Design of Electric Machines

Lecture 2

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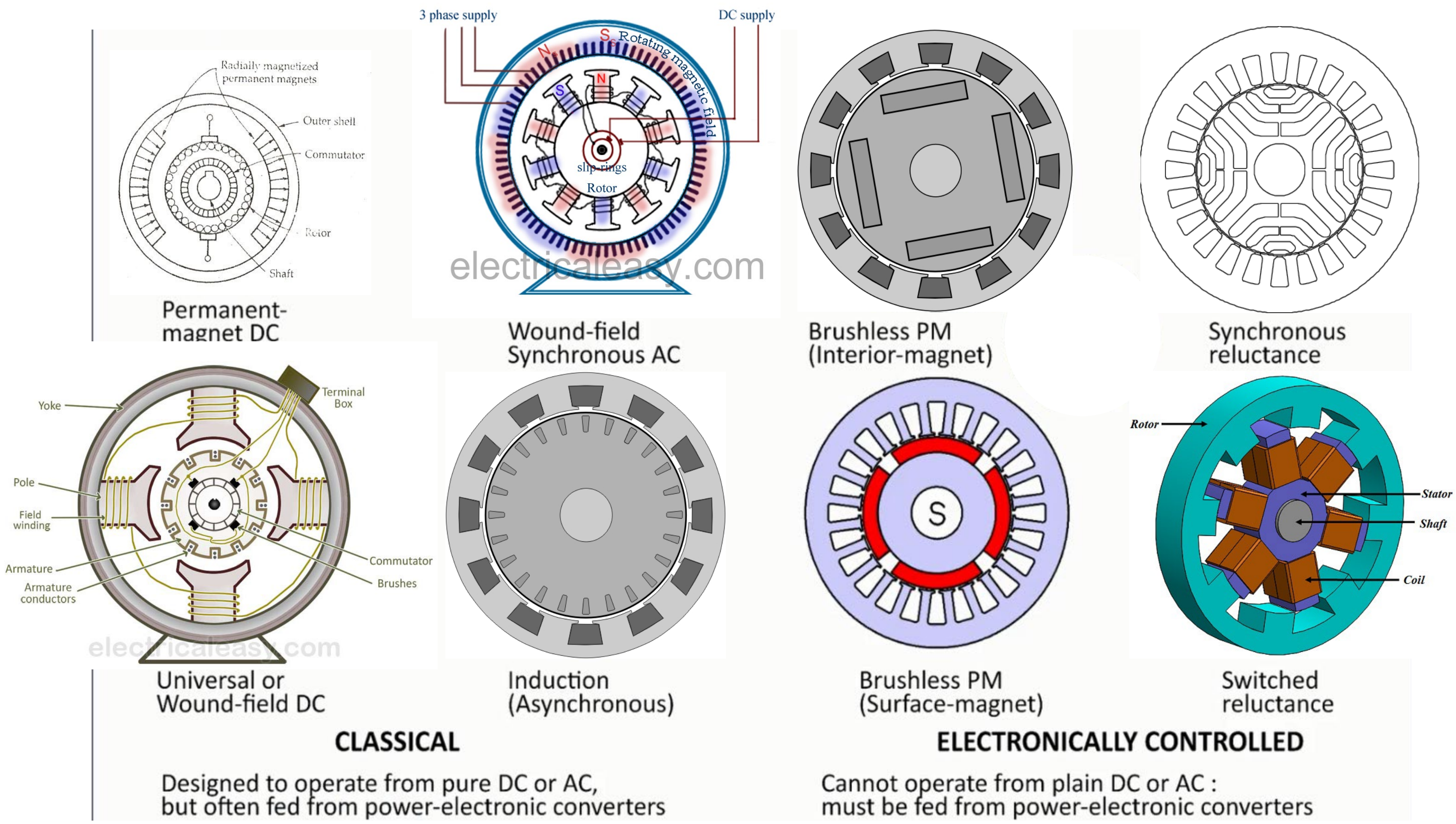
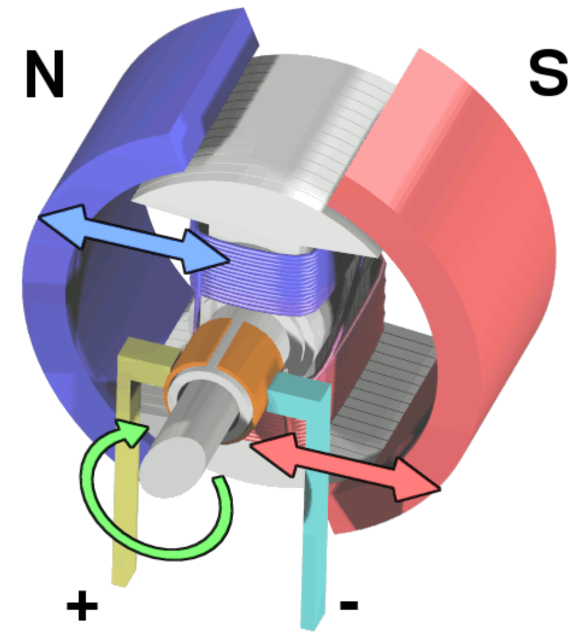
Classifications of Electric Machines



T. Finken, M. Felden and K. Hameyer, "Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles," *2008 18th International Conference on Electrical Machines*, Vilamoura, 2008, pp. 1-5, doi: 10.1109/ICELMACH.2008.4800044.

What are the pros of DC motors

- DC motors have an excellent control behavior (Linear relation between current and torque).
- No complex power electronic converters are needed.
- Low cost of production.

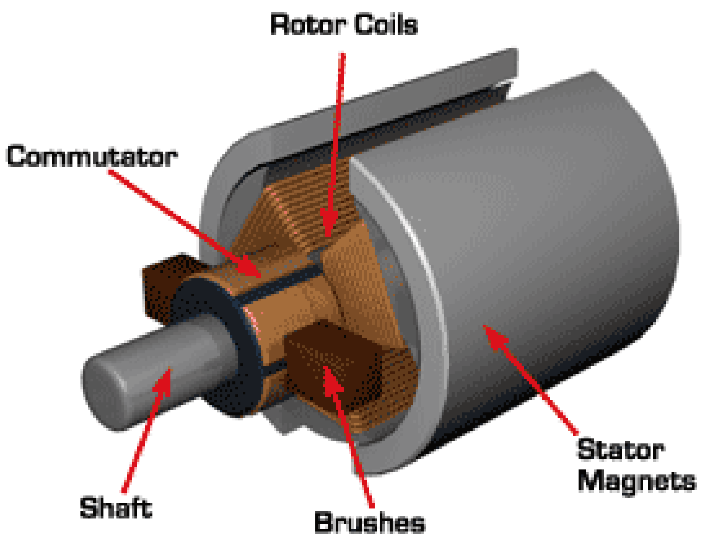


What are the cons of DC Motors

- Mechanical Wear, noise and wear of brushes and commutator.
- Electrochemical corrosion of the brushes.
- Compensation windings are needed.

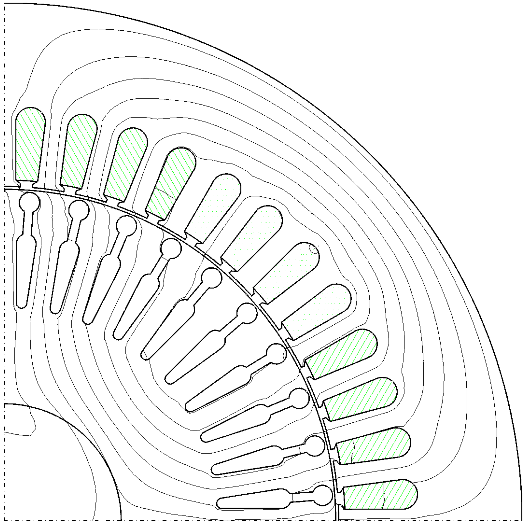
Contd. What are the cons of DC Motors

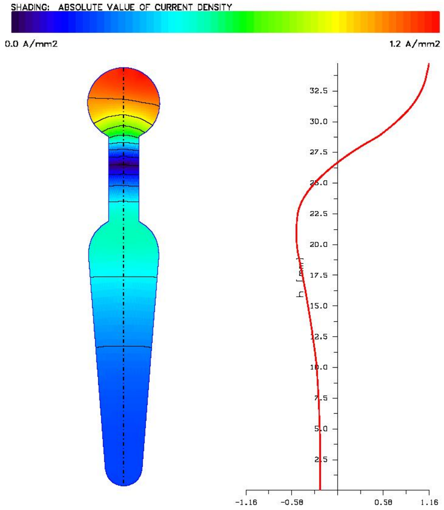
- Usage of permanent magnets increase power density, but you do not have the option for flux weakening at high speeds.



