Permanentmagnet-Synchron-Maschinen

Grundlagen des Betriebs und der Auslegung

Seminar

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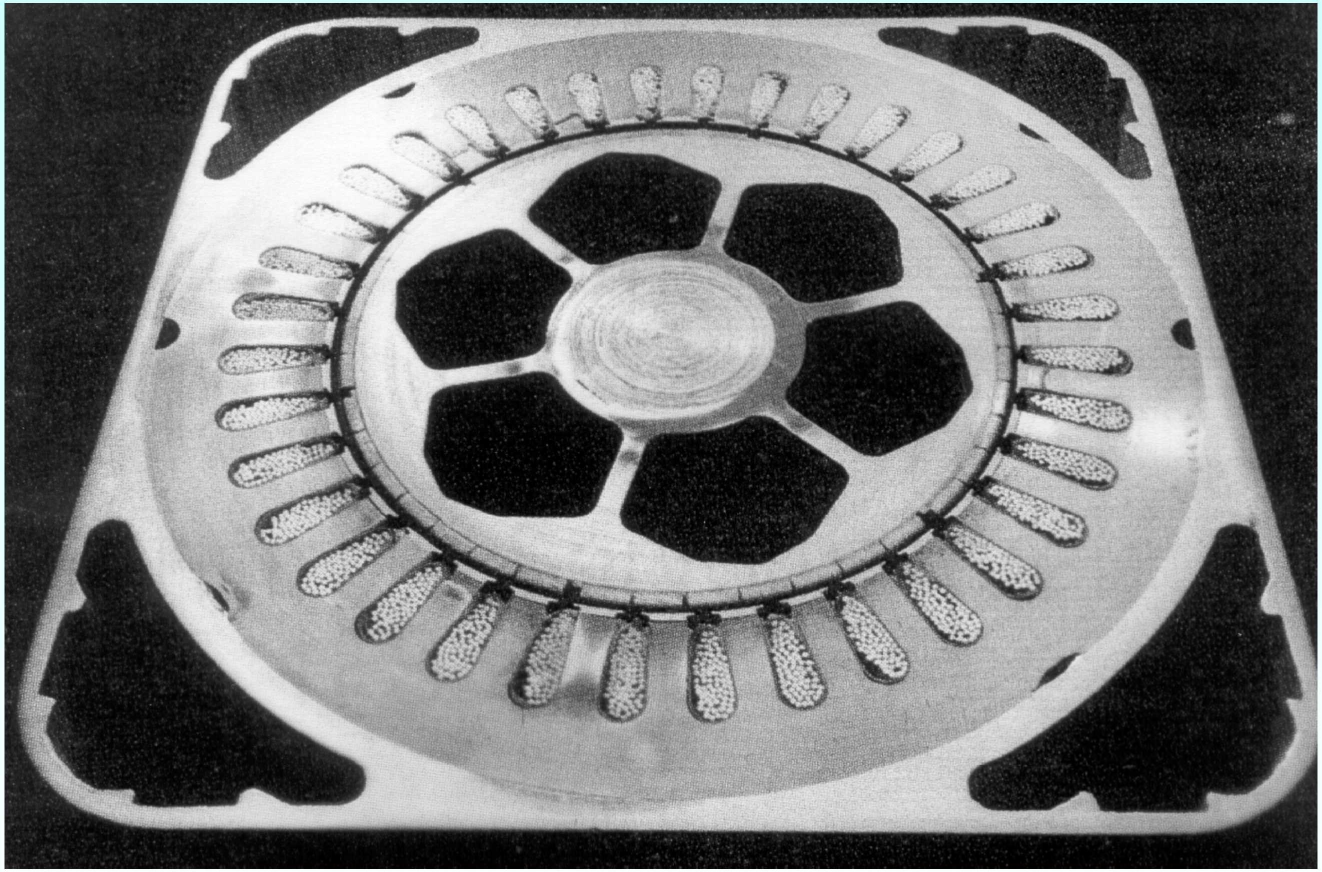
Inhalt des Seminars

- 1. Auslegung der Permanentmagnet-Synchronmaschine
- 2. Ansteuerung von PM-Maschinen
- 3. Feldschwächung von PM-Maschinen
- 4. Reluktanzmomente

1. Auslegung der Permanentmagnet-Synchronmaschine

Typischer Querschnitt einer PM-Synchronmaschine mit Oberflächenmagneten



6 Pole, 36 Ständernuten, verteilte 3-strängige Einschicht-Drehstromwicklung, q = 2 Ganzlochwicklung, Ständernuten um eine Nutteilung geschrägt, NdFeB-Magnete unterteilt, 100% Polbedeckung, Niederspannungsrunddraht-Wicklung 400 V, Sternschaltung

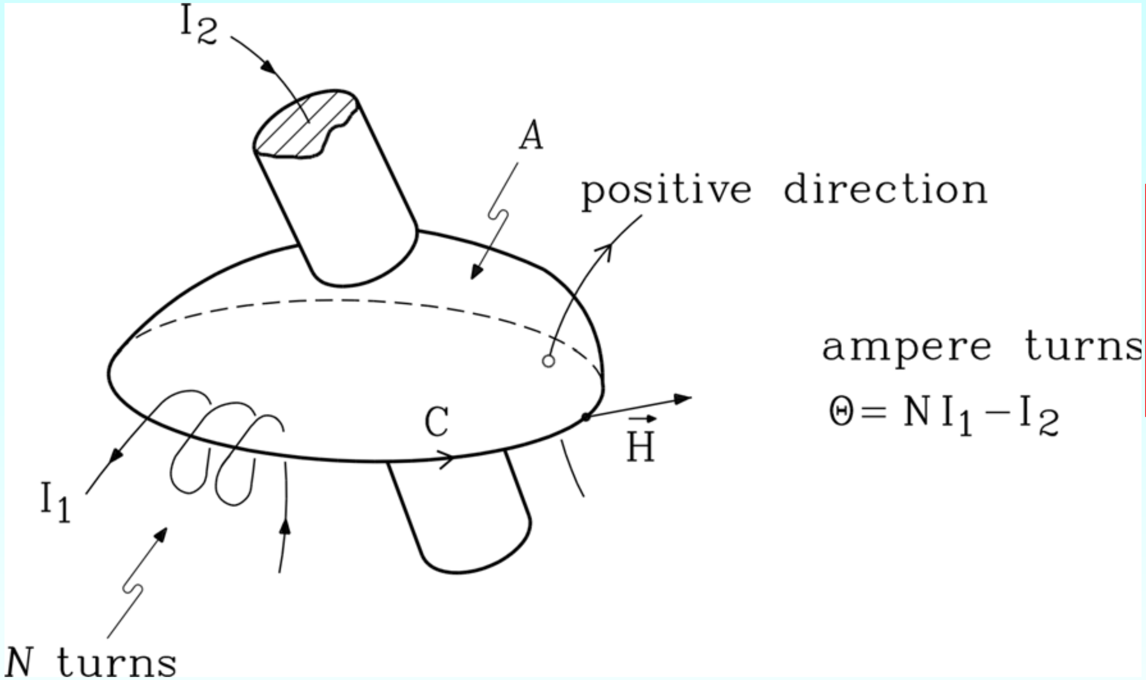
AMPERE´s law: Excitation of magnetic field by electric current

Example:

Two different currents I_1, I_2 with two different numbers of turns 1 and N and two different flow directions:

Ampere turns Θ:

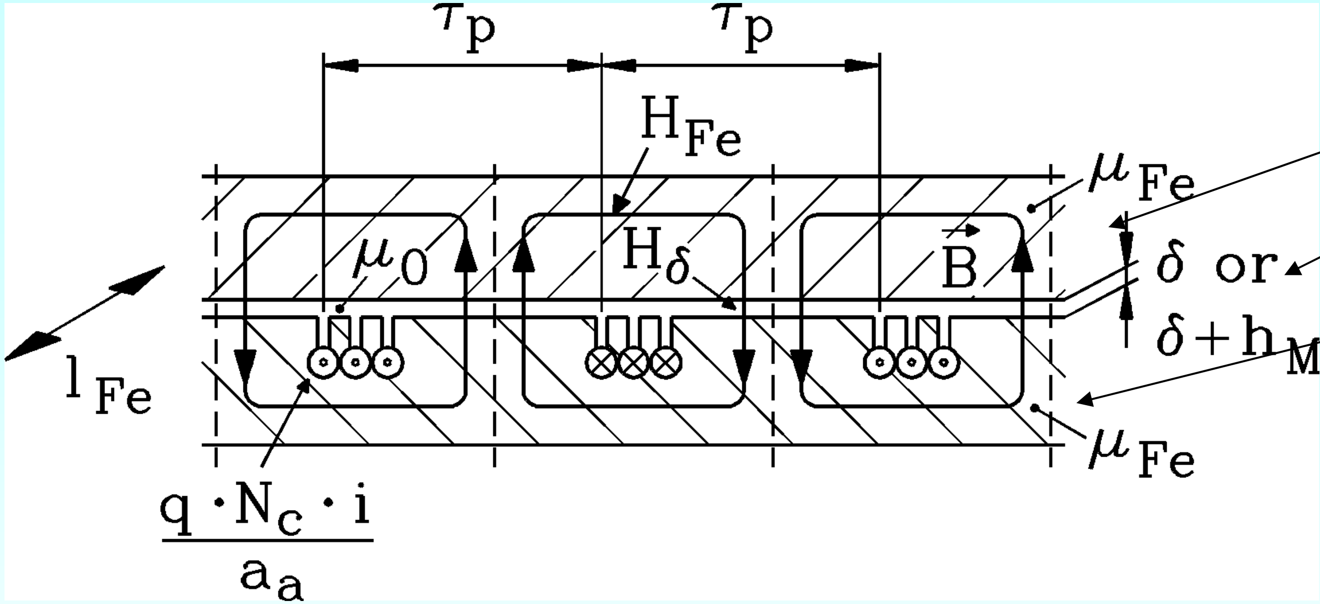
$\Theta = N I_1 - I_2$



$$\oint_C \vec{H} \cdot d\vec{s} = \Theta$$

- **The integration of magnetic field strength *H* along closed loop (curve *C*), which spans the area *A*, is equal to the resulting current flow (Ampere turns Θ) penetrating through the area *A*.**
- **Positive field direction is connected to positive current flow direction by RIGHT HAND RULE.**

Verteilte Wicklung - ein Strang erregt (hier: *q* = 3)



Electric machine:

Unslotted rotor

Air gap

Slotted stator:

Inserted coils with two coil sides each, where coil current *i* flows

*Ampere´*s law for air gap field: $\oint_C \vec{H} \bullet d\vec{s} = H_{Fe,s} \cdot s_{Fe,s} + H_{Fe,r} \cdot s_{Fe,sr} + H_{\delta,right} \cdot \delta + H_{\delta,left} \cdot \delta = \Theta_Q$

Infinite iron permeability μ_{Fe} assumed: $\oint_C \vec{H} \bullet d\vec{s} = H_{\delta,right} \cdot \delta - H_{\delta,left} \cdot \delta = \Delta V_\delta(x) = \Theta_Q(x)$

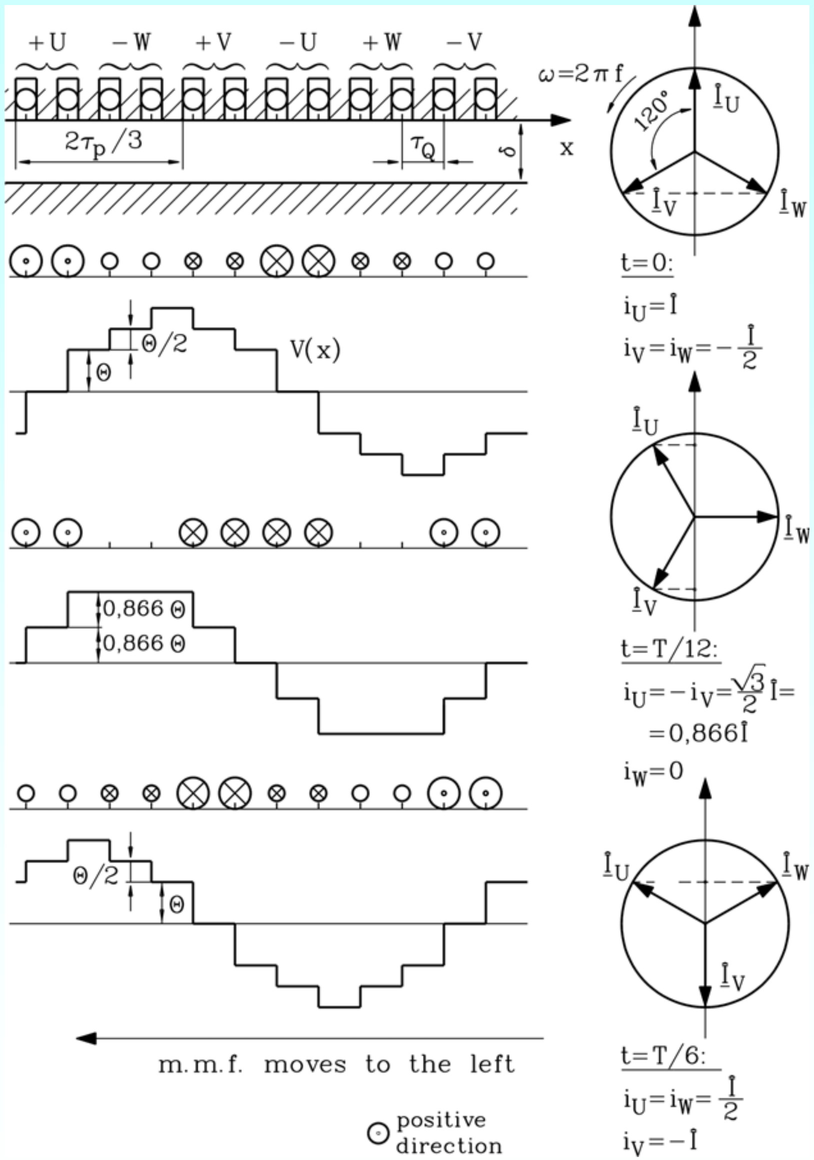
Magnetomotive force distribution in air gap: $V_\delta(x)$

Magnetic field strength distribution in air gap: $H_\delta(x)$

Magnetic flux density distribution in air gap: $B_\delta(x)$

$$V_\delta = H_\delta \cdot \delta$$

$$B_\delta = \mu_0 V_\delta / \delta$$



Stator-Wanderfeld: 3-phasiges Sinusstrom-system speist die verteilte Wicklung

- Field curve moves with increasing time *t* to the left !
- After time *T* the field curve has passed the distance $2\tau_p$
- Velocity of <u>linear</u> movement is called

$$\boxed{v_{syn} = \frac{2\tau_p}{T} = 2f\tau_p}$$

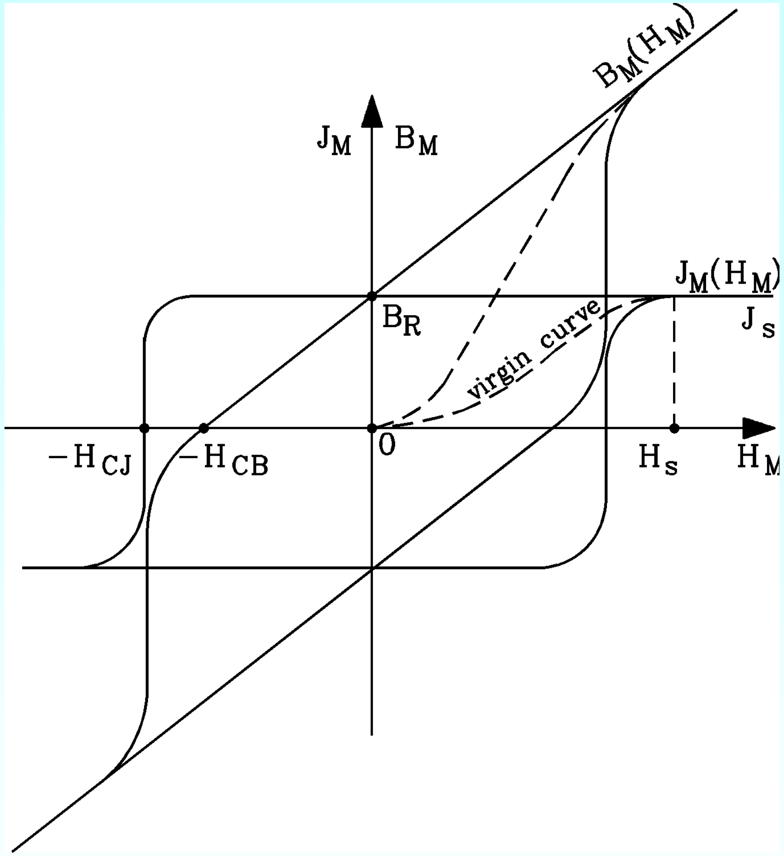
synchronous velocity !

Synchronous rotational speed n_{syn}
in case of <u>rotating</u> field arrangement:

$$\omega_{syn} = 2\pi n_{syn} = \frac{v_{syn}}{d_{si}/2} = \frac{v_{syn}}{p\tau_p/\pi} = \frac{2\pi f}{p}$$

$$\boxed{n_{syn} = \frac{f}{p}}$$

Permanent magnet technology



Permanent magnets:

- AlNiCo,
- Ba-Ferrite and Sr-Ferrite,
- Rare earth magnets SmCo and NdFeB

Magnetic field inside permanent magnet:

$$B = \mu_0 H + J$$

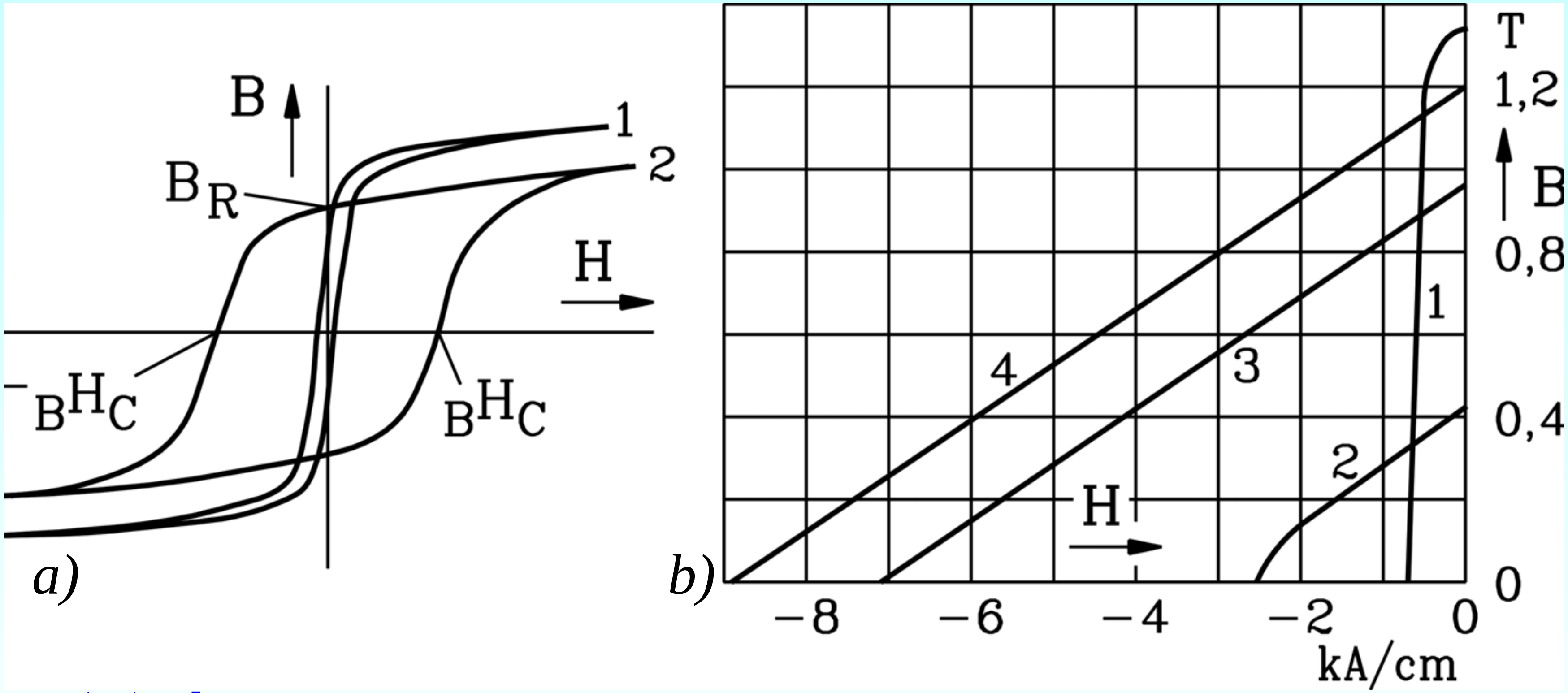
J: magnetic polarization

Saturated values: Subscript *s*

Remanence flux density: $B_R = J_R$

Coercive field strength: H_{CJ} and H_{CB}

Permanent magnet properties

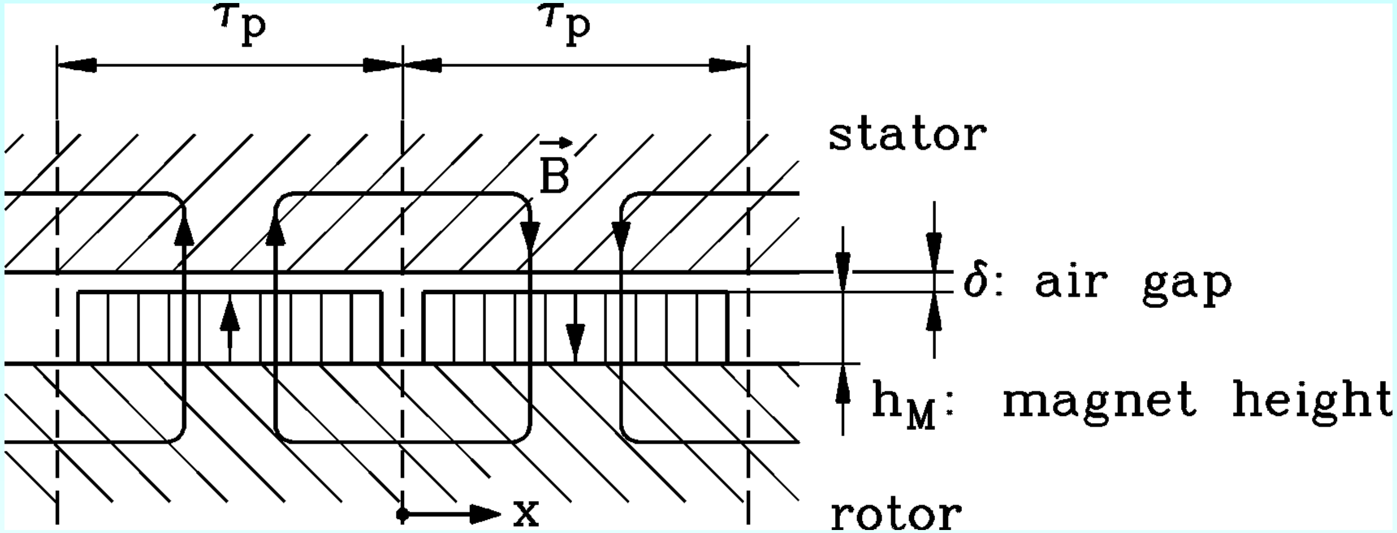


B(H)-characteristics:

a) (1) Soft magnetic material, (2) PM magnet,

b) PM magnets: Second quadrant at 20°C; (1) Al-Ni-Co, (2): Ba-Ferrit, (3): Sm_2Co_{17} (ϑ_{max} = 350°C) (4): NdFeB (ϑ_{max} = 180°C)

Design of magnet dimensions



Magnet field at no-load: No electric current in stator winding !

*Ampere´*s law: $\oint_C \vec{H} \bullet d\vec{s} = 2(H_\delta \delta + H_M h_M) = \Theta = 0$

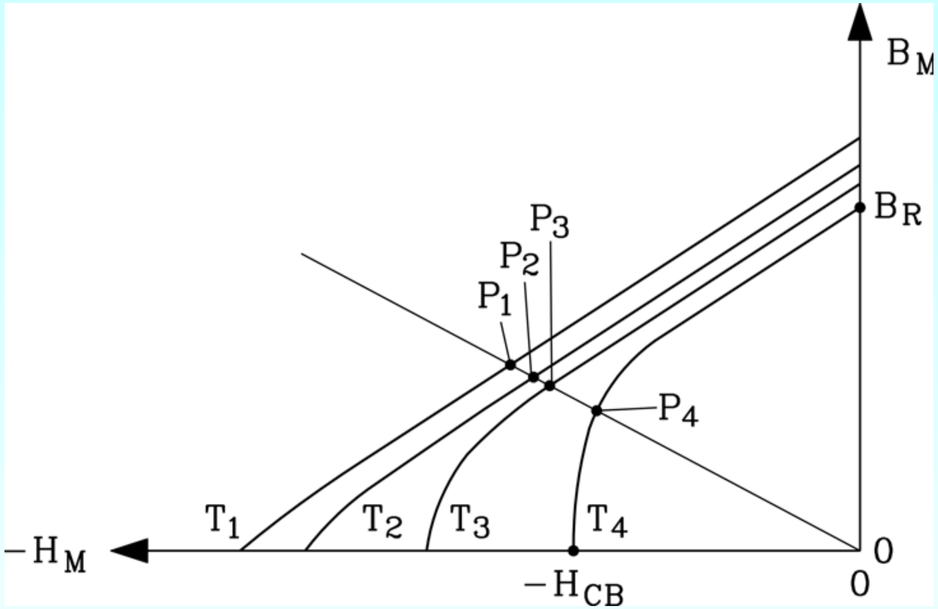
Flux continuity: $\Phi = B_M A_M = B_\delta A_\delta$

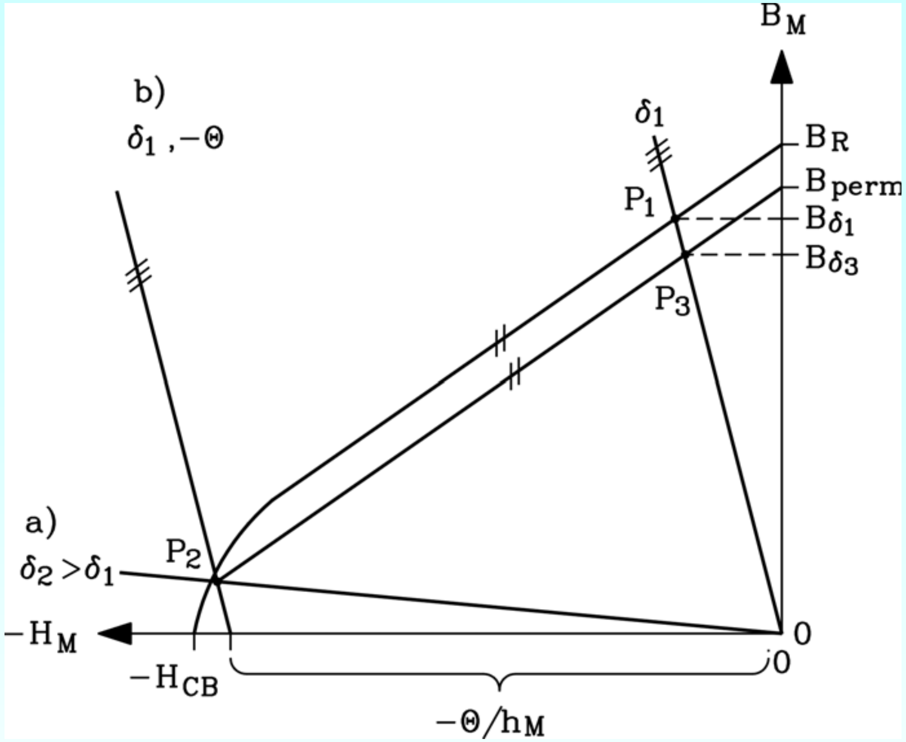
Surface mounted magnets: $A_M = A_\delta$, hence: $B_M = B_\delta$

Operation of magnets in 2nd quadrant:

$$\boxed{B_\delta = \mu_0 H_\delta = -\mu_0 \frac{h_M}{\delta} H_M = B_M}$$

Operation of magnets in 2^{nd} quadrant of *B(H)*-plane



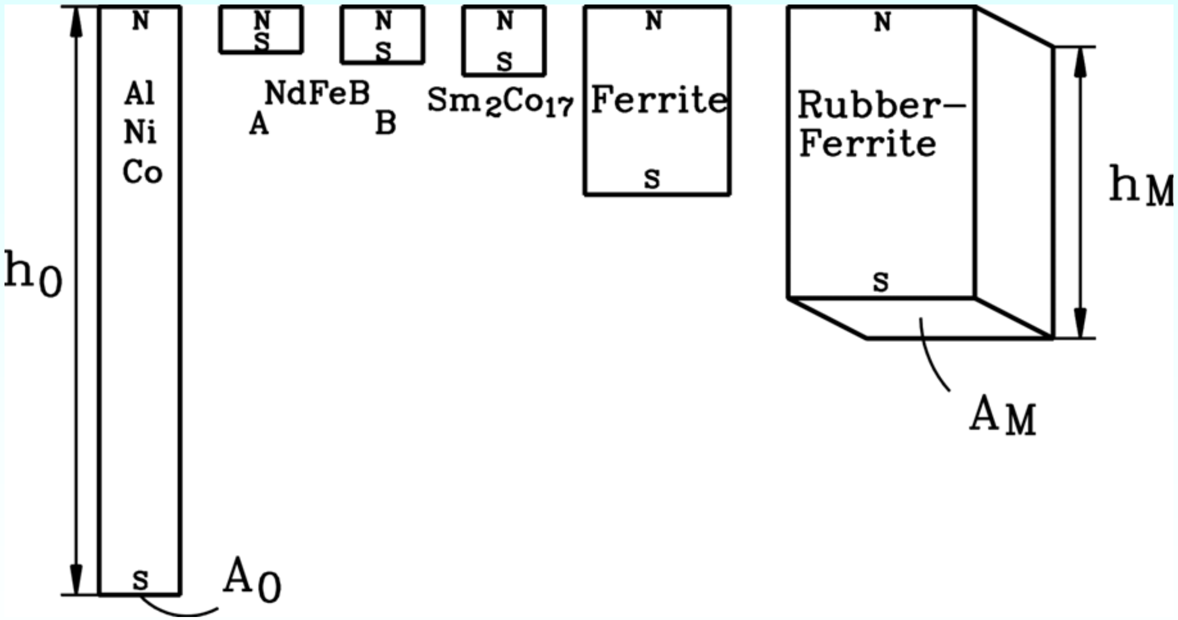


Reversible demagnetization of permanent magnet by air gap. The operating region of the magnet is the second quadrant. With increased temperature the remanence and coercive field is decreasing, yielding reduced air gap flux density according to operation points P_1 to P_4.

Irreversible demagnetization of permanent magnet a) by increased air gap $\delta_1 < \delta_2$ b) by external opposite field $-\Theta/h_M$, reaching an operating point P_2 below the "knee" of the hysteresis loop.

