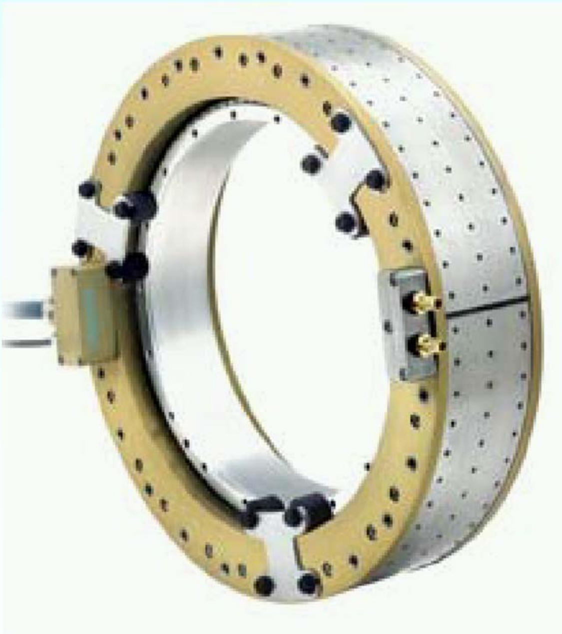
1. Permanent magnet synchronous machines as “brushless DC drives”

1.5 High torque machines

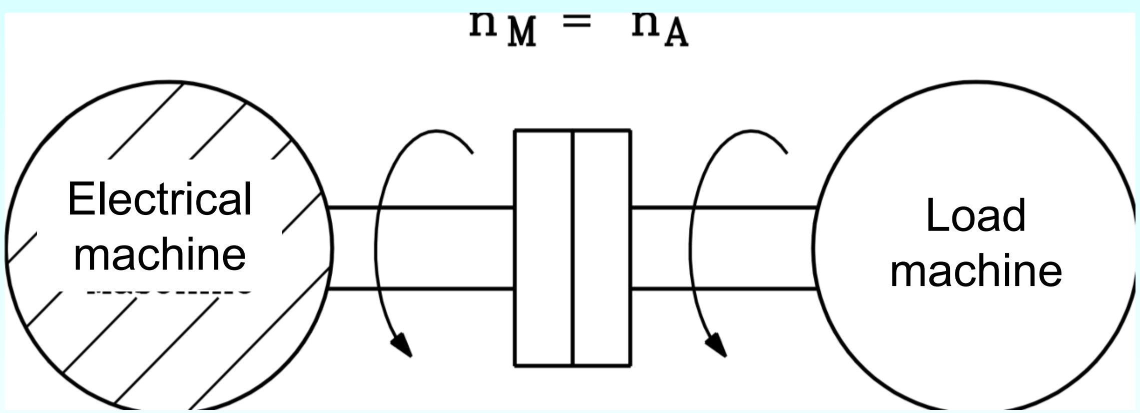


Source:
Siemens AG, München

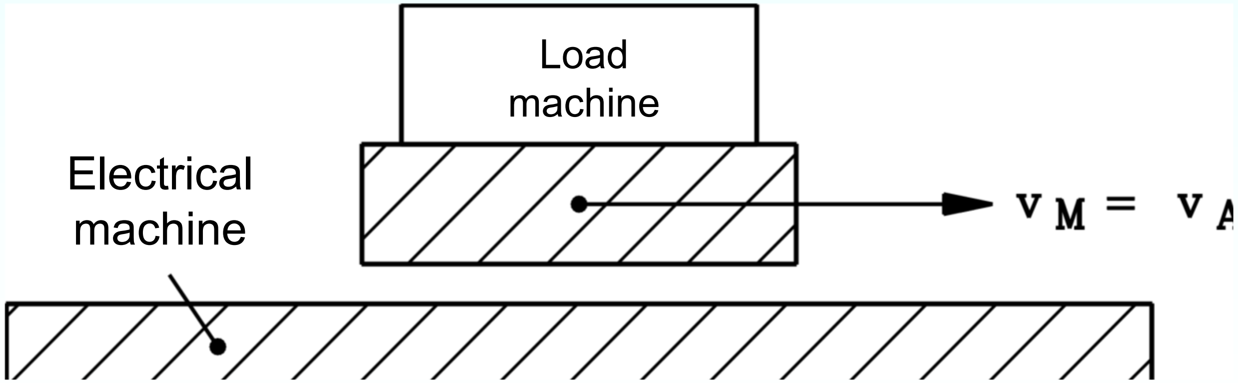
High-torque machines for direct drives

Direct drive: Electrical machine and load machine are directly coupled without any gear or mechanical transmission in between. Speed and torque of the load are identical with that of the driving motor.

Rotational direct drive:

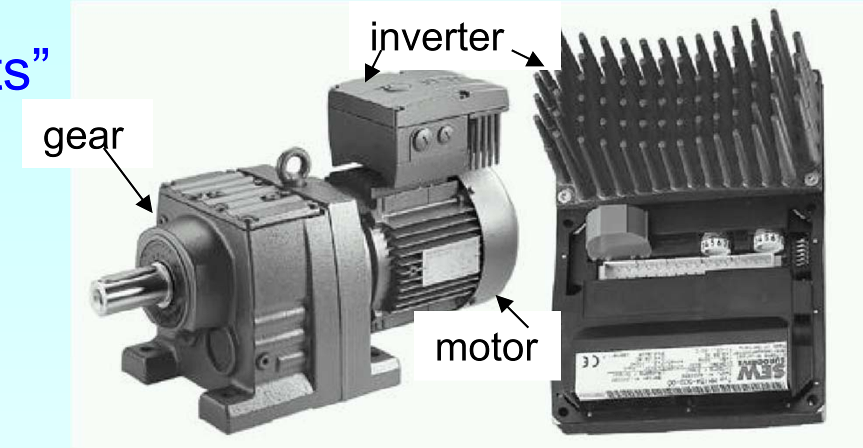


Linear direct drive:



Conventional drive technology

- Design of drives with "standardized components"
- Standard induction machines
- Grid- or inverter operation
- Gears for speed level adjustment of the load at
  - very HIGH speed
  or
  - very LOW speed



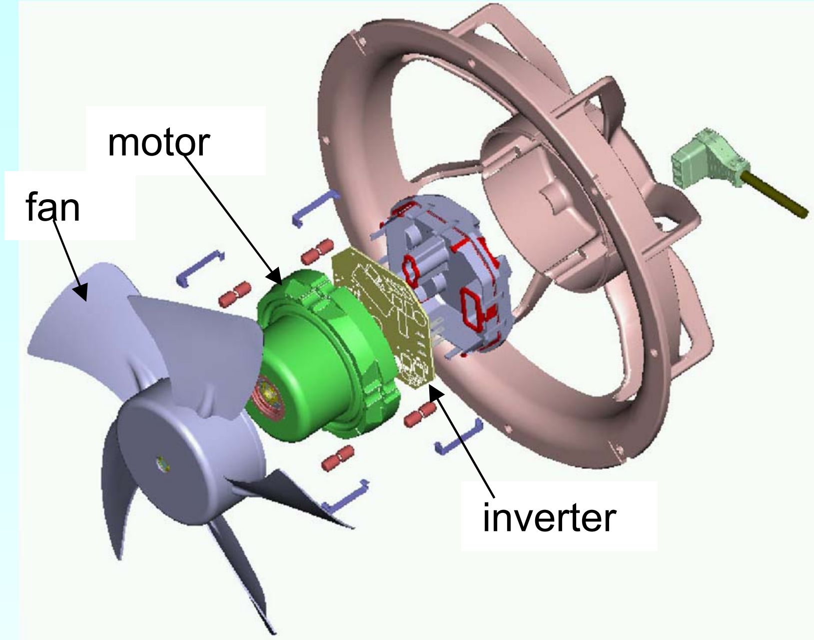
Inverter, induction motor and gear

Source: SEW-Eurodrive, Germany

- *Example A:* Very HIGH speed: Two-stage screw compressor: TEFC induction motor $2p$ =2 with inverter operation, 1st stage: n_M = 4900/min, 80.5 Hz, 90 kW, screw speed of 2nd stage: 18130/min, gear ratio i = 1/3.7 = 4900/18130
- *Example B:* Very LOW speed: Wind turbine with induction generator at the grid: Trans-standard motor $2p$=4, 640 kW, 50 Hz, 1514/min, Turbine speed 30.3/min, gear ratio i = 50 = 1514/30.3

Advantages of direct drives: NO gear

- No gear cost
- No oil
  - enhances environment safety
  - „clean“ working process
- Reduced maintenance (no oil exchange)
- Less wear (no gear teeth!)
- No gear losses (higher efficiency!)
- Reduced acoustic noise (no cog wheel frequency!)
- No mechanical play (no teeth clearance needed!)
- Increased overload capability (weak points are the gear teeth at sudden short circuit torque)
- No sealing problems (no oil loss)

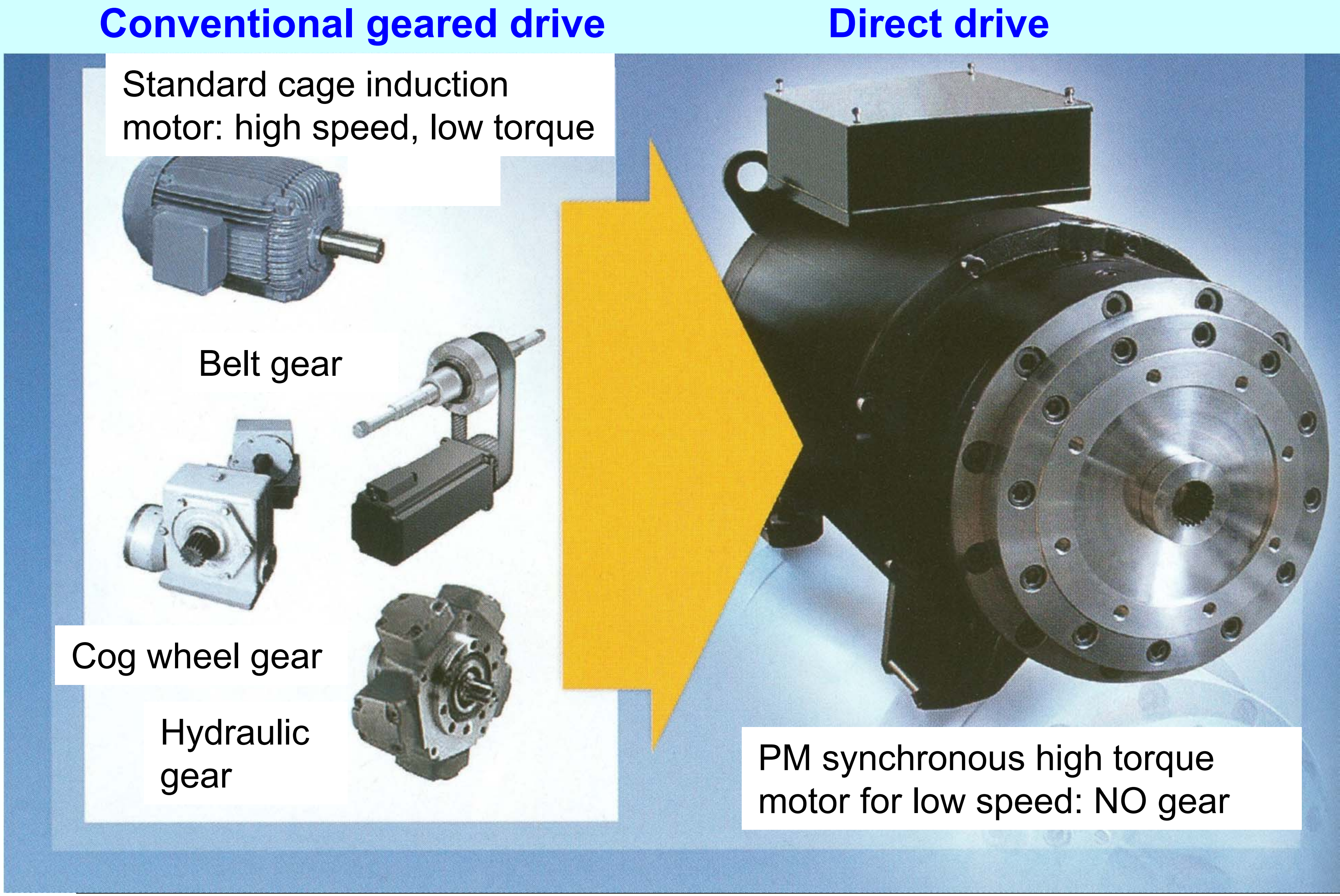


Gearless PM synchronous motor with integrated inverter as a fan drive (ca. 500 W)
Source*: ebm-Pabst, Germany*

Direct drive as integrated drive

- Compact construction through integration with less volume
- Less spare parts
- Reduced mass through reduction of "dead" masses like couplings etc.
- Increased mechanical stiffness via shorter dimensions, yielding higher natural vibration frequencies
- New design aspects for the customer via better integration of the motor into the complete system
- Additional features without much extra cost (e.g. increased mobility of large cruising ships via integrated AZIPOD-drives)

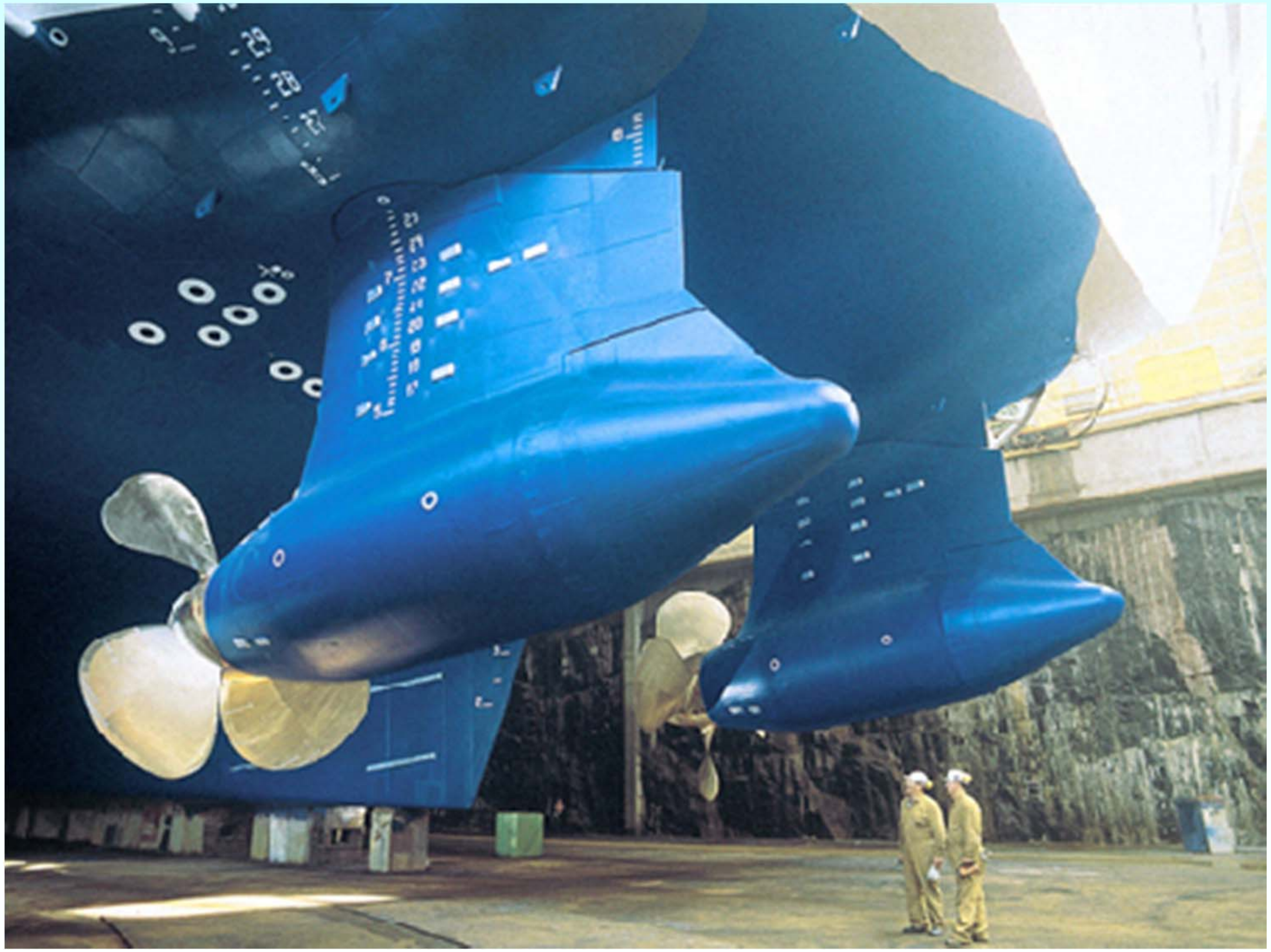
Conventional geared drive solution vs. direct drive



Source: Baumueller, Nuremberg, Germany

Example: Integrated ship propulsion drive

- Increased mobility for big ships in small harbors with gearless screw direct drives, taking over the role of the steering rudder



Smaller radius of curves of ship movement possible

Less energy via speed variation with inverter fed drives

No steering rudder

Gearless ship propulsion as AZIPOD-drive with electrically excited synchronous motor and cyclo converter, “MS Elation”, 2x14 MW, 0 ... 150/min

Source: ABB, Finland

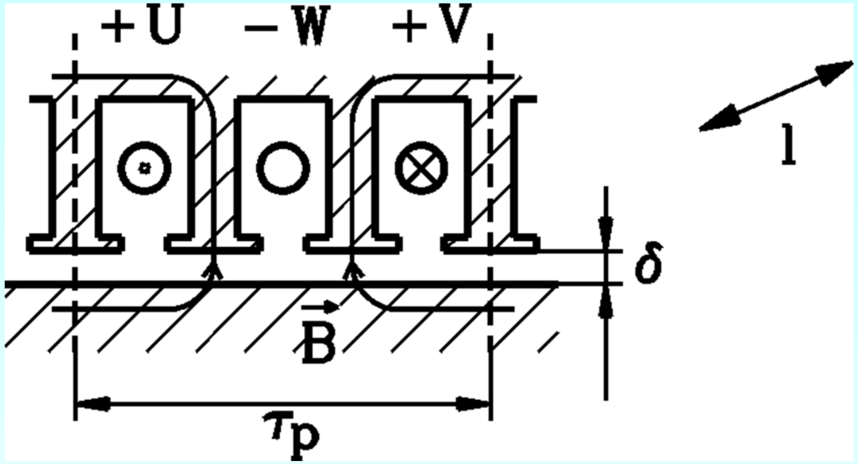
Direct drives at LOW speed and grid operation

- Grid frequency f = 50 Hz (or 60 Hz) and synchronous speed $n_{syn} = f/p$ determine the speed
- "SLOW motion": High pole count 2*p* necessary.
- Speed is constant !
- *Classical direct drive at low speed*:
  Synchronous hydro generators in river power plants

  Example: *Danube* river: Bulb turbine hydro power plant with *Kaplan* turbines and directly coupled salient pole synchronous generators with high pole count at *Freudenau/Vienna, Austria*:
  Each generator has a rating of 32 MVA, 50 Hz, 65.2/min, 92 poles

Result: At fixed speed a high pole count is necessary for low speed operation, but no speed variation is possible. For ultra-low speed (e.g. 15/min) the pole count is too high (e. g. $2p$ = 400 at 50 Hz !)!

High pole count induction machines not useful due to high magnetizing current



- Magnetizing current $I_m \sim U/(2\pi L_s) \sim \delta/\tau_p$
  Inductance per phase $L_s = L_{s\sigma} + L_h$ $\quad L_h \sim l \cdot \tau_p/\delta$
- (a) High pole count: $2p$ big $\Rightarrow$ pole pitch $\tau_p = d\pi/(2p)$ small
  (b) Mechanical lower limit for air-gap δ $\Rightarrow$ ratio τ_p/δ *too small*

	P/kW	n/min^{-1}	f/Hz	$2p$	d/m	τ_p/mm	δ/mm	δ/d /%	τ_p/δ	l/m	$\cos\varphi$	I_m/I_N
I	750	28	22.4	96	5	164	5	0.1	32.8	0.35	0.6	0.8
II	640	1514	50	4	0.45	353	2	0.4	176.5	0.66	0.91	0.27

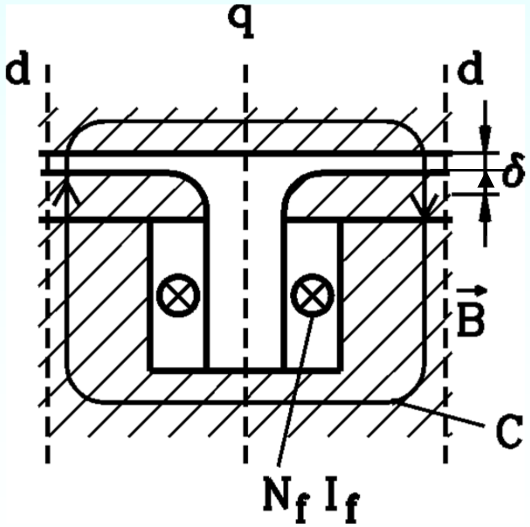
I: Direct drive with high pole count of 96 poles

II: Trans-standard induction machine frame size 400mm with gear i = 50

Electrically excited synchronous machine with high pole count

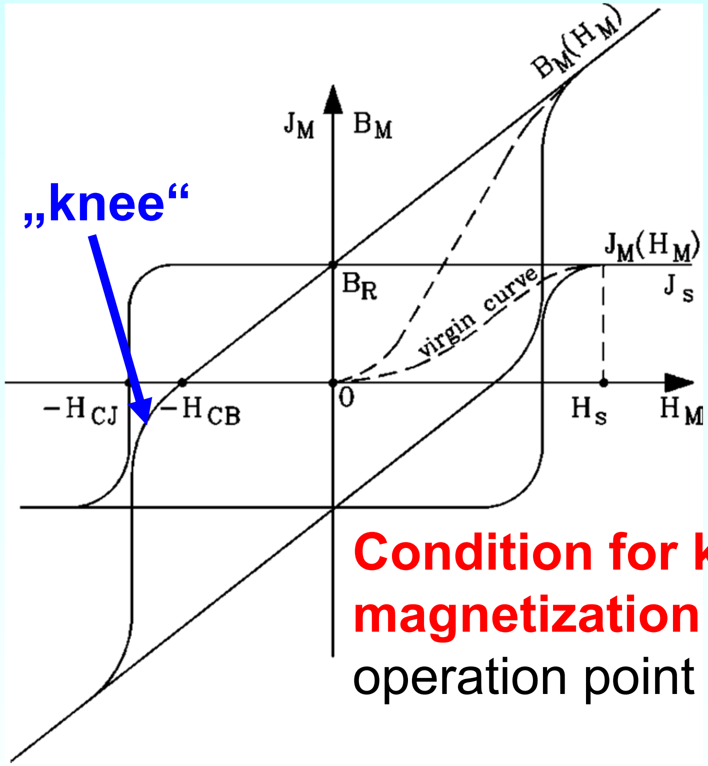
- Rotor: DC excitation of field coils, so variable over-excited operation or $\cos\varphi = 1$ possible.
- BUT: Necessary Ampere-turns increase with pole count.
  Specifications are: Torque $M \sim A \cdot B_\delta \cdot d^2 \cdot l$, temperature limit $\Delta\vartheta \sim A \cdot J$ (J: current density), so the air gap flux density B_δ is given.

  Acc. to *Ampere´s* law along curve C the flux density $B_\delta = \mu_0 N_f I_f / \delta$ **is independent of 2*p***
  ($N_f I_f = \Theta_f$: *Ampere*-turns per pole, N_f: number of rotor winding turns/pole, I_f : DC field current).
  ⇒ Excitation losses in the rotor $P_f = 2pP_{f,Pole} \sim 2p \cdot \Theta_f^2$ **increase with pole count 2*p***
  ⇒ So **permanent magnet** excitation is better especially for high pole count

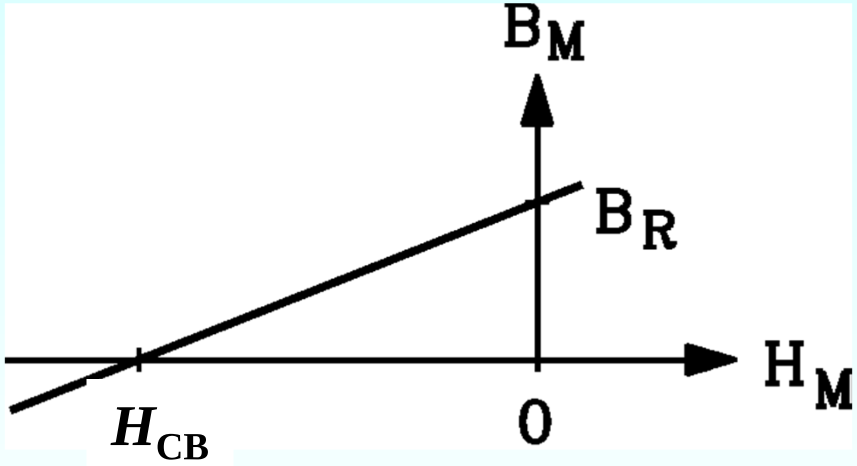


De-magnetization limit is easier kept at high pole count

- **Danger of irreversible de-magnetization** at over-load due to the stator field. Simplified condition with assumed linear magnet characteristic $B_M(H_M)$ till H_{CB}:



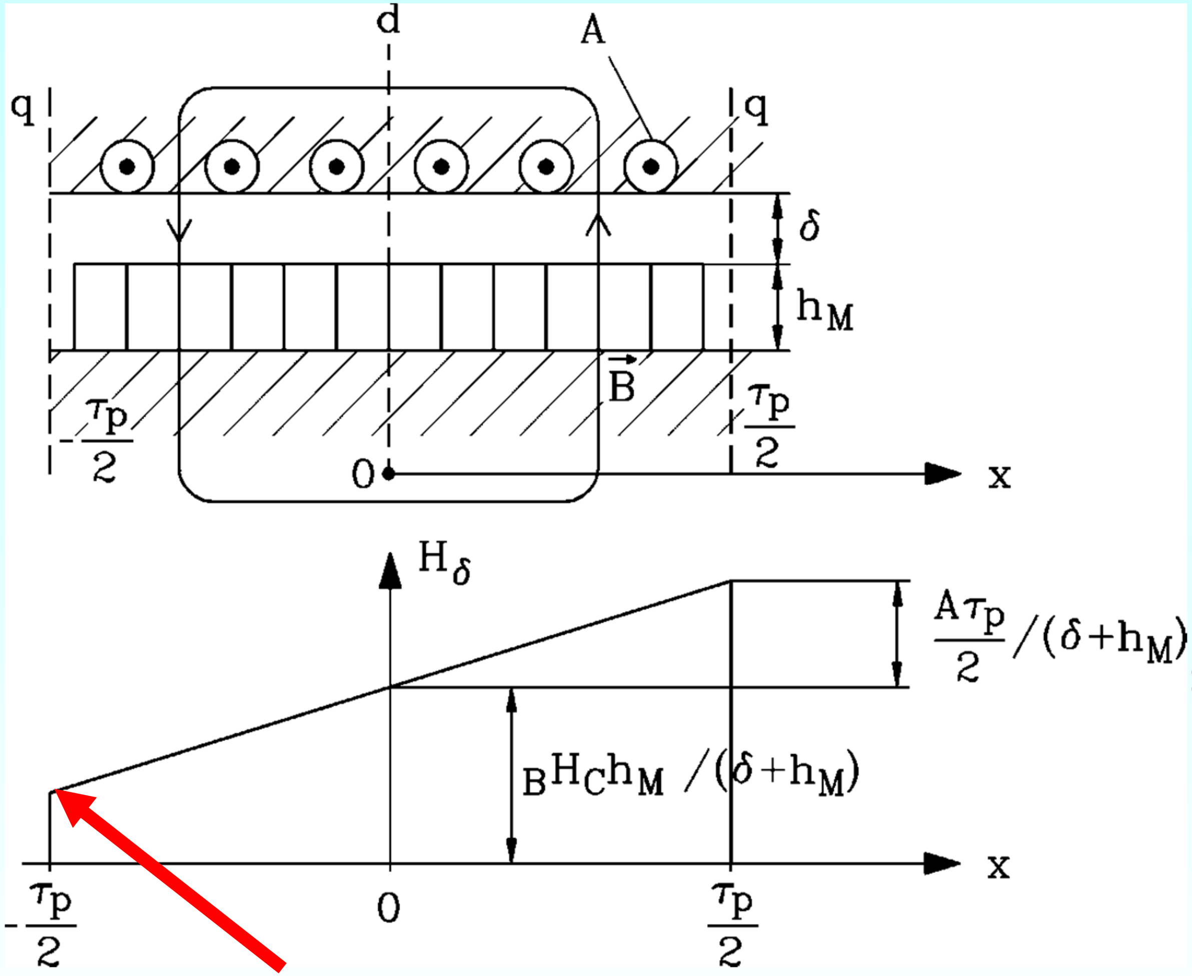
a) $H_{CB} \cdot h_M > A \cdot \tau_p / 2 \quad \Rightarrow \quad H_{CB} \cdot h_M > A \cdot d\pi / (4p)$



Condition for keeping the de-magnetization limit: Magnetic operation point above the $B_M(H_M)$-"knee"

- ***Result:*** With rising pole count $2p$ and a fixed current loading A the de-magnetizing stator field $H_{\delta,s}$ decreases, as the *Ampere*-turns per pole are getting smaller.
So permanent magnet excitation is well suited for high pole count design.

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:

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

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

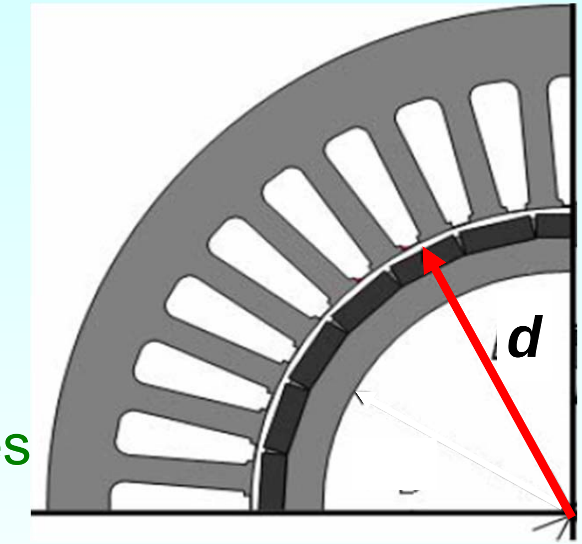
Assumption: "Knee" of $B_M(H_M)$-curve at $H_\delta = 0$: Condition for safe magnet operation without irreversible demagnetization under load: $A\tau_p / 2 < H_{CB} \cdot h_M$

Design criteria for low speed, high torque machines

High-torque machine (low speed n, high torque M):

- Big stator outer diameter d_{se}: "Disc-like" motor shape
  $M \sim A \cdot B_{\delta} \cdot d^2 \cdot l$ A: Current loading, B_{δ}: Air-gap flux density amplitude
  d: Bore diameter, l: Axial stack length

  „**Tangential thrust**“ $$\tau = F/(d\pi l) = \frac{M}{d/2} \cdot \frac{1}{d\pi l} \approx A \cdot B_{\delta}$$



- High pole count $2p$: PMSM preferred, because
  - Induction machine has big magnetizing current
  - El. excited synchronous machine has high excitation losses

- Coarse slotting due to small pole pitch (Q_s/p < 3 ... 6):
  - Distributed fractional slot winding
  - Concentrated fractional slot winding (tooth-coil winding)

  (increased harmonic field wave spectrum)

  - or

  Special machines are used: like Transversal flux machines

Source: Siemens AG

Advantages of high pole count PM motors

- ***Note:*** For constant **current load** A, **flux density** B, rotor diameter d_r, axial length l_{Fe} the motor torque is constant:

$$S_\delta = C \cdot (d_{si}^2 \cdot l_{Fe}) \cdot n_{syn} \qquad S_\delta = 2\pi \cdot n_{syn} \cdot M_e \qquad M_e = \frac{\pi}{2\sqrt{2}} \cdot k_w \cdot A \cdot B_\delta \cdot (d_{si}^2 \cdot l_{Fe})$$

- **Increase of pole count** by the ratio $x = p_2/p_1 > 1$,
  - flux per pole is reduced by $1/x$: $\Phi = B_\delta \cdot l_{Fe} \cdot d_{si} / p = (2/\pi) \cdot \tau_p l_{Fe} B_\delta$
  - yoke heights are reduced by $1/x$: $h_y = (B_\delta / B_y) \cdot (d_{si} /(2p)) \quad \Phi_y = B_y h_y l_{Fe} = \Phi / 2$
  - winding overhangs $l_b \sim \tau_p$ are shortened by $1/x$ due to reduced pole pitch.

- Result: - Copper and iron mass are reduced by increased $2p$.
  - Demagnetizing stator field is reduced: $H_{\delta,s}(x = \tau_p / 2) = \dfrac{A \cdot d_{si} \pi}{4p \cdot (\delta + h_M)}$

  Magnet height and so its mass may be reduced by $m \sim 1/x$.

Torque per mass is increased = "Torquer", "High torque machine"

Disadvantages of high pole count PM motors

- Pole increase ratio $x = p_2/p_1$

- For given speed v_{syn} the frequency has to be increased by x:

$$v_{syn} = 2 f_s \tau_p = f_s d_{si} \pi / p$$

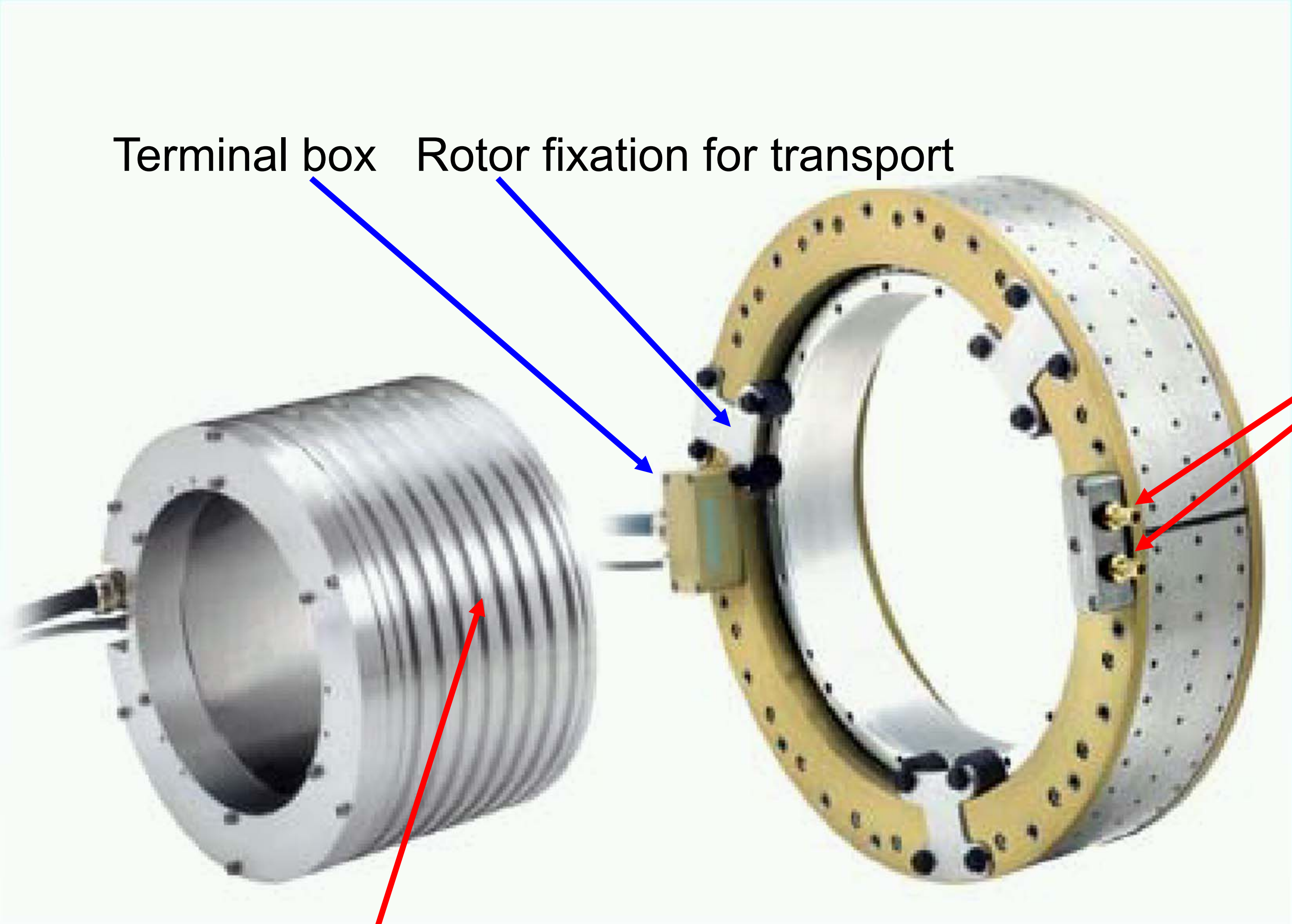
- High fundamental frequency causes increased iron losses according to

$$P_{Fe} \sim m_{Fe} \cdot f^2 \sim (1/x) \cdot x^2 = x$$

- Thus high-torque motors are especially **well suited for low speed**.

