GaN FET-Based CCM Totem-Pole Bridgeless PFC

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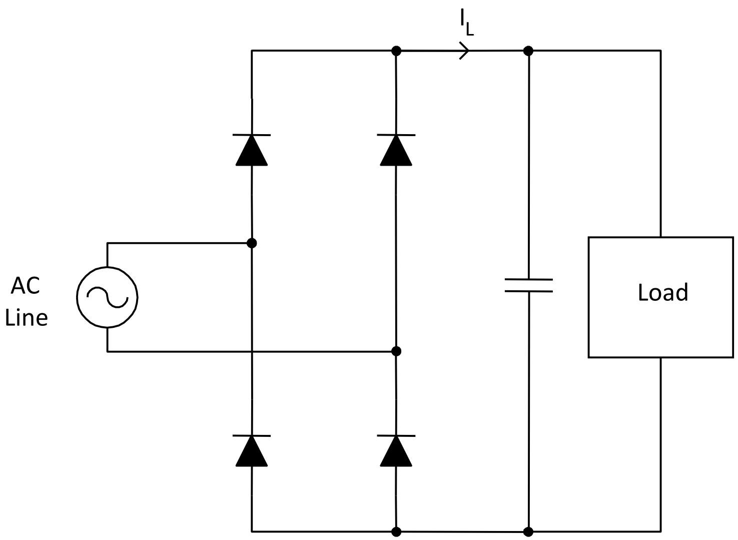
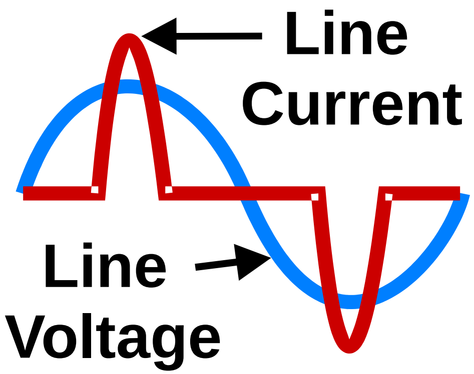
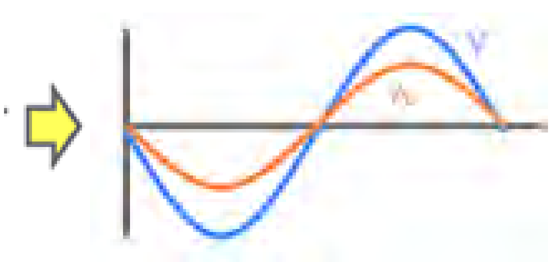






Agenda

- AC/DC efficiency standard and PFC efficiency requirement
- Bridgeless PFC topologies and development trends
- GaN (Gallium Nitride) FET overview
- Totem-pole CCM bridgeless PFC control
  - UCD3138 control implementation
  - Ideal diode emulation
  - AC crossover detection and control
- GaN device test in FET mode and diode mode
- Totem-pole CCM bridgeless PFC test
- Summary

AC/DC Efficiency Level Certifications

80 Plus Test Type	115 V				230 V			
Fraction of rated load	10%	20%	50%	100%	10%	20%	50%	100%
80 Plus		80%	80%	80%				
80 Plus Bronze		82%	85%	82%		81%	85%	81%
80 Plus Silver		85%	88%	85%		85%	89%	85%
80 Plus Gold		87%	90%	87%		88%	92%	88%
80 Plus Platinum		90%	92%	89%		90%	94%	91%
80 Plus Titanium	90%	92%	94%	90%	90%	94%	96%	91%

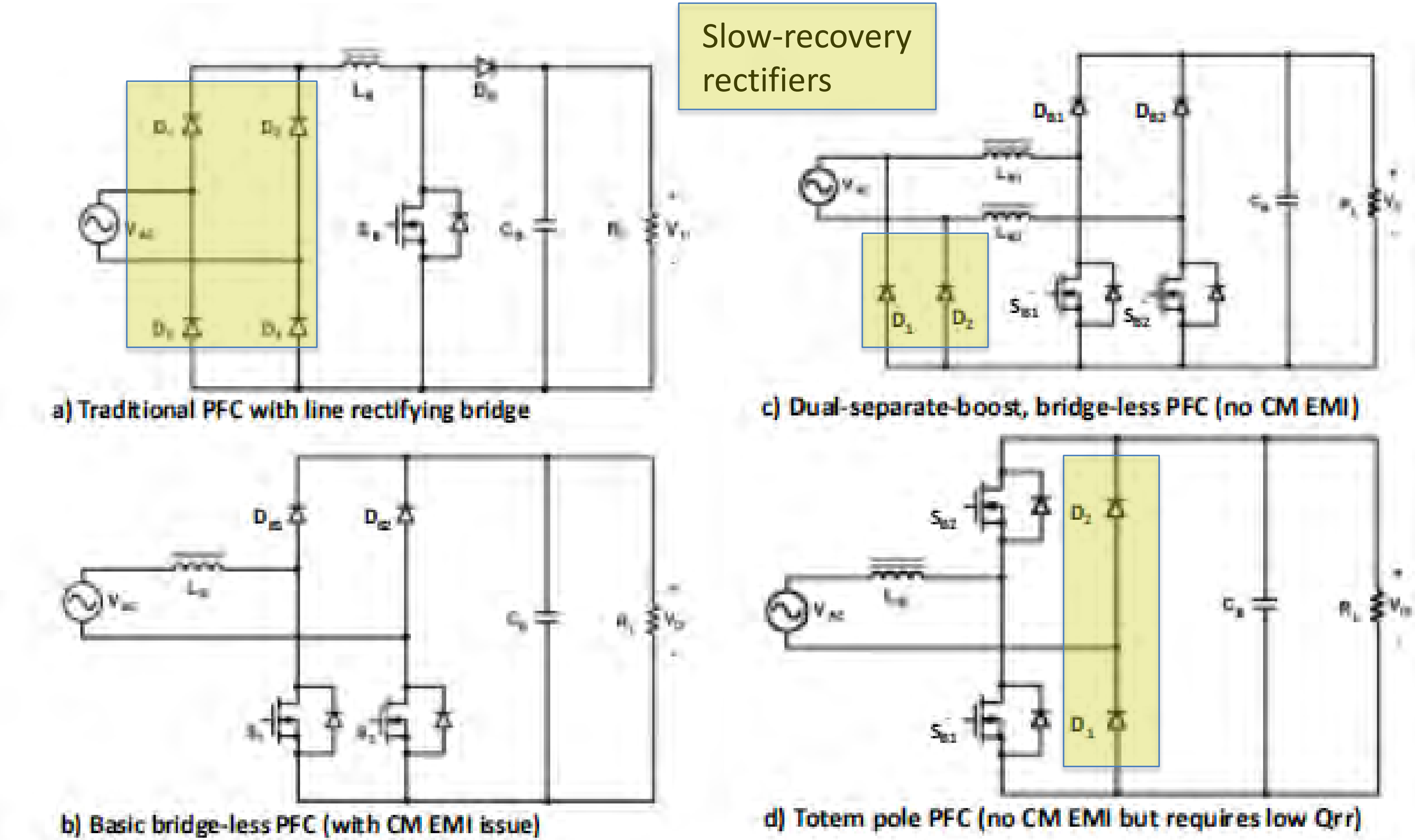
Energy Star Specification

PFC Efficiency Budget

80 Plus Test Type		Efficiency at 115 V				Efficiency at 230V			
Fraction of rated load		10%	20%	50%	100%	10%	20%	50%	100%
80 Plus Platinum	PFC		95.8%	95.4%	93.7%		95.7%	97.4%	95.8%
	DC/DC		94%	96.5%	95%		94%	96.5%	95%
80 Plus Titanium	PFC	95.5%	95.8%	96.4%	93.8%	95.8%	98%	98.5%	94.8%
	DC/DC	94%	96%	97.5%	96%	94%	96%	97.5%	96%

- PFC design becomes more challenging at Platinum level efficiency and much harder at Titanium level efficiency
- Well designed single-phase PFC and interleaved PFC achieve around 97.5% efficiency and are just able to meet Platinum efficiency requirement
- Bridgeless seems to be the only way to reach Titanium efficiency level

What is Bridgeless PFC?



