Chapter 9

DC Inductor Design Using Powder Cores

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Introduction

Powder cores are manufactured from very fine particles of magnetic materials. The powder is coated with an inert insulation to minimize eddy current losses and to introduce a distributed air gap into the core structure. The insulated powder is then compacted into toroidal and EE cores. The magnetic flux in a toroidal powder core can be contained inside the core more readily than in a lamination or C core, as the winding covers the core along the entire magnetic path length. The design of an inductor also frequently involves consideration of the effect of its magnetic field on devices near where it is placed. This is especially true in the design of high-current inductors for converters and switching regulators used in spacecraft.

Toroidal powder cores are widely used in high-reliability military and space applications because of their good stability over wide temperature ranges, and their ability to withstand high levels of shock, vibration, and nuclear radiation without degradation. Other applications for these cores are:

1. Stable, high-Q filters operating in the frequency range of 1kHz to 1 MHz.
2. Loading coils used to cancel out the distributed capacitance in telephone cables.
3. Pulse transformers.
4. Differential mode EMI noise filters.
5. Flyback transformers.
6. Energy storage, or output inductors, in circuits with large amounts of dc current flowing.

Molybdenum Permalloy Powder Cores (MPP)

Molybdenum Permalloy Powder Cores (MPP) are manufactured from very fine particles of an 81% nickel, 17% iron, and a 2% molybdenum alloy. The insulated powder is then compacted into EE and toroidal cores. The toroidal cores range in size from 0.1 inch (0.254 cm) to 5 inches (12.7 cm) in the outside diameter. MPP cores are available in permeabilities ranging from 14 up to 550. See Table 9-1

High Flux Powder Cores (HF)

High Flux Powder Cores (HF) are manufactured from very fine particles of a 50% nickel, and 50% iron. The insulated powder is then compacted into EE and toroidal cores. The toroidal cores range in size from 0.25 inch (0.635 cm) to 3 inches (7.62 cm) in the outside diameter. HF cores are available in permeabilities ranging from 14 up to 160. See Table 9-1.

Sendust Powder Cores (Magnetics Kool Mμ)

Sendust powder cores are manufactured from very fine particles of an 85% iron, 9% silicon, and 6% aluminum. The insulated powder is then compacted into EE and toroidal cores. The toroidal cores range in size from 0.14 inch (0.35 cm) to 3 inches (7.62 cm) in the outside diameter. Sendust cores are available in permeabilities ranging from 26 up to 125. See Table 9-1

Iron Powder Cores

The low cost iron powder cores are typically used in today's low and high frequency power switching conversion applications for differential-mode, input and output, power inductors. The distributed air gap characteristic of iron powder produces a core with permeability ranging from 10 to 100. This feature, in conjunction with the inherent high saturation point of iron, makes it very difficult to saturate. While iron powder cores may be limited in their use because of low permeability or rather high core loss at high frequency, they have become a very popular choice in either EE or toroidal as a core material for high-volume commercial applications. They are popular due to their low cost compared with other core materials. The toroidal cores range in size from 0.3 inch (0.76 cm) to 6.5 inches (16.5 cm) in the outside diameter. See Table 9-1

Table 9-1. Standard Powder Core Permeability

Standard Powder Core Permeabilities				
Powder Material	MPP	High Flux	Sendust (Kool Mμ)	Iron Powder
Initial Permeability, μ_i				
10				X
14	X	X		
26	X	X	X	
35				X
55				X
60	X	X	X	X
75			X	X
90			X	
100				X
125	X	X	X	
147	X	X		
160	X	X		
173	X			
200	X			
300	X			
550	X			

Inductors

Inductors that carry direct current are used frequently in a wide variety of ground, air, and space applications. Selection of the best magnetic core for an inductor frequently involves a trial-and-error type of calculation.

The design of an inductor also frequently involves consideration of the effect of its magnetic field on other devices in the immediate vicinity. This is especially true in the design of high-current inductors for converters and switching regulators used in spacecraft, which may also employ sensitive magnetic field detectors. For this type of design problem, frequently it is imperative that a toroidal core be used. The magnetic flux in a powder core can be contained inside the core more readily than in a lamination or C core, as the winding covers the core along the entire magnetic path length. The author has developed a simplified method of designing optimum dc carrying inductors with powder cores. This method allows the correct core permeability to be determined without relying on the trial and error method.

