Design process of rotating electrical machines

- **Magnetic circuit**

- **Windings**

- Mechanical design
  - Shaft
  - Centrifugal forces
  - Critical speeds
  - Frame and support structures

- Electrical connections
  - Terminal box
  - Connections of windings
  - Control equipment
  - Protection system

Standards for rotating electrical machines

IEC 60034

- IC classes (methods of cooling)
- IM classes (construction and mounting)
- IP classes (protection provided by enclosures)

- Temperature rise
- Testing
- Tolerances in operation
- Shaft heights and mounting dimensions

Other standards: IEEE, UL, ANSI, NEMA, BS, CSA, etc.

Essential information needed for the design

- rated voltage U_N,
- rated frequency f_N,
- number of phases m,
- rated power as apparent S_N and/or active power P_N,
- rotation speed as a synchronous speed n_s or number of poles p,
- operation mode (continuous S1, partial S2-20 min, ...),
- construction (IM class), enclosure (IP class) and cooling (IC class),
- standards (IEC, NEMA, UL, ANSI, CSA, ...),
- special requirements (starting torque, maximum torque, starting current, etc.) and
- knowledge of material and production costs for economic optimisation.

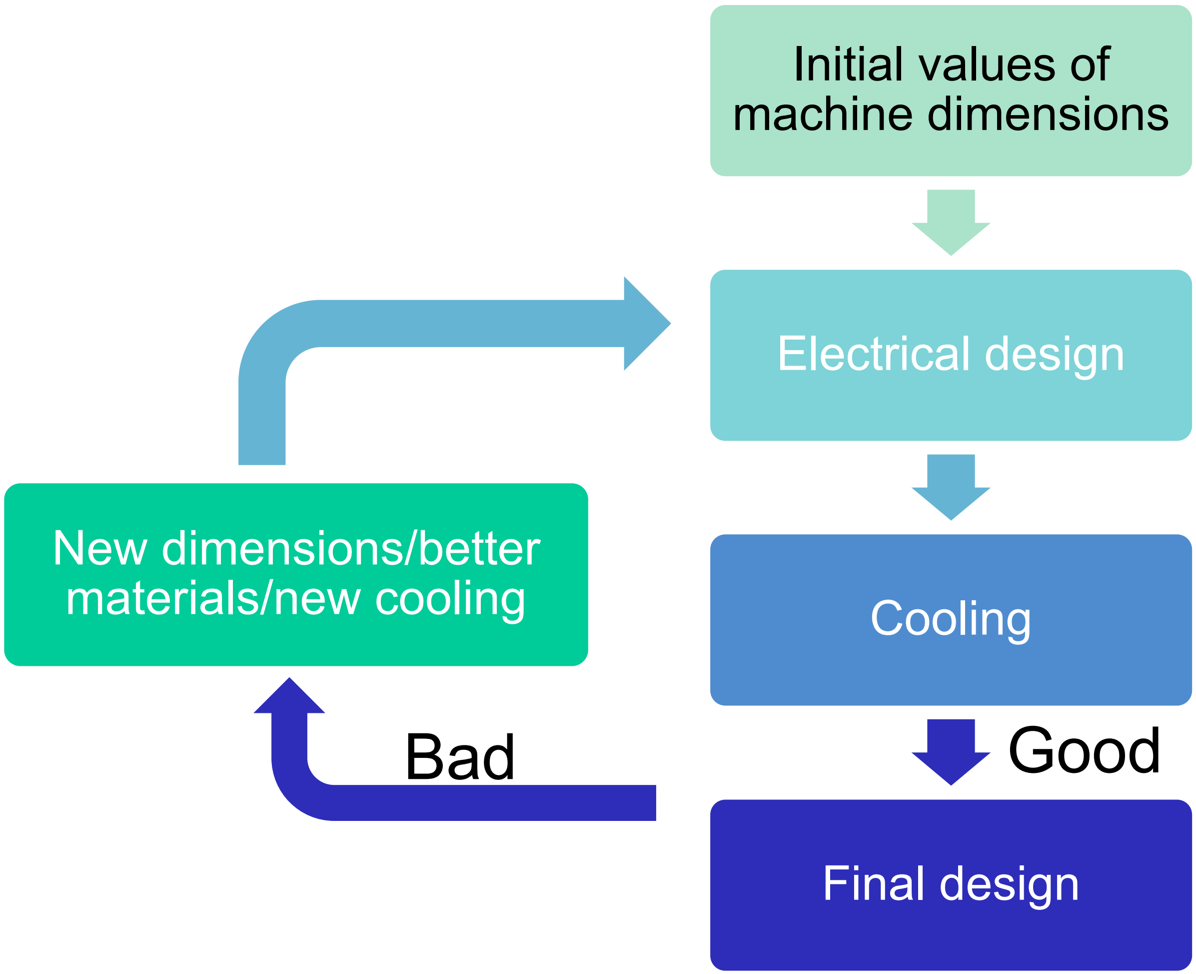
Information needed for the design

There are 30 – 40 parameters that have to be fixed in the design of an electrical machine. It would be too time consuming to optimise all of them. Typically, such parameters that vary only slightly from machine to machine are fixed to their basic values and about 10 parameters are left as free ones to be optimised.

Typical free parameters are

- core diameters,
- core length,
- air-gap length,
- slot height and width,
- air-gap flux density,
- etc.

