Topologies for High Voltage GaN Applications in Consumer & Personal Electronics Power Supplies

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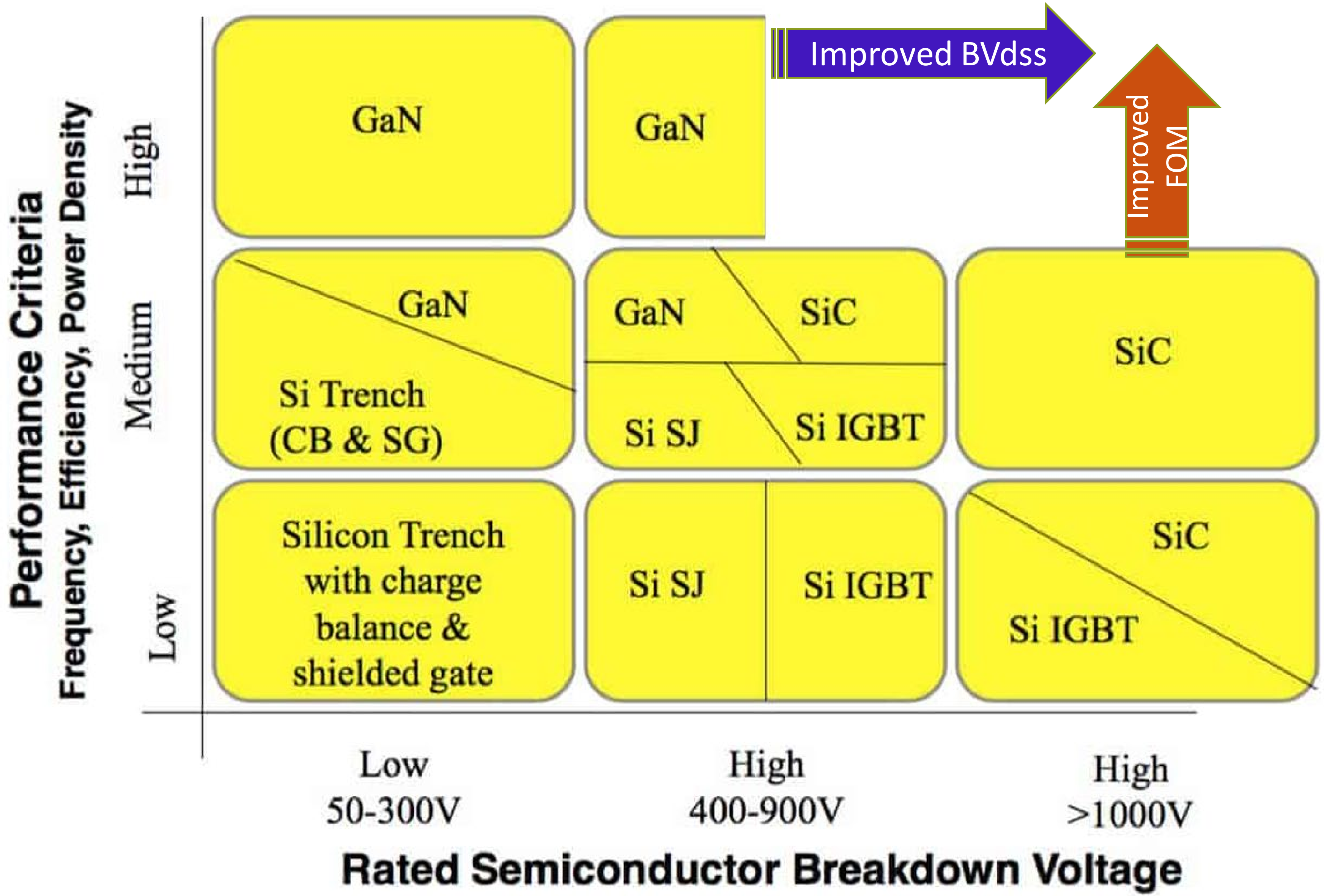
Highest Performance, Highest Reliability GaN

Agenda

- Introduction to GaN Application Space vis-à-vis other Power Technologies
- Application of 650V GaN in 30W to 10+kW Power Levels
  a. 30W to 65W – Adapters, LED Lighting
  b. 75W to 150W – Adapters, Gaming Notebooks, Computers, LED Lighting, Monitors
  c. 150W to 1.5kW – Computing, 2-wheeler (e-bikes, e-scooters), LED Lighting, PV, Gaming Monitors, Large form-factor TVs, Personal Power devices
  d. 1kW to 10+kW – PV, UPS, Server Power, EV
- Approaches and Topologies for Different Applications
- Comparison of GaN with Si MOSFETs in Select Topologies

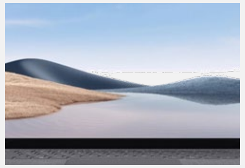
Device Comparison – Silicon, GaN and SiC



Markets for GaN by Power Levels

GaN is ripe to replace Silicon SJ or SiC in most markets up to 6kW

All-in-One PC

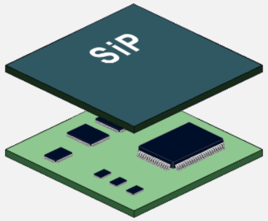


Laptop Adapters

Smartphone, Tablet Chargers

Low-Power
Discrete
45W - 300W

System in Pkg
(SIP)
25W - 140W



System in Package (SIP)

eMobility

Lighting

Solar Microinverters

OLED/HD TVs

Mid-Power
300W – 1.5kW

High-Power
1.5kW – 6kW+

Data Centers

Industrial UPS

EV Charging

eMobility

Various GaN Suppliers have Commercial Success in Low- through High-Power Segments of the Market

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Major GaN & SiC Companies & Key Markets

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	GaN Systems, transphorm, Innoscience, Navitas, Power Integrations, Infineon, TI, VisIC Technologies, ST (life.augmented)	Wolfspeed, Infineon, ON Semiconductor, ST (life.augmented), UnitedSiC, Navitas, Microchip
40V to 200V	400V to 750V	Up to 1700V

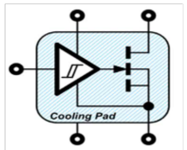
VOLTAGE →

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

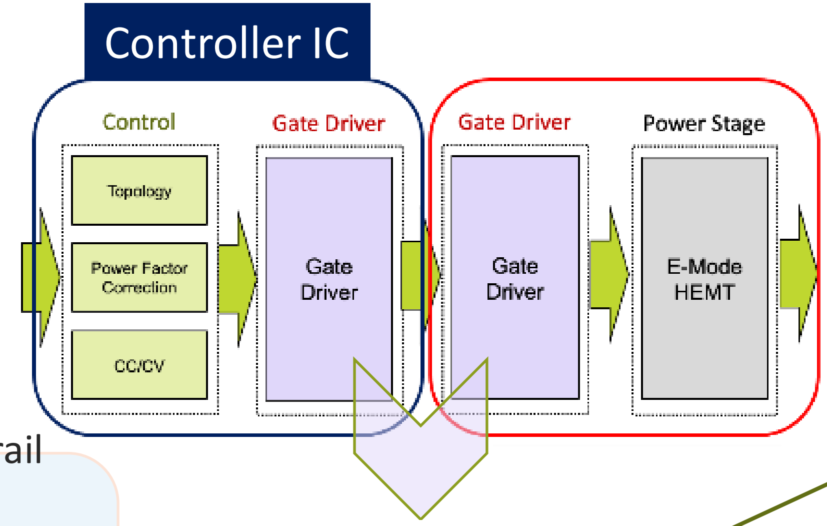
Comparison of E-mode, D-mode, Drv+GaN

Single Ended Topologies

DR+GaN
(Navitas)



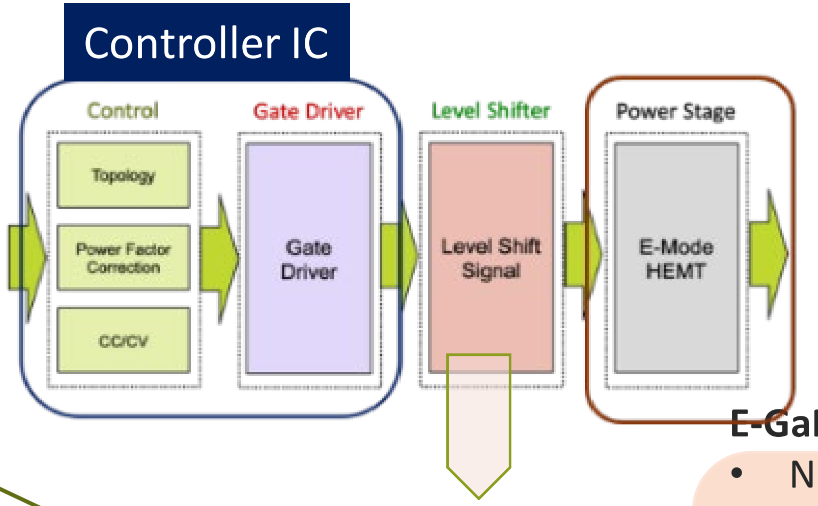
Simplified schematic

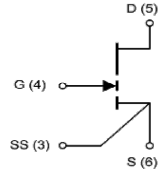


Duplicate Gate Drive

DR+GaN
- Requires bias rail
- Possible duplication of driver
- Added functionality possible but limited

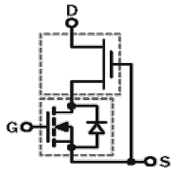
DISCRETE
(GS, NVTS, INNO, Infineon etc.)



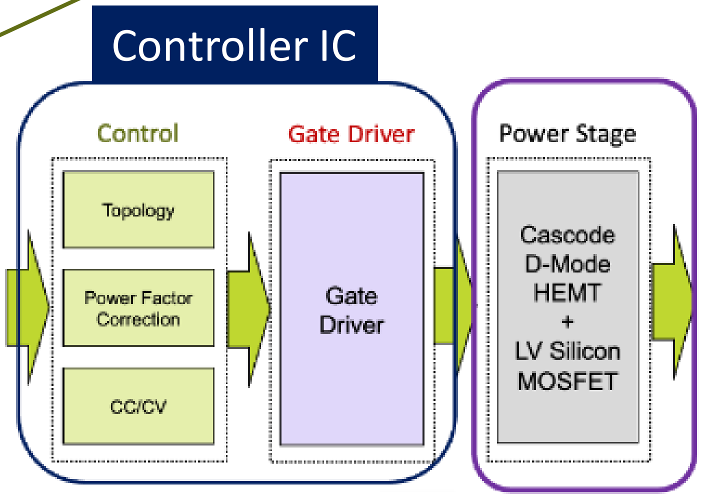


Added BOM

E-GaN Discrete
- Needs level shift with std. silicon driver
- Protect gate to 6V Max
- New 5.5V gate drivers, still need protection



Cascode Device Structure



2-switch Normally Off
- SIMPLEST to Use
- Higher efficiency
- No protection needed
- Multiple Packages

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Comparing TPH GaN-HEMT vs. leading SJ-MOSFET

	Parameters	Cool MOS IPB65R150CFD	GaN-HEMT TP65H150G4LSG	
Static	V_{DS}	650V @ 25 ^oC	650V (spike rating 800V)	
	R_{DS} (25^{o}C) Rds (150^{o}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

Note: Parametric differences exist between D-mode & E-mode GaN

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Power Level, Applications & 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 750W	Gaming consoles, Computer, TV, Servers, Appliances, e-bike chargers, E 2/3W OBC, UPS, Lighting, PV	PFC Boost + DC-DC, Totempole PFC + DC-DC, Inverter
>750W to 1.5kW	Computing, Electric 2/3W Chargers, 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

Topologies for Adapters 30W to 330W

Mobile Phones, Tablets, Notebooks, All-in-One, Gaming Consoles

Variations of the Flyback and Two-stage Topologies

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

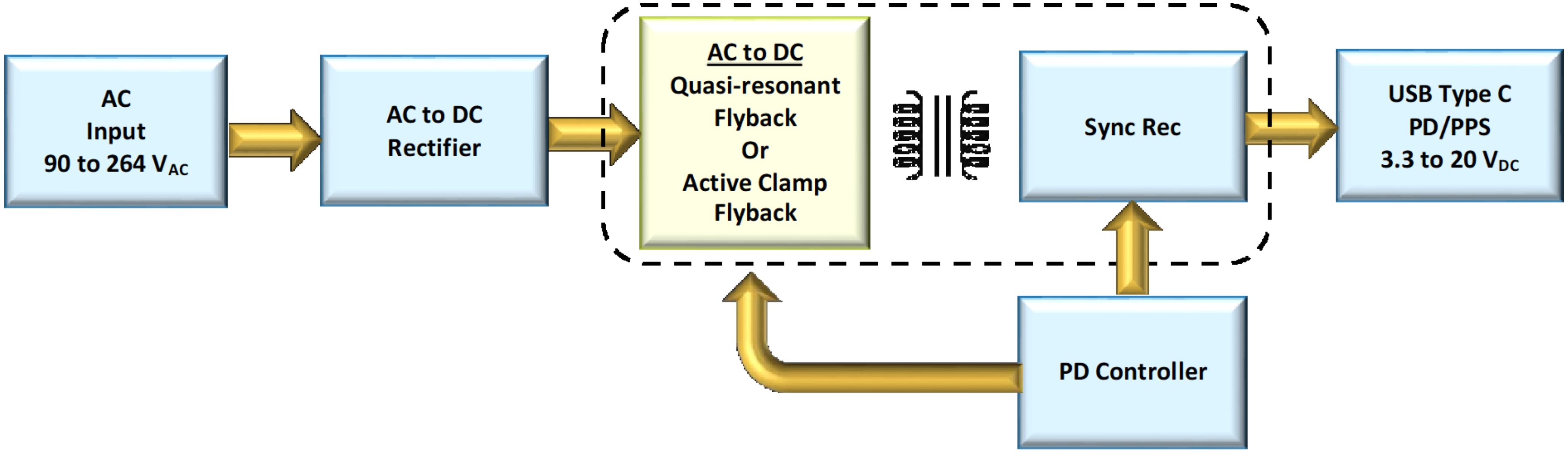
Other applications growing fast too

- Fastest Adopter of GaN-on-Si products
  - Almost every mobile phone, notebook and accessory adapter maker is making GaN based products and plans to replace power MOSFETs with GaN
- Power Levels
  - 33W to 140W – with new extensions coming
  - 65W adapter most popular, but penetration growing in lower and higher wattages
- 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*

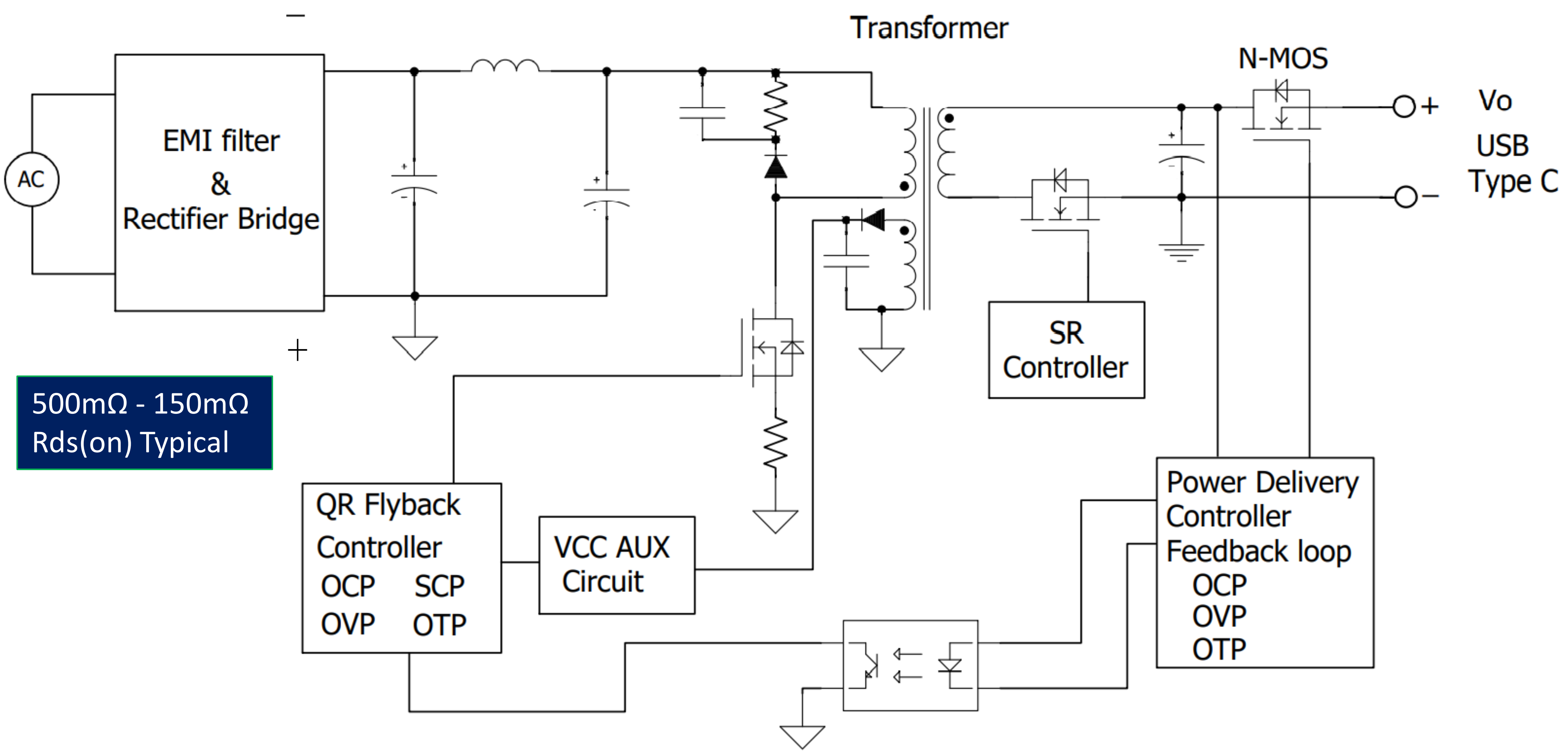
USB-C Adapters (<70W Considerations)

- Several power IC companies have 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



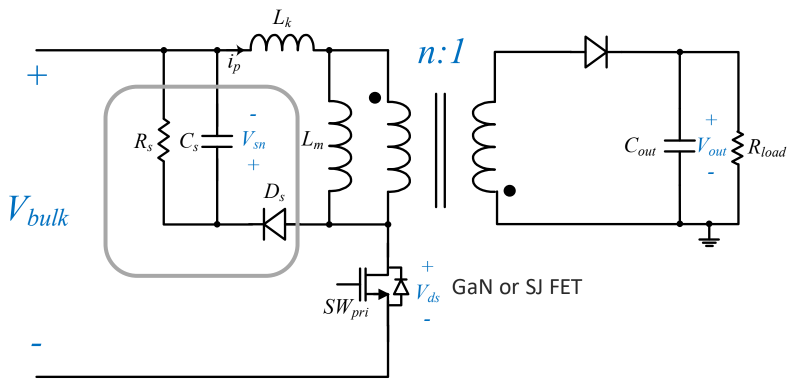
30W-65W Adapter Block Diagram

(Quasi-resonant Flyback Topology)



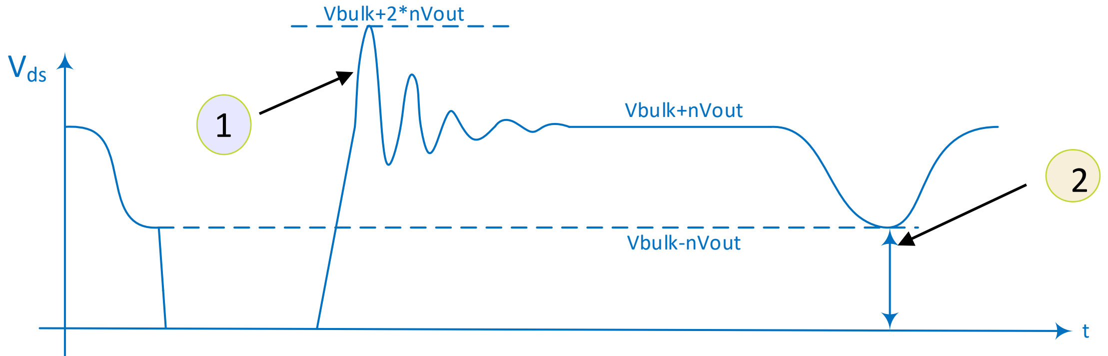
500mΩ - 150mΩ
Rds(on) Typical

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!)