Relationship of, A_p, to Inductor's Energy-Handling Capability

The energy-handling capability of a core is related to its area product, A_p, by the equation:

$$A_p = \frac{2(\text{Energy})(10^4)}{B_m J K_u}, \quad [\text{cm}^4] \quad [9\text{-}1]$$

Where: Energy is in watt-seconds.
B_m is the flux density, tesla.
J is the current density, amps-per-cm^2.
K_u is the window utilization factor. (See Chapter 4)

From the above factors, such as flux density, B_m, window utilization factor, K_u, (which defines the maximum space that may be used by the copper in the window), and the current density, J, which controls the copper loss can be seen. The energy-handling capability of a core is derived from:

$$\text{Energy} = \frac{LI^2}{2}, \quad [\text{watt-seconds}] \quad [9\text{-}2]$$

Relationship of, K_g, to Inductor's Energy-Handling Capability

Inductors, like transformers, are designed for a given temperature rise. They can also be designed for a given regulation. The regulation and energy handling ability of a core is related to two constants:

$$\alpha = \frac{(\text{Energy})^2}{K_g K_e}, \quad [\%] \quad [9\text{-}3]$$

Where α is the regulation, %.

The constant, K_g, is determined by the core geometry:

$$K_g = \frac{W_a A_c^2 K_u}{\text{MLT}}, \quad [\text{cm}^5] \quad [9\text{-}4]$$

The constant, K_e, is determined by the magnetic and electrical operating conditions:

$$K_e = 0.145 P_o B_m^2 \left(10^{-4}\right) \quad [9\text{-}5]$$

The output power, P_o, is defined in Figure 9-1.

$$P_{o(L1)} = V_{(01)} I_{(01)} \quad P_{o(L2)} = V_{(02)} I_{(02)} \quad [9\text{-}6]$$
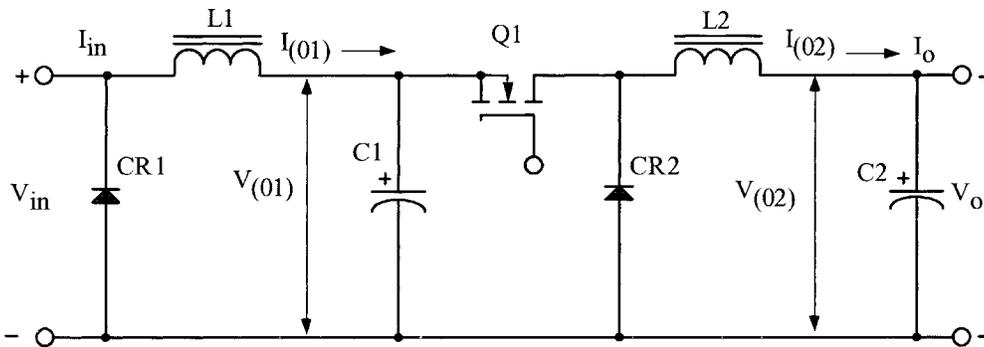
Figure 9-1. Defining the Inductor Output Power.

The operating flux density, B_m, is:

$$B_m = B_{dc} + \frac{B_{ac}}{2}, \quad [\text{tesla}] \quad [9\text{-}7]$$

From the above, it can be seen that the flux density, B_m, is the predominant factor in governing size.

Fundamental Considerations

The design of a linear reactor depends upon four related factors:

1. Desired inductance, L.
2. Direct current, I_{dc}.
3. Alternating current, ΔI.
4. Power loss and temperature, T_r.

With these requirements established, the designer must determine the maximum values for, B_{dc}, and B_{ac}, that will not produce magnetic saturation and must make trade-offs that will yield the highest inductance for a given volume. The core permeability chosen dictates the maximum dc flux density that can be tolerated for a given design.