Induction Machines

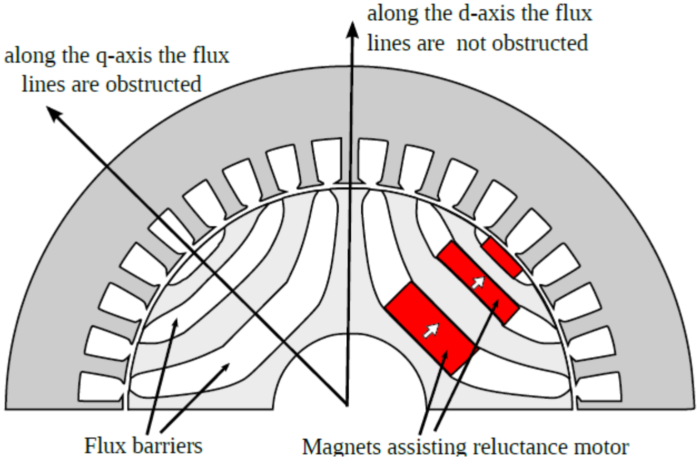
- Squirrel cage induction motors offer better power density and efficiency compared with DC motors.
- The most dominant losses are stator and rotor losses.
- The heat from rotor needs better cooling and lower overload capacity.
- Good field weakening capabilities.





Synchronous Reluctance Machines (SynRM)

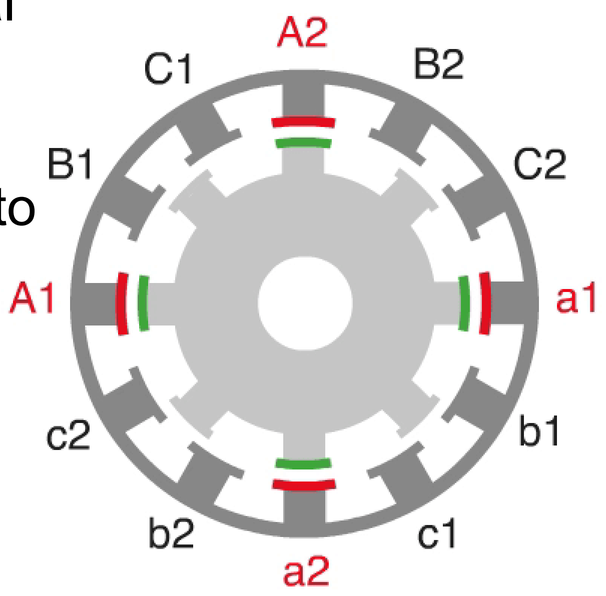
- It is a single excited machine.
- The torque production depends on the difference between d and q axis inductances.
- Poor power factor machine.
- Use of ferrite PMs enhances the power density and efficiency.



N. Bianchi, S. Bolognani, E. Carraro, M. Castiello, and E. Fornasiero, “Electric Vehicle Traction Based on Synchronous Reluctance Motors,” *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4762–4769, Nov. 2016.

Switched Reluctance Machines (SRM)

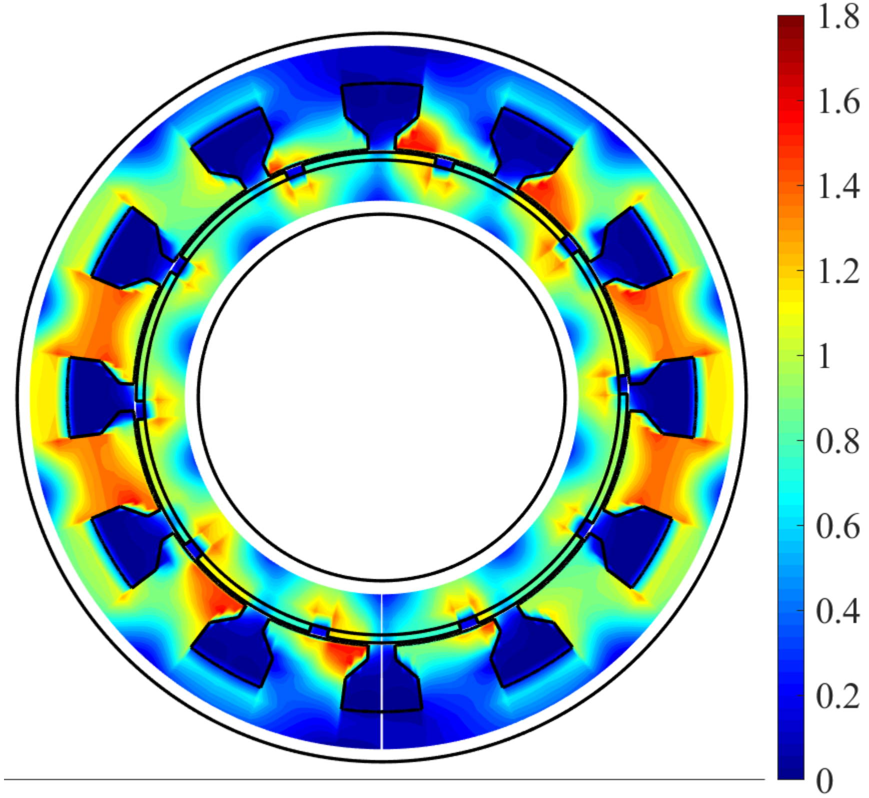
- The torque production is based on a uni-directional switches excitation that aligns the rotor poles with the corresponding stator poles
- The power density and efficiency are comparable to induction machines.
- No rotor windings.
- Better rotor cooling and overload capacity.
- Higher torque ripple.
- Higher noise due to higher air gap flux density requirements.
- Needs complex control scheme and power electronic converters.



https://www.kehui.com/products/srm-srd-introduction/

Brushless PM machine

- High energy density from the permanent magnets (PMs).
- Low losses in the rotor.
- Most dominant losses occur in the stator iron losses.
- Better efficiency and power density.
- Restricted field weakening capabilities due to the risk of PM demagnetization.



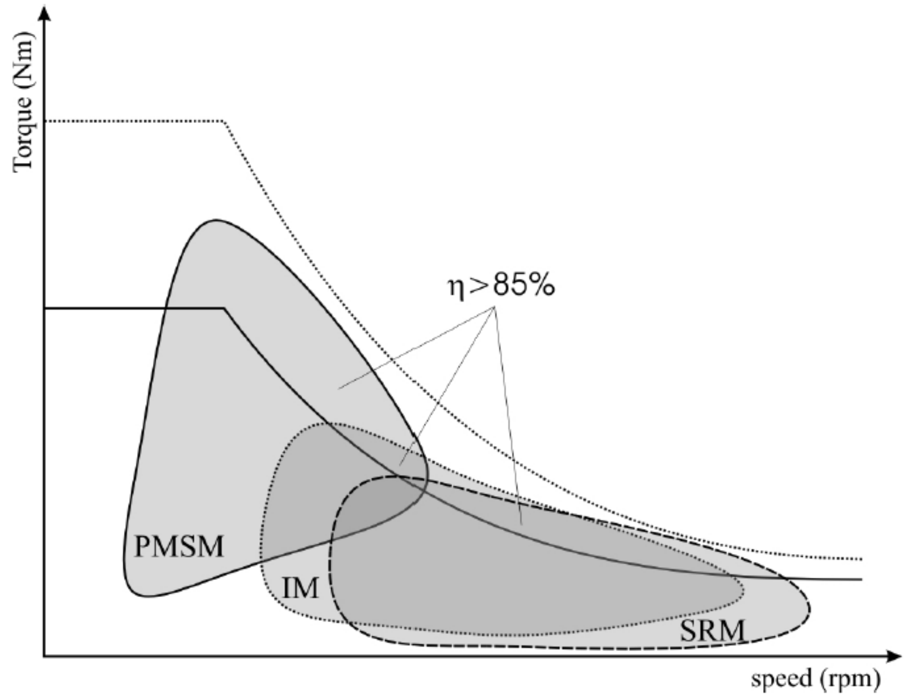
Comparison of Different Types of Electric Machines

	DC	IM	PMSM	SRM
power density	$\ominus\ominus$	$\odot$	$\oplus\oplus$	$\odot$
efficiency	$\ominus$	$\oplus$	$\oplus\oplus$	$\oplus$
costs	$\oplus$	$\oplus\oplus$	$\ominus$	$\oplus$
reliability	$\ominus$	$\oplus\oplus$	$\odot$	$\oplus$
technical maturity	$\oplus$	$\oplus$	$\odot$	$\odot$
controlability, costs	$\oplus\oplus$	$\odot$	$\oplus$	$\ominus$

$\oplus\oplus$	very good
$\oplus$	good
$\odot$	neutral
$\ominus$	bad
$\ominus\ominus$	very bad

T. Finken, M. Felden and K. Hameyer, "Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles," *2008 18th International Conference on Electrical Machines*, Vilamoura, 2008, pp. 1-5, doi: 10.1109/ICELMACH.2008.4800044.

Torque Speed Comparison



T. Finken, M. Felden and K. Hameyer, "Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles," *2008 18th International Conference on Electrical Machines*, Vilamoura, 2008, pp. 1-5, doi: 10.1109/ICELMACH.2008.4800044.

Magnetic Device Design

- Magnetic Core Construction.
  - The cores.
  - The bobbin.
  - The winding.

- Design Outcomes
  - Core size.
  - Number of turns.
  - Wire size.

