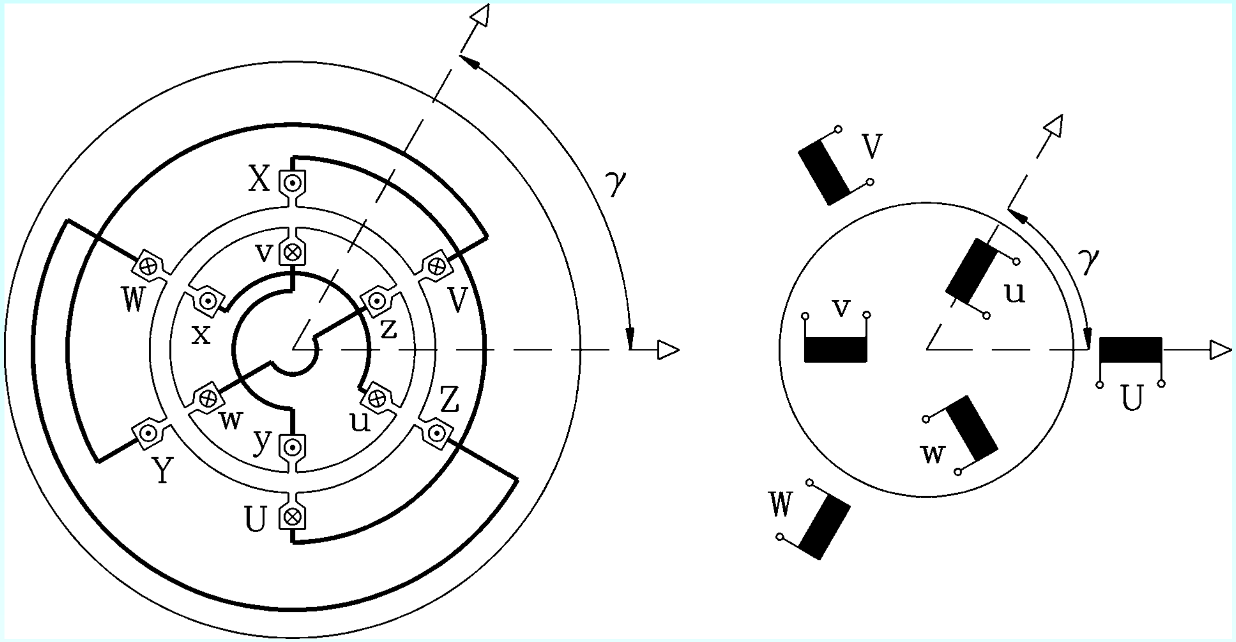
5. Induction machines with wound rotor

Source:

Winergy, Germany

Three phase winding in stator and rotor



- In stator and in rotor each a three-phase winding is arranged:
- in stator: 3 phases between terminals U-X, V-Y, W-Z, subscript *s*,
- in rotor: 3 phases between terminals u-x, v-y, w-z, subscript *r*.

- We assume: **Rotor** is at rest (stand still), and is turned by angle γ with respect to **stator.**

γ = angle between winding axis of stator and rotor winding (= centre of coils).

NOTE: $\gamma = 2\pi$, if rotor is shifted to stator by 2 poles: $2\tau_p$.

- Pole numbers of stator and rotor winding must be identical $2p$!

Mutual inductance between stator and rotor phase

	Stator	Rotor
Pole count	$2p$	$2p$
Phase count	m_s	m_r
Turns/Phase	N_s	N_r
Pitching	W_s/τ_p	W_r/τ_p
Coils/group	q_s	q_r
Slot count	Q_s	Q_r

From now on only fundamental field waves considered !

- **Mutual inductance:** e. g.: Stator air gap wave $B_\delta(x,t)$ induces voltage in rotor winding:

$B_\delta(x,t) = \hat{B}_\delta \cdot \cos(\frac{\pi x}{\tau_p} - \omega_s t)$ with amplitudes $\hat{B}_\delta = \frac{\mu_0}{\delta}\frac{\sqrt{2}}{\pi}\frac{m_s}{p} N_s k_{ws} I_s$

- Amplitudes of induced voltages in rotor winding:

$U_{i,r} = \sqrt{2}\pi f_s \cdot N_r \cdot k_{wr} \cdot \frac{2}{\pi}\tau_p l \hat{B}_\delta$ Rotor frequency f_r (at **locked** rotor = stand still): $f_r = f_s$.

