FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Theory of Electric Machines 2

KEV/TS2

Karel Hruska / r20201025

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Permanent Magnet Synchronous Machines

Permanent Magnet Synchronous Machines

- For the purpose of excitation of the magnetic field they use permanent magnets
- Often used as alectric machines of very low powers (clock motors, optical drives etc.)
- The usage of permanent magnets allows decrease of dimensions while keeping output power
- By using permanent magnets it is also possible to reduce machine losses
- Permanent magnets are often used in combination with so-called tooth winding

Permanent Magnet Synchronous Machines

- Permanent magnet motors categories:
  - Direct current machines with external (permanent magnet) excitation
  - BLDC
    - brushless “direct current” machines
  - PMSM
    - permanent magnet synchronous machines

Permanent Magnet Synchronous Machines

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Permanent Magnet Synchronous Machines

- In contrast to other types of machines an inverse construction is very common for permanent magnet machines – the rotor with permanent magnets rotates around the stator with the winding
- For driving the BLDC and PMSM motors a converter with feedback is necessary
  - Position sensor (PMSM)
  - Hall sensors (BLDC)
- Sensorless control of permanent magnet machines is a subject of intensive development :-)

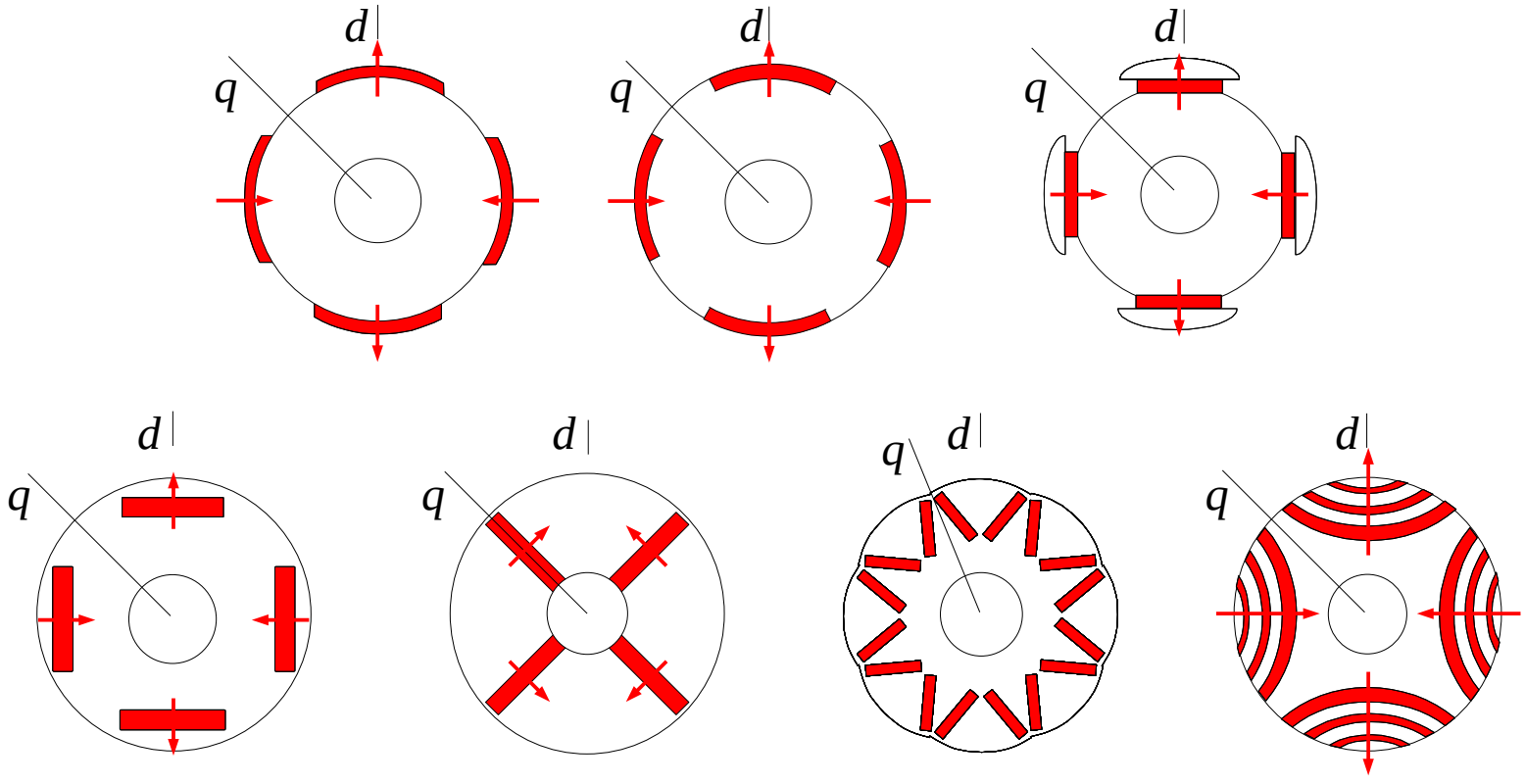
Permanent Magnet Synchronous Machines

- Permanent magnet synchronous machines are available in a large variety of variations
  - sPMSM
    - Surface-mounted permanent magnet synchronous machines
    - None or only minimal reluctance torque
  - iPMSM
    - Interior permanent magnet synchronous machines
    - Significant reluctance torque, however the mot important is the electromagnetic component of the torque

Permanent Magnet Synchronous Machines

- Permanent magnet synchronous machines are available in a large variety of variations
  - PMaSynRM
    - Permanent magnet assisted synchronous reluctance machine
    - Significant reluctance torque, which forms the main component of the torque
    - Permanent magnets improve the power factor and efficiency of the machine

Permanent Magnet Synchronous Machines



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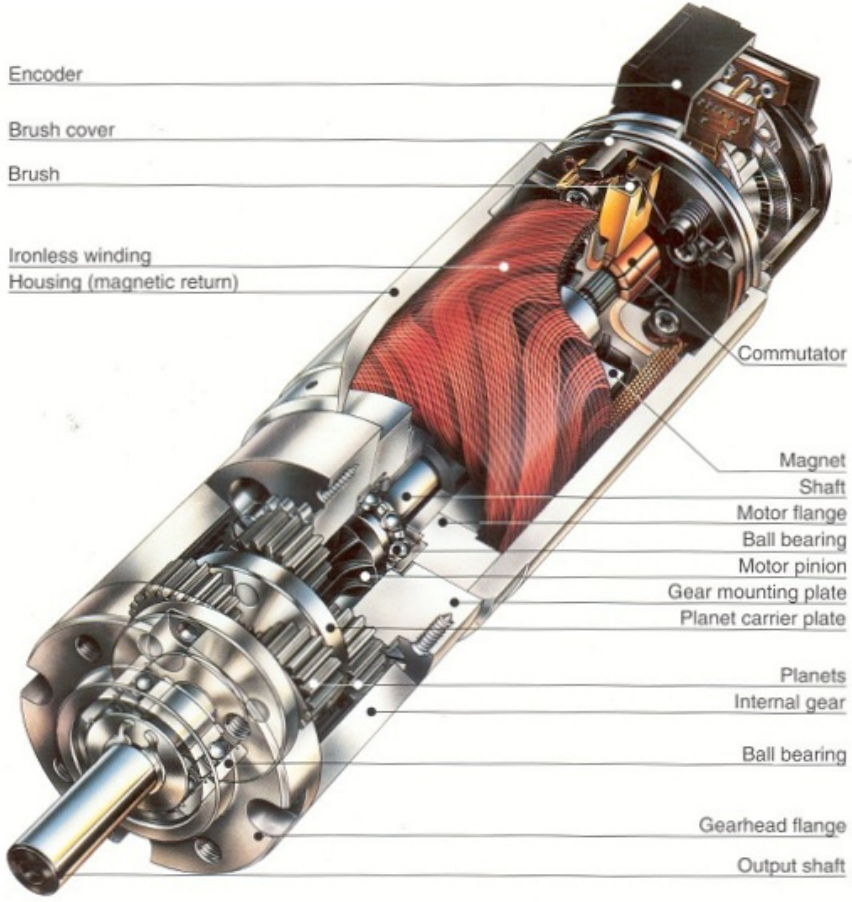
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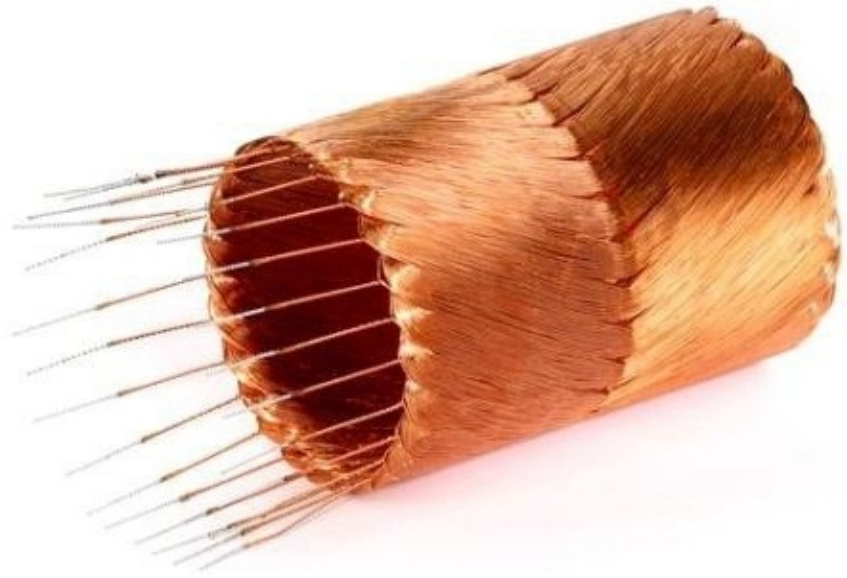
Mechanical Design of Permanent Magnet Synchronous Machines