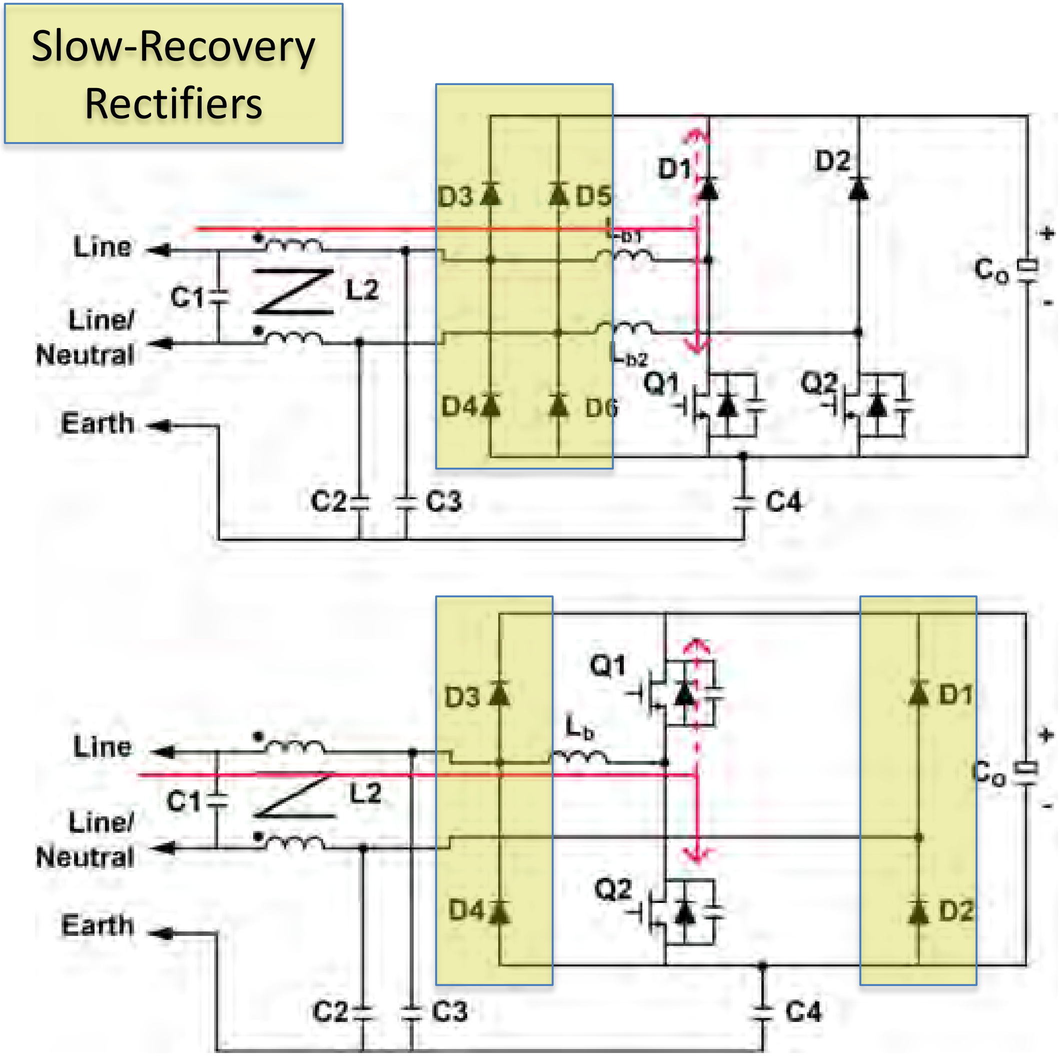
a) Traditional PFC with line rectifying bridge

b) Basic bridge-less PFC (with CM EMI issue)

c) Dual-separate-boost, bridge-less PFC (no CM EMI)

d) Totem pole PFC (no CM EMI but requires low Qrr)

Existing Bridgeless PFC Application Status



Basic Bridgeless PFC

- \+ Good efficiency
- \+ Easy control
- \- High component count
- \- **Poor** component utilization
- \- Low density

Totem-Pole Bridgeless PFC

- \+ Good efficiency
- \+ Fixed frequency
- \+ Easy control
- \- DCM only
- \- For power < 300 W

New PFC Development Trends

Transition-Mode Totem-Pole PFC

- ZVS operation
- Interleaved configuration for high power application (around max 300 W per phase)
- Variable frequency control
- Phase shedding and adding to optimize light load efficiency
- Suitable for MOSFET applications

Continuous-Conduction-Mode Totem-Pole PFC

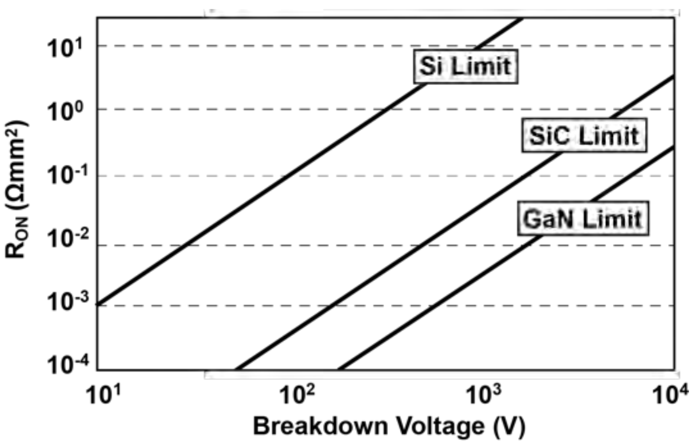
- Low component count
- Fixed switching frequency, zero reverse recovery switch should be used
- GaN is a good candidate for the application
- Possible to operate TM and ZVS at light loads

GaN Versus Silicon and SiC

Key electrical properties of three semiconductor materials

Properties	GaN	Si	SiC
E_G(eV)	3.4	1.12	3.2
E_{BR}(MV/cm)	3.3	0.3	3.5
V_S(x 10^7cm/s)	2.5	1.0	2.0
μ(cm^2Vs)	990-2000	1500	650

Theoretical on-resistance vs blocking voltage



E_g: **Wide band-gap energy-** more energy to cross band gap-> low leakage current > high temp stability

E_{BR}: **Critical field break down voltage** – avalanche breakdown

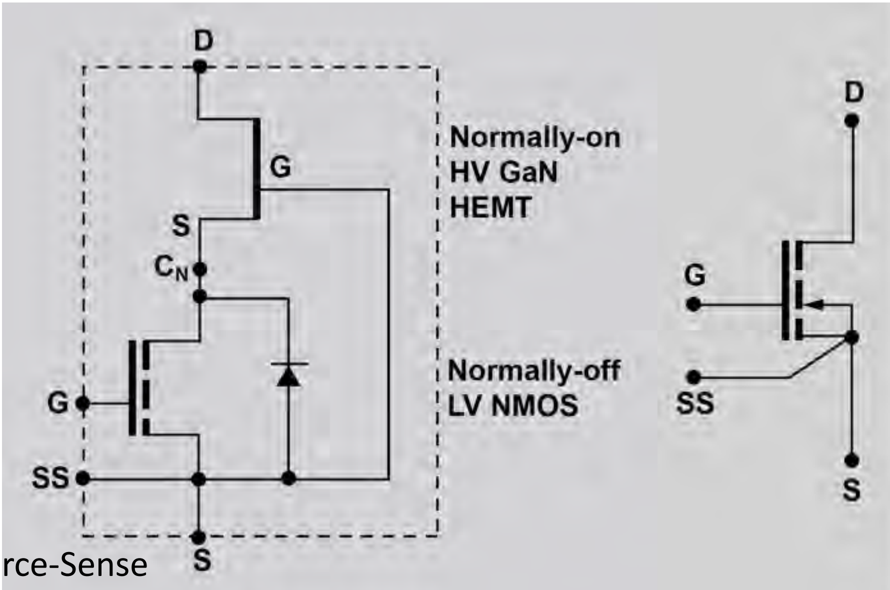
V_S: **Saturation velocity** - determines switching frequency limitation

μ: **Electron mobility** -inversely proportional to on-resistance

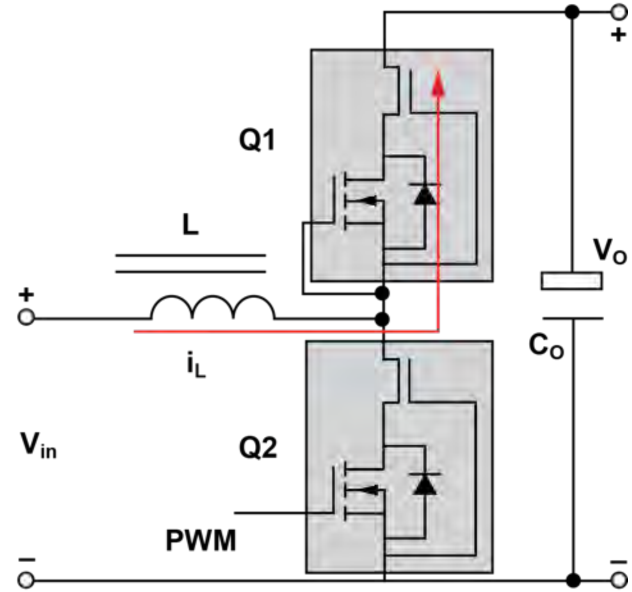
$$r_{ON} \alpha \frac{1}{\mu \times E_{BR}^{3}}$$

Reference:
EPC, Gallium Nitride (GaN) technology overview

Cascode GaN FET Structure



Cascode GaN FET internal structure



Example of a boost configuration

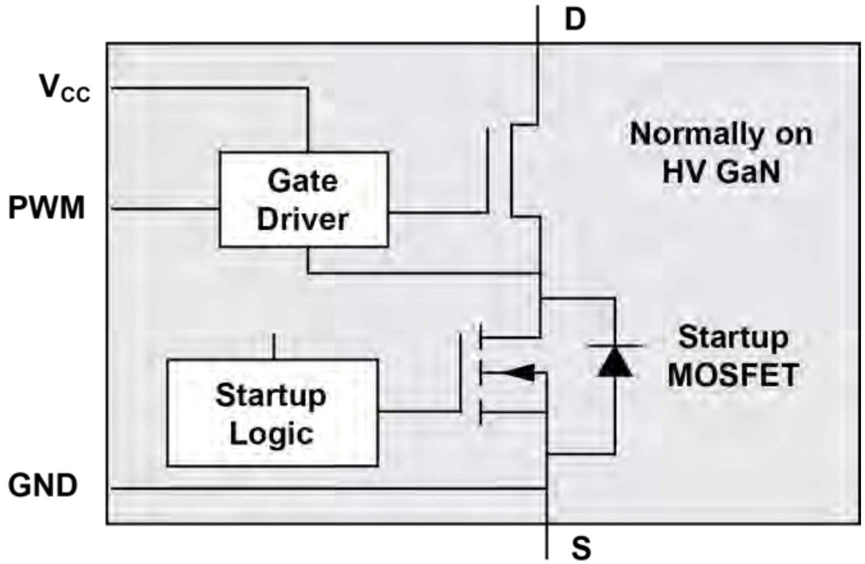
Advantages:

