BE1M13VES

Manufacturing of Electrical Components

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Prague, 2017

Overview

TOPIC

Inductors

- Devices with the lowest portfolio on the market, very pure mass-production.
- Often must be inductance designed „on-demand“ during designing process.

Types according to the design:

- coils without magnetic core (air-wounded)
- coils with ferromagnetic core:
  - polycrystalline - printed cores, powder cores,
  - amorphous cores - magnetic glasses, oxides (ferrite - Manganese + Zinc, Nickel + Zinc)

Inductors - parameters

Parameters:

- L... inductance (H)
- I... nominal current (A)
- Q... quality factor (-)
- ... temperature dependence
- ... current and voltage dependence
- ... frequency dependence

Quantities

- B... magnetic flux density (T)
- H... magnetic excitation (A/m)
- ϕ... magnetic flux (Wb)
- μ... permeability (H/m)

Inductance Calculation

There is no typical topology for inductance calculation. The resulting formulas can be quite complicated. There are three definitions of inductance:

1. Static definition:

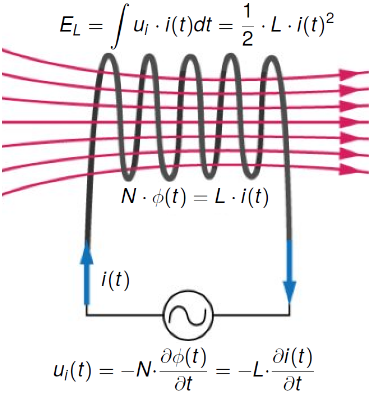
$$N \cdot \phi(t) = L \cdot i(t)$$

2. Dynamic definition:

$$u_i(t) = -L \cdot \frac{\partial i(t)}{\partial t}$$

3. Energy definition:

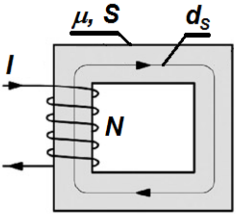
$$E_L = \frac{1}{2} \cdot L \cdot I^2$$



Inductance of coils with ferromagnetic cores

Inductance is very often computed via core constant A_L

$$\oint H dx = N \cdot I \Rightarrow H \cdot d_S = N \cdot I$$



$$B = N \cdot I \cdot \frac{\mu}{d_S} \Rightarrow \phi = N \cdot I \cdot \frac{\mu \cdot S}{d_S}$$

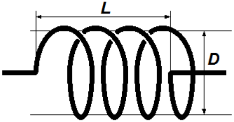
Then for inductance:

$$L = \frac{N^2 \cdot \mu \cdot S}{d_S} = N^2 \cdot A_L$$

Inductance of air coils

Inductance is primary given by a geometric shape and dimensions of coil and by the number of turns (N). For design and computing are often used empiric formulas, e.g. Nagaoko's formula:

$$L = 0.03948 \cdot \frac{D^2 \cdot N^2 \cdot K}{4 \cdot L}$$



D/L	0.00	0.25	0.50	0.75
K	1.000	0.902	0.818	0.748
D/L	1.00	1.25	1.50	2.00
K	0.688	0.638	0.595	0.525
D/L	2.50	3.00	3.50	4.00
K	0.472	0.429	0.394	0.365

Inductance of air coils

L is inductance (μH), D (cm) is a diameter of coil, l (cm) is the length of coil and K is a ration coefficient from the table.

For preliminary estimation of inductance can be used another simplified formula: (nH; cm)

$$L = \frac{\pi^2 \cdot N^2 \cdot D^2}{1 + 0.4 \cdot D}$$

TOPIC

Coils without Core (Air)

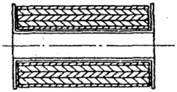
- coils with relatively low inductance (as small as 100 nH up to 1 mH),
- stable parameters and quite linear characteristics,
- ideal for low-power and high frequency applications,
- the design (diameter, wire surface...) is affected by quality factor requirements.

Air Coils - Winding

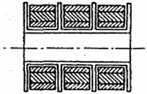
- Single or multi-layer winding made from a wire with rounded or square cross-section,
- windings are sometimes separated into chambers (sectors), especially for minimizing self-capacity,
- for high frequency (about 50 kHz) is sometimes used basket winding.
  - Smaller proximity effect,
  - smaller self capacitance.