Mechanical Design of Permanent Magnet Synchronous Machines



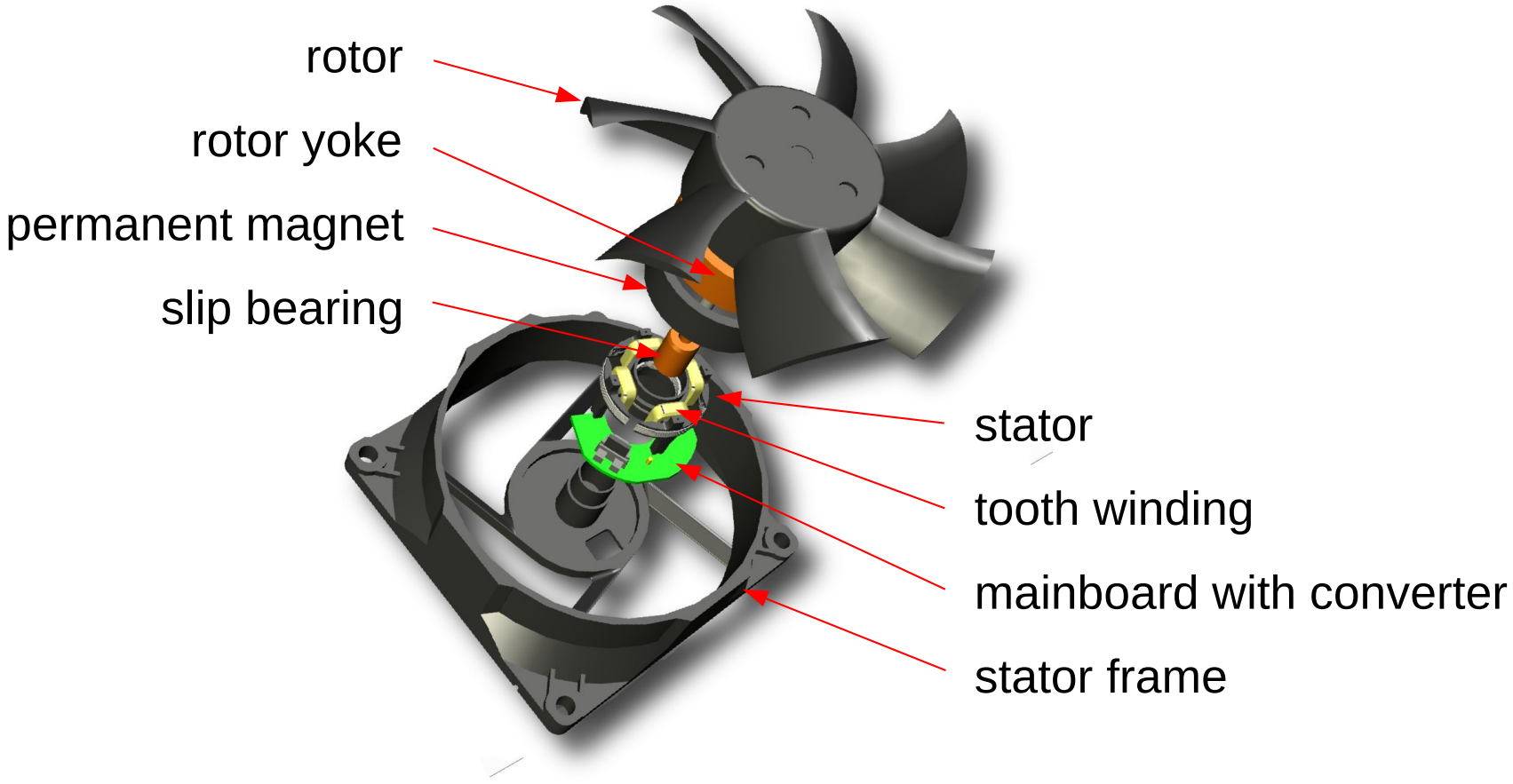
Maxon high-speed PMSM

Mechanical Design of Permanent Magnet Synchronous Machines

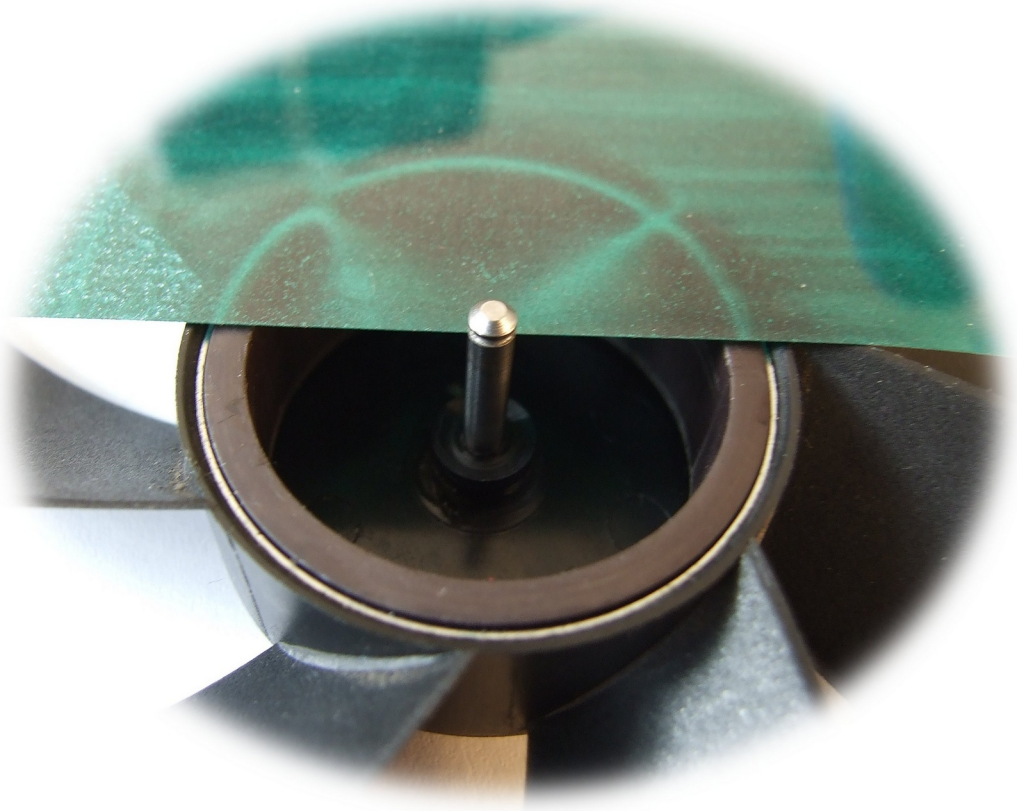


Maxon slotless winding

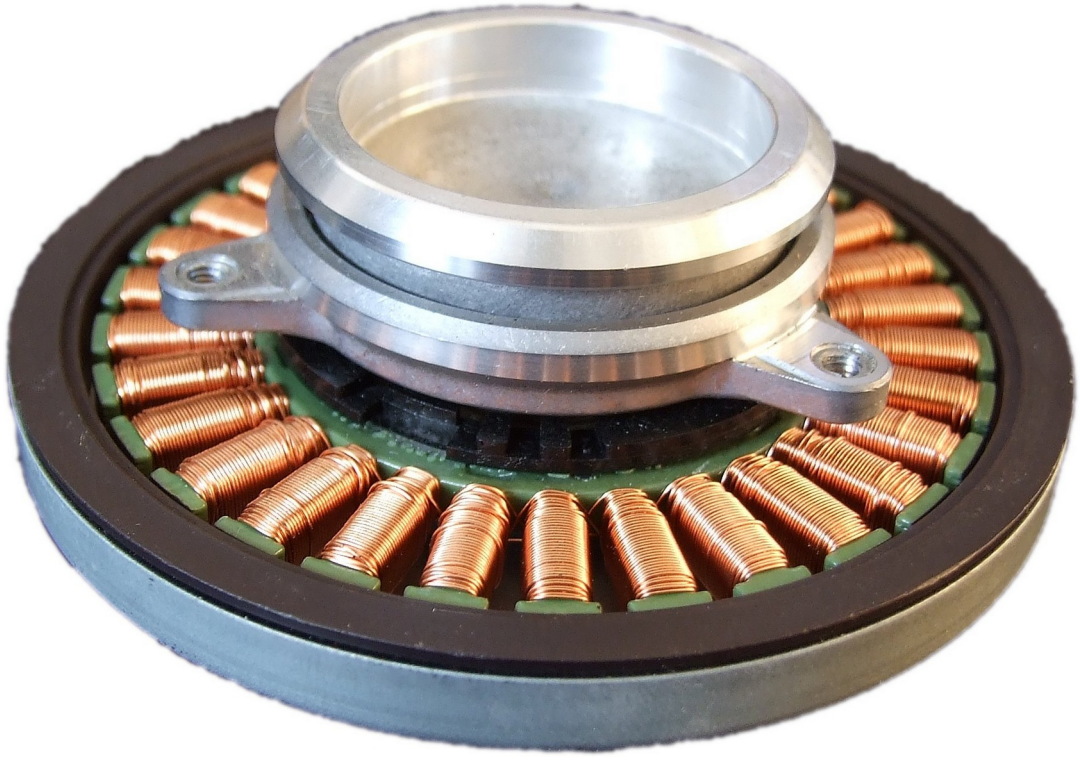
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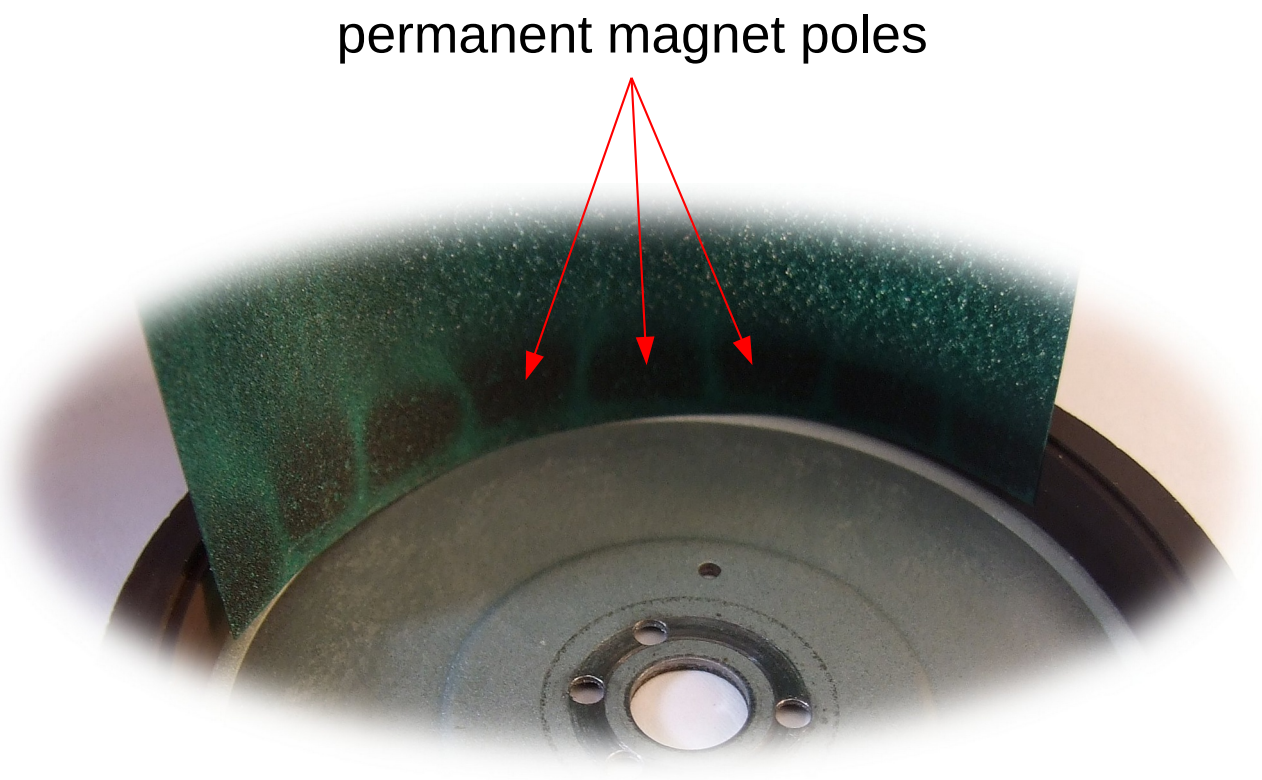
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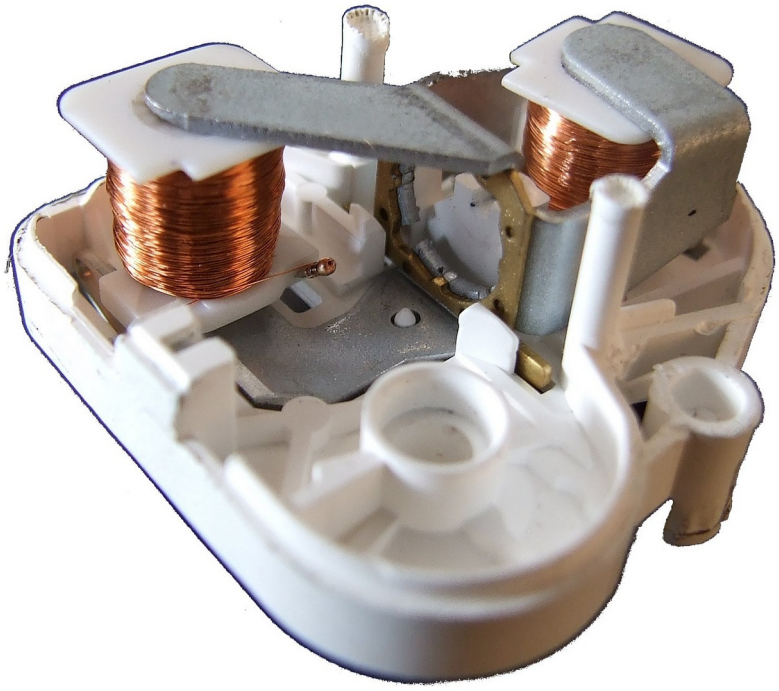
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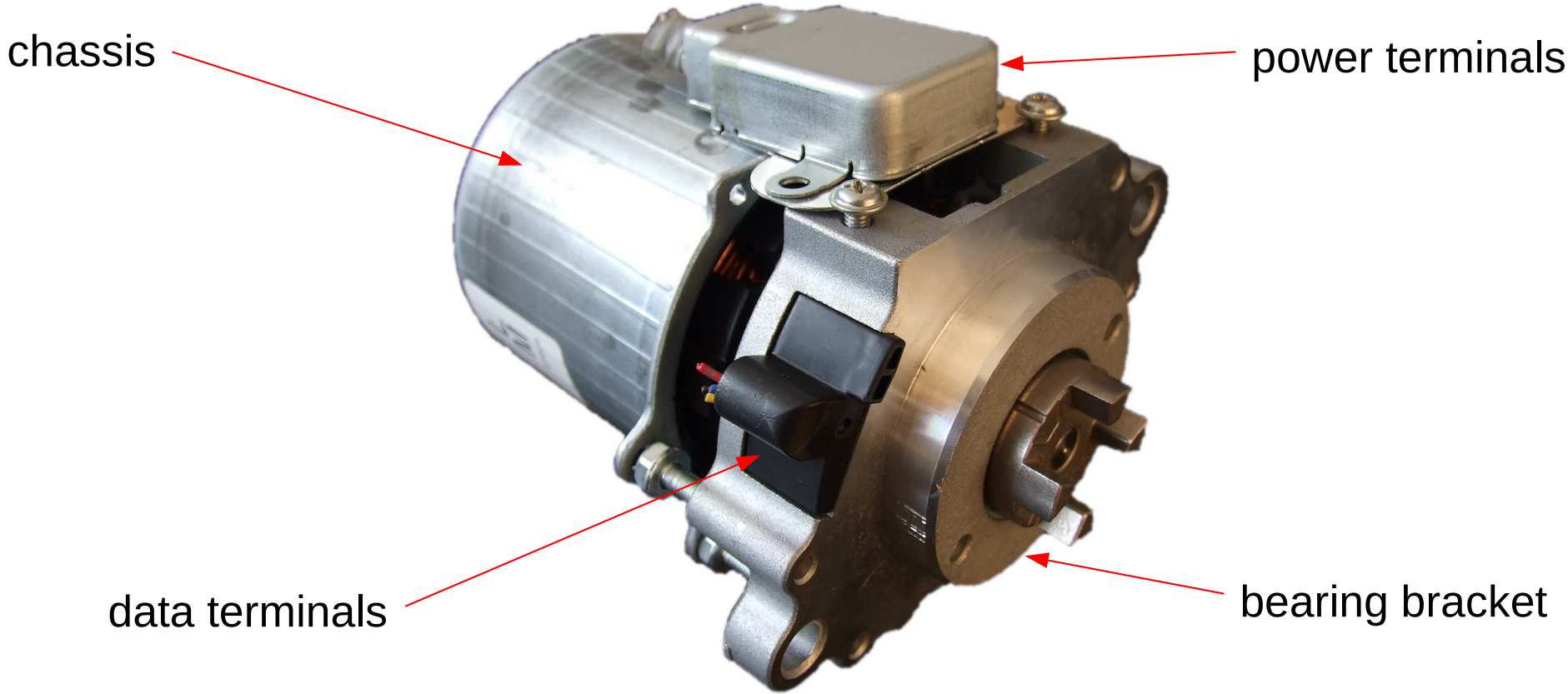


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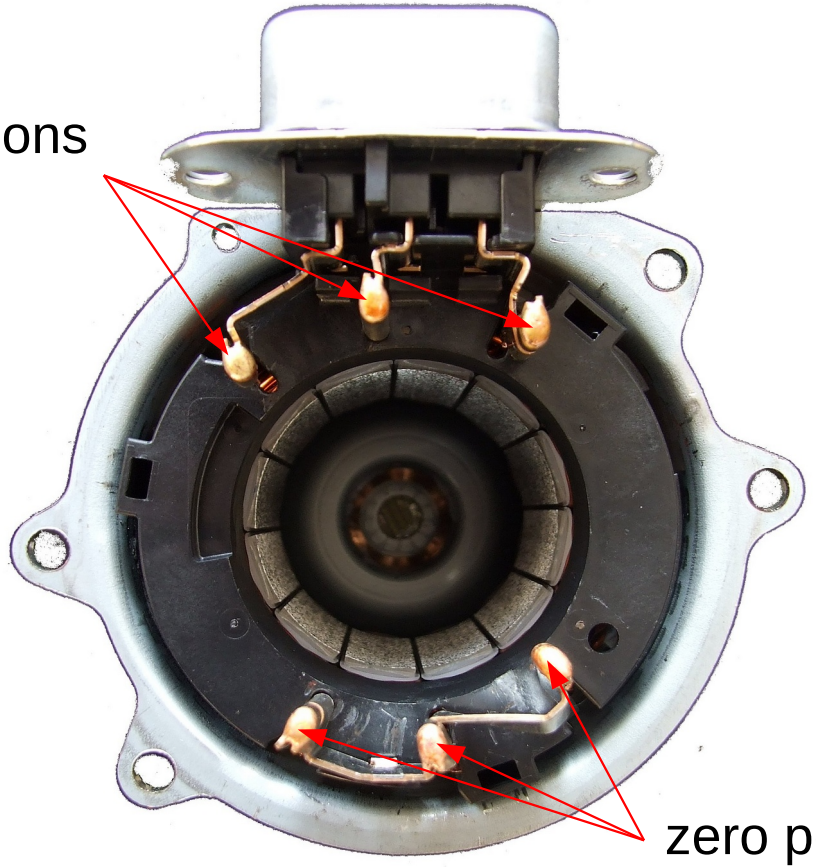


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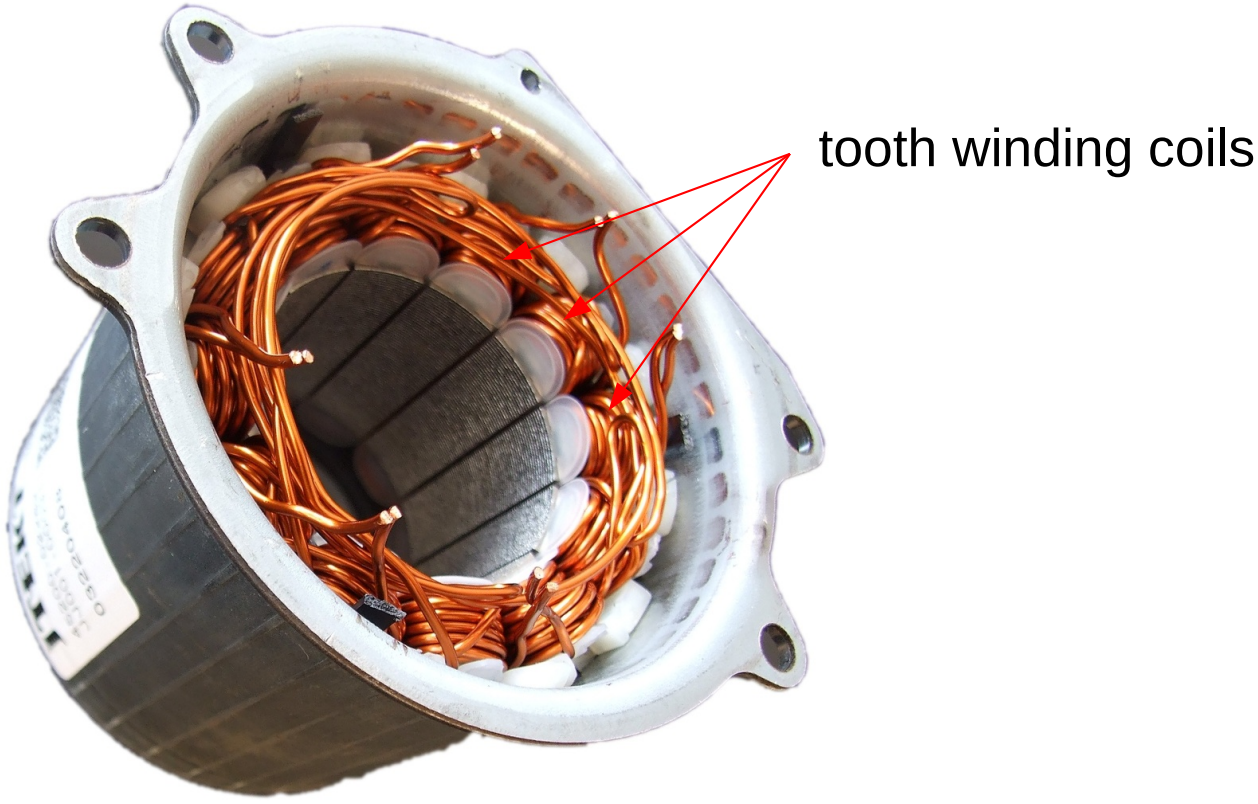
Mechanical Design of Permanent Magnet Synchronous Machines

