EE-365 - W4
INDUCTOR DESIGN
FEW EXTRAS

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BUILD OR BUY?

Typical catalog parts

Few variable parameters – same spec – sub-optimal design is acceptable – many customers

Figure 1 Power systems: distribution transformer

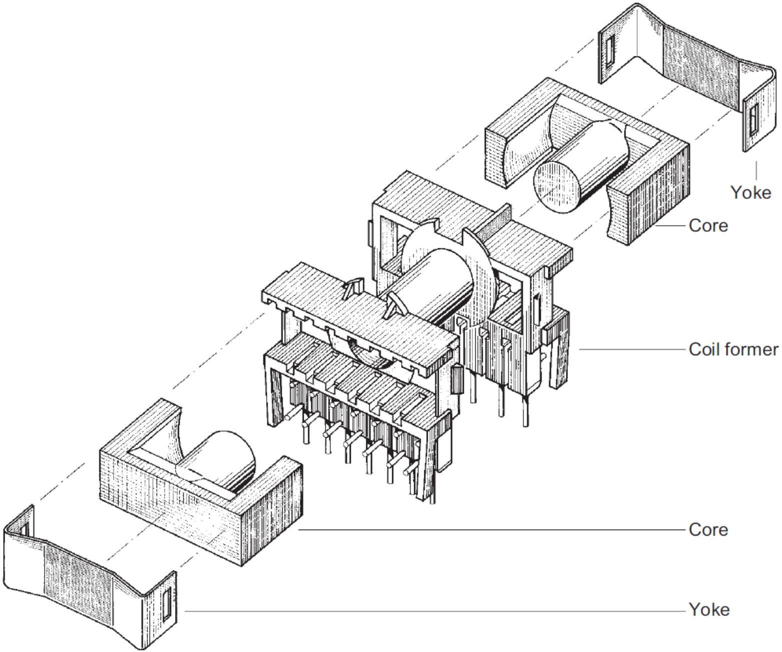
Figure 2 EMI filters: common mode chokes

Figure 3 Low power SMPS: SMD inductors

Custom inductive components

- niche applications: railway, medicine, aerospace, research (e.g. CERN),...
- highly optimized converters: efficient PV inverters, cheap mass products,...
- power electronic converters: plethora of topologies × myriad of parameters

CORE ASSEMBLY SET: CORE HALVES, COIL FORMER, YOKES ... WIRE AND AN AIR GAP



EXPECTED RESULTS AND INDUCTOR DESIGN PROCEDURE

Results to deliver: Inductor specification

Electrical specification

- nominal inductance L_{nom}
- peak current I_{pk}
- current ripple ΔI_{pkpk}
- ripple frequency f_{sw}

Core specification

- core shape and size
- core material
- air gap length l_{g}

Winding specification

- wire diameter
- number of turns

Losses and diagrams

- core and winding losses
- LCR meter results
- $L(I)$ diagram
- Thermal image for nominal dc current

Discrete component values, multiobjective optimization → an iterative process

1. Find a prospective core size
2. Find wire diameters

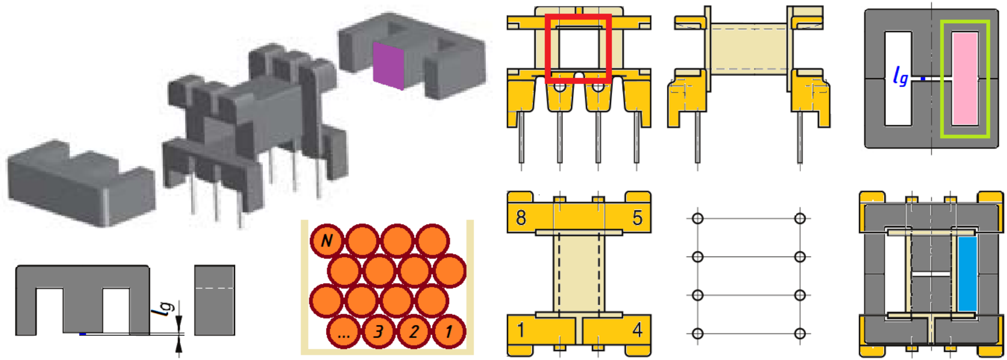
} Calculations (steps 1–2)

