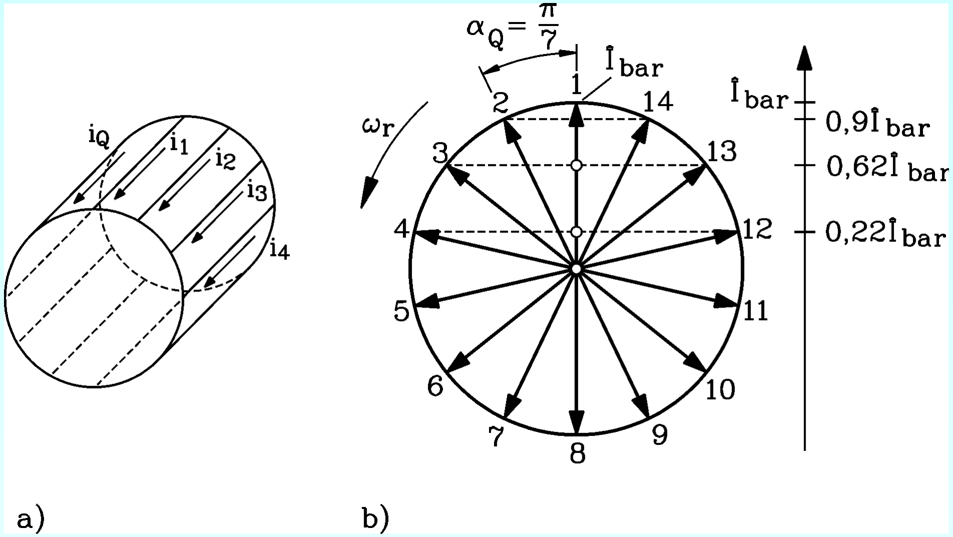
6. Induction machines with cage rotor

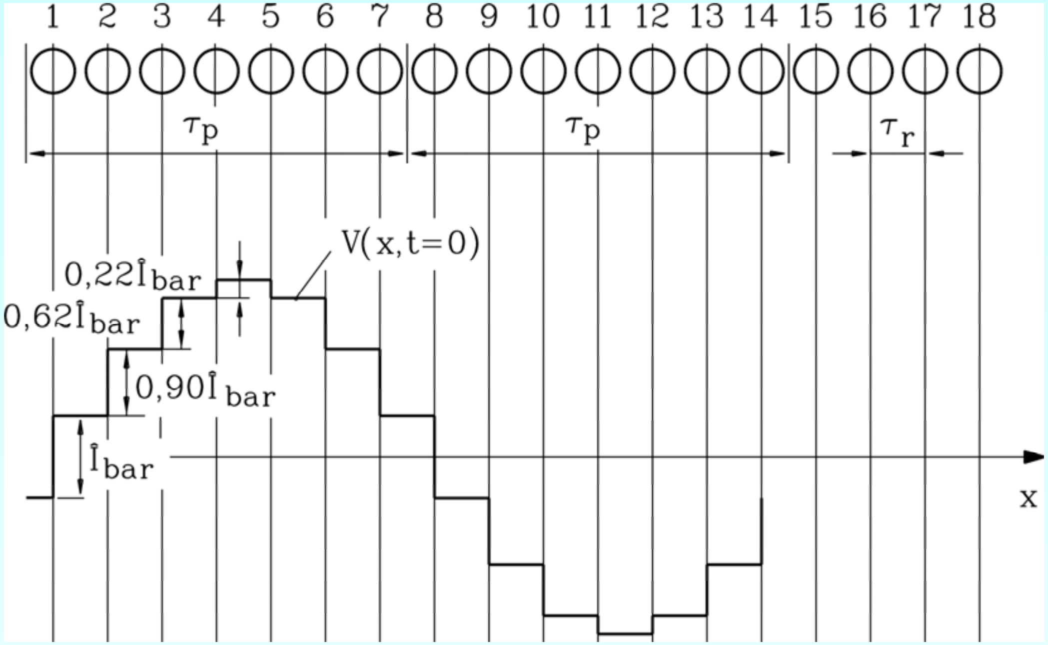
Source:

Breuer Motors,

Germany

Magnetomotive force and air gap field of squirrel cage winding





a) Rotor: Squirrel cage: Q_r *conductive* bars (copper, aluminium) in Q_r slots. Bars are short-circuited by 2 *conductive* rings an the front ends.

b) Symmetrical rotor current system: In each bar flows a **sinusoidal bar current** with a constant phase shift to the current of the adjacent bar**.** Thus each bar **is a phase of a Q_r-phase system.**

Example: Q_r = 28 bars, $2p$ = 4: Bar current system repeats after Q_r/p = 14 bars. Phase shift is **"slot angle"** $\alpha_Q = 2\pi p/Q_r = \pi/7$.