winding connections

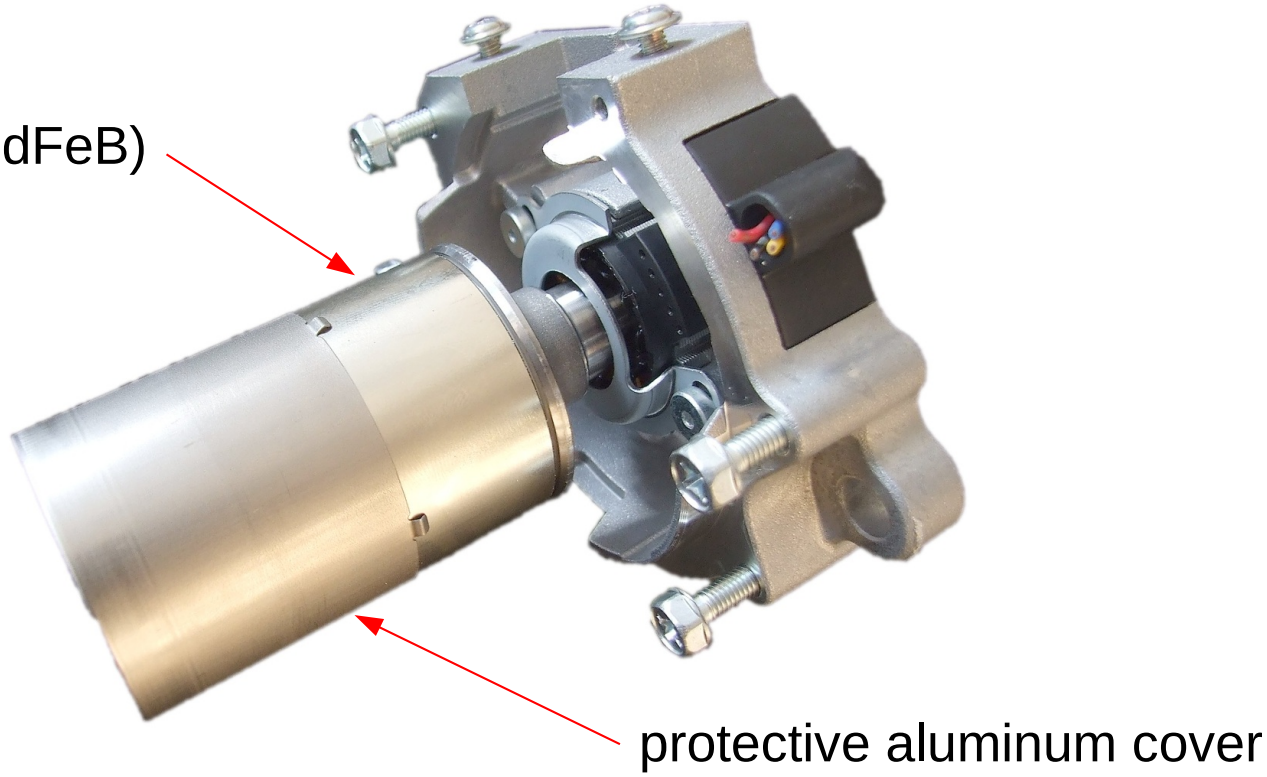


zero point

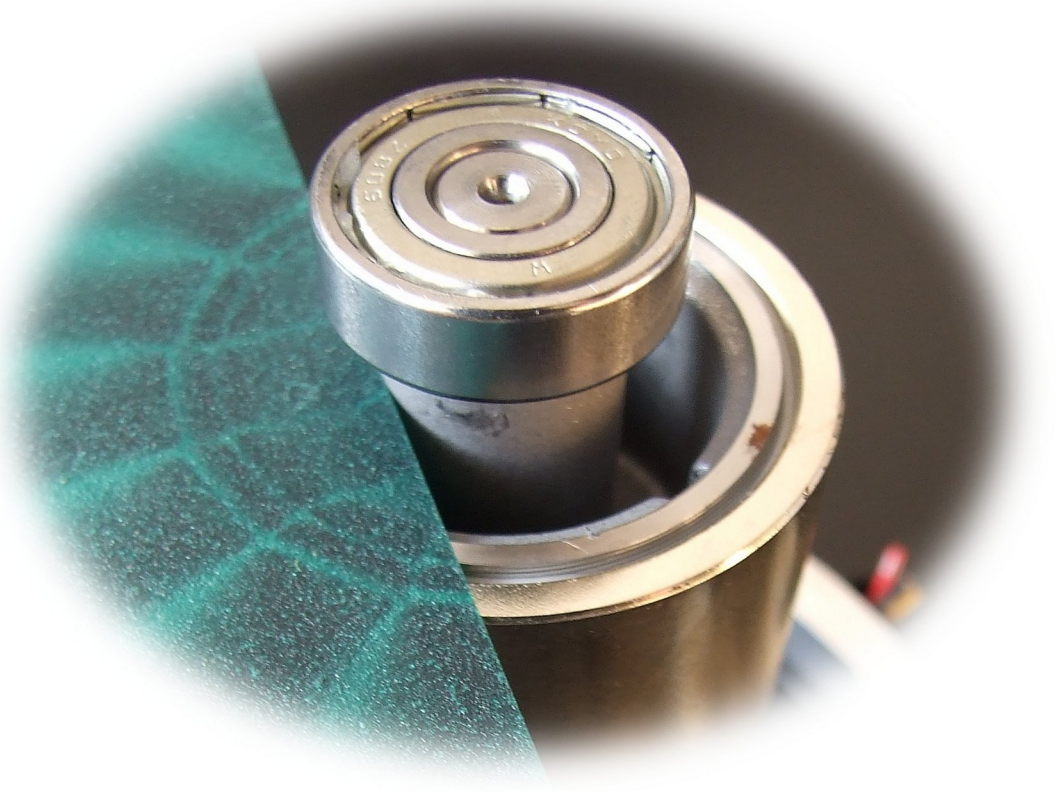
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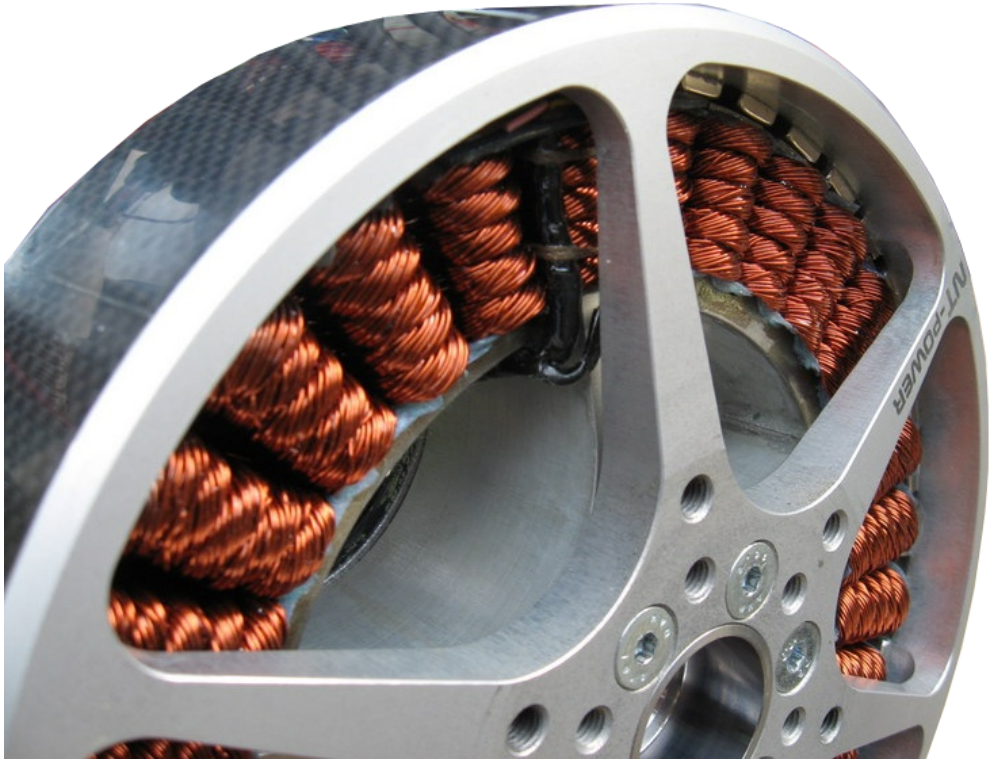
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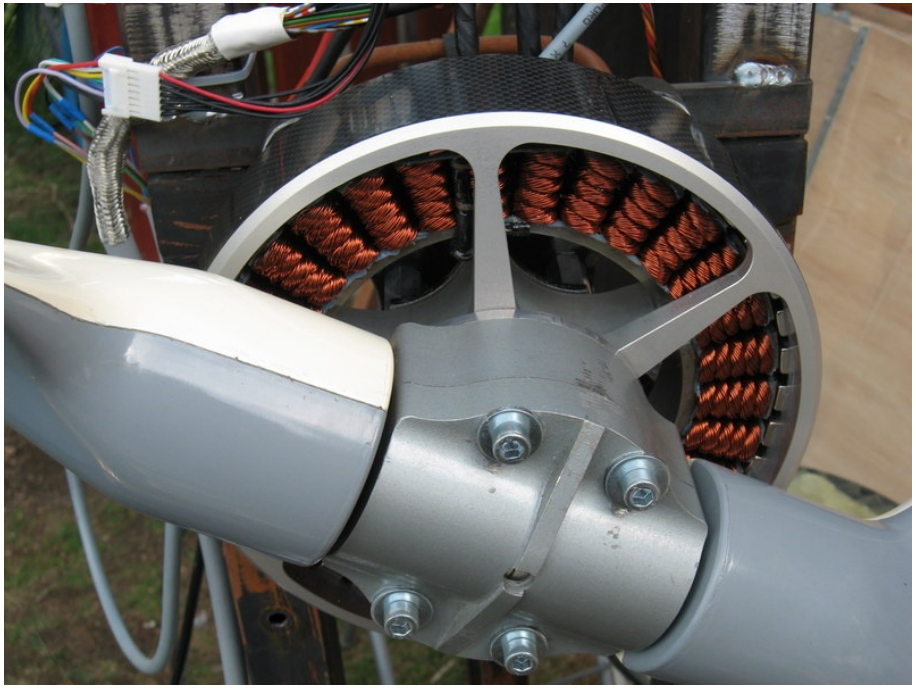


Mechanical Design of Permanent Magnet Synchronous Machines



Mechanical Design of Permanent Magnet Synchronous Machines





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Permanent Magnets

Permanent Magnets

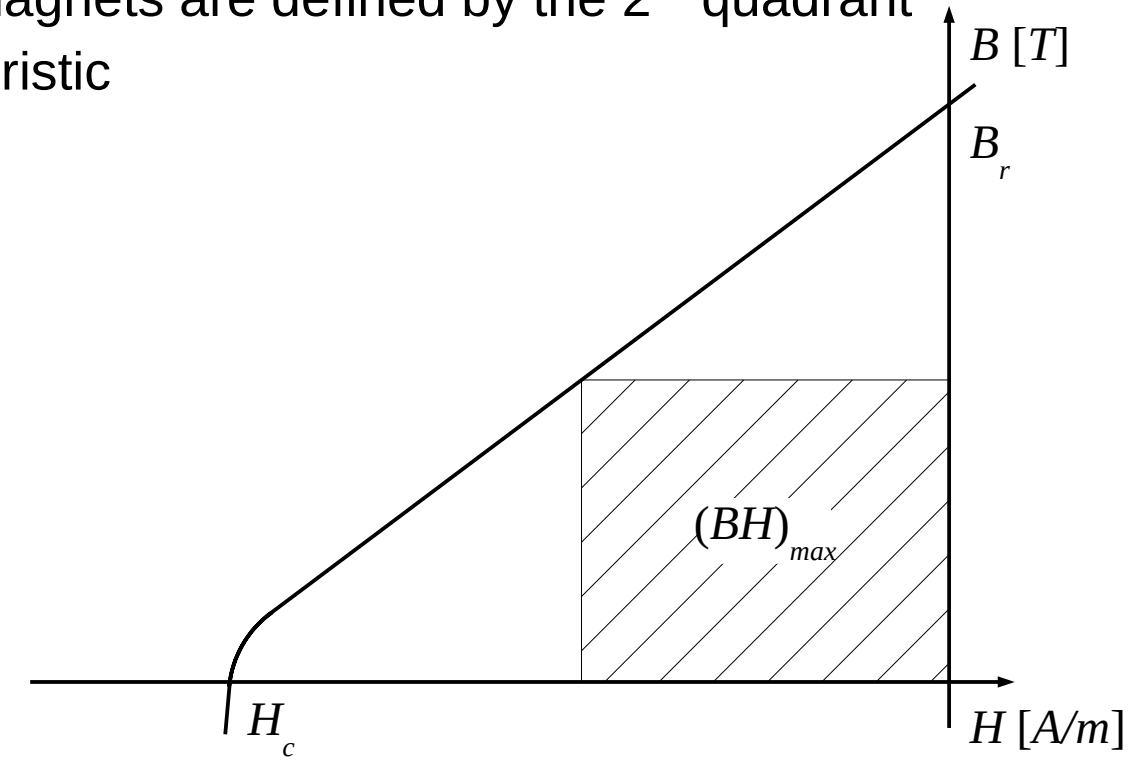
- Magneticallly hard materials
- A large variety of types:
  - Ferrite PM
  - AlNiCo (Alni, Alcomax, Hycomax, Columax, Ticonal)
  - SmCo ($SmCo_5$, Sm_2Co_{17})
  - NdFeB ($Nd_2Fe_{14}B$)
  - But NdFeN also appear...
- In electrical machines, the ferrites (small machines), SmCo and NdFeB (larger machines) are commonly used

Permanent Magnets

- The properties of permanent magnets are defined by the 2nd quadrant of their magnetization characteristic

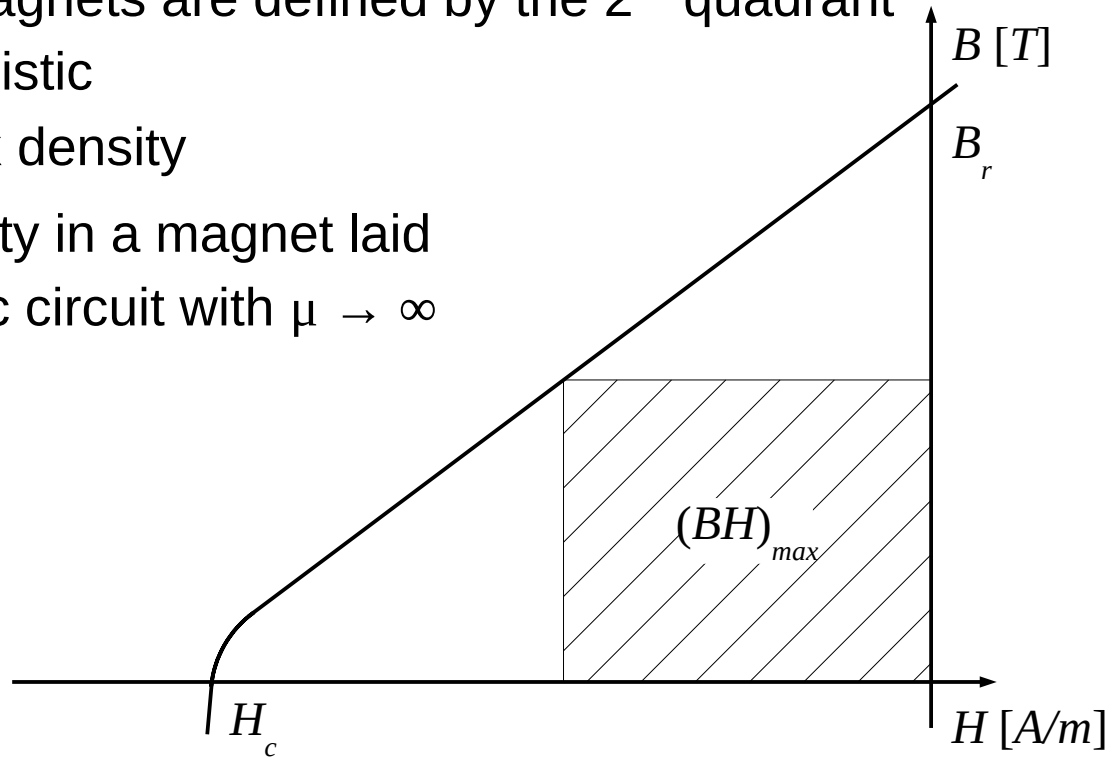
Permanent Magnets

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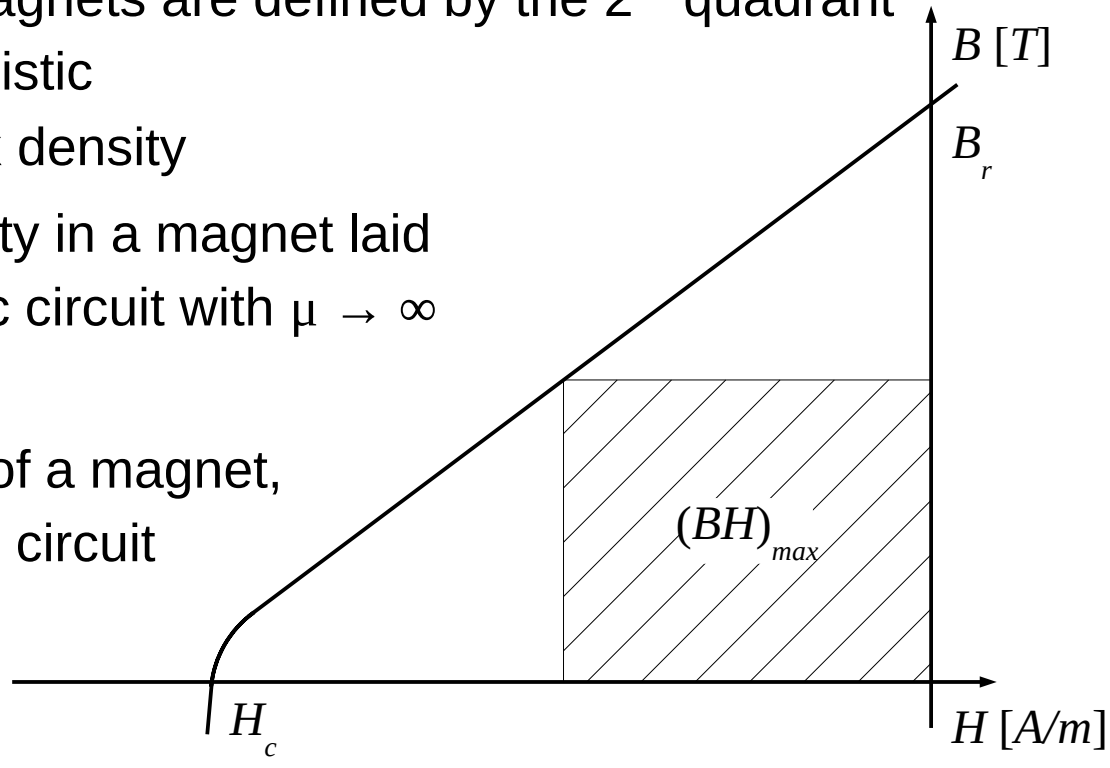
Permanent Magnets

- The properties of permanent magnets are defined by the 2nd quadrant of their magnetization characteristic
  - B_r – remanent magnetic flux density
    - The magnetic flux density in a magnet laid in an enclosed magnetic circuit with $\mu \rightarrow \infty$



