CERN ACCELERATOR SCHOOL
Power Converters

Passive components

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Overview

- **Part 1: Inductors (to be designed)**
- **Part 2: Capacitors (to be selected)**
- **Part 3: A new component: The Supercapacitor, component and applications**

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Inductors

Overview, typical applications

- -AC-applications
- -DC applications
- -Filtering
- -Smoothing (limiting di/dt)
- -Components of resonance circuit

References:

P. Robert, « Matériaux de l'électrotechnique, Traité d'électricité, Vol II, PPUR, ISBN 2-88074-042-8
M. Jufer, F. de Coulon, Introduction à l'électrotechnique, Traité d'électricité, Vol I, PPUR, ISBN 2-88074-042-8
T. Undeland, N. Mohan, P. Robbins, Power Electronics, Converters, Applications and Design, Wiley, ISBN 0-471-58408-8

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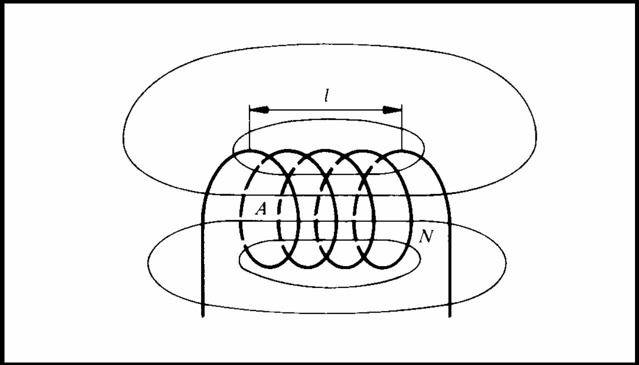
Inductors

- **2 main types:**
  - **- Air inductors**
  - **- Inductors with magnetic core**

Solenoid (air)

$$L = N^2 \mu_0 A / l$$

A: area of coil
L: length of coil
N: number of turns



Toroid (core)

$$L = N^2 \mu A / \pi d_m$$

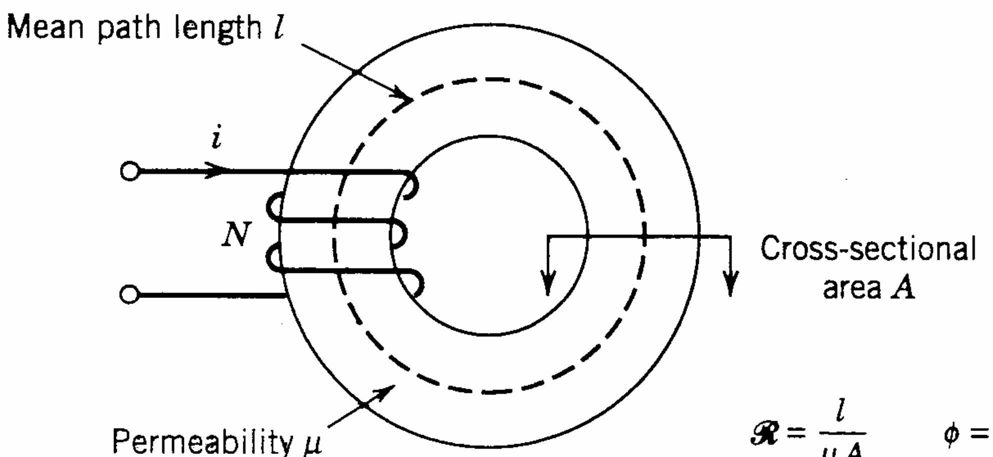
A: section of core
d_m: mean diameter of tore
N: number of turns

Toroidal inductor

Permeance of a magnetic circuit is defined as the reciprocal of its reluctance:

$$\mathcal{P} = \frac{1}{\mathcal{R}}$$

$l = \pi * d_m$



$$\mathcal{R} = \frac{l}{\mu A} \qquad \phi = \frac{Ni}{\mathcal{R}}$$

Figure 3-14 Magnetic reluctance.

