GaN FET-Based High CCM Totem-Pole Bridgeless PFC

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Agenda

• AC/DC efficiency standard and PFC efficiency requirement
• Bridgeless PFC topologies and development trend
• 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

<table>
<thead>
<tr>
<th>80 Plus Test Type</th>
<th>115 V Internal Non-Redundant</th>
<th>230 V Internal Redundant</th>
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<tr>
<td>Fraction of rated load</td>
<td>10% 20% 50% 100%</td>
<td>10% 20% 50% 100%</td>
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<tr>
<td>80 Plus</td>
<td>80% 80% 80%</td>
<td>80% 80% 80%</td>
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<tr>
<td>80 Plus Bronze</td>
<td>82% 85% 82%</td>
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<tr>
<td>80 Plus Silver</td>
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<td>80 Plus Gold</td>
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<td>80 Plus Platinum</td>
<td>90% 92% 89%</td>
<td>90% 94% 91%</td>
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<tr>
<td>80 Plus Titanium</td>
<td>90% 92% 94%</td>
<td>90% 94% 96%</td>
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**Energy Star Specification**
### PFC Efficiency Budget

<table>
<thead>
<tr>
<th>80 Plus Test Type</th>
<th>Efficiency at 115 V Internal Non-Redundant</th>
<th>Efficiency at 230 95.5%V Internal Redundant</th>
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<tr>
<td>Fraction of rated load</td>
<td>10% 20% 50% 100%</td>
<td>10% 20% 50% 100%</td>
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<tr>
<td>80 Plus Platinum</td>
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<td></td>
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<tr>
<td>PFC</td>
<td>95.8% 95.4% 93.7%</td>
<td>95.7% 97.4% 95.8%</td>
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<tr>
<td>DC/DC</td>
<td>94% 96.5% 95%</td>
<td>94% 96.5% 95%</td>
</tr>
<tr>
<td>80 Plus Titanium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFC</td>
<td>95.5% 95.8% 96.4% 93.8% 95.8% 98% 98.5% 94.8%</td>
<td></td>
</tr>
<tr>
<td>DC/DC</td>
<td>94% 96% 97.5% 96% 94% 96% 97.5% 96%</td>
<td></td>
</tr>
</tbody>
</table>

- 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.
Existing Bridgeless PFC Application Status

**Basic Bridgeless PFC**
- Good efficiency
- Easy control
- High component count
- Low component utilization
- Low density

**Totem-Pole Bridgeless PFC**
- Good efficiency
- Fixed frequency
- Easy control
- DCM only
- For power < 300 W

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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

<table>
<thead>
<tr>
<th>Properties</th>
<th>GaN</th>
<th>Si</th>
<th>SiC</th>
</tr>
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<tr>
<td>$E_g$ (eV)</td>
<td>3.4</td>
<td>1.12</td>
<td>3.2</td>
</tr>
<tr>
<td>$E_{BR}$ (MV/cm)</td>
<td>3.3</td>
<td>0.3</td>
<td>3.5</td>
</tr>
<tr>
<td>$V_s$ ($x 10^7$cm/s)</td>
<td>2.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\mu$ (cm$^2$/Vs)</td>
<td>990-2000</td>
<td>1500</td>
<td>650</td>
</tr>
</tbody>
</table>

$E_g$: Wide band-gap energy

$E_{BR}$: Critical field breakdown voltage

$V_s$: Saturation velocity

$\mu$: Electron mobility

Theoretical on-resistance vs blocking voltage

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

Reference:
EPC, Gallium Nitride (GaN) technology overview
Figure of Merit Comparison

Figure of Merit depicts fundamental characteristics of switching devices – $R_{ds_{on}}, Q_g, C_{OSS}$ and breakdown voltage

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Cascode GaN FET Structure

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

Positive switching cycle
- Active switching stage

- Q1 and Q2 are low frequency switches.
- Q3 and Q4 are an active switch and a SyncFET.
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
  
  DCM  Load increasing  CCM  Load decreasing  Stuck at CCM
  
  Negative current detection and SyncFET soft off control is needed

- Freewheel stage current sensing for zero current detection

Db is chopped off at ZCD point
UCD3138 – Based Control Circuit

ADC + CLA + DPWM

Crossover Detection

Main FET and SyncFET Selection

Current Loop

Voltage Loop

ADC

ADC

Kf

1/Vrms^2

KmABC

Vrms

Gv

Vref

Iref

Iac

IS

Vs

Vo

ZCD

Main FET

SyncFET

Programmable NCD Ref

EADC + CLA + DPWM

UDC3138 Digital Controller

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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 $dV/dt = 79$ V/nS
- $C_{oss}$ is linearly charged up to $V_O$ at turn-off
- About 18 V ringing when freewheel diode conducts
Test Results – GaN FET Forward Voltage Drop in Diode Mode

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
• $\frac{dI}{dt}$ 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

- Rectifier FETs
- Active GaN FETs
- Integrator Running
- Integrator Stall
- Integrator Running
- Soft Turning On
- Turn-on Delay
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

Partial ZVS at low line input and light loads
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
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