High VOLT Interactive

Where power supply design meets collaboration

Choosing the right PFC topology: 100W to several kW

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What will I get out of this session?

Purpose:

- In this session we will look at the key features and trade-offs between 6 popular PFC topologies
- Readily available reference designs for each of the mentioned topologies will be highlighted

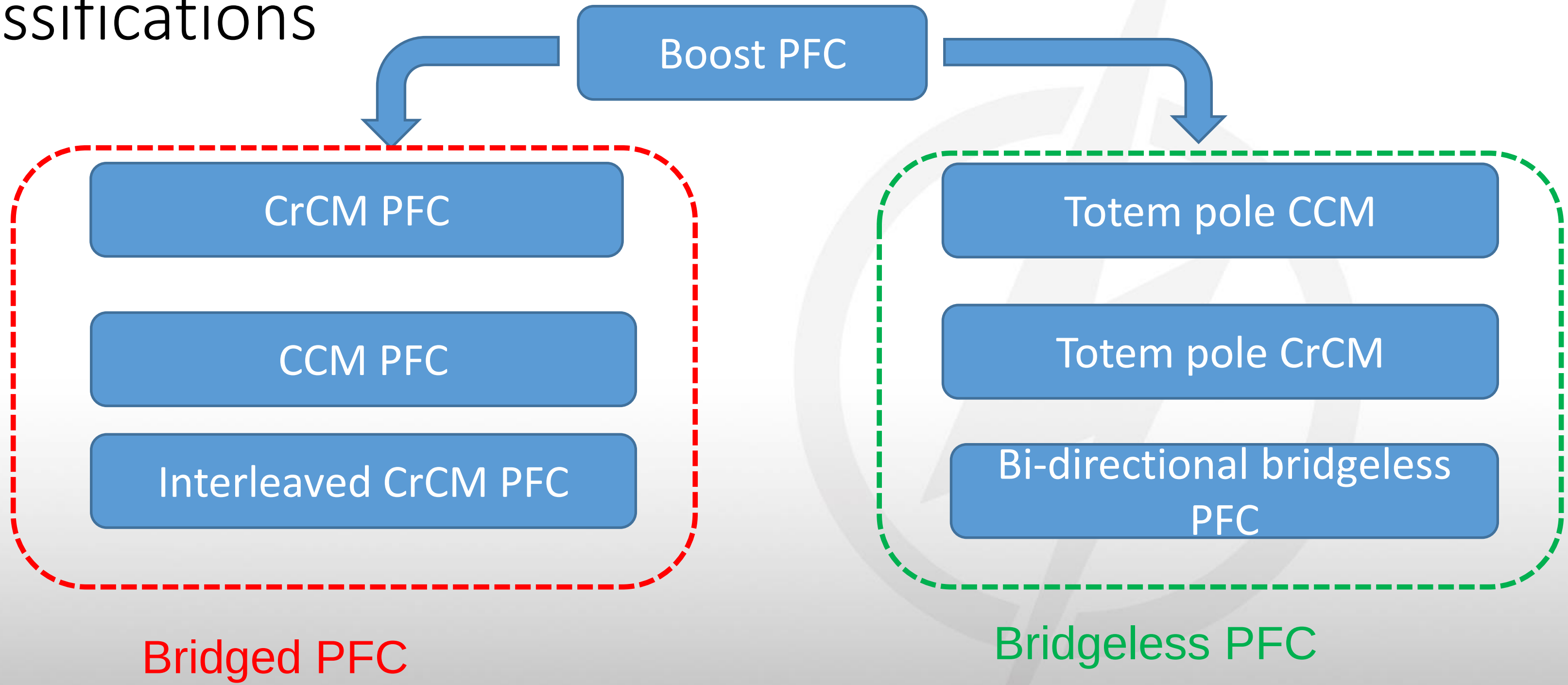
Part numbers mentioned:

- UCC28180
- UCC28056
- UCC28064
- UCD3138

Reference designs mentioned:

- TIDA-01494
- TIDA-01557
- TIDA-010015
- TIDA-00707
- PMP20873

Classifications



Efficiency analysis

For all bridged PFC topology

Specification	Value
Output power	300W
V_{in} AC	115V
Assumed efficiency	95%
Average switching frequency	100kHz

$IPD60R190P6$

Symbol	Parameter	Value
C_{iss}	Input capacitance	1750 pf
C_{rss}	Reverse transfer capacitance	3.25pF
R_{gate}	Gate resistance	5Ω
Q_{gd}	Miller charge	13nC
V_{pl}	Miller plateau voltage	5.5V
V_{th}	Threshold voltage	3V
R_{dson}	$at\ 50C$	0.2 ohm

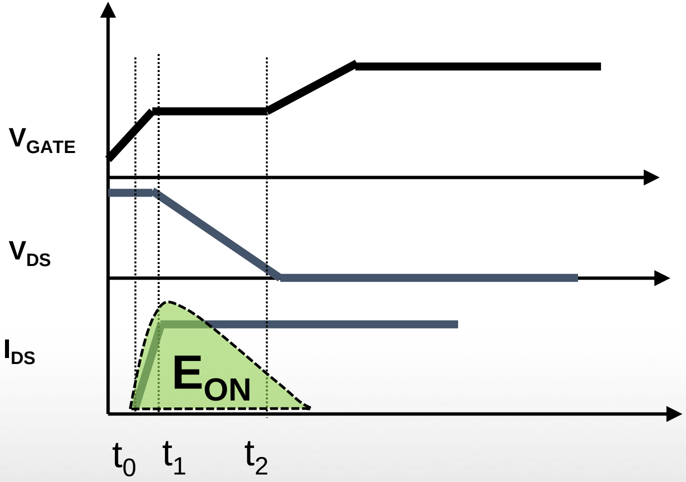
Input current

$$Iin_{avg} = \left(\frac{2\sqrt{2}}{3\pi}\right) * Pin/Vac_{\min} = 2.46A$$

Diode bridge losses:

$$P_{bridge} = 2 * \mathrm{Iin_{avg}} * \mathrm{Vf} = 4.92\mathrm{W}$$

Switching loss turn-on



$$t_{on} = t_1 + t_2$$

$$t_{on} = \left(\frac{Q_{gd}}{V_{ds}}\right) * Rgate * \left(\frac{V_{ds} - Vpl}{V_{gate} - Vpl}\right) + Ciss * Rgate * Ln\left(\frac{V_{gate} - Vth}{V_{gate} - Vpl}\right)$$

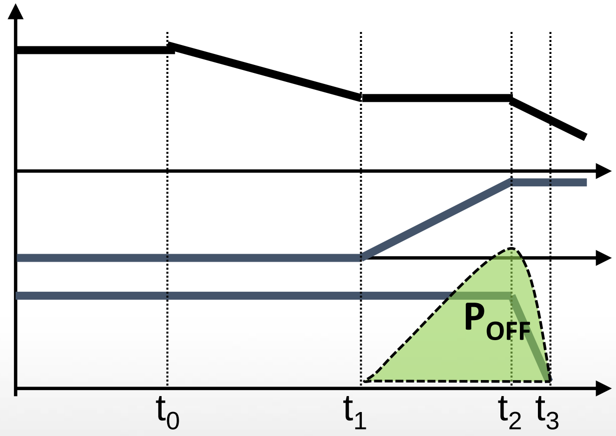
$$Pon_{overlap} = 0.5 * Vds * IHV_{on} * ton * Fsw$$

$$Pon_{coss} = 0.5 * Coss(er) * Vds^2 * Fsw$$

- Turn-on loss due to V_{ds} & I_{ds} overlap
- Additional losses at turn-on due to C_{oss} MOSFET output capacitance

