State-of-the-Art Mobile Charging: Topologies, Technologies and Performance

PSMA Industry Session IS05: Mobile Applications

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• Topology / technique
  • Hard-switch $\rightarrow$ Soft switch (ZVS)
  • New technology enables new topologies to be commercially viable

• Switch technology
  • Si Bipolar $\rightarrow$ Si FET $\rightarrow$ Discrete / Cascoded GaN $\rightarrow$ GaN Power ICs

• Magnetic Materials
  • New compounds / alloys, optimized for high frequency
Adapter Density 2016:

- **FinSix (93.4%)** Stacked Half-Bridge
- **Zolt 90%** Active Clamp Flyback
- **QR Flyback**

Efficiency at full load, 120V AC:
- 91%
- 92%

Frequency range: 65-100-150kHz
Adapter Density 2017:
Frequency Drives Size

- **Efficiency at full load, 120V\textsubscript{AC}**
  - 92% for QR Flyback
  - 91% for Active Clamp Flyback
  - 91.9% for CPES (Apr’16)
  - 92.8% for Navitas (Jan’16)

- **Power Density (W/in\textsuperscript{3})**
  - 65-100kHz
  - 100-150kHz
  - 300kHz+

- **Adapter Power (W)**
  - CPES (Aug’16, 94.9%)
  - Navitas (Q1’17, 94%)
  - Finisix (93.4%)
  - Stacked Half-Bridge
  - Zolt (90%)
  - Customer Estimate
  - Navitas (Nov’16, 95%)

- **Technology**
  - PFC + LLC
GaN Power IC: High-Speed FET, Driver & More

- Proprietary AllGaN™ technology
- **Monolithic** integration of GaN FET, GaN Driver, GaN Logic
- 650 V eMode
- 20x lower drive loss than silicon (<35 mW at 1 MHz)
- Driver impedance matched to power device
- Very fast (prop delay and turn-on/off of 10-20 ns)
- Zero inductance turn-off loop
- High dV/dt immunity (200 V/ns) with control
- Digital input
- Complete layout flexibility

GaN Power IC – Fast & Efficient

- 500 V Switching
- No overshoot / spike
- No oscillations
- ‘S-curve’ transitions
- Zero Loss Turn-on
- Zero Loss Turn-off
- Sync Rectification
- High frequency
- Small, low cost magnetics

1 MHz ZVS

V_DS of Low Side FET

V_GS of Low Side FET

ZVS soft switching

Zero Loss Turn-off

High Side Sync Rect

Low Side Sync Rect

200ns/div
Half-Bridge iDrive GaN Power IC

- Internal level-shift, bootstrap
- Range from (2x) 160-560 mOhm (650V)
- Single component
- Ground-referenced control
- Active Clamp Flyback, Half-Bridge, LLC, etc.
High Frequency Magnetics

N59 optimized for 2MHz

TDK/EPCOS N59/PC200
Hitachi Metals ML91S
ACME P61

3F & 4F up to 10MHz

# Fast Chargers ... going “GaN Fast”

3x Fast Charging with 50% Energy Savings

<table>
<thead>
<tr>
<th>Existing Si-based 15W</th>
<th>AllGaN™ 2016 25W</th>
<th>AllGaN™ 2017 25W</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>100 kHz</strong>&lt;br&gt;Up to 6.5 W/in³</td>
<td><strong>300-500 kHz</strong>&lt;br&gt;11 W/in³</td>
<td><strong>&gt;1 MHz</strong>&lt;br&gt;17.5 W/in³</td>
</tr>
<tr>
<td><strong>88%</strong></td>
<td><strong>&gt;92%</strong></td>
<td><strong>&gt;95%</strong></td>
</tr>
</tbody>
</table>

Quasi-Resonant (QR) vs. Active Clamp Flyback (ACF)

- High loss in RCD snubber circuit
- Partial hard switching at high line
- Losses increase with switching frequency

