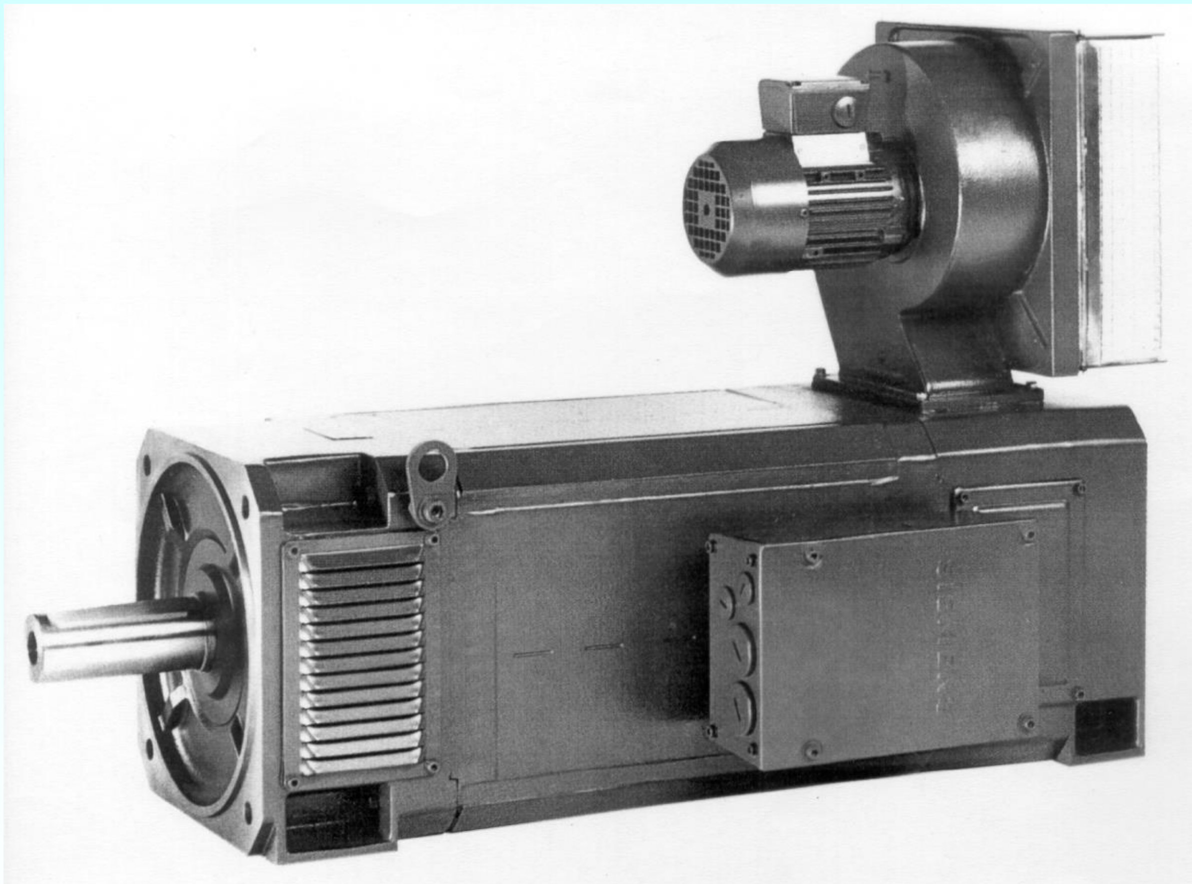
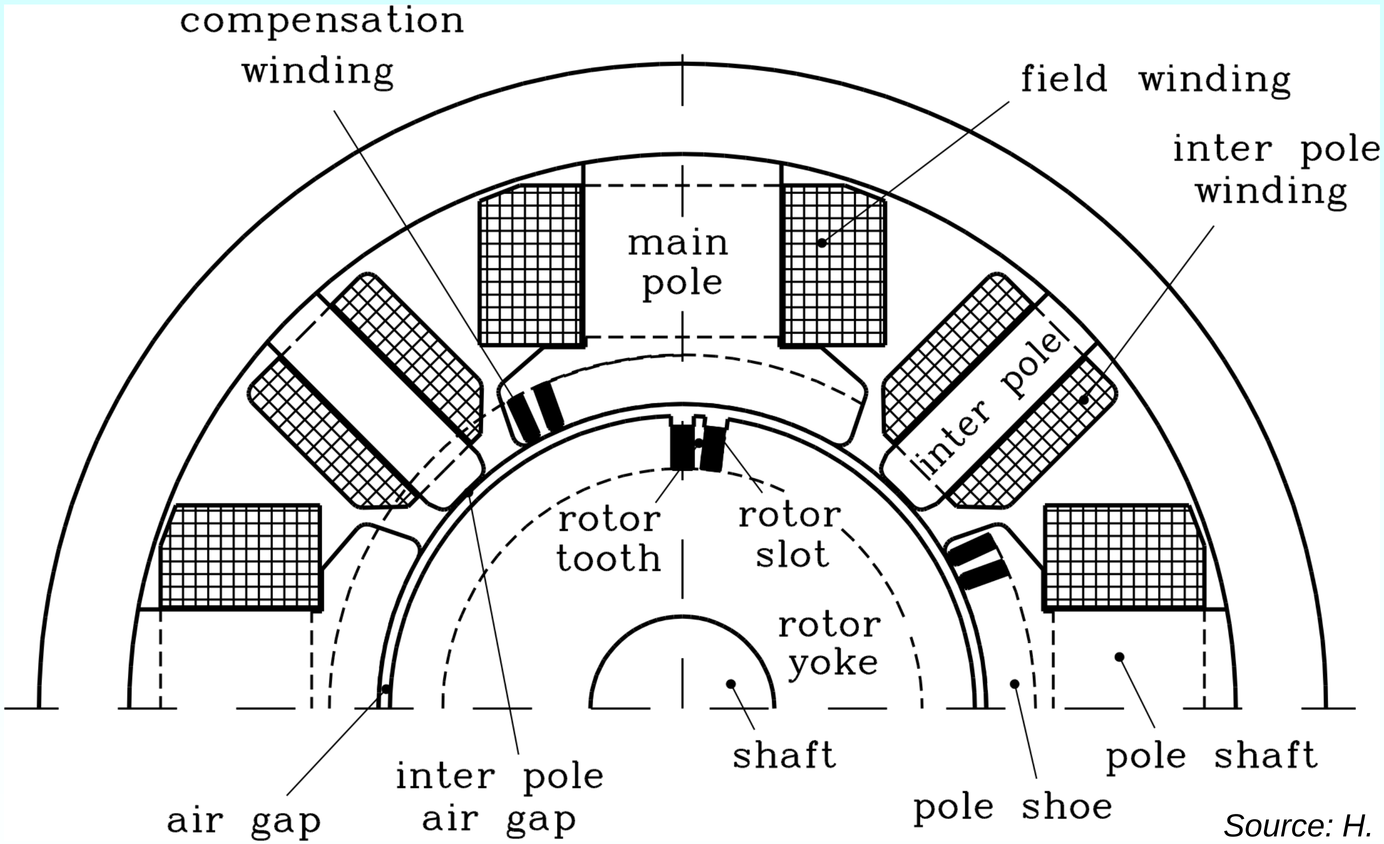
10. DC Drives



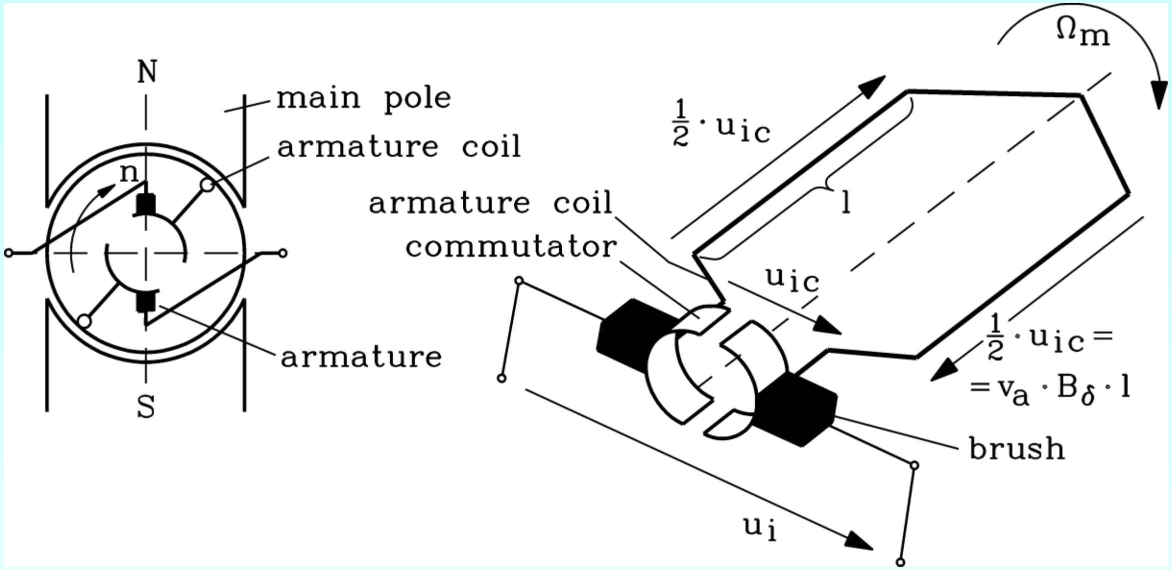
Source: Siemens AG

10.1 Principles of Operation of DC Machines

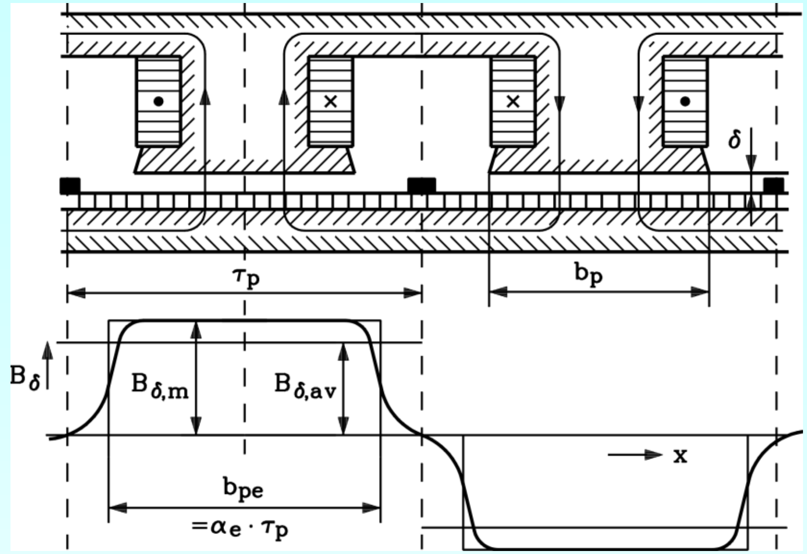


Source: H. Kleinrath, Studientext

Basic function of DC machine



Rotor coil rotates in stator DC magnetic field; voltage is induced and rectified by commutator and brushes



Stator air gap magnetic field distribution, electrically excited

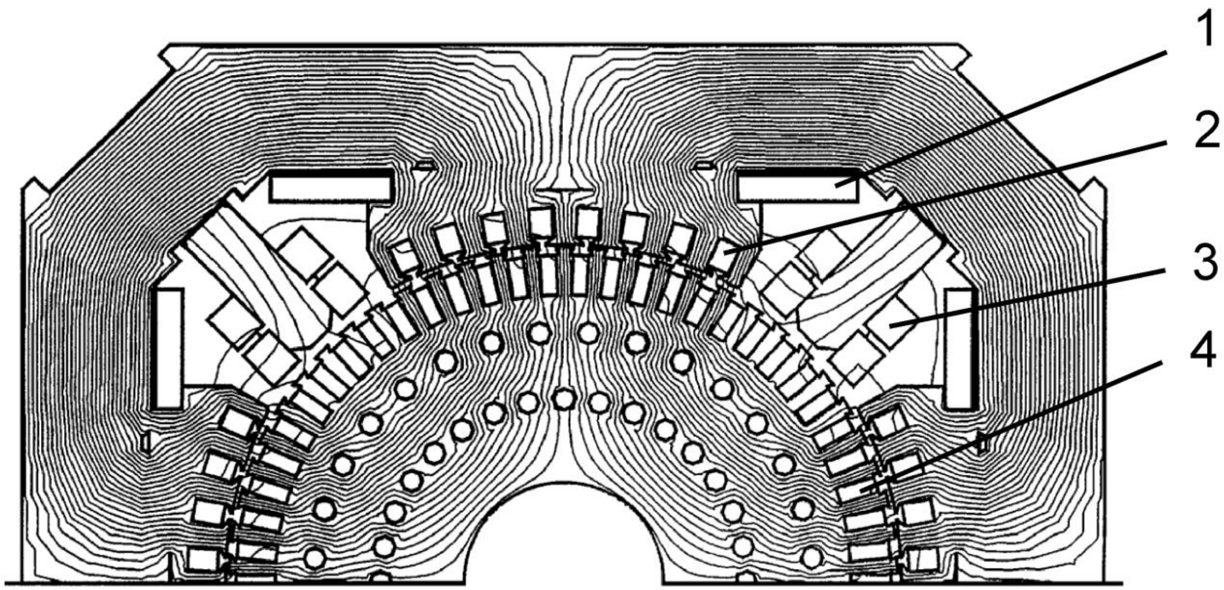
– In each moving coil side (turns per coil N_c, stack length l, speed n) an AC voltage $u_{i,c}$ is induced via induction due to movement : Amplitude $u_{i,c,m} = 2 v_a B_{\delta,m} N_c l$

– Rectification (via commutator & brushes): $u_{i,c} \rightarrow u_i$; **average DC voltage:** $u_{i,av} = \alpha_e u_{i,m}$

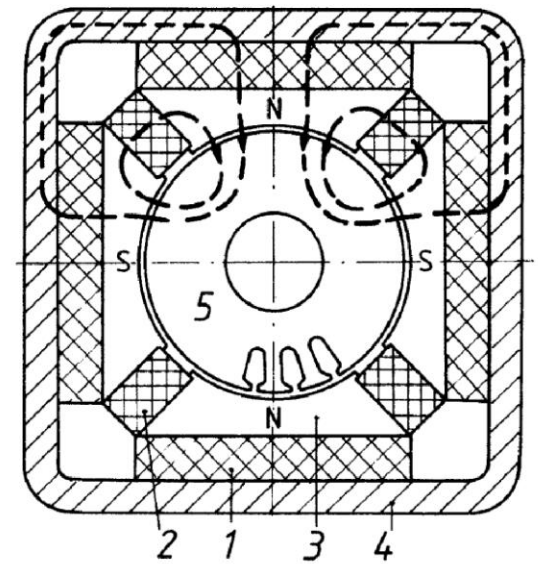
– Rotor diameter d_r: $v_a = d_r \pi n = 2 p \tau_p \cdot n$, average air gap flux density: $B_{\delta,av} = \alpha_e B_{\delta,m}$

Flux/pole: $\underline{\underline{\Phi}} = l \int_0^{\tau_p} B_\delta(x) dx = \underline{\underline{\alpha_e \tau_p l B_{\delta,m}}}$ Number of rotor conductors $z = 2N_c$: $\underline{\underline{u_{i,av} = 2z \cdot n \cdot \Phi}}$

DC machine – excitation of stator field



Source: ABB Sweden



Source: Siemens AG, Germany

Electrical excitation

Example: Four-pole machine:

1: Field coil, 2: Compensation winding

3: Inter-pole winding, 4: Armature winding

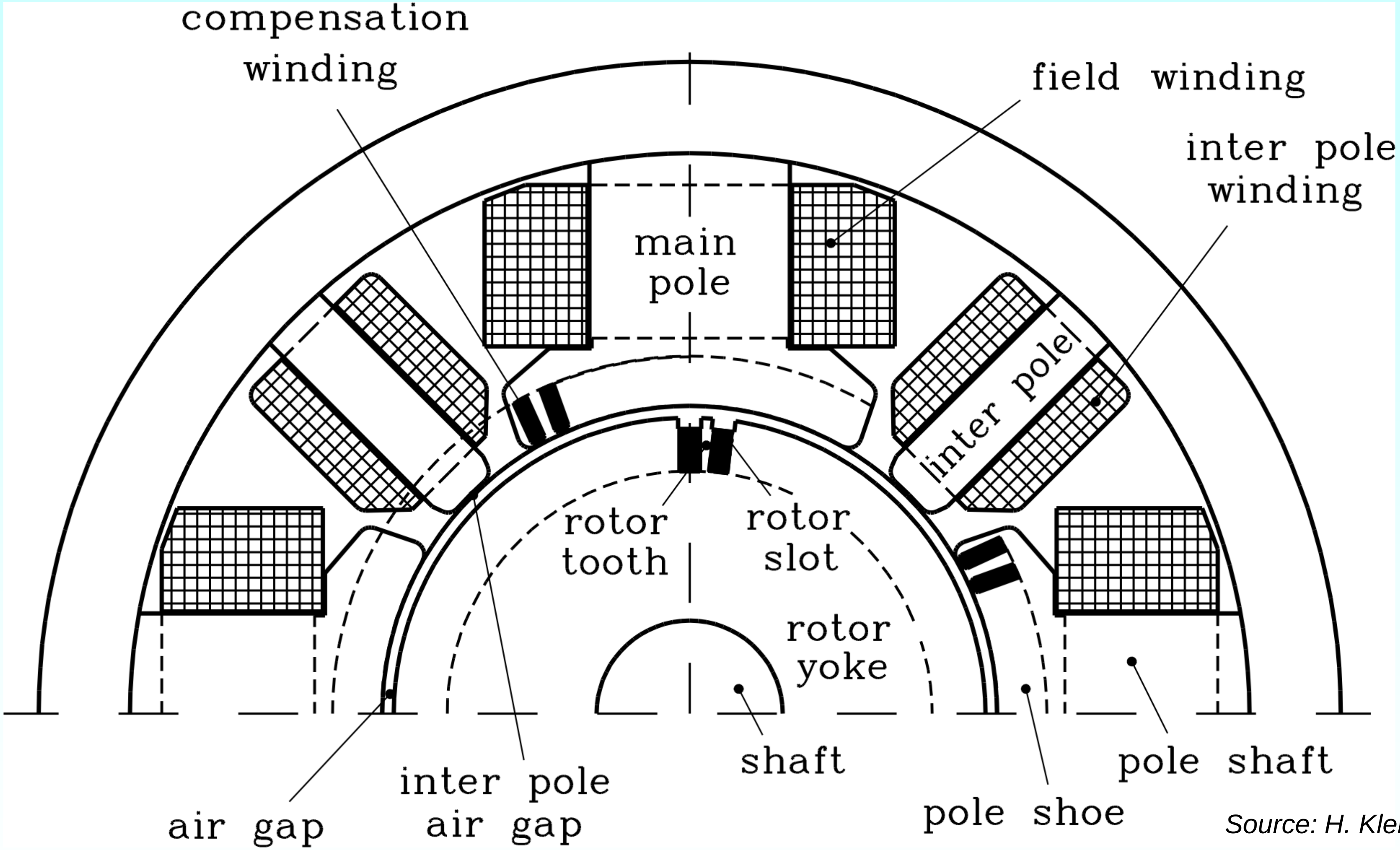
Permanent magnet excitation

Example: Four-pole machine:

1, 2: Field magnets, 3: Pole shoe iron,

4: Housing as iron back

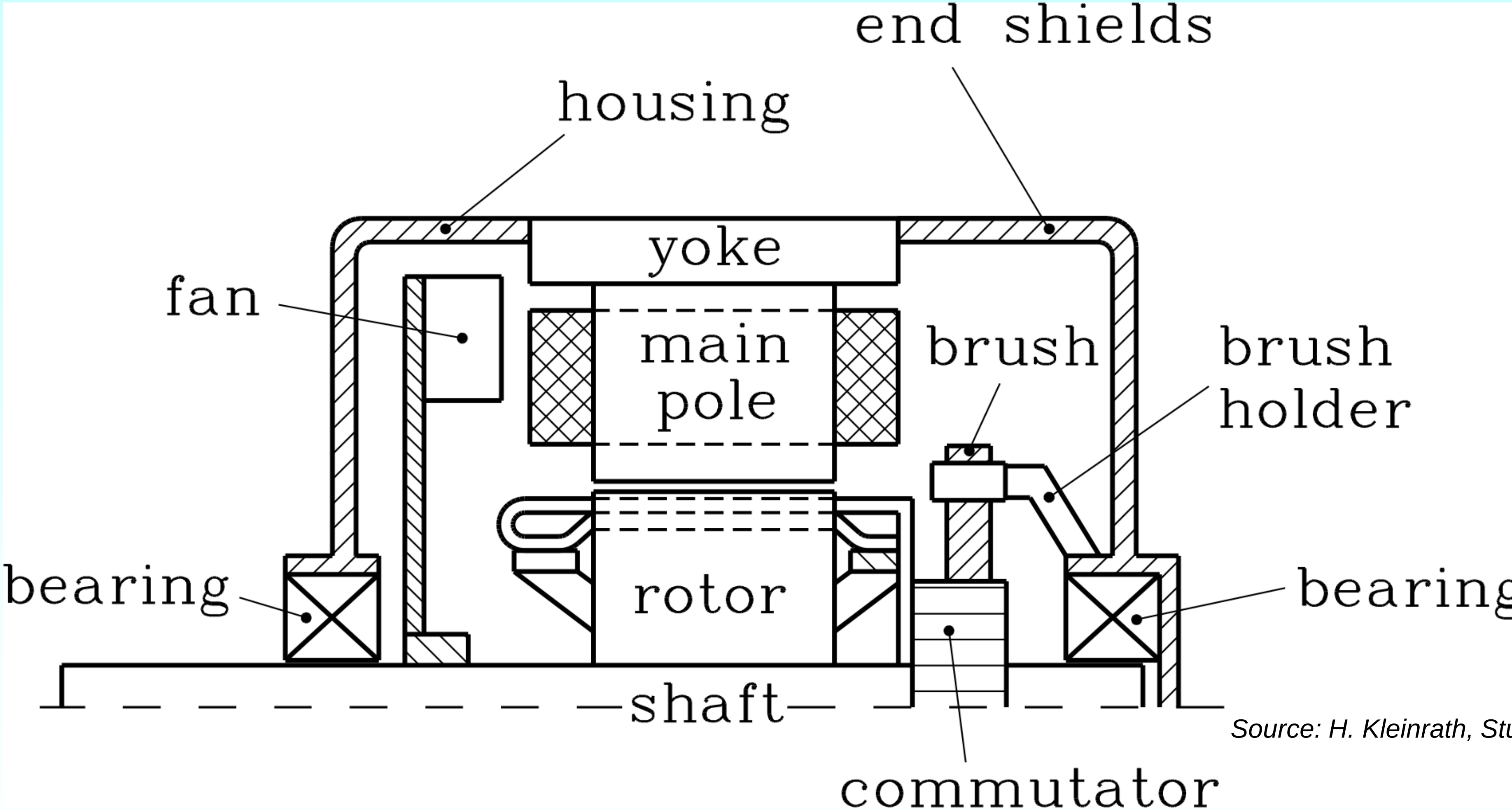
DC machine - components (1)



Source: H. Kleinrath, Studientext

Electrical field excitation / Example: Four-pole machine

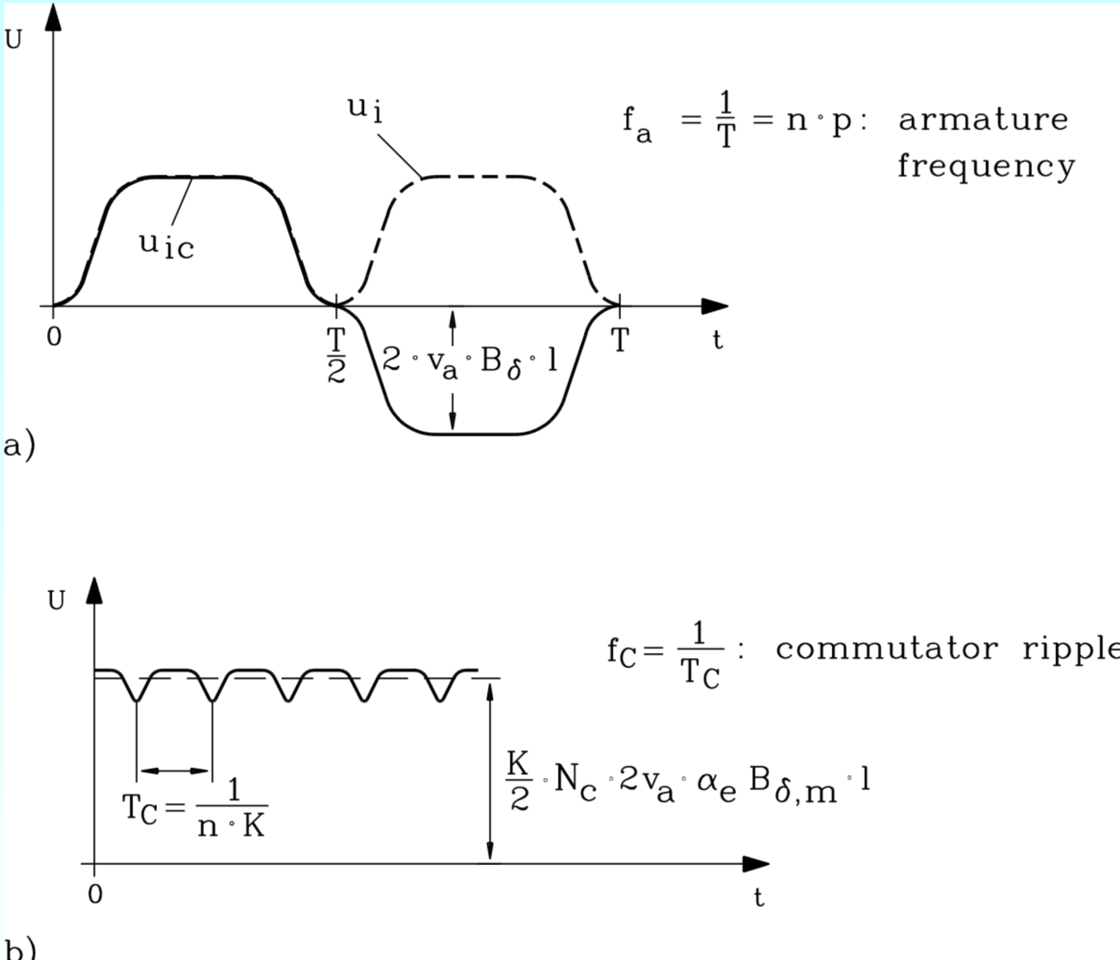
DC machine - components (2)

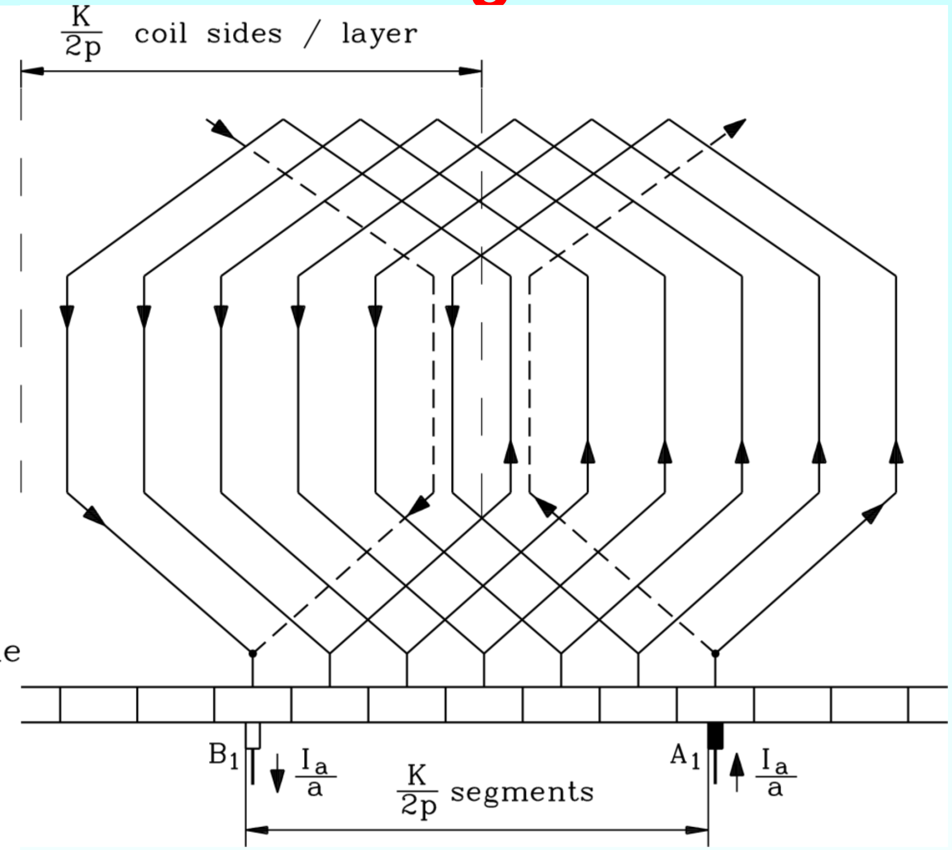


Source: H. Kleinrath, Studientext

Electrical field excitation / Example: Four-pole machine

Smoothed induced rotor DC voltage





a) AC voltage of one coil u_{ic} is rectified as DC voltage u_i with deep sags (here: $2p = 2$)

b) Increased number of series connected rotor coils - displaced by a slot pitch each - , arranged in Q_r rotor slots, lead to a sum of rectified coil voltages as a **smoothed total DC voltage**

Induced voltage (Back EMF)

Max. voltage per coil:

$$u_{i,c,m} = 2v_a B_{\delta,m} N_c l$$

Average voltage per coil:

$$u_{i,c,av} = 2v_a \cdot \alpha_e B_{\delta,m} \cdot N_c l$$

Flux per pole: $\Phi = \alpha_e \tau_p l B_{\delta,m}$

Rotor circumference velocity: $v_a = 2p\tau_p \cdot n$

$$u_{i,c,av} = 2 \cdot 2p \cdot N_c \cdot n \cdot \Phi$$

Average voltage at $K/(2p)$ coils:

$$u_{i,av} = \frac{K}{2p} \cdot 2 \cdot 2p \cdot N_c \cdot n \cdot \Phi$$

$$u_{i,av} = (2 \cdot K \cdot N_c) \cdot n \cdot \Phi$$

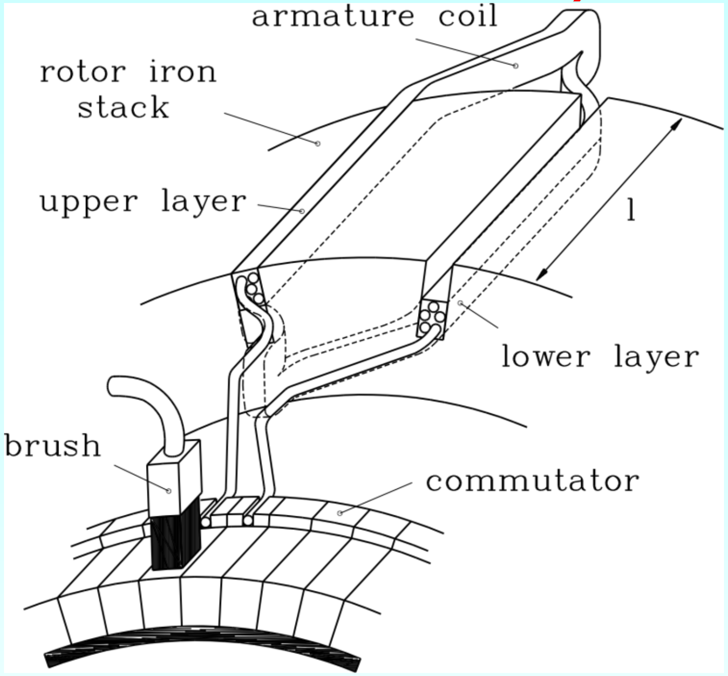
Total number of rotor conductors: $z = 2 \cdot K \cdot N_c$

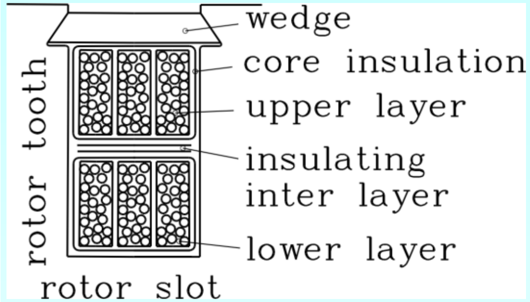
$$\boxed{u_{i,av} = U_i = z \cdot n \cdot \Phi}$$

2*p* poles, 2*a* parallel branches:

$$\boxed{U_i = z \cdot \frac{p}{a} \cdot n \cdot \Phi}$$

Rotor coils, commutator, brushes, slot design





Source: H. Kleinrath, Studientext

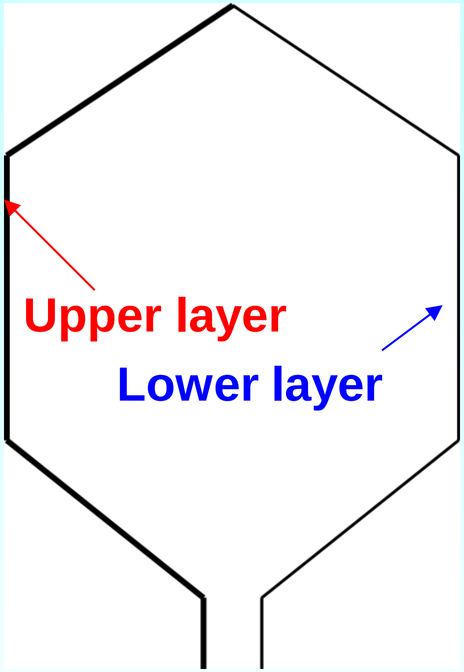
Source: Fa. Brenner, Bürstadt

- Two layers per slot (Upper & lower layer) = increases number of coils by 2
- Several (= u) coil sides side by side in slot layer = reduction of lot number possible
- Two parallel rotor armature branches per pole pair. In both voltage $u_{i,av}$ is induced.
- By adding p-1 pole pairs we get further parallel armature branches with induced voltage $u_{i,av}$.
  This results in 2a = 2p parallel armature branches in a 2p pole machine.

