GaN in Practical Applications
CCM Totem Pole PFC
PFC: applications and topology

Typical AC/DC PSU for industrial, medical, telecomm and server applications.

PFC inductor is used to regulate input current in phase with the input voltage.

Line frequency Silicon MOSFET active rectifier

Totem-Pole PFC

600V GaN half-bridge

85-265 V_{AC} → PFC → 400V_{DC} → LLC → 12, 24, 48V_{DC}
CCM PFC: topologies

**Diode-bridge PFC**
- Low cost
- Good EMI performance
- Moderate power density
- Low efficiency
- Heat not distributed

**Dual-boost PFC**
- Good EMI performance
- Distributed heat
- Good efficiency
- Low power density

**Totem-pole PFC**
- High power density
- High efficiency
- Distributed heat
- EMI performance
CCM PFC: power loss comparison

**Semiconductor Power Losses of PFC Topologies**

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Diode-bridge Boost - SJ</th>
<th>Dual Boost - SJ</th>
<th>Dual Boost - GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching FET - Conduction</td>
<td>0.6 W</td>
<td>0.6 W</td>
<td>0.6W</td>
</tr>
<tr>
<td>SiC Diode Conduction</td>
<td>3.5W</td>
<td>3.5W</td>
<td>3.5W</td>
</tr>
<tr>
<td>Rect Diodes / FETs</td>
<td>8.19 W</td>
<td>0.45 W</td>
<td>0.45 W (FET)</td>
</tr>
<tr>
<td>FET $E_{oss}$ / SiC Diode $Q_{oss}$</td>
<td>3.1 W</td>
<td>3.1 W</td>
<td>2.56W</td>
</tr>
<tr>
<td>I-V Overlap</td>
<td>1.47 W</td>
<td>1.47 W</td>
<td>0.95W</td>
</tr>
<tr>
<td>Total Losses</td>
<td><strong>16.86W</strong></td>
<td><strong>9.12W</strong></td>
<td><strong>8.06W</strong></td>
</tr>
</tbody>
</table>

**Switching Losses**

- **I-V Overlap Losses**: $(I_{RMS} \times V_{DC} \times t_{SW} \times f_{PWM})/2$
- **Output Charge Losses**: $(V_{DC} \times Q_{OSS} \times f_{PWM})$
- **Reverse Recovery Losses**: $(V_{DC} \times Q_{rr} \times f_{PWM})$

- Same heat sinking and RDSon for superjunction (SJ) and GaN - both 70mΩ
- Switching frequency is 100 kHz. $V_o=400V$, $P_o=1kW$
- $Q_{oss}$ of SJ=360nC; $E_{oss}$ of SJ=13μJ
- $Q_{oss}$ of TI GaN=60nC; $E_{oss}$ of TI GaN=7.6μJ
- $Q_{oss}$ of SiC diode=65nC
Totem-pole PFC: operation

Positive half cycle

Active GaN FET is on

Negative half cycle

Active GaN FET is on
# GaN Totem-pole PFC: 2X power density of SJ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>85 – 265 V&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Input Frequency</td>
<td>50 – 60 Hz</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>385 V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Output Power</td>
<td>1 kW</td>
</tr>
<tr>
<td>Input Inductance</td>
<td>481 μH</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>100 kHz / 140 kHz</td>
</tr>
<tr>
<td>GaN</td>
<td>LMG3410</td>
</tr>
</tbody>
</table>

156 W/in<sup>3</sup>  
99% Efficiency

GaN FET Daughter Card LMG3410-HB-EVM

Switching Stage and Inductor

GaN Totem-pole PFC: 2X power density of SJ
Totem-pole PFC: getting to >99% efficiency

• GaN Losses
• Thermal design
  – Use high thermal conductivity TIM
  – Board thickness and Thermal vias – number of vias, diameter
• PCB design
  – Minimize power loop
  – Minimize switch node overlap
• Control
  – Minimize dead-time through adaptive and predictive digital control
• Passive Component Selection
  – Inductor – core and wire size
  – EMI inductors – low DCR
  – DC bus capacitor – low ESR
**Totem-pole PFC: loss breakdown and efficiency**

Loss breakdown of 1kW PFC

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Power Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMI Inductor Loss</td>
<td>0.4W</td>
</tr>
<tr>
<td>PFC Inductor Copper Loss</td>
<td>1.2W</td>
</tr>
<tr>
<td>PFC Inductor Core Loss</td>
<td>1.64W</td>
</tr>
<tr>
<td>DC Capacitor Loss</td>
<td>0.54W</td>
</tr>
<tr>
<td>GaN Conduction Loss</td>
<td>1.76W</td>
</tr>
<tr>
<td>GaN Q_{oss} + Switch Node Cap Loss</td>
<td>2.6W</td>
</tr>
<tr>
<td>GaN I-V Overlap Loss</td>
<td>0.9W</td>
</tr>
<tr>
<td>Relay + Si FET + PCB Losses</td>
<td>0.95W</td>
</tr>
<tr>
<td><strong>Total Power Loss</strong></td>
<td><strong>9.98W</strong></td>
</tr>
</tbody>
</table>

*_{T_amb}=25^\circ C, \ fs=100kHz, \ V_{dc}=387V*

99% efficiency 60% to 100% load

Note: Excludes bias losses
1MHz LLC
**LLC: Applications and topology**

85-265 V\(_{AC}\)

- **PFC**
- **LLC**

400 V\(_{DC}\) → 12, 24, 48 V\(_{DC}\)

Resonance set up with L\(_r\), C\(_r\) (& L\(_m\)), this network determines regulation characteristics.