Design process

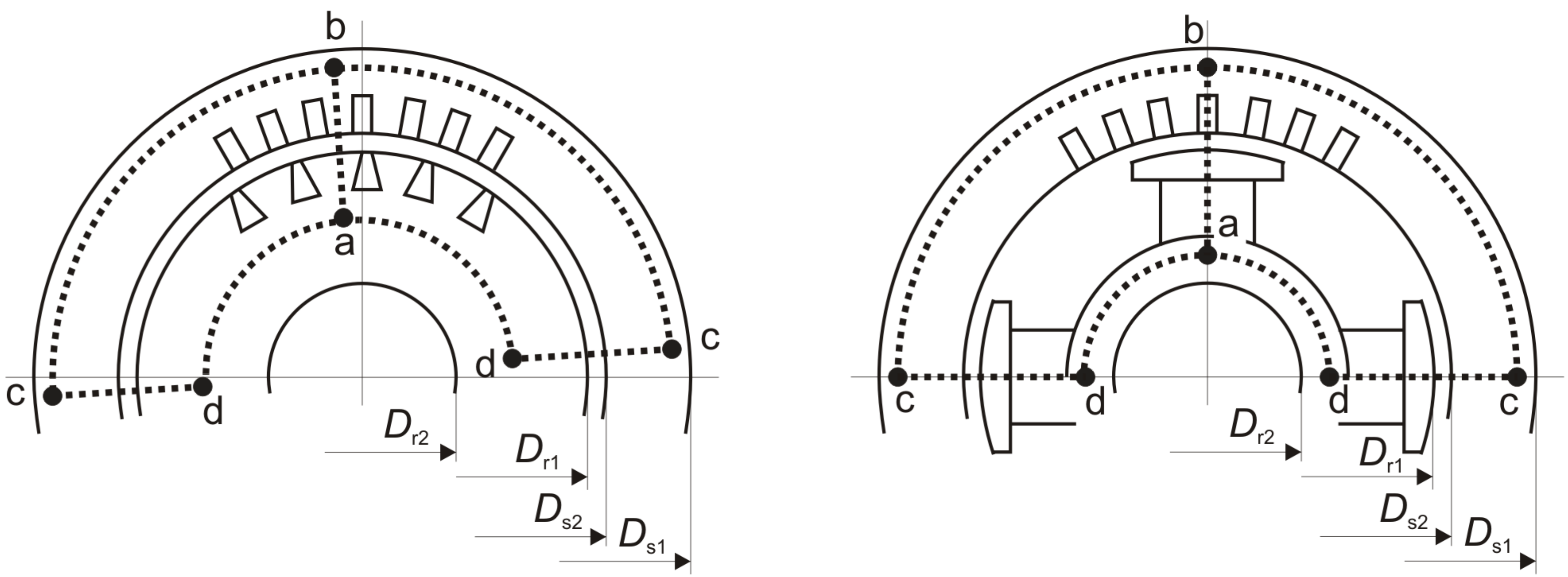


Magnetic circuit

The line integral of $\boldsymbol{H}$ along any closed path should be equal to the total current flowing through that path

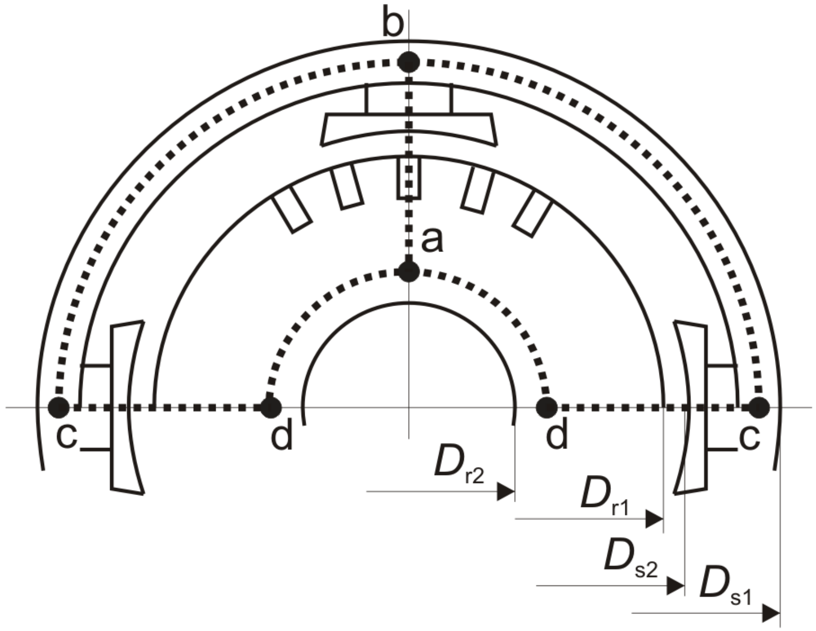
$$\oint \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l} = \sum_i F_i = I_{\mathrm{tot}}$$

This is the basic equation for calculating the magnetisation current and designing the magnetic circuit.