Switching loss turn-off

$IPD60R190P6$



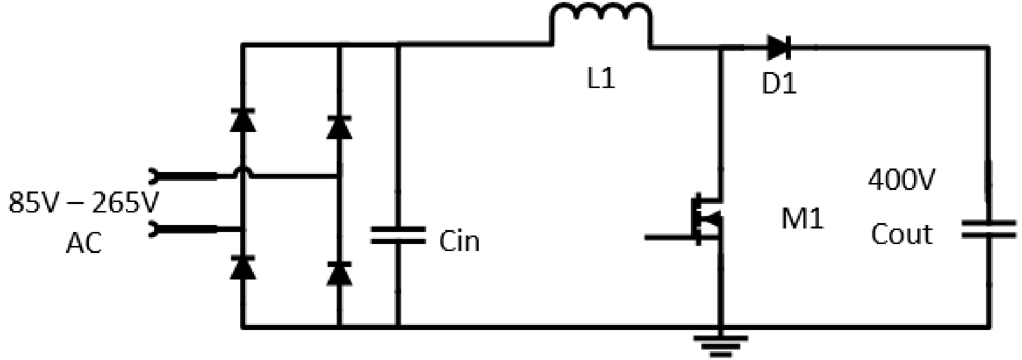
$$t_{off} = t_2 + t_3$$

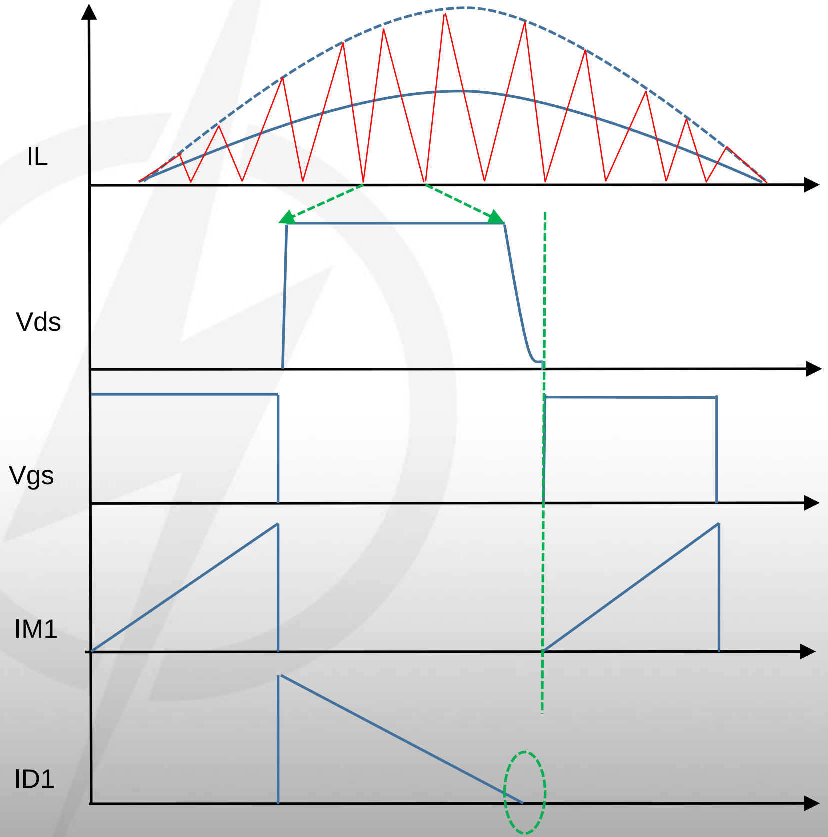
$$t_{off} = \left(\frac{Q_{gd}}{V_{ds}}\right) * Rgate * \left(\frac{V_{ds} - Vpl}{V_{pl}}\right) + Ciss * Rgate * ln * \left(\frac{V_{pl}}{V_{th}}\right)$$

$$Poff_{overlap} = 0.5 * Vds * IHV_{off} * tof_f * Fsw$$

– Turn-off loss due to V_{ds} & I_{ds} overlap

CrCM boost PFC





- Main MOSFET M1 undergoes valley switching:
  - ZCS at turn-on
  - Reduces or ~0 C_{oss} loss at turn-on
- Diode D1 undergoes ZCS at turn-off resulting in no reverse recovery loss
- Inductor current has 200% ripple, resulting in increased RMS currents and core loss

Component losses: CrCM boost PFC

Inductor current:

$$Il_{rms} = \left(\frac{\pi}{\sqrt{6}}\right) * Iin_{avg} = 3.16A$$

$$Ilpk = 2\sqrt{2} * Iin_{rms} = 8.94A$$

MOSFET conduction losses:

$$Isw_{rms} = Il_{pk} * \sqrt{\frac{1}{6} - \left(\frac{4\sqrt{2}\,Vac_{min}}{9\pi \ * Vout}\right)} = 2.95A$$

$$Psw_{cond} = Isw_{rms}^2 * Rds \ = 1.74W$$

MOSFET turn-on & turn-off loss:

$$Psw_{on} = 0W$$

$$Psw_{off} = 0.5 * Vds * (\frac{2 * Ilpk}{\pi}) * ton \ * Fsw = 1.13W$$

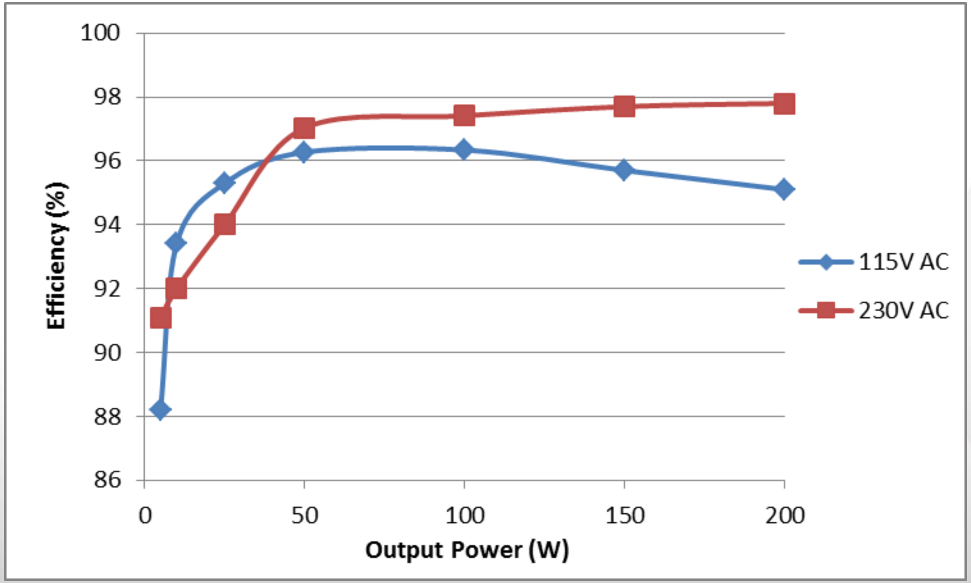
Boost diode losses:

$$Idiode_{avg} = Iou_t = 0.75A$$

$$P_{diode} = Idiode_{avg} * Vf = 0.7W$$

Higher RMS currents, turn-off loss but low turn-on loss

Results: TIDA-01557 (CrCM boost PFC)