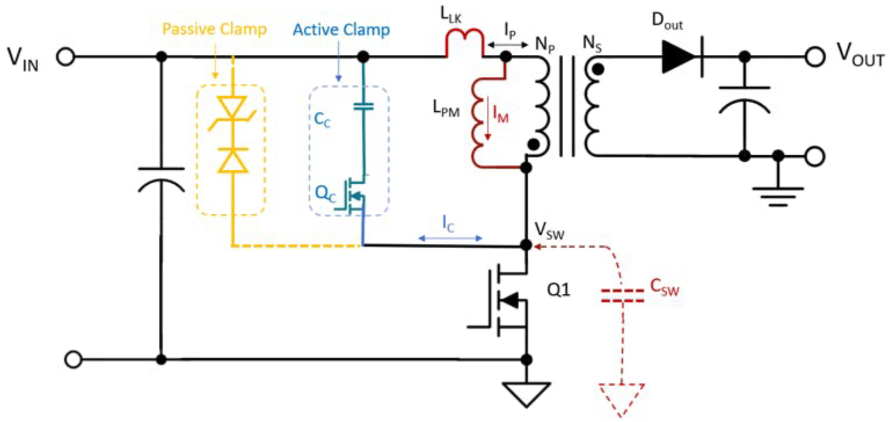


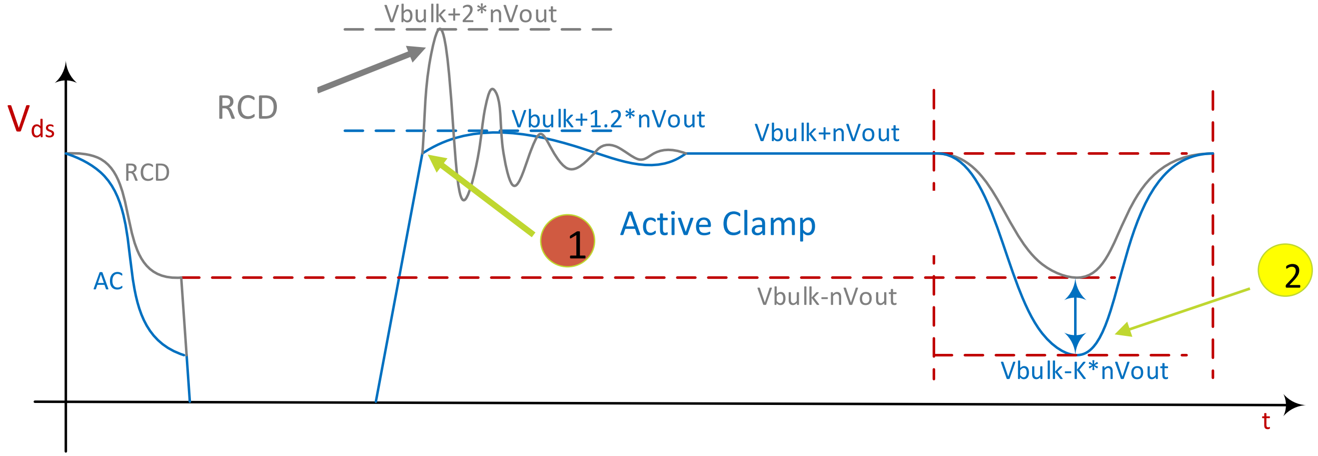
1. High voltage spike and ringing at primary FET drain
   - → energy is wasted as heat
   - → contributes to EMI
   - → need proper design to avoid exceeding rating

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

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

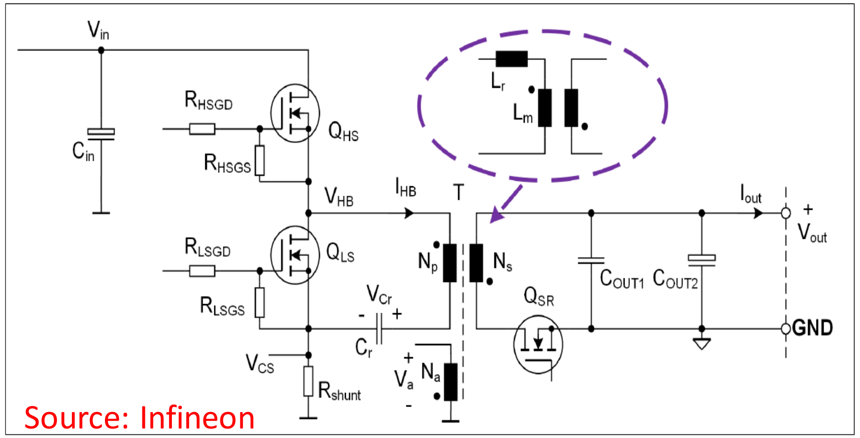
2 Active Clamp → QR valley is well below 200V (near ZVS of main switch)

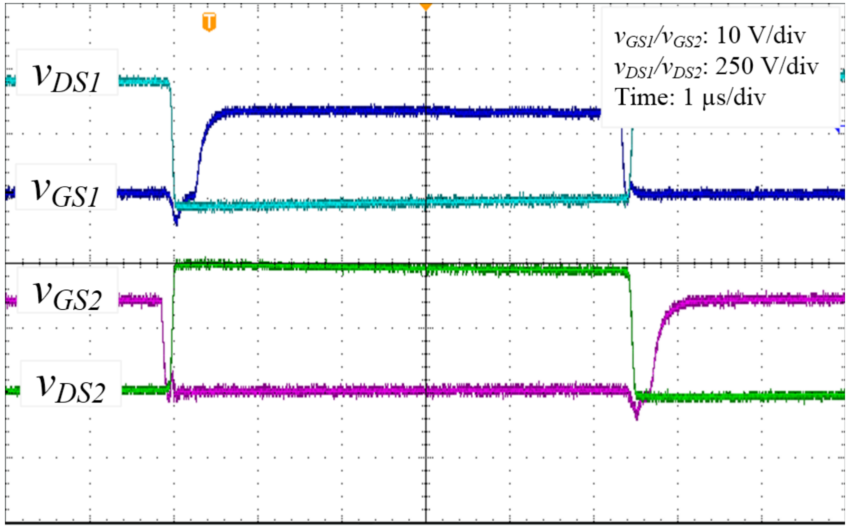
- Higher efficiency due to lower switching losses
- Lower EMI due to smaller switching voltage

Higher efficiency and lower EMI

Hybrid Flyback Controller (Same as AHB)

Step-up over QR & ACF on Vds(max) but lags cost of QR & efficiency of ACF



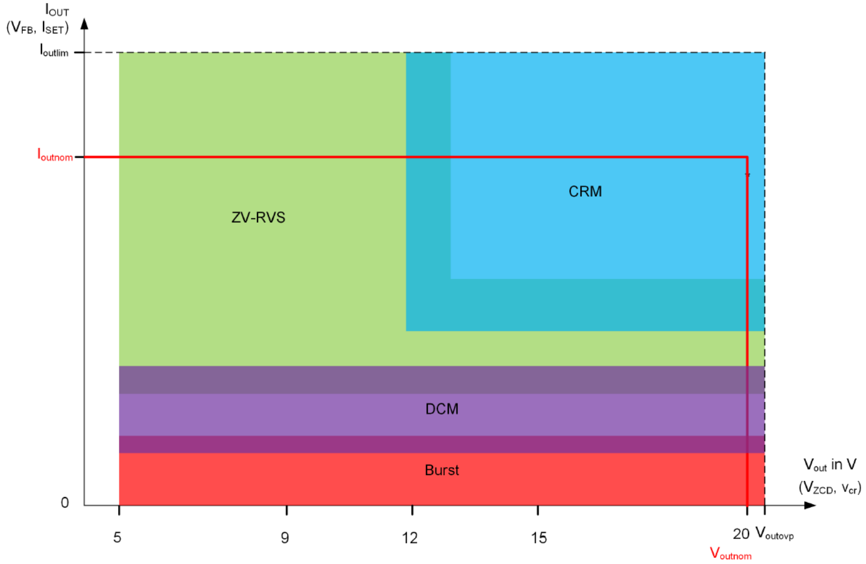


1 Cross-over between Flyback and the HB-LLC

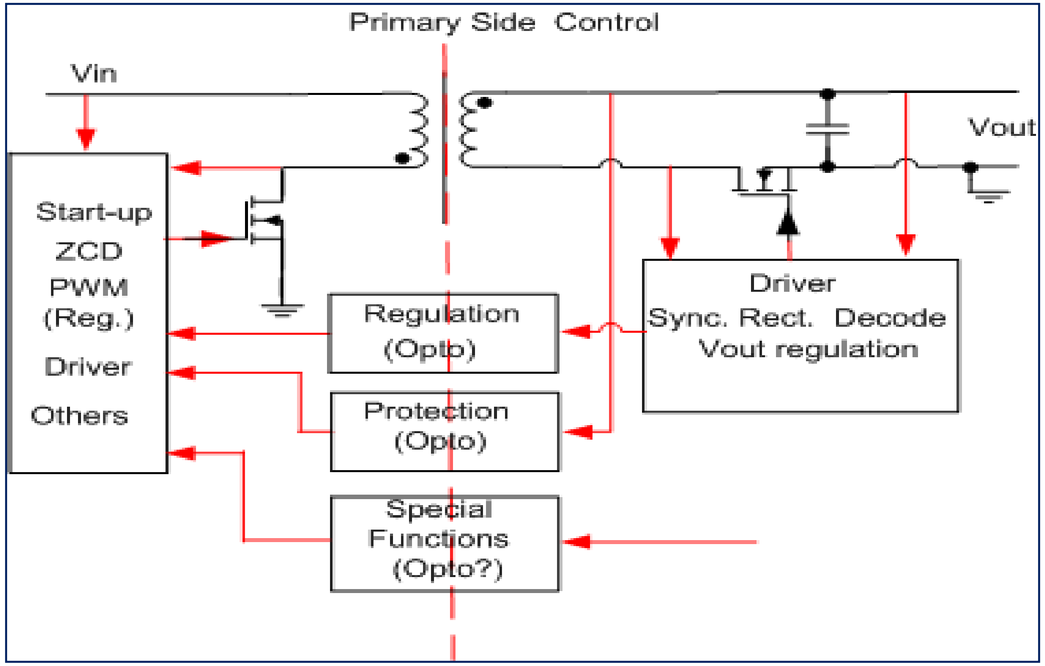
- Peak voltage is reduced, Vds = Vbus, lower SR FET voltage rating
- Storing energy in the transformer
- Recycles leakage energy, higher efficiency
- Needs two symmetric switches

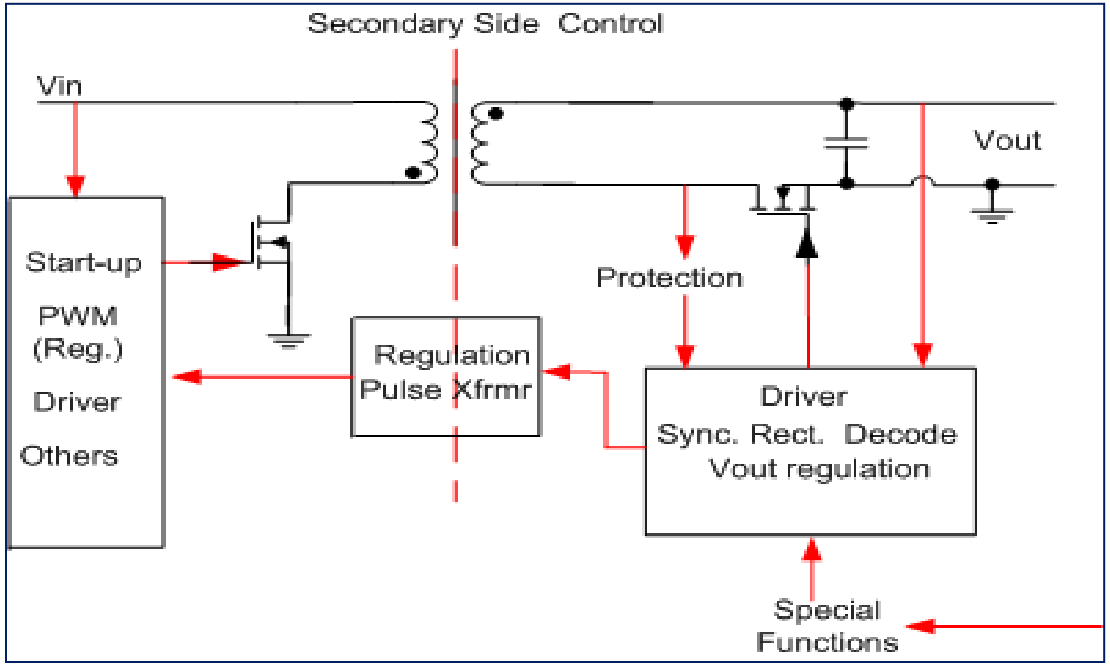
2 Boundary condition of ZVS Operation

- Higher efficiency due to lower switching losses
- True ZVS if input voltage is stable (DC_in)
- Lower EMI due to smaller switching voltage



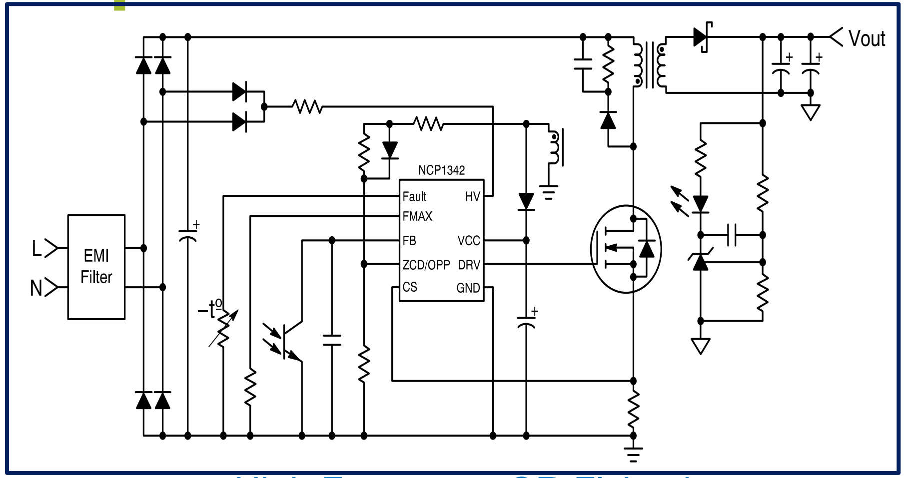
Primary vs. Secondary-side Control



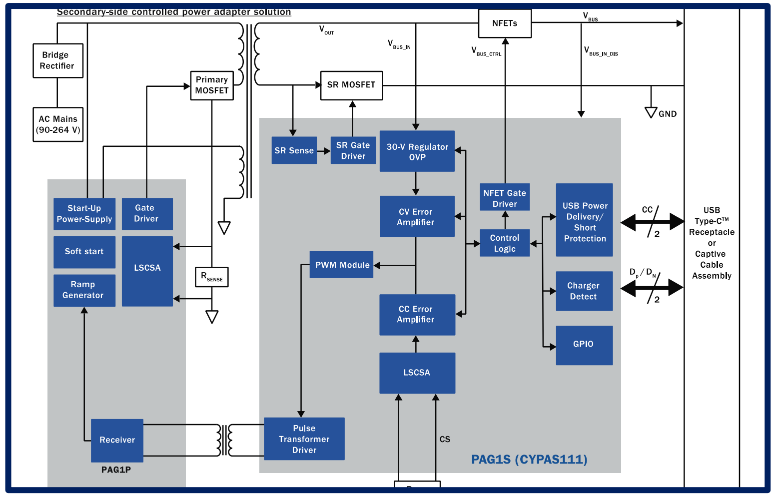


- In secondary-side control, the controller on primary side in only has:
  - Start-up regulator
  - Gate driver
  - Fast protection functions

Adapter - QR Flyback Solutions Summary



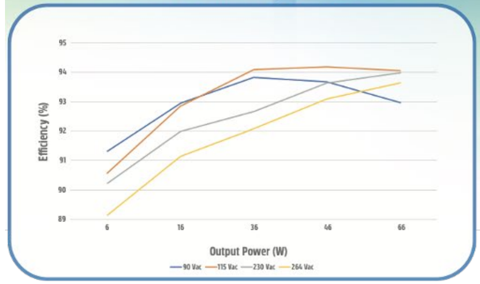
High Frequency QR Flyback
ON - NCP1342/3



SSR - Cypress PAG-1P & PAG-1S

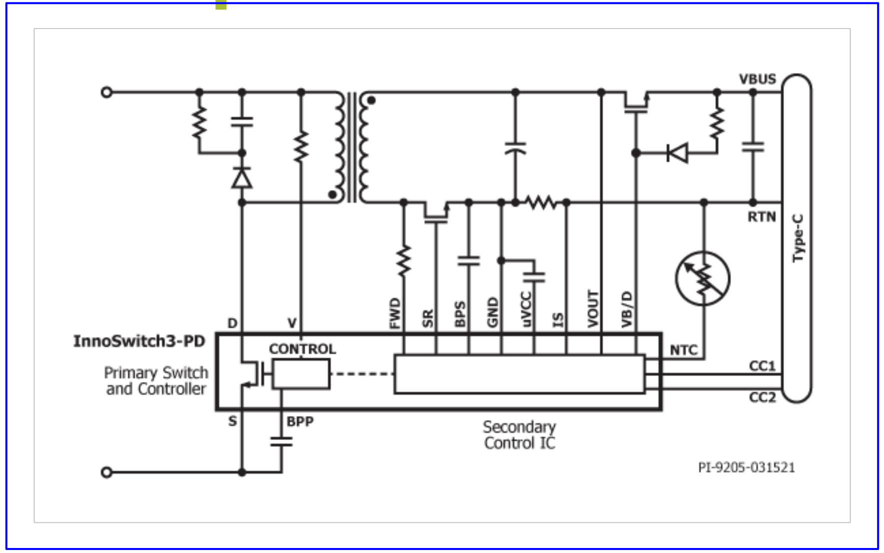
Most popular for the 65W adapters
Several controllers Available in market:
ON, Diodes, Weltrend, HALO, Infineon, China IDH etc.

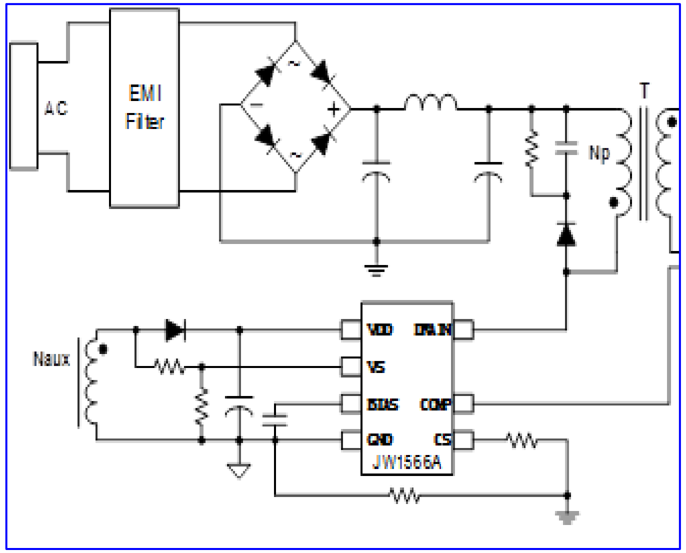
Power Efficiency Curves

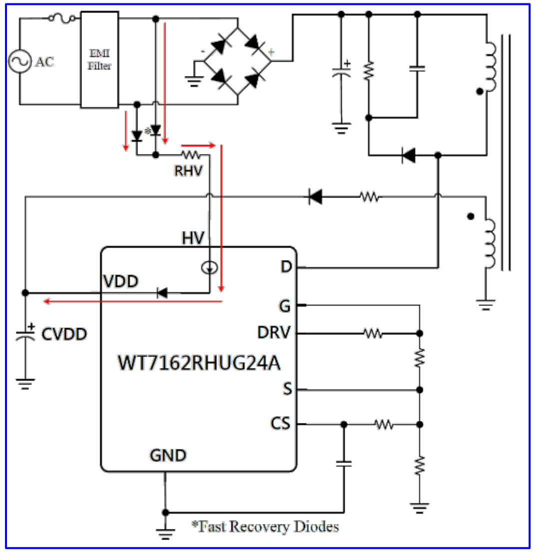


Vin	Iout	Efficiency (%)
90 Vac @ 50 Hz	3.25A	93.04%
115 Vac @ 60 Hz	3.25A	94.04%
230 Vac @ 50 Hz	3.25A	93.85%
265 Vac @ 50 Hz	3.25A	93.46%

Emerging Theme – Integration or SIP (Examples)





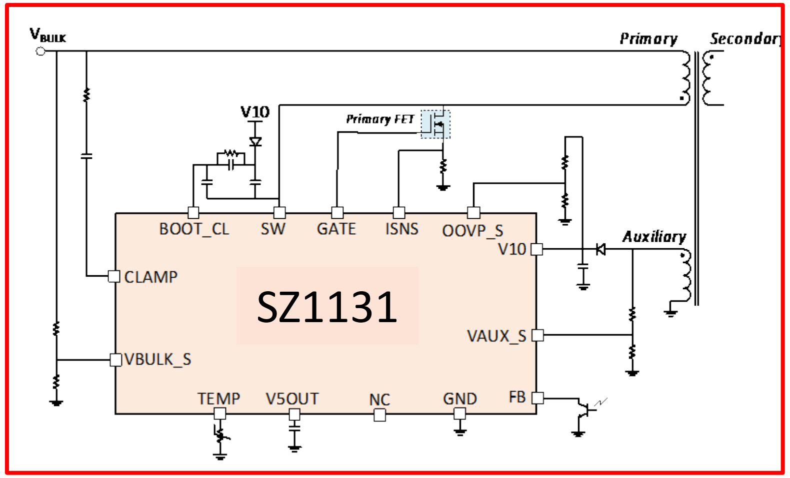


<u>Various Approaches & Trade-offs (performance, size, power density)</u>

- Multiple die in a package (Controller, GaN, SR and USB-PD) along with isolation – Power Integrations
- GaN FET and gate drive logic (Monolithic driver or level shifter, driver IC) – Navitas, CGD
- GaN FET with QR flyback controller & gate driver – Southchip & Kiwi (w/ Innoscience), Weltrend (w/ Transphorm), Navitas (w/ own IC)
- Market will see a rush of SIPs that will add functionality, reduce cost and allow differentiation

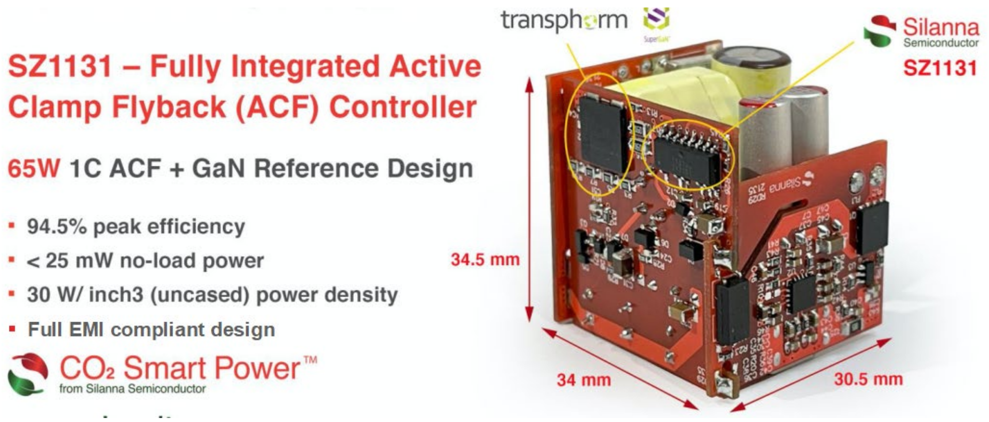
Active Clamp Flyback – still delivers the best efficiency

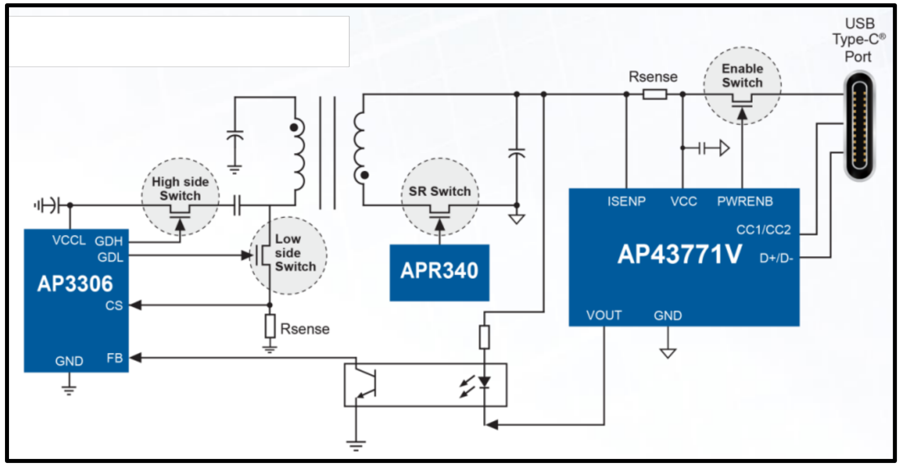
Over 94.5% efficiency @ >30W/in³ – verified with Transphorm GaN