- Depletion-mode GaN: low cost and better performance (compared to enhancement-mode GaN)
- Same MOSFET driver used
- Low forward voltage drop in diode mode

Disadvantages:

- Same reverse recovery of the cascode MOSFET body diode
- Potential MOSFET avalanche at high V_{ds} slew rate
- Large gate charge (same as the MOSFET)

Dmode-GaN + Safety FET Structure



Advantages:

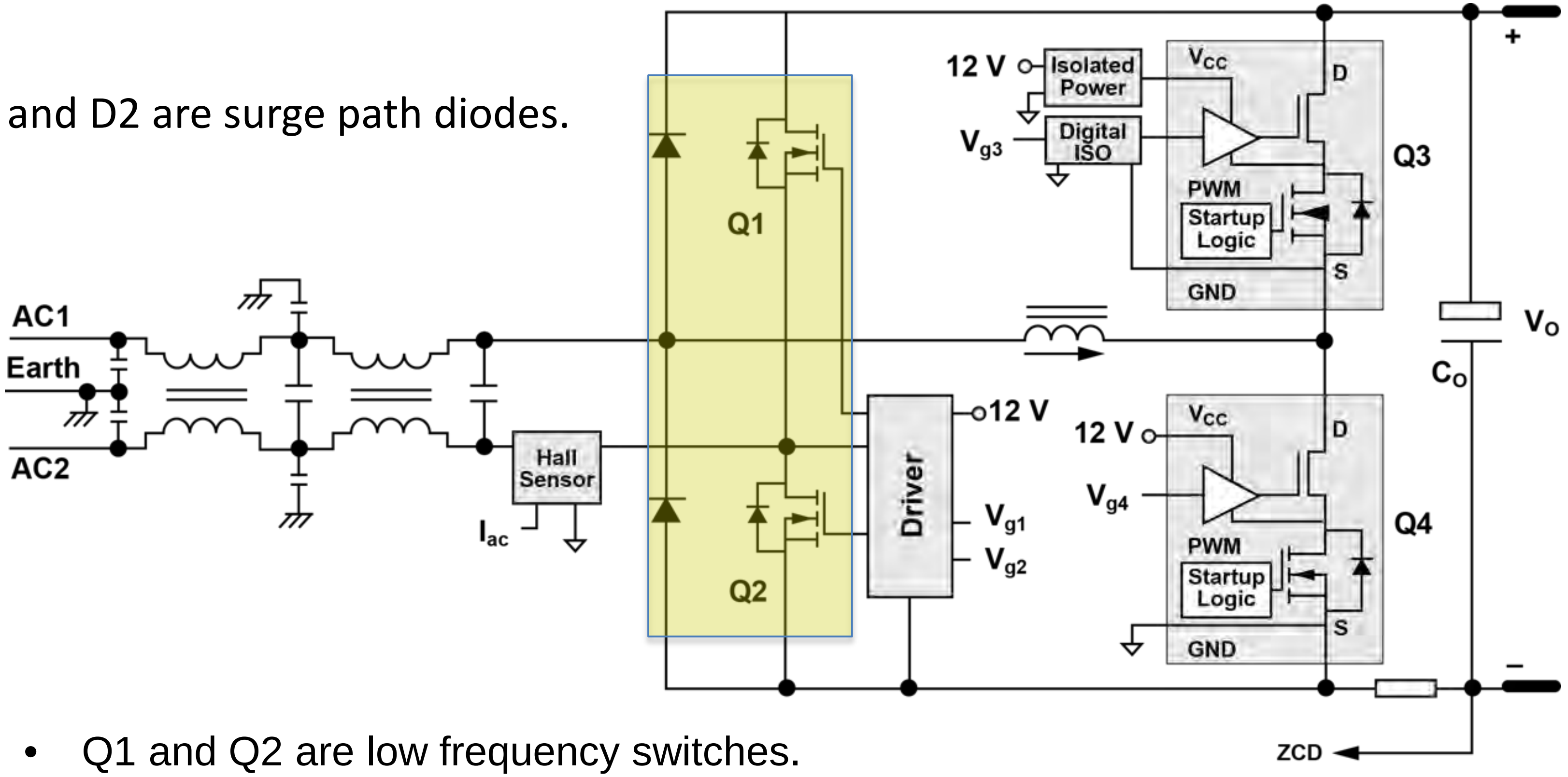
- Zero reverse recovery
- Low gate charge
- No LV MOSFET switching loss
- Suitable for high switching frequency applications
- Integrated gate driver circuit to ease applications

Disadvantages:

- High forward voltage drop in diode mode
- Complicated gate driver circuit (IC design)

GaN-Based CCM Totem-Pole Bridgeless PFC Power Stage

D1 and D2 are surge path diodes.

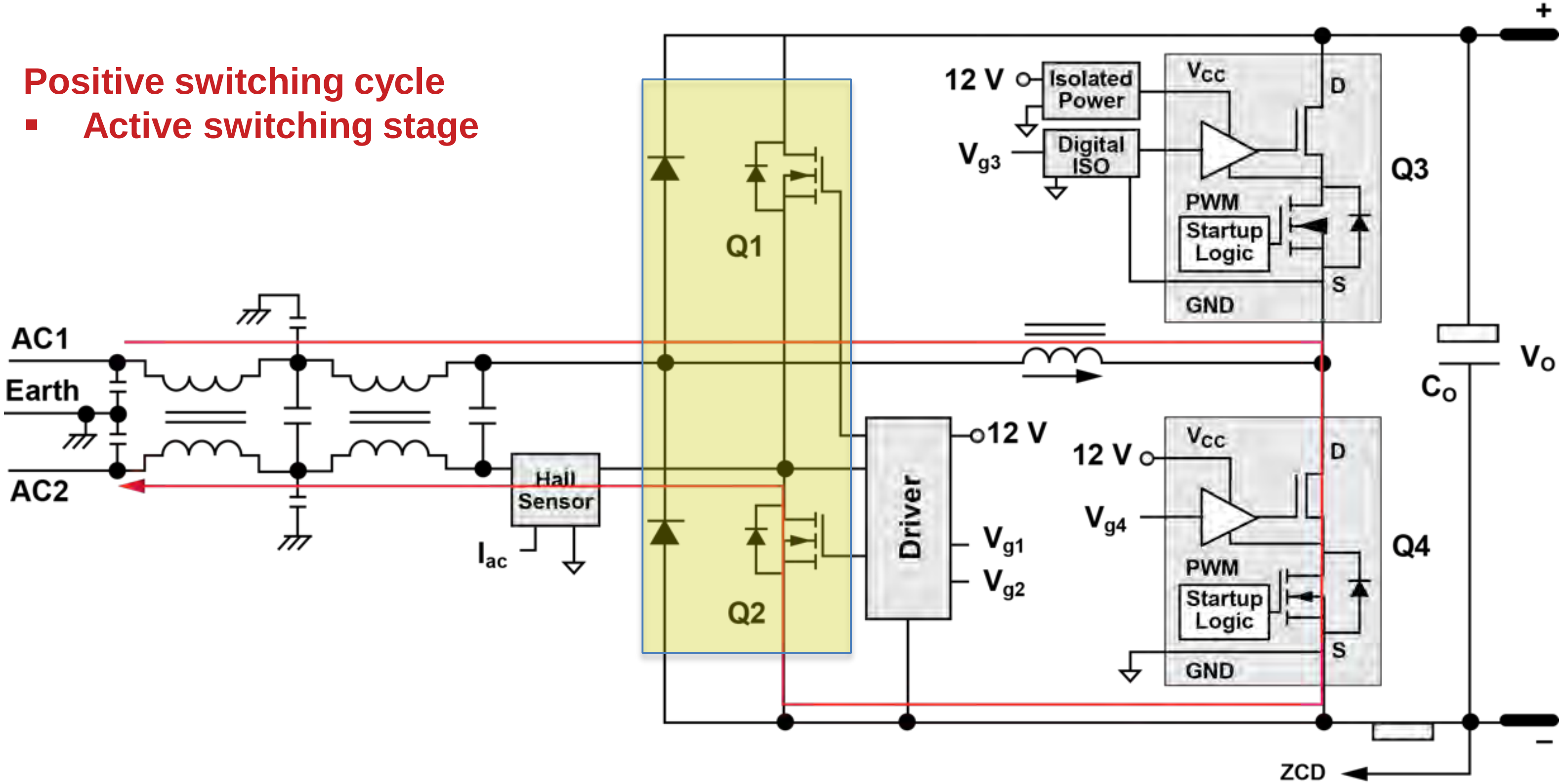


- Q1 and Q2 are low frequency switches.
- Q3 and Q4 are an active switch and a SyncFET

  (depending on input AC voltage's polarity)

