SMALLER-FASTER-LOWER COST

Magnetic Materials for Today’s High-Power Fast-Paced Designs

Donna Kepcia
Technical Sales Manager
Magnetics
DISCUSSION OVERVIEW

- Semiconductor Materials, SiC, Silicon Carbide & GaN, Gallium Nitride -- higher frequency switching
- Available Magnetic Materials
  Ferrite -- Powder Cores—Strip Wound Products
- Usable Flux Density
- Design Trends
  Higher Frequency, Higher Efficiency, Lower Cost, Faster to Market
- 500 Watt Power Factor Correction comparison
- 80 Amp High Current Application comparison
- 0.75 Amp 500 kHz ferrite design
SWITCHING FREQUENCIES INCREASING

New Semiconductor materials
SiC – Silicon Carbide
GaN—Gallium Nitride

ADVANTAGES IN POWER APPLICATIONS

- Higher voltage
- Higher operating temperature & Lower resistance
- Cooling system simpler and smaller
- Higher switching frequency
  - smaller transformers and inductors
  - fewer large capacitors
- Improve the power density and efficiency of the power supply
AVAILABLE MAGNETIC MATERIALS

- **Ferrite**
  - Manganese Zinc
  - Nickel Zinc

- **Powder Cores**
  - MPP 80% Nickel Iron
  - High Flux 50% Nickel Iron
  - Kool Mu® & Kool Mu® MAX
  - Iron Silicon Aluminum
  - XFLUX® Iron Silicon
  - Iron Powder
  - Amorphous powder

- **Strip Wound Cores**
  - Toroids & Cut cores
  - Nickel-Iron alloys
  - Cobalt-Iron alloys
  - Amorphous alloys
  - Nanocrystalline alloys

FREQUENCY RANGE OF MAGNETIC MATERIALS
**Ampere’s Law**

\[ H = \frac{4\pi NI}{le} \]

**Faraday’s Law**

\[ V = 4.44B A_c N f \times 10^{-8} \]

**ALL MATERIALS ARE GOVERNED BY THE SAME RELATIONS**

**Usable Flux Density vs Frequency for Core Materials**

![Graph showing usable flux density vs frequency for different core materials.](image)
# Inductor Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Alloy</th>
<th>Core loss 60 perm 100 kHz, 100 mT mW/cm³</th>
<th>Core loss 60 perm 200 kHz, 70 mT mW/cm³</th>
<th>DC Bias 60 perm 50% A-T/cm typ.</th>
<th>Cost 1” toroid powder gapped PQ</th>
<th>Saturation Flux Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPP</td>
<td>Fe Ni Mo</td>
<td>450</td>
<td>480</td>
<td>84</td>
<td>€3.420</td>
<td>0.75 T</td>
</tr>
<tr>
<td>Blends</td>
<td>Custom</td>
<td>450-1500</td>
<td>480-2000</td>
<td>84-139</td>
<td>€0.65-€2.24</td>
<td>0.75 – 1.6T</td>
</tr>
<tr>
<td>Ferrite</td>
<td>Fe O</td>
<td>60</td>
<td>70</td>
<td>30</td>
<td>€0.740</td>
<td>0.45 T</td>
</tr>
<tr>
<td>Kool Mµ Max</td>
<td>Fe Si Al</td>
<td>500</td>
<td>632</td>
<td>107</td>
<td>€1.008</td>
<td>1.0 T</td>
</tr>
<tr>
<td>High Flux</td>
<td>Fe Ni</td>
<td>900</td>
<td>1463</td>
<td>131</td>
<td>€2.240</td>
<td>1.5 T</td>
</tr>
<tr>
<td>XFlux®</td>
<td>Fe Si</td>
<td>2000</td>
<td>2400</td>
<td>139</td>
<td>€0.748</td>
<td>1.6 T</td>
</tr>
<tr>
<td>Kool Mµ®</td>
<td>Fe Si Al</td>
<td>550</td>
<td>689</td>
<td>75</td>
<td>€0.505</td>
<td>1.0T</td>
</tr>
</tbody>
</table>

- **High Flux**
- **XFlux®**
- **Kool Mµ®**
- **MPP**
- **Blends**
- **Ferrite**
Inductor Design Trends

TALL TOROIDS

Eliminate stacking and cementing
Adapt to fit space available
Support more current
**DESIGN BOOST PFC—EFFICIENCY TARGET 98%**

- Examine inductor current
  - At low line voltage
  - At high line voltage
- Determine the AC ripple permitted
- Inductance required to support worst-case V ripple
- Highest current to be supported
- $L I^2$ product---Select core
- Using the core chosen recalculate inductor current
  - At low line voltage
  - At high line voltage
- Combine results to obtain waveform and RMS current
- Choose wire
- Calculate losses - Core losses + copper losses
- Estimate temperature rise
- Calculate and measure efficiency.
- Compare costs
PFC Boost  500 Watt

C058071A2 High Flux  2 Toroids stacked
N=104 turns of two strands AWG#21,  fill factor 33.6%
L=1320 µH at no load
L= 950 µH at rated current (5.68A)
Inductor Max Ripple = 16%
Core losses 100 kHz = 0.99 W
Copper losses = 4.89 W
Total losses = 5.88 W
ΔT estimate ≈ 43°C

Efficiency = Power Out/Power In
500.00/505.88=98.8% efficient
## Inductance comparison—Powder Materials