Design Procedure

- Applicable Constraints (Thermal Limits, Peak Flux Density, Inductance Value)
- What to minimize and maximize.
  - Size of the core.
  - Total losses inside the core.
- Application type of magnetic device used.
  - Core loss and AC losses.
  - Saturation flux density.
  - Air gap?
- Sometimes iterative design is necessary. Many different designs can be accepted.

Trade-offs between both criteria's

Design of an electrical machine

Electromagnetic loading

Loading is typically expressed using

Magnetic flux density B
Electric current density J

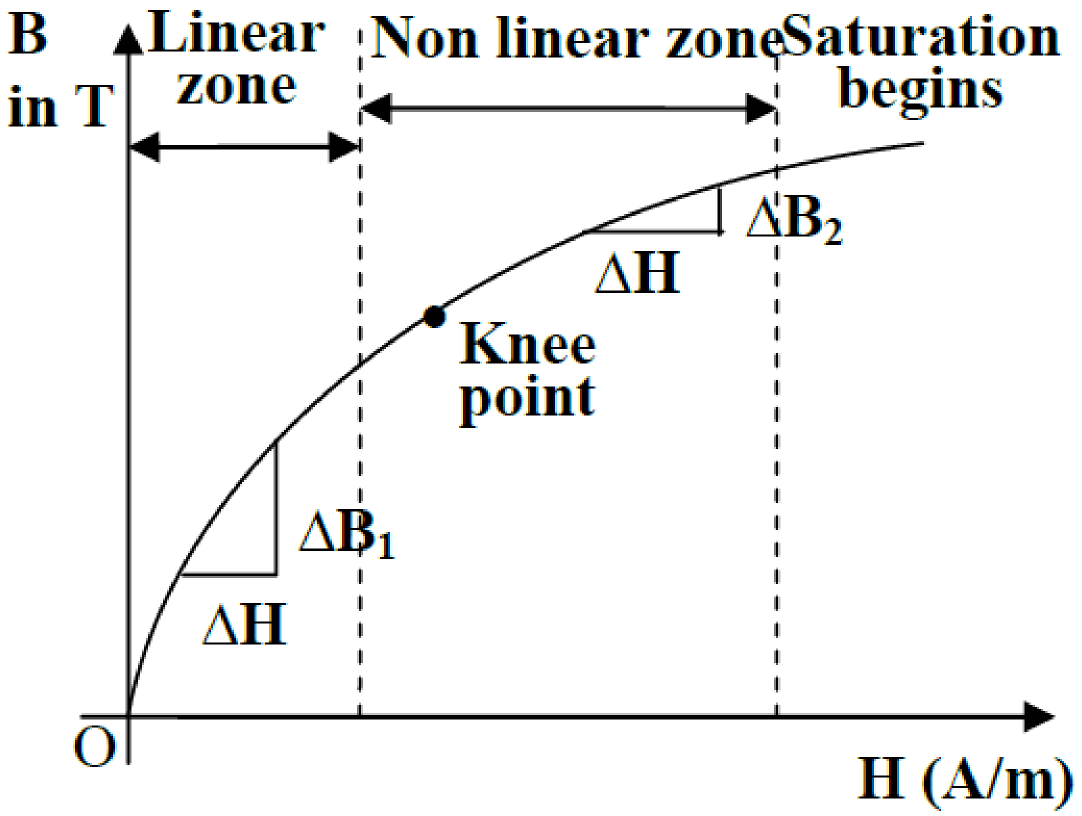
as these quantities have relatively constant maximum values set by the magnetic saturation and temperature rise.

Loading is closely related to the losses. Efficiency of cooling sets an upper limit for the allowed maximum loss.

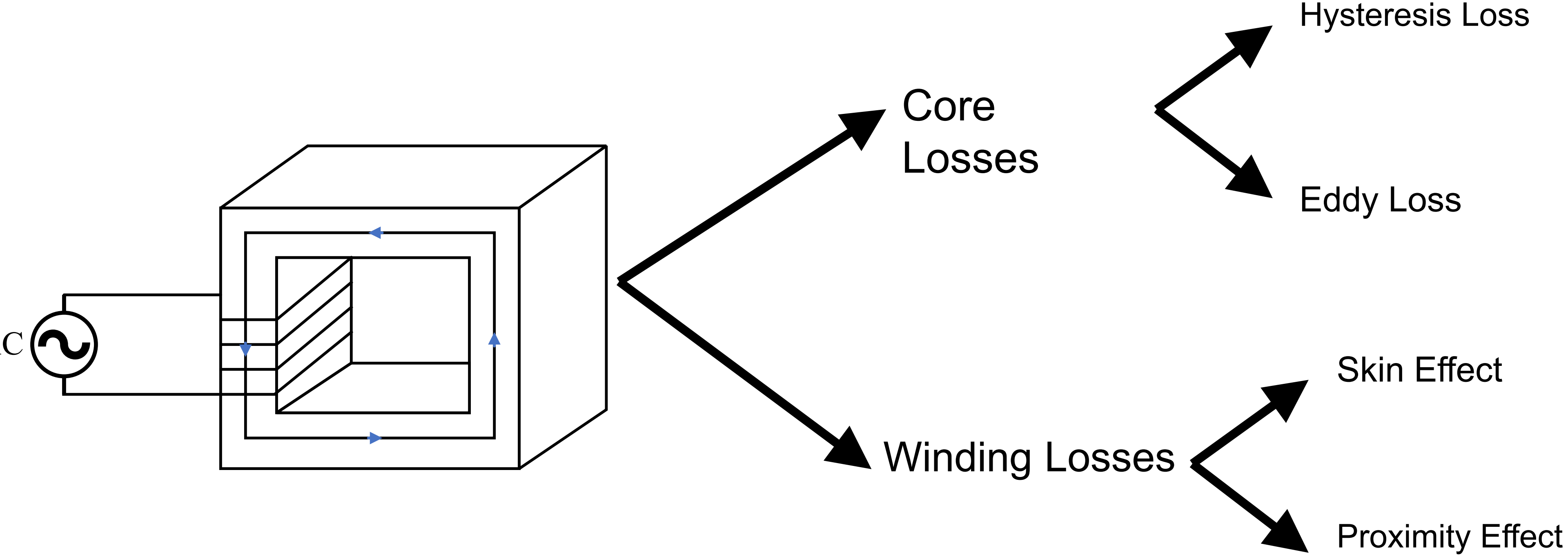
Losses and cooling set an upper limit for the continuous maximum power available from an electrical machine.

Magnetic Material Characteristics

- When magnetic saturation occurs, high magnetic field is required. Therefore, additional copper losses occur.



Types of Losses in Magnetic Core



Resistive losses

Resistive losses

$$P_{\mathrm{cu}} = I^2 R$$

$$= I^2 \rho_{\mathrm{cu}} \frac{l_{\mathrm{cu}}}{A_{\mathrm{cu}}} = \left(\frac{I}{A_{\mathrm{cu}}} \right)^2 \rho_{\mathrm{cu}} \, l_{\mathrm{cu}} A_{\mathrm{cu}}$$

$$= J^2 \rho_{\mathrm{cu}} V_{\mathrm{cu}}$$

Core losses

$$P_{\mathrm{fe}} = P_{\mathrm{fe,h}} + P_{\mathrm{fe,r}}$$

$$= m_{\mathrm{fe}} \left(\varepsilon_{\mathrm{h}} f + \varepsilon_{\mathrm{r}} f^2 \right) \hat{b}^2$$

$$= \rho_{\mathrm{fe}} V_{\mathrm{fe}} \left(\varepsilon_{\mathrm{h}} f + \varepsilon_{\mathrm{r}} f^2 \right) \hat{b}^2$$

where ε_{h} and ε_{r} are hysteresis and eddy-current loss coefficients given by the manufacturers of core materials.

Utilisation factor

The continuous power available from an electrical machine can be expressed

$$S = CV_{\phi} \quad \text{or} \quad P = CV$$

where V is a volume and C is the utilisation factor. For certain types of machines and cooling solutions, C stays approximately constant. For a rotating machine, V is typically taken as the rotor volume. For transformers, V is typically the volume of the iron core. Typical values of C are listed, for instant, in textbooks dealing with the design of electrical machines.