GaN-Based CCM Totem-Pole Bridgeless PFC Power Stage

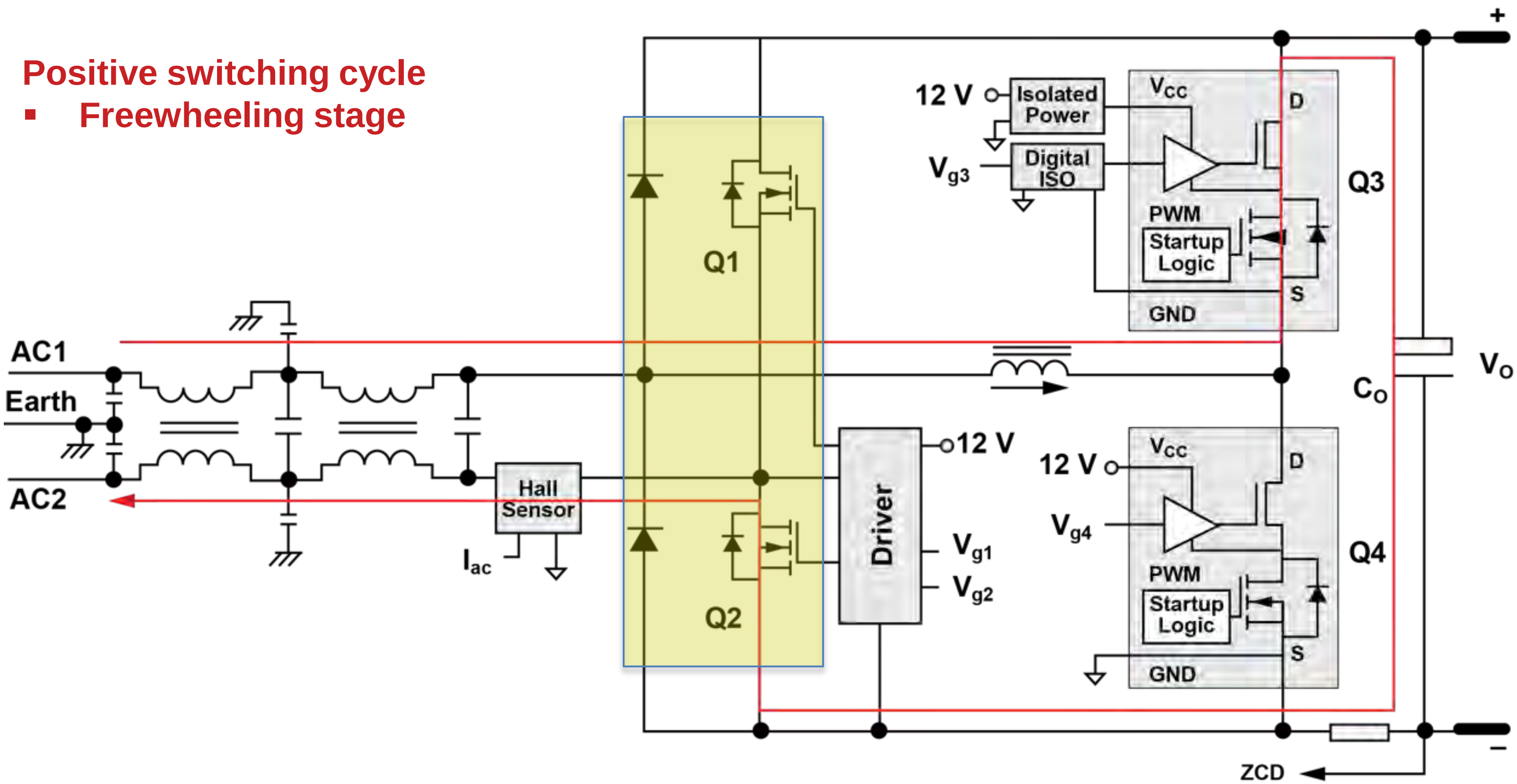
Positive switching cycle
- Active switching stage



Positive switching cycle – active switching stage

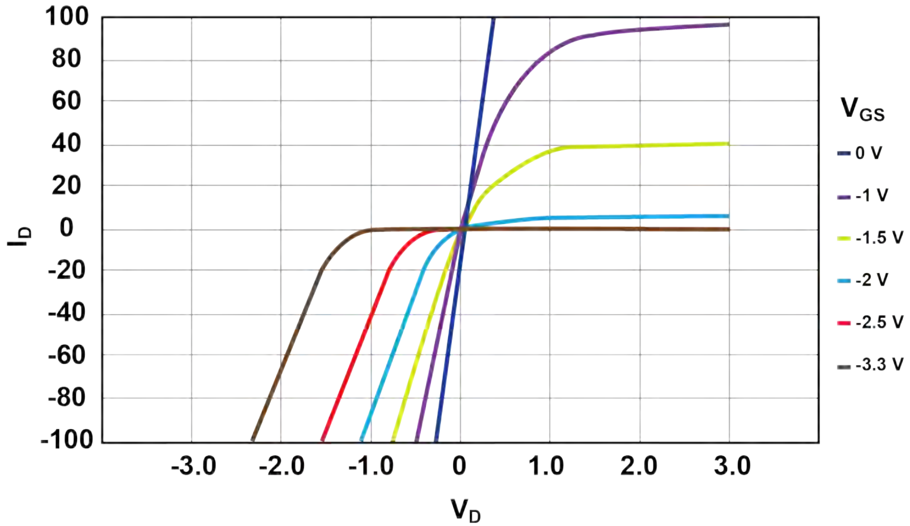
GaN-Based CCM Totem-Pole Bridgeless PFC Power Stage

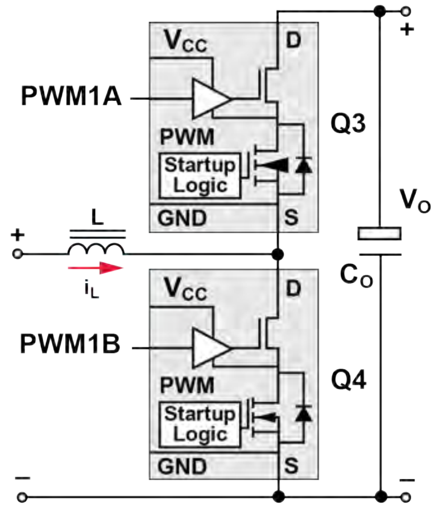
Positive switching cycle
- Freewheeling stage



Positive switching cycle – freewheel stage

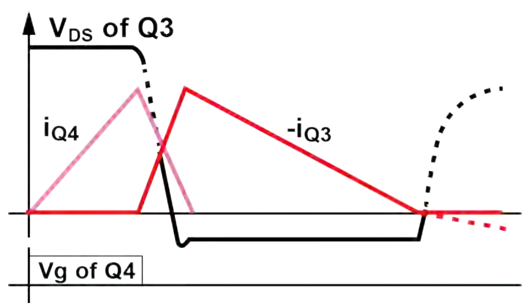
GaN FET Forward Voltage Drop and Ideal Diode Emulation Control



