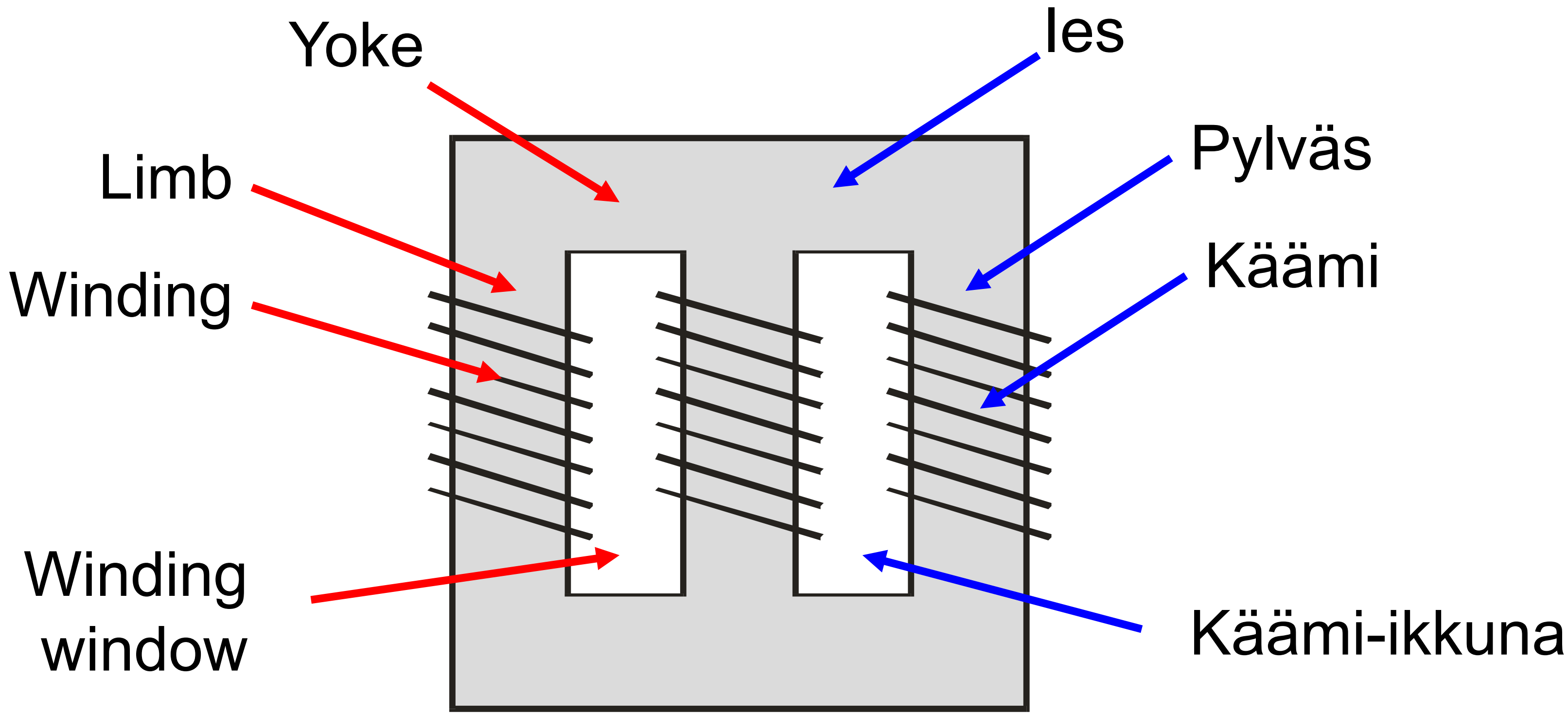
Transformers - I

- Static device; no moving parts
- Two or more stationary electrical circuits linked by a common magnetic circuit
- Electrical energy transfer happens between the coils without change in frequency.
- Highly efficient 95-98%

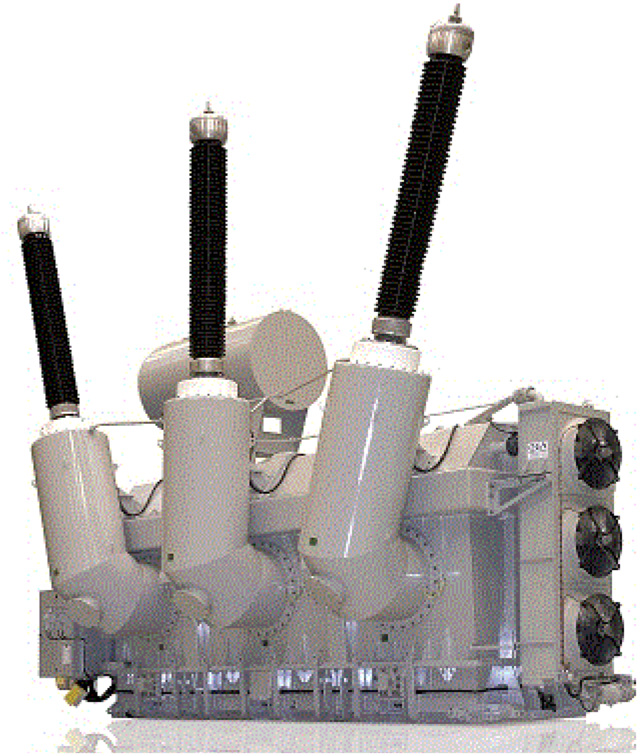
Transformer design – Basic terms

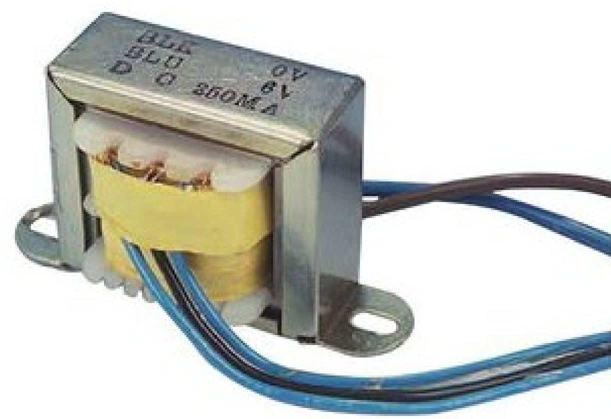


- Primary and secondary winding a.k.a Low voltage or high voltage winding
- Magnetic core : Made of silicon steel, laminated 0.3 – 0.5 mm thick

Types

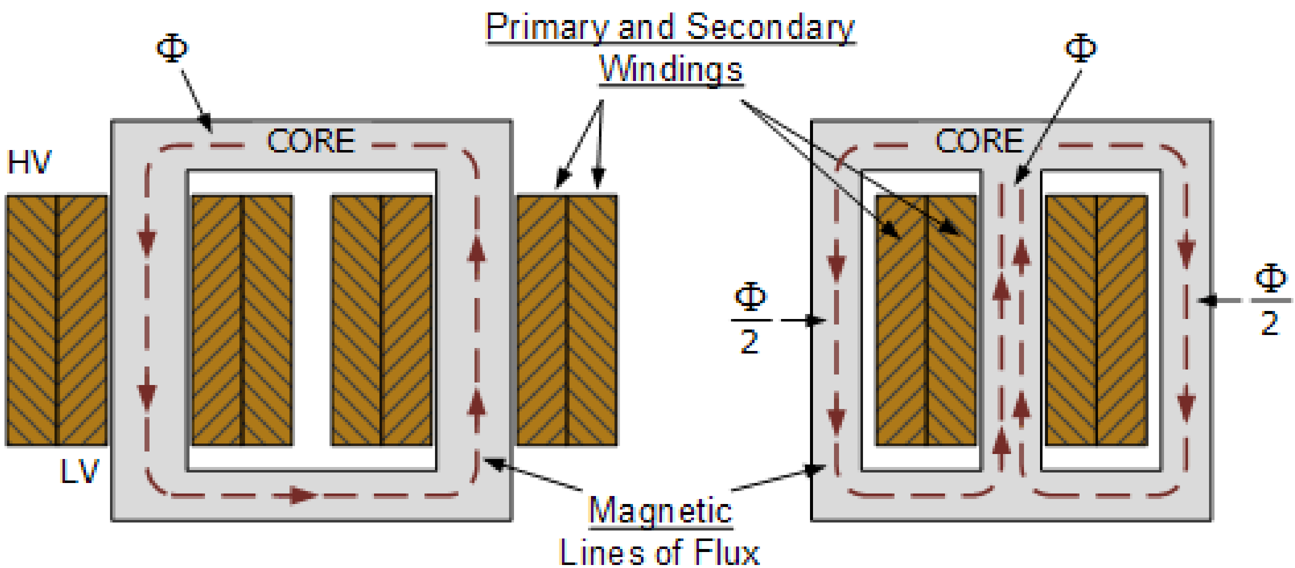
- Power transformer
- Distribution transformer
- Step-up/step-down transformer
- Instrument / isolation transformer
- Autotransformer
- Core type and shell type transformer
- Single and three phase transformer





Core Type

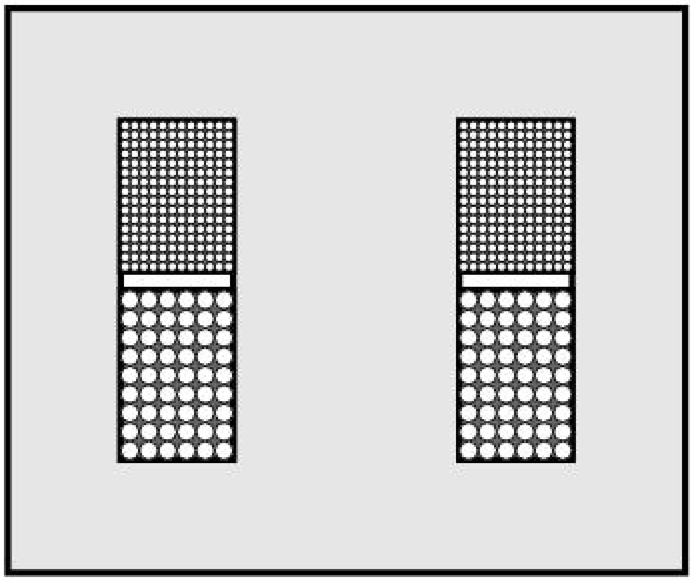
Shell Type

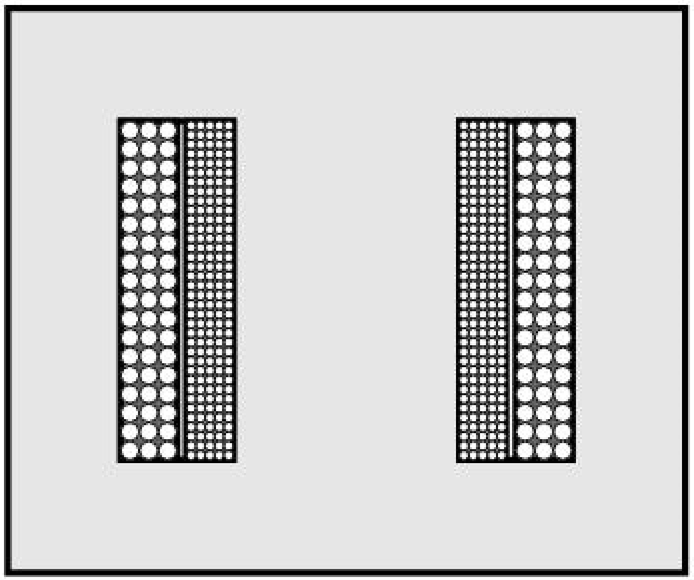


- Winding encircles core
- Preferred for low voltage transformers
- Concentric coils
- Natural cooling quite effective
- Repair and maintanence easy

