Gapped ferrite toroids for power inductors
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Introduction

Toroids are well known for their magnetic properties. They achieve the highest inductance per unit of volume due to the uniform cross-section and a fluent magnetic path without corners. The latter means that not only the cross-section, but also the flux density is uniform, which is especially important to fully exploit the material saturation level. Also stray flux is very low for a toroid.

FERROXCUBE has introduced a range of gapped ferrite toroids, intended primarily for power inductor applications. They are made from toroids in the high flux, frequency stable material 3C20 by precision machining a small gap. Finally, the core is completely coated with nylon and ready for winding as if it were ungapped.

The gap helps to avoid saturation in applications where there is a large current. This can be either a DC bias current or an AC current swing. For every size of toroid there is a range of gaps, providing a range of $A_L$ values to fit the required inductance value. The high flux, frequency stable material 3C20 has very low power losses, outperforming in this respect iron powder and all metal alloy powders. Even if a slightly larger core is required, ferrite could beat certain metal alloys on price.

Features

- Simple economic shape
- Available in high flux, frequency stable material 3C20
- Range of toroid sizes and $A_L$ values
- Compact and robust product

Applications

These products will mainly be found as power inductors. These carry larger currents and a gap is required to avoid saturation. There are many types of power inductors, in accordance with many types of power converters:
- Output filter inductor in forward or push-pull converter (DC bias)
- Resonant inductor in half or full bridge converter (AC swing)
- Buck or boost inductor in DC voltage converter (DC bias)
- Power factor correction choke (AC bias)
- Differential filter inductor (DC or AC bias)

A possible application is also a fly-back transformer. This is a transformer with such gap that the stray inductance can be used as output filter inductor. For practical reasons, it is often difficult however to realize with a toroid. There can be more than one output winding and the electrical isolation between primary and secondary side must guarantee a distance of separation.

Type number structure

Gapped toroids can be named quite easily. The general type number structure is explained in figure 1 below.

The inner diameter is determined by the outer diameter, because only standard toroid sizes are used that already exist without gap. In such a way, all too long type numbers are avoided when the toroid is gapped.

![Fig. 1 : Type number structure](image)

<table>
<thead>
<tr>
<th>core type</th>
<th>coating type</th>
</tr>
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<tbody>
<tr>
<td>core size D / H (uncoated core dimensions)</td>
<td>- N - polyamide 11 (nylon)</td>
</tr>
<tr>
<td>special version</td>
<td>$A_L$ value (nH)</td>
</tr>
<tr>
<td>gapped</td>
<td>core material</td>
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# Product range and specifications

<table>
<thead>
<tr>
<th>Core type</th>
<th>dimensions (mm)</th>
<th>effective core parameters</th>
<th>Core loss (W) at</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>outside diameter D (mm)</td>
<td>inside diameter d (mm)</td>
<td>height H (mm)</td>
</tr>
<tr>
<td>TN 13/7.5/5</td>
<td>13 ± 0.35</td>
<td>6.6 ± 0.35</td>
<td>5.4 ± 0.3</td>
</tr>
<tr>
<td>TN 17/11/6.4</td>
<td>17.5 ± 0.5</td>
<td>9.9 ± 0.5</td>
<td>6.85 ± 0.35</td>
</tr>
<tr>
<td>TN 20/10/6.4</td>
<td>20.6 ± 0.6</td>
<td>9.2 ± 0.4</td>
<td>6.85 ± 0.35</td>
</tr>
<tr>
<td>TN 23/14/7.5</td>
<td>24.0 ± 0.7</td>
<td>13.0 ± 0.6</td>
<td>8.1 ± 0.45</td>
</tr>
<tr>
<td>TN 26/15/11</td>
<td>26.8 ± 0.7</td>
<td>13.5 ± 0.6</td>
<td>11.6 ± 0.5</td>
</tr>
</tbody>
</table>

The cores are coated with polyamide 11 (PA11), flame retardant in accordance with “UL94V-2”, UL file number E 45228 (M). The inner and outer diameters apply to the coated toroid. Contacts are applied on the edge of the toroid for isolation voltage test, which is also the critical point for the winding operation.
$A_L$ versus DC bias curves
$A_L$ versus DC bias curves (continued)
Influence of winding position

All curves above are for a winding, evenly distributed over the circumference of the toroid.
$P_v$ versus temperature curves

$P_v$ versus temperature for TN13/7.5/5-3C20

$P_v$ measured on ungapped toroids, see note on page 12.
The same loss density values hold for all $A_L$ values and core sizes.
Comparison with metal powder cores

Several other material categories are used for power inductors. Metal powders form an important group. The metal can be pure iron or an alloy. In the form of a powder they have a distributed gap and don't need to be gapped as a core.

