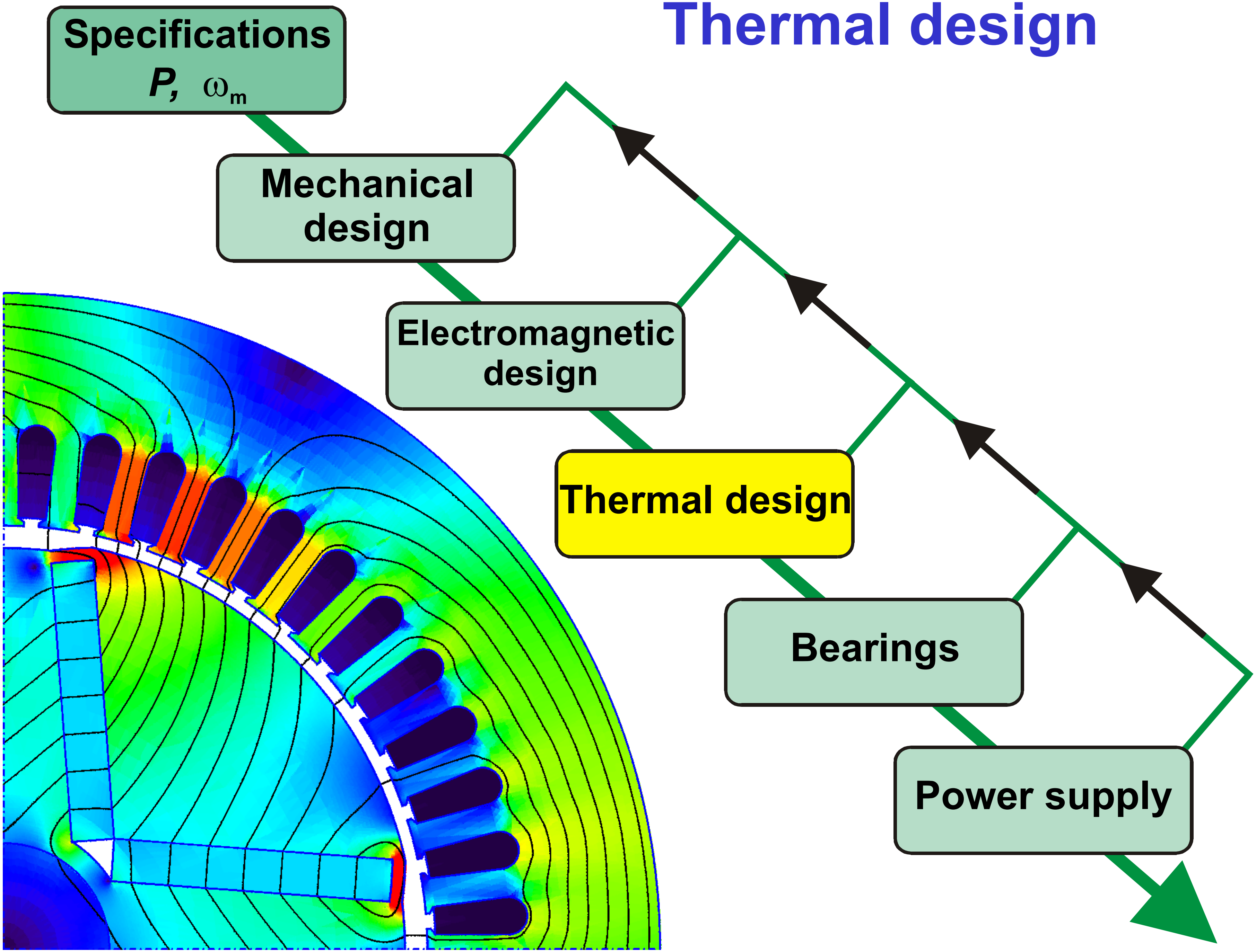
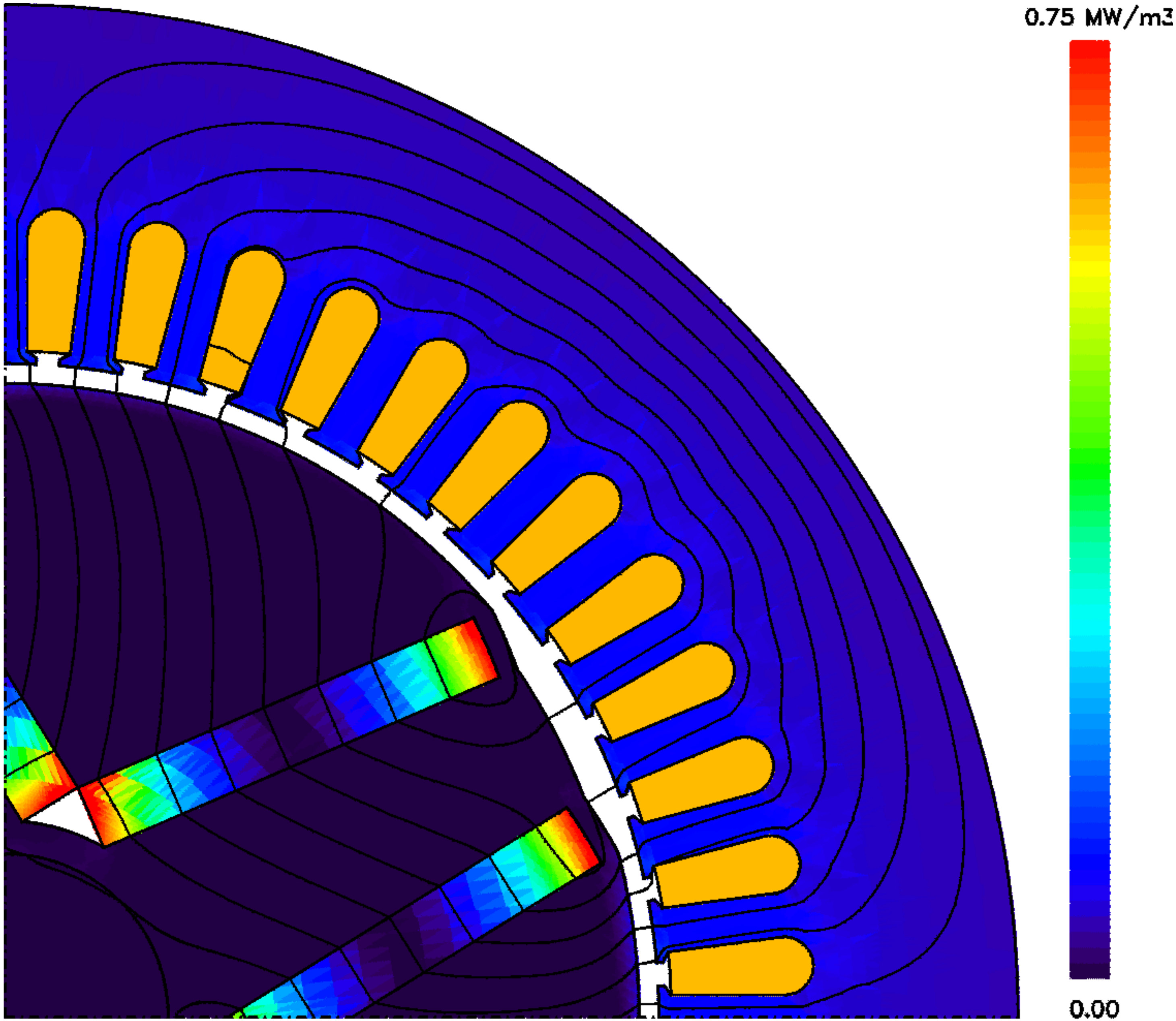
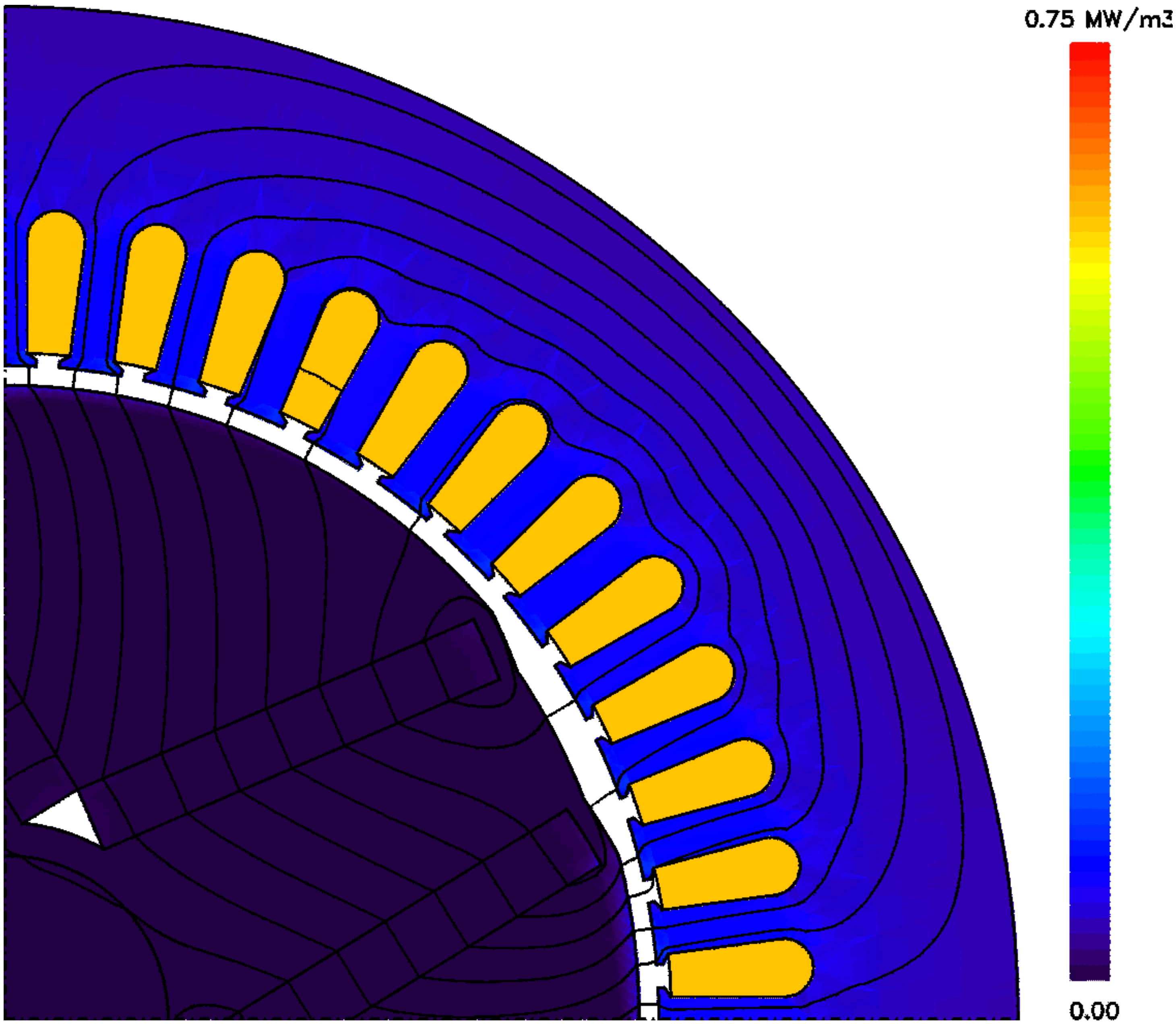
Thermal design