If an inductance is to be constant with the increasing direct current, there must be a negligible drop in inductance over the operating current range. The maximum H (magnetizing force) then is an indication of a core's capability, as shown in Figure 9-2.
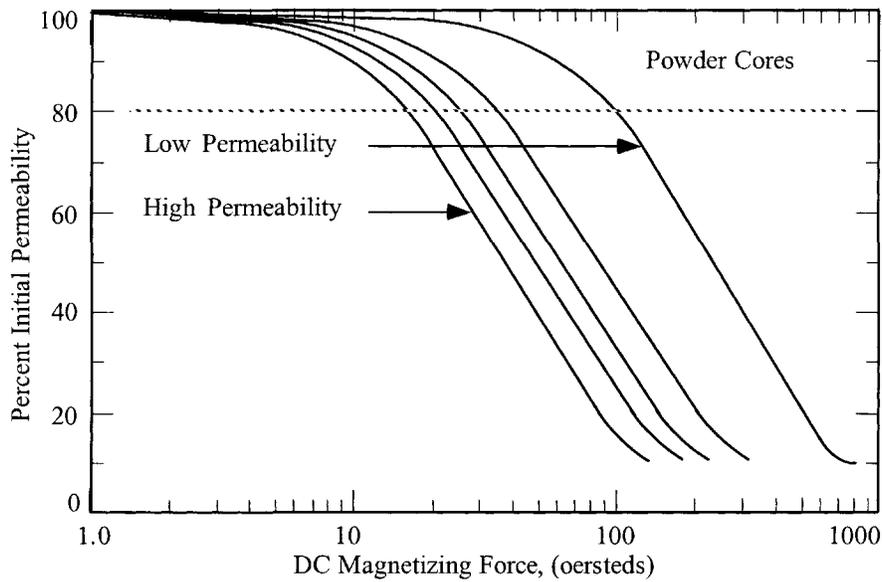
Figure 9-2. Typical Permeability Versus dc Bias Curves for Powder Cores.

Most manufacturers give the dc magnetizing force, H in oersteds:

$$H = \frac{0.4\pi NI}{\text{MPL}}, \quad [\text{oersteds}] \quad [9\text{-}8]$$

Some engineers prefer amp-turns:

$$NI = 0.8H(\text{MPL}), \quad [\text{amp-turns}] \quad [9\text{-}9]$$

Inductance decreases with increasing flux density, B, and magnetizing force, H, for various materials of different values of permeability. The selection of the correct permeability for a given design is made using Equation [9-10].

$$\mu_\Delta = \frac{B_m(\text{MPL})(10^4)}{0.4\pi W_a J K_u} \quad [9\text{-}10]$$

It should be remembered the maximum flux, B_m, depends upon, $B_{dc} + B_{ac}$, in the manner in Figure 9-3.

$$B_m = B_{dc} + \frac{B_{ac}}{2}, \quad [\text{tesla}] \quad [9\text{-}11]$$

$$B_{dc} = \frac{0.4\pi N I_{dc}\,\mu\left(10^{-4}\right)}{MPL}, \quad \text{[tesla]} \quad [9\text{-}12]$$

$$B_{ac} = \frac{0.4\pi N\left(\dfrac{\Delta I}{2}\right)\mu\left(10^{-4}\right)}{MPL}, \quad \text{[tesla]} \quad [9\text{-}13]$$

$$B_{pk} = \frac{0.4\pi N\left(I_{dc} + \dfrac{\Delta I}{2}\right)\mu\left(10^{-4}\right)}{MPL}, \quad \text{[tesla]} \quad [9\text{-}14]$$
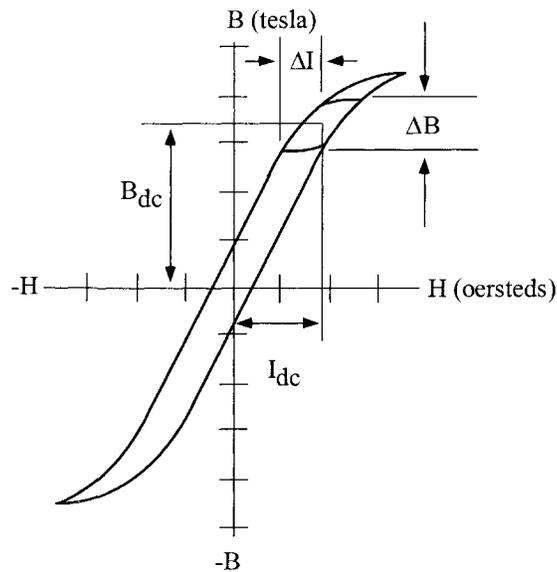
Figure 9-3. Inductor Flux Density Versus $I_{dc} + \Delta I$ Current.