Squirrel cage induction machine

- **Copper squirrel cage**:

  for big power machines > 50 ... 100 kW and for traction machines:

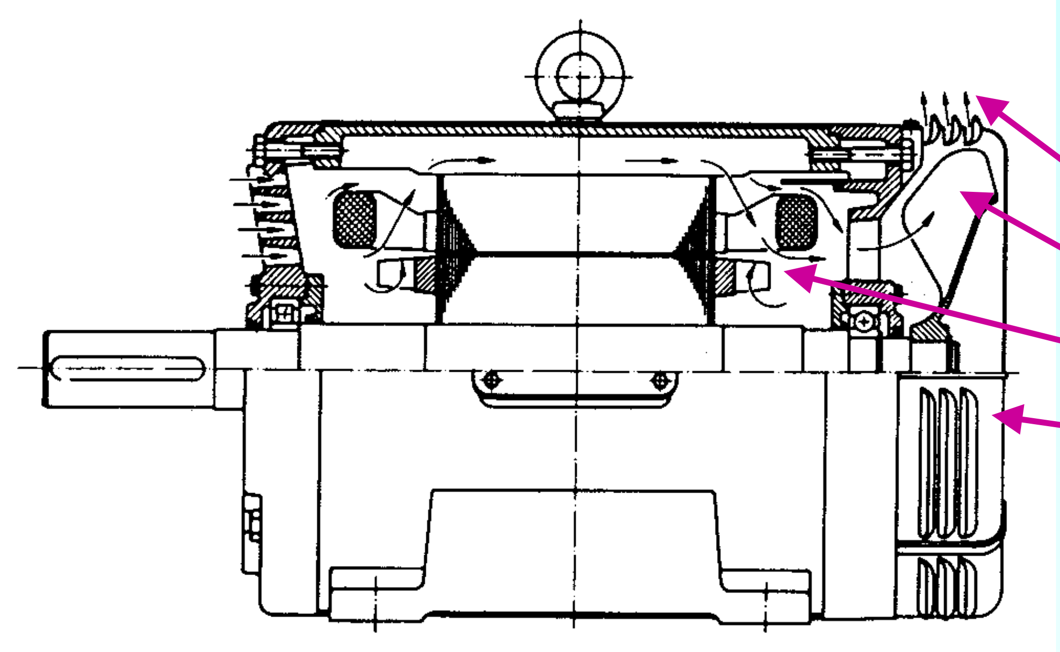
  Massive, non-insulated copper bars in rotor slots. At both front ends short-circuited by two copper end rings by welding. Sometimes copper die cast rotors for smaller machines to increase efficiency.

- **Aluminium copper squirrel cage**:

  Die cast cage for smaller machines < 50 .. 100 kW: The whole cage is cast as one piece with liquid aluminium. Additional fan blades for cooling at the end rings and balancing bolts are cast at the same time.

- **Two adjacent bars** form with the in between ring segments rotor loops, where stator rotating field induces the rotor voltage. This causes rotor bar current & end ring segment current. Rotor bar current together with stator field creates electromagnetic torque.

Aluminium die cast squirrel cage induction machine



Cage induction machine, open ventilated, air cooling

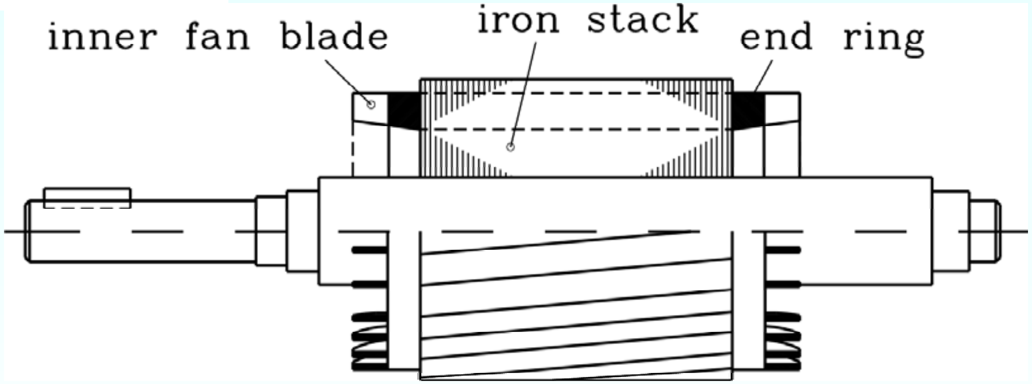
Air flow

Shaft-mounted fan

Cage end ring with fan blades

Fan hood for guidance of air

Aluminium die cast squirrel cage rotor, skewed by one stator slot to reduce losses, caused by slot harmonics



Induced rotor voltage per bar

- **Stator fundamental air gap wave** (amplitude $\hat{B}_{\delta,s}$) moves relatively to the rotor with speed $sv_{syn} = v_{syn} - v_m$. Two rotor bars, distanced by pole pitch τ_p = ” **rotor loop".** Magnetic flux per loop:

$$\Phi = \frac{2}{\pi}\tau_p l\hat{B}_{\delta,s}$$ **Magnetic flux per loop**

- **Induced voltage per loop**, induced with frequency $f_r = s f_s$:

