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

Boost PFC

CrCM PFC

CCM PFC

Interleaved CrCM PFC

Bridged PFC

Totem pole CCM

Totem pole CrCM

Bi-directional bridgeless PFC

Bridgeless PFC
Efficiency analysis
For all bridged PFC topology

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>300W</td>
</tr>
<tr>
<td>V_{in} AC</td>
<td>115V</td>
</tr>
<tr>
<td>Assumed efficiency</td>
<td>95%</td>
</tr>
<tr>
<td>Average switching frequency</td>
<td>100kHz</td>
</tr>
</tbody>
</table>

Input current

\[
I_{in \text{avg}} = \left( \frac{2\sqrt{2}}{3\pi} \right) \times \frac{P_{in}}{V_{ac \min}} = 2.46A
\]

Diode bridge losses:

\[
P_{bridge} = 2 \times I_{in \text{avg}} \times Vf = 4.92W
\]
Switching loss turn-on

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

\[ t_{on} = t_1 + t_2 \]

\[ t_{on} = \left( \frac{Q_{gd}}{V_{ds}} \right) \times R_{gate} \times \left( \frac{V_{ds} - V_{pl}}{V_{gate} - V_{pl}} \right) + C_{iss} \times R_{gate} \times \ln \left( \frac{V_{gate} - V_{th}}{V_{gate} - V_{pl}} \right) \]

\[ P_{on\, overlap} = 0.5 \times V_{ds} \times I_{HVon} \times t_{on} \times F_{sw} \]

\[ P_{on\, coss} = 0.5 \times C_{oss} \times V_{ds}^2 \times F_{sw} \]
Switching loss turn-off

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

$$t_{off} = t_2 + t_3$$
$$t_{off} = \left(\frac{Q_{gd}}{V_{ds}}\right) \cdot R_{gate} \cdot \left(\frac{V_{ds} - V_{pl}}{V_{pl}}\right) + C_{iss} \cdot R_{gate} \cdot \ln \left(\frac{V_{pl}}{V_{th}}\right)$$

$$P_{off_{overlap}} = 0.5 \cdot V_{ds} \cdot IH_{V_{off}} \cdot tof \cdot F_{sw}$$
Main MOSFET M1 undergoes valley switching:
- ZCS at turn-on
- Reduces or ~0 \( C_{\text{oss}} \) 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:

\[ I_{l_{rms}} = \left( \frac{\pi}{\sqrt{6}} \right) * I_{in_{avg}} = 3.16A \]
\[ I_{l_{pk}} = 2\sqrt{2} * I_{in_{rms}} = 8.94A \]

MOSFET conduction losses:

\[ I_{sw_{rms}} = I_{l_{pk}} * \sqrt{\frac{1}{6} - \left( \frac{4\sqrt{2} V_{ac_{min}}}{9\pi * V_{out}} \right)} = 2.95A \]
\[ P_{sw\_cond} = I_{sw_{rms}}^2 * R_{ds} = 1.74W \]

MOSFET turn-on & turn-off loss:

\[ P_{sw\_on} = 0W \]
\[ P_{sw\_off} = 0.5 * V_{ds} * \left( \frac{2 * I_{l_{pk}}}{\pi} \right) * ton * F_{sw} = 1.13W \]

Boost diode losses:

\[ I_{diode_{avg}} = I_{ou_{t}} = 0.75A \]
\[ P_{diode} = I_{diode_{avg}} * V_{f} = 0.7W \]

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
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:

\[
I_{l_{rms}} = \left( \frac{\pi}{2\sqrt{2}} \right) \times I_{in_{avg}} = 2.73A
\]

MOSFET conduction losses:

\[
I_{sw_{rms}} = \left( \frac{Po}{Vac_{\_min}} \right) \sqrt{1 - \frac{8\sqrt{2} \times Vac_{\_min}}{3 \times \pi \times Vou_t}}
= 2.21A
\]

\[
P_{sw_{cond}} = I_{sw_{rms}}^2 \times Rds = 0.97W
\]

MOSFET turn-on loss:

\[
P_{sw_{oncross}} = 0.5 \times Vout \times I_{in_{avg}} \times ton \times Fsw
= 0.382W
\]

\[
P_{sw_{coss}} = 0.5 \times V_{out}^2 \times Cos_s \times Fsw = 0.488W
\]