The flux density for the initial design for Molypermalloy powder cores should be limited to 0.3T maximum for, $B_{dc} + B_{ac}$, as shown in Figure 9-4.
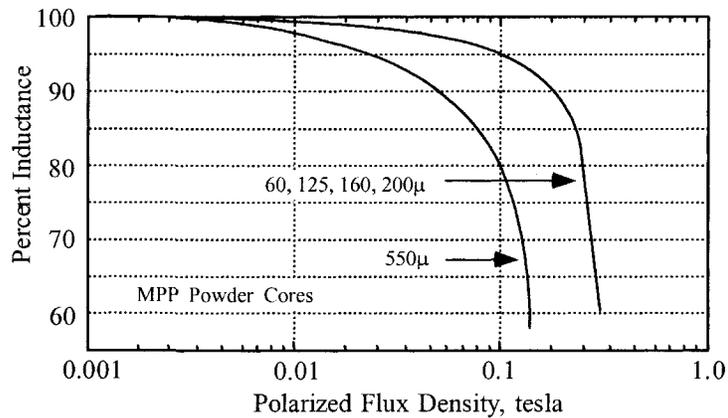
Figure 9-4. Inductance Versus dc Bias.

Toroidal Powder Core Design Using the Core Geometry, K_g, Approach

This design procedure will work with all powder cores.

Step No. 1 Design a linear dc inductor with the following specifications.

1. Inductance, L .... = 0.0025 henrys
2. dc current, I_o .... = 1.5 amps
3. ac current, ΔI .... = 0.2 amps
4. Output power, P_o .... = 100 watts
5. Regulation, α .... = 1.0 %
6. Ripple Frequency .... = 20 kHz
7. Operating flux density, B_m .... = 0.3 tesla
8. Core Material .... = MPP
9. Window utilization, K_u .... = 0.4
10. Temperature rise goal, T_r .... = 25°C

Step No. 2 Calculate the peak current, I_{pk}.

$$I_{pk} = I_o + \frac{\Delta I}{2}, \quad [\text{amps}]$$

$$I_{pk} = (1.5) + \frac{(0.2)}{2}, \quad [\text{amps}]$$

$$I_{pk} = 1.6, \quad [\text{amps}]$$

Step No. 3 Calculate the energy-handling capability.

$$\text{Energy} = \frac{L I_{pk}^2}{2}, \quad [\text{watt-seconds}]$$

$$\text{Energy} = \frac{(0.0025)(1.6)^2}{2}, \quad [\text{watt-seconds}]$$

$$\text{Energy} = 0.0032, \quad [\text{watt-seconds}]$$

Step No. 4 Calculate the electrical conditions coefficient, K_e.

$$K_e = 0.145 P_o B_m^2 (10^{-4})$$

$$K_e = 0.145(100)(0.3)^2 (10^{-4})$$

$$K_e = 0.0001305$$

Step No. 5 Calculate the core geometry coefficient, K_g.

$$K_g = \frac{(\text{Energy})^2}{K_e \alpha}, \quad [\text{cm}^5]$$

$$K_g = \frac{(0.0032)^2}{(0.0001305)(1.0)}, \quad [\text{cm}^5]$$

$$K_g = 0.0785, \quad [\text{cm}^5]$$

Step No. 6 Select a MPP powder core from Chapter 3. The data listed is the closest core to the calculated core geometry, K_g.