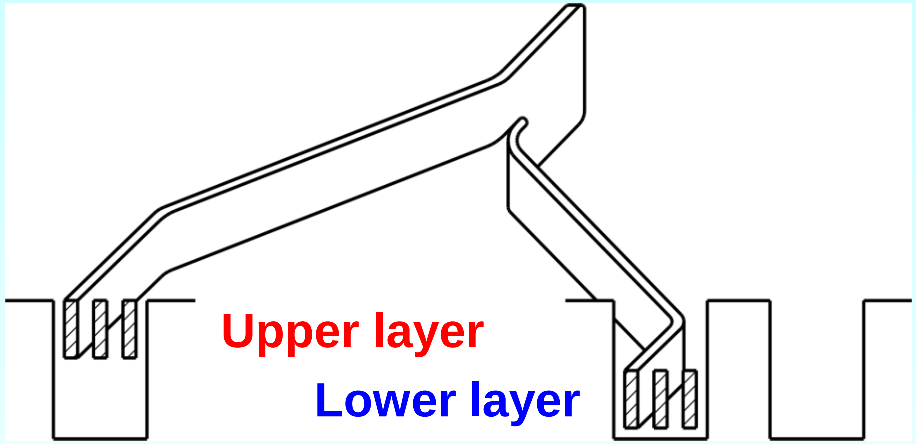
Facit: *With p pole pairs the **induced voltage (back EMF) $U_i = u_{i,av}$** occurs between each plus- and minus brush (A = Plus, B = Minus).*

The total number of rotor conductors is: $z = 2 \cdot u \cdot N_c \cdot Q_r$

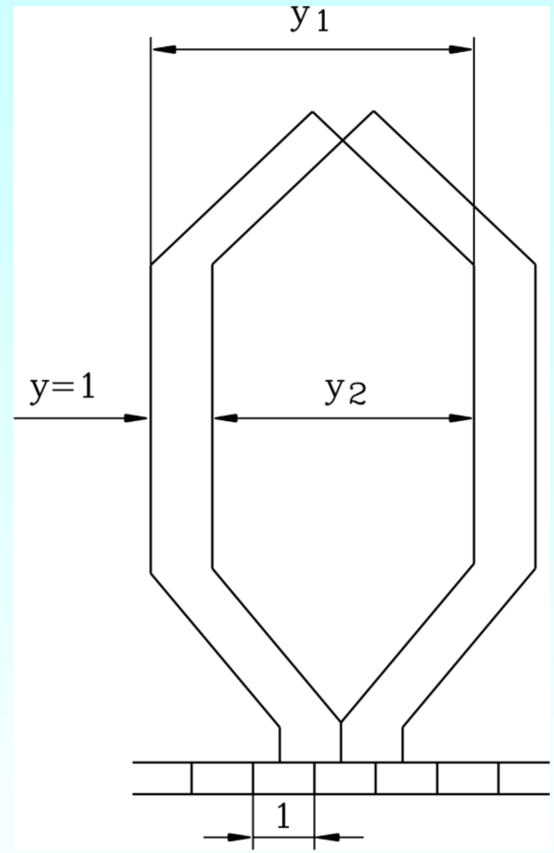
Elements of lap-wound armature winding



An armature coil as basic element of the winding



Inserting an armature coil into the rotor slots

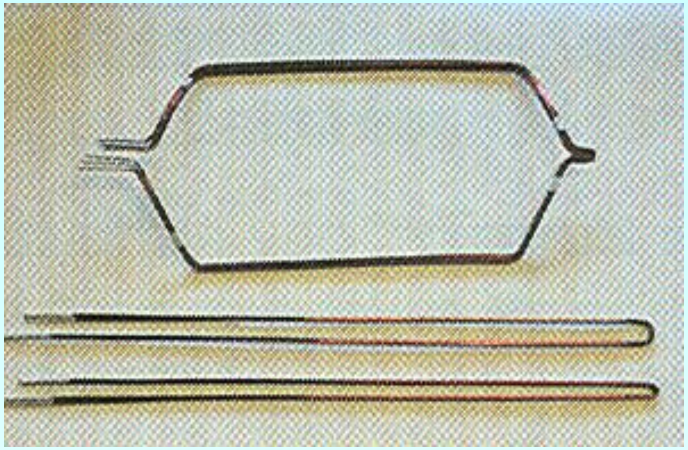


Connection to adjacent armature coil at the commutator

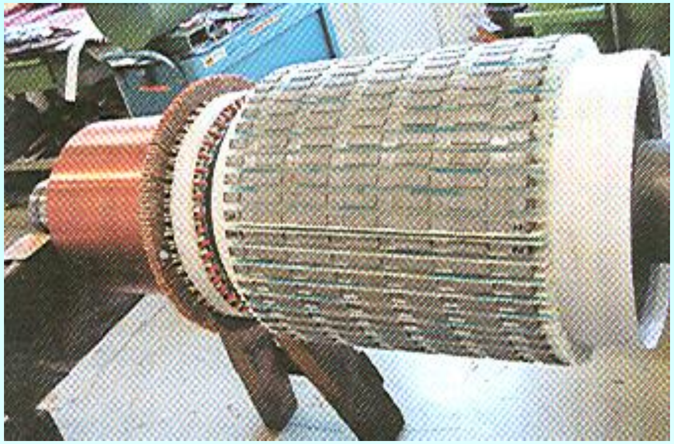
y_1: Width of a coil = about one pole pitch !

$y = y_1 - y_2 = 1$: Coil “step” at commutator

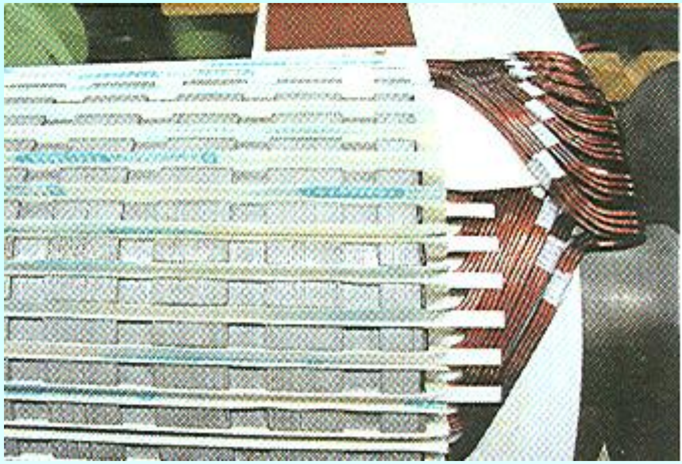
Manufacturing of armature coils and rotor with commutator



Armature coil:
Below: first step - unformed
Above: formed



Rotor iron stack:
Insulation in slots
left: commutator



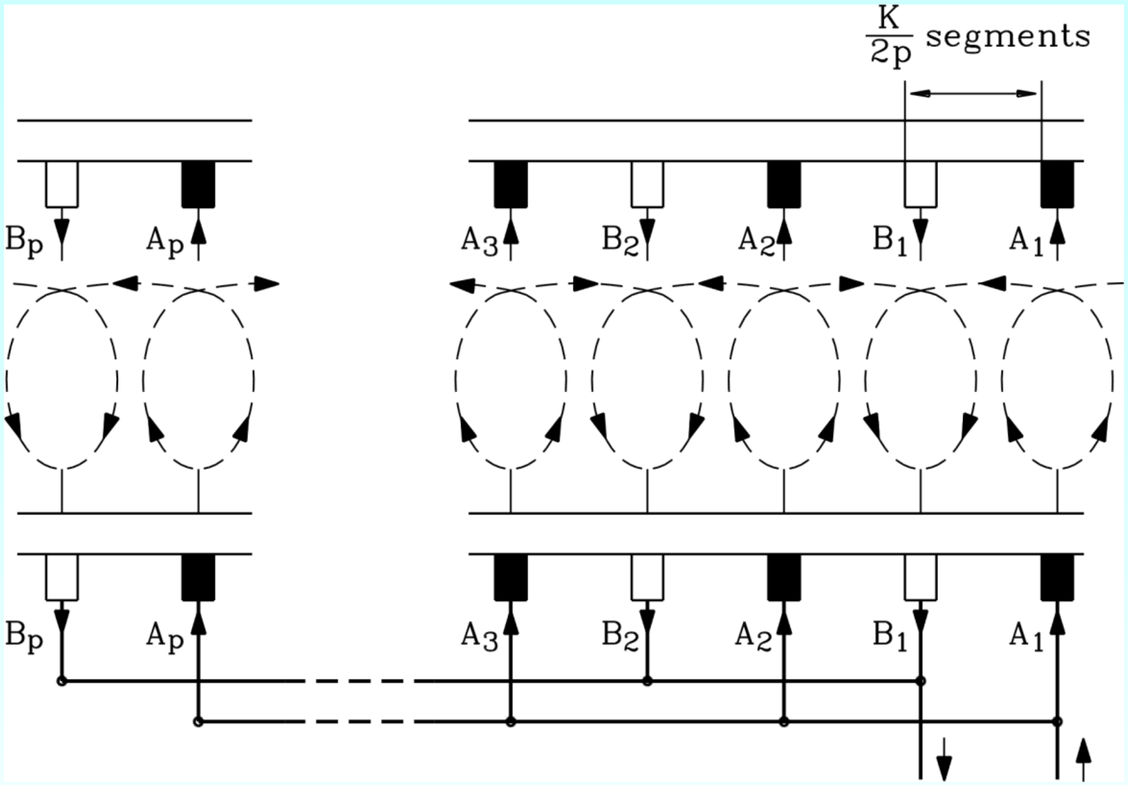
Inserting armature coils:
Two-layer winding
Upper and lower layer

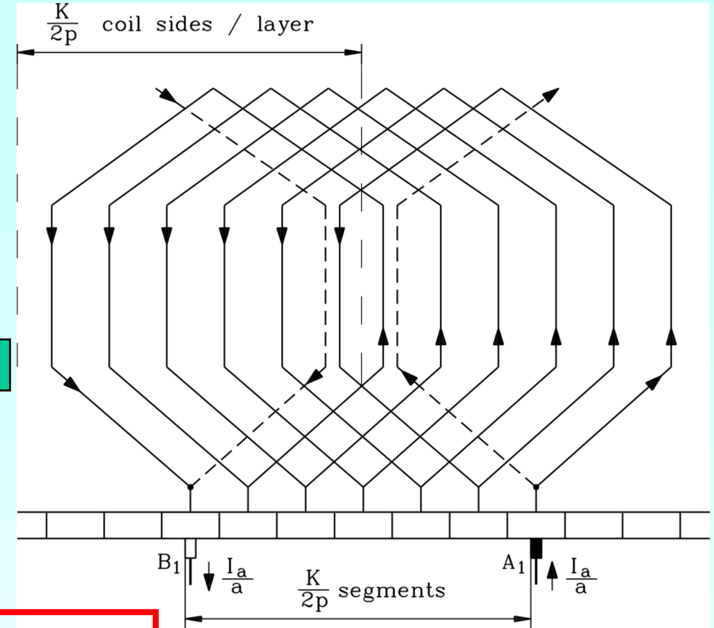
Soldering of the armature coil ends to the commutator segments:

Upper and lower layer coil ends are soldered into the slits of the commutator segments

Source: Fa. Brenner/Bürstadt, Germany

Induced rotor armature voltage = back EMF





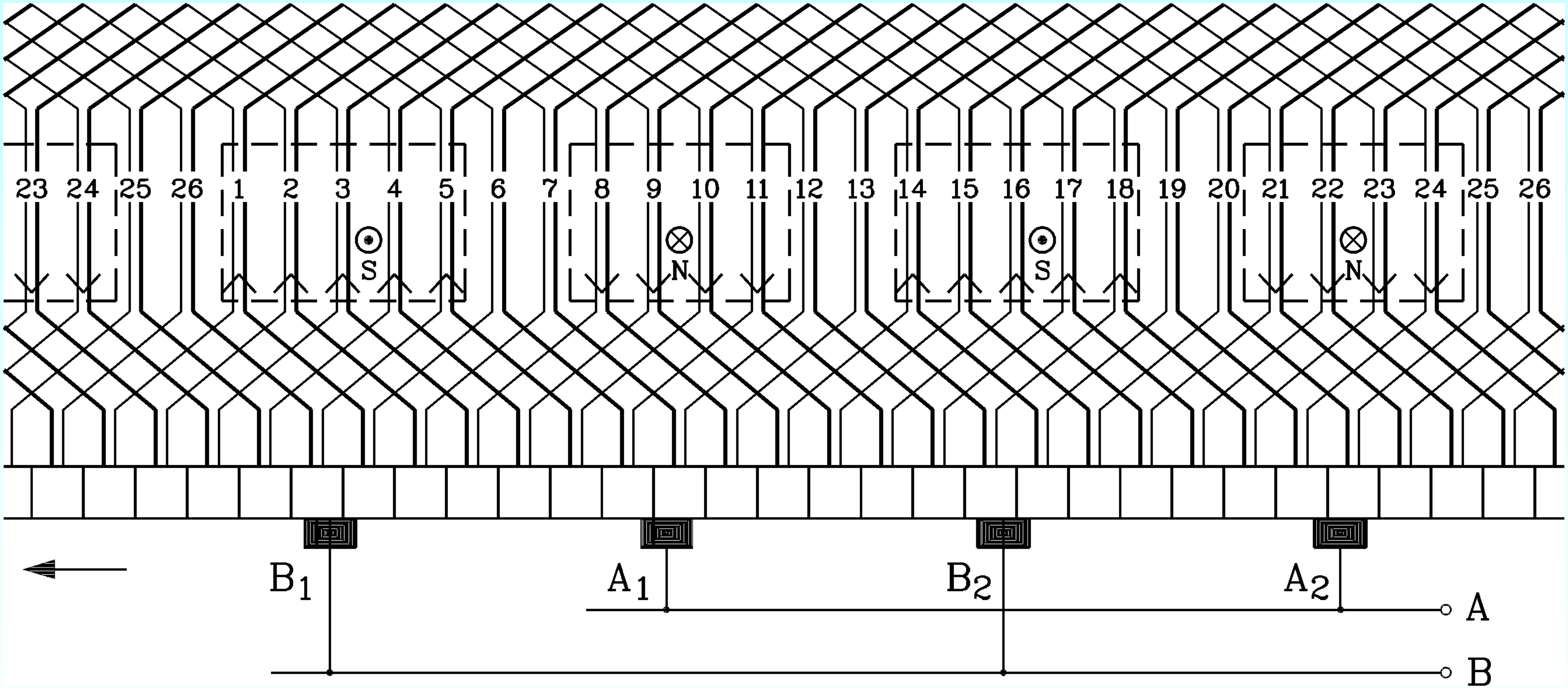
$$2a = 2p$$

A 6-pole (in general: a 2*p* pole machine) machine is derived from a 2-pole arrangement by continuation of the armature coil sequence and corresponding commutator segments with brushes **("LAP WINDING").**

– **Induced voltage:** $U_i = z \cdot \frac{p}{a} \cdot n \cdot \Phi = k_1 \cdot n \cdot \Phi$ $\quad U_i = k_2 \cdot \Omega_m \cdot \Phi \quad k_2 = \frac{k_1}{2\pi}$

– Each coil starts / ends at adjacent commutator segments with total number: $K = u \cdot Q_r$

Complete four-pole DC lap winding



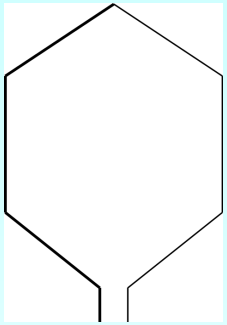
Source: Dr. Holzer, TU Wien

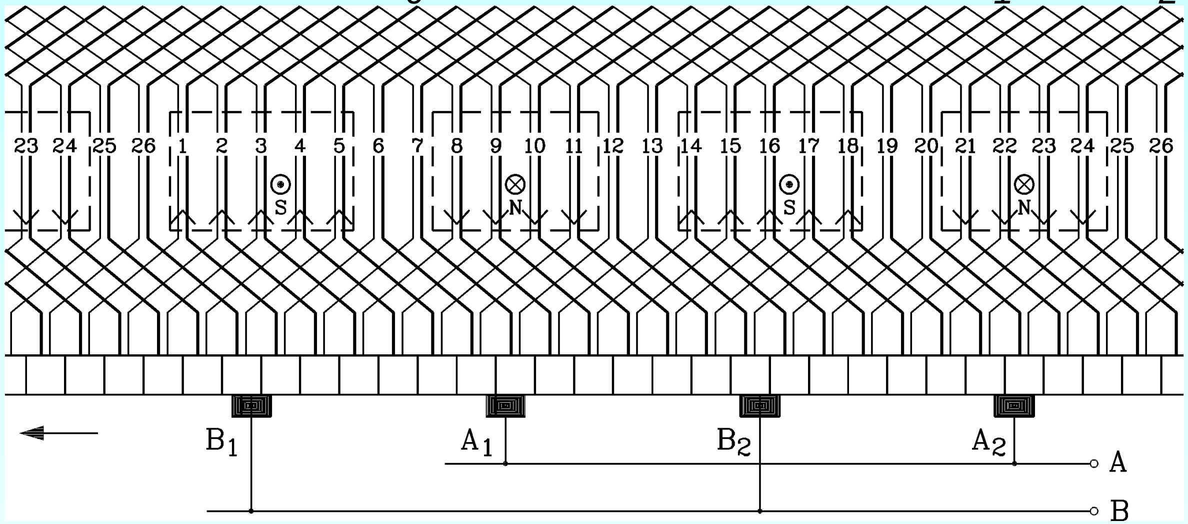
Simplex lap winding:

Data: $Q_r = 26$, $2p = 4$, $u = 1$, $N_c = 1$, $a = p = 2$, $K = 26$, $y_1 = 6$, $y_2 = 5$, $y = 1$

Simplex lap winding: $2a = 2p$

Example: $Q_r = 26$, $2p = 4$, $u = 1$, $N_c = 1$, $a = p = 2$, $K = 26$, $y_1 = 6$, $y_2 = 5$, $y = 1$

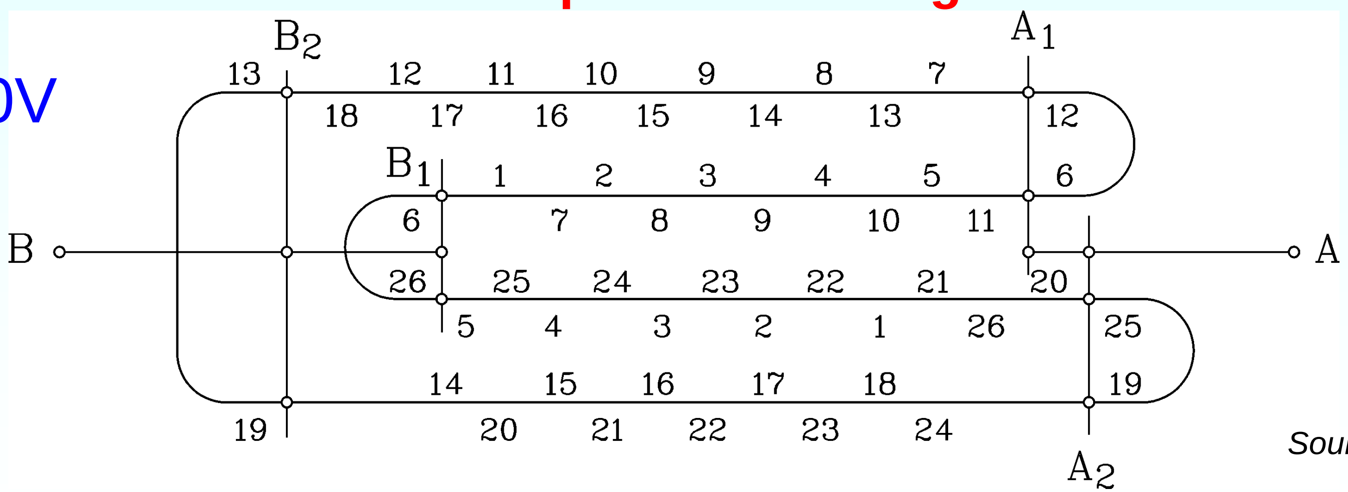




Pole count = Number of parallel winding branches: $2a = 2p = 4$

$U_a = 440$V

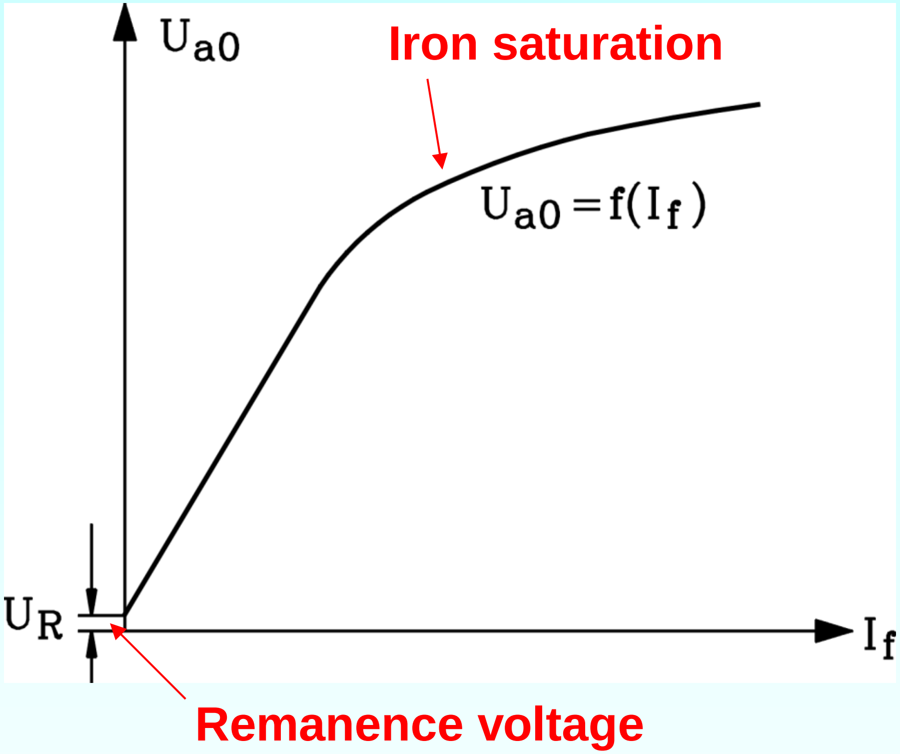
-220V



+220V

Source: Dr. Holzer, TU Wien

Induced voltage = back EMF = No-load voltage (Generator)



No-load characteristic:

- Armature voltage measured at open circuit and constant speed *n*: $U_{a0} = U_i$ = back EMF (generator no-load)

- Back EMF increases **LINEAR** with flux Φ. Flux variation by field current. Due to iron saturation flux increases non-linear with field current *If* and so does back EMF.

$$U_{a0} = U_i = z \cdot \frac{p}{a} \cdot n \cdot \Phi(I_f) = k_1 \cdot n \cdot \Phi$$

Example: Rotor armature winding of 200 kW-DC machine

Data: Rotor rated DC voltage 430 V, rated speed n = 1470/min, rotor diameter d_r = 400 mm,

Pole count $2p = 4$, rotor iron stack length l = 190 mm, slot number $Q_r = 58$,

coil sides per slot and layer $u = 4$, number of turns per coil $N_c = 1$,

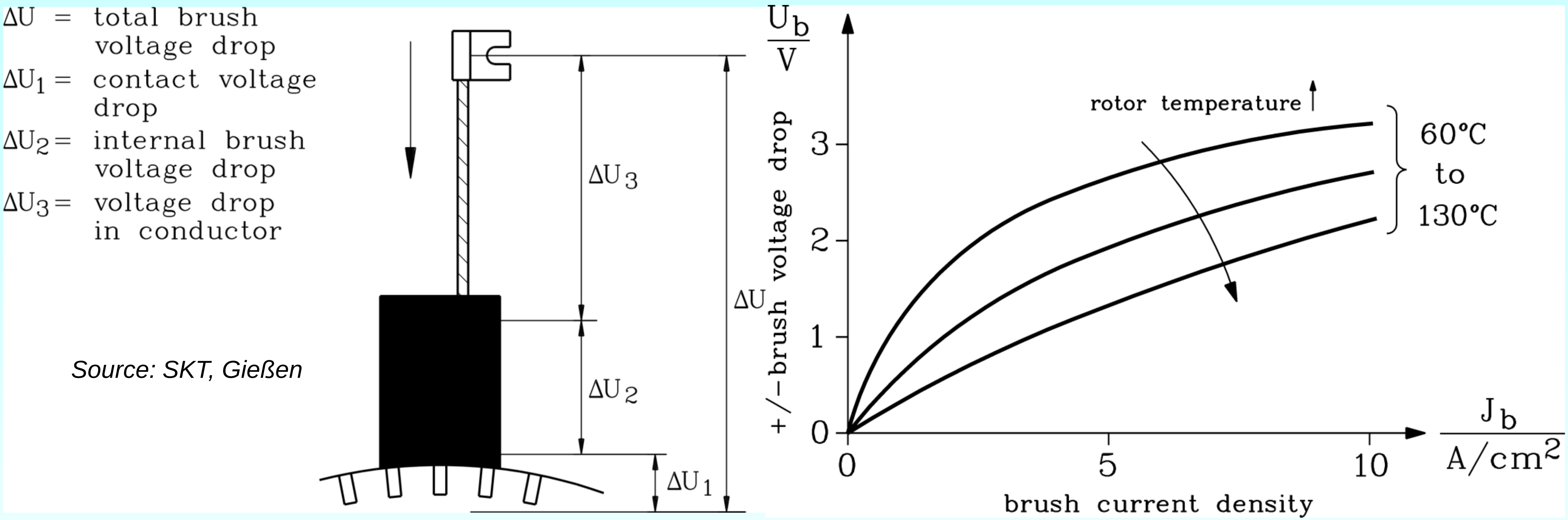
equivalent pole coverage ratio $\alpha_e = 0.7$, maximum air gap flux density: $B_{\delta,m} = 0.86$ T

We calculate from that:

- Number of commutator segments: $K = Q_r \cdot u = 58 \cdot 4 =$ <u>232</u>
- Total number of rotor conductors $z = 2 \cdot K \cdot N_c = 2 \cdot 232 \cdot 1 =$ <u>464</u>
- Pole pitch $\tau_p = d_r\pi/4 = 400\ \pi/4 =$ <u>314.2 mm</u>
- Flux per pole $\Phi = \alpha_e \cdot \tau_p \cdot l \cdot B_\delta = 0.7 \cdot 0.3142 \cdot 0.19 \cdot 0.86 =$ <u>35.9 mWb</u>
- **Induced rotor voltage ($U_i = z \cdot (p/a) \cdot n \cdot \Phi = 464 \cdot (2/2) \cdot (1470/60) \cdot 0.0359 =$ <u>408.5 V</u>**

- Average value of DC voltage between 2 commutator segment must not exceed 408.5/(232/4) = 7 V < 18...20V (**otherwise flash-over between 2 segments !**)
- **Between adjacent segments at 0.3 mm mica is placed as insulation, but has in parallel air (with carbon dust !)**

The brush-copper contact

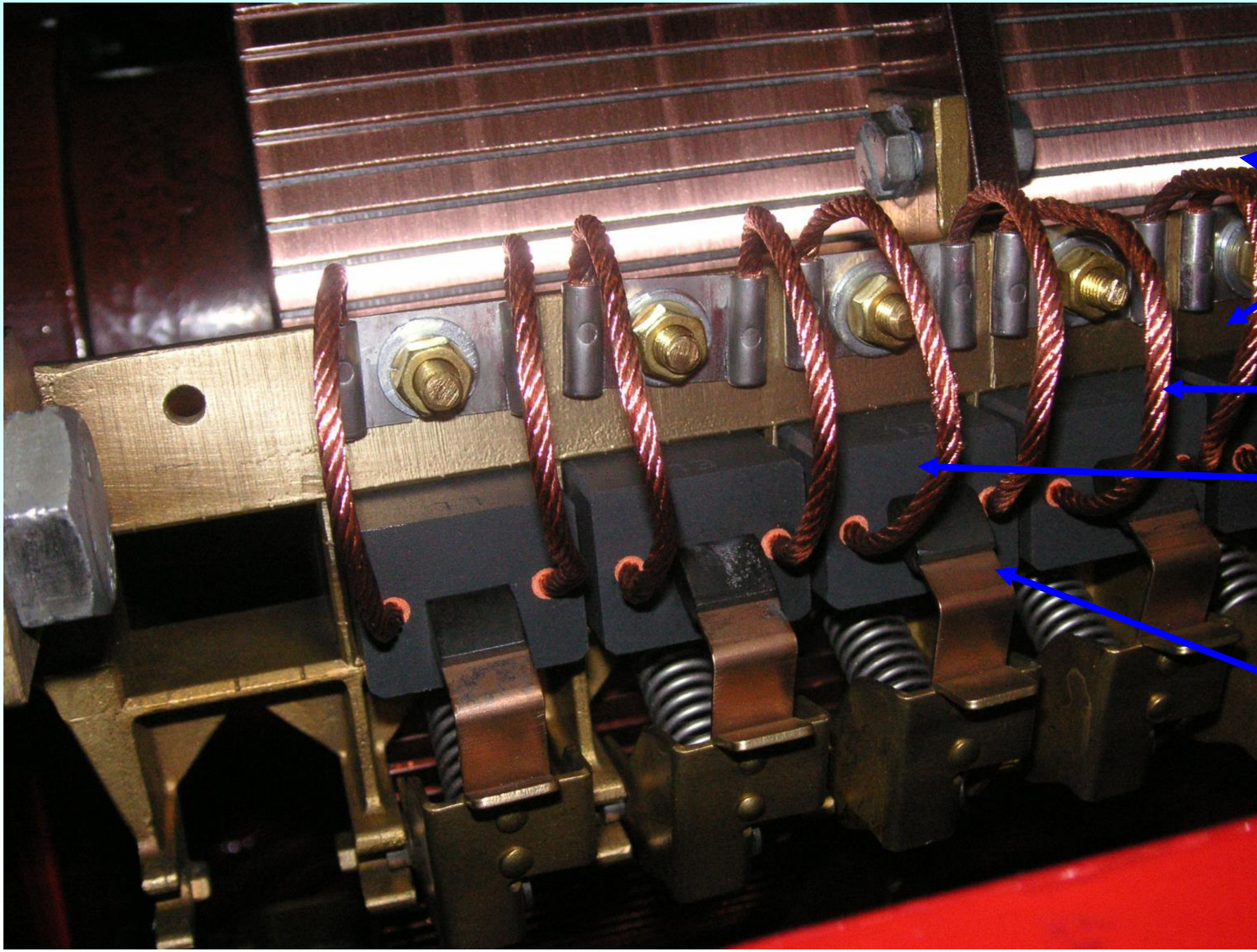


a) The *brush-copper contact resistance* is the main part of voltage drop at the brushes: ΔU_1 is about 80% of total voltage drop ΔU. Resulting brush voltage drop $U_b = \Delta U_A + \Delta U_B$ = ca. 2 V.

b) Brush voltage drop U_b rises non-linear with brush current density J_b ; and decreases with increasing temperature. *Brush current density* J_b **:** 1/100 of *coil current density* (< 10 A/cm^2).

c) Brushes are *short-circuiting rotor coils* at that moment, when coil sides are located in "neutral zone" (= inter-pole gap), where air gap flux density is zero ($B_\delta = 0$), so induced voltage is zero.

Commutator und graphite brushes



Commutator-segments

Insulation

Brush holder (bronze)

copper litz wire

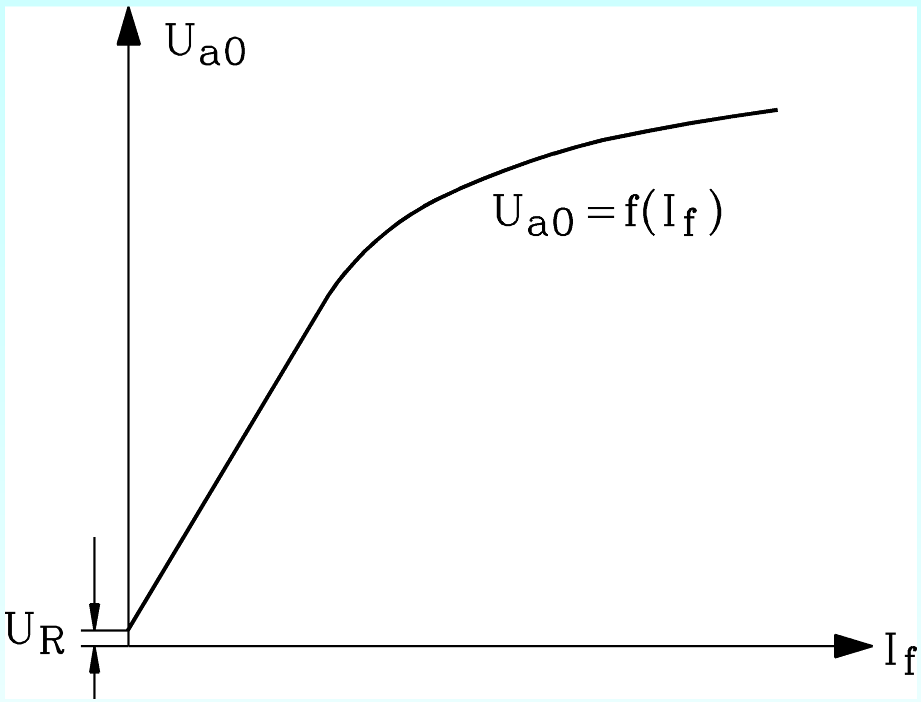
5 graphite brushes in parallel per holder

spring force

Source:

Brenner, Bürstadt

Variation of back EMF



$$U_i = z \cdot \frac{p}{a} \cdot n \cdot \Phi = k_1 \cdot n \cdot \Phi$$

- At turned off field current remanence flux density B_R of stator iron poles remains, which induces a small back EMF U_R .

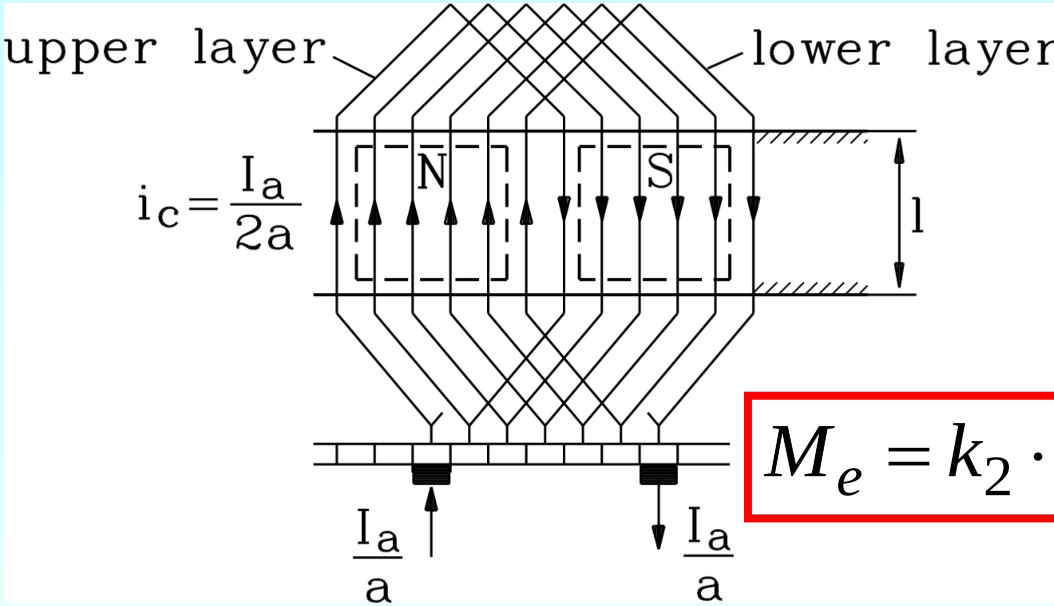
- Back EMF rises **LINEAR** with speed *n*.

- In case of MOTOR operation, applied armature voltage between the brushes U must be bigger than back EMF U_i to drive DC current **(Armature current) I_a** in rotor winding:

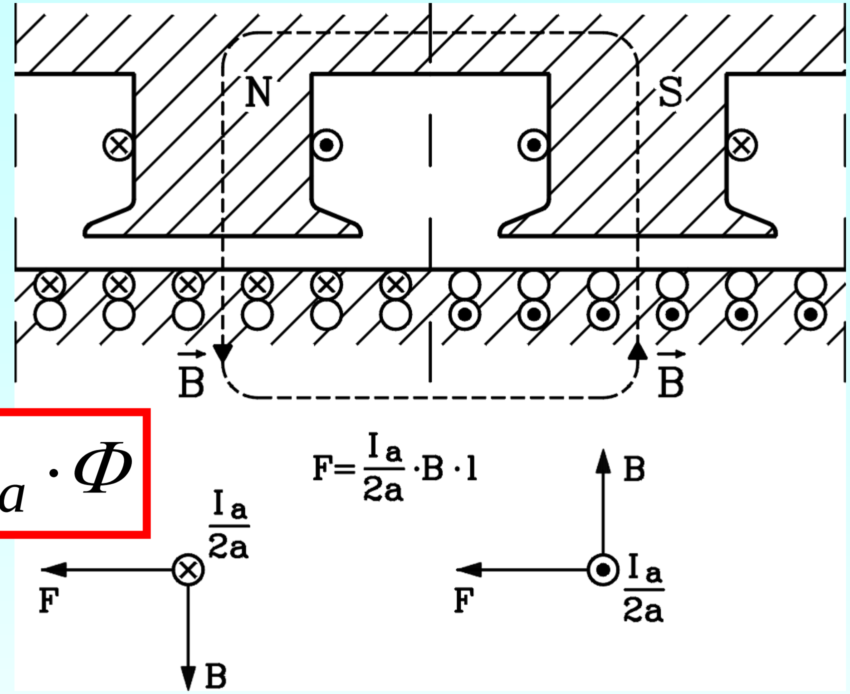
$$U = U_i + I_a R_a + U_b$$

- Armature resistance R_a is small; brush voltage drop U_b = ca. 2V.

Electromagnetic torque



$$M_e = k_2 \cdot I_a \cdot \Phi$$

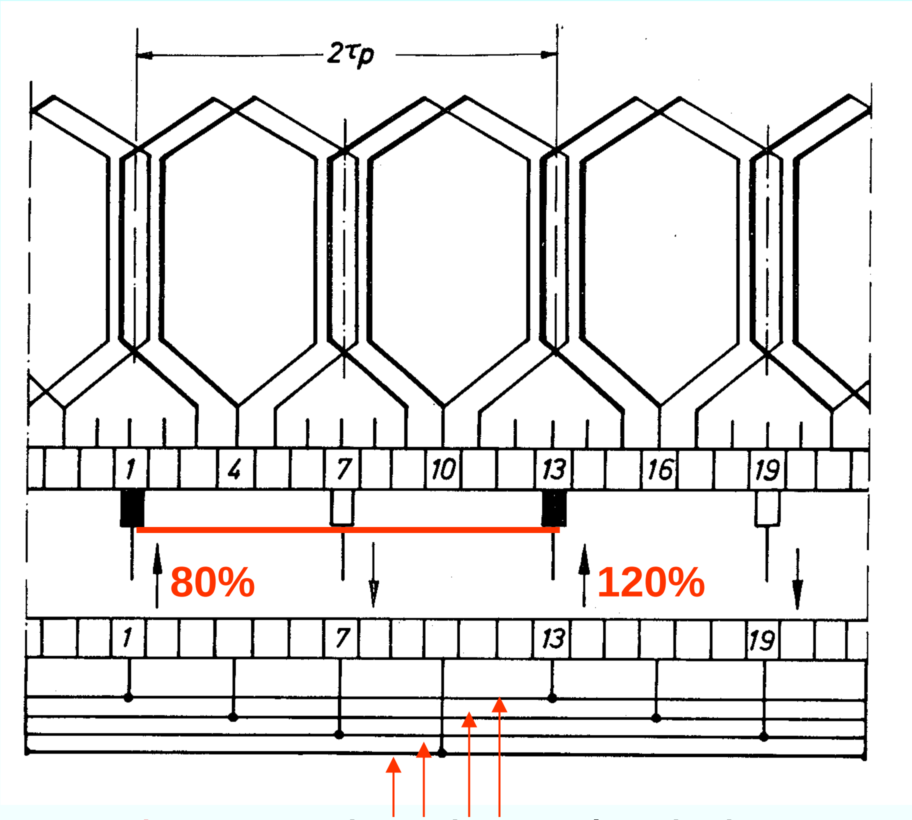


a) Per pole only **one** polarity of rotor current exists. Armature current is flowing in 2*a* parallel winding branches: $I_c = I_a/(2a)$. In rotor winding it is an AC current i_c in each coil, at the brushes it as a DC current I_a.

b) Electromagnetic forces on each rotor conductor due to air gap field B_δ: $F_c = I_c B_\delta l$. Average force per conductor: $F_{c,av} = I_c \alpha_e B_{\delta,m} l$. **Torque** (lever $d_r/2 = p\tau_p/\pi$) for all *z* conductors:

$$M_e = z \cdot \frac{p\tau_p}{\pi} \cdot \frac{I_a}{2a} \cdot \alpha_e B_{\delta,m} l = \frac{z \cdot (p/a)}{2\pi} \cdot I_a \cdot \alpha_e \tau_p l B_{\delta,m}$$

Lap winding needs potential equalizers (of 1st kind)



Example: Data:

$2p = 4$, $2a = 4$, $u = 2$, $Q_r = 12$, $K = 12 \cdot 2 = 24$,

$y_V = K/p = 24/2 = 12$: e. g. commutator segments 1 and 13 have to be connected by equalizer.

Reason: In reality no machine is ideally symmetric.

So electric potential (induced back EMF) between parallel connected positive or negative brushes is not exactly identical.

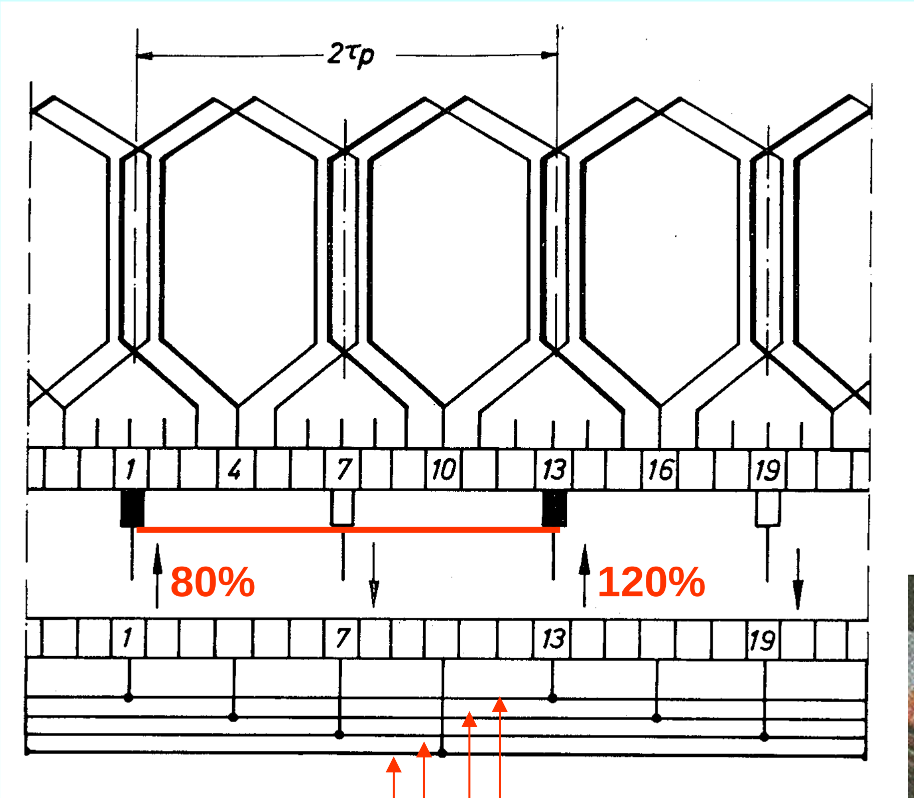
Already small voltage differences will lead due to small R_a to rather big asymmetric current sharing in parallel brushes I_a/a.

Example: $2p = 4$: $2a = 4$: Brush A_1 shares 120%, brush A_2 *only* 80 % of rated brush current.

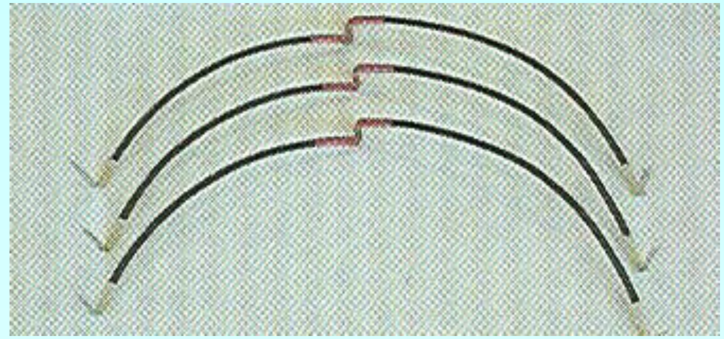
Result: ⇒ Brush A_1 is overloaded, **wears out very quickly.**

- Counter-measure: **Potential equalizers of 1st kind Art =** Copper wires, connecting commutator segments, which (theoretically) have identical electric potential.
- ***Example:*** Current flow in equalizer is 20 % of rated brush current, whereas both brushes A_1 and A_2 carry only 100% current. So brushes are not overloaded.

Mounting of potential equalizers (1^{st} kind)

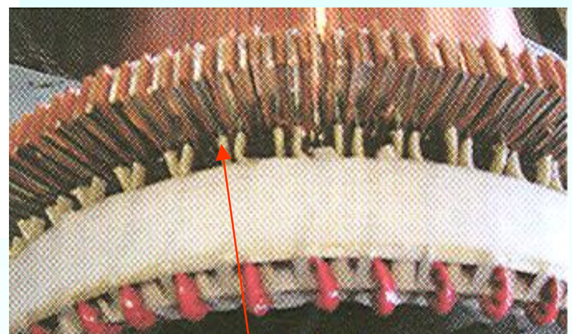


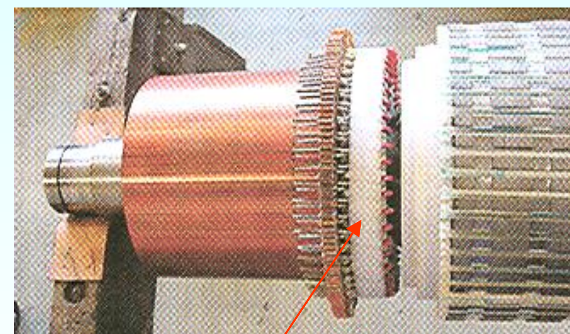
Potential equalizers of 1^{st} kind



Potential equalizers of 1^{st} kind for four-pole winding: Equalizer "step" = 2 pole pitches = half circumference

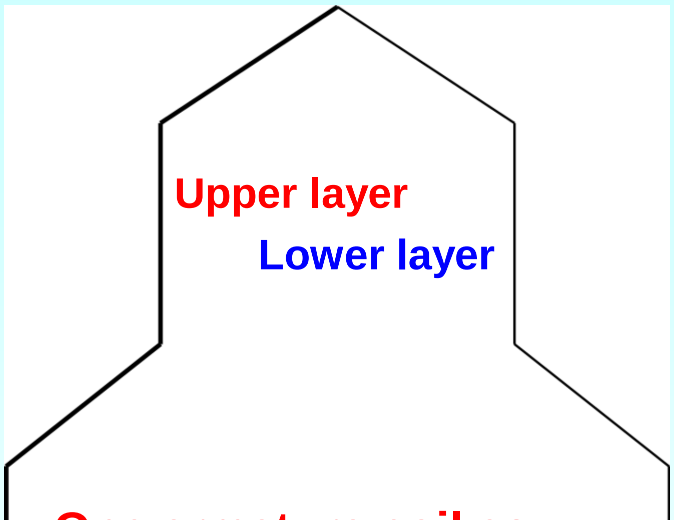
Source: Fa. Brenner, Bürstadt



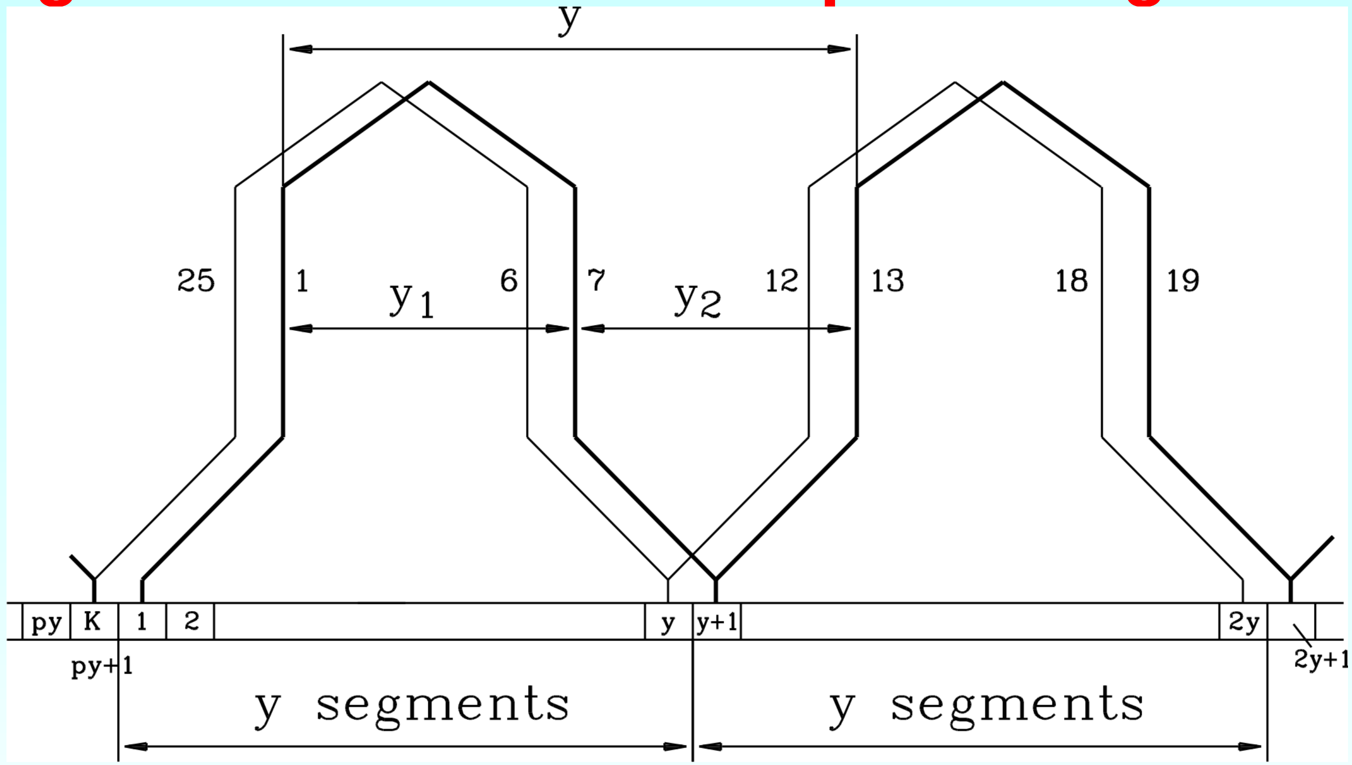


Potential equalizers (1^{st} kind) beneath the bandage

The wave winding – an alternative to lap winding



One armature coil as basic element

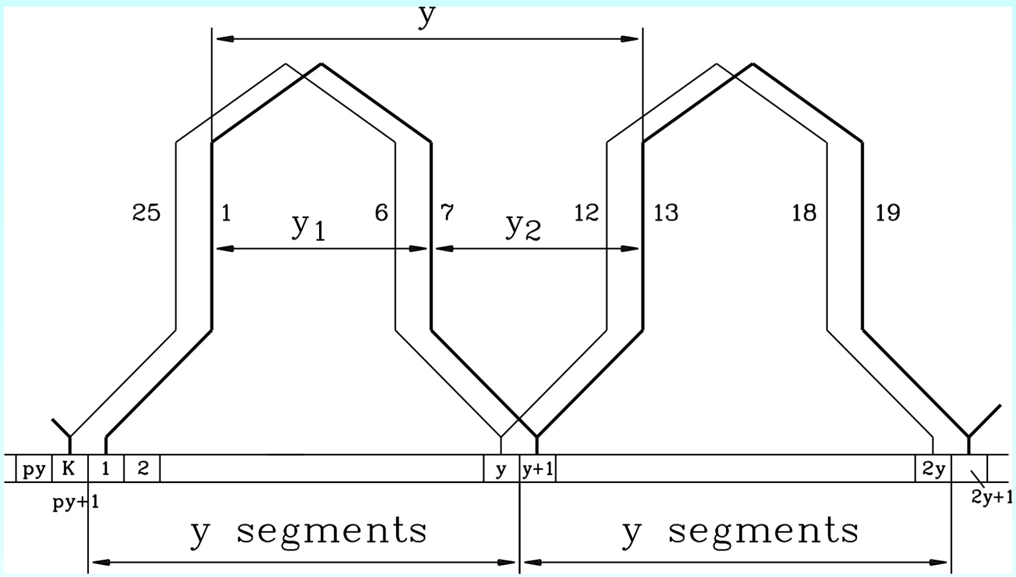


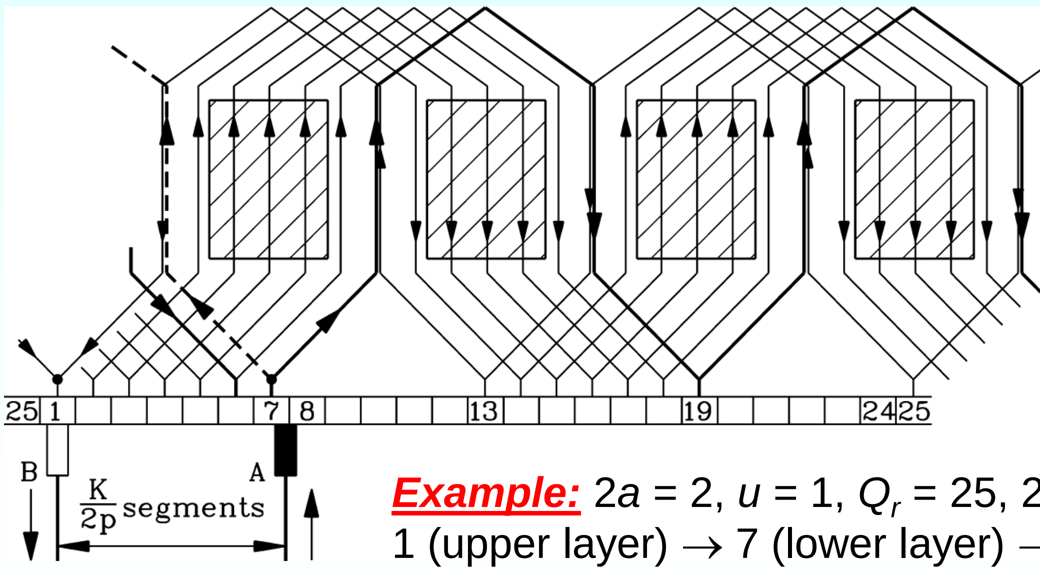
Example: $2a = 2$, $u = 1$, $Q_r = 25$, $2p = 4$,

$K = 25$, "step" for one coil at commutator $y = (K-1)/p = 12$:

1 (Upper layer) → 7 (Lower layer) → 13 (UL) →19 (LL) →25 (UL) → 6 (LL)..., and so on

Armature wave winding





- Series connected **"wave-shaped" armature coils**: Beginning and end of complete "wave line" are distanced by one segment pitch (segment 1 to segment K = 25).

- Next series-connected wave-line start at K, ends at K-1; it is shifted by one segment pitch.