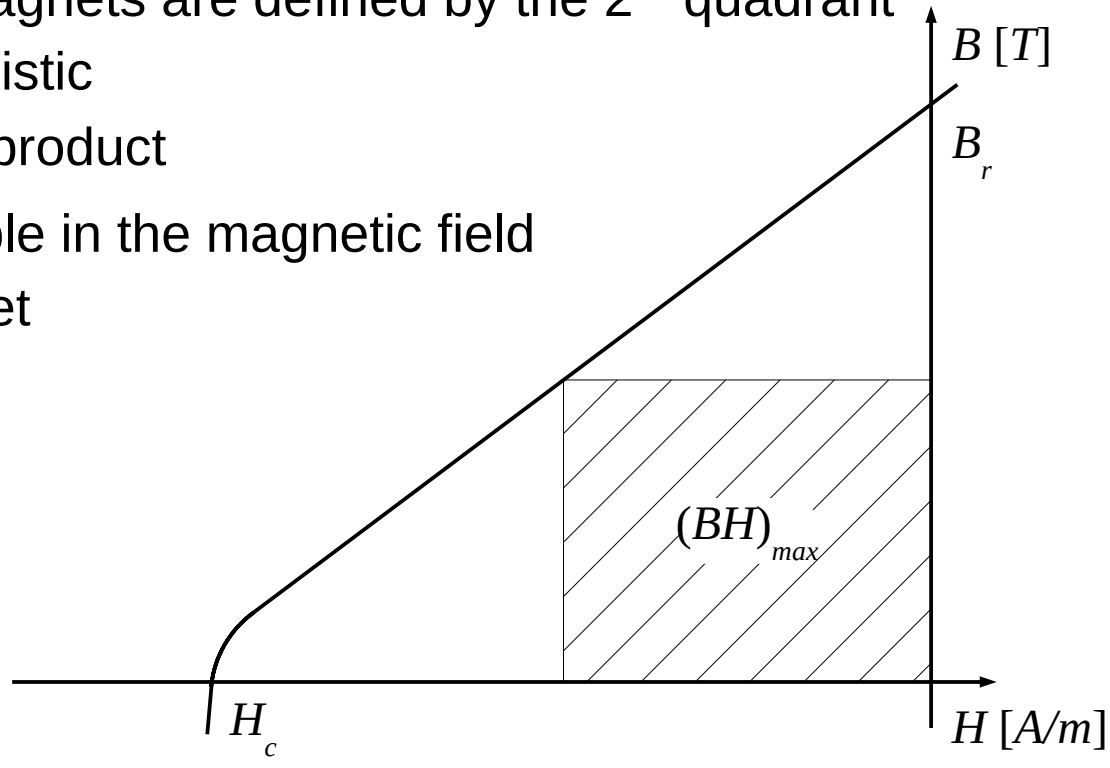
Permanent Magnets

- The properties of permanent magnets are defined by the 2nd quadrant of their magnetization characteristic
  - B_r – remanent magnetic flux density
    - The magnetic flux density in a magnet laid in an enclosed magnetic circuit with $\mu \rightarrow \infty$
  - H_c – coercive force
    - Magnetic field strength of a magnet, which is not in magnetic circuit

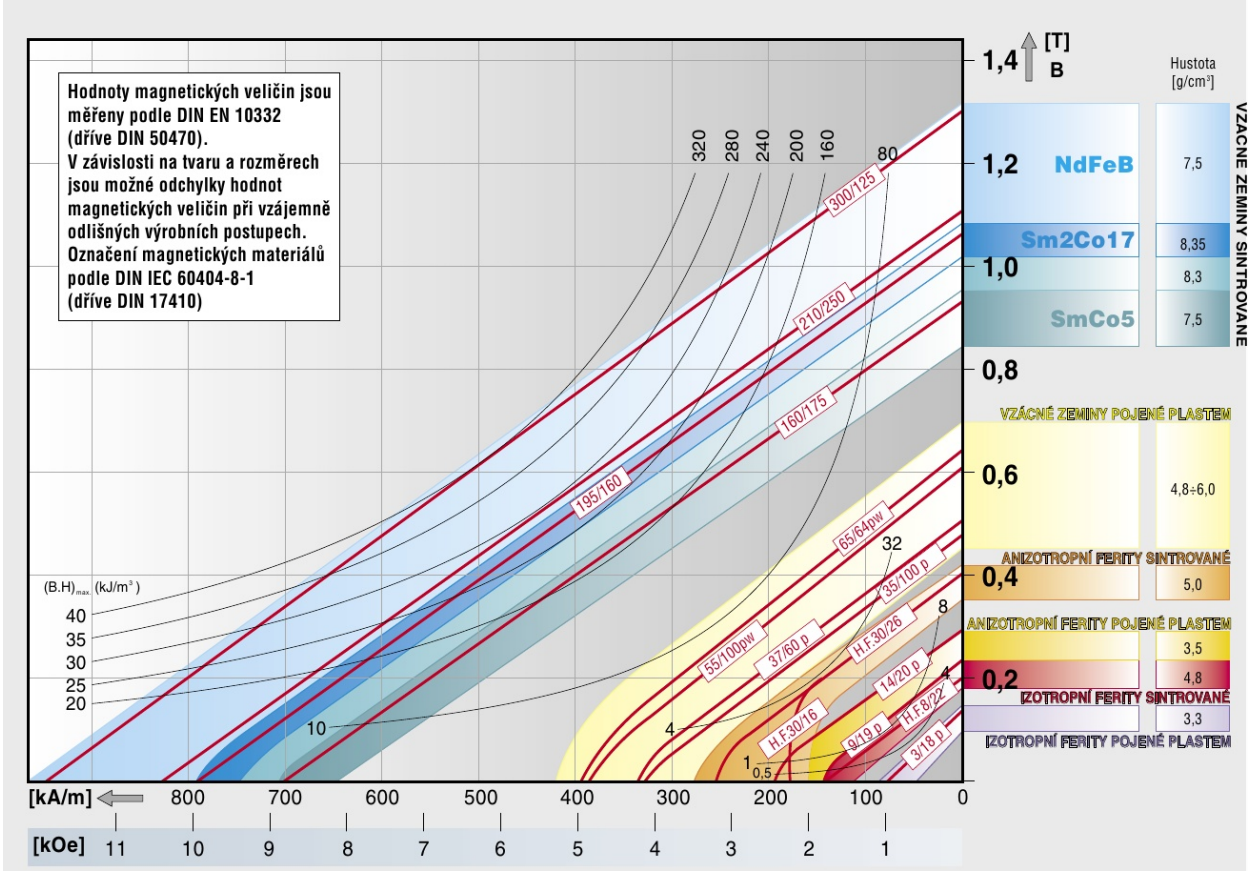


Permanent Magnets

- The properties of permanent magnets are defined by the 2nd quadrant of their magnetization characteristic
  - $(BH)_{\max}$ – maximum energy product
    - The total energy available in the magnetic field of the permanent magnet



Permanent Magnets



Permanent Magnets

- Further important parameters (commonly available in datasheets):
  - Permanent magnet material permeability μ_{PM} $[H/m]$
  - Electrical and thermal conductivity γ $[\Omega/m]$ a λ $[W/m.K]$
  - Thermal coefficients k_{Br} $[\%/K]$ and k_{Hc} $[\%/K]$
  - Thermal class
  - Ambient environment endurance

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Design of Permanent Magnet Excitation

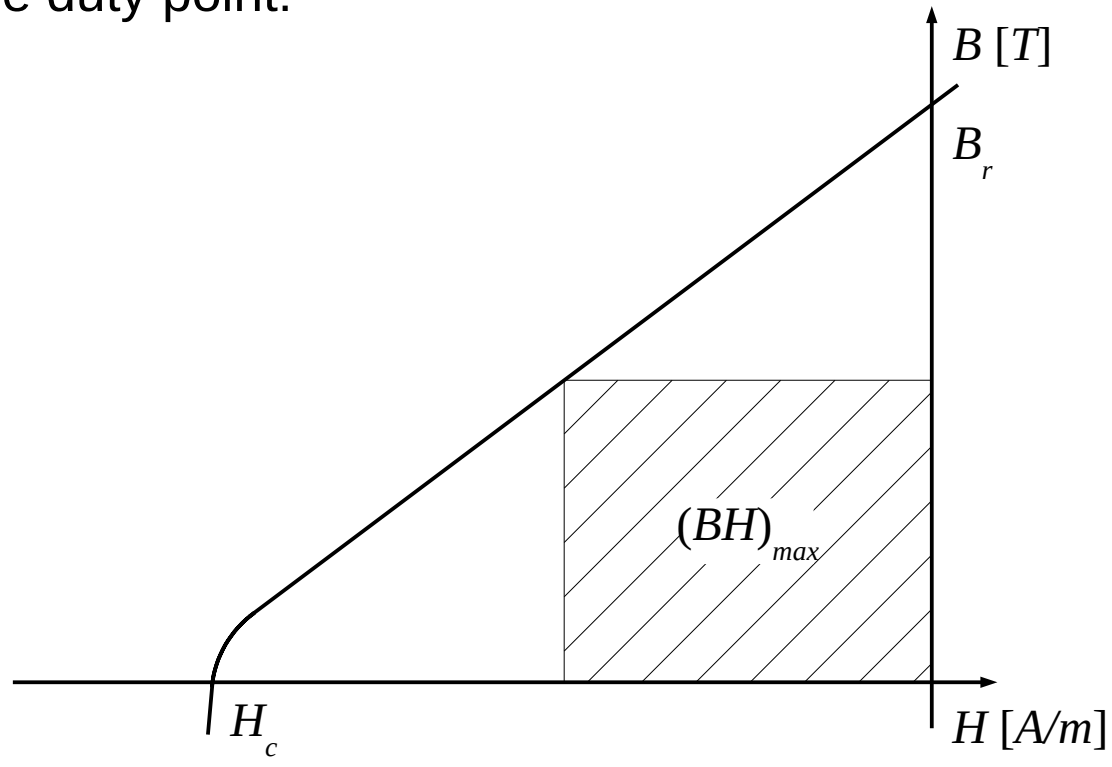
Design of Permanent Magnet Excitation

- Results from the duty point setting and calculation of the magnetic circuit of the machine
- Physically optimal duty point is near to the one half of the demagnetization characteristic

  => the magnet works near to $(BH)_{max}$
- This point cannot be used for electrical machines → a demagnetization of permanent magnets due to armature magnetic field could occur

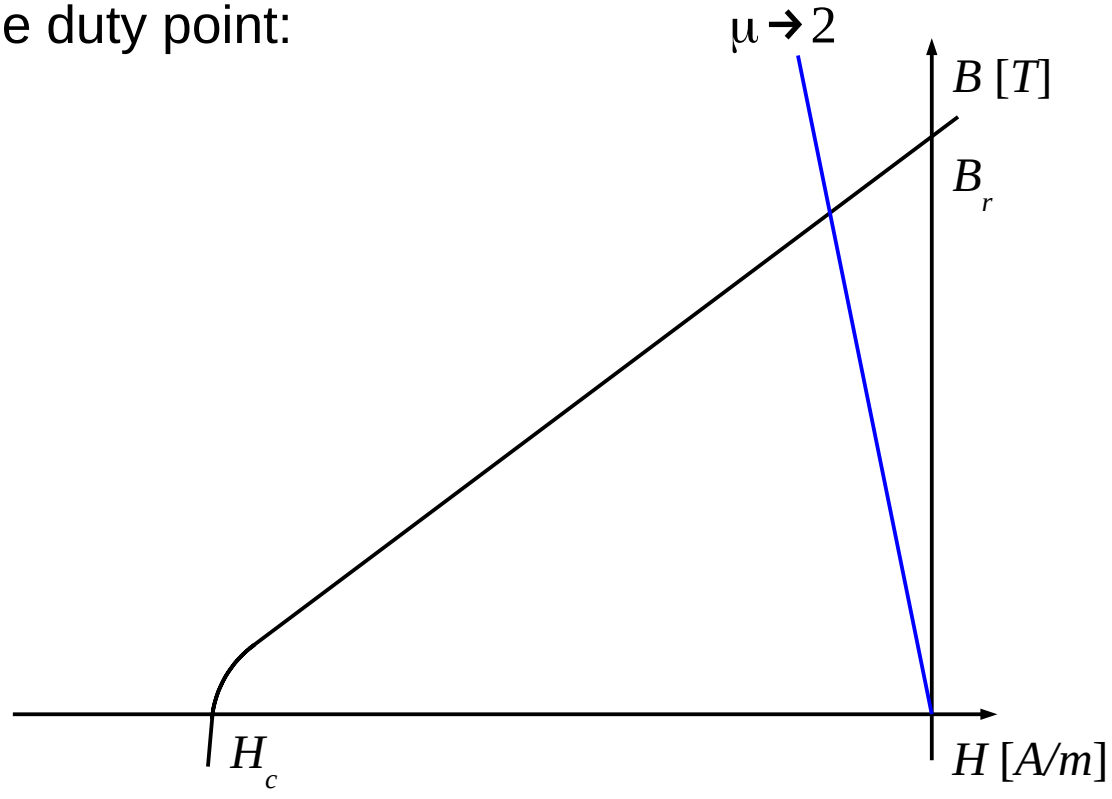
Design of Permanent Magnet Excitation

- Real position of the duty point:



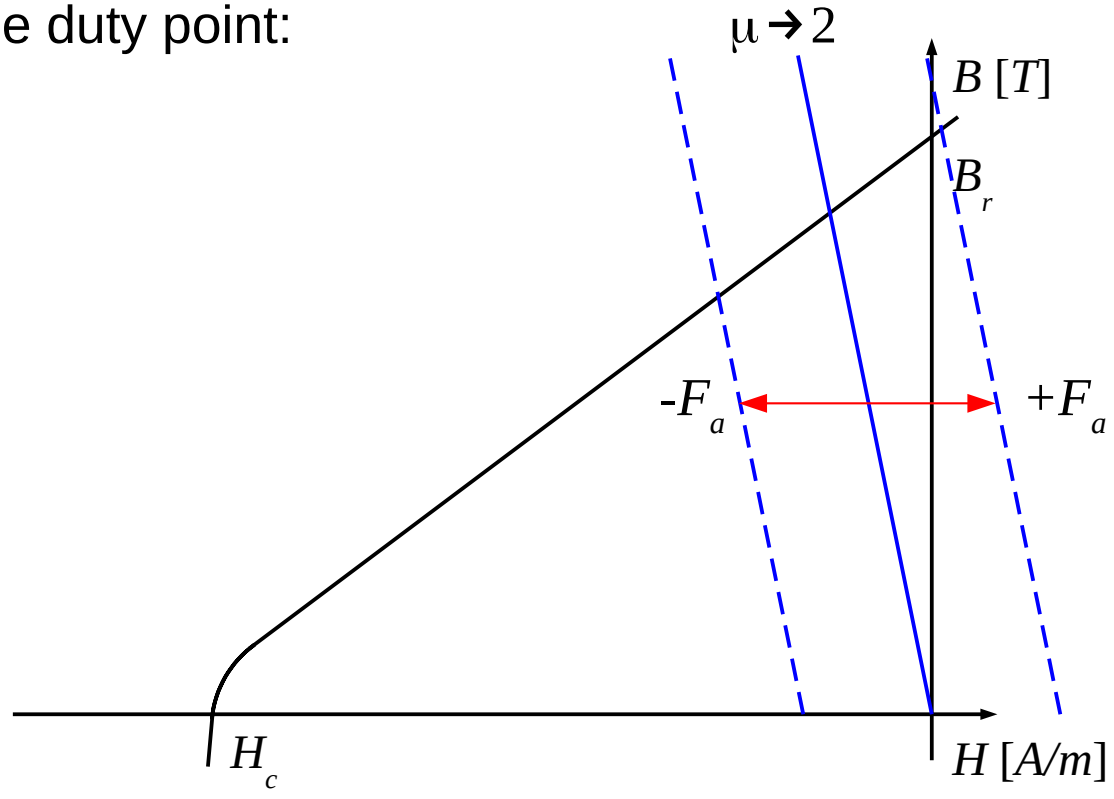
Design of Permanent Magnet Excitation

- Real position of the duty point:



Design of Permanent Magnet Excitation

- Real position of the duty point:



Design of Permanent Magnet Excitation

- Real position of the duty point:
  … i.e. near to 80% of B_r, for the NdFeB permanent magnets the duty point is commonly set to a range of $B_{PM} = (0{,}9 - 1{,}1)\ T$
- The magnetic flux density in the permanent magnet results from known magnetic flux

$$\Phi_{PM} = \int_S B_{PM}\, dS$$

  where the area S results from the width of permanent magnets and their length

$$\Phi_{PM} = \int_{b_{PM}} \int_{l} B_{PM}\, dx\, dy = B_{PM}\, b_{PM}\, l$$

Design of Permanent Magnet Excitation

- The resulting permanent magnet width

$$b_{PM} = \frac{\Phi_{PM}}{B_{PM} l}$$

- Between the poles equipped with permanent magnets a certain leakage of magnetic flux exists – the leakage flux coefficient ν
- The magnetic flux through permanent magnets is then in relation to the air gap magnetic flux given by

$$\Phi_{PM} = (1 + \nu)\,\Phi_{\delta}$$

Design of Permanent Magnet Excitation

- For surface-mounted permanent magnets it is possible to determine the mechanical pole cover factor α_{PM}

$$\alpha_{PM} = \frac{b_{PM}}{t_p}$$

- Commonly the value of α_{PM} is set between 0,6 and 0,8

Design of Permanent Magnet Excitation

- The height of the permanent magnets results from calculation of the magnetic circuit of the machine
- The permanent magnets act as a real source of the magnetomotive force