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

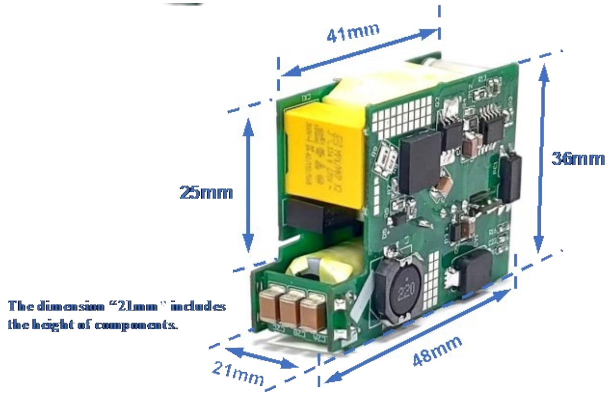
Silanna – SZ1131





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

Diodes – AP3306



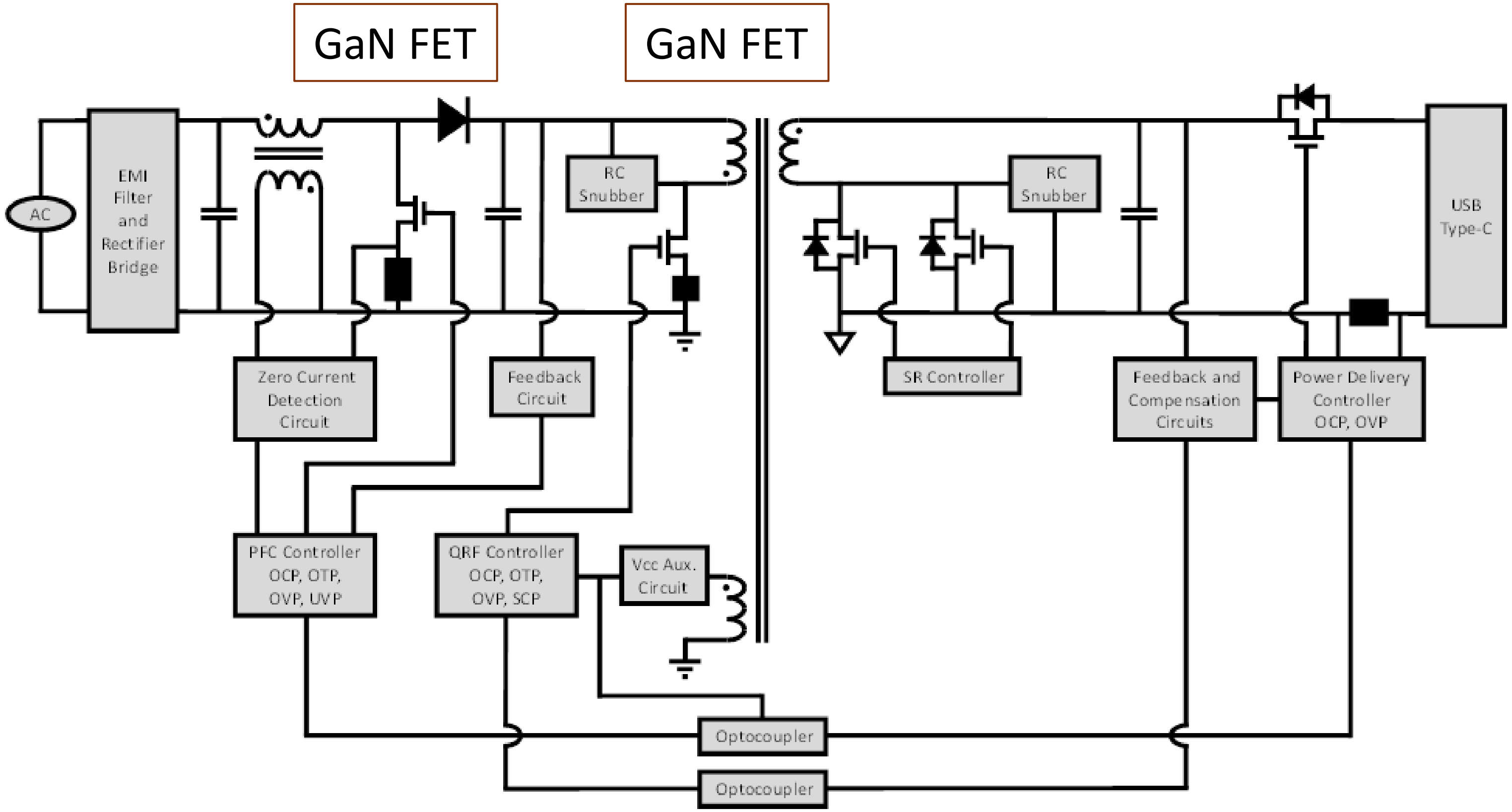
AP3306 – Flexible Active Clamp Flyback (ACF) Controller

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 140W, 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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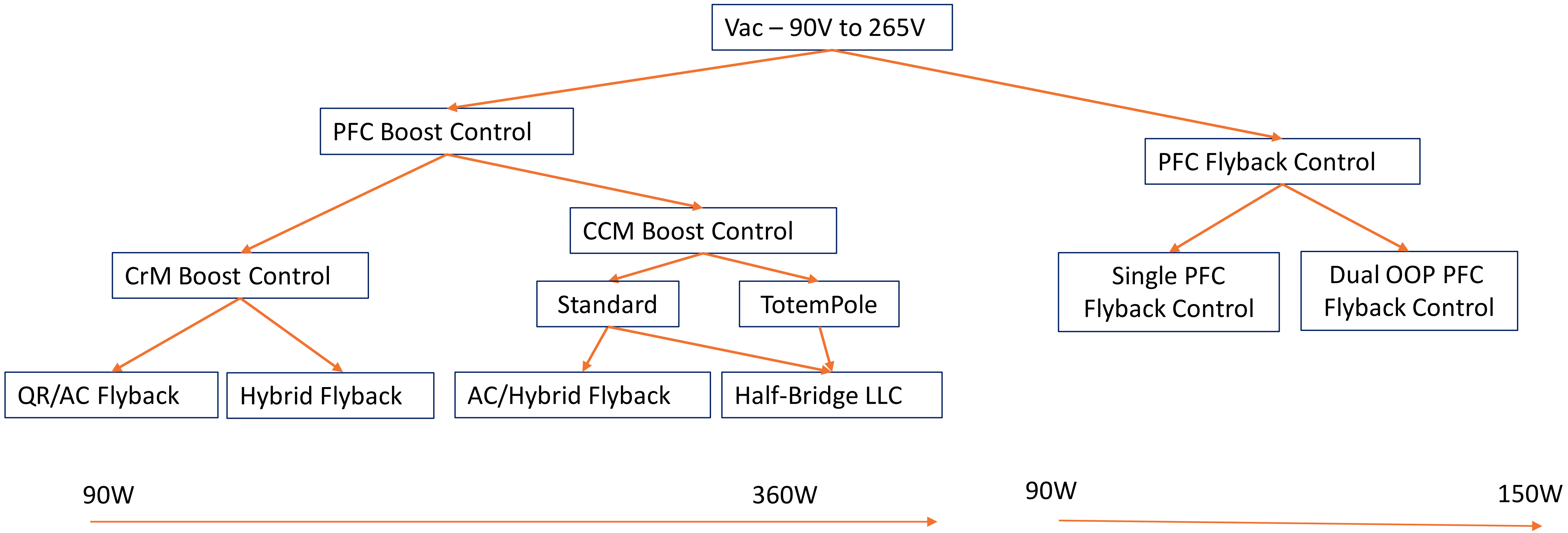
USB-C Adapters/Computer Supplies (70W to 330W)

Topology choices have expanded, just over the past year

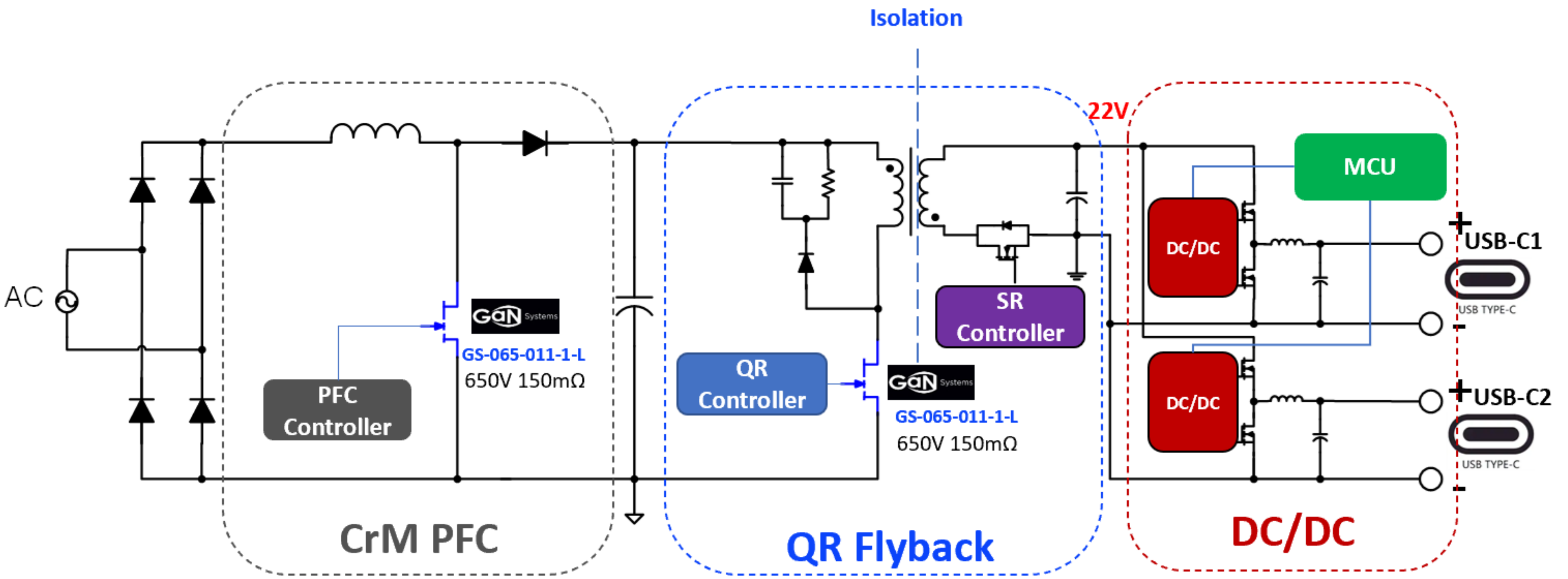


Pros: Smaller bulk cap and PFC O/P Cap
Cons: Complex 2-stage design especially if multi-output

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

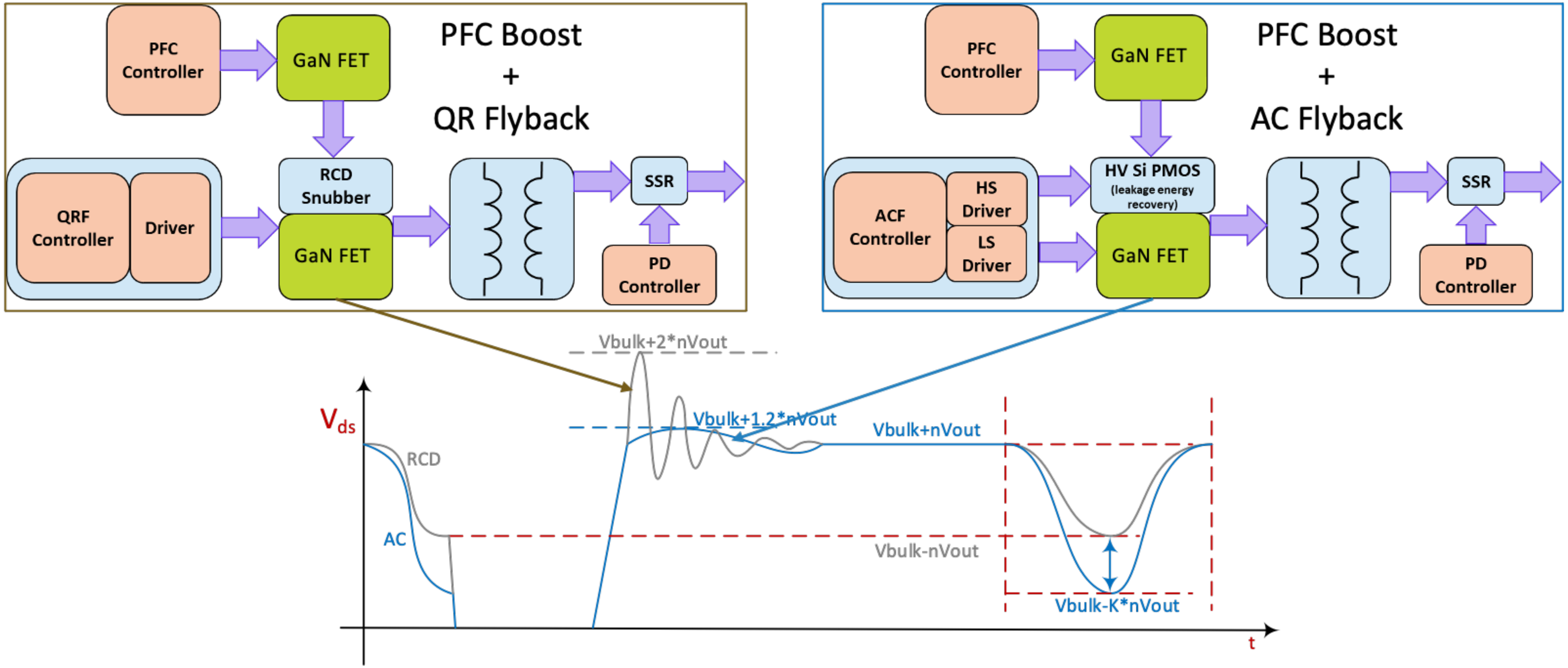
USB-C Adapters (>70W Considerations)

- Furthermore, most adapters have more than one output, as shown below
- The SKUs could have any permutation & combination of multiple USB-C and/or USB-A outputs – eg.
- All GaN Suppliers have solutions and offerings for this topology



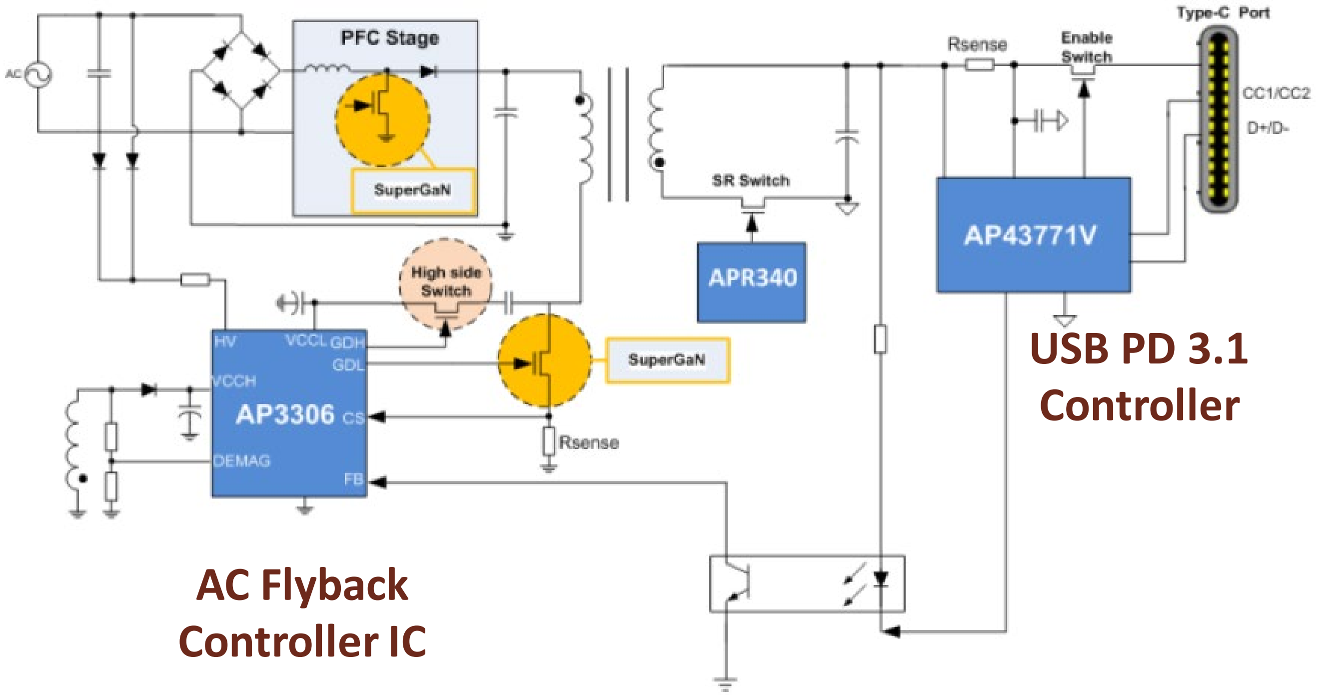
Voltage Stress Considerations in 2-stage topologies

- 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
- When higher input voltage is required (especially industrial 277V), ACF second stage is safer



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)