3. Tune the inductance by setting the air gap
4. Verify the design parameters

} Experiment (steps 3–4)

5. Iterate to fit the design values into the limits / to improve the design

E CORE AND COIL FORMER. QUICK REVIEW OF SOME NOTIONS



■ ferrite core	■ bare copper wire	■ A_c: core c-s area	■ MLT: mean length per turn	■ W_A: core window area
■■ coil former	■ copper wire insulation	■ l_g: air gap length	■ MPL: magnetic path length	■ $W_{A,eff}$: usable window area

Number of turns	N_1, N_2, N_3	Window utilization factor	$K_u = \sum_{x=1}^{3} N_x \cdot A_{wx}/W_A =$ ■/■
Area of a bare copper wire	A_{w1}, A_{w2}, A_{w3}	Area product	$A_p = W_A \times A_c =$ ■ × ■ or $W_{A,eff} \times A_c =$ ■ × ■
Conductor area	$\sum_{x=1}^{3} N_x \cdot A_{wx} =$ ■	Core geometry constant	$K_g = W_A \cdot (A_c^2)/MLT =$ ■ × ■ × ■/■ or ■ × ■ × ■/■
Wire area	■ + ■		Some notions vary: understand what you calculate!

AREA PRODUCT - A_p (INDUCTOR CASE)

Two constraints:

- Core window area should fit the winding

$$W_{\mathrm{A_i}} = \frac{N_i \cdot A_{\mathrm{w_i}}}{K_\mathrm{u}} \geq \frac{N_i \cdot I_{\mathrm{rms_i}}}{J_\mathrm{w} \cdot K_\mathrm{u}}$$

$$W_\mathrm{A} \geq \frac{N_1}{K_\mathrm{u} \cdot J_\mathrm{w}} \sum_{i=1}^{3} \frac{N_i}{N_1} I_{\mathrm{rms_i}}$$

- Core should not saturate

$$A_\mathrm{c} \geq \frac{\Psi_\mathrm{max}}{N_1 \cdot B_\mathrm{max}} = \frac{L \cdot I_{\mathrm{peak_1}}}{N_1 \cdot B_\mathrm{max}}$$

Recall:

- Flux linkage Ψ

$$\Psi = N \cdot \Phi = \int v_L dt = L \cdot I$$

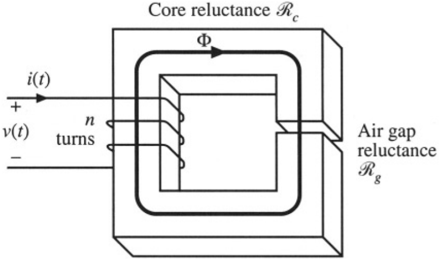
Merged Constraints

- Very approximate assumption for quick core search:
- Area Product A_p ($[A_\mathrm{p}] = m^4$)

$$A_\mathrm{p} = W_\mathrm{A} A_\mathrm{c} \geq \frac{L \cdot I_{\mathrm{peak_1}} \sum_{i=1}^{3} \frac{N_i}{N_1} I_{\mathrm{rms_i}}}{K_\mathrm{u} \cdot B_\mathrm{max} \cdot J_\mathrm{w}}$$

- LHS: core geometry related parameters: $A_\mathrm{c}, W_\mathrm{A}$ ($W_\mathrm{A,eff}$ if a coil former is used)
- RHS: design specifications: $I_\mathrm{max}, I_\mathrm{rms}, L, B_{max}, K_\mathrm{u}, J_\mathrm{w}$
- Degrees of freedom: N, l_g

Inductor Geometry



Limits for N

- lower limit: higher core losses, upper limit: higher copper losses

$$\frac{\Psi_\mathrm{max}}{B_\mathrm{max} \cdot A_\mathrm{c}} < N_1 < \frac{W_\mathrm{A} \cdot K_\mathrm{u} \cdot J_\mathrm{w} - \sum_{i=2}^{3} N_i I_{\mathrm{rms_i}}}{I_{\mathrm{rms_1}}}$$