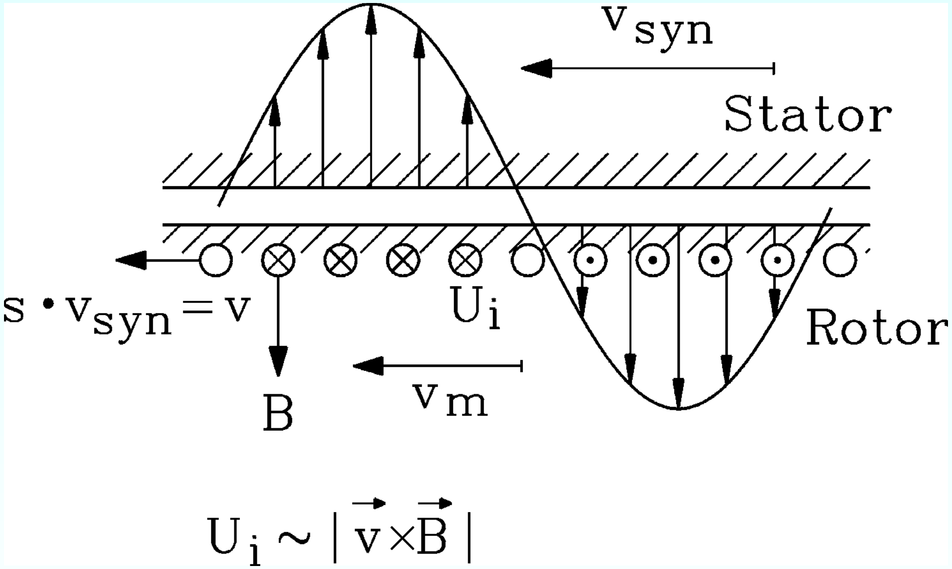
$$\hat{U}_{i,c} = 2\pi \cdot sf_s \cdot \frac{2}{\pi}\tau_p l\hat{B}_{\delta,s} = s\cdot 2(2f_s\tau_p)\cdot l\cdot \hat{B}_{\delta,s} = s\cdot 2v_{syn}\cdot l\cdot \hat{B}_{\delta,s}$$

Per bar = half loop:

half voltage $\hat{U}_{i,bar} = \hat{U}_{i,c}/2$

= **Rotor bar voltage**

$$\boxed{\hat{U}_{i,bar} = sv_{syn}\hat{B}_{\delta,s}l}$$



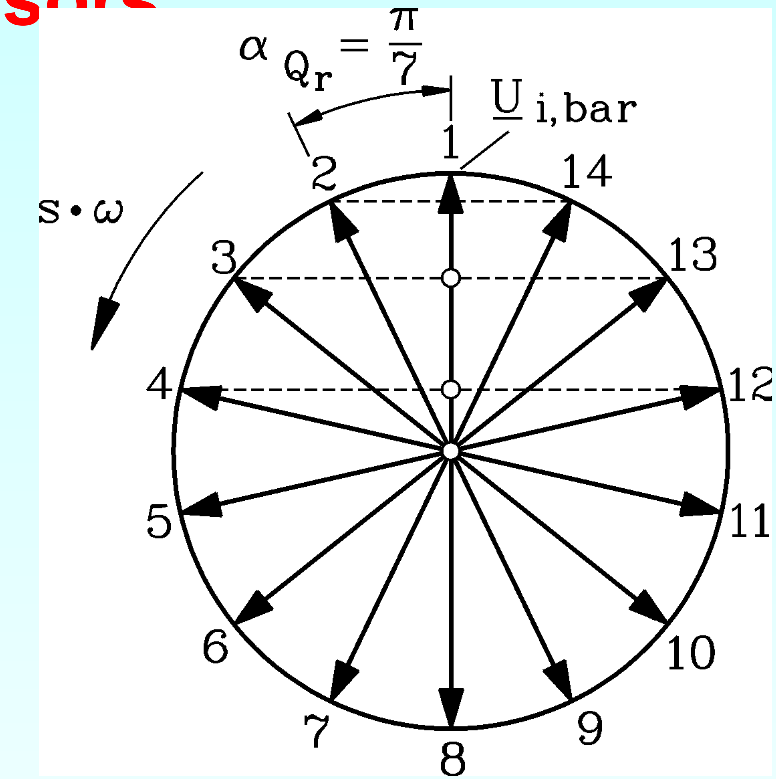
Rotor bar voltages form regular “bundle” of phasors

- Distance between two bars = rotor slot pitch τ_{Qr} . It yields phase shift between adjacent bar voltages =

= **Rotor slot angle** $\alpha_{Qr} = \dfrac{2\pi p}{Q_r}$

- ***Facit:***

Voltage phasors of all rotor bars form on complex plane a regular “bundle” of phasors.



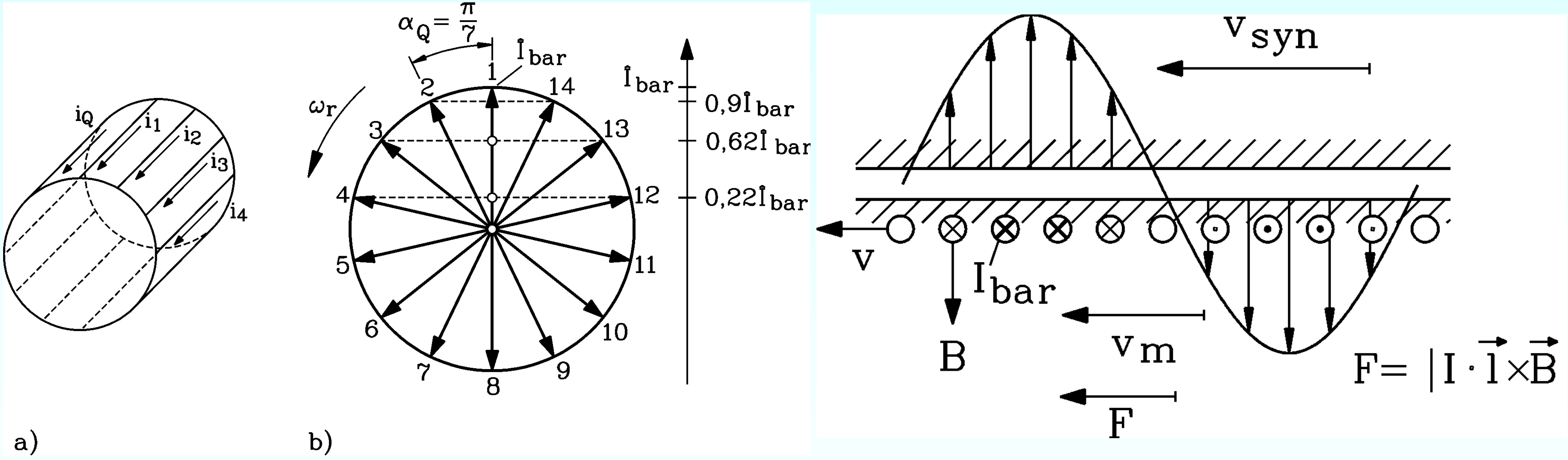
- ***Example:*** **Four pole cage rotor with Q_r/p= 14 bars per pole pair. Two adjacent bar voltage phasors are phase shifted by rotor slot angle** $\alpha_{Qr} = \dfrac{2\pi p}{Q_r} = \dfrac{2\pi \cdot 2}{28} = \pi / 7$
- **After 2 poles phase bundle is repeated: The bar voltages of bar 1 and 15, 2 and 16 etc. are in phase.**