USB PD 3.1 Controller

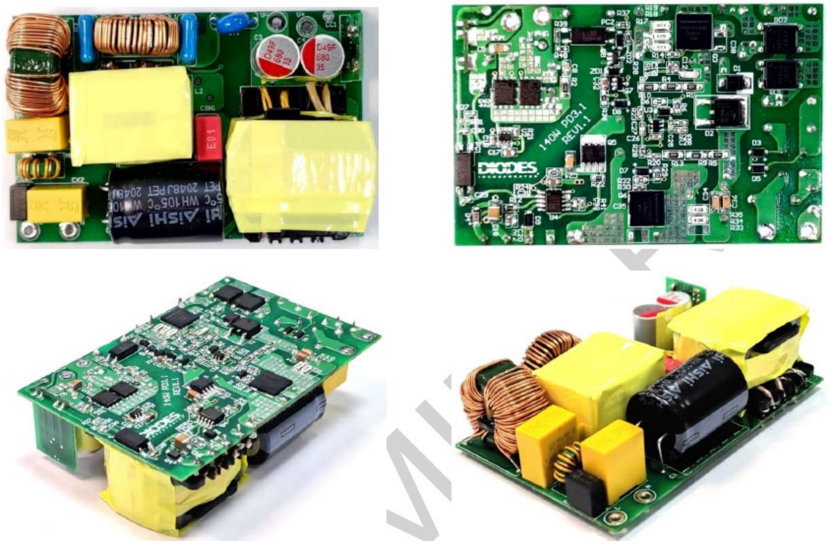
AC Flyback Controller IC

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

Comparison of a Leading ACF vs. AHB Comparison

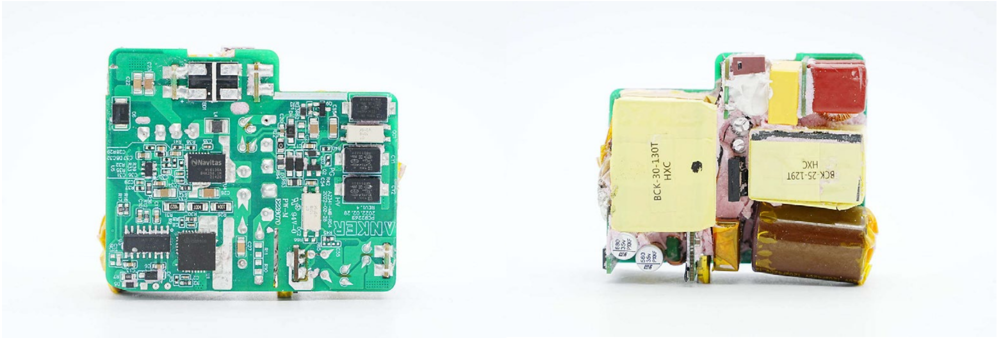
DIODES AP3306

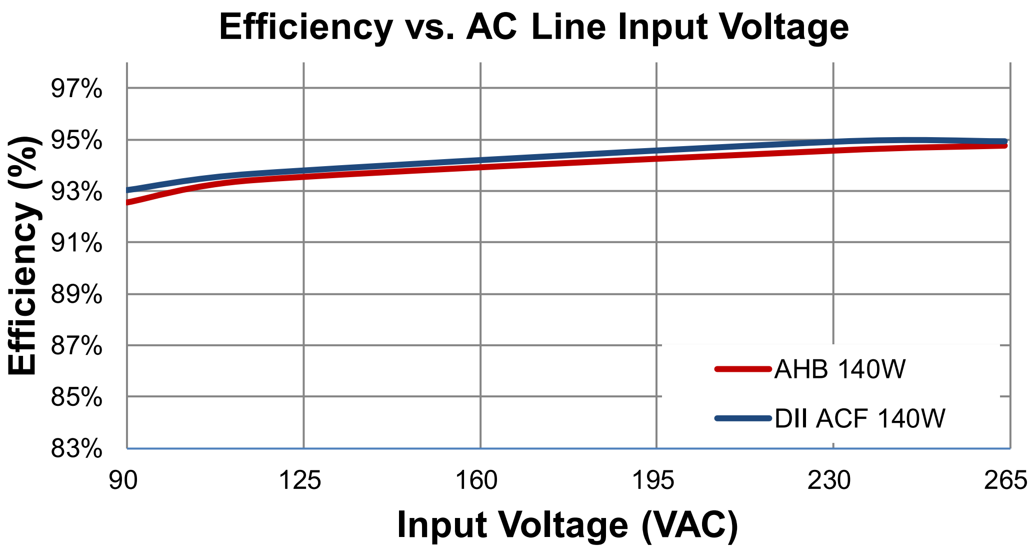
Model No: 140CC 140W ACF EVB



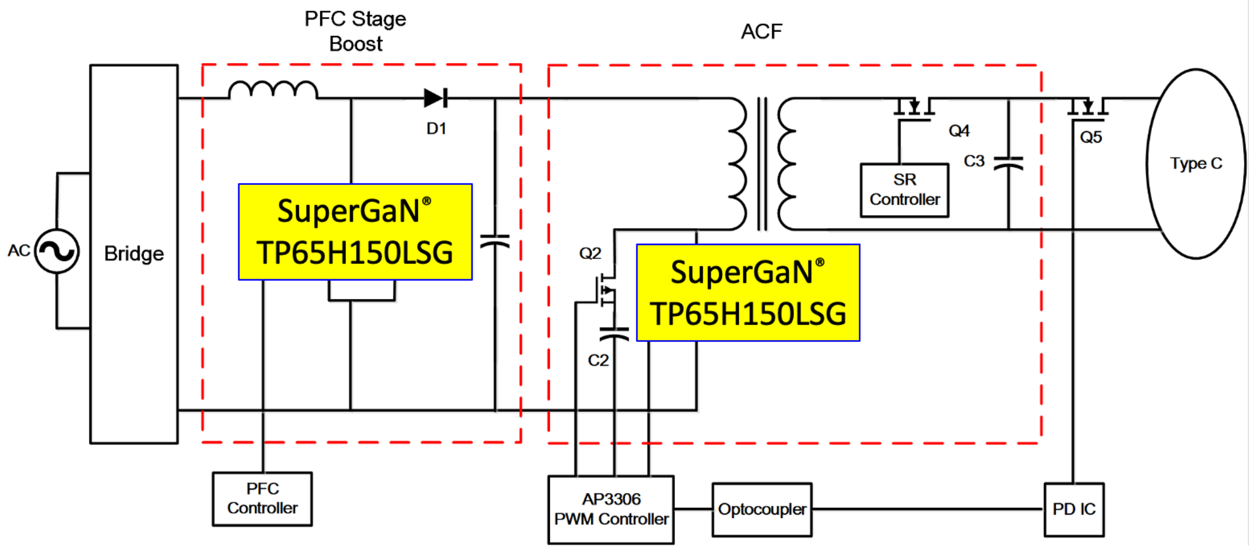
Infineon XDPS2201

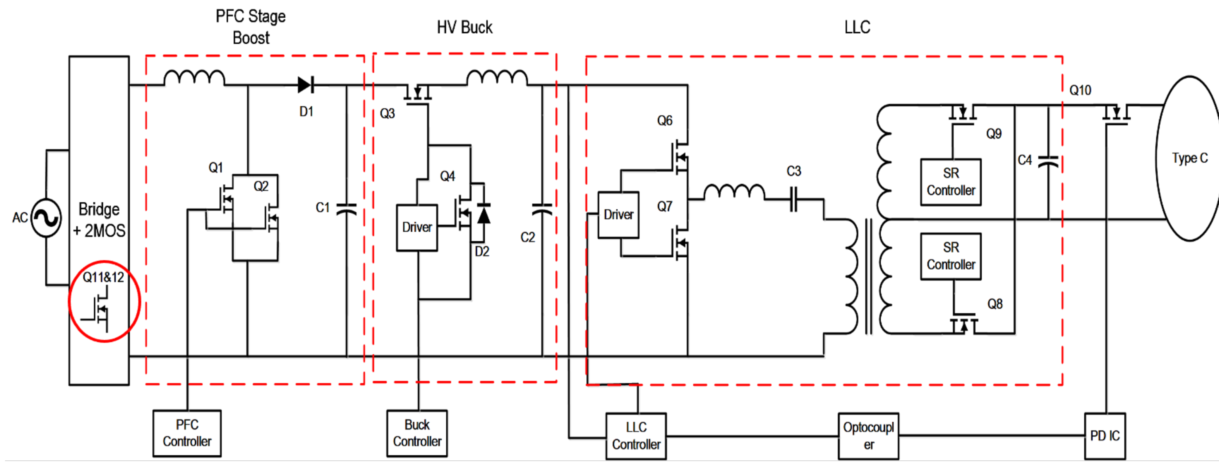
Model No: ANKER 120CC_XDPS2201_140W





140W PD3.1 Topology Comparison



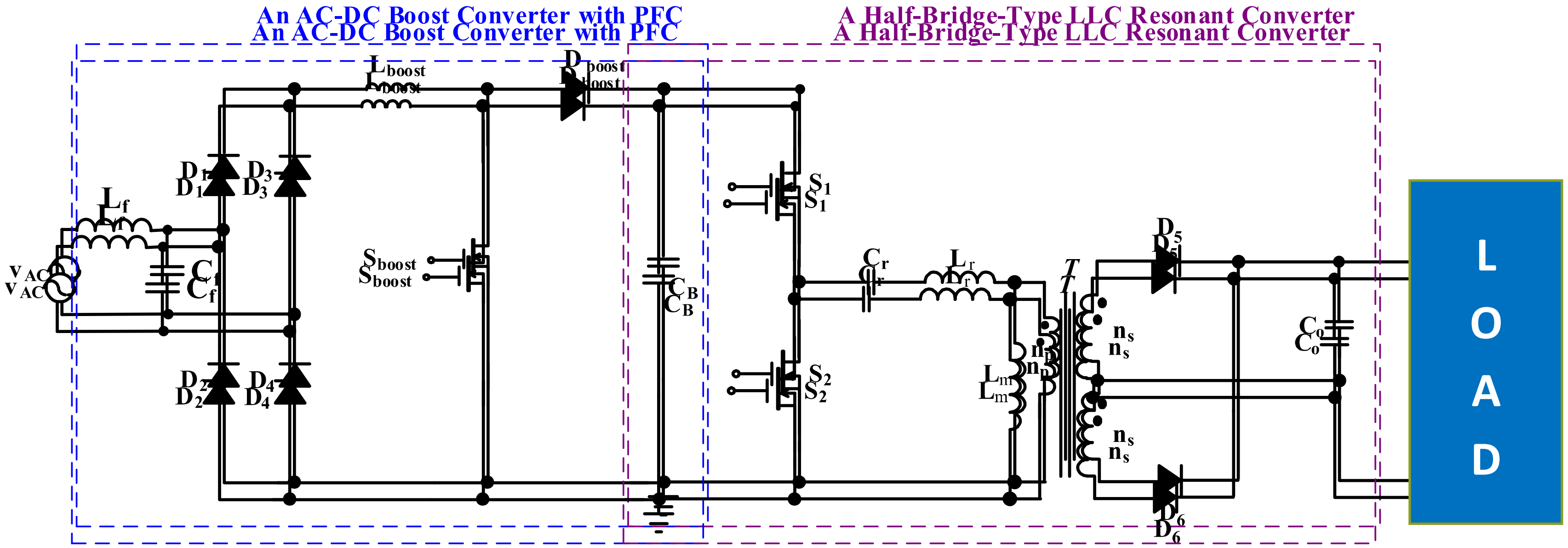


- Uses <120 components
- 3 HV Power Devices
- Q1/Q3 – GaN devices, Q2 is HV PMOS
- Uses off the shelf controllers, simpler with high efficiency & density

- Uses ~ 400 components
- Uses 8 high voltage power devices
- Topology complex, flexible, robust with excellent efficiency at low-line
- Conservative Approach

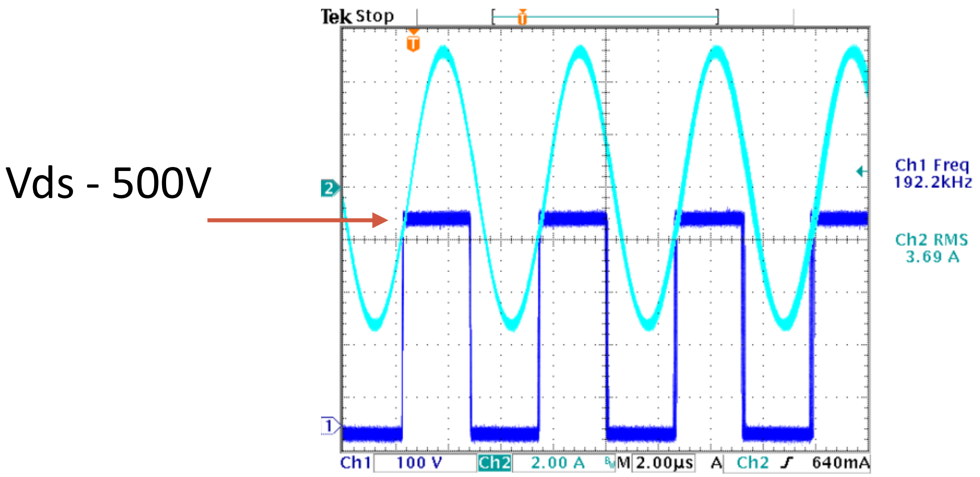
Computer, Display Power Supplies & LED Drivers

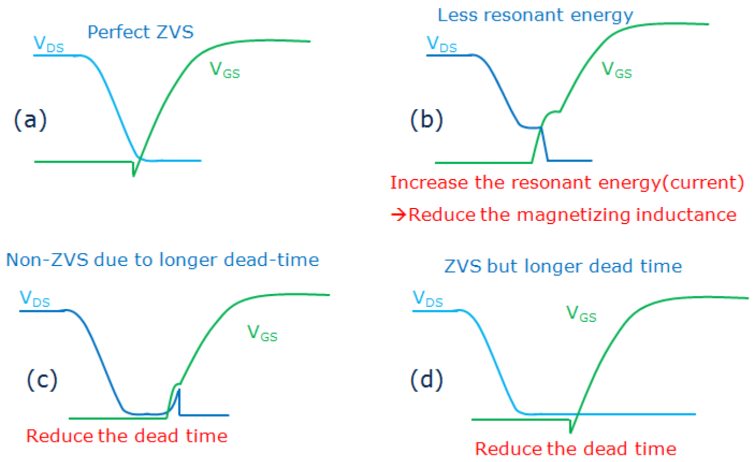
- For >150W (or even lower levels) up to 1kW (or higher), power factor correction followed by a half-bridge resonant topology is implemented
- Advantages of HB-LLC resonant topology include:
  - ZVS, which produces high efficiency and allows shrinking transformer
  - Limits dv/dt and di/dt, which reduces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



Considerations for a Half-Bridge LLC using GaN

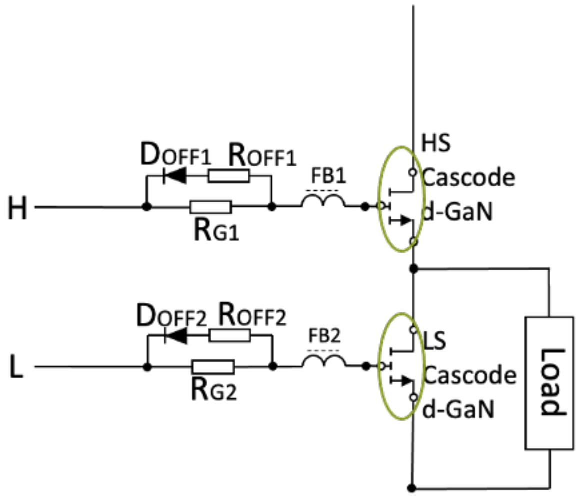
- Keeps stress on the bridge switches below 500V, compared to QR flyback and ACF flyback, thus making it is ideal for GaN
- Higher efficiency compared to AHB topology
- ZVS switching, which begs the question - Why is GaN preferred over Super Junction MOSFETs?
- Both efficiency and size can be optimized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

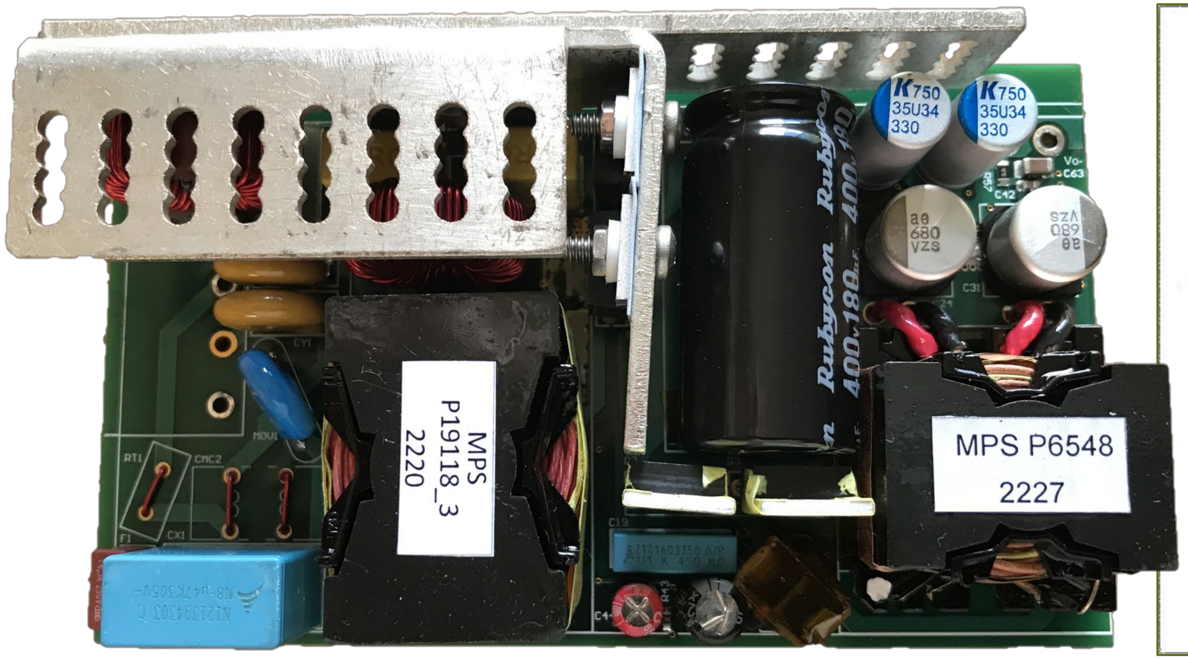


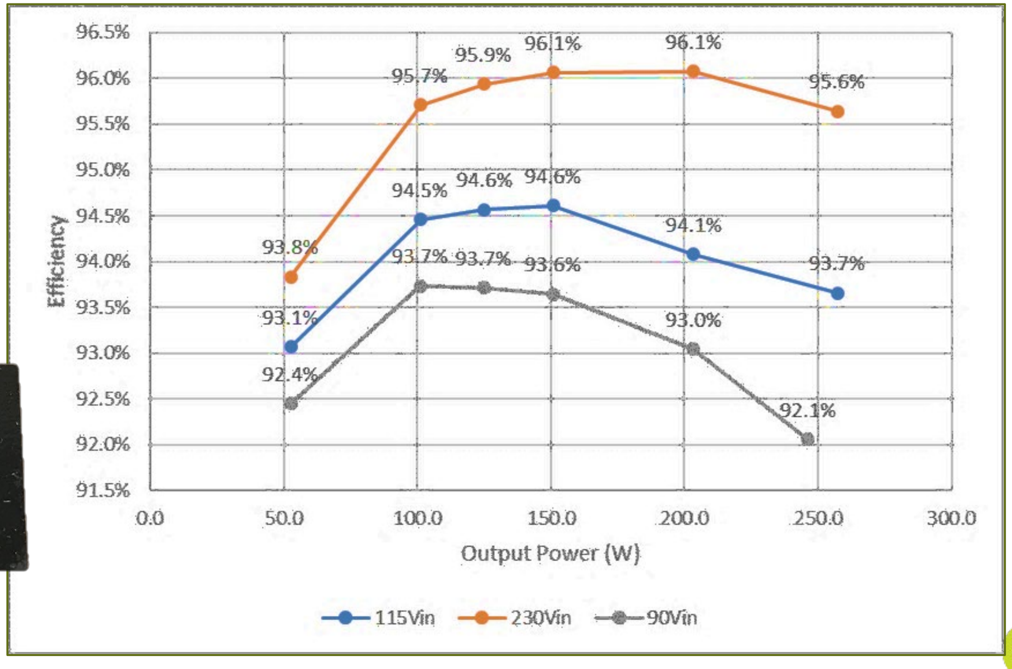


250W Solution & Drive Considerations

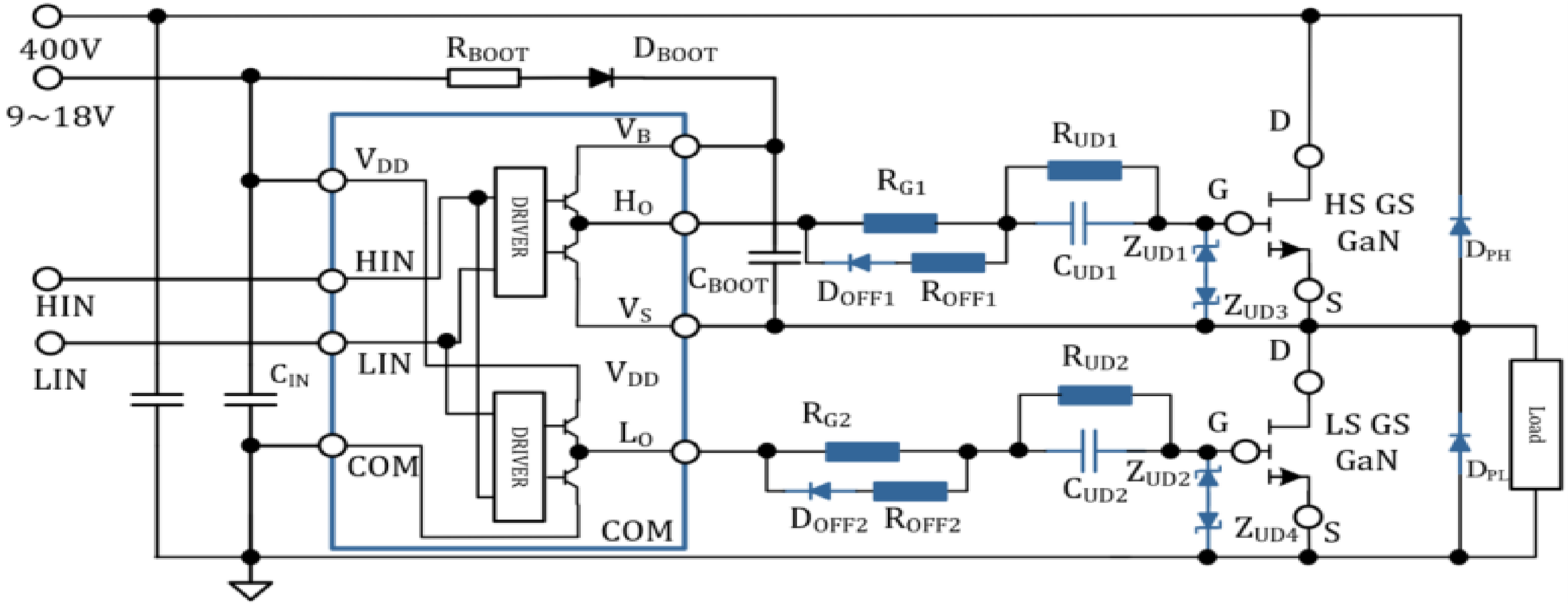
- Vin = 90 – 265Vac, Vo = 24V, Po = 250W
- Switching frequency: 133kHz(PFC), 172-180kHz(LLC)
- Board dimensions: 110mm*60mm*25mm (4.3" x 2.35" x 1")
- High Power density: 24.8W/in^3 – significantly higher than silicon
- Over 96% total system peak efficiency at 230V AC input







Half Bridge with e-GaN – Drive Considerations



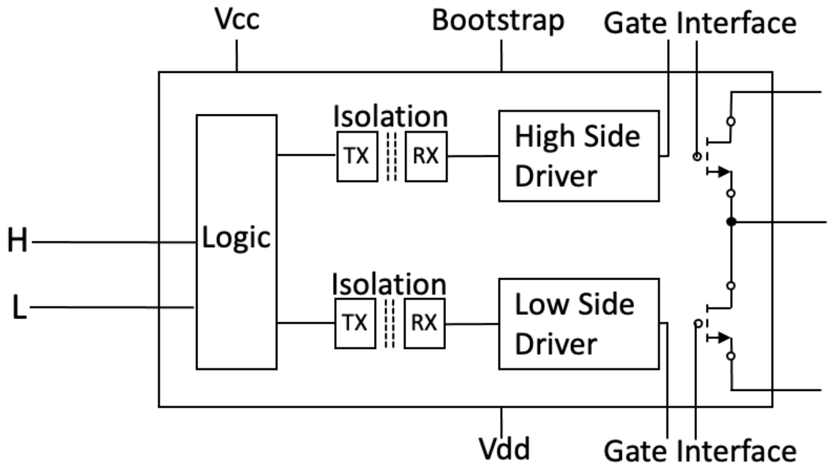
Source: GaN Systems Applications Note

- Vt is low ~ 1.2V, Vgs(rating) ~ -10V to +7V
- Either level shifter is needed or dedicated 6V (max) gate driver
- For single ended topology, same applies except for one e-GaN HEMT
- Improvements in driving e-GaN is a trend

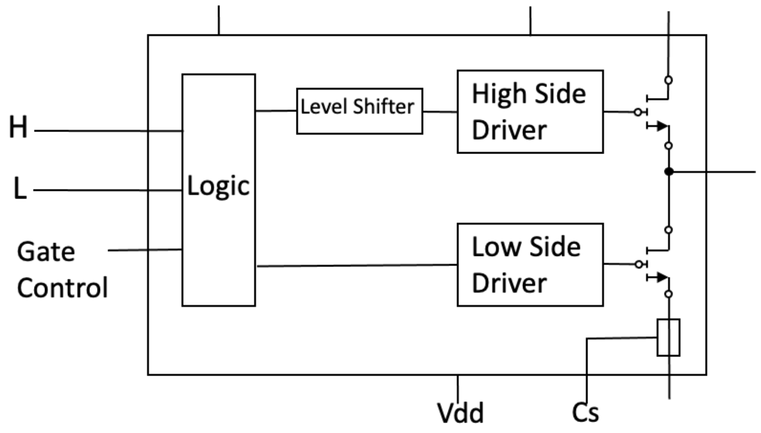
Half Bridge with e-GaN – Drive Considerations

Recent examples of integration to ease e-GaN drive issues

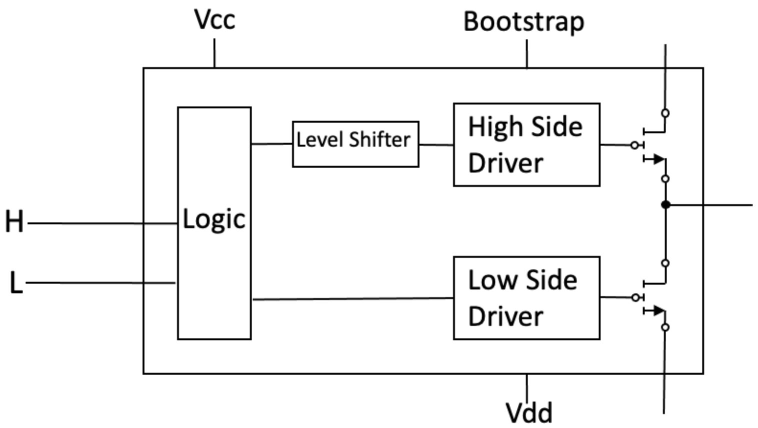
- Companies bringing approaches depending on their capabilities
- Reduces flexibility and has max power dissipation constraints
- Bundle the GaN+Driver in package with their controllers



Infineon CoolGaN Integrated Power Stage (IPS)



