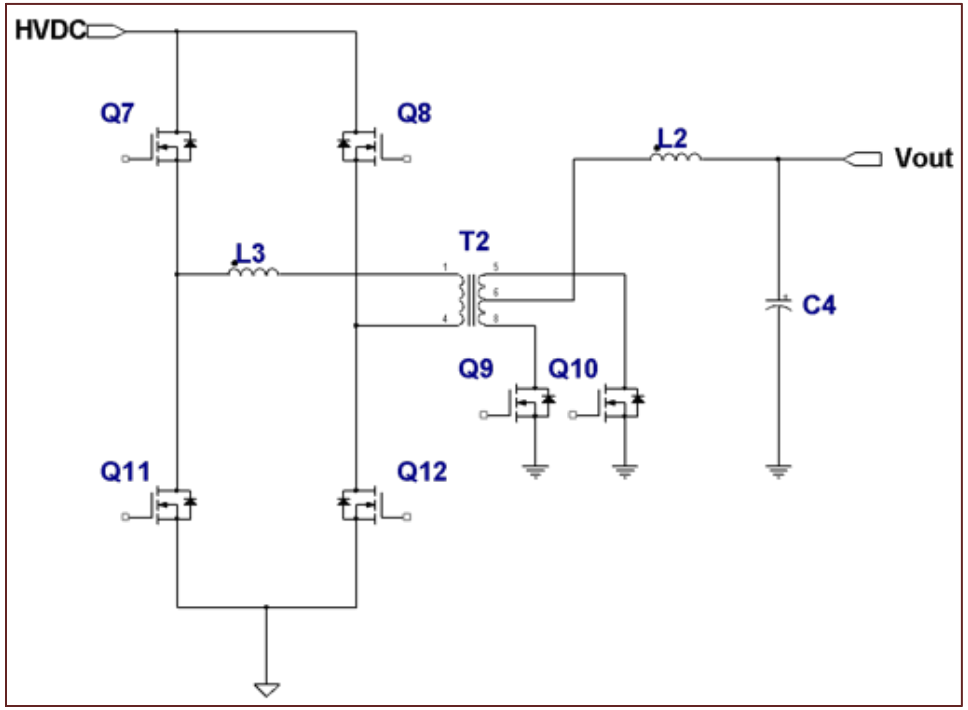


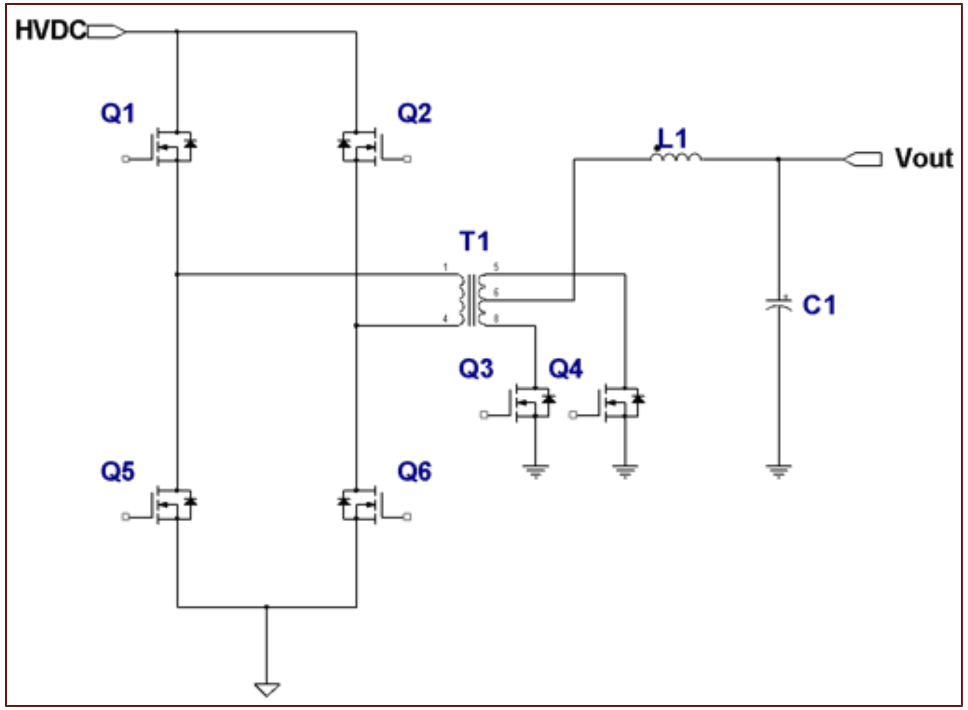
- Pros
  - Fewer power devices
- Cons
  - Higher current stress on power devices
  - Higher losses from hard switching
  - Voltage Mode control



- Pros
  - ZV Switching
  - Higher Efficiency
- Cons
  - Limited Voltage range, fixed 50% duty
  - Requires power passive components
  - Higher Current stress on power devices

Full-Bridge (Phase-shifted & Resonant LLC)





- Pros
  - ZV Switching
  - Higher efficiency & power density
  - Lower stress on passives
  - Wider input and output voltage range
- Cons
  - 4 switches

- Pros
  - ZV Switching
  - Higher Efficiency than HB with half the current stress
- Cons
  - 4 switches
  - Limited input / output voltage range
  - Higher stress on passives

Design Example of a PSFB DC-DC Converter

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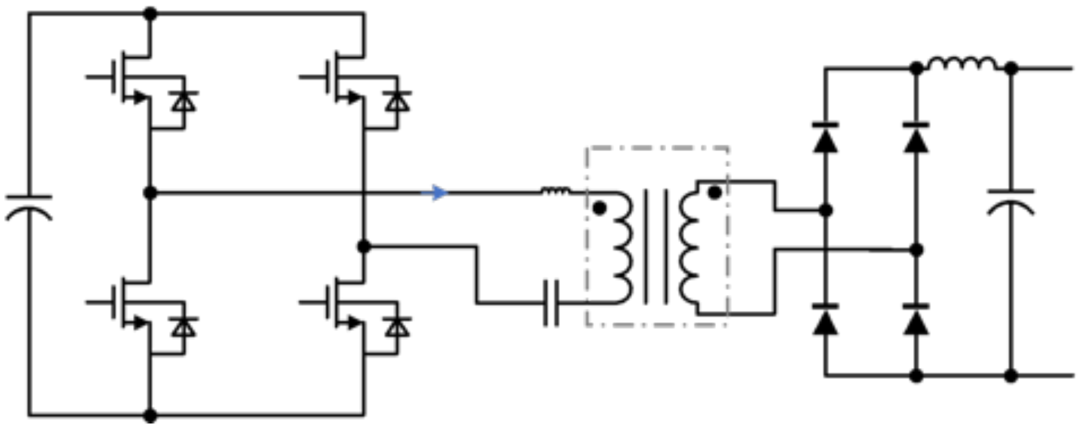
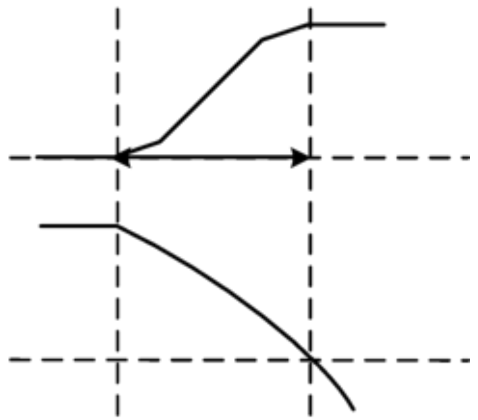