<table>
<thead>
<tr>
<th></th>
<th>Kool M(\mu)(^\text{®}) Max</th>
<th>XFlux(^\text{®})</th>
<th>Kool M(\mu)(^\text{®}) High Flux</th>
<th>MPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0079071A7</td>
<td>0078071A7</td>
<td>0077071A7</td>
<td>C058071A2</td>
</tr>
<tr>
<td>Measured</td>
<td>Measured</td>
<td>Measured</td>
<td>Measured</td>
<td>Measured</td>
</tr>
<tr>
<td>Inductance, Full load, mH</td>
<td>0.949</td>
<td>0.970</td>
<td>0.998</td>
<td>1.13</td>
</tr>
<tr>
<td>Inductance, No load, mH</td>
<td>1.496</td>
<td>1.558</td>
<td>1.231</td>
<td>2.63</td>
</tr>
<tr>
<td># turns</td>
<td>113</td>
<td>113</td>
<td>103</td>
<td>114</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
I_{\text{avg}} &= 5.68 \text{ A} \\
I_{p,k} &= 6.02 \text{ A} \\
L &= 946 \text{ \(\mu\)H}
\end{align*}
\]
<table>
<thead>
<tr>
<th>Summary</th>
<th>Kool Mu® Max</th>
<th>XFlux®</th>
<th>Kool Mu® High Flux</th>
<th>MPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0079071A7</td>
<td>0078071A7</td>
<td>0077071A7</td>
<td>C058071A2</td>
</tr>
<tr>
<td></td>
<td>0.949</td>
<td>0.970</td>
<td>1.054</td>
<td>0.948</td>
</tr>
<tr>
<td>Core losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core losses</td>
<td>0.70</td>
<td>2.64</td>
<td>0.87</td>
<td>0.99</td>
</tr>
<tr>
<td>Copper losses</td>
<td>5.38</td>
<td>4.84</td>
<td>7.22</td>
<td>4.89</td>
</tr>
<tr>
<td>Total losses Watts</td>
<td>6.08</td>
<td>7.48</td>
<td>8.09</td>
<td>5.88</td>
</tr>
<tr>
<td># turns</td>
<td>113</td>
<td>113</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td>DCR</td>
<td>194.0</td>
<td>165.9</td>
<td>183.1</td>
<td>149.1</td>
</tr>
<tr>
<td>Temperature rise</td>
<td>43.3</td>
<td>52.4</td>
<td>44.4</td>
<td>42.8</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>68.3</td>
<td>77.2</td>
<td>73.6</td>
<td>67.8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>98.7</td>
<td>98.5</td>
<td>98.4</td>
<td>98.8</td>
</tr>
<tr>
<td>Core Cost</td>
<td>2 cores</td>
<td>€2.72</td>
<td>2 cores</td>
<td>€1.62</td>
</tr>
<tr>
<td>Estimated Wire Cost</td>
<td>€1.34</td>
<td>€0.91</td>
<td>€1.36</td>
<td>€0.92</td>
</tr>
<tr>
<td>Core &amp; Wire cost</td>
<td>€4.06</td>
<td>€2.53</td>
<td>€2.47</td>
<td>€6.34</td>
</tr>
</tbody>
</table>
Core Losses Measured at 50 kHz, 100 kHz 200 kHz
\[ I_{\text{avg}} = I_{\text{out}} \left( \frac{1}{1 - D} \right) \]

**INDUCTOR CURRENT**

At Low Line Voltage

\[ I_{\text{avg}} = 1.25 \left( \frac{1}{1 - 0.78} \right) = 5.68 \text{Amps} \]

At High Line Voltage

\[ I_{\text{avg}} = 1.25 \left( \frac{1}{1 - 0.34} \right) = 1.89 \text{Amps} \]

**PFC Boost 500 Watt**

At 200 KHz the duty cycle Changes to be 5 \( \mu \text{sec} \)

\[ t_{\text{on}} + t_{\text{off}} = 5.0 \mu \text{sec} \]

Duty Cycle \( (D) = \frac{t_{\text{on}}}{5.0 \mu \text{sec}} \)
WORST CASE RIPPLE OCCURS AT HIGH LINE VOLTAGE

\[ \Delta I = 1.89 \times (25\%) \times (2) \]
\[ \Delta I = 0.945 \text{ A} \]
\[ I_{pk} = 2.36 \text{ A} \]
\[ L = 473 \mu\text{H} \]

Now \( L \) = half of the original inductance required
C058930A2 High Flux 2 Toroids stacked

N= 50 turns of 2 strands AWG#21, giving a fill factor of 31%

L=785 µH at no load
L=494 µH at rated current (5.68A)