a **b**

Magnetic circuit

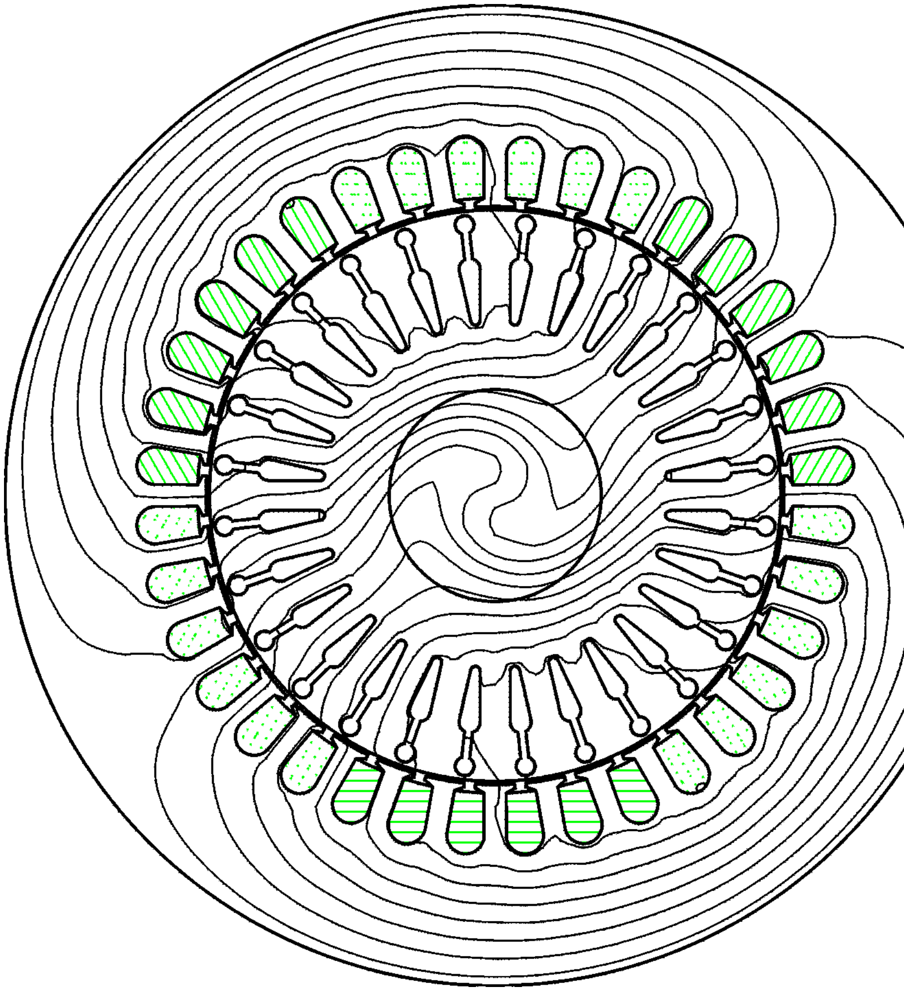


c

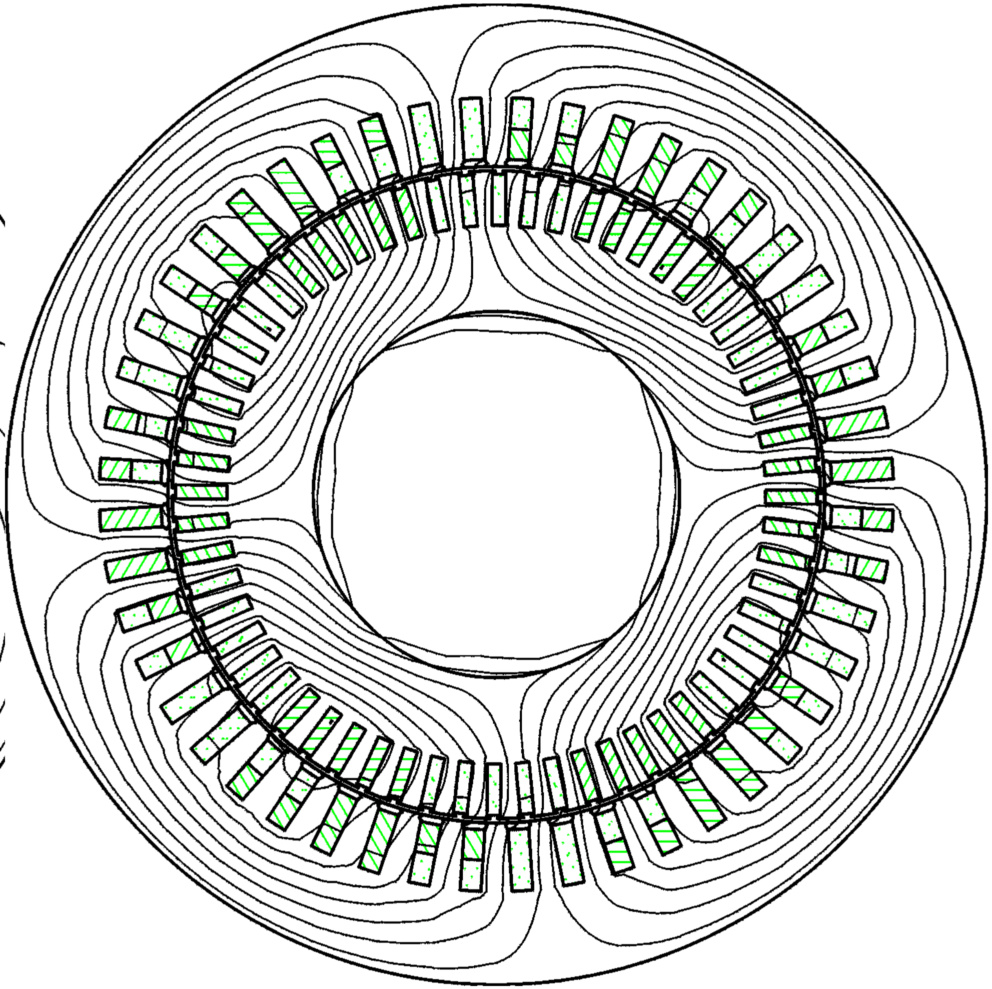
The magnetomotive force F is divided in to components

$$\begin{cases} F_{\mathrm{m}} = 2V_{\mathrm{m}\delta} + 2\left(V_{\mathrm{mz,s}} + V_{\mathrm{mz,r}}\right) + V_{\mathrm{mj,s}} + V_{\mathrm{mj,r}} & \text{, Figure a} \\ F_{\mathrm{m}} = 2V_{\mathrm{m}\delta} + 2\left(V_{\mathrm{mz,s}} + V_{\mathrm{mp,r}}\right) + V_{\mathrm{mj,s}} + V_{\mathrm{mj,r}} & \text{, Figure b} \\ F_{\mathrm{m}} = 2V_{\mathrm{m}\delta} + 2\left(V_{\mathrm{mp,s}} + V_{\mathrm{mz,r}}\right) + V_{\mathrm{mj,s}} + V_{\mathrm{mj,r}} & \text{, Figure c} \end{cases}$$

