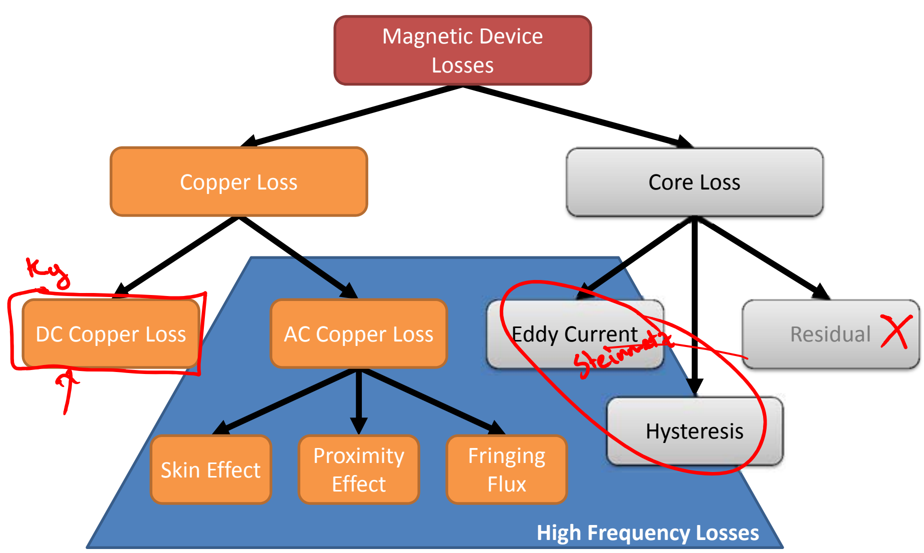
Announcements

- SAIS open now – please fill it out
  - Remaining students:
    - ~~15~~ 9 in 481
    - ~~2~~ 0 in 599
- Final Exam:
  - Posted online after final class
  - Due before end of scheduled exam time
    - Monday, Dec 7th, 10:00 am

13.3 Magnetics Losses



The K_g Method

① $L = \frac{\mu_0 n^2 A_c}{l_g}$

② $I_{max} = \frac{B_{max} l_g}{n \mu_0}$

③ $A_w n \le K_u W_A$

④ $R_{dc} = \rho \frac{n\,MLT}{A_w}$

① & ② eliminate l_g

$$I_{max} = \frac{B_{max}}{\cancel{n\mu_0}}\left(\frac{\cancel{\mu_0} n^{\cancel{2}} A_c}{L}\right) = \frac{B_{max}\, n A_c}{L}$$

③ & ④ eliminate A_w

$$R = \rho \frac{n^2\, MLT}{K_u W_A}$$

$$I_{max}^2 = \frac{B_{max}^2 A_c^2}{L^2} \cdot \frac{R K_u W_A}{\rho\, MLT}$$

core geometry

constants & circuit params →

$$\boxed{\frac{I_{max}^2 L^2 \rho}{B_{max}^2 R K_u} \le \frac{W_A A_c^2}{MLT} = K_g}$$

K_g Method

① solve circuit operation for L, I_{max}, R

pick a core

$$K_g \ge \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u} 10^8 \quad (\mathrm{cm}^5)$$

$$\ell_g = \frac{\mu_0 L I_{max}^2}{B_{max}^2 A_c} 10^4 \quad (\mathrm{m})$$

$$n = \frac{L I_{max}}{B_{max} A_c} 10^4$$

$$A_W \le \frac{K_u W_A}{n} \quad (\mathrm{cm}^2)$$

$$R = \frac{\rho n\,(MLT)}{A_w} \quad (\Omega)$$

Notes:

① only DC copper loss is included
- should check core loss after to make sure it is acceptable

② May need to iterate due to rounding to integer n, AWG

Discussion

$L\uparrow$ $I_{max}\uparrow$
$R\downarrow$ $B_{max}\downarrow$

$$K_g = \frac{A_c^2 W_A}{(MLT)} \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u}$$

K_g is a figure-of-merit that describes the effective electrical size of magnetic cores, in applications where the following quantities are specified:

- Copper loss
- Maximum flux density

How specifications affect the core size:

A smaller core can be used by increasing

$B_{max} \Rightarrow$ use core material having higher B_{sat}

$R \Rightarrow$ allow more copper loss

How the core geometry affects electrical capabilities:

A larger K_g can be obtained by increase of

$A_c \Rightarrow$ more iron core material, or

$W_A \Rightarrow$ larger window and more copper

Fundamentals of Power Electronics 11 *Chapter 14: Inductor design*

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Alternate Applications

- Can be applied to multiple-winding magnetics as long as design goals apply
  - Core loss negligible
  - Saturation is limiting peak flux density
- 14.3 shows how the method changes

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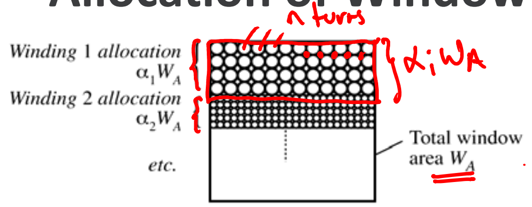
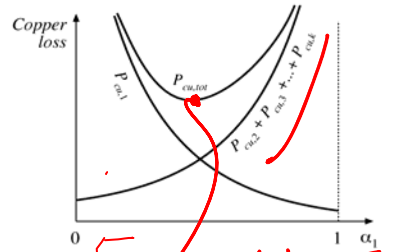
Allocation of Window Area





$$0 < \alpha_j < 1$$
$$\alpha_1 + \alpha_2 + \cdots + \alpha_k = 1$$

$$\boxed{\alpha_m = \frac{V_m I_m}{\sum_{n=1}^{\infty} V_j I_j}}$$

Apparent power in winding j is

$V_j I_j$

where V_j is the rms or peak applied voltage

I_j is the rms current

Window area should be allocated according to the apparent powers of the windings

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Chapter 15: Transformer Design

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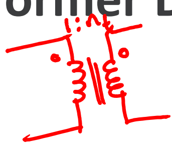
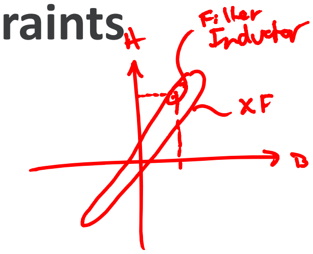
Transformer Design Constraints





Design Goals:

① correct turns ratios

② Minimize $P_{loss} = P_{fe} + P_{cu,DC}$

P_{fe} ← steinmetz

$P_{cu,DC}$ ← $R = \rho \frac{n\,MLT}{A_w}$

Design Parameters:

① n_1

② Core

Power Loss Tradeoffs

$$P_{fe} = A_c l_m \underbrace{K_m (\Delta B)^\beta f_s^\alpha}_{\text{steinmetz}}$$

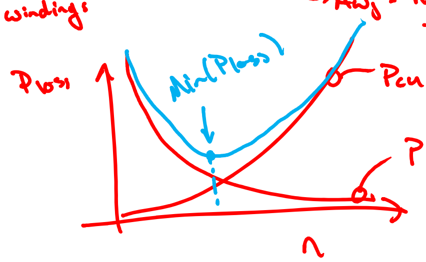
$$\Delta B = \frac{1}{n_1 A_c}\int v_1\, dt$$

$$P_{fe} \propto \left(\frac{1}{n}\right)^\beta$$

$$P_{cu} = \sum_{\text{all windings}} I_{rms,j}^2\, \rho \frac{n_j\, MLT}{A_{wj}}$$

$$A_{wj} = \frac{W_A \alpha_j K_u}{n_j}$$

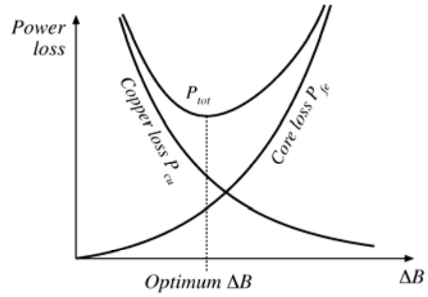
$$P_{cu} \propto n^2$$



$$\text{Min}(P_{loss}) = \frac{\partial (P_{fe} + P_{cu})}{\partial n} = 0$$

Minimizing Total Loss

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



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

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

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

Calculation of Total Loss

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

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

Rearrange as follows:

$\lambda_1 = \int v_1 dt$

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

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

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

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

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

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

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

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

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