Utilisation factor

Electromotive force induced by flux variation

$$e = -N\frac{\mathrm{d}\phi}{\mathrm{d}t} \quad \Rightarrow \quad E = \frac{\omega}{\sqrt{2}}N\hat{\phi}$$

Power of an m-phase machine

$$S = mEI$$

$$= m\frac{\omega}{\sqrt{2}}N\hat{\phi}I = m\frac{\omega}{\sqrt{2}}N\,\hat{b}\,A_{\phi}\,J\,A_{\mathrm{cu}}$$

Utilisation factor

After regrouping variables

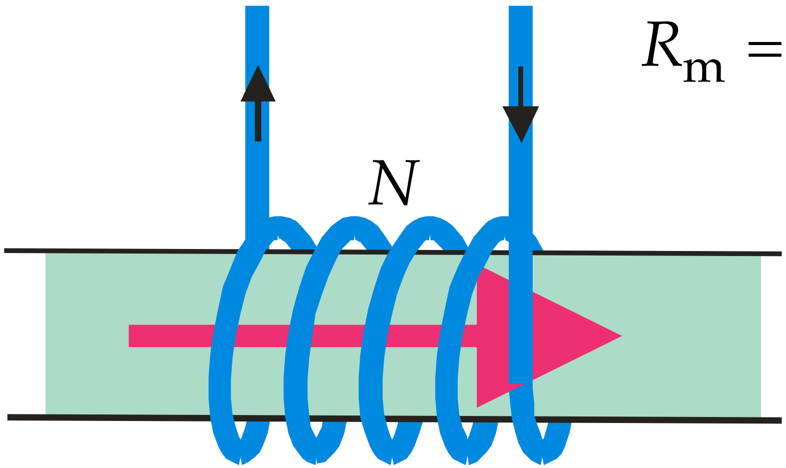
$$S = \frac{\omega}{\sqrt{2}}\hat{b}\,m\,A_\phi\,J\,N A_{\text{cu}}$$

$$= \frac{\omega}{\sqrt{2}}\hat{b}\underbrace{mA_\phi l_\phi}_{V_\phi}\underbrace{\frac{JNA_{\text{cu}}}{l_\phi}}_{A} = \frac{\omega}{\sqrt{2}}\hat{b}A\,V_\phi = CV_\phi$$

where A is the linear current density.

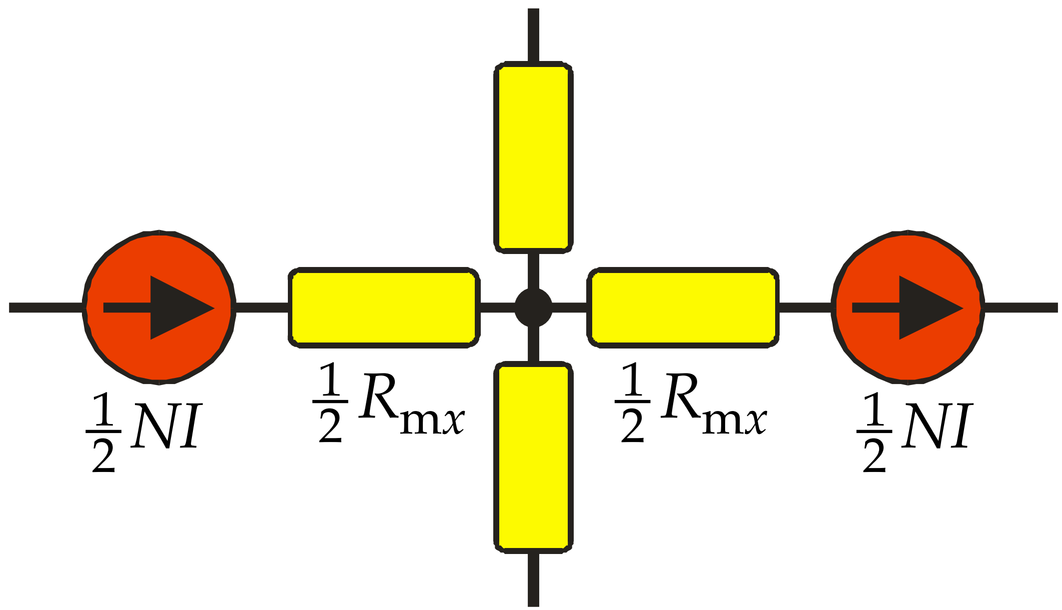
A typical value for the utilisation factor of a cage induction motor (37 kW, four poles, 50 Hz) is about 5 MW/m^3.

Basic element of a 2D reluctance model

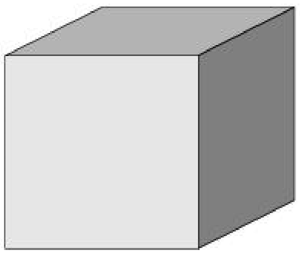


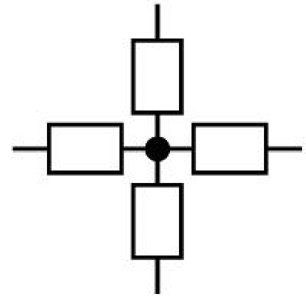
$$\mathcal{R}_{\mathrm{m}} = \frac{l}{\mu A} = \frac{F}{\Phi}$$

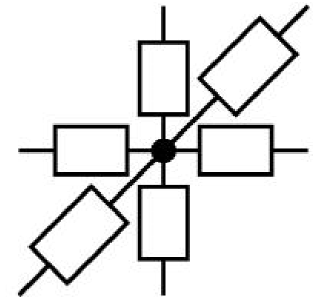
F = magnetomotive force
Φ = magnetic flux



Reluctance models







1D model

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

2D model

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

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

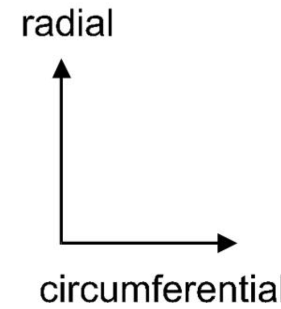
3D model

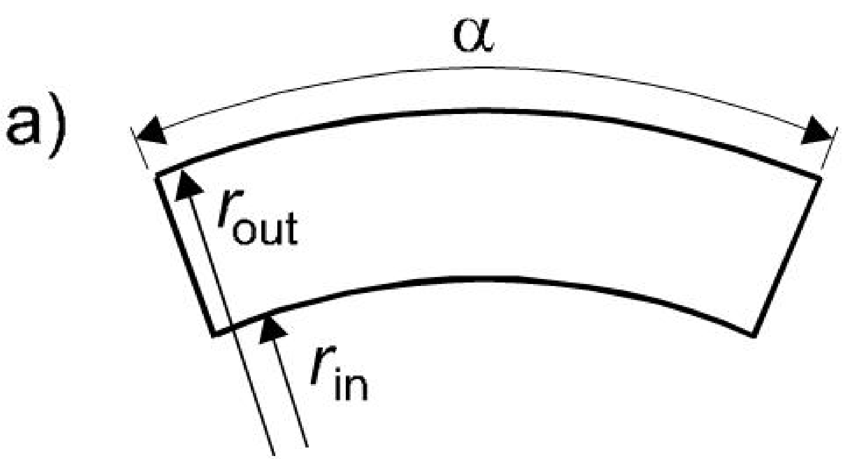
$$R_{\mathrm{m}x} = \frac{l_{\Phi x}}{\mu A_{\Phi x}}$$

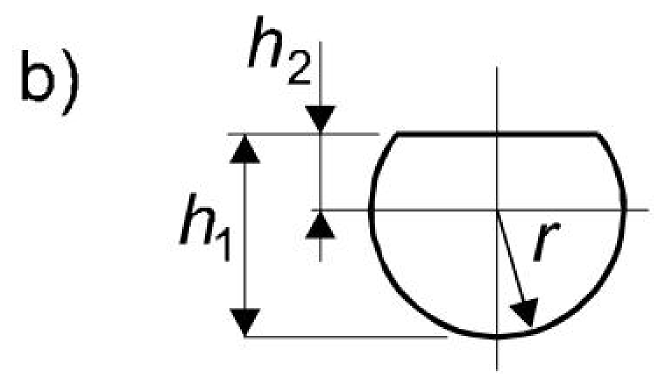
$$R_{\mathrm{m}y} = \frac{l_{\Phi y}}{\mu A_{\Phi y}}$$

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

Reluctance values





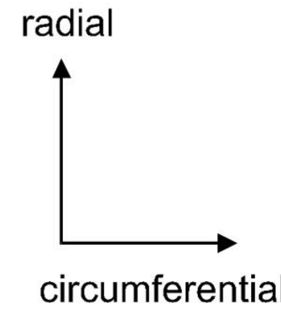


$$a)\ \begin{cases} R_{mr} = \dfrac{1}{\mu l}\dfrac{1}{\alpha}\ln\left(\dfrac{r_{out}}{r_{in}}\right) \\ R_{m\varphi} = \dfrac{1}{\mu l}\dfrac{\alpha}{\ln\left(\dfrac{r_{out}}{r_{in}}\right)} \end{cases}$$

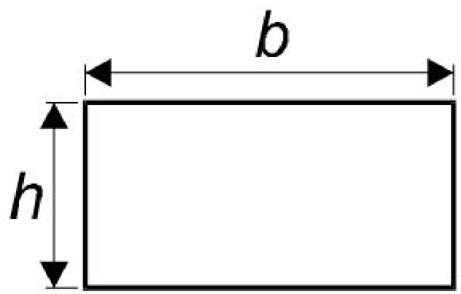
$$b)\ \begin{cases} R_{mr} = \dfrac{1}{2\mu l}\left[\arcsin\left(\dfrac{h_2}{r}\right)+\arcsin\left(\dfrac{h_1-h_2}{r}\right)\right] \\ R_{m\varphi} = \dfrac{1}{\mu l}\dfrac{2}{\arcsin\left(\dfrac{h_2}{r}\right)+\arcsin\left(\dfrac{h_1-h_2}{r}\right)} \end{cases}$$

l is the length of the reluctance element in the third dimension.