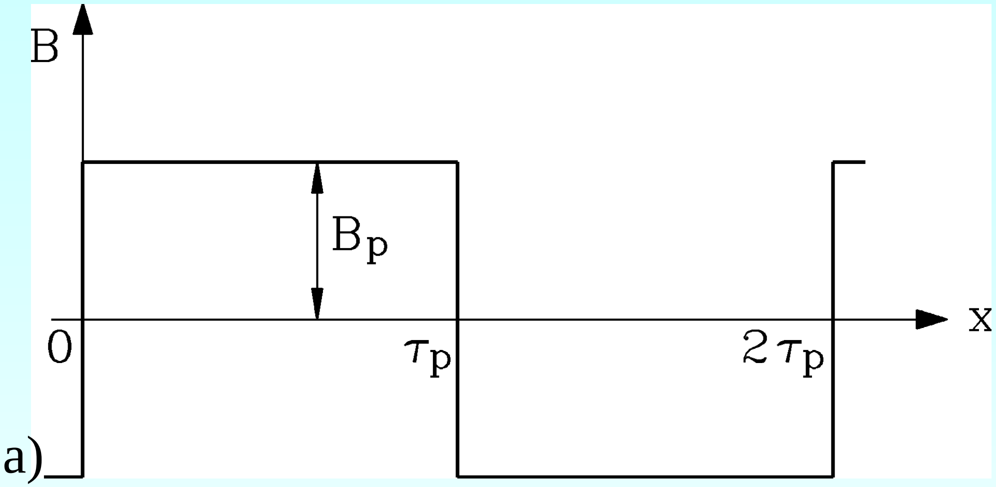
Comparison of different magnetic material for the same flux and demagnetization limit

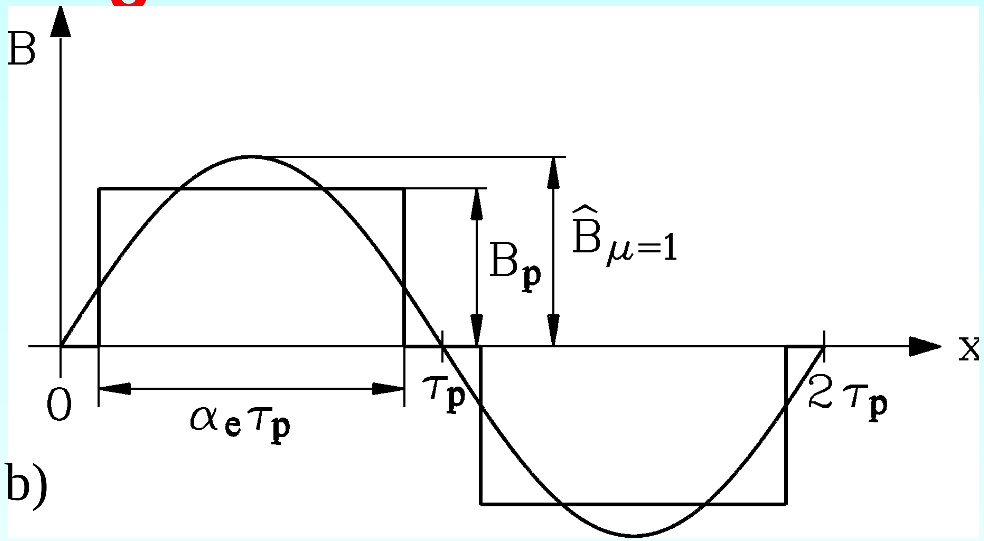
at 20°C	AlNiCo	NdFeB, A	NdFeB, B	Sm_2Co_{17}	Ba-ferrite	rubber ferrite
B_R / T	1.3	1.4	1.2	0.95	0.4	0.24
H_{CB} / kA/m	90	1100	900	710	270	175
A_M/A_0	*1*	*0.93*	*1.08*	*1.36*	*3.25*	*5.4*
h_M/h_0	*1*	*0.08*	*0.1*	*0.13*	*0.33*	*0.51*
V_M/V_0	*1*	*0.076*	*0.11*	*0.18*	*1.08*	*2.8*



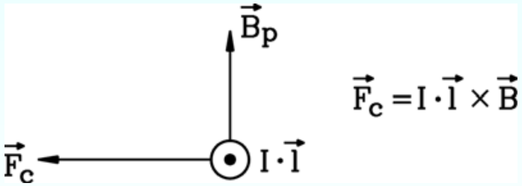
Rare earth magnets allow for the same flux and the same demagnetization limit a much smaller magnetic volume of only about 10%, which yields compact PM motors, but it is expensive.

Torque generation in PM machines with surface mounted magnets

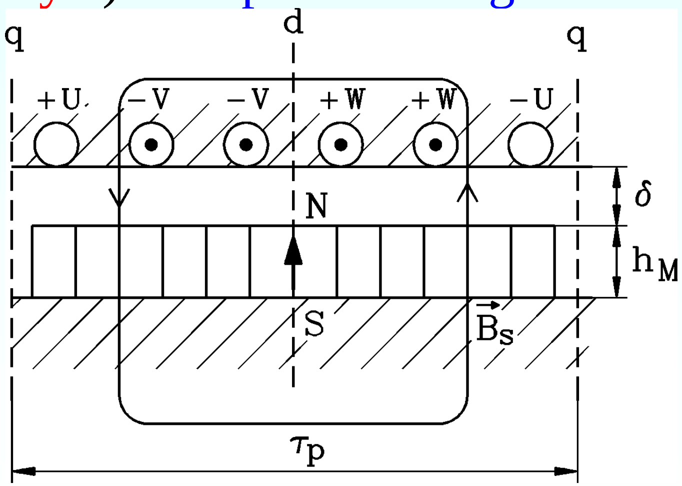




No-load air gap magnetic flux density a) with pole coverage ratio $\alpha_e = 1$, and b) with $\alpha_e < 1$



Tangential *Lorentz*-force per conductor

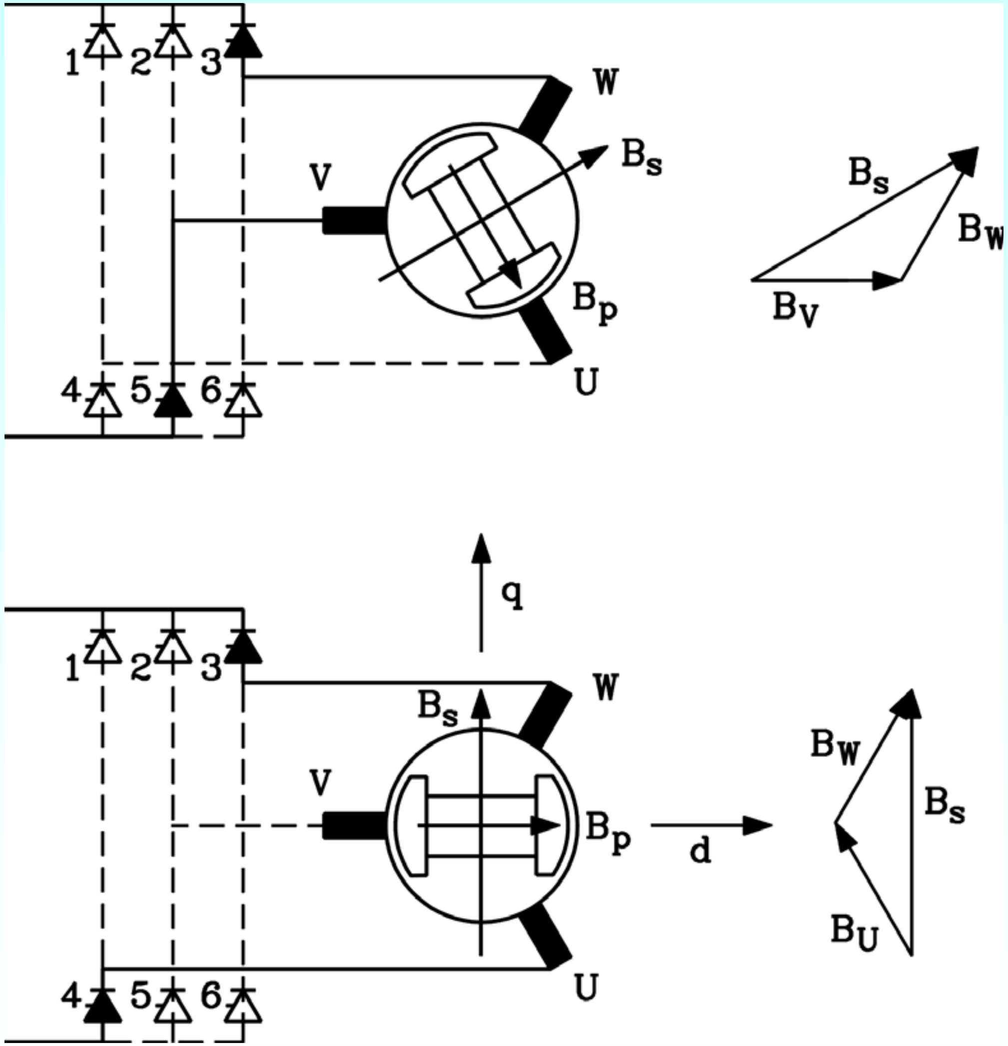


Current flow in stator coils produces with rotor PM air gap field a tangential force on rotor.

Force gives torque !

$$M_e = F \cdot d_{si} / 2$$

How to get maximum force resp. torque for given current amplitude ?



