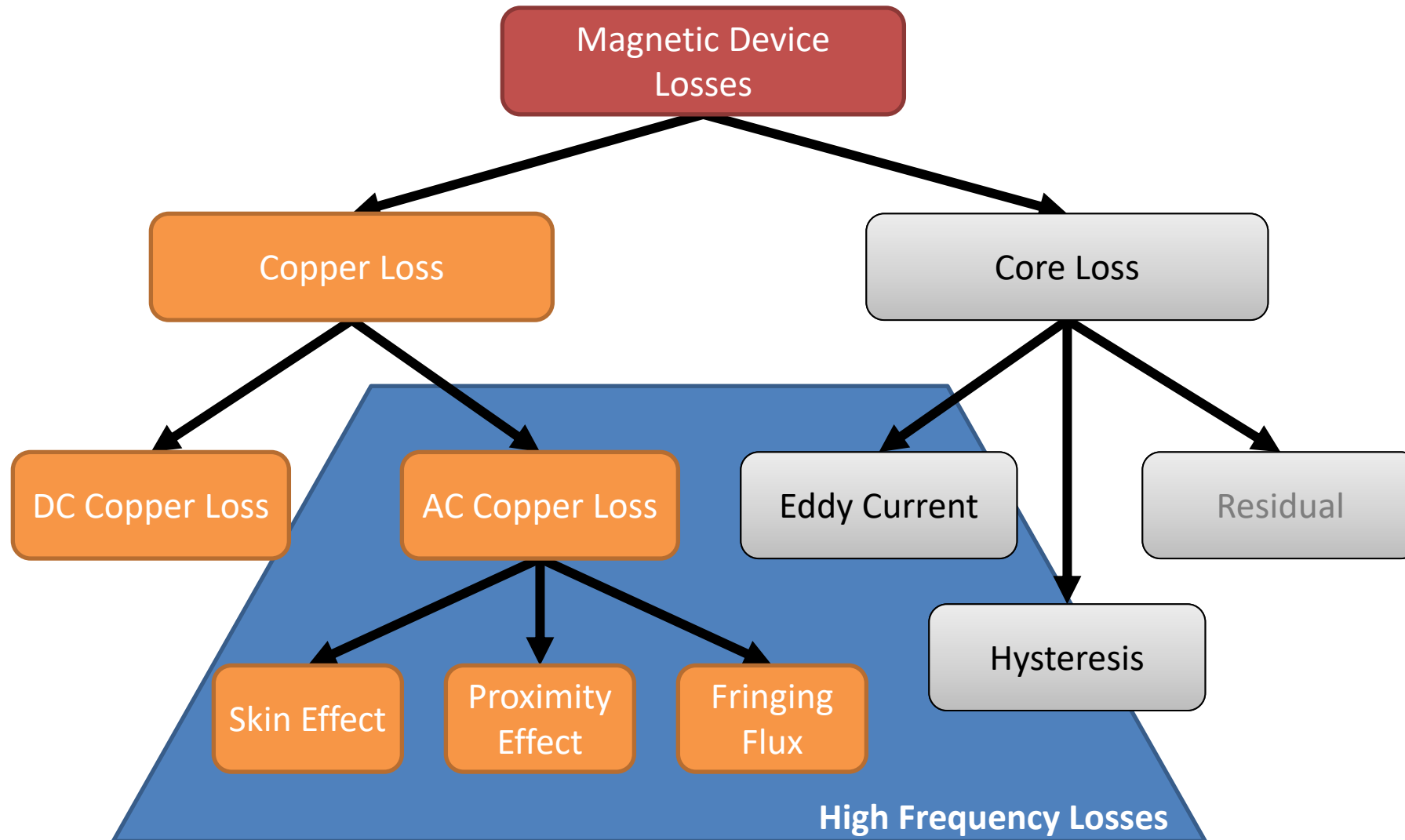


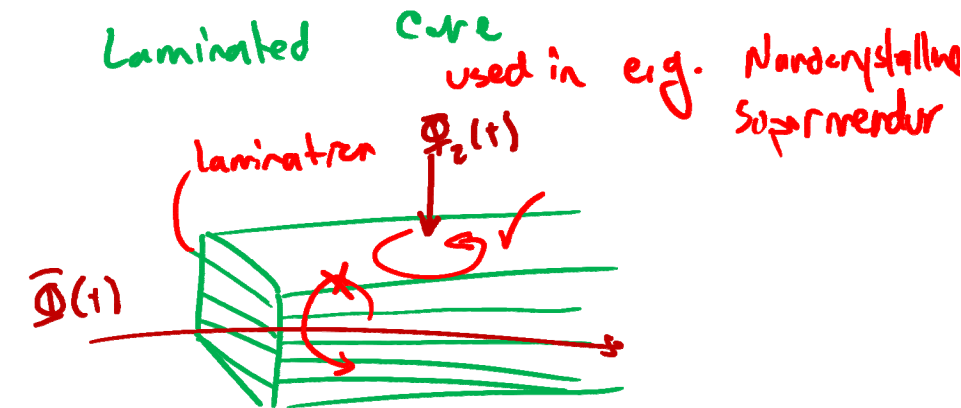
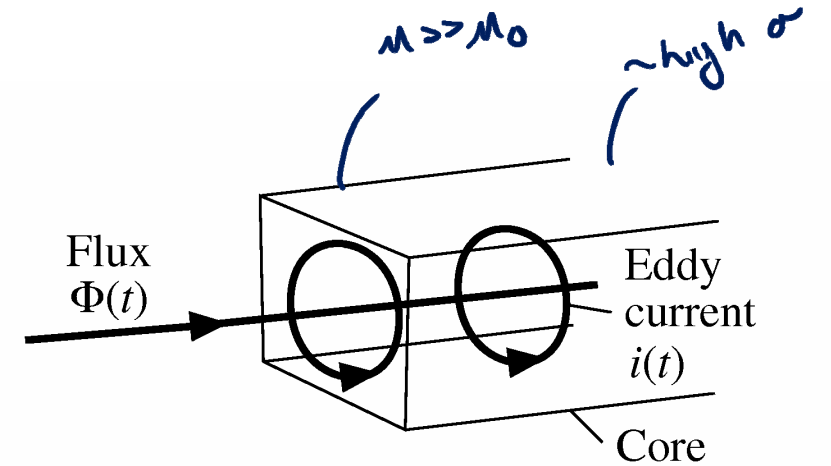
13.3 Magnetics Losses

10.3



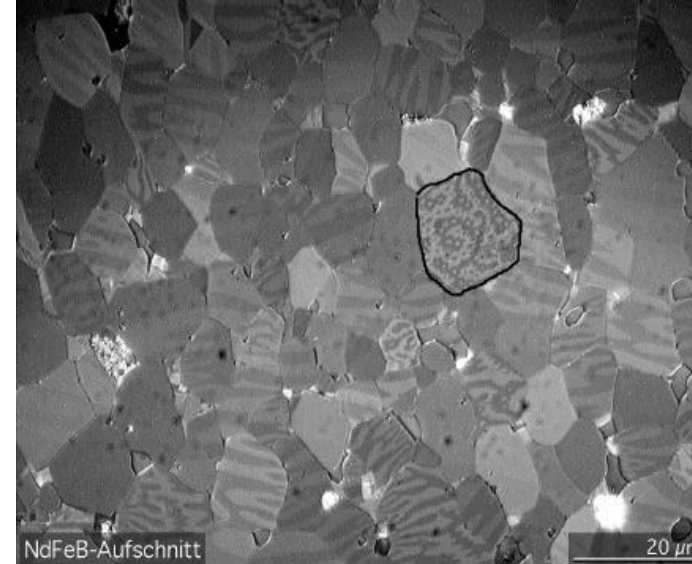
Eddy Currents in Magnetic Materials

if core material is resistive
 Pddy $\propto f^2$
 things like Ferrite are resistive + capacitive
 Pddy $\propto f^4$