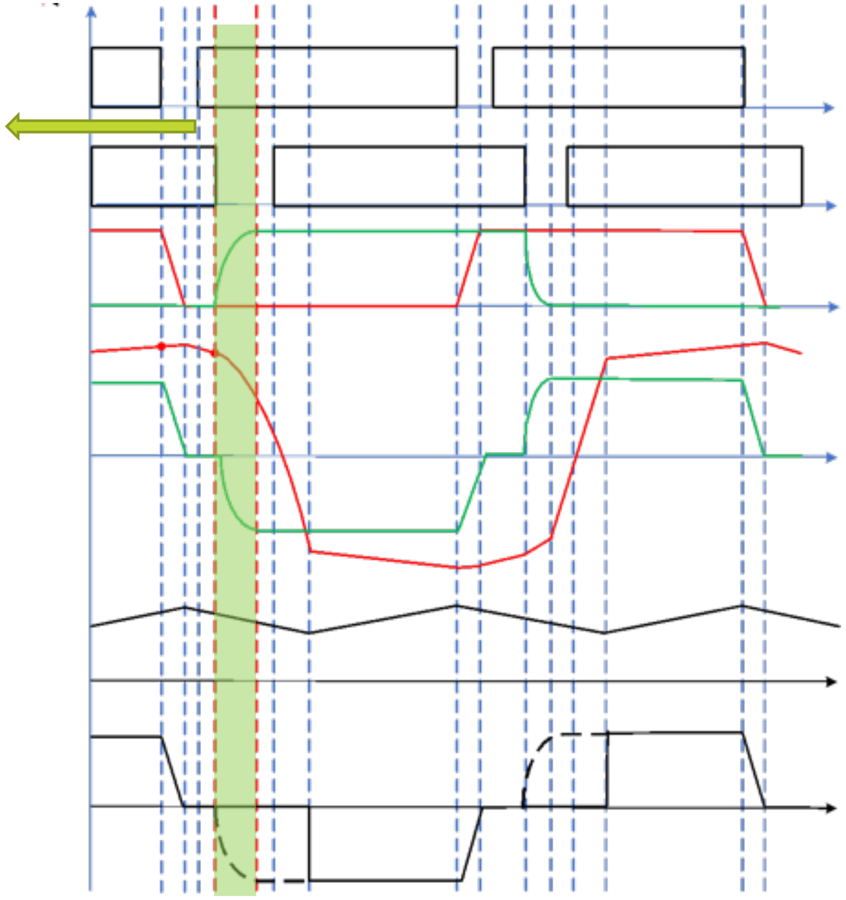
Phase-shift Full Bridge DC-DC converter
Vin=400V, Vo=250-450V battery



ZVS condition for lagging leg:

$$\begin{cases} E = \frac{1}{2} L_s I_L^2 > 2C_{oss}V_{in}^2 \\ 2Q_{oss} = 0.5 \cdot t_{dead} I_L \end{cases}$$

$$t_{dead} = \frac{T_{res}}{4} = \frac{\pi}{2}\sqrt{2L_s C_{o(tr)}}$$



Q1-Q4	TP65H050G4	IPW60R070CFD7
Rds(on)	50 mΩ	57 mΩ
Co(tr)	142 pF	990 nC
Co(er)	142 pF	96 pF
t_{dead}	64.3 ns	115 ns
I_L(ZVS)	6.43 A	10.83 A

$L_s = 2.7\mu H$

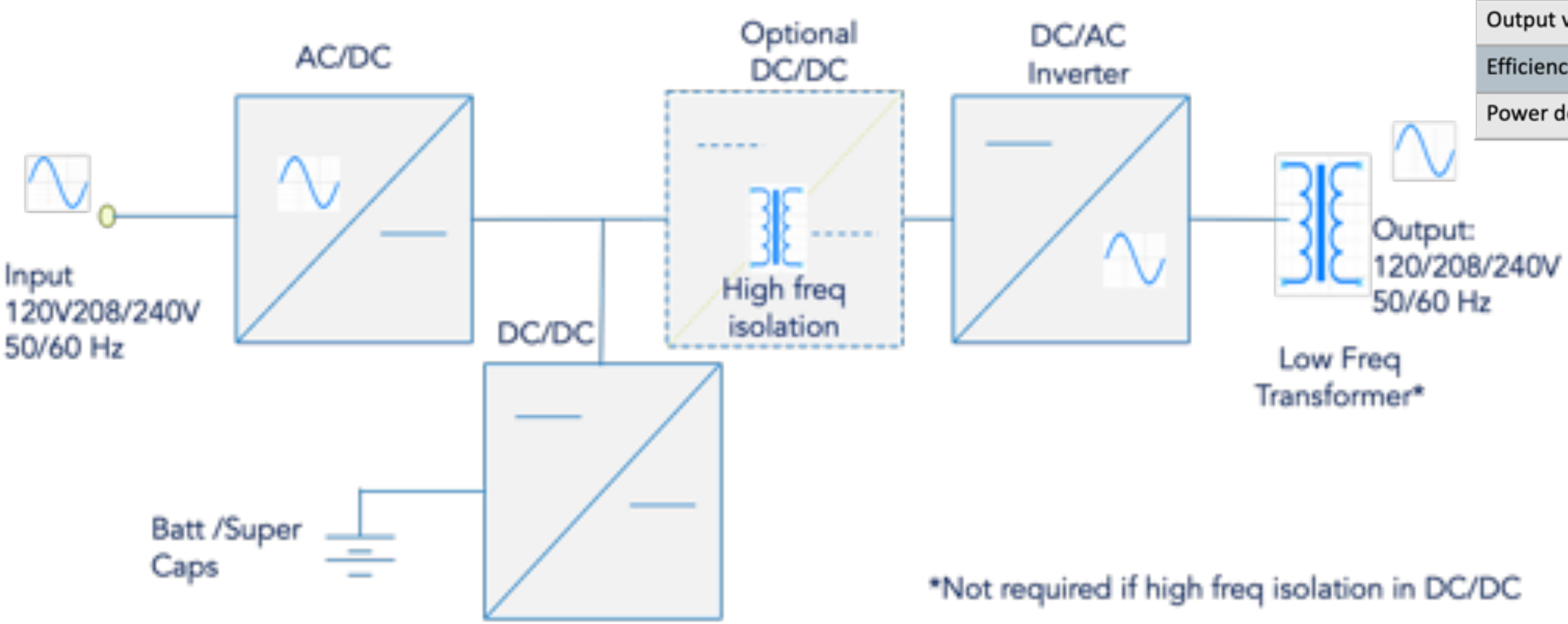
- GaN offers over 40% shorter dead time than Si-MOSFET to charge/discharge Qoss
- GaN offers over 40% lower inductance current than Si-MOSFET to achieve ZVS

Topology for Uninterrupted Power Systems (UPS)

High Level Block Diagram of Standard UPS

Used in Computer, Networking, Energy Management

Specification	Value
Power Level (max)	3 kVA
Output voltage (max)	120 Vac
Efficiency (peak)	93.3%
Power density	2.5x higher (2U→1U)