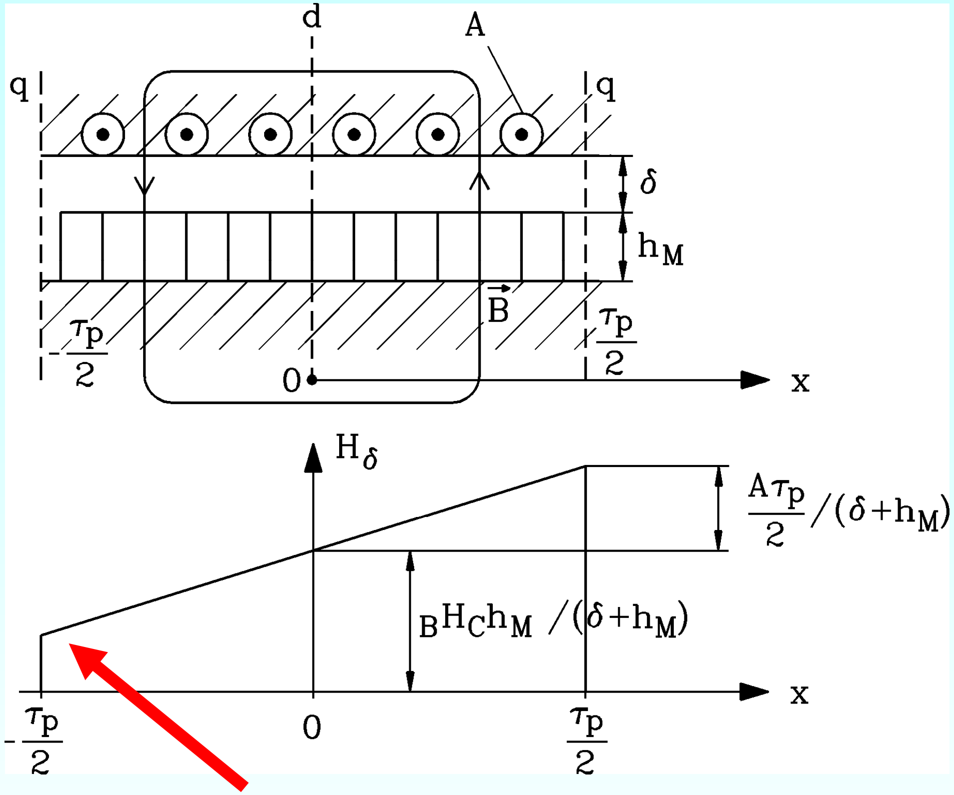
Stator air gap field B_s must be perpendicular to rotor PM field B_p to get maximum torque. The ALL phase currents have the same polarity under one pole and give there fore the **SAME force direction. This is like in DC machines = brushless DC Drive system !**

Stator field is directed into gaps between rotor magnetic poles (rotor q-axis) = q-axis current operation !

By rotor position sensor the stator currents are switched with inverter to get the right phase shift for q-current operation !

An inverter is needed !

Air gap magnetic flux density for one pole under load



„Current layer" (loading):

$$A = \Theta / \tau_p = \frac{2 \cdot m \cdot N_s \cdot I_s}{2p \cdot \tau_p}$$

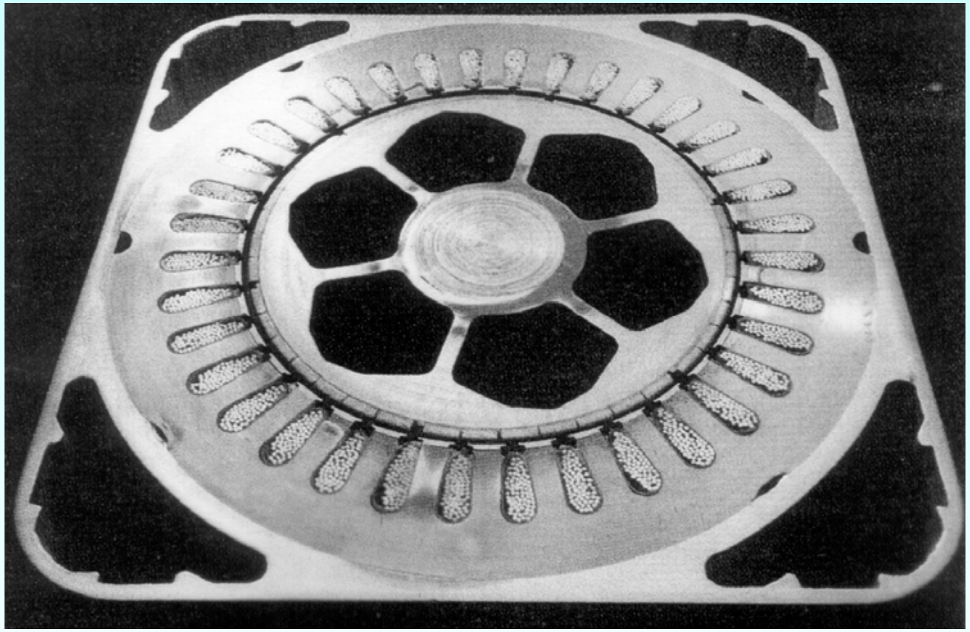
Ampere´s law gives stator field:

$$\oint_C \vec{H} \bullet d\vec{s} = 2 \cdot H_{\delta,s} \cdot (\delta + h_M) = 2 \cdot A \cdot x$$

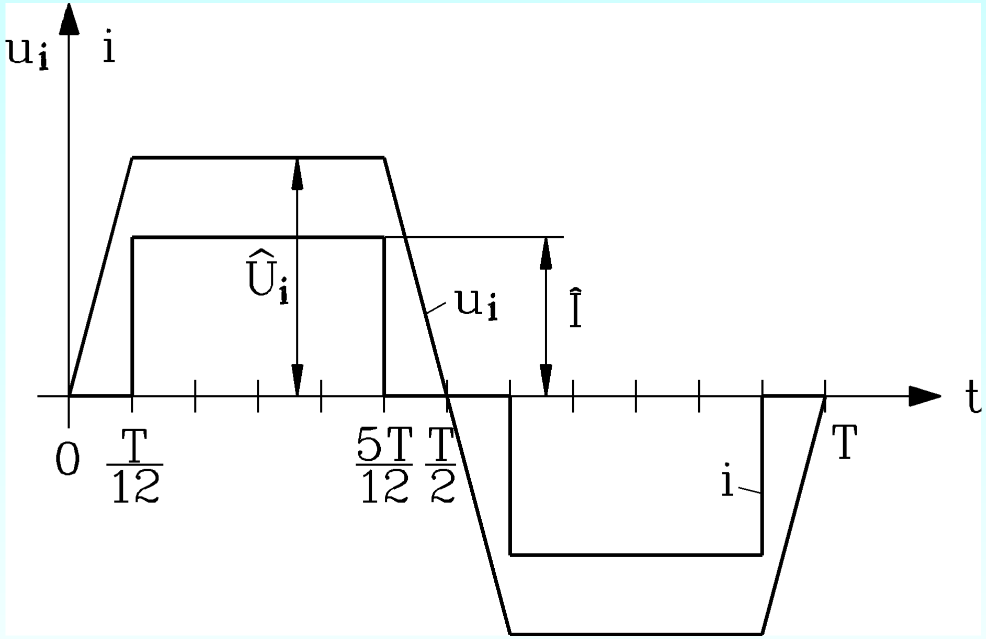
$$\Rightarrow \quad H_{\delta,s} = \frac{A}{\delta + h_M} \cdot x$$

Under load surface mounted rotor magnets experience danger of demagnetization at the trailing pole edge, especially when magnet is hot (typically 150 °C).

Block current feeding



a)

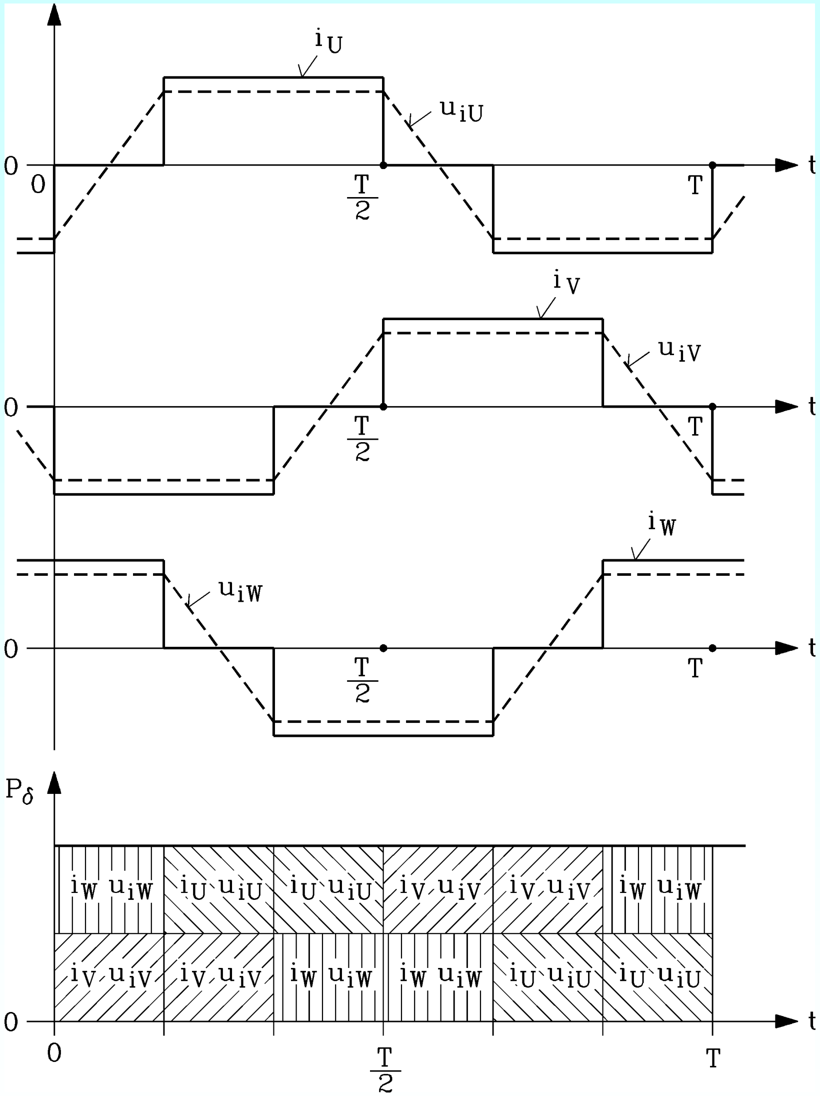


b)

a) Cross section of PM synchronous machine with 100% pole coverage ratio

b) Trapezoidal no-load stator phase voltage (back EMF); block shaped current impressed in phase with back EMF

Torque generation with block current feeding, calculated via internal power



Torque generation with block current feeding, calculated via internal power.