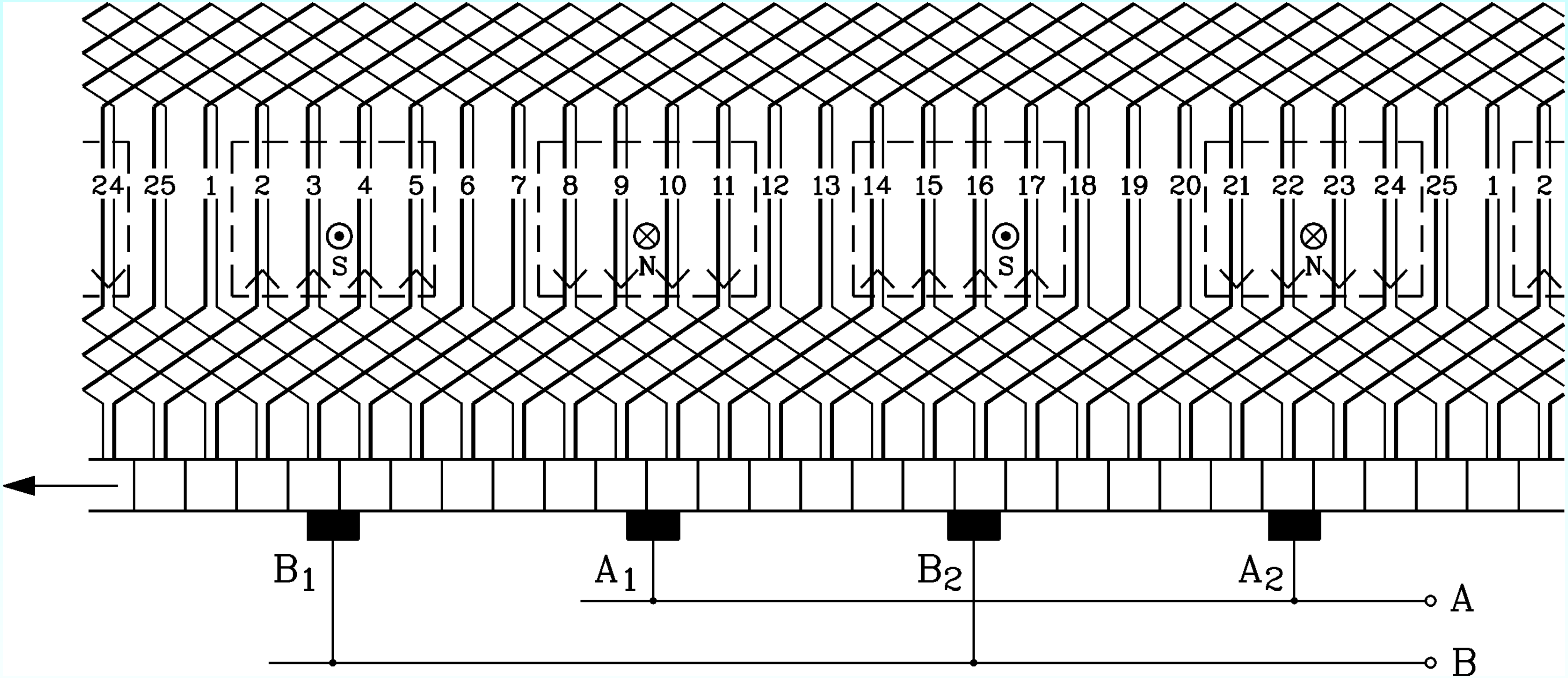
- **One winding branch** covers all upper layer positions from 1 … 7, 13 … 19 (N-poles), and lower layer positions in between (S-poles).

- **Second winding branch** does the same to the left (start at 7, ends at 13):

Simplex wave winding has always two parallel branches: a = 1, 2a = 2.

Example: $2a = 2$, $u = 1$, $Q_r = 25$, $2p = 4$, $K = 25$, Span at commutator $y = (K-1)/p = 12$:
1 (upper layer) → 7 (lower layer) → 13 (UL) →19 (LL) →25 (UL) → 6 (LL)..., etc.

Complete simplex wave winding



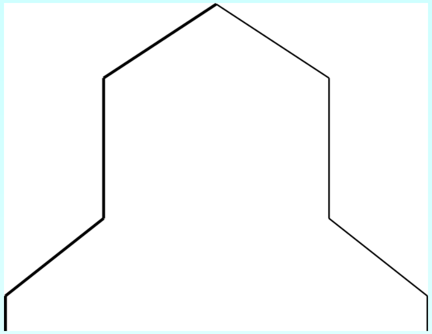
Simplex wave winding: Example:

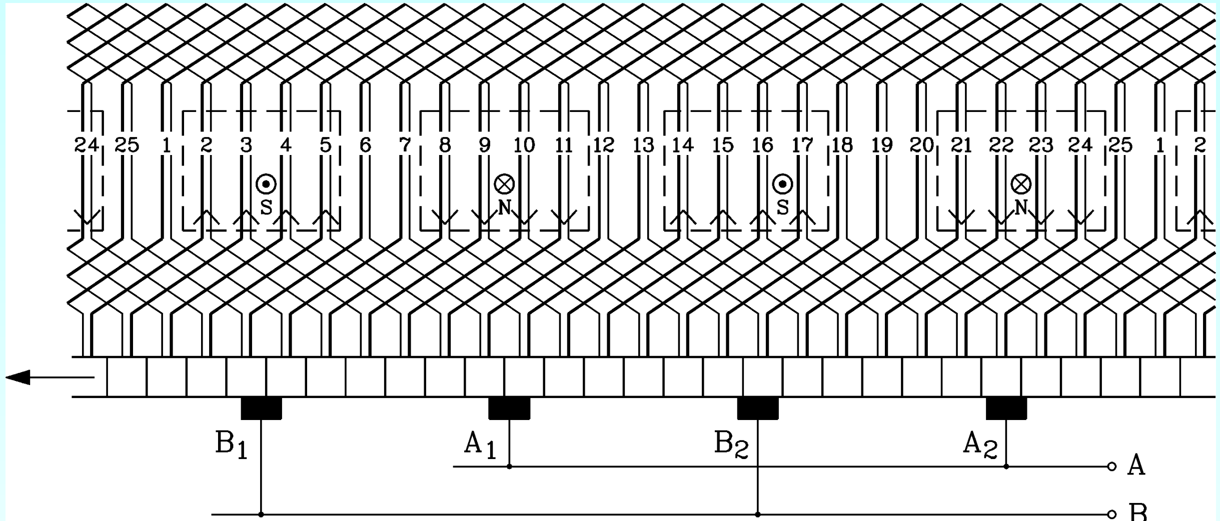
Source: Dr. Holzer, TU Wien

$Q_r = 25,\ 2p = 4,\ u = 1,\ N_c = 1,\ a = 1,\ K = 25,\ y_1 = 6,\ y_2 = 6,\ y = 12$

Simplex wave winding: $2a = 2$

Example: $Q_r = 25$, $2p = 4$, $u = 1$, $N_c = 1$, $a = 1$, $p = 2$, $K = 25$, $y_1 = 6$, $y_2 = 6$, $y = 12$



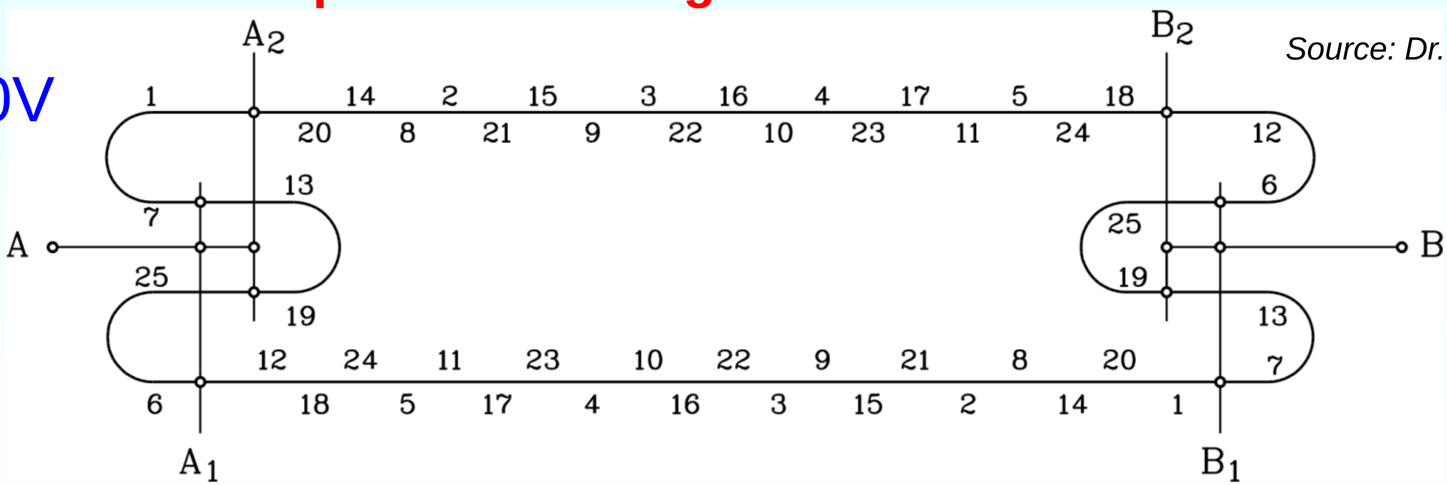


Number of parallel winding branches ALWAYS 2: $2a = 2$

$U_a = 440V$

-220V

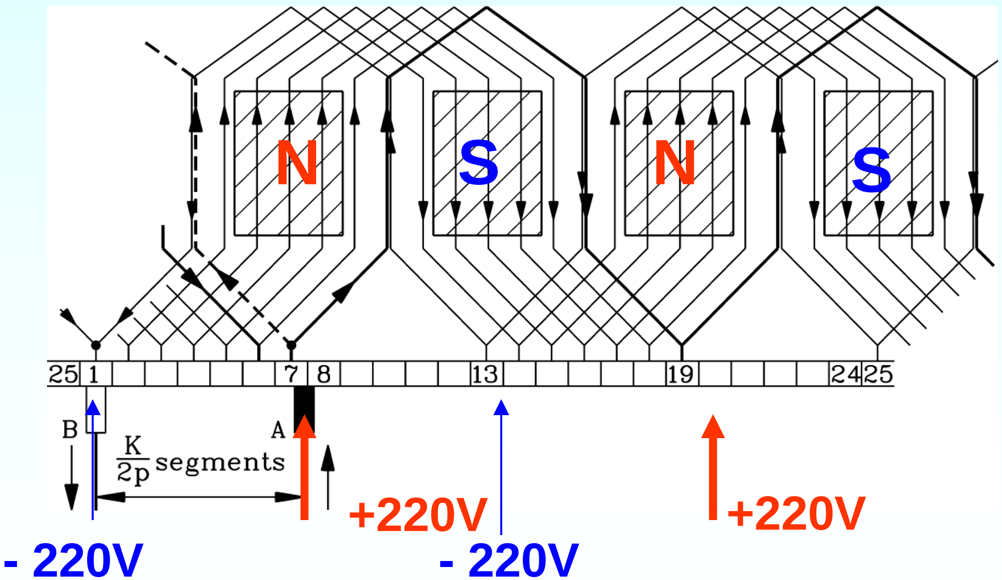
+220V

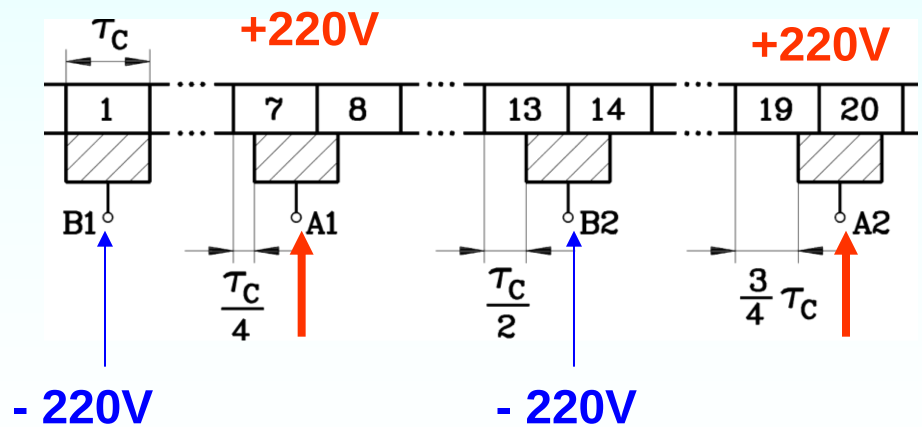


Source: Dr. Holzer, TU Wien

Wave winding – 2 brushes are sufficient, BUT …

- Only one Plus- and Minus-brush sufficient, as only 2 parallel branches. BUT: Big brush cross section necessary (should be avoided !)
- Brush-contacted coils are positioned in neutral zone (= zero field), so **no voltage** induced there
- **Hence:** Additional A-Brushes may be placed, distanced by double pole pitch, and connected in parallel: e.g.: at commutator segments 7 & 19 or 8 & 20 …): **THUS:**
- ***p* Plus- and *p* Minus-brushes with reduced cross section 1/p are used.**

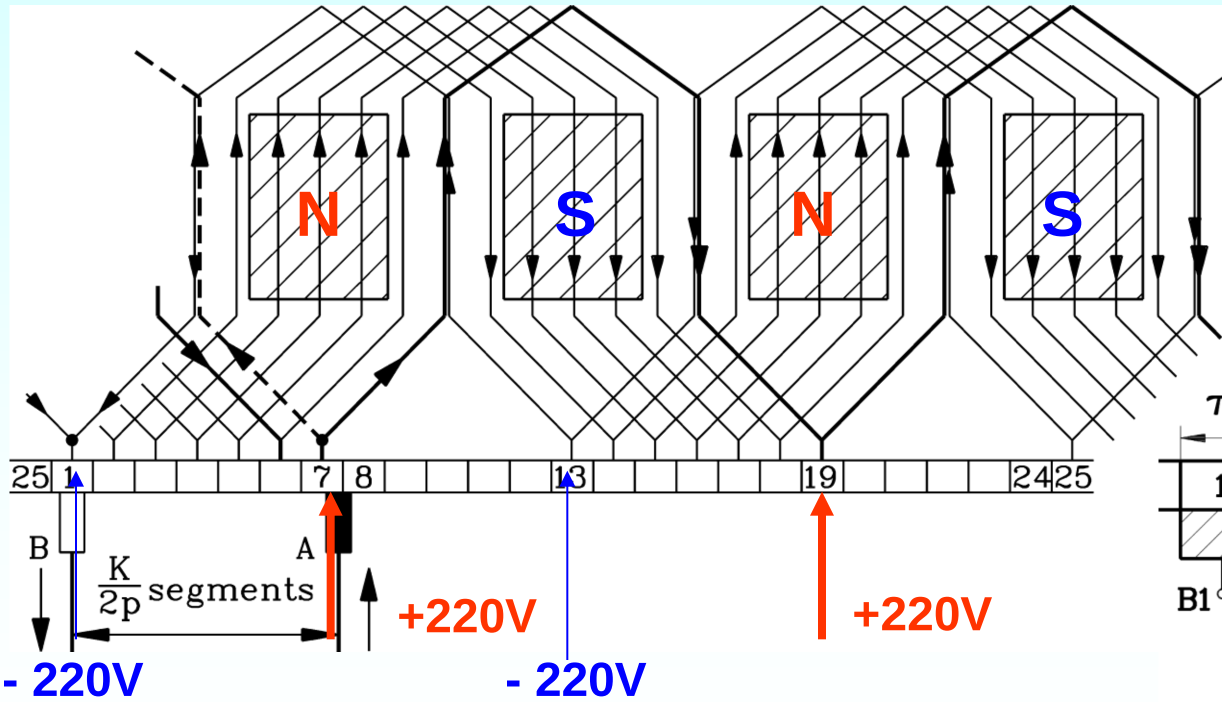




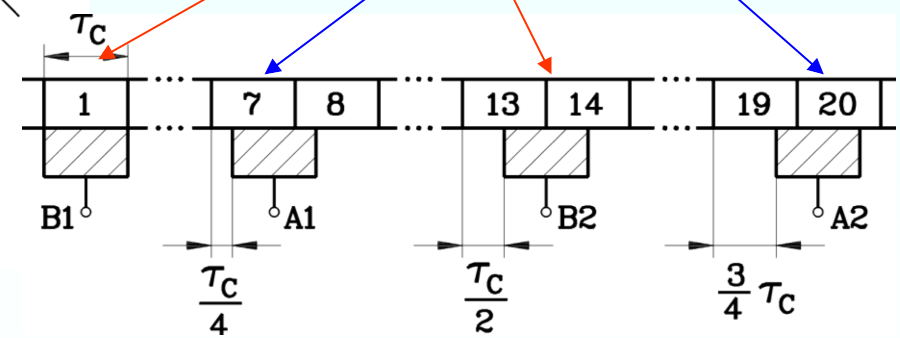
Wave winding – NO potential equalizers necessary

- The coils in neutral zone (no voltage) act as potential equalizers 1st kind (= they connect equal potentials A1 and A2 at $2p = 4$, B1 and B2).

Facit: The wave winding is **self-equalizing.**



At the same potential



Comparison: Lap and wave armature winding

$$U_i = \frac{z \cdot p}{a} \cdot n \cdot \Phi$$

Lap winding	***Wave winding***
Number of parallel winding branches = pole count $2a = 2p$	Number of parallel winding branches always 2 $2a = 2$
Equalizers of 1st kind necessary	No equalizers necessary
High currents possible due to many parallel branches	Current limited to ca. 500 A, as maximum ca. 250 A / parallel branch
Voltage increases in proportion to *z*.	High voltage, because it increases in proportion to $z \cdot p$.
High rated power possible (typically up to 12 MW)	**Limited power (ca. 300 kW)**

Result: - DC machines for **big** power are designed with lap winding.

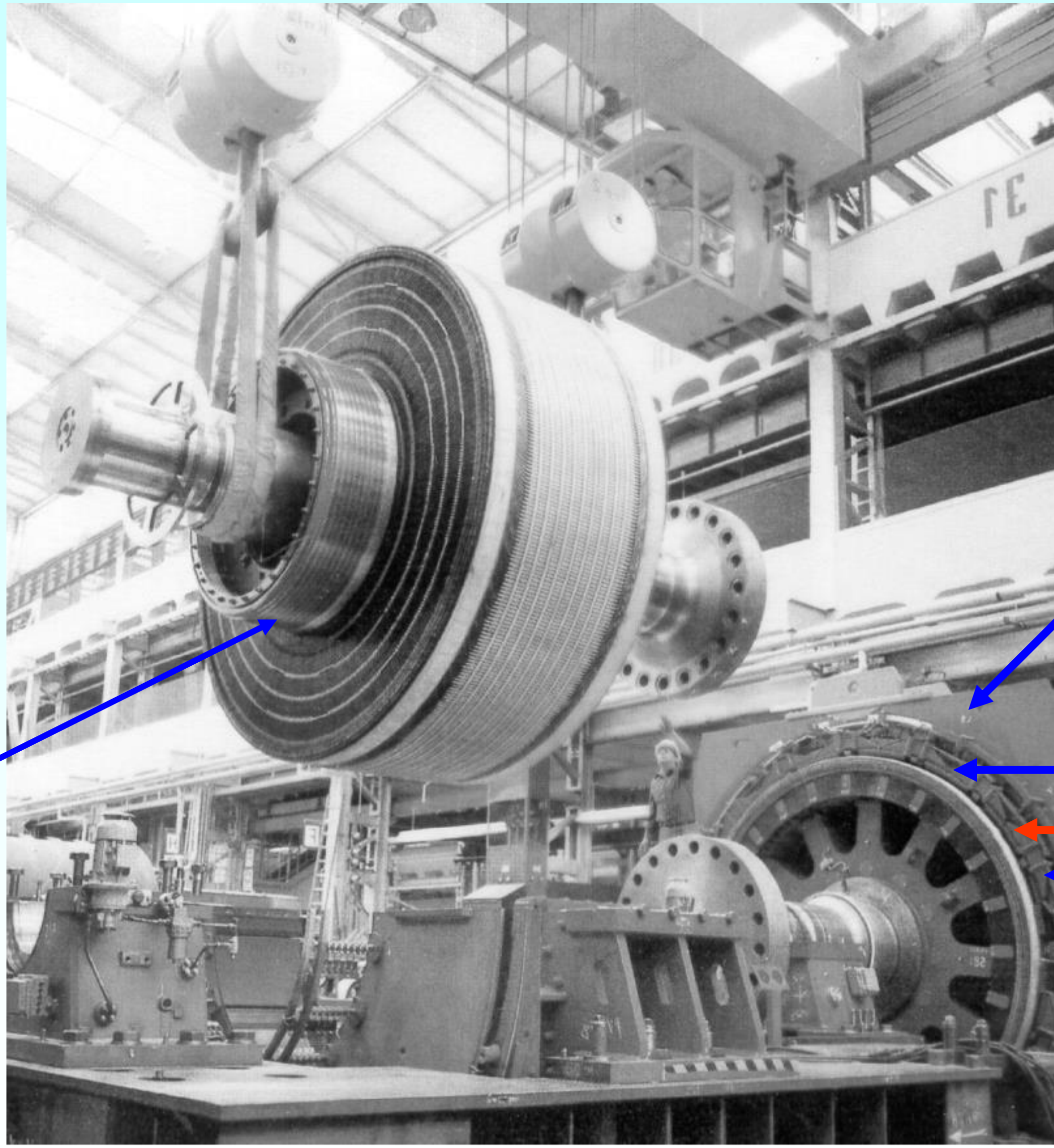
Example: 6 MW-cold strip mill drive. Machine with 18 poles, so with 18 parallel winding branches.

- DC machines with **smaller** power are designed with wave winding (cheaper); sufficient high voltage also at small flux per pole Φ.

Big DC machine

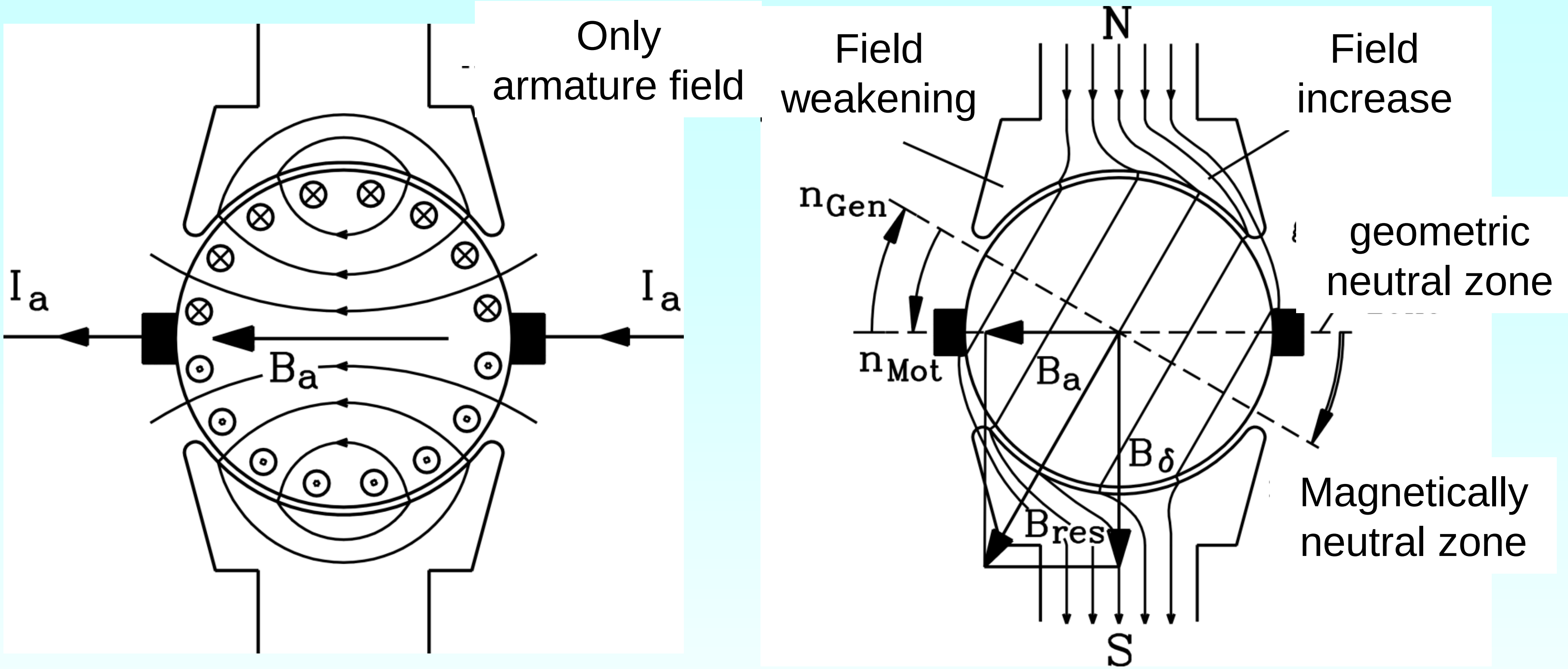
- 1st stage of mill strip motor 12 MW

Lap winding



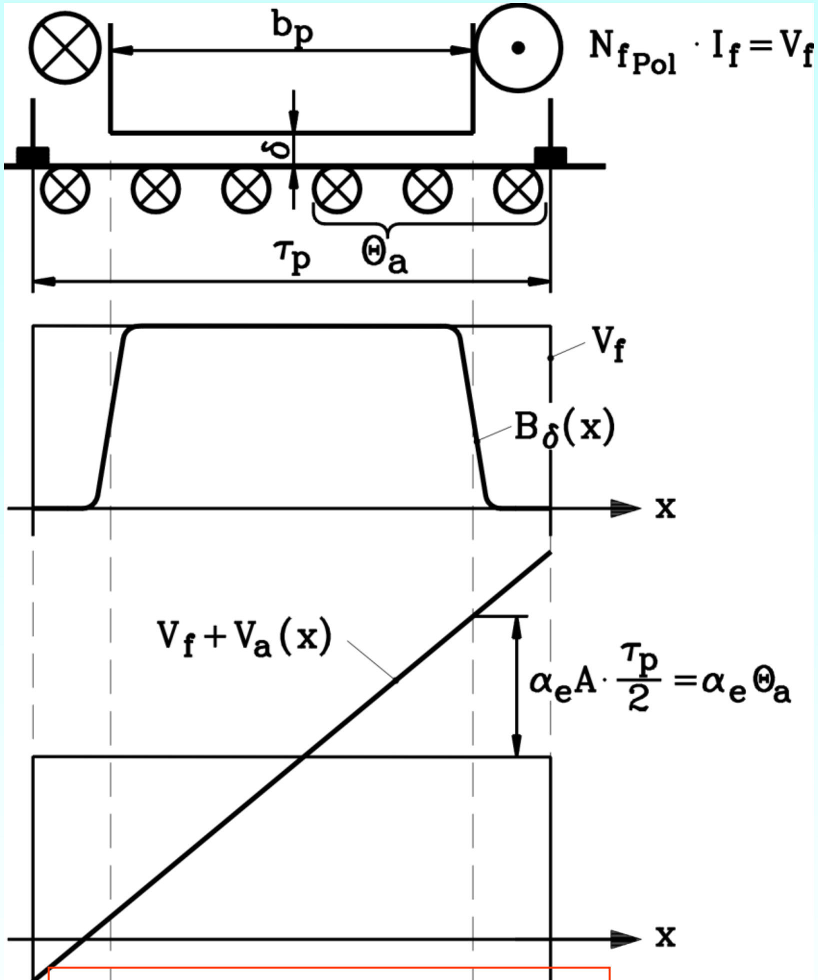
Source: Siemens AG

Lines of force are the flux lines



- Superposition of armature field with main field of stator poles gives resulting magnetic field.
- Flux lines act like "rubber strings" (MAXWELL´s magnetic pull) and move the rotor anti-clockwise (MOTOR operation).

Field distortion due to armature field



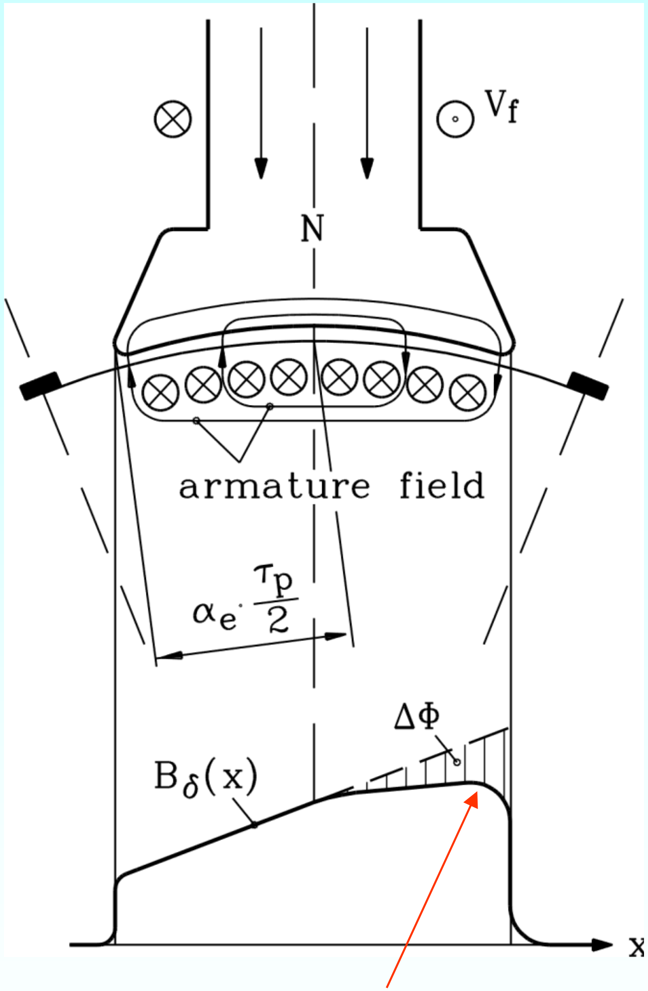
$$B_\delta(x) = \mu_0 \cdot \frac{V_f + V_a(x)}{\delta(x)}$$

• **I_a = 0 :** Air gap field $B_{\delta 0}$ at **no-load** (armature current = 0) beneath poles nearly constant, because of constant air gap δ.

• **I_a > 0 :** At **load** (armature current flows) the **armature field** B_a is excited. It is super-imposed on the main field and results in field distortion (**Armature reaction**).

- Left half of pole: $B_\delta = B_{\delta 0} - B_a$
- Right half of pole: $B_\delta = B_{\delta 0} + B_a$

Flux reduction due to armature field reaction



Additional saturation

- Increase of flux density at right pole side leads to iron **saturation.** So resulting field is NOT

$B_\delta = B_{\delta 0} + B_a$, but $B_\delta < B_{\delta 0} + B_a$.