- Core encircles winding
- Preferred in high voltage transformer
- Multilayer or sandwich coils
- Natural cooling is difficult
- Winding maintence difficult

Transformer designs – Basic terms

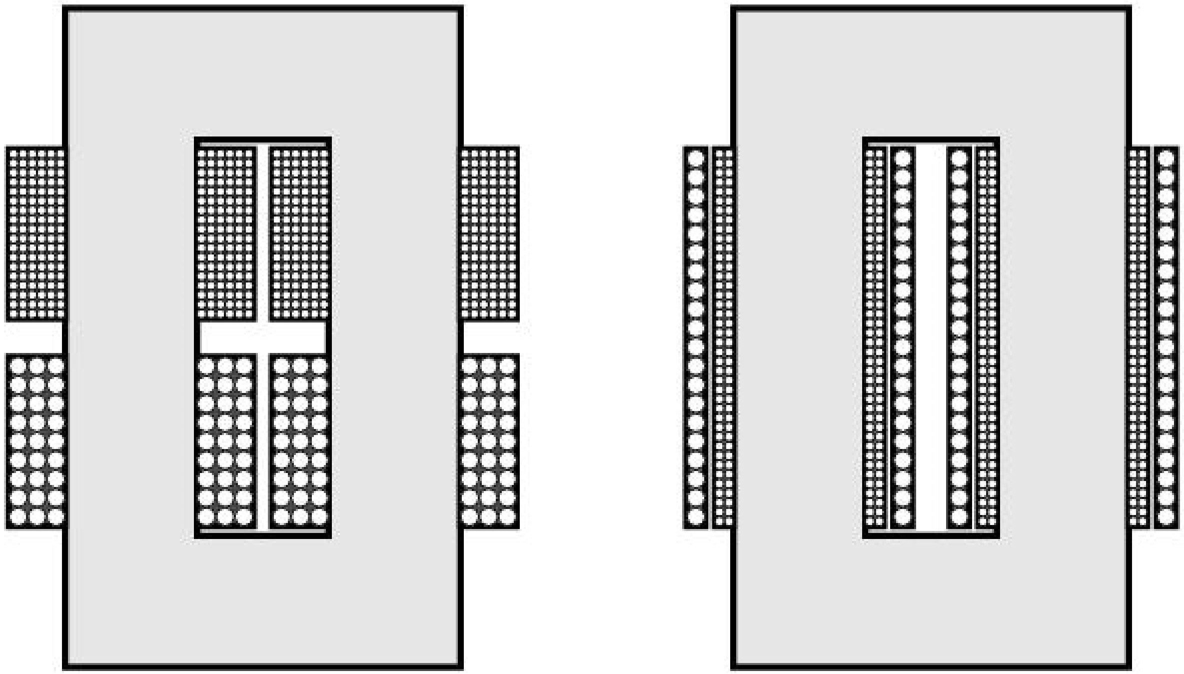




Single-phase single-limb shell-type transformers
Split windings on the left, concentric windings on the right

Yksivaiheisia vaippamuuntajia
Vasemmalla lokerokäämitys, Oikealla sylinterikäämitys

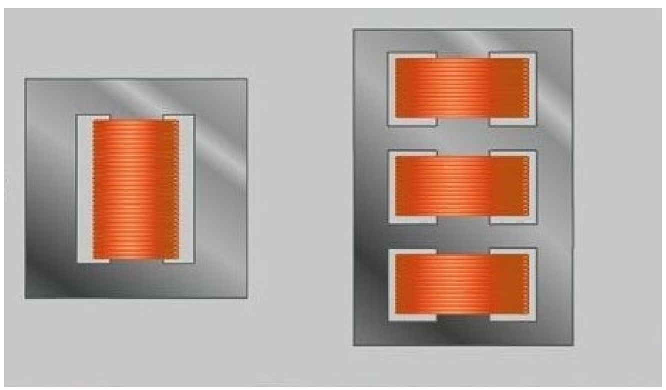
Transformer designs – Basic terms

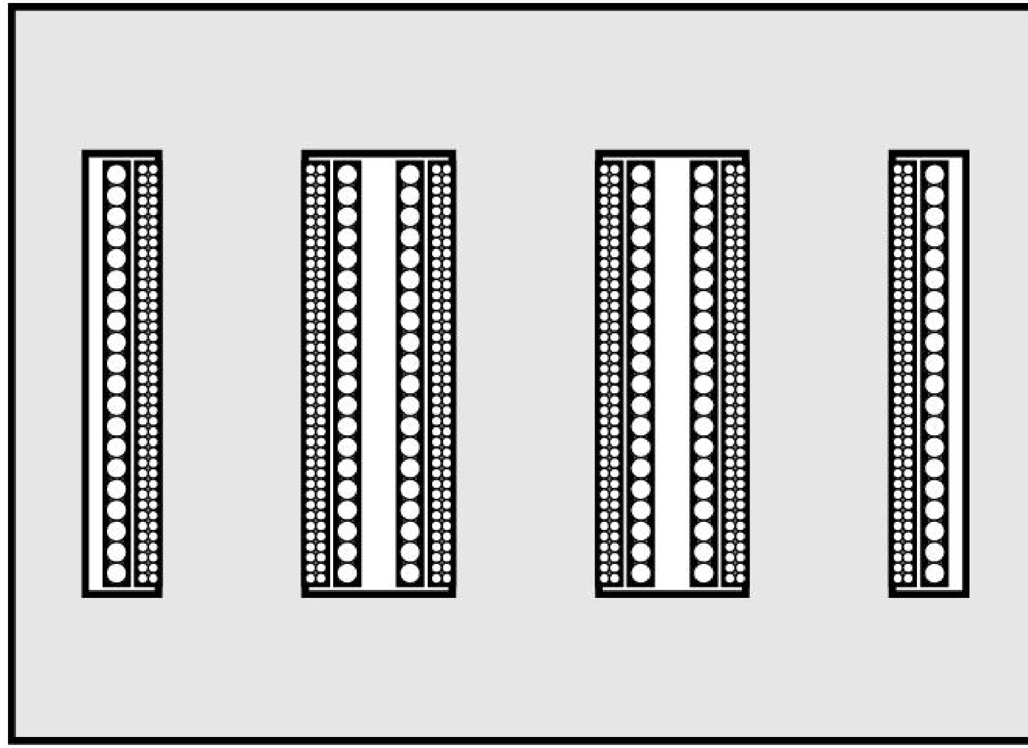


Single-phase double-limb core-type transformers
Split windings on the left, concentric windings on the right

Yksivaiheisia sydänmuuntajia
Vasemmalla lokerokäämitys, Oikealla sylinterikäämitys