- DC/AC Inverters are crucial to on-line (depicted) and off-line UPS systems
- Most work as Voltage Source Inverters (VSI) with input PFC
- Most standard UPS systems use a Battery Back-up; Ultra capacitor or super capacitor driven inverters used for very short power backups

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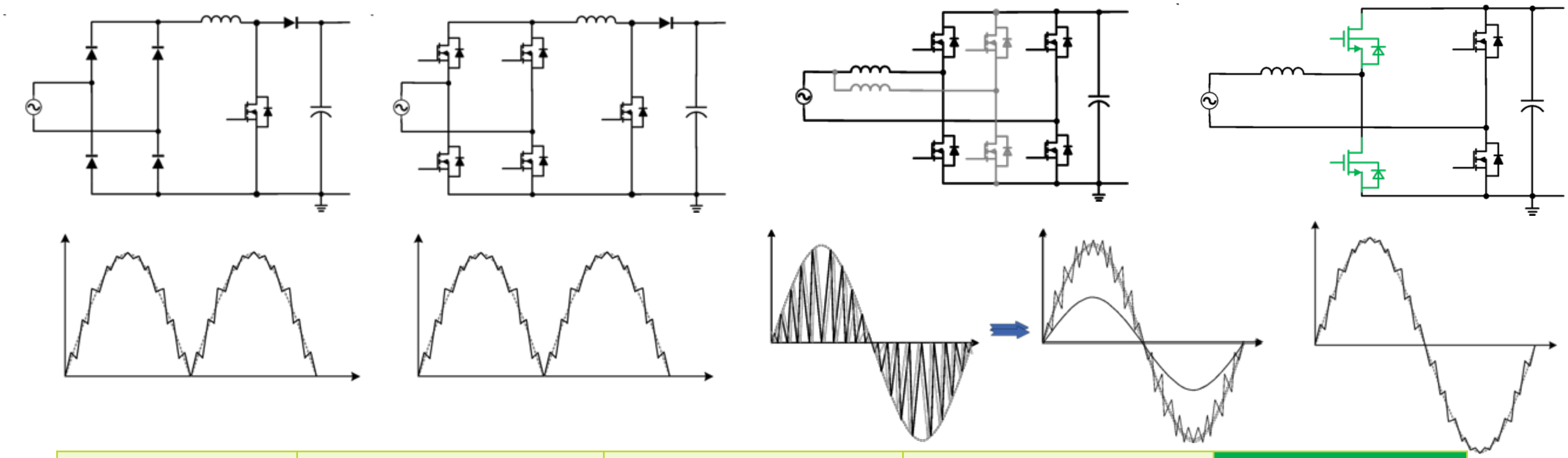
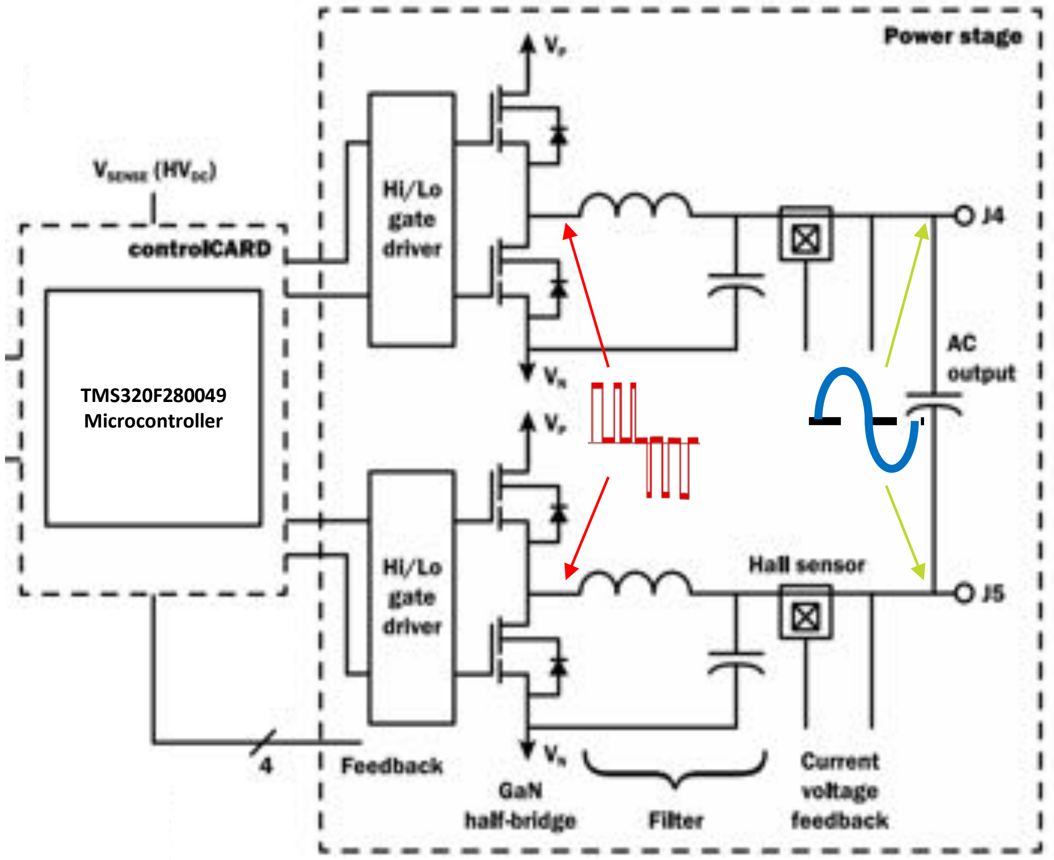
AC-DC PFC Converter Options (revisted)



Topology	Diode Bridge Boost PFC	MOSFET Bridge Boost PFC	CRM Bridgeless Totem Pole PFC		CCM Bridgeless Totem Pole PFC
			Single Leg	Interleaved	
Efficiency (high line)	98.2%	98.6%	99 %	> 99%	> 99.2%
Power level	Mid	Mid to High	Low	Mid to High	Mid to Very High
Issue	High Power Loss	Low Surge Tolerance	High EMI	Complex Ctrl	
Components Count	Mid	Very High	Low	High	Low
Cost	Low	High	Moderate	High	Moderate

Inverter Implementation using a DSP Controller



- Already reviewed the operation of the PFC section
- A typical single-phase inverter consists of a full bridge inverter and an output filter.
- Goal of the controller is to maintain the output voltage constant, irrespective of the line and load disruptions.
- LC filters are commonly used as output filter
- Single Phase(1PH) Inverter
  Vin = 0Vdc - 400Vdc,
  Vout = Vdc/√2 Vrms 60/50Hz
  Pmax = 3500W
  Switching frequency = 50 kHz (programmable in firmware)
- Voltage Source Inverter (VSI) for standalone operation with output voltage control
- Control law is implemented using an inner current loop and an outer voltage loop
- Proportional resonant controller is used for voltage loop to zero out the tracking error for the selected output AC frequency