1. Core Number .... = 55586
2. Magnetic Path Length, MPL .... = 8.95 cm
3. Core Weight, W_{tfe} .... = 34.9 grams
4. Mean Length Turn, MLT .... = 4.40 cm
5. Iron Area, A_c .... = 0.454 cm^2
6. Window Area, W_a .... = 3.94 cm^2
7. Area Product, A_p .... = 1.79 cm^4
8. Core Geometry, K_g .... = 0.0742 cm^5
9. Surface Area, A_t .... = 64.4 cm^2
10. Permeability, μ .... = 60
11. Millihenrys-per-1k, A L .... = 38 mh

Step No. 7 Calculate the current density, J, using the area product Equation, A_p.

$$J = \frac{2(\text{Energy})(10^4)}{B_m A_p K_u}, \quad [\text{amps-per-cm}^2]$$

$$J = \frac{2(0.0032)(10^4)}{(0.3)(1.79)(0.4)}, \quad [\text{amps-per-cm}^2]$$

$$J = 298, \quad [\text{amps-per-cm}^2]$$

Step No. 8 Calculate the rms current, I_{rms}.

$$I_{rms} = \sqrt{I_o^2 + \Delta I^2}, \quad [\text{amps}]$$

$$I_{rms} = \sqrt{(1.5)^2 + (0.2)^2}, \quad [\text{amps}]$$

$$I_{rms} = 1.51, \quad [\text{amps}]$$

Step No. 9 Calculate the required bare wire area, $A_{w(B)}$.

$$A_{W(B)} = \frac{I_{rms}}{J}, \quad [\text{cm}^2]$$

$$A_{W(B)} = \frac{(1.51)}{(298)}, \quad [\text{cm}^2]$$

$$A_{W(B)} = 0.00507, \quad [\text{cm}^2]$$

Step No. 10 Select a wire from the Wire Table in Chapter 4. If the area is not within 10%, take the next smallest size. Also, record micro-ohms per centimeter.

$$AWG = \#20$$
$$\text{Bare, } A_{W(B)} = 0.00519, \quad [\text{cm}^2]$$
$$\text{Insulated, } A_W = 0.00606, \quad [\text{cm}^2]$$
$$\left(\frac{\mu\Omega}{\text{cm}}\right) = 332, \quad [\text{micro-ohm/cm}]$$

Step No. 11 Calculate the effective window area, $W_{a(eff)}$. Use the window area found in Step 6. A typical value for, S_3, is 0.75, as shown in Chapter 4.

$$W_{a(eff)} = W_a S_3, \quad [\text{cm}^2]$$

$$W_{a(eff)} = (3.94)(0.75), \quad [\text{cm}^2]$$

$$W_{a(eff)} = 2.96, \quad [\text{cm}^2]$$

Step No. 12 Calculate the number turns possible for, N. Use the insulated wire area, A_w, found in Step 10. A typical value for, S_2, is 0.6, as shown in Chapter 4.

$$N = \frac{W_{a(eff)} S_2}{A_W}, \quad [\text{turns}]$$

$$N = \frac{(2.96)(0.60)}{(0.00606)}, \quad [\text{turns}]$$

$$N = 293, \quad [\text{turns}]$$

Step No. 13 Calculate the required core permeability, μ.

$$\mu_\Delta = \frac{B_m (\text{MPL})(10^4)}{0.4\pi W_a J K_u}$$

$$\mu_\Delta = \frac{(0.30)(8.95)(10^4)}{(1.26)(3.94)(298)(0.4)}$$

$$\mu_\Delta = 45.4$$

Note:

The permeability of 45.4 is close enough to use a 60μ core. Also note that there are other permeabilities available, See Table 9-1. Because of size, Chapter 3 has listed only 60μ Tables for MPP, High Flux, Sendust and a 75μ Table for Iron powder. For cores with other than 60μ, use the manufacturer's catalog.

Step No. 14 Calculate the number of turns, N_L, required.

$$N_L = 1000\sqrt{\frac{L}{L_{(1000)}}}, \quad \text{[turns]}$$

$$N_L = 1000\sqrt{\left(\frac{2.5}{38}\right)}, \quad \text{[turns]}$$

$$N_L = 256, \quad \text{[turns]}$$

Step No. 15 Calculate the winding resistance, R_L. Use the MLT from Step 6 and the micro-ohm per centimeter from Step 10.

$$R_L = (\text{MLT})(N_L)\left(\frac{\mu\Omega}{\text{cm}}\right)(10^{-6}), \quad \text{[ohms]}$$

$$R_L = (4.4)(256)(332)(10^{-6}), \quad \text{[ohms]}$$

$$R_L = 0.374, \quad \text{[ohms]}$$

Step No. 16 Calculate the copper loss, P_{cu}.