Loss distribution in an inverter-fed motor



Loss distribution for sinusoidal supply



High-frequency flux related to the inverter supply

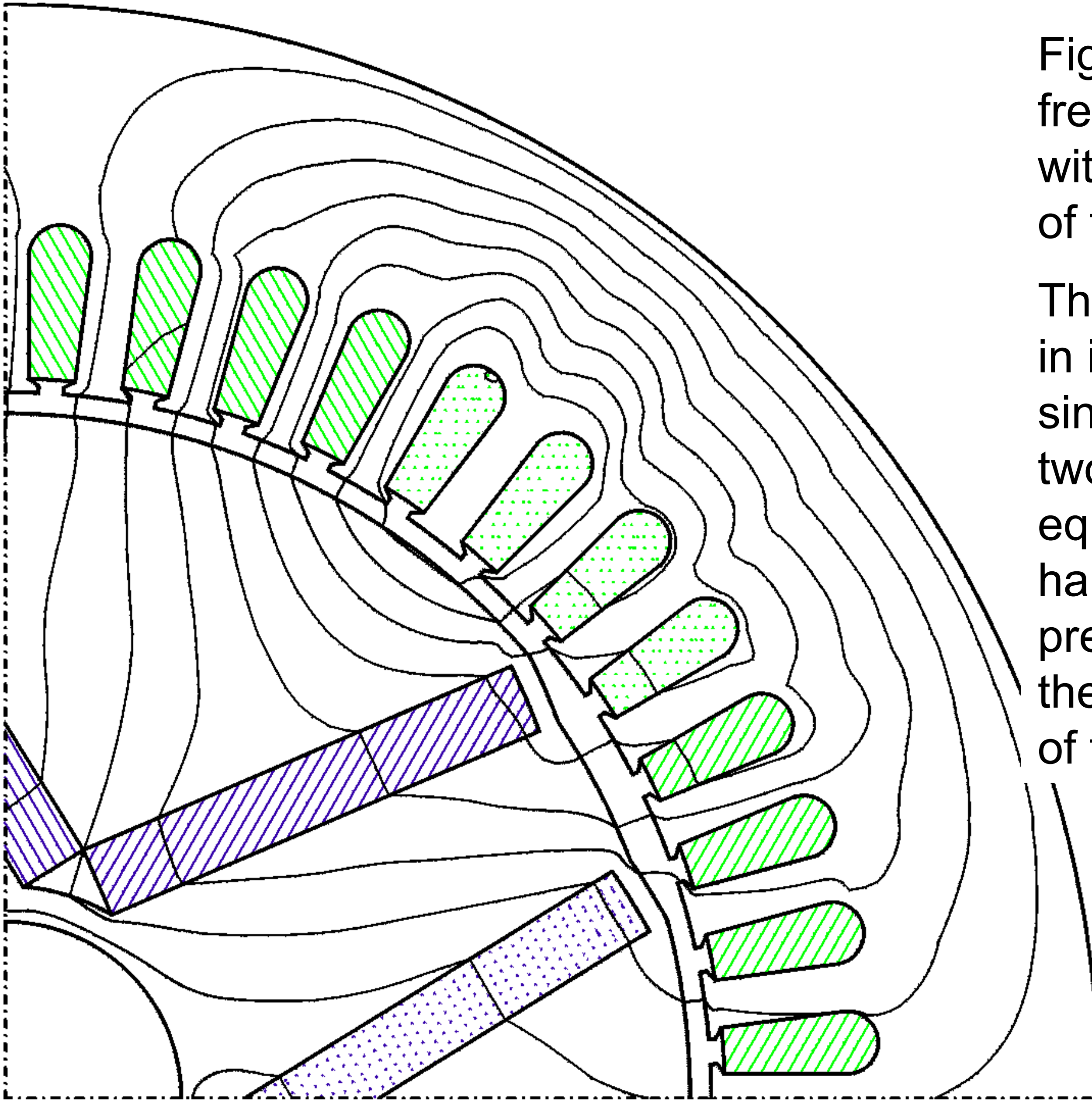
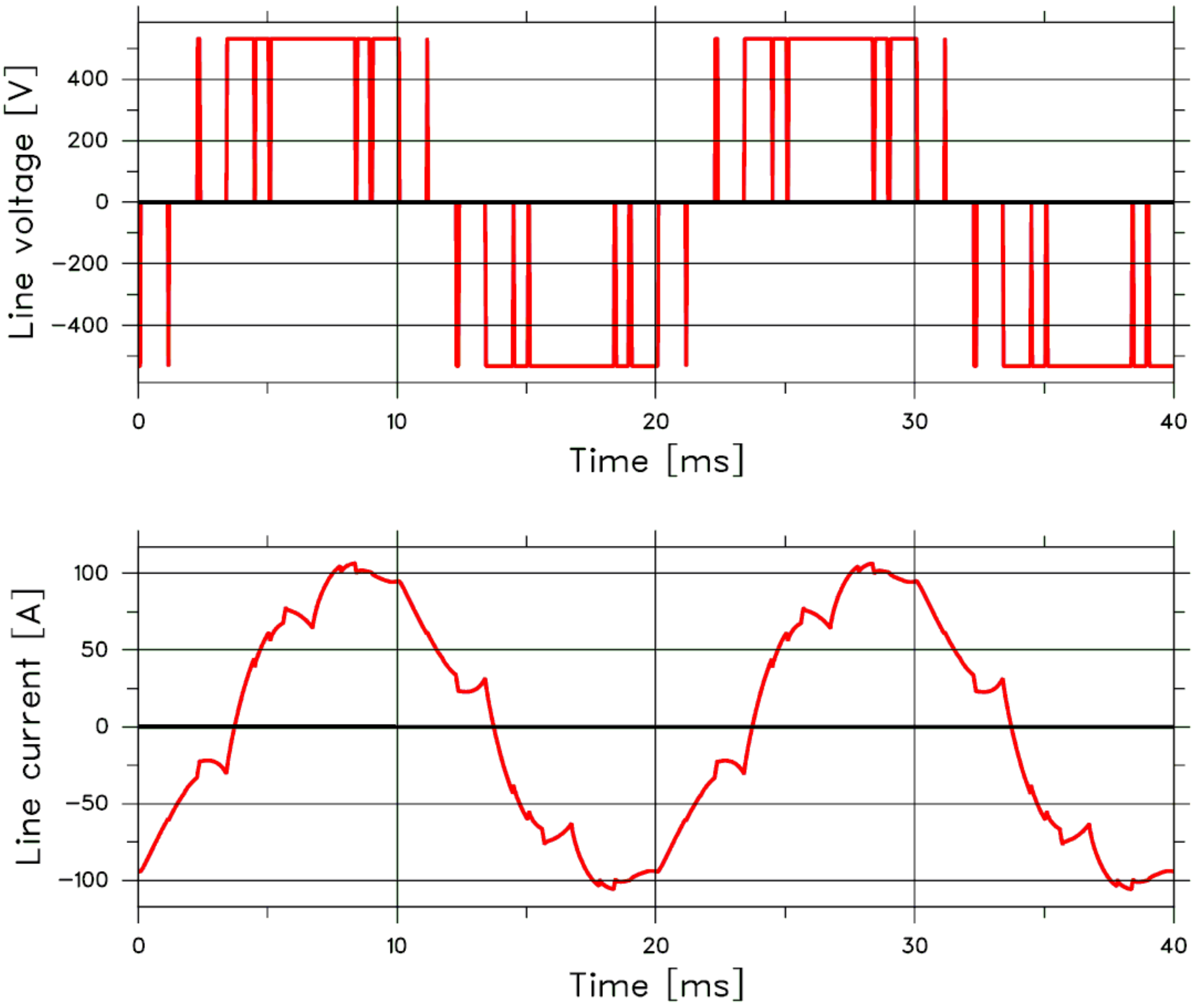