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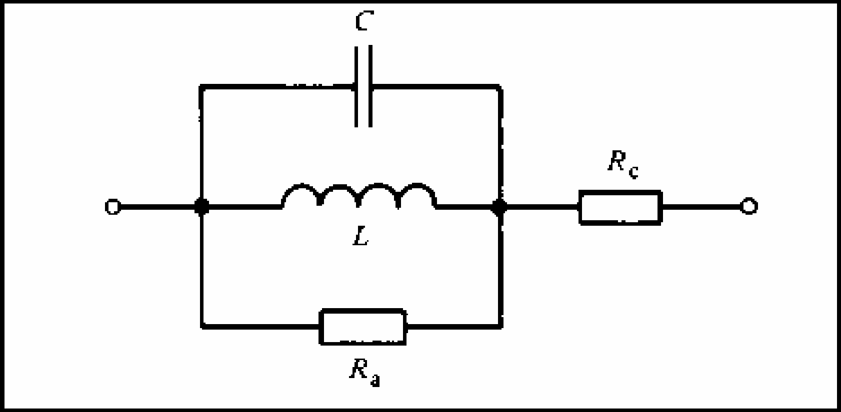
Inductors

- **Main parameters of inductors**
  - **Inductance**
  - **Quality factor**
  - **Capacity**
  - **Rated current**

- **Equivalent scheme**



R_a: Losses related to AC current component
R_c: Resistance of winding
C: Capacity of winding

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Inductors

Relations

For: $\omega^2 LC << 1$

$$\underline{Z} \cong R' + j\omega L'$$

with

$$R' = R_c + R_a / (1 + Q_a^2)$$

$$Q_a = R_a / \omega L$$

if $Q_a^2 >> 1$

$$L' \cong L$$

$$R' \cong R_c + \omega^2 L^2 / R_a$$

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Inductors

Factor of losses and quality factor

for $Q_a^2 >> 1$

$$\tan\delta = R'/\omega L' \cong R_c/\omega L + \omega L/R_a$$

$$\tan\delta = \tan\delta_c + \tan\delta_a$$

$$Q = 1/\tan\delta = \omega L'/R'$$

Important factor for resonant circuits

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Inductors

- **Magnetic materials and cores**
  - **2 main classes of materials**

1) Iron based

- **Alloys of iron with chrome and silicon (small amounts)**
  - **⇒Electrical conductivity**
  - **⇒Large value of saturation limit**
- **Powdered iron cores (small iron particles isolated from each other)**
  - **⇒Greater resistivity, smaller eddy current losses**
  - **⇒Suited for higher frequencies**
- **Amorphous alloys of iron with other transition metals (METGLAS)**

Inductors

- **Magnetic materials and cores**

2) Ferrites

Oxide mixtures of iron and other magnetic elements

⇒Large electrical resistivity

⇒ Low saturation flux density (0.3T)

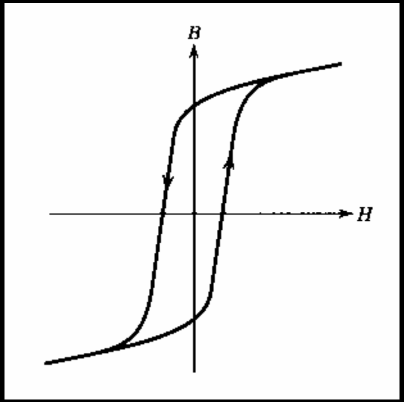
⇒Have only hysteresis losses

⇒No significant eddy current losses

Inductors

- **Hysteresis losses**

$$P_{m,sp} = kf^{a}(B_{ac})^{d}$$ (specific loss)