Induction machines

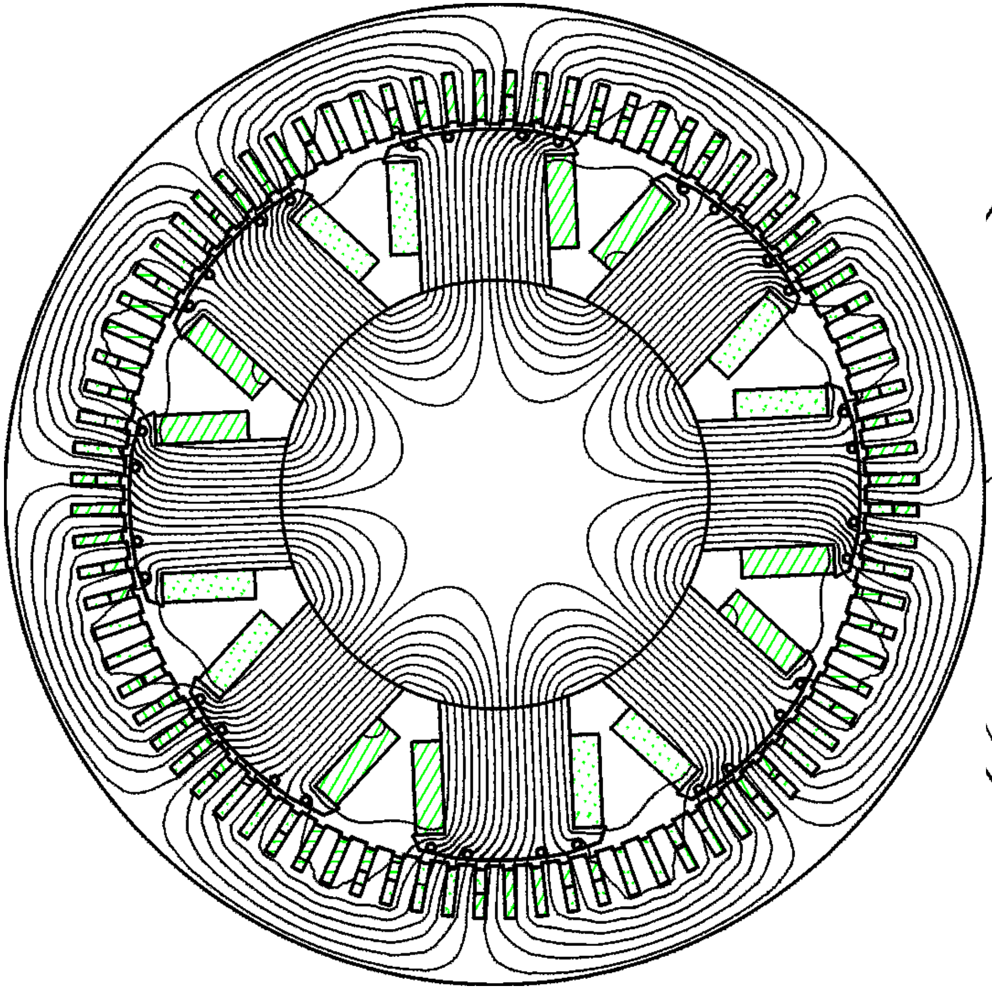


30 kW cage induction motor

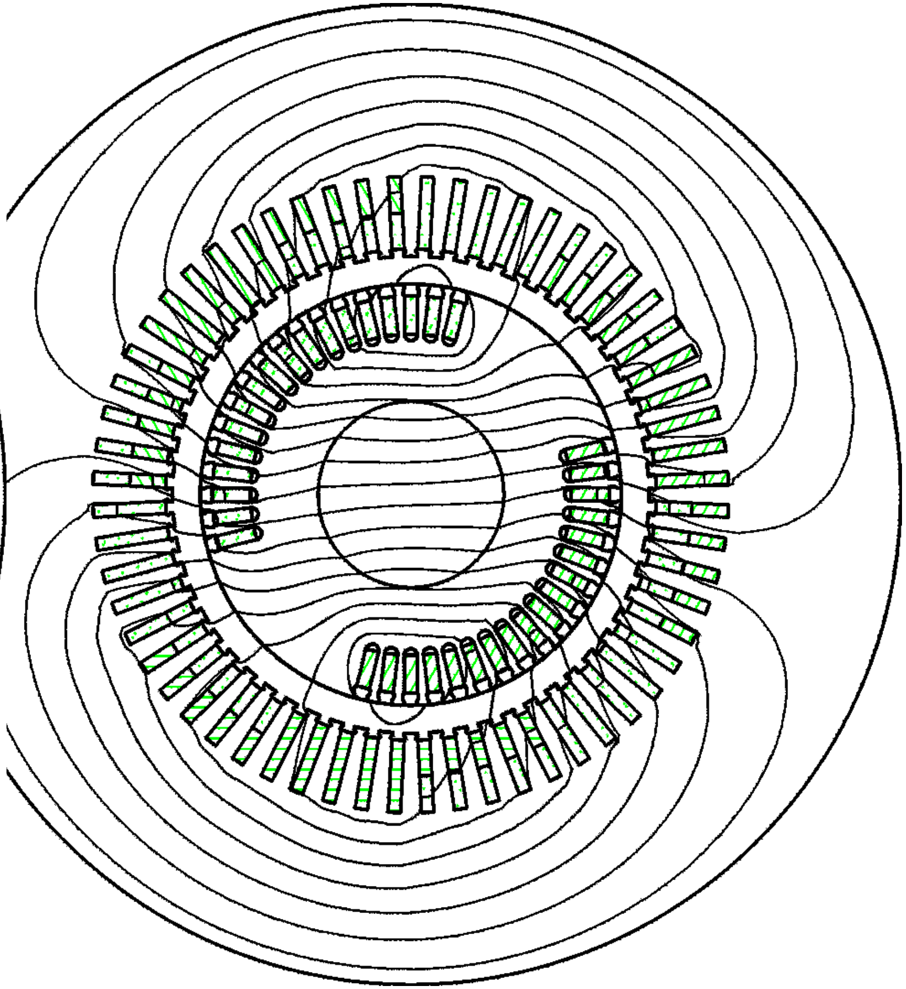


1.7 MVA slip-ring generator

Synchronous machines



8 MVA diesel-generator



270 MVA turbo-generator

Choice of the main dimensions

The <u>utilisation factor C</u> for a rotating electrical machine is defined

$$P = \omega_\mathrm{r} C V_\mathrm{r} \quad \Rightarrow \quad D_\mathrm{i}^2 l_\mathrm{i} = \frac{\dfrac{P}{2\pi n}}{C\dfrac{\pi}{4}}$$

Mech. Angular freq.

Rotor Volume

The **length to diameter ratio** $l_\mathrm{i}/D_\mathrm{i}$ of the rotor varies relatively little

For a DC machine $$\frac{l_\mathrm{i}}{D_\mathrm{i}} = \frac{0.8 \;\mathrm{K}\; 1.6}{p}$$

For a cage induction machine $$\frac{l_\mathrm{i}}{D_\mathrm{i}} \approx \frac{\pi}{2p}\sqrt[3]{p}$$

Choice of the main dimensions

For a synchronous machine

$$\begin{cases} \dfrac{l_\mathrm{i}}{D_\mathrm{i}} \approx \dfrac{\pi}{4p}\sqrt{p} & , p > 1 \\ \dfrac{l_\mathrm{i}}{D_\mathrm{i}} \approx 1\mathrm{K}\ 3, p = 1 \end{cases}$$

The **radial air-gap length** δ for an induction machine is

$$\begin{cases} \dfrac{\delta}{[\mathrm{mm}]} = 0.1 + 0.225\sqrt[3]{\dfrac{P_\mathrm{N}}{[\mathrm{kW}]}} & , p = 1 \\ \dfrac{\delta}{[\mathrm{mm}]} = 0.1 + 0.145\sqrt[3]{\dfrac{P_\mathrm{N}}{[\mathrm{kW}]}} & , p > 1 \end{cases}$$

Choice of the main dimensions

A typical **radial air-gap length** for a DC machine or synchronous machine is

$$\frac{\delta}{[\mathrm{mm}]} = \mathrm{k}\,\frac{\tau_{\mathrm{p}}}{[\mathrm{m}]}\,\frac{\dfrac{A_{\mathrm{s}}}{[\mathrm{A/m}]}}{\dfrac{\hat{b}_{\delta}}{[\mathrm{T}]}}$$

where τ_{p} is the pole pitch, A_{s} the linear current density and b_{δ} the air-gap flux density.