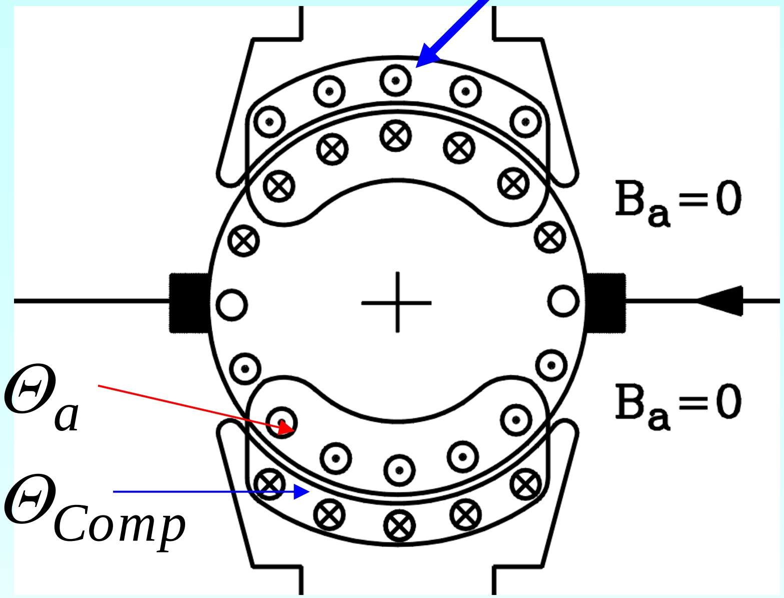
-Thus field increase on right pole side is smaller then field decrease on left pole side. Hence per pole a **decrease of flux** $\Delta\Phi$ occurs.

Result:

With increasing armature current I_a the magnetic flux per pole Φ is decreasing at constant field current I_f.

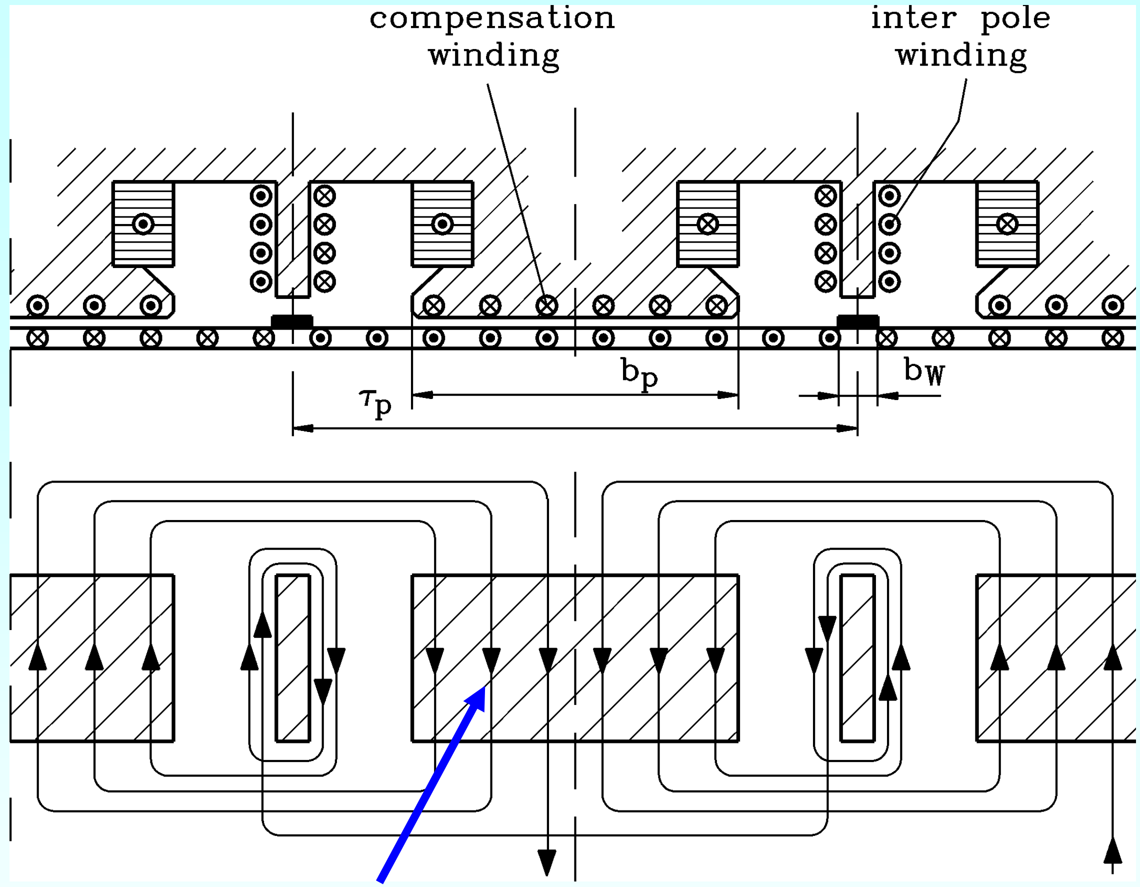
Counter-measure: ***Compensation winding*** **in the stator pole shoes. This winding has to be excited by the armature current.**

Compensation winding



$$\oint_C \vec{H}_a \cdot d\vec{s} = \Theta_a - \Theta_{Comp} = 0$$

Armature field B_a is cancelled !

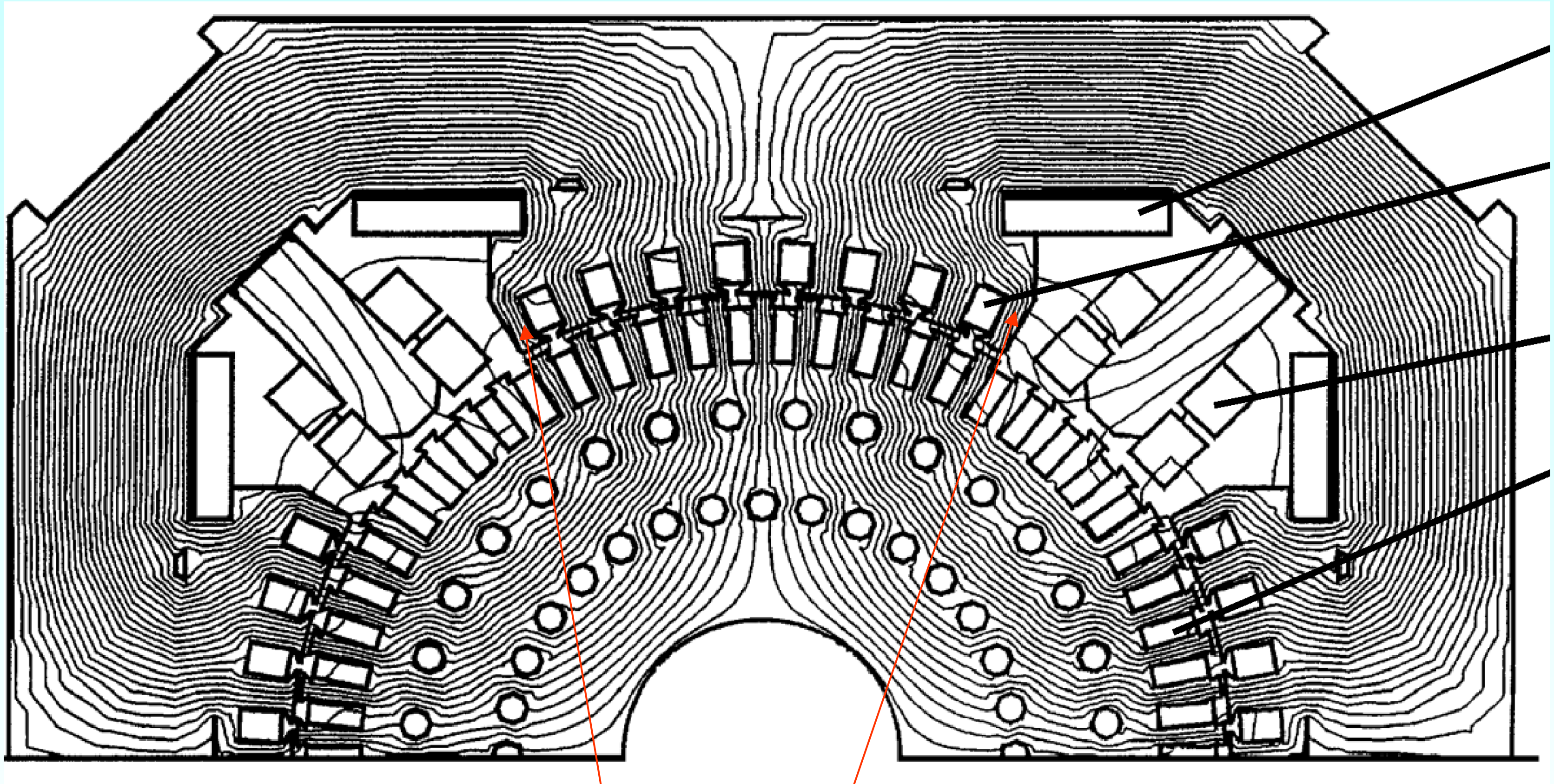


Compensation winding & inter-pole winding

in series with armature winding

- Armature current I_a feeds compensation winding in the stator pole shoes; direction of current flow opposite to current flow direction in rotor winding: Ampere-turns of rotor armature and of compensation winding **cancel**: $B_a = 0$.

Compensated four-pole DC machine

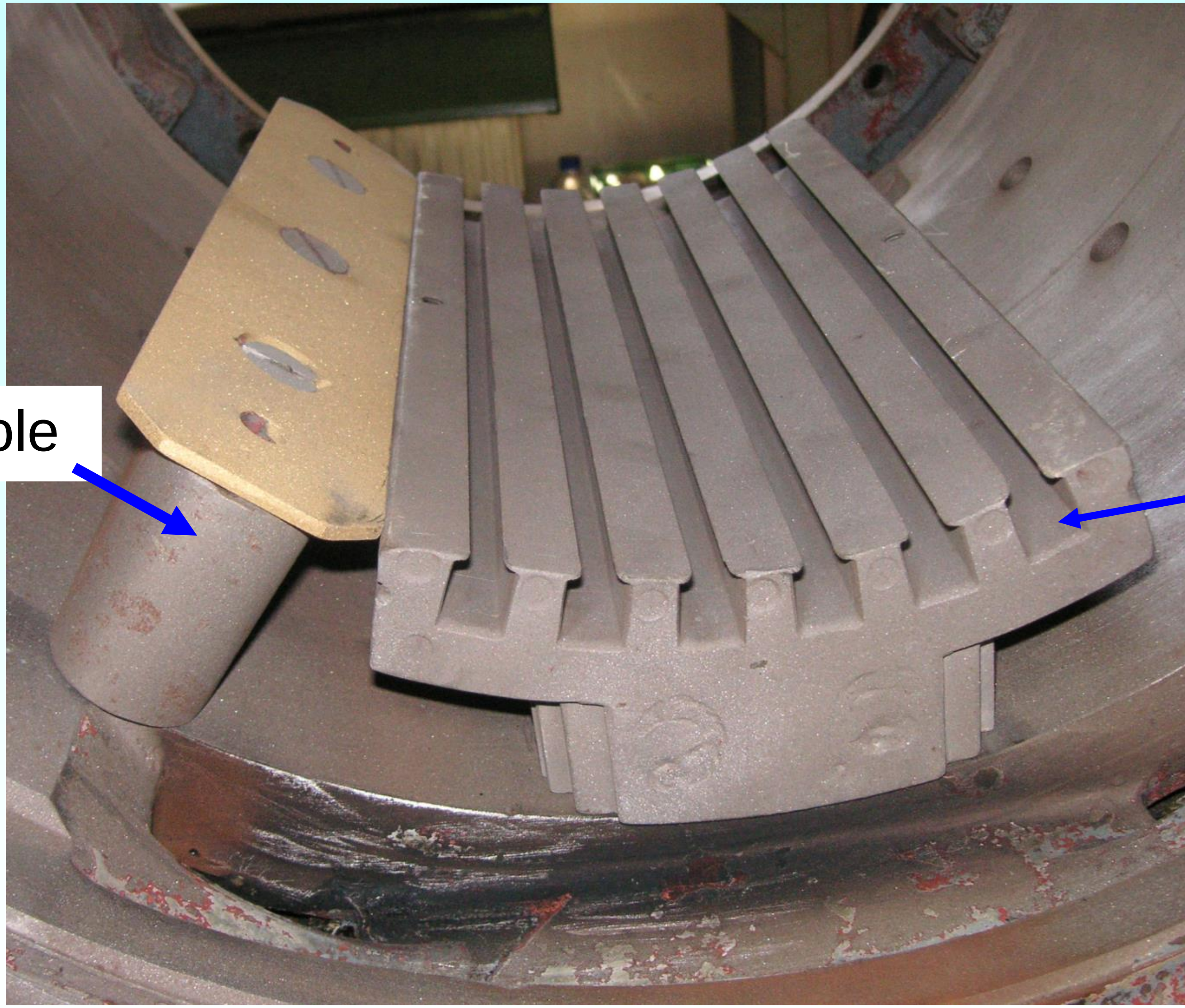


Source: ABB

Density of flux lines at left and right pole edge IDENTICAL = NO field distortion !

Compensation winding necessary above 200 … 300 kW !

DC-machine – stator poles without winding



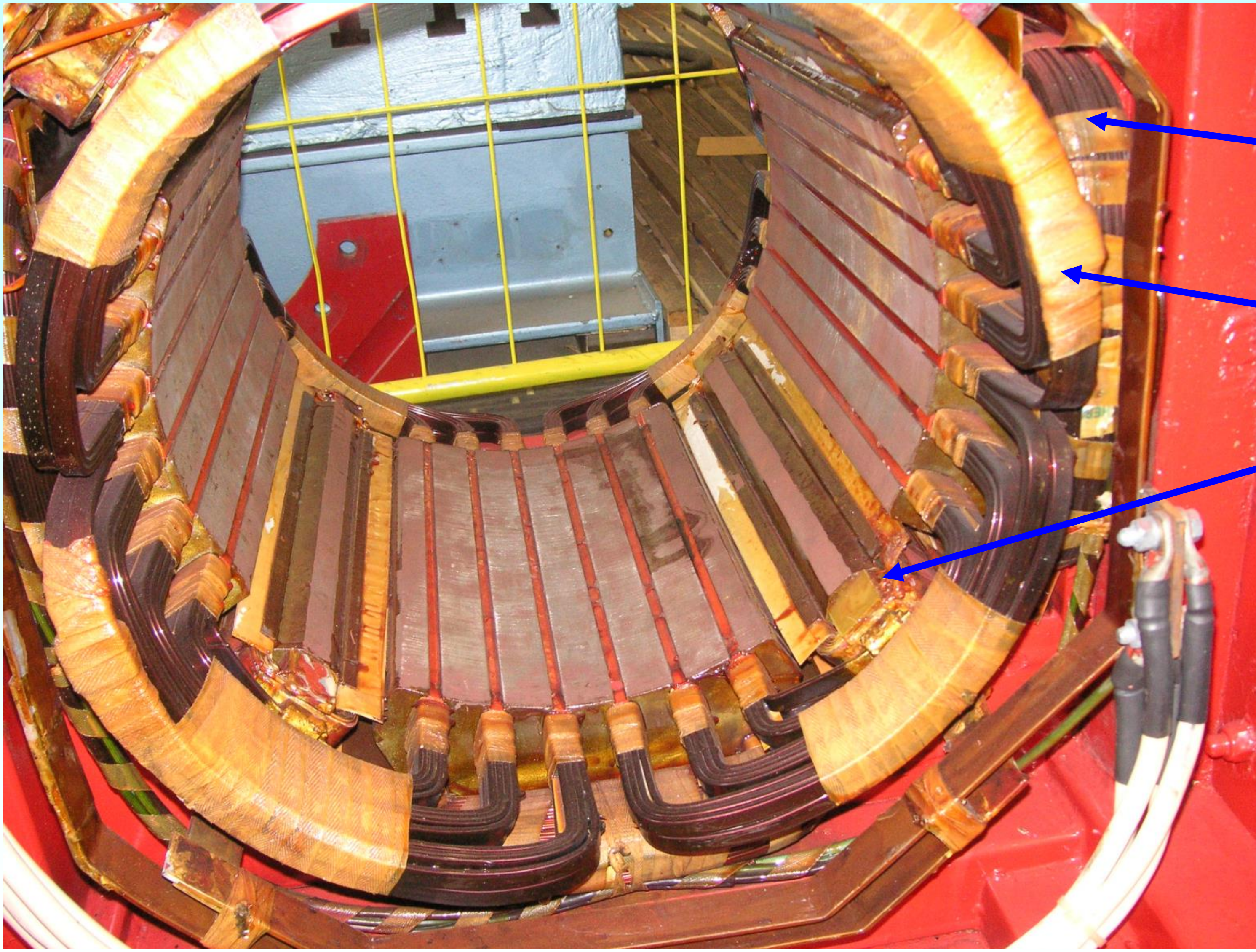
Inter pole

Main pole with slots for compensation winding

Source:

Brenner, Bürstadt

Four-pole stator – with stator windings

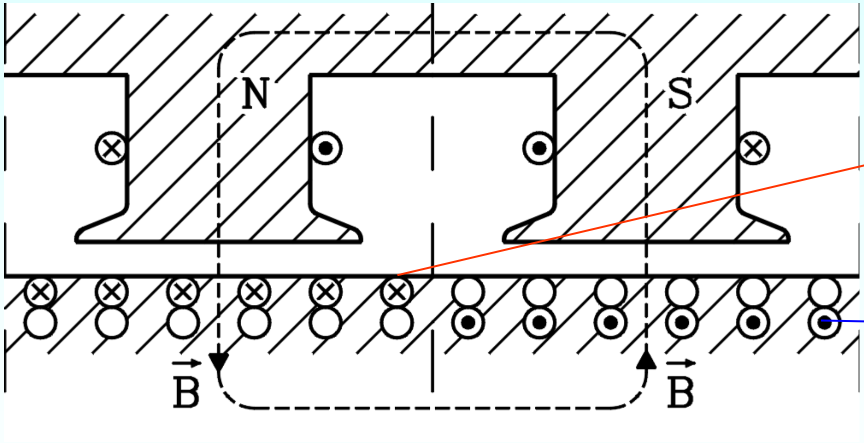


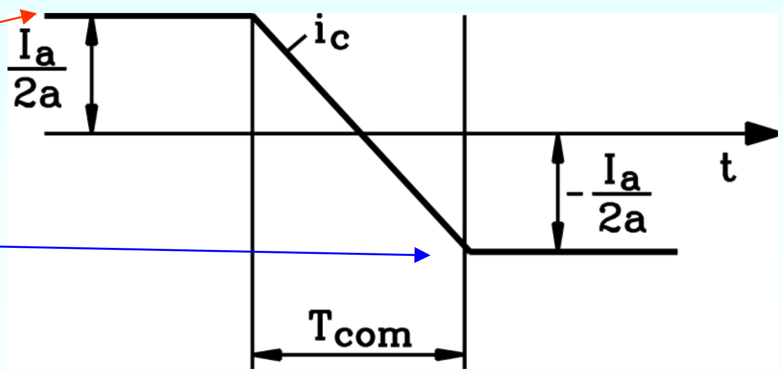
Source:

Brenner, Bürstadt

Commutation (current reversal) of armature current

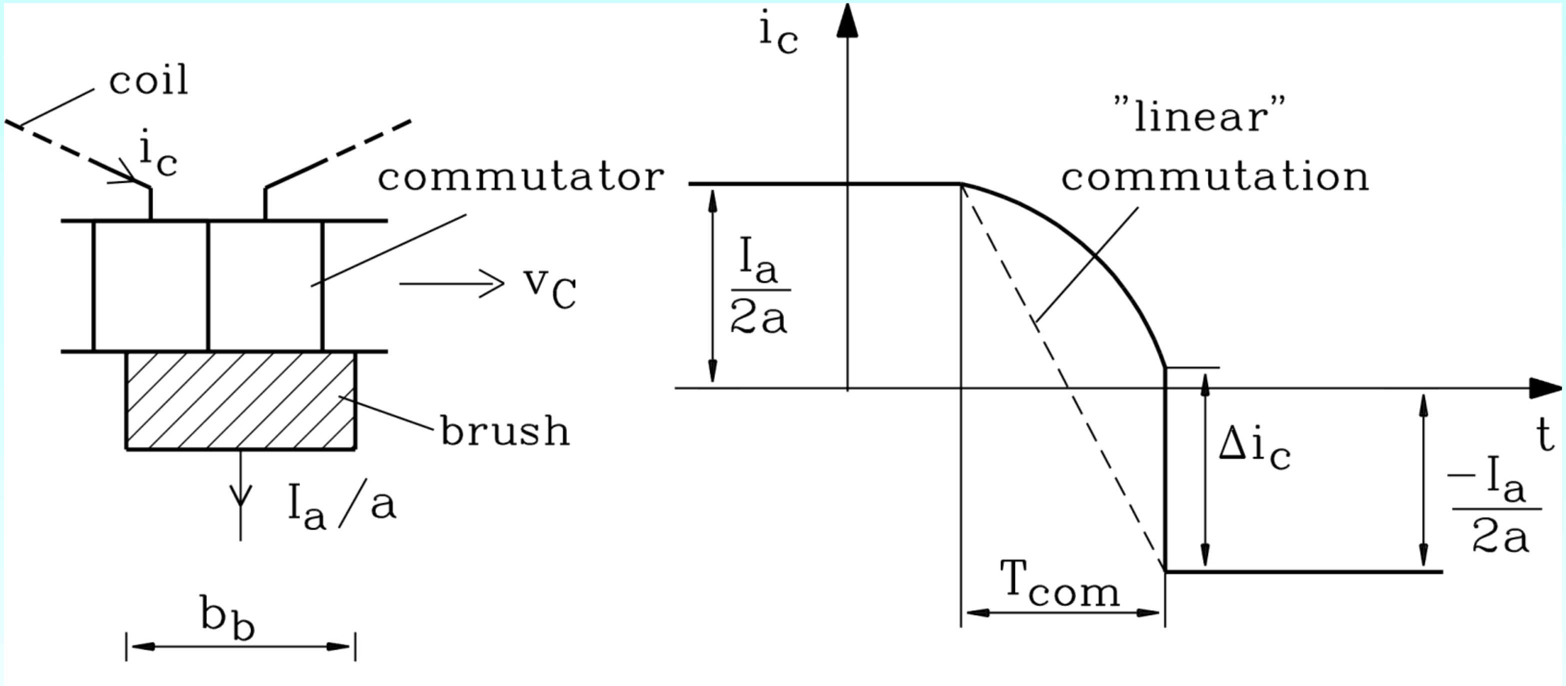
- The armature coil current i_c is an **ac current**.
- It changes from its positive value $I_a/(2a)$ to its negative value $-I_a/(2a)$ and vice versa, when the brush **short-circuits** the two coil ends (= neighbouring commutator segments).
- At this time, both coil sides are located in the neutral zone ($B_\delta = 0$). **No voltage** is induced by motion induction.





Moving direction of rotor

Commutation (current reversal) of armature current



- An armature coil has the inductance L_c (slot and winding overhang leakage field).
- A current change causes a self-induced voltage (**"reactance voltage of commutation"**) u_R.
- With approximation of **"linear commutation":**

$$u_R = L_c \frac{di_c}{dt} \approx L_c \frac{I_a}{aT_{com}} = k_R n I_a \qquad T_{com} = b_b / v_C \sim 1/n \quad \Rightarrow \quad u_R = k_R \cdot n \cdot I_a$$

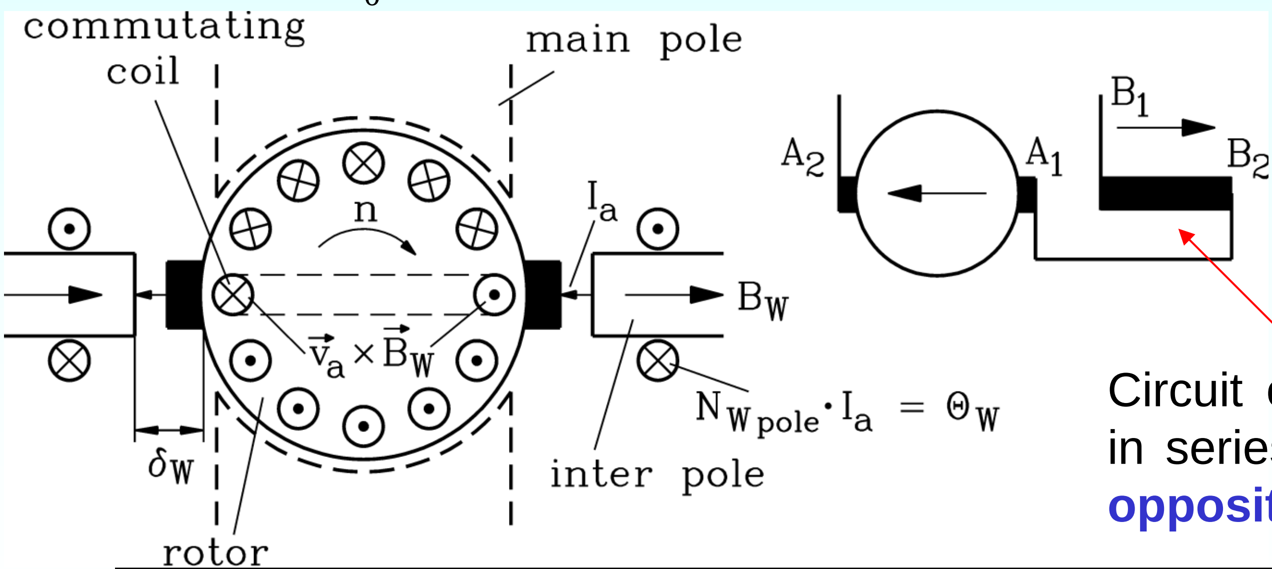
Inter-poles reduce reactance voltage of commutation u_R

- u_R increases with a) increasing load (M resp. I_a), b) with speed n.
- u_R “ignites" **sparks** between brush and commutator $\Rightarrow$ rapid brush erosion.
- **Remedy:** ***Inter-poles***, excited by armature current (commutation winding, number of turns $N_{W,Pole}$).
- **Commutating field** $B_{\delta W}$ induces via motion induction a **compole voltage** u_W opposite to the reactance voltage **and cancels the effect of** u_R.

$$u_W = 2N_c \int_0^l (\vec{v}_a \times \vec{B}_{\delta W}) \cdot d\vec{s} = 2N_c \cdot v_a \cdot l \cdot B_{\delta W} \quad \longrightarrow \quad v_a \sim n, \; B_{\delta W} \sim I_a$$

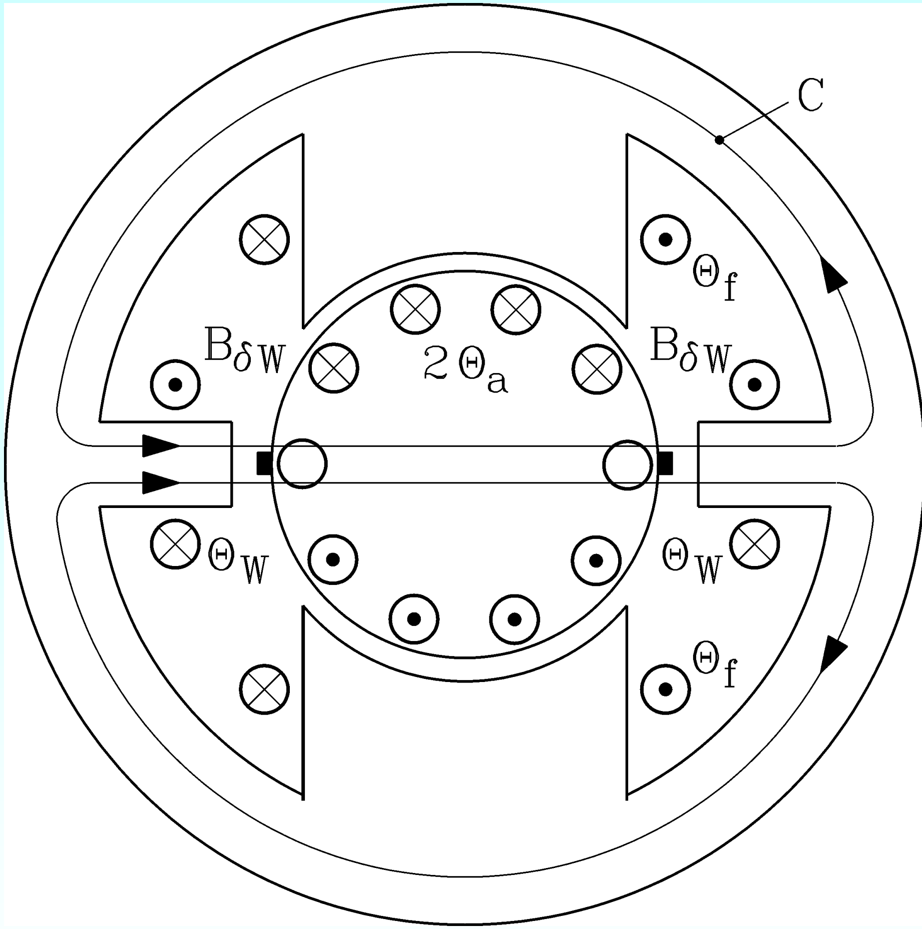
$$\boxed{u_W = k_W \cdot n \cdot I_a}$$

Demand: $\boxed{u_R - u_W = 0}$



Circuit of the inter-pole winding B1-B2 in series with the armature A1-A2 with **opposite winding direction**.