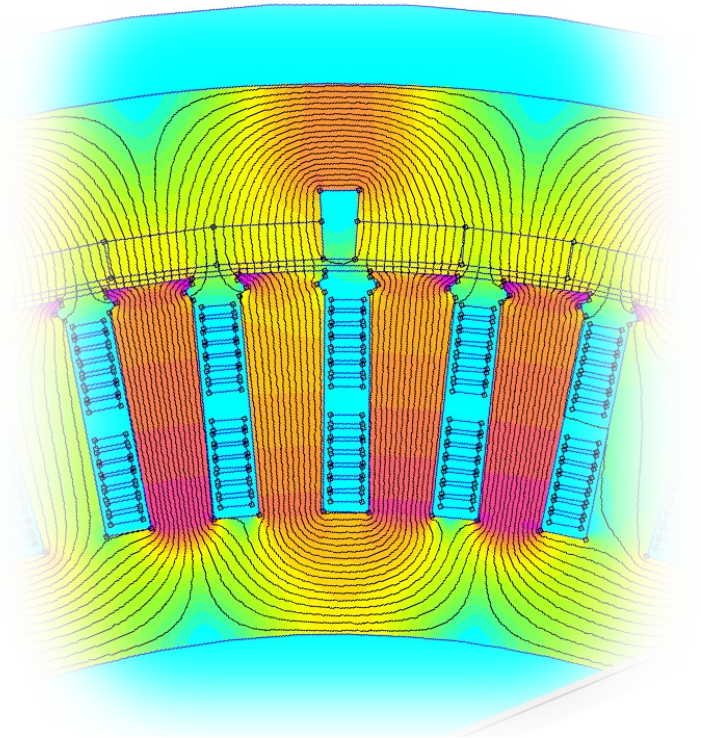
$$F_m = \int_{h_{PM}} H_c \, dz = H_c \, h_{PM}$$

- The inner resistance of this “voltage source” is the dependent on the permanent magnet magnetic field strength and the magnetomotive force drop on the inner resistance is

$$\Delta U_m = \int_{h_{PM}} H_{PM} \, dz = H_{PM} \, h_{PM}$$

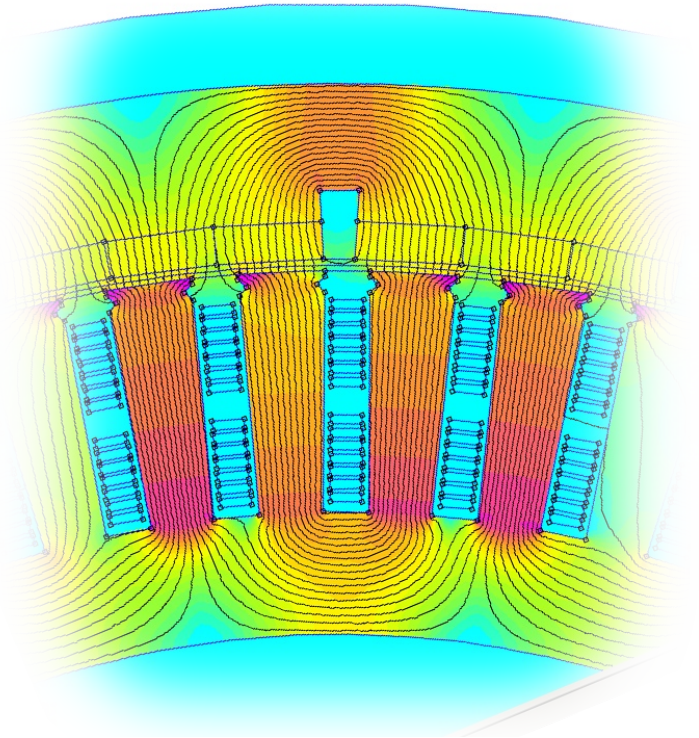
Design of Permanent Magnet Excitation

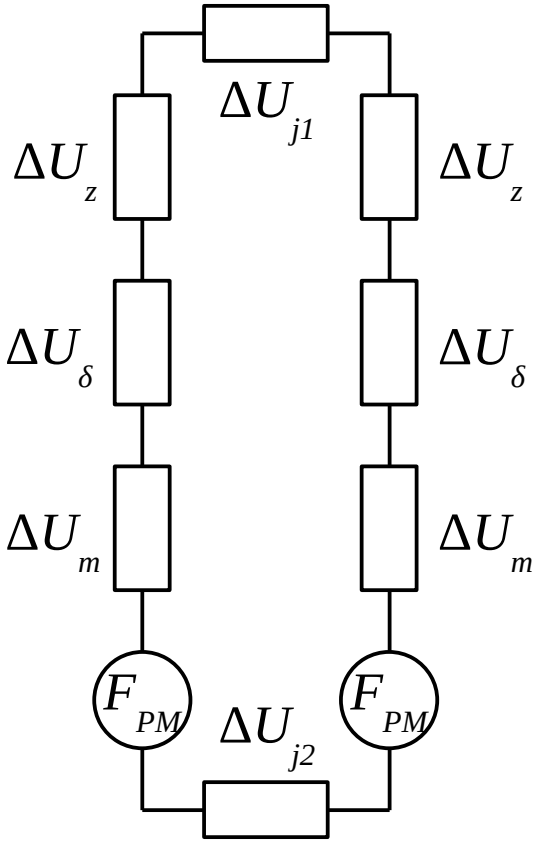
- Real magnetic circuit layout:



Design of Permanent Magnet Excitation

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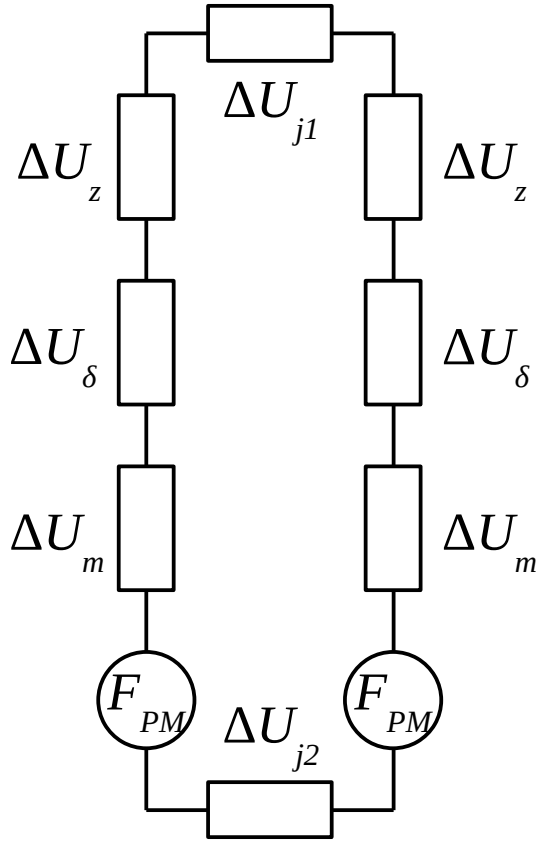




Design of Permanent Magnet Excitation

- The remaining part of the magnetic circuit of the machine acts as resistive load of permanent magnets with magnetic field strength
  - H_z in stator teeth
  - H_{j1} in stator yoke
  - H_{j2} in rotor yoke
  - H_δ in the air gap, whereas

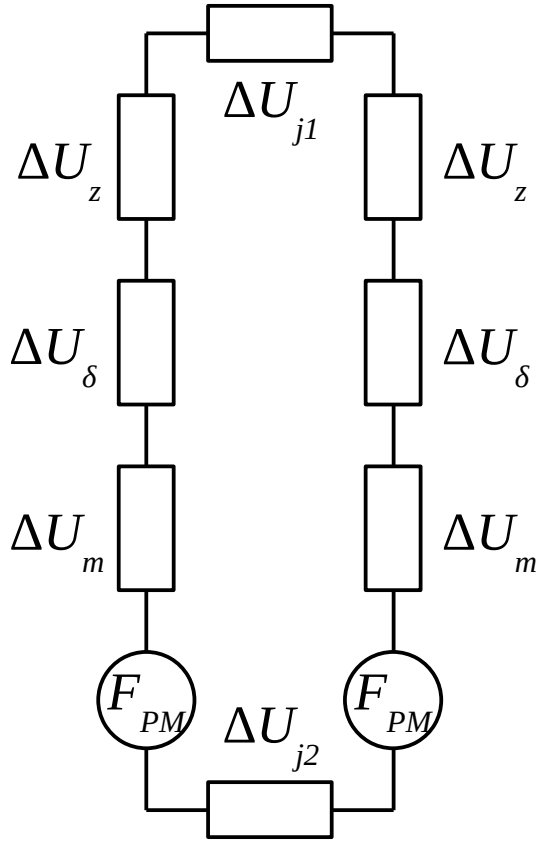
$$H_\delta = \frac{B_\delta}{\mu_0}$$



Design of Permanent Magnet Excitation

- The total magnetomotive force drop on all magnetic circuit components is

$$\Delta U_c = \sum_n \int_{l_i} H_i \, dl$$



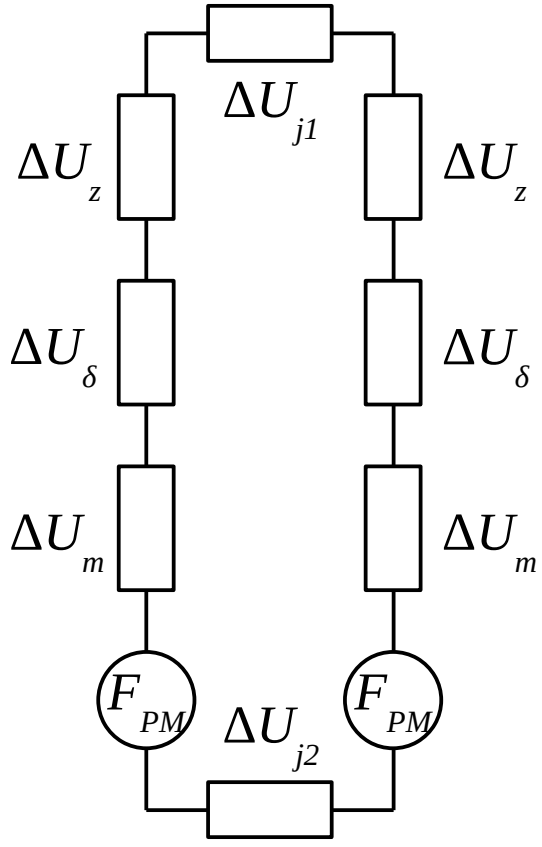
Design of Permanent Magnet Excitation

- The total magnetomotive force drop on all magnetic circuit components is

$$\Delta U_c = \sum_n \int_{l_i} H_i \, dl$$

- In this case:

$$\Delta U_c = 2\int_{h_{PM}} H_{PM}\,dl + 2\int_{\delta''} H_\delta\,dl + 2\int_{h_z} H_z\,dl + \int_{l_{j1}} H_{j1}\,dl + \int_{l_{j2}} H_{j2}\,dl =$$
$$= 2H_{PM}h_{PM} + 2H_\delta\delta'' + 2H_z h_z + H_{j1}l_{j1} + H_{j2}l_{j2}$$



Design of Permanent Magnet Excitation

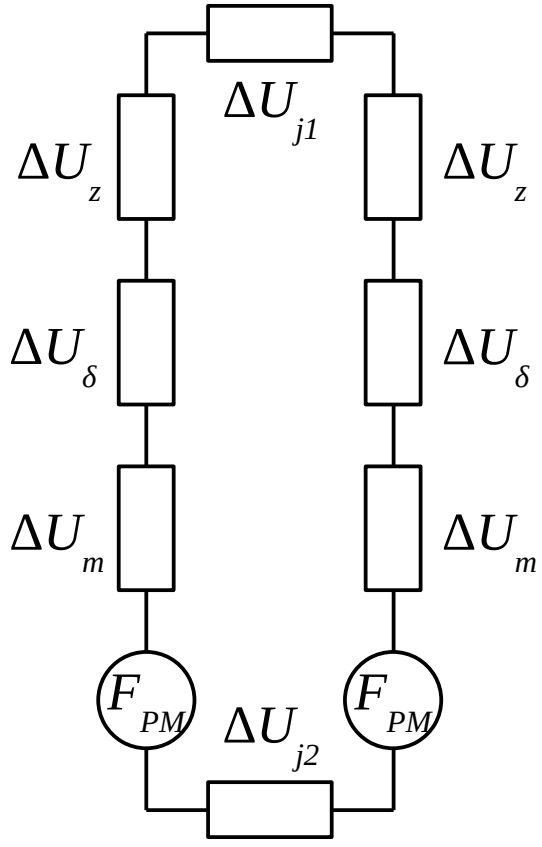
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- In this case:

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$$= \underbrace{2H_{PM}h_{PM}}_{\Delta U_m} + \underbrace{2H_\delta\delta''}_{\Delta U_\delta} + \underbrace{2H_z h_z}_{\Delta U_z} + \underbrace{H_{j1}l_{j1}}_{\Delta U_{j1}} + \underbrace{H_{j2}l_{j2}}_{\Delta U_{j2}}$$



Design of Permanent Magnet Excitation

- Thus we have

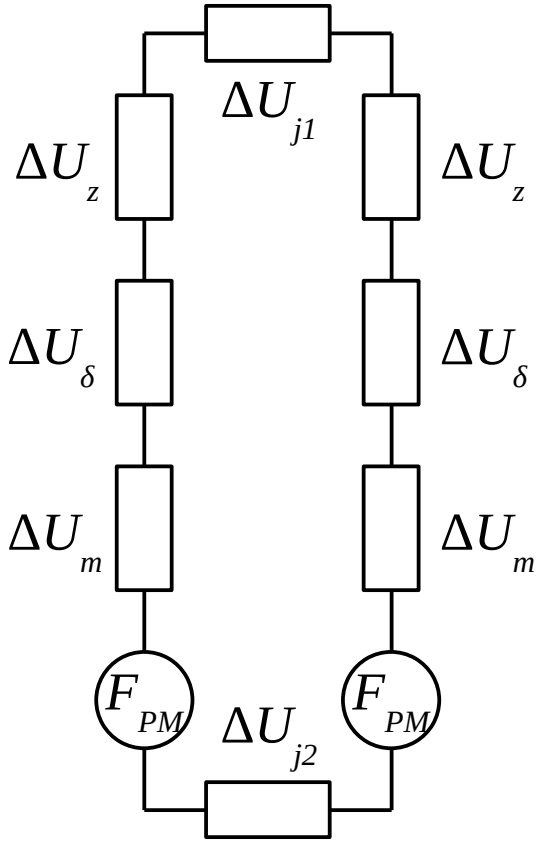
$$F_{PM} = \Delta U_m$$

- After substitution to

$$F_{PM} = \Delta U_m + \Delta U_\delta + \Delta U_z + \Delta U_{j1} + \Delta U_{j2}$$

we obtain for the permanent magnet height

$$2 H_c h_{PM} = 2 H_{PM} h_{PM} + \Delta U_\delta + \Delta U_z + \Delta U_{j1} + \Delta U_{j2}$$



Design of Permanent Magnet Excitation

- Thus we have

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- After substitution to

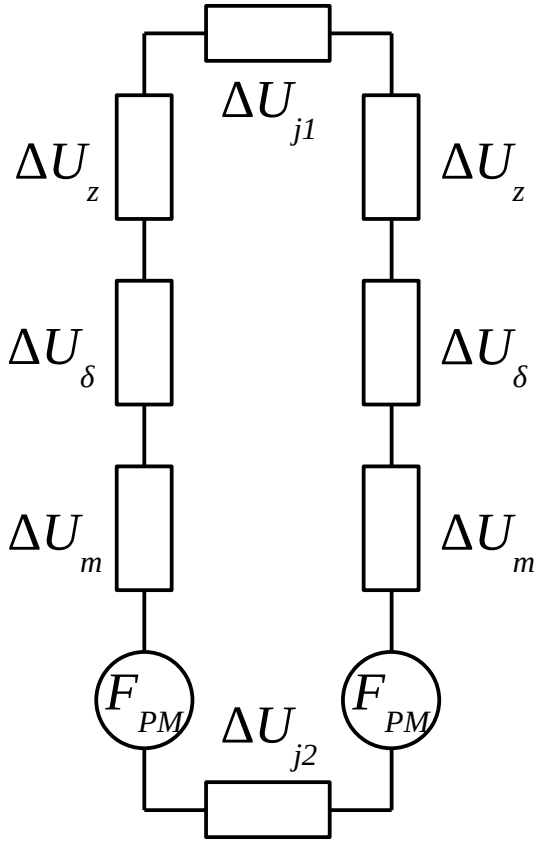
$$F_{PM} = \Delta U_m + \Delta U_\delta + \Delta U_z + \Delta U_{j1} + \Delta U_{j2}$$

we obtain for the permanent magnet height

$$2 H_c h_{PM} = 2 H_{PM} h_{PM} + \Delta U_\delta + \Delta U_z + \Delta U_{j1} + \Delta U_{j2}$$

- The necessary height of the permanent magnet is

$$h_{PM} = \frac{\Delta U_\delta + \Delta U_z + \Delta U_{j1} + \Delta U_{j2}}{2\left(H_c - H_{PM}\right)}$$



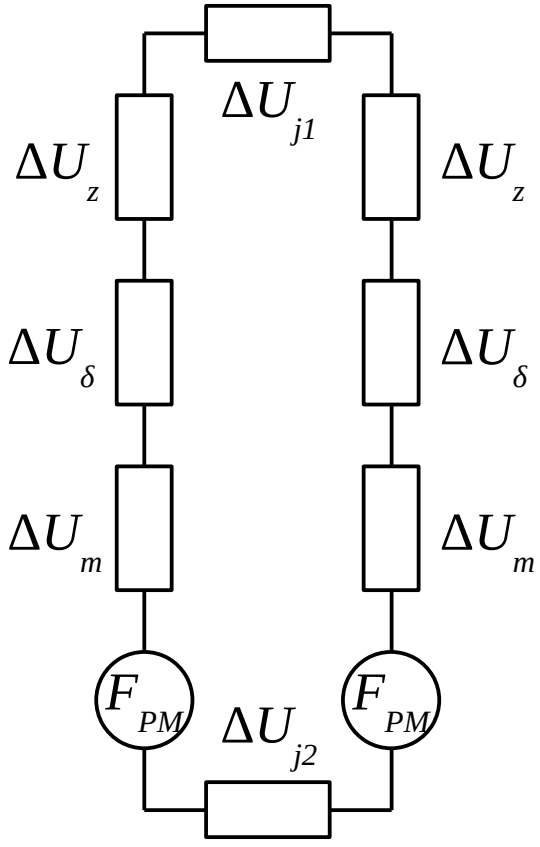
Design of Permanent Magnet Excitation

- The full form of derived equation is

$$h_{PM} = \frac{2H_{\delta}\delta'' + 2H_z h_z + H_{j1} l_{j1} + H_{j2} l_{j2}}{2\left(H_c - H_{PM}\right)}$$

