The Effect of Direct Current on the Inductance of a Ferrite Core

Introduction

If ferrite cores are used in the design of transformers, chokes or filters, which are required to carry direct current, it is necessary to predict the degree of inductance degradation caused by the static field. When dc flows through the winding of a ferromagnetic device, it tends to pre-magnetize the core and reduce its inductance. The permeability of a ferrite material measured with superimposed dc might increase slightly for very low values of dc ampere-turns, but then it progressively decreases as the dc field is increased and the core approaches saturation. This permeability is referred to as the incremental permeability μ_Δ. If an air gap is introduced into the magnetic path of a core, the reluctance is increased hence the inductance is decreased. However, the core's capacity for dc ampere-turns without a degradation in inductance is significantly improved, albeit at the expense of a lower effective permeability.

DC Bias in Gapped Cores

The use of graphs such as the Hanna* curves has simplified the tedious trial and error methods often employed when designing inductors with superimposed dc. A Hanna curve is created by measuring the inductance vs. dc bias of various core sizes and gap lengths of the same material grade. The measured data is used to create curves such as those plotted in Figure 1 (this curve is specific for a set of 9478015002 E cores). A line is drawn connecting the individual curves through the point of tangency. The graphs are then normalized by dividing the vertical scale of Figure 1 by the effective core volume V_e and the horizontal scale and the gap lengths by the effective path length l_e of the core set. The individual curves, once normalized, overlay creating the Hanna curve. Figure 2 is such a curve for Fair-Rite 78 material and can be used for all core sets in that material.

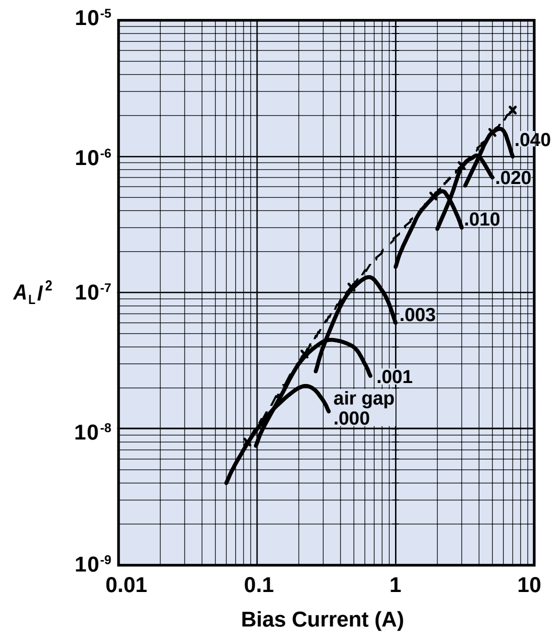

Figure 1 Product inductance factor and current squared vs. DC current for a pair of 9478015002 E cores.

Design Example

For a typical output choke application, the designer knows a number of design criteria such as the required inductance, the direct current, alternating ripple current and allowable dc resistance. He will also have requirements for core size, ambient temperature an often a preference for a particular core geometry.

*Footnote: C.R. Hanna presented a paper "Design of Reactances and Transformers which Carry Direct Current" at the 1927 Winter Convention of AIEE. The paper provided a method of calculating the air gap that will yield the maximum inductance for a given number of turns, with a specified amount of dc, for a particular material.

Technical Information

The following example illustrates the use of the Hanna curve in the design of an inductor.

Inductor specifications:

Minimum inductance	L	$= 1$ mH
Direct current	I_{dc}	$= 1$ A
Alternating ripple current	I_{ac}	$= 0.2$ A
Maximum dc resistance	R_{dc}	$< 0.2\ \Omega$

Step 1. Initial Core Selection.

Using the Hanna curve for 78 material of Figure 2, select a value for LI^2/V_e approximately mid range on the vertical axis, that is between 10^{-4} and 10^{-3}. Any value greater than 10^{-3} will work the ferrite too hard and the dc resistance is apt to be high. Anything lower than 10^{-4} will result in a conservative design and the dc resistance will be quite low.

Select therefore $LI^2/V_e = 3.5\ 10^{-4}$

Calculate V_e from:

$V_e = LI^2/3.5\ 10^{-4}$

$L_{min} = 1$ mH, design for $L = 1.1\ 10^{-3}$ H

$I = I_{dc} + I_{ac}/2 = 1 + 0.2/2 = 1.1$ A

$V_e = 1.1\ 10^{-3} \times 1.1^2/3.5\ 10^{-4} = 3.8$ cm^3

Select E core (preferred core shape), based upon the calculated core volume of 3.8 cm^3 from the catalog, pages xx and xx. Two Fair-Rite E cores are considered:

9478015002 $V_e = 1.95$ cm^3 and

9478014002 $V_e = 3.92$ cm^3.