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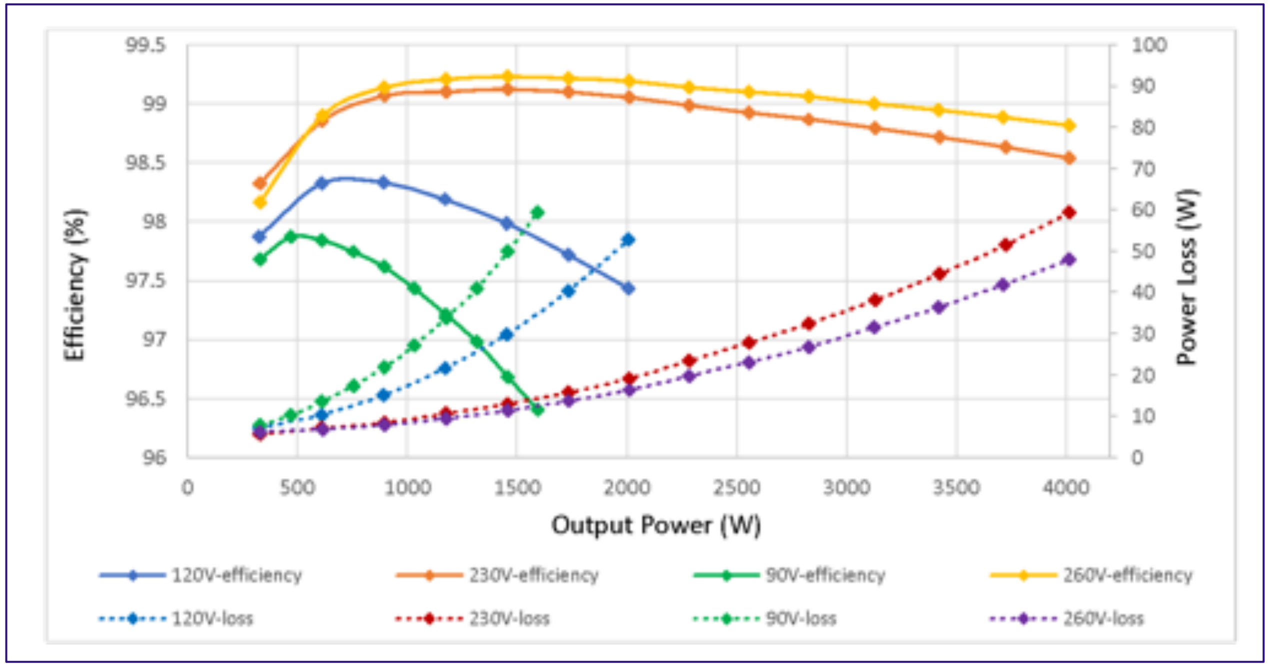
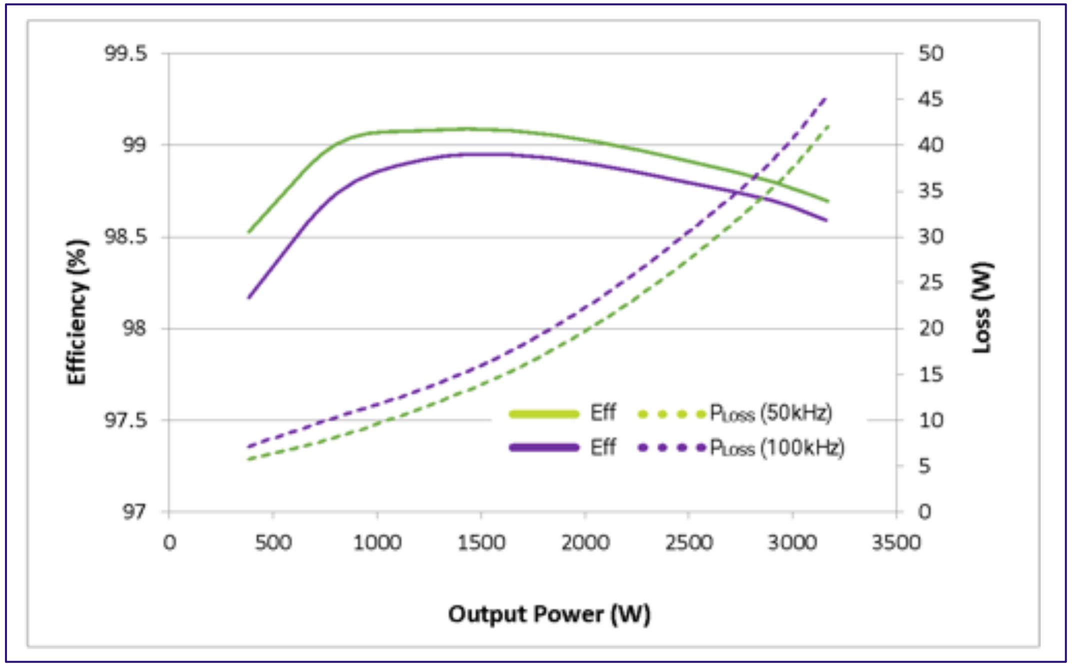
UPS Efficiency Signature from PFC & Inverter





https://www.transphormusa.com/en/evaluation-kit/tdttp4000w066c-kit/

https://www.transphormusa.com/en/evaluation-kit/tdinv3000w050-kit/

- Excellent full-load and peak efficiency
- High frequency, hard switching operation with GaN

GaN Solutions for EV Applications

(Best Option for up to 650V)

DC-DC Aux. Power Module (APM)
(1 kW – 7 kW)

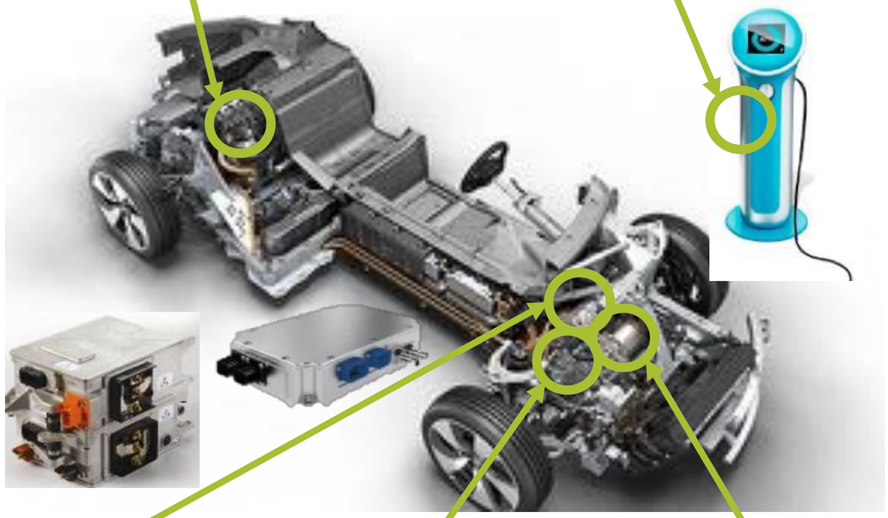
GaN Solutions for Today's EV Challenges

- **Possibly cuts total power-stage losses ~ 20% vs. SiC**
- **Up to ~40% OBC weight/volume savings vs. Si**
- **Range extension and design freedom**
- **Applicable to OBC, DC to DC, and DC to AC (non-drive) - Today**
- **Future Possibility:**
  - **Fast-charging support for AC Charging Pole (Level I & II) and fast DC charging (50+ kW)**
  - **Inverter power density 25kW/L (today) to > 75kW/L (future)[4,5] , 50 => 150 kW Power**