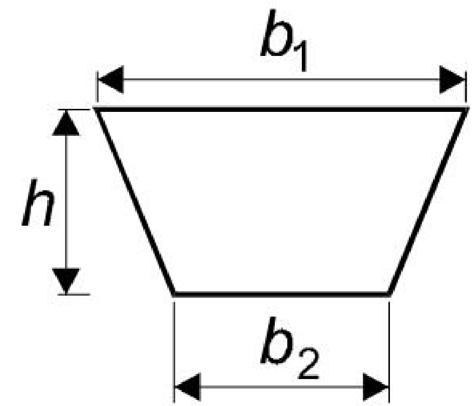
Reluctance values



c)



d)

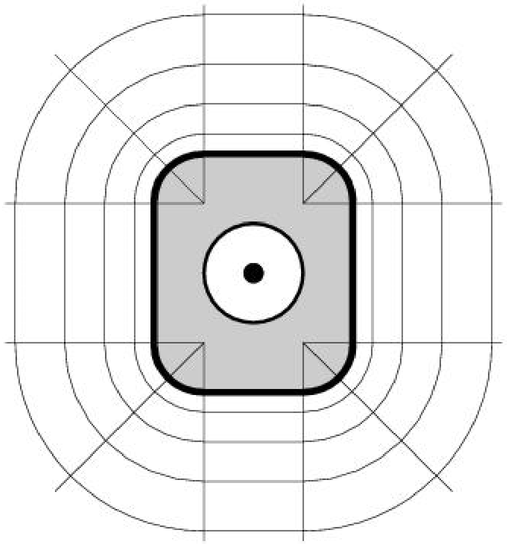


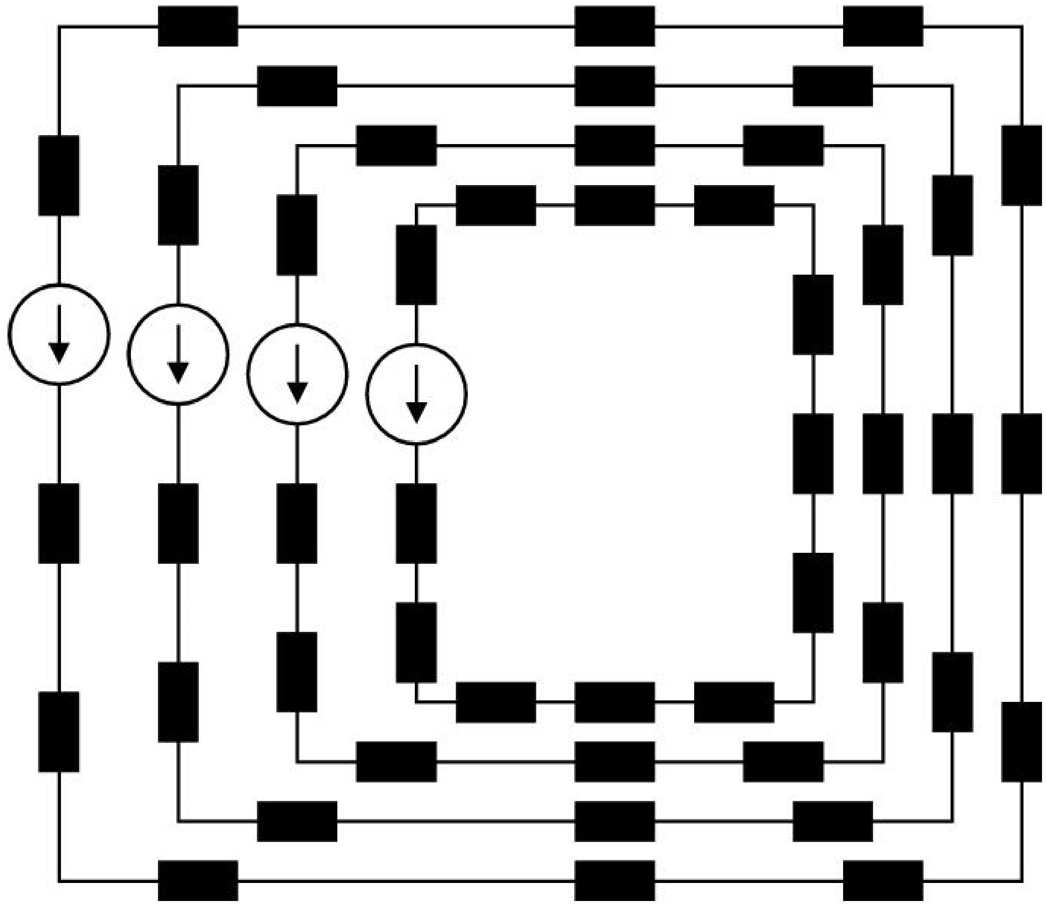
$$c)\begin{cases} R_{\mathrm{m}r} = \dfrac{1}{\mu l}\dfrac{h}{b} \\[2ex] R_{\mathrm{m}\varphi} = \dfrac{1}{\mu l}\dfrac{b}{h} \end{cases}$$

$$d)\begin{cases} R_{\mathrm{m}r} = \dfrac{1}{\mu l}\dfrac{h}{b_1 - b_2}\ln\left(\dfrac{b_1}{b_2}\right) \\[2ex] R_{\mathrm{m}\varphi} = \dfrac{1}{\mu l}\dfrac{b_1 - b_2}{h}\dfrac{1}{\ln\left(\dfrac{b_1}{b_2}\right)} \end{cases}$$

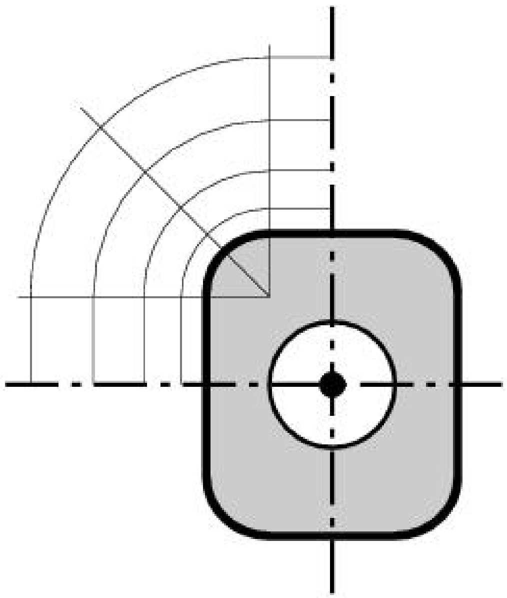
l is the length of the reluctance element in the third dimension.

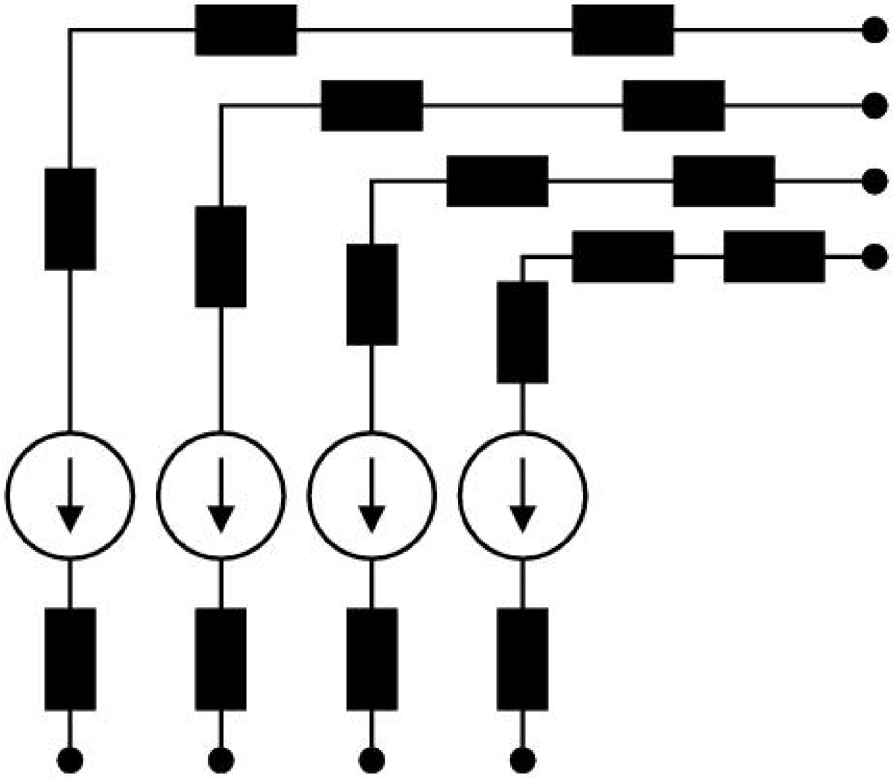
Magnetic field around a straight conductor