The 9478014002 is closest and will be used in this inductor design. The core parameters for this E core set are:

$l_e = 4.9$ cm, $A_e = .80$ cm^2 and $V_e = 3.92$ cm^3.

Recalculate

$LI^2/V_e = 1.1\ 10^{-3} \times 1.1^2/3.92 = 3.4\ 10^{-4}$.

Step 2. Number of Turns, Wire Size and Wire Fit.

From Figure 2, a $LI^2/V_e = 3.4\ 10^{-4}$ yields a H value of 17 oersted.

Calculate turns N from the formula $H = .4\ \pi\ NI / l_e$ oersted.

$N = 17 \times 4.9/.4 \times \pi \times 1.1 = 60.3$ or 61 turns.

From the core dimensions, the core winding area can be calculated, see Table 1.

Winding area for a set of E cores 9478014002 is:

$A_w = D\ (E-F)$ in inch^2.

$A_w = .255\ (.740-.250) = .125$ inch^2.

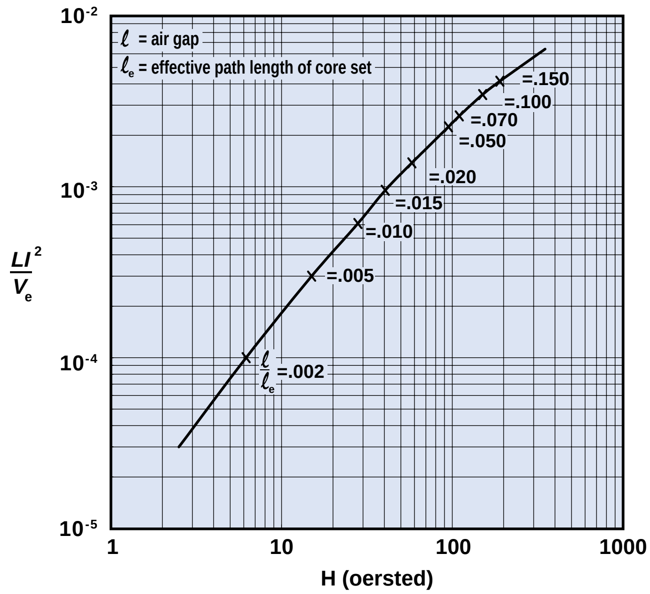

Figure 2 Hanna curve for core sets in 78 material.

Table 1 Core Winding Area (inch^2)	
E Cores	D(E-F)
ETD Cores	D(E-F)
PQ Cores	D(E-F)
Pot Cores	D(E-F)
EP Cores	D(E-F)

Since the winding area of the appropriate bobbin is smaller than the core winding area, a correction factor F_c has to be used to determine the bobbin winding area. Figure 3 gives this correction factor F_c as a function of the calculated core winding area A_w. A set of E cores 9478014002 has a $A_w = .125$ inch^2, from Figure 3 can be determined that the $F_c = .55$, therefore the bobbin winding area is $.55 \times .125 = .069$ inch^2. Using a conservative current density of 1 mA per circular mil or 1275 A per inch^2, an initial wire size selection of 20 AWG can be made from the Wire Table on page xx. To determine the dc resistance of the winding, first find the average length of turn from Table 2.

Table 2 Mean Length of Turn (inch)	
E Cores	2 (C+E)
ETD Cores	.5 π (E+F)
PQ Cores	.5 π (E+F)
Pot Cores	.5 π (E+F)
EP Cores	.5 π (E+F)

Technical Information

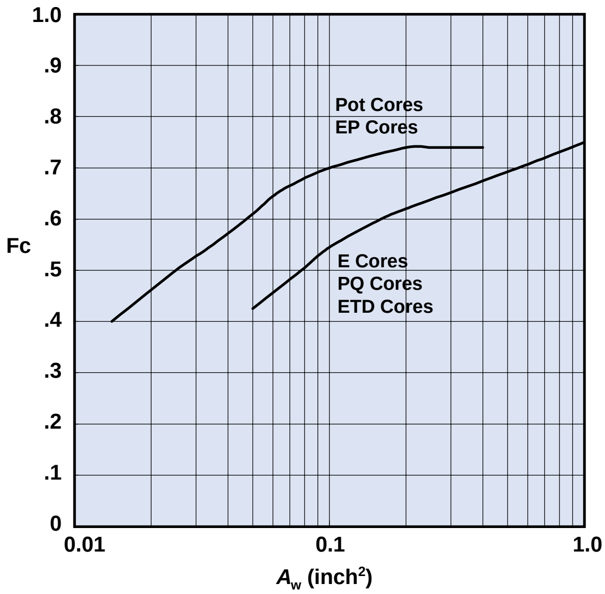

Figure 3 Correction factor F_c vs. core winding area A_w.