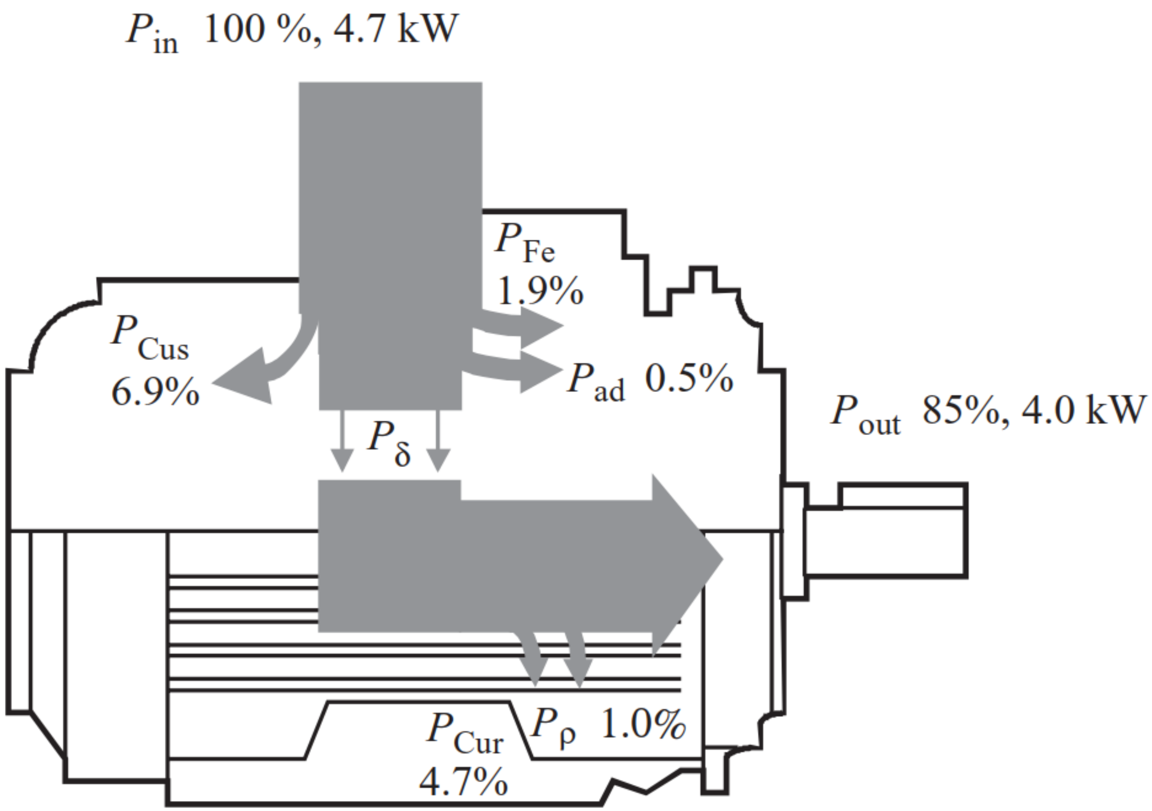
Figure presents the high-frequency flux associated with the harmonic voltages of the inverter supply.

The machine was analysed in inverter supply and sinusoidal supply with the two supply voltages having equal fundamental harmonics. The flux presented in the figure is the difference of the fluxes of the two supply modes.

Voltage and current in the loss simulation



Why proper heat transfer ?



700 W of power removed from the machine.
With improper heat transfer,

- Insulation breakdown
- PM demagnetisation

Insulation classes for windings

Insulation class Old system	130 B	155 F	180 H
Maximum temperature [°C] Average temperature rise [K]	130 80	155 105	180 125

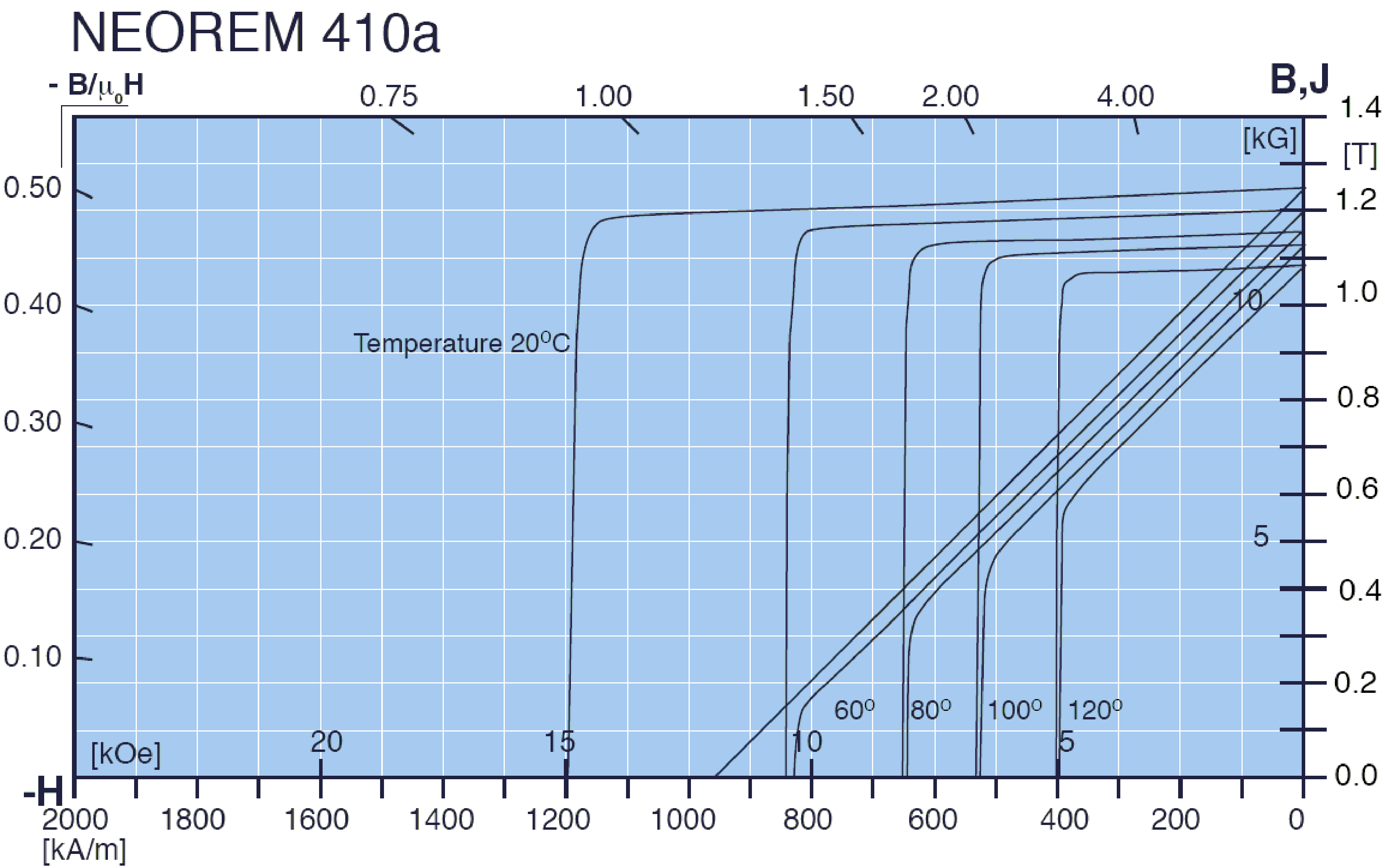
A winding should stand for **20 000 h** the temperature defined by the insulation class (IEC 60216-1).

Montsinger's rule / Arrhenius equation

A temperature rise of 10 K halves the expected live time of an insulation system

$$L\left(T+10\ \mathrm{K}\right)\approx 0.5L\left(T\right) \qquad L\left(T\right)=B\mathrm{e}^{\frac{\varphi}{kT}}$$

Characteristics of a permanent magnet



Methods of heat transfer - 1

Conduction

Heat conduction in a solid (or static fluid)

$$\phi_{\mathrm{th}} = -\lambda S \nabla T$$

Heat flow rate

Thermal conductivity

Heat transfer area

Temperature gradient

$$\boldsymbol{q} = -\lambda \nabla T \quad \text{(in } W/m^2\text{)}$$

Thermal conduction resistance

$$R_c = \frac{l}{\lambda S}$$

Length of heat flow path

Equations of heat conduction

Conservation of energy

$$\frac{\partial(\rho c_p T)}{\partial t} + \nabla \cdot \boldsymbol{q} = p_\mathrm{h}$$

Heat equation

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = p_\mathrm{h}$$

λ = heat conductivity
ρ = density
c_p = specific heat
p_h = power density

Thermal conductivities of some materials

Material / Part	λ [W/mK]
Copper	370
Aluminium	240
Casted iron	58
Steel (0.1 % C)	52
Stainless steel	15 – 25
Laminated core (radial direction)	18 – 40
Laminated core (axial direction)	1 – 4
NeFeB magnets	10
Enamel coating of conductors	0.20
Slot insulation	0.2 – 0.3
Air at 50 °C	0.028
Water at 20 °C	0.60

Diamond ……. 2200 W/mK

Methods of heat transfer - 2

Convection

Heat transfer between region of higher temperature (typically solid surface in machines) and a cooler region (fluid/coolant used), which occurs due to movement of coolant relative to the solid surface.

$$\boxed{q_{\mathrm{c}} = \alpha_{\mathrm{c}}\left(T_{\mathrm{m}} - T_{\mathrm{a}}\right)}$$