k, a, d, constants depending from the material

Loss increase with f and with B_{ac}

$$B_{ac} = \hat{B}$$ If no time average

$$B_{ac} = \hat{B} - B_{avg}$$ If time average

Inductors

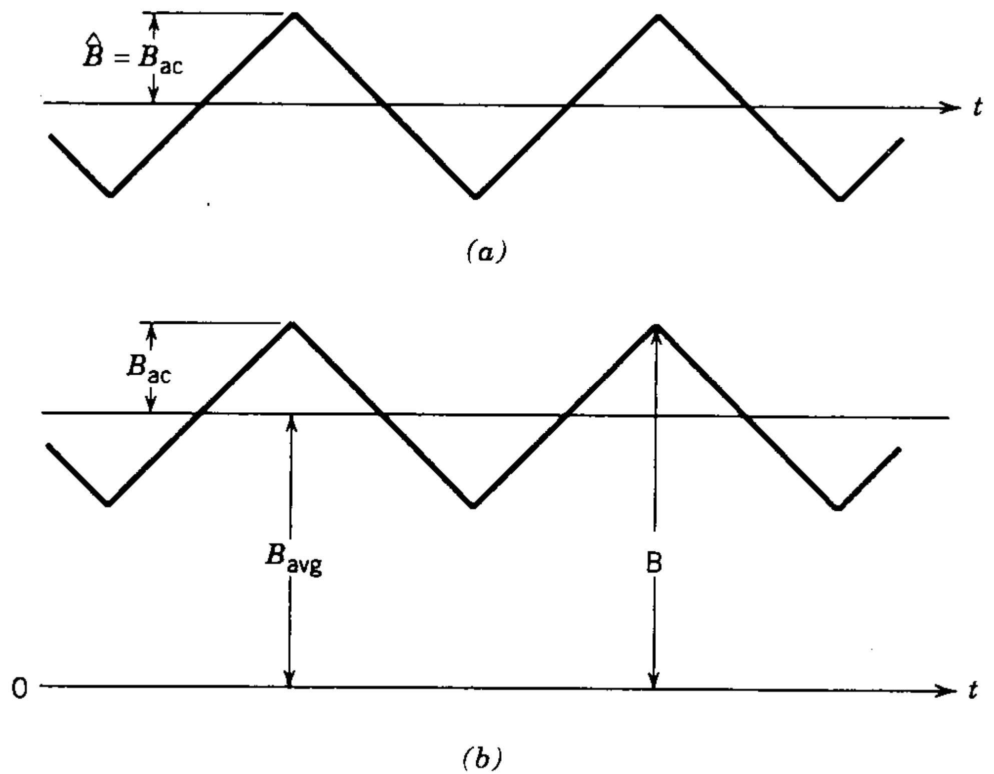


Figure 30-1 Magnetic flux density waveforms having (*a*) no time average and (*b*) with a time average.

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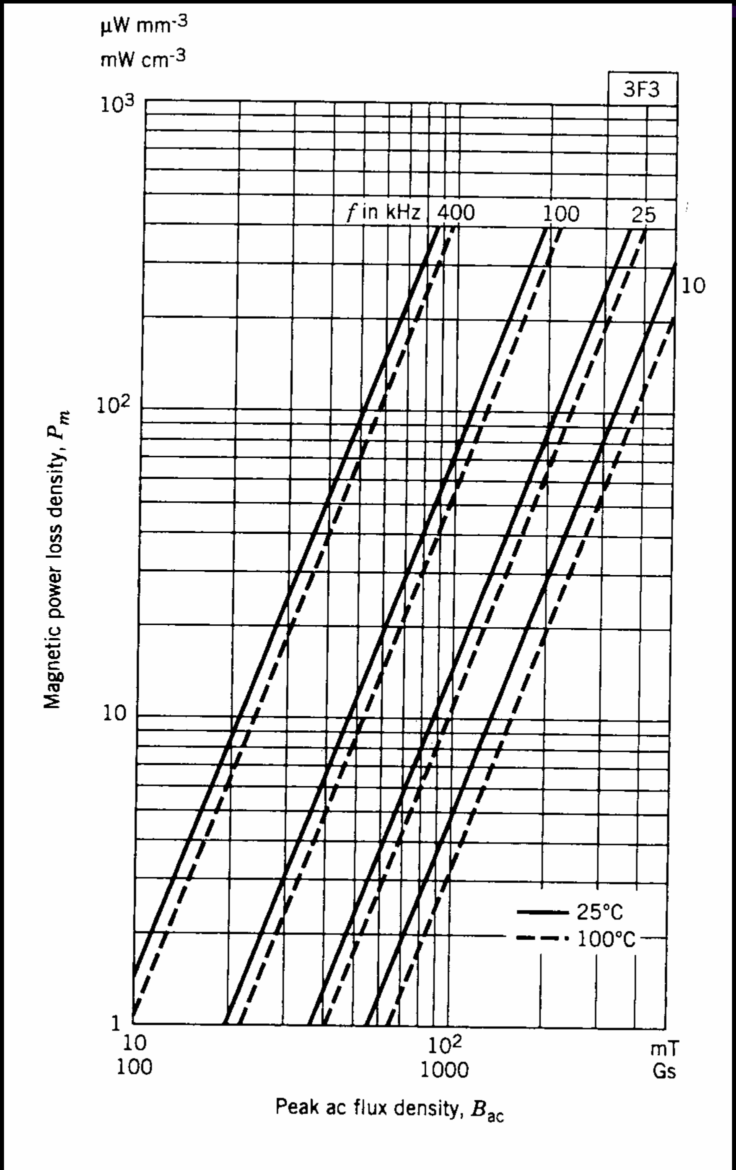
Inductors