- High torque motors are **special and usually expensive**. Often a standard induction motor with gear is a cheaper for high torque, but has increased maintenance.

Examples for “High Torque” motors



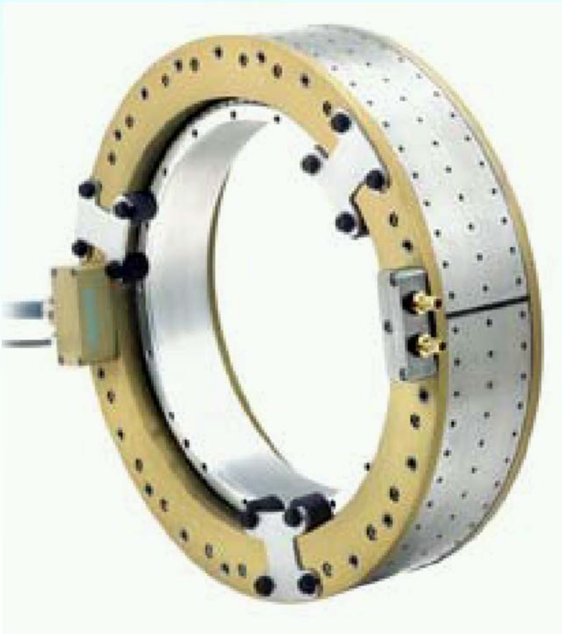
Source:
Siemens AG, Munich

Stator with spiral water channel and sealed winding overhang

Stator and PM rotor with water jacket cooling

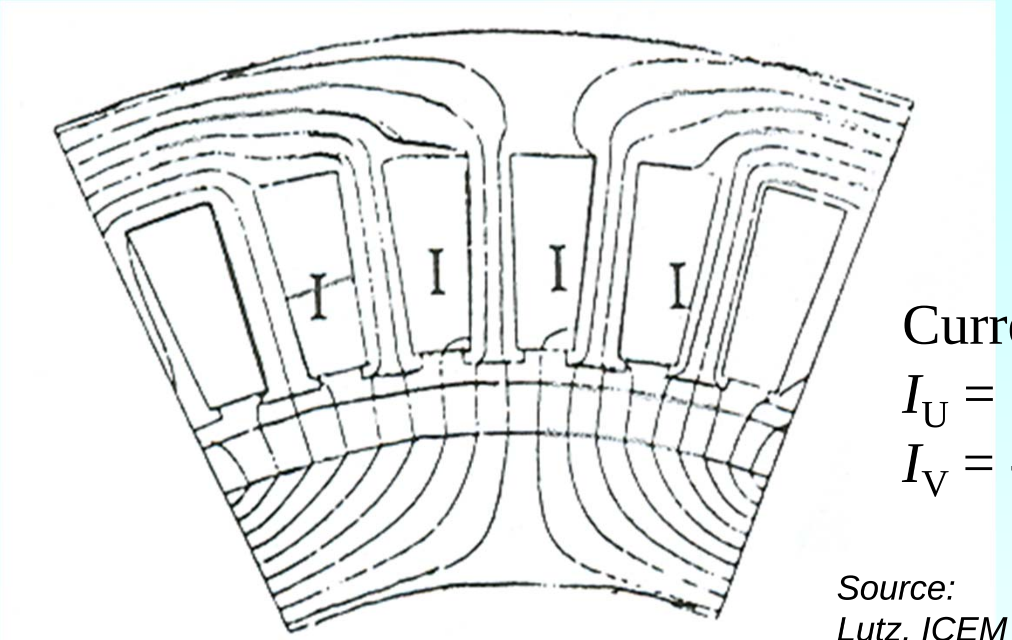
1. Permanent magnet synchronous machines as "brushless DC drives"

1.5.1 High torque machines with distributed winding



Source:
Siemens AG, Munich

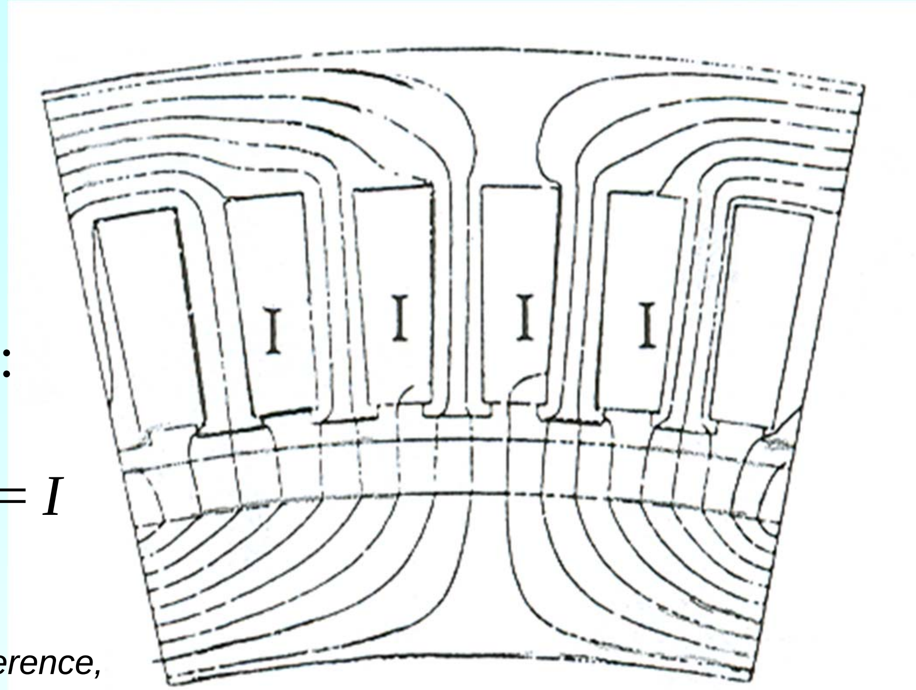
High torque machines with distributed winding



A: 8-pole

Currents:
$I_U = 0$,
$I_V = -I_W = I$

Source:
Lutz, ICEM Conference,
Vigo, 1996



B: 16-pole

Example: PM synchronous motor, 70 Nm, 100 A, sine wave commutation, stator water jacket cooling.

IDENTICAL main data of motors A and B: Same torque *M*, speed *n*, phase voltage & current *U* and *I*; current loading *A*

- *SAME* air gap flux density B_p = 0.67 T, winding current density J = 12 A/mm^2; air gap δ, q = 2, IDENTICAL slot, pole pitch, tooth width, tooth length, copper wire cross section, yoke height, winding overhangs

Calculation of mass reduction

- ***Example:*** **8- (A) and 16-pole (B)** PM synchronous motor, 70 Nm, 100 A, sine wave commutation, stator water jacket cooling.
- Main data of both motors A and B are identical:
  torque M, speed n, phase voltage & current U and I; current loading A
  air gap flux density B_p = 0.67 T, winding current density J = 12 A/mm^2;
  air gap δ, q = 2
- Same cross section of slot, pole pitch, tooth width b_d, tooth length l_d, copper wire cross section q_{Cu}, yoke height h_y, winding overhangs l_b

Motor B is derived from motor A by simply increasing the number of poles.

Result: Active mass is reduced, motor gets a ring-like shape !

Calculation of mass reduction: A vs. B

Motor	*A*	*B*	*Changes*
Pole count	*8*	*16*	+100%
Q_s	48	96	+100 %
d_{si} / mm	95	190	+100 %
l_{Fe} / mm	305	76	-75 %
R_s / mOhm	25	19	-25 %
NdFeB magnet mass / kg	1.25	0.79	-36 %
Iron active mass: yoke, teeth/ kg	17.2	8.3	-50 %
Copper mass / kg	3.1	2.3	-25 %

Torque $M \sim A \cdot B_p \cdot d_{si}^2 \cdot l_{Fe}$

Yoke mass $m_y \sim d_{si} \cdot h_y \cdot l_{Fe}$

Teeth mass $m_d \sim Q_s \cdot b_d \cdot l_d \cdot l_{Fe}$

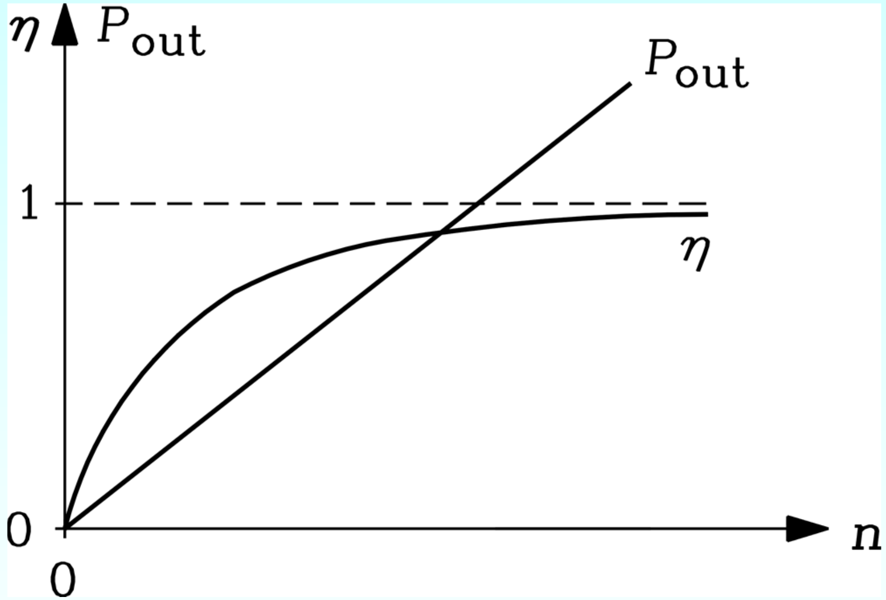
Copper mass $m_{Cu} \sim q_{Cu} \cdot N \cdot 2(l_{Fe} + l_b)$

Winding resistance $R_s \sim N \cdot 2(l_{Fe} + l_b) / q_{Cu}$

Do low speed machines have a good efficiency ?

- At a given rated torque the efficiency rises at dominant I^2R-losses with the speed.
- Because: Torque $M \sim A \cdot B_{\delta} \cdot d^2 \cdot l_{Fe} \sim p \cdot \Phi I$ = "Flux x Current"

  Efficiency $\eta = P_{out}/P_{in} \approx 2\pi nM / (2\pi nM + mRI^2)$ $m = 3$ *(three-phase winding)*



- Alternative: High-speed drive with gear: Gear losses also reduce efficiency

  Example: Wind turbine drive system

  (a) Conventional drive: 640 kW – Induction generator, $2p = 4$, 1514/min: $\eta_G = 96.6\%$

  Gear $i = 50$ (two-stage): $\eta_{Gear} = 97.0\%$ $\Rightarrow \eta = \eta_G \eta_{Gear} = 93.7\%$

  (b) Direct drive: 750 kW – permanent magnet excited synchronous generator: $\eta = 95.3\ \%$
- *Facit:* Also low-speed drive with good overall efficiency available.

Examples for low speed, high torque drives

- **Rotating mill drives:** High pole count electrically excited synchronous machines with cyclo-converter feeding, since 30 years well established, MW-power range at ca. 10/min, machine integrated around the mill body.
- **Straight-Flow turbines:** Horizontal *Kaplan* or propeller turbines with the rotor of the synchronous generator fixed to the turbine blades: Grid-operation, since 30 years well established, MW-power range, ca. 50..100/min, integrated turbine-generator drive system.
- **Ship propulsion:** Electrical or PM excited synchronous motors with cyclo-converter feeding, MW-power range, manufactured as Pod-Drives: They feature improved cooling by the sea water, improved efficiency due to speed variation, better ship mobility in small harbors, short rotating shafts.
- **Wind turbines:** Directly coupled synchronous generators with electrical or PM excitation, built up to 6 MW, IGBT-voltage DC link inverter feeding.
- **Wheel hub drives:** Geared induction machines or gearless PM synchronous machines, 50..100kW-power range, for street cars, heavy trucks etc. with IGBT-voltage source inverter feeding.
- **Elevator drives:** Gearless inverter-operated PM synchronous machines, integrated with the rope drum, extra room for drive system can be spared.

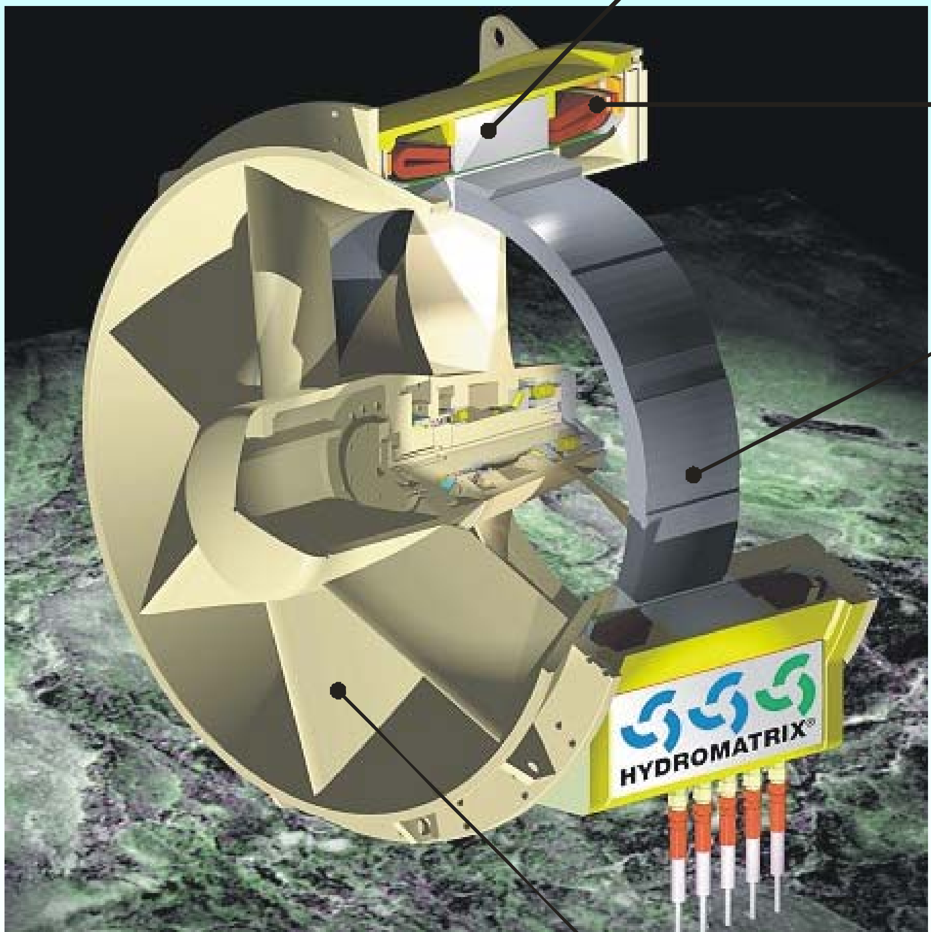
Example: PM-Generator for „Small Hydro Power"

Straight flow
Turbine with PM-rotor at outside of blade runner

Cylindrical tube is sealing stator bore

PM-rotor is running in water without any sealing

Application e.g. in matrix turbines



Source: Andritz Hydro, Austria

Generator operates at the grid, copper cylinder as damper cage necessary

Matrix turbine arrangement „Small Hydro Power“

Freudenau power plant, River Danube, Austria

Djebel Aulia, River Nile, Sudan

Matrix turbine:

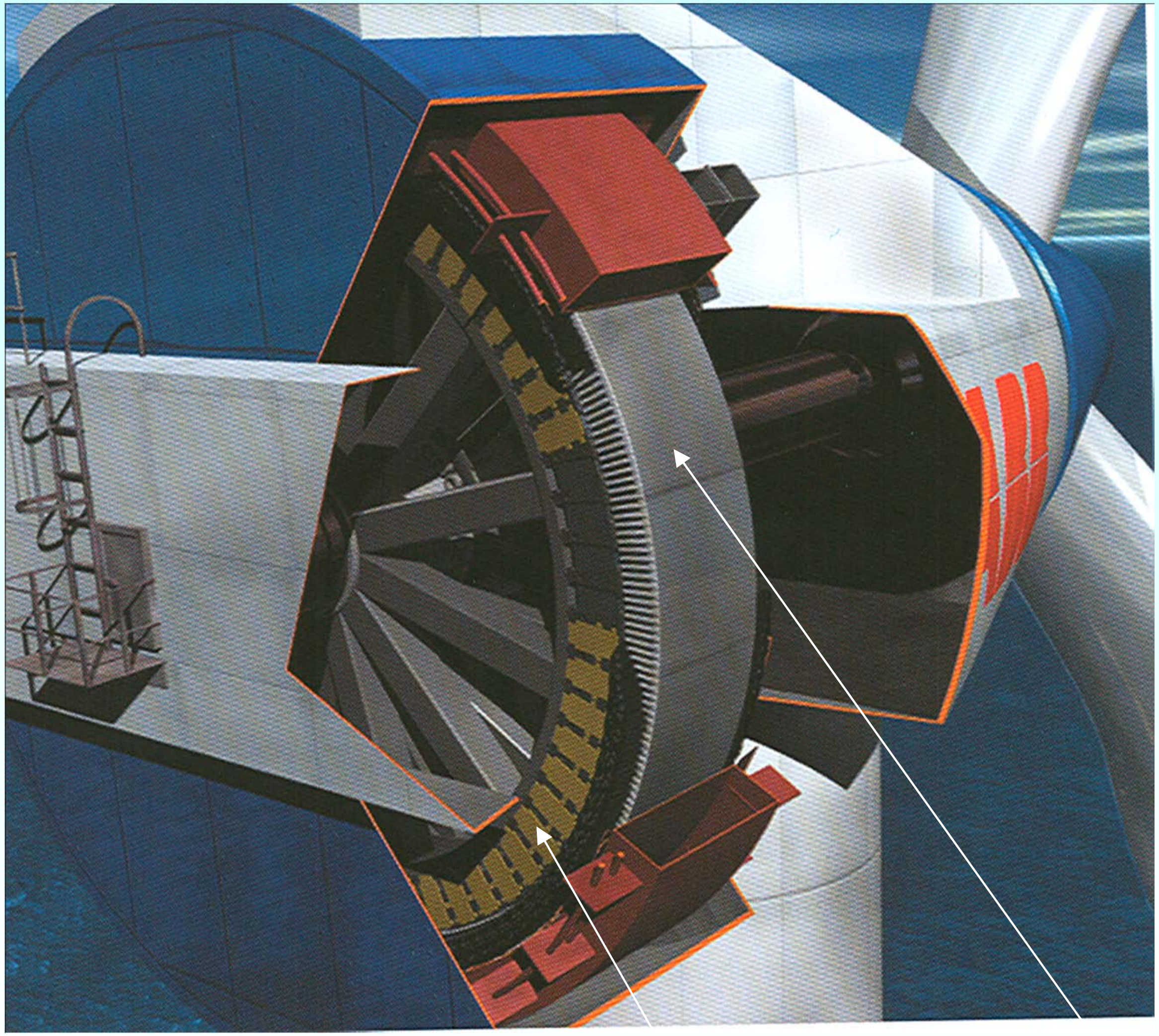
e.g. with induction generators

Source: Andritz Hydro, Austria

Use of river water for electric energy generation: Integration of many small *Kaplan*-turbines with fixed blades (propeller turbines) in river dams

Asynchronous generators need inductive reactive power: Compensation with capacities necessary, hence: PM-generators are better used !

Integrated gearless wind generator



High pole count generators: small yoke height.

Machine is easy to integrate in nacelle: **"Ring generator"**

Source: ABB, Finland

Design example: Ferrite Magnet Rotor

Stator with 3-phase winding

Example: Gearless wind turbine

Data of wind generator with NdFeB-magnets:

3 MW, 606 V, 3360 A, frequency 13.6 Hz (inverter needed)

cos phi = 0.85 under-excited, 17 / min, efficiency 95.5%

Rated torque: 1685 k Nm (!)

Outer diameter of generator: ca. 5.8 m, axial length: ca. 2.3 m

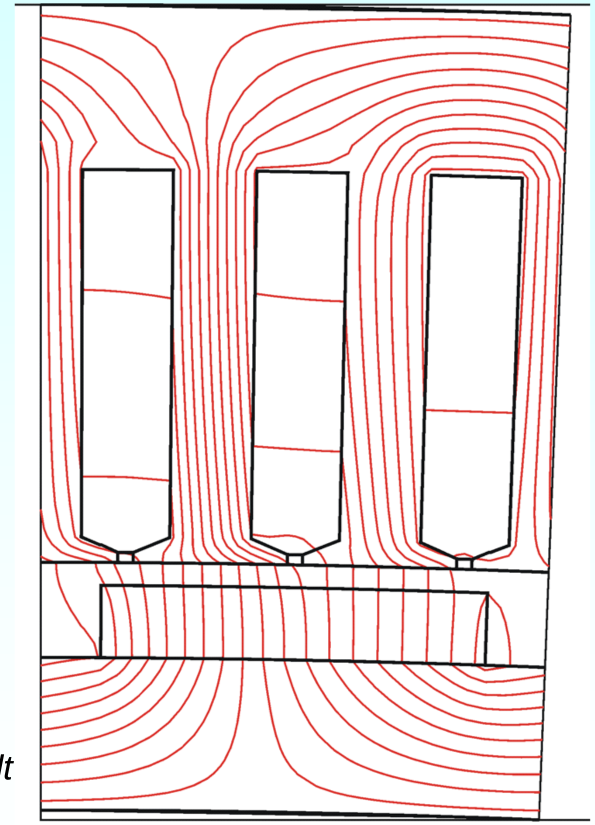
mass ca. 85 t, high pole count: typically 90 ... 100 poles

Scanwind project, Norway

Source: Siemens AG

Example:
q = 1, m = 3,
one pole pitch,
full load field

Source: TU Darmstadt

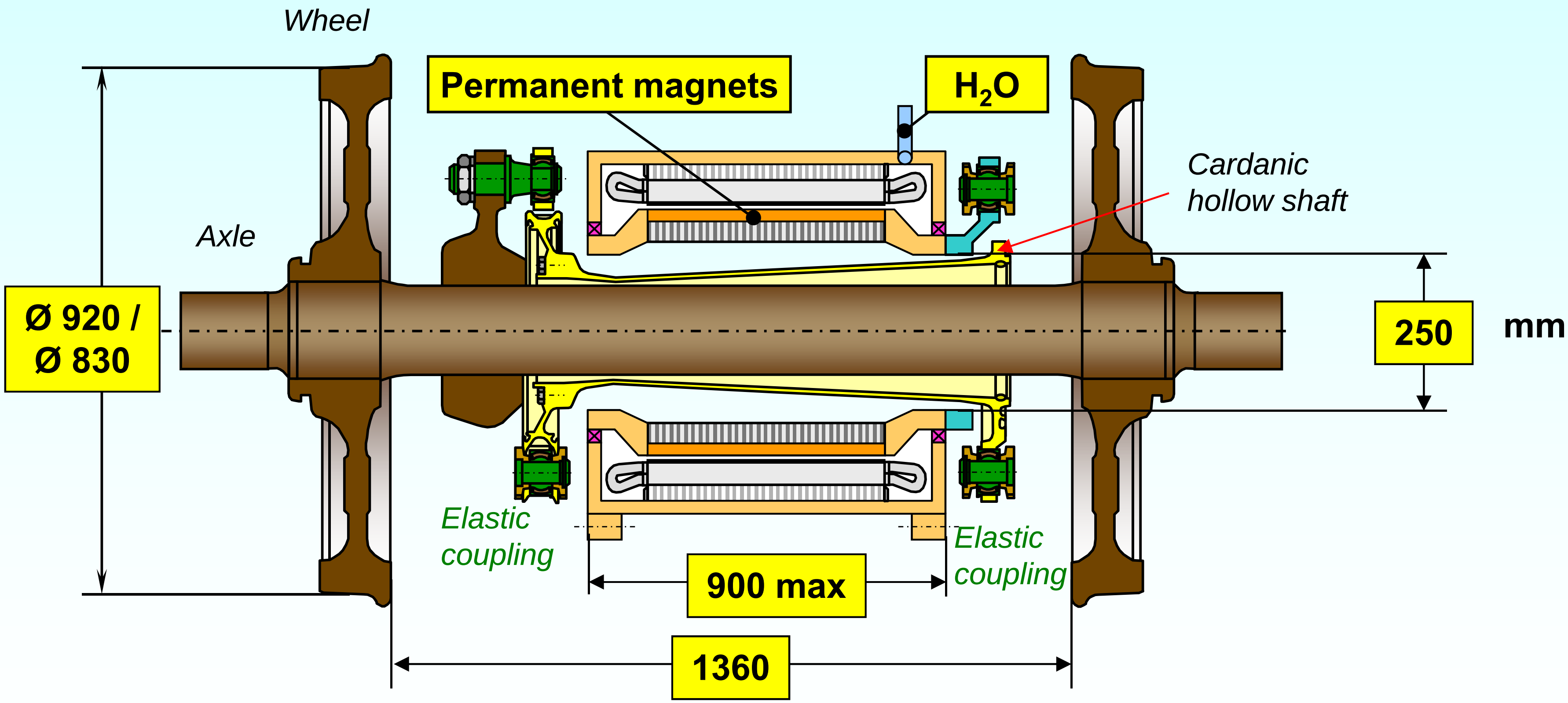


ICE3-direct drive with PM-Motor: no gear, low motor-speed

Prototype drive: Rated power of motor 500 kW

Cardan hollow shaft as elastic coupling between motor and axle

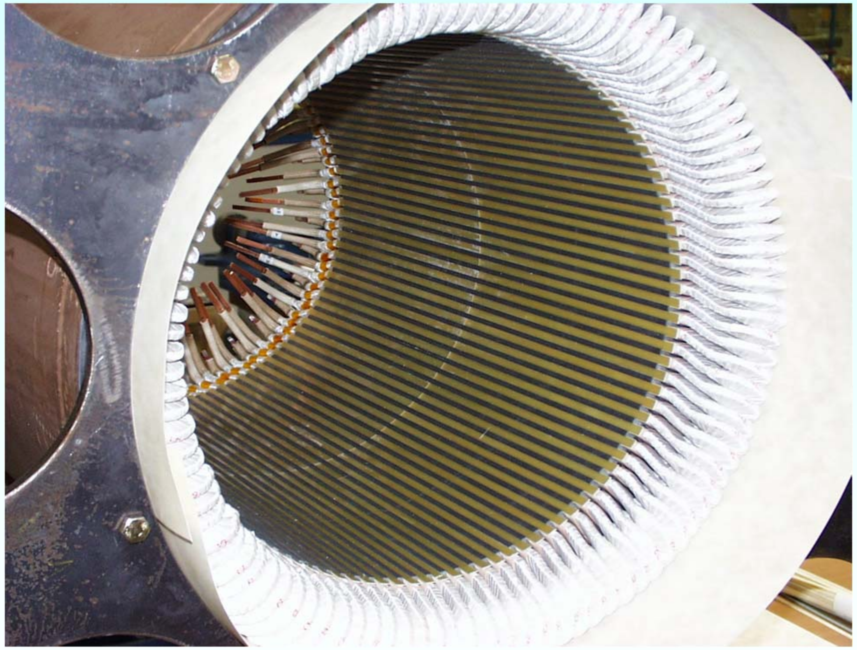
Motor speed up to 2100/min, corresponds with 330km/h



Source:
Siemens AG

ICE3 direct drive: Prototype manufacturing

- Standard-Form wound coils, MICALASTIC-T® Insulation system Thermal Class 200
- Standard steel sheets M330-50A (= 3.3 W/kg at 50 Hz, 1.5 T) in stator
- NdFeB-Magnets on rotor surface
- Bandage on rotor, made from glass fiber Polyglass®



Stator winding „white = green“ before resin impregnation, q = 1.5

Source: Siemens AG

Magnets glued to rotor before bandage is wound on rotor

Distributed integer and fractional slot winding $q \geq 1$ (1)

- Integer slot winding: q is integer number!
- Fractional slot winding: q is fractional number: $q = q_Z/q_N$

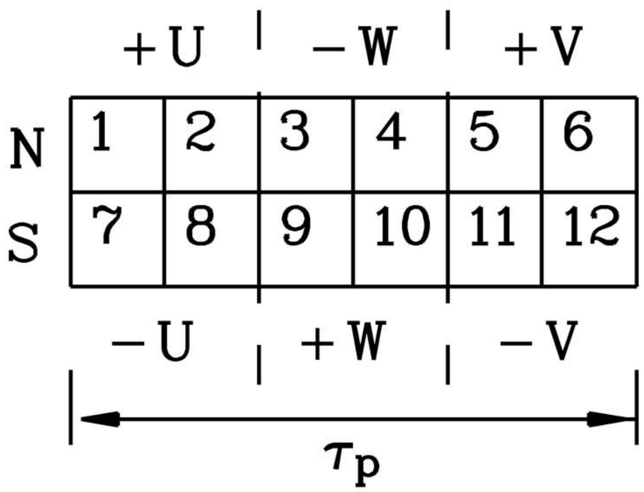
$$q = \frac{Q}{2p \cdot m}$$

Example: q = 2, pitched double-layer three-phase distributed winding

TINGLEY-scheme: phase belt and slot numbering arranged in a row for each pole, until winding scheme repeats periodically

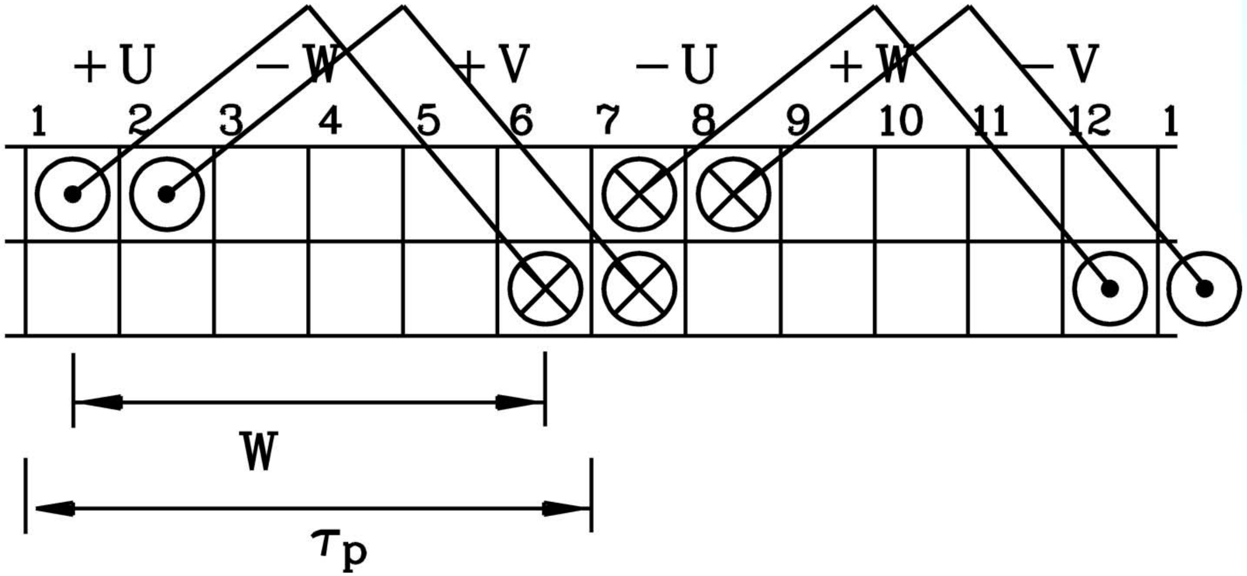
N- and S-pole field profile are identical: Field harmonics with only odd ordinal number occur!

$$\nu = 1 + 2mg = 1 + 2 \cdot 3g = 1, -5, 7, -11, 13, \ldots \quad g = 0, \pm 1, \pm 2, \ldots$$



Coil groups of phase U

Pitching W/τ_p = 5/6



Distributed integer and fractional slot winding $q \geq 1$ (2)

- Integer slot winding: q is integer number!
- Fractional slot winding: q is fractional number: $q = q_Z/q_N$

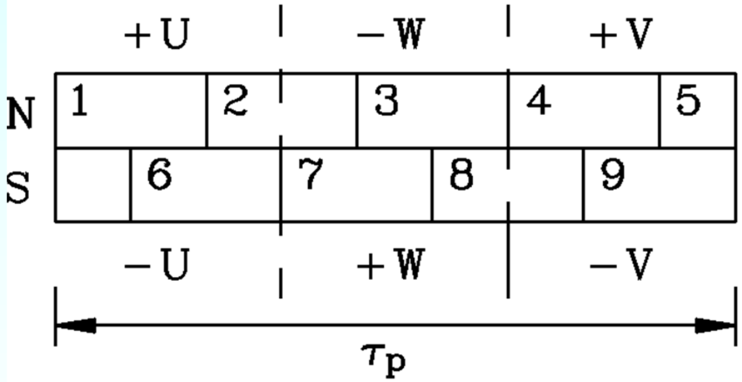
$$q = \frac{Q}{2p \cdot m}$$

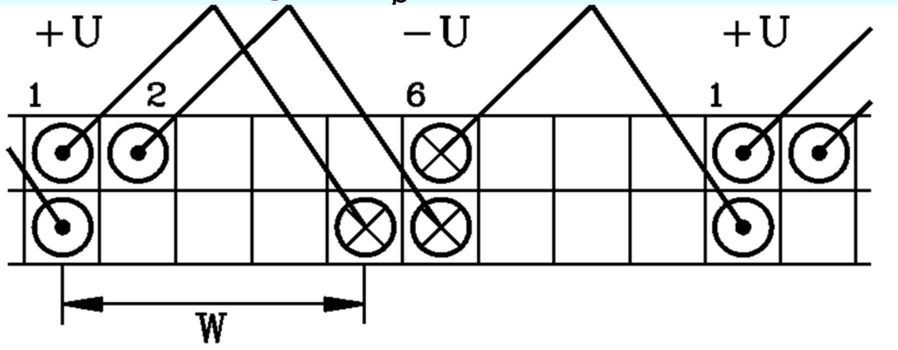
<u>Example:</u> $q = 1.5 = 3/2$, pitched double-layer three-phase distributed winding

Coil groups of phase U

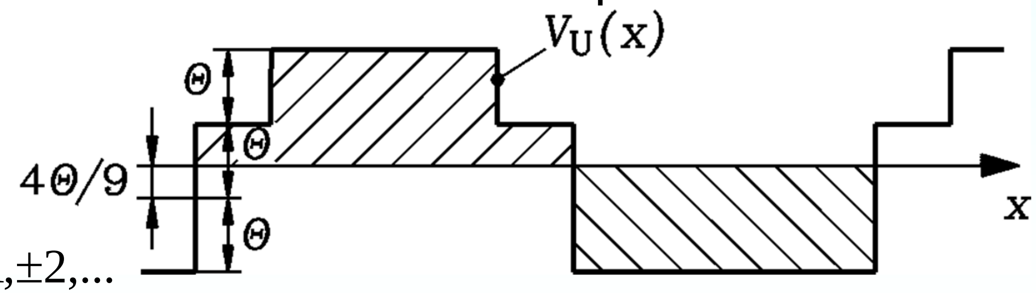
Pitching $W/\tau_p = 4/4.5 = 8/9$

TINGLEY-scheme: phase belt and slot numbering





mmf distribution of phase U



N- and S-pole field profile not identical: Field harmonics with even ordinal number occur!

$$\nu = 1 + mg = 1 + 3g = 1, -2, 4, -5, 7, -8, 10, -11, 13, \ldots \quad g = 0, \pm 1, \pm 2, \ldots$$

Distributed fractional slot winding $q \geq 1$

- Ordinal numbers of harmonics for fractional slot winding: $q = q_Z/q_N$
- General rules:

- N- and S-pole field profile not identical = increased number of field harmonics
- Winding scheme repeats after $2p'$ pole pairs ("basic period")
- Slot number per pole differs from pole to pole = cogging torque reduced!
- General rule for ordinal numbers of windings with equally spaced slots:

a) q_N is an even number: b) q_N is an odd number:

$$a)\quad \nu = \frac{2}{q_N}\cdot(1+mg) \quad g = 0,\pm 1,,\pm 2,...$$

$$b)\quad \nu = \frac{1}{q_N}\cdot(1+2mg) \quad g = 0,\pm 1,,\pm 2,...$$

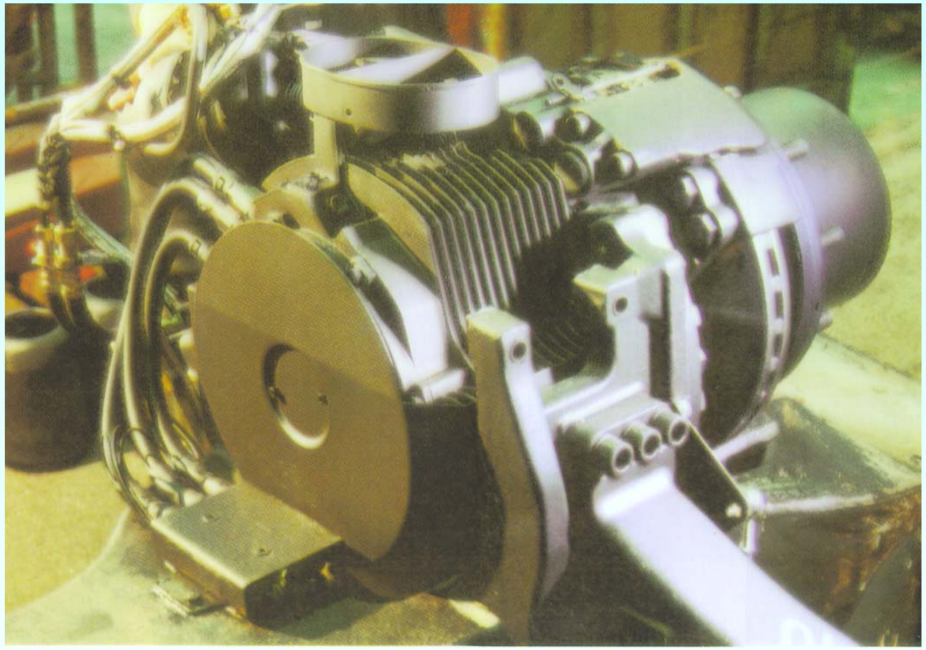
- Example: $q = 7/4$ $\quad q_N = 4, m = 3: \quad \nu = \frac{2}{4}\cdot(1+3g) = \frac{1}{2},-1,2,-\frac{5}{2},\frac{7}{2},-4,5,-\frac{11}{2},\frac{13}{2},-7,8,...$