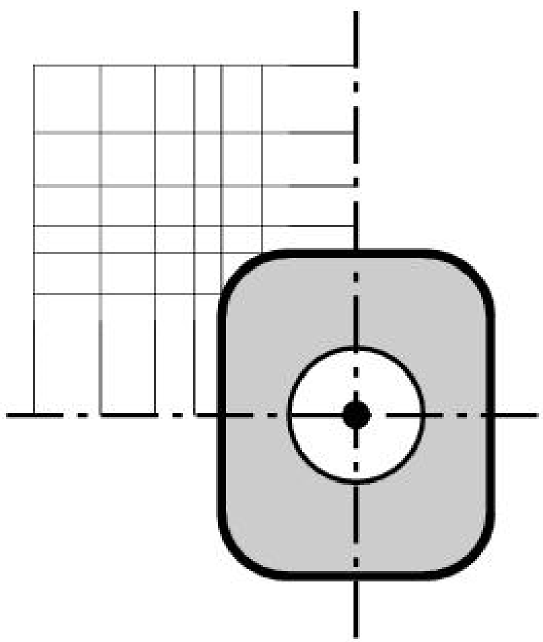


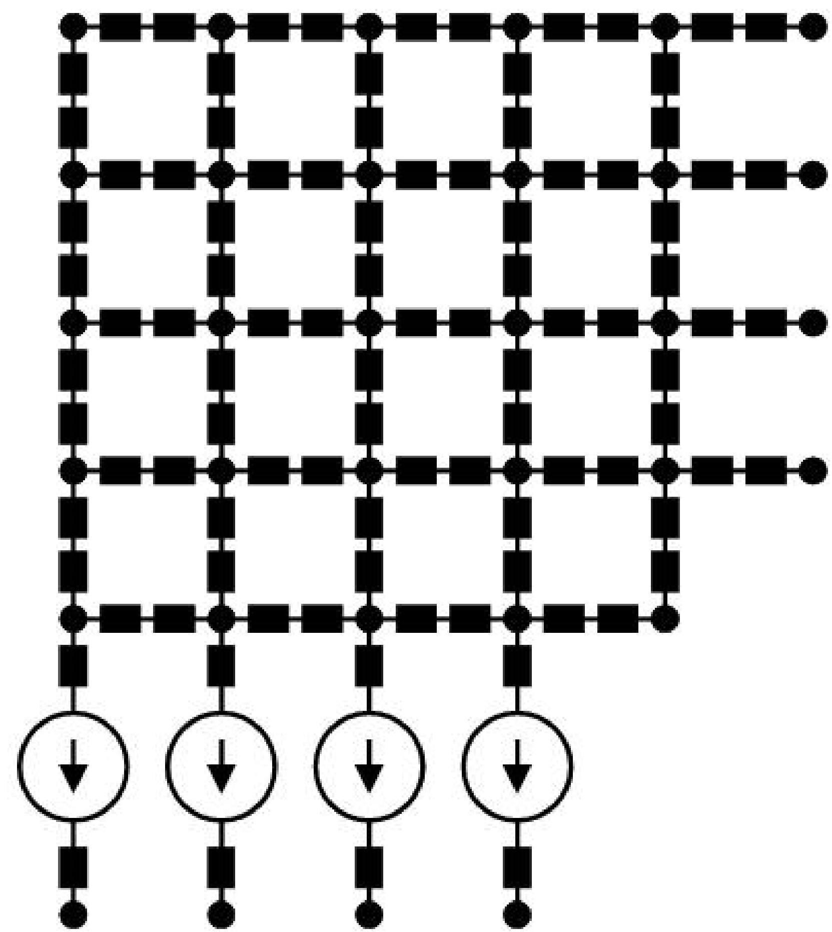
Utilising the symmetry



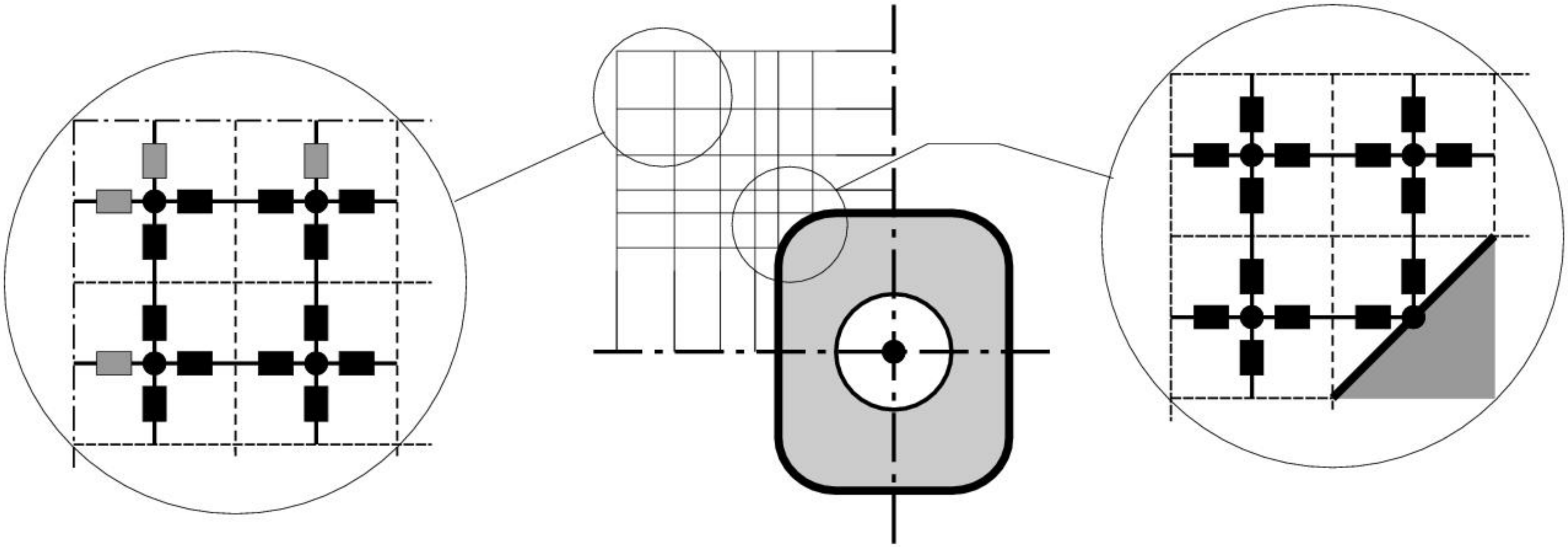


Reluctance network allowing more general flux flow

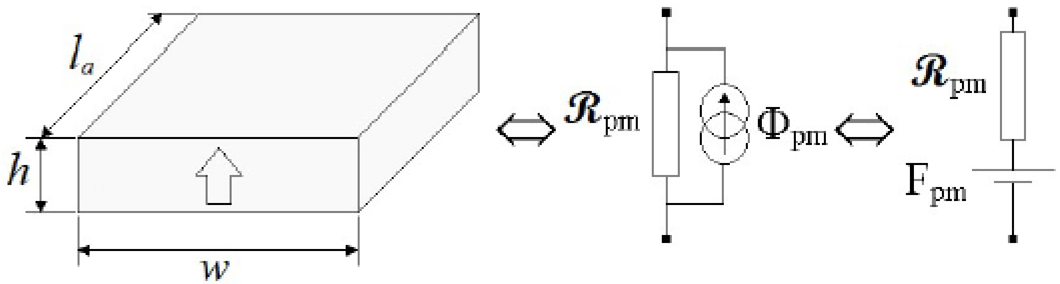




Effects of the boundary



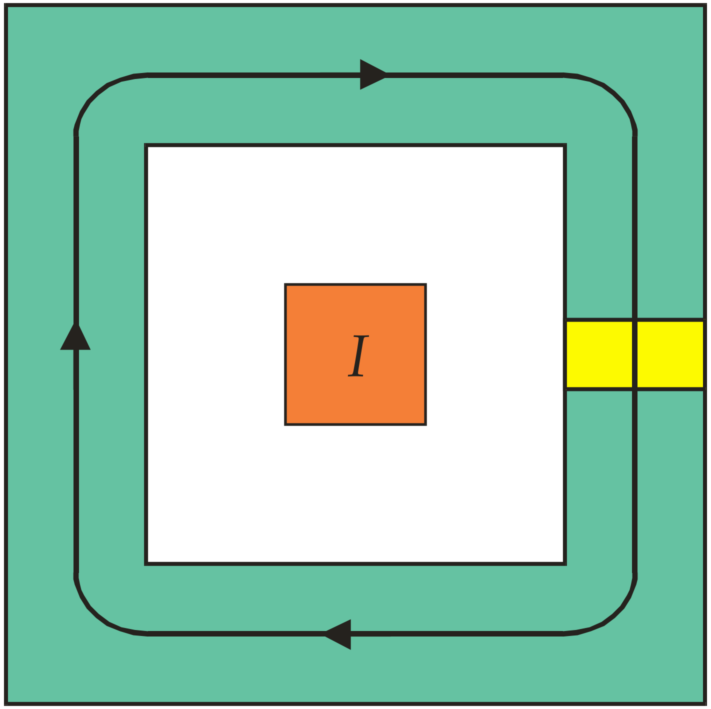
Permanent Magnet Modeling



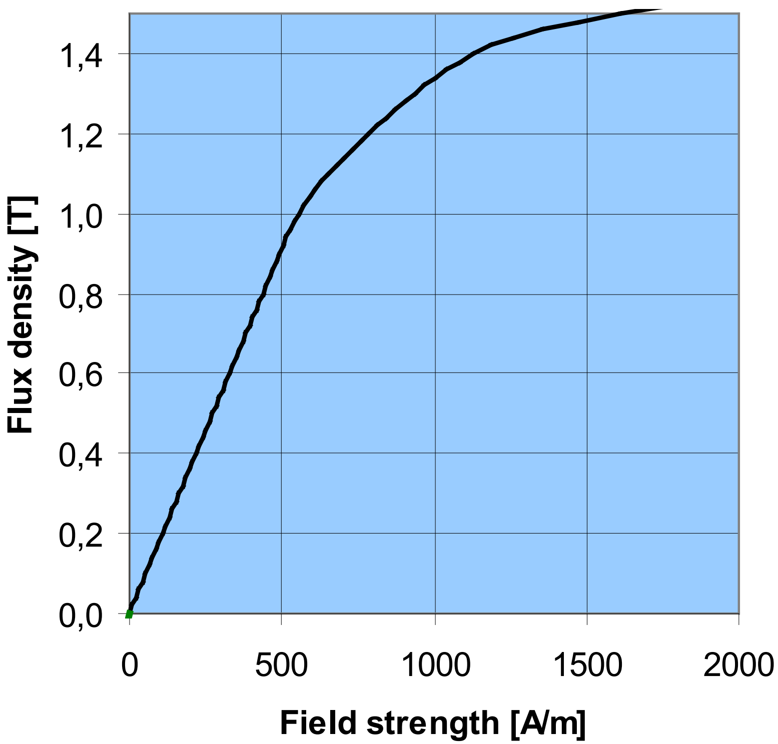
$$\begin{cases} \mathcal{R}_{pm} = \dfrac{1}{\mu_0 \mu_{rpm}} \dfrac{h}{l_a w} \\ \Phi_{pm} = B_r l w \\ F_{pm} = \dfrac{B_r}{\mu_0 \mu_{rpm}} h \end{cases}$$