Setting the L value: by adjusting the gap length l_g

- recall:

$$L = \frac{N_1^2}{\mathrm{Re_c} + \mathrm{Re_g}} \approx \frac{N_1^2}{\mathrm{Re_g}} = \frac{\mu_0 A_\mathrm{c} N_1^2}{l_\mathrm{g}}$$

FRINGING FLUX FACTOR

Fringing flux

- Magnetic flux is forced to flow through the air gap, whereby $\mathrm{Re}_\mathrm{g} >> \mathrm{Re}_\mathrm{c}$
- Magnetic flux spreads out into the volume around the gap
- Result: lower air gap reluctance
- Consequently higher inductance than with flux through the air gap cross-section area only
- Fringing flux factor F_fringe (unitless) describes this increase of inductance (G: length of the core window):

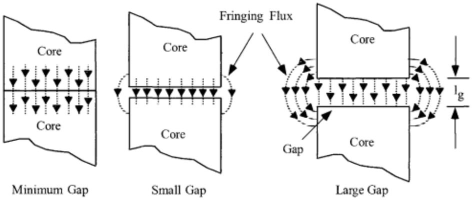
$$F_\mathrm{fringe} = 1 + \frac{l_\mathrm{g}}{\sqrt{A_\mathrm{c}}} \cdot \ln\left(\frac{2 \cdot G}{l_\mathrm{g}}\right)$$

Increased copper losses

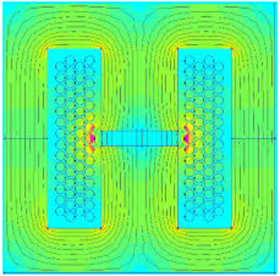
- fringing flux induces eddy currents in conductive materials placed in its volume
- same principle as inductive heating
- significant additional power losses $\longrightarrow$ hot spot!
- solutions: distance to the gap, number of gaps, distributed gap materials

Other copper loss factors to consider at high frequency (not covered by lecture and exercise): Skin effect and proximity effect

Fringing flux at the air gap

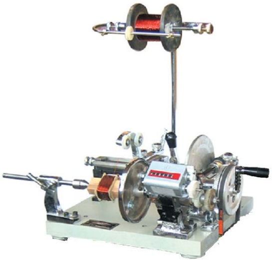


Fringing flux induced copper losses



DESIGN STEPS AT ONE GLANCE - FROM PAST PROJECTS

1. Specification and constraints: $L_{\mathrm{min}}, I_L, \Delta I_L, f_{\mathrm{sw}}, B_{\mathrm{max}}, K_{\mathrm{u}}, J_{\mathrm{w}}, R_L$
2. Pre-selection of cores
   - 2.1 Calculate the peak current I_{pk}
   - 2.2 Calculate the energy handling capability: $L \cdot I_{\mathrm{pk}}^2$
   - 2.3 Calculate the approximate air gap l_{g} to store this energy
3. Select one core to start with using the area product A_{p}
4. Select a wire diameter
   - 4.1 Calculate I_{rms}
   - 4.2 Calculate the required bare wire area for the J_{w} constraint
   - 4.3 Select a wire within 10 % range
5. Calculate the required air gap length l_{g} and adjust N
   - 5.1 Calculate the number of possible turns $N_{1,2,3_{\mathrm{max}}}$
   - 5.2 Calculate the required air gap length l_{g}
   - 5.3 Calculate the fringing flux factor F_{fringe}
   - 5.4 Calculate the new number of turns $N_{1,2,3}$ by inserting F_{fringe}
6. Verify the design constraints
   - 6.1 Calculate the window utilization K_{u}
   - 6.2 Calculate the winding resistance $R_{L_{1,2,3}}$ for a hot wire.
   - 6.3 Estimate the copper loss P_{Cu}
   - 6.4 Calculate the ac and peak flux densities B_{ac} and B_{pk}
   - 6.5 Estimate the core loss P_{Core}
   - 6.6 Estimate the temperature rise ΔT
7. Build the inductor and tune its value
8. Verify the winding direction of all 3 windings
9. Verify the core saturation
10. Verify the temperature rise