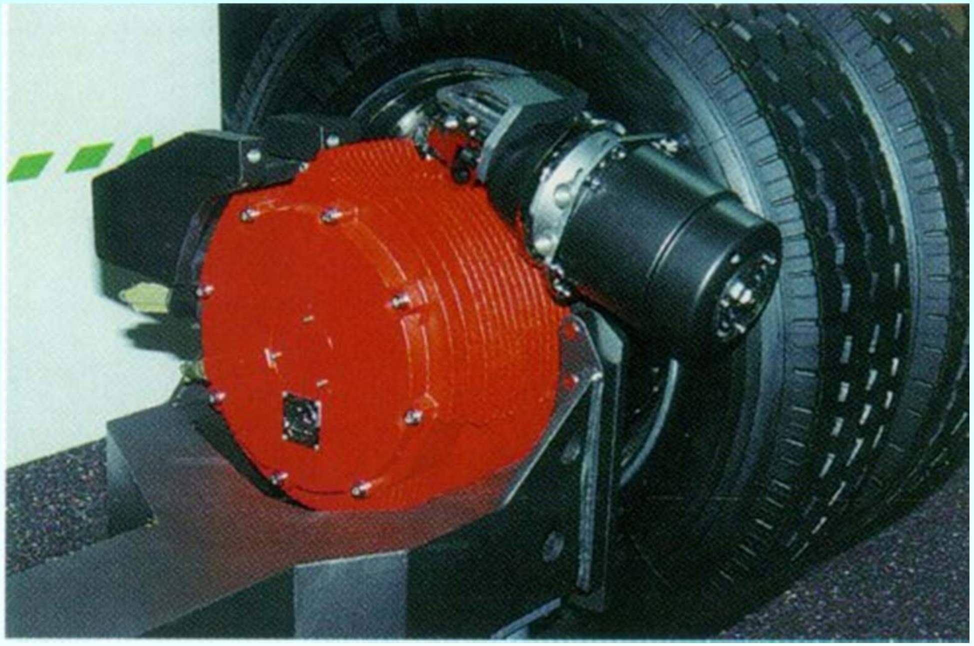
The basic scheme comprises $2p'$ = 4 poles with 21 slots, so per pole 21/4 = 5 ¼ slots.
A sub harmonic wave occurs: $\nu = 1/2$

- Example: $q = 8/5$ $\quad q_N = 5, m = 3: \quad \nu = \frac{1}{5}\cdot(1+6g) = \frac{1}{5},-1,\frac{7}{5},-\frac{11}{5},\frac{13}{5},-\frac{17}{5},\frac{19}{5},-\frac{23}{5},5,...$

The basic scheme comprises $2p'$ = 10 poles with 48 slots, so per pole 24/5 = 4 4/5 slots.
A sub harmonic wave occurs: $\nu = 1/5$

Wheel-hub drives for electrical vehicles





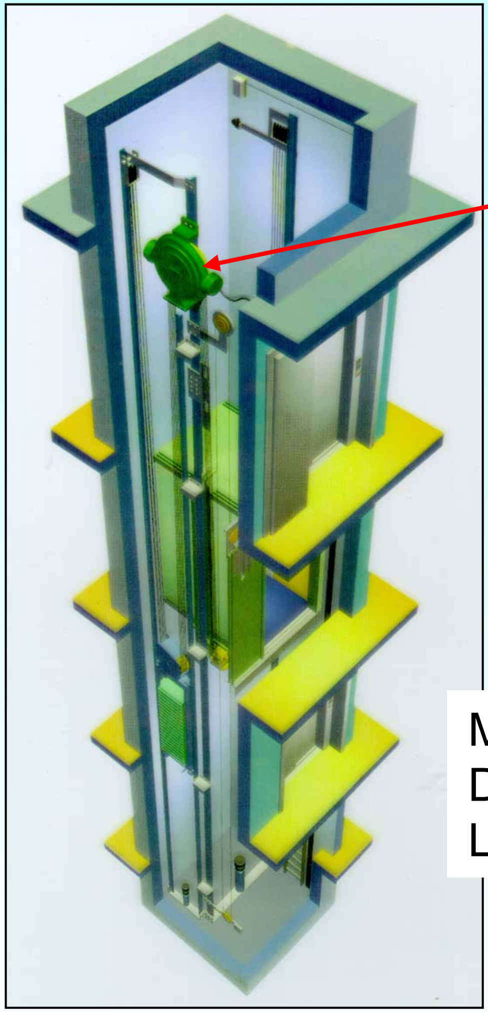
Geared induction motor wheel-hub drives

Source: Daimler-Chrysler, Stuttgart

Source: Oswald, Miltenberg

Wheel-hub drives for low floor city busses, e.g. with a fuel cell as energy source

Elevator direct drives

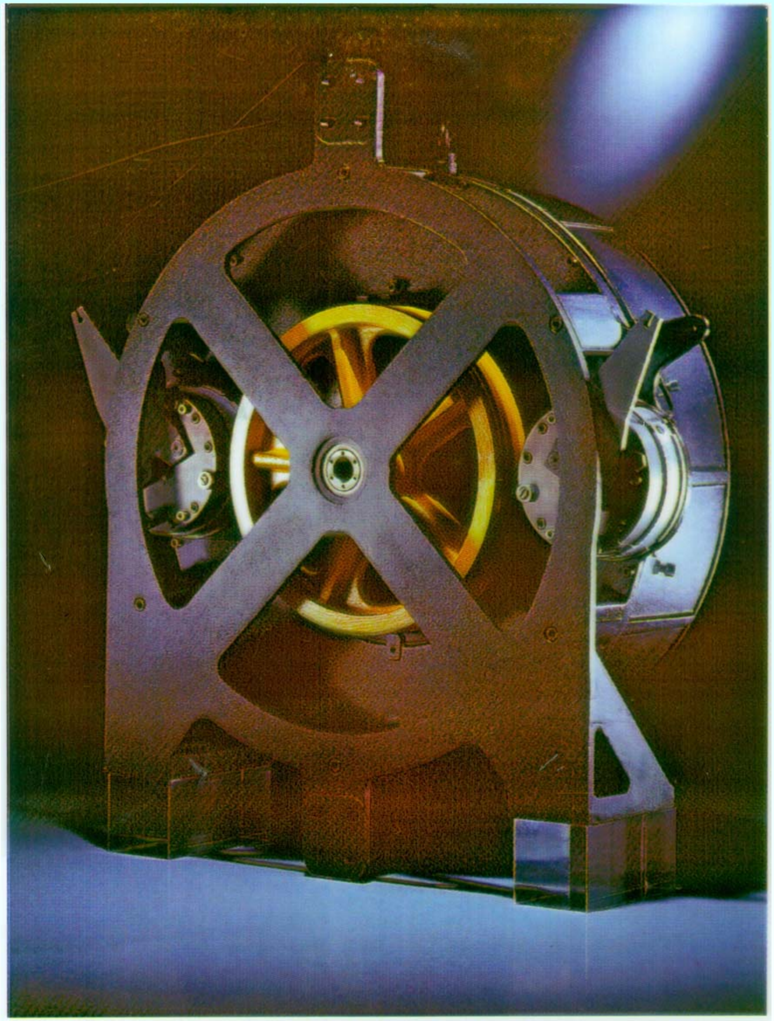


PM synchronous motor

Motor data:
Diameter: 0.7 m
Length: 0.27 m

PM-Axial flux synchronous machine, for 1 t pay-load

Source: Kone / Finland



Typical data:

800 … 1300 Nm

60 … 190/min

Outer rotor

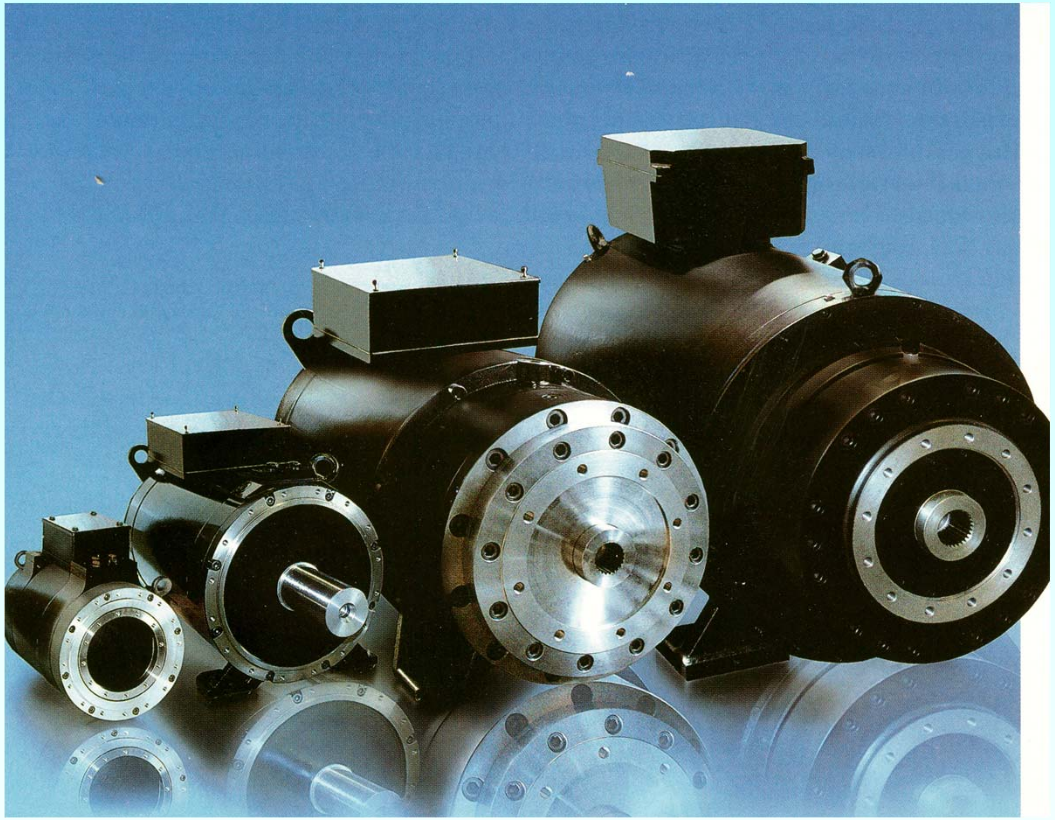
Diameter ca. 0.7 m

Length: ca. 0.15 m

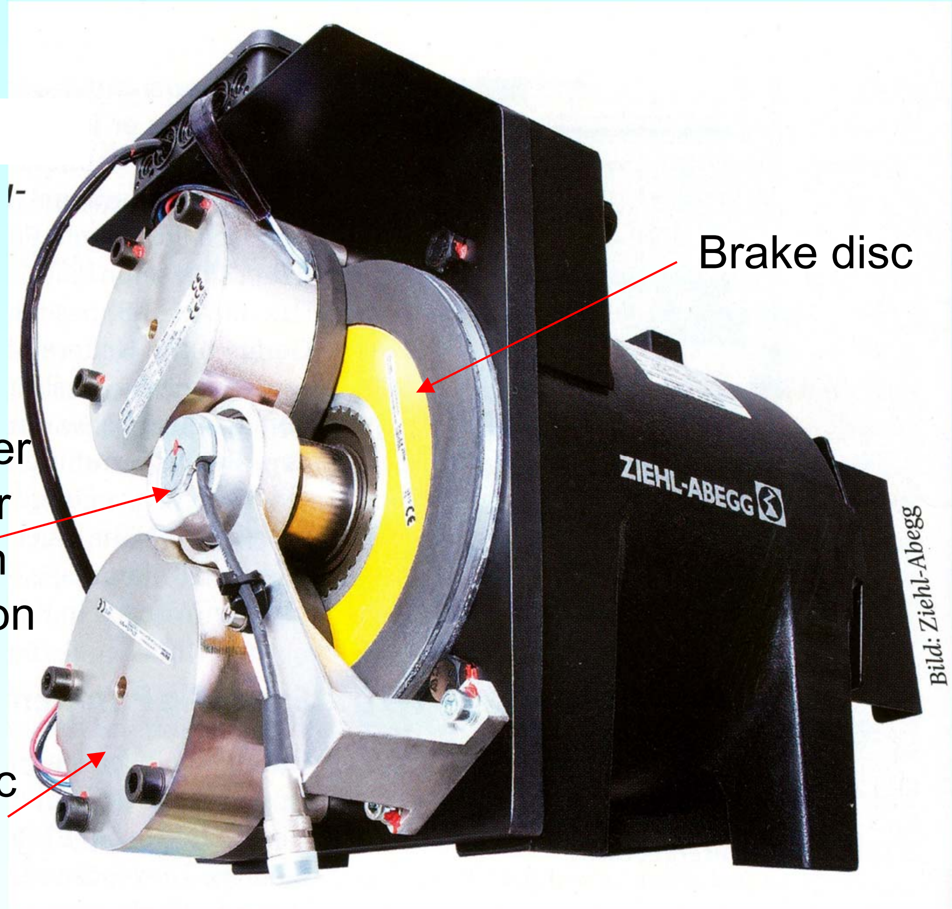
PM-synchronous machine with high pole count as direct drive

Source: Siemens AG

Elevator direct drives



Source: Baumueller, Nuremberg, Germany



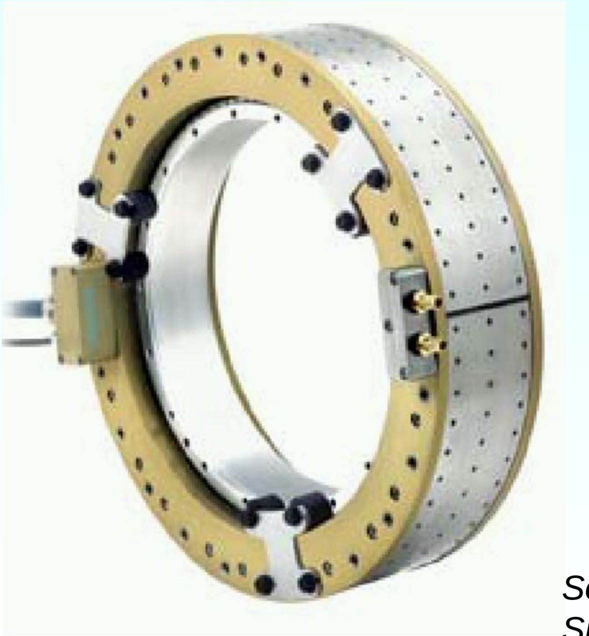
Source: Ziehl Abegg, Künzelsau, Germany

PM synchronous motors as direct drives, water jacket cooling, torque range up to 32 000 Nm

PM synchronous machine as direct drive for elevators, water jacket cooling

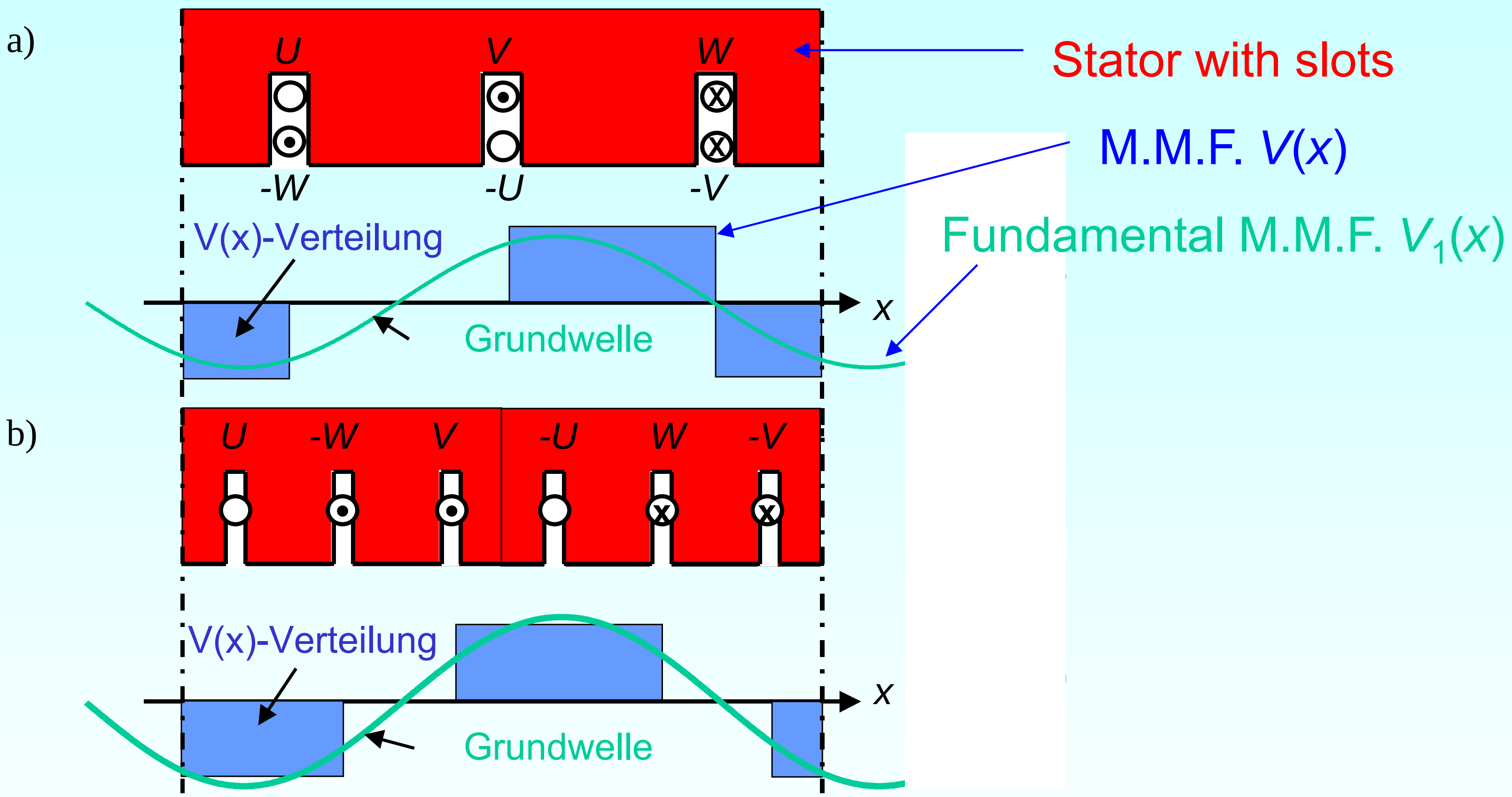
1. Permanent magnet synchronous machines as “brushless DC drives”

1.5.2 Modular synchronous machines



Source: Siemens AG, Munich

Modular synchronous machines



Magnetic flux density distribution and fundamental in constant air gap:

a) fractional slot winding q = ½,

b) Integer slot winding q = 1, current flowing in marked slots ($i_U = 0$, $i_V = - i_W = I$).

Double-layer concentrated fractional slot winding $q < 1$

- Concentrated fractional slot winding "Tooth coil winding": $q = q_Z/q_N \sim 1/m$, but $\neq 1/m$

- N- and S-pole field profile not identical = increased number of field harmonics
- Winding scheme repeats after $2p'$ pole pairs ("basic period")
- Slot number per pole differs from pole to pole = cogging torque reduced!
- Short winding overhangs
- No crossings of winding overhangs of different phases

a) q_N is an even number:

$$a) \quad \nu = \frac{2}{q_N} \cdot (1 + mg) \quad g = 0, \pm 1, , \pm 2, \ldots$$

b) q_N is an odd number:

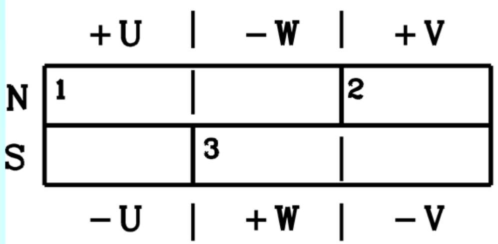
$$b) \quad \nu = \frac{1}{q_N} \cdot (1 + 2mg) \quad g = 0, \pm 1, , \pm 2, \ldots$$

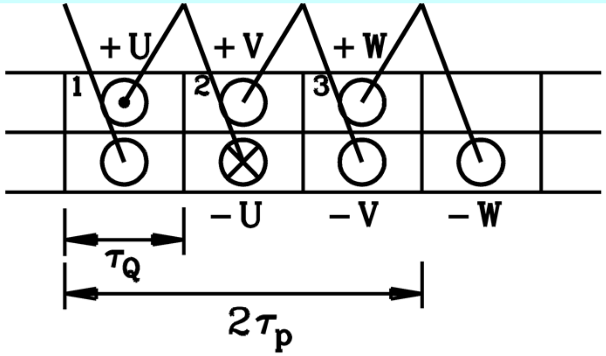
- *Example*: $q = 1/2$ $\quad q_N = 2, m = 3: \quad \nu = \frac{2}{2} \cdot (1 + 3g) = 1, -2, 4, -5, 7, -8, 10, -11, 13, \ldots$

The basic scheme comprises $2p' = 2$ poles with 3 slots, so per pole 1 1/2 slots.
No sub harmonic wave occurs in this example.

Double-layer concentrated fractional slot winding q = ½ & 1/4

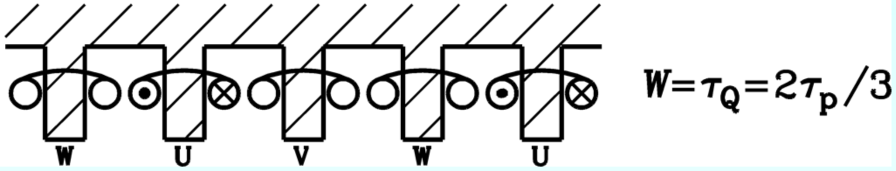
- *Example*: $q = 1/2$



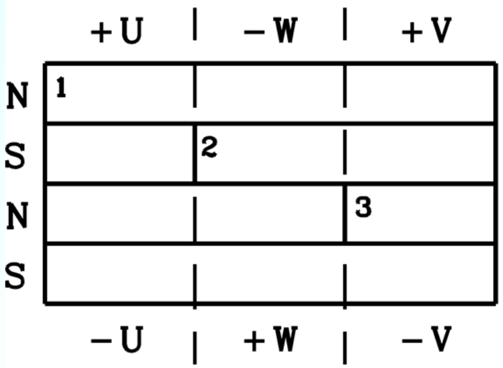


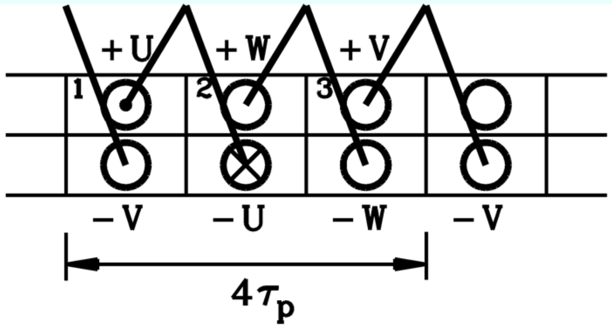
The basic scheme comprises $2p' = 2$ poles with 3 slots, so per pole 3/2 slots.
No sub harmonic wave occurs in this example.

The identical stator winding is combined
a) with 2 rotor magnet poles,
b) with 4 rotor magnet poles.

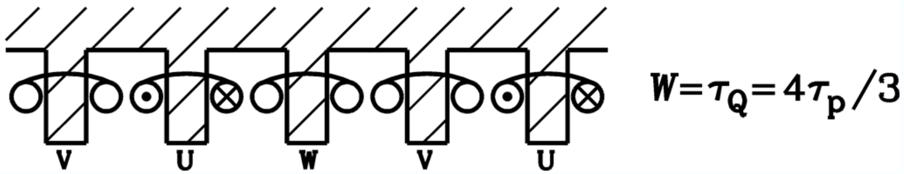


- *Example*: $q = 1/4$





The basic scheme comprises $2p' = 4$ poles with 3 slots, so per pole 3/4 slots.
One sub harmonic wave occurs in this example.



$$q_N = 4, m = 3: \quad \nu = \frac{2}{4}\cdot(1+3g) = \frac{1}{2}, -1, 2, -\frac{5}{2}, \frac{7}{2}, -4, 5, \ldots$$

Single vs. double layer concentrated fractional slot winding

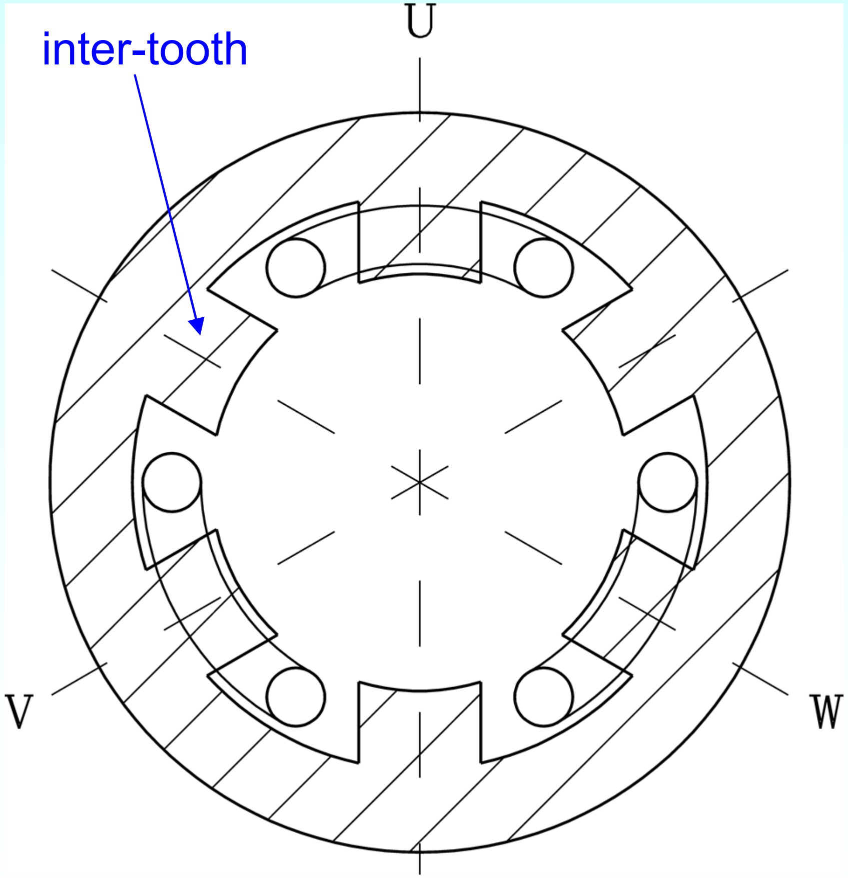
- *Example*: $q = 1/2$ Operated with a PM rotor with 4 rotor poles

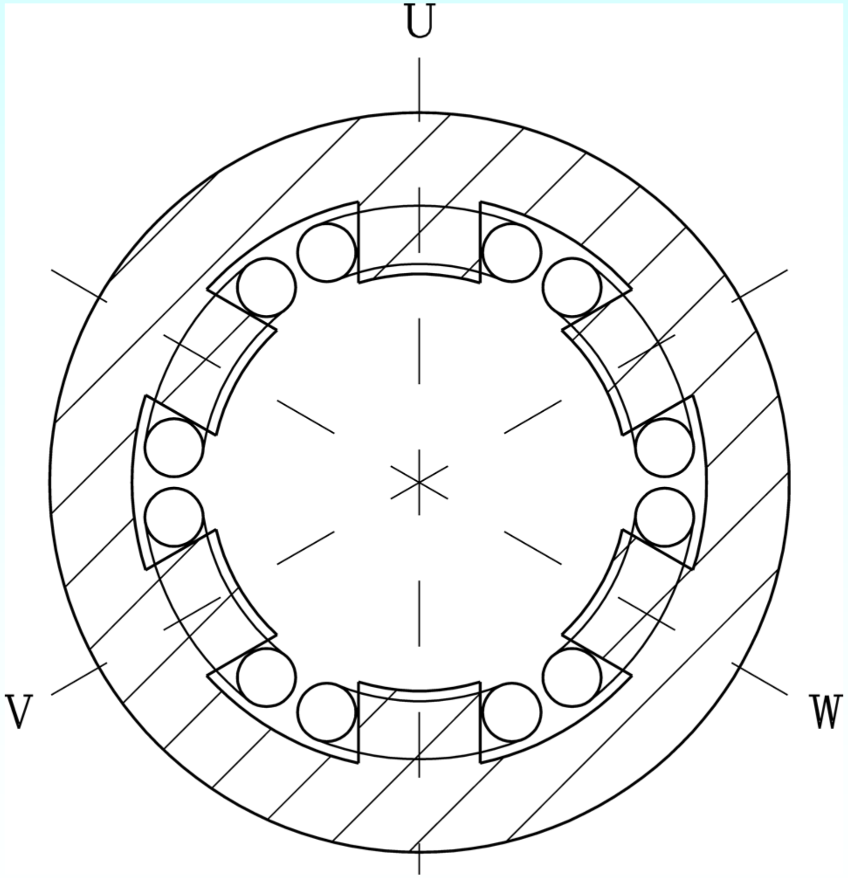
Single layer winding

- One sub-harmonic field wave
- $W = \tau_p$: possible, by narrow inter-teeth

Double layer winding

- No sub-harmonic field wave
- $W \neq \tau_p$: $W = (2/3)\cdot\tau_p$

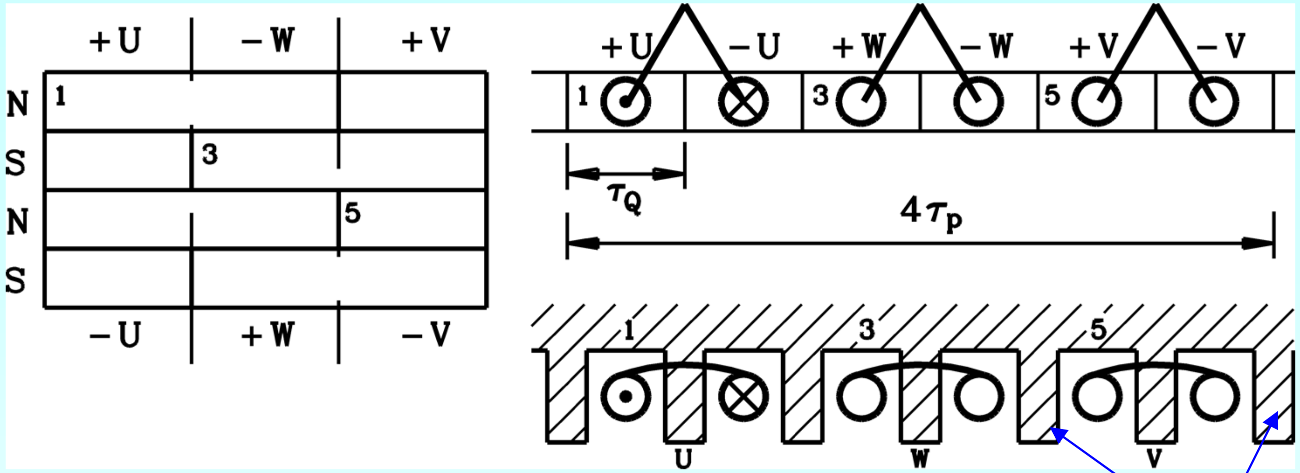




Single layer concentrated fractional slot winding $q = ½$

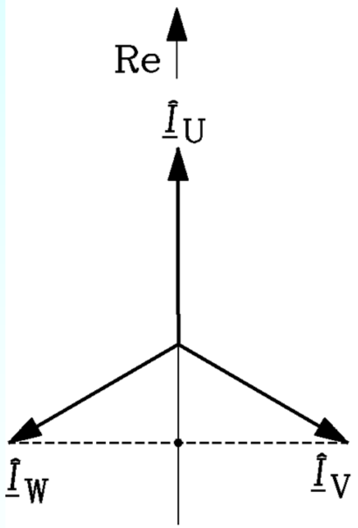
- *Example*: $q = 1/2$

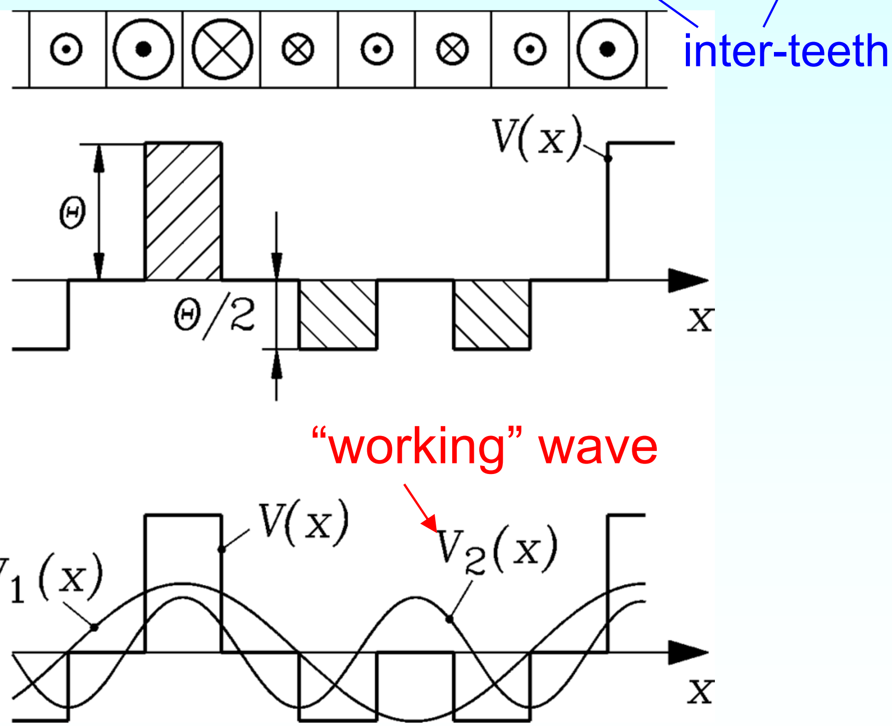
$W = \tau_p$ is possible by narrow inter-teeth to get $k_{w,\nu=1} = 1$



mmf distribution for:

$$i_U = \hat{I},\ i_V = i_W = -\hat{I}/2$$

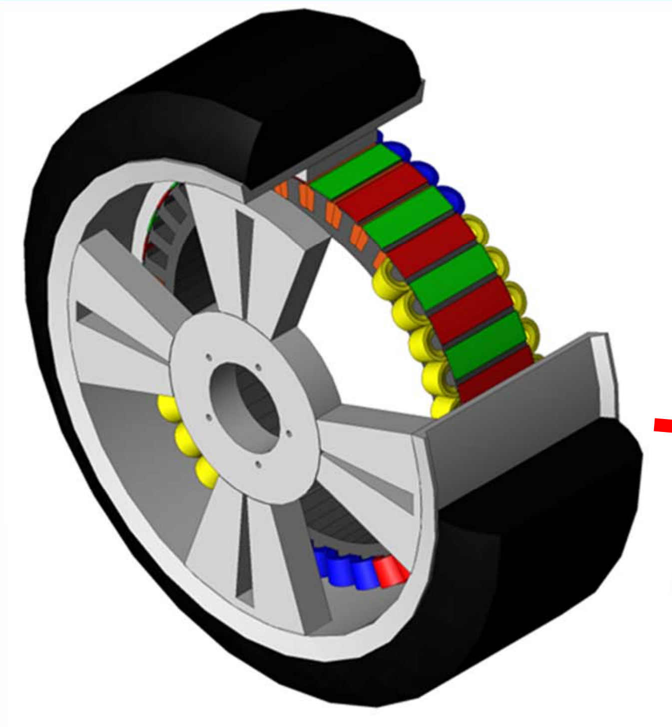




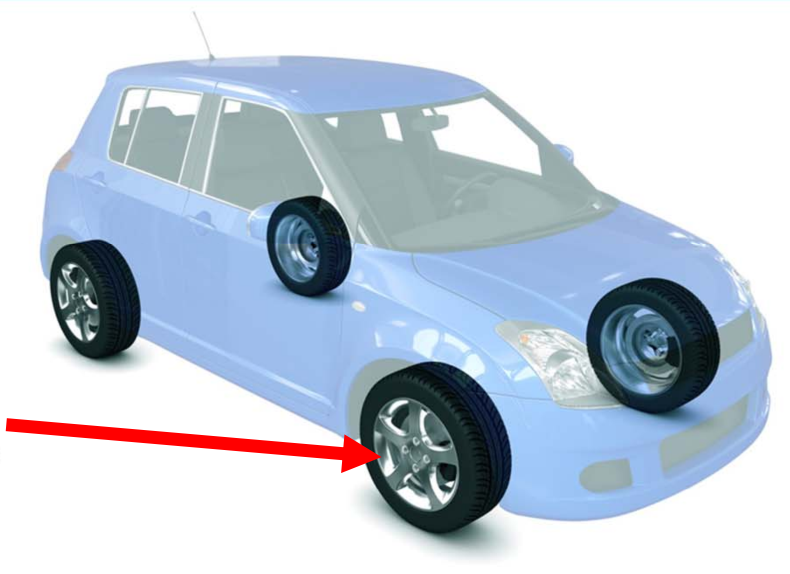
FOURIER analysis of mmf distribution for the first two ordinal numbers