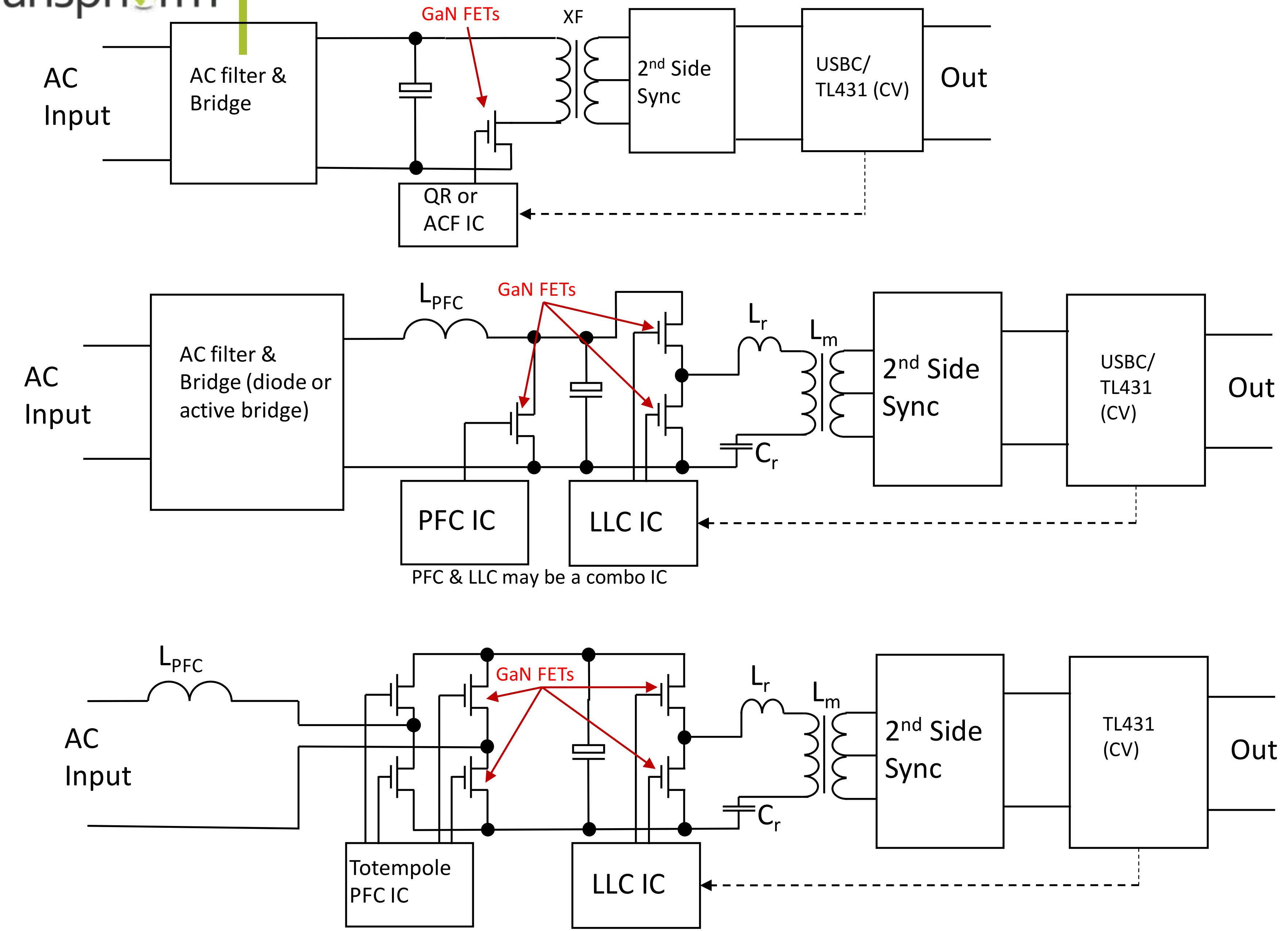
Navitas GaNFast HB Bridge Power IC



ST Master GaN HB Driver+GaN

Modifications to Topologies for CV, CC-CV (Non-USB, Battery Charging & LED Lighting)

Standard Constant Voltage Design - USB



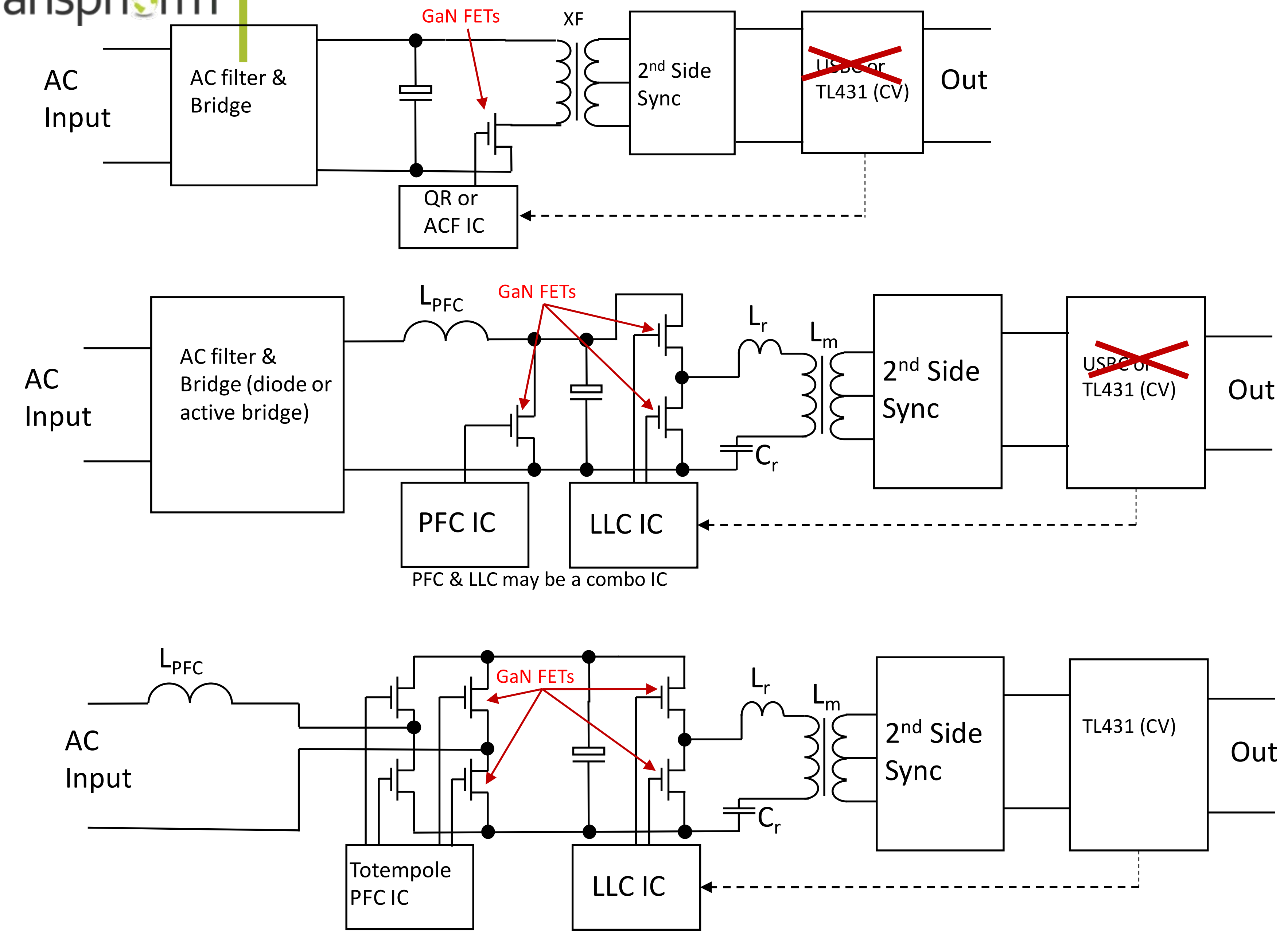
45W, 65W USB-C Adaptor Forms

100W - 140W USB-C, 240W in CV Adapter

240W – 330W in CV Adaptor

Increased Power Level

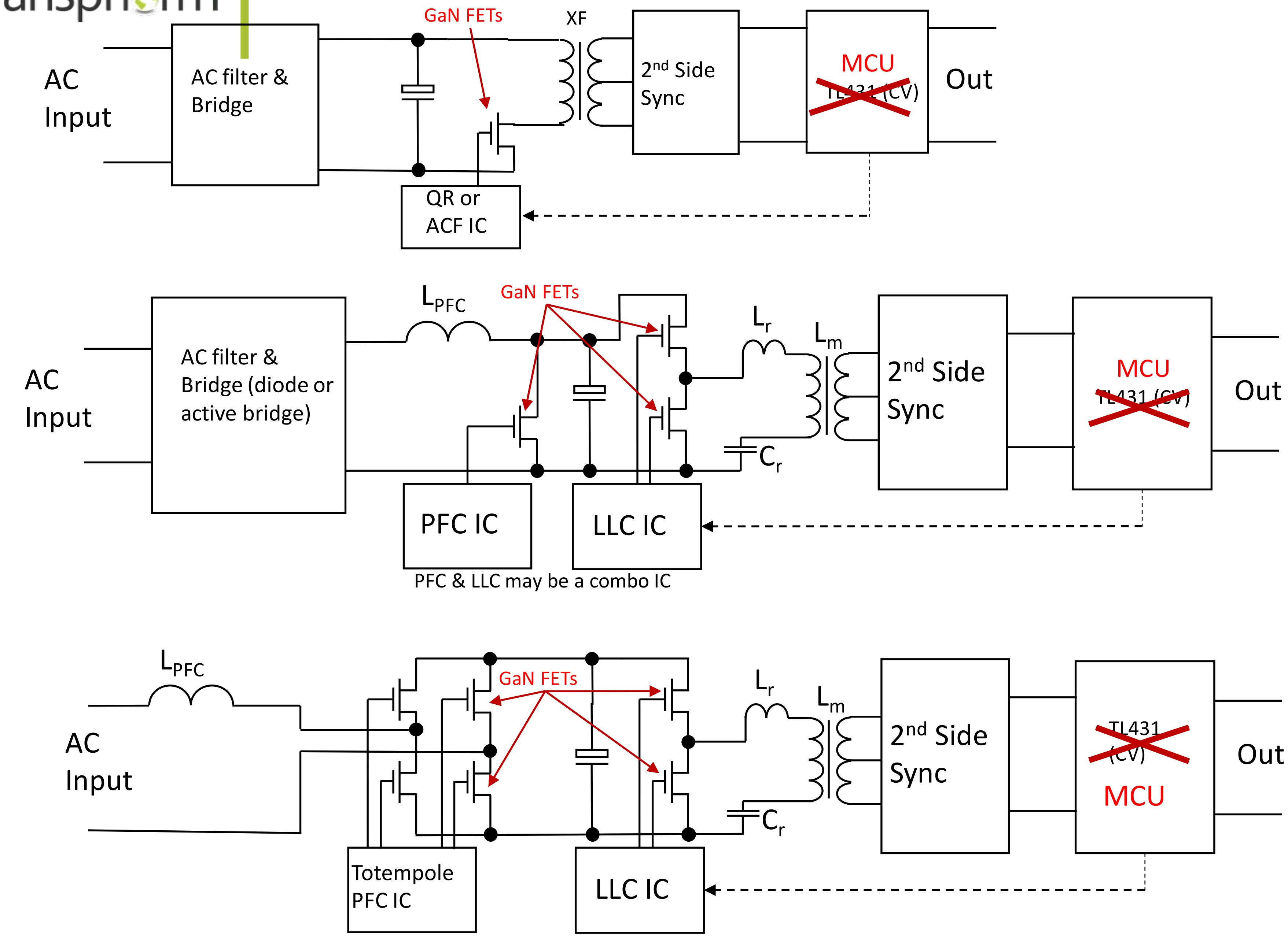
Non-USB Constant Voltage (CV) Designs



Remove USB-C PD controller circuit and add CV (TL431) circuit

Increased Power Level

Battery Charger (CC-CV) Designs

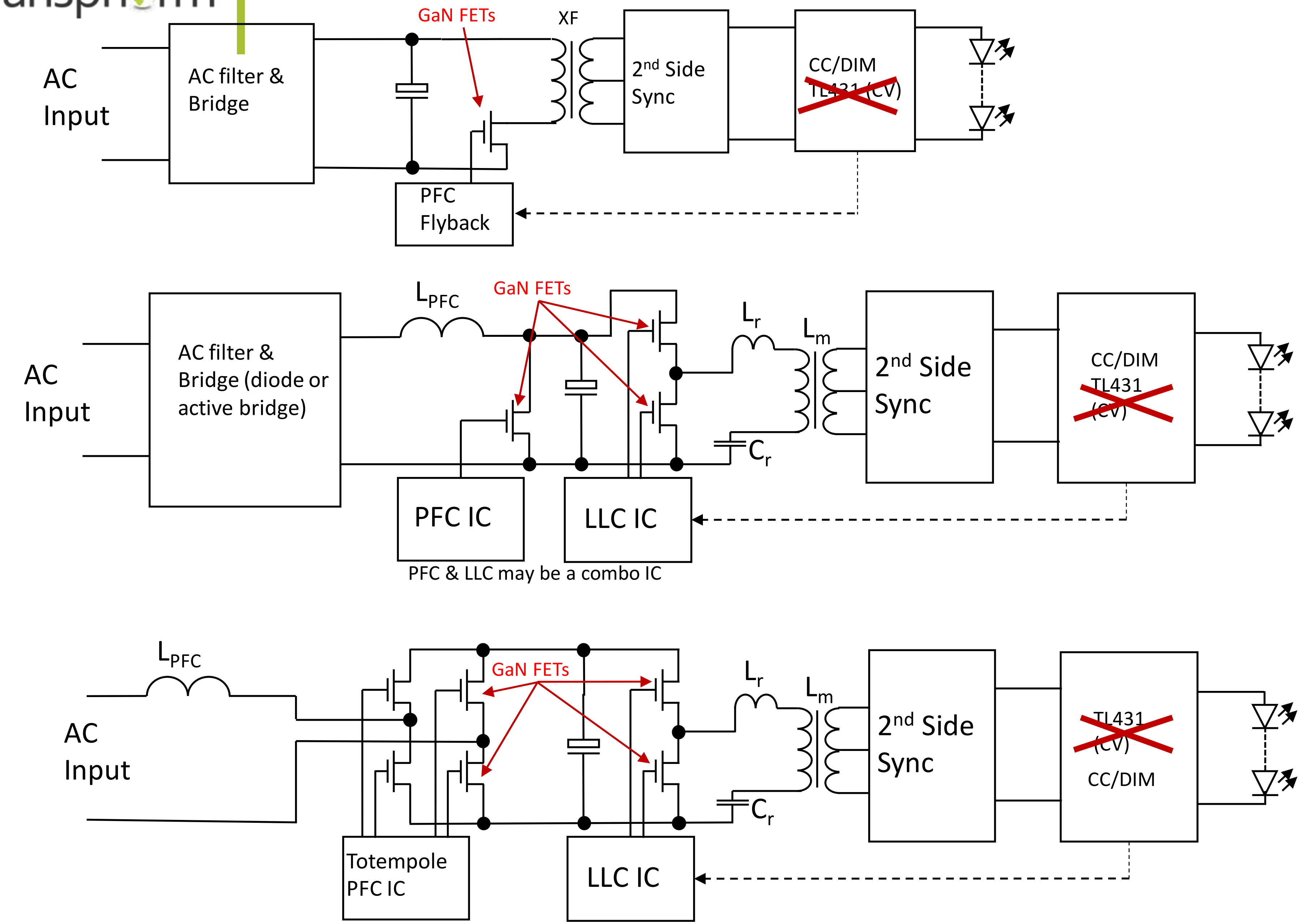


1. Remove TL431 circuit, use MCU for CC-CV.
2. Needs firmware capability (maintain, program and adapt to various field requirements)
3. Custom analog CC-CV circuits available

Power stage designs for CV only application may not apply to CC-CV.

Increased Power Level

LED Lighting (CC-CV) Designs



1. Approaches for CCCV (Processor or custom CCCV analog circuit) can be adapted for LED Lighting for simple dimming.
2. Power stage designs for CV or CCCV application may not be suitable for LED Lighting with deep dimming requirement <10%.
3. A PFC + a dedicated CC stage may be more appropriate.

Increased Power Level

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Approaches for Power Factor Correction

	Devices operating at line speed	High Speed Devices in Phase 1 (GaN)	High Speed Devices in Phase 2 (GaN)	FET Drivers	Pros	Cons
Conventional Boost	0	1	0	1 Low Side	1. Simple 2. Many off-the shelf controllers	1. Lower efficiency 2. Higher component stress
Conventional Interleaved	0	2	0	2 Low Side	1. Higher power 2. Lower ripple currents	1. Fewer controllers 2. Higher complexity
Dual Bridgeless	2	1	1	4 Low Side	1. Higher efficiency 2. No high-side drivers	1. No standard ASIC 2. Lower efficiency than Totem Pole
Totem Pole	2	2	0	2 Low Side 2 High Side	1. Highest efficiency 2. Small footprint	1. Few controllers 2. More complex design

- CCM, DCM or CRM can be chosen based on power levels
- Switching frequencies can also be optimized depending on the application

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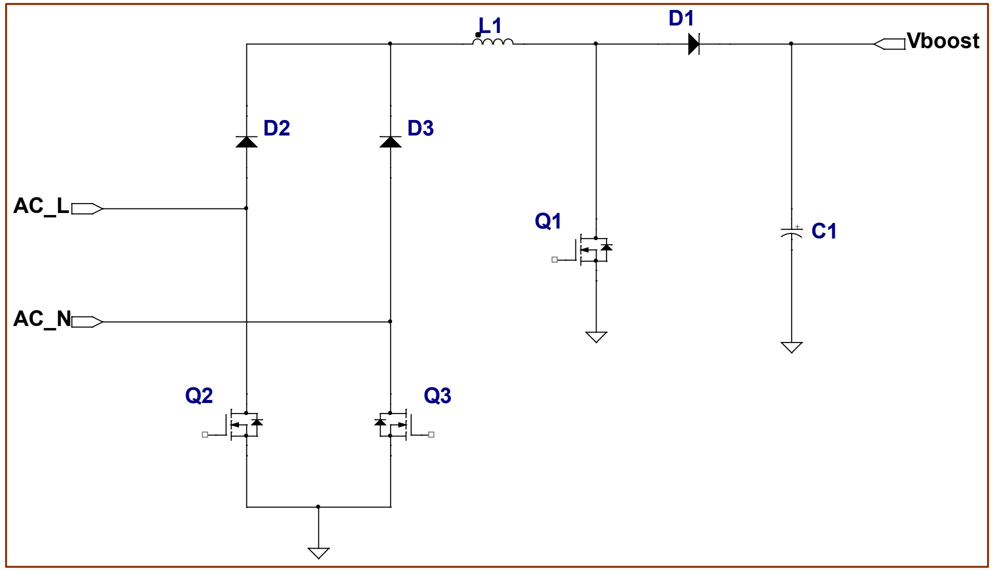
PFC Variations with Half & Full Active Bridge

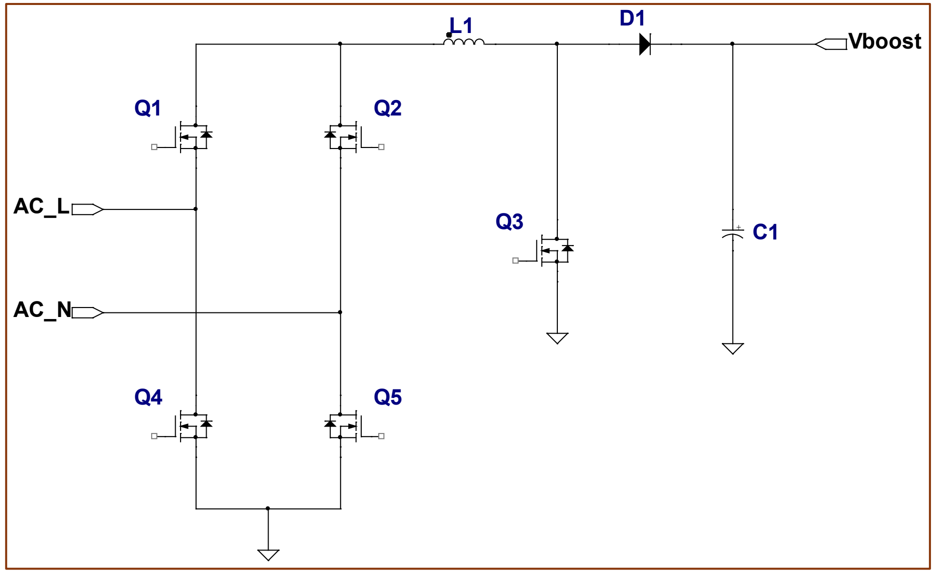
	Devices operating at line speed	High Speed Devices in Phase 1 (GaN)	High Speed Devices in Phase 2 (GaN)	FET Drivers	Pros	Cons
Half Active Bridge (Conventional)	2	1	0	3 Low Side	1. No high-side drivers 2. Improvement over diode bridge	1. Limited power level 2. Fewer controllers
Full Active Bridge (Conventional)	4	1	0	3 Low Side 2 High Side	1. More efficient 2. Line frequency switching	1. Requires high-side drivers 2. Fewer controllers

- The half or full active bridge can be used with conventional or interleaved topologies

Half & Full Active Bridge Conventional Boost PFC



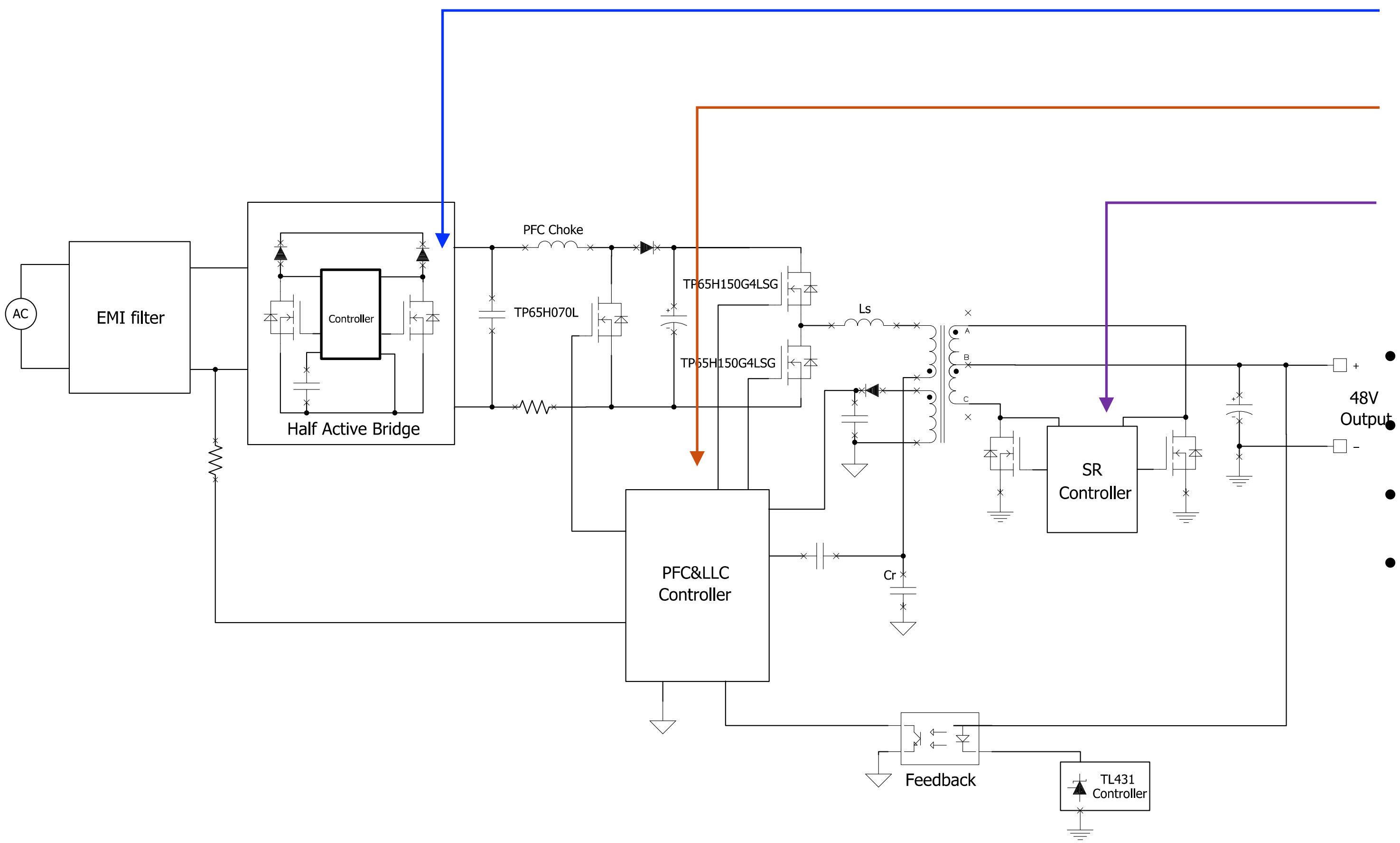
- The bottom rectifiers are replaced with FETs to reduce conduction losses
- Q2 & Q3 switch at the line rate
- The boost is conventional and may be single or multi-phase CCM, DCM, or CrM