	k
DC machine	
non-compensated	$3{,}6 \times 10^{-4}$
compensated	$2{,}2 \times 10^{-4}$
Synchronous machine	
Salient pole constant air gap	$7{,}0 \times 10^{-4}$
Salinet pole, sinusoidal air gap	$4{,}5 \times 10^{-4}$
Non-salient pole	$2{,}5 \times 10^{-4}$

Calculation process step by step

1. The utilisation factor C is chosen from a table.
2. The length-to-diameter ratio is chosen for the rotor.
3. The air-gap diameter D_i and effective length l_i are calculated.
4. The radial air-gap length δ is defined.
5. The slot numbers for the stator and rotor are chosen. The stator and rotor slot pitches are typically

	τ_u mm
Asynchronous machine	10 ... 45
Synchronous machine	30 ... 70
DC machine	13 ... 35

$$\tau_{u,s} = \frac{\pi \left(D_i + \delta \right)}{Q_s}, \quad \tau_{u,r} = \frac{\pi \left(D_i - \delta \right)}{Q_r}$$

Calculation process step by step

6. The winding factor ξ is calculated.
7. The peak value of air-gap flux density $\hat{b}_\delta$ is chosen

	Induction machine	Salient pole synchronous machine	Non-salient synchronous machine	DC machine
Flux density	**[T]**	**[T]**	**[T]**	**[T]**
Air gap	0,7 ... 0,9	0,6 ... 0,9	0,5 ... 0,7	0,6 ... 1,0
Stator				
- tooth, narrowest point	1,6 ... 2,1	1,7 ... 2,1	1,5 ... 1,9	1,6 ... 2,0
- tooth, middle point	1,4 ... 1,7	1,3 ... 1,6	1,3 ... 1,5	
- pole body	–	–	–	1,2 ... 1,7
- commutation pole	–	–	–	0,9 ... 1,3
- yoke	1,0 ... 1,4	0,9 ... 1,3	1,0 ... 1,3	1,0 ... 1,5
Rotor				
- tooth, narrowest point	1,7 ... 2,2	–	1,5 ... 2,0	2,0 ... 2,5
- tooth, middle point	1,5 ... 1,8	–	1,3 ... 1,7	1,8 ... 2,0
- pole body	–	1,1 ... 1,4	–	–
- yoke	1,0 ... 1,6	1,0 ... 1,4	0,9 ... 1,3	1,0 ... 1,5

Calculation process step by step

8. The electromotive force induced in the winding is calculated

   - for a motor $E \approx 0.96\, U_{\mathrm{N}}$

   - for a generator $E \approx 1.05\, U_{\mathrm{N}}$

   where U_{N} is the rated voltage of the winding.

9. The number of effective turns in a phase winding is calculated

$$N = \frac{\sqrt{2}\, E}{\omega\, \xi\, \underbrace{\alpha_{\mathrm{i}}\, \hat{b}_{\delta}}_{\text{Avg value of flux density over one pole surface}}\, \tau_{\mathrm{p}}\, l_{\mathrm{i}}}$$

peak Airgap flux density

for a sinusoidally distributed air-gap flux density, $\alpha_{\mathrm{i}} = \dfrac{2}{\pi}$

Calculation process step by step

10. The number of effective turns in a slot is defined from the number of effective turns in the phase winding N

$$N_{\mathrm{u}} = \frac{2\,a\,m}{Q}\,N$$

where

a is the number of parallel paths,

(no: of current paths between terminals of machine)

m is the number of phases and

Q the number of slots.

The equation above typically gives a fractional number for the number of turns in a slot N_{u}. In a real winding, this has to be an integer. The nearest integer is chosen, and a new value is calculated for the number of effective turns in the winding N.

Calculation process step by step

11. The peak value of the air-gap flux density must also be recalculated because of the choice of the number of turns

$$\hat{b}_\delta = \frac{\sqrt{2}\,E}{\omega \xi \alpha_\mathrm{i}\, N\, \tau_\mathrm{p}\, l_\mathrm{i}}$$

α_i is the ratio of the average and peak values of flux density. It depends on the saturation level of the iron core.

12. The peak values for the flux densities in the teeth have to be chosen based on the flux-density table shown earlier.

13. The widths of the stator and rotor teeth are calculated from the chosen flux-density values

$$b_\mathrm{z,s} = \frac{\hat{b}_\delta}{\hat{b}_\mathrm{z,s}} \tau_\mathrm{u,s}, \quad b_\mathrm{z,r} = \frac{\hat{b}_\delta}{\hat{b}_\mathrm{z,r}} \tau_\mathrm{u,r}$$

where $\tau_\mathrm{u,s}$ and $\tau_\mathrm{u,r}$ are the stator and rotor slot pitches.

Calculation process step by step

14. The rms values of current densities in the stator and rotor winding (J_s and J_r) are chosen based on the table below

	Induction machine	Salient pole synchronous machine	Non-salient synchronous machine	DC machine
Current density	**[A/mm2]**	**[A/mm2]**	**[A/mm2]**	**[A/mm2]**
Stator				
- slot winding	4 ... 7	3 ... 6	3 ... 6	–
- pole winding	–	2 ... 3	–	1,2 ... 3,5
- commutating winding	–	–	–	2,5 ... 4,0
- compensation winding	–	–	–	2,5 ... 4,0
Rotor				
- slot winding	5 ... 8	–	4 ... 7	4 ... 7
- cage winding	7 ... 10	–	–	–
- pole winding	–	3 ... 4	–	–

Calculation process step by step

15. The stator and rotor currents (I_s and I_r) are defined. For an induction motor

$$\begin{cases} I_s = \dfrac{P_N}{m\, U_s\, \eta \cos(\varphi)} \\ I_r = \mu\, I_s \cos(\varphi) \end{cases}$$

where η is the efficiency,
$\cos(\varphi)$ is the displacement factor and
μ is the transformation ratio between the stator and rotor windings.