Advantages

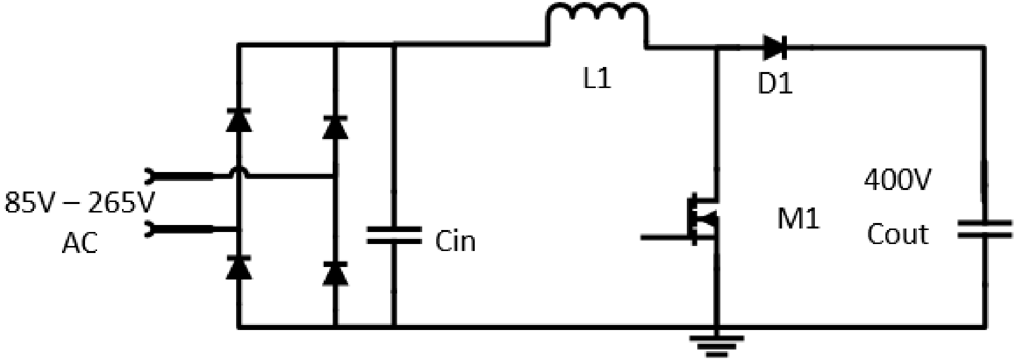
- High efficiency for <300W PFC
- Reduced common mode EMI
- No Q_{rr} loss enables use of low cost ultra-fast diode
- Easy to implement peak current/fixed-on time control

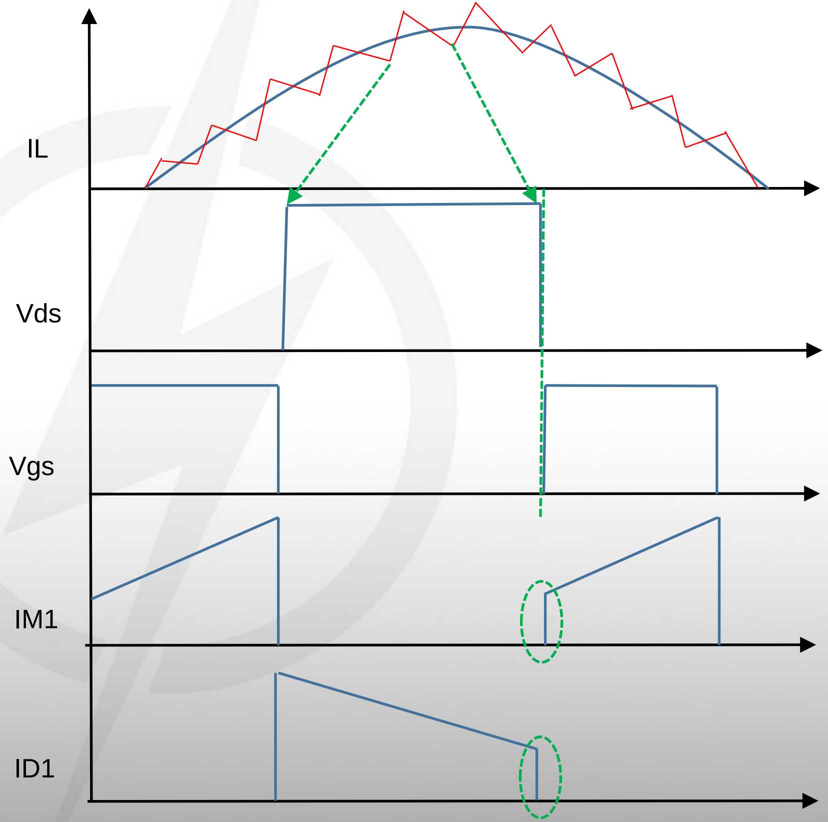
Disadvantages

- High differential mode EMI due to 200% inductor ripple results in bigger EMI filter
- High RMS currents increase conduction losses as output power requirements increase

Ideal for 75W-300W applications with universal input voltage applications

CCM boost PFC





- Main MOSFET M1 undergoes hard switching
- Diode D1 undergoes hard commutation, need to use SiC diode to eliminate reverse recovery loss
- Reduced inductor current resulting in lower RMS currents and core loss

Component losses: CCM boost PFC

Inductor current:

$$Il_{rms} = \left(\frac{\pi}{2\sqrt{2}}\right) * Iin_{avg} = 2.73A$$

MOSFET conduction losses:

$$Isw_{rms} = (Po/Vac\_\min) * \sqrt{1 - \frac{8\sqrt{2} * Vacmin}{3 * \pi * Vou_t}} = 2.21\ A$$

$$Psw_{cond} = Isw_{rms}^2 * Rds = 0.97W$$

MOSFET turn-on loss:

$$Psw_{oncross} = 0.5 * Vout * Iin_{avg} * ton * Fsw = 0.382W$$

$$Psw_{coss} = 0.5 * V_{out}^2 * Cos_s * Fsw = 0.488W$$

Total turn-on loss $= 0.87W$

MOSFET turn-off loss:

$$Psw_{off} = 0.5 * Vout * Iin_{avg} * tof_f * Fsw = 0.54W$$

Boost diode losses: (assuming silicon carbide)

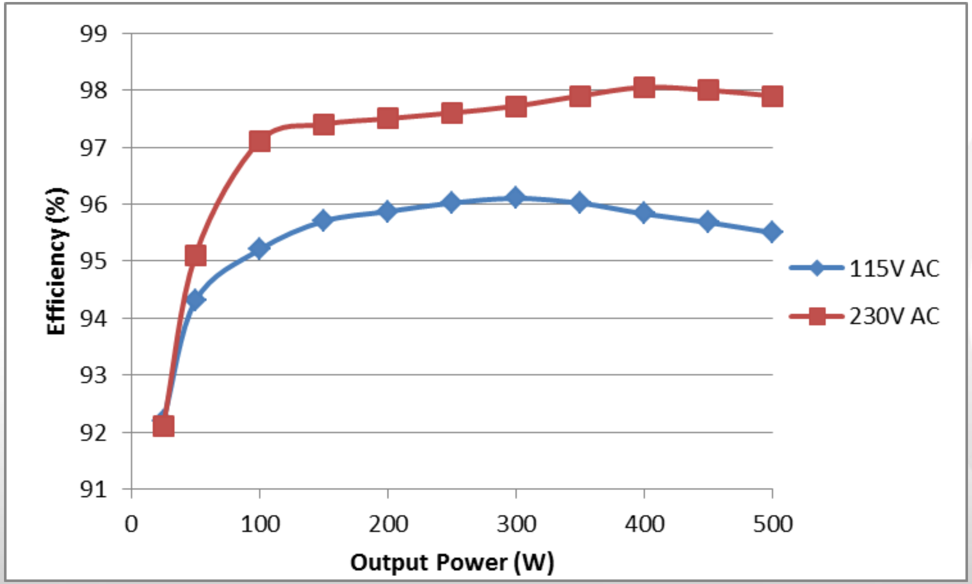
$$Idiode_{avg} = Io = 0.75A$$

$$Pdiode_{cond} = Idiode_{avg} * Vf = 0.87W$$

$$Pdiode_{sw} = 0.5 * Vo * Qc * Fsw = 0.2W$$

Lower RMS currents, conduction loss but higher turn-on loss

Results:TIDA-01494 (CCM boost PFC)