- The bridge rectifiers are replaced with FETs to reduce conduction losses
- Q1, Q2, Q4 & Q5 switch at the line rate
- The boost is conventional and may be single or multi-phase CCM, DCM, or CrM

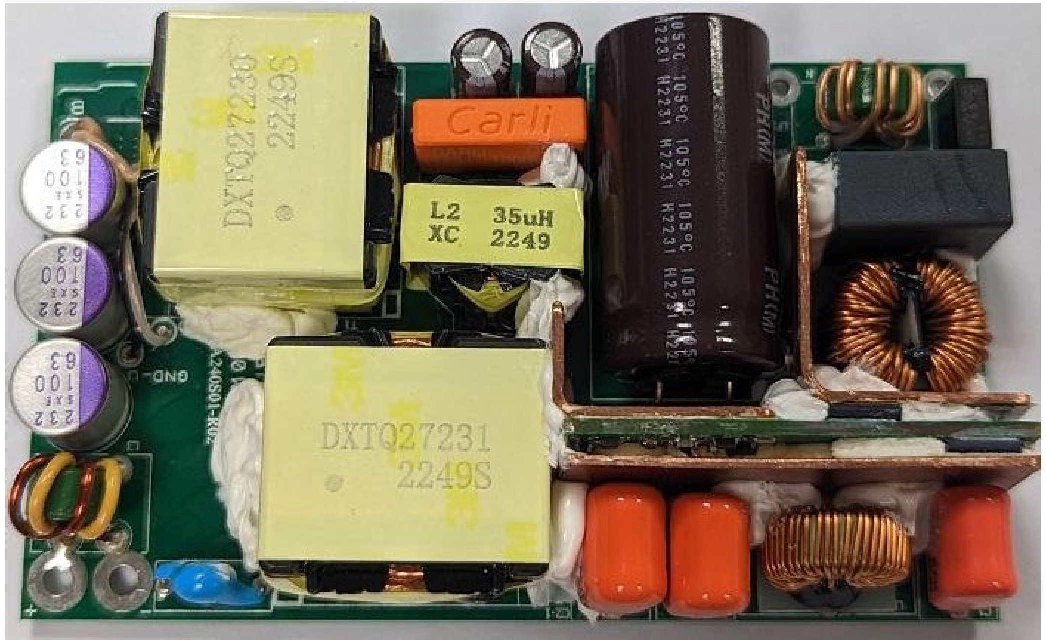
Enhancing Density using Half-active Bridge

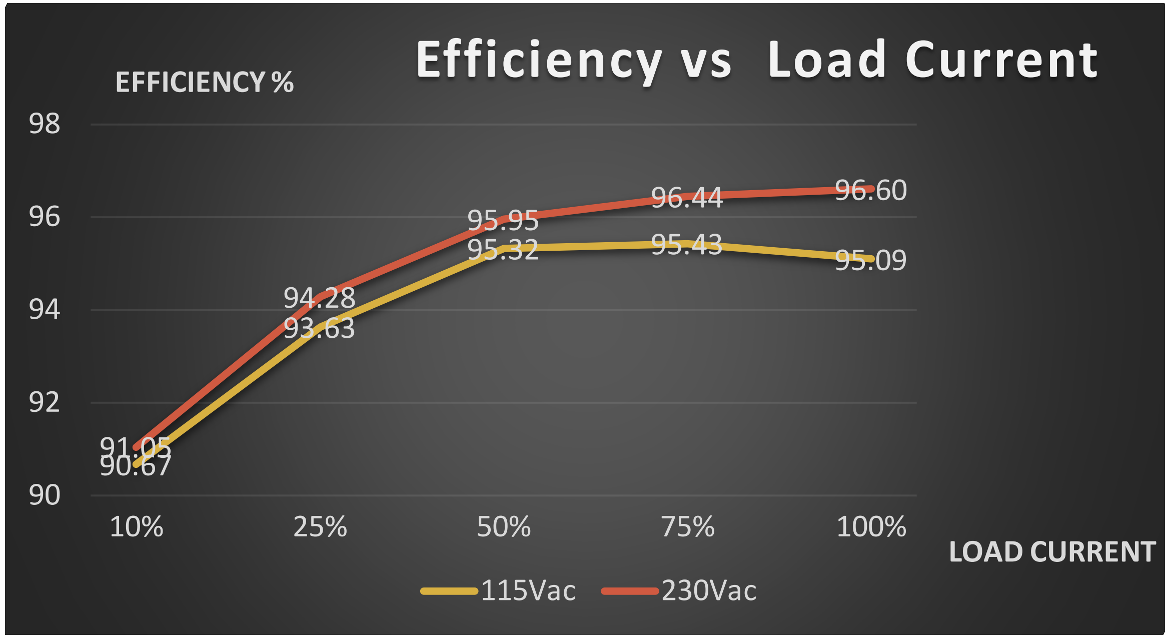
240W / 48V output system Example



- The power supply uses
  - TEA2206T(Half Active Bridge)
  - TEA2017(PFC, LLC)
  - SR(TEA2096) controller.
- PFC design Fsw 250KHz, GaN – 50 to 70mOhm
- LLC design Fsw 200KHz, GaN – 110 to 150mOhm
- Power density target > 28W/in^3
- Target Peak Efficiency >96%

High Density 240W Design - Implementation





- Board dimensions: 100mm*60mm*23mm
- Power density: 28.5W/in^3 without case
- Compact implementation
- Low component temperature

Vin	Iout	Efficiency (%)	PF
90 Vac @ 60 Hz	5A	94.03	0.9956
115 Vac @ 60 Hz	5A	95.09	0.9985
230 Vac @ 50 Hz	5A	96.60	0.9903
264 Vac @ 50 Hz	5A	96.74	0.9821

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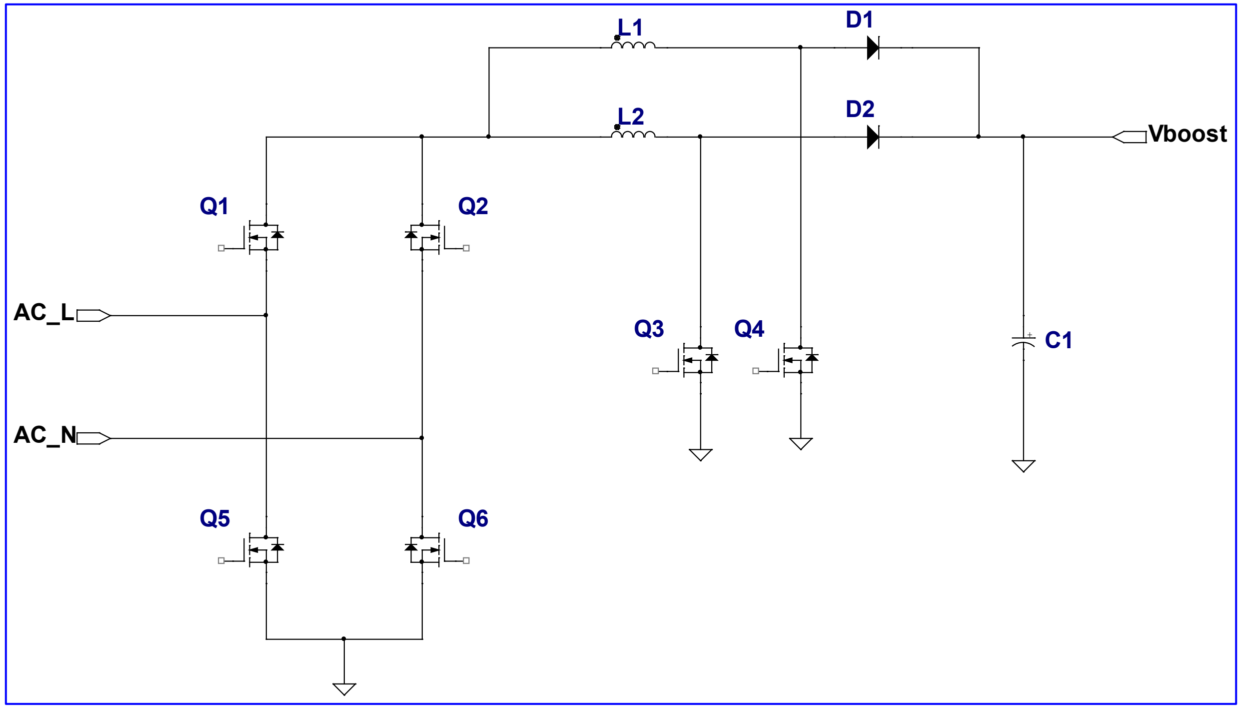
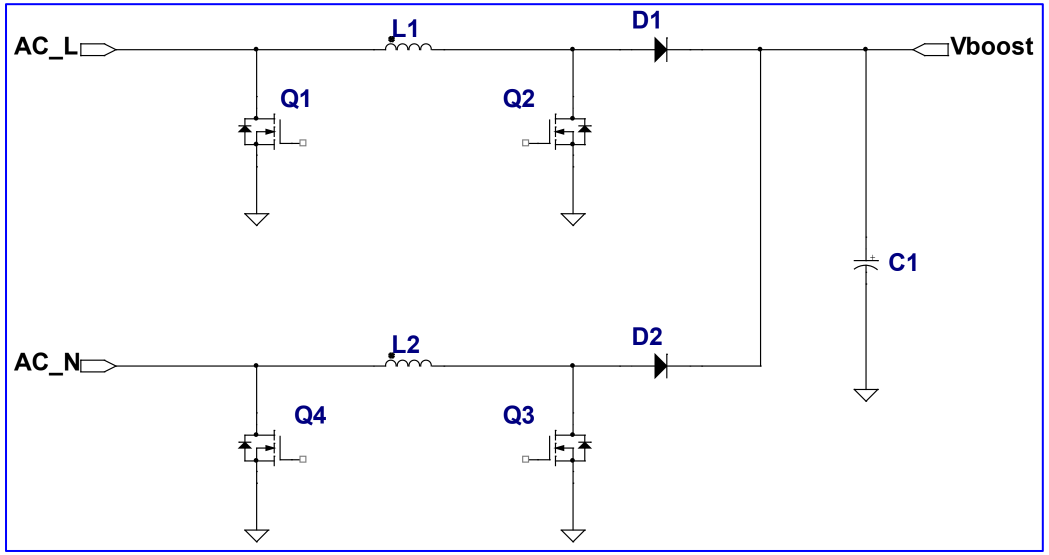
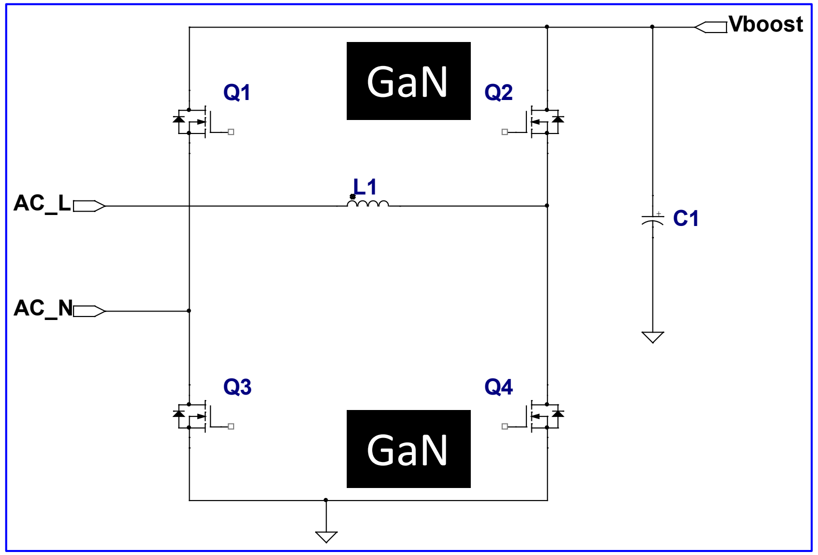
Dual-out-of-phase Boost PFC



- Distributes power stress in the two switches Q3 and Q4
- Reduces input & output ripple current
- Can work with half & full active bridge rectifiers (circuit shows full active bridge)
- CCM, DCM, or CrM, but CCM is most popular, several controller available
- Popular topology – now being challenged by bridgeless topologies

Bridgeless Boost PFC – Standard & TotemPole

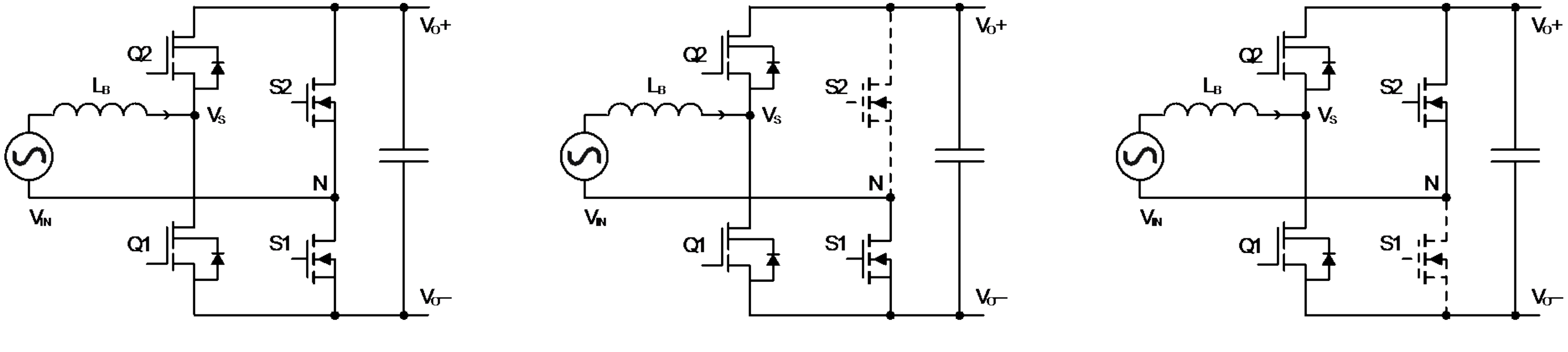




- The dual resembles the interleaved because it has 2 parallel power stages.
- 2 power stages operate on opposite half cycle
- No ripple cancellation or power sharing
- Gain in efficiency from eliminating diode bridge
- Q1 & Q4 operate at the line rate while Q2 & Q3 operate at high frequency
- All gate drive is referenced to ground, no HS Drive
- Requires both inductors to deliver full power but thermally only need to support 50% of power

- 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
- Can be used with transistors (Q1 and Q3) in slow leg or with diodes to reduce cost
- Requires only 1 boost inductor

GaN Totem Pole Bridgeless Boost PFC Notes



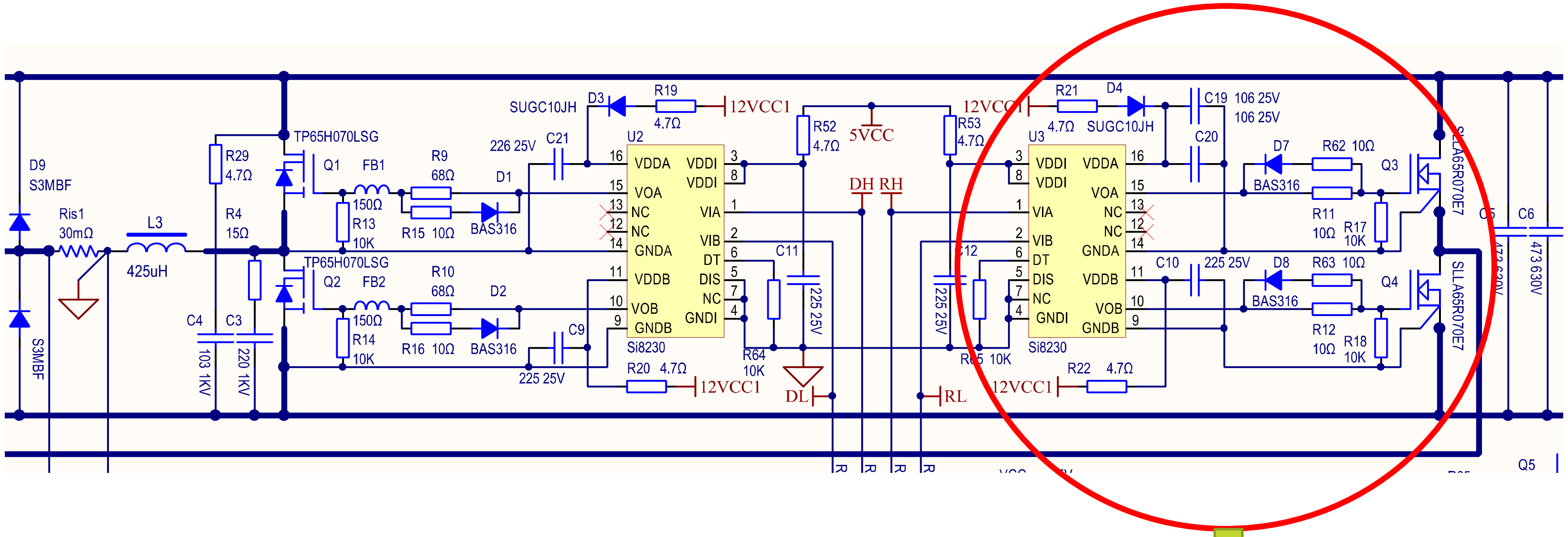
(a) (b) (c)

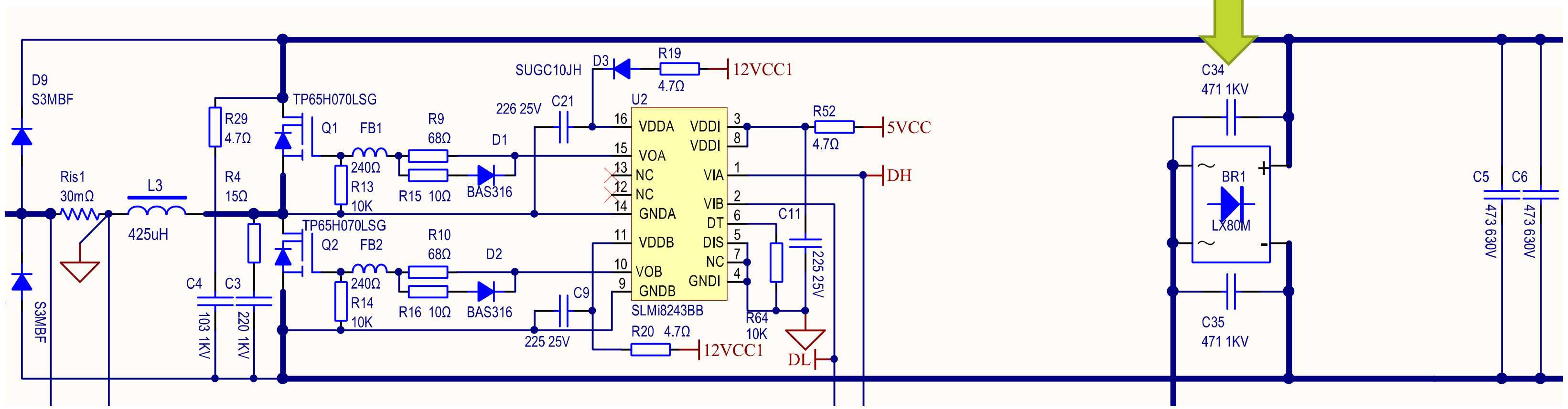
https://www.transphormusa.com/en/document/tdttp2500p100-kit-user-guide/

- 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.

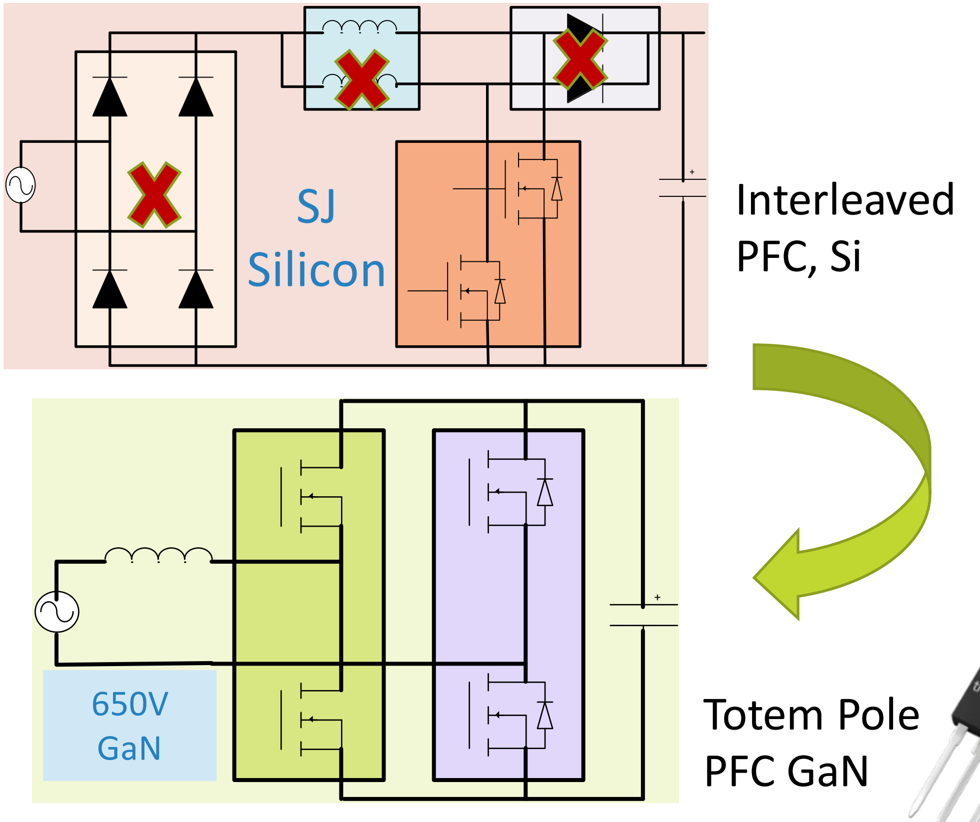
Strategies for Totempole (TTP) PFC configurations

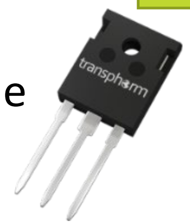
- TTP PFC traditionally used digital controllers
- Cost and ease-of-use enabling analog/mixed-signal ICs
- Compromise of efficiency and cost is important
- Current sensing and ZCD sensing allow innovation
- ON Semi, Inventchip, MPS have analog ICs on the market





Corsair Gaming PC: Lower BOM + Higher Efficiency





PFC Results	Interleaved	Bridgeless Totem Pole
Efficiency	97.8 %	98.65 %
Total Cost	100%	90%

- Increase AC-DC efficiency: to 99% (80+ Titanium)
- Increased output power: 6.5%
- Smaller enclosure size: 11%
- Lower cost per watt: 6.3% ($0.28 vs. $0.30)

CORSAIR

AX1600i Digital ATX Power Supply — 1600 Watt Fully-Modular PSU

$449.99 USD

AX1500i Digital ATX Power Supply — 1500 Watt Fully-Modular PSU

$449.99 USD

"The Corsair AX1600i is the best PSU that money can buy today, period."