Semi-empirical heat transfer coefficient for the surface

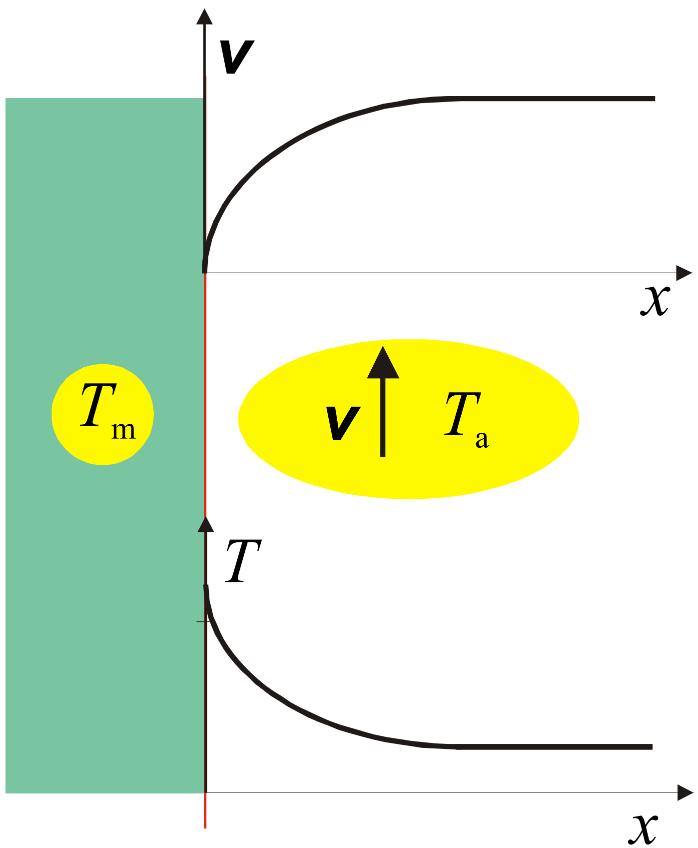
Temperature gradient

Thermal convection resistance

$$R_{cv} = \frac{1}{\alpha_{\mathrm{c}} S}$$

Area of solid in contact with coolant motion

Problem: Heat transfer from solid to fluid



What is velocity distribution?

Turbulent or laminar flow?

Conduction or convection?

What is thermal distribution?

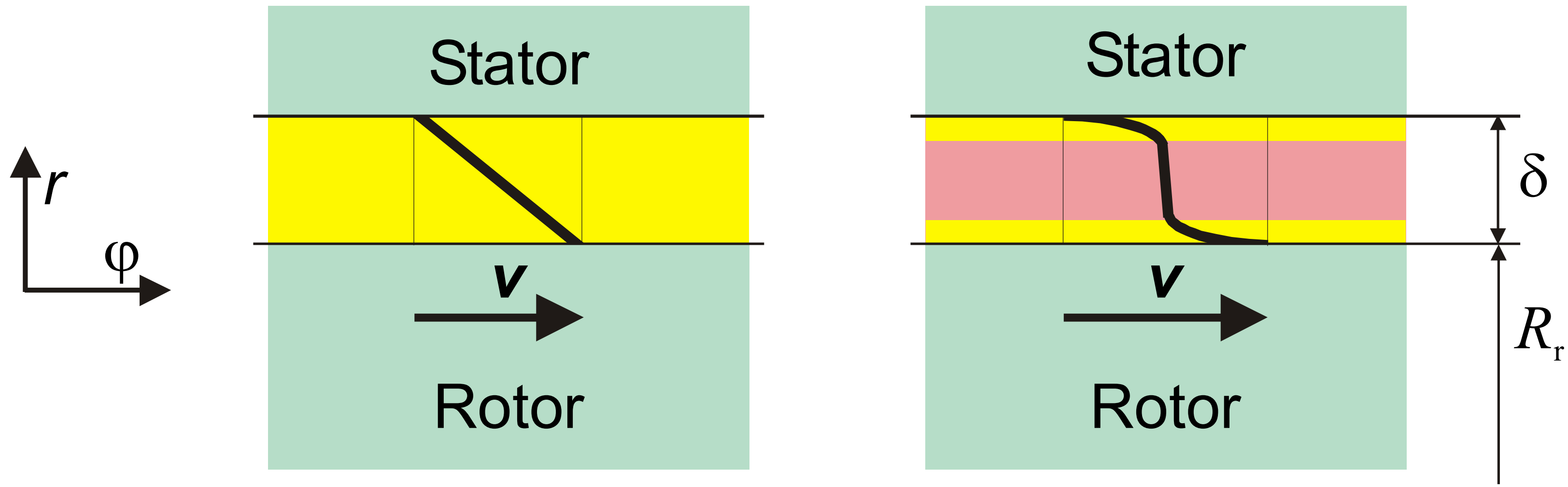
=>

FIND: Semi-empirical heat transfer coefficient for the surface α_c from

$$\alpha_c = \frac{\lambda}{\delta} Nu$$

Nusselt Number

Circumferential flow pattern in air-gap



Laminar flow

Turbulent flow

Dimensionless parameter

Reynolds number

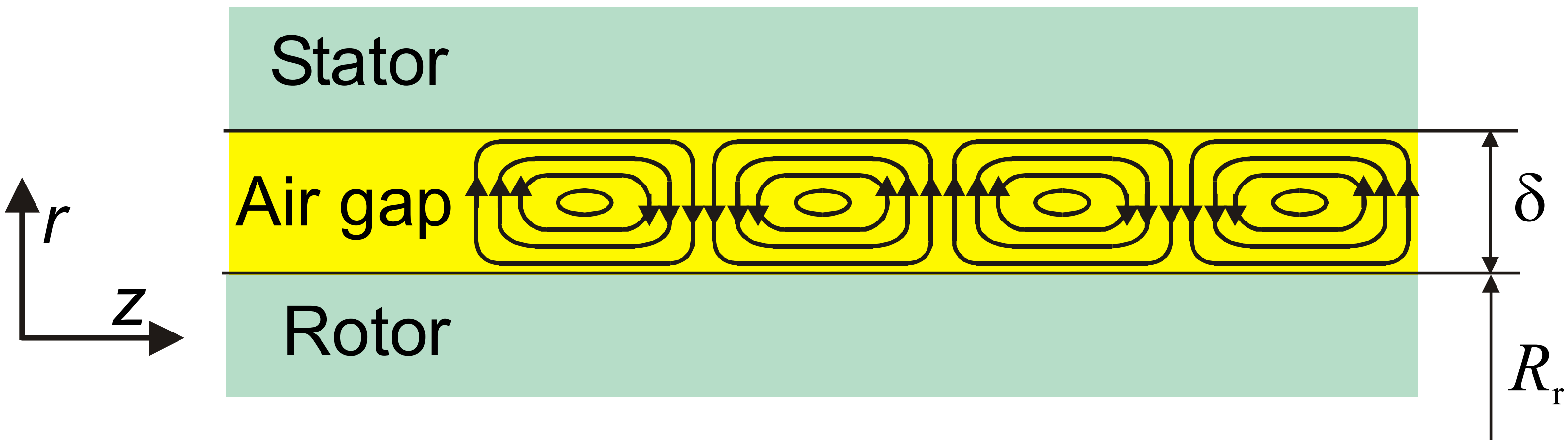
$$Re = \frac{\rho v \delta}{\eta} = \frac{\rho R_r \omega_m \delta}{\eta}$$

ρ = density, δ = radial air-gap length, R_r = rotor radius,
η = dynamic viscosity

Re < 2000 => laminar flow; Re > 5000 => turbulent flow

Flow distribution in *r,z*-plane

Couette flow with Taylor vortices:



Taylor number $$Ta = Re^2 \frac{\delta}{R_r} = \frac{\rho^2 \omega_m^2 \delta^3 R_r}{\eta^2}$$

Taylor vortices appear in air-gap flow, if $Ta > 1700$

Heat-transfer in the air-gap flow

- Heat-transfer coefficient for the air-gap surfaces

From one surface to the air flow in the middle of air gap

$$\alpha_{\mathrm{c}} = \frac{\lambda}{\delta} Nu \; ; \qquad \begin{cases} Nu = 2 & , \; Ta_{\mathrm{m}} < 1700 \\ Nu = 0.128 \cdot Ta_{\mathrm{m}}^{0.367}, & 1700 \le Ta_{\mathrm{m}} \le 10^4 \\ Nu = 0.409 \cdot Ta_{\mathrm{m}}^{0.241}, & 10^4 < Ta_{\mathrm{m}} < 10^7 \end{cases}$$

Nu = Nusselt number
Ta_{m} = Modified Taylor number ($Ta_{\mathrm{m}} \approx Ta$ for air-gap flow)

Becker K.M. and Kaye J. 1962. *Measurements of diabatic flow in an annulus with an inner rotating cylinder*. Transactions of the ASME, Journal of Heat Transfer, Vol. 84, May, pp. 97–105.