For an induction motor with a rotor cage $\mu = \dfrac{N_u\, Q_s}{a\, Q_r}$

Calculation process step by step

For a synchronous machine

$$\begin{cases} I_\mathrm{s} = \dfrac{P_\mathrm{N}}{m\,U_\mathrm{s}\,\eta\cos(\varphi)} & \text{, motor} \\ I_\mathrm{s} = \dfrac{S_\mathrm{N}}{m\,U_\mathrm{s}} & \text{, generator} \end{cases}$$

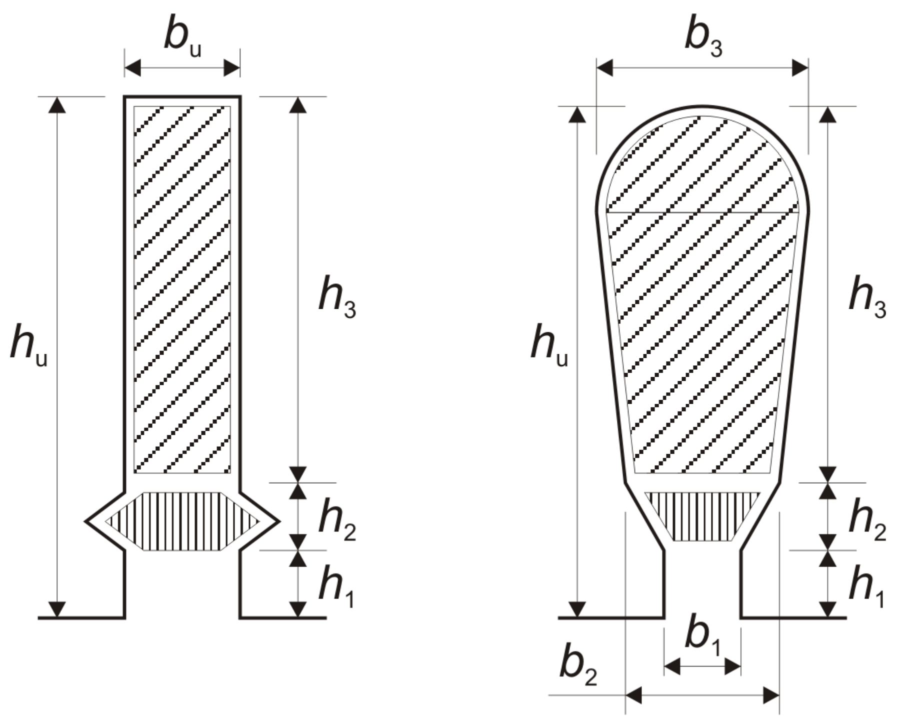
16. The cross-sectional areas of the conductors A_cu and conductor areas in the slot A_u are defined

$$A_\mathrm{cu} = \frac{I}{n\,a\,J} \qquad A_\mathrm{u} = \frac{n\,N_\mathrm{u}\,A_\mathrm{cu}}{\eta_\mathrm{cu}}$$

where n is the number of parallel sub-conductors, a is the number of parallel paths and η_cu is the filling factor of the slot.

Calculation process step by step

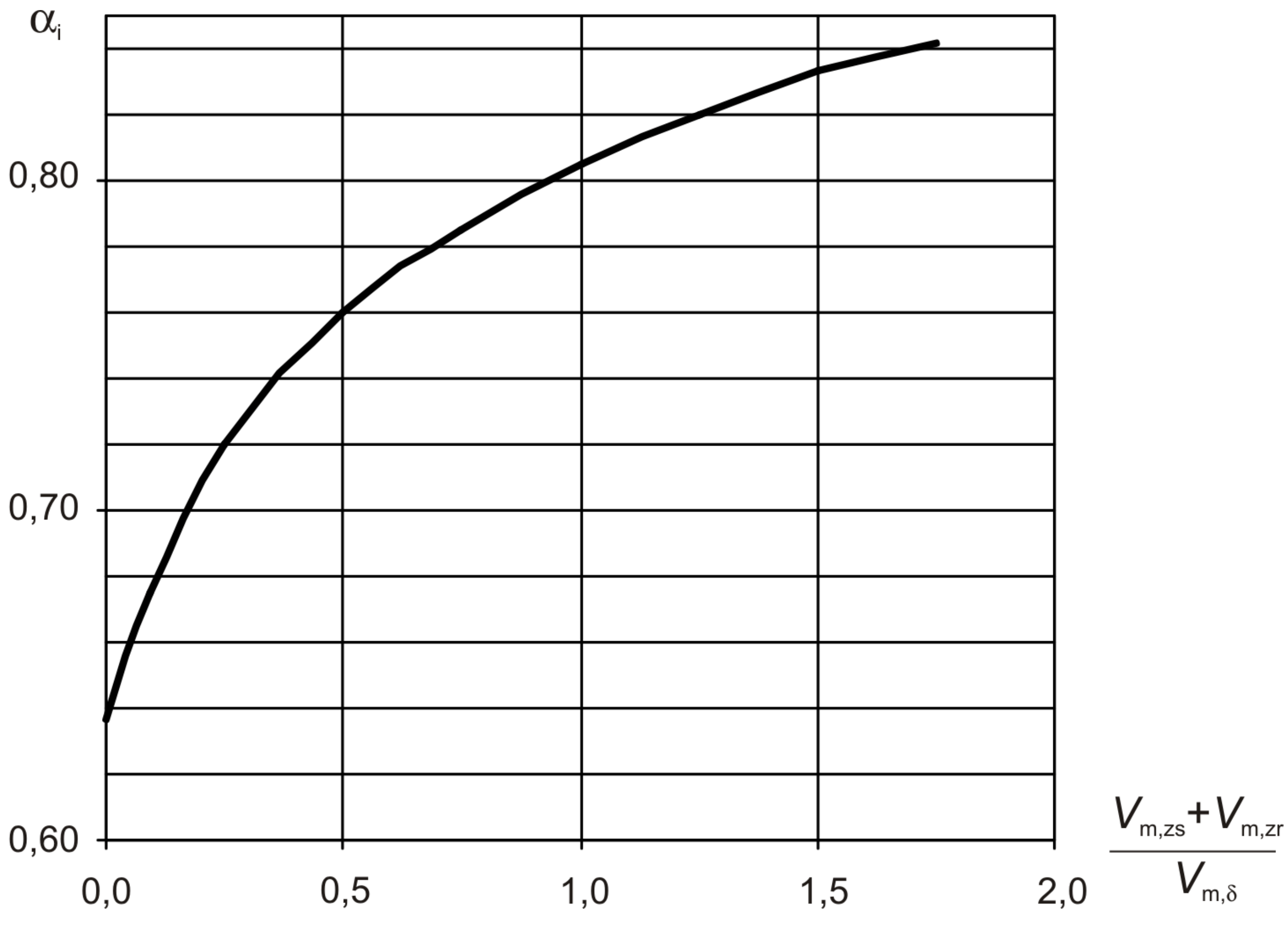
17. The dimensions of the slots are defined.



18. The magnetomotive forces $V_{m,\delta}$, $V_{mz,s}$ and $V_{mz,r}$ needed to drive the main flux are defined.

Calculation process step by step

19. The saturation level of the motor $\dfrac{V_{\mathrm{m,zs}} + V_{\mathrm{m,zr}}}{V_{\mathrm{m},\delta}}$ is calculated and the corresponding flux-density ratio α_{i} is defined.