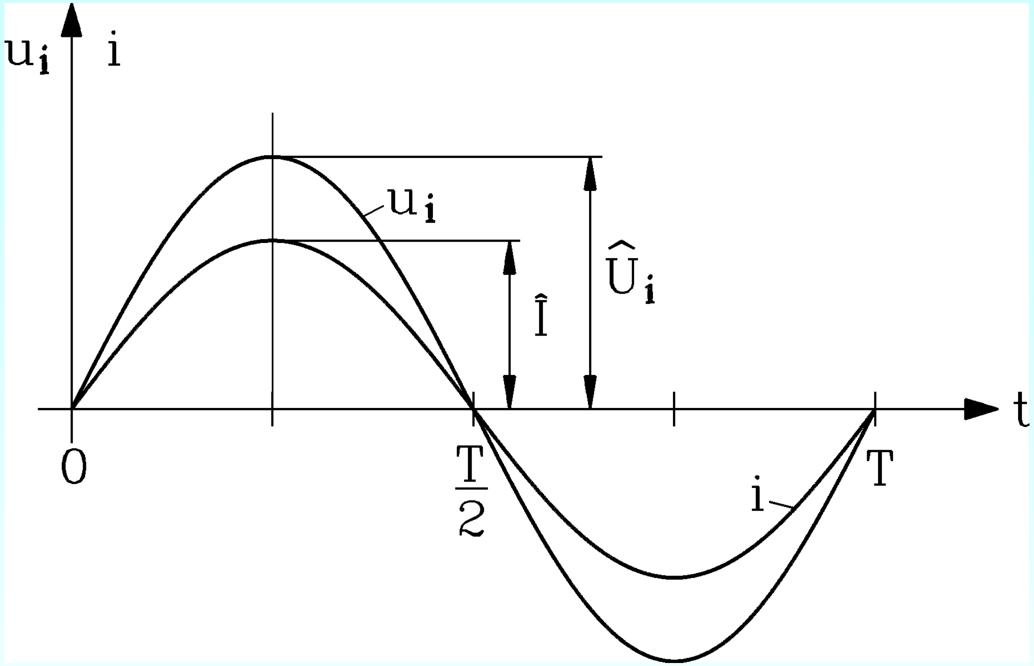
Air gap power: $P_\delta = 2\pi \cdot n_{syn} \cdot M_e$

$$p_\delta(t) = u_{pU}(t) \cdot i_U(t) + u_{pV}(t) \cdot i_V(t) + u_{pW}(t) \cdot i_W(t)$$

Electromagnetic torque: $\boxed{M_e = \frac{2 \cdot \hat{U}_p \cdot \hat{I}}{2 \cdot \pi \cdot n}}$

A smooth torque without any ripple is theoretically produced with contribution of two phases at each moment.

Torque generation with sine wave current feeding



Sinusoidal phase current is impressed by inverter in phase with sinusoidal back EMF, resulting in

a) pulsating power per phase, but

b) smooth constant power and constant torque for all three phases.

Using internal power per phase we get

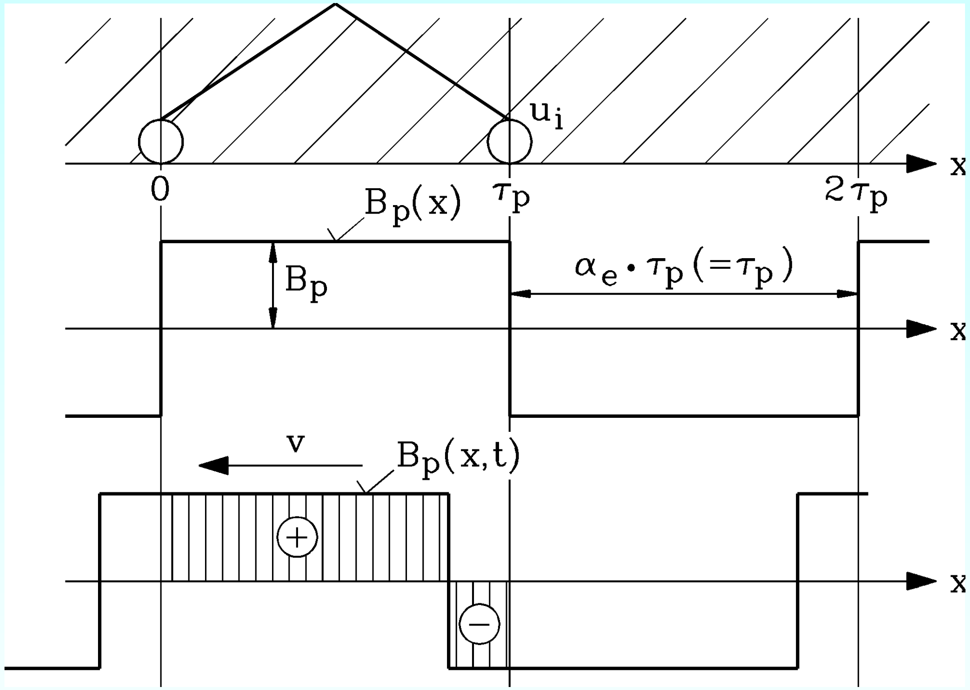
constant resulting power:

$$p_\delta(t) = \hat{U}_p\cos(\omega t)\cdot\hat{I}\cos(\omega t) + \hat{U}_p\cos(\omega t - 2\pi/3)\cdot\hat{I}\cos(\omega t - 2\pi/3) + \hat{U}_p\cos(\omega t - 4\pi/3)\cdot\hat{I}\cos(\omega t - 4\pi/3)$$

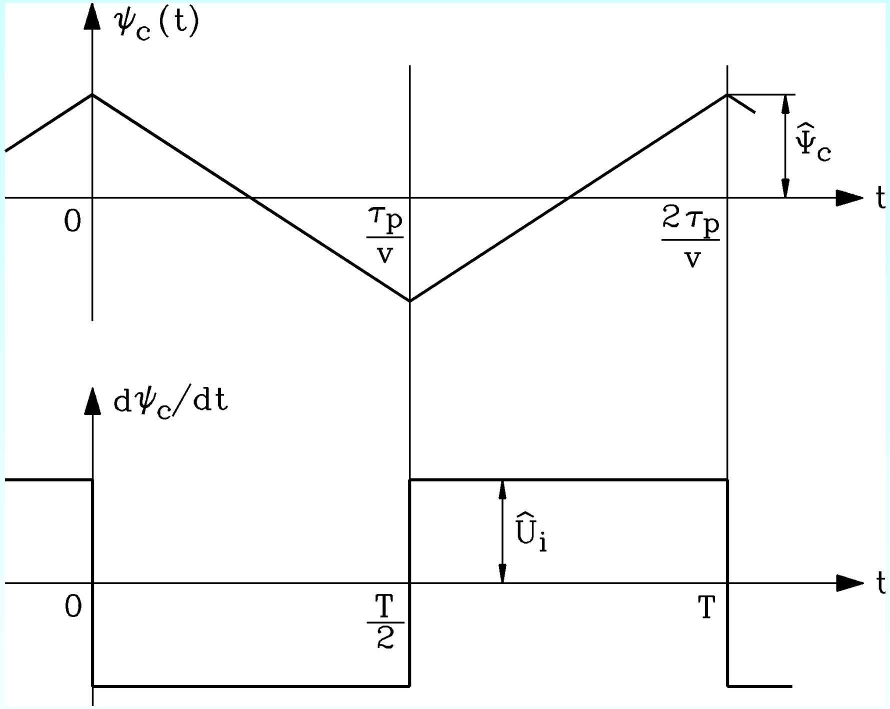
$$p_\delta(t) = \frac{\hat{U}_p\hat{I}}{2}\cdot[\cos(2\omega t)+1] + \frac{\hat{U}_p\hat{I}}{2}\cdot\left[\cos(2\omega t - \frac{4\pi}{3})+1\right] + \frac{\hat{U}_p\hat{I}}{2}\cdot\left[\cos(2\omega t - \frac{8\pi}{3})+1\right]$$

$$\boxed{p_\delta(t) = m\frac{\hat{U}_p\hat{I}}{2} = const.} \qquad \boxed{M_e = \frac{(3/2)\cdot\hat{U}_p\cdot\hat{I}}{2\cdot\pi\cdot n}}$$

Induced no-load voltage ("back EMF") in one coil at 100% pole coverage ratio



a)



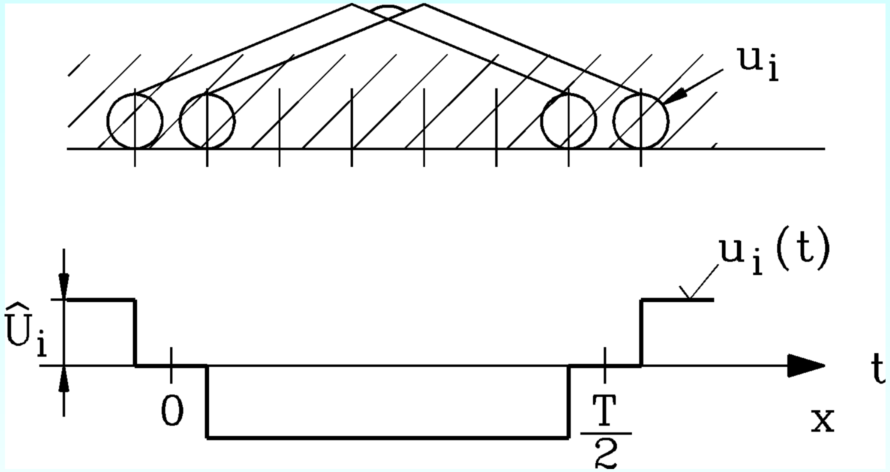
b)

a) Rectangular air gap flux density distribution = 100% pole coverage ratio leads to

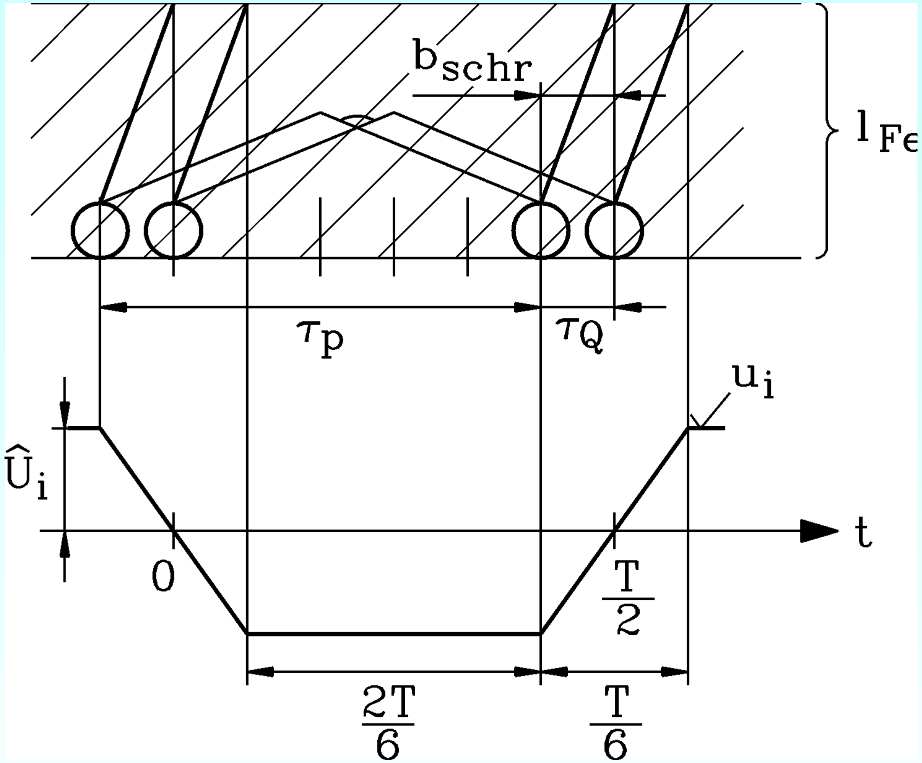
b) triangular coil flux linkage time function, causing rectangular shaped induced coil voltage $u_{i,c} = -d\psi_c/dt$