STEP 7: AIR GAP TUNING AND RLC METER MEASUREMENT

Figure 4 Tools and material available to set and trim the air gap length

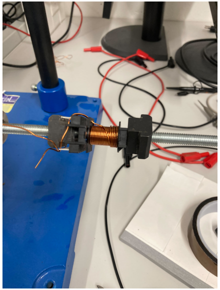


Figure 5 After winding N_1

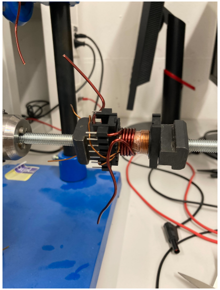


Figure 6 After winding N_2

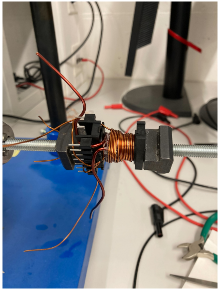


Figure 7 After winding N_3

1. Wind the primary N_1 turns on the coil former, add a tape layer when done.
2. Wind the secondary N_2 turns on the coil former, add a tape layer when done.
3. Wind the auxiliary N_3 turns on the coil former.
4. Use the Kapton tape to create the air gap on the two sides of the core.
5. Clamp the inductance using the yoke.

STEP 8: WINDING DIRECTION AND RLC MEASUREMENTS

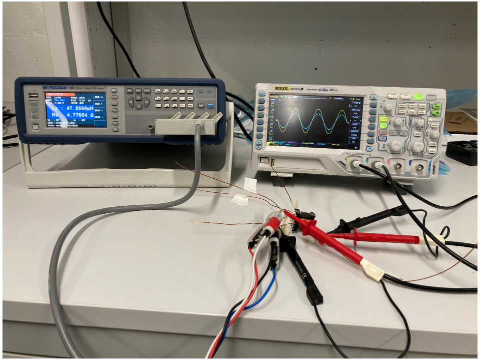


Figure 8 Winding direction test

1. Set the frequency on the RLC to 10kHz
2. Mark the primary winding terminal connected to the high potential of the RLC
3. Measure the voltage across the secondary and auxiliary winding
4. If the voltage is in phase with the primary voltage, mark the positive terminal, otherwise mark the negative terminal

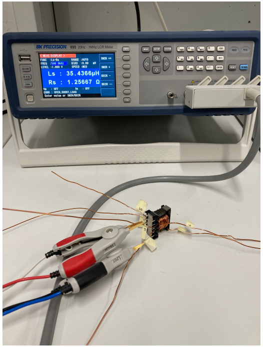


Figure 9 RLC measurements

1. Disconnect the oscilloscope
2. Measure primary inductance with open secondary and auxiliary windings
3. Measure primary inductance with shorted secondary and auxiliary windings
4. Repeat measurements using the Bode100

STEP 9: CORE SATURATION LIMIT VERIFICATION WITH THE POWER CHOKE TESTER

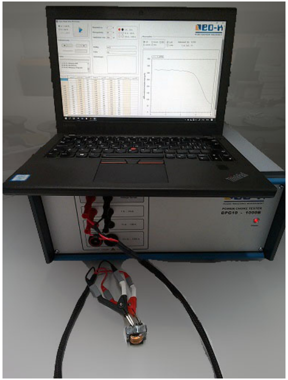


Figure 10 Power choke tester

The Hardware Setup for the choke test:

- Keep the secondary and auxiliary winding open
- Connect both the Force and Sense cable to the power choke meter and to the terminals of the primary inductance
- Once connected, cover with Plexiglas box and do not touch until the end of the measuring process

The Software settings for the choke test:

- The max current value corresponds to your maximum input current rounded up
- The measured voltage value corresponds to your maximum input voltage
- For the pulse time enter 10ms

Results:

- Provide both the secant and incremental inductance measurements and show that they don’t staurate

Figure 11 Heat-run test setup

Verify the dc losses and the temperature rise

1. Position the camera safely and focus at the inductor windings.
2. Provide primary and secondary windings with their respective rms currents.
3. Take a picture of the test-setup as well as two thermal images, one done prior to the test and one after 15 minutes of test.

Attention: beware of reflections and non-black surfaces.