Dimensioning of the commutation winding



- u_R and u_W depend on n and I_a: at **EACH** operation point (n, I_a) valid: $k_W = k_R$.

$$u_R - u_W = (k_R - k_W) \cdot n \cdot I_a = 0$$

- **Inter-pole Ampere-turns Θ_W:**

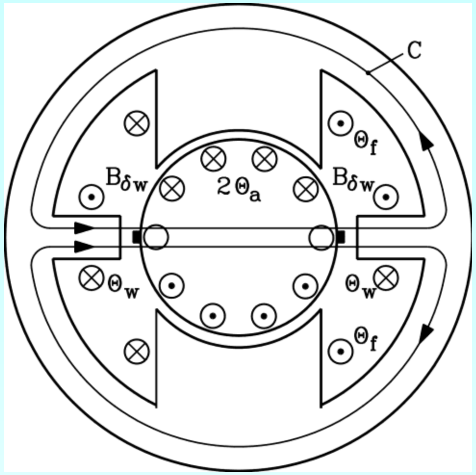
Demand: Inter-pole magnetic circuit is unsaturated

$$\oint_C \vec{H} \cdot d\vec{s} = 2H_{\delta,W}\delta_W = 2\Theta_W - 2\Theta_a + \Theta_f - \Theta_f = 2(\Theta_W - \Theta_a)$$

$$B_{\delta W} = \mu_0 \frac{\Theta_W - \Theta_a}{\delta_W} = \mu_0 \frac{N_{W,Pol} I_a - N_{a,Pol} I_a}{\delta_W} \sim I_a$$

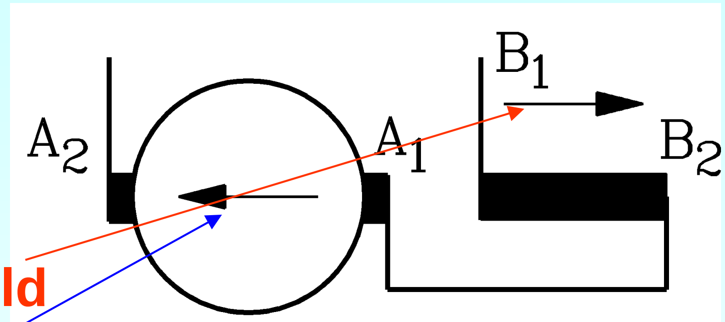
- *Inter-pole Ampere turns $N_{W,Pol} I_a$ must be chosen bigger than armature Ampere-turns $N_{a,Pol} I_a = z/(8ap) \cdot I_a$ to get in the inter-pole air gap δ_W a positive commutating field $B_{\delta W}$: (ca. 10% … 12% bigger).*

Connection of commutating winding



- Commutating field must be opposite to armature field

- Hence: Opposite sense of winding direction



Commutating field

Armature field

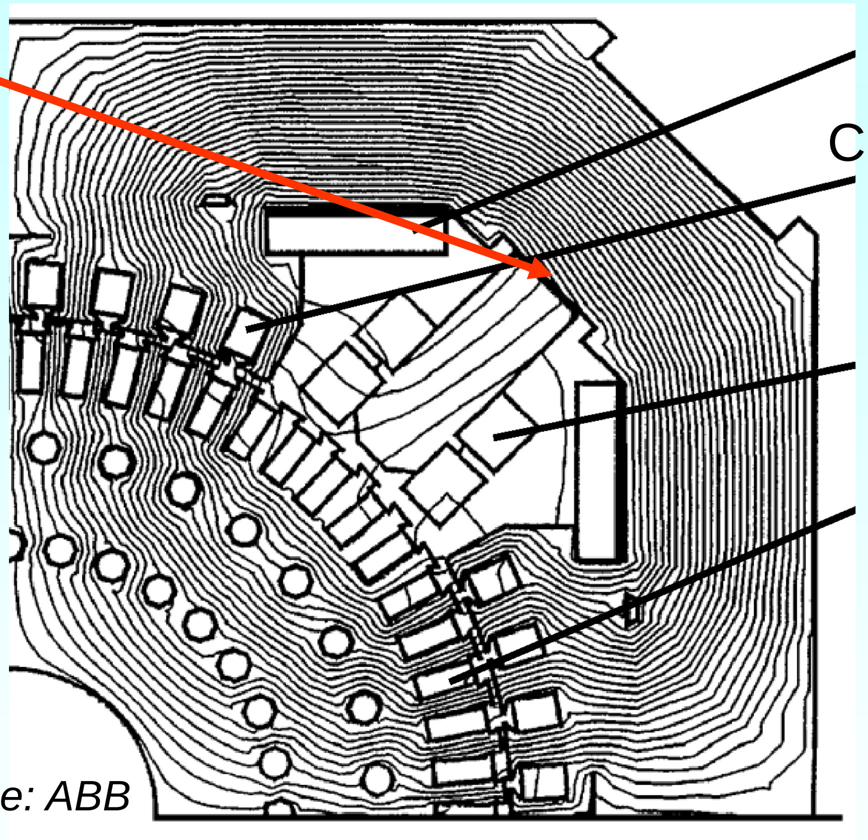
Resulting commutating field

• For $k_W = k_R$ inter-pole air gap δ_W and $N_{W,Pol}/N_{a,Pol}$ must be chosen properly.

• Optical check, if brushes are "sparking". If so, then commutating field is either too strong or too weak **("Over-/Under-Commutation")**!

• Removing/Placing of additional small iron sheets at the inter-poles increases/ /decreases inter-pole air gap δ_W and decreases/increases commutating field.

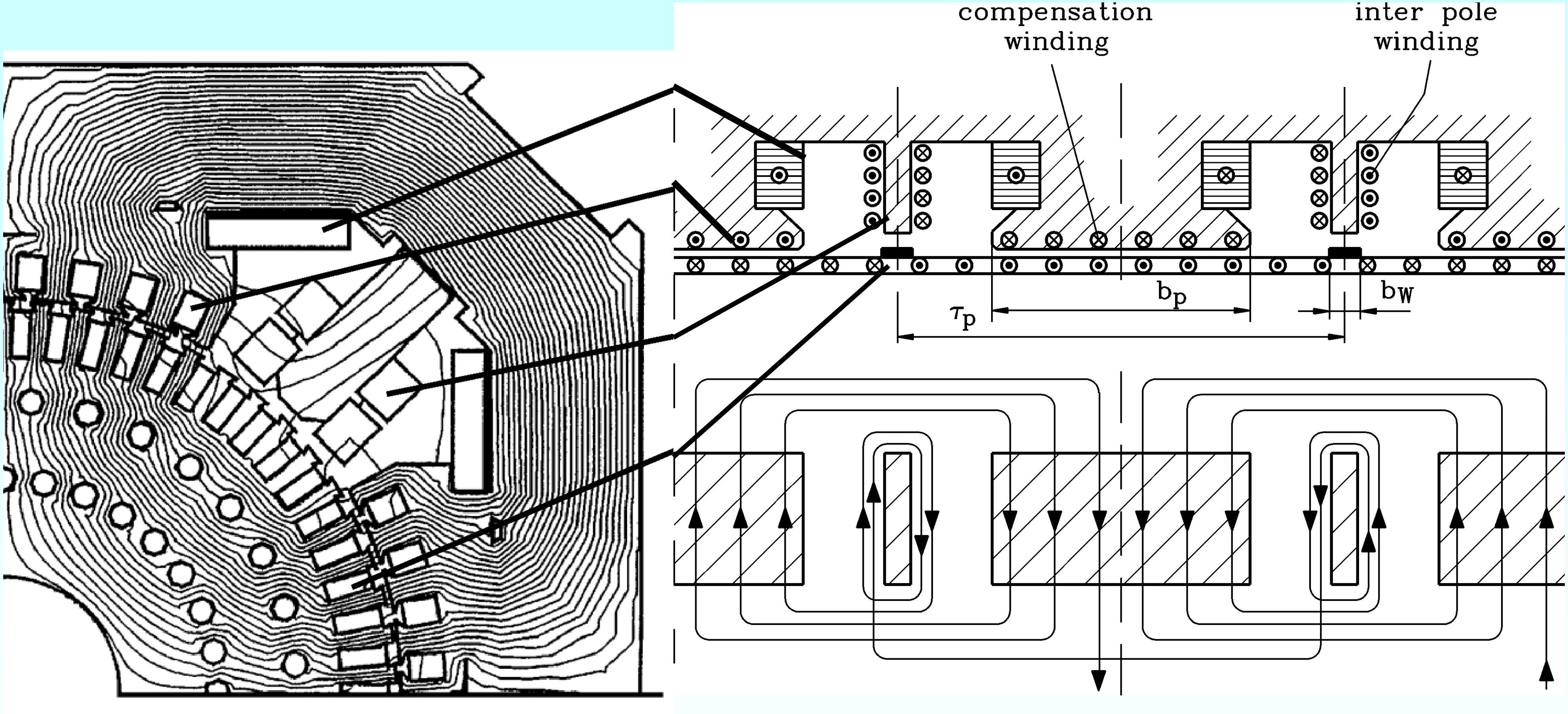
Inter-poles of a four pole DC machine



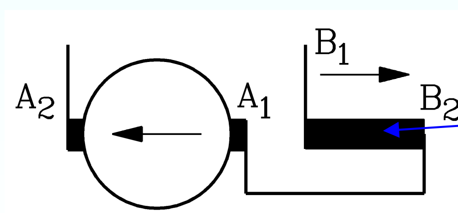
Source: ABB

Inter-poles necessary above ca. 1 kW !

Inter-poles of a four pole DC machine



Source: ABB



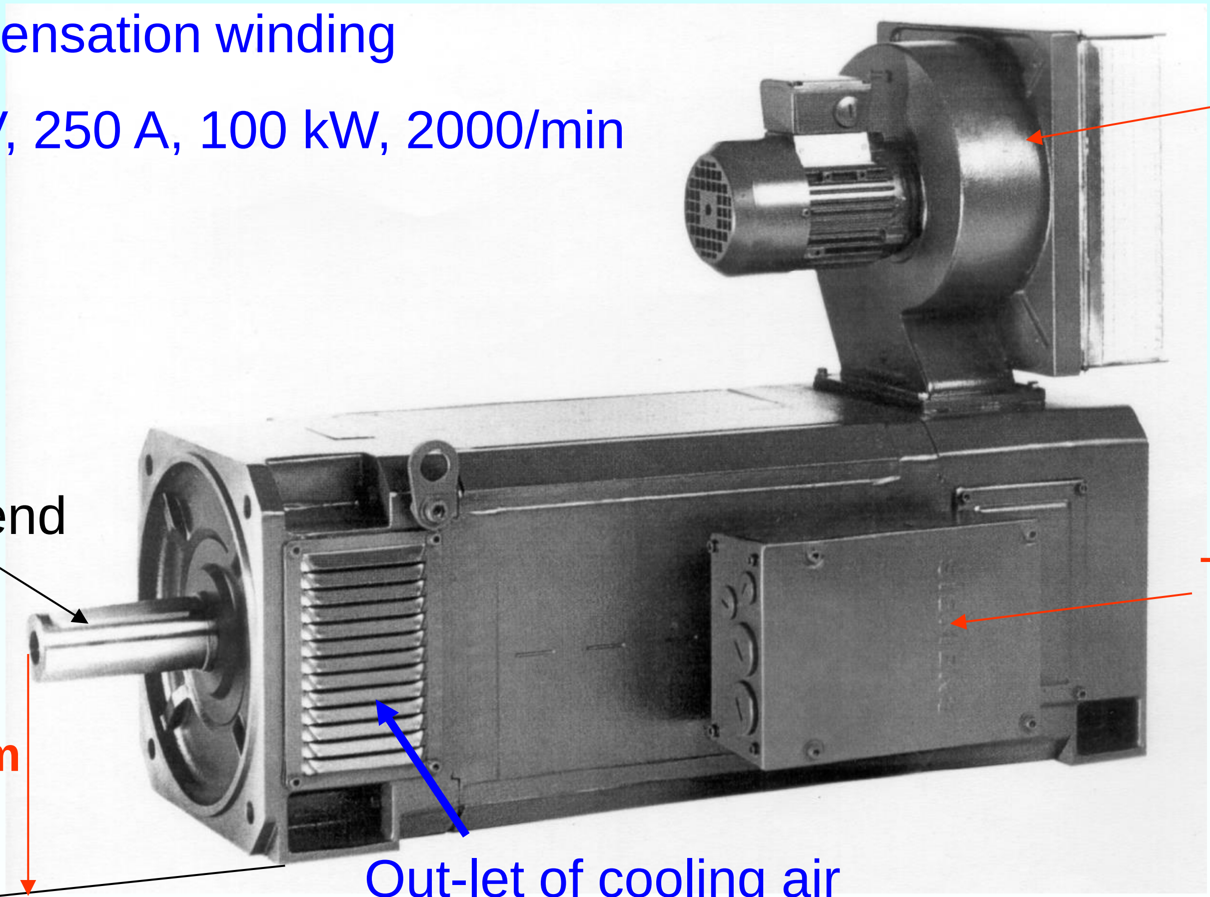
Compensation winding & **inter-pole winding**

in series with armature winding

Separately excited DC machine

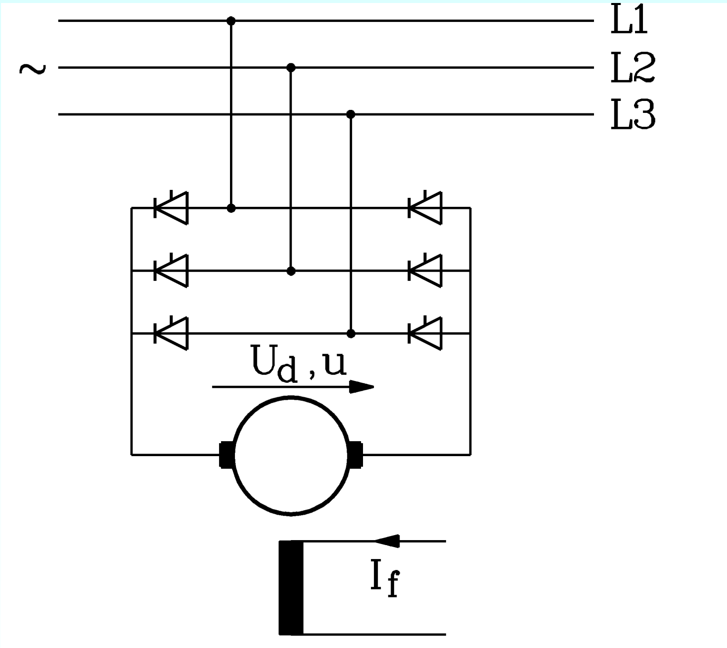
Four-pole DC machine with inter-poles, but NO compensation winding

400 V, 250 A, 100 kW, 2000/min



Source: Siemens AG, Bad Neustadt/Saale, Germany

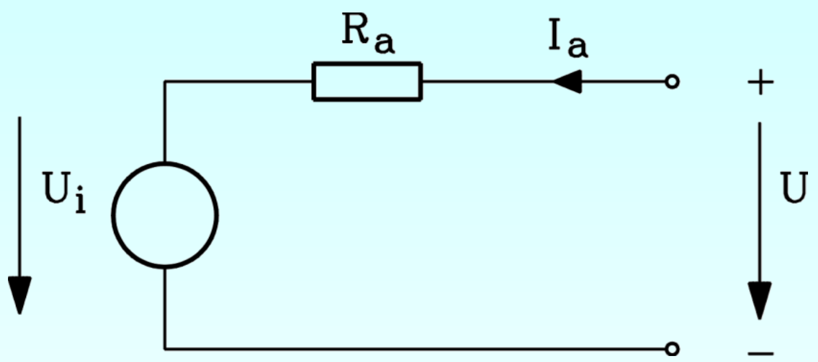
10.2 Drive technology with DC machines



Equivalent circuit of the separately excited dc machine

- Armature conductors, commutation- and compensating winding = total **armature resistance** R_a.

- **Separate excitation:** field current I_f adjustable independent of I_a.



$$U = R_a I_a + U_b + U_i, \quad U_i = k_2 \Omega_m \Phi(I_f)$$

- U_b: brush voltage drop ca. 2 V

- **Braking rotor losses**: Iron losses, friction losses, additional losses (AC skin effect in conductors) will be neglected here !

- **Internal power** P_δ: Air gap power P_δ is converted via the *LORENTZ*-forces into mechanical power P_m (via the electromagnetic torque M_e).

$$P_\delta = U_i I_a = \Omega_m M_e = P_m \quad \Rightarrow \quad M_e = U_i I_a / \Omega_m = (k_2 \cdot \Omega_m \cdot \Phi / \Omega_m) \cdot I_a = k_2 \cdot I_a \cdot \Phi$$

Example: Power flow in a DC motor

Example :

200 kW motor, U = 430 V, n = 1470/min, η = 92%, U_i = 408.5 V

- electrical input power

$$P_{e,in} = P_{m,out} / \eta = 200 / 0.92 = 217.4 kW = U \cdot I_a$$

- armature current

$$I_a = P_e / U_a = 217400 / 430 = \underline{506 A}$$

- internal power

$$P_\delta = U_i I_a = 408.5 \cdot 506 = \underline{206.7 kW} > P_m \,!$$

- **braking rotor losses** cause: $P_\delta > P_m$

- Electromagnetic torque:

M_e = 206.7/(2π · 1470/60) = <u>1.343 kNm</u>

- Torque at the shaft:

$M = P_{m,out}/\Omega_m$ = 200/(2π · 1470/60) = <u>1.299 kNm</u>

Balance of losses of the dc machine

Example: 200 kW dc motor, separately excited, I_a = 506 A,

- Total losses: = **17.4 kW** converted into **heat** **17.4 kW**

1. Hereof in the **armature circuit 217.4 - 206.7 = 10.7 kW** 10.7 kW

2. In the **brushes**: 2V · 506A = 1.0 kW **1.0 kW**

3. In the armature resistance: $P_{Cu,a} = P_{d,a} - P_b = 10.7 - 1.0 = 9.7$ kW **9.7 kW**

4. Mechanical braking torque M_d of the rotor as difference between electromagnetic and shaft torque:

$M_d = M_e - M =$ 1.343 -1.299 = 0.044 kNm,

5. This corresponds to the **rotor losses** $P_{Fe} + P_R + P_z = 2\pi n M_d = P_\delta - P_{m,out} =$

= 206.7-200 = 6.7 kW. 6.7 kW

6. **Iron losses P_{Fe}:** Eddy-current and hysteresis losses in the rotor iron sheets

7. **Additional losses P_z:** Eddy-currents in the slot conductors due to current displacement, as the conductors carry an AC current

8. **Friction and windage losses P_R** in the bearings and brushes and caused by the cooling air flow.

- Additionally: **Excitation losses P_f** = 1.5 kW **1.5 kW**

Stationary basic equations of separately excited DC machine

- **Stationary basic equations (consumer reference system):**

$$U_a = I_a R_a + U_i (+U_b) \qquad U_i = k_2 \Omega_m \Phi(I_f)$$

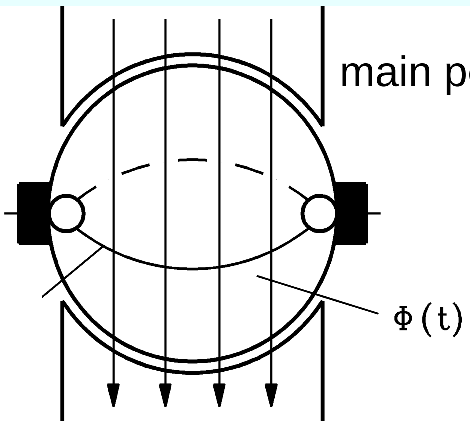
$$U_f = R_f I_f \qquad M_e = k_2 I_a \Phi(I_f) \qquad M_e \approx M_s$$

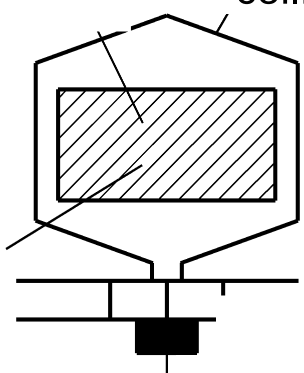
- Neglecting friction losses, iron losses, additional rotor losses:
  Shaft torque $M_s \cong$ internal (electromagnetic) torque M_e

Dynamic equations of separately excited DC machine

- **Dynamic basic equations:**
  Speed, armature current, armature voltage, field excitation current & voltage and main flux are subject to change.
- Armature field: **Armature self-inductance** L_a
  Main field: **Field self-inductance** L_f .

Mutual inductance M_{af} only between a) commutating armature coils (= short-circuited by brushes) and b) field coil, otherwise **zero.**





$$u(t) = i_a(t) \cdot R_a + L_a \cdot di_a(t)/dt + u_i(t)$$

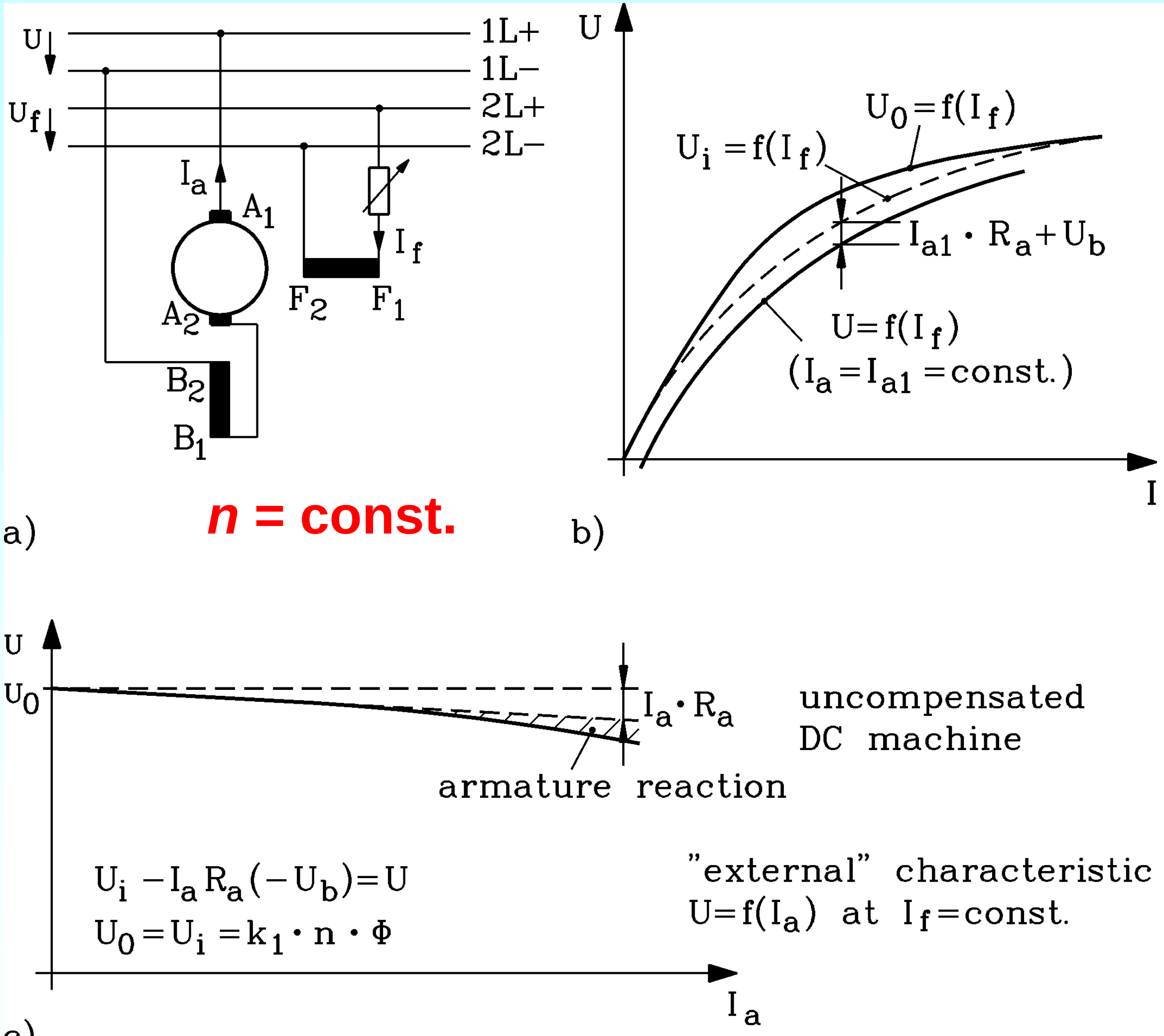
$$u_i(t) = k_2 \Omega_m(t) \Phi(t), \quad \Phi(t) = \Phi(i_f(t))$$

$$u_f(t) = i_f(t) \cdot R_f + L_f \cdot di_f(t)/dt$$

$$M_e(t) = k_2 \Phi(t) i_a(t)$$

$$J \cdot d\Omega_m(t)/dt = M_e(t) - M_s(t)$$

Separately excited dc generator



a) Machine operated with ***n* = const.,** field winding F1-F2 supplied by a **separate** dc voltage source U_f.

b1) **Open-circuit characteristic:** no-load voltage U_0 (= induced voltage) measured at varied field current I_f (I_f changed by a **field regulating resistor**):

$$U_0 = k_1 \cdot n \cdot \Phi(I_f)$$

b2) **Internal characteristic:** in case of un-compensated machine the flux is **reduced due to saturation** by the value $\Delta\Phi$ caused by increasing armature current :

$$U_i = k_1 \cdot n \cdot \Phi(I_f, I_a) < U_0$$

b3) **Load characteristic:** armature voltage

$$U(I_a) = U_i - I_a R_a - U_b$$

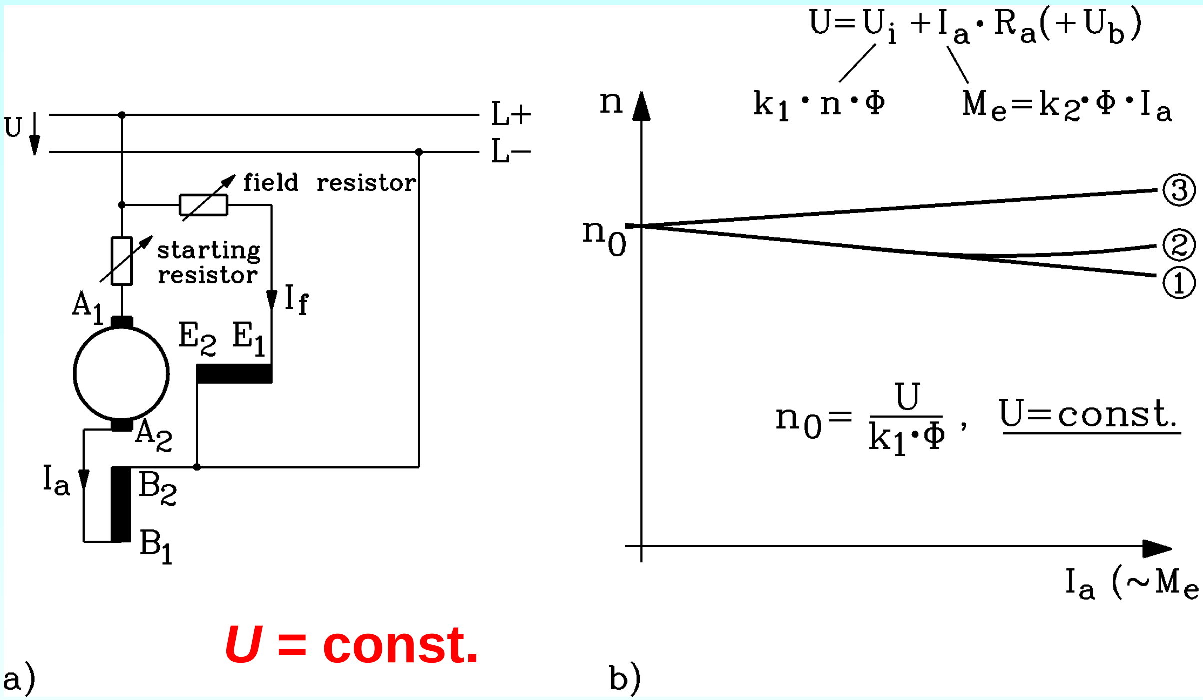
depending on I_f at I_a = const.

c) **External characteristic:** armature voltage

$$U(I_f) = U_i(I_f) - I_a R_a - U_b$$

depending on I_a at I_f = const.

Shunt wound-/separately excited dc motor



a) machine supplied with ***U* = const.**, field current I_f is **adjustable.**
terminals: E1-E2: shunt wound operation
terminals: F1-F2: separate U_f-source

b) motor characteristic *n(M)*: From

$$U=U_i+I_aR_a(+U_b),\ U_i=k_1n\Phi$$

we get: $$n=\frac{U_i}{k_1\Phi}=\frac{U-I_aR_a}{k_1\Phi}$$

$$\boxed{n=n_0-\frac{M_eR_a}{k_1k_2\Phi^2}}$$

- **no load**: motor is only loaded by its small loss torque M_d (friction, iron losses):

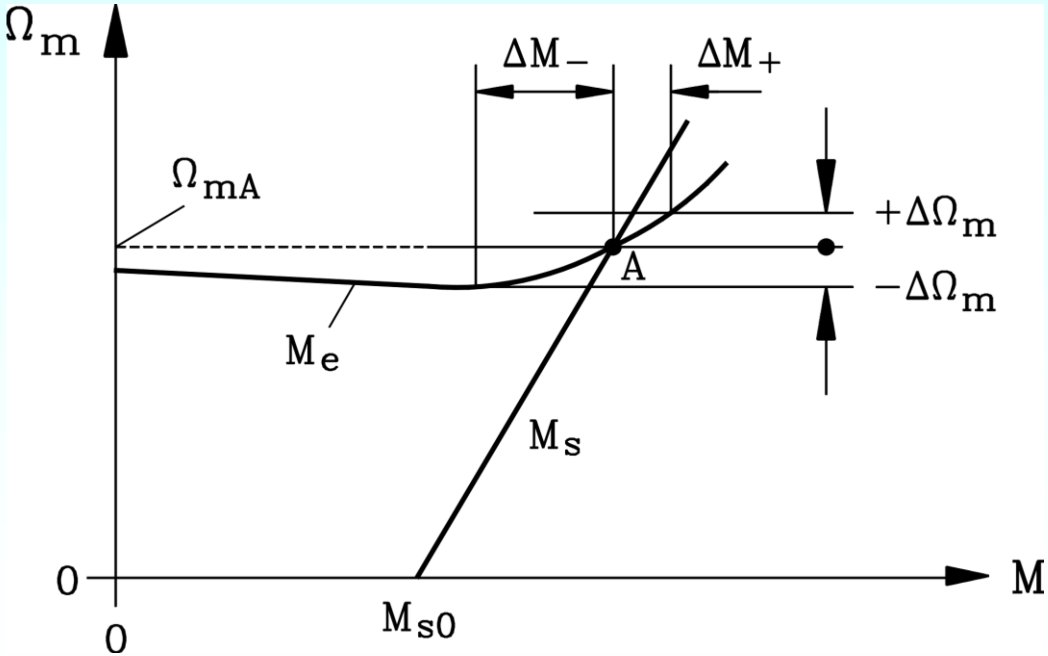
$M_e=M_d\cong 0$. **No load speed** n_0: $\boxed{n_0=U/(k_1\Phi(I_f))}$

Result: *Separately excited and shunt-wound motors have a decreasing speed-torque-characteristic with a small slope, as the armature voltage drop is small compared to the armature terminal voltage.*
(Fig b) curve 1: compensated machine).

