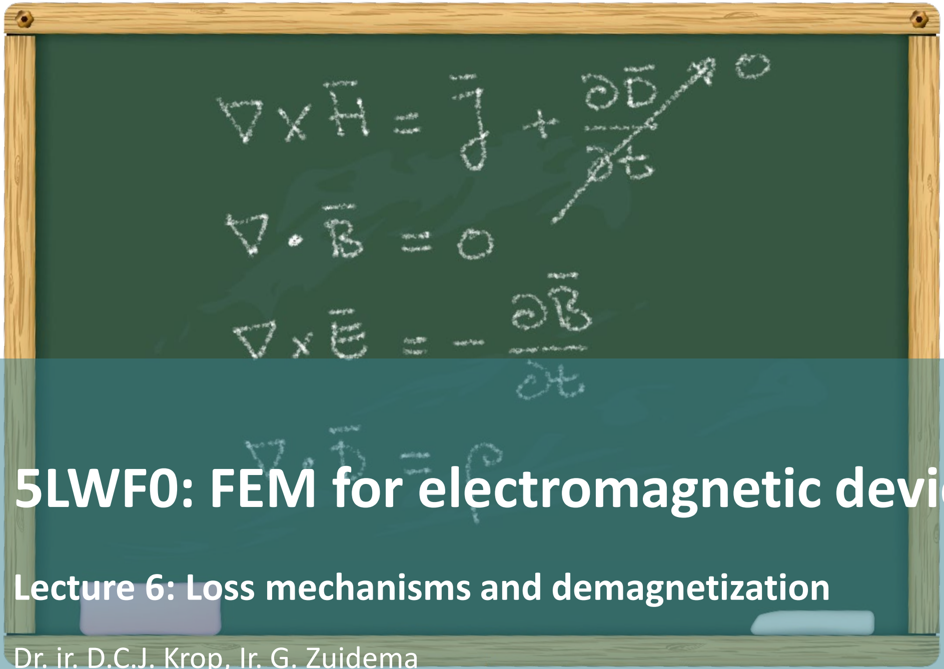
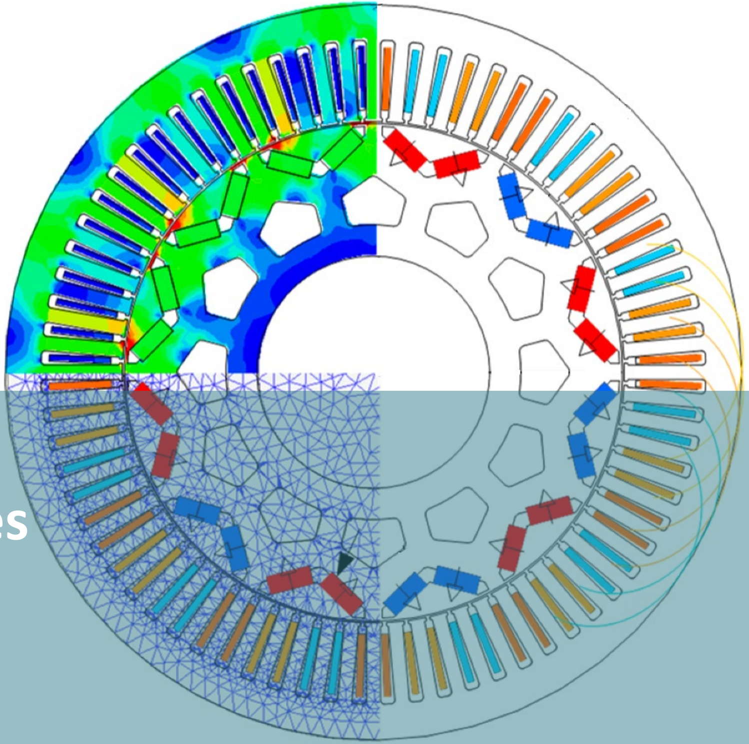




5LWF0: FEM for electromagnetic devices

Lecture 6: Loss mechanisms and demagnetization

Dr. ir. D.C.J. Krop, Ir. G. Zuidema
22 June 2026

Outline and topics of the previous lecture

Creating complex machine geometries in FLUX2D using Overlay

Outline for the lecture of week 6

Loss mechanism in electrical machines

- Copper losses
- Eddy current losses in conductive **bulk** materials
- Iron/Core losses in **laminated** steel
  - Classical losses (eddy currents in sheets)
  - Hysteresis losses
  - Excess losses

Demagnetization

- Risks of irreversible alternation of permanent magnet material properties under (certain) conditions of operation
- Performing a demagnetization check in FEM