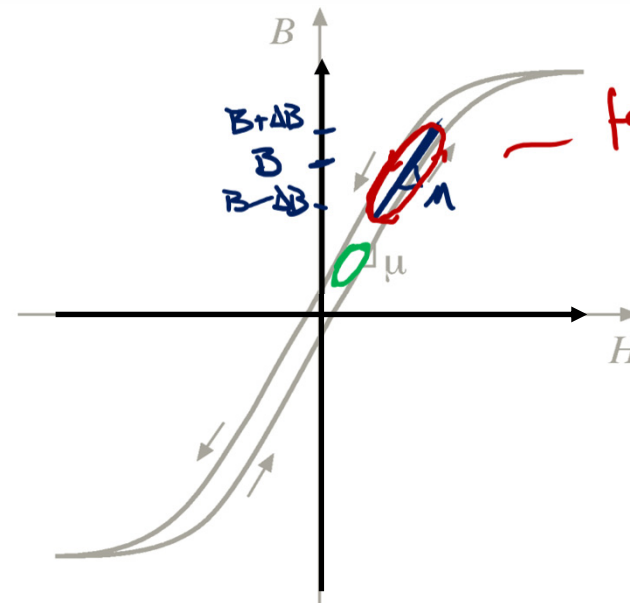
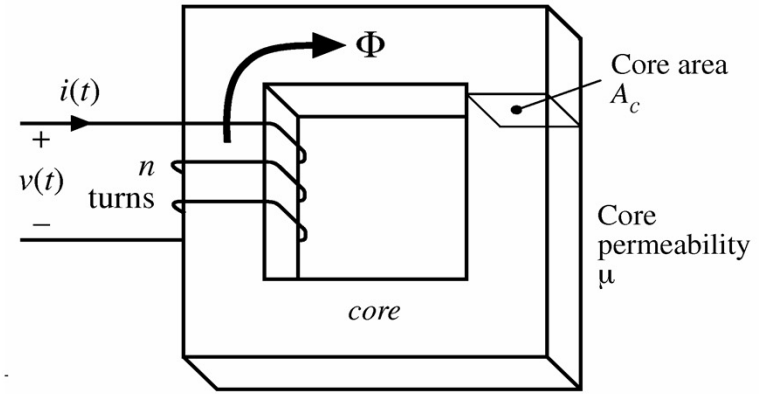
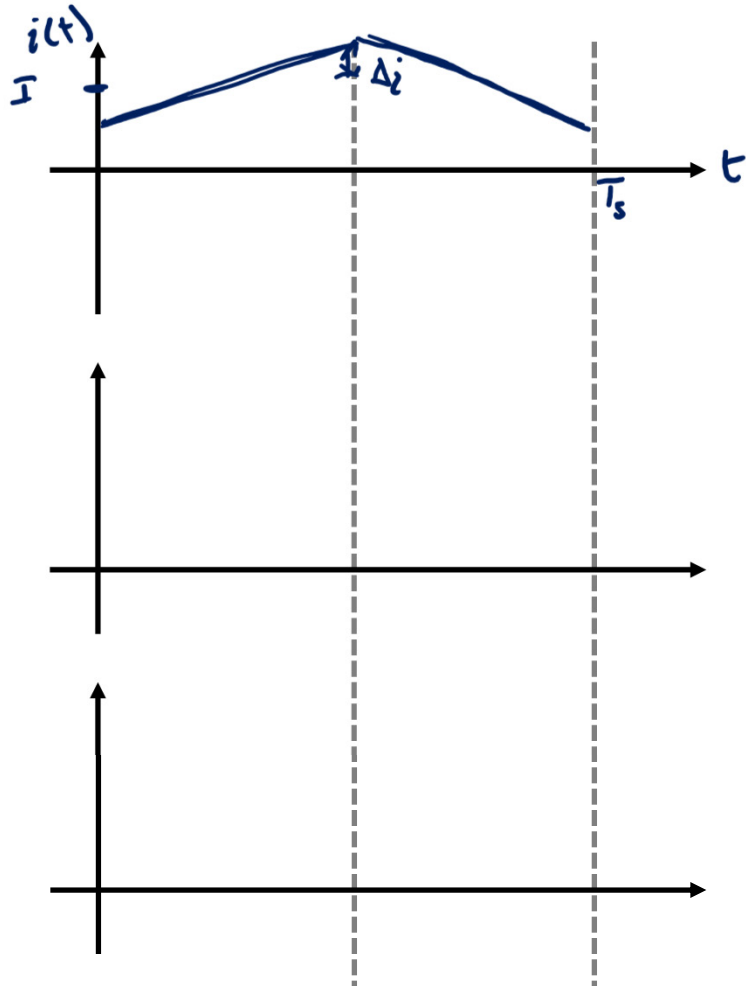
Core Loss