Bar currents, bar forces, torque

- **Rotor bar currents** form **regular current phasor bundle**, which excite a rotor air gap field wave. Only fundamental further considered. Together with stator fundamental field it forms the **resulting air gap magnetic field**.

- The **bar currents** and the stator fundamental air gap field create per bar ***per bar the tangential LORENTZ*-force**: $\boxed{\hat{F}_{bar} = \hat{I}_{bar} l \hat{B}_{\delta,s}}$

All bar forces form with the "lever" $d_r/2$ the electromagnetic torque M_e.



a) b)

c)

Equivalent circuit for cage induction machine

- **Use of transfer ratios $\ddot{u}_U$, $\ddot{u}_I$ in the stator and rotor voltage equations:**

$$\underline{U}_s = j\omega_s \cdot \ddot{u}_I M_{rs} \cdot (\underline{I}_r / \ddot{u}_I) + j\omega_s L_h \underline{I}_s + j\omega_s L_{s\sigma} \underline{I}_s + R_s \underline{I}_s$$

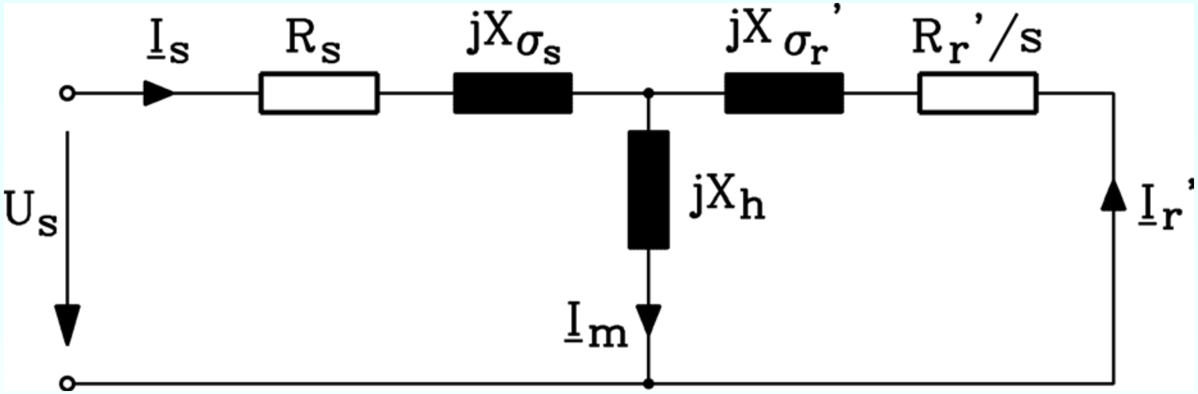
$$j\omega_r \ddot{u}_U M_{sr} \underline{I}_s + j\omega_r \ddot{u}_U \ddot{u}_I L_{r,h} \cdot (\underline{I}_r / \ddot{u}_I) + j\omega_r \ddot{u}_U \ddot{u}_I L_{r\sigma} \cdot (\underline{I}_r / \ddot{u}_I) + \ddot{u}_U \ddot{u}_I R_r \cdot (\underline{I}_r / \ddot{u}_I) = 0$$

- $$\underline{U}_s = j\omega_s L_h \underline{I}'_r + j\omega_s L_h \underline{I}_s + j\omega_s L_{s\sigma} \underline{I}_s + R_s \underline{I}_s$$
  $$0 = js\omega_s L_h \underline{I}_s + js\omega_s L_h \underline{I}'_r + js\omega_s L'_{r\sigma} \underline{I}'_r + R'_r \underline{I}'_r$$

$$\boxed{\underline{U}_s = R_s \underline{I}_s + jX_{s\sigma} \underline{I}_s + jX_h (\underline{I}_s + \underline{I}'_r)}$$

$$\boxed{0 = \frac{R'_r}{s} \underline{I}'_r + jX'_{r\sigma} \underline{I}'_r + jX_h (\underline{I}_s + \underline{I}'_r)}$$