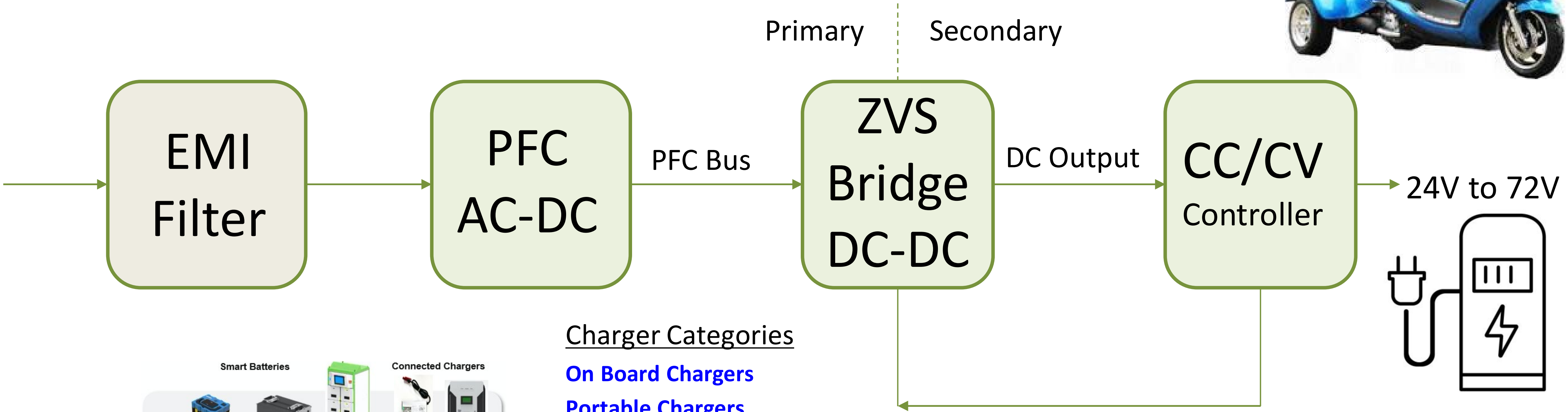
tom's HARDWARE

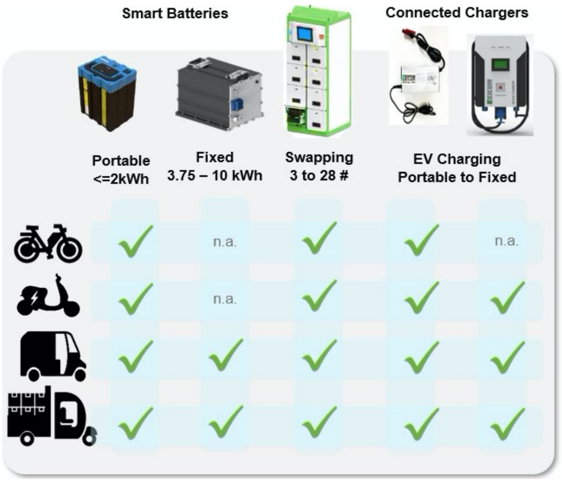
Topologies used in 300W to 1kW+ Applications

For e-Bikes, Electric 2/3 Wheelers and Personal Power Devices

Bridge Topology variations with Battery charging Electronics

Electric 2/3 Wheeler Charger Architecture





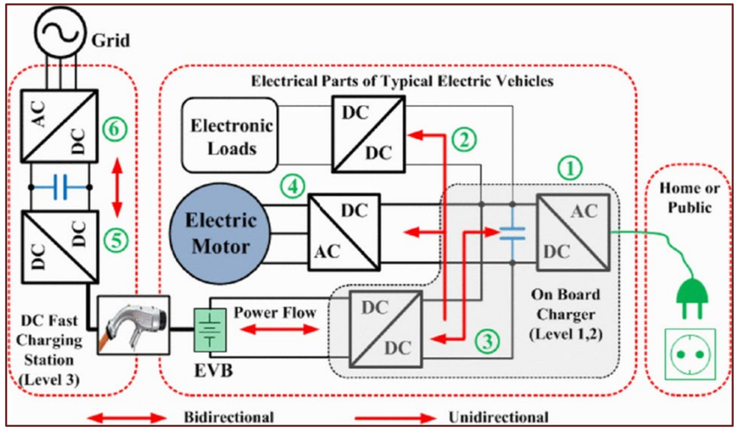
Charger Categories

On Board Chargers

Portable Chargers

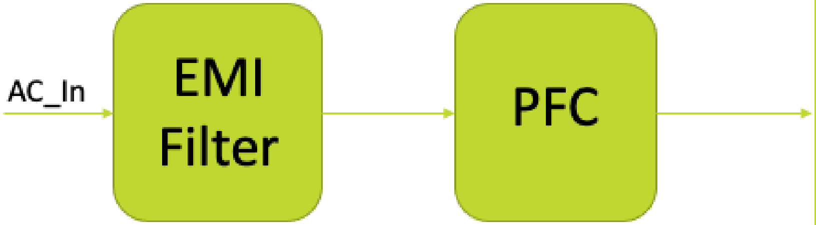
Pole Chargers

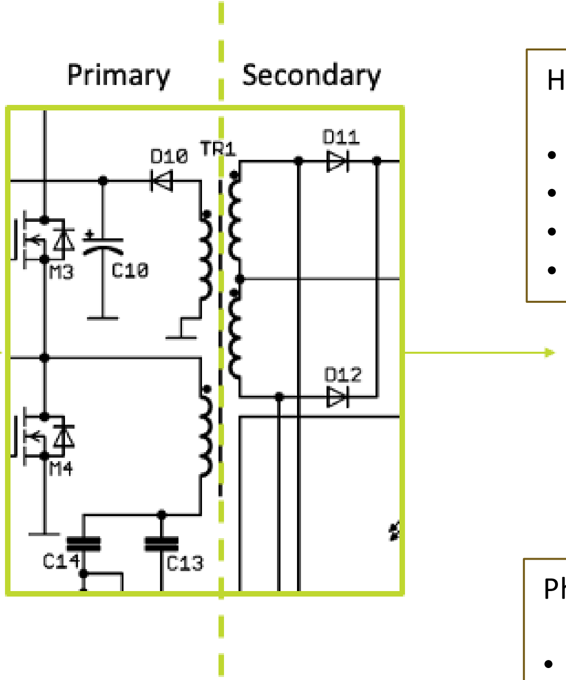
Battery Swapping



Strategies for Bridge Controllers in DC-DC

300W-2kW LLC

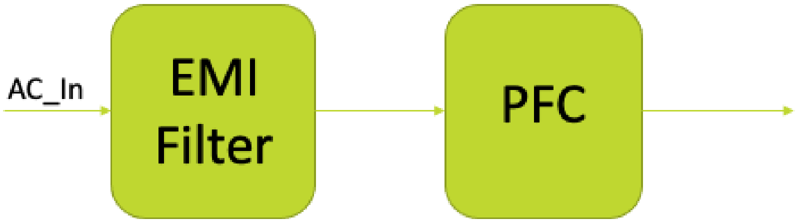


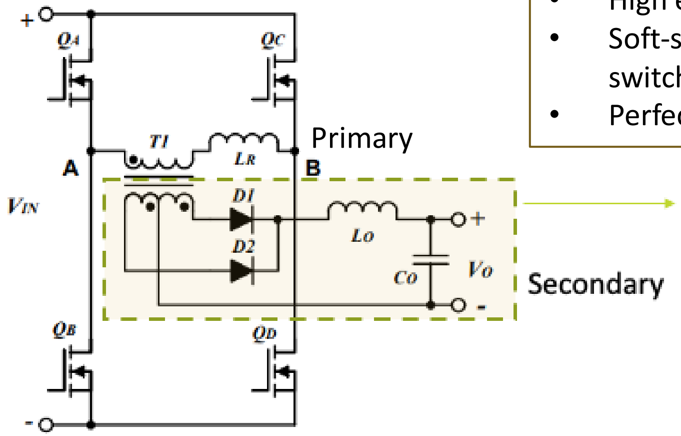


Half-bridge LLC

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

500W-5kW 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!

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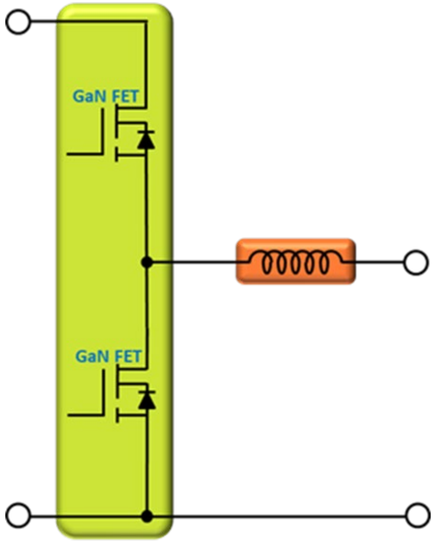
GaN allows higher performance in Bridges

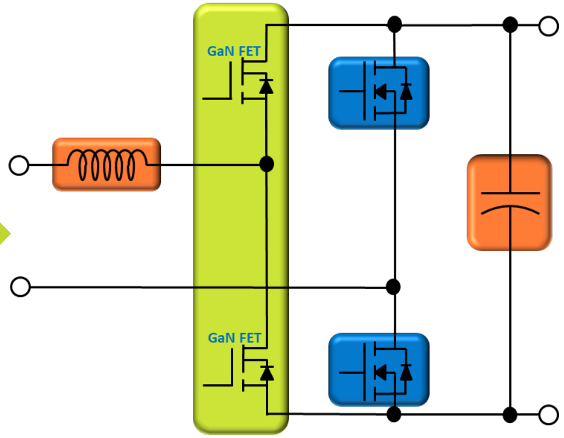
Half Bridge & Full Bridge Topologies

Basic building block to using GaN



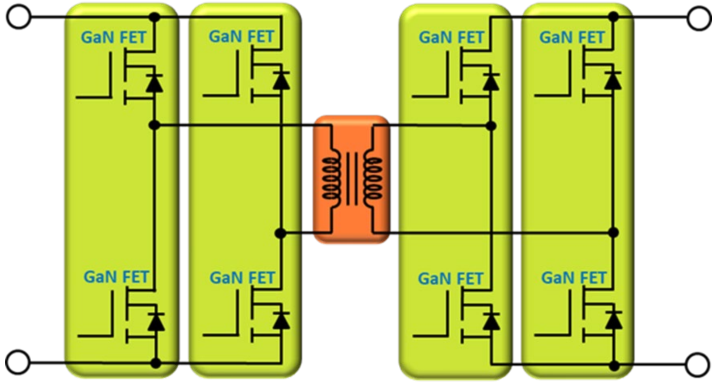
Hard Switched Standard Half Bridge

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

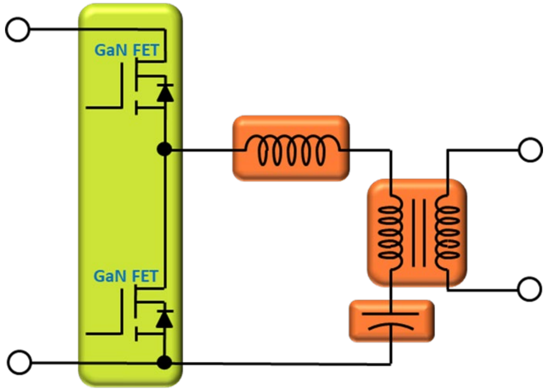


Bridgeless Totem-pole PFC (hard switched)

FOM
Ron * Q_{oss}
Bi-directional
Adv



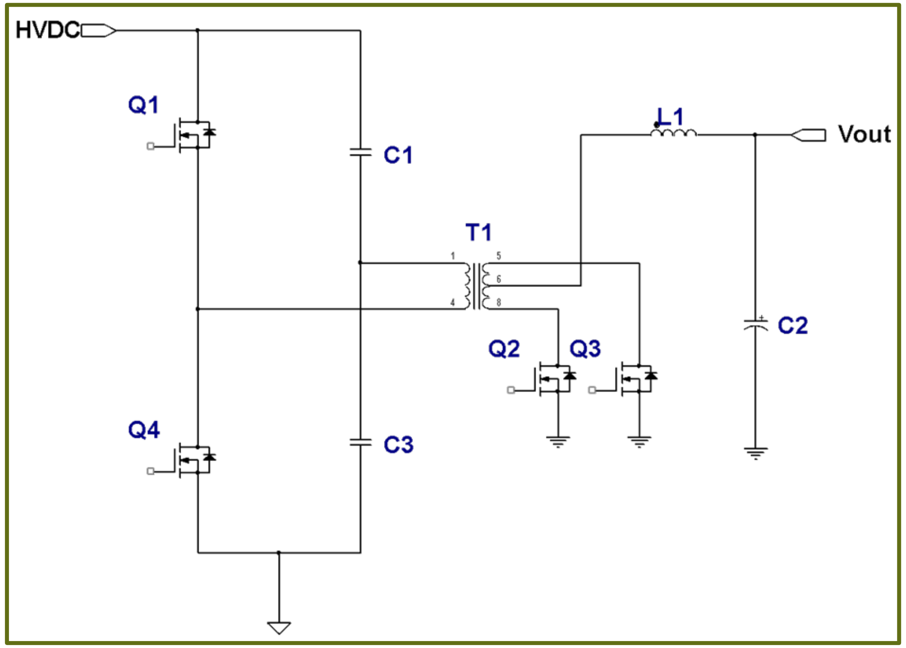
Isolated Phase Shifted Full Bridge (PSFB)

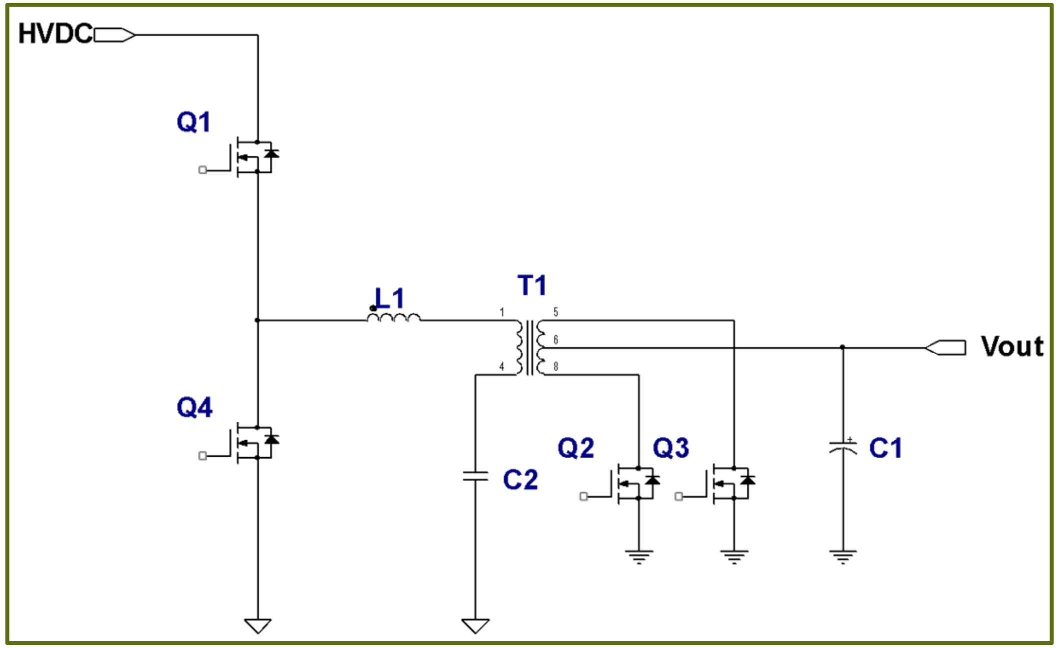


Half Bridge (LLC)

- 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

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

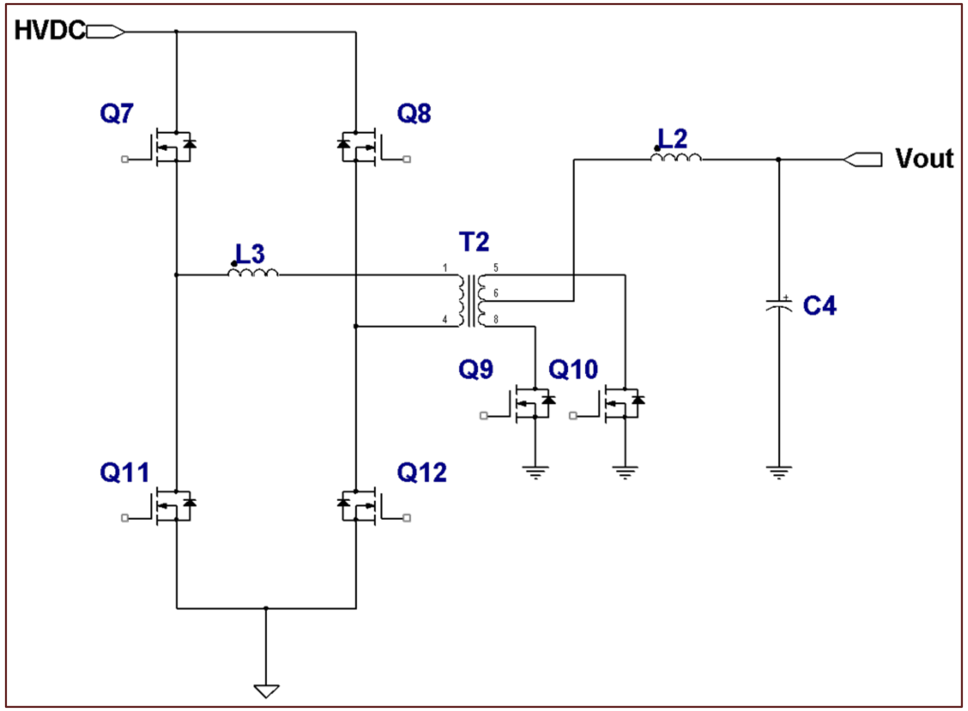


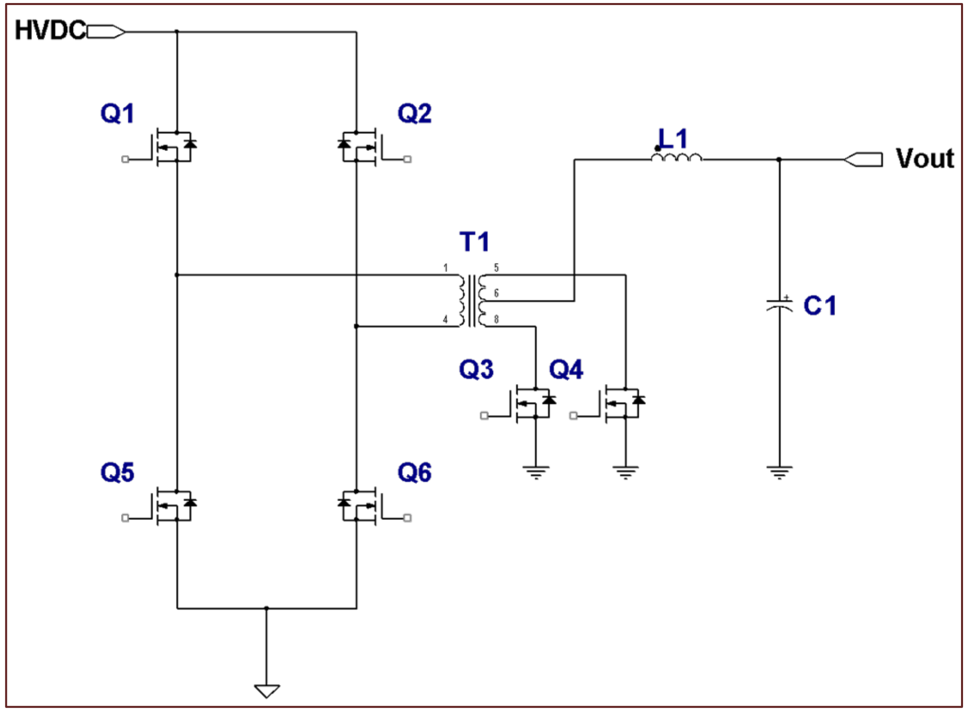


- Pros
  - Simpler control
  - Lower cost – suitable for good GaN devices
- Cons
  - Higher current stress on power devices
  - Voltage Mode control

- Pros
  - ZV Switching
  - Higher Efficiency
- Cons
  - Limited Voltage range, fixed 50% duty
  - Requires power passive components
  - Difficult design
  - Problem shifted from power devices to magnetics

Full-Bridge (Phase-shifted & Resonant LLC)





- Pros
  - ZV Switching
  - Higher efficiency & power density
  - Lower stress on passives
  - Wider input and output voltage range
- Cons
  - Peak efficiencies lower than resonant LLC

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

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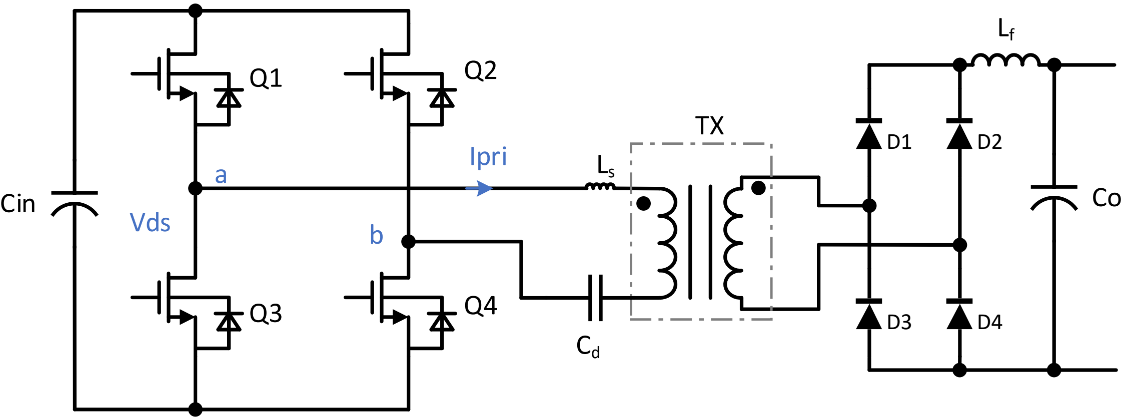
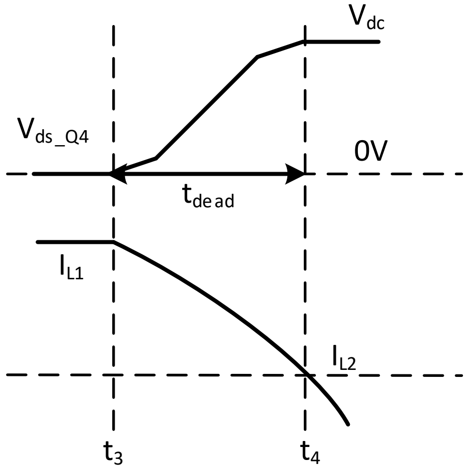
Design Example of a PSFB DC-DC Converter