Inductor Max Ripple = 16%

Core losses 200 kHz = 2.93 W
Copper losses = 2.0 W
Total losses =4.93 W

ΔT estimate ≈46°C

Efficiency = Power Out/Power In
500.00/505.25=99% efficient
## Design Comparison

<table>
<thead>
<tr>
<th></th>
<th>C058071A2 100 kHz</th>
<th>C058930A2 200 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inductance @ 5.68 A</strong></td>
<td>949 μH</td>
<td>494 μH</td>
</tr>
<tr>
<td><strong>Delta B/2</strong></td>
<td>0.0305 T</td>
<td>0.0357 T</td>
</tr>
<tr>
<td><strong>Turns</strong></td>
<td>104</td>
<td>50</td>
</tr>
<tr>
<td><strong>Wires</strong></td>
<td>21 AWG x 2</td>
<td>25 AWG x 6</td>
</tr>
<tr>
<td><strong>Core loss</strong></td>
<td>2.46 W</td>
<td>2.93 W</td>
</tr>
<tr>
<td><strong>Copper loss</strong></td>
<td>6.95 W</td>
<td>2.57 W</td>
</tr>
<tr>
<td><strong>Package size</strong></td>
<td>41 x 30 mm</td>
<td>33 x 29 mm</td>
</tr>
<tr>
<td><strong>Temp Rise</strong></td>
<td>44°C</td>
<td>46°C</td>
</tr>
</tbody>
</table>

### Estimate Cost

<table>
<thead>
<tr>
<th></th>
<th>Cores</th>
<th>Wire</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cores</td>
<td>€5.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire</td>
<td>€0.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>€6.34</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Cores</th>
<th>Wire</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cores</td>
<td>€3.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire</td>
<td>€0.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>€3.85</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### High Current Output Inductor Design Comparison

<table>
<thead>
<tr>
<th>Output Inductor</th>
<th>20 kHz Si</th>
<th>50 kHz SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>50 μH</td>
<td>20 μH</td>
</tr>
<tr>
<td>Frequency</td>
<td>20 kHz</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Rated current</td>
<td>80 A</td>
<td>80 A</td>
</tr>
<tr>
<td>Ripple current p-p</td>
<td>20 A</td>
<td>20 A</td>
</tr>
</tbody>
</table>
Software Inductor Design Tool

Step 1: Design Input
- Material Selection: XFlux
- DC Current: 80 Amps
- Peak to Peak Ripple: 20 Amps
- Frequency: 20 KHz
- Full Load (L): 0.0533 mH
- Specified Current: 90 Amps
- Temp Rise: 100 °C
- Stack Cores: 3

Step 2: Enter Selected Part Number
- Part Number: 78907

Design Output
- Inductance @ Full Load min: 0.052 mH
- Inductance @ No load nom: 0.074 mH
- Specified Current: 0.06 mH
- Core Loss: 8.42 W
- Copper Loss: 17.43 W
- Total Loss: 25.86 W
- Temperature Rise: 40.1 °C
- Number of Turns: 17
- Wire Size: 14 AWG
- Winding Factor: 17.3%
- DC Resistance: 2.69 mΩ
- Finished OD: 89.6 mm
- Finished HT: 62.0 mm
- Total Wire Length: 2596.8 mm

Adjust
- Adjust TURNS: 17
- Adjust AWG: 14
- Adjust Strand: 8
<table>
<thead>
<tr>
<th></th>
<th>20 kHz Si</th>
<th>50 kHz SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance @ peak 90 Amps</td>
<td>53.3 µH</td>
<td>21.5 µH</td>
</tr>
<tr>
<td>Cores</td>
<td>0078907A7 x 3</td>
<td>0077192A7 x 3</td>
</tr>
<tr>
<td>Turns</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>Wires</td>
<td>14 AWG x 8 strands</td>
<td>17 AWG x 16 strands</td>
</tr>
<tr>
<td>Core loss</td>
<td>8.42 W</td>
<td>4.07 W</td>
</tr>
<tr>
<td>Copper loss</td>
<td>17.4 W</td>
<td>11.0 W</td>
</tr>
<tr>
<td>Package size</td>
<td>90 x 62 mm</td>
<td>69 x 60 mm</td>
</tr>
<tr>
<td>Temp Rise</td>
<td>40°C</td>
<td>37°C</td>
</tr>
<tr>
<td>Estimate Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cores</td>
<td>€12.19</td>
<td>€4.39</td>
</tr>
<tr>
<td>Wire</td>
<td>€6.29</td>
<td>€4.11</td>
</tr>
<tr>
<td>Total</td>
<td>€18.48</td>
<td>€8.50</td>
</tr>
</tbody>
</table>
INTRODUCING KOOL Μµ MAX®

- Kool Μµ MAX is a superior version of Kool Μµ!
- Improved DC Bias performance and lower losses at a reduced price compared with MPP and High Flux.

<table>
<thead>
<tr>
<th>General Information</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>26µ, 40µ, 60µ</td>
</tr>
<tr>
<td>Alloy Composition</td>
<td>Fe/Si/Al</td>
</tr>
<tr>
<td>Saturation Flux Density</td>
<td>1 Tesla</td>
</tr>
<tr>
<td>Curie Temperature</td>
<td>500°C</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-55 to 200°C</td>
</tr>
<tr>
<td>OD Size Range (mm)</td>
<td>13.5 - 134</td>
</tr>
<tr>
<td>Coating Color</td>
<td>Black</td>
</tr>
</tbody>
</table>
### KOOL Mµ MAX