Transformer designs – Basic terms

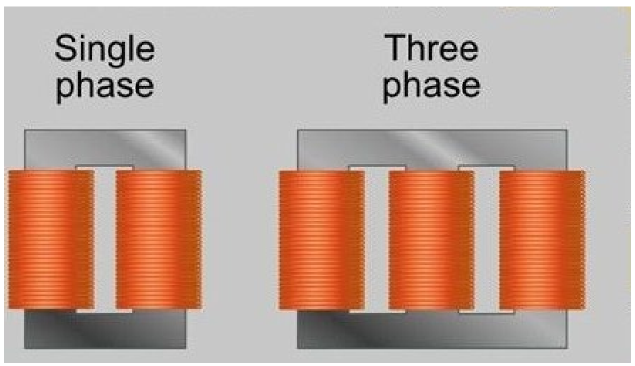


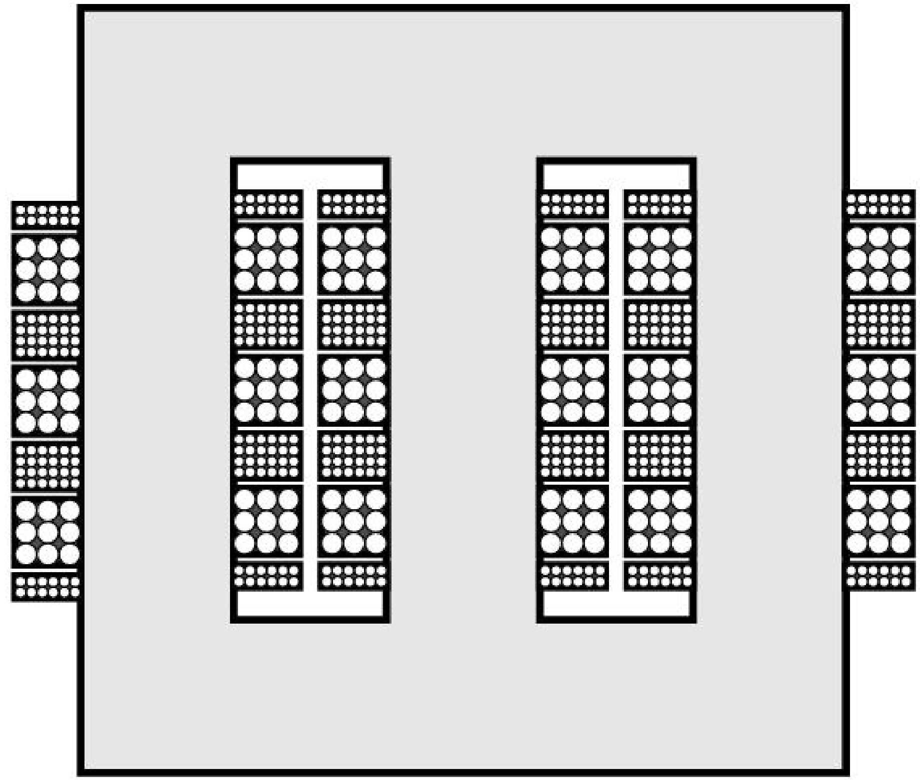


Three-phase three-limb **shell-type** transformers with concentric windings

Kolmivaiheinen vaippamuuntaja sylinterikäämityksellä

Transformer designs – Basic terms

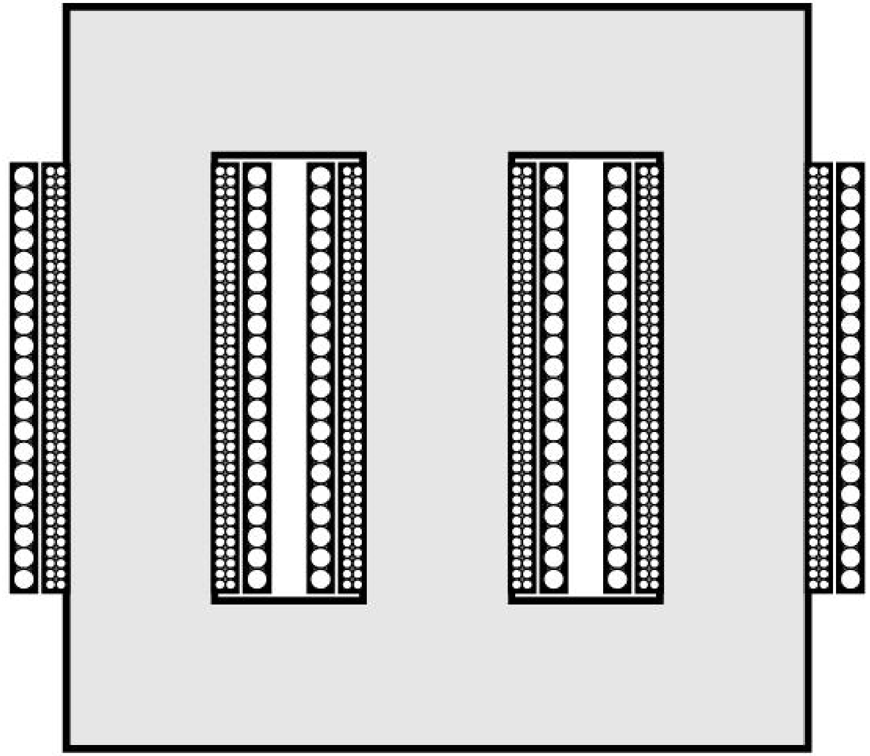




Three-phase three-limb **core-type** transformer with sandwich winding

Kolmivaiheinen sydänmuuntaja vuorottaiskäämityksellä

Transformer designs – Basic terms



Three-phase three-limb core-type transformer with concentric windings

Kolmivaiheinen sydänmuuntaja sylinterikäämityksellä

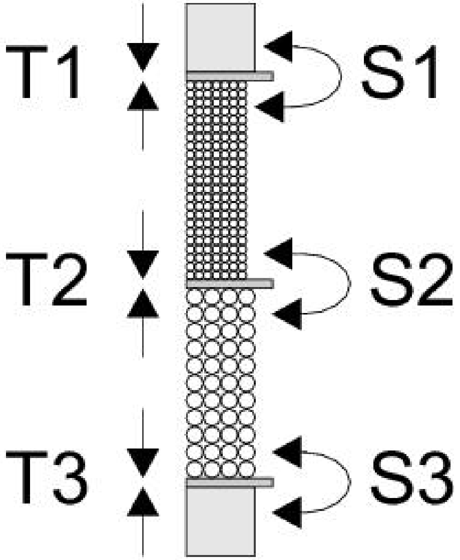
About the positions of the windings

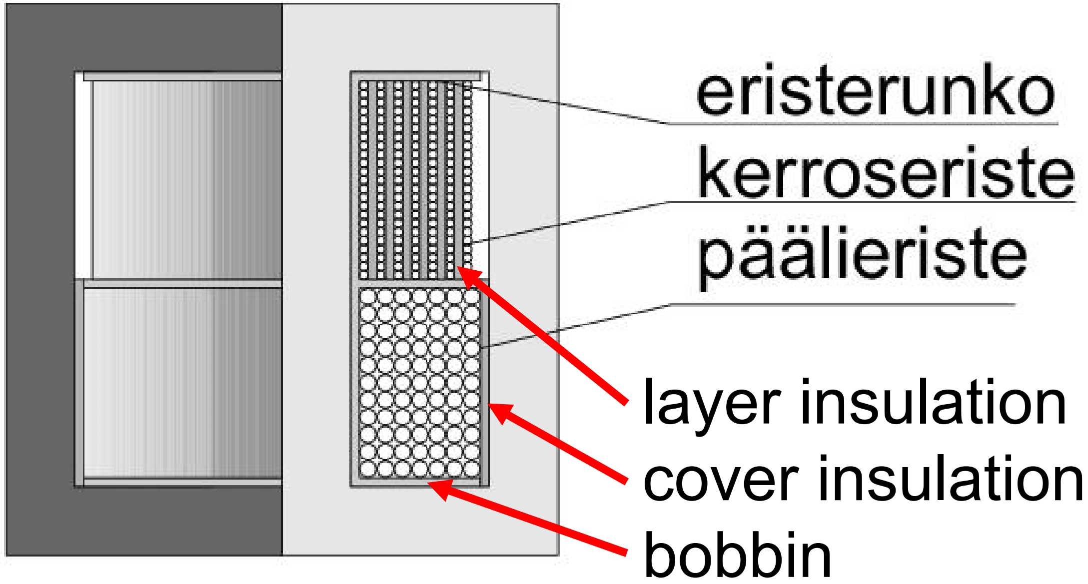
- In a low-voltage transformer, the easiness of production defines the position or order of the windings. If there are several secondary windings, the single primary winding is typically the innermost one (concentric windings).

- In a high-voltage transformer, the winding having the lowest voltage level is typically placed close to the core (concentric windings). The windings are referred to as the low-voltage and high-voltage windings.

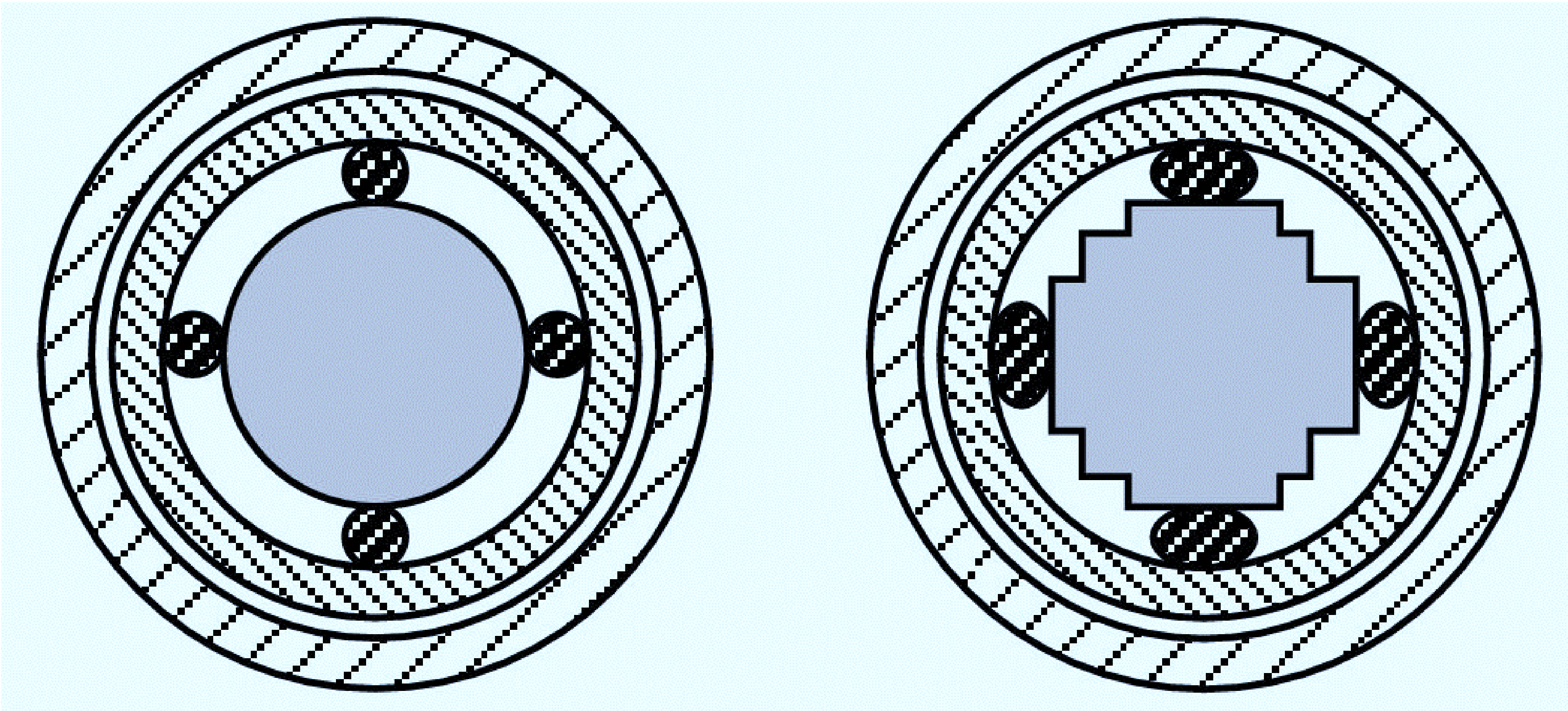
About the insulations

Both the dielectric strength of insulation material (insulation thickness) and possibility of surface discharges have to be considered.