Advantages

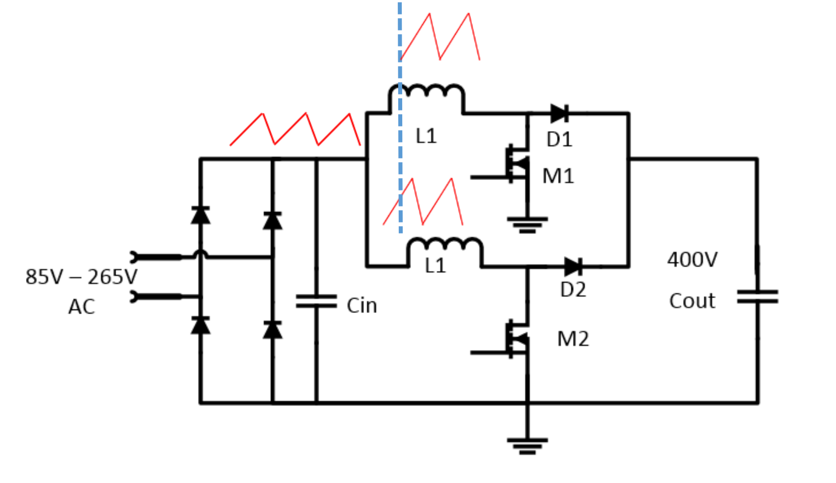
- Reduced RMS currents
- Reduced input and output ripple currents reduce differential EMI
- Smaller EMI filter

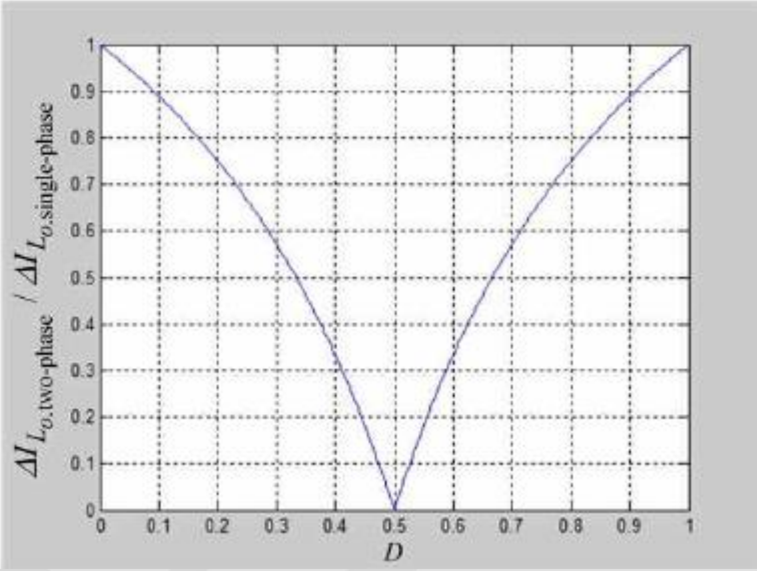
Disadvantages

- Complex current mode control
- Reverse recovery (Q_{rr}) losses necessitate use of ultra-fast or SiC diode
- Higher common mode EMI

Ideal for > 200W to few kW applications

Interleaved - CrCM boost PFC





- Input current ripple limits the output power of a single phase CrCM PFC
- Interleaving allows us to overcome this
- Interleaving multiple phases operating out of phase

- Reduction in per-phase currents, result in significant reduction in conduction losses
- Improves thermal reliability and enables thin profile power stages

Component losses: interleaved CrCM PFC

Inductor current: (per phase)

$$Il_{rms} = \left(\frac{\pi}{2\sqrt{6}}\right) * Iin_{avg} = 1.58A$$

$$Il_{pk} = \sqrt{2} * Iin_{rms} = 4.47A$$

MOSFET conduction losses: (per phase)

$$Isw_{rms} = Il_{pk} * \sqrt{\frac{1}{6} - \left(\frac{4\sqrt{2}\, Vacm_{in}}{9\pi \; * Vout}\right)} 1.475A$$

$$Psw_{cond} = Isw_{rms}^2 * Rds \; = 0.435W$$

In effect, conduction loss reduces to ½ when compared with CrCM PFC

MOSFET turn-on& turn-off loss: (per phase)

$$Psw_{on} = 0W$$

$$Psw_{off} = 0.5 * Vds * \left(\frac{2 * Ilpk}{\pi}\right) * ton \; * Fsw$$
$$= 0.665\, W$$

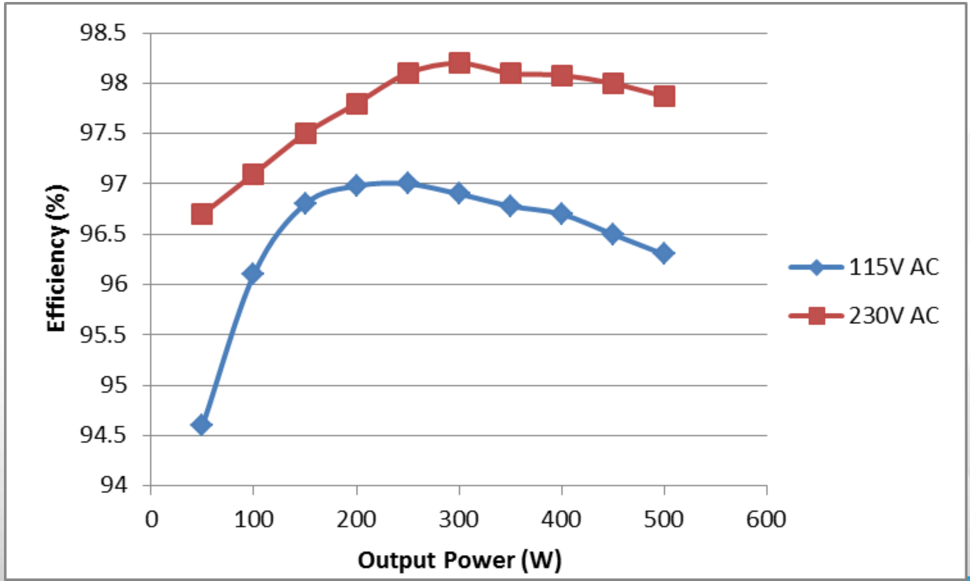
Boost diode losses:

$$Idiode_{avg} = Iout/2 = 0.375A$$

$$P_{diode} = Idiode_{avg} * Vf = 0.35W$$

Lower turn-off losses due to lower turn-off currents

Results: TIDA-010015 (interleaved CrCM boost PFC)



Advantages

- Interleaving reduces input and output ripple currents reducing differential EMI
- Reduced RMS currents lower conduction loss on MOSFET and diode
- Can result in highest efficiency up to 500-600W

Disadvantages

- Needs 2x number of MOSFET, boost diode and PFC inductor

Due to reduced per component RMS currents interleaved CrCM PFC converters can be used from 200W-700W. Interleaved CCM PFC can be used in multi kW applications.