Gearless wheel-hub drives for electrical vehicles with PM synchronous motors

Source: Protean Electric Ltd, 2013



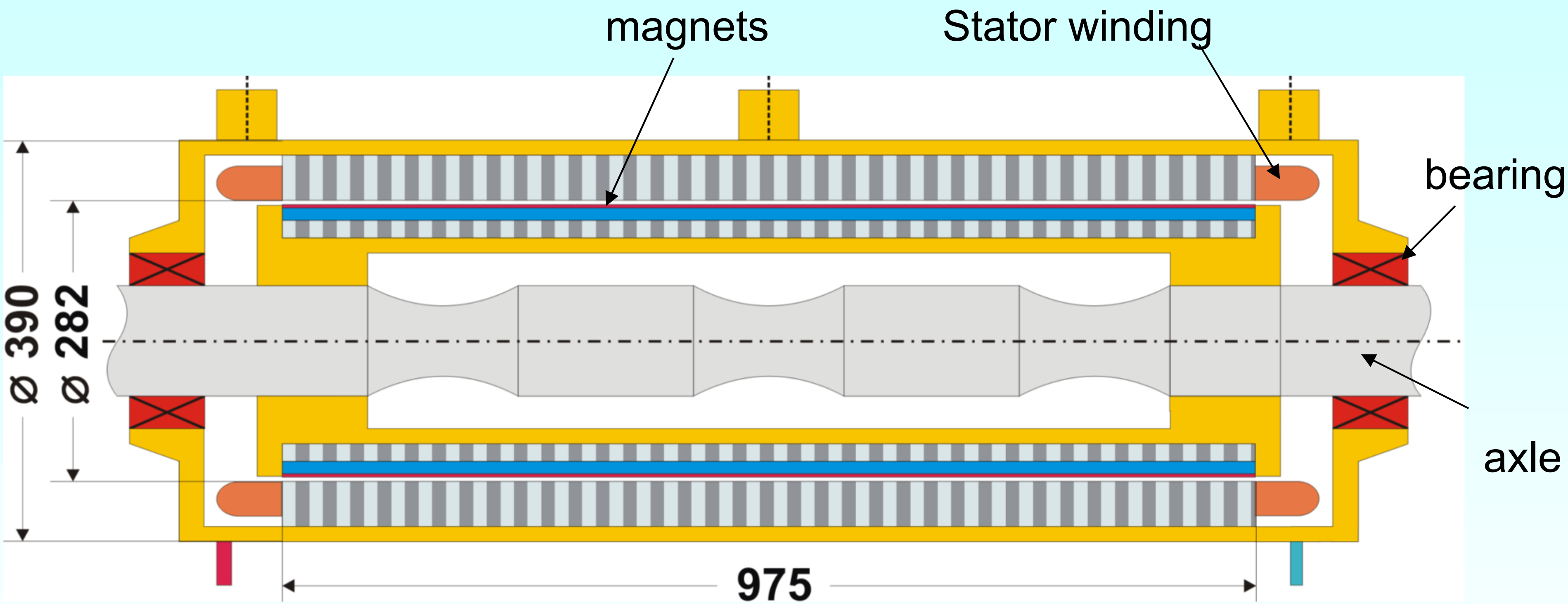
Source: TU Darmstadt



Wheel-hub drives for medium-sized passenger electric vehicles

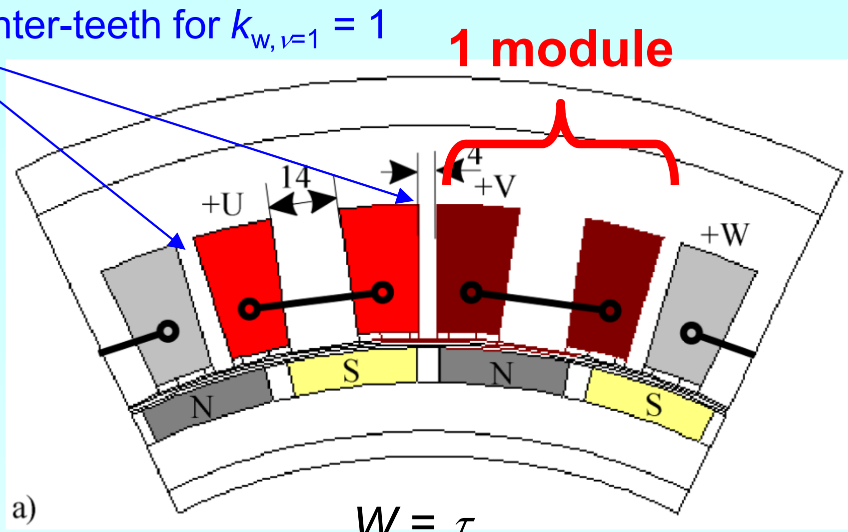
With outer rotor and inner stator tooth-coil winding

Synchronous modular machine as direct drive for metro transportation

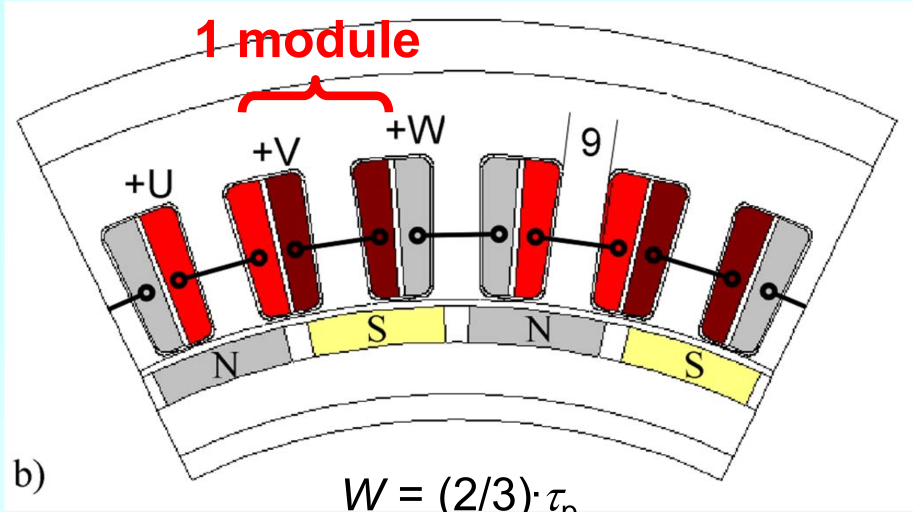


Cross section of direct drive PM modular synchronous machine with rotor directly mounted on axle shaft of metro wheel set

Source: Siemens AG



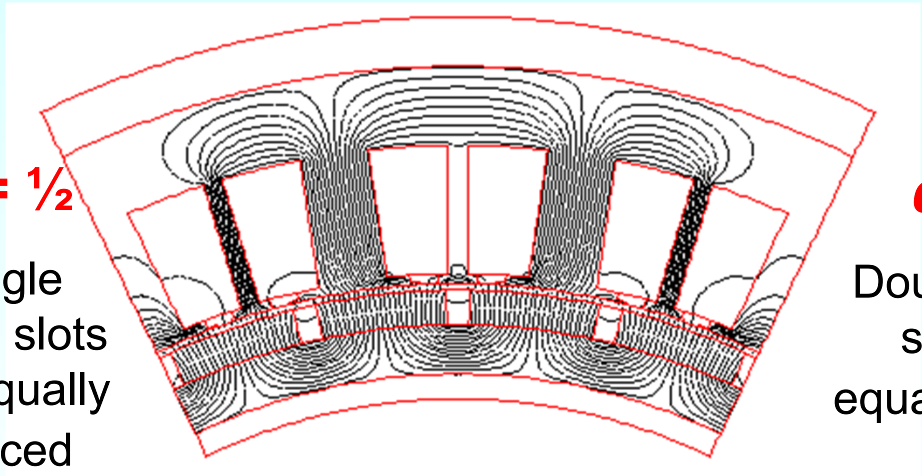
$W = \tau_p$



$W = (2/3)\cdot\tau_p$

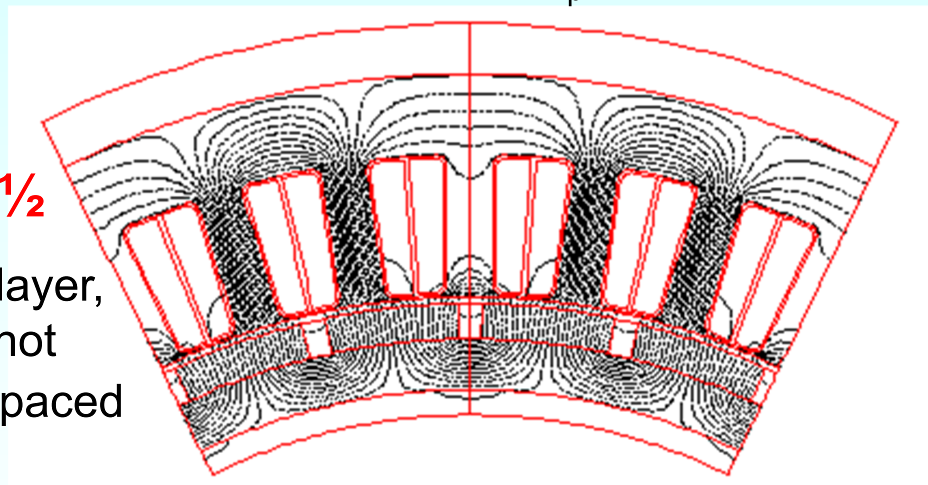
q = ½

Single layer, slots not equally spaced



q = ½

Double layer, slots not equally spaced



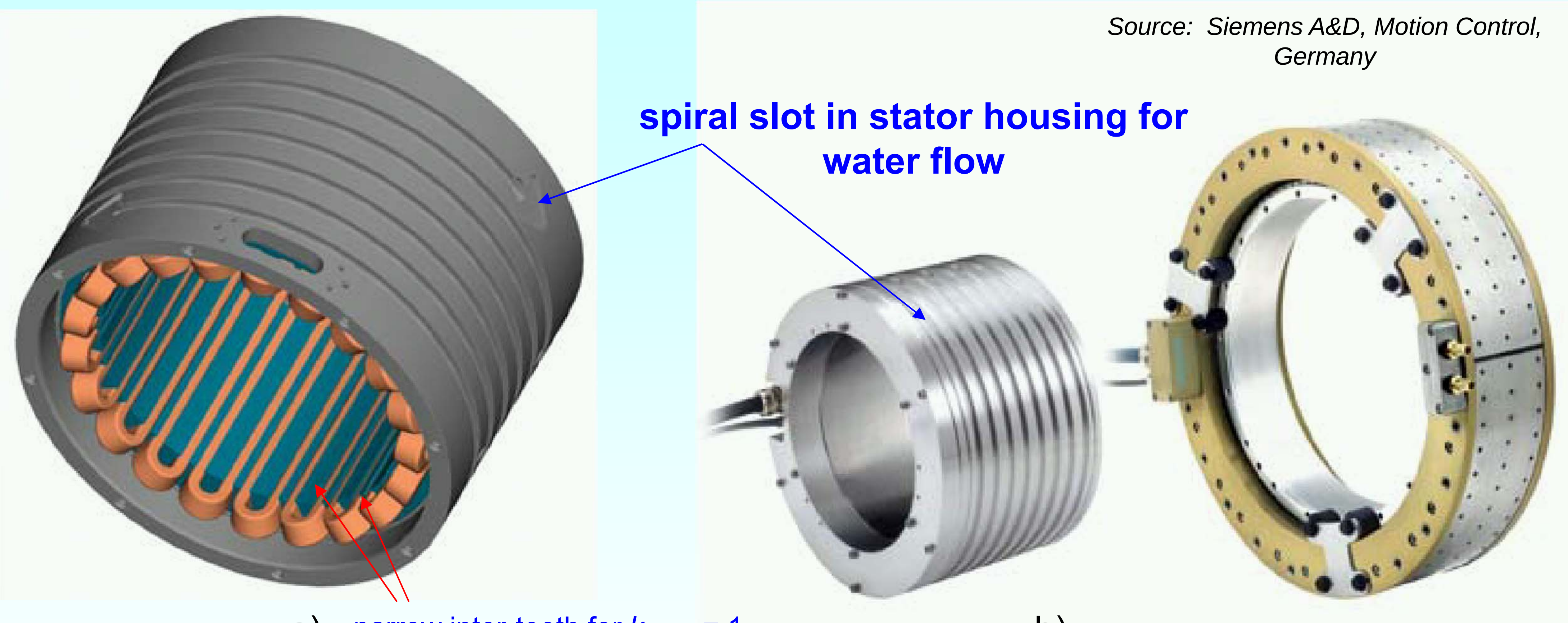
Numerically calculated magnetic flux density distribution at no-load (current is zero) for **2 pole pairs** of PM synchronous machines with tooth-wound fractional slot winding:

a) q =1/2 single layer (with 4 mm narrow inter-tooth to separate tooth coils),

b) q =1/2 double layer

Source: TU Darmstadt

High torque motor with tooth-wound coils



a) narrow inter-teeth for $k_{w,\nu=1} = 1$ b)

a) stator with 3 phases, 21 tooth coils, broad and narrow teeth, 42 slots, q = ½ single layer winding ("with narrow inter teeth), 28 rotor poles

$$q = \frac{Q}{m \cdot 2p} = \frac{42}{3 \cdot 28} = \frac{1}{2}$$

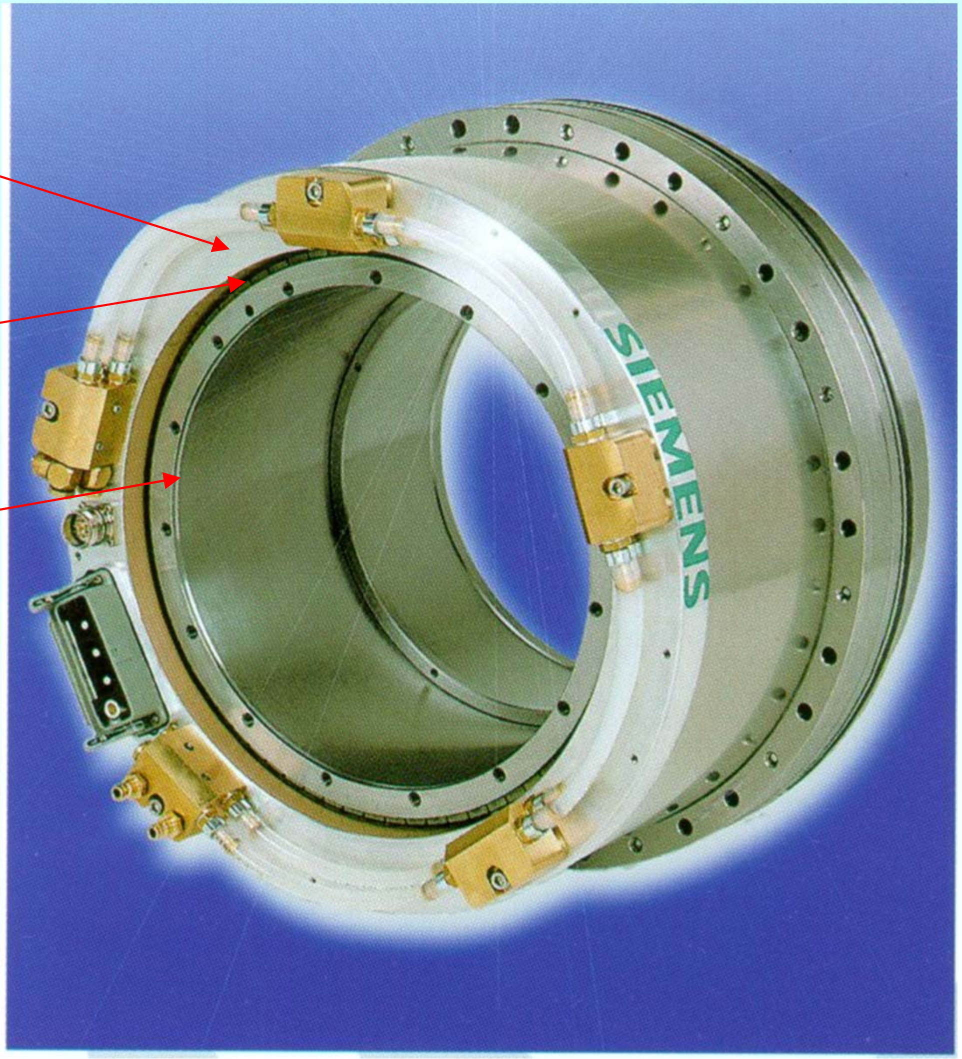
b) complete motor with water jacket cooling

Modular synchronous machine as high torque-motor

Stator

PM

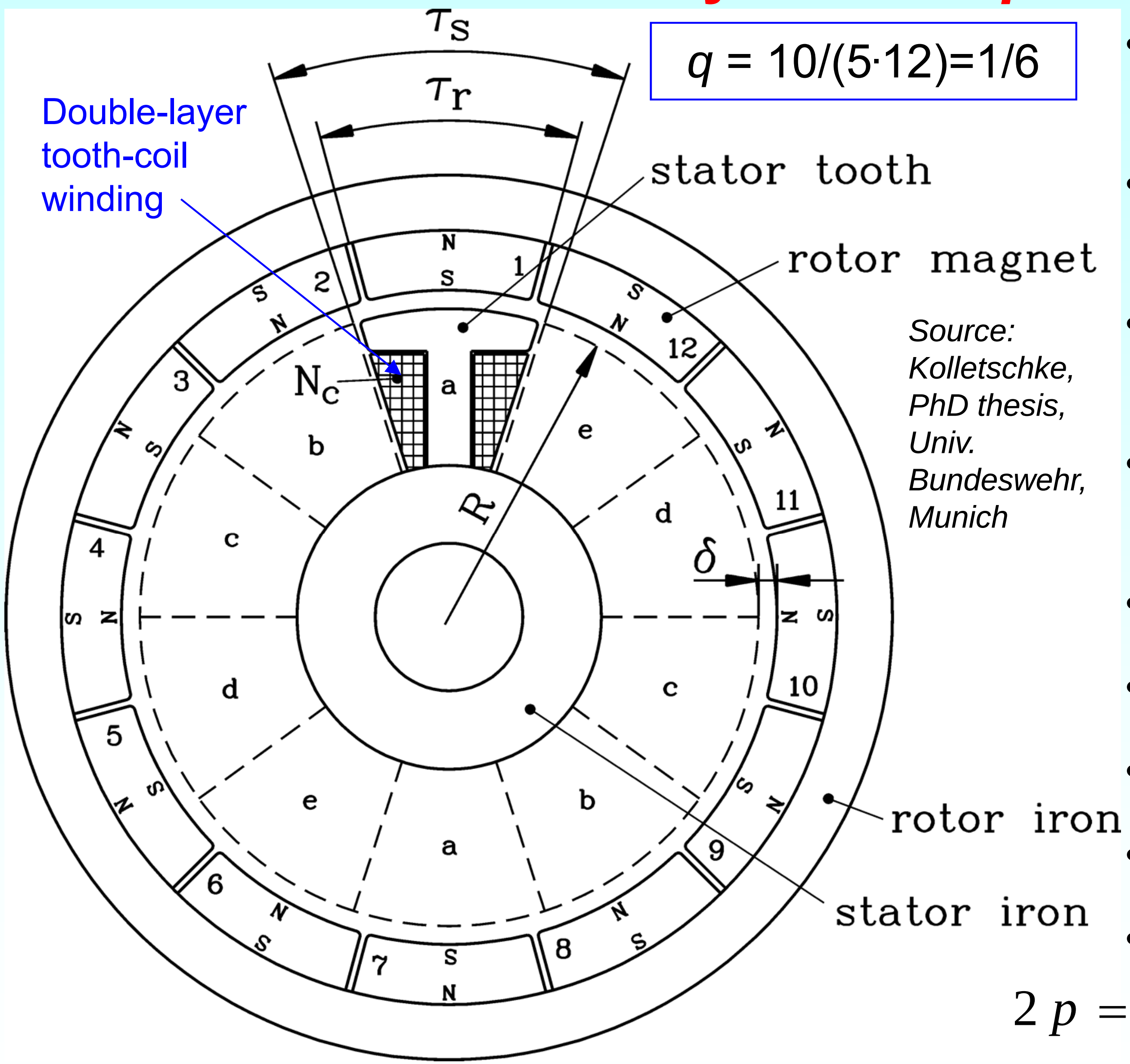
Rotor



Source:
Siemens AG

- High torque at low speed
- High precision drive with minimized torque ripple, e.g. positioning of co-ordinate round table for tooling machines
- Gearless drive, integrated rotor, low mass
- High efficiency due to permanent magnet excitation

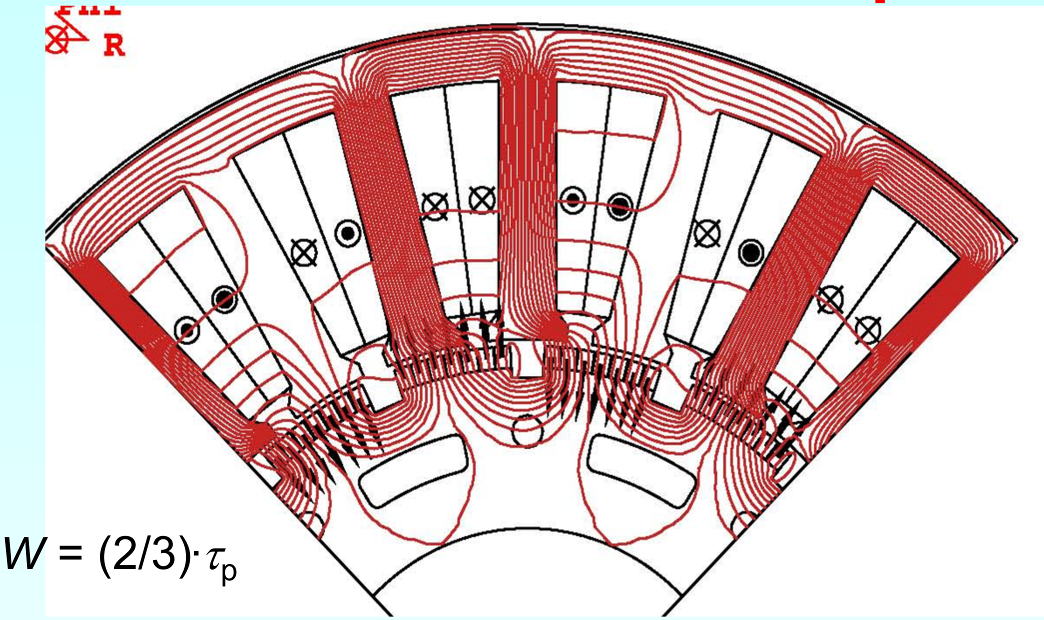
Modular synchronous machine as outer rotor wheel-hub drive for military vehicle $q = 1/6 \approx 1/m = 1/5$

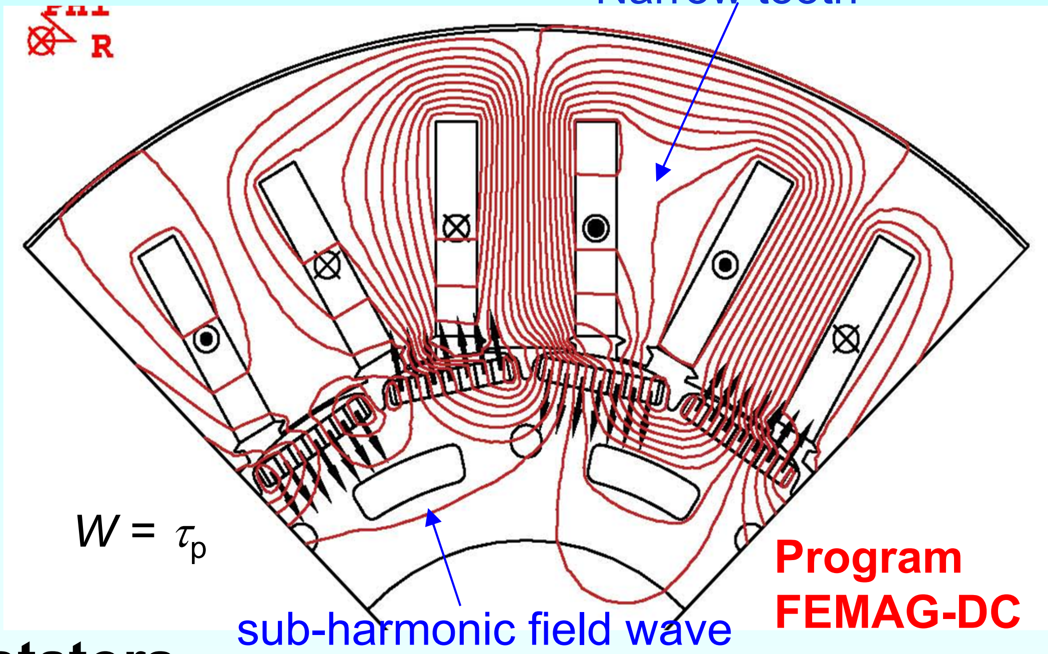


- Outer rotor is fixed directly to the wheel.
- For redundancy a five phase system is used.
- Five winding legs fed from five independent single-phase inverters
- Note: A three phase system is not self-starting, if one phase fails
- Number of basic schemes: $z_S = 2$
- Slots per module: $Q_M = 1$
- Number of phases: $m = 5$
- number of slots: $Q_s = z_S \cdot m \cdot Q_M = 10$
- number of poles:

$$2p = z_S \cdot (Q_M \cdot m + 1) = 2 \cdot (1 \cdot 5 + 1) = 12$$

Comparison of q = ½ (single vs. double layer) for a 16-pole PM motor





Source: TU Darmstadt

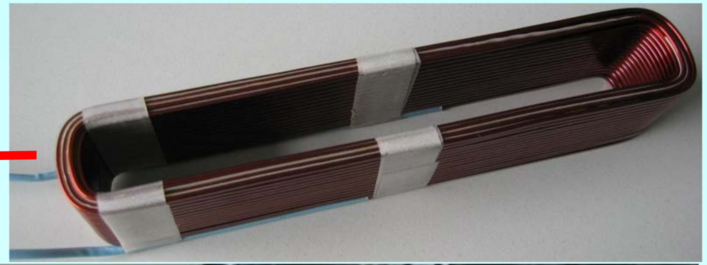
16-pole stators

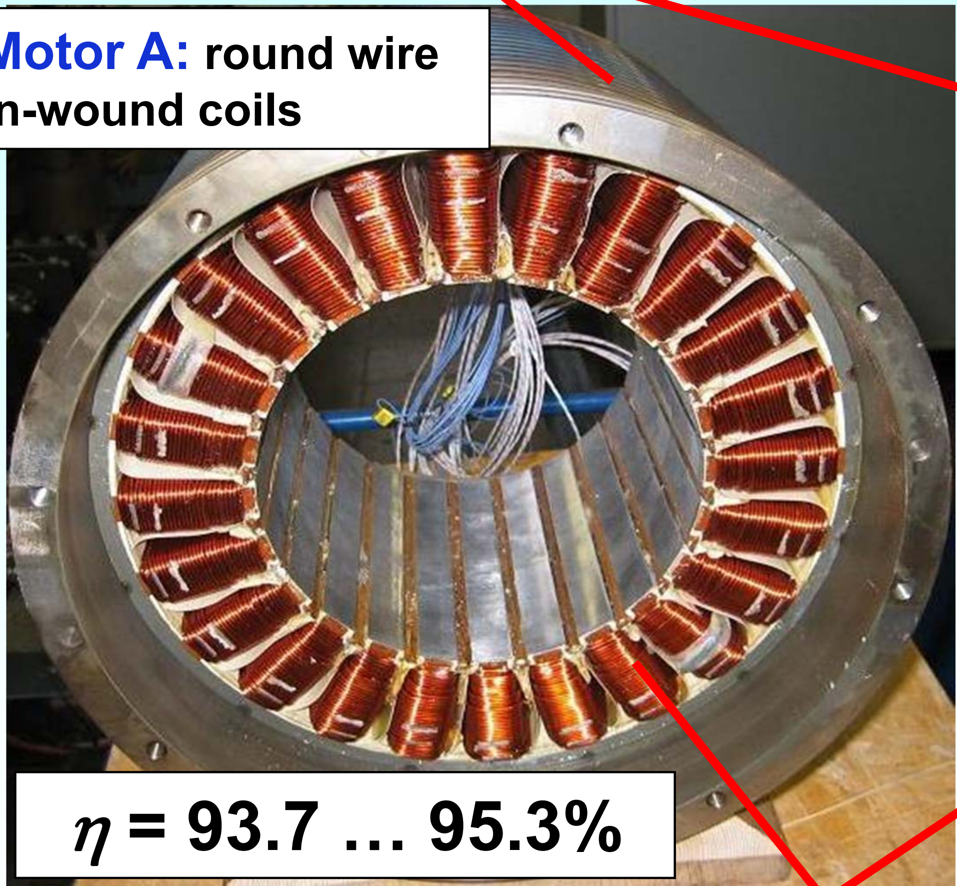
	Motor A: q = 0.5, double layer	**Motor B: q = 0.5, single layer**
Efficiency *)	93.7% / 95.3 %	92.8 % / 93.3 %
at 45 kW	1000 / 3000/min	1000 / 3000/min
Magnet temperature	87°C	115°C

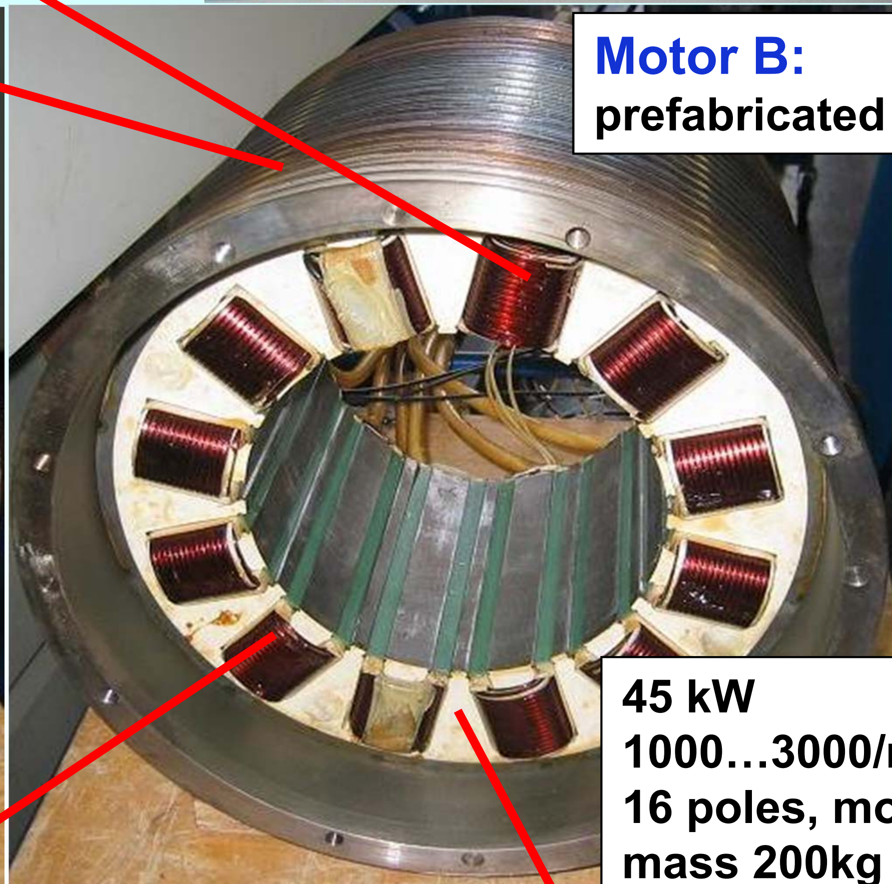
*) *directly measured via torque transducer and electronic wattmeter at: inverter operation, sinusoidal currents, Thermal Class F, 45 °C water inlet*

Prototype stators, $q = ½$, 16 poles: Motor A vs. Motor B

Compact tooth coil winding – reduced I^2R-losses





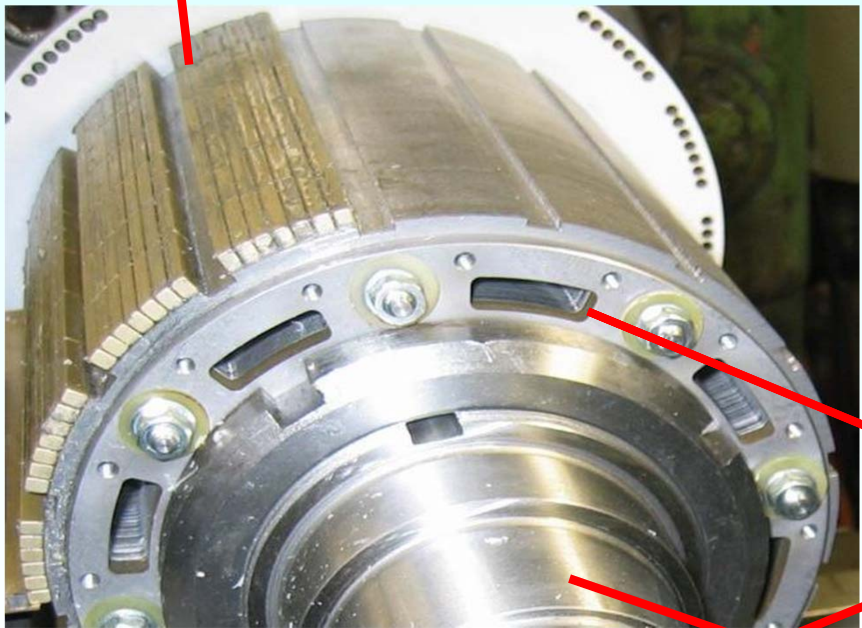


Source: TU Darmstadt

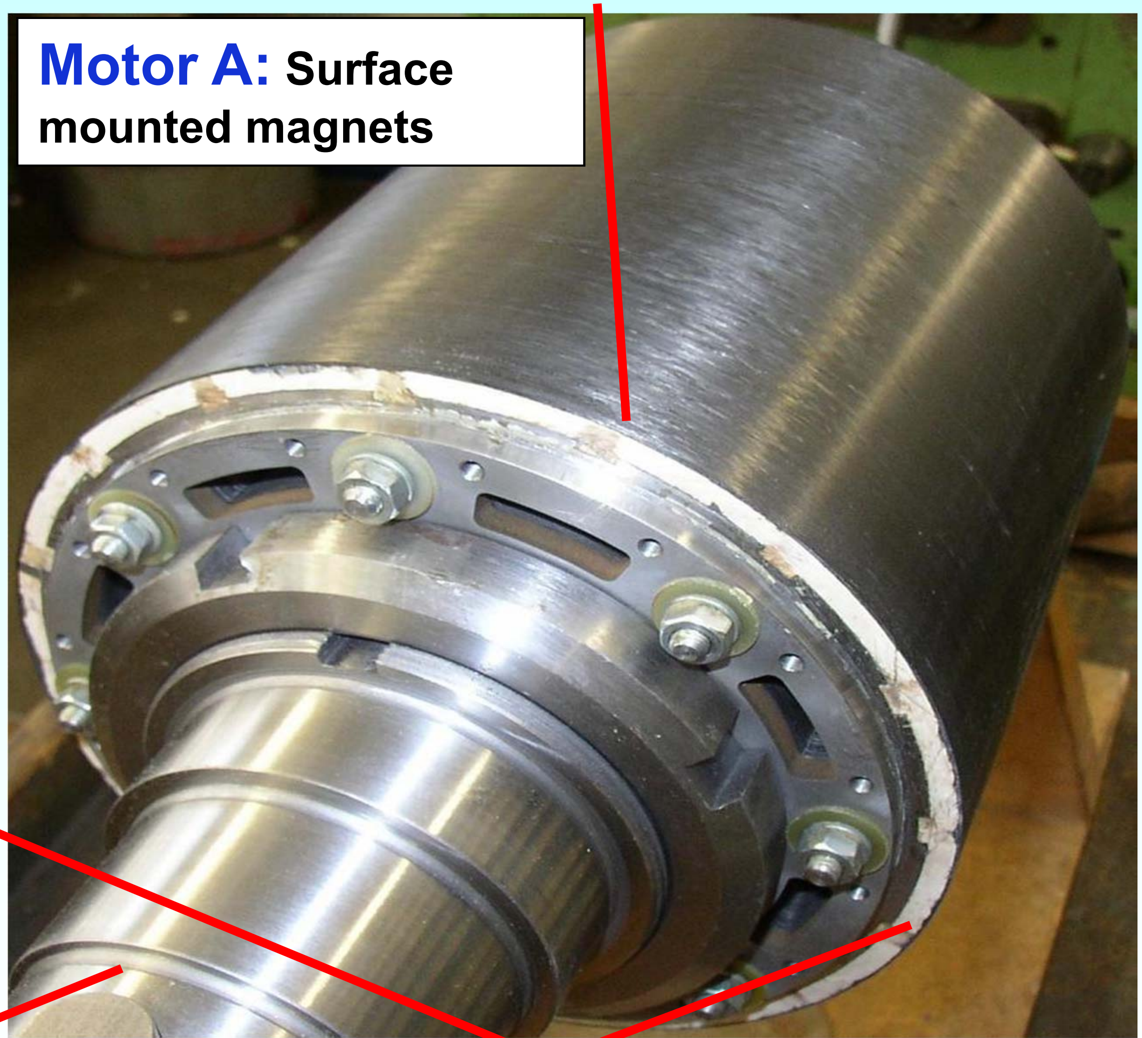
Reduction of rotor eddy current losses by segmented magnets