S. Yang et al., "Introduction to mesh based generated lumped parameter models for electromagnetic problems," in CES Transactions on Electrical Machines and Systems, vol. 5, no. 2, pp. 152-162, June 2021, doi: 10.30941/CESTEMS.2021.00019.

Example: Inductor with a permanent magnet



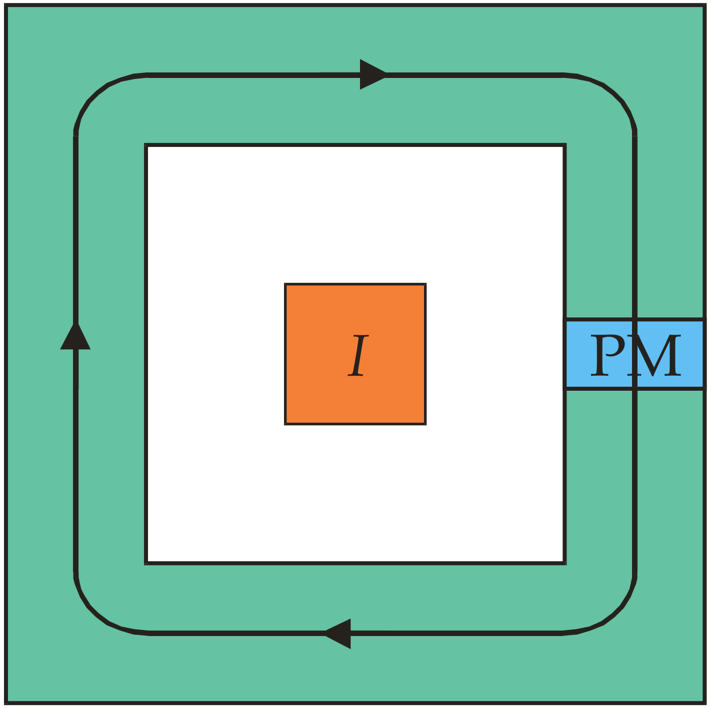
Basic geometry of an inductor

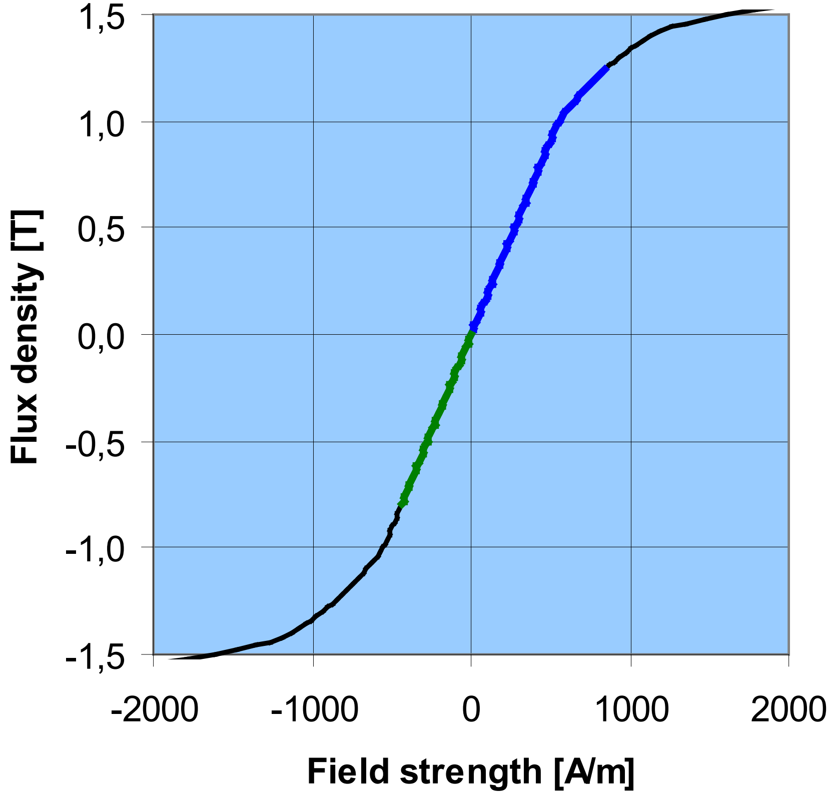


Magnetisation curve of the iron core

Problem: The linear region (constant inductance) is quite limited because of the saturation of iron.