<table>
<thead>
<tr>
<th>60 Perm Material</th>
<th>DC Bias at x Ls (A-T/cm)</th>
<th>Core Loss (mW/cm³)</th>
<th>Cost Ratio</th>
<th>Price Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80%</td>
<td>50%</td>
<td>W&lt;sub&gt;1000 G, 50 kHz&lt;/sub&gt;</td>
<td>W&lt;sub&gt;1000 G, 100 kHz&lt;/sub&gt;</td>
</tr>
<tr>
<td>Kool Mµ® MAX</td>
<td>54</td>
<td>107</td>
<td>190</td>
<td>500</td>
</tr>
<tr>
<td>Kool Mµ®</td>
<td>34</td>
<td>75</td>
<td>212</td>
<td>550</td>
</tr>
<tr>
<td>75-Series</td>
<td>56</td>
<td>119</td>
<td>570</td>
<td>1515</td>
</tr>
<tr>
<td>XFlux®</td>
<td>70</td>
<td>139</td>
<td>680</td>
<td>1550</td>
</tr>
<tr>
<td>High Flux</td>
<td>69</td>
<td>131</td>
<td>353</td>
<td>900</td>
</tr>
<tr>
<td>MPP</td>
<td>48</td>
<td>84</td>
<td>174</td>
<td>450</td>
</tr>
</tbody>
</table>
Kool μ MAX vs. Kool μ - DC Bias
Kool Mu Max vs. Kool Mu - Core Loss
<table>
<thead>
<tr>
<th>Summary</th>
<th>Kool Mu® Max</th>
<th>XFlux ®</th>
<th>Kool Mu® High Flux</th>
<th>MPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0079071A7</td>
<td>0078071A7</td>
<td>0077071A7</td>
<td>C058071A2</td>
</tr>
<tr>
<td></td>
<td>C055071A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.949</td>
<td>0.970</td>
<td>1.054</td>
<td>0.948</td>
</tr>
<tr>
<td>Core losses</td>
<td>0.70</td>
<td>2.64</td>
<td>0.87</td>
<td>0.99</td>
</tr>
<tr>
<td>Copper losses</td>
<td>5.38</td>
<td>4.84</td>
<td>7.22</td>
<td>4.89</td>
</tr>
<tr>
<td>Total losses Watts</td>
<td>6.08</td>
<td>7.48</td>
<td>8.09</td>
<td>5.88</td>
</tr>
<tr>
<td># turns</td>
<td>113</td>
<td>113</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td>DCR</td>
<td>194.0</td>
<td>165.9</td>
<td>183.1</td>
<td>149.1</td>
</tr>
<tr>
<td>Temperature rise</td>
<td>43.3</td>
<td>52.4</td>
<td>44.4</td>
<td>42.8</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>68.3</td>
<td>77.2</td>
<td>73.6</td>
<td>67.8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>98.7</td>
<td>98.5</td>
<td>98.4</td>
<td>98.8</td>
</tr>
<tr>
<td>Core Cost</td>
<td>2 cores: €2.72</td>
<td>2 cores: €1.62</td>
<td>3 cores: €1.11</td>
<td>2 cores: €5.42</td>
</tr>
<tr>
<td>Estimated Wire Cost</td>
<td>€1.34</td>
<td>€0.91</td>
<td>€1.36</td>
<td>€.92</td>
</tr>
<tr>
<td>Core &amp; Wire cost</td>
<td>€4.06</td>
<td>€2.53</td>
<td>€2.47</td>
<td>€6.34</td>
</tr>
</tbody>
</table>
### 60 perm MPP

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Flux Density in Tesla/ Gauss</th>
<th>Core loss mW/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 kHz</td>
<td>0.010 T / 100 G</td>
<td>42.6</td>
</tr>
<tr>
<td>500 kHz</td>
<td>0.025 T / 250 G</td>
<td>276.4</td>
</tr>
<tr>
<td>500 kHz</td>
<td>0.030 T / 300 G</td>
<td>400.8</td>
</tr>
<tr>
<td>1 MHz</td>
<td>0.001 / 10 G</td>
<td>1.02</td>
</tr>
<tr>
<td>1 MHz</td>
<td>0.010 / 100 G</td>
<td>111.6</td>
</tr>
<tr>
<td>1 MHz</td>
<td>0.020 / 200 G</td>
<td>458.9</td>
</tr>
</tbody>
</table>

60 perm **Kool Mµ® Max**

MPP 60 perm flat to 1 MHz - 5% at 4 MHz
Transformer Core Materials Utility Performance Factor vs. Frequency (at 100 mW/cm³ max.)

MATERIALS FOR TRANSFORMERS

- Power Ferrites
- Manganese-Zinc Ferrites
- Nickel-Zinc Ferrites
- Nanocrystalline and Amorphous strip materials
Magnetics ferrites R, P, T, F and L materials provide superior saturation, high temperature performance, low losses and product consistency.

**T material -- 3000 perm** is our power material for consistent performance over a wide temperature range.

**L material -- 900 perm** is our new power material for high frequency and high-temperature applications.

**R material -- 2300 perm** provides the best core losses for frequencies up to 500 kHz.

**P material -- 2500 perm** offers similar properties to R material, but is more readily available in some sizes.

**F material -- 3000 perm** is an established material with a relatively high permeability and 210 degree C Curie temperature.