- Physical origin due to magnetic domains
- Modeling Approaches
 - Empirical (curve fit) models of materials
 - Direct measurement-based models
 - Physics-based models



B-H Curve: Filter Inductor

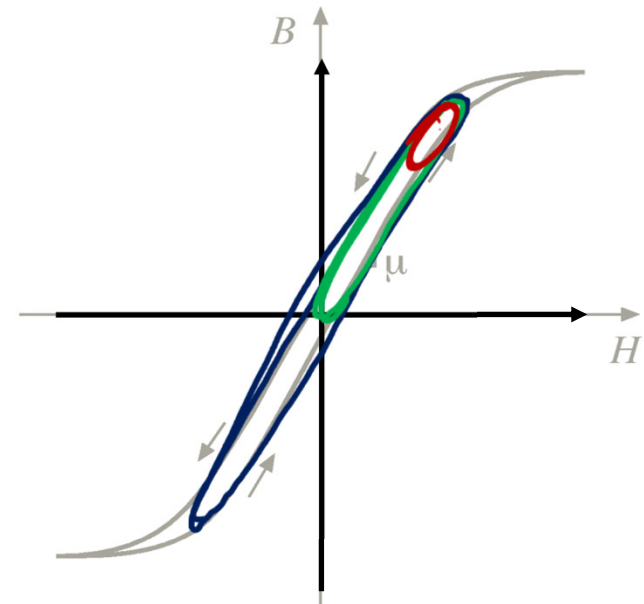
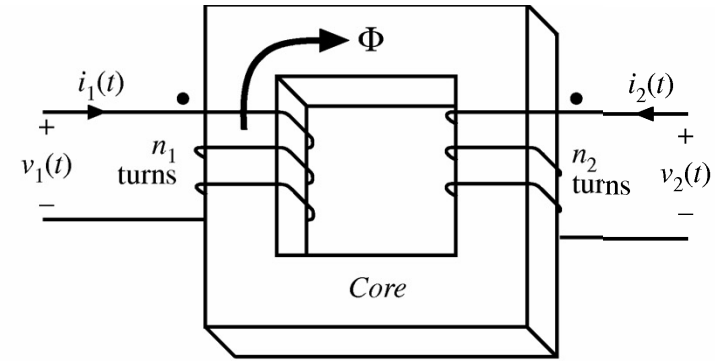
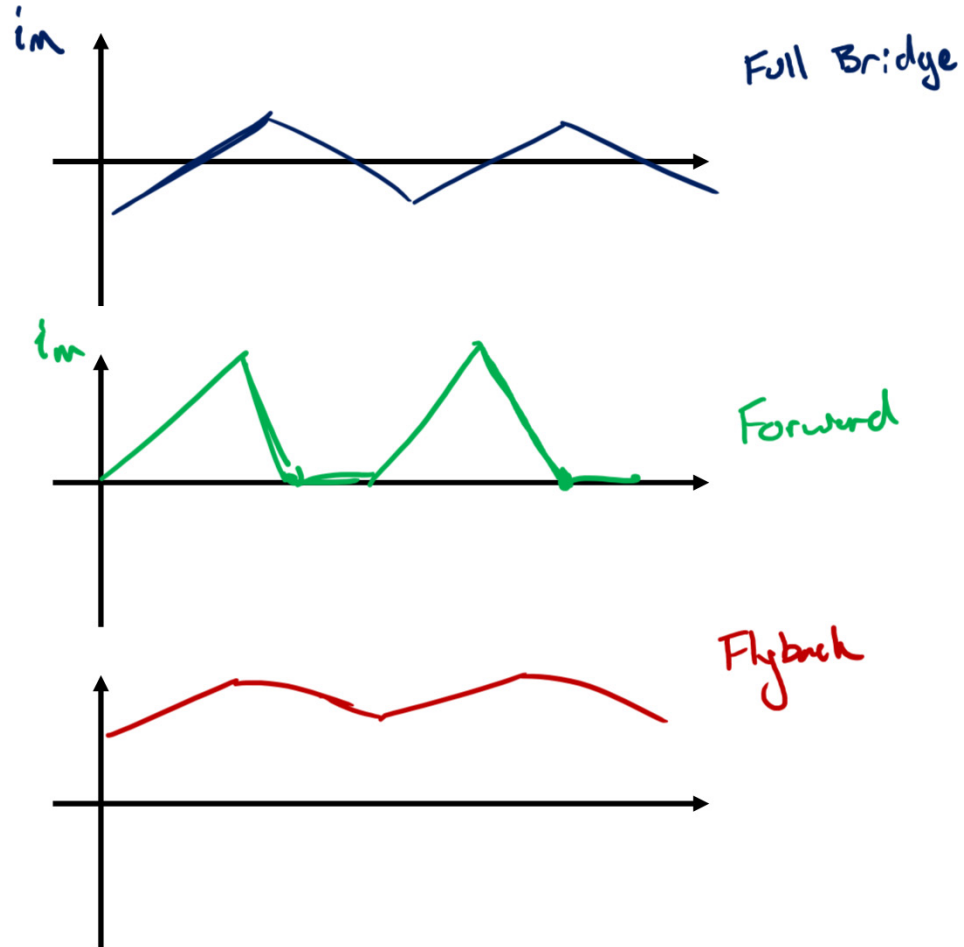
$n \frac{d\Phi}{dt} = v(t)$
 $L \frac{di}{dt} = v(t)$
 $n\Phi = Li$
 $nBA_c = Li$
 $B = \frac{L}{nA_c} i$