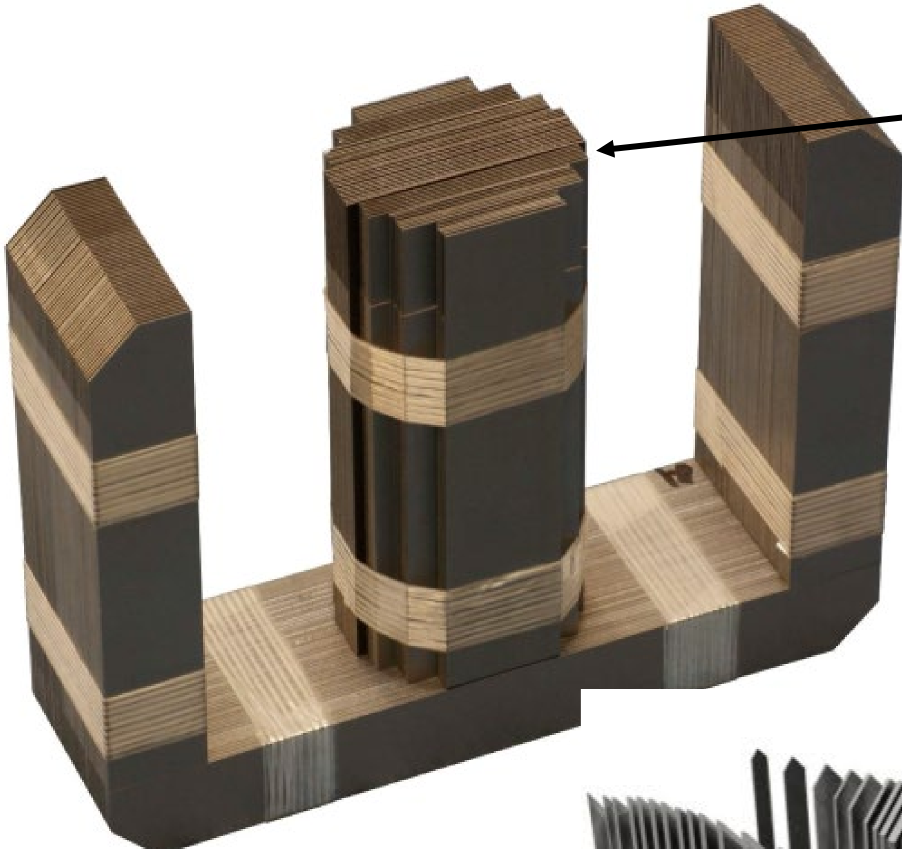
Transformer cores



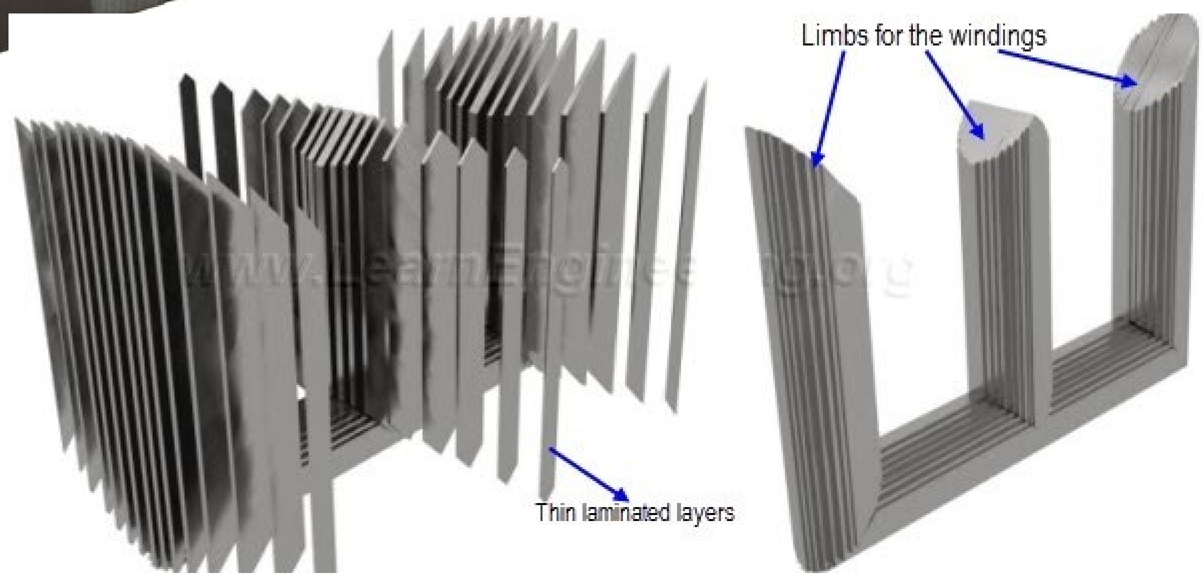
An ideal core with circular cross-section for a power transformer. Such a shape would produce a smooth distribution of electric field.

More practical core shape for a power transformer. The limb is typically made of oriented electrical steel sheets of 0.28 … 0.35 mm thickness.

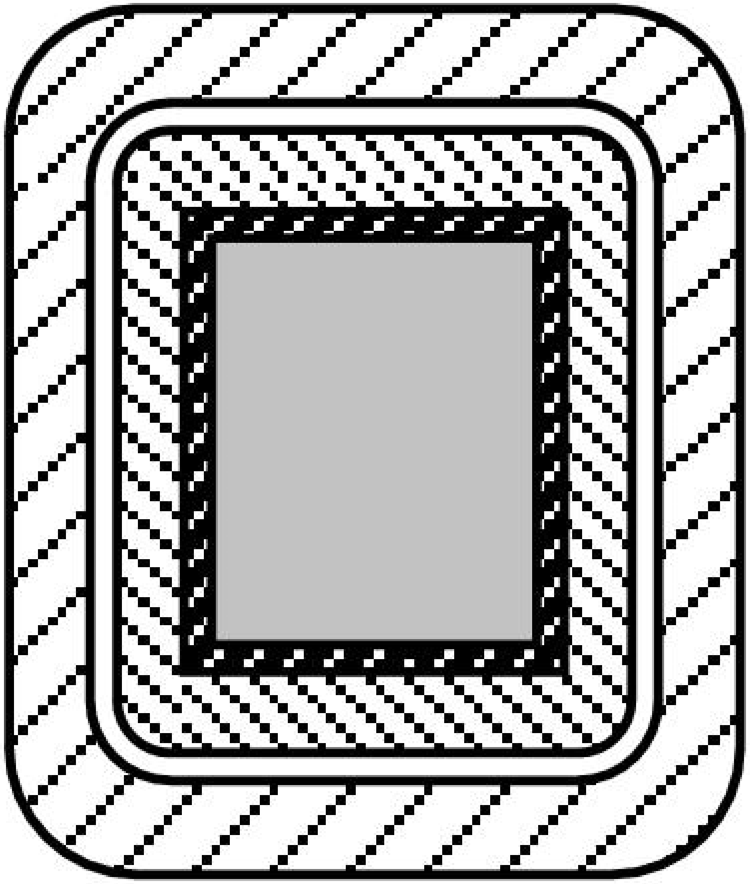
Circular Transformer core



Four stepped cruciform core



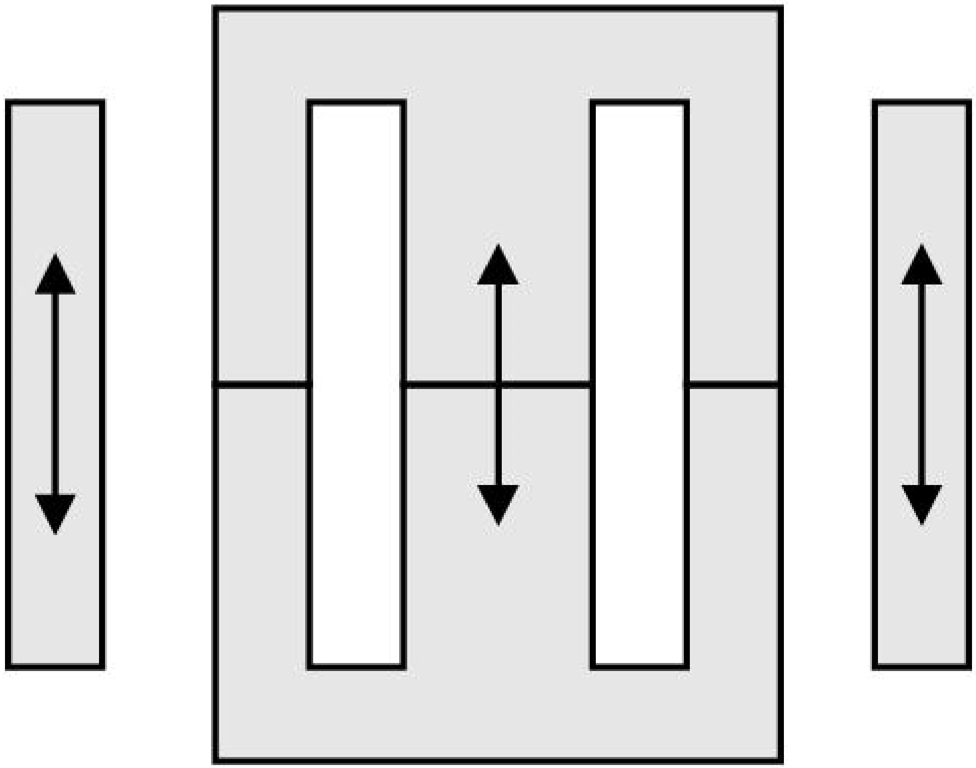
Transformer cores



Typical limb of a low-voltage transformer has a rectangular cross section. The core is assembled from EI or UI sheets having standardised dimensions.

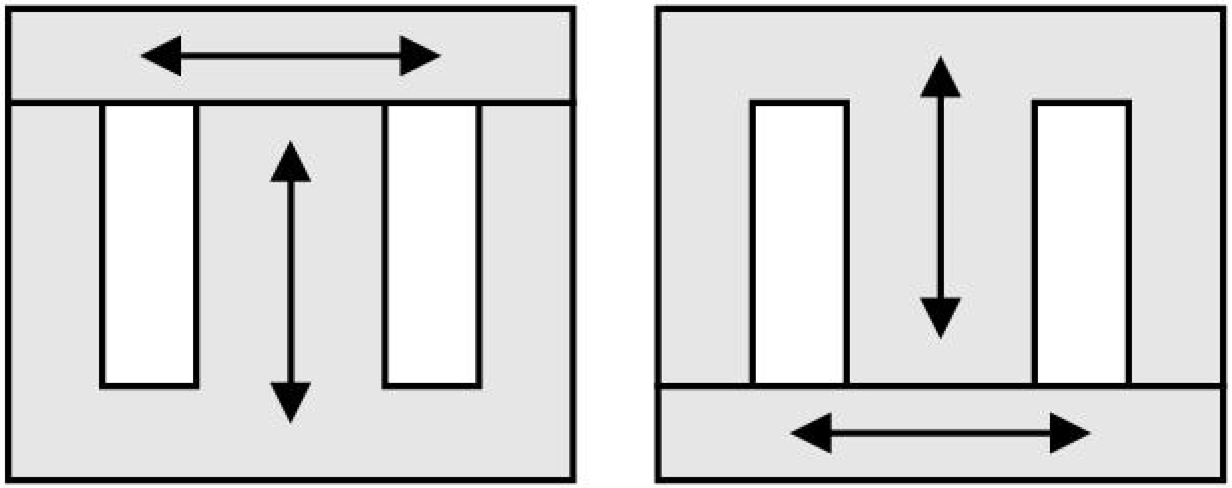
The sheet material may be oriented or non-oriented. The thickness is typically 0.35 or 0.50 mm. The sheets are insulated from each other by a thin insulation layer. A typical filling factor is 0.95 – 0.97.

Sheets for small transformers



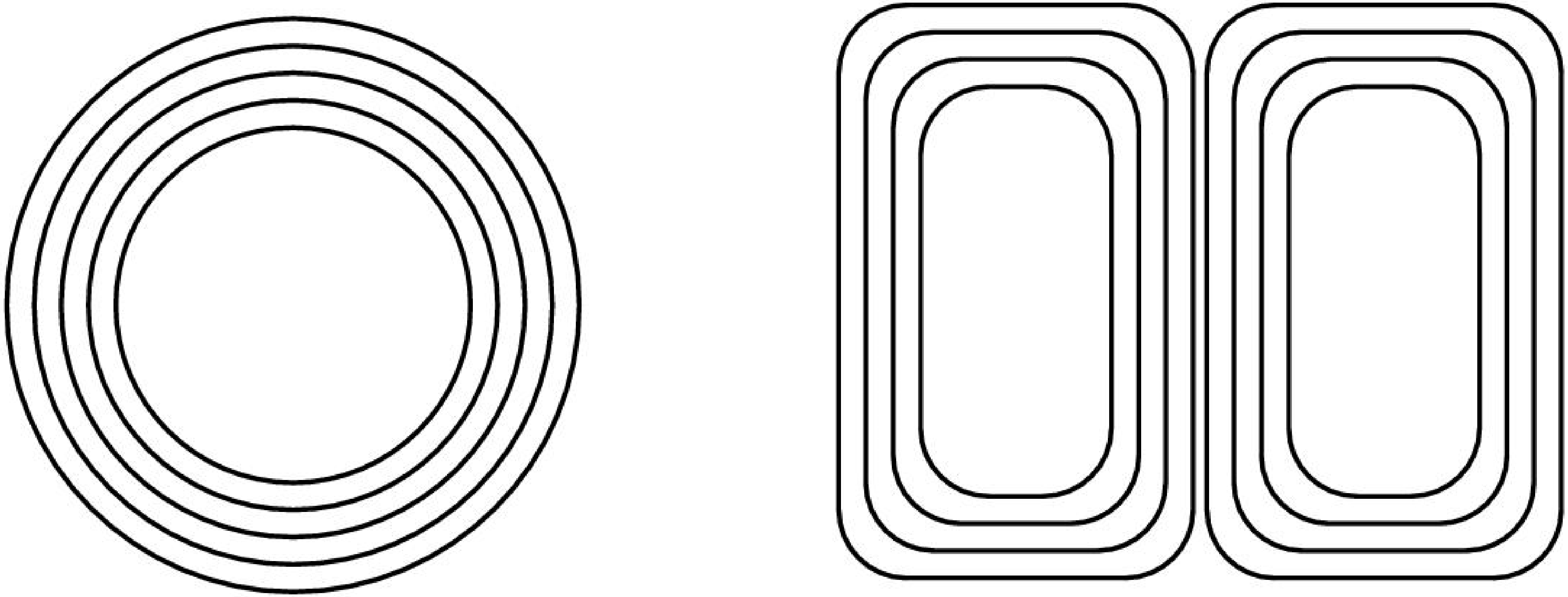
Cutting the sheets of a small transformer from a continuous strip. The rolling direction is indicated by the arrows. The dimensions are so designed that the stamping produces no left-over parts.