...whereas during the machine design we use B_{δ}

$$h_{PM} = \frac{2\frac{B_{\delta}\delta''}{\mu_0} + 2H_z h_z + H_{j1} l_{j1} + H_{j2} l_{j2}}{2\left(H_c - H_{PM}\right)}$$



Design of Permanent Magnet Excitation

- The full form of derived equation is

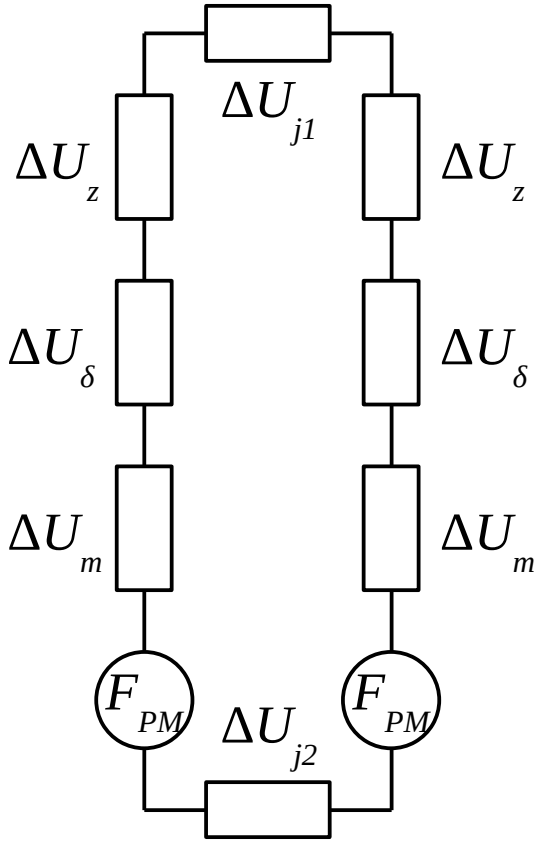
$$h_{PM} = \frac{2H_\delta \delta'' + 2H_z h_z + H_{j1} l_{j1} + H_{j2} l_{j2}}{2\left(H_c - H_{PM}\right)}$$

...whereas during the machine design we use B_δ

$$h_{PM} = \frac{2\frac{B_\delta \delta''}{\mu_0} + 2H_z h_z + H_{j1} l_{j1} + H_{j2} l_{j2}}{2\left(H_c - H_{PM}\right)}$$

- In case we neglect the magnetic circuit saturation

$$h_{PM} = \frac{B_\delta \delta''}{\mu_0\left(H_c - H_{PM}\right)}$$



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MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Permanent Magnet Leakage Flux

Permanent Magnet Leakage Flux

- Numerically expressed using magnetic flux leakage factor
- Physically it is an equivalen to inter-pole leakage flux known from electrically excited synchronous machines
- Expresses the fact, that a certain part of the magnetic flux of the permanent magnet returns through its neighbourhood instead of stator
- The reason is low permeability of the air gap and high permeability of other machine components (rotor)
- Depends on form of placement of the permanent magnets on the rotor of the machine
- Phisically it is a solution of a magnetic circuit in the neighbourhood of the permanent magnet

Permanent Magnet Leakage Flux

- Let us define a permanent magnet leakage flux coefficent as

$$\nu = \frac{\Phi_\sigma}{\Phi_\delta} = \frac{\Phi_{PM}}{\Phi_\delta} - 1$$

- For further calculation let us presume:
  - Non-saturated parts of the magnetic circuit of the machine have nearly infinite permeability $\mu_r \rightarrow \infty$
  - The saturated parts are saturated to μ_{sat}
  - The magnetic flux lines enter the air gap and the leakage paths only from the top of the permanent magnet and return back only from the bottom side

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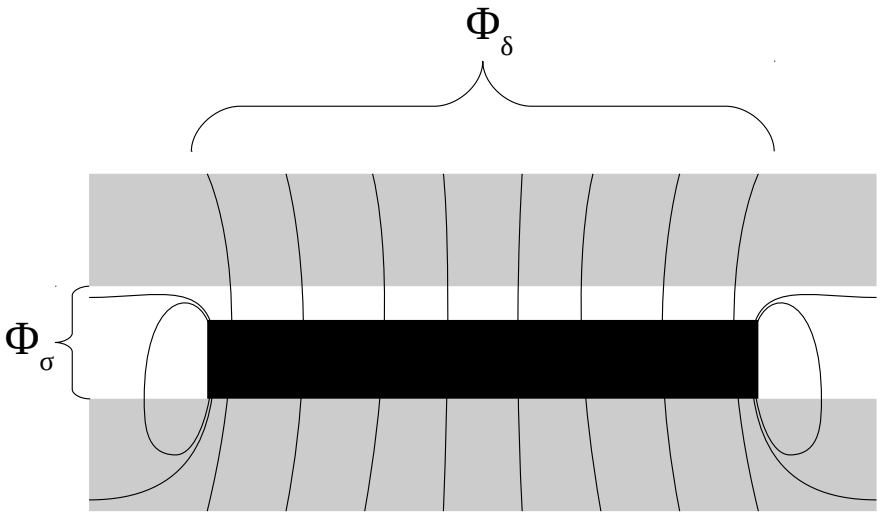
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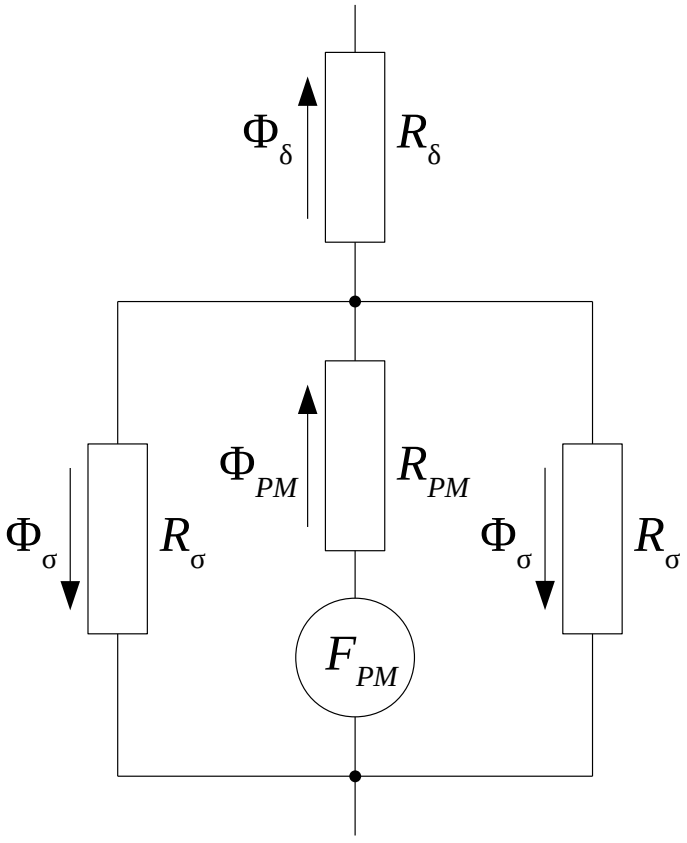
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Surface-Mounted Permanent Magnets

Surface-Mounted Permanent Magnets

- For each permanent magnet placement it is necessary to solve following magnetic circuit:



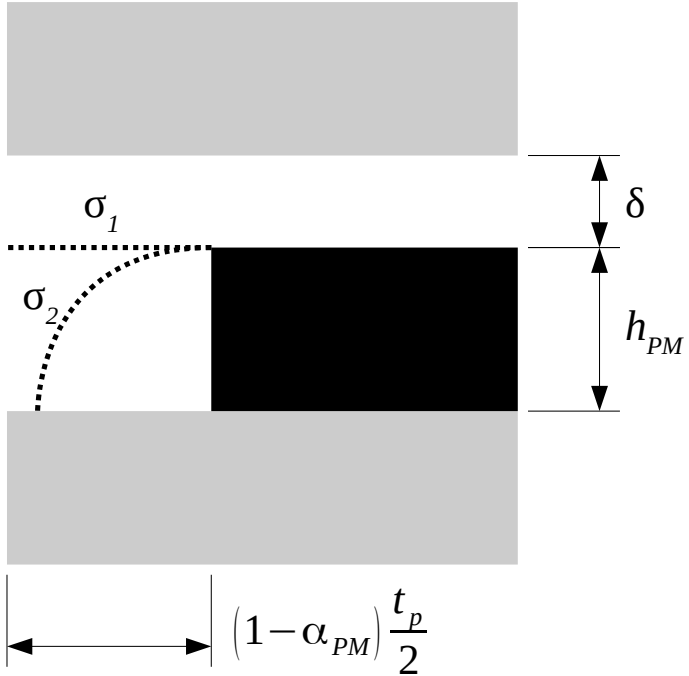


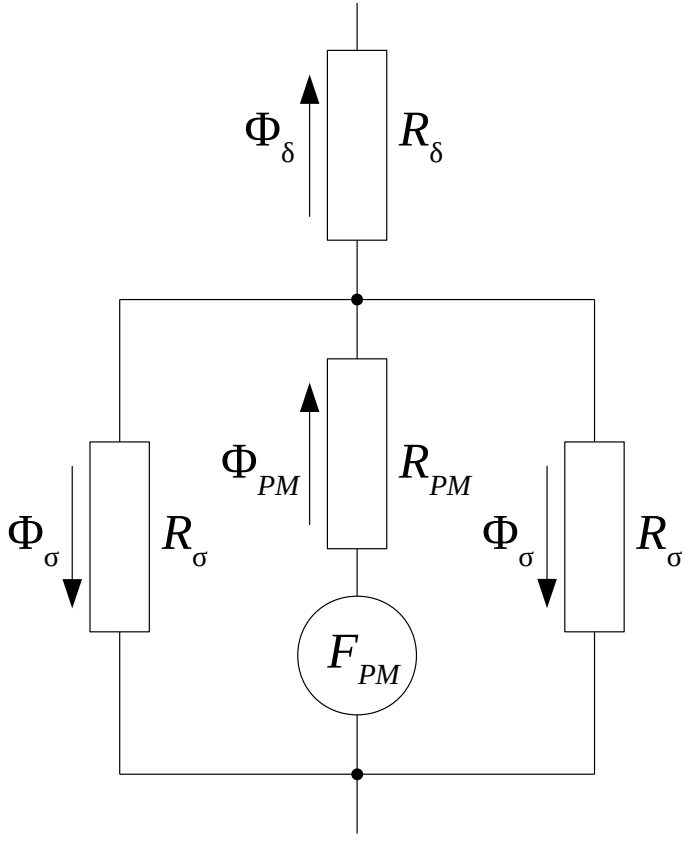
Surface-Mounted Permanent Magnets

- The leakage path is formed by two parallel ones:

$$l_{\sigma 1} = \left(1 - \alpha_{PM}\right)\frac{t_p}{2}$$

$$l_{\sigma 2} = \frac{1}{2}\pi h_{PM}$$





Surface-Mounted Permanent Magnets

- The magnetomotive force drop on the leakage paths is further equal to the magnetomotive force drop on the air gap:

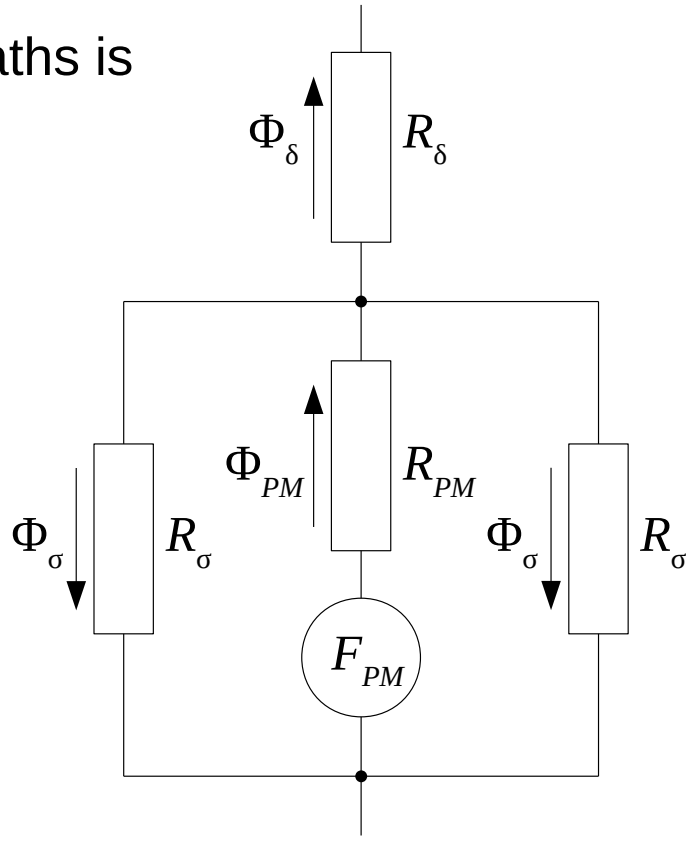
$$F_\sigma = H_\delta \delta' = H_{\sigma 1} l_{\sigma 1} = H_{\sigma 2} l_{\sigma 2}$$

- Thus

$$B_{\sigma 1} = \mu_0 H_{\sigma 1} = \mu_0 H_\delta \frac{\delta'}{\left(1 - \alpha_{PM}\right)\frac{t_p}{2}}$$

or

$$B_{\sigma 2} = \mu_0 H_{\sigma 2} = \mu_0 H_\delta \frac{\delta'}{\frac{\pi h_{PM}}{2}}$$



Surface-Mounted Permanent Magnets

- The total magnetic flux through permanent magnet is

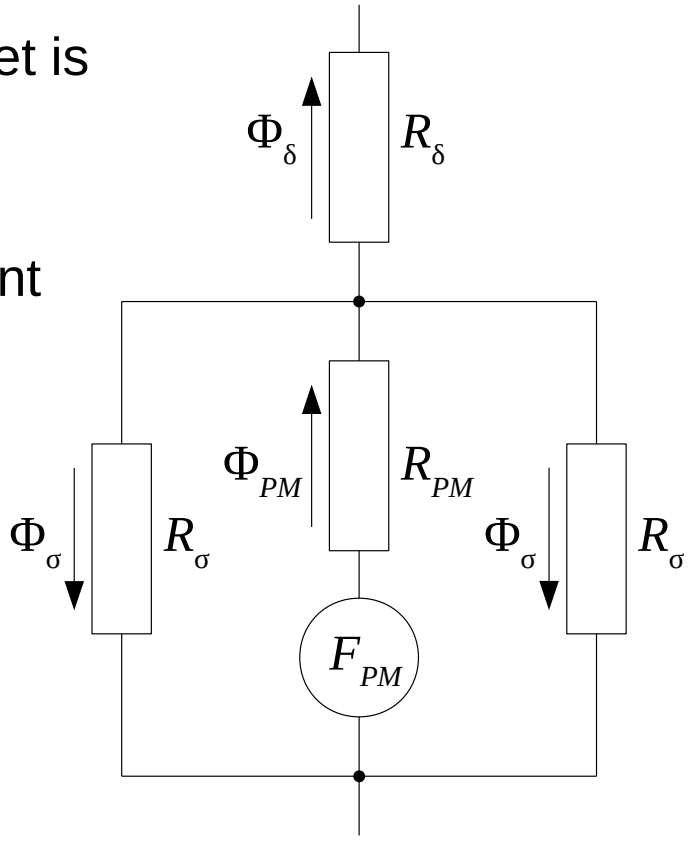
$$\Phi_{PM} = \Phi_{\delta} + 2\left(\Phi_{\sigma 1} + \Phi_{\sigma 2}\right)$$

- And the permanent magnet leakage flux coefficient for surface mounted permanent magnets results

$$\nu = \frac{\alpha_{\delta}\mu_0 H_{\delta} t_p l + 2\left[\mu_0 H_{\delta}\frac{2\delta\delta' l}{\left(1-\alpha_{PM}\right)t_p} + \mu_0 H_{\delta}\frac{\delta' l}{\pi}\right]}{\alpha_{\delta}\mu_0 H_{\delta} t_p l} - 1$$

after modification:

$$\nu = 2\left[\frac{2k_c\delta^2}{\alpha_{\delta}\left(1-\alpha_{PM}\right)t_p^2} + \frac{k_c\delta}{\pi\alpha_{\delta}t_p}\right]$$