Characteristics of air-gap flow

$$Re = \frac{\rho R_r \omega_m \delta}{\eta}$$

$\boxed{Re < 2000}$ => laminar flow; $\boxed{Re > 5000}$ => turbulent flow

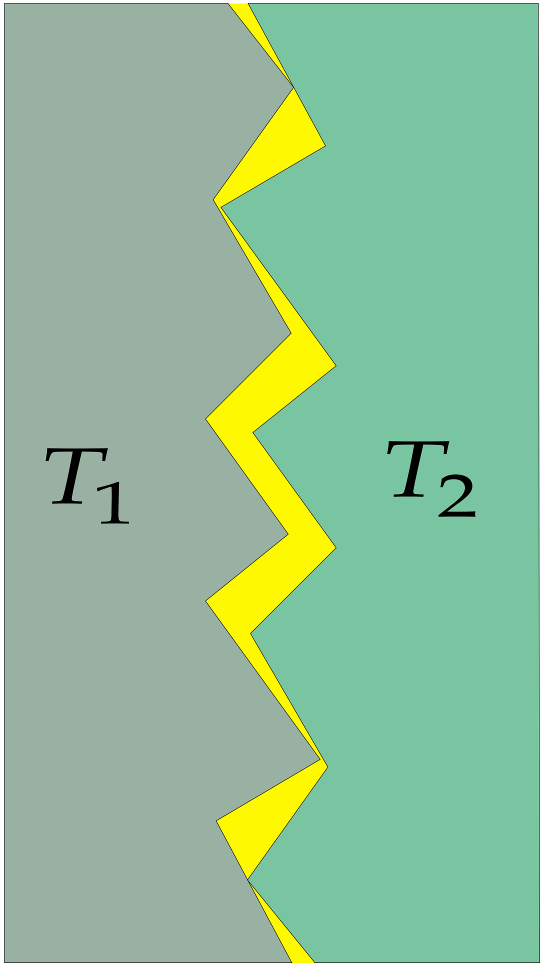
ρ = density, R_r = rotor radius, ω_m angular speed, δ = air gap,

η = dynamic viscosity

Machine A: Turbo-generator 270 MVA, 3000 1/min
Machine B: Hydro-generator 21 MVA, 125 1/min
Machine C: Cage induction motor 4.75 MW, 1500 1/min
Machine D: Cage induction motor 37 kW, 1500 1/min

	Machine A	Machine B	Machine C	Machine D
Re	660219	21678	13838	702
Ta	5.7E+10	1.6E+06	2.5E+06	3941

Heat flow over solid-solid boundaries with an imperfect contact



An imperfect contact between two solids affects heat flow rate

=>

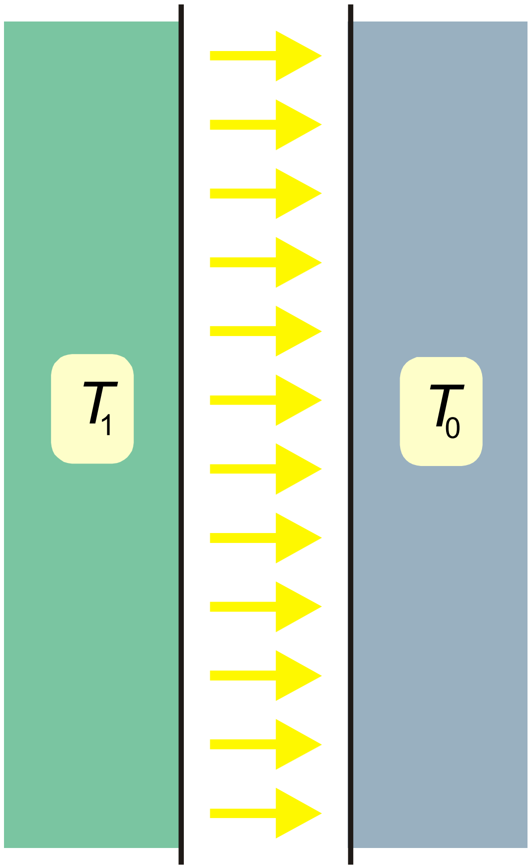
Semi-empirical heat-transfer coefficient α_c for the surface

$$q_c = \alpha_c (T_1 - T_2)$$

Contact	α [W/m²K]
Aluminium frame – Stator core	350 - 550
Cast iron frame – Stator core	650 - 870
Rotor bar – Rotor core	430 - 2600

Methods of heat transfer - 2

Radiation



Stefan-Boltzmann law

$$q_r = \sigma \varepsilon A\left(T_1^4 - T_0^4\right)$$

$$\sigma = 5.67 \cdot 10^{-8} \ \frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}^4}$$

Radiation: $T_1 = 400$ K, $T_0 = 300$ K

=> $q = 992$ W/m^2

Natural convection: $\alpha_c = 14$ W/m^{2}K,

$\Delta T = 100$ K

=> $q = 1400$ W/m^2

Analogy of the heat flow and electric current flow

Static fields

Heat flow

$$\dot{q} = -\lambda \nabla T$$

Electric current density

$$\vec{J} = -\sigma \nabla \Phi$$

Conservation of energy

$$\nabla \cdot \dot{q} = p_{\mathrm{h}}$$

Conservation of charge

$$\nabla \cdot \vec{J} = 0$$

Temperature field

$$\nabla \cdot (\lambda \nabla T) = -p_{\mathrm{h}}$$

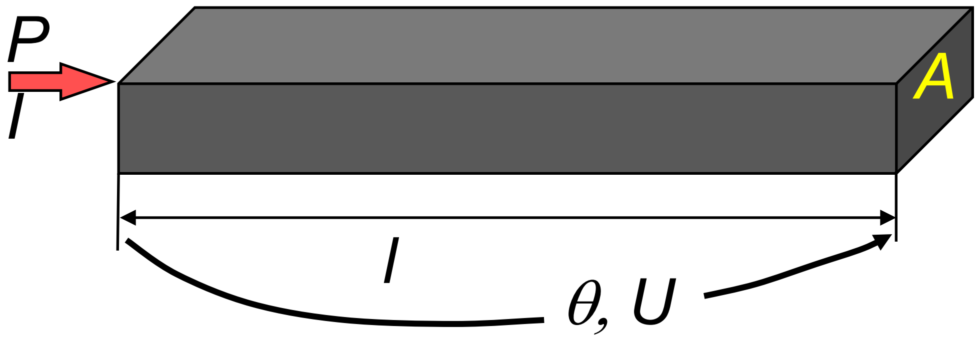
Electric scalar potential

$$\nabla \cdot (\sigma \nabla \phi) = 0$$

=> The tools developed for electric circuit analysis can be used to study heat flow

Thermal resistance

A conductor having a constant cross-sectional area



P = Power,
$\theta =$ Temperature difference

Equations for the heat flow and electric current (p_h = 0)

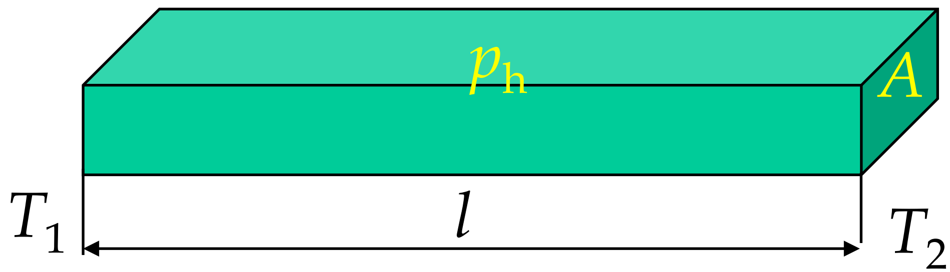
$$P = \int_A \vec{q} \cdot d\vec{A} = \int_A -\lambda \nabla T \cdot d\vec{A} = \lambda \frac{\theta}{l} A = \frac{\theta}{R}$$

$$R = \frac{l}{\lambda A}$$

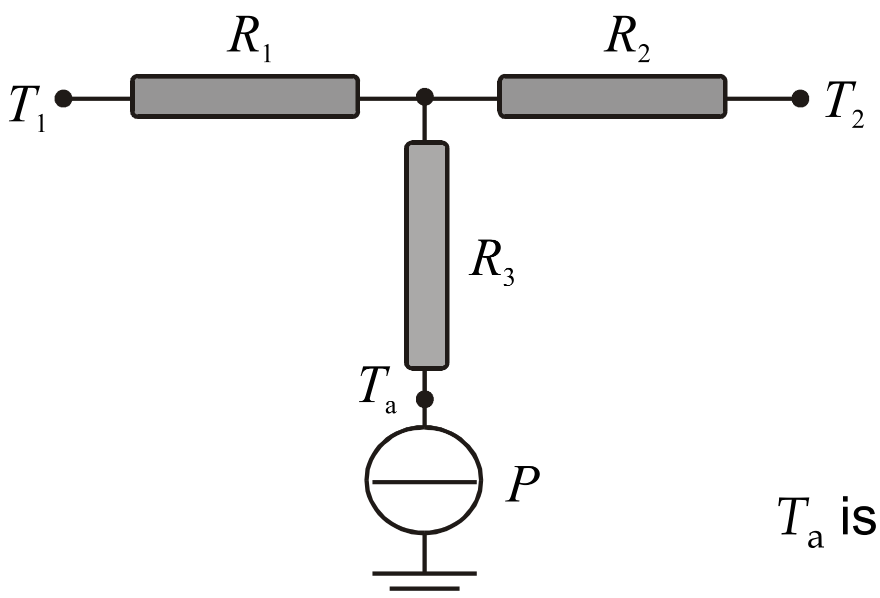
$$I = \int_A \vec{J} \cdot d\vec{A} = \int_A -\sigma \nabla \phi \cdot d\vec{A} = \sigma \frac{U}{l} A = \frac{U}{R_e}$$

$$R_e = \frac{l}{\sigma A}$$

Thermal network for 1D heat flow



A thermal network for conducting bar with power generation (1D heat flow)