EV Applications

DC-AC Aux Inverter √

AC Charging Pole



DC-DC Aux. Power Module √

On Board Charger (OBC) √

EV Powertrain

DC-AC Auxiliary Inverter
(1.5 kW – 2 kW)

AC-DC On Board Charger (OBC)
(3.3 kW- 11 kW)

Future of Electric Vehicles

Cooler

Greener

Lighter

Efficient

- **300+ mile Battery-Powered Electric Vehicles**
- **OBC: 2kW to 8kW; 80% within 15 mins**
- **DC to DC 3 kW to 5 kW**
- **~$250 savings per inverter[2]**
- **Life expectancy 150K to 300K miles by 2025[2]**
- **Cost < 3 years gas savings[2]**

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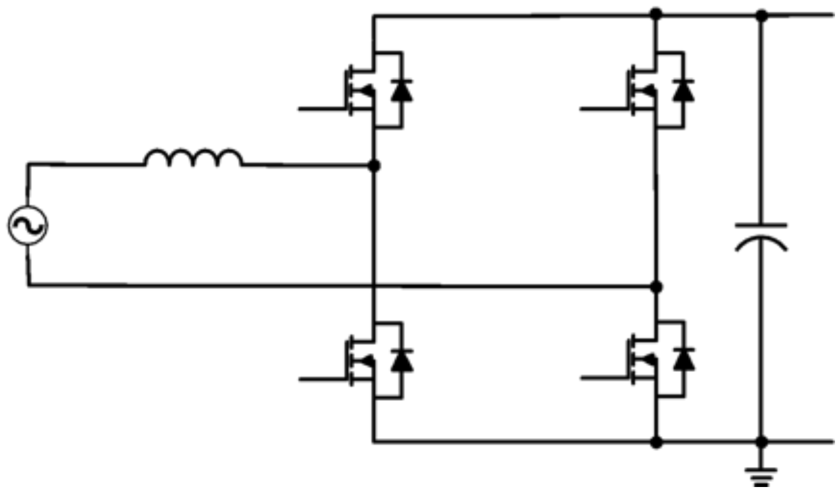
AC to DC Stage: 7- and 11-kW Onboard Charger Examples

Input: *230Vac :* ***Output:*** *400 Vdc :* ***Power:*** *7 and 11 kW (single device solutions)*

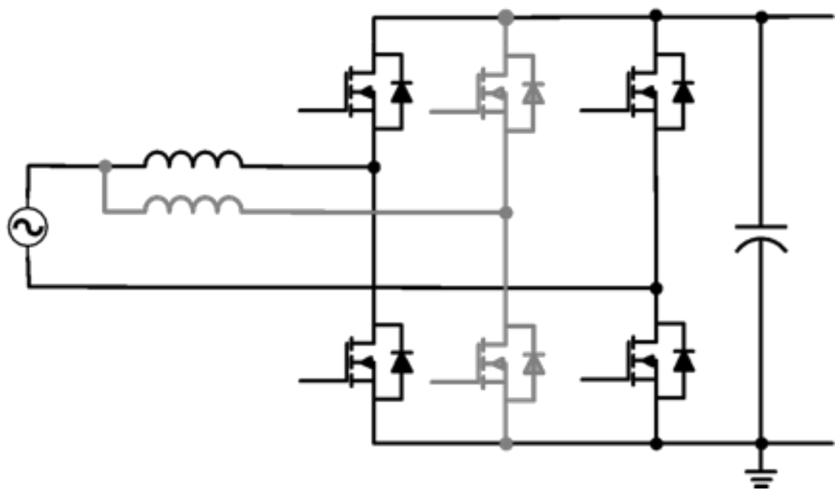


Case Study

Input: 230 Vac : Output: 400 V : Output: 7 kW : Freq(sw.): 55 kHz

Single Phase Bridgeless Totem-pole PFC using TP65H015G5WS				
IQ1, IQ2(RMS)	Conduction Loss on Q1 (100°C)	Switching Loss on Q1	Total Loss on Q1	Total Loss on Q1, Q2
25.4 A	15.4 W	9.96 W*	25.4 W	50.8 W

* The switching loss is an estimate



Case Study

Input: 230 Vac : Output: 400 V : Output: 11 kW : Freq(sw.): 55 kHz

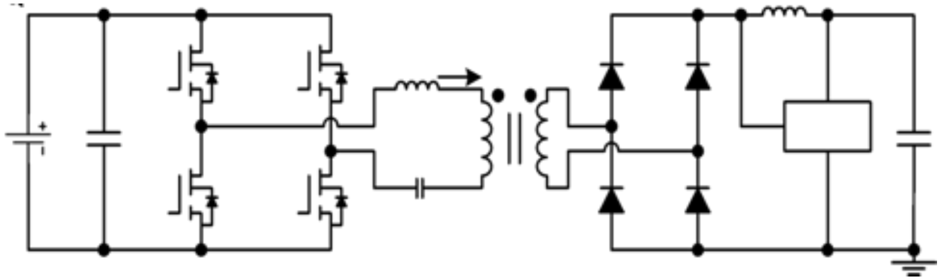
Single Phase Interleaved Bridgeless Totem-pole PFC using TP65H015G4WS				
IQ1, IQ2(RMS)	Conduction Loss on Q1 (100°C)	Switching Loss on Q1	Total Loss on Q1	Total Loss on Q1, Q2
19.9 A	9.53 W	9.57 W	**19.1 W**	38.2 W

Absolute maximum power loss rating for TO-247 is 25 – 30 W

DC to DC Stage: 7 kW Uni-directional Onboard Charger

***Input:* 400 Vdc : *Output:* 240 to 480Vdc : *Output:* 7kW**

DC to DC Power Stage: PSFB



Phase Shift Full Bridge

Key Points of the Full Bridge PSFB

- Suitable for high power application > 1 kW
- Wide conversion range with high efficiency
- ZVS operation at high power
- Hard switching at low power – advantage GaN
- Runs at a constant frequency
- Easy to parallel stages for higher power
- Synchronous rect. Easy due to constant frequency

DC to DC Power Stage: PSFB

- **Project:**
  - Input: 400 Vdc Output: 240 to 480 Vdc
- Topology:
  - ***Phase Shifted Full Bridge***
- Device(s):
  - TP65H035G4WSQA/QSQA
- Configuration:
  - 7 kW: Single Phase (TP65H035G4WSQA)

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6.6 kW CLLLC Bi-directional Resonant Converter

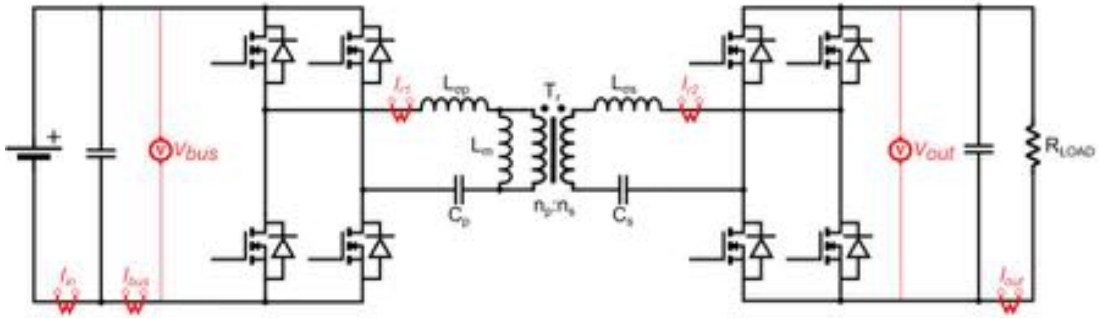
TP90H050WS GaN FET Offers Higher Performance and Flatter Profile vs. C3M0030090K SiC MOSFET