Instability of shunt-wound/separately excited dc motors

- In **uncompensated** machines, operated with currents above roughly rated current, the main flux Φ drops to $\Phi' = \Phi - \Delta\Phi$ with increasing armature current due to additional saturation caused by armature reaction.
- With big currents I_a **(= big flux loss $\Delta\Phi$)** speed increases again, because the first addend in the speed equation increases faster than the second one decreases.

$$\Omega_m = \frac{U}{k_2 \cdot (\Phi - \Delta\Phi(I_a))} - \frac{R_a \cdot M}{k_2^2 \cdot (\Phi - \Delta\Phi(I_a))^2}$$

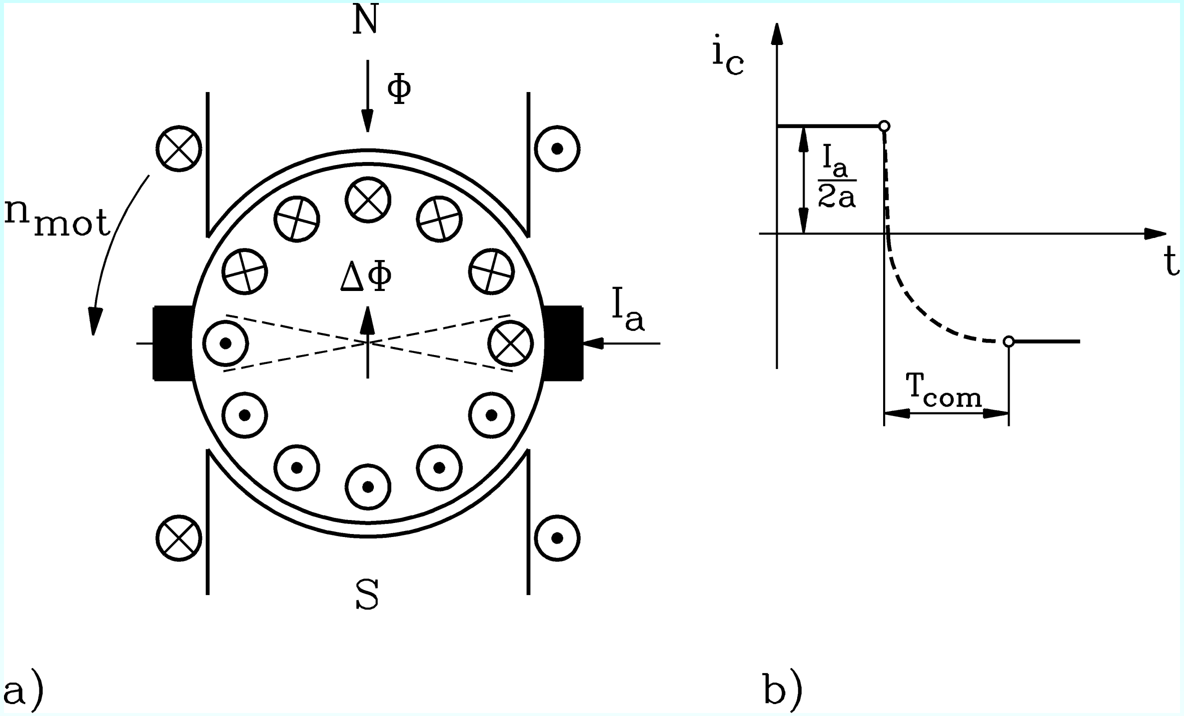


- **Stability criterion** (derivation see IM):

$$\frac{dM_e}{d\Omega_m} - \frac{dM_s}{d\Omega_m} < 0 \quad \Rightarrow \quad stable$$

Example: UNSTABLE: **Increase of speed with increasing load:** machine **"overspeeds"**, without any braking it accelerates to very high speed up to self-destruction.
Counter-measure: compensation winding or speed control !

Instability of over-commutated motors



a) Over-commutation: Commutating coil has already reversed ampere-turns. It excites a coil flux $\Delta\Phi$ which reduces the main flux Φ .

b) Over-commutation: Current reversal too quick, caused by a too strong commutation field !

- **Over-commutating causes a** coil flux $\Delta\Phi \sim I_a$, which opposes and thus **reduces** the main flux Φ.

- $\Delta\Phi \sim I_a$ occurs already at small currents !
- Speed characteristic has a positive inclination already at no-load speed. This may lead to **instability !**

$$\Omega_m = \frac{U}{k_2 \cdot (\Phi - \Delta\Phi(I_a))} - \frac{R_a \cdot M}{k_2^2 \cdot (\Phi - \Delta\Phi(I_a))^2}$$

Counter-measure: Reduction of the commutation field by adjusting the inter-poles !

Starting resistor in armature circuit to start a dc machine

- **Motor at standstill:** *n* = 0: induced voltage is zero:

$$U = U_i + I_a R_a = 0 + I_a R_a \quad \Rightarrow \quad \underline{\underline{I_a = U / R_a}}$$

Armature resistance is very small (except for small motors) : armature current at stand still **VERY BIG**: motor winding would **burn !**

- **Counter-measures: Current limiting starting resistor** in the armature circuit: offers the opportunity to start the motor with rated current.

$$(R_{starter} + R_a) \cdot I_N = U \quad \Rightarrow \quad R_{starter} = \frac{U}{I_N} - R_a$$

After the start-up the induced voltage limits the current; the starting resistor is then short-circuited to avoid unnecessary resistive losses.

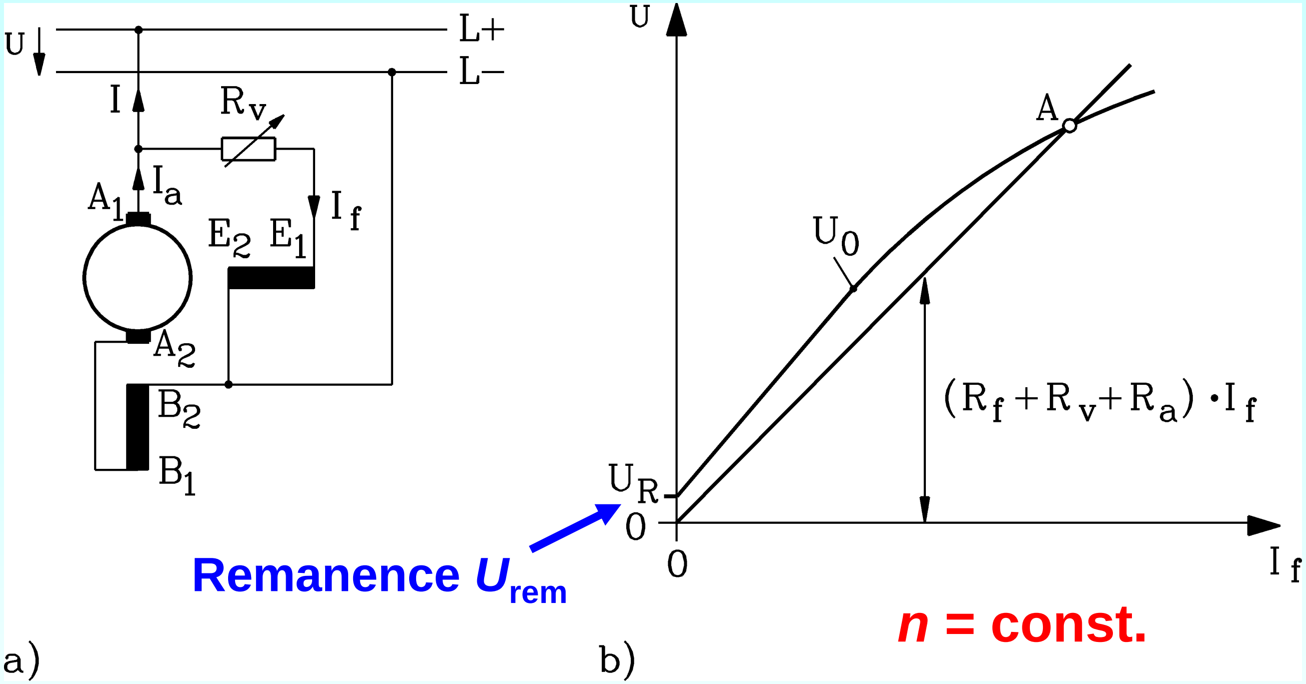
- ***Example***: DC motor: U_N = 430 V, P_N = 200 kW, η = 92% (without excitation losses), R_a = 37.9 mΩ

rated current: $I_N = P_N / (\eta \cdot U_N) = \underline{\underline{506}}\ \mathrm{A}$

Starting without starting resistor: $I_a = U_N / R_a = 430 / 0.0379 = \underline{\underline{11350}}\ \mathrm{A} = \underline{\underline{22.4}} \cdot I_N$

Required starting resistor: $R_{starter} = U_N / I_N - R_a = 430 / 506 - 0.0379 = \underline{\underline{0.8}}\ \Omega$

Shunt-wound generator (self-excitation)



a) Excitation in parallel (= **shunt-circuit**) to the armature.

b) Driven generator can generate voltage without any auxiliary voltage source.

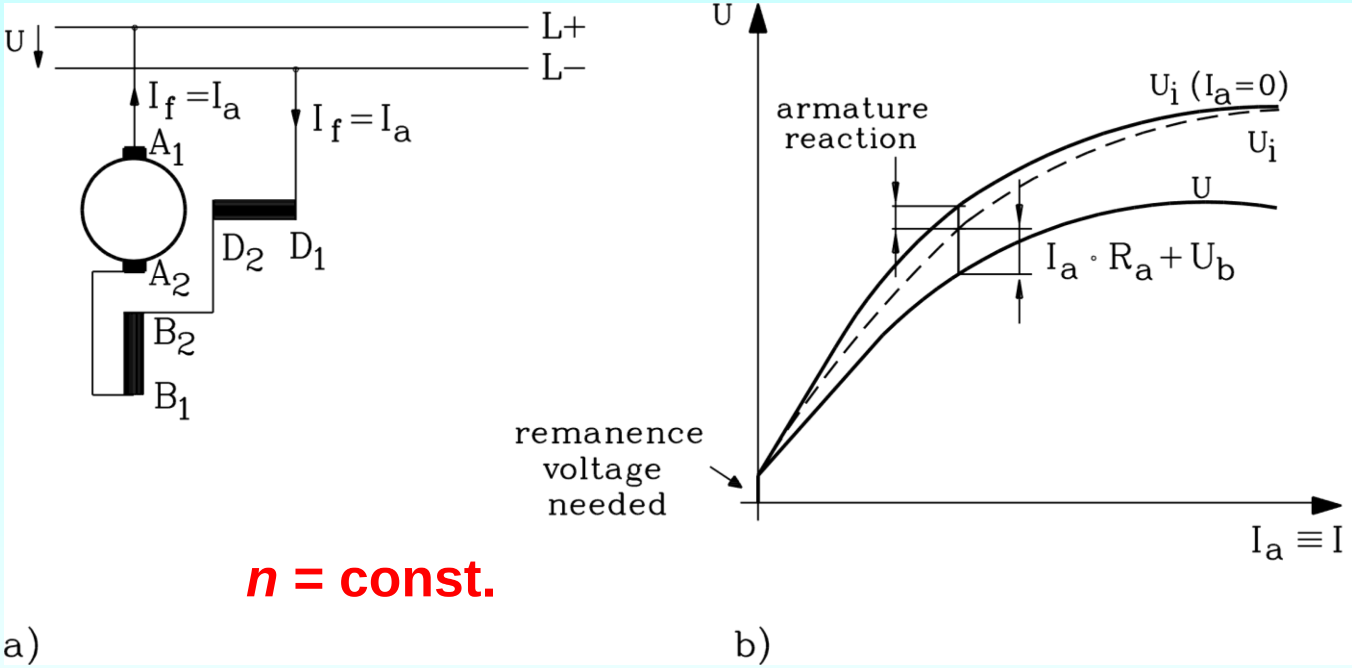
Self-excitation: Remanence flux of the stator poles Φ_R induces a small "**remanence voltage**" into the rotating armature coil.

$$U_{rem} = k_1 \cdot n \cdot \Phi_R$$

- U_{rem} causes a field current $I_f = U_{rem}/(R_a + R_f + R_v)$. The corresponding main flux $\Phi(I_f)$ increases remanence flux. This increases the induced voltage, so field current, which again increases the field … and so on ***= SELF EXCITATION !*** Process stops in operating point A (voltage equilibrium). First published 1866 by ***Werner von SIEMENS*** as **dynamoelectric principle**.

Suicide Control: With exchanged terminals E1, E2 the field current causes a flux that **opposes** the remanence flux instead of supporting it: **NO self-excitation** !

Series-wound generator



a) **Series-**connection of armature and field: $I_a = I_f$

b) **no-load voltage:** $U_i(I_a = 0)$ measurable in case of separate excitation.

Internal characteristic:

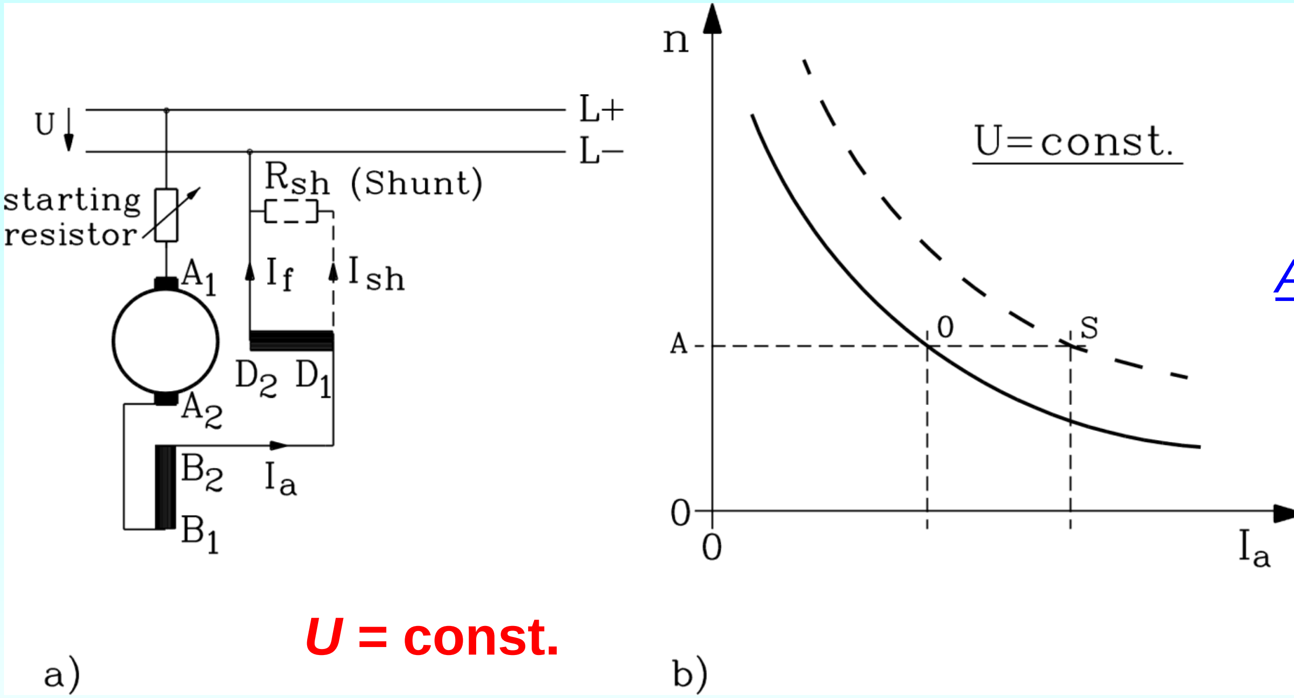
$$U_i(I_a > 0)$$

Load characteristic:

$$U = U_i - I_a R_a - U_b$$

- Remanence voltage U_{rem} is the „initial voltage". The voltage *U* increases only with increasing load (= armature current I_a), as the load current is the field current also.
- Increasing I_a: Linear rise of armature voltage drop $I_a R_a$, due to iron saturation the induced voltage U_i rises less than linear: Terminal voltage *U* **drops again after a maximum.**
- **Application:** Regenerative braking of series-wound machines (e.g. electric trains, electric cars).

Series-wound motor



Field current = armature current

Torque: $M_e = k_2 \Phi(I_a) I_a$

Approximation: saturation = constant:

$\Phi = L' \cdot I_a$, L' = const.,

Torque rises with the **square** of the armature current:

$$M_e = k_2 \cdot L' I_a^2$$

With small armature currents and thus small flux this is valid exactly, because iron saturation occurs at stronger flux only.

- ***n(M)*-characteristic:** $n = \frac{U - I_a R_a}{2\pi k_2 \Phi} = \frac{1}{2\pi k_2 L'}\left(\frac{U}{I_a} - R_a\right) = \frac{U}{2\pi\sqrt{k_2 L'}} \cdot \frac{1}{\sqrt{M_e}} - \frac{R_a}{2\pi k_2 L'}$

The speed of a series-wound motor decreases at constant saturation hyperbolically with the load M_e to the value zero during starting.

Importance of the series-wound motor

- Series-wound motors **must not be operated at no-load**, as at $M_s = 0$ the motor would accelerate to theoretically infinite speed („**overspeeding**“) and would be destroyed.

- The strong decrease of speed with increasing load is called **“soft characteristic” (“series characteristic”)**.

- **Application: DC traction (railway: e.g. Italy 3 kV, DC-grid), electric car (DC battery grid)**

  a) low speed (“starting”): high torque = good acceleration

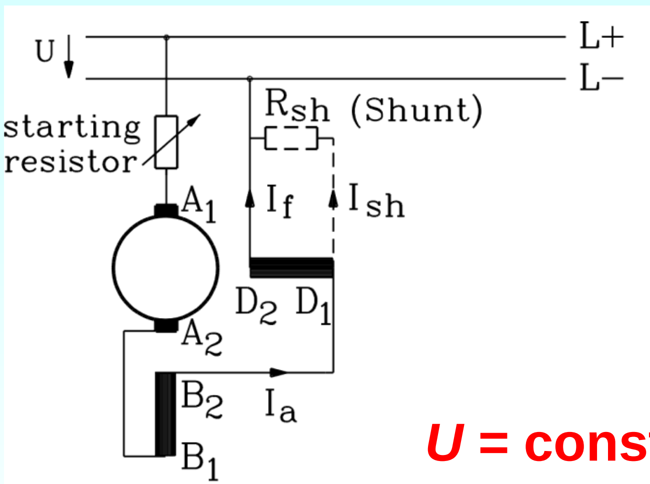
  b) wheel-rail contact (rolling resistance) and aerodynamic resistance **always load the machine**, preventing the machine from over-speeding under normal operating conditions.

- In case of slipping wheels (e.g. wet rails) an **over-speed protection** has to protect the motor.

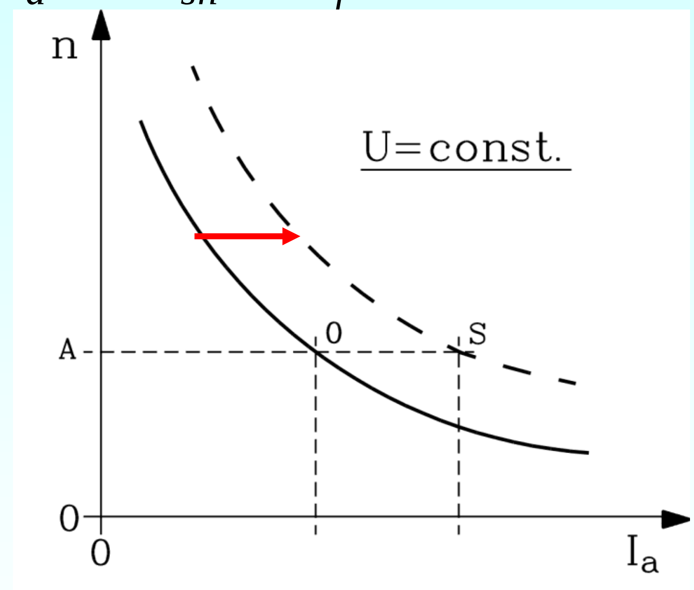
Speed variation of series-wound DC motor

- Resistor R_{sh} in parallel to the field winding (**shunt resistor**)
- Reduction of field current = **reduction of flux = increase of speed.**

$$I_f R_f = I_{sh} R_{sh} = (I_a - I_f) R_{sh} \quad \Rightarrow \quad \frac{I_f}{I_a} = \frac{R_{sh}}{R_{sh} + R_f} = \xi < 1$$



***U* = const.**



- **Operation with single phase ac current:**

- Traction (e.g. Deutsche Bahn, 16.7 Hz)
- domestic appliances: *universal motor:* vacuum cleaner, n_{max} = c.a. 40000/min, hair dryer, drilling machine, ...

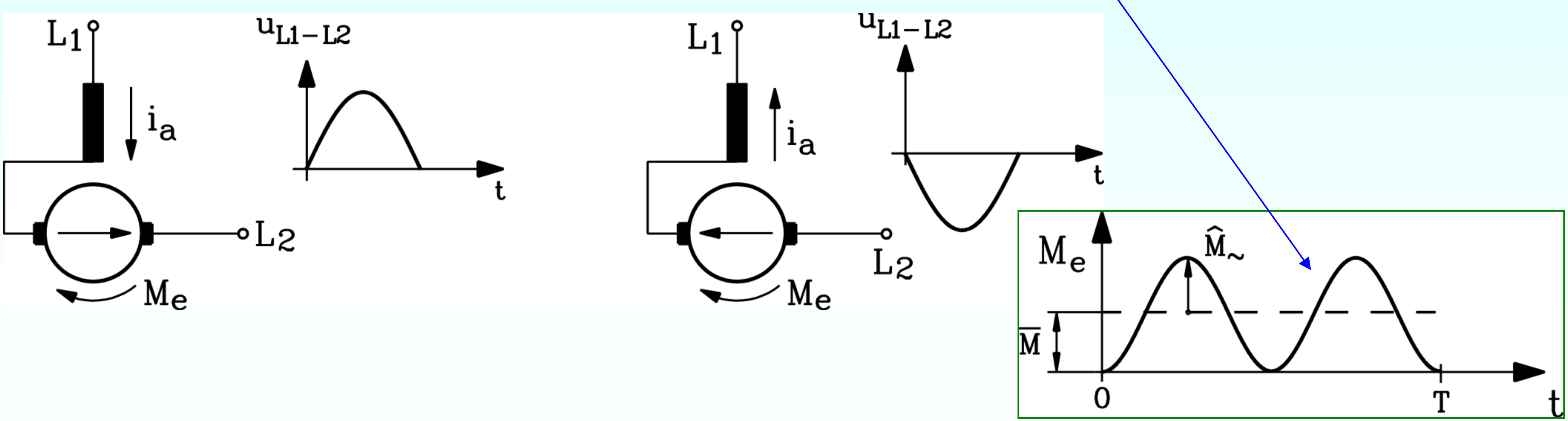
Single phase AC commutator machine

- Excitation and armature winding are SERIES connected, being operated at single phase AC grid (Single phase series-wound motor).

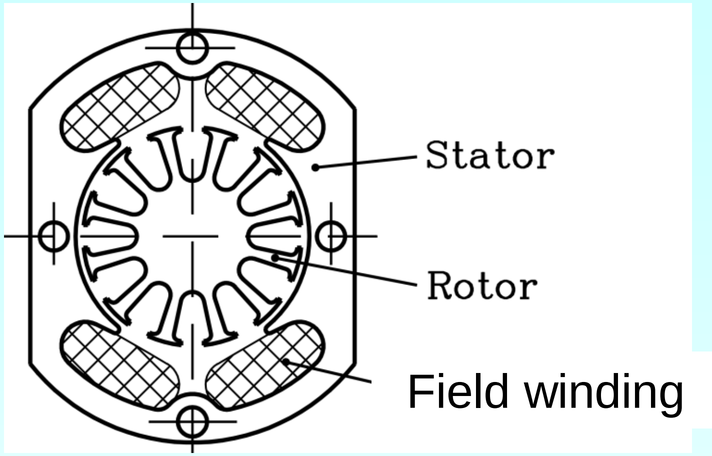
- Field current = armature current i_a = AC current (frequency f). Armature current excites main flux Φ, which pulsates in phase with i_a: Φ and i_a reverse polarity at the same time.

$$M_e \sim \Phi \cdot i_a = (-\Phi) \cdot (-i_a)$$

- Torque has always same polarity, but pulsates with double frequency $2f$.



Universal motor



Source: R. Fischer, hanser-Verlag

- Small two-pole motors for high speed (up to ca. 30 000 /min), low cost for mass production, no inter-poles (low number of operating hours, consumer drives).
- Operation at e.g. 230 V/ 50 Hz: armature current is AC current !

$$i_a(t) = \hat{I}_a \sin(2\pi \cdot f \cdot t)$$

- AC flux and armature current $\Phi \sim i_a$ give pulsating torque at 50 Hz-grid with double frequency 2*f* = 2x50 = 100 Hz !

$$M_e(t) = k_2 \Phi(t) i_a(t) = k_2 \hat{\Phi} \sin(2\pi f t) \cdot \hat{I}_a \sin(2\pi f t)$$

$$M_e(t) = k_2 \frac{\hat{\Phi}}{\sqrt{2}} I_{a,rms} \cdot (1 - \cos(2\pi \cdot 2f \cdot t))$$

$$\overline{M}_e = k_2 \hat{\Phi} I_{a,rms} / \sqrt{2}$$

- Average torque value may only be used for driving.
- Thermal AC power **IS ONLY 70% of DC operation !**

Variable speed DC drive (1)

$$n = \frac{U - I_a R_a}{k_1 \Phi(I_f)} = \frac{U}{k_1 \Phi} - \frac{I_a R_a}{k_1 \Phi} = n_0 - \frac{R_a}{k_1 \Phi} \cdot I_a$$

- **Separately excited dc motor: <u>speed variation</u>** by

  <u>a) Variation of armature voltage *U*:</u> no-load speed n_0 changes, $n(I_a)$-characteristic parallelly shifted, "base speed range": $0 < n < n_N$ corresponds to $0 < U < U_{max} = U_N$ at $\Phi = \Phi_{max}$ = const.

  <u>b) Flux weakening Φ:</u> no-load speed n_0 increases, slope of $n(I_a)$ increases, "field weakening range": $n_N < n < n_{max}$ corresponds to $\Phi_{max} > \Phi > \Phi_{min}$ at $U = U_{max} = U_N$ = const.

  <u>c) Increase of resistance $R+R_a$:</u> no-load speed n_0 constant, slope of $n(I_a)$ increases, e.g. starting with "starting resistor" (otherwise not used, due to additional losses in *R*)

Variable speed DC drive (2)

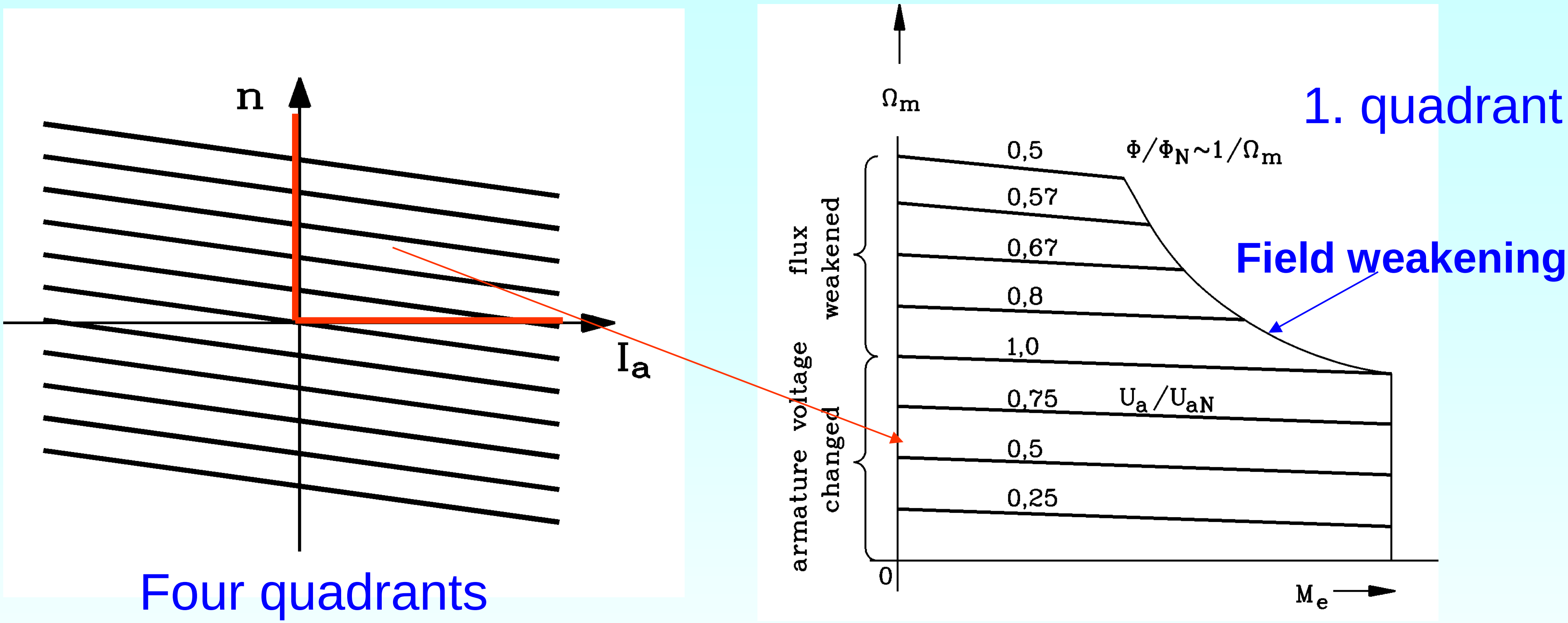
- **speed reversal** by
  (A) polarity reversal of the armature voltage from $+U$ to $-U$ or
  (B) polarity reversal of the flux Φ to $-\Phi$. (A) is quicker than (B), as the armature time constant $T_a = L_a/R_a$ is considerably smaller than the field time constant $T_f = L_f/R_f$.