for filter inductor
 large bias,
 small ripple
 on $I \neq B$



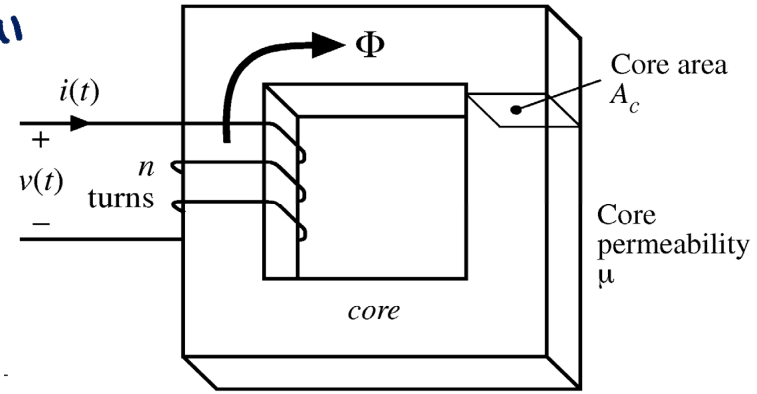
B-H Curve: Transformer



Hysteresis Loss

$$W = \int N \cdot i \, dt = \phi \text{ for ideal inductor}$$

one period in steady-state



Faraday : $v(t) = n \frac{d\Phi(t)}{dt} = n A_c \frac{dB(t)}{dt}$

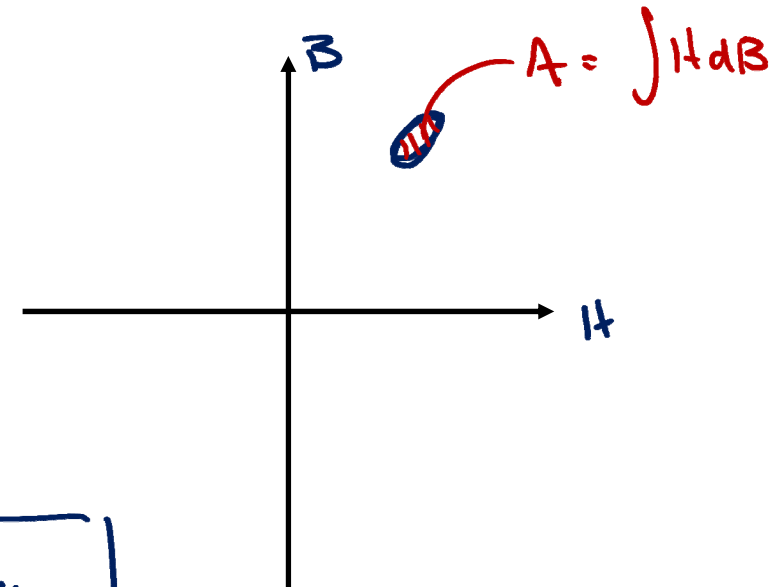
Ampere : $n i(t) = H(t) l_m$

$$W = \int_{\text{one cycle}} \left(n A_c \frac{dB(t)}{dt} \right) \cdot \left(\frac{H(t) l_m}{n} \right) dt$$

$$= A_c l_m \int_{\text{one cycle}} H(t) \frac{dB(t)}{dt} dt = A_c l_m \int H dB$$