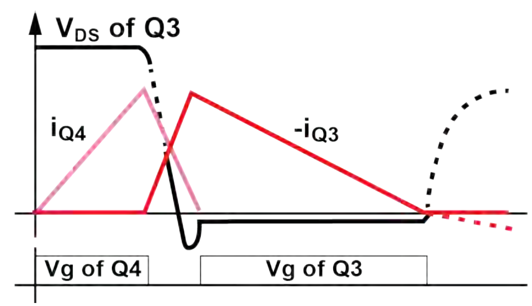


Output characteristics of a typical depletion mode GaN FET

Ref: Transphorm datasheet

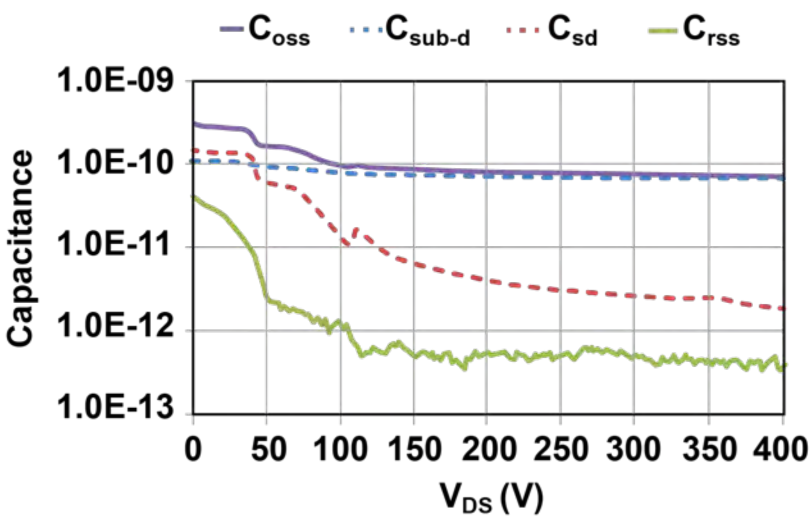


GaN FET operates at diode mode



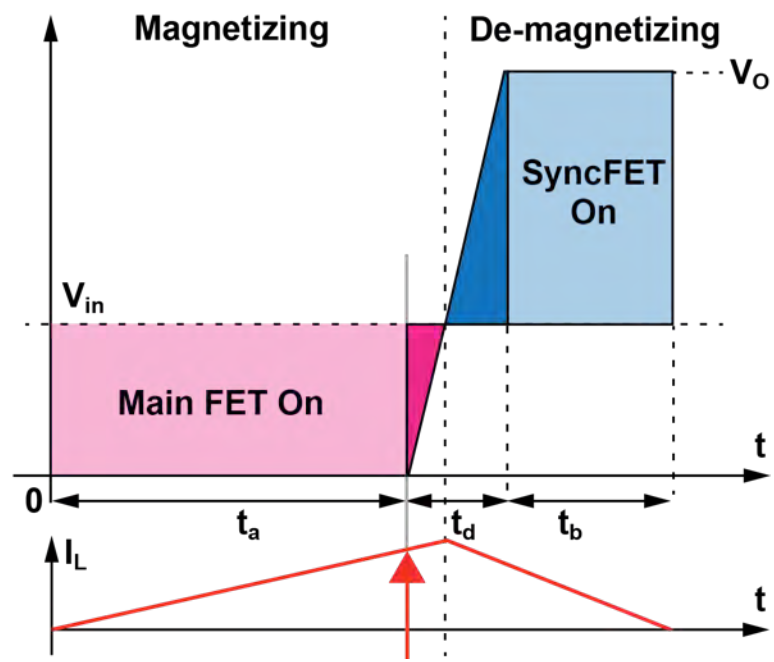
GaN FET operates at ideal diode mode

Adaptive Dead-Time Control for SyncFET to Turn On



C_{sub_d}, C_{sd} and C_{rss} add to form C_{oss}

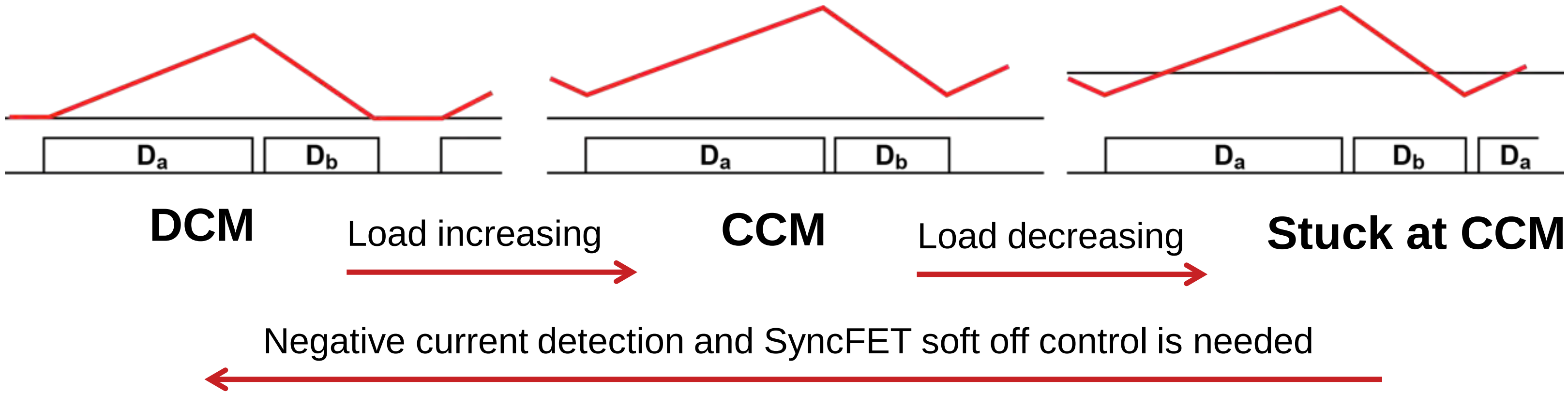
$$t_d = \frac{2C_{oss} \times V_O}{I_{L\_peak}}$$



Current sampling point

Hardware-Assisted IDE Control

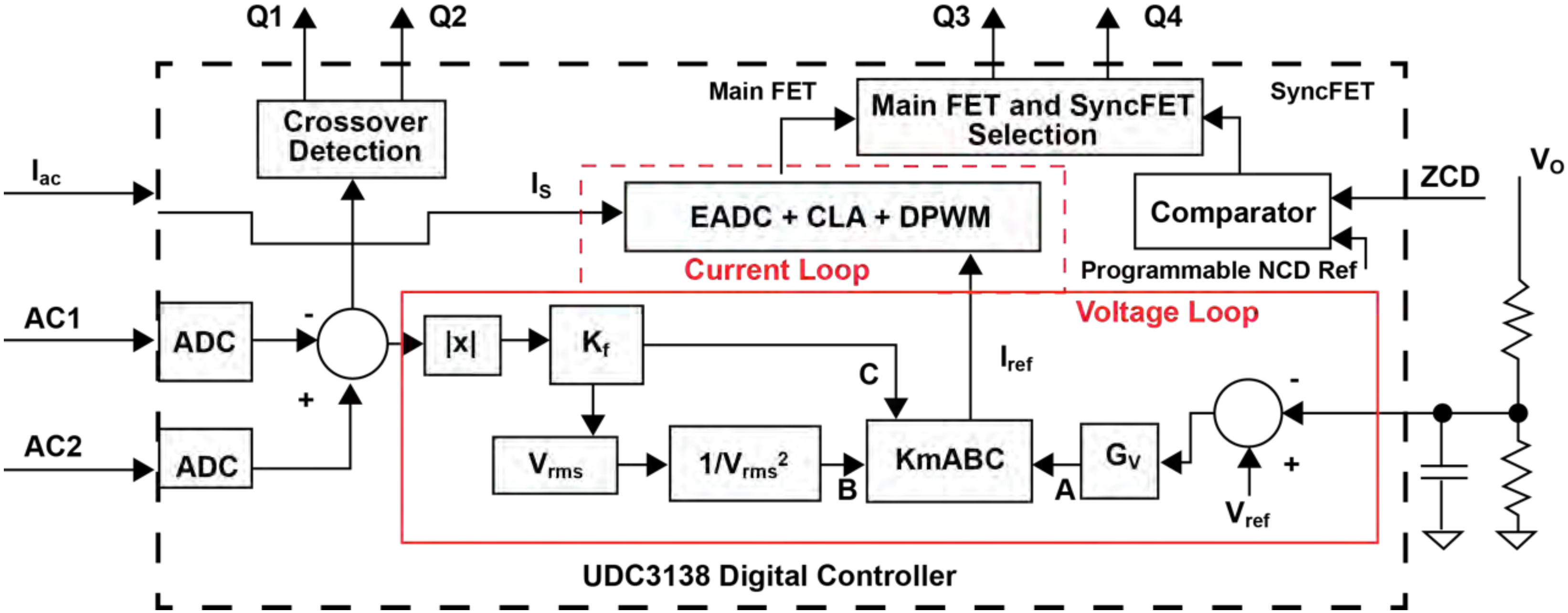
- **Difficulty of volt-second control for Ideal Diode Emulation**



- **Freewheel stage current sensing for zero current detection**

Db is chopped off at ZCD point

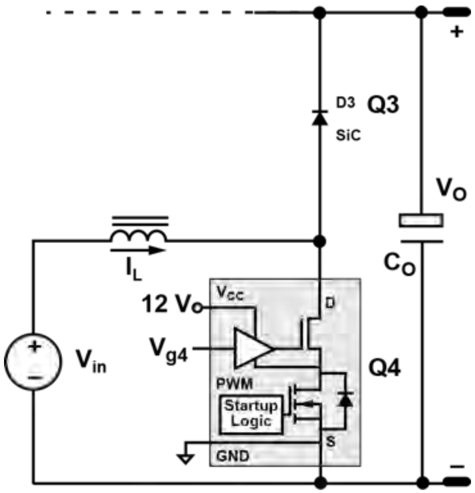
UCD3138 – Based Control Circuit



- ADCs sense AC line voltage for AC crossover detection.
- ADCs sense absolute AC line voltage difference for PFC voltage loop control.
- UCD3138 firmware implements PFC voltage loop.
- PFC current control implemented by UCD3138 hardware digital loop.
- UCD3138 generates main FET gate drive signal and syncFET gate drive signal.
- Crossover detection block generates gate signal Q1 and Q2 for AC bridge FETs.
- Crossover detection block provides main FET and syncFET selection logic for Q3 and Q4.
- Analog negative current is sensed, compared w/ UCD internal reference for ZCD or negative current control.

- UCD3138 hardware executes cycle-by-cycle IDE control.