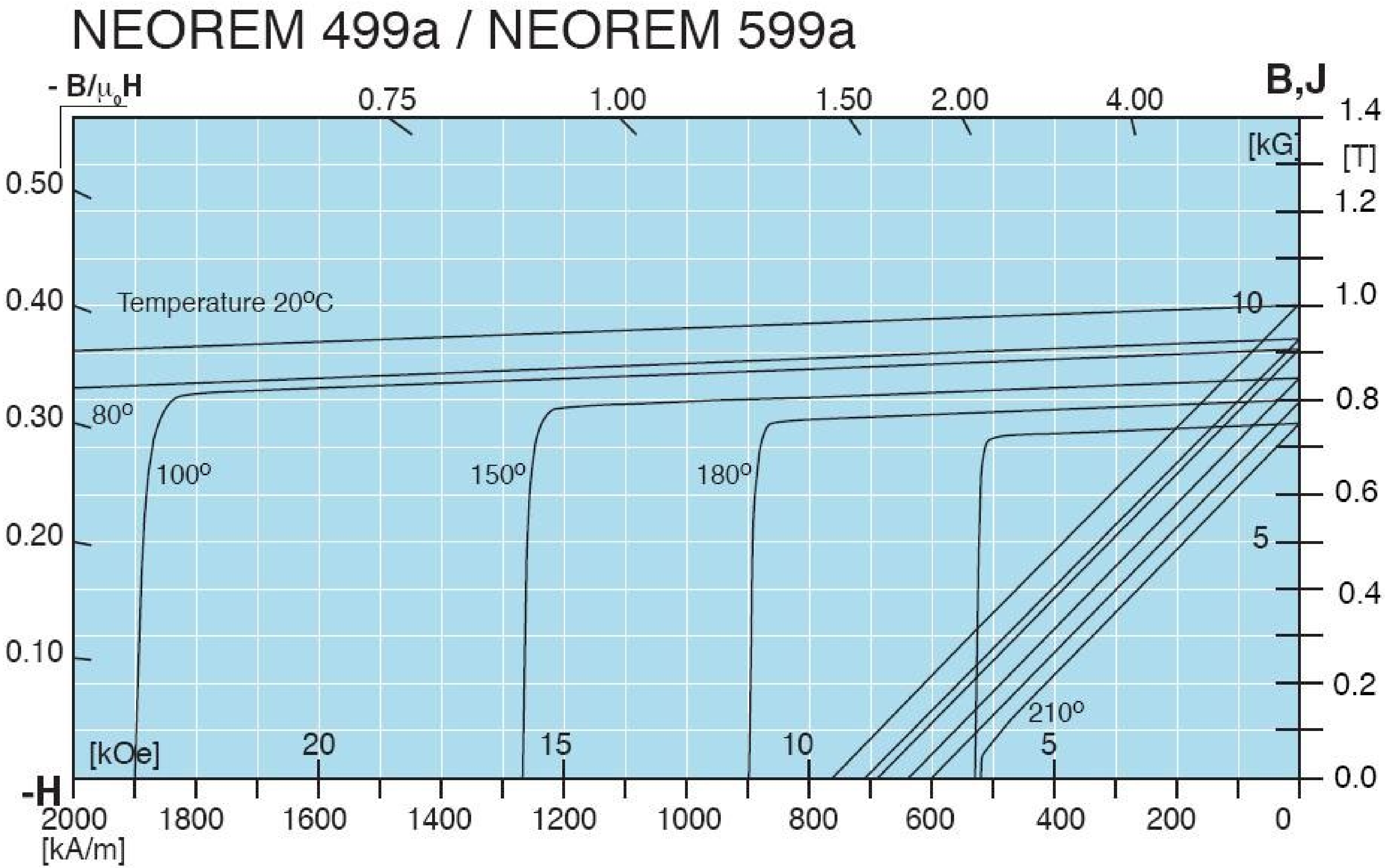
Inductor with a permanent magnet



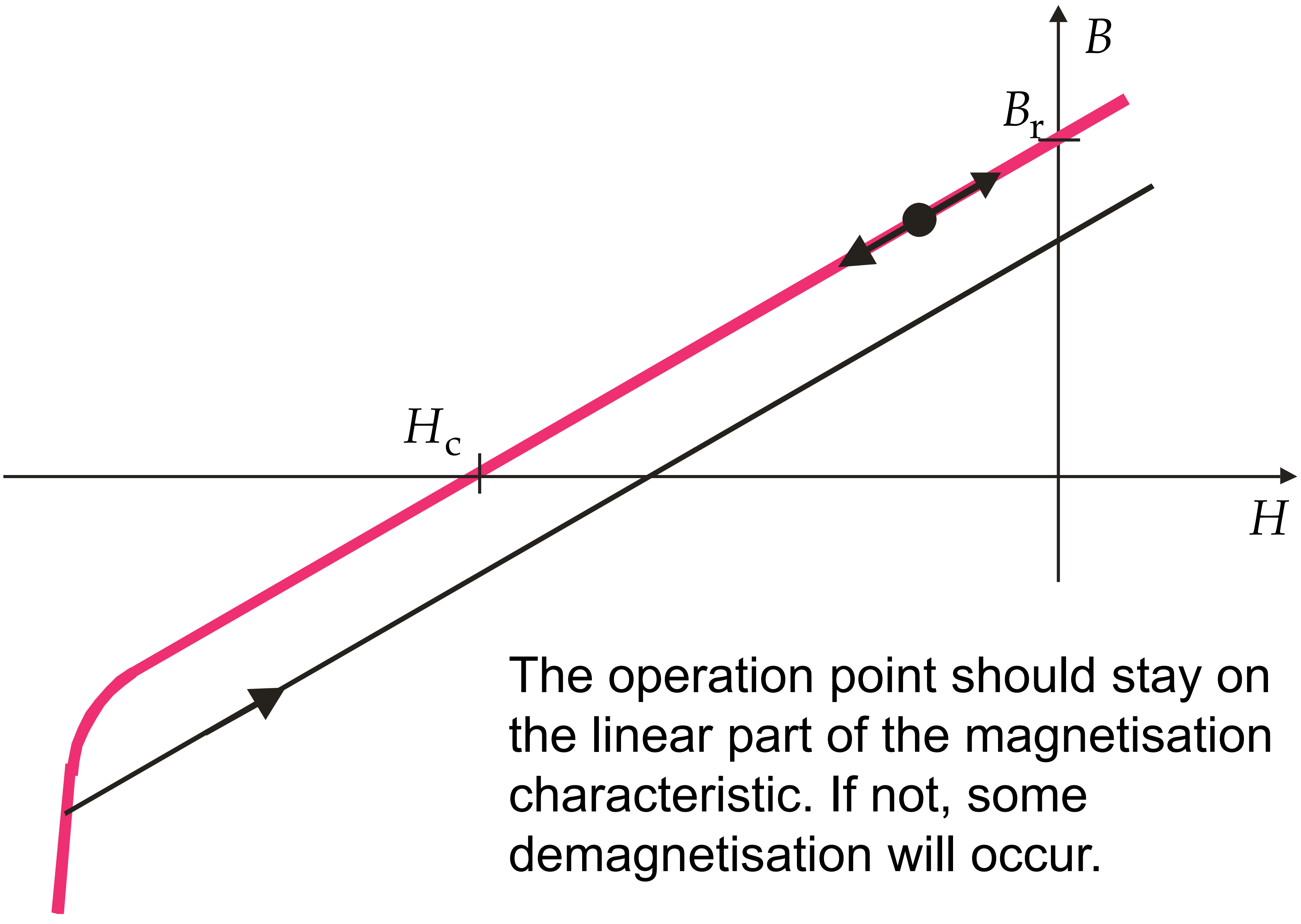


If the magnetic field is biased with a permanent magnet, the linear region can be significantly increased.

Characteristics of a permanent magnet



Characteristic of a permanent magnet

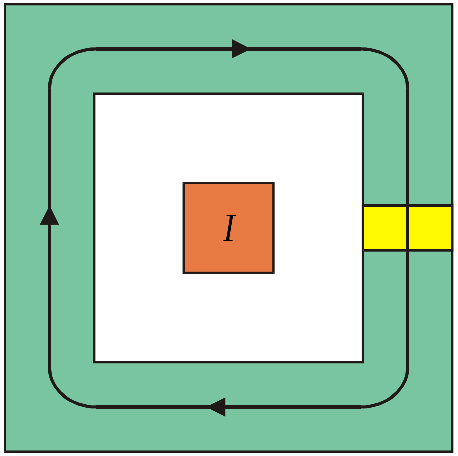


The operation point should stay on the linear part of the magnetisation characteristic. If not, some demagnetisation will occur.

Inductor without a permanent magnet

Let us assume that the iron core is approximately linear to a flux density of 1.25 T, that the average length of the core (along the flux lines) is 0.4 m and the air gap is 0.001 m.

The maximum current that can be used becomes



$$B_{\mathrm{Fe}} = B_{\mathrm{ag}} = 1{,}25\ \mathrm{T} \qquad \text{BH-curve:} \qquad H_{\mathrm{Fe}} = 875\ \mathrm{A/m}$$

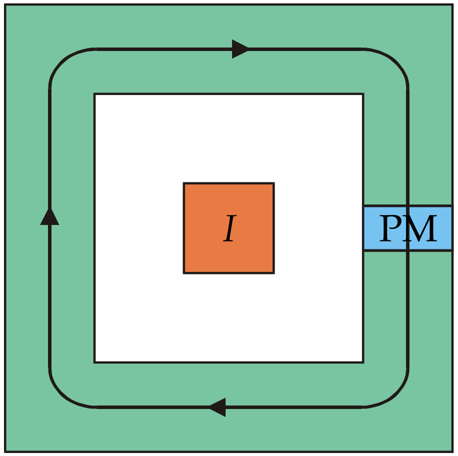
$$B_{\mathrm{ag}} = \mu_0 H_{\mathrm{ag}} \quad => \quad H_{\mathrm{ag}} = \frac{B_{\mathrm{ag}}}{\mu_0} = 995000\ \mathrm{A/m}$$

$$\oint \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l} = \sum_k I_k \quad => \quad I = H_{\mathrm{Fe}} l_{\mathrm{Fe}} + H_{\mathrm{ag}} l_{\mathrm{ag}}$$

$$I = 875\ \mathrm{A/m} \cdot 0{,}40\ \mathrm{m} + 995000\ \mathrm{A/m} \cdot 0{,}001\ \mathrm{m} \boxed{= 1345\ \mathrm{A}}$$

Inductor with a permanent magnet

The assumptions are the same as before but a permanent magnet in the air gap is used to bias the initial field to about – 0.90 T. In this case, the maximum current that still keeps the flux density below 1.25 T becomes



$$B_{\mathrm{Fe}} = B_{\mathrm{ag}} = 1{,}25\ \mathrm{T} \qquad \text{BH-curve:} \quad H_{\mathrm{Fe}} = 875\ \mathrm{A/m}$$

$$B_{\mathrm{ag}} = -B_r + \mu H_{\mathrm{ag}} \approx -B_r + \mu_0 H_{\mathrm{ag}}$$

$$\Rightarrow \quad H_{\mathrm{ag}} = \frac{1}{\mu_0}\left(B_{\mathrm{ag}} + B_r\right) = \frac{1}{\mu_0}(1{,}25\ \mathrm{T} + 0.9\ \mathrm{T}) = 1710\ \mathrm{kA/m}$$

$$\oint \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l} = \sum_k I_k \quad \Rightarrow \quad I = H_{\mathrm{Fe}} l_{\mathrm{Fe}} + H_{\mathrm{ag}} l_{\mathrm{ag}}$$

$$I = 875\ \mathrm{A/m} \cdot 0{,}40\ \mathrm{m} + 1710\ \mathrm{kA/m} \cdot 0{,}001\ \mathrm{m} \boxed{= 2060\ \mathrm{A}}$$

Interpretation

When applying a permanent magnet, the value of dc current could be increased by a factor of 1.53 and still stay within the linear region. This means

- The original inductor can be used at a larger current or
- The number of turns can be increased resulting in a larger inductance value

However, the thermal aspects should also be considered.