Typical AC/DC PSU for industrial, medical, telecomm and server applications.

600V Superjunction or GaN half-bridge

Low-voltage Si or GaN synchronous rectifier
**LLC: key benefits**

- Soft-switching over entire load range
- Low component stresses
- Easy magnetic integration

Waveform @\(f_{sw} < f_r\)

- Low MOSFET turn-off current
- Primary ZVS
- Secondary ZCS
GaN: superior solution for LLC

- **Reduced Output Capacitance** $C_{OSS}$
  - reduces dead-time, increasing the time when current delivered to the output
  - allows larger magnetizing inductance and lower circulating current losses as well as transformer fringe-field losses
- **Reduced Gate Driver Losses**
- **System Optimization**
  - GaN enables higher switching frequency to reduce magnetic components significantly
  - GaN enables LLC converter with higher efficiency and higher power density
LLC solution: 1MHz isolated DC-DC converter

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (V)</td>
<td>380 ~ 400</td>
</tr>
<tr>
<td>Output voltage (V)</td>
<td>48V Nom unregulated</td>
</tr>
<tr>
<td>Power (W)</td>
<td>1000</td>
</tr>
<tr>
<td>Size (in)</td>
<td>2 x 2.1 x 1.7</td>
</tr>
<tr>
<td>Power density (W/in^3)</td>
<td>140 <strong>High power density</strong></td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;97% <strong>High Efficiency</strong></td>
</tr>
<tr>
<td>Switching frequency</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>
LLC solution: 1MHz isolated DC-DC converter

- **Topology**: LLC
- **Frequency**: 1MHz
- **Density (W/in³)**: 140

### Comparison Table

<table>
<thead>
<tr>
<th></th>
<th>GaN</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>LLC</td>
<td>LLC</td>
</tr>
<tr>
<td>Frequency</td>
<td>1MHz</td>
<td>100-200 kHz</td>
</tr>
<tr>
<td>Density (W/in³)</td>
<td>140</td>
<td>95* commercial server LLC</td>
</tr>
</tbody>
</table>

**Figure:**
- Integrated transformer
- LMG3410 daughter card
- UCD3138A Controller card
- Bias supply
- Digital controller card

**Dimensions:**
- Integrated transformer: 51mm
- LMG3410 daughter card: 42mm
- Digital controller card: 53mm

**Source:** Texas Instruments
1MHz LLC: integrated transformer design details

- PCB windings integrated with SR FETs & output capacitors for low interconnect and leakage loss
- Interleaved structure for lower winding loss
- "∞" shaped winding structure to achieve high power density
- Better thermal performance
Test results: measured efficiency

![Graph showing efficiency vs. power for different voltage inputs: 380Vin, 390Vin, 400Vin. Efficiency increases with power, and there are slight variations between the curves.](image-url)
Motor Drive
**GaN: advantages in motor drives**

- GaN reduces or eliminates heatsink
- GaN reduces or eliminates switch node oscillations
  - Lower radiated EMI, no additional snubber network (space, losses) required
- GaN increases PWM frequency and reduces switching losses
  - Drive very low inductance PM synchronous motors or BLDC motors
  - Precise positioning in servo drives/steppers through minimum torque ripple
  - High-speed motors (e.g. drone) achieves sinusoidal voltage above 1-2kHz frequency
- GaN eliminates dead-time distortions of phase voltage
  - Better light load and THD performance
TIDA-00909: 48V/10A high frequency 3-phase GaN inverter

Design features
- Inverter w/ three 80V/10A half-bridge GaN power modules LMG5200
- Interfaced with C2000 MCU LaunchPad
- Up to 100-kHz PWM inverter with wide input voltage range 12-60V<sub>DC</sub>

Design benefits
- Very low switching losses, efficiency up to 98.5% at 100-kHz PWM
- No heatsink
- Tested up to 100kHz PWM to drive low inductance/high-speed motors
GaN inverter: 100kHz 3-phase design

48V/10A with 98.5% efficiency

Board dimension 54mm * 79mm

No heatsink!

Natural Convection
High accuracy LiDAR enabled by GaN

- Next generation scanning LiDAR requires:
  - Increased range (300m): need more power (>40A/ 75W)
  - Eye safety: <2ns pulse width
  - Depth accuracy of <10cm: <2ns pulse, <500ps rise time

- GaN and the LMG1020 LiDAR GaN driver enables optimal power and speed in the laser design, not possible with MOSFET drivers
LMG1020: 1ns 100W light output

Light output, 1ns ½ power peak power >100W

Receiver falling edge BW limited