Loss mechanism in electrical machines

Loss mechanism in electrical machines

Copper losses (P_{Cu})

- Current in resistive wires of coils

Iron/Core losses (P_{Fe})

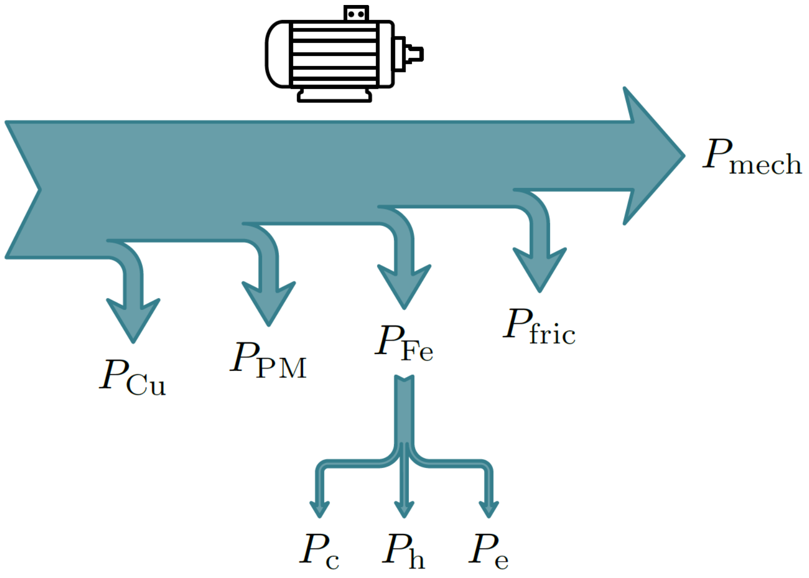
- Time-varying magnetic field in laminated soft-magnetic materials
  - Classical eddy current losses (P_{c})
  - Hysteresis losses (P_{h})
  - Excess losses (P_{e})

Eddy current losses in conductive PMs (P_{pm})

Mechanical friction losses (P_{fric})

- (Air) drag and bearing friction

Sankey diagram



Copper losses (per coil of *N* turns)

$$P_{\mathrm{Cu}} = I^2 R = I^2 \frac{N\rho\ell}{A_{\mathrm{Cu}}} = \frac{N\rho\ell}{\frac{k_{\mathrm{f}} A_{\mathrm{slot}}}{N}} = I^2 \frac{N^2\rho\ell}{k_{\mathrm{f}} A_{\mathrm{slot}}}$$

$$= \left(\frac{J_{\mathrm{slot}} A_{\mathrm{slot}}}{N}\right)^2 \frac{N^2\rho\ell}{k_{\mathrm{f}} A_{\mathrm{slot}}}$$

$$= \frac{\rho\ell J_{\mathrm{slot}}^2 A_{\mathrm{slot}}}{k_{\mathrm{f}}} \quad (\ell > 2L_{\mathrm{ax}}!)$$

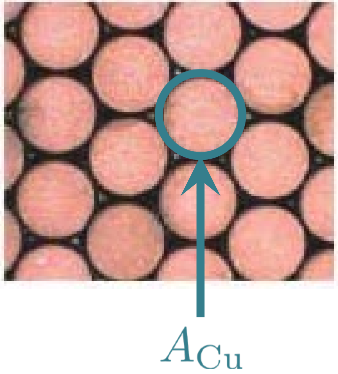
ρ : bulk resistivity [Ωm]

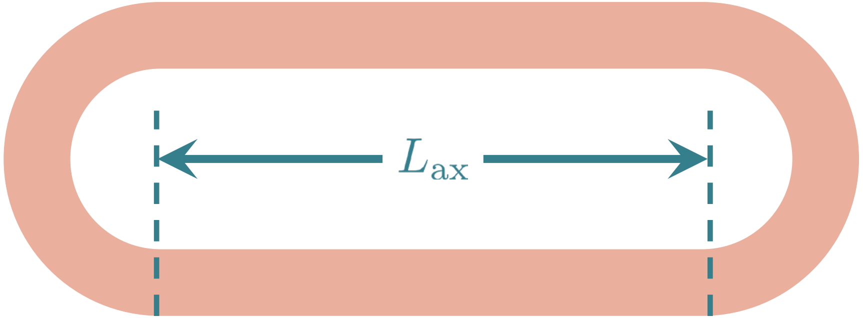
ℓ : single-turn length [m]

J_{slot} : slot current-density [$\mathrm{Am^{-2}}$]

A_{slot} : slot surface area [$\mathrm{m^2}$]

k_{f} : filling factor [-]