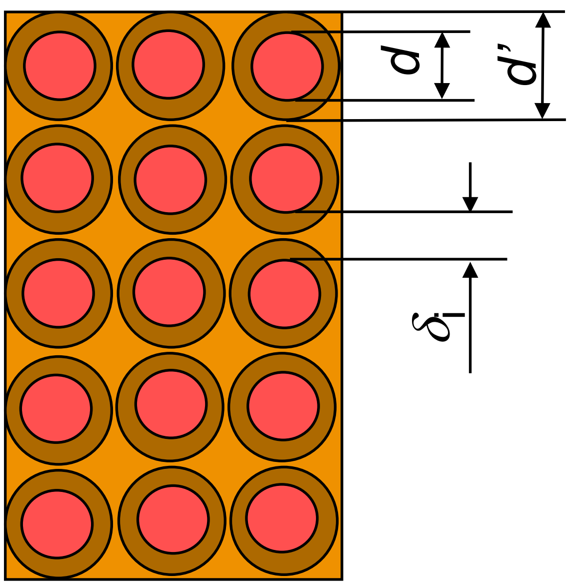
$$R_1 = R_2 = \frac{l}{2\lambda A}$$

$$R_3 = -\frac{l}{6\lambda A}$$

T_a is the average temperature of the bar

Matrix of round wires

Equivalent thermal conductivity for round conductors in a stator slot



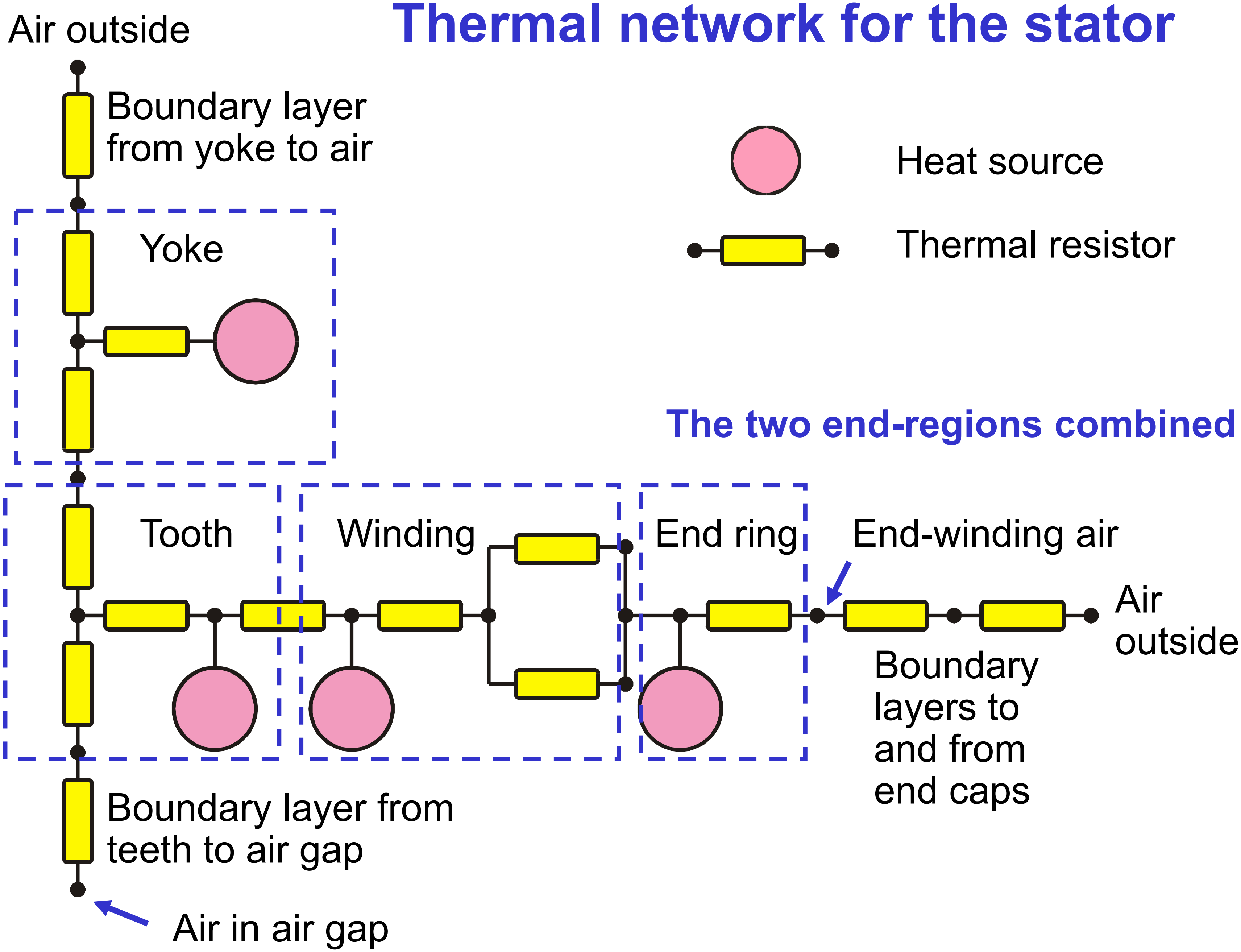
$$\lambda_{\mathrm{r}} \approx \lambda_{\mathrm{i}}\left(\frac{d}{\delta_{\mathrm{i}}} + \frac{\delta_{\mathrm{i}}}{d'}\right)$$

Simple thermal network for the PM machine

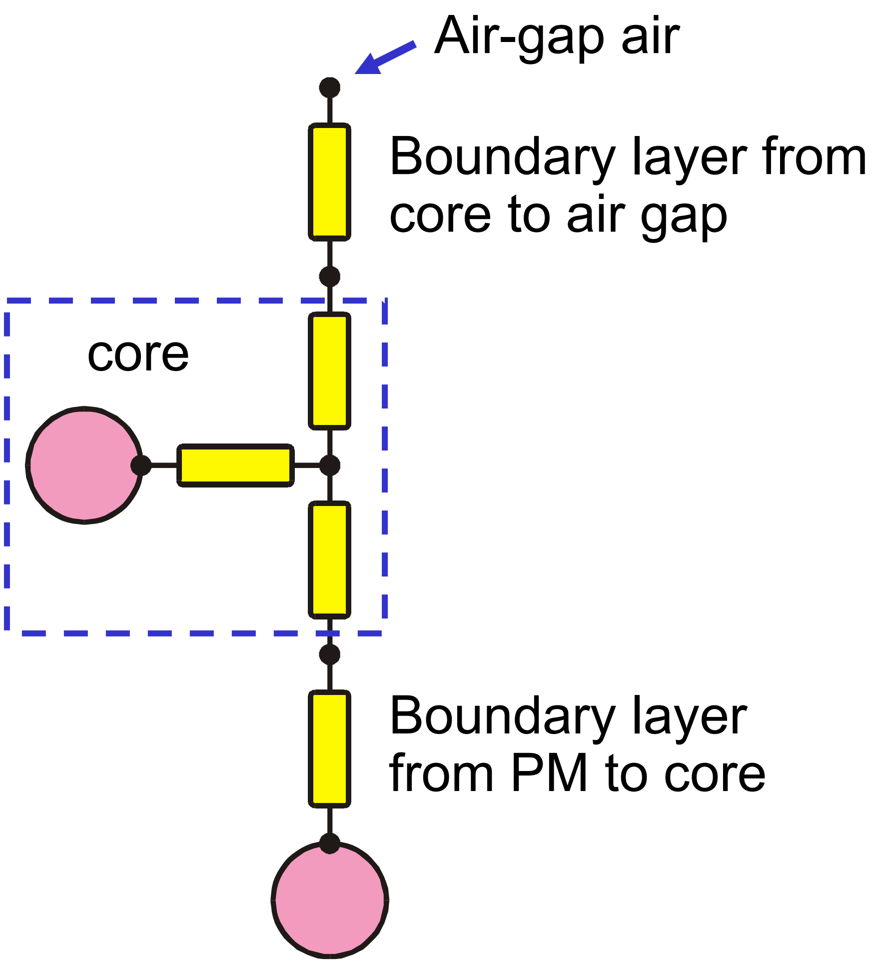
Basic assumptions

- Temperature distribution is symmetric with respect to the centre plane of the machine ($z = 0$ plane)
- There is no axial cooling flow in the air gap
- Core sheets conduct heat only in radial direction
- Heat from the permanent magnets flow to the core, only. There is no direct heat flow from PM to the end-region air
- The heat-transfer coefficients can be “calibrated” based on the temperature-rise tests done for the 37 kW cage induction motor