Example of ferrite material (3F3)

$$P_{m,sp} = 1.5*10^{-6} f^{1.3} (B_{ac})^{2.5}$$

$P_{m,sp}$ in mW/cm^3 when f in kHz and B_{ac} in mT

For METGLAS:

$$P_{m,sp} = 3.2*10^{-6} f^{1.8} (B_{ac})^{2}$$

For 100 kHz and 100 mT:
$P_{m,sp} = 127 mW/cm^3$

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Inductors

- Empirical performance factor PF=f*B_{ac}

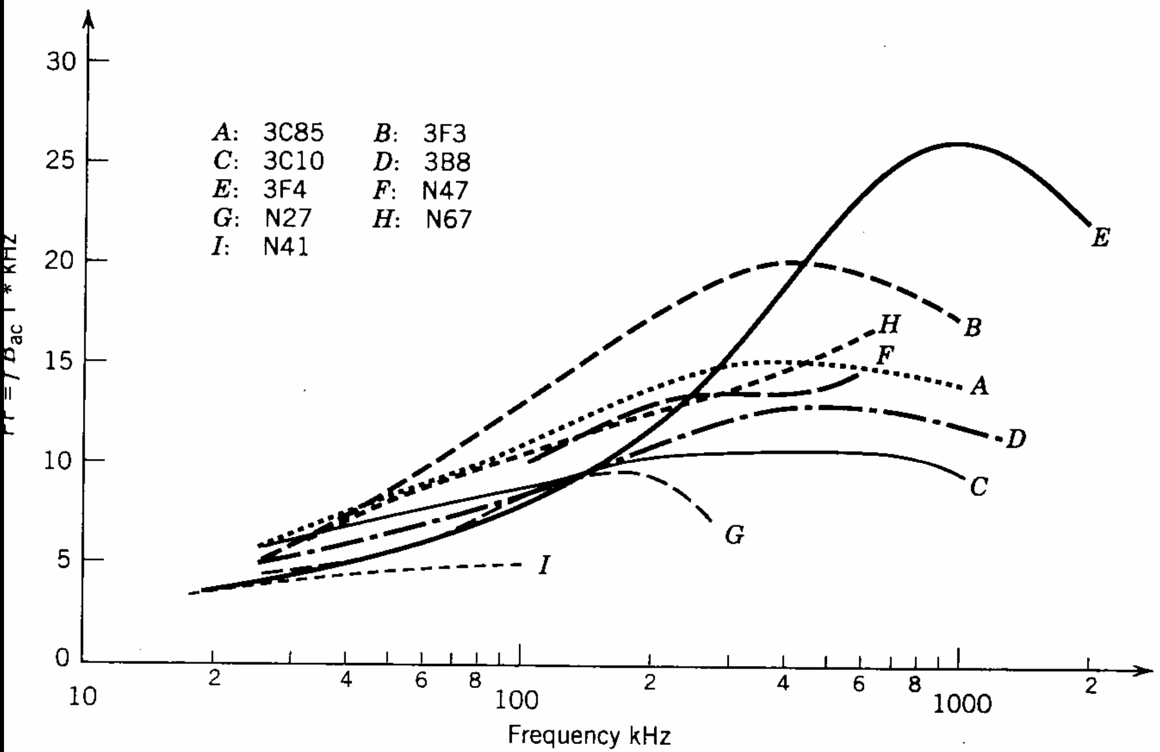


Figure 30-3 Empirical performance factor PF $= fB_{ac}$ versus frequency for various ferrite core materials. Measurements are made at a power density P_{core} = 100 mW/cm^3.