NdFeB permanent magnets excite the rotor field

Magnets



Carbon fiber bandage



Source: TU Darmstadt

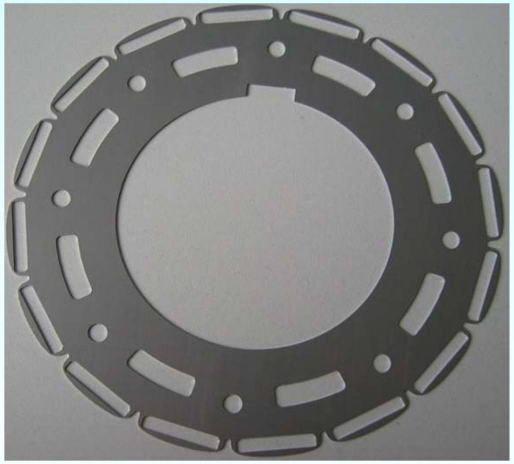
Shaft

Rotor iron stack

Motor B: Buried segmented magnets

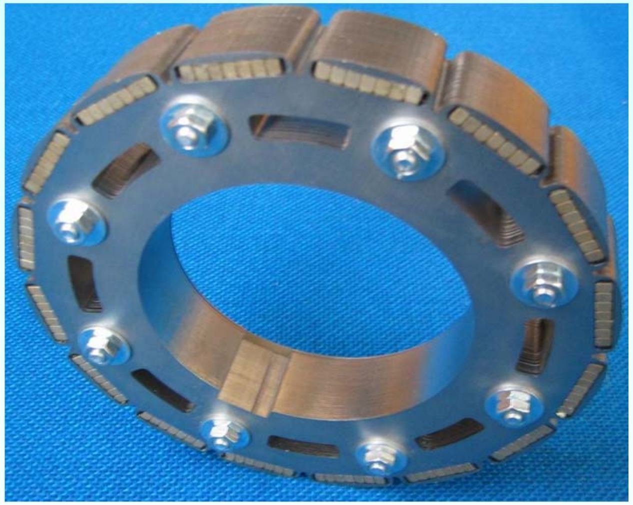
Motor B

Magnets

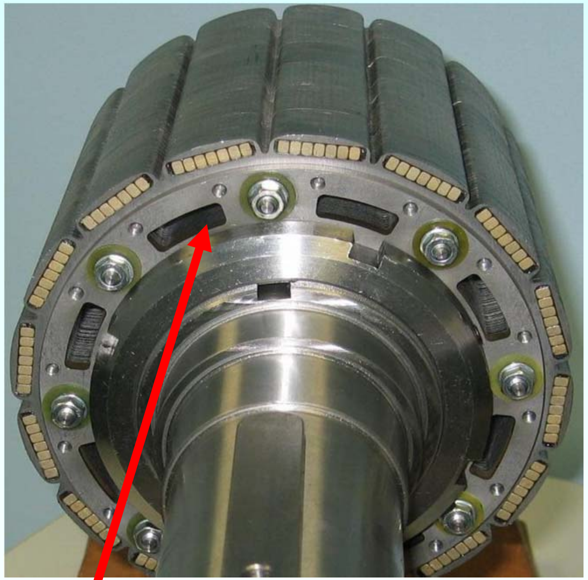


Rotor iron sheet

6 rotor iron stacks



Complete rotor B



Source: TU Darmstadt

Internal air flow cooling ducts

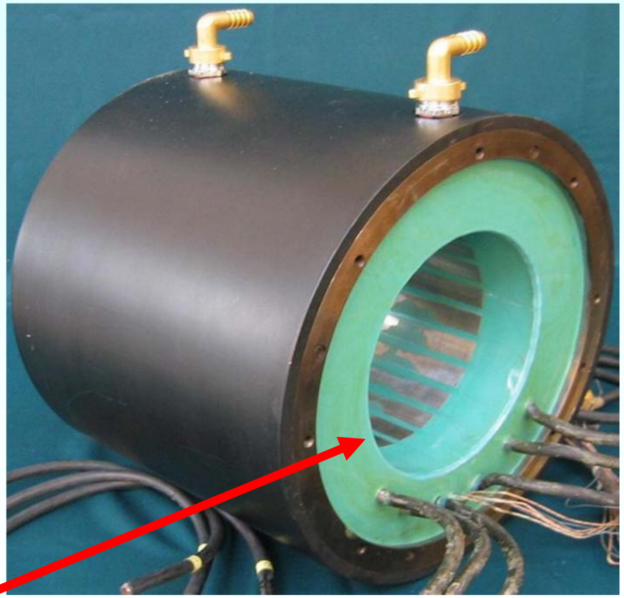
Intensified water jacket cooling

- **Water jacket cooling**
- **Internal air flow**
- **Resin casting of stator end winding – for thermal coupling of the winding to the water jacket**

Active stator parts

Water jacket inner part

Completed stator



Resin casting

Source: TU Darmstadt

Outer rotor washing machine motor

$$Q = 36$$

$$m = 3$$

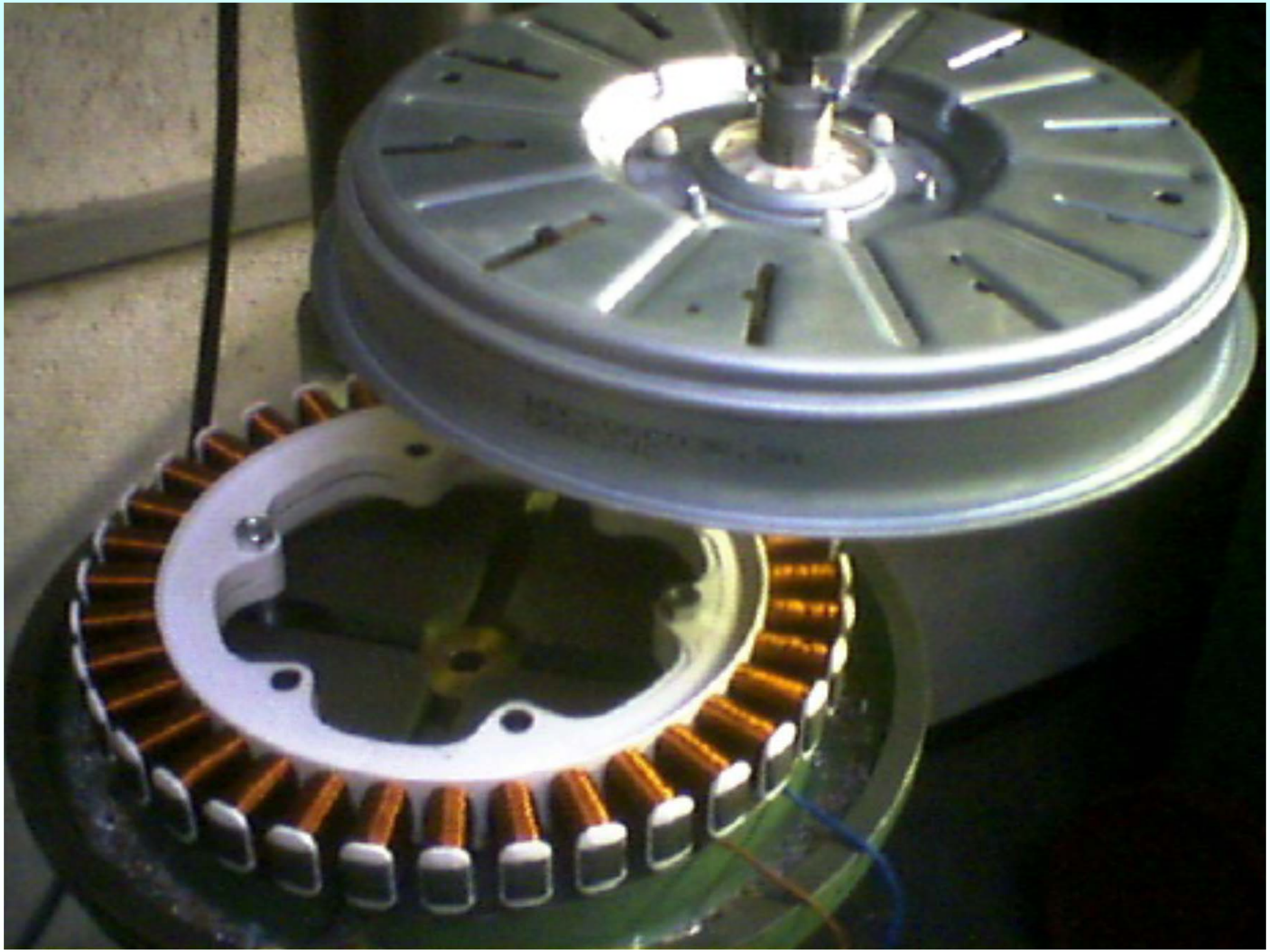
$$2p = 24$$

$$q = 36/(3 \cdot 24) = \frac{1}{2}$$

q = 0.5, double layer winding, three phases

Source:

Thien, Lustenau, Austria



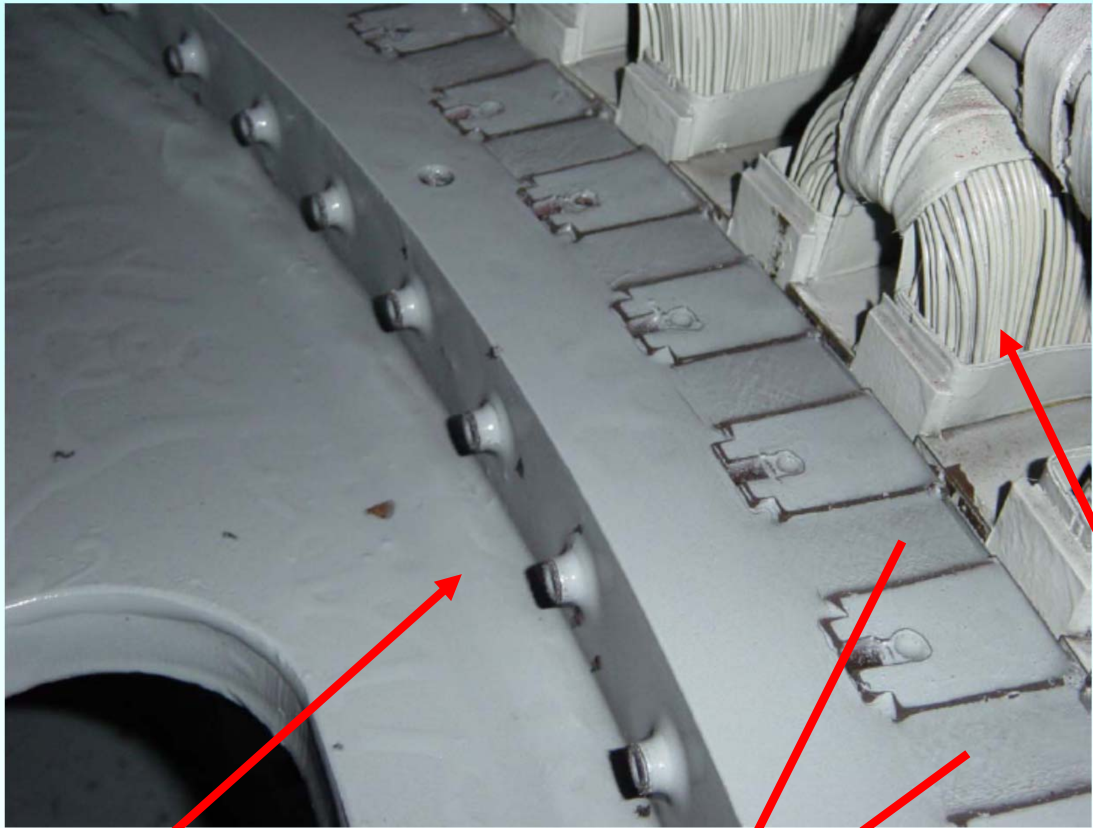
Direct drive for cable cars: 1st prototype

Mountain station of the cable car (for ski sports)

Synchronous PM excited motor as a direct drive with a tooth coil winding and a vertical shaft

Source: Leitner, Italy

Stator-Rotor detail of the direct drive for cable cars



Rotor mass: 1.2 t

Magnets: h_M = 15 mm

Source: Leitner, Italy

- Synchronous PM excited motor as a direct drive with a single layer tooth coil winding and a vertical shaft
- 200 kNm at 15/min, 300 kW, $\cos\varphi = 0.7$, U_s = 600 V, U_p = 300 V
- Speed range 15 … 30/min, max. 15 Hz, $2p$ = 60, one slot pitch ≈ 1.1-times one pole pitch
- Two winding systems and inverters: 2 x 200 kVA for redundancy
- Easy to repair stator winding, tooth-coil per each second tooth, open slots
- Round wire winding
- Buried magnets with tangential magnetization (NdFeB) for flux concentration: B_δ = 1.3 T instead of 0.9 T

2nd prototype of a direct drive for cable cars

200 kNm at 15/min, 300 kW, $\cos\varphi = 0.7$, speed range 15 … 30/min

Source: Leitner, Italy

Second prototype: Stator tooth coil winding

Stator manufacturing with tooth coils

Easy to repair stator winding, tooth-coil per each second tooth, open slots with profile copper wire winding

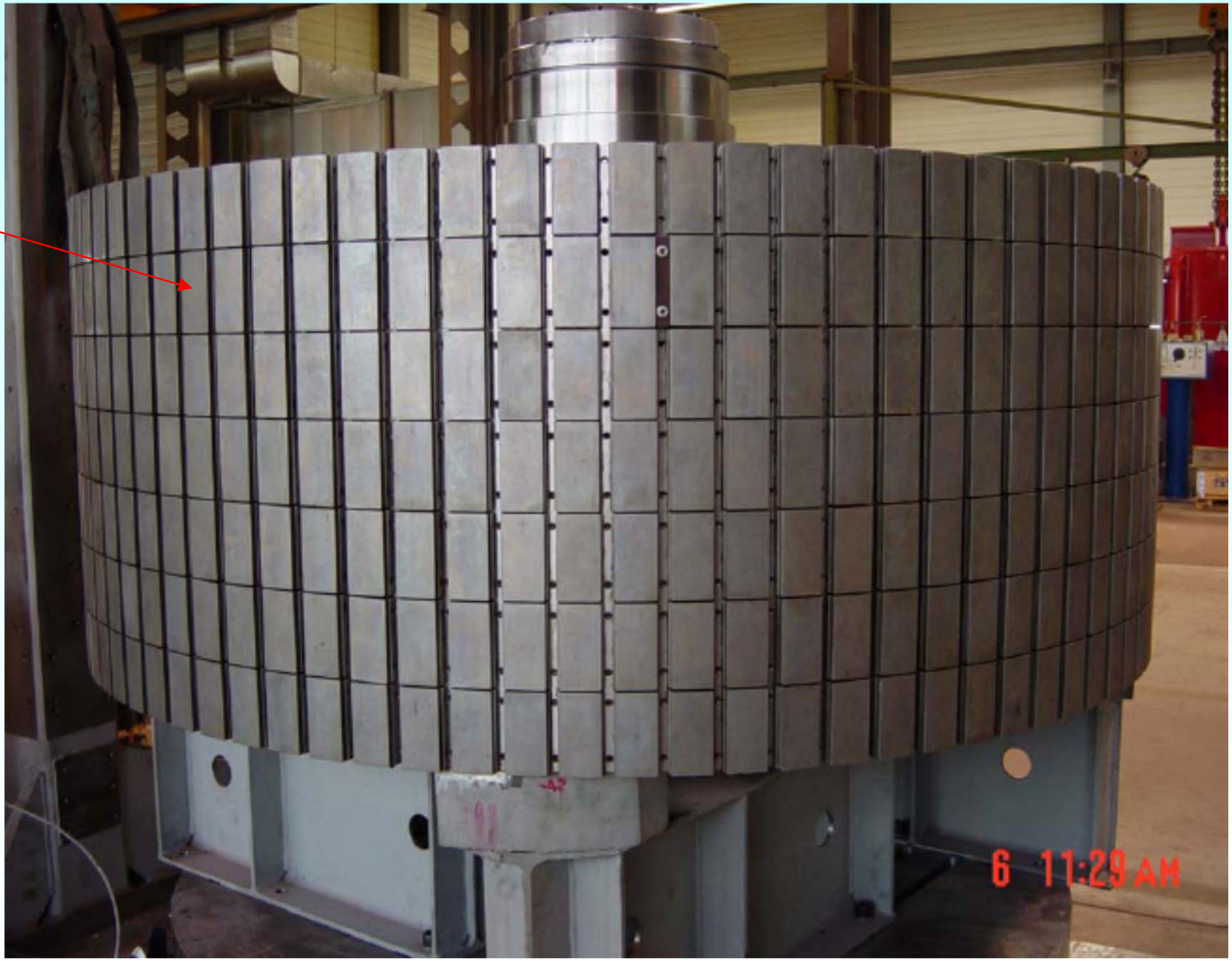
Source: Leitner, Italy

and

Otto Bartholdi AG, Koblenz, Switzerland

Second prototype: NdFeB PM rotor with flux concentration

Laminated rotor iron pole shoe



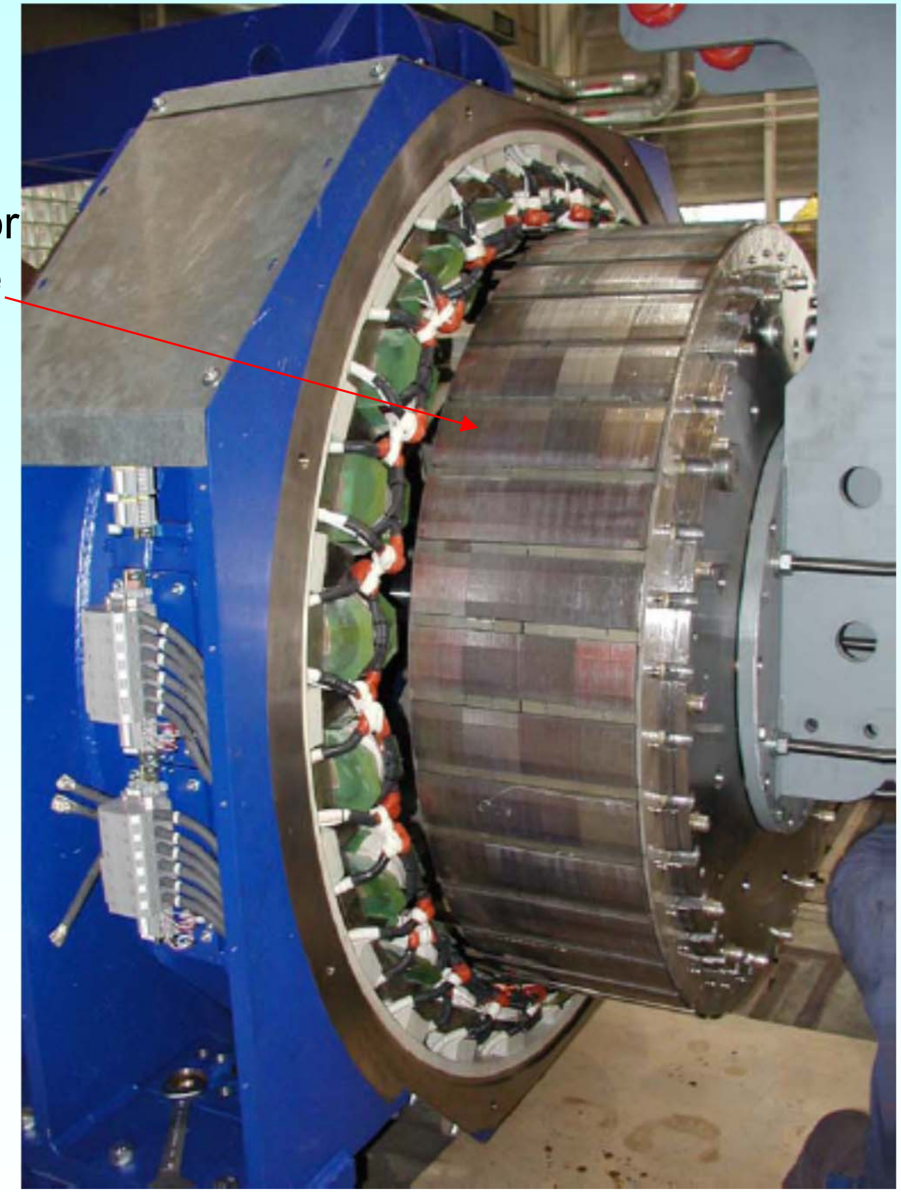
Source:
Leitner, Italy

and

Otto Bartholdi AG, Koblenz, Switzerland

Elevator drive with tooth coil winding for sky scrapers

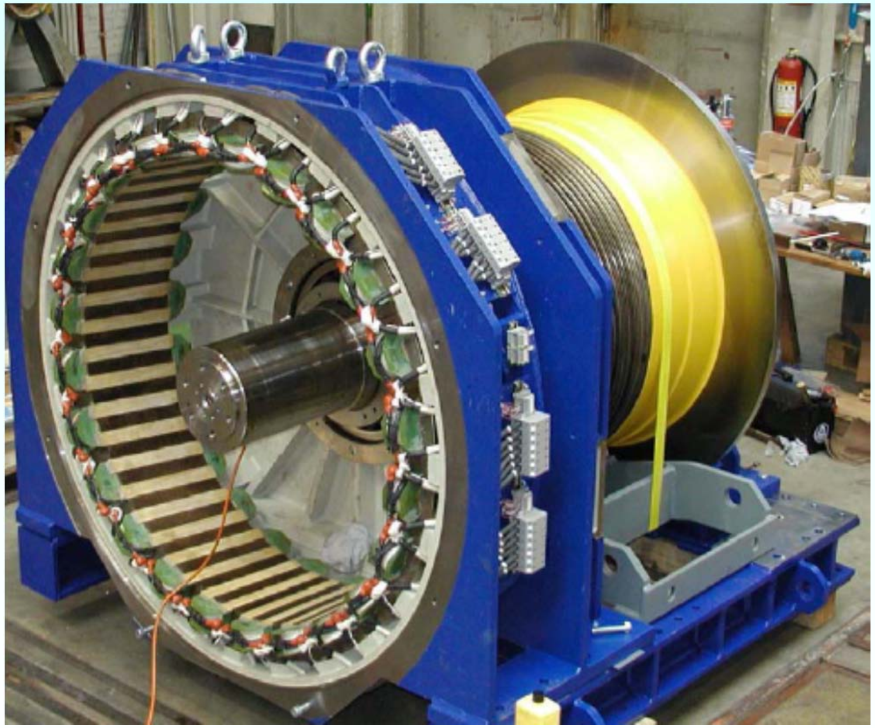
Laminated rotor iron pole shoe



Source: Thyssen, Germany

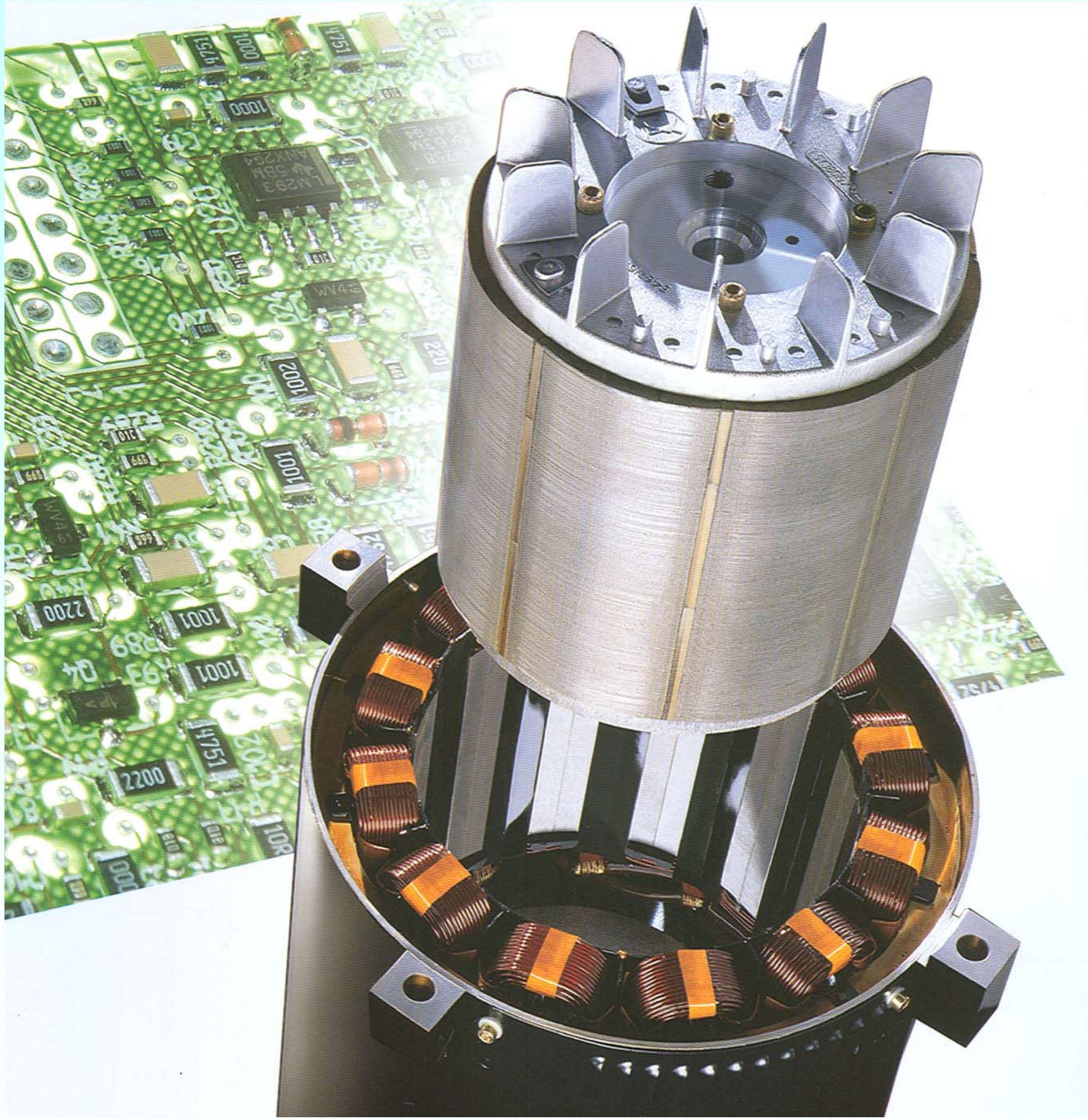
Easy to repair single layer stator winding, tooth-coil per each second tooth, open slots, all teeth of same width

Rotor with NdFeB magnets and flux concentration



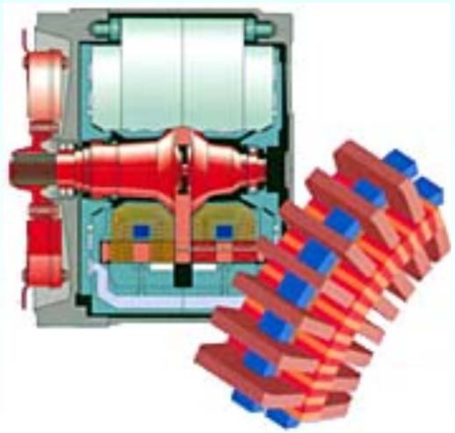
8-pole PM synchronous machine

- 8-pole PM synchronous machine
- Buried rare earth permanent magnets in the rotor
- Aluminium fan blades in the rotor
- Stator two-layer tooth coil winding for low copper losses
- 12 stator coils: $q = ½$ slots per pole and phase = no sub-harmonic field waves for low additional rotor losses



Source: Emerson (Leroy Somer), Angouleme, France

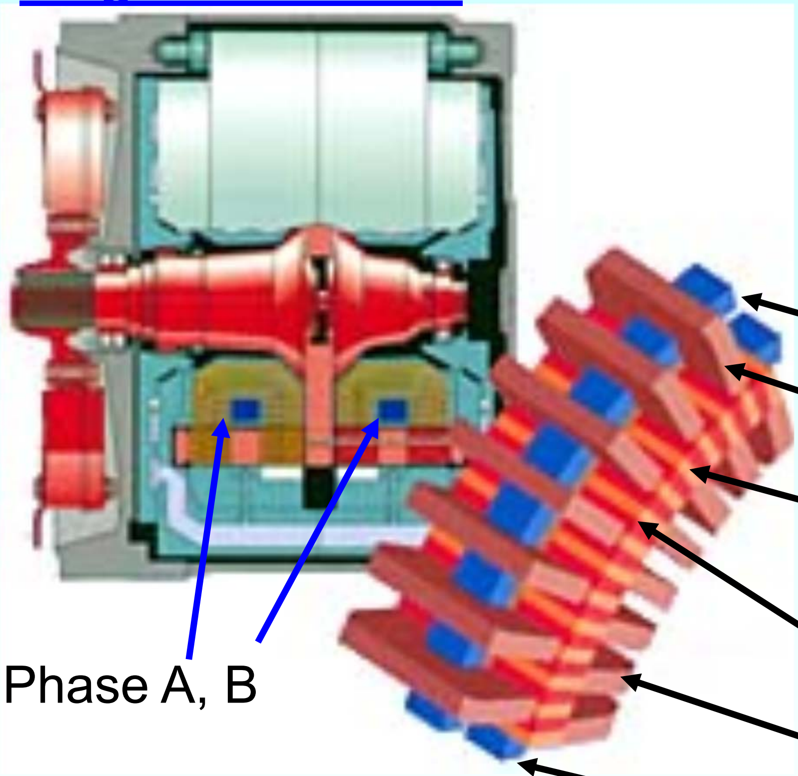
1.5.3 Transversal flux machines



Source:
Voith, Heidenheim, Germany

Two-phase PM excited transversal flux machine

Single sided TFM: No outer stator ring coil



One phase of a **double-sided** transversal flux machine:

Outer stator ring coil

Outer stator U-yokes

Rotor permanent magnets (flux concentration arrangement)

Rotor iron inter-pole pieces

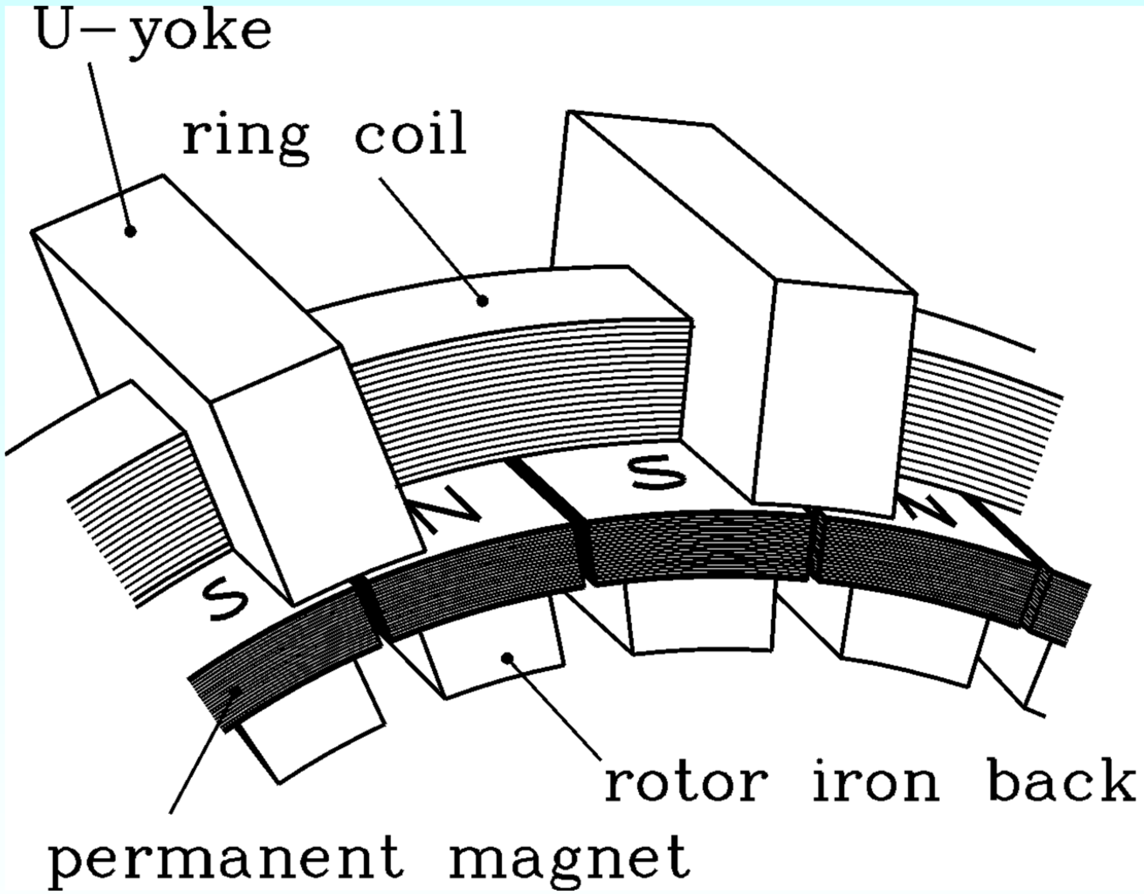
Inner stator U-yokes

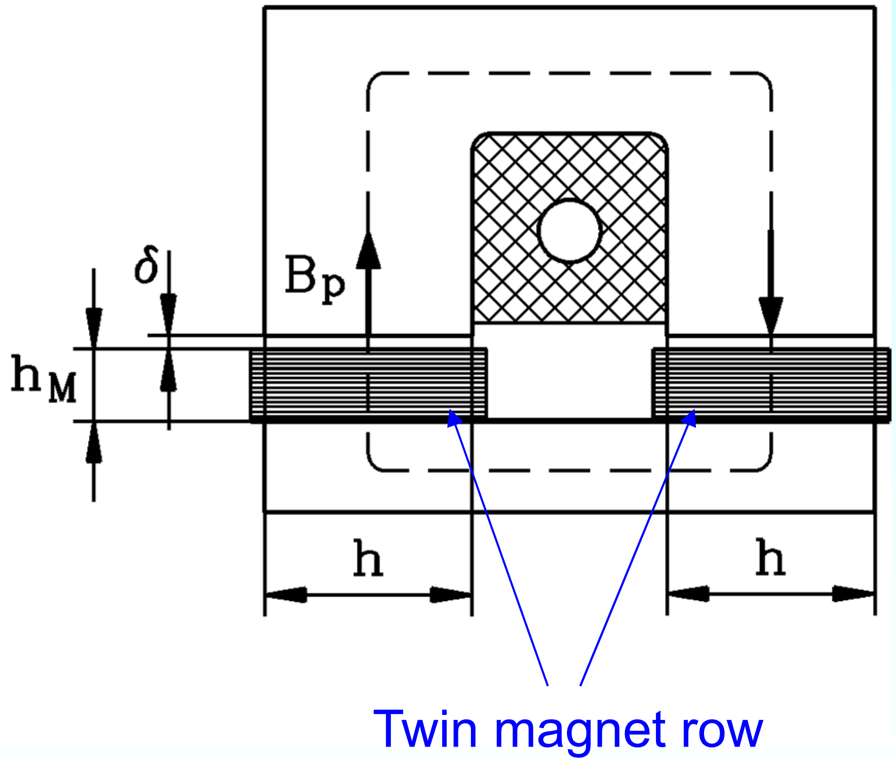
Inner stator ring coil

Source:
Voith, Heidenheim, Germany

One phase of a PM excited transversal flux machine

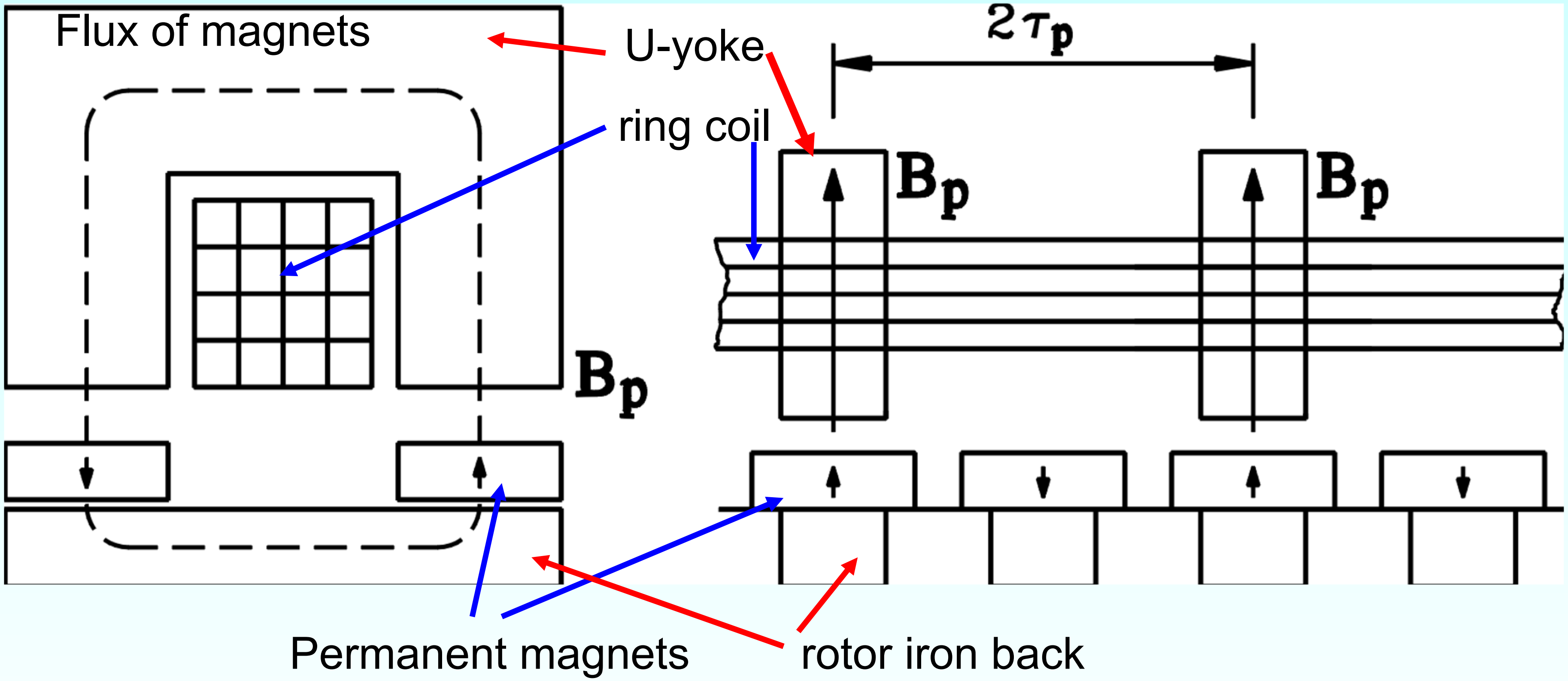
Single sided TFM: No inner stator ring coil