The graphs in Figures 4 through 8 show the inductance factors or A_L values as a function of the air gaps for the different core types and sizes.The air gap determined in the design example and the air gaps shown in Figures 4 through 8 represent the total air gap. The most practical way to obtain this air gap is to grind this gap into the center leg of one of the core halves. Non-metallic shims can also be used to obtain the desired air gap. This is usually done by placing shims between the outer legs or outside rims of the core halves. In cores with a uniform cross-sectional area, the A_L value or inductance index will be the same whether the core is gapped or shims are used that have a thickness half the total air gap. For cores that have a non-uniform cross-sectional area the shim thickness can be calculated from:

$$\text{Shim thickness} = \text{total air gap} \times \frac{\text{center mating area}}{\text{total mating area}}$$

The above example of the E core 9478014002, a core with a uniform cross-sectional area, can therefore use .006 inch shims between the outer legs.

Average length of turn for E 9478014002 is:

$l_{avg.} = 2\ (C+F)$

$l_{avg.} = 2\ (.500 + .740) = 2.48$ inch.

$R_{dc} = 2.48 \times 61 \times 10.2/12000 = 0.13\ \Omega$

(From the Wire Table, 1000 ft of 20 AWG has a resistance of 10.2 Ω)

To check for winding fit, multiply the number of turns per square inch for 20 AWG from the Wire Table with the bobbin winding area of .069 inch^2. For 20 AWG, the bobbin winding area can accommodate 854 x .069 = 58.9 turns. This is too close to the calculated turns for an easily manufactured magnetic design. Use 21 AWG wire instead.

$R_{dc} = 2.48 \times 61 \times 12.8/12000 = 0.16\ \Omega$.

Winding fit for 21 AWG:

N = 1065 x .069 = 73.5, well above the require 61 turns.

Step 3. Air gap.
Going back to Figure 2, for $LI^2/V_e = 3.4\ 10^{-4}$ and a H = 17 oersted, a l/l_e ratio of approximately .006 is found.

The gap length = .006 x l_e.
l = .006 x 4.9/2.54 = .012 inch.

To summarize:

E core 9478014002	N = 61 turns
Wire size 21 AWG	Gap length .012 inch

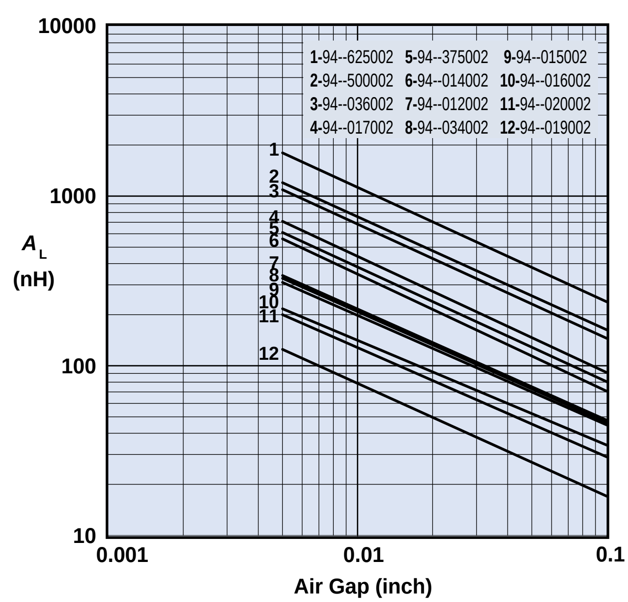

Figure 4 A_L vs. gap for E cores in 77 and 78 material.

Technical Information

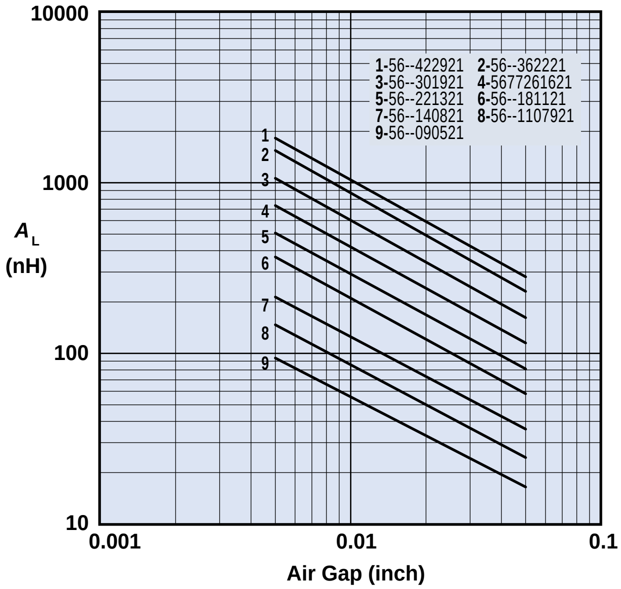

Figure 5 A_L vs. gap for pot cores in 77 and 78 material.

