Core loss is generated by the changing magnetic flux field within a material, since no magnetic materials exhibit perfectly efficient magnetic response. Core loss density (PL) is a function of half of the AC flux swing ($\frac{1}{2} \Delta B_{AC}$) and frequency ($f$). It can be approximated from core loss charts or the curve fit loss equation:

$$PL = aB_p^b \times f^c$$

where $a$, $b$, and $c$ are constants determined from curve fitting, and $B_p$ is defined as half of the AC flux swing:

$$B_p = \frac{\Delta B_{AC}}{2} = \frac{B_{ACmax} - B_{ACmin}}{2}$$

Units typically used are (mW/cm²) for PL; Tesla (T) for $B_p$; and (kHz) for $f$.

The task of core loss calculation is to determine $B_p$, from known design parameters.

Method 1 – Determine $B_{pk}$ from DC Magnetization Curve, $B_{pk} = f(H)$

Flux density ($B$) is a non-linear function of magnetizing field ($H$), which in turn is a function of winding number of turns ($N$), current ($I$), and magnetic path length ($l$). The value of $B_{pk}$ can typically be determined by first calculating $H$ at each AC extreme:

$$H_{ACmax} = \frac{N}{l} (I_{BC} + \frac{\Delta I}{2})$$

$$H_{ACmin} = \frac{N}{l} (I_{BC} - \frac{\Delta I}{2})$$

Units typically used are (A-T/cm) for $H$.

From $H_{ACmax}$, $H_{ACmin}$, and the BH curve or equation (listed as DC Magnetization, pgs. 47-50), $B_{ACmax}$, $B_{ACmin}$ and therefore $B_{pk}$ can be determined.

Example 1 - AC current is 10% of DC current:

Approximate the core loss of an inductor with 20 turns wound on Kool Mu p/n 77894A7 p. 76 ($60 \mu$, $i_r=6.35$ cm, $A_r=0.654$ cm², $A_s=75$ nH/T²). Inductor current is 20 Amps DC with ripple of 2 Amps peak-peak at 100kHz.

1.) Calculate $H$ and determine $B$ from BH curve (p. 48) or curve fit equation (p. 50):

$$H_{ACmax} = \frac{20}{6.35} (20 + \frac{2}{2}) = 66.14 \text{ T} \rightarrow B_{ACmax} \approx 0.40 \text{ T}$$

$$H_{ACmin} = \frac{20}{6.35} (20 - \frac{2}{2}) = 59.84 \text{ T} \rightarrow B_{ACmin} \approx 0.37 \text{ T}$$

$$\rightarrow B_{pk} = \frac{\Delta B}{2} = \frac{0.40 - 0.37}{2} = 0.015 \text{ T}$$

2.) Determine Core Loss density from chart or calculate from loss equation p. 46:

$$PL = (62.65)(0.015^{0.74})(100^{0.65}) \approx 18.5 \text{ mW/cm}^2$$

3.) Calculate core loss:

$$P_r = (PL)(I_r)(A_r) \approx \frac{18.5(6.35)(0.654)}{77 \times 10^{-6}} \approx 77 \text{ mW}$$

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Example 2 - AC current is 40% of DC current:
Approximate the core loss for the same 20-turn inductor, with same inductor current of 20 Amps DC but ripple of 8 Amps peak-peak at 100kHz.

1.) Calculate $H$ and determine $B$ from BH curve fit equation p. 50:

$$ H_{ac,max} = \frac{20}{6.35} \left( 20 + \frac{8}{2} \right) = 75.59 \text{ A/m} \rightarrow B_{ac,max} = 0.44 \text{T} $$

$$ H_{ac,min} = \frac{20}{6.35} \left( 20 - \frac{8}{2} \right) = 50.39 \text{ A/m} \rightarrow B_{ac,min} = 0.33 \text{T} $$

$$ \rightarrow B_{av} = \frac{B_{av}}{2} = 0.44 + 0.33 = 0.055 \text{T} $$

2.) Determine Core Loss density from chart or calculate from loss equation p. 46:

$$ PL = (62.65)(0.055^{1.39})(100^{1.39}) \approx 188 \text{ mW/cm}^2 $$

3.) Calculate core loss:

$$ P_c = (PL)(l)(A_c) = (188)(6.35)(0.654) \approx 781 \text{ mW} $$

Note: Core losses result only from AC excitation. DC bias applied to any core does not cause any core losses, regardless of the magnitude of the bias.