- **T-Equivalent circuit per stator phase:**

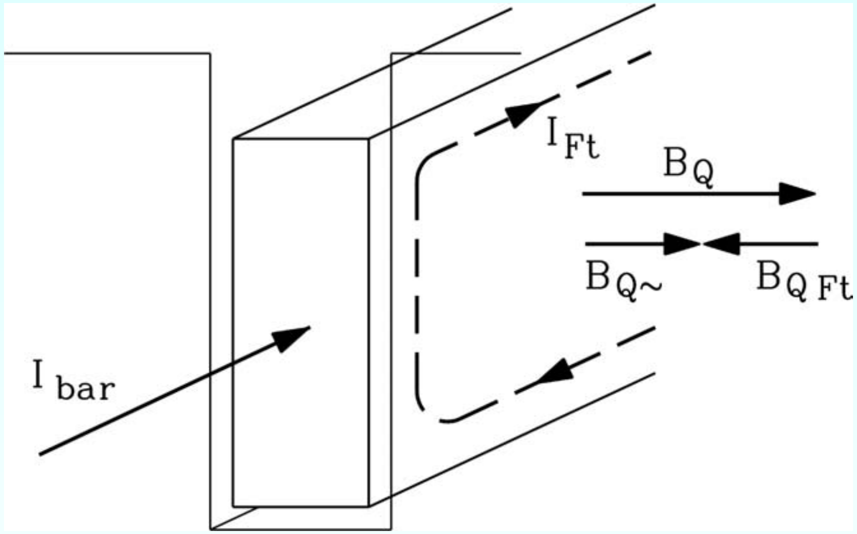


- ***<u>Facit:</u> We get the SAME equivalent circuit as with wound rotor induction machines.***

Current displacement in rotor bars

- **Slot flux density** is pulsating with rotor frequency, penetrating the rotor bar from the side. High rotor bars form a "massive short circuit loop". *FARADAY´ s* law yields: $\boldsymbol{B_Q}$ induces voltage $u_i = -d\Phi/dt$ in bar, which causes **eddy current flow I_{Ft}.** Self field of that eddy current B_{QFt} is directed opposite to $\boldsymbol{B_Q}$ due to *LENZ´ s rule*.

- Hence the **eddy current** I_{Ft} flows in upper bar region IN direction of bar current I_{bar}, and in lower bar region OPPOSITE to bar current.



- ***Facit 1:***

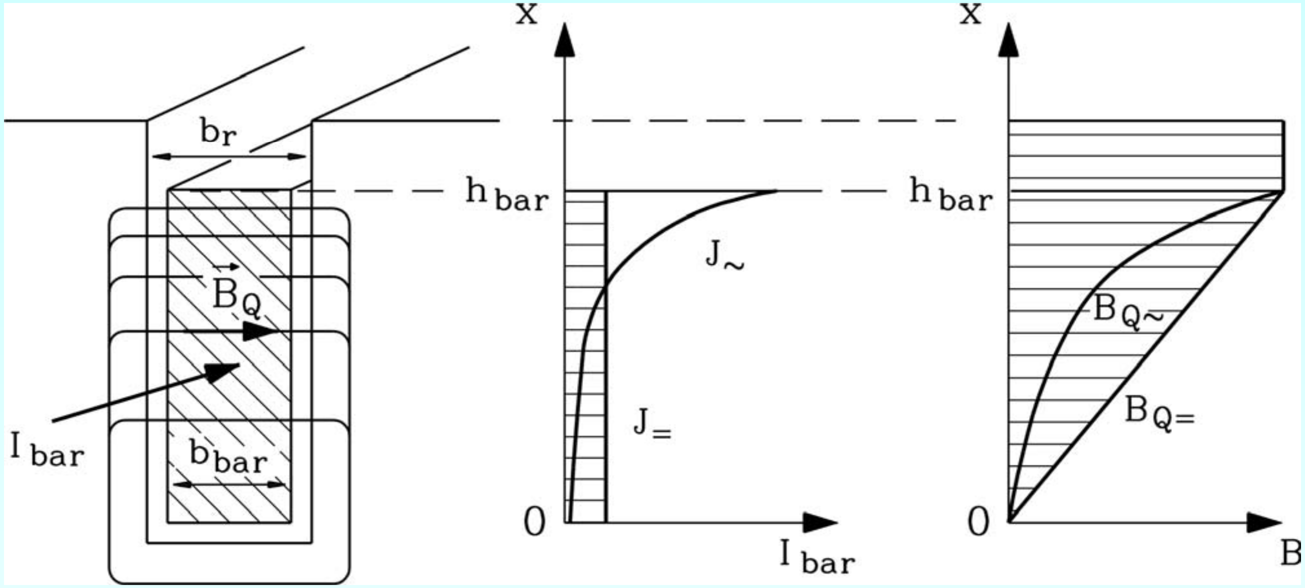
Due to I_{Ft} the resulting bar current density is HIGHER in upper bar region: **Current displacement towards upper bar region ("Skin effect").**

- ***Facit 2:***

The **resulting** slot stray flux density $B_{Q\sim}$ is due to B_{QFt} **reduced.**

- **Current displacement INCREASES** with increasing rotor frequency f_r, with increasing electric bar-conductivity κ, with increasing bar height h_{bar} and with increasing permeability μ of conductor. (***Note:*** Copper and aluminium´ s permeability is $\mu = \mu_0$!)