Inductors

- $P_{m,sp}$ depends finally on how efficiently theheat dissipated is removed

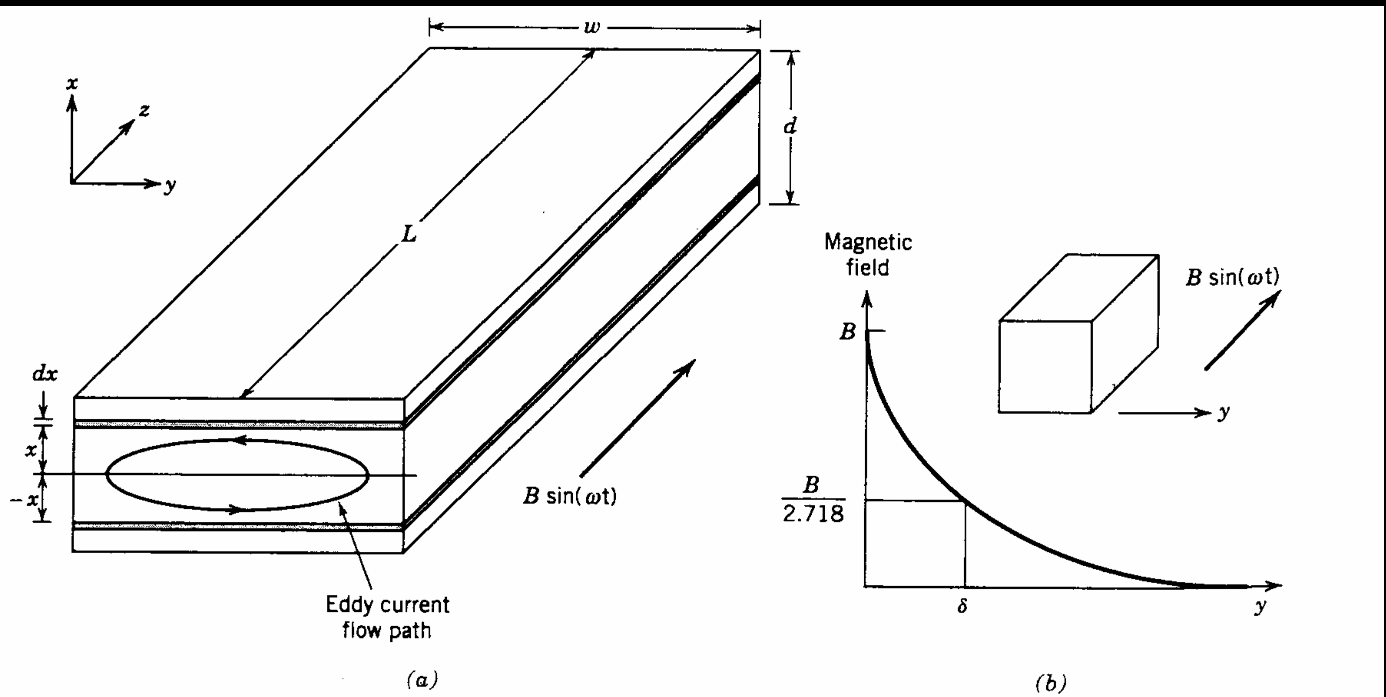
- $P_{m,sp}$ is even smaller because of presence of eddy current loss

Inductors

- **Skin effect limitations (in core)**

  - If conducting material is used: circulation of currents when the magnetic field is time-varying (eddy currents)
  - The magnetic field in the core decays exponentially with distance into the core

$$B(y) = B_0 e^{-y/\delta}$$



Skin depth: δ

$$\delta = \sqrt{2/\omega\mu\sigma}$$

$\omega = 2\pi f$

μ : permeability

σ : conductivity

Inductors

Typical value of skin depth

(Material with large permeability)

1mm at 60 Hz !