Total turn-on loss = 0.87W

MOSFET turn-off loss:

\[
P_{sw_{off}} = 0.5 \times Vout \times I_{in_{avg}} \times tof_f \times Fsw = 0.54W
\]

Boost diode losses: (assuming silicon carbide)

\[
I_{diode_{avg}} = I_o = 0.75A
\]

\[
P_{diode_{cond}} = I_{diode_{avg}} \times V_f = 0.87W
\]

\[
P_{diode_{sw}} = 0.5 \times V_o \times Qc \times Fsw = 0.2W
\]

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)

\[ I_{rms} = \left( \frac{\pi}{2\sqrt{6}} \right) \times I_{in\,avg} = 1.58\,\text{A} \]

\[ I_{pk} = \sqrt{2} \times I_{in\,rms} = 4.47\,\text{A} \]

MOSFET conduction losses: (per phase)

\[ I_{sw\,rms} = I_{pk} \times \frac{1}{\sqrt{6}} - \left( \frac{4\sqrt{2} \, V_{ac\,in}}{9\pi \times V_{out}} \right) = 1.475\,\text{A} \]

\[ P_{sw\,cond} = I_{sw\,rms}^2 \times R_{ds} = 0.435\,\text{W} \]

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

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

\[ P_{sw\,on} = 0\,\text{W} \]

\[ P_{sw\,off} = 0.5 \times V_{ds} \times \left( \frac{2 \times I_{lpk}}{\pi} \right) \times \text{ton} \times F_s \]

\[ = 0.665\,\text{W} \]

Boost diode losses:

\[ I_{diode\,avg} = I_{out}/2 = 0.375\,\text{A} \]

\[ P_{diode} = I_{diode\,avg} \times V_f = 0.35\,\text{W} \]

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Output power</td>
<td>500W</td>
</tr>
<tr>
<td>$V_{in}$, AC</td>
<td>115V</td>
</tr>
<tr>
<td>Assumed efficiency</td>
<td>97%</td>
</tr>
<tr>
<td>Average switching frequency</td>
<td>100kHz</td>
</tr>
</tbody>
</table>

For totem-pole PFC using LMG3410 for analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{oss}$</td>
<td>Output capacitance</td>
<td>95 pF</td>
</tr>
<tr>
<td>$R_{ds(on)}$ @ $50^\circ C$</td>
<td>0.077 ohm</td>
<td></td>
</tr>
<tr>
<td>$t_r$</td>
<td>$t_{off}$ (in switching analysis)</td>
<td>5 nS</td>
</tr>
<tr>
<td>$t_f$</td>
<td>$t_{on}$ (in switching analysis)</td>
<td>4.2 nS</td>
</tr>
</tbody>
</table>

For bi-directional bridgeless PFC using IPP60R099C7 for analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{iss}$</td>
<td>Input capacitance</td>
<td>1819 pF</td>
</tr>
<tr>
<td>$C_{rss}$</td>
<td>Reverse transfer capacitance</td>
<td>3.5 pF</td>
</tr>
<tr>
<td>$R_{gate}$</td>
<td>Gate resistance</td>
<td>5 Ω</td>
</tr>
<tr>
<td>$Q_{gd}$</td>
<td>Miller charge</td>
<td>14 nC</td>
</tr>
<tr>
<td>$V_{pl}$</td>
<td>Miller plateau voltage</td>
<td>5.5 V</td>
</tr>
<tr>
<td>$V_{th}$</td>
<td>Threshold voltage</td>
<td>3 V</td>
</tr>
<tr>
<td>$R_{ds(on)}$ @ $50^\circ C$</td>
<td>0.11 ohm</td>
<td></td>
</tr>
<tr>
<td>$C_{oss}$</td>
<td>Output capacitance</td>
<td>62 pF</td>
</tr>
</tbody>
</table>
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 $R_{ds(on)}$ 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
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 commutated.