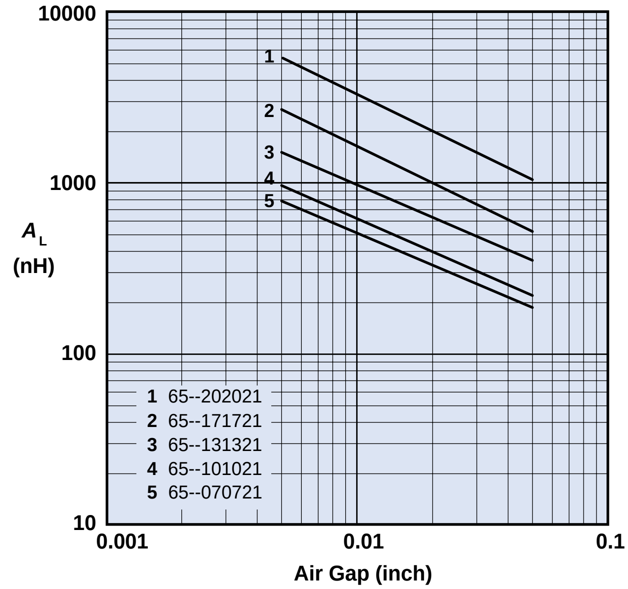

Figure 6 A_L vs. gap for EP cores in 77 and 78 material.

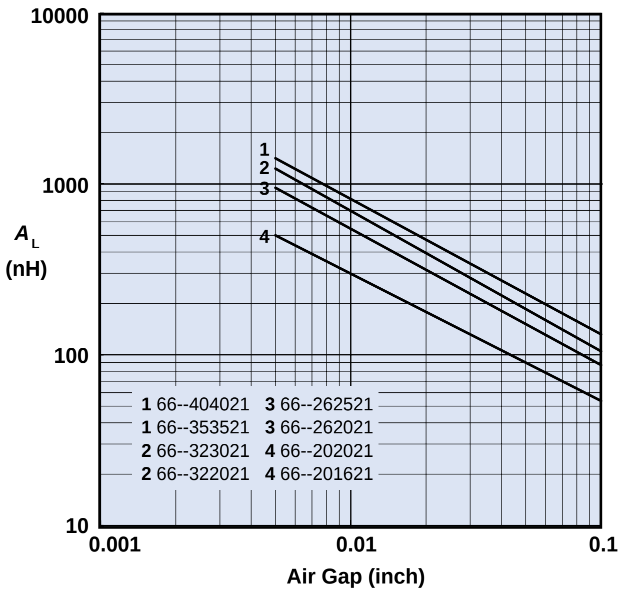

Figure 7 A_L vs. gap for PQ cores in 77 and 78 material.

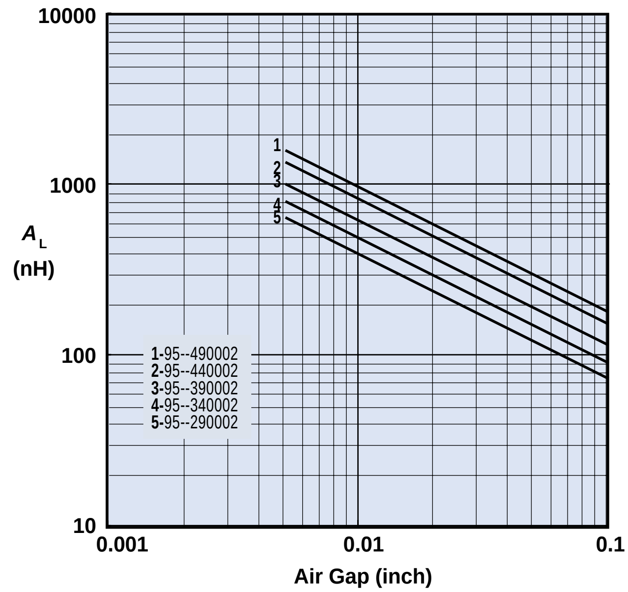

Figure 8 A_L vs. gap for ETD cores in 77 and 78 material.

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