> Thin laminations with each isolated from the other

> Stacking factor (0.9…0.95)

Materials with increased resistivity: increase of skin depth but reduces the magnetic properties

Reasonable compromise for transformers (50/60 Hz):
Iron alloy, 97%iron, 3% silicon) and a lamination thickness of 0.3 mm

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Inductors

- **Example of stacking steel laminations**

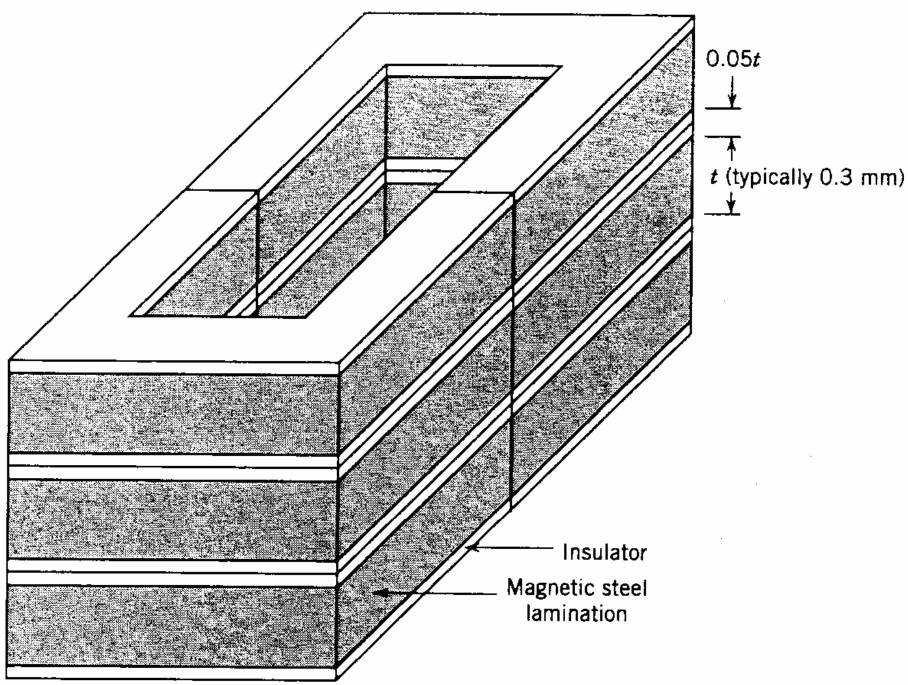

Figure 30-5 Magnetic core for a transformer or inductor made from a stack of magnetic steel laminations separated by insulators.

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Inductors

- **Eddy current loss in laminated cores**

Specific eddy current loss (estimated optimistic minimum)

$$P_{ec,sp} = \frac{d^2 \omega^2 B^2}{24 \rho_{core}}$$

d: thickness of the lamination

d < δ (skin depth)

$$B(t) = B \sin(\omega t)$$

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Inductors

- **Core shapes and optimum dimensions**

Cross-sectional area of the bobbin: $A_w = h_w \cdot b_w$

Widely used core: Double-E core

$b_a = a$, $d = 1{,}5a$, $h_a = 2{,}5a$, $b_w = 0{,}7a$, $h_w = 2a$

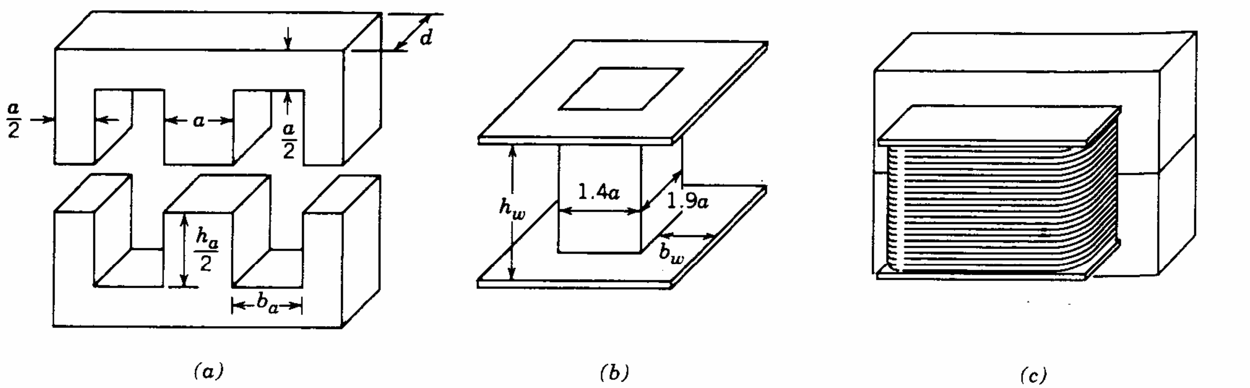

Figure 30-6 Dimensioned diagram of (*a*) a double-E core (*b*) bobbin, and (*c*) assembled core with winding.