Example 3 – pure AC, no DC:
Approximate the core loss for the same 20-turn inductor, now with 0 Amps DC and 8 Amps peak-peak at 100kHz.

1.) Calculate $H$ and determine $B$ from BH curve fit equation p. 50:

$$ H_{ac,max} = \frac{20}{6.35} \left( 12.60 + \frac{8}{2} \right) = 12.60 \text{ A/m} \rightarrow B_{ac,max} \approx 0.092 \text{T} $$

$$ H_{ac,min} = \frac{20}{6.35} \left( 12.60 - \frac{8}{2} \right) = -12.60 \text{ A/m} \rightarrow B_{ac,min} \approx -0.092 \text{T} $$

$$ \rightarrow B_{av} = \frac{B_{av}}{2} \approx 0.092 \text{T} $$

Note: Curve fit equations are not valid for negative values of $B$. Evaluate for the absolute value of $B$, then reverse the sign of the resulting H value.

2.) Determine Core Loss density from chart or calculate from loss equation p. 46:

$$ PL = (62.65)(0.092^{1.39})(100^{1.39}) \approx 470 \text{ mW/cm}^2 $$

3.) Calculate core loss:

$$ P_c = (PL)(l)(A_c) = (470)(6.35)(0.654) \approx 1.96 \text{ W} $$

Plotted below are the operating ranges for each of the three examples.

Note the significant influence of DC bias on core loss, comparing Example 3 with Example 2. Lower permeability results in less $B_{av}$, even if the current ripple is the same. This effect can be achieved with DC bias, or by selecting a lower permeability material.
Powder Core Loss Calculation

Method 2, for small $\Delta H$, approximate $B_{pk}$ from effective perm with DC bias.

$$B_{pk} = f(\mu_e, \Delta H)$$

The instantaneous slope of the BH curve is defined as the absolute permeability, which is the product of permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$) and the material permeability ($\mu$), which varies along the BH curve. For small AC, this slope can be modeled as a constant throughout AC excitation, with $\mu$ approximated as the effective perm at DC bias ($\mu_e$):

$$\frac{dB}{dH} = \mu_e \mu_s \rightarrow \Delta B = \mu_e \mu_s \Delta H \quad B_{pk} = \frac{\Delta B}{2} = 0.5 \mu_e \mu_s \Delta H$$

The effective perm with DC bias is shown in this catalog as % of initial perm and can be obtained from the DC bias curve or curve fit equation, page 29-34

$$B_{pk} = (0.5)(\mu_e)(%\mu_e)(\mu)(100)(\Delta H) \quad \text{where} \quad \Delta H = \frac{N\Delta l}{I_s}$$

$\Delta H$ is multiplied by 100 because $I_s$ is expressed in cm, while $B_{pk}$ units include m.

**Reworking Example 1** (20 Amps DC, 2 Amps pk-pk)

$$H_{dc} = \left[\frac{20}{6.35}\right] = 63 \frac{^\circ}{cm} \rightarrow \text{from curve or curve fit equation, } \%\mu_e = 0.58$$

$$\mu_e = 60$$

$$\Delta H = \frac{N\Delta l}{I_s} = \frac{20(2)}{6.35} = 6.3 \frac{^\circ}{cm}$$

$$B_{pk} = 0.5(4\pi \times 10^{-7})(0.58)(60)(100)(6.3) \approx 0.014 T \quad \text{(this compares to 0.015T using Method 1)}$$