Back EMF in coil group with *q* >1 coils

Example: $q = 2$



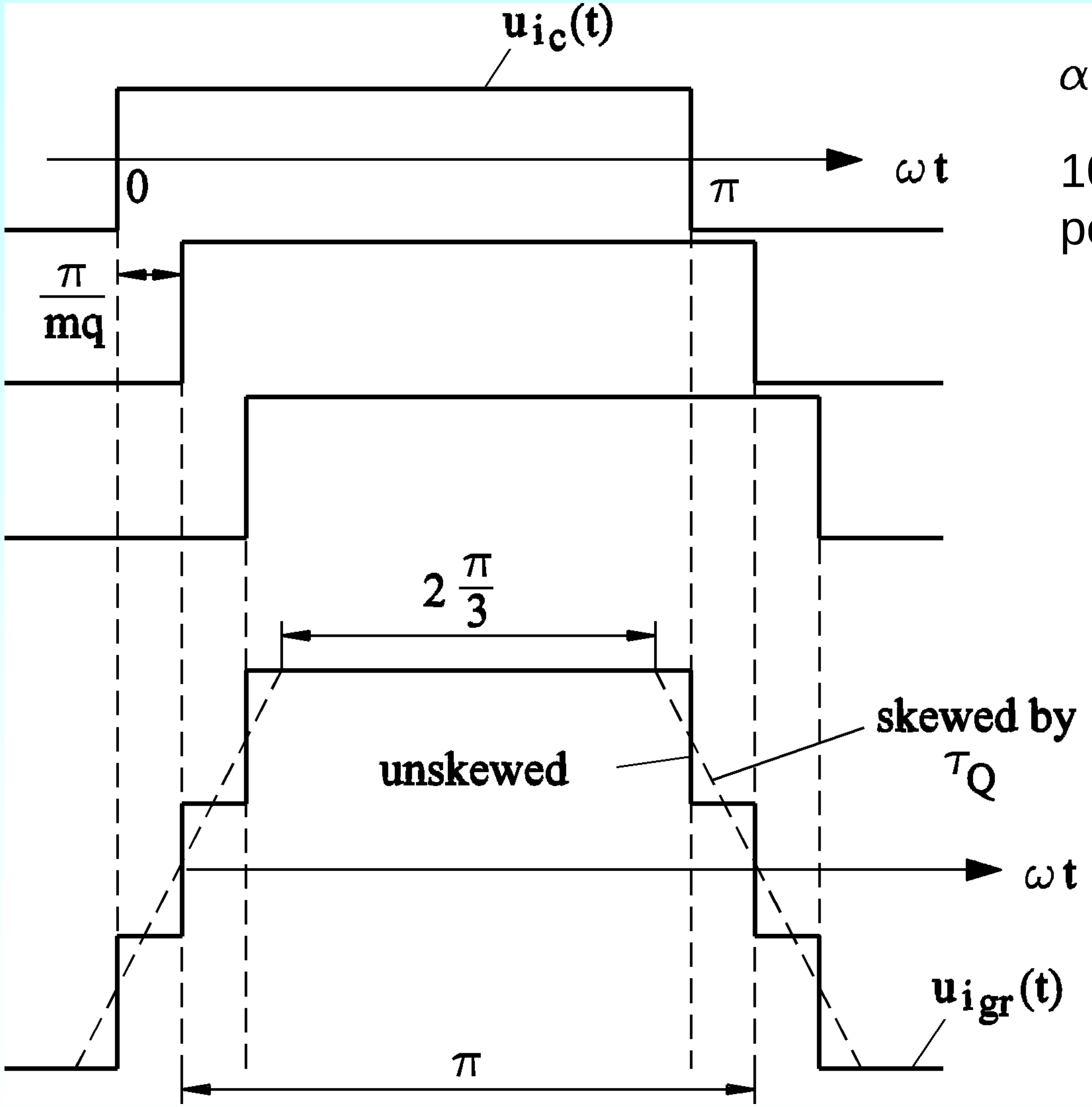
a) Unskewed coils:
The induced back EMF is step-like, when being induced by rectangular air gap flux density distribution !



b) Coils skewed by one slot pitch yield a trapezoidal back EMF

Coil skew: b_{schr} or b_{sk}

Example: Coil group with *q* = 3 coils



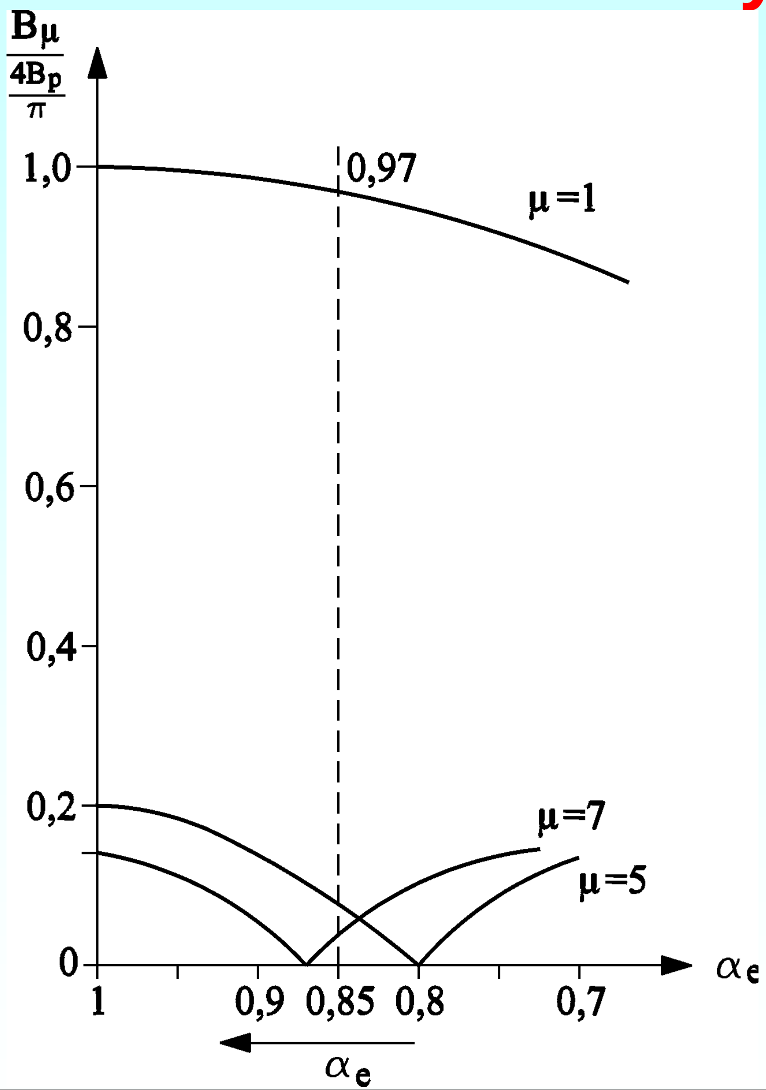
$\alpha_e = 1,\ q = 3$

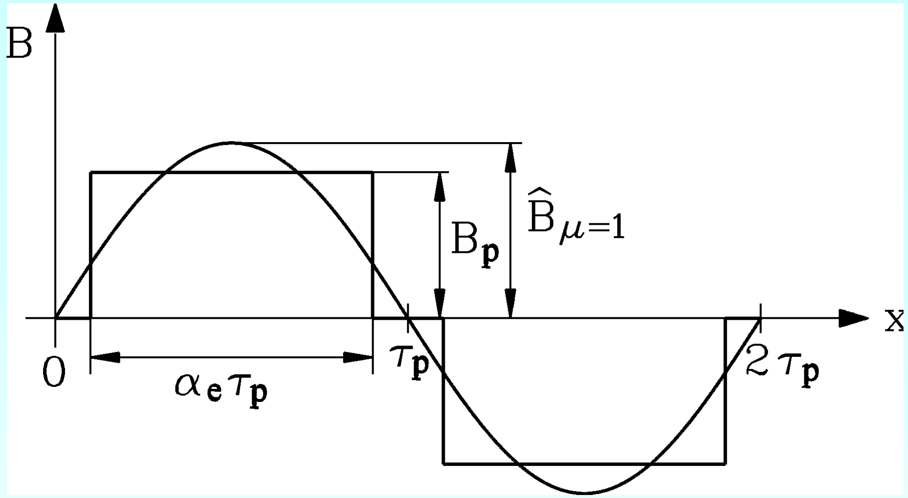
100 % pole coverage ratio, 3 slots per pole and phase

Unskewed coils:
The induced back EMF is step-like !

Coils - skewed by one slot pitch - yield a trapezoidal back EMF !

Influence of pole coverage ratio α_e on the rotor flux density amplitudes





Rotor air gap field amplitudes:

$$\boxed{B_{\delta,\mu} = \frac{4 \cdot B_\delta}{\pi \cdot \mu} \cdot \sin(\mu \cdot \alpha_e \cdot \pi / 2)}$$

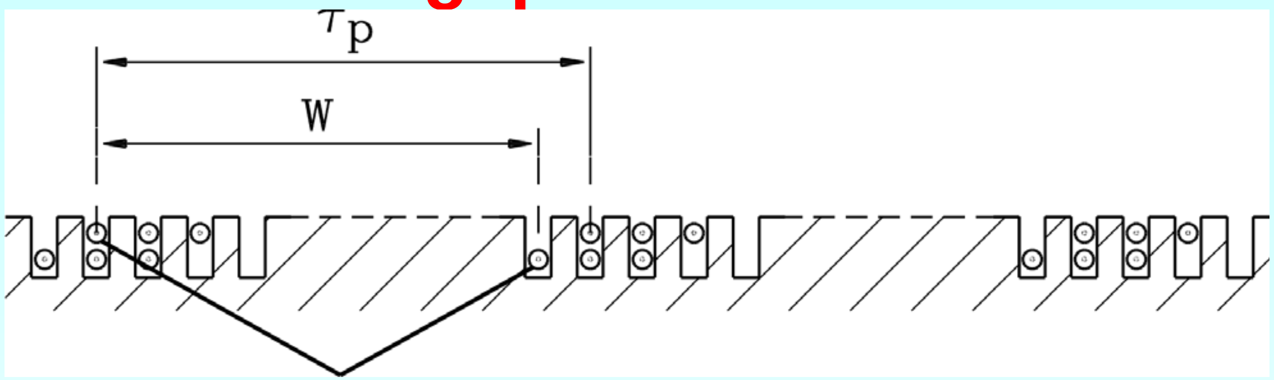
At α_e = 0.85 the fundamental amplitude is reduced by 3%, but 5th and 7th harmonic are reduced drastically.