- Pure iron
  Composition : Fe 100 %
  Permeability : up to 90
  Highest saturation flux density
- Molybdenum Permalloy Powder (MPP)
  Composition : Ni 80 % − Fe 20 %, some substitution by Mo
  Permeability : up to 550 (because of the high intrinsic permeability of permalloy)
  Power loss volume density closest to ferrite

- High Flux
  Composition : Ni 50 % − Fe 50 %
  Permeability : up to 160
  Highest saturation flux density of metal alloys
- Sendust (sold under various brand names)
  Composition : Fe 85 % − Si 10 % − Al 5 %
  Permeability : up to 125
  Saturation flux density & power loss volume density intermediate

Ferrite comes into the picture where the limiting condition is power loss rather than saturation, so especially for high frequency and also for resonant inductors (large AC swing). For a certain set of application conditions, the limiting condition for metal powder can well be the power loss, while for ferrite it is the saturation. Even if that leads to a slightly larger core size, the gapped ferrite toroid could be more economical than expensive materials like MPP or high flux.

3C20 has an improved saturation level which makes it well-suited as an inductor material.

![Fig. 2: Relative position of materials with respect to application conditions](image-url)
Pure iron, high flux and sendust have a soft saturation curve due to the distributed gap. The permeability starts dropping early, but the slope doesn’t increase fast. MPP has a much more abrupt saturation curve due to the very high intrinsic permeability of permalloy. The hysteresis loop is therefore extremely sheared.

Ferrite toroids have a single gap and the fringing effect compensates the slow intrinsic permeability drop until real saturation occurs.

In the following graph we can see a comparison between a gapped ferrite toroid (TN 26/11-3C20-A201) and a powder core (MPP, 26.9x14.7x11.2mm, A201). We can see the frequency behavior of the different pieces. The stability with frequency is better for gapped ferrite than for MPP.

Below 2 graphs comparing the saturation behaviour between a gapped ferrite toroid (TN 13/5-3C20-A79) and a powder core (MPP, 12.7x7.6x4.8 mm, A79) for the first graph and TN 23/7.5-3C20-A90 and MPP, 22.9 x 14 x 7.6, A90 for the second.
Finally 2 graphs comparing the core losses of a gapped ferrite toroid (TN13/7.5/5-3C20) and a powder core (MPP, 12.7 x 7.6 x 4.8 mm), at 50 and 100 °C. The difference is at least a full decade.
Product performance calculation

With the aid of the foregoing graphs, 2 basic performance parameters can be calculated: minimum inductance (at maximum load) and total core loss.

- The required inductance determines the number of turns: \( n = \sqrt{\frac{L_o}{A_{L,o}}} \)
  This is rounded to an entire number.

- The bias current determines the \( A_L \) reduction: \( A_{L,min} = A_L \cdot (n \cdot I_{bias}) \)

- The inductance reduces with the same factor: \( \frac{L_{min}}{L_o} = \frac{A_{L,min}}{A_{L,o}} \)

- Voltage and frequency determine the flux density
  for sinusoidal flux and voltage variation: \( B_{max} = \frac{V_{rms}}{\sqrt{2} \cdot \pi \cdot n \cdot f \cdot A_e} \), \( V_{rms} = \frac{V_{max}}{\sqrt{2}} \)
  for triangular flux and rectangular voltage variation: \( B_{max} = \frac{V_{rms}}{4 \cdot n \cdot f \cdot A_e} \), \( V_{rms} = V_{max} \)

- Core loss follows from flux density and frequency: \( P = P_v(B,f) \cdot V_e \)

\( L_o \) = inductance without bias current
\( A_{L,o} \) = \( A_L \) value without bias current
\( L_{min} \) = inductance with maximum bias current
\( A_{L,min} \) = \( A_L \) value with maximum bias current

If the minimum \( A_L \) value doesn't comply the requirements, then a lower \( A_L \) value or else a larger core size is necessary.