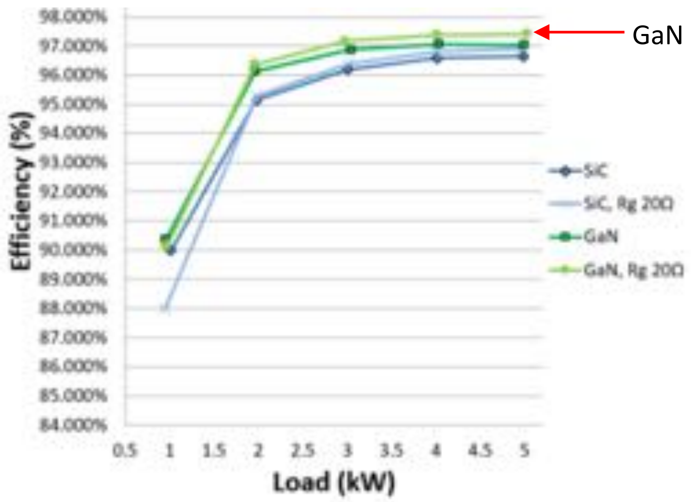
900V: GaN vs. SiC

Properties	Cree C3M0030090K (SiC)	Transphorm TP90H050WS (GaN Cascode)
Maximum V_{DS} (V)	900	900
Package	TO 247-4	TO 247-3
Maximum V_{GS} (V)	-8/+19	±20
Typ. $R_{DS(on)}$ @ 25°C (mΩ)	30	50
Typ. $R_{DS(on)}$ @ 150°C (mΩ)	37	105
Input Capacitance C_{iss} @ V_{DS} 600 V (pF)	1747	1000
Output Capacitance C_{oss} @ V_{DS} 600 V (pF)	131	115
Reverse Transfer Capacitance C_{RSS} @ V_{DS} 600 V (pF)	8	3.5
Diode V_{SD} (V)	4.8 @ 17.5 A	2.2 @ 22 A
Reverse Recovery Q_{rr} (nC)	545 (35 A, 600 V, di/dt 2680 A/μs)	156 (22 A, 600 V, di/dt 1000 A/μs)
Typ. $R_{θJC}$ (°C/W)	0.62	1.05

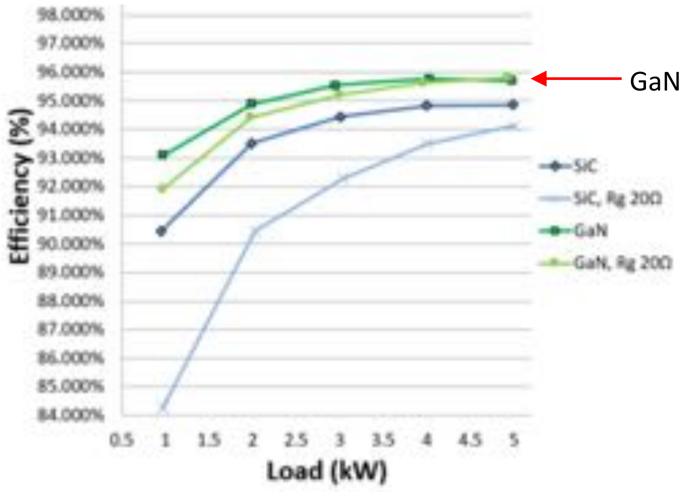
Table 2 Semiconductors used in this work

$f_{s,range}$ (kHz)	300-700
$f_{s,nom}$ (kHz)	500
$V_{IN,range}$ (V)	380-600
$V_{OUT,range}$ (V)	280-450
$P_{OUT,max}$ (kW)	6.6





Fs: 500 kHz, Vout: 400 V
Result: 0.5-1% or 25 to 50 W lower



Fs: 638 kHz, Vout: 400 V
Result: 1% or 50 W lower

Source: PCIM: A comparison among wide bandgap devices using a CLLLC bi-directional resonant converter

Summary

- Different applications at power levels addressed by GaN have been discussed
- Applications range from 45W to 10kW
- Approaches and topologies for different applications discussed
- Performance of GaN is compared and contrasted with Si and SiC power devices
- GaN improves efficiency and power density which is driving adoption of GaN in the addressable applications

Thanks

-> Backup

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USB-C Adapters – The Volume Driver for GaN-on-Si

- Fastest Adopter of GaN-on-Si products
  - Almost every mobile phone, notebook and accessory adapter maker has announced products and/or plans for replacing power MOSFETs with GaN
- Power Levels
  - 33W to 140W
  - 65W adapter most popular, but penetration growing in lower and higher wattages as well
- Topologies < 70W (no Power Factor Correction requirement)
  - Quasi-resonant flyback most popular, followed by active-clamp flyback
  - Frequencies still <300kHz for mainstream to mitigate EMI issues
- Topologies > 70W (Power Factor > 0.9 required, with exceptions)
  - Two-stage or three-stage topologies required due to Boost PFC in the front-end
  - QR Flyback, AC Flyback, Hybrid Flyback or Bridge topologies are deployed

** External power supplies; category has non USB-C supplies as well*

Transphorm High Power Applications Examples

Over 50 design wins in high power markets, shipping to major customers WW

CORSAIR

"The Corsair AX1600i is the **best PSU** that money can buy today, period."
tom's HARDWARE

bel POWER SOLUTIONS & PROTECTION

"Transphorm's GaN in a totem-pole PFC configuration proved the **most reliable**, **highest performing** solution possible today,"

"Ease of drivability and designability—**does not require custom drivers**. Proven reliability— JEDEC and AEC-Q101"

"Based largely on the power semiconductors' proven quality and reliability as well as the team's reputation for **successful collaboration**,"

TDK

"We're expanding the reach of **medical care**, and Transphorm's GaN is helping us do it"

