Power-Inductors with Multi-layer Windings

Single layer toroids are inexpensive and popular but not the only option. For higher powers or inductors requiring a large number of turns in a compact volume, core+bobbin assemblies are frequently used.

One advantage of segmented cores is that air-gaps can be incorporated easily, allowing the designer greater control over the effective permeability.

Unlike the single-layer toroid in which the winding is constrained by a linear dimension (the inner diameter), multiple-layer windings are constrained by an available winding area, called the window area.

We will develop two commonly-used approaches for core selection that can be easily extended to other core types:

- The area-product method (similar to the area-diameter product for single-layer toroids)
- The core geometry method
Area-Product ($A_p$) Method

Most of the same constraints hold for all geometries. The only change is the available area for windings:

1) Inductance: 
   \[ L = \mu_e N^2 \frac{A_e}{l_e} = N^2 A_L \]

2) $B < B_{\text{max}}$ 
   \[ I_{\text{max}} \leq \frac{NB_{\text{max}} A_e}{L} \]

3) Window area: 
   \[ A_b \geq \frac{NA_{bw}}{K_w} = \frac{NI_{\text{rms}}}{K_w J_{\text{max}}} \]

4) Winding Loss 
   \[ P_{Cu} = \rho_{Cu} \frac{N(MLT)}{A_{bw}} I_{\text{rms}}^2 \]

The product of core cross sectional area and window area is the “area product” $A_p$: 

\[ A_p \equiv A_e A_b \geq \frac{LI_{\text{max}} I_{\text{rms}}}{B_{\text{max}} K_w J_{\text{max}}} \]

This gives a quick method for choosing cores. Some manufacturers specify the area product for various cores. Typically the window utilization factor is assumed to be: 

\[ K_w = 0.4 - 0.5 \]

Note: look for the area product in the bobbin specification! 

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Gapped Cores

Once the core geometry is chosen, the required inductance factor can be determined from (1) and (2):

\[ A_L \leq \frac{B_{\text{max}}^2 A_e^2}{L I_{\text{max}}^2} \]

Usually the cores are made from a high permeability ferrite, and an air-gap is used to engineer the desired effective permeability or inductance factor. From earlier work we can get a quick estimate of the required gap:

\[ A_L \approx \frac{\mu_0}{g} A_e \implies g \geq \frac{\mu_0 L I_{\text{max}}^2}{B_{\text{max}}^2 A_e} \]

Some manufacturers sell some pre-gapped core sets with certain pre-determined values of inductance factor. Often one of those will work fine.

For customized gaps the manufacturer will often provide information like the chart at right. This aids core selection as well. This data should account for fringing flux around the gap which increases the effective cross section.

The effect can be approximated by assuming the fringing increases the cross-sectional dimensions by the gap length:

\[ A_{\text{gap}} \approx \left( \sqrt{A_e + g} \right)^2 \approx A_e + 2g \sqrt{A_e} \quad L \approx \mu_0 N^2 \frac{A_{\text{gap}}}{g} \]

\[ R_{\text{gap}} \approx \frac{1}{\mu_0} \frac{g}{A_{\text{gap}}} \quad \frac{N I_{\text{max}}}{R_{\text{gap}}} \leq B_{\text{max}} A_e \implies L I_{\text{max}}^2 \leq A_e \frac{g}{1 + 2g / \sqrt{A_e}} \]

\[ \text{Flux in gap} = \text{flux in core} \]

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**Design Example**

Circuit Spec: Assumptions:

\[ L = 200 \mu H \quad B_{\text{max}} = 0.3 \text{T} \]

\[ I_{dc} = 2 \text{ A} \quad K_u = 0.5 \]

\[ \Delta I = 0.4 \text{ A} \quad J_{\text{max}} = 400 \text{ A/cm}^2 \]

Required Area Product:

\[ A_p > 1520 \text{ mm}^4 \]

E25/10/6 core satisfies this criterion. Using this core, the design requires:

\[ A_L < 145 \text{ nH} \]

For 3C81 ferrite (a general purpose material for <200kHz) a standard gapped core is available with:

\[ A_L = 100 \text{ nH} \]

From this we find:

\[ N = \sqrt{\frac{L}{A_L}} = 47 \text{ turns} \]

\[ P_{Cu} \approx 0.3 \text{ Watt} \]
Core-Geometry ($K_g$) Method of Core Selection

Unlike the area-product method, the core-geometry method explicitly includes the winding loss as part of the core selection process.

The condition (2) for $B \leq B_{\text{max}}$ can be written as:

$$\mu_e \frac{N I_{\text{max}}}{I_e} \leq B_{\text{max}}$$

Using this, the inductance relation (1) gives:

$$L \leq \frac{NA_e B_{\text{max}}}{I_{\text{max}}} \quad \iff \quad N \geq \frac{LI_{\text{max}}}{A_e B_{\text{max}}}$$

Condition (3) gives:

$$A_{bw} \leq \frac{K_w A_b}{N}$$

Using the last two results the winding loss is:

$$P_{Cu} \geq \rho_{Cu} \frac{\text{MLT}}{K_w A_b} I_{\text{rms}}^2 \left( \frac{LI_{\text{max}}}{A_e B_{\text{max}}} \right)^2$$

This result combines all the important constraints on the inductor design. If we group all the parameters relating to the core geometry on the left we get:

$$K_g \geq \frac{\rho_{Cu} I_{\text{rms}}^2}{P_{Cu} K_w} \left( \frac{LI_{\text{max}}}{B_{\text{max}}} \right)^2$$

where

$$K_g = \frac{A_b A_e^2}{\text{MLT}}$$

$K_g$ is the core-geometry constant. It can usually be calculated for any core-bobbin combination, and thus gives a method for choosing a core when power loss is specified.

Once the core is selected, the air-gap is chosen as outlined previously.