$$P_{cu} = I_{rms}^2 R_L, \quad \text{[watts]}$$

$$P_{cu} = (1.51)^2 (0.374), \quad \text{[watts]}$$

$$P_{cu} = 0.853, \quad \text{[watts]}$$

Step No. 17 Calculate the regulation, α.

$$\alpha = \frac{P_{cu}}{P_o}(100), \quad [\%]$$

$$\alpha = \frac{(0.853)}{(100)}(100), \quad [\%]$$

$$\alpha = 0.853, \quad [\%]$$

Step No. 18 Calculate the ac flux density, B_{ac}.

$$B_{ac} = \frac{0.4\pi N_L \left(\frac{\Delta I}{2}\right) \mu (10^{-4})}{\text{MPL}}, \quad [\text{tesla}]$$

$$B_{ac} = \frac{(1.25)(256)\left(\frac{0.2}{2}\right)(60)(10^{-4})}{(8.95)}, \quad [\text{tesla}]$$

$$B_{ac} = 0.0215, \quad [\text{tesla}]$$

Step No. 19 Calculate the watts per kilogram for the appropriate MPP powder core material in Chapter 2. Watts per kilogram can be written in milliwatts per gram.

$$\text{mW/g} = k f^{(m)} B_{ac}^{(n)}$$

$$\text{mW/g} = (0.00551)(20000)^{(1.23)} (0.0215)^{(2.12)}$$

$$\text{mW/g} = 0.313$$

Step No. 20 Calculate the core loss, P_{fe}.

$$P_{fe} = (\text{mW/g})(W_{tfe})(10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = (0.313)(34.9)(10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = 0.011, \quad [\text{watts}]$$

Step No. 21 Calculate the total loss copper plus iron, P_{Σ}.

$$P_{\Sigma} = P_{fe} + P_{cu}, \quad [\text{watts}]$$

$$P_{\Sigma} = (0.011) + (0.853), \quad [\text{watts}]$$

$$P_{\Sigma} = 0.864, \quad [\text{watts}]$$

Step No. 22 Calculate the watt density, ψ. The surface area, A_t can be found in Step 6.

$$\psi = \frac{P_{\Sigma}}{A_t}, \quad [\text{watts/cm}^2]$$

$$\psi = \frac{(0.864)}{(64.4)}, \quad [\text{watts/cm}^2]$$

$$\psi = 0.0134, \quad [\text{watts/cm}^2]$$

Step No. 23 Calculate the temperature rise, T_r.

$$T_r = 450(\psi)^{(0.826)}, \quad [^\circ C]$$

$$T_r = 450(0.0134)^{(0.826)}, \quad [^\circ C]$$

$$T_r = 12.8, \quad [^\circ C]$$

Step No. 24 Calculate the dc magnetizing force, H.

$$H = \frac{0.4\pi N_L I_{pk}}{\text{MPL}}, \quad [\text{oersteds}]$$

$$H = \frac{(1.26)(256)(1.6)}{(8.95)}, \quad [\text{oersteds}]$$

$$H = 57.7, \quad [\text{oersteds}]$$

Step No. 25 Calculate the window utilization, K_u.

$$K_u = \frac{N_{L(new)} A_{w(B)\#20}}{W_a}$$

$$K_u = \frac{((256)(0.00519))}{(3.94)}$$

$$K_u = 0.337$$

Note:
The big advantage in using the core geometry design procedure is that the current density is calculated. Using the area product design procedure, the current density is an estimate at best. In this next design the same current density will be used as in core geometry.

Toroidal Powder Core Inductor Design, Using the Area Product, A_p, Approach

Step No. 1 Design a linear dc inductor with the following specifications.