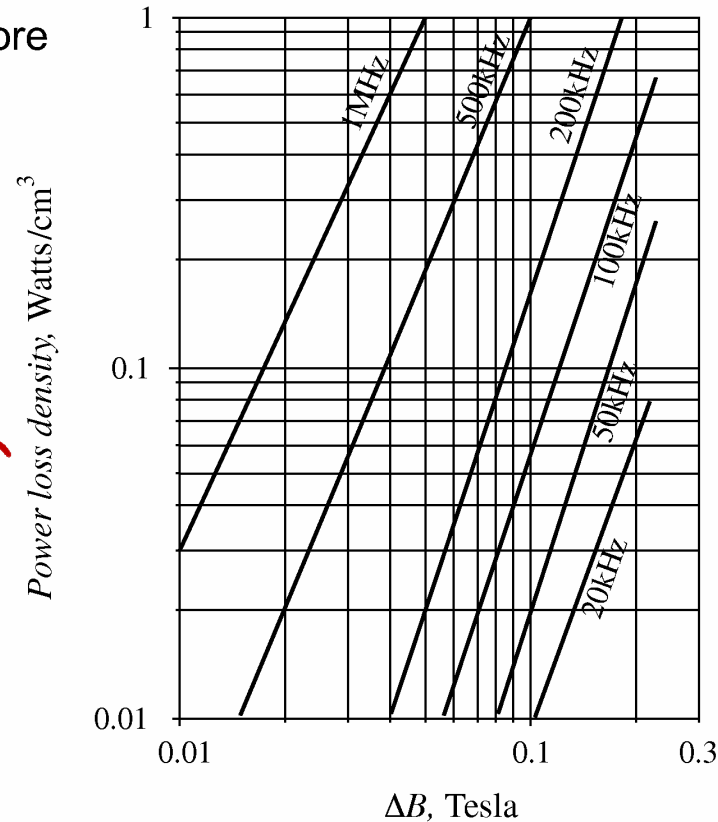
$$P = A_c l_m f_s \int H dB$$

$V_e \rightarrow$ effective volume



The Steinmetz Equation

Ferrite core material



Limits

- ① only accurate for sinusoidal bias waveforms
- ② P_{fe} is a nonlinear function so superposition doesn't apply

Empirical equation, at a fixed frequency:

$$P_{fe} = K_{fe} (\Delta B)^\beta A_c \ell_m$$

K_{fe} , β → empirical curve fit params

Alternately:

$$P_v = K_m f^\alpha (\Delta B)^\beta$$

Steinmetz Equation: Notes

- Purely empirical; not physics-based
- Parameters α , β , K vary with frequency
- Correct only for sinusoidal excitation
 - Nonlinear; Fourier expansion of waveforms cannot be used
- Modified empirical equations perform better with nonsinusoidal waveforms
 - MSE
 - GSE
 - iGSE
 - i^2 GSE

Transformer Design Constraints

① obtain designer $n_1 : n_2$

③ Make windings fit in window

② Minimize $P_{\text{loss}} \approx P_{\text{Rac}} + P_{\text{fe}}$
DC copper loss \rightarrow P_{Rac}
core loss \rightarrow P_{fe}