Surface-Mounted Permanent Magnets

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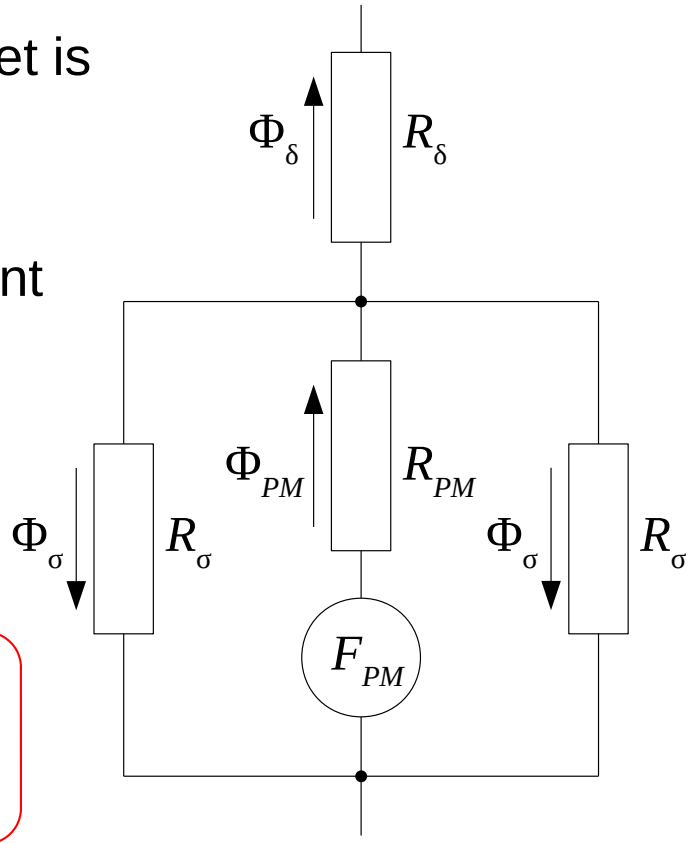
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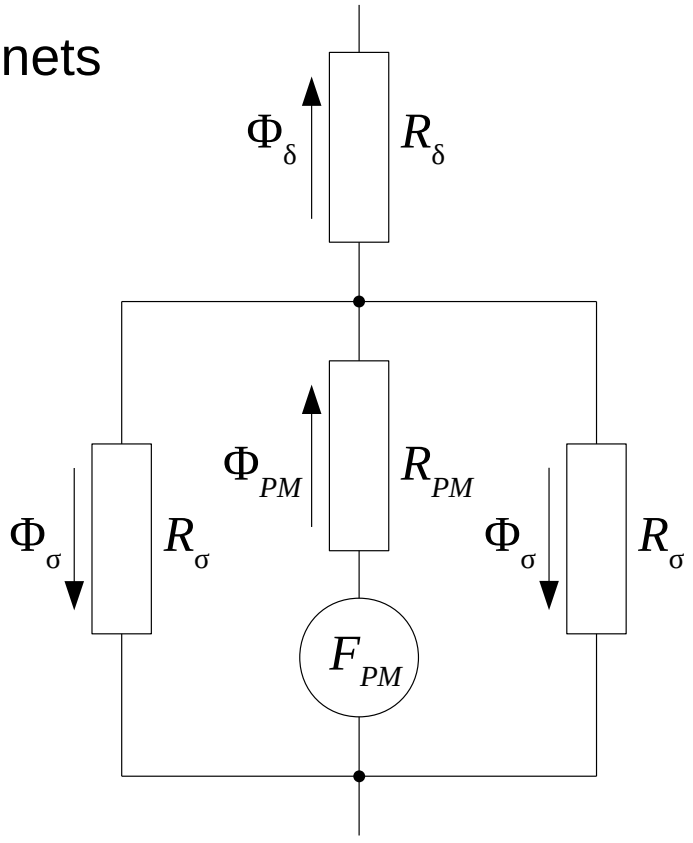


Surface-Mounted Permanent Magnets

- A very similar solution is valid for permanent magnets with variable height
  - “Bread”-shaped magnets
- By introduction of coefficient

$$k_\delta = \frac{\delta_{max}}{\delta}$$

- It is possible to express the height of the edge of the permanent magnet

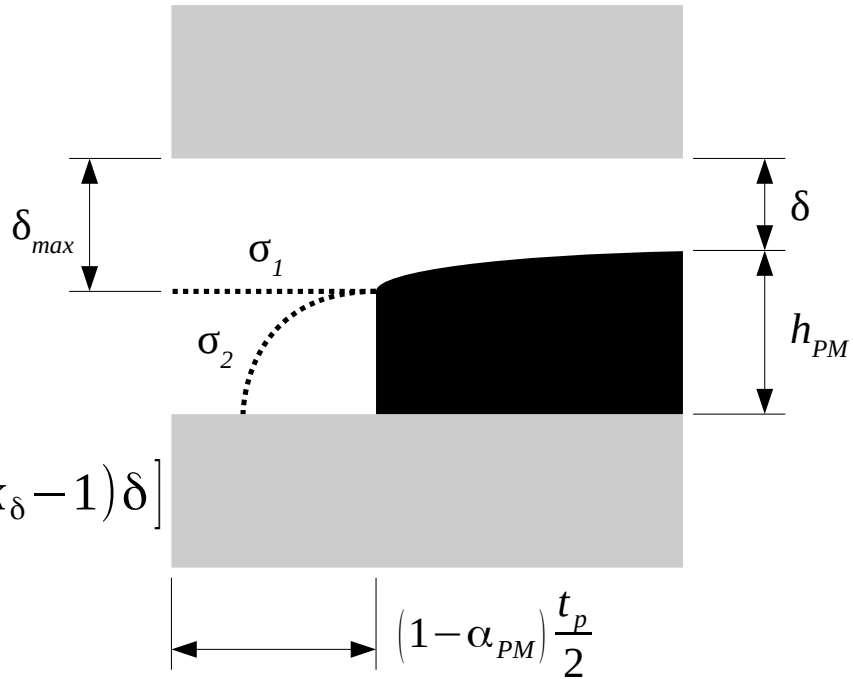


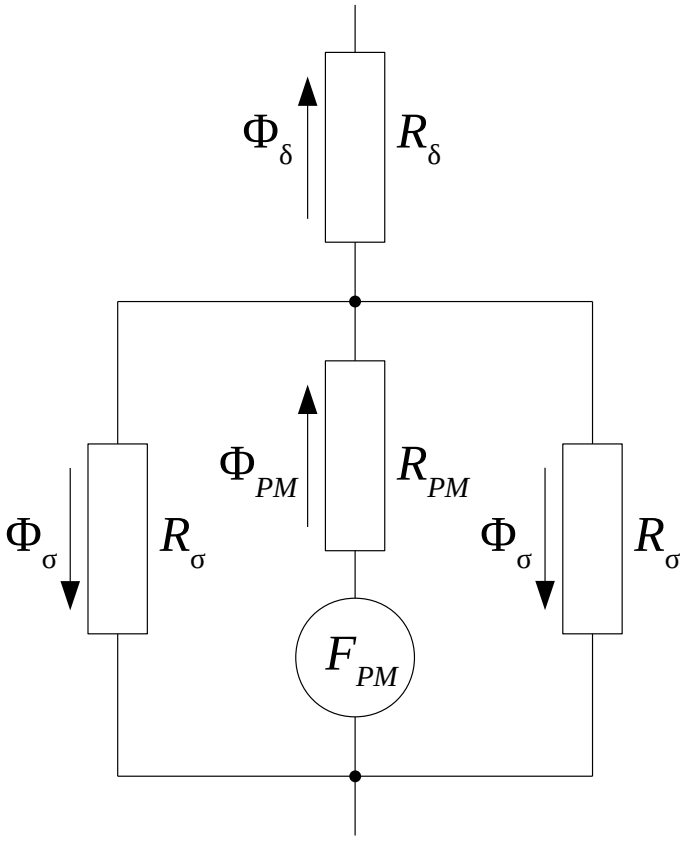
Surface-Mounted Permanent Magnets

- Then the magnetic flux lines lengths are

$$l_{\sigma 1} = \left(1 - \alpha_{PM}\right) \frac{t_p}{2}$$

$$l_{\sigma 2} = \frac{1}{2} \pi \left[h_{PM} - \left(k_\delta - 1\right) \delta \right]$$

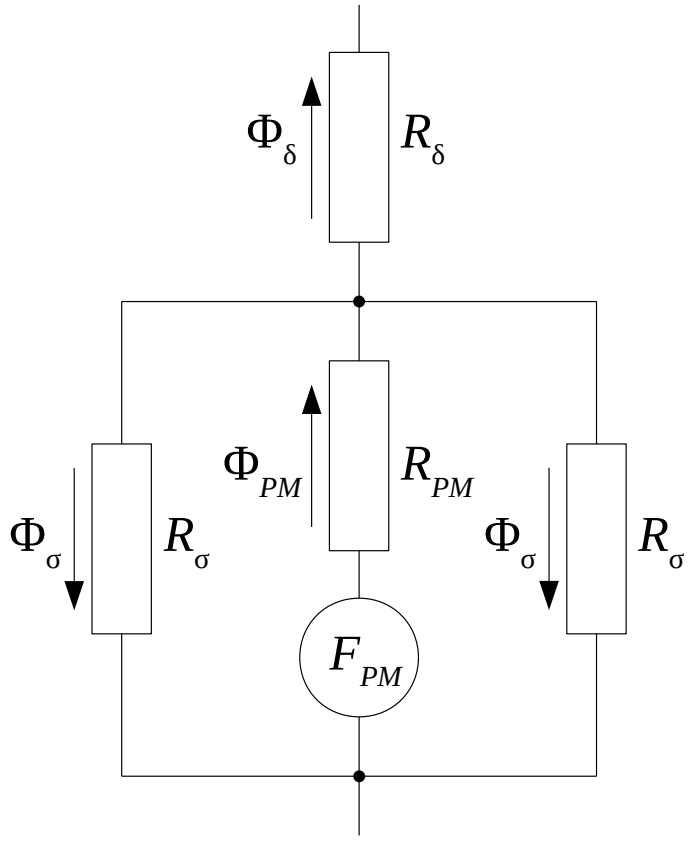




Surface-Mounted Permanent Magnets

- Using equivalent approach as in previous case we obtain:

$$\nu = 2\left[\frac{2k_\delta k_c \delta^2}{\alpha_\delta\left(1-\alpha_{PM}\right)t_p^2} + \frac{k_c \delta}{\pi \alpha_\delta t_p}\right]$$

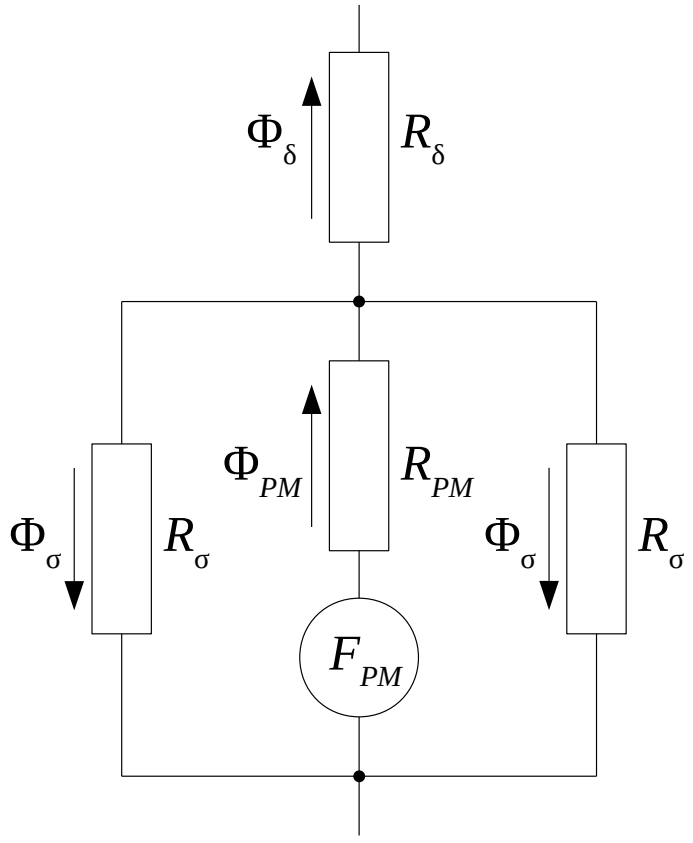


Surface-Mounted Permanent Magnets

- Using equivalent approach as in previous case we obtain:

$$\nu = 2\left[\frac{2k_\delta k_c \delta^2}{\alpha_\delta\left(1-\alpha_{PM}\right)t_p^2} + \frac{k_c \delta}{\pi \alpha_\delta t_p}\right]$$

… which is, in fact, a general solution for $k_\delta \neq 1$



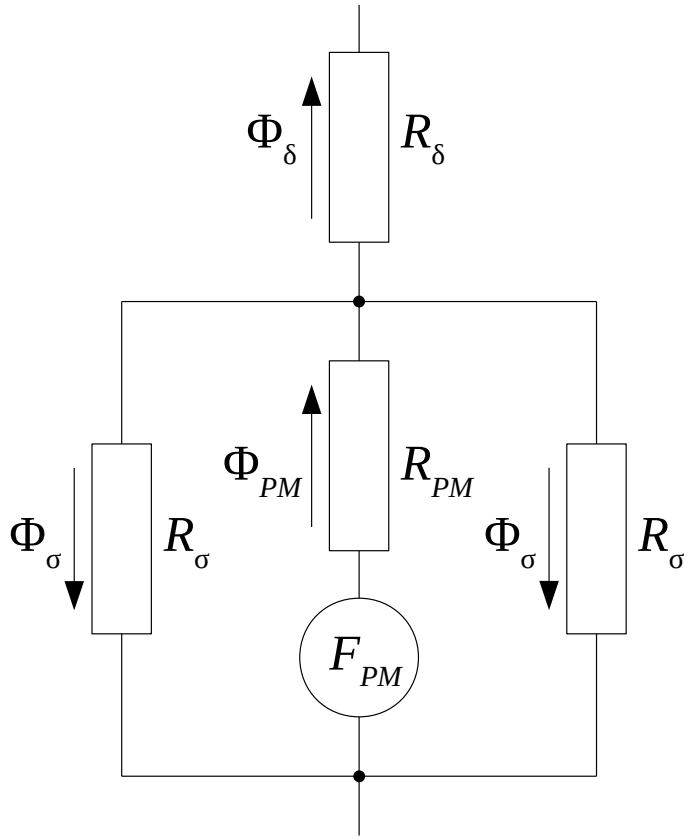
Surface-Mounted Permanent Magnets

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$$\nu = 2\left[\frac{2k_\delta k_c \delta^2}{\alpha_\delta\left(1-\alpha_{PM}\right)t_p^2} + \frac{k_c \delta}{\pi \alpha_\delta t_p}\right]$$

… which is, in fact, a general solution for $k_\delta \neq 1$

- The same relation is valid also for permanent magnets placed under pole shoes



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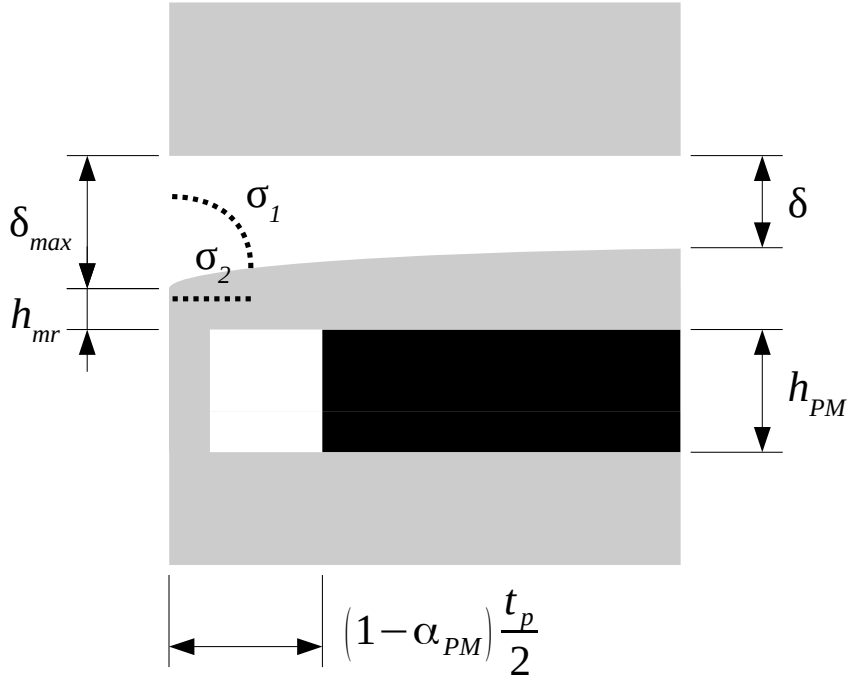
Interior Permanent Magnet Rotors

Interior Permanent Magnet Rotors

- Relative common for the purpose of protection of permanent magnets against slot harmonic components
- Permanent magnets are placed in pockets under the rotor surface
  - Limited mechanical strength
  - Permanent magnets are placed in an environment with high permeability
    => exceptional increase of the permanent magnet leakage flux
- Leads to increase of difference between inductances in the d and q axes
    => reluctance torque

Interior Permanent Magnet Rotors

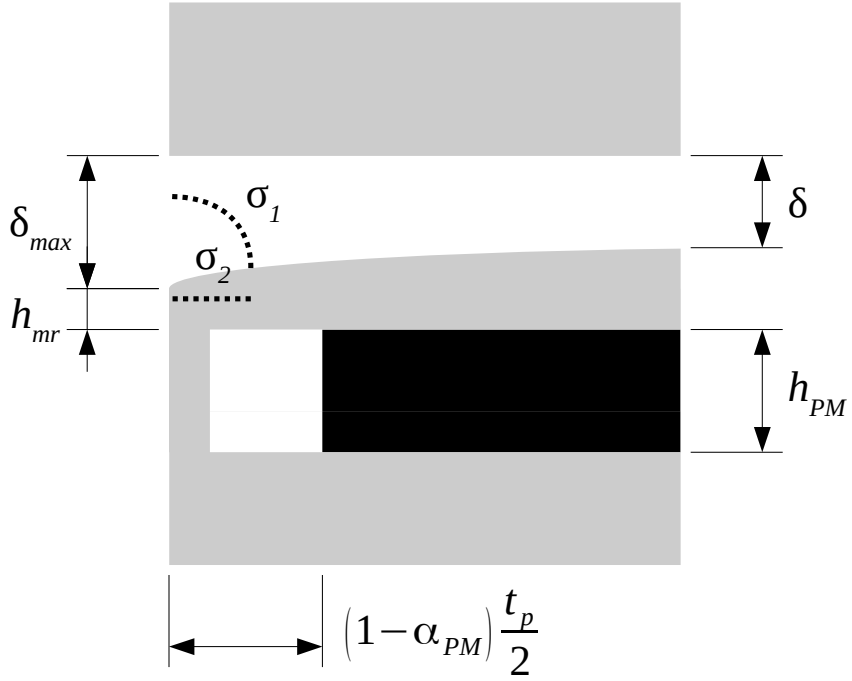
- Simple tangential pockets:



Interior Permanent Magnet Rotors

- Simple tangential pockets:

  Presumption: we consider the area behind ½ of the pocket bridge as fully saturated



Interior Permanent Magnet Rotors

- Leakage path 1:
  - Length of the leakage path

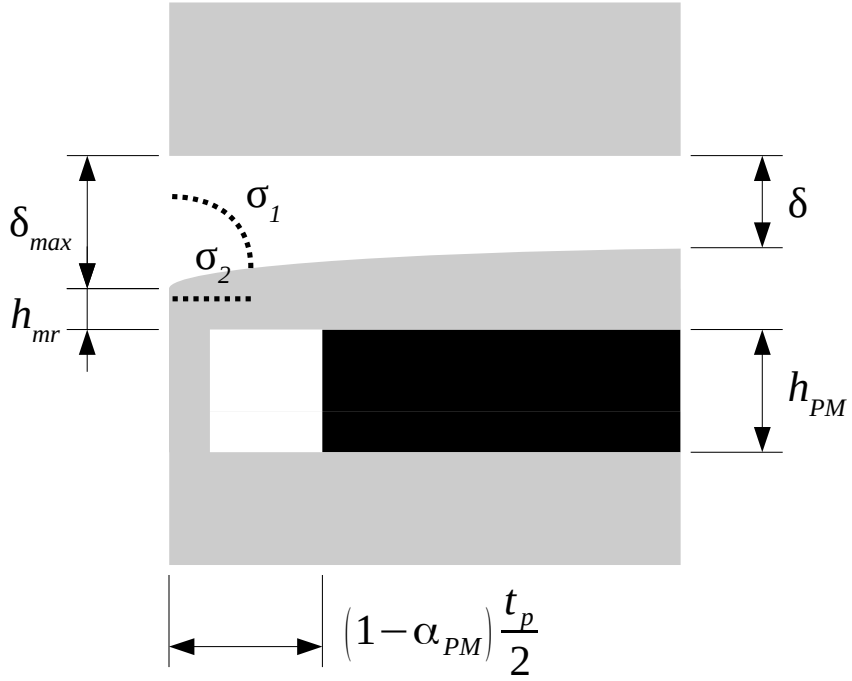
$$l_{\sigma 1} = \pi \left(1 - \alpha_{PM}\right) \frac{t_p}{8}$$

  - Magnetic field strength

$$H_{\sigma 1} = H_{\delta} \frac{8\,\delta'}{\pi \left(1 - \alpha_{PM}\right) t_p}$$

  - Leakage flux through the air gap

$$\Phi_{\sigma 1} = B_{\sigma 1}\, \delta_{max}\, l = \mu_0 H_{\delta} \frac{8\, k_{\delta}\, k_c\, \delta^2\, l}{\pi \left(1 - \alpha_{PM}\right) t_p}$$



Interior Permanent Magnet Rotors

- Leakage path 2:
  - Length of the leakage path

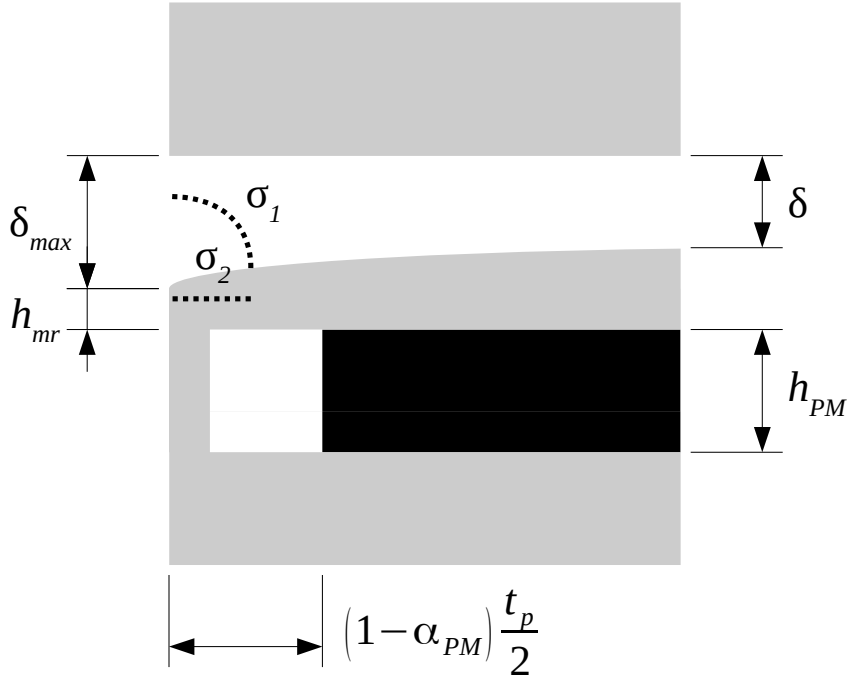
$$l_{\sigma 2} = \frac{1}{2}\left(1-\alpha_{PM}\right)\frac{t_p}{2}$$

  - Magnetic field strength

$$H_{\sigma 2} = H_{\delta}\frac{4\,\delta'}{\left(1-\alpha_{PM}\right)t_p}$$

  - Leakage flux through the bridge

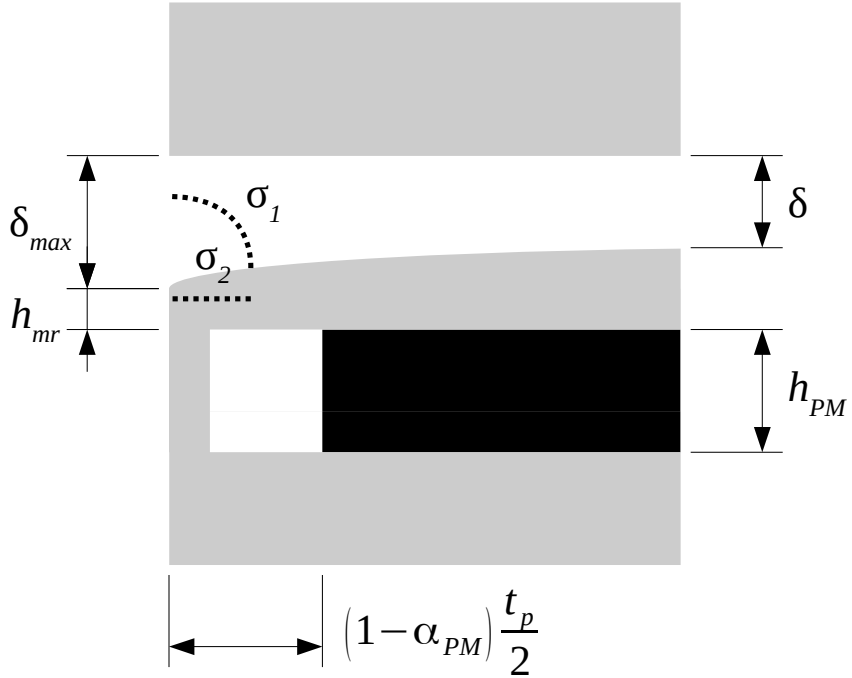
$$\Phi_{\sigma 2} = \mu_{sat} H_{\delta}\frac{4\,k_c\,\delta\,h_{mr}\,l}{\left(1-\alpha_{PM}\right)t_p}$$



Interior Permanent Magnet Rotors

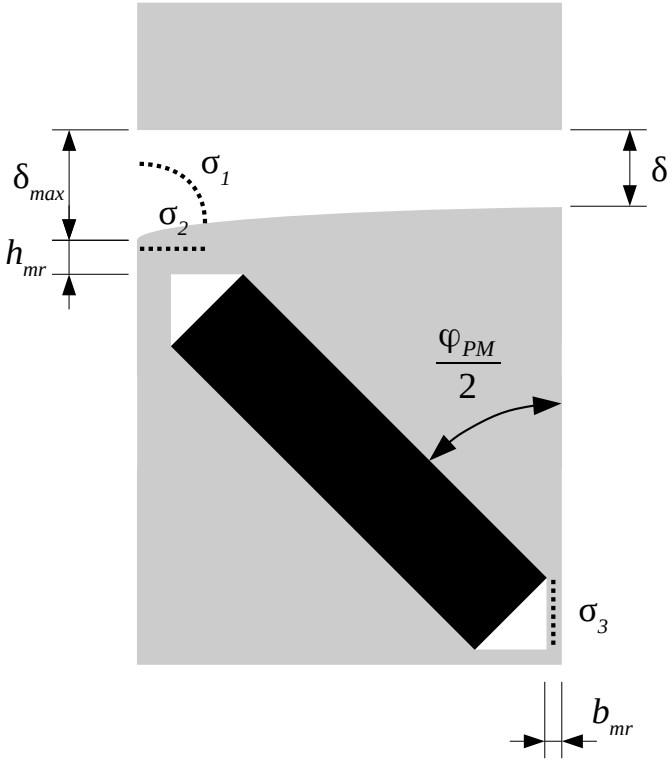
- After solution the leakage flux coefficient results

$$\nu = 2\left[\frac{8 k_\delta k_c \delta^2}{\alpha_\delta \pi \left(1-\alpha_{PM}\right) t_p^2} + \mu_{rsat} \frac{4 k_c \delta h_{mr}}{\alpha_\delta \left(1-\alpha_{PM}\right) t_p^2}\right]$$



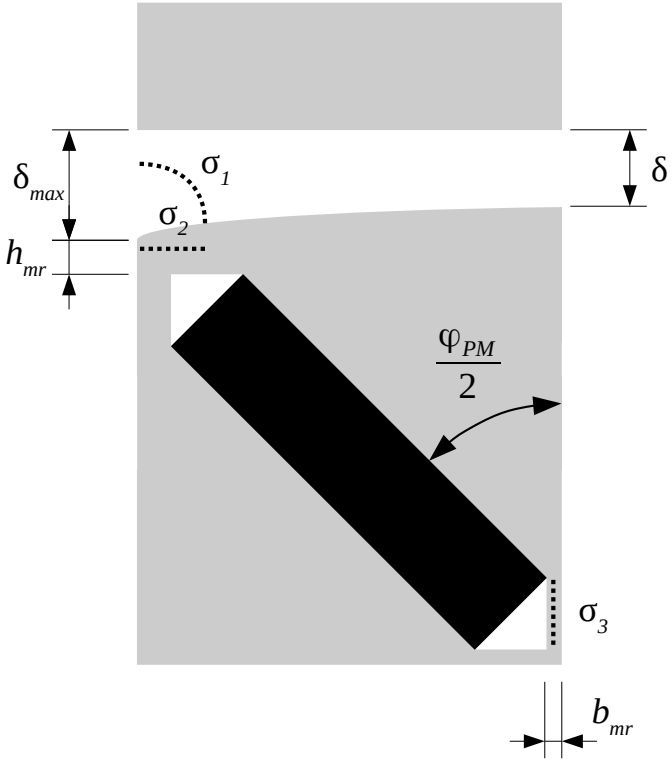
Interior Permanent Magnet Rotors

- „V“-placed permanent magnets:



Interior Permanent Magnet Rotors

- „V“-placed permanent magnets:
- There is an additional 3rd leakage path
- While skewing the magnets the bridge is shortened
  - The permanent magnet area increases
  - In theory it is possible to increase the B_δ, but for the price of a large permanent magnet leakage flux
- Leads to further increase of the permanent magnet leakage flux coefficient

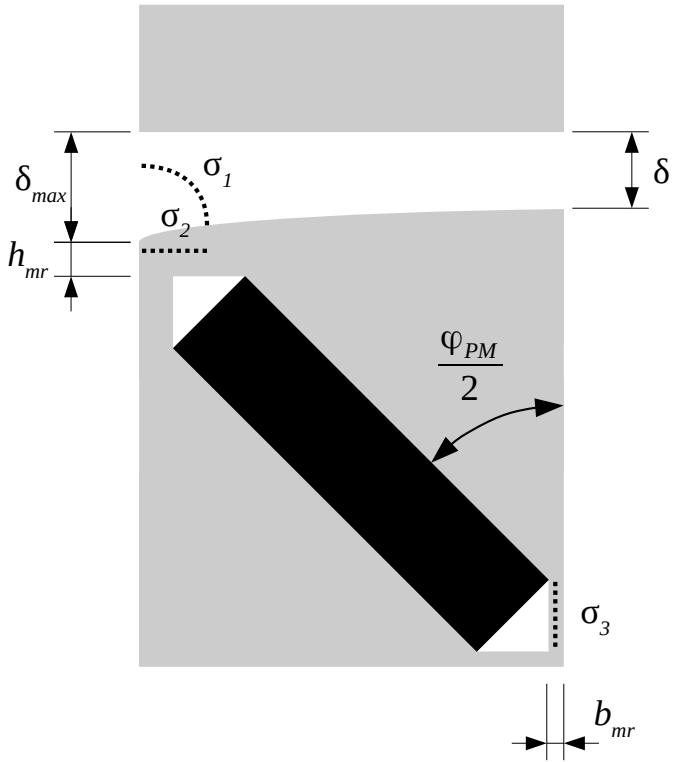


Interior Permanent Magnet Rotors

- By using equivalent approach we obtain:

$$\nu = 2\left[\frac{2\,k_\delta k_c \delta^2}{\alpha_\delta t_p \pi\left(\frac{h_{PM}}{2}\cos\frac{\varphi_{PM}}{2}+b_{mr}\right)}+\mu_{rsat}\frac{k_c\delta h_{mr}}{\alpha_\delta t_p\left(\frac{h_{PM}}{2}\cos\frac{\varphi_{PM}}{2}+b_{mr}\right)}+\ldots\right.$$

$$\left.\ldots+\mu_{rsat}\frac{k_c\delta b_{mr}}{\alpha_\delta h_{PM}\sin\frac{\varphi_{PM}}{2}t_p}\right]$$



Interior Permanent Magnet Rotors

- Although a simplified approach was applied, the results are relatively accurate
- In case of studied machine:

placement	k_σ [-]	$k_{\sigma FEM}$ [-]	δk_σ [%]
S	1,028	1,022	0,59
B	1,037	1,026	1,04
U	1,210	1,266	-4,39
V	1,264	1,275	-0,92
P	1,031	1,026	0,57

Note: the purpose of the table is to reflect the accuracy in relation to the air gap magnetic flux thus coefficient $k_\sigma = 1 + \nu$ is used instead

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Notes on Permanent Magnet Design

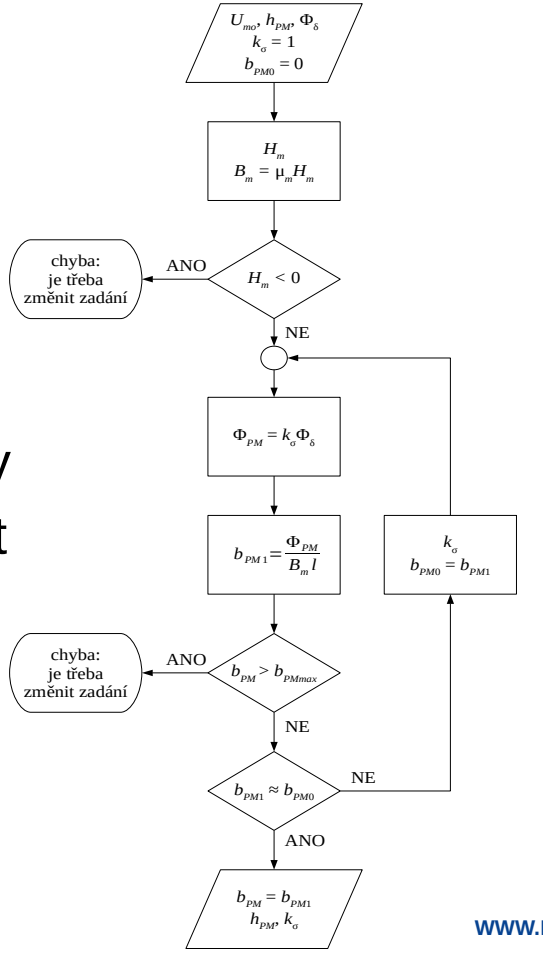
Notes on Permanent Magnet Design

- It is obvious, that the permanent magnet leakage flux coefficient is a result of certain geometry and it cannot be guessed with reasonable precision
- The reason is, that the permanent magnet width results from the total permanent magnet flux and this results from the leakage flux of given geometry
- And the permanent magnet leakage flux coefficient results from the width of permanent magnets, etc...

Notes on Permanent Magnet Design

- It is obvious, that the permanent magnet leakage flux coefficient is a result of certain geometry and it cannot be guessed with reasonable precision
- The reason is, that the permanent magnet width results from the total permanent magnet flux and this results from the leakage flux of given geometry
- And the permanent magnet leakage flux coefficient results from the width of permanent magnets, etc...

=> an **iterative approach** is necessary



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Thank You for Your Attention!

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