Power Supplies, DC-DC Converters, Handheld Devices, High Power Control (gate drive) and EMI Filters are just a few of the applications that are typical for Magnetics ferrite power materials.
At 100 KHz
assume $B = 1000$ Gauss
as frequency increases decrease $B$ accordingly
At 500 kHz
$B = 250$ Gauss

P Material 2500 Perm
GaN HIGH FREQUENCY LOWER CURRENT

Inductance
- Si: 500 uH
- GaN: 100 uH

Frequency
- Si: 100 kHz
- GaN: 500 kHz

Rated current
- Si: 0.75 A
- GaN: 0.75 A

Ripple current p-p
- Si: 0.1 A
- GaN: 0.1 A
<table>
<thead>
<tr>
<th></th>
<th>Si ER Core</th>
<th>GaN EFD Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance @ peak</td>
<td>503 uH 100 kHz</td>
<td>100 uH 500 kHz</td>
</tr>
<tr>
<td>0.8 A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cores</td>
<td>0P41826A260</td>
<td>0L41212A160</td>
</tr>
<tr>
<td>Turns</td>
<td>44</td>
<td>25</td>
</tr>
<tr>
<td>Wires</td>
<td>26 AWG</td>
<td>26 AWG</td>
</tr>
<tr>
<td>Copper loss</td>
<td>0.11 W</td>
<td>0.03 W</td>
</tr>
<tr>
<td>Package size</td>
<td>18 x 6.6 x 9.7 mm</td>
<td>12.5 x 12.4 x 3.5 mm</td>
</tr>
<tr>
<td>Temp Rise</td>
<td>40°C</td>
<td>12°C</td>
</tr>
<tr>
<td>Estimate Cost</td>
<td>€0.31</td>
<td>€0.23</td>
</tr>
</tbody>
</table>
Thank you !!!

• Questions???
• Comments
• Suggestions
• PPAP Production Part
  • High Temperature Exposure
    Temperature: 150±3℃
    Duration: 1000±12-0 hours
    Recovery: 24±2HR
  • Moisture Resistance
    Apply the 24hrs heat (25 to 65℃) and humidity (80 to 98%)
    10 consecutive times
    Recovery: 24±2HR
  • Biased Humidity
    Temperature: 85±2℃ Humidity: 85%
    Applied voltage: 100VDC Duration: 1000 hours
    Recovery: 24±2HR
  • Operational Life
    Temperature: 125±3℃ Applied voltage: 200VDC
    Duration: 1000±12-0 hours (*1)
    Recovery: 24±2HR
  • Solvent Resistance
    Isopropyl alcohol and three other solvents
  • Shock
    100g, 6msec, Half-sine wave
  • Vibration
    Frequency: 10~2000Hz, Amplitude: 1.5mm
    Duration: 24 hours
PFC BOOST WITH TALL TOROIDS
PHEV—PFC

- 3.3 kWatt  70 kHz  15 A  2 A p-p Ripple  400 μH
- Suggested cores:

<table>
<thead>
<tr>
<th>Part number</th>
<th>Perm</th>
<th>Finished OD</th>
<th>Finished HT</th>
<th>Temp Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>0077111A7HT30</td>
<td>26</td>
<td>72.5 mm</td>
<td>44.2 mm</td>
<td>57 °C</td>
</tr>
<tr>
<td>0077192A7HT32</td>
<td>60</td>
<td>67.5 mm</td>
<td>41.9 mm</td>
<td>58 °C</td>
</tr>
<tr>
<td>0077189A7HT32</td>
<td>40</td>
<td>72.3 mm</td>
<td>46.6 mm</td>
<td>45 °C</td>
</tr>
<tr>
<td>0078439A7HT38</td>
<td>60</td>
<td>57.1 mm</td>
<td>47.5 mm</td>
<td>58 °C</td>
</tr>
</tbody>
</table>
EMI FILTERING
DIFFERENTIAL MODE CHOKE
PLANAR POWDER CORES U CORES

Custom sizes available
Coated for direct application to bus bar

<table>
<thead>
<tr>
<th>PART NO</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D(min)</th>
<th>E(min)</th>
<th>L(nom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OOK3112U***</td>
<td>mm</td>
<td>31.24±0.51</td>
<td>11.2±0.26</td>
<td>12.1±0.39</td>
<td>2.54</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>1.230±0.020</td>
<td>0.440±0.010</td>
<td>0.475±0.015</td>
<td>0.100</td>
<td>0.560</td>
</tr>
<tr>
<td>OOK4110U***</td>
<td>mm</td>
<td>40.64±0.51</td>
<td>11.2±0.51</td>
<td>9.53±0.39</td>
<td>2.54</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>1.600±0.020</td>
<td>0.440±0.020</td>
<td>0.375±0.015</td>
<td>0.100</td>
<td>0.930</td>
</tr>
<tr>
<td>OOK4111U***</td>
<td>mm</td>
<td>40.64±0.51</td>
<td>11.2±0.26</td>
<td>12.1±0.39</td>
<td>2.54</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>1.600±0.020</td>
<td>0.440±0.010</td>
<td>0.475±0.015</td>
<td>0.100</td>
<td>0.930</td>
</tr>
<tr>
<td>OOK4119U***</td>
<td>mm</td>
<td>40.64±0.51</td>
<td>11.2±0.26</td>
<td>19.1±0.39</td>
<td>2.54</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>1.600±0.020</td>
<td>0.440±0.010</td>
<td>0.750±0.015</td>
<td>0.100</td>
<td>0.930</td>
</tr>
</tbody>
</table>
Differential Mode Choke for Busbar Applications
Planar Powder U-Cores

Testing at 10 kHz.