How to get sinusoidal induced back EMF from NON-sinusoidal rotor air gap field ?

Use of pitched coils:

(= two-layer winding needed!)

Flux linkage of pitched coil:



$$\psi_{c\mu}(t) = N_c l_{Fe} \int_{-W/2}^{W/2} B_{\delta,\mu}(x,t) \cdot dx = N_c \cdot \frac{2}{\pi} \cdot \frac{\tau_p}{\mu} l_{Fe} B_{\delta\mu} \cdot \sin(\mu \cdot \frac{W}{\tau_p} \cdot \frac{\pi}{2}) \cdot \cos(\mu\omega t)$$

Pitch factor: $$\boxed{k_{p\mu} = \sin(\mu \cdot \frac{W}{\tau_p} \cdot \frac{\pi}{2})}$$

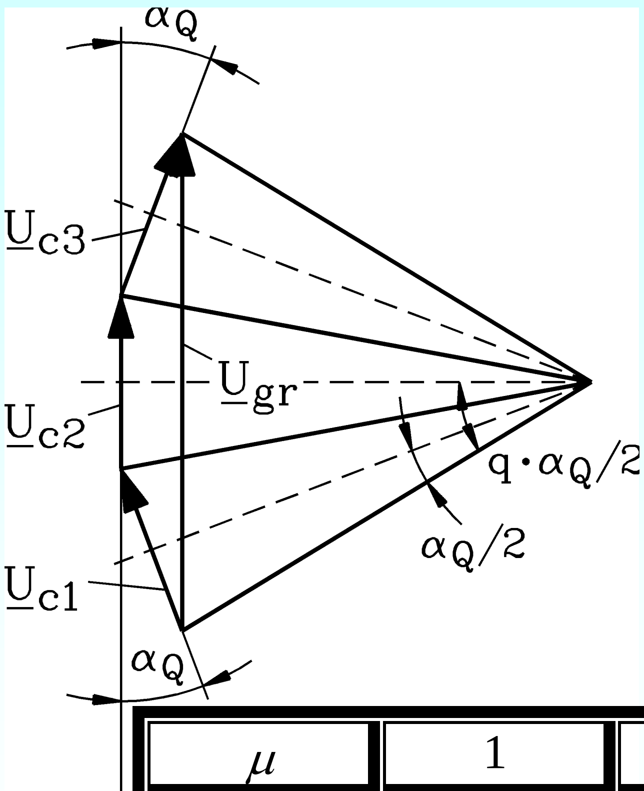
μ	1	3	5	7	9	11	13
$k_{p\mu}$	0.966	-0.707	0.259	0.259	-0.707	0.966	0.966

Reduction of coil flux linkage due to chording $W/\tau_p = 5/6$.

Coil groups help to get sinusoidal voltage !

Example: Three-phase winding, 9 slots per pole, $q = 3$ coils per pole and phase.

$$\alpha_{Q\mu=1} = \alpha_Q = \pi \cdot (\tau_Q / \tau_p) = \pi / 9 \leftrightarrow 180° / 9 = 20°$$



Distribution factor:

$$k_{d,\mu} = \frac{\hat{U}_{i,gr,\mu}}{q\hat{U}_{i,c,\mu}} = \frac{2\sin\left(q\dfrac{\alpha_{Q,\mu}}{2}\right)}{q\cdot 2\sin\left(\dfrac{\alpha_{Q,\mu}}{2}\right)} = \frac{\sin\left(\mu\dfrac{\pi}{2m}\right)}{q\cdot\sin\left(\mu\dfrac{\pi}{2mq}\right)}$$

μ	1	3	5	7	9	11	13
$k_{d\mu}$	0.960	0.667	0.218	-0.177	-0.333	-0.177	0.218

Reduction of coil flux linkage due to coil group arrangement $q = 3$.

Star connected three phase winding suppresses 3rd harmonic line-to-line voltages and 3rd phase currents

Harmonic induced voltage:

$$u_{i\mu}(t) = \mu\omega \cdot N_s \cdot k_{w\mu} \cdot \frac{2}{\pi} \cdot \frac{\tau_p}{\mu} l_{Fe} B_{\delta\mu} \cdot \sin(\mu\omega t) = U_{i\mu} \cdot \sin(\mu\omega t)$$

If the stator winding is **star connected**, the third harmonic voltages in all three phases U, V, W are IN phase and IDENTICAL:

$$u_{U3}(t) = U_3 \cdot \cos(3\omega t)$$
$$u_{V3}(t) = U_3 \cdot \cos(3(\omega t - 2\pi/3)) = U_3 \cdot \cos(3\omega t) = u_{U3}(t)$$
$$u_{W3}(t) = U_3 \cdot \cos(3(\omega t - 4\pi/3)) = U_3 \cdot \cos(3\omega t) = u_{U3}(t)$$

Therefore the line-to-line voltages show NO 3rd harmonic component:

$$u_{UV3}(t) = u_{U3}(t) - u_{V3}(t) = u_{U3}(t) - u_{U3}(t) = 0$$

$$\underline{I}_3 = \underline{U}_3 / \underline{Z}_3 \quad \Rightarrow \quad \underline{I}_{U3} + \underline{I}_{V3} + \underline{I}_{W3} = 3\underline{I}_3 = 0 \quad \Rightarrow \quad \underline{I}_3 = 0$$

Skewing helps to suppress slot harmonic back EMF

Skewing by the distance b_{sk} reduces flux linkage and therefore induced voltage further by the so-called **skewing factor**

$$\boxed{\chi_\mu = \sin(S_\mu)/S_\mu \qquad S_\mu = \frac{\mu\pi b_{sk}}{2\tau_p}}$$

Example: Six pole machine, rotor speed 1500/min, 5/6 chorded coils, q = 2, 85% pole coverage ratio, magnets skewed by one stator slot pitch

Ordinal Number	Stator frequency	Flux density	Winding Factor	Skewing factor	Induced phase voltage	Induced line-line voltage
μ	μf	$B_{\delta\mu}$	$k_{w\mu}$	$\chi_{skew,\mu}$	$U_{i\mu}$	$U_{i\mu,LL}$
1	**75 Hz**	**100 %**	**0.933**	**0.989**	**100 %**	**100 %**
3	**225 Hz**	**-26.1 %**	**0.50**	**0.900**	**12.7 %**	**0**
5	**375 Hz**	**7.9 %**	**0.068**	**0.738**	**0.37 %**	**0.37 %**
7	**525 Hz**	**1.2 %**	**0.068**	**0.527**	**0.04 %**	**0.04 %**
9	**675 Hz**	**-5.8 %**	**0.50**	**0.300**	**0.88 %**	**0**
11	**825 Hz**	**7.8 %**	**0.933**	**0.090**	**0.67 %**	**0.67 %**

Auslegungsrichtlinien für PM-Motoren

- Bemessungsgrössen: Strombelag A, Flussdichte B, Stromdichte J
  Läufer-/mittlerer Lagerdurchmesser d/ d_m, Läuferlänge l_{Fe}

- Leistung: $P \sim d^2 l_{Fe} \cdot A \cdot B \cdot n$

- Wicklungserwärmung (Stromwärme): $\Delta\vartheta \sim A \cdot J$ *(Einfluss Kühlung)*

  ABER: *Ummagnetisierungsverluste* $P_{Fe} \sim B^2 \cdot n^x$, x = ca. 1.8

  Reibungsverluste $P_R \sim d \cdot l_{Fe} \cdot n^y$, $y = 2 \ldots 3$

  Zusatzverluste $P_{ad} \sim I^2 \cdot n^z$, z = ca. $1.5 \ldots 2$

- Mechan. Spannung durch Fliehkraft: $\sigma \sim v_u^2$, $v_u = d \cdot \pi n$ *(Umfangsgeschwindig.)*

- Mechanische Steifigkeit: $f_e \sim d / l_{Fe}^2$ *(Läufer-Biegeeigenfrequenz)*

- Lagerung: Spezial-Kugellager $v_m = d_m \cdot \pi n \sim d_m \cdot n$

⇒ **Sonderkühlung / Abmessungsgrenzen / Sonderkonstruktion für Festigkeit**

Utilization of electrical machines

Electromagnetic utilization *C* ("*Esson´s number*") of electric machines is (inner) apparent machine power *S* versus speed and "bore volume" (factor $\pi/4$ neglected in that definition)

$$\boxed{C = \frac{(S/n)}{d_{si}^2 l_{Fe}}} \qquad \boxed{C = \frac{\pi^2}{\sqrt{2}} \cdot k_w \cdot A \cdot B_\delta}$$

For raising power output of a given motor, either speed can be raised or current load and flux density.

Due to **iron saturation** the air gap flux density B_δ amplitude cannot be raised much above 1 T.

Current loading *A* can be increased by increasing the current (or the number of conductors), but this also means increased losses in the stator. Therefore high current loading is only possible for intensive cooling.

"Power from speed" - "Torque from size"

Low speed machines:

a) Totally enclosed PM servo motor with self cooling (without any fan):

40.5 Nm, 1000/min, A = 145 A/cm, B_δ = 0.65 T,

d_{si} = 154 mm, l_{Fe} = 175 mm, k_w = 0.933, C = 1.0 kVAmin/m^3, P_δ = 4.24 kW

b) High torque PM motor with water jacket cooling:

737 Nm, 600/min, A = 611 A/cm, B_δ = 0.8 T,

d_{si} = 280 mm, l_{Fe} = 200 mm, k_w = 0.866, C = 4.9 kVAmin/m^3, P_δ = 46.32 kW

High speed machine: PM motor with water jacket cooling:

12 Nm, 24000/min, A = 225 A/cm, B_δ = 0.7 T

d_{si} = 90 mm, l_{Fe} = 90 mm, k_w = 0.933, C = 1.7 kVAmin/m^3, P_δ = 30.0 kW

Facit:

With only 70% higher electromagnetic utilization C the motor c) has about 7 times higher output power than motor a), as speed is increased by factor 24.