Sheets for small transformers



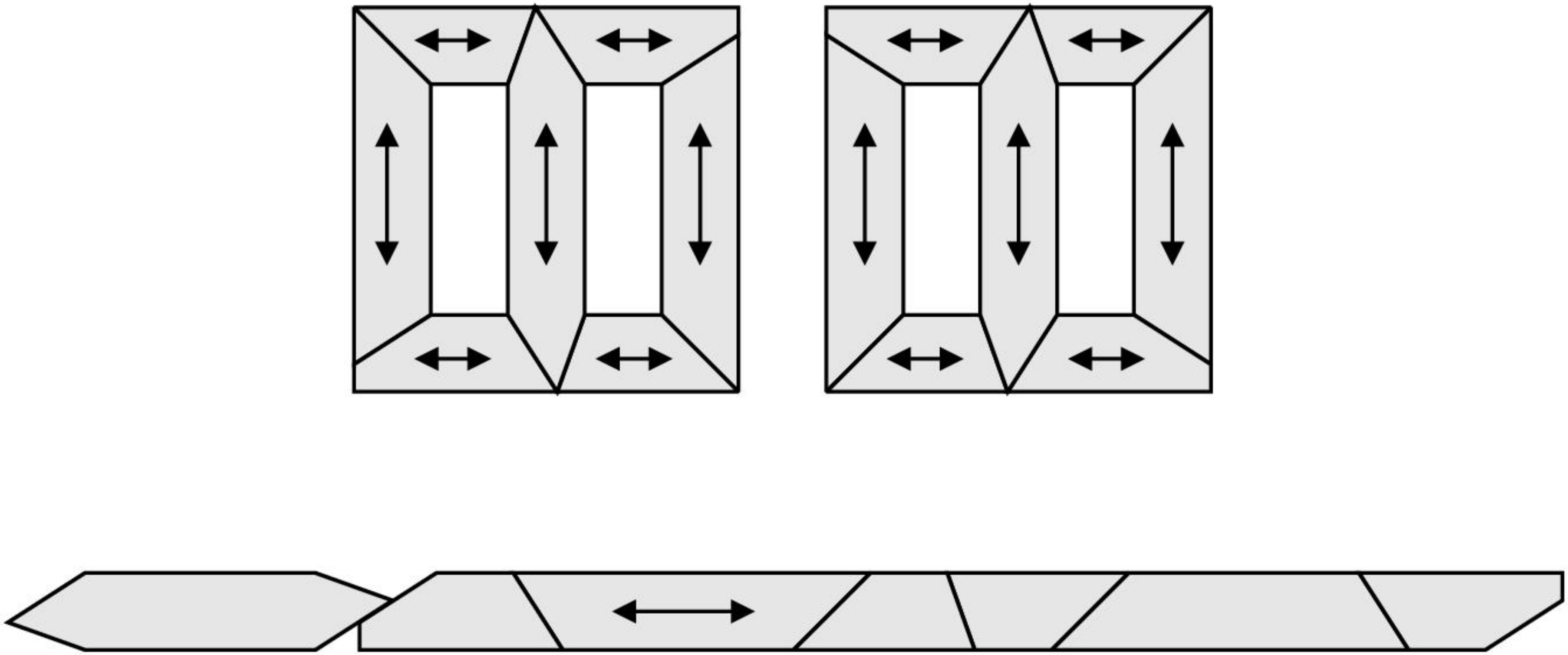
Two successive layers when assembling a small transformer. The easy direction of magnetisation i.e. the rolling direction is indicated by the arrows.

Sheets for small transformers



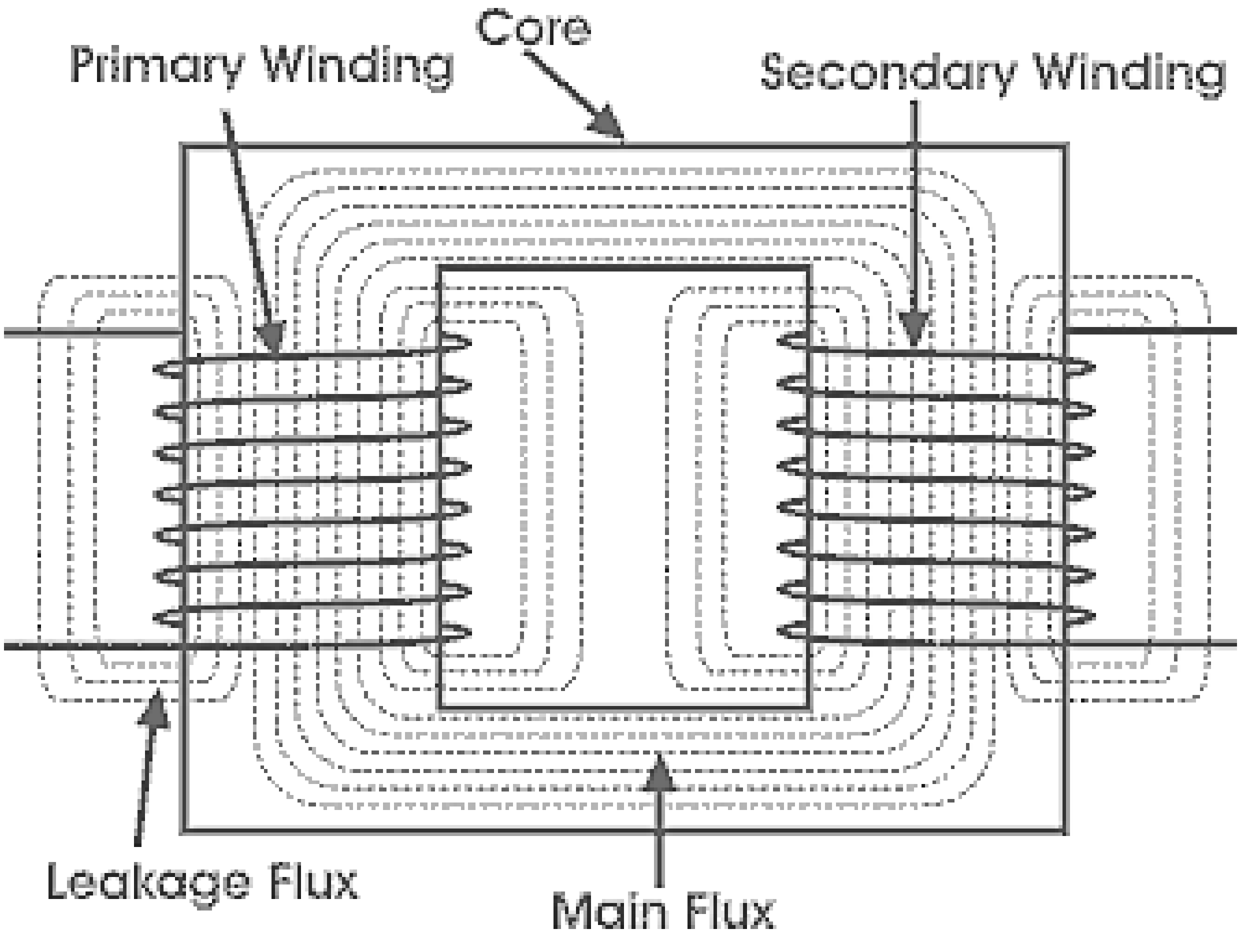
A ring-shaped core and EI-core made of a narrow continuous strip of electrical steel sheet, or in some special cases, of an amorphous ferromagnetic material.

Sheets for power transformers

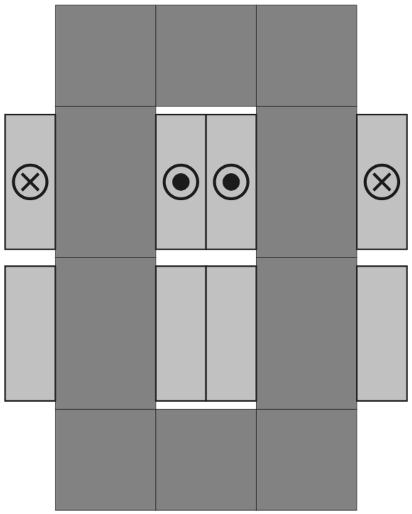


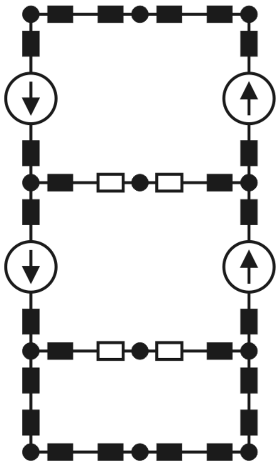
Two successive layers when assembling a small transformer. The easy direction of magnetisation i.e. the rolling direction is indicated by the arrows.