**Reworking Example 2** (20 Amps DC, 8 Amps pk-pk)

From example 1,

$$H_{dc} = 63 \frac{^\circ}{cm}, \%\mu_e = 0.58; \mu_e = 60$$

$$\Delta H = \frac{N\Delta l}{I_s} = \frac{20(8)}{6.35} = 25.2 \frac{^\circ}{cm}$$

$$B_{pk} = 0.5(4\pi \times 10^{-7})(0.58)(60)(100)(25.2) = 0.055 T \quad \text{(this compares to 0.055T using Method 1)}$$

**Reworking Example 3** (0 Amps DC, 8 Amps pk-pk)

From example 2,

$$\Delta H = 25.20 \frac{^\circ}{cm}$$

$$H_{dc} = 0 \frac{^\circ}{cm}, \%\mu_e = 1$$

$$B_{pk} = 0.5(4\pi \times 10^{-7})(1)(60)(100)(25.2) = 0.095 T \quad \text{(this compares to 0.092T using Method 1)}$$
Powder Core Loss Calculation

Method 3, for small $\Delta H$, determine $B_{pk}$ from biased inductance. $B_{pk} = f(L, I)$

$B$ can be rewritten in terms of inductance by considering Faraday’s equation and its effect on inductor current:

$$V_c = NA \quad \frac{dB}{dt} = L \frac{dl}{dt} \quad \rightarrow \quad dB = \frac{L}{NA} \cdot dl$$

$L$ varies non-linearly with $I$. For small AC, $L$ can be assumed constant throughout AC excitation and is approximated by the biased inductance ($L_{dc}$).

$$\Delta B = \frac{L_{dc} \cdot \Delta I}{NA} \quad \rightarrow \quad B_{pk} = \frac{L_{dc} \cdot \Delta I}{2NA_s}$$

Another way of looking at this is by rewriting the relationship between $B$ and $L$ as:

$$\rightarrow \quad \frac{dB}{dH} = \frac{L}{NA_s} \cdot \frac{dl}{dh}$$

Substituting $(dl/dH)$ with $(N/l_s)$ and $A$ with $A_s$:

$$\rightarrow \quad \frac{dB}{dH} = \frac{L \cdot l_s}{N^2A_s}$$

$L$ varies non-linearly with $H$. For small AC, the slope of the BH curve is assumed constant throughout AC excitation, and $L$ is approximated by the biased inductance ($L_{dc}$).

$$\frac{\Delta B}{\Delta H} = \frac{L_{dc} \cdot l_s}{N^2A_s} \quad \rightarrow \quad \Delta B = \frac{L_{dc} \cdot l_s}{N^2A_s} \cdot \Delta H = \frac{L_{dc} \cdot \Delta I}{NA_s} \quad \rightarrow \quad \Delta B_{pk} = \frac{L_{dc} \cdot \Delta I}{2NA_s}$$
Powder Core Loss Calculation

Reworking Example 1:

\[ L_{\text{ac}} \text{ (no load)} = (A_0 \cdot N^2) = (75 \text{ nH/T}^2) (20^2) = 30 \mu\text{H} \]
\[ L_{\text{dc}} \text{ (20A)} = (% \mu) (L_0) = (0.58) (30) = 17.4 \mu\text{H} \]
\[ B_{\text{m}} = \frac{(17.4)(10^{-5})(2)}{2(20)(0.654)(10^{-7})} = 0.013 \text{T} \quad \text{(this compares to 0.015T per Method 1, 0.014T per Method 2).} \]

Reworking Example 2:

\[ B_{\text{m}} = \frac{(17.4)(10^{-5})(8)}{2(20)(0.654)(10^{-7})} = 0.053 \text{T} \quad \text{(this compares to 0.055T per Method 1, 0.055T per Method 2).} \]

Reworking Example 3:

\[ B_{\text{m}} = \frac{(30)(10^{-5})(8)}{2(20)(0.654)(10^{-7})} = 0.092 \text{T} \quad \text{(this compares to 0.092T per Method 1, 0.095T per Method 2).} \]

The plot below illustrates the difference between Method 1 and Method 2.