Copper losses

$$P_{\mathrm{Cu}} = \frac{\rho \ell J_{\mathrm{slot}}^2 A_{\mathrm{slot}}}{k_{\mathrm{f}}}$$

- Copper losses only dependent on geometry
- Copper loss calculation independent of the number of turns (N.O.T.) for the **same** filling factor
- N.O.T. to be determined in conjunction with driver specs **afterwards**
- Resistivity is temperature dependent:

$$\rho = \rho_0 \left[1 + \alpha \left(T - T_0\right)\right]$$

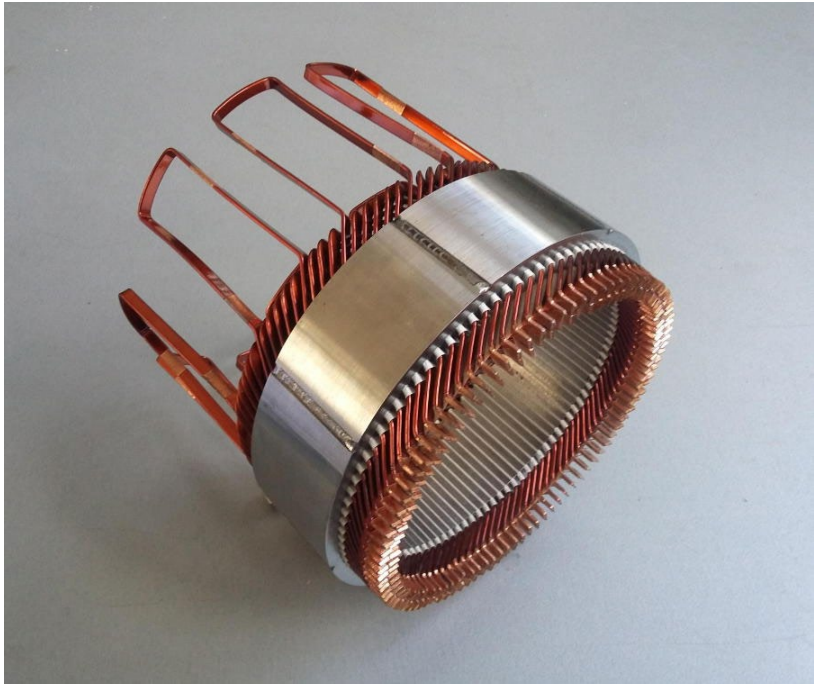
$\alpha_{\mathrm{Cu}} = 3.9 \cdot 10^{-3}\ \mathrm{K}^{-1}$

Copper losses

Means to reduce the copper losses

- Use of low resistive materials
- Decrease the current density
- Shorten end-turn length
- Increase filling factor

$$P_{\mathrm{Cu}} = \frac{\rho \ell J_{\mathrm{slot}}^2 A_{\mathrm{slot}}}{k_{\mathrm{f}}} = \frac{\rho \ell J_{\mathrm{slot}} \mathcal{F}_{\mathrm{slot}}}{k_{\mathrm{f}}}$$



Eddy current losses in permanent magnets

Permanent magnets are solid-material objects with nonzero electric conductivity

When exposed to time-varying fields, eddy currents are induced in the PM

- Variation in the reluctance seen by the PM due to its own relative movement with respect to stationary body induces eddy currents
  - losses under no-load conditions
- Higher or sub harmonic content in the magnetic field from the coils induces eddy currents
- Eddy-currents in conductive materials lead to dissipation (heat generation)
- Heat generation occurs at the expense of torque generation
  - damping torque
- Simulations of eddy currents in PMs can only be done with the transient solver
  - damping forces are taken into consideration!

Eddy current losses in permanent magnets in FLUX

The eddy current distribution in the PM are calculated in the transient solver

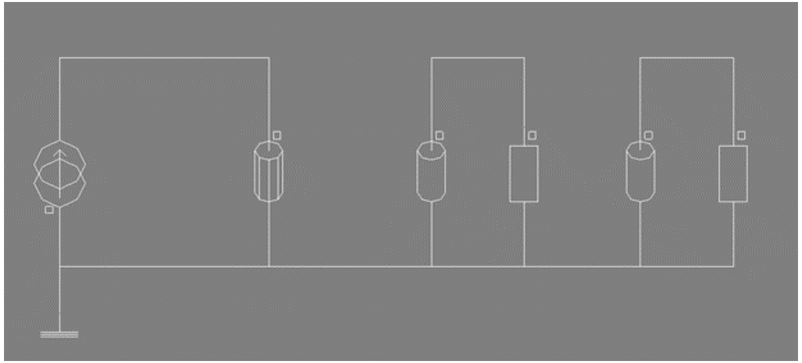
- Define the PM as a solid conductor (SC) with electrical properties (J(E)-tab)
  - NdFeB-magnets typically have a resistivity of 1.1-1.6 μΩm
- **Open circuit SC**
  - Front and rear faces electrically **not** connected → **no** net eddy-current flow into or out of the 2D plane of interest
- **Short circuit SC**
  - Front and rear face electrically shorted→ a **nonzero** net eddy-current flow into or out of the 2D plane of interest
- **Circuit**
  - To be used when separate conductive bodies share a common boundary, but form separate, electrically non-connected, entities in reality! (e.g. adjacent, touching PMs)