Efficiency analysis

For all bridgeless PFC topology

Specification	Value
Output power	500W
V_{in} AC	115V
Assumed efficiency	97%
Average switching frequency	100kHz

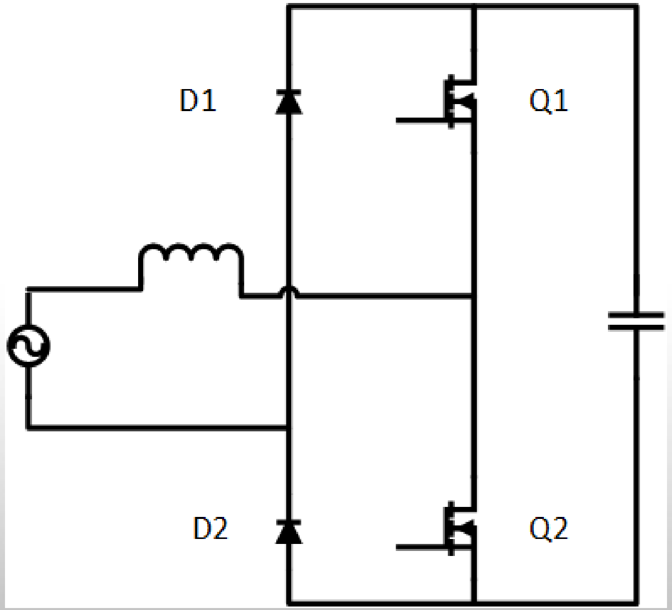
For totem-pole PFC using LMG3410 for analysis

Symbol	Parameter	Value
C_{oss}	Output capacitance	$95\ pf$
R_{dson}	$at\ 50C$	$0.077\ ohm$
t_r	t_{off} $(in\ switching\ analysis)$	$5nS$
t_f	$t_{on}$$(in\ switching\ analysis)$	$4.2nS$

For bi-directional bridgeless PFC using IPP60R099C7 for analysis

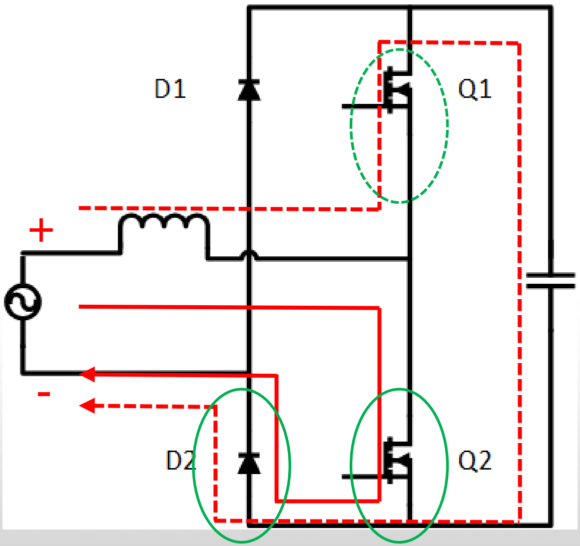
Symbol	Parameter	Value
C_{iss}	Input capacitance	$1819pf$
C_{rss}	Reverse transfer capacitance	$3.5pF$
R_{gate}	Gate resistance	5Ω
Q_{gd}	Miller charge	$14nC$
V_{pl}	Miller plateau voltage	$5.5V$
V_{th}	Threshold voltage	$3V$
R_{dson}	$at\ 50C$	$0.11\ ohm$
C_{oss}	$Output\ capacitance$	$62pF$

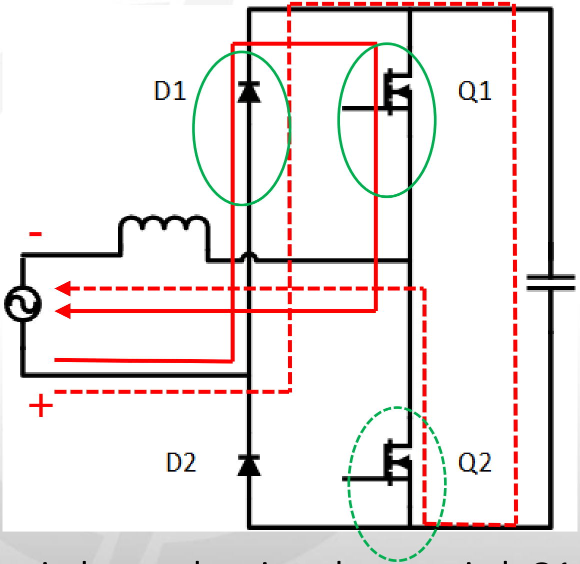
Totem pole PFC



- One of the widely used bridgeless PFC topologies
- Compared to conventional PFC, totem pole has two switches in place of a switch and a diode
- Can implement CCM as well as CrCM control
- Multiple stages can be interleaved to increase power handling capability
- To increase efficiency, the "slow" diodes D1 & D2 can be replaced with low R_{dson} MOSFET switches
- Efficiencies ~99% at 230V AC & ~98% at 115V AC are achievable

Working in both half-cycles

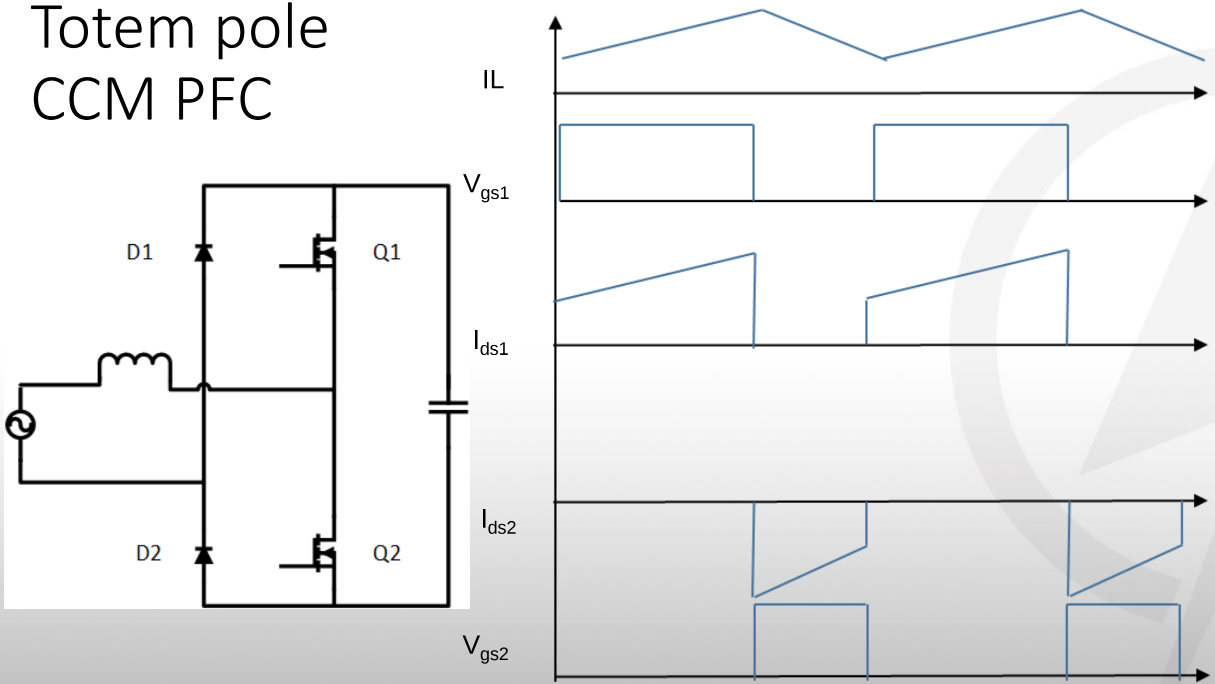




- In the inductor charging phase, switch Q2 and D2 conduct current
- In the freewheeling phase, switch Q1 and D2 conduct the inductor current

- In the inductor charging phase, switch Q1 and D1 conduct current
- In the freewheeling phase, switch Q2 and D1 conduct the inductor current