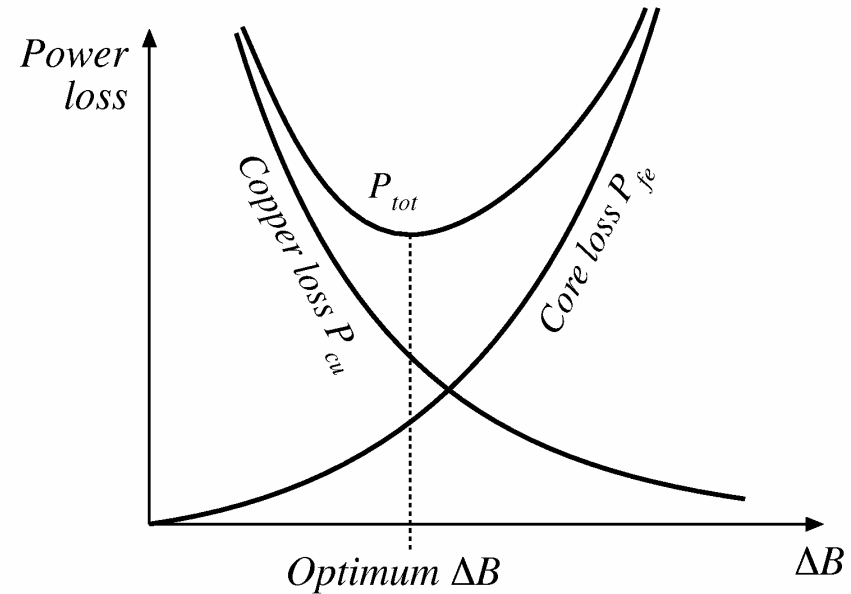
Minimizing Total Loss

There is a value of ΔB that minimizes the total power loss

$$P_{tot} = P_{fe} + P_{cu}$$

$$P_{fe} = K_{fe}(\Delta B)^\beta A_c \ell_m$$

$$P_{cu} = \left(\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u} \right) \left(\frac{(MLT)}{W_A A_c^2} \right) \left(\frac{1}{\Delta B} \right)^2$$



Calculation of Total Loss

Substitute optimum ΔB into expressions for P_{cu} and P_{fe} . The total loss is:

$$P_{tot} = \left[A_c \ell_m K_{fe} \right]^{\left(\frac{2}{\beta+2} \right)} \left[\frac{\rho \lambda_1^2 I_{tot}^2}{4K_u} \frac{(MLT)}{W_A A_c^2} \right]^{\left(\frac{\beta}{\beta+2} \right)} \left[\left(\frac{\beta}{2} \right)^{-\left(\frac{\beta}{\beta+2} \right)} + \left(\frac{\beta}{2} \right)^{\left(\frac{2}{\beta+2} \right)} \right]$$

Rearrange as follows:

$$\frac{W_A (A_c)^{2(\beta-1)/\beta}}{(MLT) \ell_m^{(2/\beta)}} \left[\left(\frac{\beta}{2} \right)^{-\left(\frac{\beta}{\beta+2} \right)} + \left(\frac{\beta}{2} \right)^{\left(\frac{2}{\beta+2} \right)} \right]^{-\left(\frac{\beta+2}{\beta} \right)} = \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}}$$

Left side: terms depend on core geometry

Right side: terms depend on specifications of the application

The K_{gfe} Method

Define
$$K_{gfe} = \frac{W_A(A_c)^{(2(\beta-1)/\beta)}}{(MLT)\ell_m^{(2/\beta)}} \left[\left(\frac{\beta}{2}\right)^{-\left(\frac{\beta}{\beta+2}\right)} + \left(\frac{\beta}{2}\right)^{\left(\frac{2}{\beta+2}\right)} \right]^{-\left(\frac{\beta+2}{\beta}\right)}$$

Design procedure: select a core that satisfies

$$K_{gfe} \geq \frac{\rho\lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u(P_{tot})^{((\beta+2)/\beta)}}$$

Appendix D lists the values of K_{gfe} for common ferrite cores

K_{gfe} is similar to the K_g geometrical constant used in Chapter 14:

- K_g is used when B_{max} is specified
- K_{gfe} is used when ΔB is to be chosen to minimize total loss

The K_{gfe} Method

$$K_{gfe} \geq \frac{\rho \lambda_1^2 I_{tot}^2 K_{fe}^{(2/\beta)}}{4K_u (P_{tot})^{((\beta+2)/\beta)}} 10^8$$

$$\Delta B = \left[10^8 \frac{\rho \lambda_1^2 I_{tot}^2}{2K_u} \frac{(MLT)}{W_A A_c^3 \ell_m} \frac{1}{\beta K_{fe}} \right]^{(\frac{1}{\beta+2})}$$

$$n_1 = \frac{\lambda_1}{2\Delta B A_c} 10^4 \quad n_k = n_1 \frac{n_k}{n_1}$$

$$\alpha_k = \frac{n_k I_k}{n_1 I_{tot}} \quad A_{wk} \leq \frac{\alpha_2 K_u W_A}{n_2}$$

Verify $B_{max} < B_{sat}$