Calculation process step by step

20. The peak values of flux densities in the stator and rotor yokes are chosen based on the flux-density table presented earlier.

21. The thicknesses of the stator and rotor yokes are calculated from the flux densities chosen.

22. The outer diameter of the stator $D_{1,\mathrm{s}}$ and the inner diameter of the rotor $D_{2,\mathrm{r}}$ are defined.

23. The magnetomotive forces $V_{\mathrm{mj,s}}$ and $V_{\mathrm{mj,r}}$ needed for the stator and rotor yokes are defined.

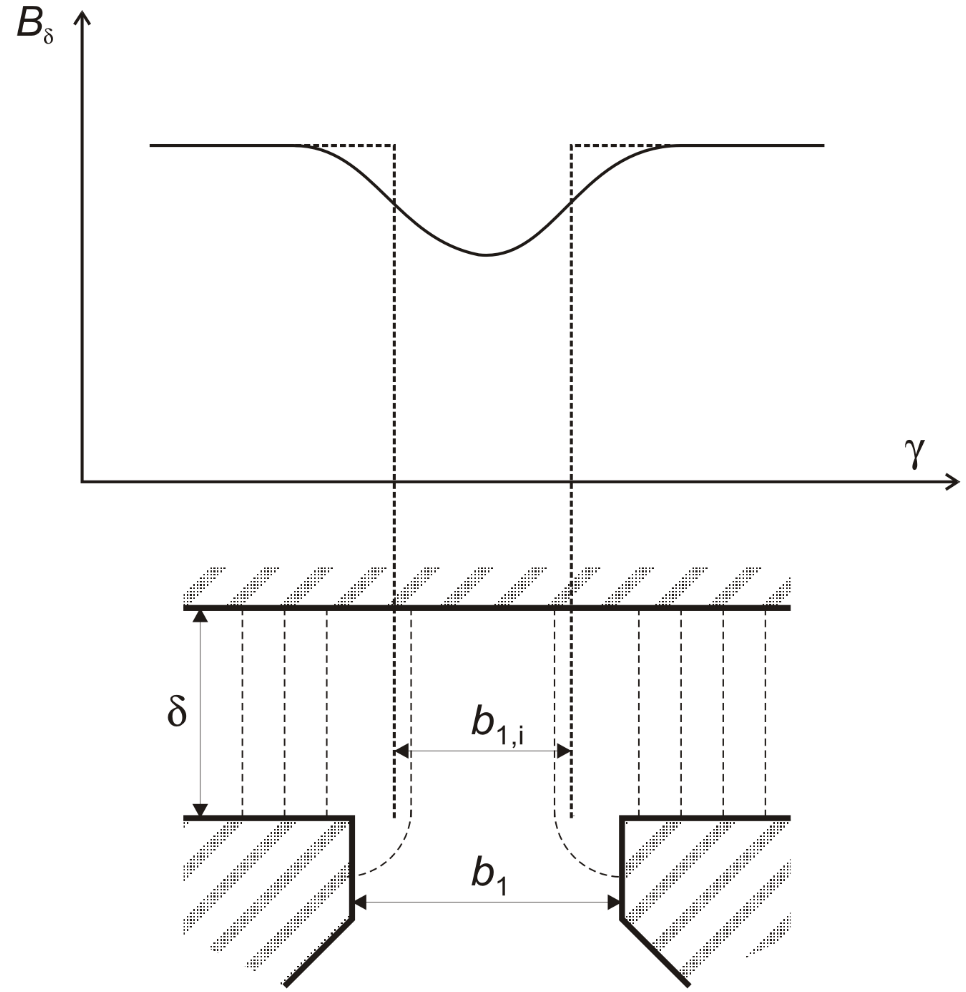
The main dimensions of the machine have now been calculated. The flux and current densities were calculated for the rated operation point of the machine. If other voltages or significantly different loadings are used, these values should be recalculated for the other voltages and loads.

Permeance and effective lengths of air gap

The permeance of air gap is

$$\Lambda_\delta = \mu_0 \frac{\pi D_i l_i}{2p\,\delta_i} = \mu_0 \frac{\tau_p l_i}{\delta_i}$$

where δ_i is the effective air gap. This simple equation is related to a constant air-gap length. However, in a real machine there are slots at one or both sides of the air gap. The effect of slotting is approximately modelled by an effective radial air-gap length



$$\delta_i = \frac{\tau_u}{\tau_u - b_{1,i}}\delta = k_C\,\delta$$

where τ_u is slot pitch, $b_{1,i}$ is the effective width of the slot (Figure above) and k_C is Carter’s factor.

Effective radial length of air gap

The effective slot opening has been estimated to be

$$b_{1,\mathrm{i}} = \frac{2}{\pi} b_1 \left\{ \arctan\left(\frac{b_1}{2\delta}\right) - \frac{2\delta}{b_1} \ln\left[\sqrt{1+\left(\frac{b_1}{2\delta}\right)^2}\right]\right\} \approx \frac{b_1}{1+5\,\dfrac{\delta}{b_1}}$$

If there is a slotting on both sides of the air gap, Carter's factor can be calculated separately for the stator and rotor surfaces and applied twice

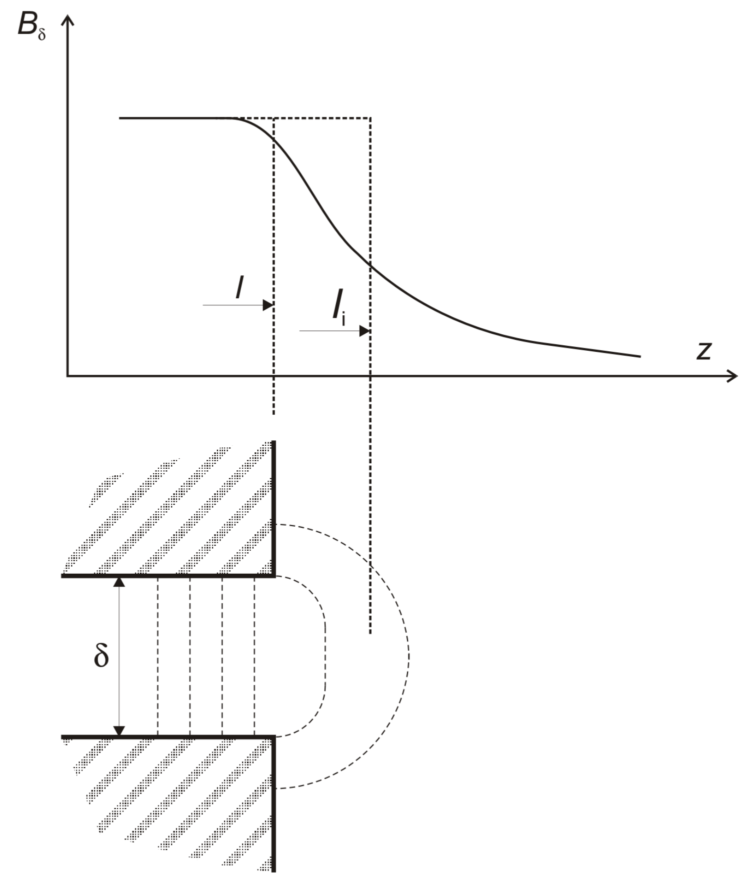
$$\delta_\mathrm{i} = \mathrm{k}_\mathrm{Cr} \mathrm{k}_\mathrm{Cs}\, \delta$$

to get the effective radial air-gap length including the contributions from both the slottings.