NEW

GaN benefit of low switching loss, 1st gaming psu with GaN in ASUS

NEW

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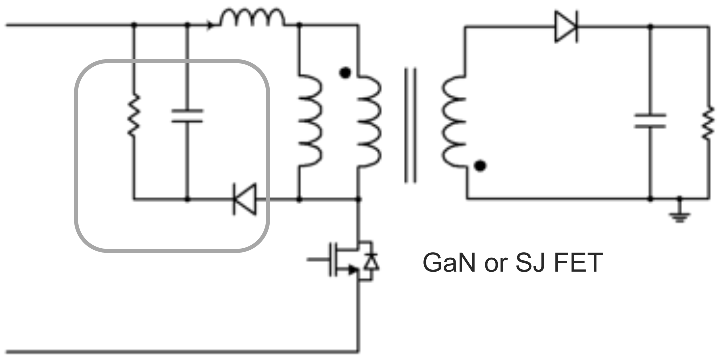
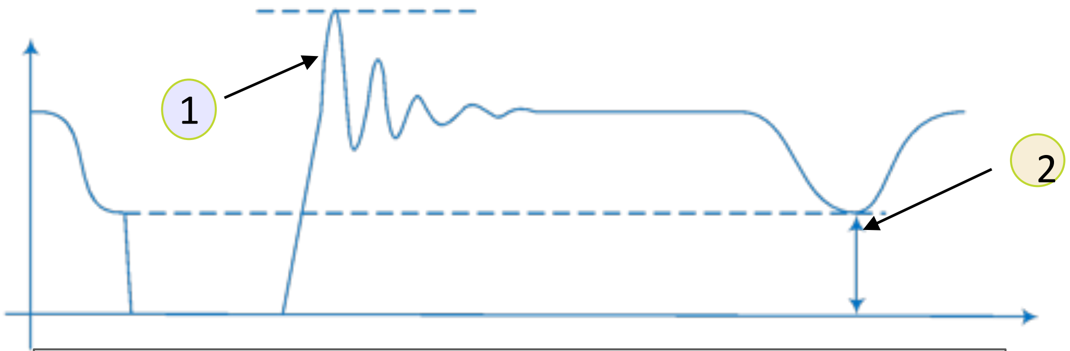
Power Levels, Applications and Topologies, for 650V GaN

Power Level	Typical Applications	Dominant Topologies
<65W	Power adapters, USB PD Type-C, LED Lighting	QRF, ACF, SSR, PFC Flyback, PFC Buck, PFC Boost
75W to 150W	Adapters, Computer, TV, Appliances, LED Lighting	PFC Boost + QRF or ACF, PFC Flyback, Dual OOP PFC FB, PFC + Forward, PFC + HB-LLC
150W to 600W	Gaming consoles, Computer, TV, Servers, Appliances, eBikes, UPS, High Bay Lighting	PFC Boost + DC-DC, Totempole PFC + DC-DC, Inverters
>750W to 1.5kW	Computing, Electric 2-3 wheeler OBC, UPS, Residential MPPT & Inverters	Sync PFC Boost + HB-LLC, BL or Totempole PFC, HB/FB-LLC, PSFB, Inverters
>1.5kW to 10+kW	Computing, 5G, EV OBC & LBC, UPS, Industrial scale MPPT & Inverters	BL PFC/TTP PFC, PSFB, HB/FB-LLC, Multi-phase HB-LLC Inverters

Conventional RCD Snubber in QR Flyback





Flyback Converter With RCD Snubber

- ❑ Transformer leakage energy is wasted as heat
- ❑ Power loss in snubber increases at higher sw. frequencies
  - ❑ $P_{sn} = \frac{1}{2} . L_{lk} . I_p^2 . \frac{V_{sn}}{V_{sn} - n.V_{out}} . f_{sw}$
  - ❑ For $V_{sn} = 2.n.V_{out}$, $P_{sn} = L_{lk}.I_p^2.f_{sw}$ (2x leakage energy!)

1 High voltage spike and ringing at primary FET drain

- energy is wasted as heat
- contributes to EMI
- need proper design to avoid exceeding rating

2 QR valley around or above 200V

- switching losses can be mitigated with other approaches
- higher EMI due to larger switching voltage

Specialized ICs with precise valley switching required to attain >92% efficiency

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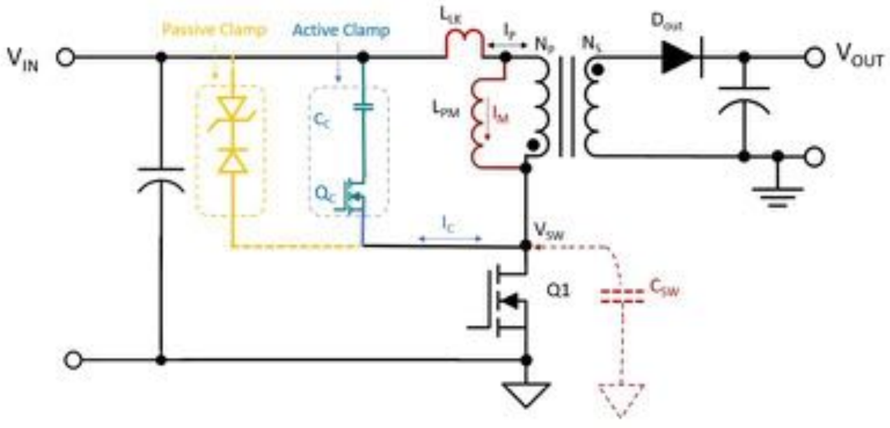
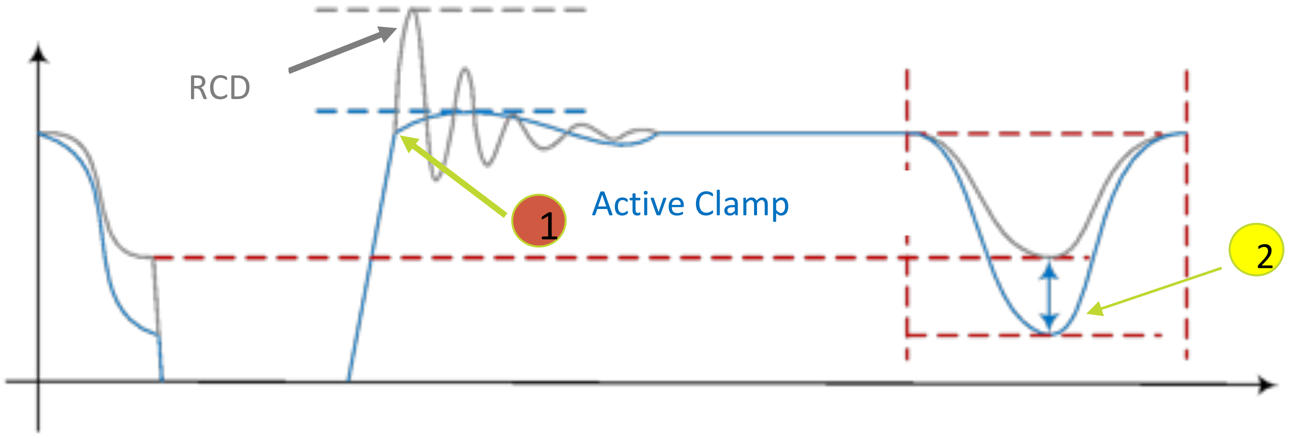
Active-Clamp Flyback Improves Performance





1 **Active clamp operation**

- Peak voltage is reduced, more aggressive transformer turns ratio is possible, lower SR FET voltage rating
- Recycles leakage energy, higher efficiency
- Soft switching of active clamp FET, lower EMI