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Inductors

- **Geometric characteristics of a near optimum core for inductors / transformer**

Table 30-1 Geometric Characteristics of a Near Optimum Core for Inductor/Transformer Design

Characteristic	*Relative Size*	*Absolute Size for a = 1 cm*
Core area A_{core}	$1.5a^2$	$1.5\ cm^2$
Winding area A_w	$1.4a^2$	$1.4\ cm^2$
Area product $AP = A_w A_c$	$2.1a^4$	$2.1\ cm^4$
Core volume V_{core}	$13.5a^3$	$13.5\ cm^3$
Winding volume V_w [a]	$12.3a^3$	$12.3\ cm^3$
Total surface area of assembled inductor/transformer [b]	$59.6a^2$	$59.6\ cm^2$

Inductors

- **Copper windings**

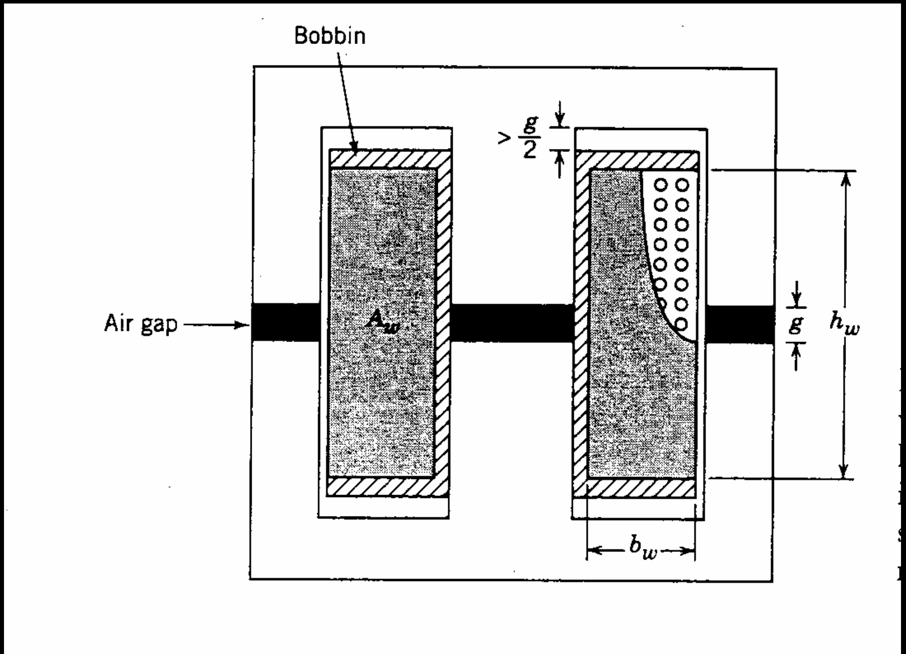
Advantages of copper: high conductivity, easy to bend

- single round wire
- Litz-wire diameter of each strand: a few hundred of microns (skin effect in copper)

Copper fill factor

$$k_{cu} = \frac{NA_{Cu}}{A_w}$$

from 0,3 (Litz) to 0,5..0,6 for round conductors



Inductors

- **Power dissipated in the winding(specific)**

$$P_{Cu,sp} = \rho_{Cu}(J_{rms})^2$$

$$J_{rms} = I_{rms} / A_{Cu}$$

or

$$P_{w,sp} = k_{Cu}\rho_{Cu}(J_{rms})^2$$

Inductors

- **Skin effect in copper windings**

Circulating winding current > magnetic field > eddy currents

➢ The eddy currents « shield » the interior of the conductor from the applied current