- No resistor needed in the snubber: no snubber loss
- Full range zero-voltage switching (ZVS): no switching loss
- ACF enables high switching frequency
25W ACF: 66% More Power

Original 15 W case

Original 15 W
Si-based QR Flyback
~100 kHz

Upgraded 25 W
Half-Bridge GaN Power IC ACF
~400 kHz
• 94.5% efficient at 220V (94.2% at 120V\textsubscript{AC}, 93.1% at 90V\textsubscript{AC})
• 23.7 W/in\(^3\) density (uncased)
• 15.7mm profile

For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang
45W CrCM ACF Operation

• Switch-node voltage ($V_{SW}$), SR FET voltage ($V_{SR}$), leakage current ($i_{LK}$) and magnetizing current ($I_{Lm}$)

• $120V_{AC}$, 0.2A load, $F_{SW} = 210kHz$

Magnetizing current (drawing)
Inductor current merges with magnetizing current, achieves SR ZCS turn-off
45W ACF: High Efficiency, Cool Temperatures

![Graph showing efficiency vs. input voltage for 90V_{AC}, 120V_{AC}, and 220V_{AC}.](image)

- **90V_{AC}:**
  - AC Rectifier: 81°C
  - GaN Power IC: 77°C

- **120V_{AC}:**
  - AC Rectifier: 68°C
  - GaN Power IC: 69°C

- **220V_{AC}:**
  - SR FET, SR IC: 70°C
  - Transformer: 70°C

- Other components:
  - Transformer: 71°C
  - Transformer: 64°C
  - Transformer: 70°C
1 MHz, 25 W, 17 W/in3 (cased) ACF (CPES 2016)

- Single-stage EMI
- Navitas GaN Power ICs
- Planar transformer
- DSP (for prototype)
MHz+ 25 W ACF

$F_{SW}=1.5\text{MHz}$

![Graph showing Efficiency vs. Load](image)

* Exclude bridge and EMI filter loss*
GaN Power ICs enable Hi-Density Adapters
3x Higher Density with 50% Energy Savings

Existing Si-based 150W

100 kHz
5-10 W/in³
88%

AllGaN™ 2016
150W

2x Higher Density

300-500 kHz
17 W/in³
>93%

AllGaN™ 2017
150W

3x Higher Density

>1 MHz
26.5 W/in³
>95%

150W AC-19V

PFC + LLC Powertrain Daughtercard
NV6117 (PFC), 2x NV6115 (LLC)

PFC + LLC Control Daughtercard
NCP1615 (PFC)
NCP1399xx (LLC) (plus opto-couplers)

EMI Filter

Bulk Cap

Res. Inductor

PFC Inductor

LLC Transformer

Output Caps

SR Daughtercard:
2x NCP43080
2x NVMFS5C628NL
Schematics (Complete Board)

HV Start-Up + X2 Cap Discharge

EMI + Rectifier

Aux $V_{CC}$ Supply

EMI

Boost PFC

LLC

SR + Output Reg

Integrated Xformer: 22nF
Discrete Xformer: 8.2nF
PFC FET $V_{DS}$, LLC $V_{SW}$ at start-up

PFC switching (zoom), 220V$_{AC}$, 150W
PFC Waveforms

PFC switching (zoom), 220V$_{AC}$, 150W
LLC Waveforms

LLC $V_{SW}$ open load, $19V_{OUT}$

LLC $V_{SW}$ skip-mode, $19V_{OUT}$, 1A

LLC $V_{SW}$ $I_L$, $19V_{OUT}$, 8A
150W: Running Cool

- **Top View**
  - LLC Transf. 85°C
  - SR FETs 90°C

- **Side View**
  - LLC Primary (2x NV6115) 65°C
  - PFC Switch (NV6117) 80°C

- **Components Temperatures**
  - DM Choke 90°C
  - PFC Inductor 85°C
  - PFC diode 90°C
  - PFC Switch (NV6117) 80°C
150W AC-19V, ~300 kHz