Air Coils - Winding

Cilindrical Winding

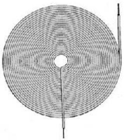


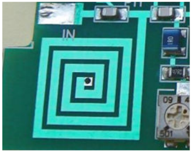
Multi-layer

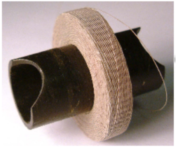


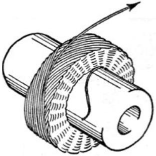
Chambers (Sectors)

Planar Winding

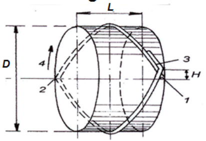




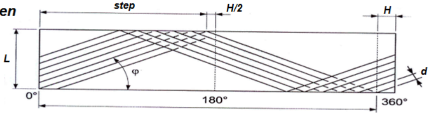




Basket Winding



There is angle $2 \cdot \varphi$ between adjecent layers

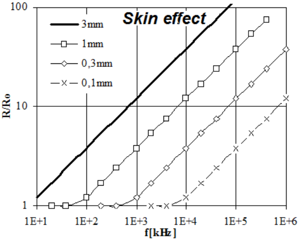


Design Example - Resonator

For high quality factor, wire must have very low resistance. Quality factor is nearly proportional to dimensions (volume) of a coil. Optimum of coil length is in the range from $0,5 \cdot D$ up to D (D is the diameter).

The quality factor is affected by the skin effect at the high frequencies:

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}}$$



Coils with Ferromagnetic Cores

Cores are used to increase the inductance (they have higher permeability μ). Disadvantages:

- non-linearity
- frequency dependence
- power-losses
  - hysteresis losses

$$\frac{P_h}{V} \approx 2 \cdot f \cdot B_m \cdot H_C \approx 2 \cdot f \cdot B_m^{\alpha}$$

  - eddy currents

$$\frac{P_{ed}}{V} \approx \pi \cdot f^2 \cdot B_m^2 \cdot d^2$$

V ... volume,

f ... frequency,

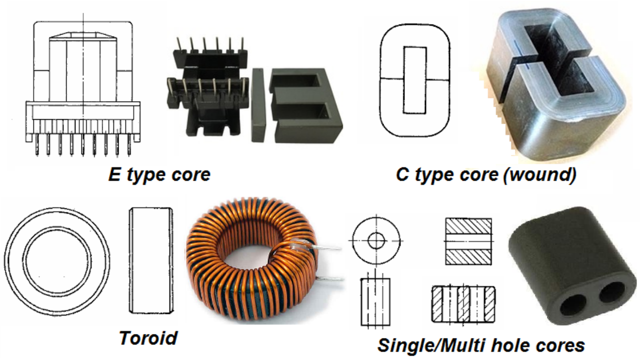
B_m ... mag. flux density (maximum),

H_C ... coercivity,

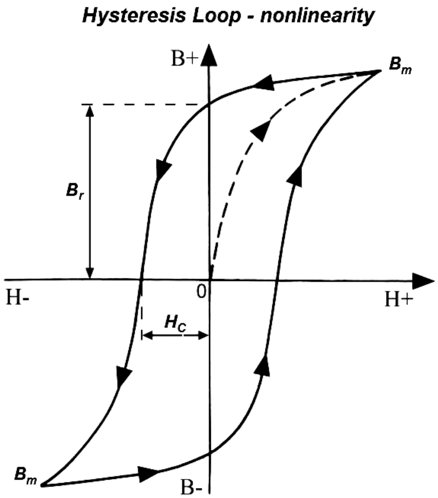
d ... thickness of the material,

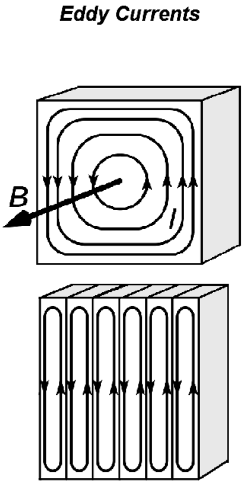
α ... approximation exponent (≈ 2)