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

\[ I_{in_{avg}} = \left( \frac{2\sqrt{2}}{\pi} \right) \times \left( \frac{Pin}{Vac_{min}} \right) = 4.03A \]

\[ I_{in_{rms}} = \frac{Pin}{Vac_{min}} = 4.48A \]

Low frequency diode loss:

\[ P_{bridge} = I_{in_{avg}} \times Vf = 4.03W \]

\[ PLV_{fet_{cond}} = I_{in_{rms}} \times Rdson_{LV} = 1.4 \text{ W} \]

\( \frac{1}{2} \) the loss compared to the bridged CCM PFC of the same output wattage
Component losses: totem pole CCM PFC

GaN FET conduction losses:
\[ I_{sw_{rms}} = \left( \frac{P_o}{V_{ac_{\min}}} \right) \sqrt{1 - \frac{8\sqrt{2} \cdot V_{ac_{\min}}}{3 \cdot \pi \cdot V_{out}}} = 3.624 \text{A} \]

\[ P_{sw_{cond}} = I_{sw_{rms}}^2 \cdot R_{ds} = 0.919 \text{W} \]

GaN FET turn-on loss:
\[ P_{sw_{on\_cross}} = 0.5 \cdot V_{out} \cdot I_{in_{avg}} \cdot \text{ton} \cdot F_{sw} = 0.44 \text{W} \]
\[ P_{sw_{on\_sw}} = 0.5 \cdot V_{out}^2 \cdot \cos_s \cdot F_{sw} = 0.76 \text{W} \]

GaN FET turn-off loss:
\[ P_{sw_{off}} = 0.5 \cdot V_{out} \cdot I_{in_{avg}} \cdot \text{tof}_f \cdot F_{sw} = 0.48 \text{W} \]

Synchronous GaN FET conduction losses:
\[ I_{diode_{rms}} = \left( \frac{P_o}{V_{ac_{\min}}} \right) \sqrt{\frac{8\sqrt{2} \cdot V_{ac_{\min}}}{3 \cdot \pi \cdot V_{out}}} = 2.66 \text{A} \]

\[ P_{diode} = I_{diode_{rms}}^2 \cdot R_{ds_{on}} = 0.49 \text{W} \]

Synchronous GaN FET switching losses:
\[ P_{synch_{sw_{on}}} = P_{synch_{sw_{off}}} = 0 \text{W} \]
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.
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:

\[ I_{in\text{avg}} = \left(\frac{2\sqrt{2}}{\pi}\right) \times (Pin/Vac_{\text{min}}) = 4.03A \]

\[ I_{in\text{rms}} = \left(\frac{\pi}{\sqrt{6}}\right) \times I_{in\text{avg}} = 5.16A \]

Low frequency diode loss:

\[ P_{\text{bridge}} = I_{in\text{avg}} \times Vf = 4.03W \]

\(\frac{1}{2}\) the loss compared to the bridged CrCM PFC

If we replace the low frequency diode with low \(R_{\text{ds}}\) MOSFET

\[ PLV_{fet_{\text{cond}}} = I_{in\text{rms}} \times R_{\text{ds}} \text{on}_{\text{LV}} = 1.86W \]
Component losses: totem-pole CrCM PFC

GaN FET conduction losses:

\[ I_{sw_{rms}} = 2\sqrt{2} \cdot I_{l_{rms}} \cdot \sqrt{\frac{1}{6} - \left(\frac{4\sqrt{2} \cdot V_{ac_{min}}}{9\pi \cdot V_{out}}\right)} \approx 5.12A \]

\[ P_{sw_{cond}} = I_{sw_{rms}}^2 \cdot R_{ds} = 1.83W \]

GaN FET turn-on loss:

\[ P_{sw_{ON}} = 0W \]

GaN FET turn-off loss:

\[ P_{sw_{off}} = 0.5 \cdot V_{ds} \cdot \left(\frac{2 \cdot I_{lpk}}{\pi}\right) \cdot t_{off} \cdot F_{sw} = 0.92W \]

Synchronous GaN FET conduction losses:

\[ I_{diode_{rms}} = 2\sqrt{2} \cdot I_{l_{rms}} \cdot \frac{4\sqrt{2} \cdot V_{ac_{min}}}{9\pi \cdot V_{out}} \approx 3.71A \]

\[ P_{diode} = I_{diode_{rms}}^2 \cdot R_{d} = 0.963W \]

Synchronous GaN FET switching losses:

\[ P_{synch_{swon}} = P_{synch_{swoff}} \approx 0W \]

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.