Thermal network for the stator

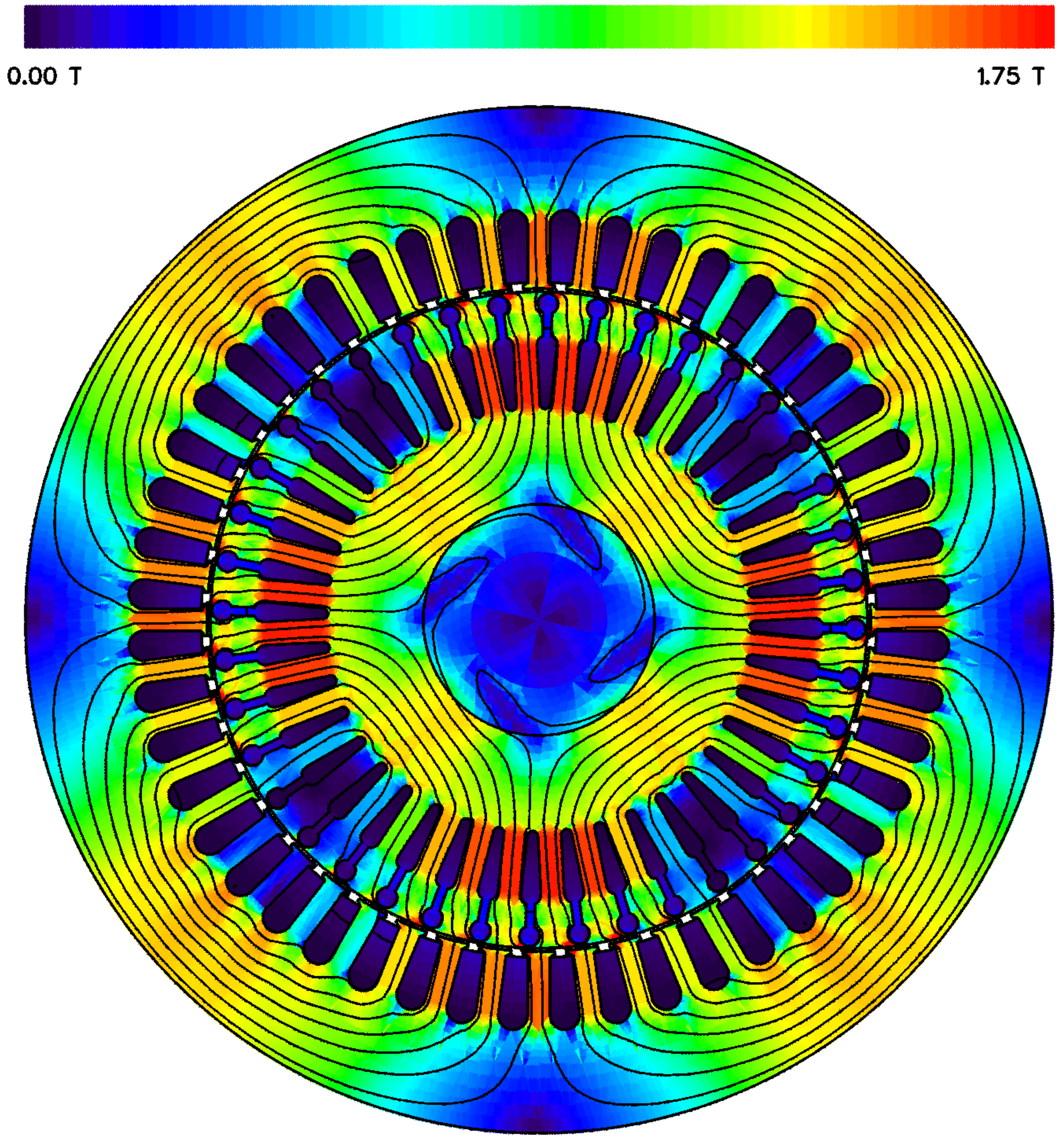


Thermal network for the PM rotor

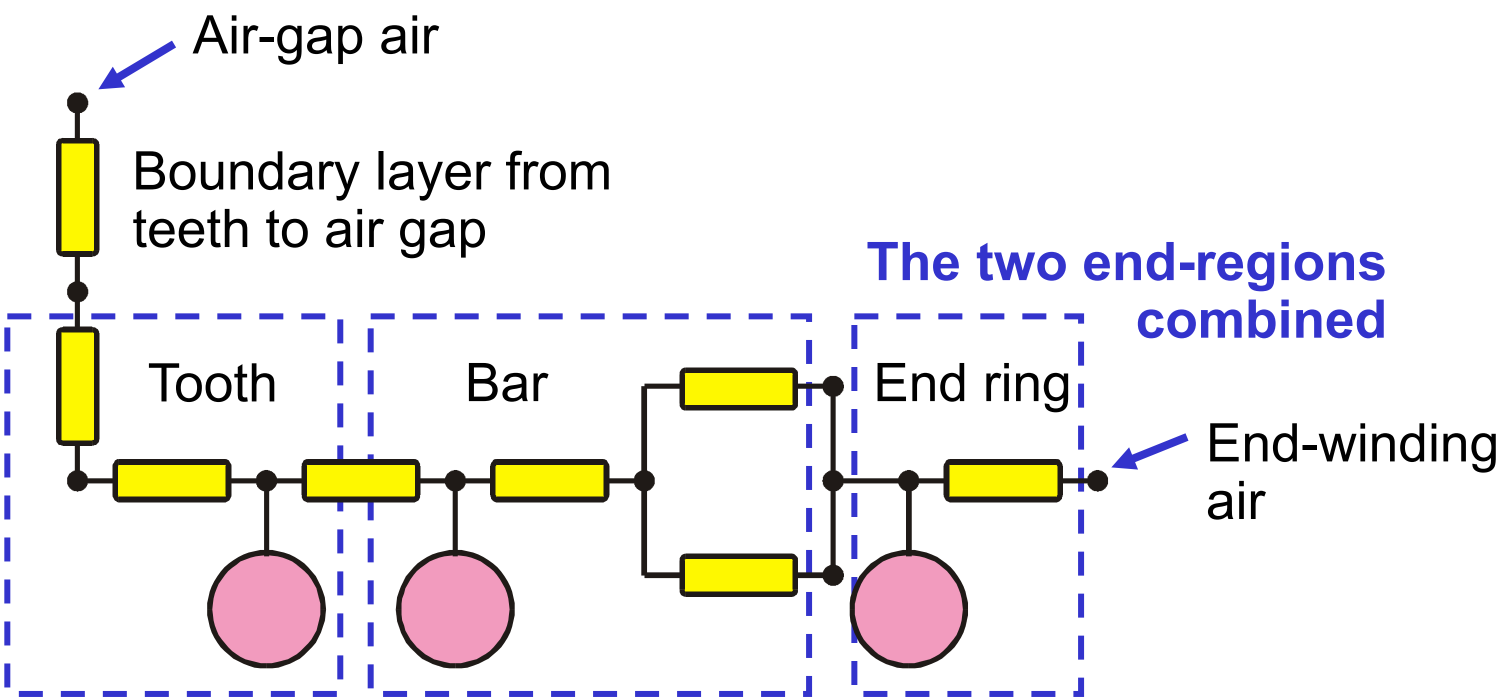


The original cage induction motor

The stator of the PM machine was borrowed from this machine.



Thermal network for a cage rotor



Results from the thermal networks

Temperature rise; P_{shaft} = 37 kW

PM machine

	ΔT [K]
Yoke	32
Stator winding	
- core region	**48**
- end winding	**51**
Air gap	47
Permanent magnet	**54**
End-winding air	21

Induction machine

	ΔT [K]
Yoke	56
Stator winding	
- core region	**84**
- end winding	**89**
Air gap	102
Rotor cage	**136**
End-winding air	86

Results from the thermal networks II

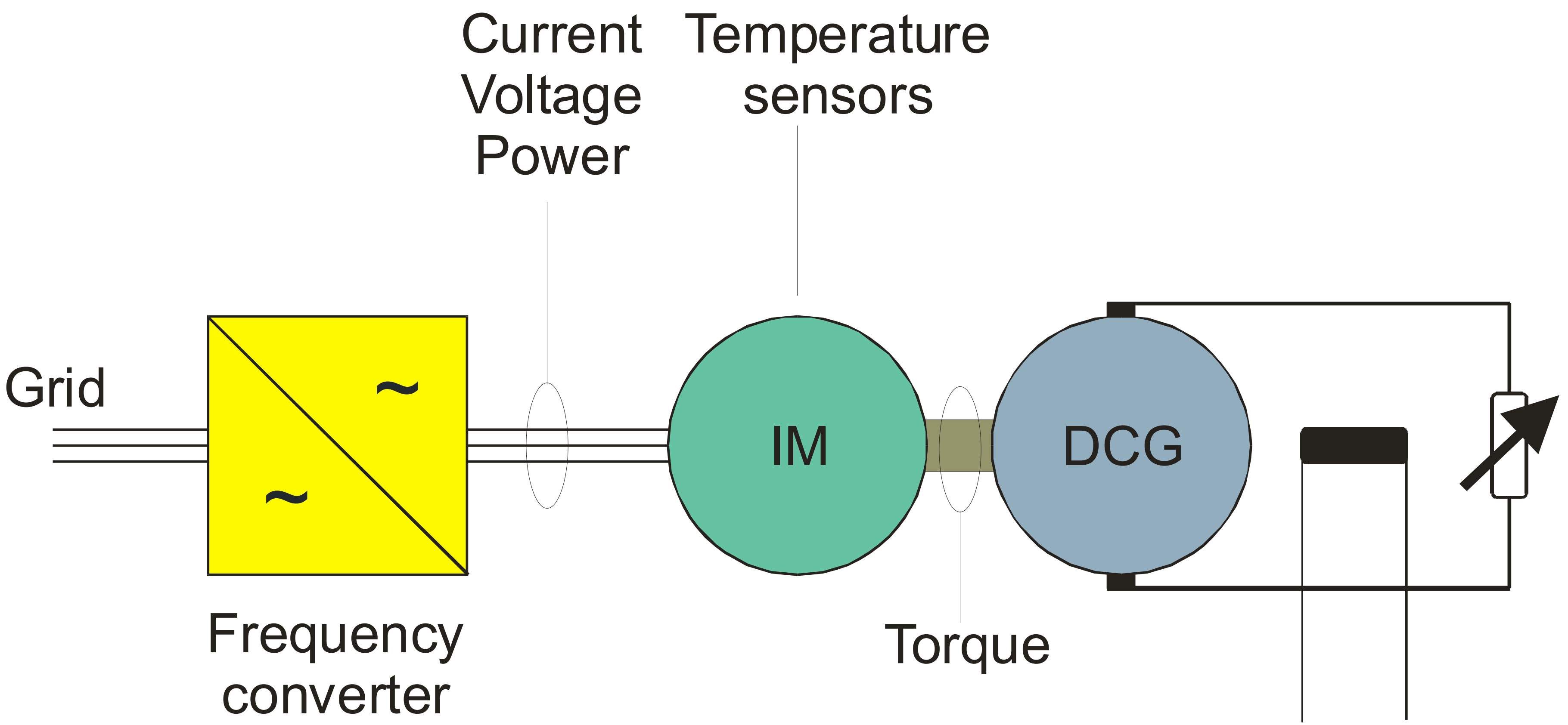
Maximum power from the PM machine if the temperature of the stator winding is allowed to rise by 90 K is