Source:
Weh, H., TU Braunschweig, Germany

Basic arrangement of transversal flux machines

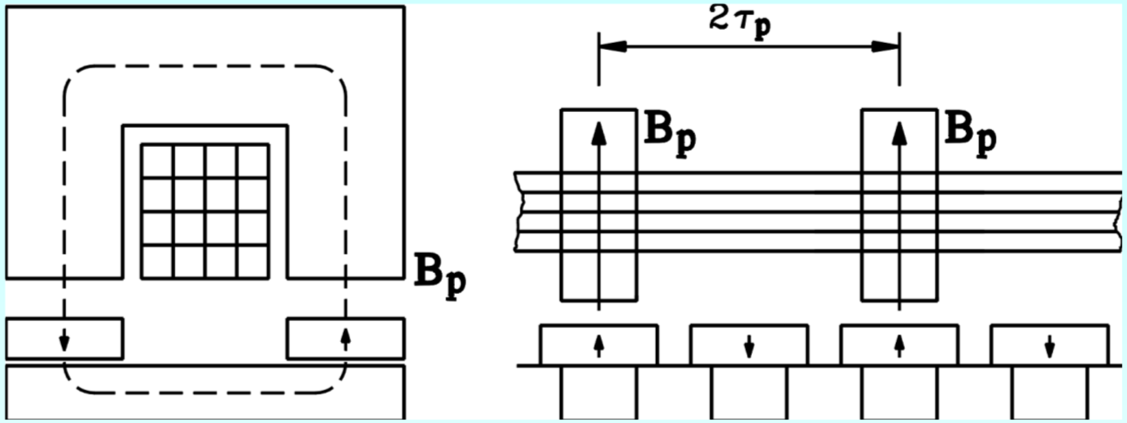


One phase (here *linear* depicted) consists of

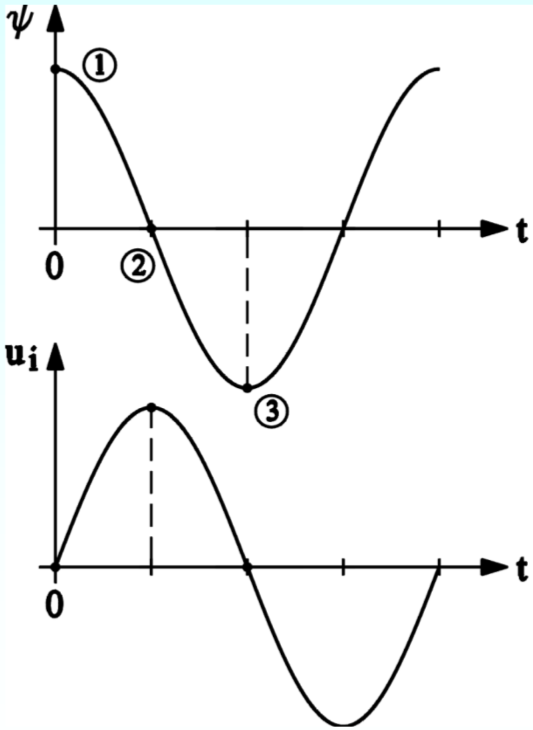
- stator: ring coil, stator U-yokes (displaced by 2 pole pitches),

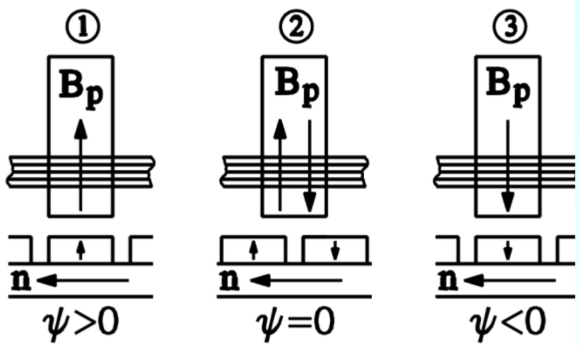
- rotor: two rows of permanent magnets with opposite sign, rotor iron back

No-load voltage induction U_p in transversal flux machines



- No-load permanent magnetic flux linkage with stator ring coil of one phase
- When rotor is moved, stator flux linkage varies !





The changing rotor permanent magnet flux linkage ψ induces back EMF u_i , which may be regarded as u_p.

Facit:
TFM is PM synchronous machine !

$$u_i = -d\psi / dt = -N_s \cdot d\Phi / dt = -u_p$$

Frequency of induced voltage:

$$f_s = n \cdot p$$

Transversal flux machine as generator at no-load

- For a three phase voltage system:
  Three ring coils are necessary and three twin magnet rows.
- Arrangement of phases:
  By shifting the magnets (or the U-yokes) by $2\tau_p/3$, the phase shift of the three induced phase voltages u_p is 120° each.

a) *m* odd number:

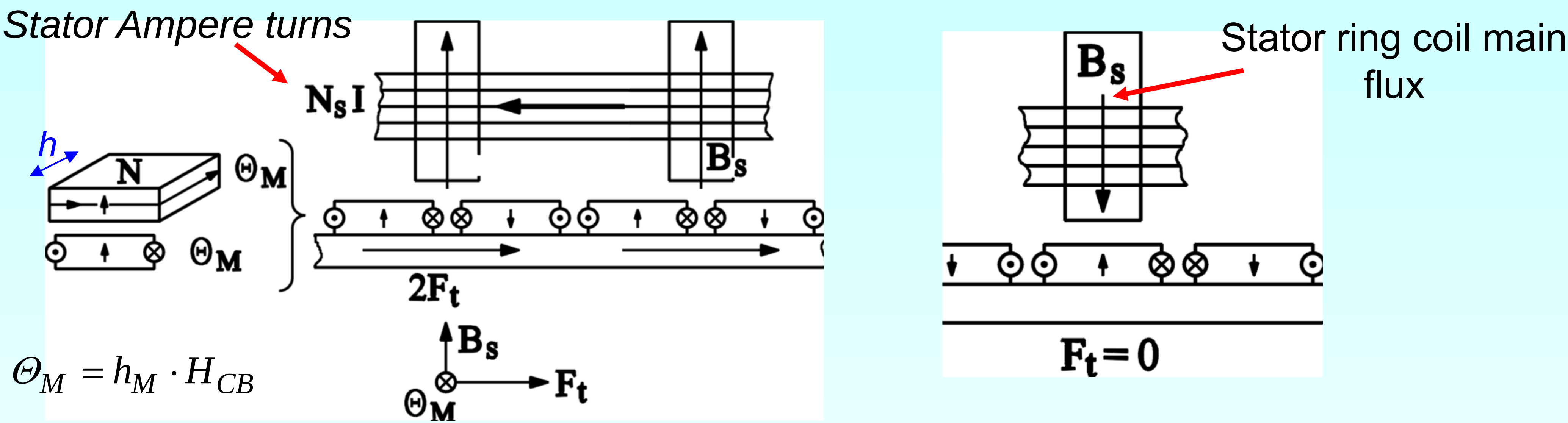
In general, if *m* ring coils are used and the shift of U-yokes or magnets is $2\tau_p/m$, we get a *m*-phase voltage system with phase shift $360°/m$.

b) *m* even number: shift of U-yokes or magnets is τ_p/m.

Special case: Two-phase system:

- $m = 2$, where 2 ring coils are used.
- U-yokes must be shifted by $2\tau_p/4$ to get two voltages with phase shift 360°/4=90°, because phase shift 360°/2=180° yields only phase opposition.

Tangential force generation in transversal flux machine



a) b) c)

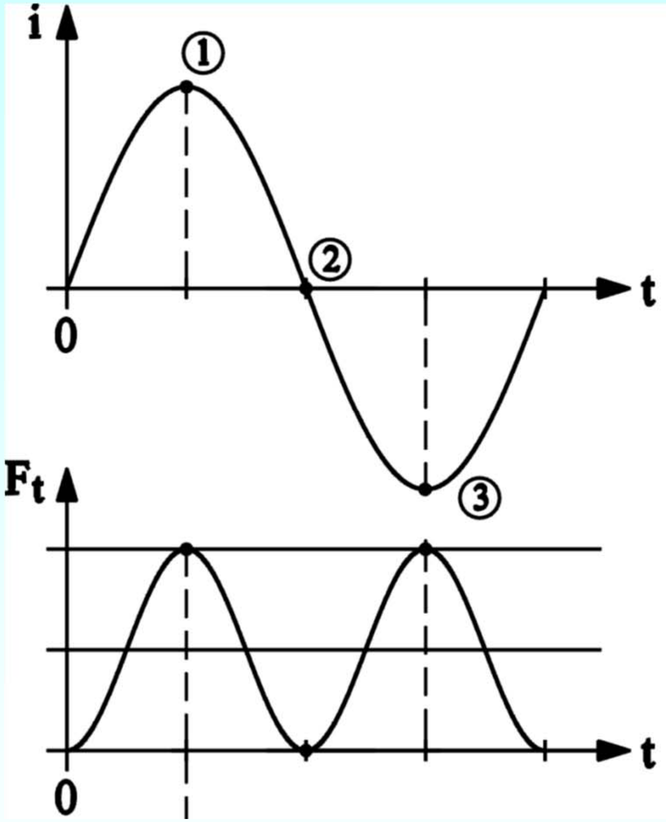
a) The permanent magnets are depicted as electrically excited ring coils for better understanding

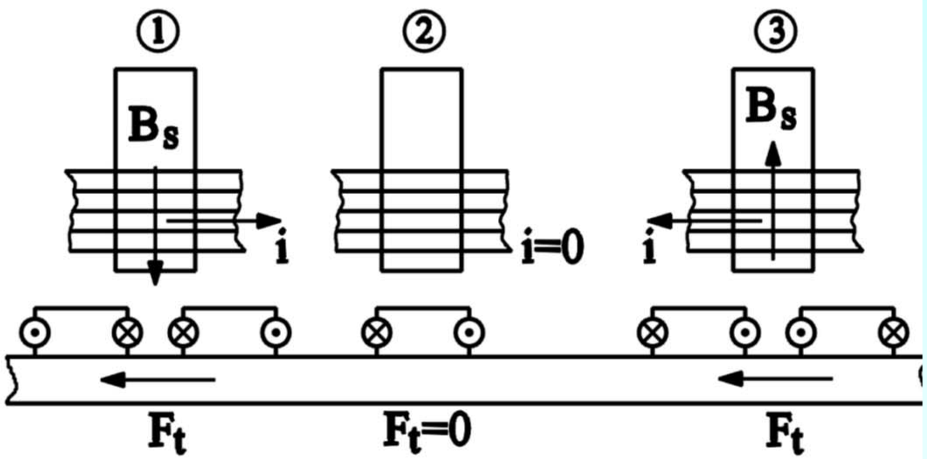
b) *q*-position: maximum tangential force generation F_t (use *LORENTZ* law)

c) *d*-position: no force generation

h: Magnet width, tangential force per magnet: $F_{t,M} = \Theta_M \cdot B_s \cdot h$

Motor operation: Tangential force generation in one phase





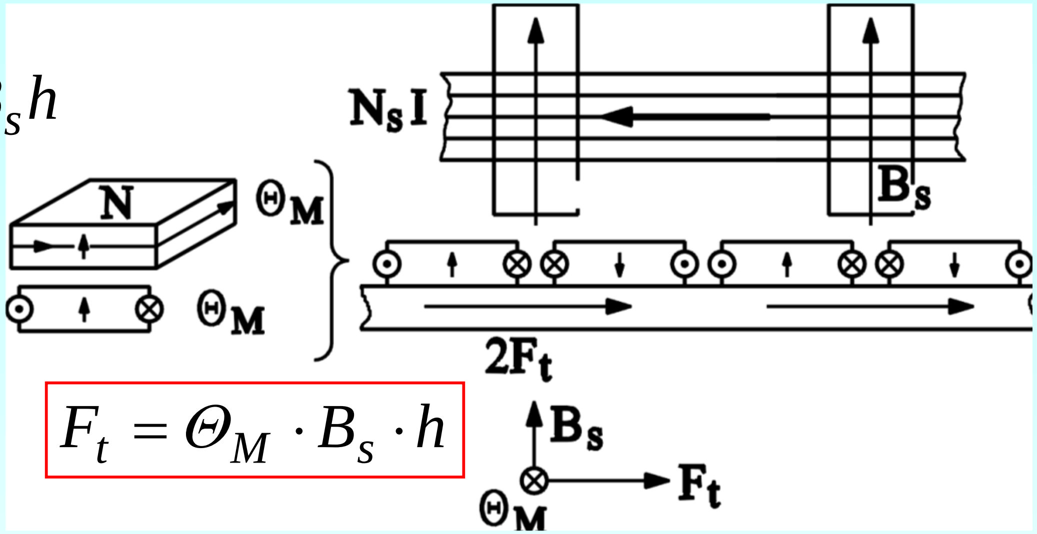
Stator AC current *i (frequency* $f_s = n \cdot p$ *)* produces positive, pulsating tangential force $F_t(t)$ in one phase of transversal flux machine.

Superposition of two phases (shifted by 90°) or three phases (shifted by 120°)

yields smooth constant torque (if cogging torque is neglected) !

Utilization of transversal flux machines

$$\hat{M}_{e,ph} = \frac{d_{si}}{2} \cdot p \cdot 2 \cdot 2F_t = \frac{p\tau_p}{\pi} \cdot p \cdot 2 \cdot 2 \cdot \Theta_M B_s h$$



$$B_s = \mu_0 H_s = \mu_0 \frac{N_s \hat{I}_s}{2 \cdot (\delta + \mu_0 h_M / \mu_M)}$$

$$\Theta_M = h_M \cdot H_{CB} = h_M \cdot B_R / \mu_M$$

$$B_p = \frac{\mu_0 h_M B_R / \mu_M}{\delta + \mu_0 h_M / \mu_M}$$

$$F_t = \Theta_M \cdot B_s \cdot h$$

$L = 2 \cdot m \cdot h$: Overall active width

$$M_e = \frac{m}{2} \hat{M}_{e,ph} = \frac{p\tau_p}{\pi} \cdot p \cdot m \cdot 2h \cdot \frac{h_M \cdot B_p \cdot (\delta + \mu_0 h_M / \mu_M)}{\mu_M \cdot (\mu_0 h_M / \mu_M)} \cdot \mu_0 \frac{N_s \hat{I}_s}{2 \cdot (\delta + \mu_0 h_M / \mu_M)}$$

$$M_e = \frac{p^2 \tau_p^2}{\pi} \cdot m \cdot 2h \cdot B_p \cdot \frac{N_s \hat{I}_s}{2\tau_p} = \frac{d_{si}^2 \pi}{4} \cdot (2m \cdot h) \cdot \sqrt{2} \cdot B_p \cdot A$$

$$M_e = \frac{d_{si}^2 \pi}{4} \cdot L \cdot \sqrt{2} \cdot B_p \cdot A$$

Rotor volume: $\frac{d_{si}^2 \pi}{4} \cdot L$

Torque per rotor volume: $M_e / V = \sqrt{2} B_p \cdot A$

Multi-phase motor operation in TFM

- Internal power of one coil:

$$p_\delta(t) = u_p(t)\cdot i(t) = \hat{U}_p \sin(\omega_s t)\cdot \hat{I}_s \sin(\omega_s t) = \frac{\hat{U}_p \hat{I}_s}{2}\cdot\left(1-\cos(2\omega_s t)\right) = v_{syn}\cdot F_t(t)$$

- Tangential force calculated from total internal power (all phases):

$$F_t = \frac{m\cdot \hat{U}_p \hat{I}_s}{2\cdot v_{syn}}$$

- Torque calculated from tangential force: with $v_{syn} = d_{si}\cdot\pi\cdot n$

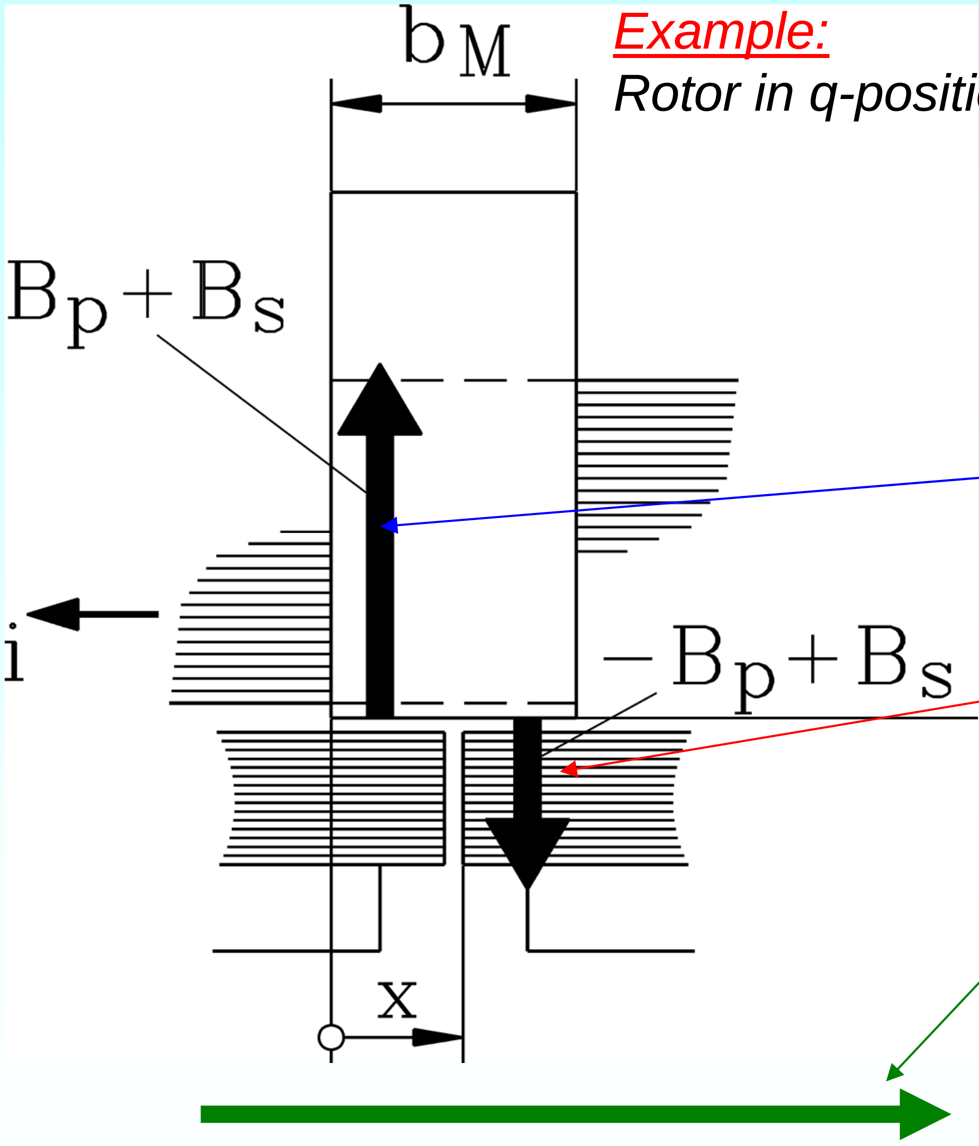
$$M_e = F_t\cdot(d_{si}/2) = \frac{p}{\omega_s}\cdot m\cdot U_p I_s$$

Facit:

The transversal flux machine is a special kind of PM synchronous machine with a high pole count, as no slots are necessary. As coil cross section and flux cross section lie in perpendicular planes (transversal arrangement), the coil cross section may be increased without influencing the magnetic flux path.

Addition of stator and rotor field in U-yoke

Example:
Rotor in q-position

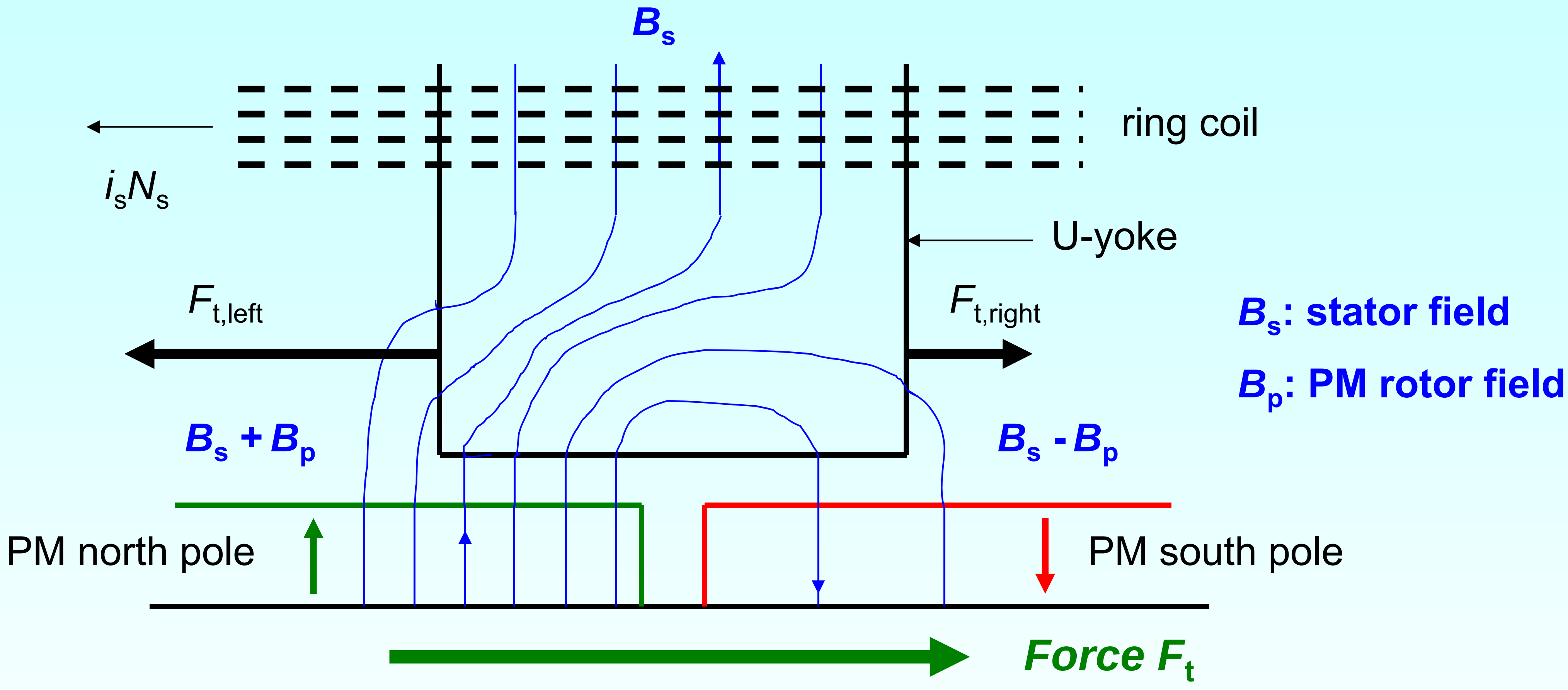


- *North AND south pole are beneath U-yoke !*
- *So:*
- *At left edge of U-yoke stator and rotor field add up = **FIELD INCREASE***
- *AT right edge stator and rotor field subtract: **FIELD DECREASE***
- *Difference in total field gives resultant magnetic TANGENTIAL PULL = resultant tangential force !*

Force F_t

Source:
Weh, H., TU Braunschweig, Germany

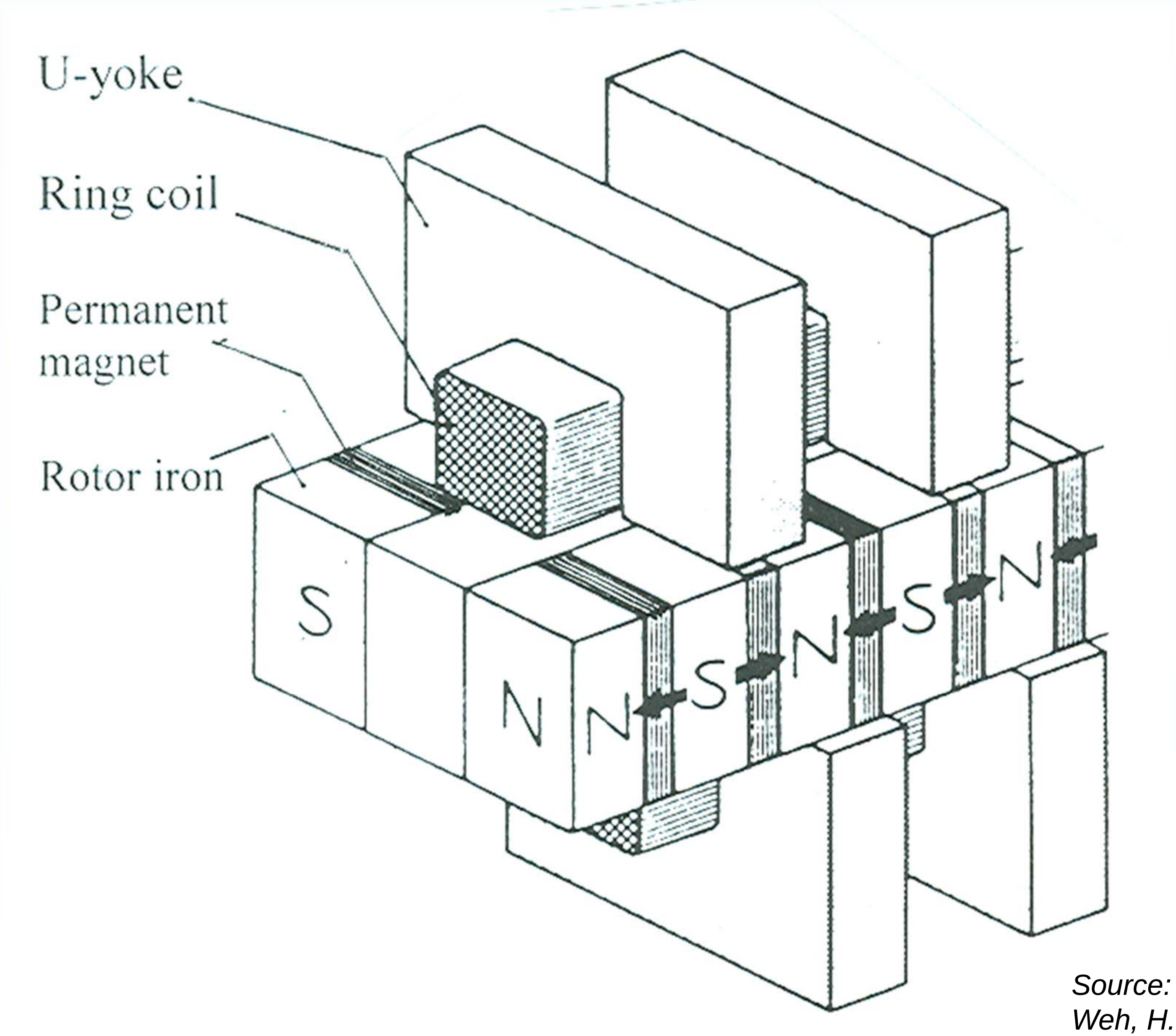
Single-sided TFM: Rotor in q-position



The resulting tangential force on the stator U-yoke $F_t = F_{t,left} - F_{t,right}$ points to the left.

The corresponding tangential rotor force points according to “actio est reactio” to the right.

Double-sided transversal flux machine with flux concentration



Double-sided machine:

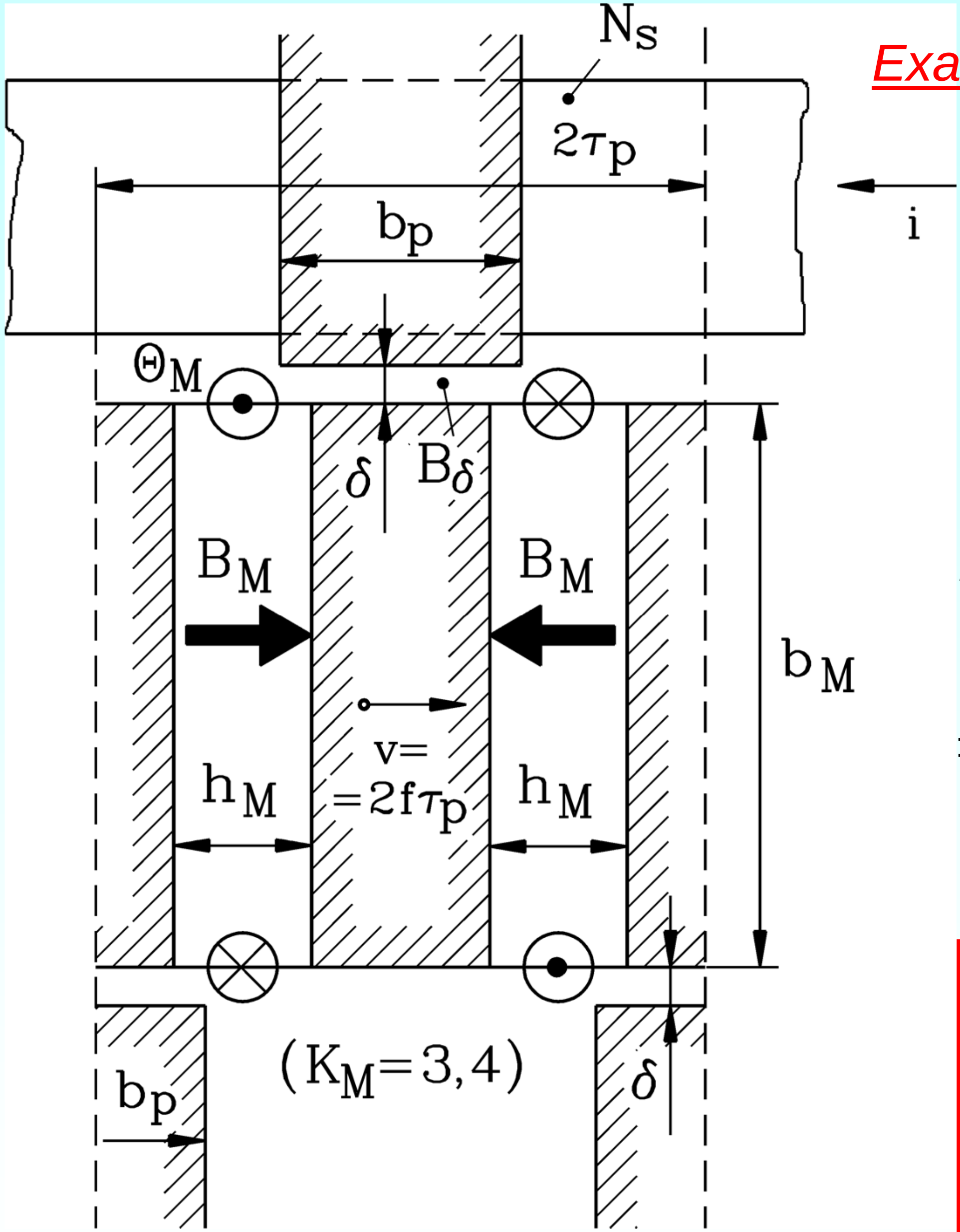
Increase of tangential force per pole by factor 2

Flux concentration:

Increase of air gap flux density

Source:
Weh, H., TU Braunschweig, Germany

Double-sided transversal flux machine with flux concentration



Example: *Rotor in d-position*

Flux per U-yoke side (= pole flux):

$$\Phi = 2 \cdot B_M \cdot (b_M \cdot h) = B_\delta \cdot \tau_p \cdot h \quad \Rightarrow$$

$$k_M = \frac{B_\delta}{B_M} = \frac{2b_M}{\tau_p} > 1$$ **Flux concentration**

$$i = 0 : \oint_C \vec{H} \bullet d\vec{s} = 2 \cdot (2H_\delta \cdot \delta + H_M \cdot h_M) = 0 \quad \Rightarrow$$

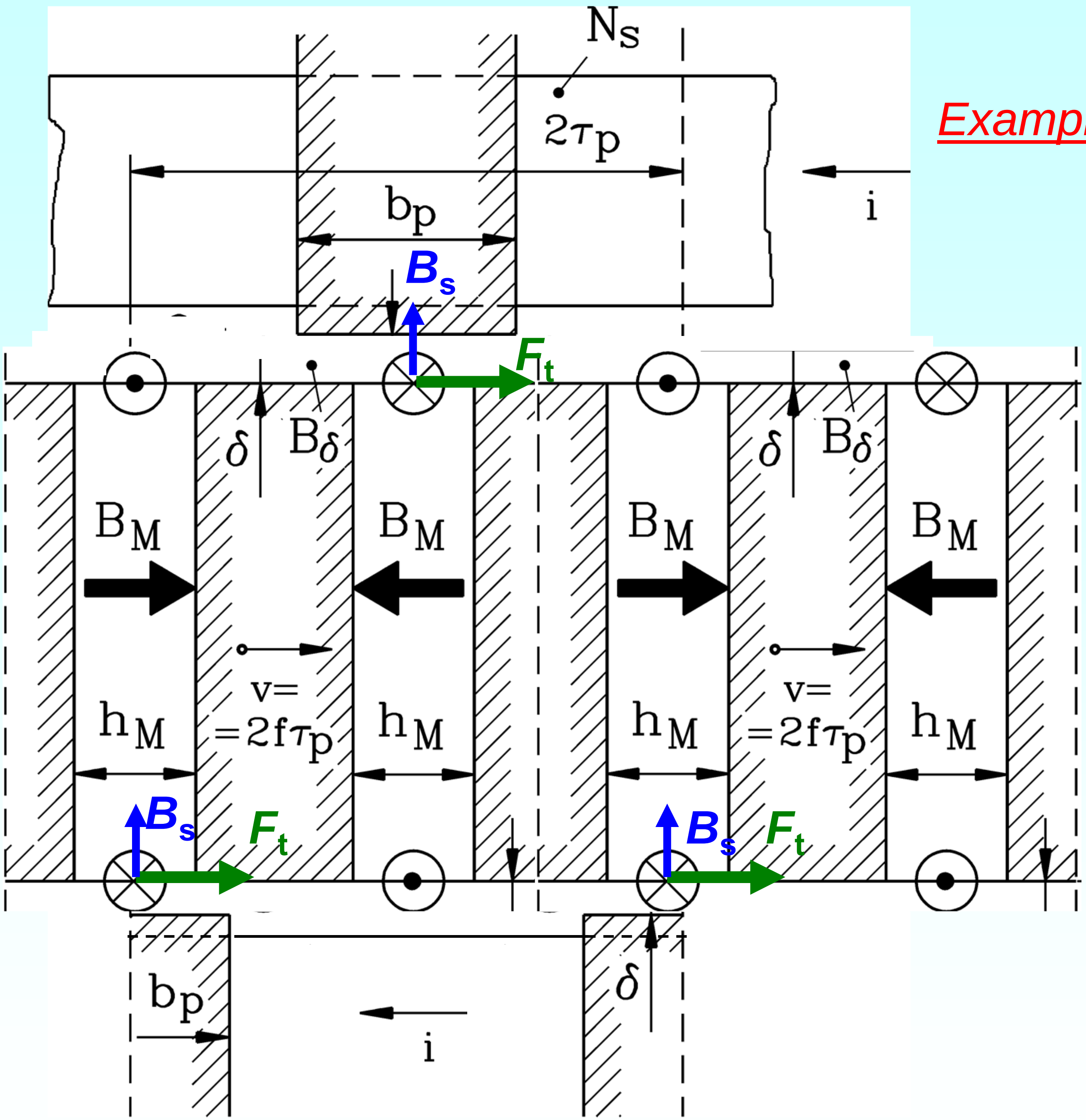
$$\Rightarrow \quad B_\delta = \mu_0 H_\delta = -\mu_0 \frac{h_M}{2\delta} \cdot H_M$$