Effects of rotor current displacement



- **At high rotor frequency (e. g. $s = 1$) major part of bar current flows in upper bar region: so only reduced bar cross section is used for current flow. Thus "AC bar resistance" $R_{bar\sim}$ is higher than "DC bar resistance" $R_{bar=}$.**

- **Due to reduction of slot stray flux density the slot leakage flux is reduced. Hence the "AC bar inductance" $L_{bar\sim}$ is smaller than the "DC bar inductance" $L_{bar=}$.**

$$\boxed{R_{bar\sim} = k_R R_{bar=} > R_{bar=}} \qquad \boxed{L_{\sigma,bar\sim} = k_L L_{\sigma,bar=} < L_{\sigma,bar=}}$$

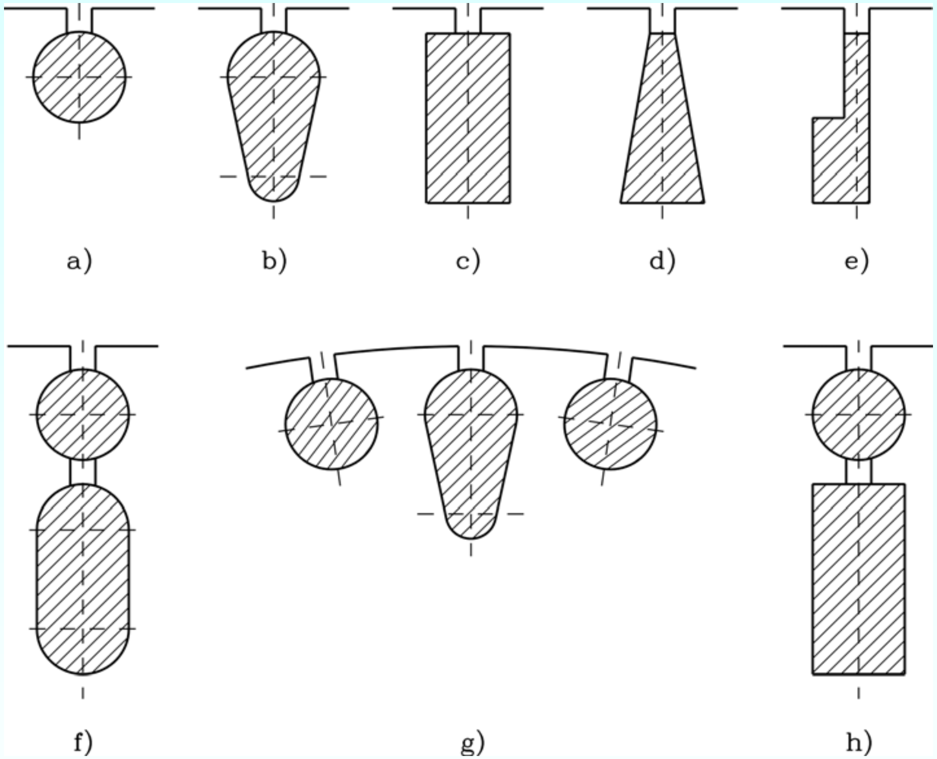
- **At low rotor frequency (e. g. $s = s_N$) <u>nearly NO current displacement occurs !</u>**

Increase of starting torque by current displacement

- **Increase of rotor losses** leads to **increase of starting torque M_1:**

$$M_e(s) = \frac{P_\delta}{\Omega_{syn}} = \frac{P_{Cu,r}/s}{\Omega_{syn}} \quad \Rightarrow \quad M_1 = M_e(s=1) = \frac{P_{Cu,r}}{\Omega_{syn}}$$

- **Special bar cross sections** for small and big starting torque:



SMALL current displacement = M_1 small:

a) Round bar, b) Oval bar,

BIG current displacement = M_1 increased:

c) Deep bar, d) Wedge bar, e) L-bar,

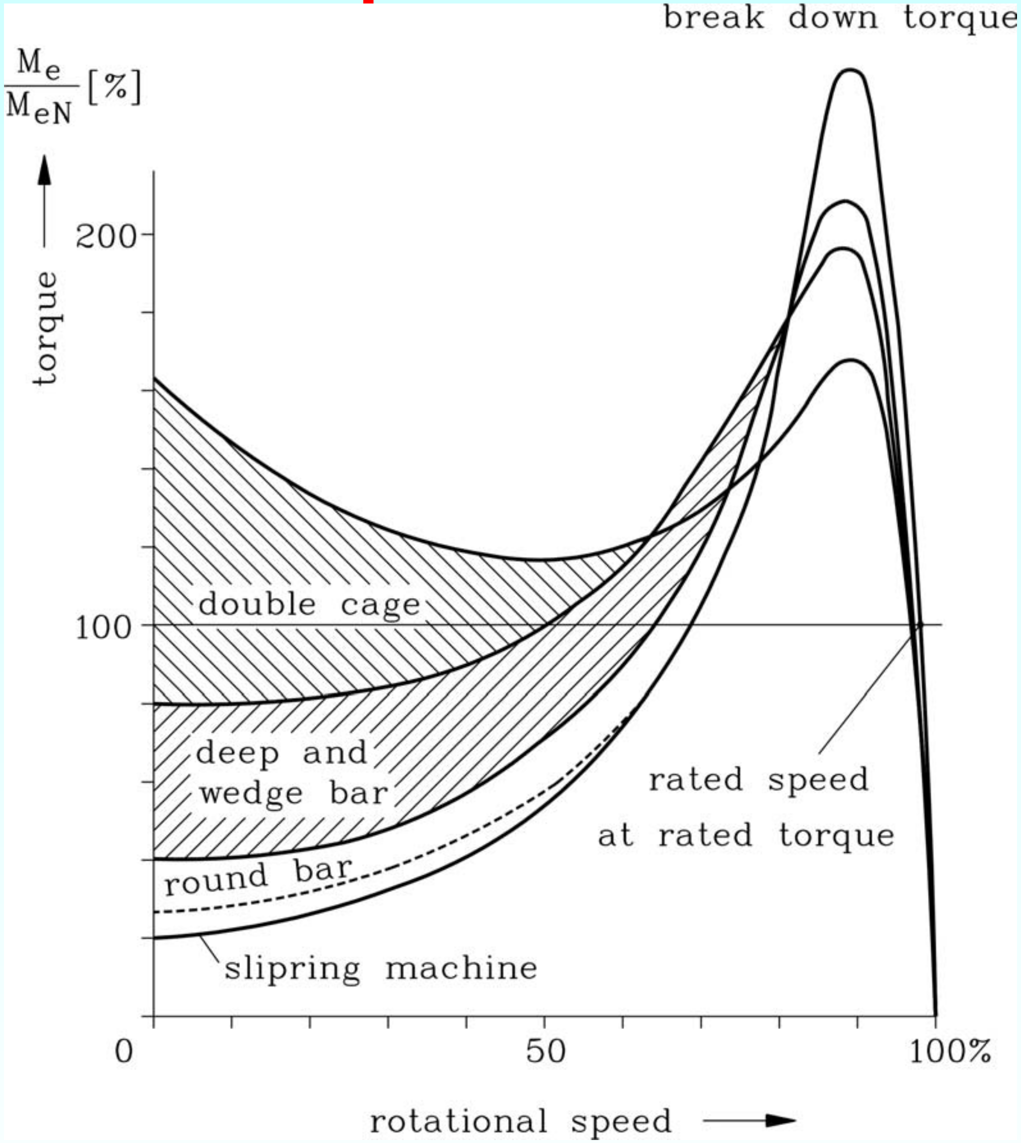
VERY BIG current displacement = M_1 big:

f) and h): **Double bars**, g) alternating bars:

Round upper bronze bars (high resistance) cause – along with current displacement from lower in upper bar – high rotor losses, M_1 is big. Lower bar nearly without current (STARTING OF MOTOR, s = 1).

At rated slip small current displacement: Current flow mainly in lower bar: low losses !

Torque characteristics of induction machines



- *M*(*n*)-characteristics of induction machines with **different rotor bar cross sections**

- In the figure torque is given per unit of rated torque, speed per unit of synchronous speed !

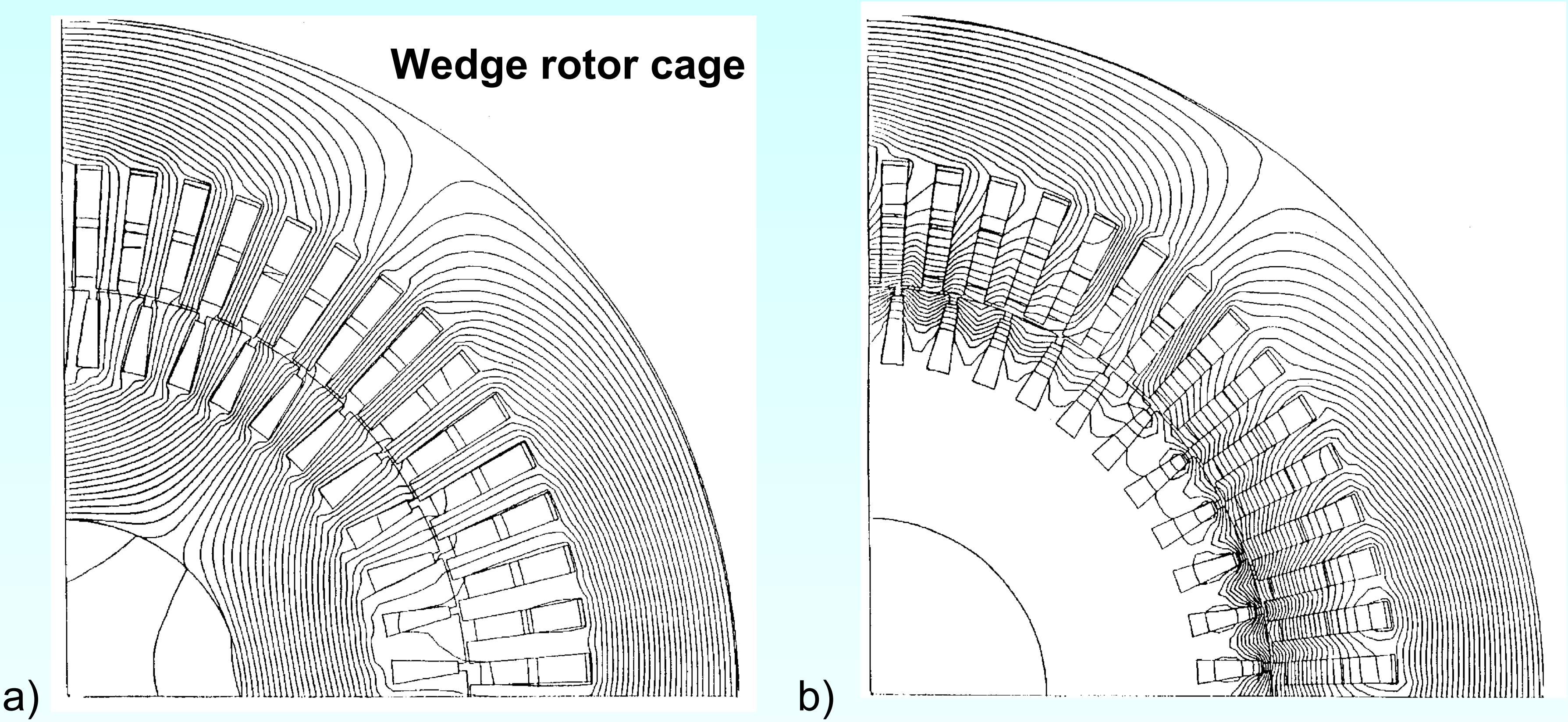
- **Wound rotor with round wire:** Rotor winding consists of many thin wires: no current displacement; similar: **Round bar rotor**

- **Wedge and deep bar rotor:** increased starting torque of about 40% ... 80%M_N; **Double cage rotor:** Starting torque reaches 160% M_N.