<table>
<thead>
<tr>
<th>Copper Bus Bar Dimensions</th>
<th>No-load Inductance</th>
<th>Calculated Busbar</th>
<th>Measured on Busbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Width</td>
<td>Height</td>
<td></td>
</tr>
<tr>
<td>100.55 mm</td>
<td>12.8 mm</td>
<td>1.58 mm</td>
<td>0.064 μH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Core Set</th>
<th>Dimensions</th>
<th>L X W X H</th>
<th>Inductance/A&lt;sub&gt;l&lt;/sub&gt;</th>
<th>With Busbar</th>
<th>Core contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>00K3112U090</td>
<td>31.24 mm</td>
<td>12.1 mm</td>
<td>22.4 mm</td>
<td>179 +/- 8%</td>
<td>0.274 μH</td>
</tr>
<tr>
<td>00K3112U090 coated 0.0015&quot;, 0.381 mm.</td>
<td></td>
<td></td>
<td></td>
<td>0.122 μH</td>
<td>0.028 μH</td>
</tr>
<tr>
<td>00K3112U060</td>
<td>31.24 mm</td>
<td>12.1 mm</td>
<td>22.4 mm</td>
<td>111 +/- 8%</td>
<td>0.199 μH</td>
</tr>
<tr>
<td>00K3112U060 coated 0.0015&quot;, 0.381 mm.</td>
<td></td>
<td></td>
<td></td>
<td>0.110 μH</td>
<td>0.016 μH</td>
</tr>
<tr>
<td>00K4110U090</td>
<td>40.64 mm</td>
<td>9.53 mm</td>
<td>22.4 mm</td>
<td>109 +/- 8%</td>
<td>0.208 μH</td>
</tr>
<tr>
<td>00K4110U090 coated 0.0015&quot;, 0.381 mm.</td>
<td></td>
<td></td>
<td></td>
<td>0.131 μH</td>
<td>0.037 μH</td>
</tr>
<tr>
<td>00K4111U090</td>
<td>40.64 mm</td>
<td>9.53 mm</td>
<td>24.2 mm</td>
<td>138 +/- 8%</td>
<td>0.237 μH</td>
</tr>
<tr>
<td>00K4111U090 coated 0.0015&quot;, 0.381 mm.</td>
<td></td>
<td></td>
<td></td>
<td>0.143 μH</td>
<td>0.049 μH</td>
</tr>
<tr>
<td>00K4119U090</td>
<td>40.64 mm</td>
<td>9.53 mm</td>
<td>38.2 mm</td>
<td>218 +/- 8%</td>
<td>0.288 μH</td>
</tr>
<tr>
<td>00K4119U090 coated 0.0015&quot;, 0.381 mm.</td>
<td></td>
<td></td>
<td></td>
<td>0.165 μH</td>
<td>0.071 μH</td>
</tr>
</tbody>
</table>

Multiple coated cores on one Busbar

<table>
<thead>
<tr>
<th>Expected sum</th>
<th>Actual sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>00K4119U090</td>
<td>0.214 μH</td>
</tr>
<tr>
<td>00K4119U090+00K4111U090+00K4110U090</td>
<td>0.251 μH</td>
</tr>
</tbody>
</table>

Conclusion: Multiple cores on the Busbar impacts the leakage flux and the self-inductance of the busbar slightly.
BUS BAR INDUCTANCE

Busbar Inductance Calculator

<table>
<thead>
<tr>
<th>Self Inductance of Rectangular Copper Conductor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Length (cm)</td>
<td>14       cm</td>
</tr>
<tr>
<td>Conductor Width (cm)</td>
<td>1.15     cm</td>
</tr>
<tr>
<td>Conductor Thickness (cm)</td>
<td>0.12     cm</td>
</tr>
<tr>
<td>Inductance of Rectangular Copper Conductor</td>
<td>0.101    µH</td>
</tr>
</tbody>
</table>

Busbar 12 V
Length 10 cm width 1.4 cm height 1.58 cm
Self inductance
0.062 uH calc.

Busbar 48 V
Length 15 cm width 1.4 cm height 1.58 cm
0.092 uH calc.
**BLENDS**

**COMBINE**

**MATERIAL CHARACTERISTICS**

Blend materials to increase DC Bias and/or reduce losses

Blend Perms to have lower perm material under the windings
Core Watt Loss Testing

- Watt Meters
- Power Analyzers
- BH Loop Tracers
- Q Meters
- LCR Meters
- IEEE 393
Thank you !!!

• Questions???
• Comments
• Suggestions
EQUATIONS AND CALCULATIONS FOR 500 WATT POWER FACTOR CORRECTION DESIGN
Power Factor Correction

- **PFC Boost**
  - 500 Watt
  - 88–264 Volts DC in
  - 400 Volts DC out
  - 100 kHz

\[ V_d = 1V \]

\[ V_{in} = 88V_{DC Min} \]
\[ V_{in} = 264V_{DC Max} \]

\[ V_o = 400V_{DC} \]

Typical Boost Circuit Schematic

Input voltage varies 88 \( V_{DC} \)–264 \( V_{DC} \)
Design Boost PFC—Efficiency target 98%

- Examine inductor current
  - At low line voltage
  - At high line voltage
- Determine the AC ripple permitted
- Inductance required to support worst-case V ripple
- Highest current to be supported
- $L I^2$ product—Select core
- Using the core chosen recalculate inductor current
  - At low line voltage
  - At high line voltage
- Combine results to obtain waveform and RMS current
- Choose wire
- Calculate losses – Core losses + copper losses
- Estimate temperature rise
- Calculate and measure efficiency.
- Compare costs
Design inputs