Totem pole CCM PFC



- When Q1 is the main switch, Q2 acts as the freewheeling switch
- The Q2 switch turns-on and turns-off in ZVS
- When Q2 is turned-off, current flows into its antiparallel diode. When Q1 is turned on, this diode is force commuted.
- If Q1, Q2 are MOSFETs, this can lead to high reverse recovery (Qrr) loss
- Need to use GaN or SiC switches
- Since Q1 is hard-switched, output capacitance limits operating frequency

Component losses: totem pole CCM PFC

Input current

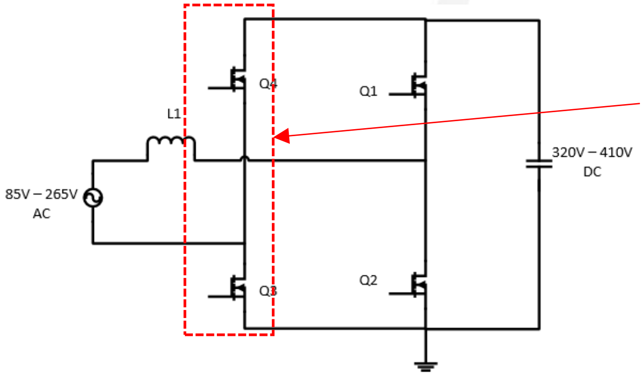
$$Iin_{avg} = \left(\frac{2\sqrt{2}}{\pi}\right) * (Pin/Vac_{\min}) = 4.03A$$

$$Iin_{rms} = Pin/Vac_{\min} = 4.48A$$

Low frequency diode loss:

$$P_{bridge} = \mathrm{Iin}_{\mathrm{avg}} * \mathrm{Vf} = 4.03\mathrm{W}$$

½ the loss compared to the bridged CCM PFC of the same output wattage



If we replace the low frequency diode with low R_{dson} MOSFET

$$PLVfet_{cond} = Iin_{rms} * Rdson_{LV} = 1.4\,W$$

Component losses: totem pole CCM PFC

GaN FET conduction losses:

$$Isw_{rms} = (Po/Vac\_\min)* \sqrt{1 - \frac{8\sqrt{2} * Vacmin}{3*\pi*Vou_t}} = 3.624A$$

$$Psw_{cond} = Isw_{rms}^2 * Rds = 0.919W$$

GaN FET turn-on loss:

$$Psw_{oncross} = 0.5 * Vout * Iin_{avg} * ton * Fsw = 0.44W$$

$$Psw_{coss} = 0.5 * V_{out}^2 * Cos_s * Fsw = 0.76W$$

GaN FET turn-off loss:

$$Psw_{off} = 0.5 * Vout * Iin_{avg} * tof_f * Fsw = 0.48W$$

Synchronous GaN FET conduction losses:

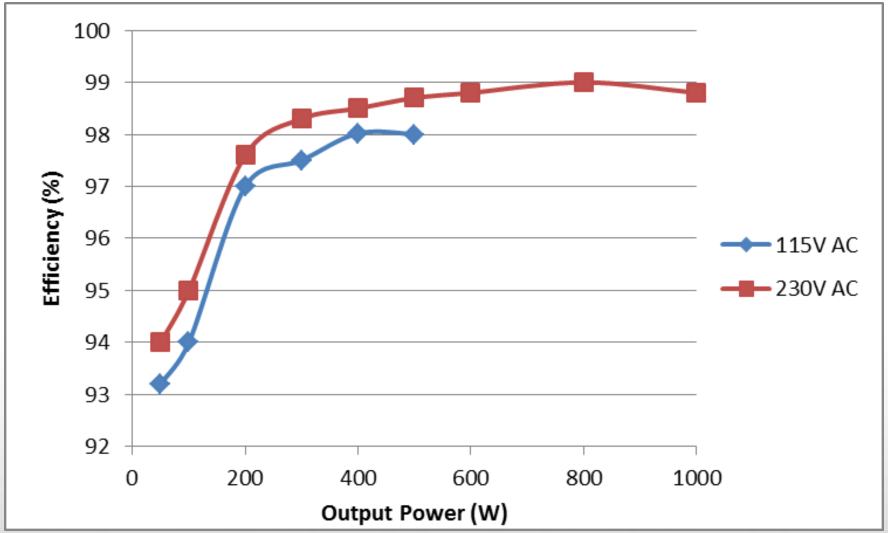
$$Idiode_{rms} = (Po/Vac\_\min)* \sqrt{\frac{8\sqrt{2} * Vacmin}{3 * \pi * Vou_t}} = 2.66A$$

$$P_{diode} = Idiode_{rms}^2 * Rds_{on} = 0.49W$$

Synchronous GaN FET switching losses:

$$Psynch_{swon} = Psynch_{swoff} = 0W$$

Results: PMP-20873 (totem pole CCM PFC)



Advantages

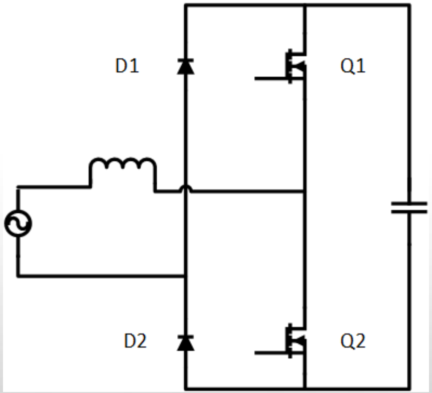
- Removes input diode bridge losses, increase efficiency by ~2% at 115V AC
- Reduced thermal requirements, high power density
- Has lower current ripple and RMS currents like conventional CCM PFC

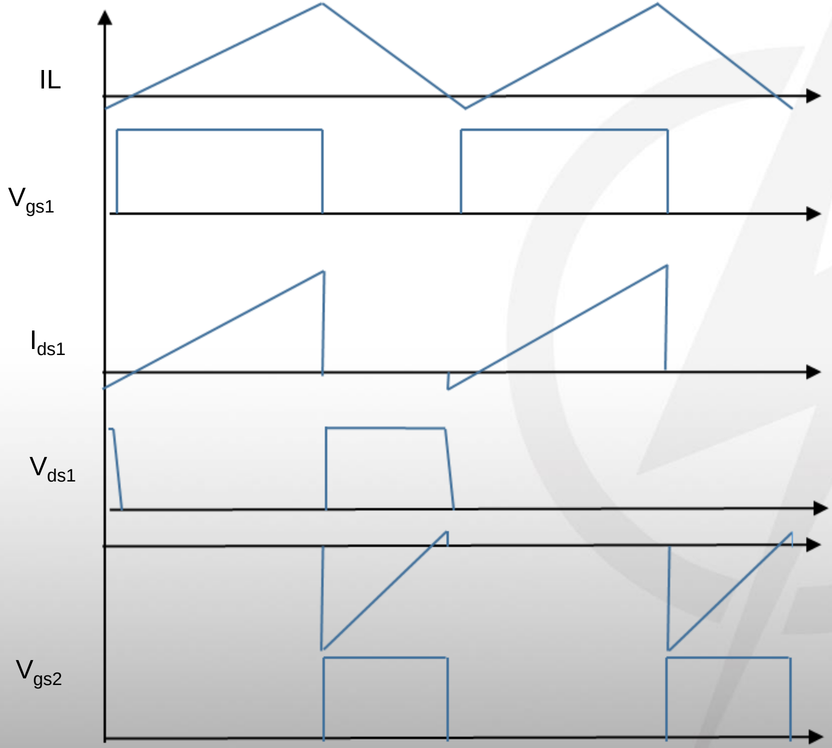
Disadvantages

- Needs to use GaN/SiC and digital control
- Higher common mode EMI filtering requirements

Suitable for >300W to few kW applications. Interleaving extends the operating power levels.