Flux paths in a transformer



Flux paths in a transformer



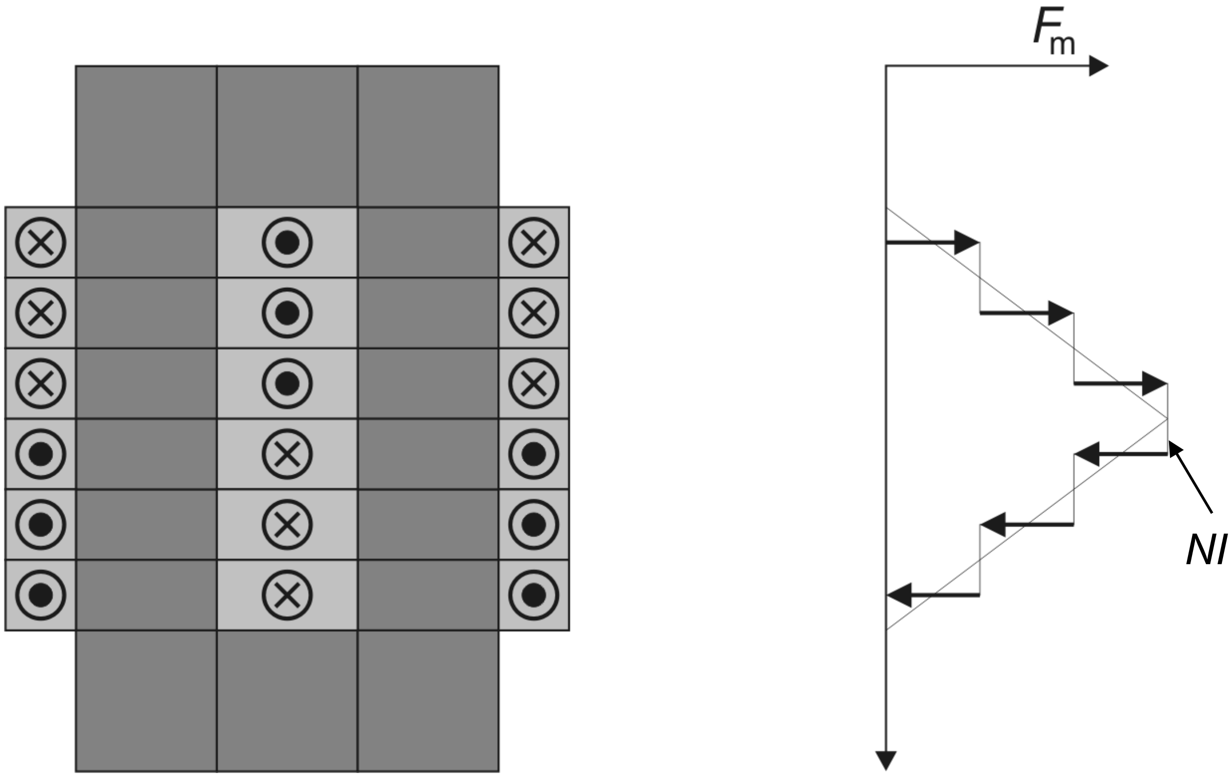


A basic reluctance network for a transformer at no load. The **primary winding is magnetised**, only. The reluctances associated with the core are marked by the black colour. **The white ones are associated with the leakage flux in the winding or air.**

$$R_{\mathrm{m}} = \frac{l_{\phi}}{\mu A_{\phi}}$$

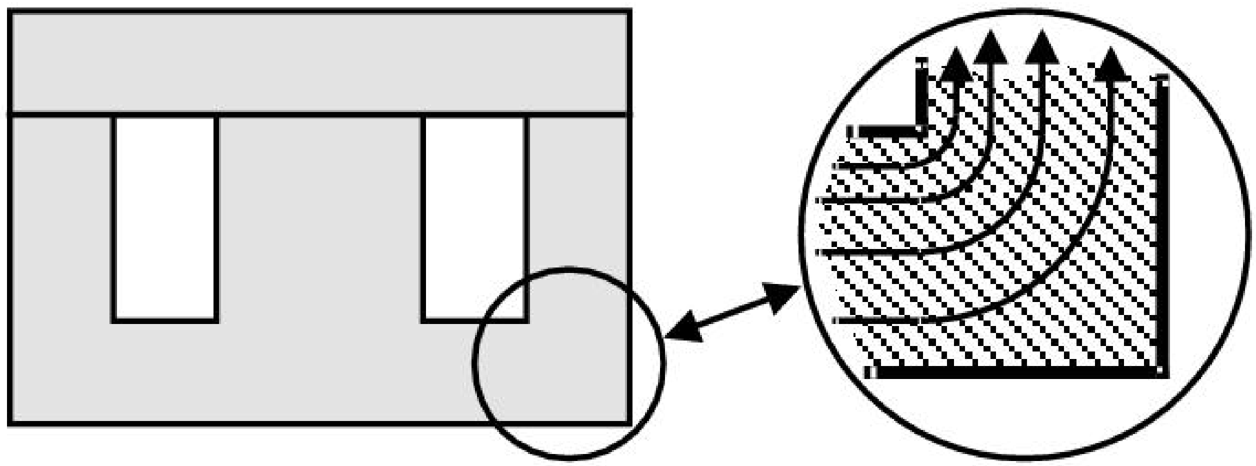
μ is permeability,
l_{ϕ} is length of the flux path and
A_{ϕ} is the cross-sectional area of the flux path.

Flux paths in a transformer

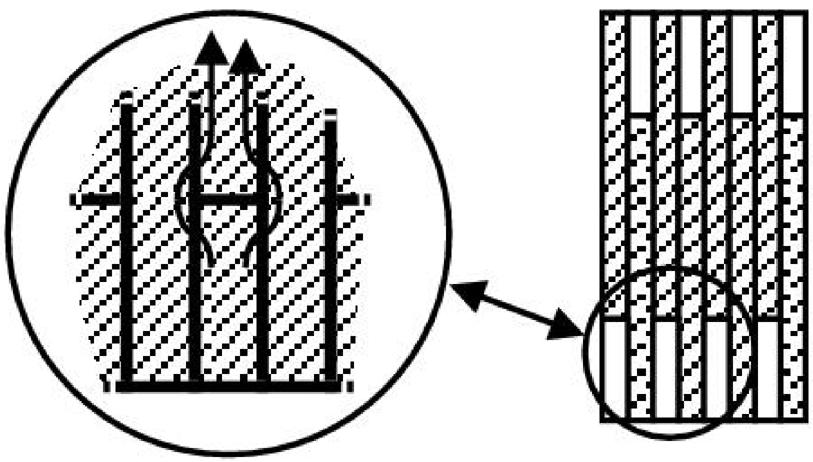


Magnetomotive force in a loaded transformer.

Flux paths in a transformer

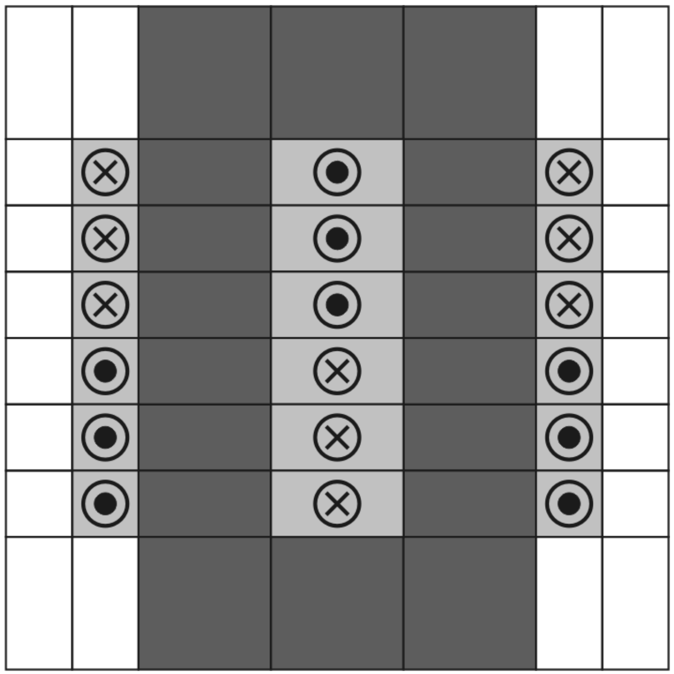


Flux flow from yoke to limb.

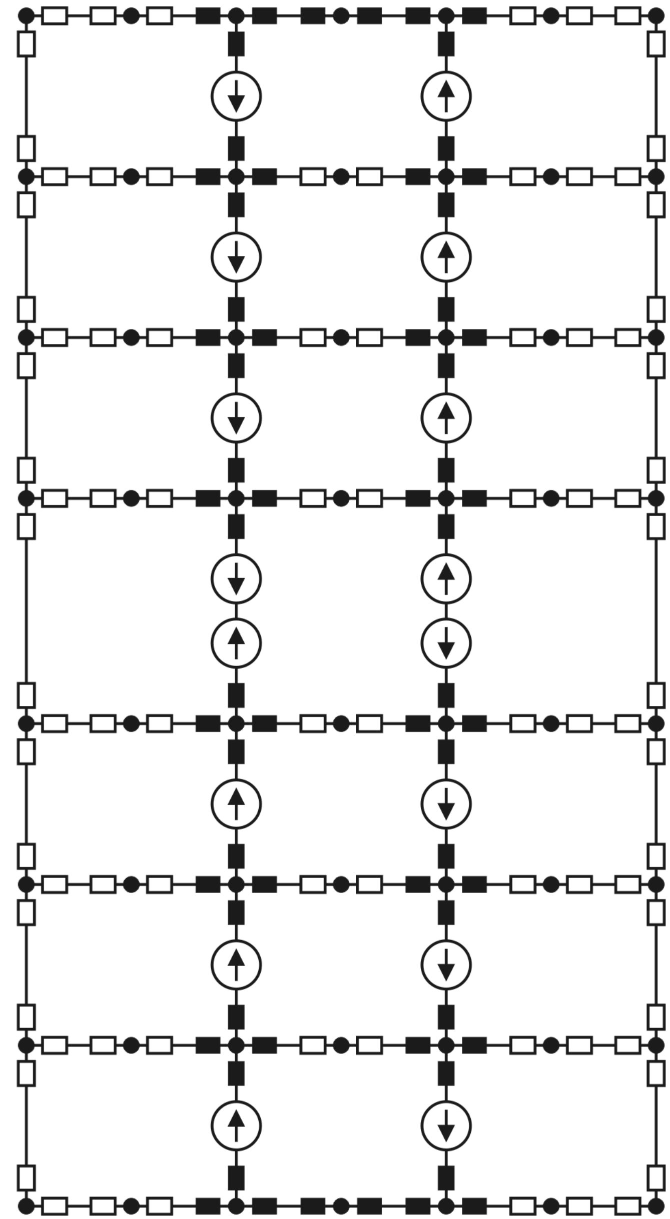


Some flux jumps from sheet to sheet.

Flux paths in a transformer

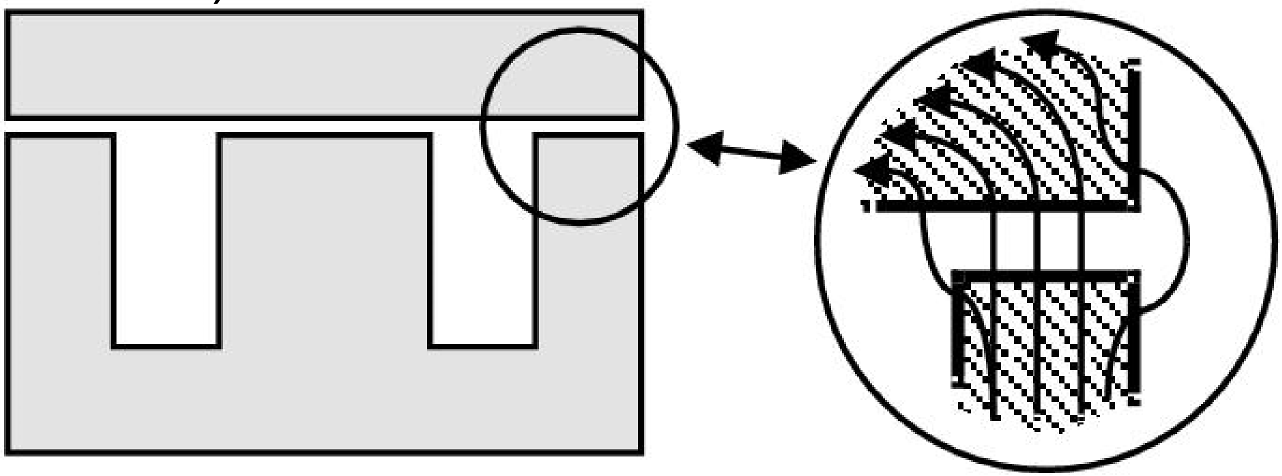


Reluctance network for a loaded core-type transformer including the leakage flux paths outside the core.