Efficiency (AC-19V) (%)

- 90Vac
- 120Vac
- 220Vac

94% average per DoE Level VI

116 x 55 x 18 mm = 115 cc
(1.31 W/cc, 21.4 W/in³)
uncased
# 150W, 19V: GaN Power IC vs. Si

<table>
<thead>
<tr>
<th>Part#</th>
<th>Technology</th>
<th>V</th>
<th>Pack</th>
<th>$R_{DS(ON)}$ (typ. mΩ)</th>
<th>$Q_G$ (typ. nC)</th>
<th>$C_{OSS}$ (er) (typ. pF)</th>
<th>$R \times Q_G$ (mΩ.nC)</th>
<th>$R \times C_{OSS}$ (er) (mΩ.pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STL34N65M5</td>
<td>Si FET</td>
<td>650</td>
<td>8x8</td>
<td>99</td>
<td>62.5</td>
<td>63</td>
<td>6,187</td>
<td>6,237</td>
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<tr>
<td>IPL60R199CP</td>
<td>Si FET</td>
<td>600</td>
<td>8x8</td>
<td>180</td>
<td>32</td>
<td>69</td>
<td>5,760</td>
<td>12,420</td>
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<tr>
<td>IPL60R299CP</td>
<td>Si FET</td>
<td>600</td>
<td>8x8</td>
<td>270</td>
<td>22</td>
<td>46</td>
<td>5,940</td>
<td>12,420</td>
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<tr>
<td>NV6115</td>
<td>GaN Power IC</td>
<td>650</td>
<td>5x6</td>
<td>160</td>
<td>2.5</td>
<td>30</td>
<td>400</td>
<td>4,800</td>
</tr>
<tr>
<td>NV6117</td>
<td>GaN Power IC</td>
<td>650</td>
<td>5x6</td>
<td>110</td>
<td>4</td>
<td>45</td>
<td>440</td>
<td>4,950</td>
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<tr>
<td><strong>GaN Benefit</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>14x</strong></td>
<td><strong>1.5-2.5x</strong></td>
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For further details of the 150 W, 21 W/in³ board, please see APEC 2017 Industry Session “State-of-the-Art Mobile Charging: Topologies, Technologies and Performance” (Mobile Applications)
Si Starts Hard Switching as Frequency Increases

- **120V_{AC}, Si CP partial hard-switching (~200kHz)**
  - Voltage spikes
  - Partial hard-switching (loss)

- **120V_{AC}, GaN clean ZVS waveforms (~200kHz)**
  - No voltage spikes / overshoot
  - Clean ZVS turn-on transition
  - Minimize deadtime for low reverse conduction loss
GaN vs. Si

High Power Density and High Switching Frequency Adapter

- Ultra high-power density up to 22 W/ in³
- Very high Efficiency up to 96 % with GaN Power FETs
- The smallest dimensions 4.6 x 1.96 x 0.78 in
- Performance ensured by NCP1399, NCP1615, NCP43080
- Up to 94 % Efficiency with Silicon Super-Junction MOSFETs

Typical applications

- High Power Laptop Adaptors, Power supplies, Power chargers
- 150 W Output Power @ 19 V with ~8.5 A current limit

Higher switching frequency enables:

- Up to 40% volume reduction, Power Density almost doubled
- Compact design / balanced price
- Keep high efficiency
MHz 150W Totem-pole + LLC (CPES 2016)

GaN-based Power Density
= 35 W/in$^3$
(uncased)
Pop Quiz! How do we shrink our power supplies?

A. Select the right ZVS topology
B. Increase switching frequency
C. Select the right magnetic material
D. Select the right GaN Power IC
E. Increase efficiency
F. **All of the above**
G. None of the above...
   ...use hard-switching topologies and Silicon switching < 100kHz.