Test Results – GaN FET Performance in FET Mode

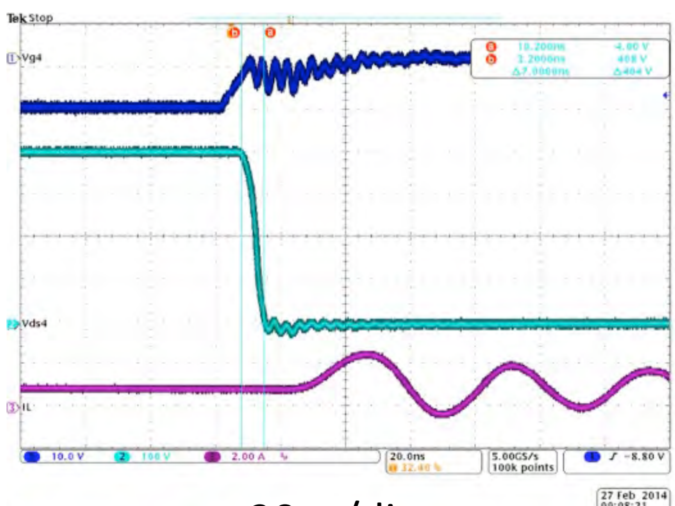


Test Conditions:

- V_{in} = 200 VDC, I_{in} = 2 ADC, V_O = 400 V
- Q4: 600 V 150 mΩ depletion-mode GaN power transistor
- D3: Cree SiC diode C3D04060A
- Gate turn-off resistance = 2.2 Ω, turn-on resistance=15 Ω

Test Results:

- Turn-on time = 9 nS
- Max turn-on d_V/d_t = 79 V/nS
- C_{oss} is linearly charged up to V_O at turn-off
- About 18 V ringing when freewheel diode conducts

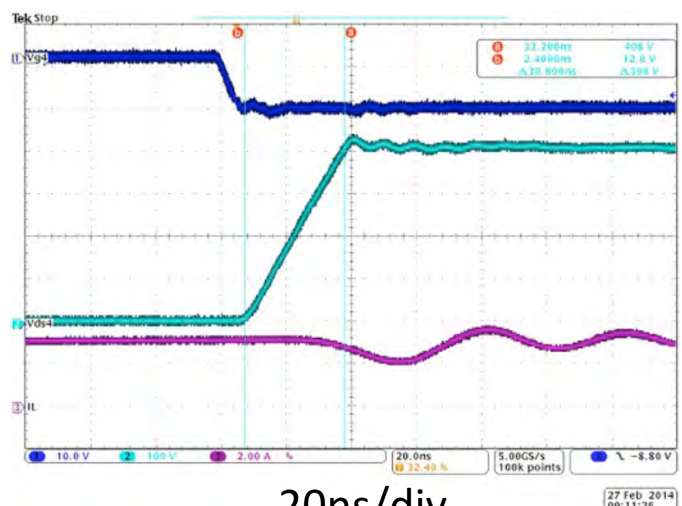


20ns/div

Vg4 (10V/)

Vds4 (100V/)

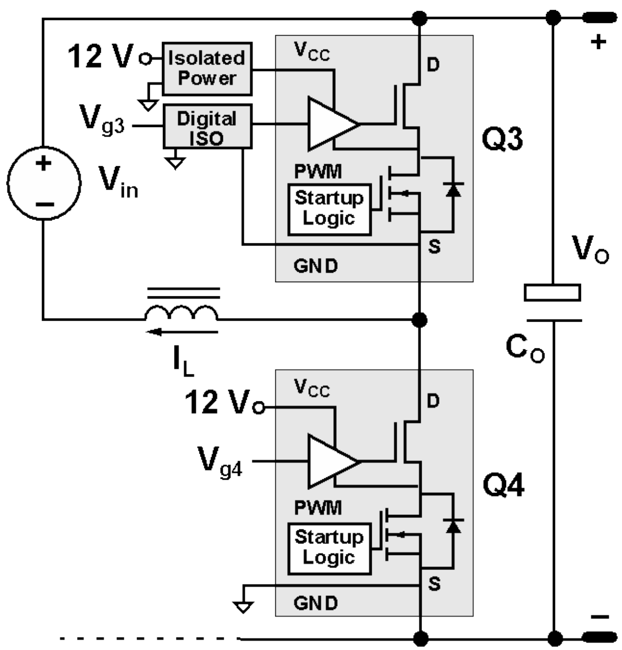
I_L (2A/)

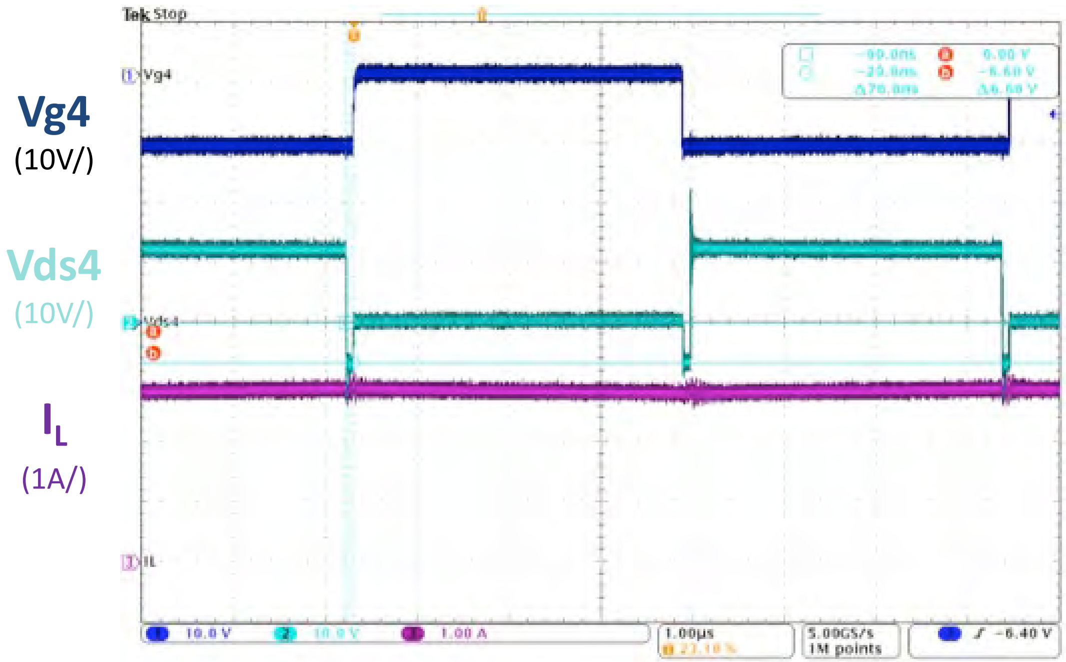


20ns/div

resonance caused by the trace leakage inductance and the output high frequency ceramic capacitor

Test Results – GaN FET
Forward Voltage Drop in Diode Mode





1us/div

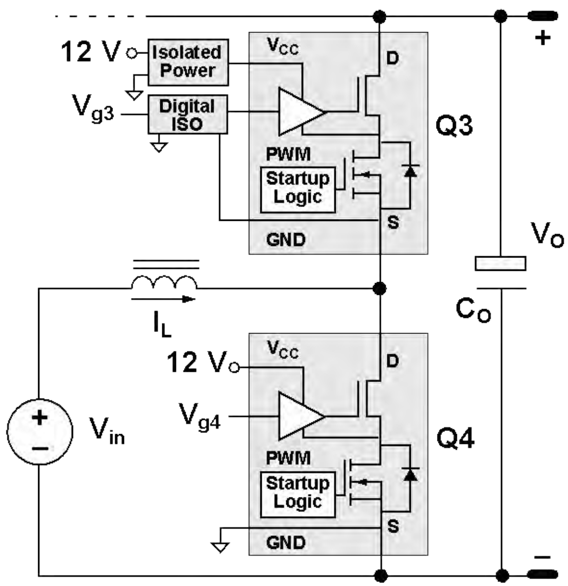
Test Conditions:

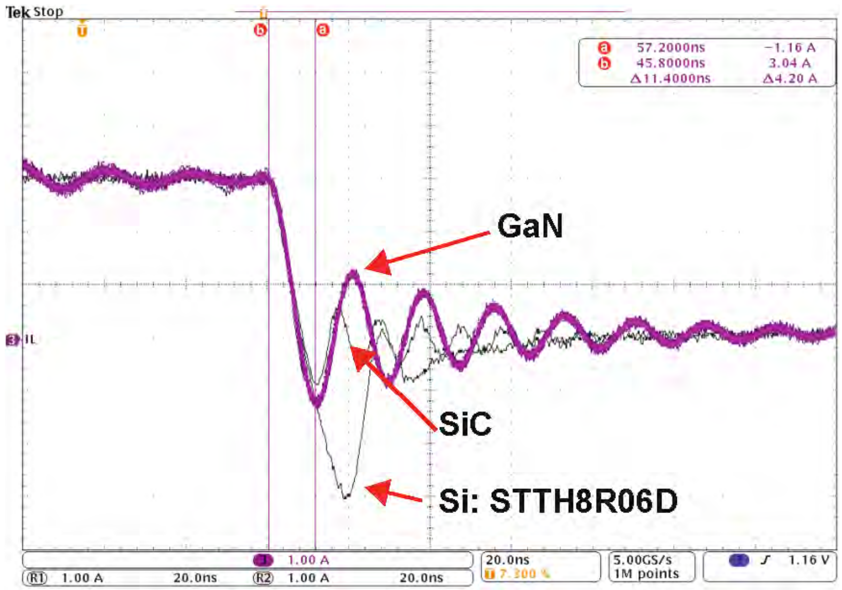
- Current = 0.1 A – 3 A, dead-time = 100 nS

Test Results:

- Forward voltage drop varies from 4.3 V to 7.3 V device-to-device when GaN is off