- **Operational limits** caused by maximum speed n_{max} and maximum armature current $I_{a,max}$!

- **Four-quadrant operation:**

2. quadrant: $n > 0$, $M < 0$: $U > 0$, $I_a < 0$ **GEN.**	1. quadrant: $n > 0$, $M > 0$: $U > 0$, $I_a > 0$ **MOT.**
3. quadrant: $n < 0$, $M < 0$: $U < 0$, $I_a < 0$ **MOT.**	4. quadrant: $n < 0$, $M > 0$: $U < 0$, $I_a > 0$ **GEN.**

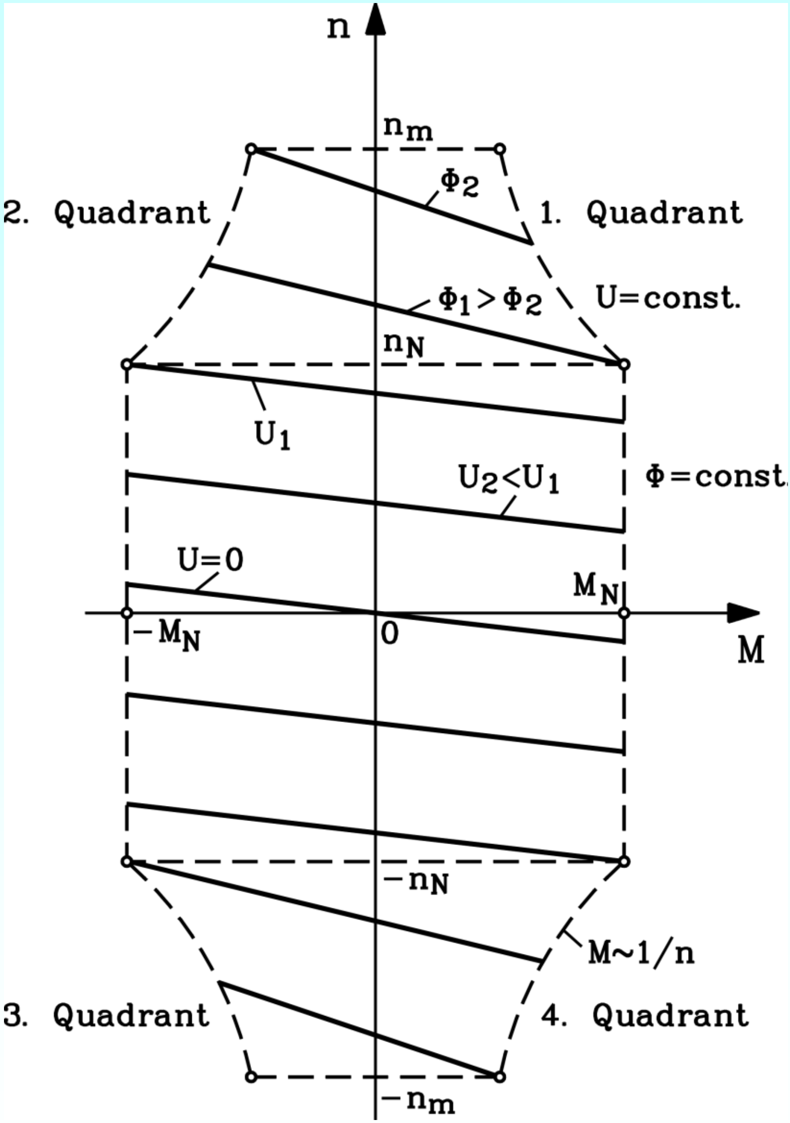
Variable speed DC drive (3)



Changing of armature voltage
U_a : *n(M)*-characteristics are shifted in parallel = speed Variation (constant flux)

If the armature voltage cannot be increased any further, speed can be increased using **field weakening.**
At constant armature current the torque decreases **(field weakening operation).**

Four quadrant operation



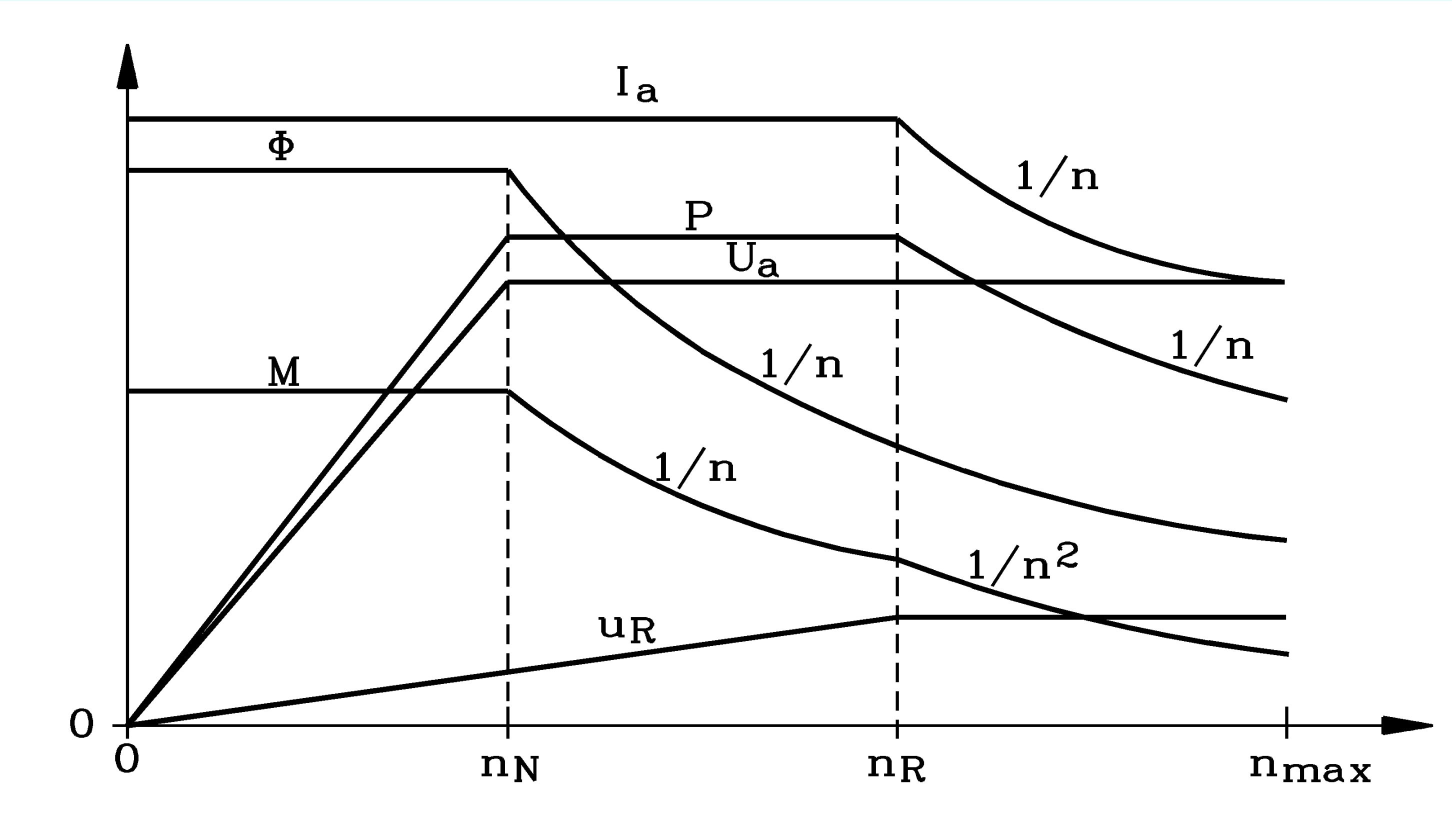
- ***n(M)*-characteristic:**

$$n = \frac{U}{2\pi k_2 \Phi} - \frac{M_e R_a}{2\pi \cdot (k_2 \Phi)^2}$$

- Via converter $U = U_d$ is variable: Speed *n* is changed between $+U_{d,max}$ and $-U_{d,max}$. At $-U_d$ (change of polarity) speed is reversed (speed reversal).

- Maximum speed $n_0 = U_{d,max}/(2\pi k_2 \Phi)$ can be raised, if flux Φ is reduced (flux weakening). Hence torque M_e is decreasing.

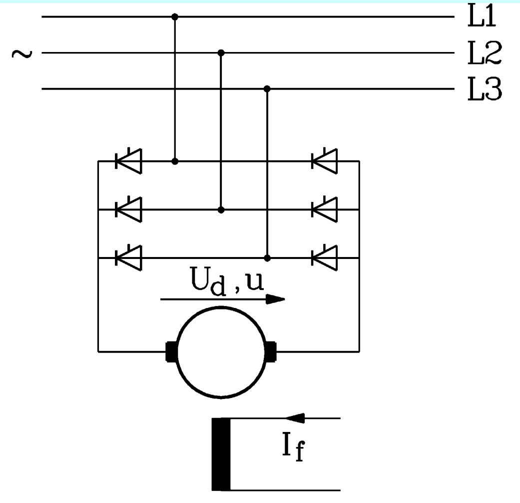
Limiting curves of separately excited DC machine



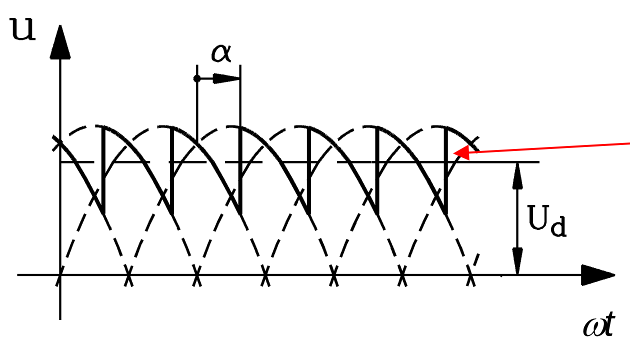
- **Limiting curves** = maximum values of the operating parameters = envelope curves !
- Up to rated speed n_N the armature voltage U_a can be increased.
- For higher speed the flux needs to be weakened.
- Above n_R the maximum armature current must be reduced to limit **„sparking“**. The reactance voltage of commutation is limited.

Thyristor-converter supplied dc machine

- **Generation of a variable armature voltage:** A dc voltage U_d for the dc drive is obtained by rectification of the three-phase grid L1, L2, L3.



Bridge for one current direction !



Controlled three-phase bridge rectifier B6C:

- Armature voltage depends on α.

If current reversal is desired, a second anti-parallel converter is necessary.

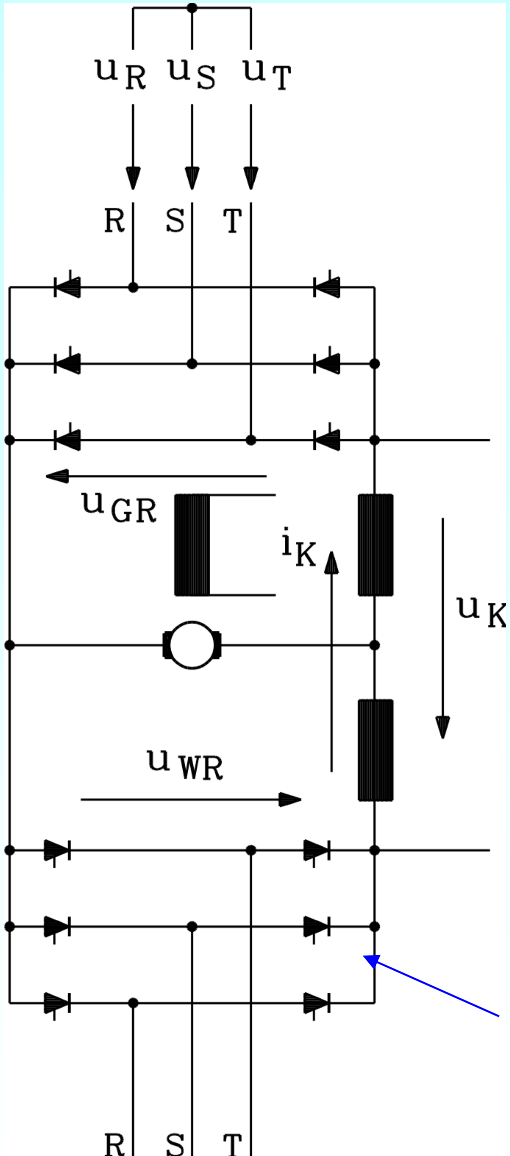
- Thyristors conduct current, if there is a positive voltage between anode A and cathode K AND a firing impulse is supplied at α to Gate G.

If this firing impulse is delayed with respect to the first moment of positive voltage between A and K by the time $\Delta t \sim \alpha$, the rectified voltage decreases **= variation of armature voltage.**

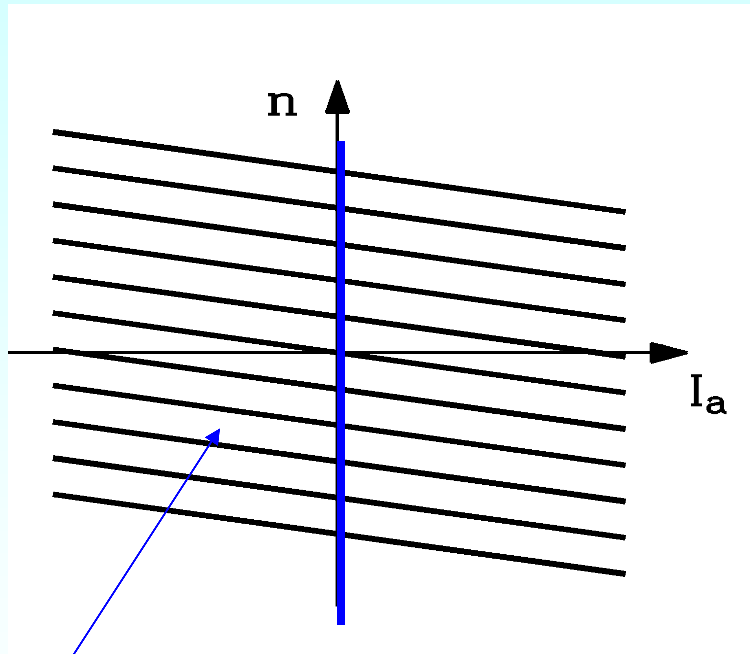
"firing angle" $\alpha = \omega \cdot \Delta t, \quad \omega = 2\pi f_{grid}$ $\qquad U_d = U_{d,\max} \cos\alpha, \quad U_{d,\max} = \sqrt{2} U_{grid} \cdot (3/\pi)$

$\underline{\alpha = 0}$: max. voltage, $\underline{\alpha = 90^\circ}$: voltage is zero, $\underline{\alpha = 180^\circ}$: max. negative voltage

(B6C)A(B6C)- Two anti-parallel thyristor bridges



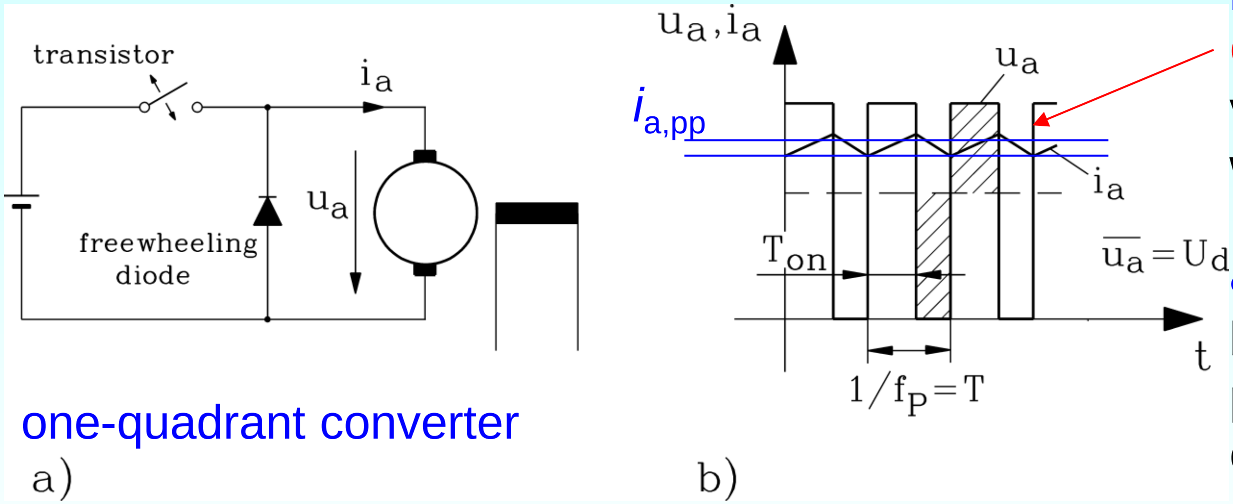
For current reversal a **second,** anti-parallel converter is necessary !



anti-parallel converter

Transistor-chopper supplied dc drive

- **Disadvantage of the thyristor-converter B6C:** dc voltage and current show a ripple with 6 times grid frequency: e.g.: at 50 Hz: $6 \cdot 50 = 300\ \mathrm{Hz}$
- Alternative to B6C-bridge: **DC chopper converter:** From a constant dc voltage (battery, diode rectifier $u_a = U_{batt}$) a variable average dc voltage is generated using **pulse width modulation (PWM)**.



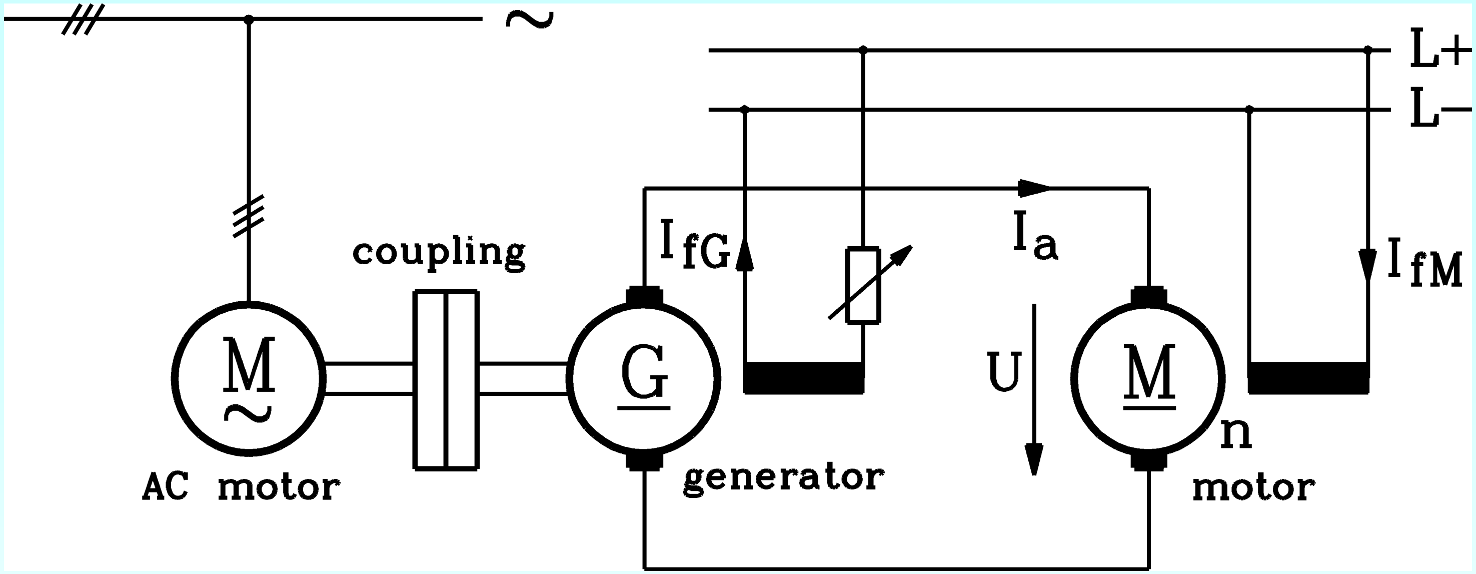
DC chopper:
Chopped armature voltage, average voltage and the armature current with ripple

- **Free-wheeling diode** required, because a current path needs to be provided for the inductive current that cannot be switched off immediately due to the time constant T_a.

- **Current ripple $i_{a,pp}$:** Due to the high switching frequency of the transistors (e.g. f_P = 2 kHz) the current ripple is small:

$$i_{a,pp} = U_{batt} \cdot (1-k) \cdot k / (f_P L), \quad k = U_d / U_{batt} = T_{on} / T$$

WARD-LEONARD-converter



- **Voltage variation for an „ideal" dc voltage** (e.g. test bay) is done with rotating machines: ***WARD-LEONARD*-converter** ! A three-phase induction motor, supplied by the grid, drives a separately excited dc generator (**„control generator"**) at almost constant speed n_{IM}. The field current is supplied by an additional rotating converter or by a battery. This generator supplies **a variable dc voltage *U*** to the dc motor, **which can be changed via I_{fG}**.

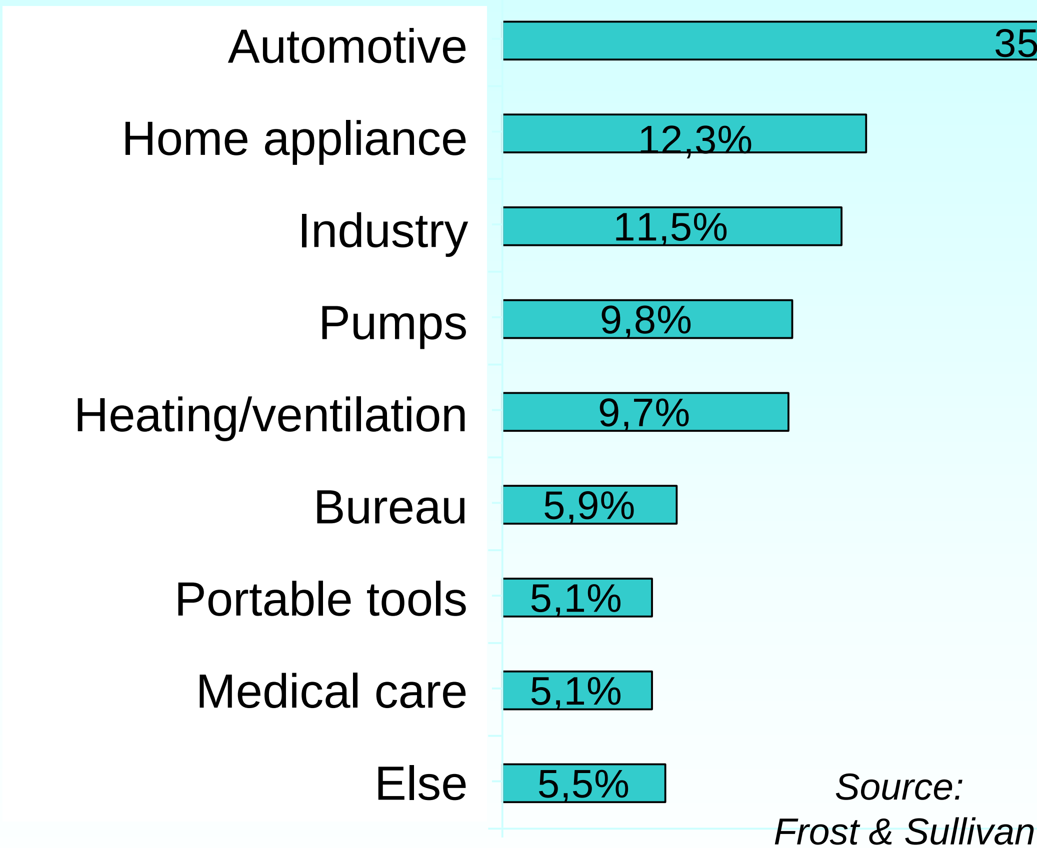
- **Disadvantages** of the *WARD-LEONARD*-converter:
  a) **three times** rated machine power needs to be installed (expensive!)
  b) **three times** the losses (e.g. efficiency per machine 90 %: total $0.9^3 = 0.73 = 73$ %)
  c) **poor dynamic**: *U*-change is slow, as the time constant $T_f = L_f / R_f$ of control generator is big.

Small motors

European market: **1999 → 2006**

4,4 Mrd US $ → 5,4 Mrd US $ +3% p.a.

Applications:



Source: Frost & Sullivan

Source: Faulhaber

Operational limits of the dc machine

• **Frame size resp. viable power per machine set ("unit power") is limited by the <u>commutator</u>.**

Source: Fa. Brenner, Bürstadt

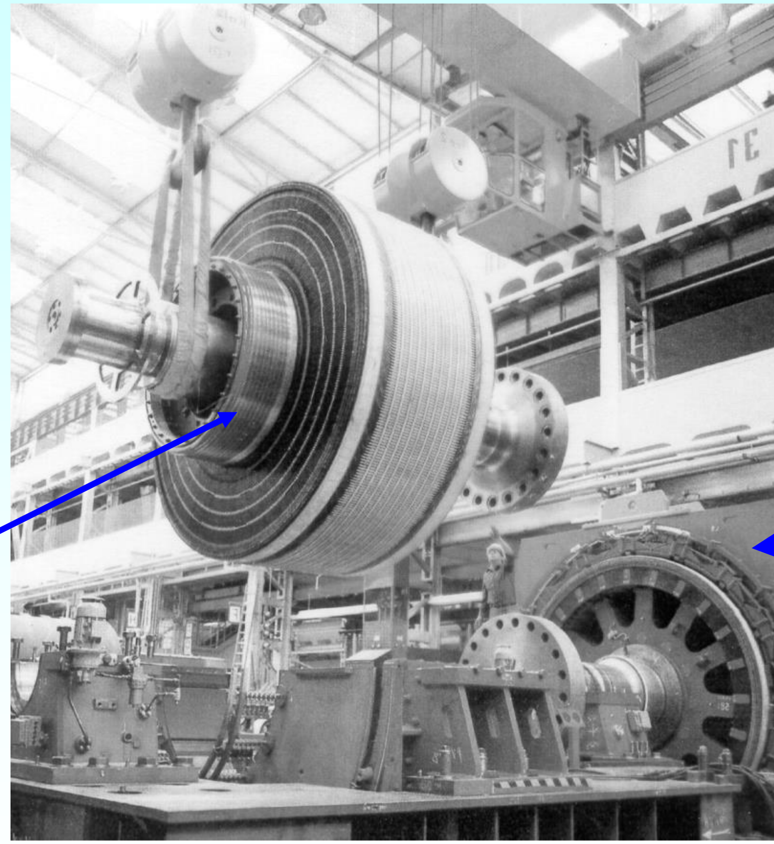
- **centrifugal force limit: prevent commutator deformation, brushes "bounce" !**
- **commutation: reactance voltage u_R < 10 V in steady-state, < 20 V transient, otherwise strong sparking !**
- **brush current density: steady-state J_b < 12 A/cm^2, < 20 A/cm^2 transient, otherwise brush damage**
- **segment voltage limit: average segment voltage $U_{s,av}$ < 20 V, local segment voltage < 35 V, otherwise flashover.**

• *<u>Uncontrolled operation:</u>* Stability limit needs to be considered, as the separately excited motor usually may only be operated in the range of negative slope of the *n(M)*-characteristic.

Large DC machines

- **Biggest DC machines** for strip mills as 1st stage drive units with typically 6 MW ... 12 MW at speed range ca. 100/min. To increase power, two machines are coupled in tandem (**"Tandem"-operation**).

Mounting of a DC rotor of a big DC machine 12 MW



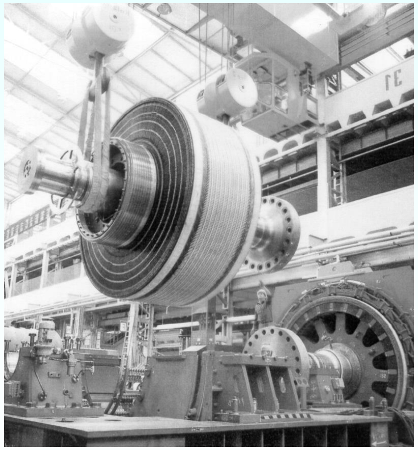
Source: Siemens AG

DC machines - perspectives

- Large DC machines are replaced – due to power limits - by
a) converter-fed synchronous machines (up to ca. 100 MW !)
  and
b) inverter-fed induction machines (up to ca. 40 MW).

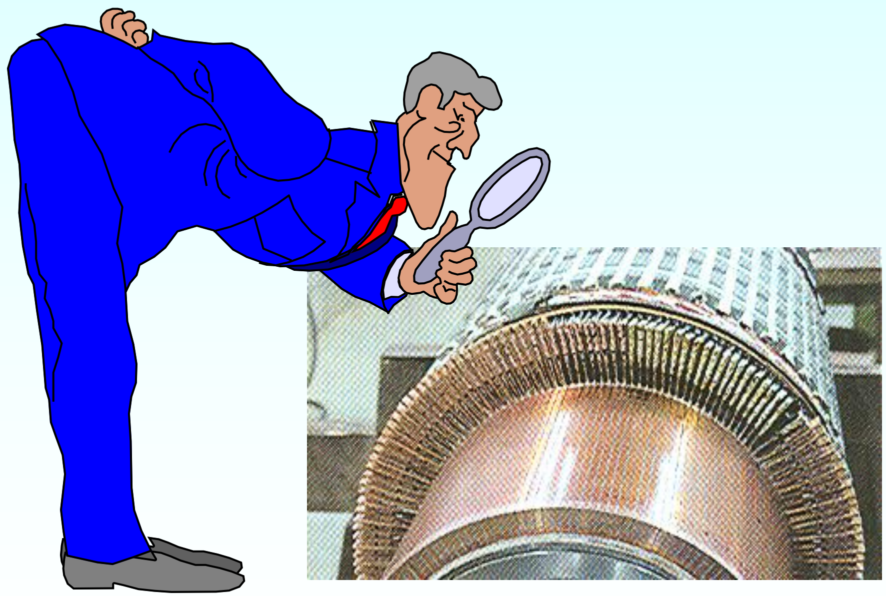
- Also in lower power range the converter-fed DC machine is replaced by the inverter-fed, robust cage induction machine with field-oriented control (due to brush maintenance !).

- Small DC motors:
In automotive application and household appliance still steadily increasing numbers (cars: 12 V / 24 V.)



Source: Siemens AG

That´s all, folks !



Source: Fa. Brenner, Bürstadt