Totem pole CrCM PFC





- 200% inductor current ripple
- When Q1 is the main switch, Q2 acts as the freewheeling switch
- Q2 switch turns-on in ZVS
- At Q2 turn-off current has changed directions, resulting in "low" turn-off loss
- No reverse recovery loss enables use of MOSFET instead of GaN/SiC
- Before Q1 turn-on, inductor current discharges its output capacitance resulting in ZVS turn-on

Component losses: totem-pole CrCM PFC

Input current:

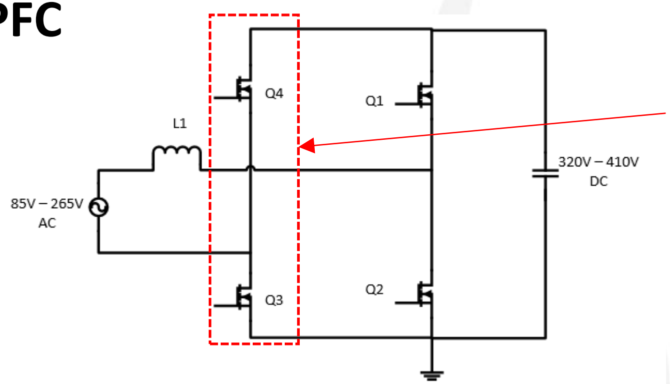
$$Iin_{avg} = \left(\frac{2\sqrt{2}}{\pi}\right) * (Pin/Vac_{\,\mathrm{min}}) = 4.03A$$

$$Iin_{rms} = \left(\frac{\pi}{\sqrt{6}}\right) * Iin_{avg} = 5.16A$$

Low frequency diode loss:

$$Pbridge = \mathrm{Iin_{avg}} * \mathrm{Vf} = 4.03\mathrm{W}$$

½ the loss compared to the bridged CrCM PFC



If we replace the low frequency diode with low R_{dson} MOSFET

$$PLVfet_{cond} = Iin_{rms} * Rdson_{LV} = 1.86\,W$$

Component losses: totem-pole CrCM PFC

GaN FET conduction losses:

$$Isw_{rms} = 2\sqrt{2} * Il_{rms} * \sqrt{\frac{1}{6} - \left(\frac{4\sqrt{2}\,Vac_{min}}{9\pi \; * Vout}\right)} = 5.12A$$

$$Psw_{cond} = Isw_{rms}^2 * Rds = 1.83W$$

GaN FET turn-on loss:

$$Psw_{ON} = 0W$$

GaN FET turn-off loss:

$$Psw_{off} = 0.5 * Vds * (\frac{2 * Ilpk}{\pi}) * toff \; * Fsw = 0.92W$$

Synchronous GaN FET conduction losses:

$$Idiode_{rms} = \; 2\sqrt{2} * Il_{rms} * \sqrt{\frac{4\sqrt{2} \; * Vacmi_n}{9 * \pi * Vou_t}} = 3.71A$$

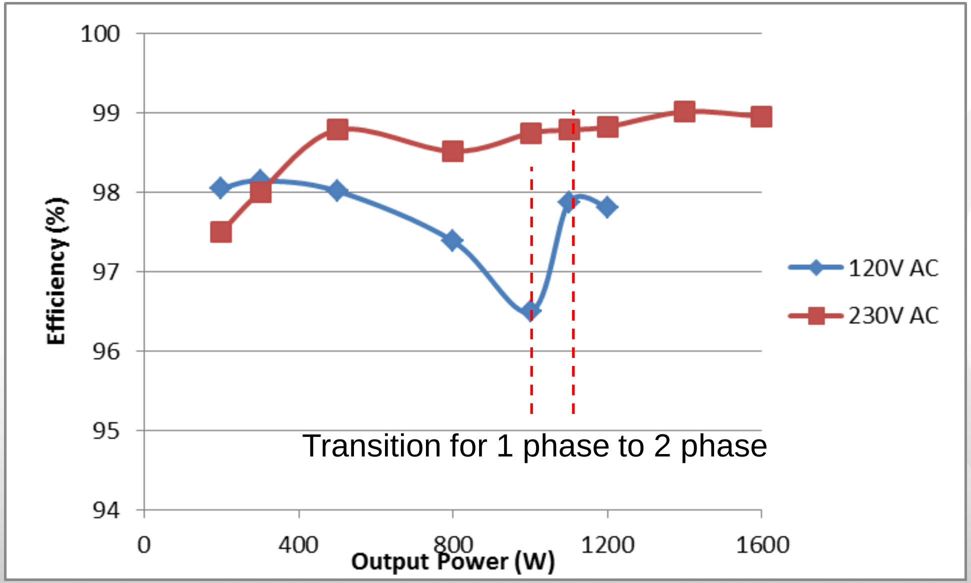
$$P_{diode} = Idiode_{rms}^2 * Rd = 0.963W$$

Synchronous GaN FET switching losses:

$$Psynch_{swon} = Psynch_{swoff} \approx 0W$$

CrCM totem pole helps in significant reduction of C_{oss} losses & turn-on losses, helping increase switching frequency

Results: TIDA-00961 (interleaved totem-pole CrCM PFC)



Advantages

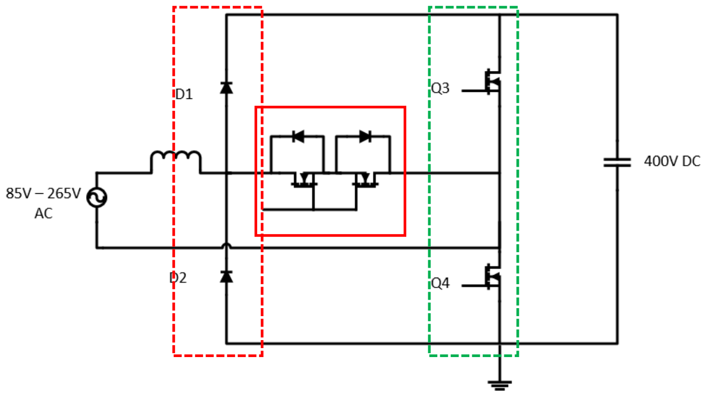
- Removes input diode bridge losses, increase efficiency by ~2% at 115V AC
- Reduced thermal requirements, high power density
- Has higher current ripple and RMS currents like conventional CrCM PFC. Interleaving helps.
- Can use Si Mosfet

Disadvantages

- and digital control
- Higher common mode EMI filtering requirements

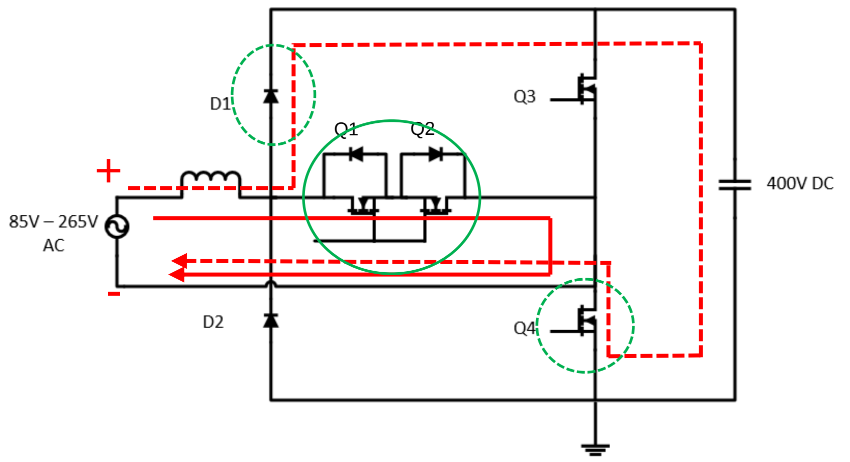
Suitable for >300W to 2 kW applications. Interleaving extends the operating power levels.