Magnet material: $B_M = \mu_M H_M + B_R$

$$B_\delta = \frac{B_R}{\frac{1}{k_M} + \frac{\mu_M \cdot 2\delta}{\mu_0 \cdot h_M}}$$

No-load air gap field

Double-sided transversal flux machine with flux concentration



Example: *Rotor in q-position*

q-position = maximum tangential force

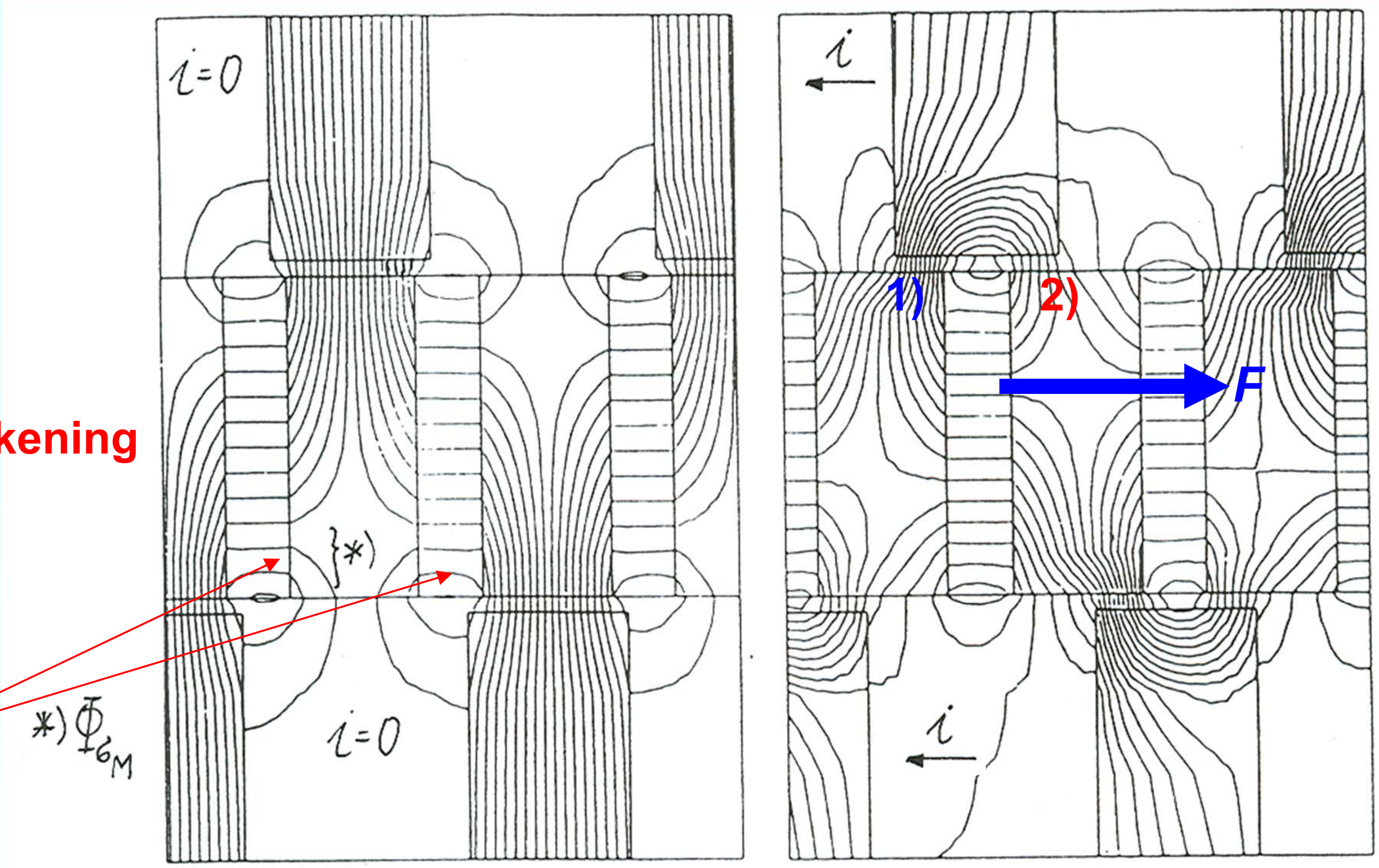
Force generation in double-sided transversal flux machine

- 2D numerical field calculation
- Stator and rotor field

1) Add up

2) Are opposing = weakening

Rotor pole stray flux
ca. 23 %



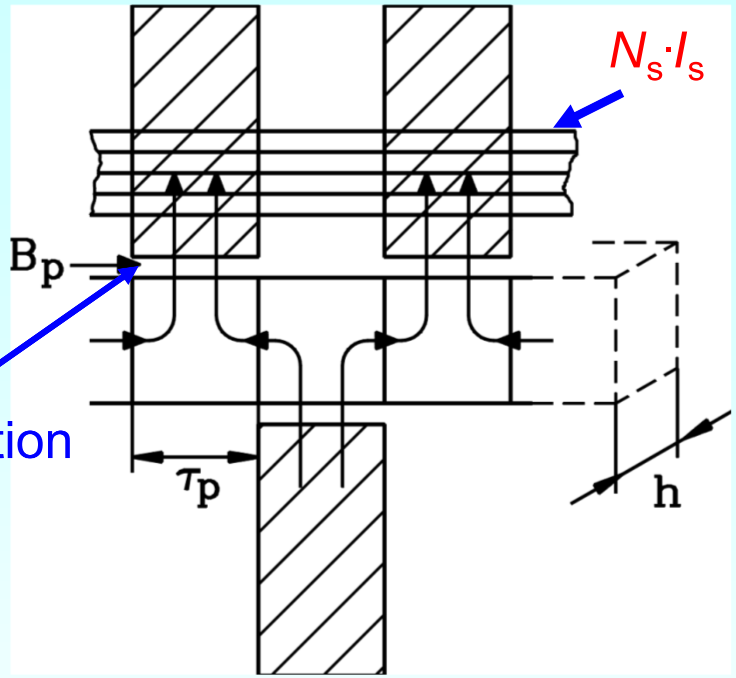
Source:
Weh, H., TU Braunschweig, Germany

Symmetric field lines | Asymmetric field lines

No tangential force | Full tangential force *F*

Stator current *i* shall be: zero | Maximum

Double-sided transversal flux machine with flux concentration



Double-sided machine:

Increase of tangential force per pole by factor 2

Flux concentration:

Increase of air gap flux density

$U_p \sim B_p$ $\qquad F_t \sim m \cdot B_p \cdot N_s \cdot I_s \sim B_p \cdot A$

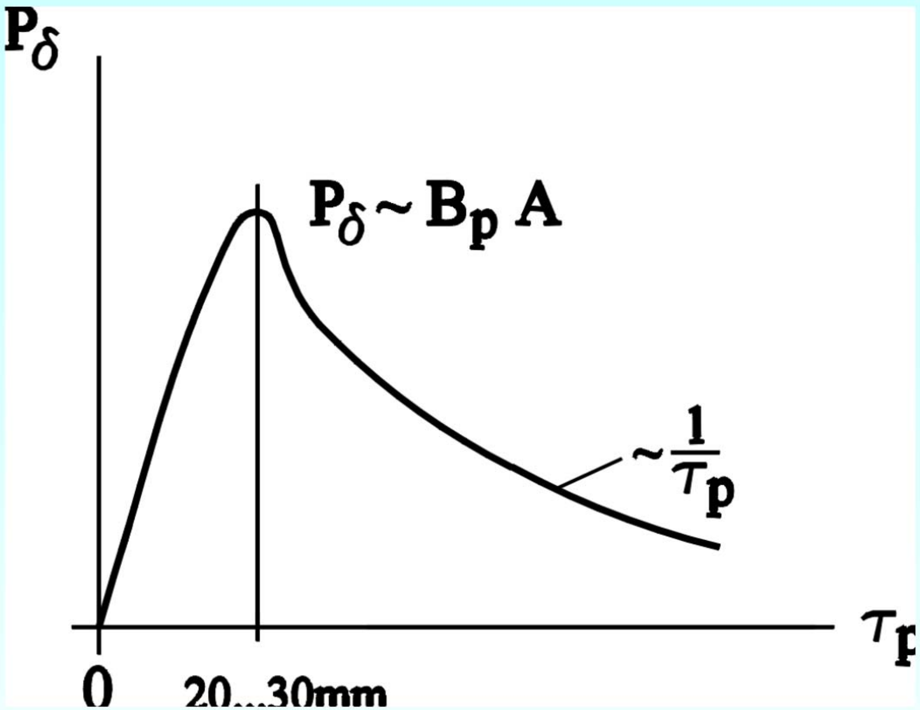
Current loading: $A = \dfrac{N_s I_s}{2\tau_p}$

$N_s I_s$ independent of pole number $2p \Rightarrow A \sim p$

$$For \quad d_{si}\pi = 2p\tau_p = const.: p\uparrow \Rightarrow \tau_p \downarrow \Rightarrow A\uparrow (A \sim p)$$

Example:	*No flux concentration*	*Flux concentration No stray flux*	*Flux concentration Stray flux 23%*
Concentration factor k_M	1	3.4	$0.77 \cdot 3.4 = 2.6$
$B_\delta(I = 0) = B_p$	0.72 T	1.34 T (+85%)	1.21 T (+68%)

High torque per active mass ratio for TFM



$M_e / V \sim B_p \cdot A$

$$A = \frac{N_s I_s}{2\tau_p}$$

The shorter the pole pitch, the bigger the current loading A;

hence the bigger the tangential force and air gap power P_δ.

***That means:** Shorter pole pitch = higher pole number = higher total tangential force !*

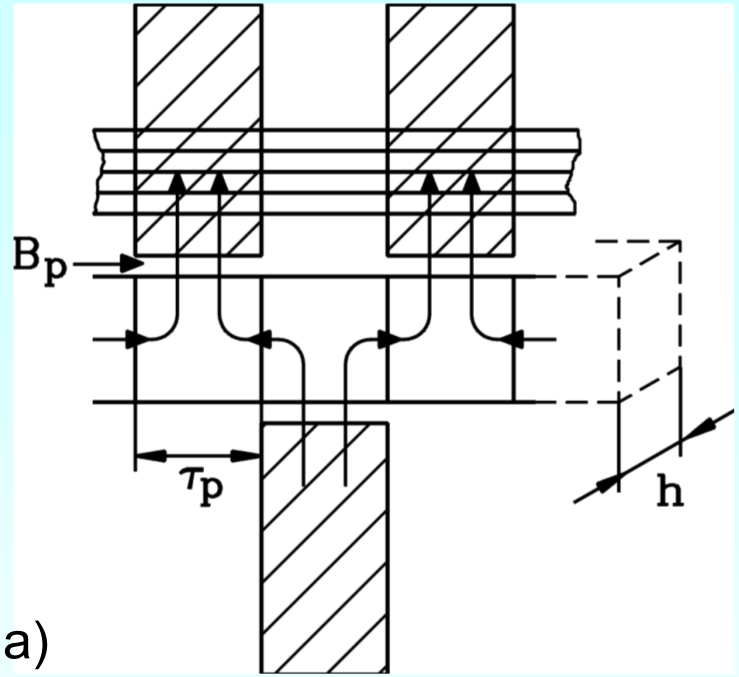
Source:
Weh, H., TU Braunschweig, Germany

Facit:

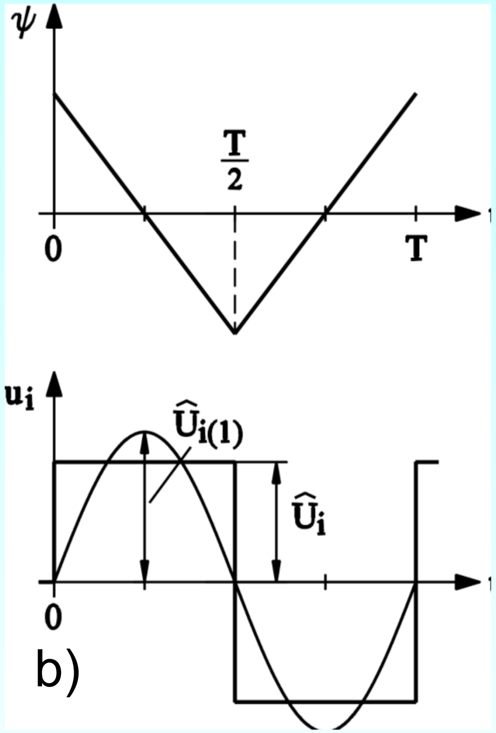
Increase of power of TFM at given motor diameter and length by increasing pole count (decreasing pole pitch τ_p) with theoretical optimum pole pitch at about 10 ... 15 mm.

Trade-off: If pole-pitch is TOO small, rotor magnets produce only rotor leakage flux, but no-air-gap flux, so power decreases.

Torque ripple at load in transversal flux machine



a)



b)

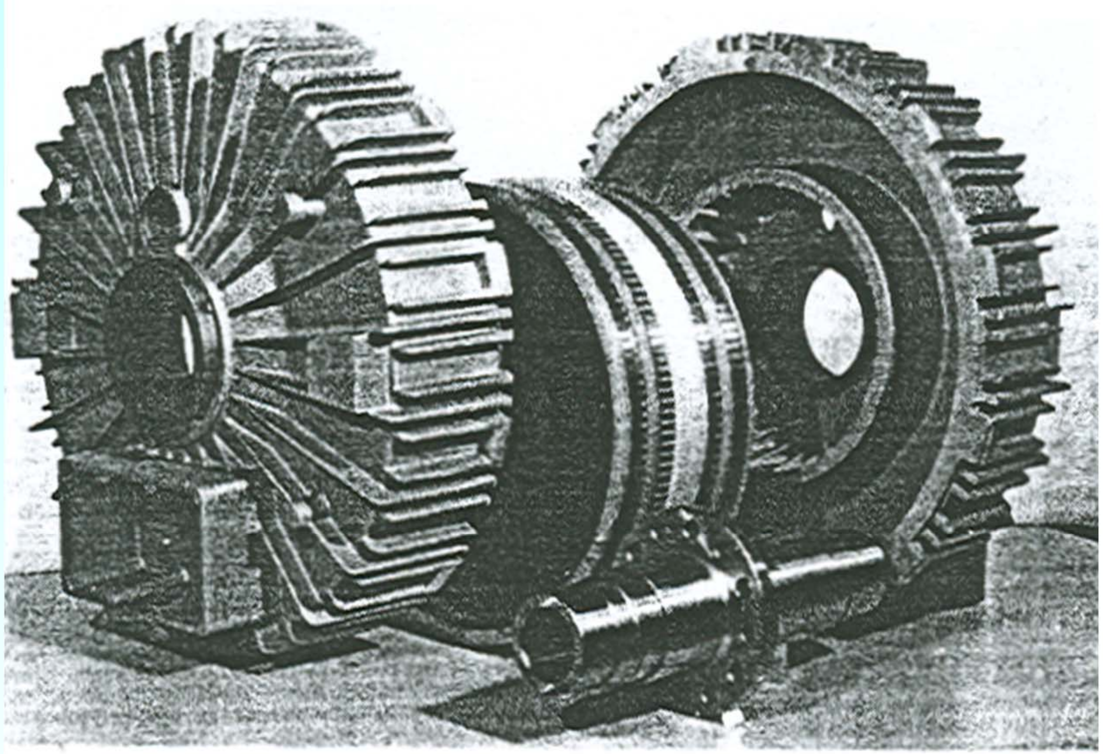
Assume constant PM flux density over pole pitch:

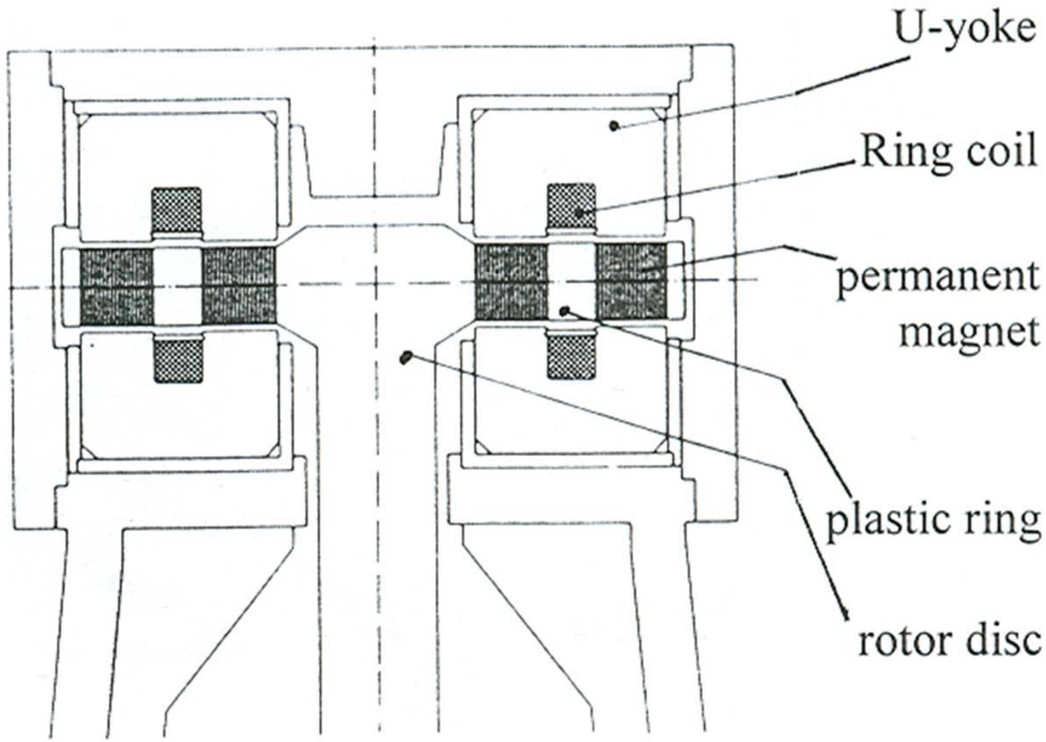
a) Permanent magnet flux linkage of ring coil at *d*-position of rotor (time t = 0)

b) Changing of flux linkage, when rotor is moving, induces rectangular shaped back EMF u_i.

Only its sinusoidal fundamental (k = 1) produces constant torque with sinusoidal current. Higher voltage harmonics produce with current harmonics torque pulsation.

2-phase prototype TFM (*Prof. Weh*)

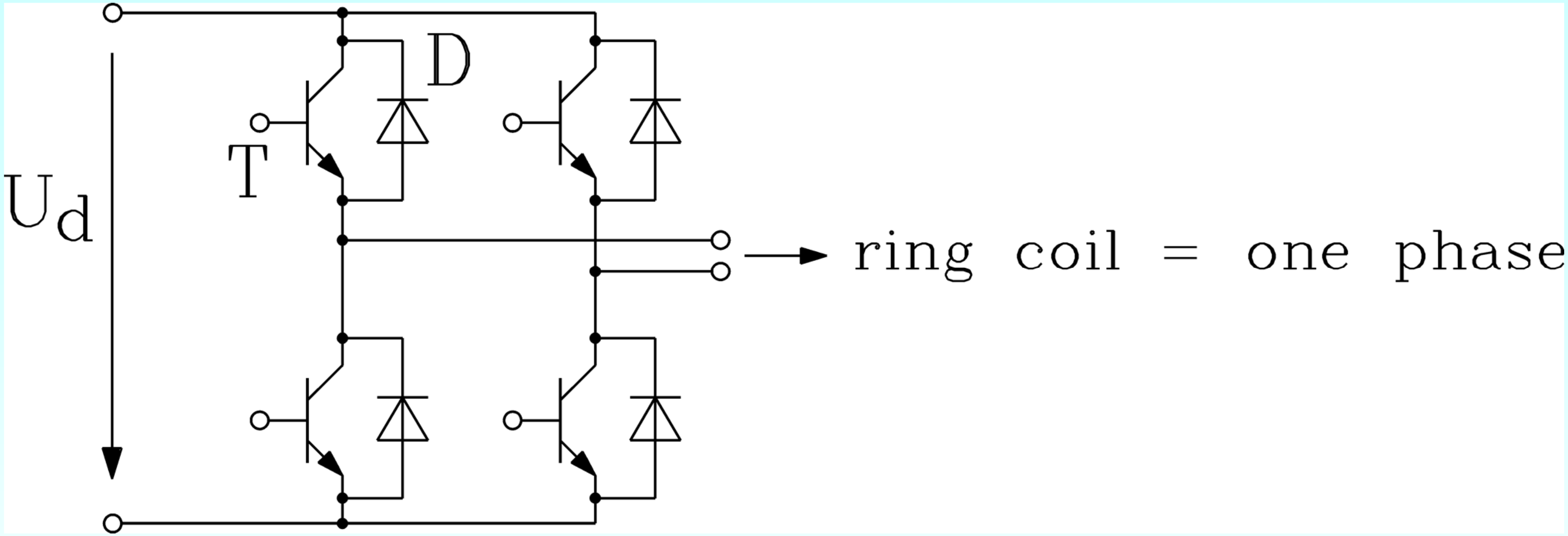




- Two phase transversal flux motor
- Inner rotor, outer and inner stator coil
- Double-sided machine, flux concentration

Source:
Weh, H., TU Braunschweig, Germany

Inverter topology for 2-phase TFM



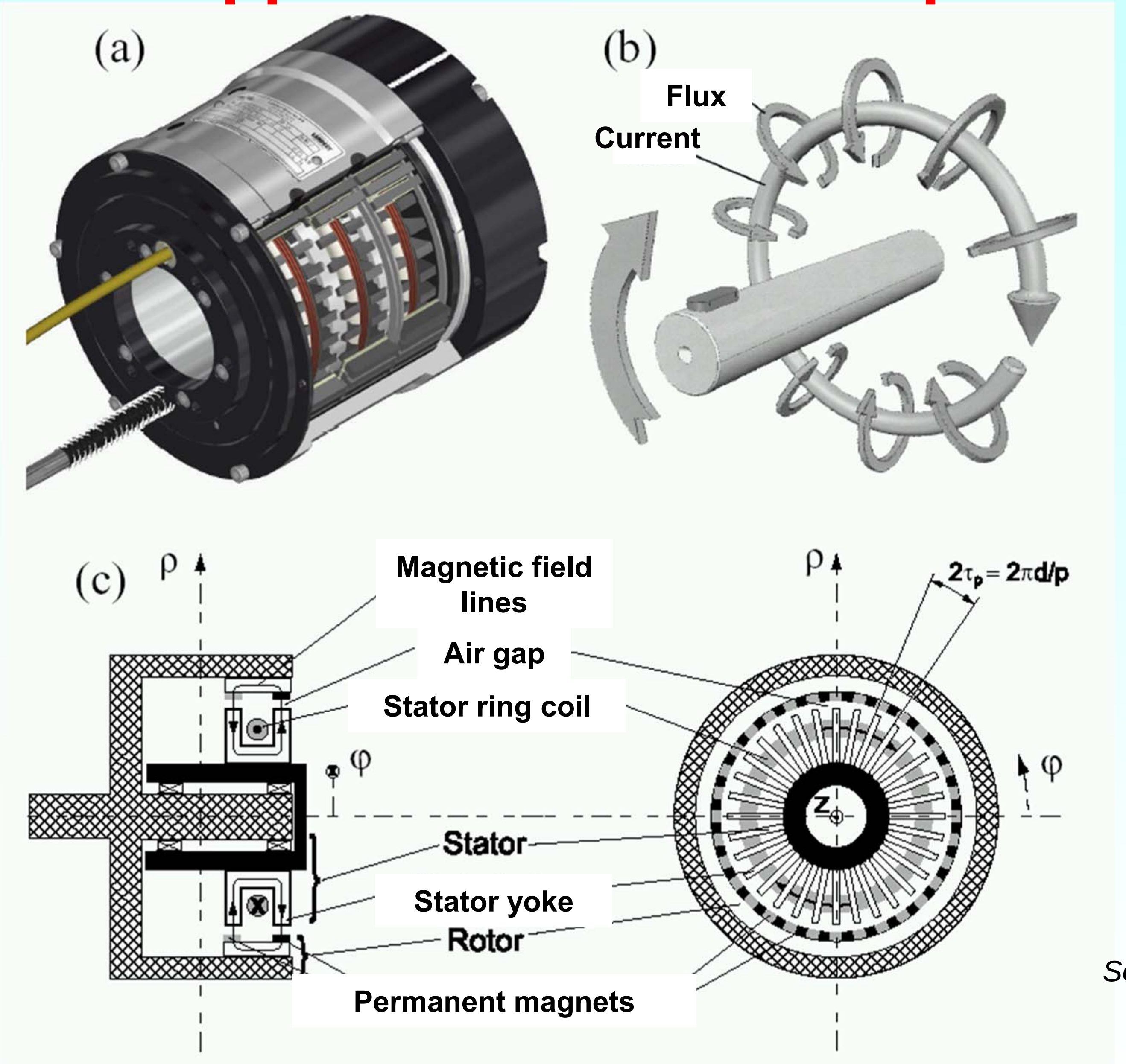
- Per phase a full H-bridge is needed for four-quadrant operation = positive and negative current flow and voltage polarity in ring coil !

- DC link U_d feeds two H-bridges for the TFM

- Compare: Three phases: 6 Transistors, 6 free-wheeling diodes

  Two phases: 8 Transistors, 8 free-wheeling diodes

Applications of TFM: Up to now only few !



Single sided three phase small transversal flux motor with outer rotor as PM servo drive !

Inner stator

Outer PM rotor

a) motor cut view,

b) ring coil with flux linkage,

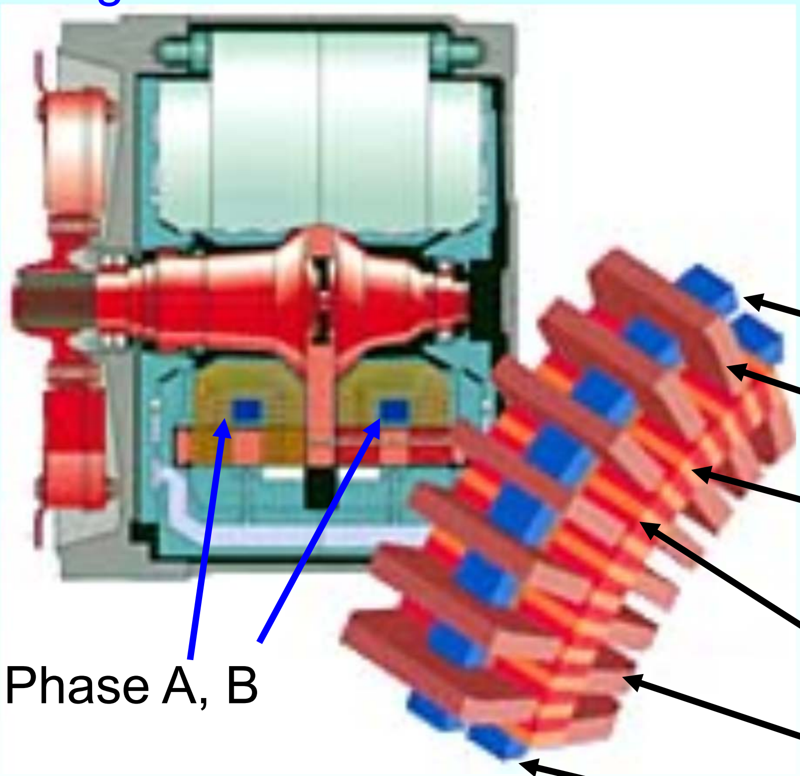
c) motor cross section,

d) axial cross section

Source: Landert, Switzerland

Two-phase PM excited transversal flux machine: Propulsion of busses with wheel-hub drive

Single sided TFM: No outer stator ring coil



One phase of a double-sided transversal flux machine:

Outer stator ring coil

Outer stator U-yokes

Rotor permanent magnets (flux concentration arrangement)

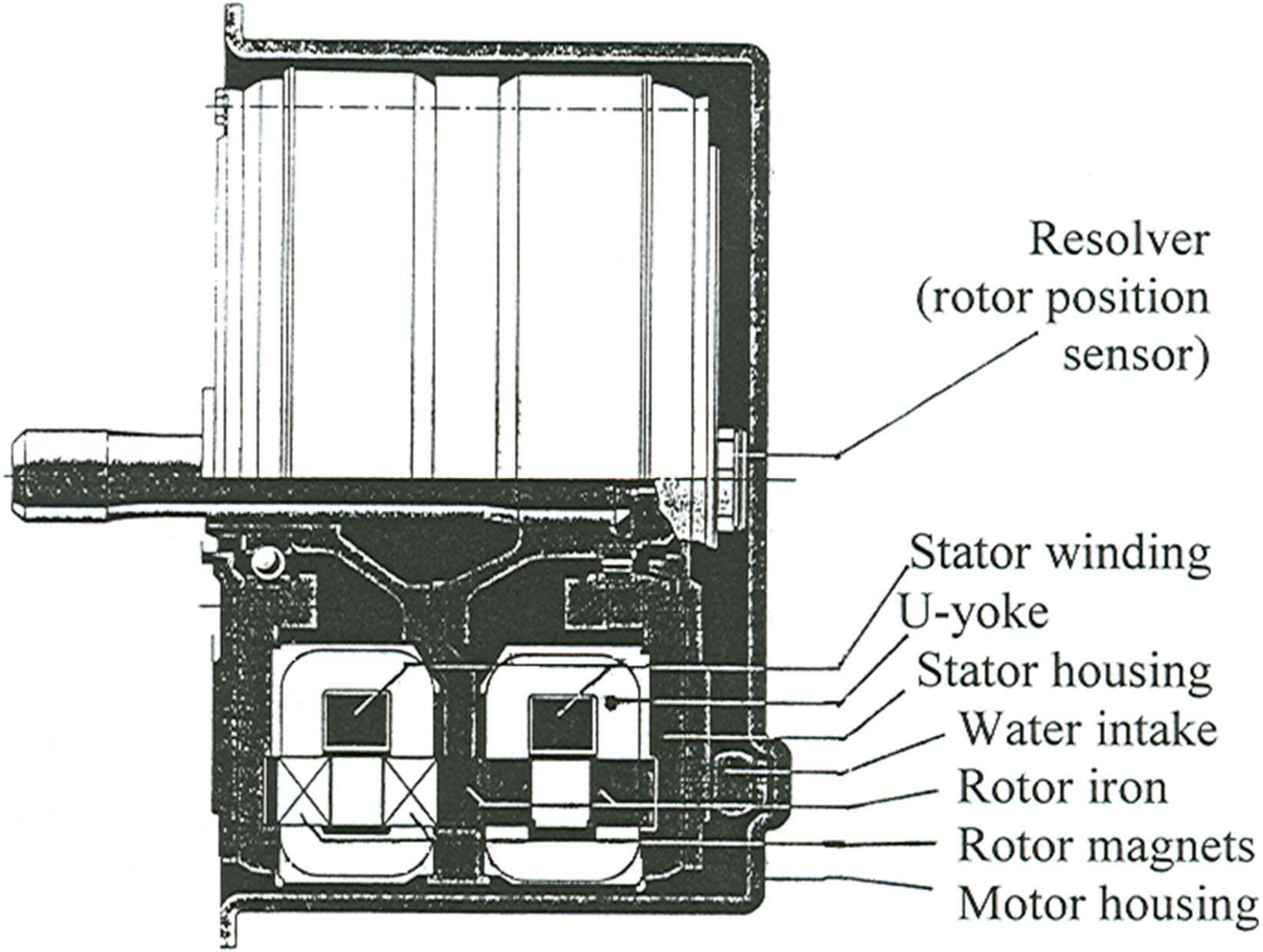
Rotor iron inter-pole pieces

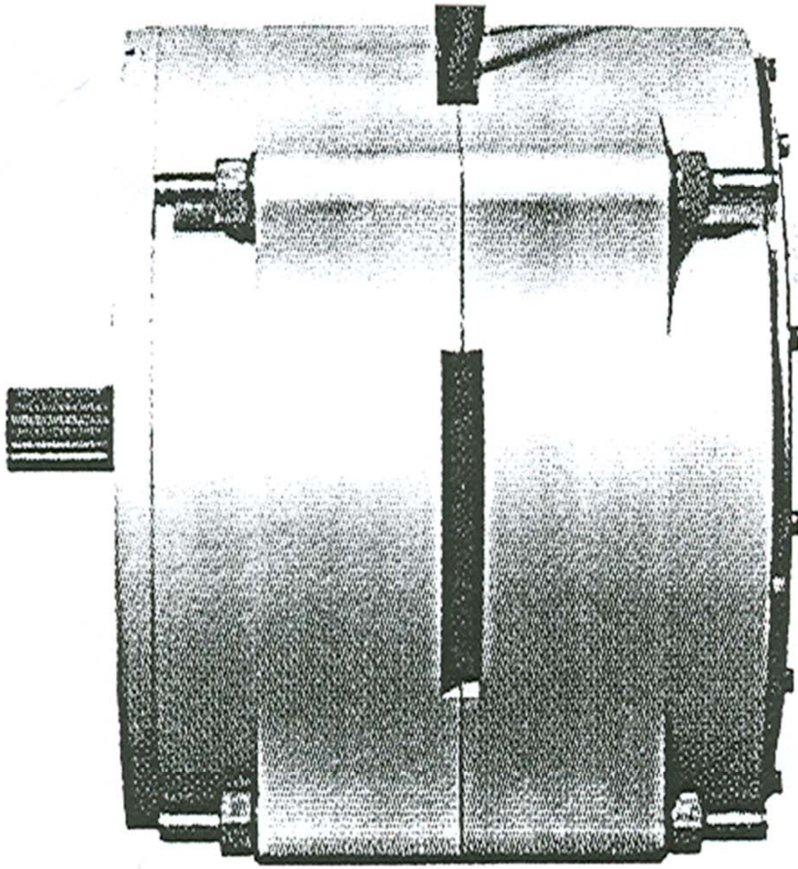
Inner stator U-yokes

Inner stator ring coil

Source:
Voith, Heidenheim, Germany

Two-phase TFM for propulsion of busses





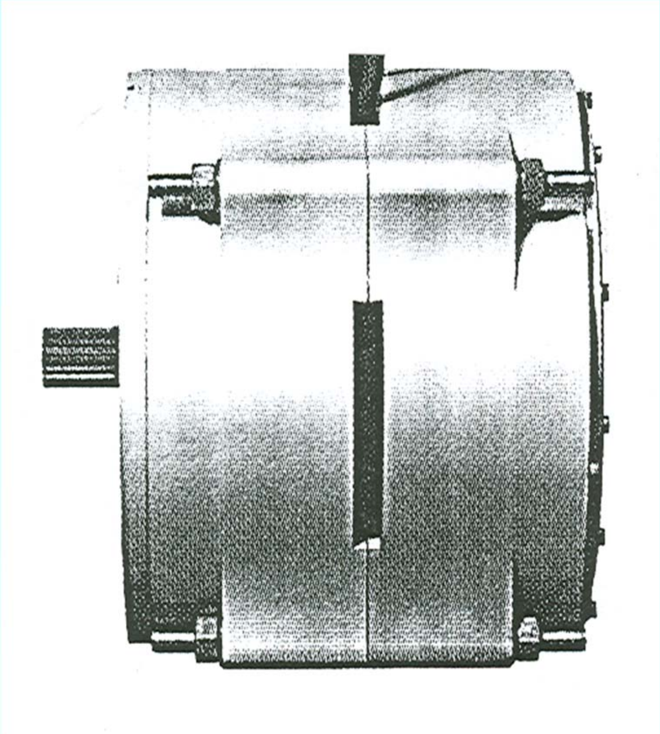
Source:
Voith, Heidenheim, Germany

Propulsion of busses with wheel-hub drive

Example:
Variable speed drive system for City-Bus

Single sided transversal flux motor:
n_{max} = 2500/min
M_{max} = 1050 Nm
f_{max} = 1375Hz,
steady state output power 57 kW