P = 55 kW

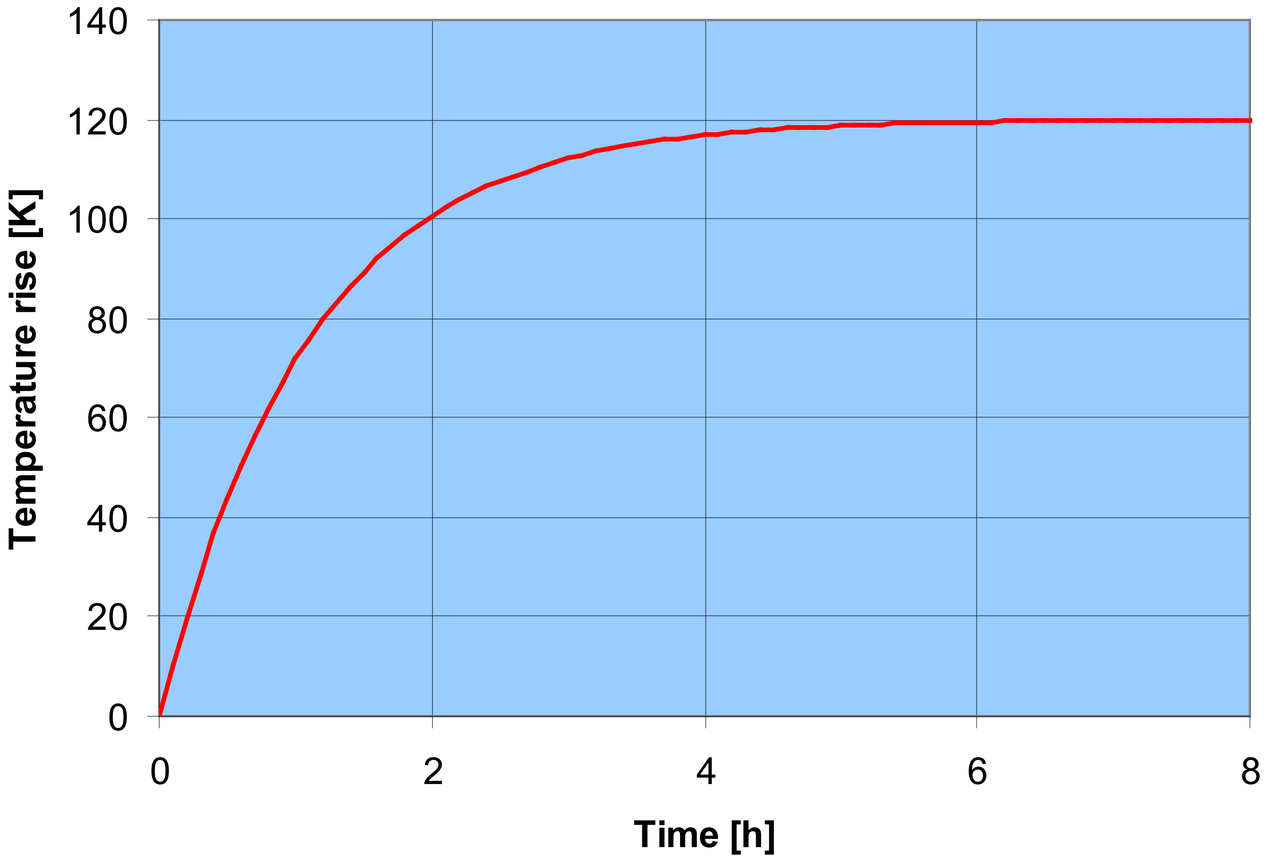
	ΔT [K]
Yoke	51
Stator winding	
- core region	**82**
- end winding	**89**
Air gap	69
Permanent magnet	**76**
End-winding air	37

Note: The temperature rise of the permanent magnets is close to a maximum that can be allowed for NdFeB magnets. If a higher temperature rise is expected, SmCo magnets could be used.

Validation – Cage induction machine

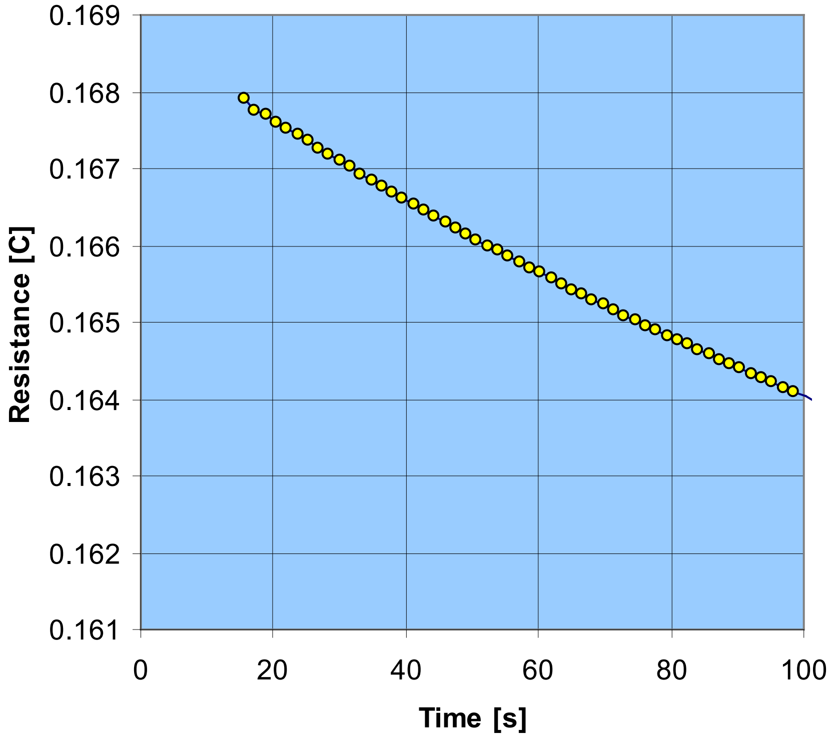


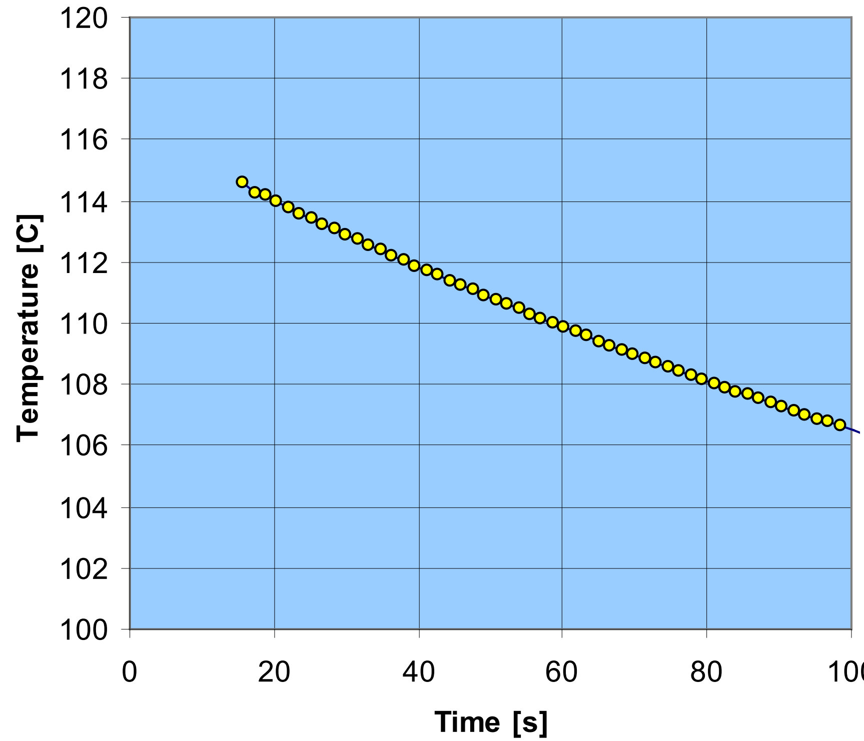
Temperature-rise test



- Thermocouples in end-windings
- Steady state when the temperature rise per half an hour is less than 1 K.

Cooling-down curve at the end of test





Stator resistance is measured after the switch-off of the supply. Switch-off at time instant *t* = 0.

$$\boxed{\frac{R}{R_0} = \frac{T + 235\ ^{\circ}\mathrm{C}}{T_0 + 235\ ^{\circ}\mathrm{C}}}$$

- Reference resistance 0.1235 Ω at 22 ºC
- Ambient temperature 29 ºC
- Temperature rise about 87 ºC

Literature on thermal analysis of electrical machines

- Lumped parameter thermal models
  - Hak J., Lösung eines Wärmequellen-Netzes mit Berücksichtigung der Kühlströme. Archiv fur Elecktrotechnik, Vol. 42, No. 3, pp. 138-154, 1956.
  - Mellor P.H.; Roberts D.; Turner D.R., Lumped parameter thermal model for electrical machines of TEFC design, Proc. Inst. Elect. Eng., pt. B, vol.138, pp.205–218, 1991.

- Numerical thermal field analysis
  - Armor A.F.; Chari M.V.K., Heat flow in the stator core of large turbine generators by the method of three-dimensional finite elements, Part I: Analysis by scalar potential formulation; Part II: Temperature distribution in the stator core"IEEE Trans. Power App. Syst., vol. PAS-95, pp.1648–1656, 1657–1668, Sept./Oct. 1976.
  - Driesen J., Coupled electromagnetic-thermal problems in electrical energy transducers. PhD Thesis, Faculty of Applied Sciences, K. U. Leuven, 2000.
  - Kolondzovski Z., Thermal and mechanical analyses of high-speed permanent-magnet electrical machines, PhD Thesis, Aalto University, 2010, available at: http://lib.tkk.fi/Diss/2010/isbn9789526032801/

Literature on thermal analysis of electrical machines

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