- Big current displacement needs deep bars = high dc bar inductance = big leakage coefficient σ. **Hence break down torque decreases.**

$$M_b = \pm \frac{m_s}{2} \frac{p}{\omega_s} U_s^2 \frac{1-\sigma}{\sigma X_s} \downarrow$$

Flux density lines without / with current displacement



a) **No-load:** Rotor frequency zero: Nor rotor current, no current displacement.

b) **Locked rotor** (*s* = 1): Rotor frequency = stator frequency: Big current displacement. Rotor current phase opposite to stator current; flows mainly in upper part of rotor bars, repulses stator field to air gap.

Pole changing cage induction motors

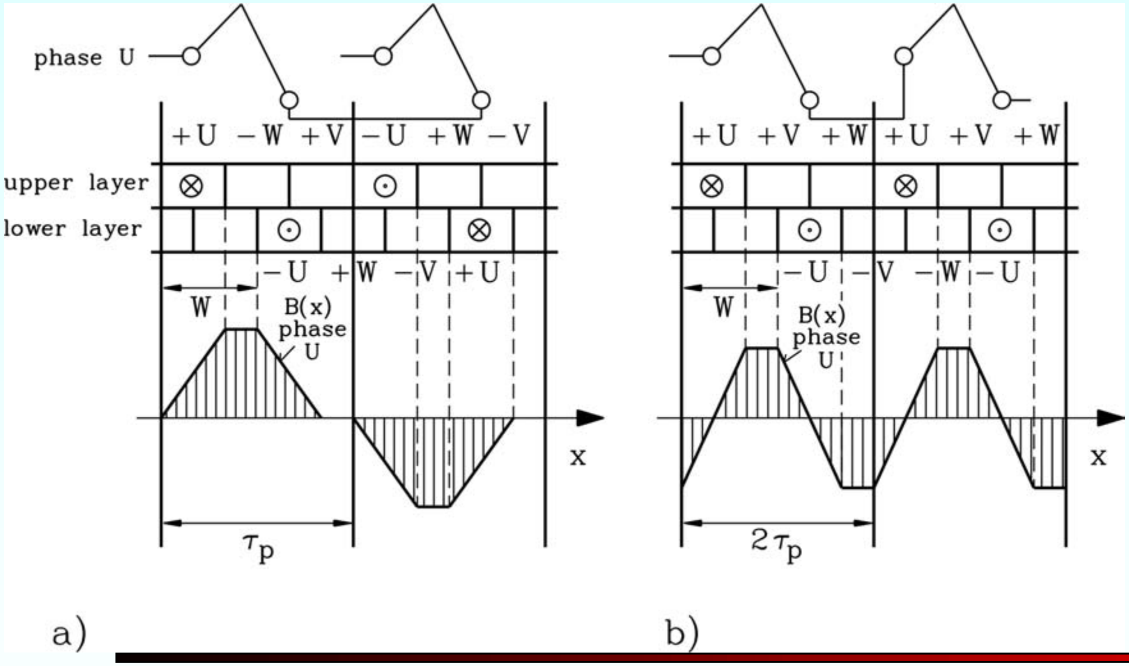
- **Several three-phase windings** with different pole count in stator slots: "step-wise" speed change through different synchronous speeds.

Example: Cage induction machine: 48 Stator slots

- 2-pole winding: $q = 8$, - 4-pole winding: $q = 4$, - 8-pole winding: $q = 2$.

Speed levels at 50 Hz-grid: 3000/min, 1500/min, 750/min.

Per winding system only 1/3 of slot cross section reduces nominal power per speed stage to 1/3. ***Note:*** **Rotor cage fits for each pole count of stator winding automatically !**



- **Special pole changing winding:**

ONE Winding system for 2 different pole numbers:

DAHLANDER-winding: $p_1 : p_2 = 1 : 2$

MMF of phase U depicted ($q \to \infty$)

a) 2-pole operation:

6-phase belt winding, pitching 0.5

b) 4-pole operation:

3-phase belt winding, fully pitched

Example: DAHLANDER-winding for wind generators

- Coarse, stepwise change of speed **in variable speed wind turbine application** often sufficient !

$$\boxed{\dot{V} \sim n}$$

Air flow per second

- **Pole changing wind generator: f_N = 50 Hz**
  (e. g. application on-shore wind turbine)

a) 4-pole operation:

n = 1500/min, $P_{Lü}$ = 800 kW, wind flow rate 100 %

b) 8-pole operation:

n = 750/min, $P_{Lü}$ = 100 kW, wind flow rate 50 %

c) switched off drive:

n = 0, P = 0, no air flow: 0 %

Water-jacket cooled cage induction wind generator

Source:

ELIN EBG Motors, Austria

Water-jacket cooled cage induction generator with pole changing:

690 V, 50 Hz

6/4-pole operation:

1000 / 1500/min

450 kW / 1.5 MW

Two separated windings