Cores - Examples



Cores - Power Loss



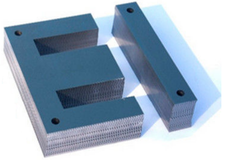


TOPIC

Metal magnetic materials

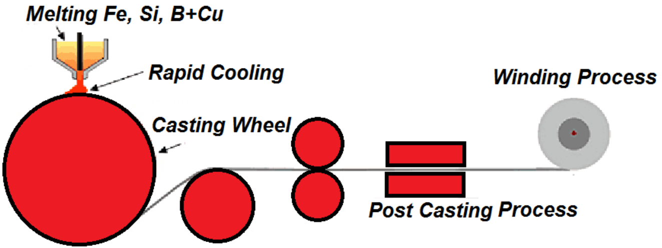
Metal sheets (plates)

- The most common type is rolled in warm state $\Rightarrow$ without any orientation of domains



- the cores with oriented texture are used for power applications - rolled sheets in cold state (better properties in defined direction)
- surface protection - insulation layer from oxide (Fe_2O_3), varnish, phosphate

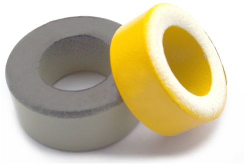
Metal Glass



- materials without crystalline structure,
- production: very fast cooling of hot liquid alloy (melt), rolling into tin foils,
- properties: better than oriented sheets, low power losses, maximum of flux density B higher than 2 T

Powder Cores

- **grains:** 1 μm to 10 μm pressed together with non-conductive binder,
- low eddy currents up to HF but also low relative permeability (μ_r max. 100 or 200) .



- **binder:** polystyrene, bakelite or similar plastics
- **ferromagnetic grains:** silit, mumetal, AlSiFer, sendast, permalloy, the oldest materials based on iron+carbon

Ferrites

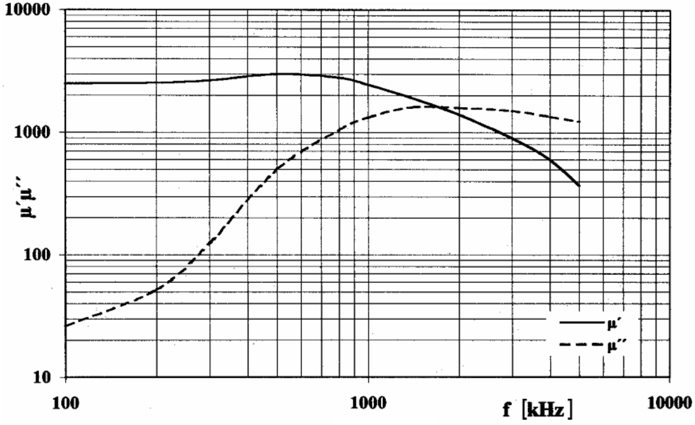
- Sintered ceramic materials, mixture of metal oxides ($MeO + Fe_2O_3$) where „*Me*“ is: *Mn*, *Co*, *Cu*, *Zn*, *Ni*
- Ferrites are not conductive (semiconductors), there are no eddy currents

- B_{max} is very low, cca 0.3 T to 0.4 T; μ_{max} depends on composition, varies from 10 to 10 000, power losses (D-power dissipation factor) are very low $0.1\% - 1\%$.

Ferrites - processing

- Similar to common ceramics: mixing of oxides, pressing, drying, burning (co-firing), final sharpen into required shape.
- **Shapes:**
  - enclosed cores: pots, EE, EI, UI, toroids;
  - open cores: bars, tubes (pipes).
- **Properties:** very fragile and hard materials, low thermal transfer. Overheating and not proper assembly can cause mechanical damage.
- **Marking:**
  - N - Ni and Zn ferrites;
  - H - Mn and Zn ferrites.

Complex permeability of manganum-ferrites



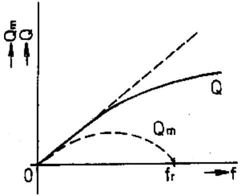
TOPIC

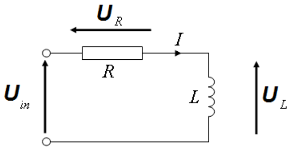
Quality Factor

- Q-factor describes amount of the losses in the inductance coil. Quality factor can be expressed as a ratio between reactive power P_r and total active power P_a, which is dissipated in the inductor. It can be expressed by the equation:

$$Q = \frac{P_r}{P_a} = \frac{\omega L}{R}$$

- Ideally Q factor increases linearly with frequency (coils without cores). The real characteristic is not linear due to the other factors like skin effect, permeability dependency and so on.





Quality Factor - Air Core Example