Eddy current losses in permanent magnets in FLUX

The necessity of using a circuit with solid conductor regions when they share a common boundary

- The software cannot distinguish the 'touching' regions
- **Open-circuit Solid Conductors interpretation**
  - The zero net eddy-current flow holds for **ALL** k touching conductive regions, i.e.:

$$\int_{\sum_k A_k} J_z \mathrm{d}S = 0 \quad \text{instead of} \quad \int_{A_k} J_z \mathrm{d}S = 0 \ \forall k$$



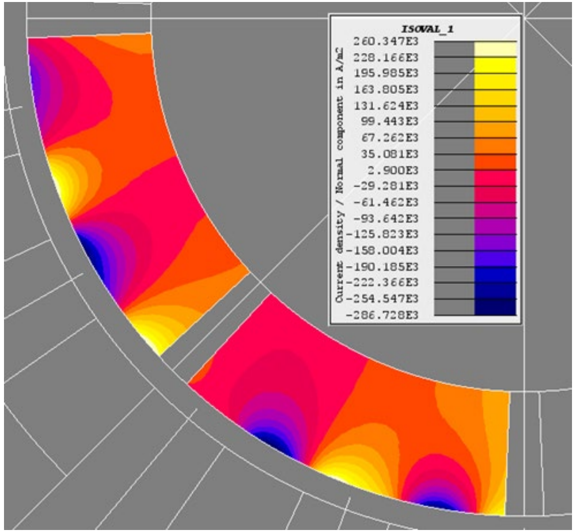
- Connect high valued resistors to the SCs (>MΩ) in the circuit to enforce separation of the regions

Eddy current losses in permanent magnets in FLUX

Approach in calculating the eddy current losses in PMs

- Initialize a transient solution with a **magnetostatic** simulation to reduce in-rush effects
- Create a 'Losses by Joule effect' sensor
- Plot the instantaneous losses
- Take the average of the instantaneous losses over a single period to find the power loss in W:
  - Make sure the considered period, *T*, is in steady-state
  - Calculate the losses:

$$P_{\mathrm{pm}} = \frac{1}{T} \int_{t_{\mathrm{end}}-T}^{t_{\mathrm{end}}} p_{\mathrm{pm}}(t)\,\mathrm{d}t$$



Eddy current losses in permanent magnets

Means to reduce the PM losses

- Segmented magnets (stacked in the axial direction)
- High resistive alloys
  - Bonded magnets (low remanence)
  - Ferrite magnets (even lower remanence)
- Dimensioning: reducing magnet volume
- Reduce higher harmonic content in coil-field
  - Winding configurations

Iron/Core losses

Time-varying fields in (conductive) **soft-magnetic** materials result in losses (dissipation)

- For periodical B variation with a fixed frequency, f, the amount of dissipated energy **per unit volume**, **per time-period** T :

$$w = \frac{\mathrm{d}W}{\mathrm{d}V} = \int\limits_{t_0}^{t_0+T} H(t)\frac{\mathrm{d}B(t)}{\mathrm{d}t}\mathrm{d}t = \int\limits_{B(t)} H\mathrm{d}B$$

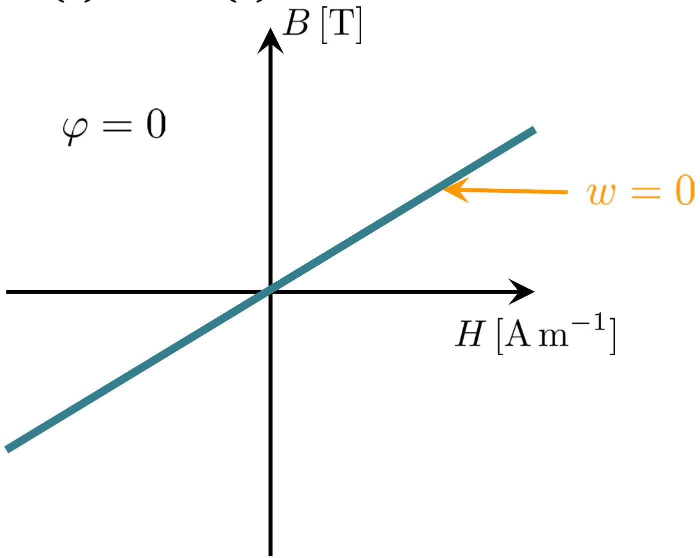
- As f cycles occur per unit time [s], the power loss is given by