Example

Required: output choke with inductance > 5 \( \mu \)H, decrease < 10 % for 15 A bias current.

Starting with the smallest toroid and \( A_L \) value leads to the following sequence:

<table>
<thead>
<tr>
<th>Toroid</th>
<th>( n )</th>
<th>Turns</th>
<th>( I_{bias} )</th>
<th>( A_{L,min} )</th>
<th>( A_L ) value</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN 13/5-3C 20-A 40</td>
<td>( \sqrt{5000/40} )</td>
<td>11.2</td>
<td>180 A.turns</td>
<td>12 turns</td>
<td>10 A.turns</td>
<td>clear saturation</td>
</tr>
<tr>
<td>TN 17/6.4-3C 20-A 52</td>
<td>( \sqrt{5000/52} )</td>
<td>9.8</td>
<td>150 A.turns</td>
<td>10 turns</td>
<td>9 A.turns</td>
<td>decrease &lt; 50 %</td>
</tr>
<tr>
<td>TN 20/6.4-3C 20-A 68</td>
<td>( \sqrt{5000/68} )</td>
<td>8.6</td>
<td>135 A.turns</td>
<td>9 turns</td>
<td>8 A.turns</td>
<td>remaining ( A_L ) value = 62 nH, decrease = 6 nH &lt; 10 %</td>
</tr>
</tbody>
</table>

This is just enough
\( A_L \) value 109 nH could reduce the turns to 7 to achieve 5 \( \mu \)H, but would not comply with 15 A bias.

Suppose the choke is driven by a rectangular voltage of 4 V amplitude, switching at 200 kHz.

Taking into account the core effective cross-section 30.5 mm\(^2\) of TN 20/6.4, peak flux density will be:
\( B_{max} = \frac{4}{(4 \cdot 9 \cdot 200 \times 10^3 \cdot 30.5 \times 10^{-6})} = 18.2 \text{ mT} \)

Ignoring the influence of bias current and non-sinusoidal waveforms, the graphs of \( P_v(T) \) can be taken as reference.

Even for lower temperatures the loss density will be below 10 mW/cm\(^3\).

With an effective volume of 1.33 cm\(^3\), the core loss will only be in the order of 10 mW.
Note on power loss measurement

Power losses as presented in this brochure have been measured on ungapped ferrite toroids, as is common practice for paired core shapes like EFD etc. Gapped cores have a much lower loss tangent \( \delta \) which reduces the loss measurement accuracy:

- Lower loss tangent

\[
\frac{\delta_e}{\mu_e} = \frac{\delta}{\mu}
\]

\[
\frac{\delta_e}{\mu_e} = \frac{\delta}{\mu}
\]

\[
\delta_e = \left(\frac{\mu_e}{\mu}\right)\delta
\]

As \( \mu_e/\mu < 1 \), the loss tangent is reduced by a gap.

- Lower measurement accuracy

\[
P = V.I.\cos\delta = V.I.\sin\delta
\]

\[
dP/d\delta = V.I.\cos\delta
\]

\[
\frac{\Delta P}{P} = \left(\frac{dP}{d\delta}\right)\Delta \delta/P = \Delta \delta/\delta = 2\pi f \Delta t/\delta
\]

\( \mu = \text{permeability without gap} \)

\( \delta = \text{loss tangent without gap} \)

\( \delta/\mu = \text{loss factor without gap} \)

\( \mu_e = \text{permeability with gap} \)

\( \delta_e = \text{loss tangent with gap} \)

\( (\delta/\mu)_e = \text{loss factor with gap} \)

For a given time accuracy \( \Delta t \) (equipment), the relative loss error \( \Delta P/P \) increases proportional with frequency \( f \) and inversely proportional with loss tangent \( \delta \) (or proportional to quality factor \( Q \)).

The above linear calculation holds for small signals, but qualitatively the result is the same for large signals and hysteresis loops.

Measuring with the same flux density \( B \) still leads to the same power loss \( P \) as for gapped ferrite toroids, apart from the core volume factor \( V_g/V_e = (A_e.(l_e-l_g))/(A_e.l_e) = 1-l_g/l_e \approx 1 \).

In the case of metal powder cores, it's impossible to measure without the (distributed) gap, but the accuracy is much higher due to the higher loss tangent \( \delta \).
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