1. Inductance, L .... = 0.0025 henrys

2. dc current, I_o .... = 1.5 amps

3. ac current, ΔI .... = 0.2 amps

4. Output power, P_o .... = 100 watts

5. Current Density, J .... = 300 amps-per-cm^2

6. Ripple Frequency .... = 20 kHz

7. Operating flux density, B_m .... = 0.3 tesla

8. Core Material .... = MPP

9. Window utilization, K_u .... = 0.4

10. Temperature rise goal, T_r .... = 25°C

Step No. 2 Calculate the peak current, I_{pk}.

$$I_{pk} = I_o + \frac{\Delta I}{2}, \quad [\text{amps}]$$

$$I_{pk} = (1.5) + \frac{(0.2)}{2}, \quad [\text{amps}]$$

$$I_{pk} = 1.6, \quad [\text{amps}]$$

Step No. 3 Calculate the energy-handling capability.

$$\text{Energy} = \frac{L I_{pk}^2}{2}, \quad [\text{watt-seconds}]$$

$$\text{Energy} = \frac{(0.0025)(1.6)^2}{2}, \quad [\text{watt-seconds}]$$

$$\text{Energy} = 0.0032, \quad [\text{watt-seconds}]$$

Step No. 4 Calculate the area product, A_p.

$$A_p = \frac{2(\text{Energy})(10^4)}{B_m J K_u}, \quad [\text{cm}^4]$$

$$A_p = \frac{2(0.0032)(10^4)}{(0.3)(300)(0.4)}, \quad [\text{cm}^4]$$

$$A_p = 1.78, \quad [\text{cm}^4]$$

Step No. 5 Select a MPP powder core from Chapter 3. The data listed is the closest core to the calculated core geometry, K_g.

1. Core Number .... = 55586
2. Magnetic Path Length, MPL .... = 8.95 cm
3. Core Weight, W_{tfe} .... = 34.9 grams
4. Mean Length Turn, MLT .... = 4.40 cm
5. Iron Area, A_c .... = 0.454 cm^2
6. Window Area, W_a .... = 3.94 cm^2
7. Area Product, A_p .... = 1.79 cm^4
8. Core Geometry, K_g .... = 0.0742 cm^5
9. Surface Area, A_t .... = 64.4 cm^2
10. Permeability, μ .... = 60
11. Millihenrys-per-1k, A L .... = 38 mh

Step No. 6 Calculate the rms current, I_{rms}.

$$I_{rms} = \sqrt{I_o^2 + \Delta I^2}, \quad [\text{amps}]$$

$$I_{rms} = \sqrt{(1.5)^2 + (0.2)^2}, \quad [\text{amps}]$$

$$I_{rms} = 1.51, \quad [\text{amps}]$$

Step No. 7 Calculate the required bare wire area, $A_{w(B)}$.

$$A_{W(B)} = \frac{I_{rms}}{J}, \quad [\text{cm}^2]$$

$$A_{W(B)} = \frac{(1.51)}{(298)}, \quad [\text{cm}^2]$$

$$A_{W(B)} = 0.00507, \quad [\text{cm}^2]$$

Step No. 8 Select a wire from the Wire Table in Chapter 4. If the area is not within 10%, take the next smallest size. Also, record the micro-ohms per centimeter.

$$AWG = \#20$$

$$\text{Bare, } A_{W(B)} = 0.00519, \quad [\text{cm}^2]$$

$$\text{Insulated, } A_W = 0.00606, \quad [\text{cm}^2]$$

$$\left(\frac{\mu\Omega}{\text{cm}}\right) = 332, \quad [\text{micro-ohm/cm}]$$

Step No. 9 Calculate the effective window area, $W_{a(eff)}$. Use the window area found in Step 5. A typical value for, S_3 is 0.75 as shown in Chapter 4.

$$W_{a(eff)} = W_a S_3, \quad [\text{cm}^2]$$

$$W_{a(eff)} = (3.94)(0.75), \quad [\text{cm}^2]$$

$$W_{a(eff)} = 2.96, \quad [\text{cm}^2]$$

Step No. 10 Calculate the number turns possible, N. Use the insulated wire area, A_w found in Step 8. A typical value for, S_2, is 0.6, as shown in Chapter 4.

$$N = \frac{W_{a(eff)} S_2}{A_W}, \quad [\text{turns}]$$

$$N = \frac{(2.96)(0.60)}{(0.00606)}, \quad [\text{turns}]$$

$$N = 293, \quad [\text{turns}]$$

Step No. 11 Calculate the required core permeability, μ.

$$\mu_\Delta = \frac{B_m (\text{MPL})(10^4)}{0.4\pi W_a J K_u}$$

$$\mu_\Delta = \frac{(0.30)(8.95)(10^4)}{(1.26)(3.94)(298)(0.4)}$$

$$\mu_\Delta = 45.4$$

Note:

The permeability of 45.4 is close enough to use a 60μ core. Also note there are other permeabilities available, See Table 9-1. Because of size, Chapter 3 has listed only 60μ tables for MPP, High Flux, Sendust and 75μ table for Iron powder. For cores with other than 60μ, use the manufacturer's catalog.