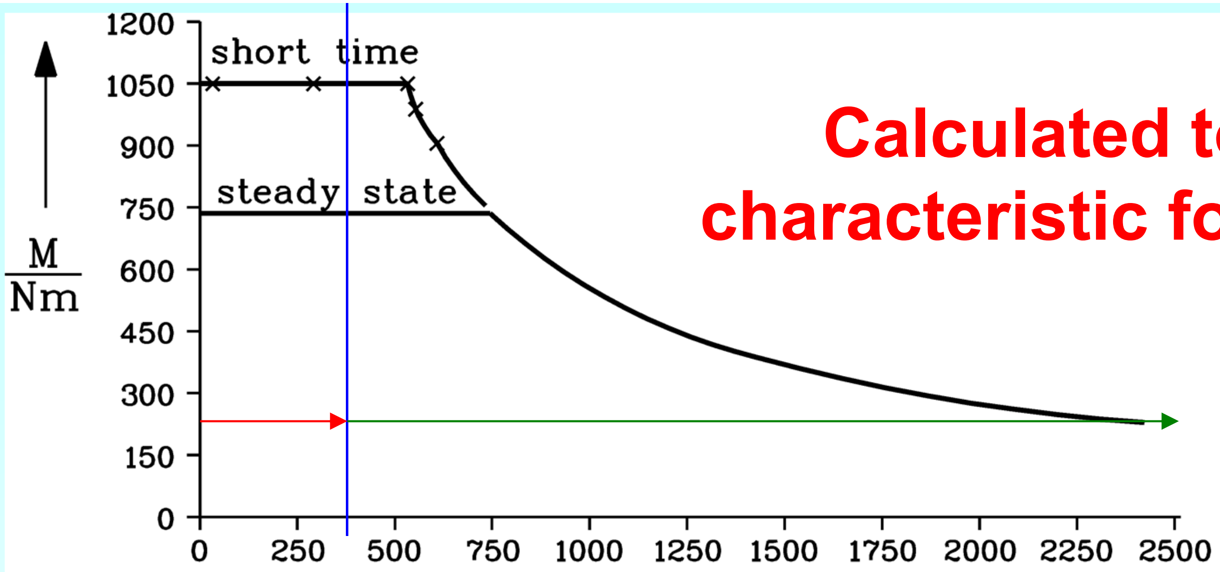
Source:
Voith, Heidenheim, Germany



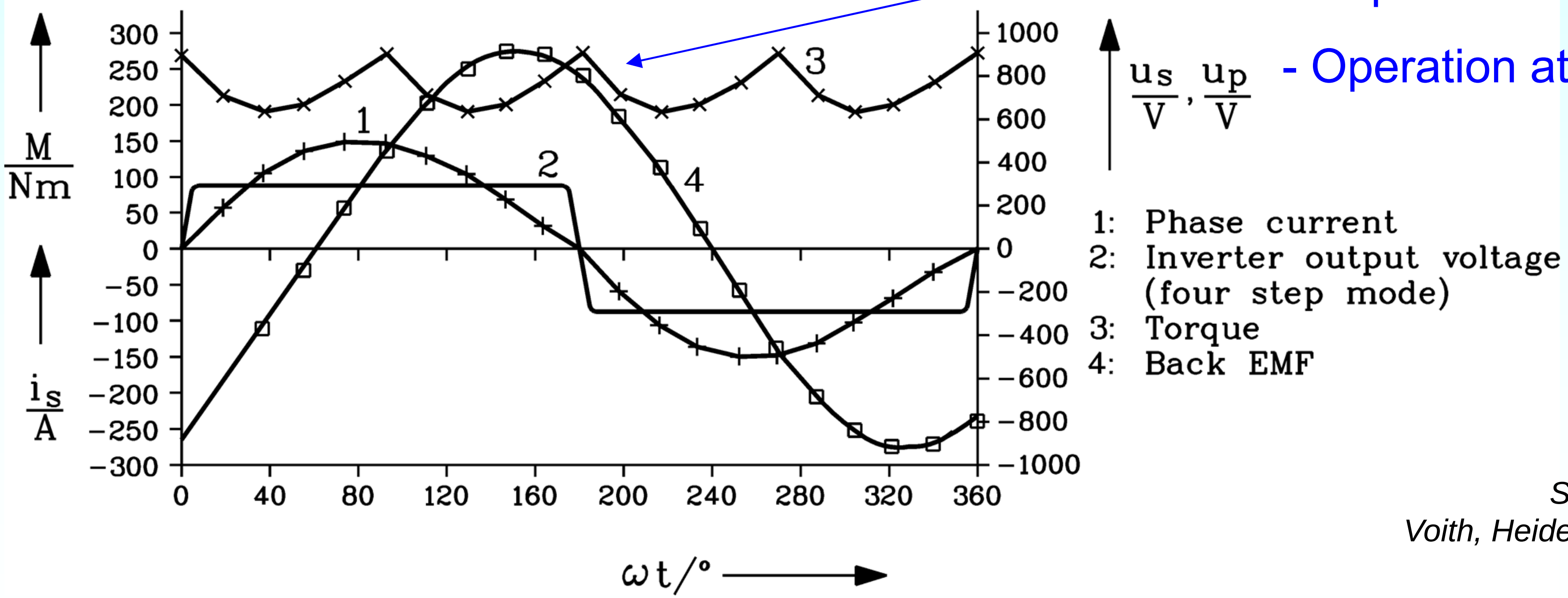
- Outer diameter 420 mm, mass 115 kg
- 300 V DC link voltage, high pole count $2p$ = 66,
- Two phase system m = 2

Base speed range: Constant torque	0...750/min	725 Nm steady state 1050 Nm overload
Constant power range	750...2500/min	725...218 Nm steady state

Calculated torque speed characteristic for TFM bus drive



PWM 4-step voltage mode

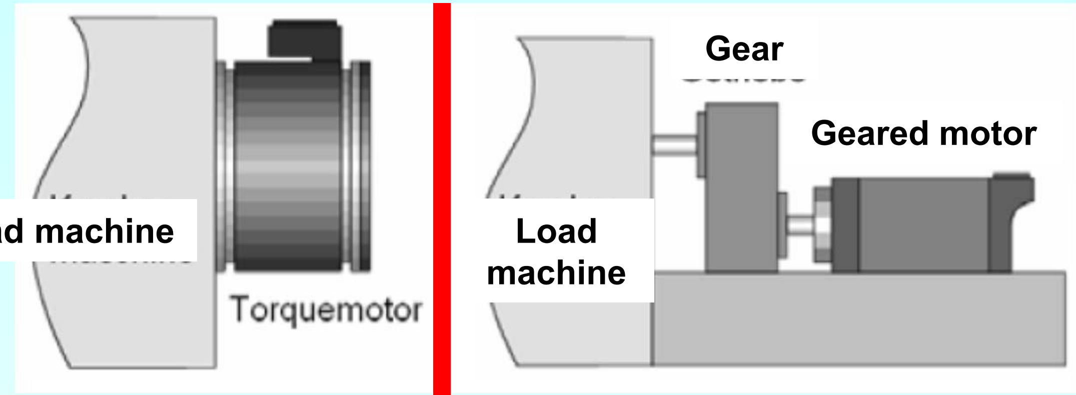


- Torque ripple due to 4-step inverter control
- Operation at max. speed

Source: Voith, Heidenheim, Germany

1.5.4 Comparison of direct drives with geared drives

Torque for direct and geared motor



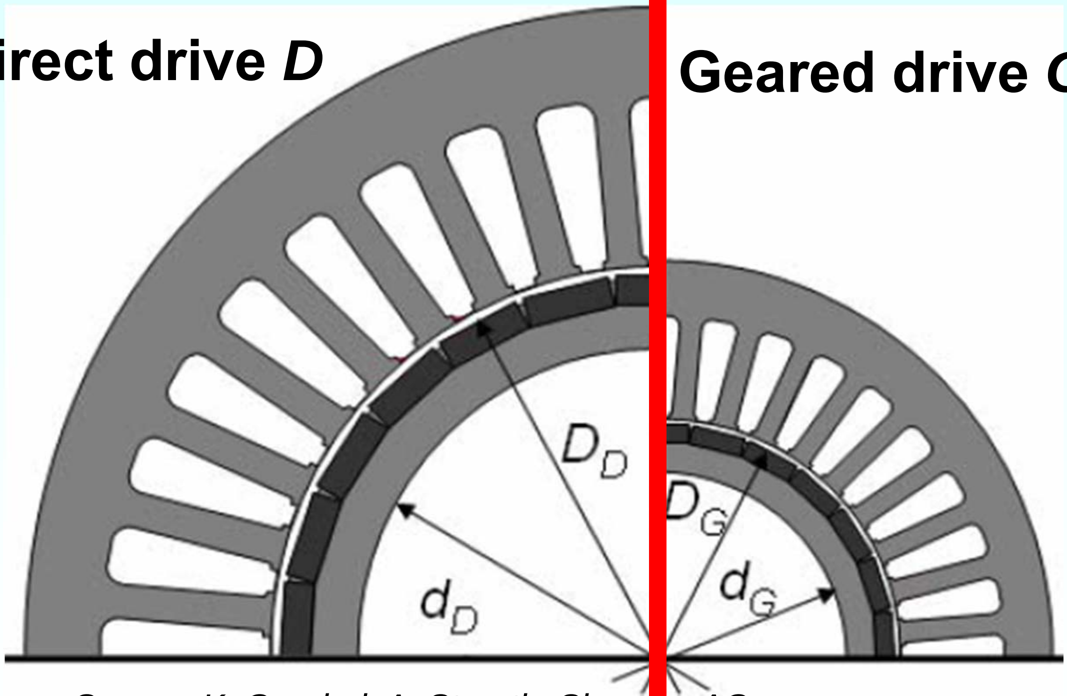
$$M_D = \tau \cdot l_D D_D \pi \cdot (D_D / 2)$$

$$M_D = \tau \cdot \lambda_D D_D^3 \cdot \pi / 2$$

$$M_G = (i \cdot \eta_G) \cdot \tau \cdot \lambda_G D_G^3 \cdot \pi / 2$$

Direct drive *D*

Geared drive *G*



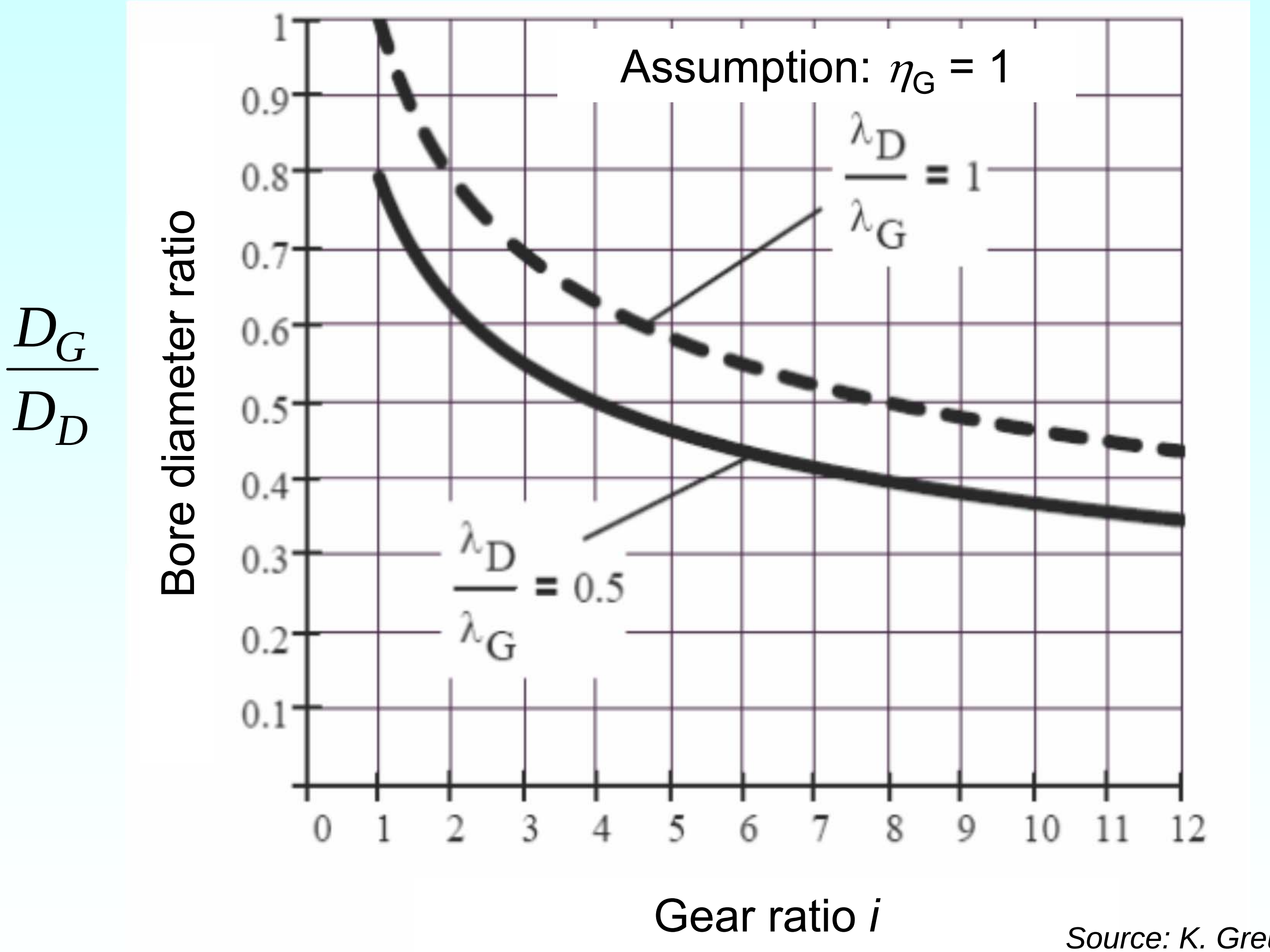
For $M_G = M_D$ we get:

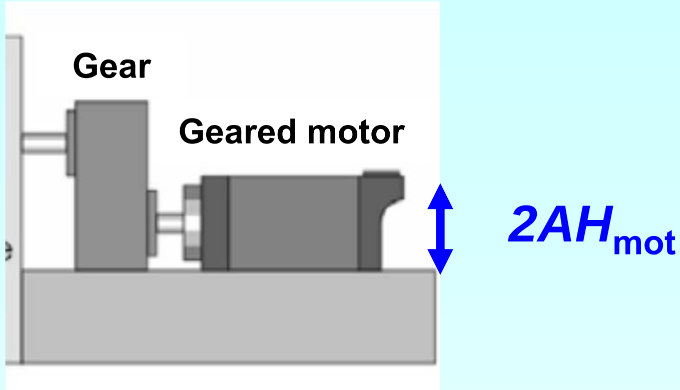
$$\frac{D_G}{D_D} = \sqrt[3]{\frac{\lambda_D}{\lambda_G} \cdot \frac{1}{i \cdot \eta_G}}$$

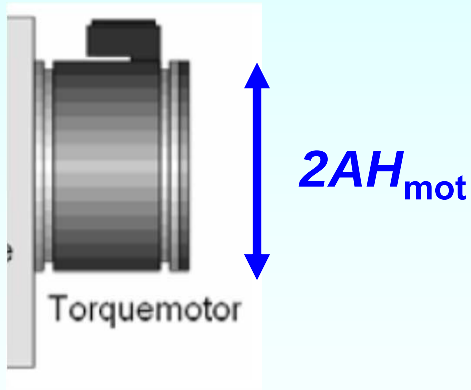
- Slimness ratio: $\lambda = l/D$
- Gear efficiency: η_G
- Gear ratio: *I*
- Tangential thrust τ

Source: K. Greubel, A. Storath, Siemens AG

With rising gear ratio *i* the frame size *AH* of the geared motor shrinks



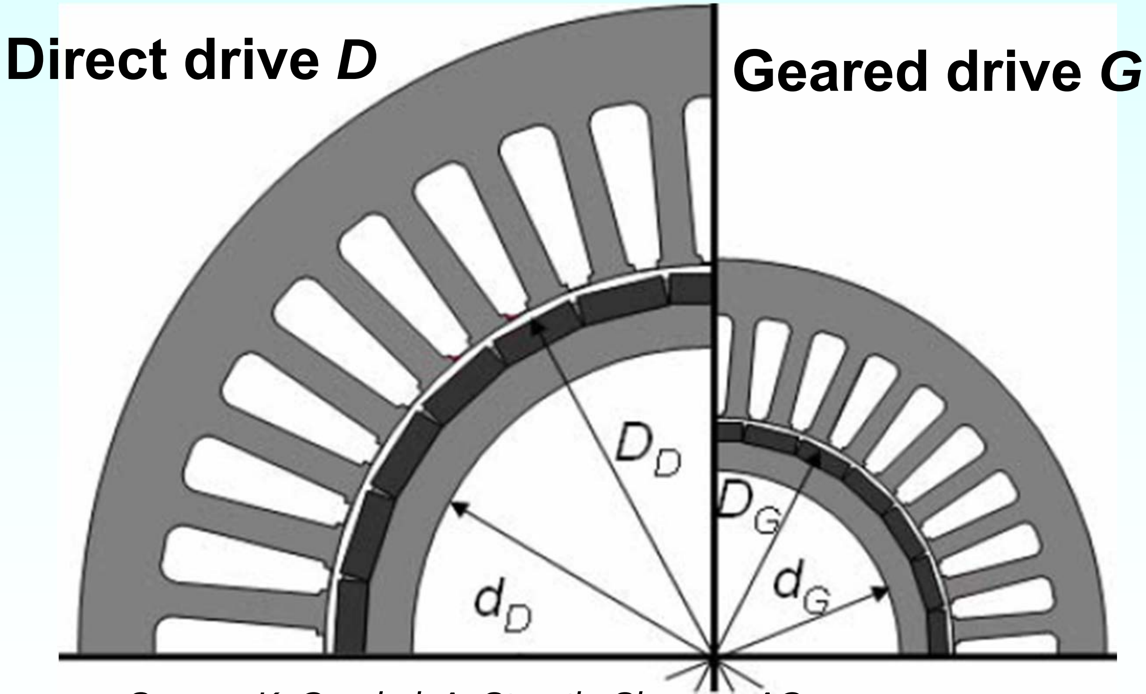




Source: K. Greubel, A. Storath, Siemens AG

Rotor inertia (of a hollow cylinder)

$$J = \gamma \cdot l \cdot \frac{(D^4 - d^4) \cdot \pi}{32} = \gamma \cdot \lambda \cdot D^5 \cdot \frac{(1 - (d/D)^4) \cdot \pi}{32}$$



Source: K. Greubel, A. Storath, Siemens AG

- Slimness ratio: $\lambda = l/D$
- Axial length: *l*
- Mass density: γ
- Tangential thrust τ

Rotor inertia: Direct- vs. Geared Drive

Ratio of inertia: G vs. D:

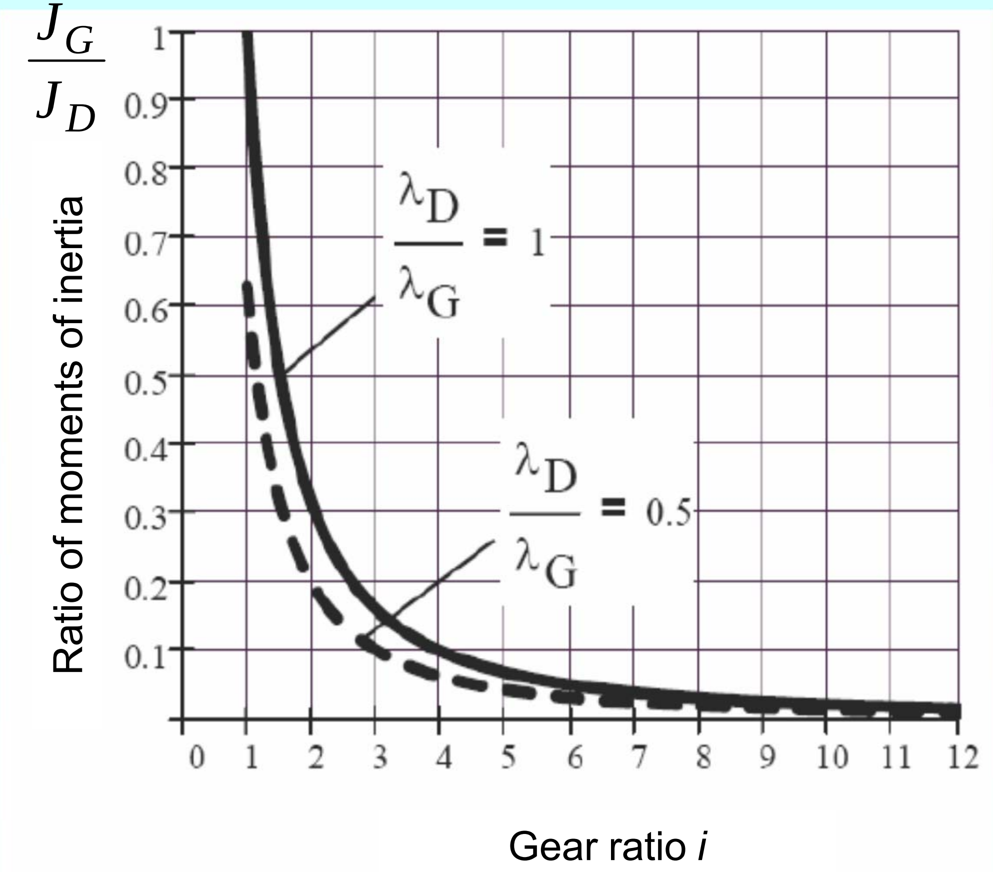
$$\frac{J_G}{J_D} = \frac{\lambda_G}{\lambda_D} \cdot \left(\frac{D_G}{D_D}\right)^5 \cdot \frac{1-(d_G/D_G)^4}{1-(d_D/D_D)^4} \approx \frac{\lambda_G}{\lambda_D} \cdot \left(\frac{D_G}{D_D}\right)^5$$

Ratio for the same torque:

$$\frac{J_G}{J_D} \approx \frac{\lambda_G}{\lambda_D} \cdot \left(\frac{D_G}{D_D}\right)^5 = \frac{\lambda_G}{\lambda_D} \cdot \left(\frac{\lambda_D}{\lambda_G}\right)^{5/3} \cdot \frac{1}{(i \cdot \eta_G)^{5/3}}$$

$$\frac{J_G}{J_D} \approx \sqrt[3]{\left(\frac{\lambda_D}{\lambda_G}\right)^2 \cdot \frac{1}{i^5}}$$

Assumption: Gear efficiency: $\eta_G = 1$



Source: K. Greubel, A. Storath, Siemens AG

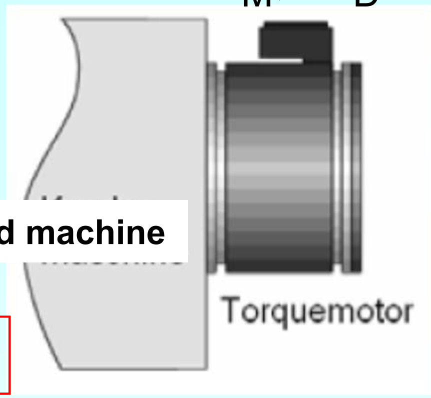
Comparison of acceleration of direct drives vs. geared drives

n_M, M_D

n_L, M_D

$n_L = n_M$

$\ddot{\gamma}_D = \ddot{\gamma}_M$



$\ddot{\gamma}_D = d(2\pi n_L)/dt$

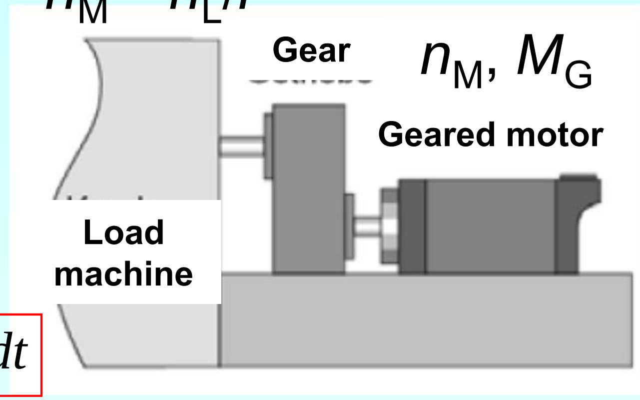
Direct drive *D*

$n_M = n_L / i$

$n_L, i \cdot M_G$

n_M, M_G

$\ddot{\gamma}_G = \ddot{\gamma}_M / i$



$\ddot{\gamma}_G = d(2\pi n_L)/dt$

Geared drive *G*

Source: K. Greubel, A. Storath, Siemens AG

Assumptions for the comparison:

- same tangential thrust τ
- same load inertia J_L
- constant ratio of rotor outer vs. inner diameter *D*/*d*

$\ddot{\gamma}_D$: load side angular acceleration of direct drive

$\ddot{\gamma}_G$: load side angular acceleration of geared drive

Equation of motion

Newton´s law: $J \cdot \frac{d(2\pi n)}{dt} = J \cdot \ddot{\gamma} = M_M - M_L \big|_{M_L=0} = M_M$

Ratio of angular acceleration (at the same shaft torque):

$$M_D = i \cdot M_G$$

$$\ddot{\gamma}_D = M_D / (J_L + J_D)$$

$$\ddot{\gamma}_G = (i \cdot M_G) / (J_L + i^2 \cdot J_G)$$

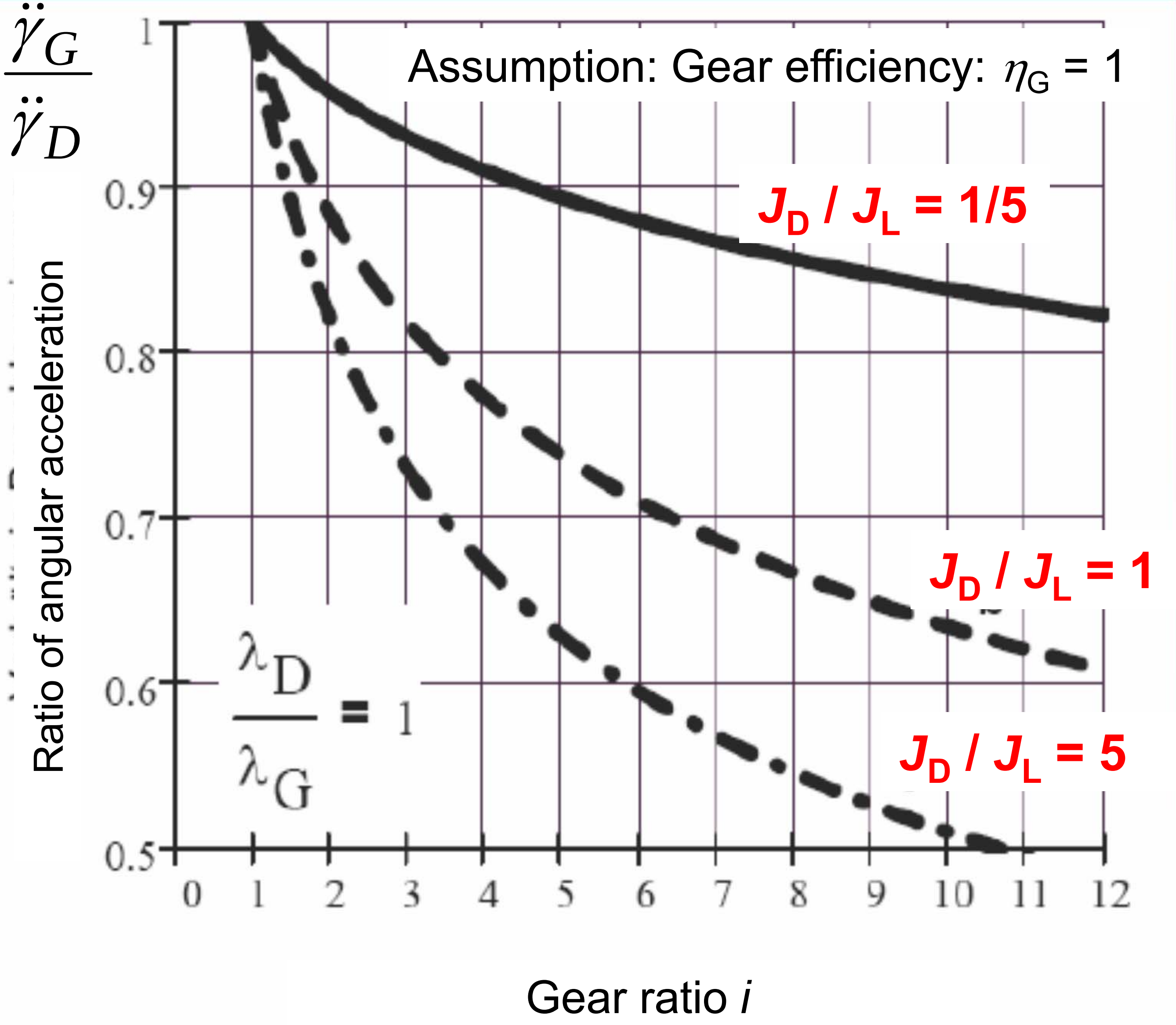
$$\left\{ \begin{array}{l} i \cdot J_G \frac{d 2\pi n_M}{dt} + J_L \frac{d 2\pi n_L}{dt} = i \cdot M_G \\ \left(i^2 \cdot J_G + J_L\right) \cdot \underbrace{\frac{d(2\pi n_L)}{dt}}_{\ddot{\gamma}_G} = i \cdot M_G \end{array} \right.$$

With $\frac{J_G}{J_D} \approx \sqrt[3]{\left(\frac{\lambda_D}{\lambda_G}\right)^2 \cdot \frac{1}{i^5}}$ we get:

$$\frac{\ddot{\gamma}_G}{\ddot{\gamma}_D} = \frac{J_D + J_L}{i^2 J_G + J_L} = \frac{1 + \frac{J_D}{J_L}}{1 + i^2 \frac{J_G}{J_D} \frac{J_D}{J_L}} \cong \frac{1 + \frac{J_D}{J_L}}{1 + \frac{J_D}{J_L} \cdot \sqrt[3]{\left(\frac{\lambda_D}{\lambda_G}\right)^2 \cdot i}}$$

Source: K. Greubel, A. Storath, Siemens AG

Angular acceleration: Direct- vs. Geared Drive



$$\frac{\ddot{\gamma}_G}{\ddot{\gamma}_D} \cong \frac{1+\frac{J_D}{J_L}}{1+\frac{J_D}{J_L}\cdot\sqrt[3]{\left(\frac{\lambda_D}{\lambda_G}\right)^2}\cdot i}$$

Facit:

- Geared motors have a smaller angular acceleration than direct drives

- This holds also true for bigger slimness ratios $\lambda_G > \lambda_D$.

Source: K. Greubel, A. Storath, Siemens AG

Optimum gear ratio for dynamic cycle operation

- Minimum run-up time t_a from zero speed to Ω_{max} of a geared motor (inertia J_G) with a load (inertia J_L) requires an optimum gear ratio: $i_{opt} = \sqrt{J_L / J_G}$

$$d\Omega / dt = \ddot{\gamma}_G = \Omega_{\max} / t_a$$

$$t_a = \Omega_{\max} \cdot (J_L + i^2 \cdot J_G)/(i \cdot M_G)$$

$$dt_a / di = 0 \quad \Rightarrow \quad d(J_L / i + i \cdot J_G)/di = 0 \quad \Rightarrow \quad -J_L / i^2 + J_G = 0$$

$$\Rightarrow \quad i_{opt} = \sqrt{J_L / J_G}$$

Example: Efficiency η of Direct- vs. Geared Drive

A: PM-High-Torque motor gearless
B: Cage induction motor with gear
C: PM Synchronous motor with gear

Comparison for: M_L = 4000 Nm, n_L = 200/min, 84 kW, Water jacket cooling
Inverter operation: Inverter nominal efficiency ca. 97% (here: 100% assumed)
Gear nominal / averaged efficiency 97% / 95%.

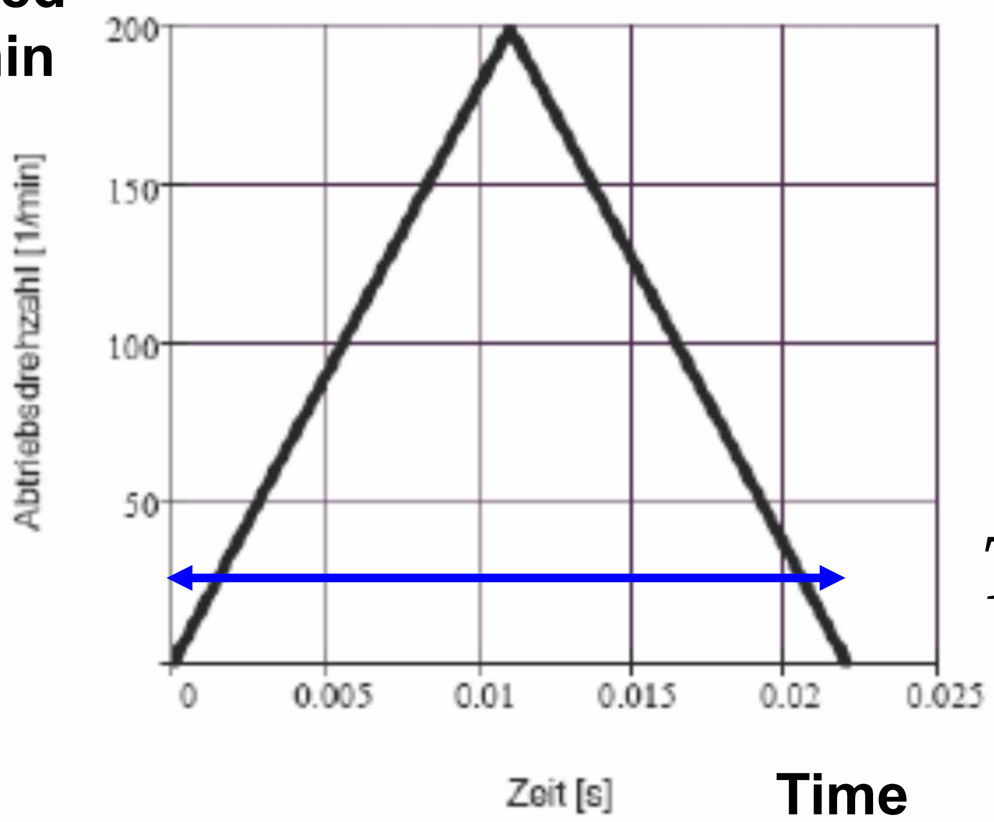
Attribute	A: PM torque motor	B: Geared cage induction motor	C: Geared PM synchronous motor
Gear ratio	- (1)	12.8	9.4
Motor speed (1/min)	200	2552	1871
Losses (W)	7365	11865	8075
Overall efficiency η (%)	91.9	87.6	91.2
Frame size AH (mm)	280	160	160

The MAXIMUM overall NOMINAL efficiency has the high-torque motor with its high pole count and tooth coil winding with 91.9%.
The geared motors have slightly lower efficiency due to the gear. The induction motor has the highest losses due to the cage losses. *Source: K. Greubel, A. Storath, Siemens AG*

Example: Dynamic cycle operation

Cycle: Linear speed-up and down,
here shown for the PM synchronous direct drive

Speed
1/min



Time

$$T = 2 \cdot \Delta t$$

Cycle period

22 ms

Source: K. Greubel, A. Storath, Siemens AG

Example: Energy consumption of Direct- vs. Geared Drive

- The lowest energy consumption W_{loss} shows the gearless drive for the investigated speed profile between 0 … 200/min, as its cycle time is shortest !

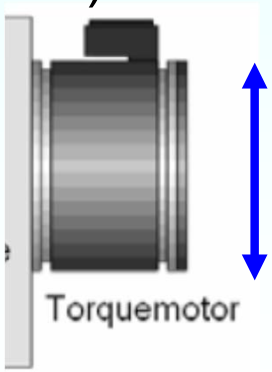
$$\varepsilon = W_{mech} / (W_{mech} + W_{loss})$$

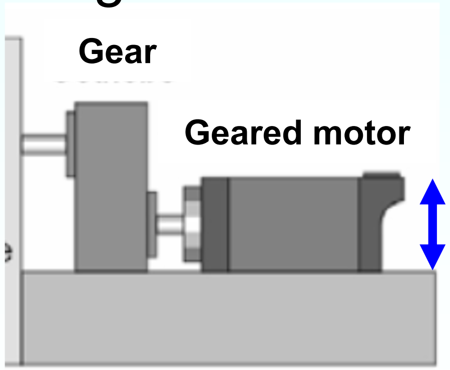
A: PM-High-Torque motor gearless ε = 86.9%
B: Cage induction motor with gear ε = 77.1%
C: PM Synchronous motor with gear ε = 85.7%

- The best dynamic performance shows the high-torque drive: ($J_L = J_D$ assumed)
  The cycle time T_c for acceleration from 0 … 200/min and deceleration from 200 … 0/min is:

A: PM-High-Torque motor gearless T_c = 22 ms
B: Cage induction motor with gear T_c = 51 ms
C: PM Synchronous motor with gear T_c = 38 ms

- BUT: a) The High-Torque motor has the biggest investment costs
  b) The size of the gearless drive is biggest: AH 280 instead of 160 mm !





Beyond a gear ratio of i = 1:10 the size of the gearless motors gets too big for industrial purpose!

Source: K. Greubel, A. Storath, Siemens AG