Active High Frequency PFC
Continuous Conduction Mode

Power = 500 Watts  Frequency = 100 kHz

\[ T = \frac{1}{f} = 10.0 \mu \text{sec.} \]

\[ I_{out} = \frac{500 \text{Watts}}{400 \text{Volts}} = 1.25 \text{Amps} \]

\[ D_{\text{max}} = 1 - \frac{88V_{\text{in min}}}{400V_{out}} = 0.78 \]
\[ D_{\text{min}} = 1 - \frac{264V_{\text{in max}}}{400V_{out}} = 0.34 \]

\( D = \text{Duty cycle} \)
Inductor Current

\[ I_{avg} = I_{out} \left( \frac{1}{1 - D} \right) \]

At Low Line Voltage

\[ I_{avg} = 1.25 \left( \frac{1}{1 - 0.78} \right) = 5.68 \text{ Amps} \]

At High Line Voltage

\[ I_{avg} = 1.25 \left( \frac{1}{1 - 0.34} \right) = 1.89 \text{ Amps} \]

At High Line Voltage

\[ t_{on} + t_{off} = 10.0 \mu \text{ seconds} \]

\[ \text{Duty Cycle}(D) = \frac{t_{on}}{10.0 \mu \text{ sec}} \]
Ripple

- Max Current Ripple = 25% for this design based upon the customer’s requirement. This is arbitrary. The inductance and loss calculations depend on this value. Actual result will be more robust because the worst case inductance and ripple do not occur together. Design can be iterated to improve ripple or improve cost/space. Typical ripple for CCM 10–35%.
- Typical ripple for CrM, DCM, and FCCrM is 5–15%.
Worst case ripple occurs at high line voltage

\[ \Delta I = 1.89(25\%) (2) \]
\[ \Delta I = 0.945 \text{ A} \]

\[ I_{pk} = 2.36 \text{ A} \]

\[ L = \frac{V \text{ across inductor}}{\Delta I} (D_{min})(t) \]

\[ L = \frac{264 - 1}{0.945}(0.34)(10.0) \]

\[ L = 946 \mu \text{H} \]
Worst case $I_{pk}$ occurs at low line voltage

$I_{pk} = 6.04 \text{ A}$

$I_{avg} = 5.68 \text{ A}$

$I_{min} = 5.32 \text{ A}$

$\Delta I = \frac{88 - 1}{946} (0.78)(10.0)$

$\Delta I = 0.717 \text{ A}$

$I_{pk} = 5.68 + \frac{0.717}{2} = 6.04 \text{ A}$

$L = 946 \mu\text{H}$
Core Selection Process

\[ LI^2 = (0.946)(6.04^2) = 34.5 \]

The customer has a width restriction of 1.65” wound. We choose 0079071 because the OD is 1.325”, we will stack two.

Kool Mu Max P/N 0079071A7

\[ A_e(2\text{cores}) = 1.312 \text{ cm}^2 \]

\[ l_e = 8.14 \text{ cm} \]

\[ \mu = 60 \]

\[ V_e = 10.7 \text{ cm}^3 \]

\[ A_L(2\text{cores}) = 122 \]

\[ MLT = 4.72 \text{ cm (37\% full)} \]
Determine # of Turns

\[ N = \sqrt{\frac{0.946 \times 10^6}{122}} = 88 \text{ turns} \]

\[ H = \frac{NI}{le} = \frac{88 \times 6.04A}{8.14 \text{ cm}} \Rightarrow H = 65 \frac{AT}{cm} \Rightarrow 27\% \text{ rolloff from curve} \]

Boost turns to achieve required inductance \( \frac{88}{0.73} = 120 \) turns

\[ H = \frac{NI}{le} = \frac{120 \times 6.04A}{8.14 \text{ cm}} \Rightarrow H = 89 \frac{AT}{cm} \Rightarrow 41\% \text{ rolloff from curve} \]

\[ L \text{ full load} = (0.59)(120^2)(122)(10^{-6}) = 1036 \, \mu H \]

\[ L \text{ full load} = (0.62)(113^2)(122)(10^{-6}) = 966 \, \mu H \]

Back off turns \( N = 113 \)

\[ H = 84 \frac{AT}{cm} \]

\[ L \text{ at no load} = 1557 \, \mu H \]
\[ \mu_{\text{eff}} = 62\% \text{ of initial perm} \]
Recalculate Inductor Current

**High Line Voltage**

Initial $I_{pk} = 2.36A \Rightarrow H = \frac{(113)(2.36A)}{8.14 \text{ cm}} = 32.8 \text{AT/cm} \Rightarrow 6\% \text{ rolloff}$

$L = 0.94(113^2)(122)(10^{-3}) = 1464 \mu H$

$\Delta I = \frac{264 - 1}{1464}(0.34)(10.0) = 0.611A$
Recalculated peak current—High Line Voltage

\[ I = 1.89 \pm \frac{0.611}{2} \ A \]

\[ I_{pk} = 2.19 \ A \Rightarrow 30.4 \ \frac{AT}{cm} \Rightarrow 6\% \text{ rolloff} \]
Recalculate Inductor Current