Step No. 12 Calculate the number of turns, N_L, required.

$$N_L = 1000\sqrt{\frac{L}{L_{(1000)}}}, \quad [\text{turns}]$$

$$N_L = 1000\sqrt{\left(\frac{2.5}{38}\right)}, \quad [\text{turns}]$$

$$N_L = 256, \quad [\text{turns}]$$

Step No. 13 Calculate the winding resistance, R_L. Use the MLT from Step 6 and the micro-ohm per centimeter from Step 10.

$$R_L = (\text{MLT})(N_L)\left(\frac{\mu\Omega}{\text{cm}}\right)(10^{-6}), \quad [\text{ohms}]$$

$$R_L = (4.4)(256)(332)(10^{-6}), \quad [\text{ohms}]$$

$$R_L = 0.374, \quad [\text{ohms}]$$

Step No. 14 Calculate the copper loss, P_{cu}.

$$P_{cu} = I_{rms}^2 R_L, \quad [\text{watts}]$$

$$P_{cu} = (1.51)^2(0.374), \quad [\text{watts}]$$

$$P_{cu} = 0.853, \quad [\text{watts}]$$

Step No. 15 Calculate the ac flux density, B_{ac}.

$$B_{ac} = \frac{0.4\pi N_L \left(\frac{\Delta I}{2}\right)\mu(10^{-4})}{\text{MPL}}, \quad [\text{tesla}]$$

$$B_{ac} = \frac{(1.25)(256)\left(\frac{0.2}{2}\right)(60)(10^{-4})}{(8.95)}, \quad [\text{tesla}]$$

$$B_{ac} = 0.0215, \quad [\text{tesla}]$$

Step No. 16 Calculate the watts per kilogram for the appropriate MPP powder core material in Chapter 2. Watts per kilogram can be written in milliwatts per gram.

$$\text{mW/g} = k f^{(m)} B_{ac}^{(n)}$$

$$\text{mW/g} = (0.00551)(20000)^{(1.23)} (0.0215)^{(2.12)}$$

$$\text{mW/g} = 0.313$$

Step No. 17 Calculate the core loss, P_{fe}.

$$P_{fe} = (\text{mW/g})(W_{tfe})(10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = (0.313)(34.9)(10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = 0.011, \quad [\text{watts}]$$

Step No. 18 Calculate the total copper loss plus iron, P_Σ.

$$P_\Sigma = P_{fe} + P_{cu}, \quad [\text{watts}]$$

$$P_\Sigma = (0.011)+(0.853), \quad [\text{watts}]$$

$$P_\Sigma = 0.864, \quad [\text{watts}]$$

Step No. 19 Calculate the watt density, ψ. The surface area, A_t can be found in Step 5.

$$\psi = \frac{P_\Sigma}{A_t}, \quad [\text{watts/cm}^2]$$

$$\psi = \frac{(0.864)}{(64.4)}, \quad [\text{watts/cm}^2]$$

$$\psi = 0.0134, \quad [\text{watts/cm}^2]$$

Step No. 20 Calculate the temperature rise, T_r.

$$T_r = 450(\psi)^{(0.826)}, \quad [°C]$$
$$T_r = 450(0.0134)^{(0.826)}, \quad [°C]$$
$$T_r = 12.8, \quad [°C]$$

Step No. 21 Calculate the dc magnetizing force, H.

$$H = \frac{0.4\pi N_L I_{pk}}{\text{MPL}}, \quad [\text{oersteds}]$$
$$H = \frac{(1.26)(256)(1.6)}{(8.95)}, \quad [\text{oersteds}]$$
$$H = 57.7, \quad [\text{oersteds}]$$

Step No. 22 Calculate the window utilization, K_u.

$$K_u = \frac{N_{L(new)} A_{w(B)\#20}}{W_a}$$
$$K_u = \frac{((256)(0.00519))}{(3.94)}$$
$$K_u = 0.337$$