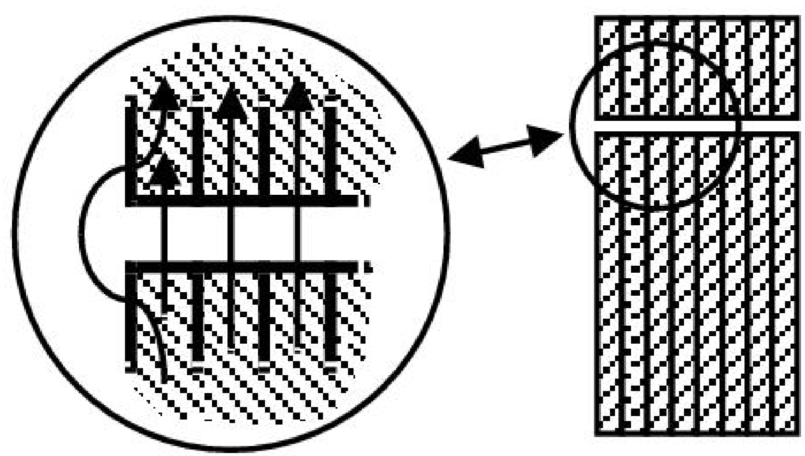


Flux of an inductor

Difference to a transformer: **Air gap**, which is mainly used to linearise the characteristics of the inductor (prevent core saturation)



The fringing flux at the air-gap region may be quite significant.



Flux of an inductor

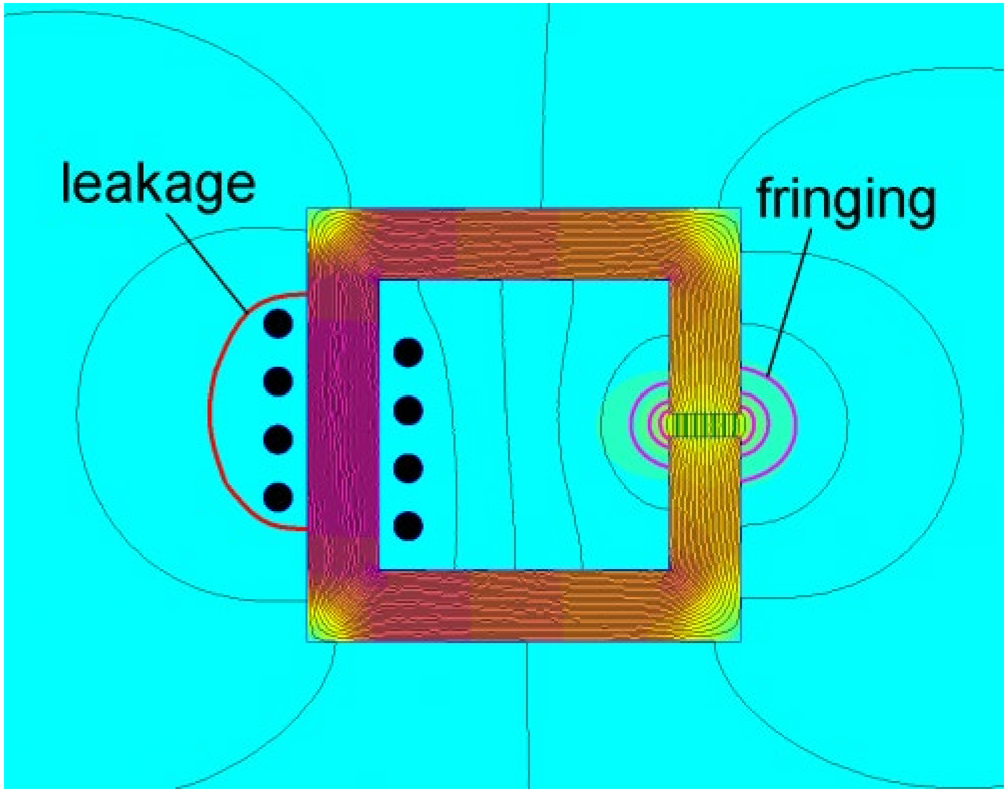


Fig. Courtesy: Stan Zurek, http://www.encyclopedia-magnetica.com/doku.php/flux_fringing

Air gap increases the effective permeability of the magnetic circuit. Therefore, *B* is lesser for the same magnetising current.

Flux of an inductor

Approximate equation for the inductance (neglecting the reluctance of the core)

$$L = N^2 \Lambda_\delta = \frac{N^2}{R_{\mathrm{m}\delta}} = N^2 \frac{\mu_0 A_\delta}{l_\delta}$$

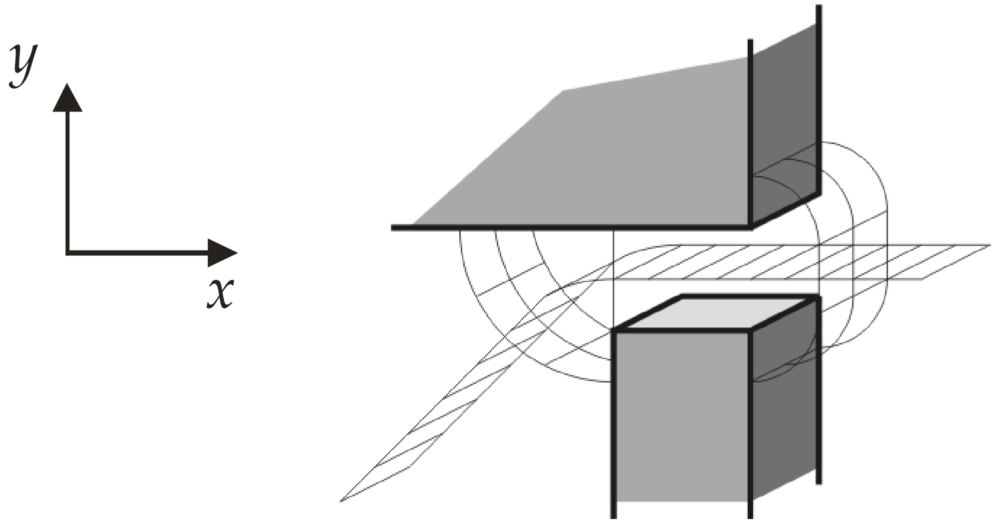
N is the number of turns,
μ_0 is permeability of free space,
l_δ is length of the air gap and
A_δ is the cross-sectional effective area of the air gap.

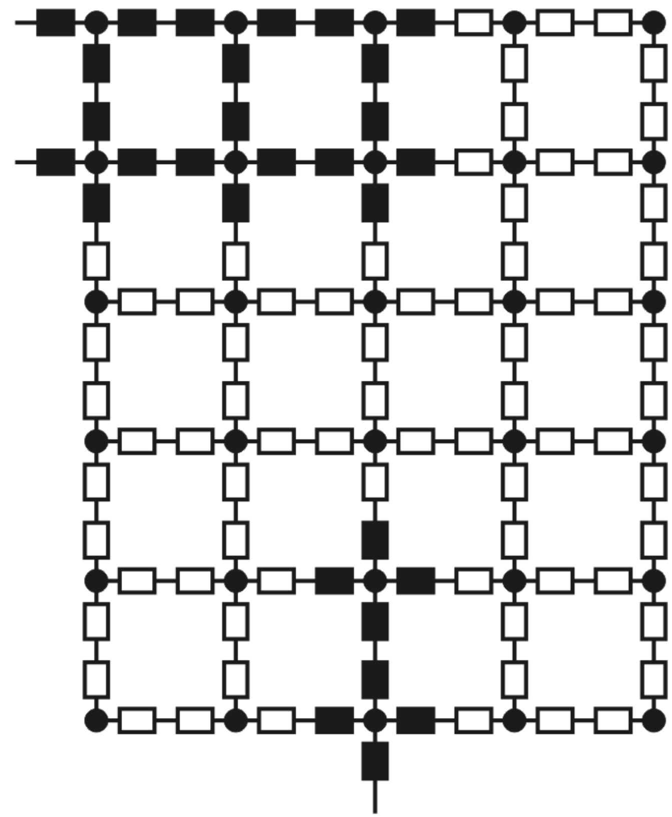
The effective area A_δ should be defined to include the contribution from the fringing flux. Approximately

$$A_\delta = b_\delta w_\delta = \left(b + 2l_\delta\right)\left(w + 2l_\delta\right)$$

where b and w are the cross-sectional dimensions of the rectangular core.

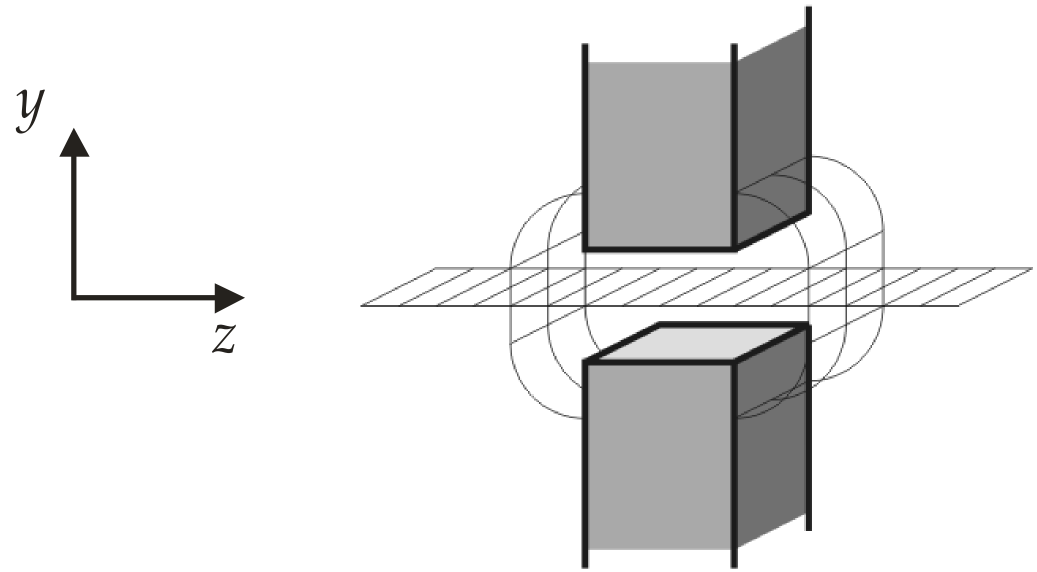
Modelling the fringing flux

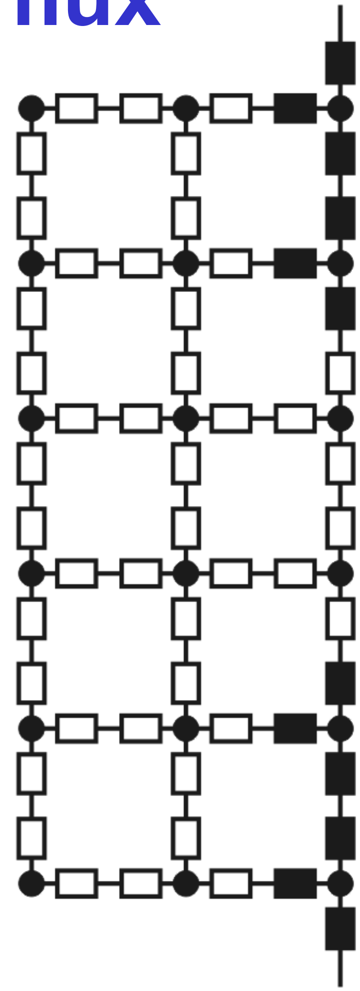




On the left, a sketch of flux lines and equipotential surface of the magnetic field. Reluctance network on the right (x,y plane).