**Low Line Voltage**

Initial \( I_{pk} = 6.04A \) ⇒ \( H = \frac{113 \times 6.04A}{8.14\ cm} = \frac{84AT}{\ cm} \) ⇒ 37% rolloff

\[
L = 0.63 \times (113^2) \times (122) \times (10^{-3}) = 981\ \mu H
\]

\[
\Delta I = \frac{88 - 1}{981} \times (0.78) \times (10.0) = 0.692A
\]

\[
I_{pk} = 5.68A + \frac{0.692}{2} = 6.02\ A
\]
Recalculated Peak Current—Low Line Voltage

Iterate:

\[ \Delta I = \frac{88 - 1}{981} (0.78)(10.0) = 0.692 A \]

\[ I_{pk} = 6.02 \, A \quad L = 981 \, \mu H \]
\[ I_{pk} = 6.02\,A \]
\[ I_{min} = 1.59\,A \]

\[ I_{RMS} = 1.89 + \frac{1}{\sqrt{2}} (5.68 - 1.89) = 4.57\,A \]
Wire

For 4.57 A current use 2 strands of AWG #21 Wire

\[ R = \frac{41.9}{2} = 20.9 \text{ mΩ/m} \quad W_a \text{ 2 strands} = 0.00968 \text{ cm}^2 \]

\[ A_w = 2.97 \text{ cm}^2 \]

Fill Factor is

\[
\frac{NW_a}{A_w} = \frac{113(0.00968)}{2.97} = 36.8\%
\]

For 2 strands in parallel AWG #21 Wire

\[ R_T = 165.86 \text{ mΩ/m} \quad W_a = 0.00968 \text{ cm}^2 \quad \text{Fill} = 36.8\% \]
Flux Density Calculations

At Low Line Voltage

\[ I_{pk} = 6.02A \Rightarrow H_{pk} = 84\text{AT/cm} \]

\[ I_{min} = 5.34A \Rightarrow H_{min} = 74\text{AT/cm} \]

\[ B_{pk} = 0.056 \text{ Tesla} \quad B_{min} = 0.052 \text{ Tesla} \]

\[ \frac{1}{2} \Delta B = 0.02 \text{ Tesla} \]
Flux Density Calculations

At High Line Voltage

\[ I_{pk} = 2.19A \quad H_{pk} = 30.4\, \text{AT/cm} \]

\[ I_{\text{min}} = 1.59A \quad H_{\text{min}} = 22.0\, \text{AT/cm} \]

\[ B_{pk} = 0.23\, \text{Tesla} \quad B_{\text{min}} = 0.16\, \text{Tesla} \]

\[ \frac{1}{2} \Delta B = 0.035\, \text{Tesla} \]
Core Losses

\[ P = 91.616B^{2.039} f^{1.388} \text{ for } 60\mu \text{ KoolMuMAX} \]

\[ P = 91.616(0.020)^{2.039}(100)^{1.388} = 19 \text{ mW/cm}^3 \text{ High Line} \]

\[ P = 91.616(0.035)^{2.039}(100)^{1.388} = 59 \text{ mW/cm}^3 \text{ Low Line} \]

\[ V_e = 10.68 \text{ cm}^3 \]

\[ \text{Power Loss} = \left( \frac{\text{mW/cm}^3}{\text{cm}^3} \right) \]

Core losses are 203 – 630 mW
Copper Losses

For #21 Wire, 2 strands

\[ R_{\text{coil}} = MLT(N)(R/\text{length}) \]

\[ R_{\text{coil}} = (70 \text{ mm/turn})(113T)(2.094 \times 10^{-5} \Omega/\text{mm}) \]

\[ R_{\text{coil}} = 165.8 \text{ m}\Omega \]

\[ \text{Power Loss}_{\text{Copper}} = (I)^2(R) \]

\[ P_{\text{cu}} = (4.57)^2(0.166) = 3467 \text{ mW} \]
Total Losses and Estimated Temperature Rise

Total losses \(203 - 630 + 3467 = 4097\) mWatts

Temperature rise with no active air flow

Wound inductor surface area \(S\)

\[
OD = 3.383\; cm\; \text{max},\; Hgt = 2.31\; cm\; \text{max}
\]

\[
S = 2 \times \left[ \pi(3.383\;cm)(2.31\;cm) + 2 \left( \pi \left( \frac{2.31}{2} \right)^2 \right) \right] = 65.86\;cm^2
\]

\[
\Delta T \approx \left[ \frac{mW}{S} \right]^{0.833} = \left[ \frac{4097}{65.86} \right]^{0.833} = 31.2^{\circ}C
\]

With airflow, \(\Delta T\) would improve
Summary
0079071A7 Kool Mu MAX 2 Toroids stacked
N=113 turns of two strands AWG#21, giving a fill factor of 36.8%
L=1557µH at no load
L=981µH at peak (6.02A)
Inductor Max Ripple = 16%
Core losses = 203–630 mW
Copper losses = 3,467 mW
Total losses = 4,097 mW
ΔT estimate ≈ 31.2°C
Efficiency = Power Out/Power In
500.00/504.097=99% efficient
Donna Kepcia
dkepcia@spang.com
Technical Sales Manager
Magnetics
110 Delta Drive
Pittsburgh, PA 15238
USA
(412) 963-5627 Work
(412) 228-8196 Cell