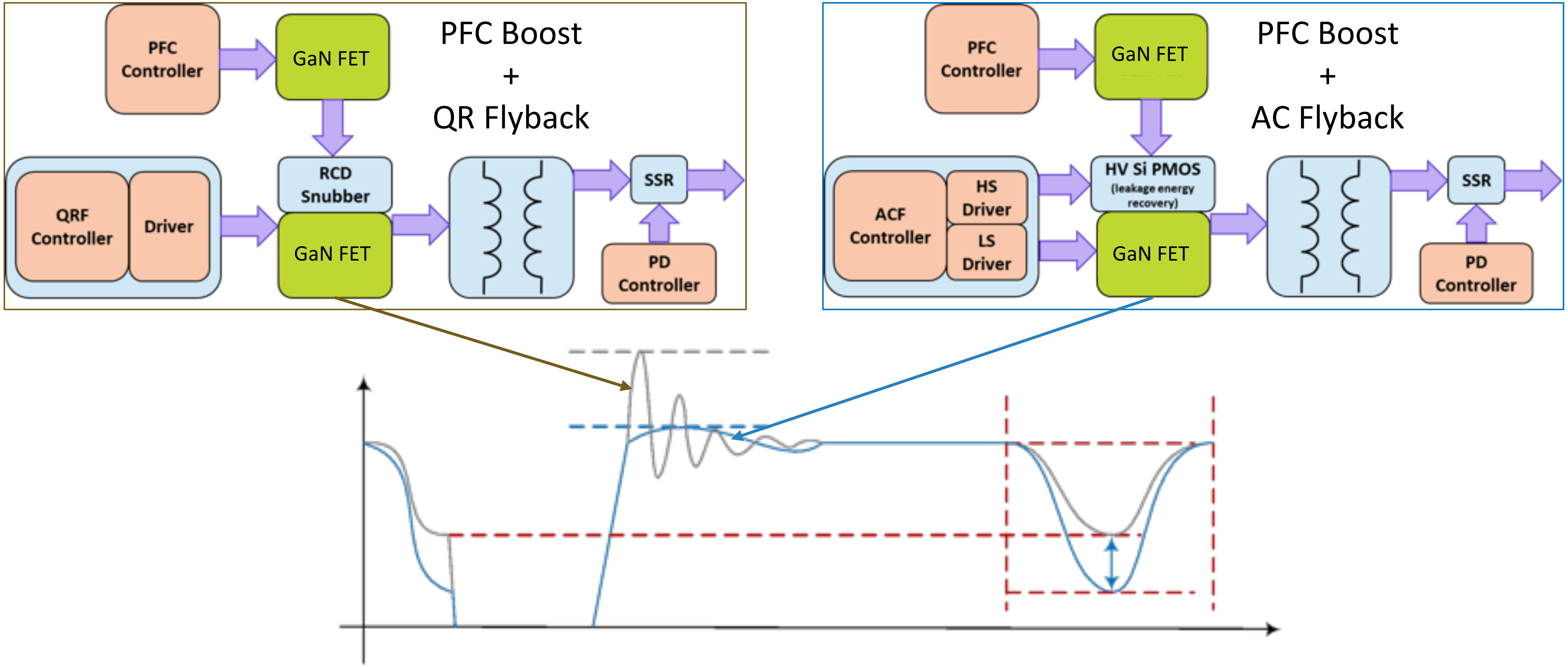
2 **Active Clamp → QR valley is well below 200V (near ZVS of main switch)**

- Higher efficiency due to lower switching losses
- Lower EMI due to smaller switching voltage

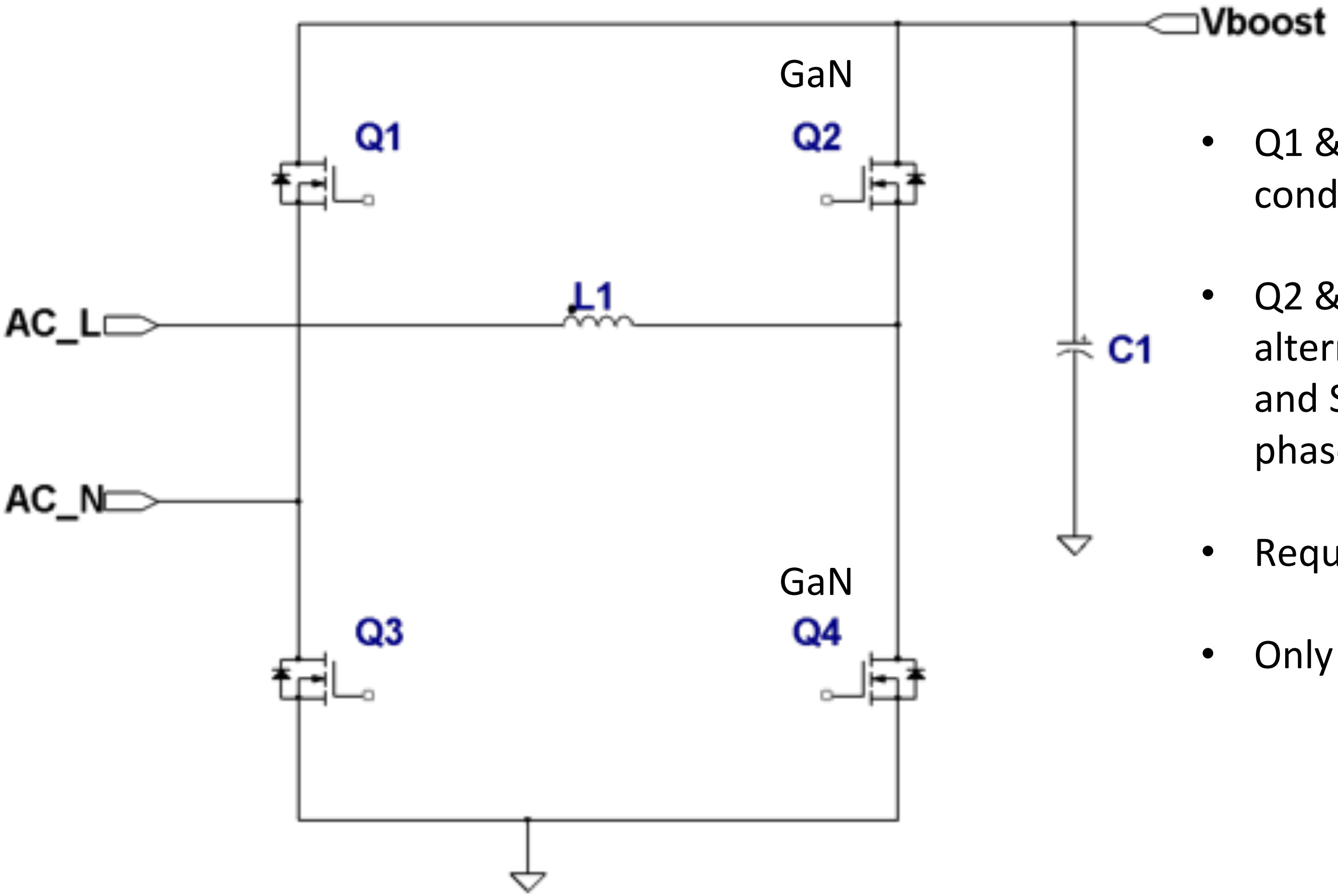
Higher efficiency and lower EMI

Voltage Stress Considerations in 2-stage topologies

- PFC Boost Output voltage ~ 400V to 410V (accounting for duty cycle) on top of Vrms
- Proper transformer design and topology need to be considered to allow for headroom on the BVDSS of the GaN devices



Totem Pole Bridgeless PFC – Highest Efficiency



- Q1 & Q3 switch at the line rate conducting on alternate half cycles
- Q2 & Q4 switch at high frequency and alternate between the main switch and SR boost diode depending on the phase of the AC line.
- Requires high and low side drivers
- Only 1 boost inductor needed