Effective axial length of air gap

There is a fringing flux between the stator and rotor at both ends of the machine. This flux belongs to the main flux of the machine and should be included in the air-gap permeance. The fringing flux slightly increases the effective length of the machine

$$\begin{cases} l_i \approx l_s + 2\delta, \text{ if } l_s = l_r \\ l_i \approx \dfrac{l_s + l_r}{2}, \text{ if } l_s \neq l_r \end{cases}$$



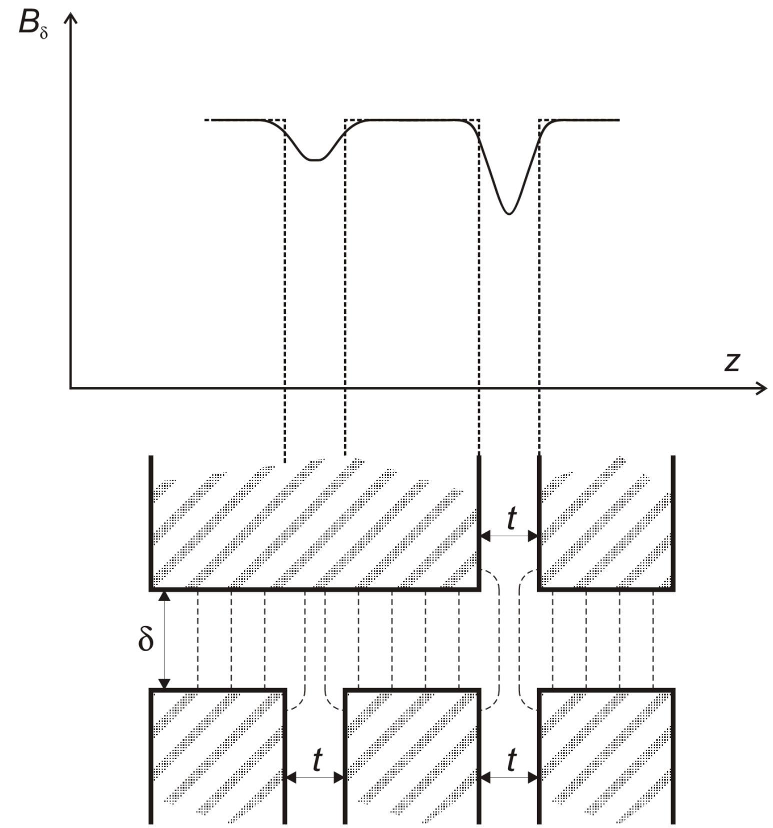
Effective axial length and cooling channels

There are radial cooling channels or ducts in larger electrical machines. There is also fringing related to these channels. The effective axial length should be modified accordingly

$$l_i = l - n\, t_i + 2\delta$$

where l is the total length of the iron core including the channels, n is the number of cooling channels and t_i is the effective width of one channel in axial direction

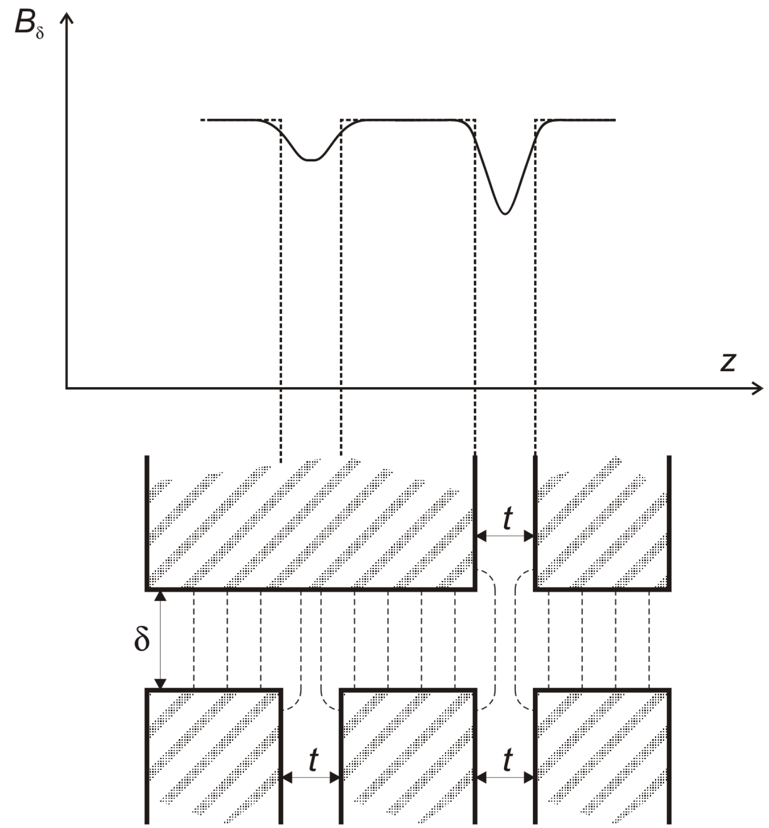
$$t_i = \frac{t}{1 + 5\dfrac{\delta}{t}}$$



Effective axial length and cooling channels

Often, there are radial channels both in the stator and rotor. In this case,

$$l_i = l - (n_s - n_{sr})\, t_{i,s} - (n_r - n_{sr})\, t_{i,r} - n_{sr}\, t_{i,sr} + 2\delta$$



where n_{sr} is the number of channels situated at the same axial positions over the air gap and $t_{i,sr}$ is the effective axial width of a pair of opposite channels

$$t_{i,sr} = \frac{t_r}{1 + 5\dfrac{\delta_{i,s}}{t_r}}$$