15.2 Step-by-step transformer design procedure

The following quantities are specified, using the units noted:
Wire effective resistivity \( \rho \) (\( \Omega \cdot \text{cm} \))
Total rms winding current, ref to pri \( I_{wa} \) (A)
Desired turns ratios \( n_2/n_1, n_p/n_I, \text{etc.} \)
Applied pri volt-sec \( \phi_t \) (V-sec)
Allowed total power dissipation \( P_{Pr} \) (W)
Winding fill factor \( K_w \)
Core loss exponent \( \beta \)
Core loss coefficient \( K_{fe} \) (W/cm\(^2\)T\(^2\))

Other quantities and their dimensions:
Core cross-sectional area \( A_c \) (cm\(^2\))
Core window area \( W_0 \) (cm\(^2\))
Mean length per turn \( MLT \) (cm)
Magnetic path length \( l_c \) (cm)
Wire areas \( A_{w1}, \ldots \) (cm\(^2\))
Peak ac flux density \( \Delta B \) (T)

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Procedure

1. Determine core size

\[
K_{ge} \geq \frac{\rho \Delta T^2 P_{Pr} K_{fe}^{(2\beta)}}{4K_w(P_{Pr})^{(\beta+2)\beta}} \times 10^8
\]

Select a core from Appendix D that satisfies this inequality.

It may be possible to reduce the core size by choosing a core material that has lower loss, i.e., lower \( K_{fe} \).
2. Evaluate peak ac flux density

\[ \Delta B = \left[ 10^8 \frac{\beta \lambda^2_1 I_d^2}{2K_g} \frac{(MLT)}{W A_i^2 I_m} \frac{1}{\beta K_j} \right]^\frac{1}{\beta + 2} \]

At this point, one should check whether the saturation flux density is exceeded. If the core operates with a flux dc bias \( B_i \), then \( \Delta B + B_i \) should be less than the saturation flux density \( B_{sat} \).

If the core will saturate, then there are two choices:

- Specify \( \Delta B \) using the \( K_j \) method of Chapter 14, or
- Choose a core material having greater core loss, then repeat steps 1 and 2

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3. and 4. Evaluate turns

**Primary turns:**

\[ n_1 = \frac{\lambda_1}{2 \Delta B A_e} \times 10^4 \]

Choose secondary turns according to desired turns ratios:

\[ n_2 = n_1 \left( \frac{n_2}{n_1} \right) \]
\[ n_3 = n_1 \left( \frac{n_3}{n_1} \right) \]
\[ \vdots \]
5. and 6. Choose wire sizes

Fraction of window area assigned to each winding:

\[ \alpha_1 = \frac{n_1 I_1}{n_1 I_{ww}} \]
\[ \alpha_2 = \frac{n_2 I_2}{n_2 I_{ww}} \]
\[ \vdots \]
\[ \alpha_k = \frac{n_k I_k}{n_k I_{ww}} \]

Choose wire sizes according to:

\[ A_{w1} = \frac{\alpha_1 K_w W_A}{n_1} \]
\[ A_{w2} = \frac{\alpha_2 K_w W_A}{n_2} \]
\[ \vdots \]

Check: computed transformer model

Predicted magnetizing inductance, referred to primary:

\[ L_M = \frac{\mu_0^2 A_e}{\ell_m} \]

Peak magnetizing current:

\[ i_{M, pk} = \frac{\lambda_1}{2L_M} \]

Predicted winding resistances:

\[ R_1 = \frac{\rho n_1 (MLT)}{A_{w1}} \]
\[ R_2 = \frac{\rho n_2 (MLT)}{A_{w2}} \]
\[ \vdots \]
Discussion: Transformer design

- Process is iterative because of round-off of physical number of turns and, to a lesser extent, other quantities
- Effect of proximity loss
  - Not included in design process yet
  - Requires additional iterations
- Can modify procedure as follows:
  - After a design has been calculated, determine number of layers in each winding and then compute proximity loss
  - Alter effective resistivity of wire to compensate: define
    \[ \rho_{ef} = \rho \cdot \frac{P_{el}}{P_{dc}} \]
    where \( P_{el} \) is the total copper loss (including proximity effects) and \( P_{dc} \) is the copper loss predicted by the dc resistance.
  - Apply transformer design procedure using this effective wire resistivity, and compute proximity loss in the resulting design. Further iterations may be necessary if the specifications are not met.

15.4 AC Inductor Design

Design a single-winding inductor, having an air gap, accounting for core loss

(note that the previous design procedure of this chapter did not employ an air gap, and inductance was not a specification)
Outline of key equations

Obtain specified inductance:

\[ L = \frac{\mu_0 A_n n^2}{\ell_n} \]

Relationship between applied volt-seconds and peak ac flux density:

\[ \Delta B = \frac{\lambda_a}{2 n A_c} \]

Copper loss (using dc resistance):

\[ P_{cu} = \frac{\rho n^2 (MLT)}{K_u W_A} I^2 \]

Total loss is minimized when

\[ \Delta B = \left[ \frac{\rho \lambda_a^2 I^2 (MLT)}{2 K_u W_A A_n L_m} \left( \frac{1}{2 K_B} \right)^{1.2} \right] \]

Must select core that satisfies

\[ K_{se} \geq \frac{\rho \lambda_a^2 I^2 K_B^{(2n)}}{2 K_u (P_m) (\theta + 2 \theta)} \]

See Section 15.4.2 for step-by-step design equations