Test Results – GaN FET Reverse Recovery in Diode Mode





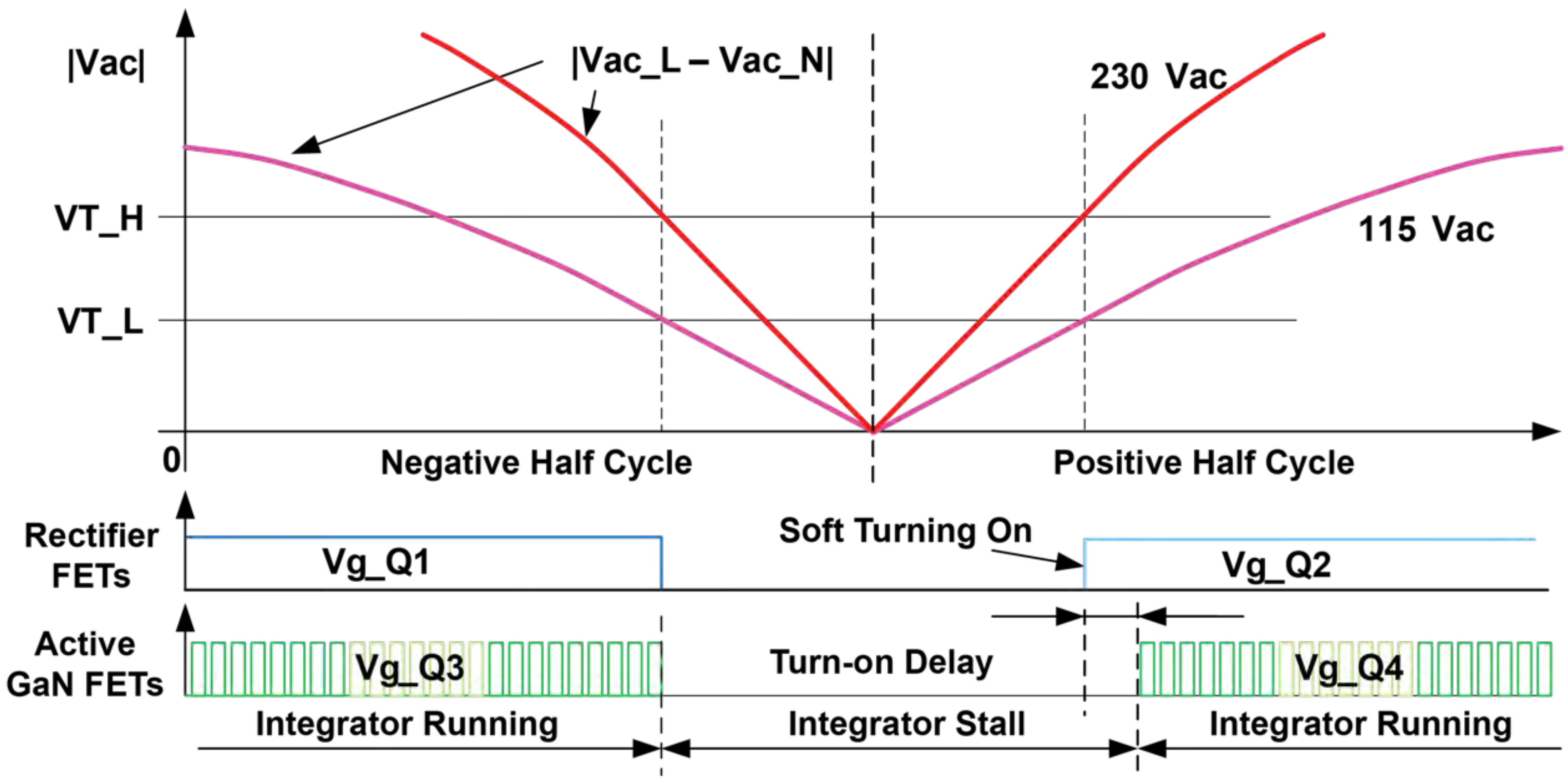
Test Conditions:

- Q3 uses GaN FET, C3D04060E and STTH8R06D
- d_i/d_t is about 368 A/µS

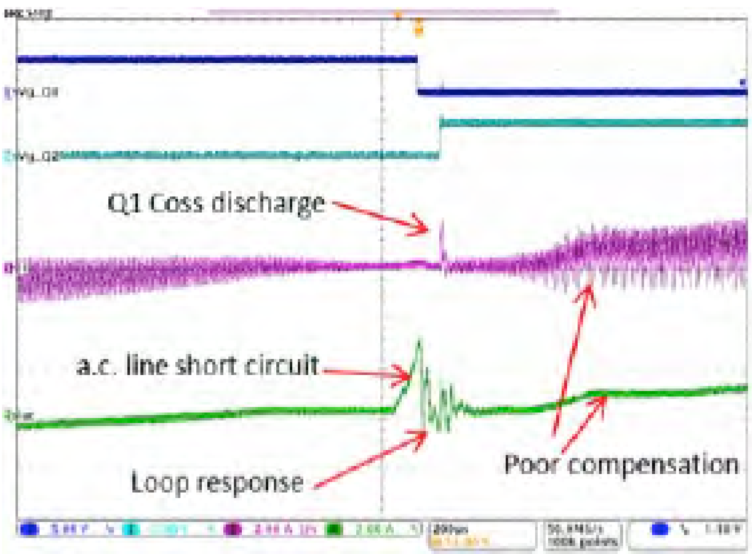
Test Results and Conclusions:

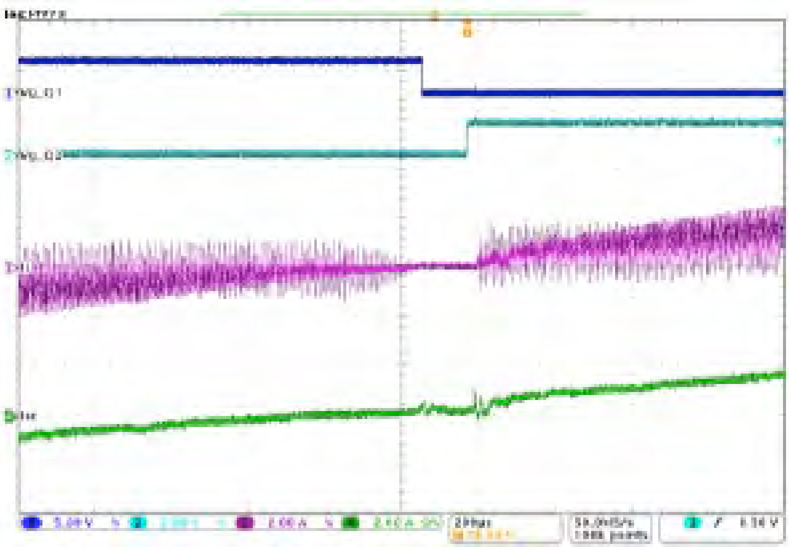
- Both GaN FET and SiC diode just have ringing current – no reverse current was observed
- STTH8R06D has a significant reverse current
- GaN FET has a larger ringing than SiC, but at lower frequency, as a result of larger output capacitance of the two GaN FETs

AC Current Crossover Control



Current Spike Root Causes and Solutions





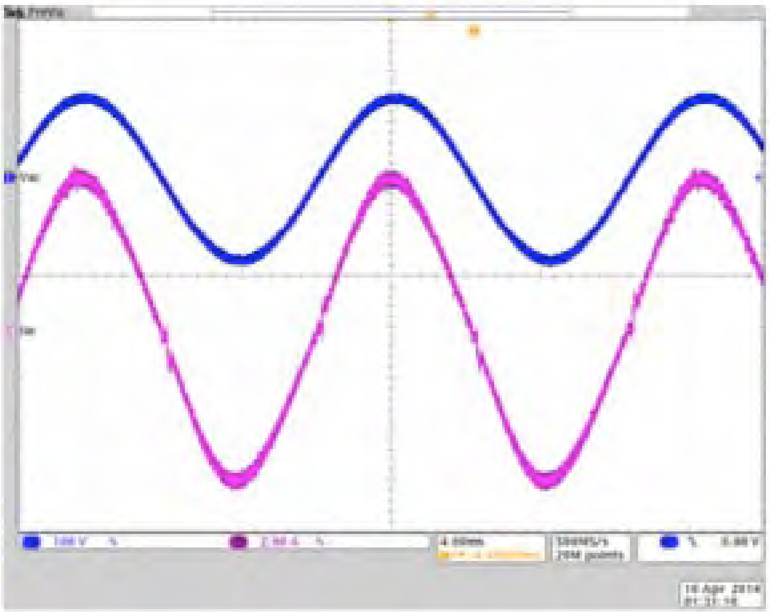
Root Causes:

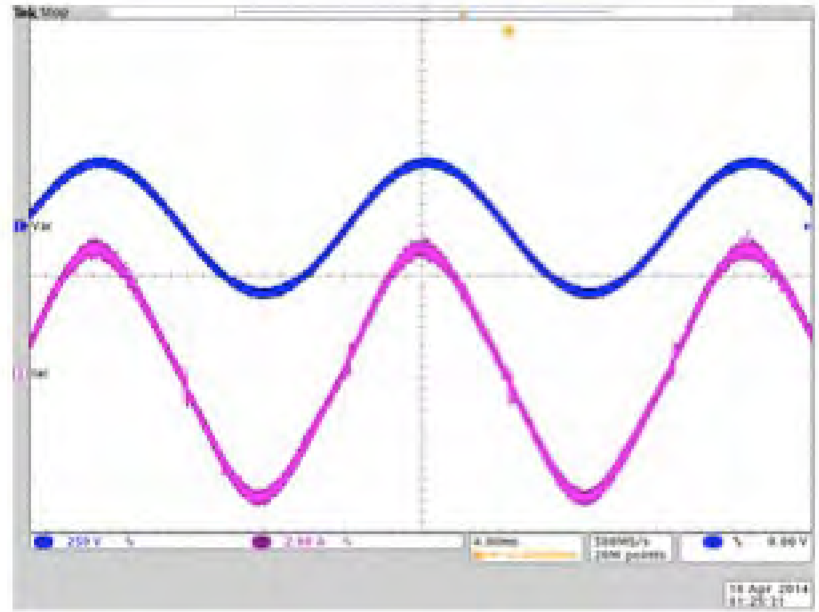
- Inaccurate a.c. voltage sensing
- Turning on rectifier FET too early cause a.c. line short circuit
- Current loop disturbed by current spike
- Rectifier FET hard switching
- Current loop compensation not optimized