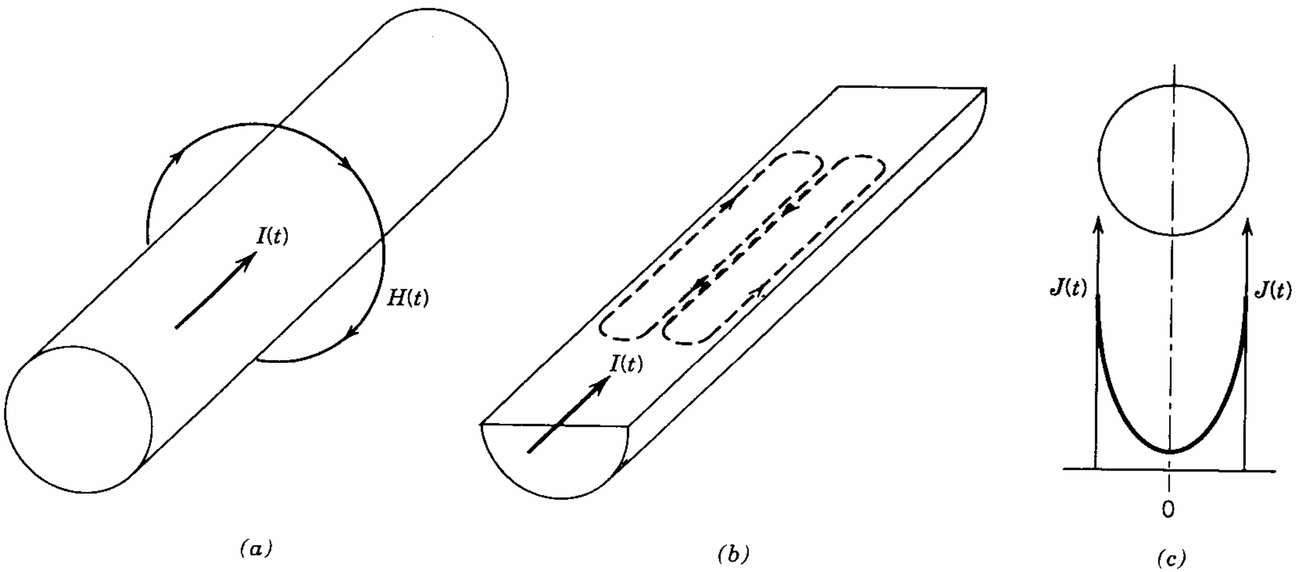


Figure 30-8 Isolated copper conductor carrying (*a*) a current $i(t)$, (*b*) eddy currents generated by the resulting magnetic field, and (*c*) the consequences of the skin effect on the current distribution.

The current density decays exponentially

« skin depth »

Inductors

- **Skin depth: δ**

Frequency	**50Hz**	**5kHz**	**20kHz**	**500kHz**
δ	**10.6 mm**	**1.06 mm**	**0.53 mm**	**0.106 mm**

Skin depth in Copper at 100°C for several different frequencies

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Inductors

- **Thermal considerations**

Temperature increase of core and winding:
- degrades the performance of the materials

-The resistivity of the copper winding increases and so the loss increases
- The value of the saturation flux density decreases

It is important to keep the core and winding temperature under a maximum value

In practice 100-125°C

Inductors

- **Design of the thermal parameters**

$R_{\theta sa}$, $R_{\theta rad}$, $R_{\theta conv}$ $$R_{\theta sa} = \frac{k_1}{a^2}$$ k_1: constant

$$\Delta T = R_{\theta sa}(P_{core} + P_w)$$

$$P_{core} = P_{c,sp} V_c \qquad P_w = P_{w,sp} V_w$$

$$P_{c,sp} \approx P_{w,sp} = P_{sp}$$ for an optimal design

V (volume) ~ a^3 so with $$P_{core} + P_w = k_2 a^2 \quad : \quad P_{sp} = \frac{k_3}{a}$$

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Inductors

Maximum current density J and specific power dissipation Psp as functions of the double-E core scaling parameter a

$$P_{sp} = \frac{k_3}{a}$$

$$J_{rms} = \frac{k_5}{\sqrt{k_{Cu} a}}$$