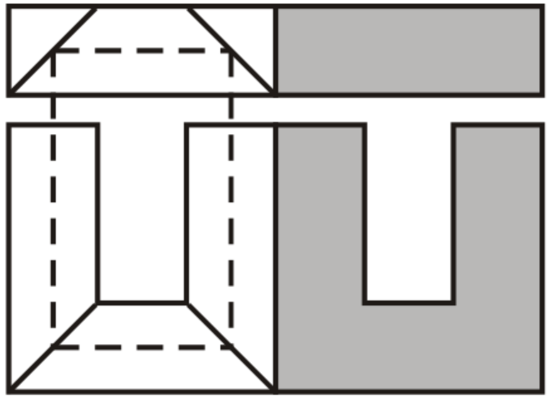
Modelling the fringing flux

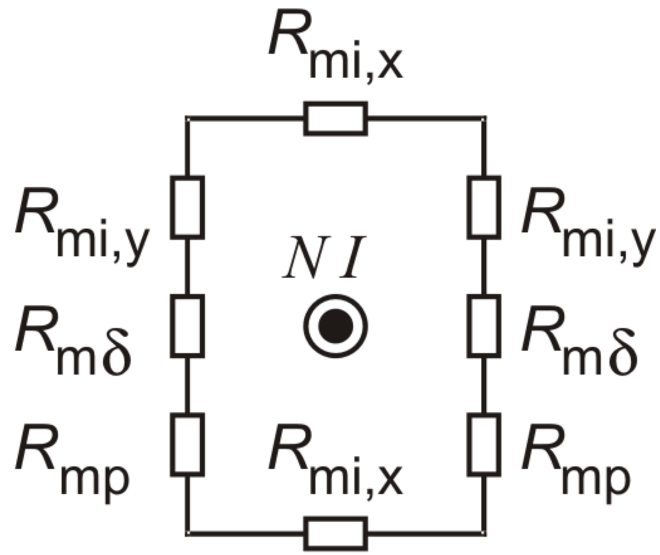




On the left, a sketch of flux lines and equipotential surface of the magnetic field. Reluctance network on the right (z,y plane).

Analysis of an inductor





Because of symmetry, it is enough to model only half of the geometry. Reluctances are associated with the yokes, limbs and air gaps of the inductor. The upper yoke is modelled with one horizontal and two vertical reluctances.

$$R_{m\delta} = \frac{l_\delta}{\mu_0 b_\delta w_\delta} \qquad 2\left(R_{mi,x} + R_{mi,y} + R_{mp} + R_{m\delta}\right)\Phi = NI$$

where I is the coil current and Φ the flux of the core.

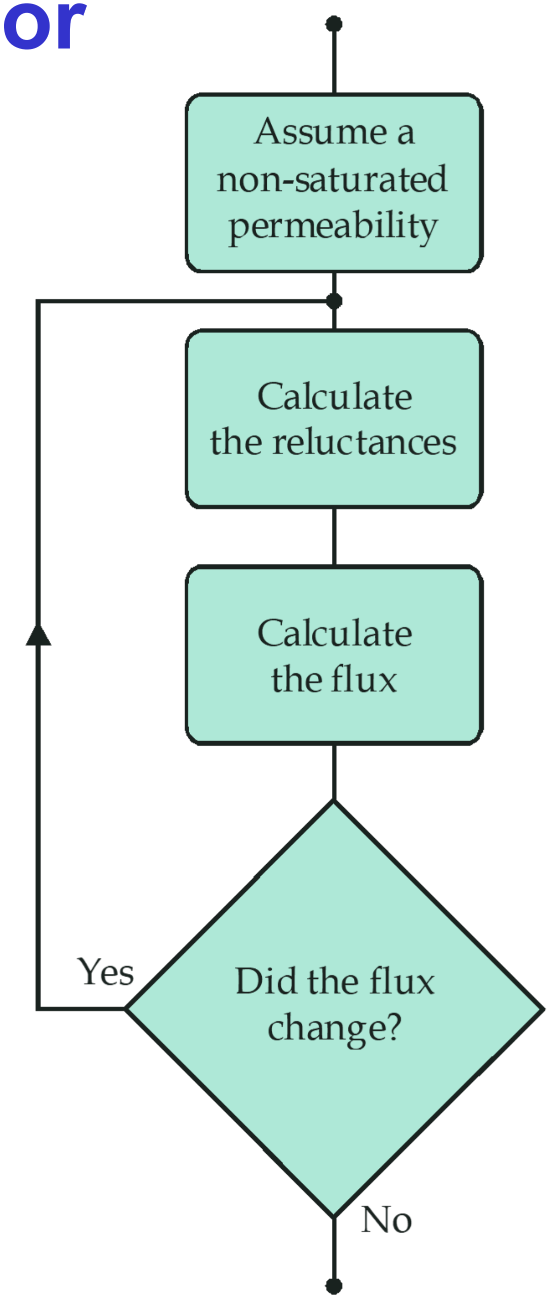
Analysis of an inductor

Because of magnetic saturation, the reluctances associated with the core are nonlinear. This leads to a nonlinear equation that has to be solved iteratively.

$$2\left(R_{\mathrm{mi,x}}(\Phi)+R_{\mathrm{mi,y}}(\Phi)+R_{\mathrm{mp}}(\Phi)+R_{\mathrm{m\delta}}\right)\Phi = NI$$

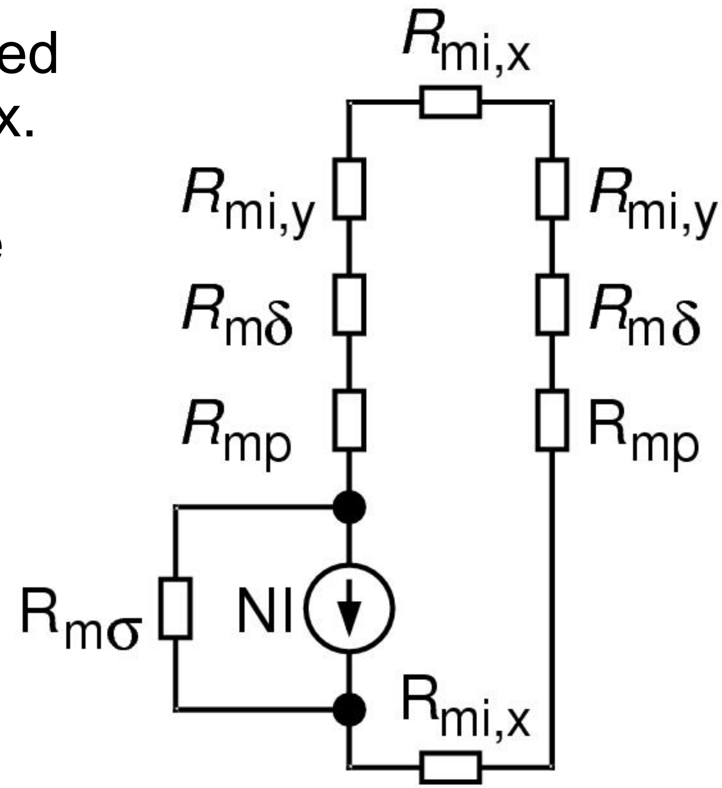
One possible iteration scheme is obtained by first solving the flux based on the non-saturated permeability, calculating the reluctances with this flux and using the reluctances to solve a new value for the flux.

This process is repeated as long as the flux changes significantly from one iteration step to the next one.



Analysis of an inductor

The simple reluctance network presented earlier does not include the leakage flux. If the core saturates, the leakage becomes important. The network to the right includes the leakage path.



$$\begin{cases} 2\left(R_{\mathrm{mi,x}} + R_{\mathrm{mi,y}} + R_{\mathrm{mp}} + R_{\mathrm{m\delta}}\right)\Phi_{\mathrm{h}} = NI \\ R_{\mathrm{m\sigma}}\Phi_{\sigma} = NI \end{cases}$$

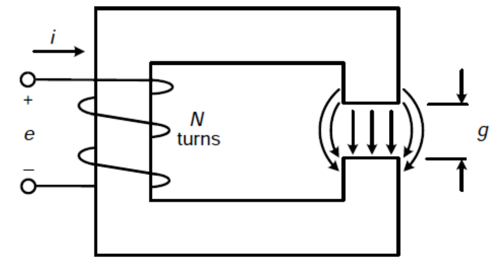
Φ_{h} is the flux in the core,
Φ_{σ} is the leakage flux.

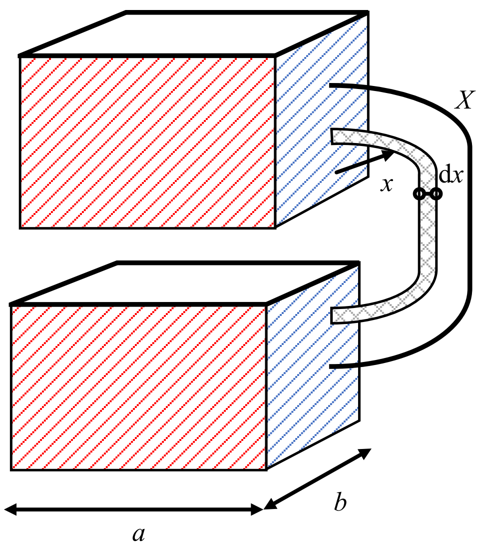
The inductance includes two components

$$L = N^2\left(\Lambda_{\sigma} + \Lambda_{\mathrm{h}}\right) = N^2\left[\frac{1}{R_{\mathrm{m\sigma}}} + \frac{1}{2\left(R_{\mathrm{mi,x}} + R_{\mathrm{mi,y}} + R_{\mathrm{mp}} + R_{\mathrm{m\delta}}\right)}\right]$$

Fringing Effect Around the Air Gap

- The fringing flux is approximately modeled by a semi circle. The total permeance in this case equals:
- $p_{\mathrm{fring1}} = \int_0^x \frac{\mu_0 b}{g+\pi x}\mathrm{d}x + \int_0^x \frac{\mu_0 a}{g+\pi x}\mathrm{d}x$
  $= \frac{\mu_0(a+b)}{\pi}\ln(1+\frac{\pi x}{g})$
- $R_{\mathrm{fring}} = \frac{1}{2p_{\mathrm{fring1}}} = \frac{\pi}{2\mu_0(a+b)\ln(1+\frac{\pi x}{g})}$,
- where L is the length of the core. x is a variable and can be set as far as from the air gap to $10g$.





Analysis of an inductor

Reluctance network for the single-phase inductor after including a leakage-flux path through the winding window. The magneto-motive force is divided into two “voltage sources” on each limb.