Solutions:

- Differential a.c. voltage sensing with low phase offset
- Using different a.c. crossover voltage thresholds for high line and low line
- Sufficient blanking time
- Disable PWM and stall integrator during blanking time
- Rectifier FET soft switching on
- Inserting PWM turn-on delay time
- Optimize current loop compensation

AC Current Waveforms





115 Vac input at 450 W

PF= 0.999

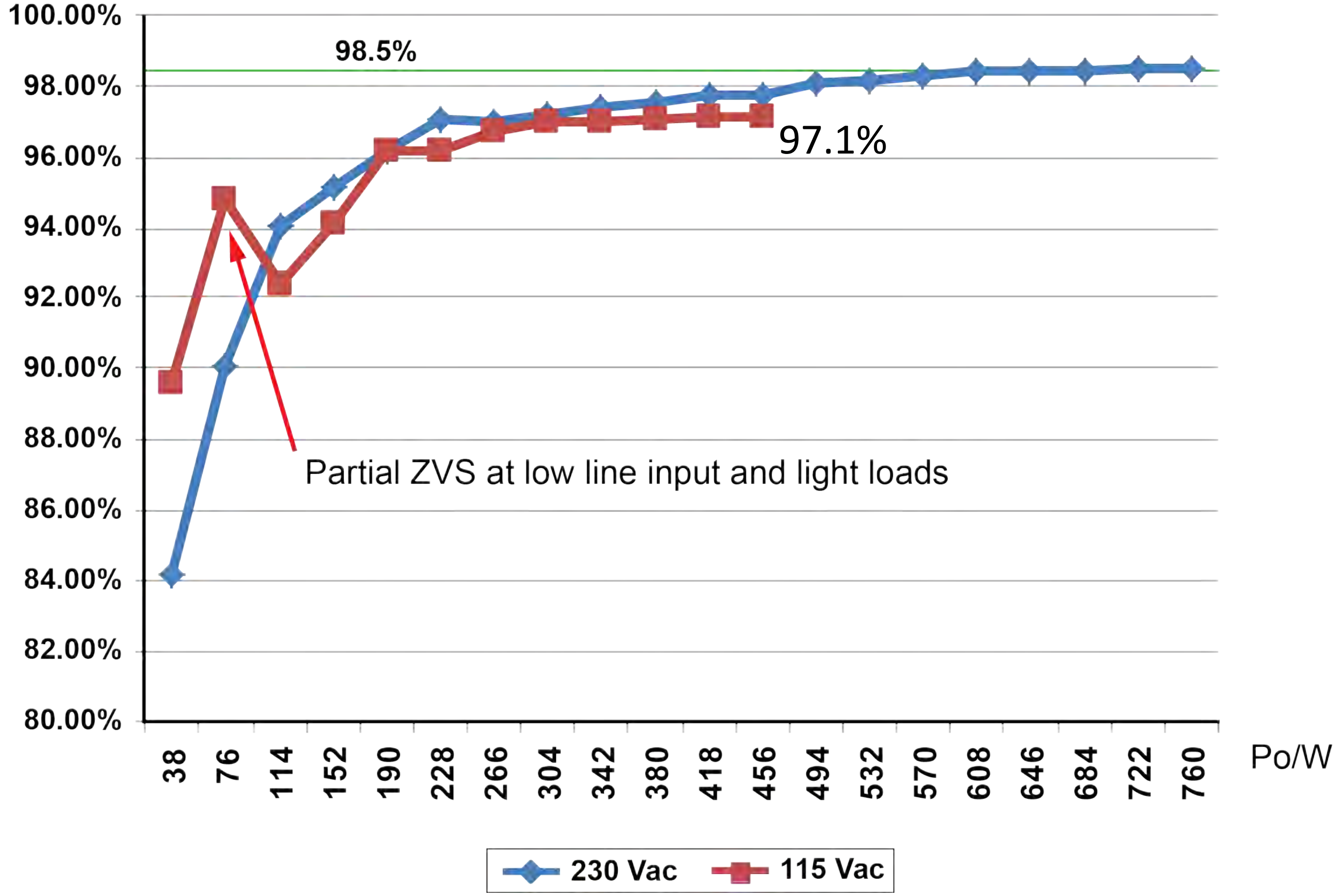
THD = 3.3%

230 Vac input at 750W

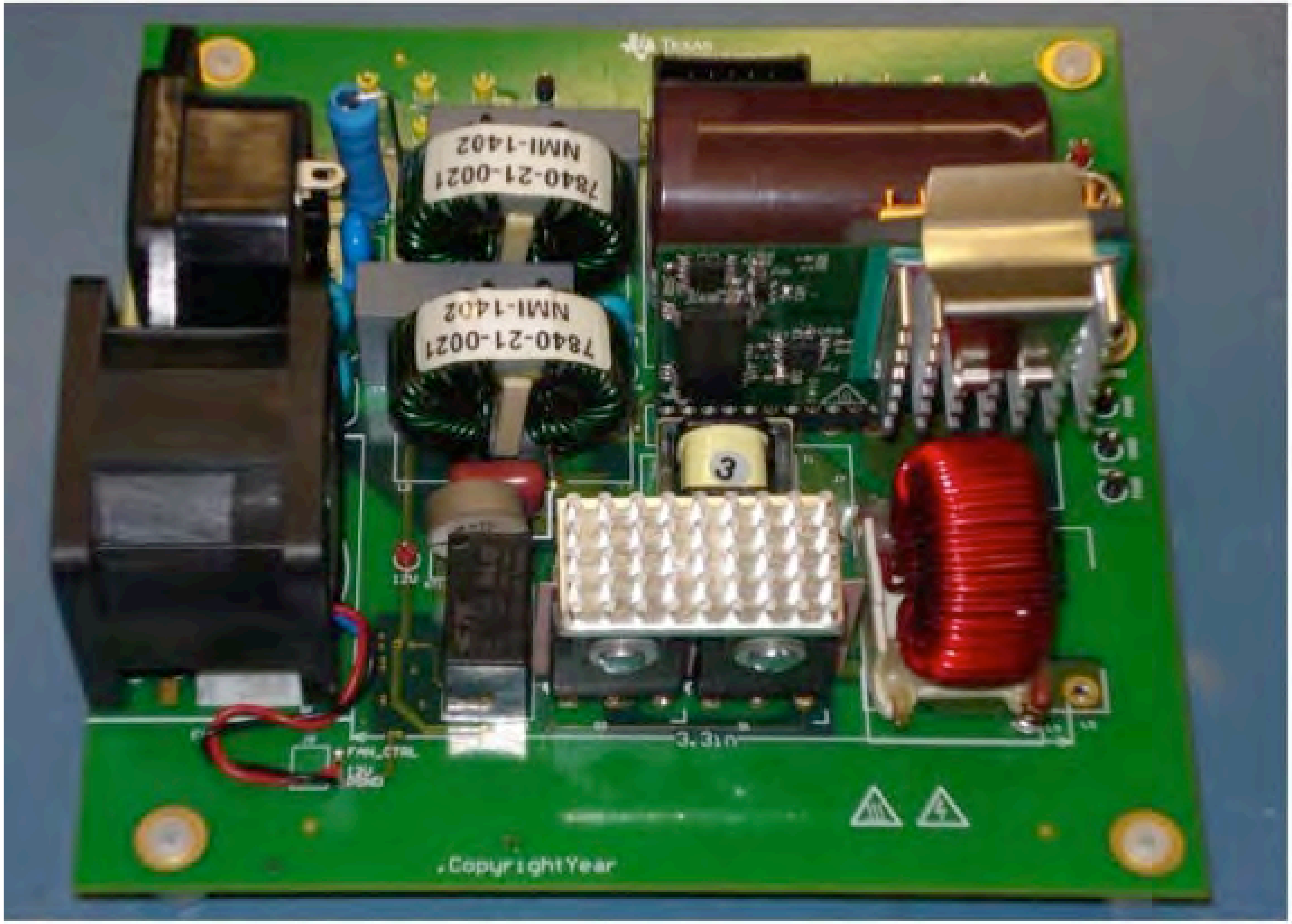
PF= 0.995

THD = 4.0%

Totem-Pole Bridgeless PFC Efficiency



750 W Totem-Pole Bridgeless PFC Prototype



Summary

- GaN FET exhibits superior switching characteristics
- Safety GaN FETs has zero reverse recovery
- Suitable for high-frequency hard-switching applications
- Relative high “body diode” forward drop
- Sophisticated ideal-diode-emulation is the key to the success of Safety GaN FET applications
- Enables Totem-Pole PFC CCM operation
- AC crossover current spike root causes were analyzed and solutions provided
- High efficiency potential
- Possible TM ZVS control to optimize light loads efficiency