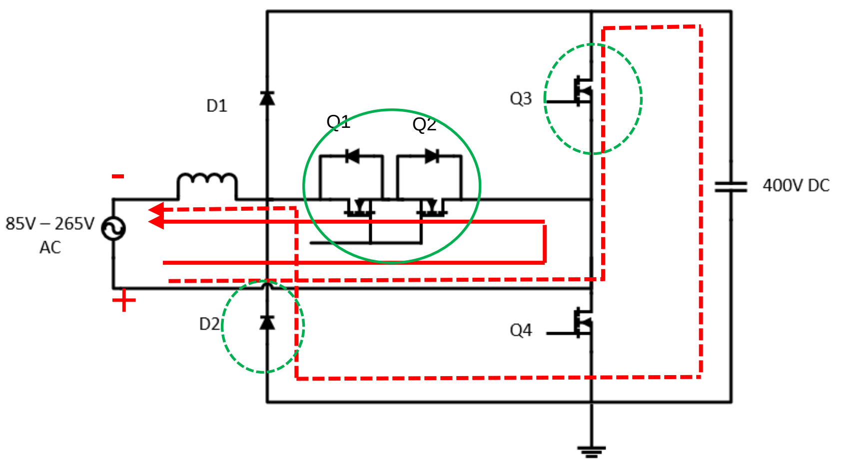
Bidirectional-bridgeless PFC



- Topology uses 2 back to back MOSFETs
- Control very similar to conventional CCM PFC
- Possible to implement using traditional analog PFC controller
- Can implement CCM as well as CrCM control
- To increase efficiency, the ”slow” diodes can be replaced with low R_{dson} MOSFET switches
- Efficiencies ~98.5% at 230V AC & >97.5% at 115V AC are achievable
- Reduced common mode EMI compared to totem pole PFC

Bidirectional-bridgeless PFC

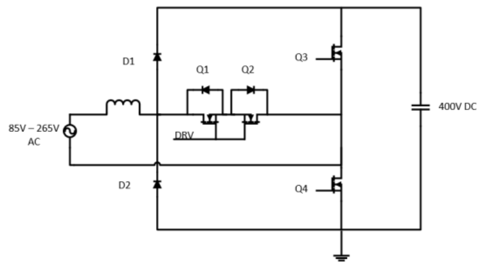


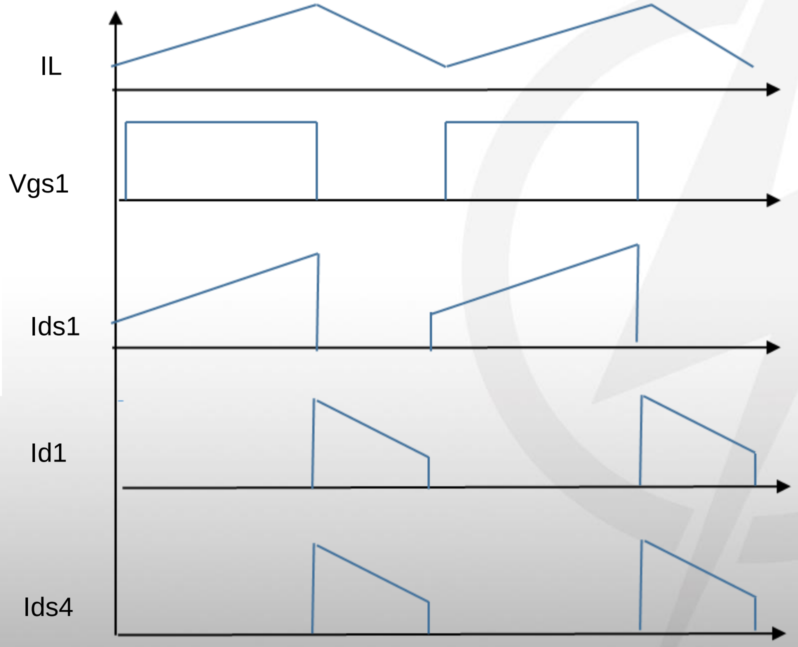


- In the inductor charging phase, switches Q1 and Q2 conduct current
- In the freewheeling phase, ultra-fast/SiC diode D1 and low freq MOSFET Q4 conduct the inductor current

- In the inductor charging phase, switches Q1 and Q2 conduct current
- In the freewheeling phase, ultra-fast/SiC diode D2 and low freq MOSFET Q3 conduct the inductor current

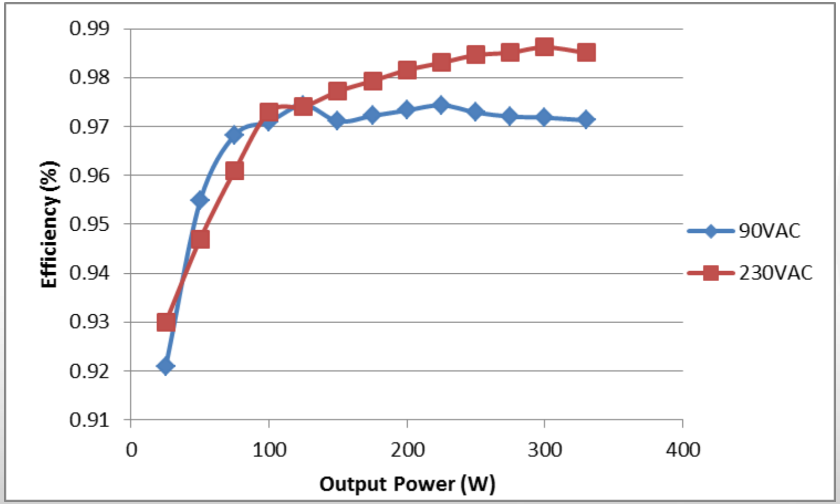
Bidirectional-bridgeless PFC





- When Q1 is the main switch, Q2 turns-on and turns-off in ZVS
- The control signal to Q1, Q2 is the same
- When Q1, Q2 is turned-off, current freewheels through D1 and Q4
- The RMS current flowing through the low freq MOSFET/diode is low as it only conducts during freewheeling phase
- Since Q1 or Q2 is hard-switched (depending on half-cycle), output capacitance limits operating frequency

Results: V1 test board (bi-directional bridgeless PFC)



Advantages

- Removes input diode bridge losses, increase efficiency by ~2% at 115V AC
- Reduced thermal requirements, high power density
- Has lower current ripple and RMS currents like conventional CCM PFC
- Can be implemented with basic PFC controller
- Lower common mode EMI

Disadvantages

- Lower efficiency than totem pole with GaN
- Need to use SiC Diodes
- Complex floating current sensing scheme required

Suitable for >200W to few kW applications

Conclusions & key takeaway

- We looked at various bridged & bridgeless PFC topologies, their operating waveforms and compared them for their key components losses.
- Reference design examples and test results for each of the topology is shown.