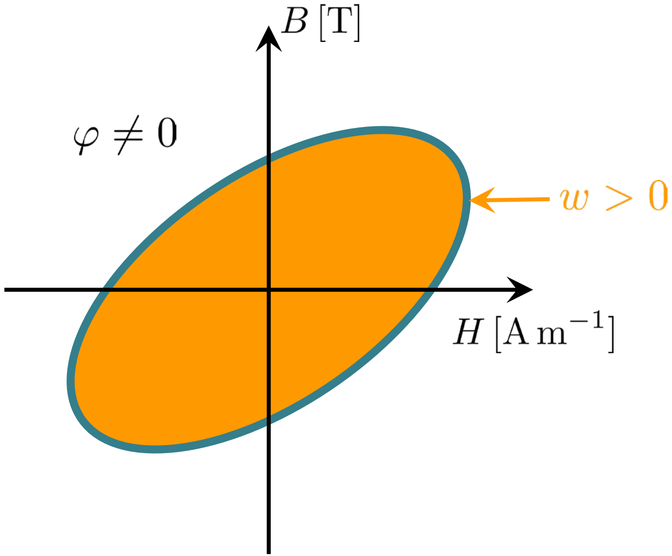
$$P = f\int\limits_{V} w\,\mathrm{dV}$$

Iron/Core losses

For **linear** soft-magnetic material for which H and B vary sinusoidally with time

- losses are associated with the area enclosed by the BH-loop due to a **phase-shift in time**, φ, between $H(t)$ and $B(t)$:

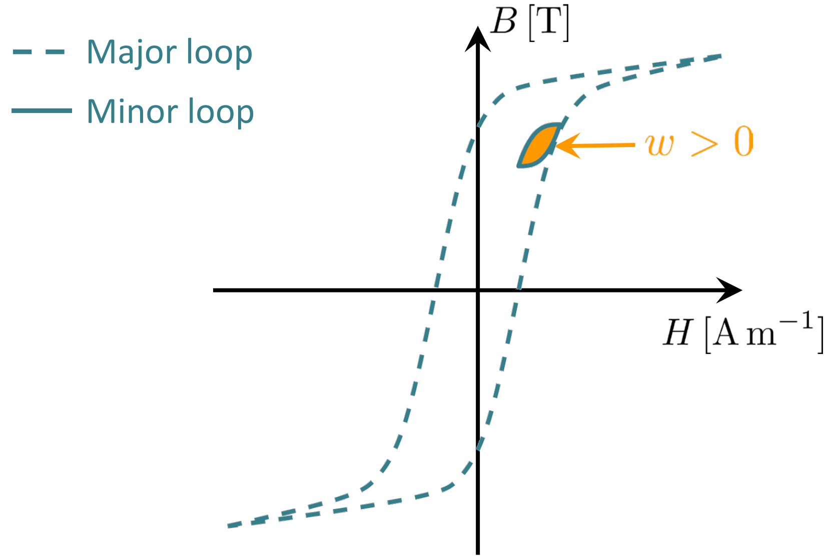




Iron/Core losses

For **nonlinear** soft-magnetic material for which H and B are time-varying

- losses are associated with the area enclosed by **hysteretic** (minor) BH-loops



Minor loops occur in pre-biased materials, e.g.

$$H(t) = H_{\mathrm{dc}} + \hat{H}_{\mathrm{ac}} \cos(\omega t)$$

Macroscopic post-processing modeling of Iron/Core losses

FLUX models **nonhysteretic** soft-magnetic materials.

The Bertotti model: phenomenological model based on decomposition of losses

1. Classical eddy current losses, P_{c}, due the nonzero conductivity of the soft-magnetic material (Faraday's Law)
2. Hysteresis losses, P_{h}, on account of very short current surges associated with domain-wall movement under time-varying magnetic field (Barkhausen jumps)
3. Excess losses , P_{e}, are the remaining losses attributed to domain-wall movement when the Barkhausen jumps are disregarded

$$P_{\mathrm{Fe}} = P_{\mathrm{c}} + P_{\mathrm{h}} + P_{\mathrm{e}}$$