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

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

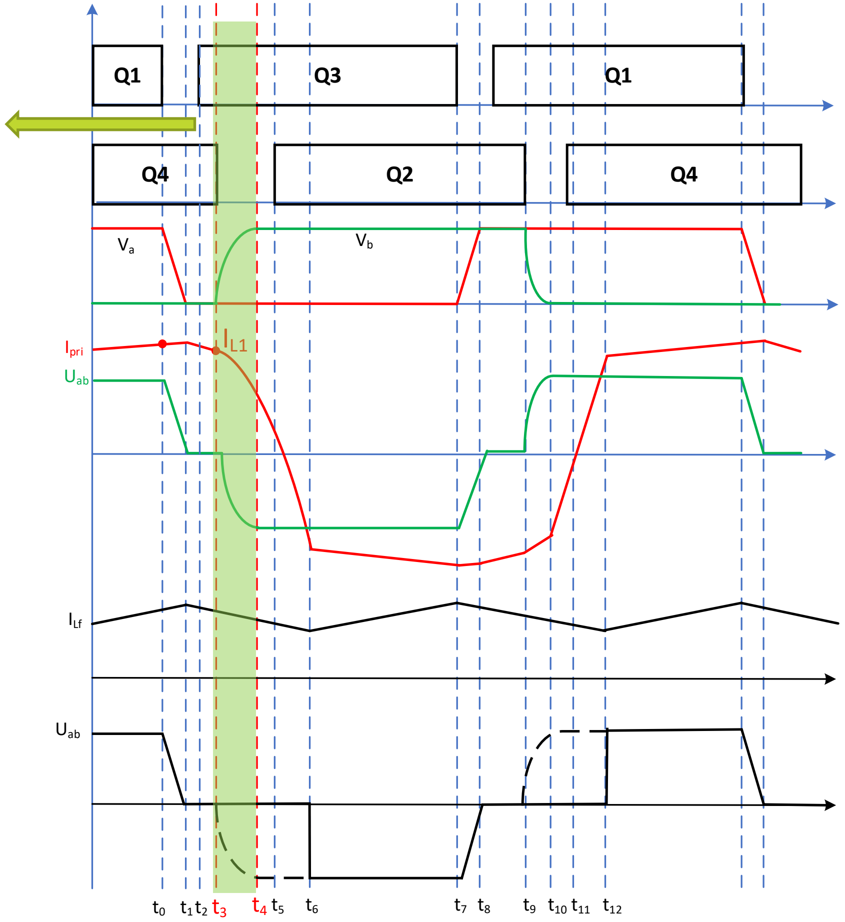
$L_s = 2.7\mu H$



ZVS condition for lagging leg:

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

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



- 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

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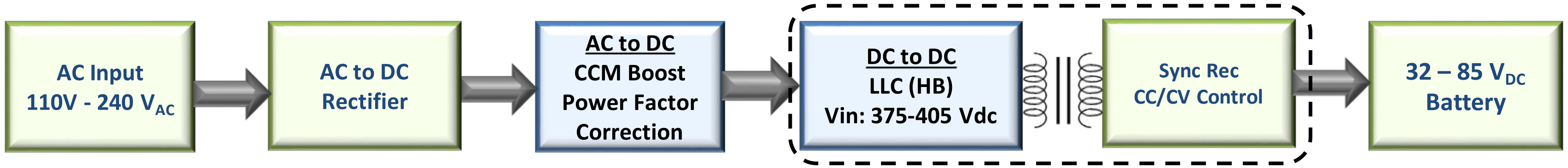
2 & 3-Wheeler OBC Power Supply Block Diagram

GaN FET Device Recommendations: Standard CCM Boost + Half-Bridge LLC



AC to DC CCM Boost PFC			
Power Level	**$R_{DS(ON)}$ (mΩ)**	**PKG**	**Device**
0.25 kW to 0.5 kW	150 70	TO-220	TP65H150G4 TP65H070G4
> 0.5 kW to 0.75 kW	70 50	TO-220 TO-263 TOLL	TP65H070G4 TP65H050G4 TP65H050G4
> 0.75 kW to 1.5 kW	50	TOLL TO-247	TP65H050G4 TP65H035G4
> 1.5 kW to 3.0 kW	35	TO-247	TP65H035G4

DC to DC (Phase Shifted Full Bridge)			
Power Level	**$R_{DS(ON)}$ (mΩ)**	**PKG**	**Device**
0.25 kW to 1.0 kW	150	PQFN88 TO-220	TP65H150G4 TP65H070G4
> 1.0 kW to 1.5 kW	70 50	TO-220 TO-263 TOLL	TP65H070G4 TP65H050G4
> 1.5 kW to 3.0 kW	50 35	TO-247 TOLL	TP65H050G4 TP65H035G4

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2 & 3-Wheeler OBC Power Supply Block Diagram

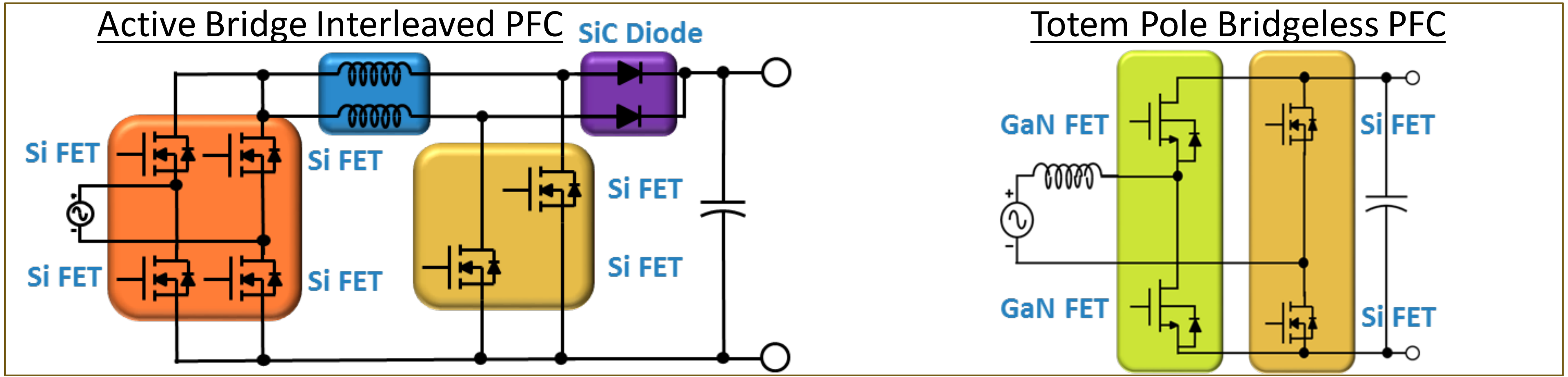
GaN FET Device Recommendations: Bridgeless Totem-pole + Phase-Shifted Full Bridge

AC to DC Bridgeless Totem-pole PFC			
Power Level	**$R_{DS(ON)}$ (mΩ)**	**PKG**	**Device**
0.3 kW to 0.75 kW	150 70	TO-220	TP65H150G4 TP65H070G4
> 0.75 kW to 1.5 kW	50 35	TO-263 TOLL TO-247	TP65H050G4 TP65H050G4 TP65H050G4
> 1.5 kW to 3.0 kW	35	TOLL TO-247	TP65H035G4 TP65H035G4

DC to DC (Phase Shifted Full Bridge)			
Power Level	**$R_{DS(ON)}$ (mΩ)**	**PKG**	**Device**
0.3 kW to 0.75 kW	300/150	PQFN88/ TO-220	TP65H300G4 TP65H150G4
> 0.75 kW to 1.5 kW	150/70	TO-220 TO-263 TOLL	TP65H070G4 TP65H050G4 TP65H050G4
> 1.5 kW to 3.0 kW	50 35	TO-247 TOLL	TP65H050G4 TP65H035G4

GaN Value Demonstration vs. Super Junction FETs

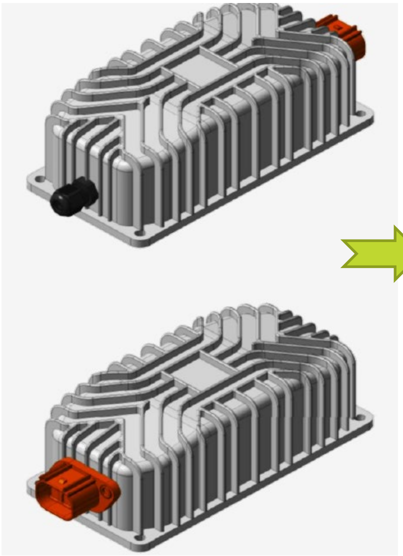
- 750W power supply
- Competition: Superjunction (silicon)
- Result: Higher efficiency, lower BOM cost
  - Reduction in part count, magnetics, EMI filter

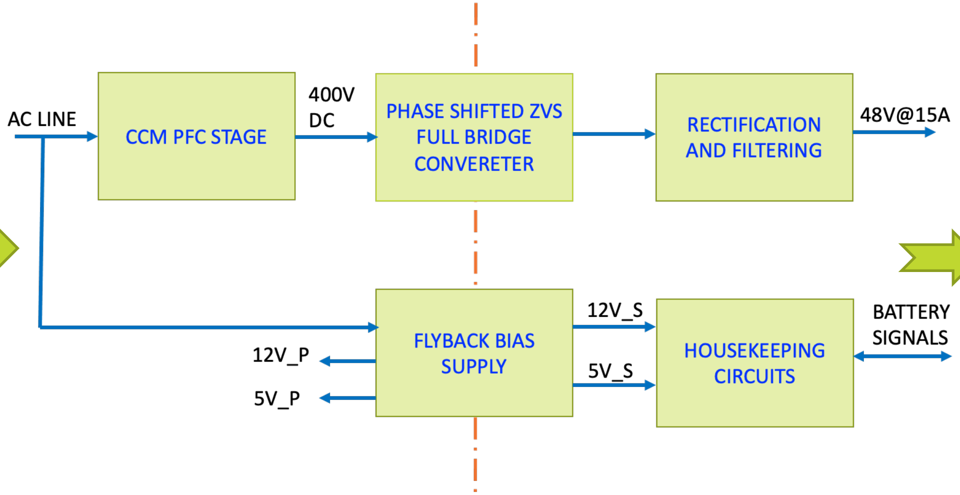


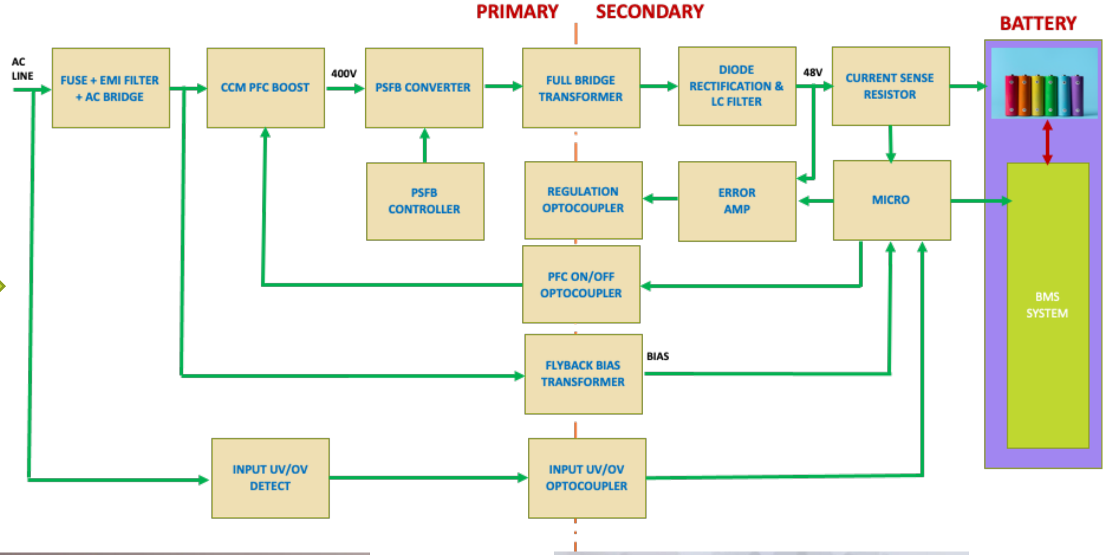
Parameter Results	Interleaved PFC	Bridgeless Totem Pole PFC
Efficiency	98.5%	98.7%
Total cost	100%	60%

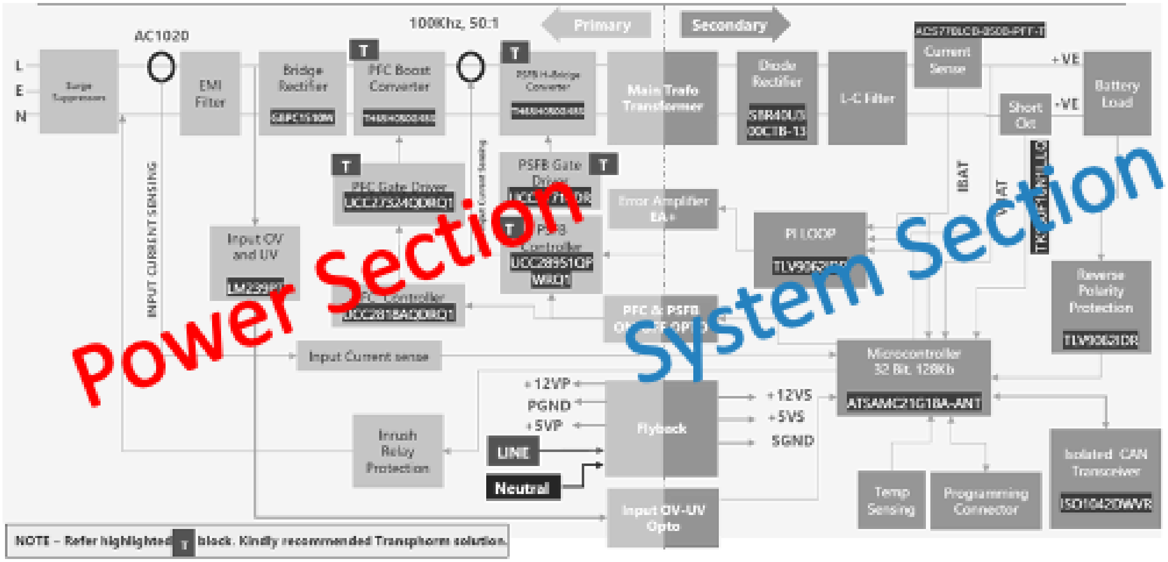
Designing a OBC for 48V battery (600W to 2kW)

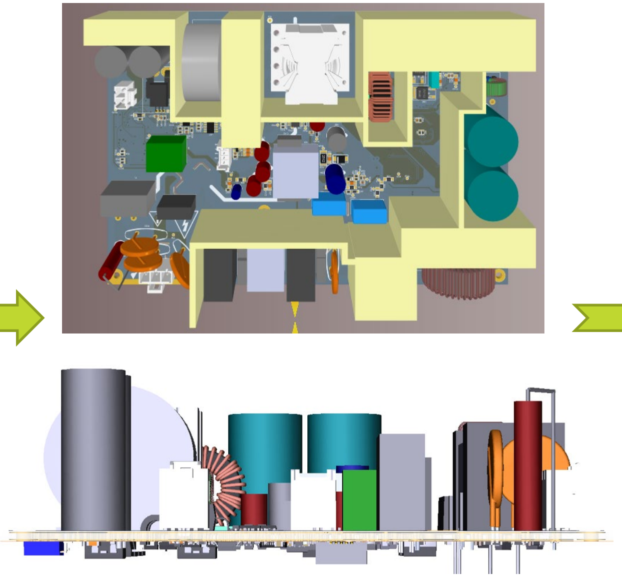
Start with Casing, i.e End Enclosure Size and Thermal Requirements!

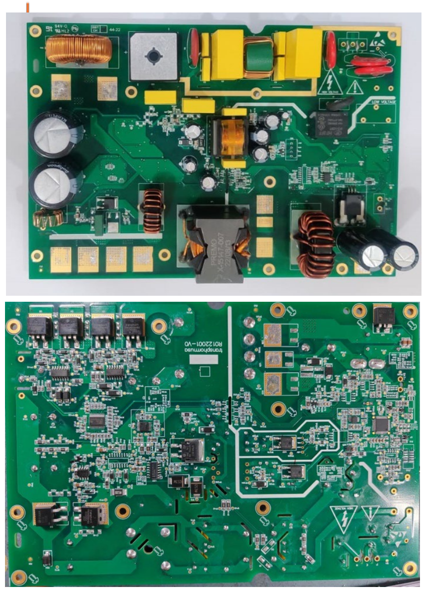












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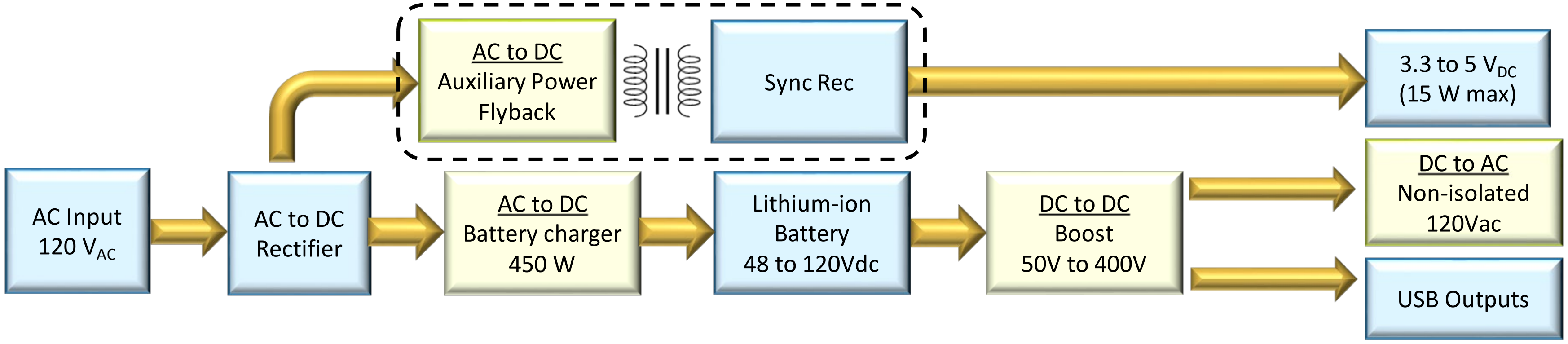
Portable Power Stations Power Stages 150W - KW+

GaN FET Devices for: Battery Charger + Boost + Inverter + Auxiliary Power Supply



AC to DC Backup Battery Power Supply (PFC)

Power Level	$R_{DS(ON)}$ (mΩ)	Package	Device
450 W	150	TO-220	TP65H150G4PS

AC to DC Backup Battery Power Supply (LLC)

Power Level	$R_{DS(ON)}$ (mΩ)	Package	Device
450 W	150	TO-220	TP65H150G4PS

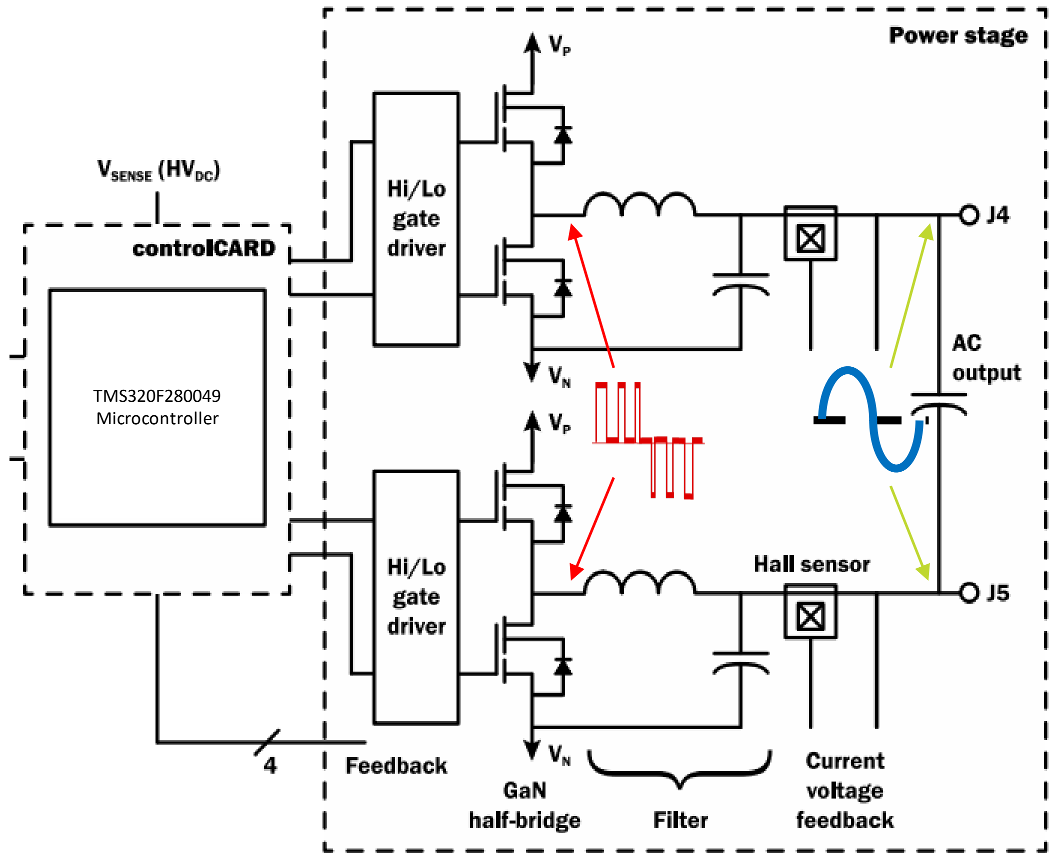
DC to DC Boost (SiC diode) Power Stage

Power Level	$R_{DS(ON)}$ (mΩ)	Package	Device
0.250kW	70	TO-220 TOLL	TP65H070G4
> 0.25kW to 0.75kW	70 50	TO-247 TOLL	TP65H050G4
> 0.75kW to 1.25kW	50 35	TO-247	TP65H050G4 TP65H035G4

DC to AC Non-inverting Power Stage

Power Level	$R_{DS(ON)}$ (mΩ)	Package	Device
0.250kW	300 150	PQFN88 TO-220	TP65H300G4 TP65H150G4
> 0.25kW to 0.75kW	150 70	PQFN88 TO-220	TP65H150G4 TP65H070G4
> 0.75kW to 1.25kW	70 50	TO-220 TO-263	TP65H070G4 TP65H050G4

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
  Switching frequency = 50kHz to 200kHz (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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Summary

- GaN device positioning has been presented
- Applications addressed by GaN in context of consumer and personal electronics with focus on low and mid-power (25W to 1.5kW) have been discussed
- End applications include adapters, LED lighting, Electric 2/3 wheelers, computers, monitors/TVs, personal power supplies etc
- Approaches and topologies for various applications discussed
- GaN adoption increasing in these markets and beyond – data centers, UPS, automotive with GaN from Transphorm and other vendors


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