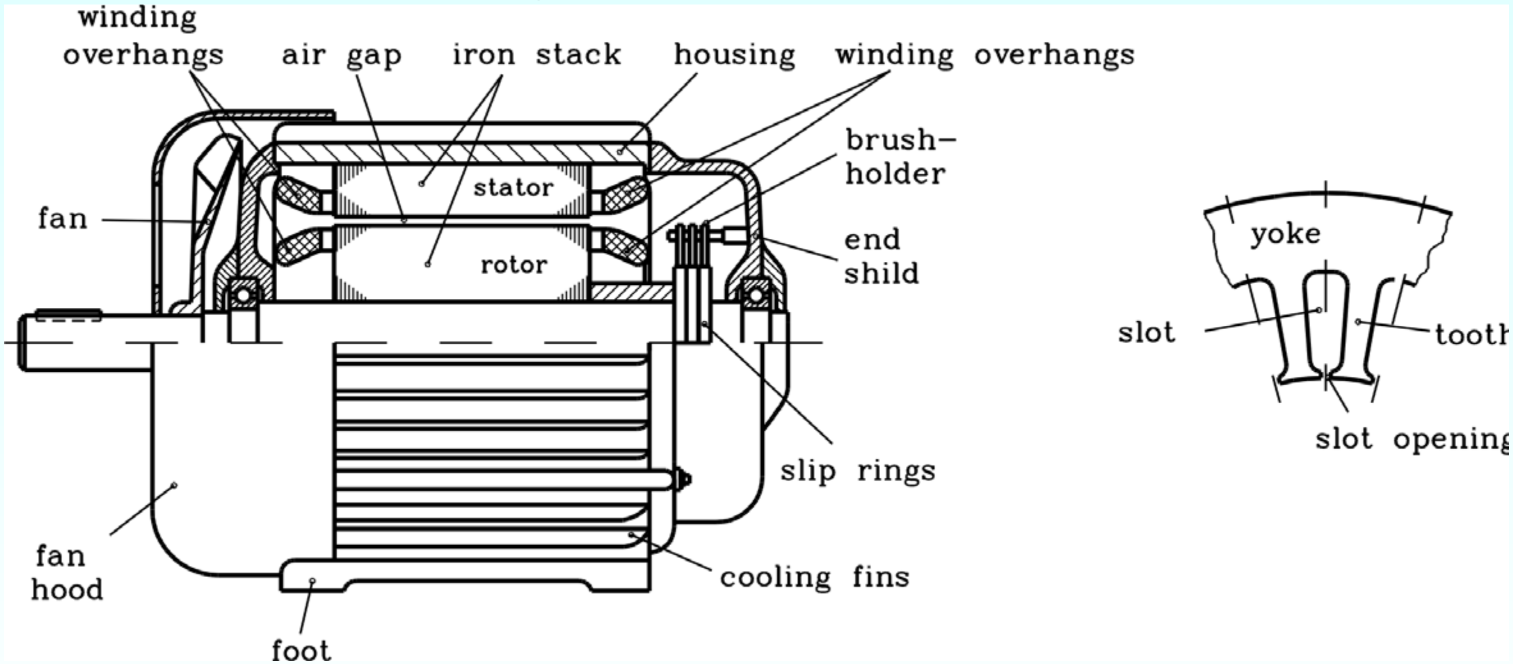
- *Fundamental* wave: **Mutual inductance per phase M_{sr} :** $U_{i,r} = \omega_s M_{sr} I_s$

$$\boxed{M_{sr} = \mu_0 N_s k_{w,s} N_r k_{w,r} \frac{2m_s}{\pi^2}\frac{1}{p}\frac{\tau_p l}{\delta}}$$

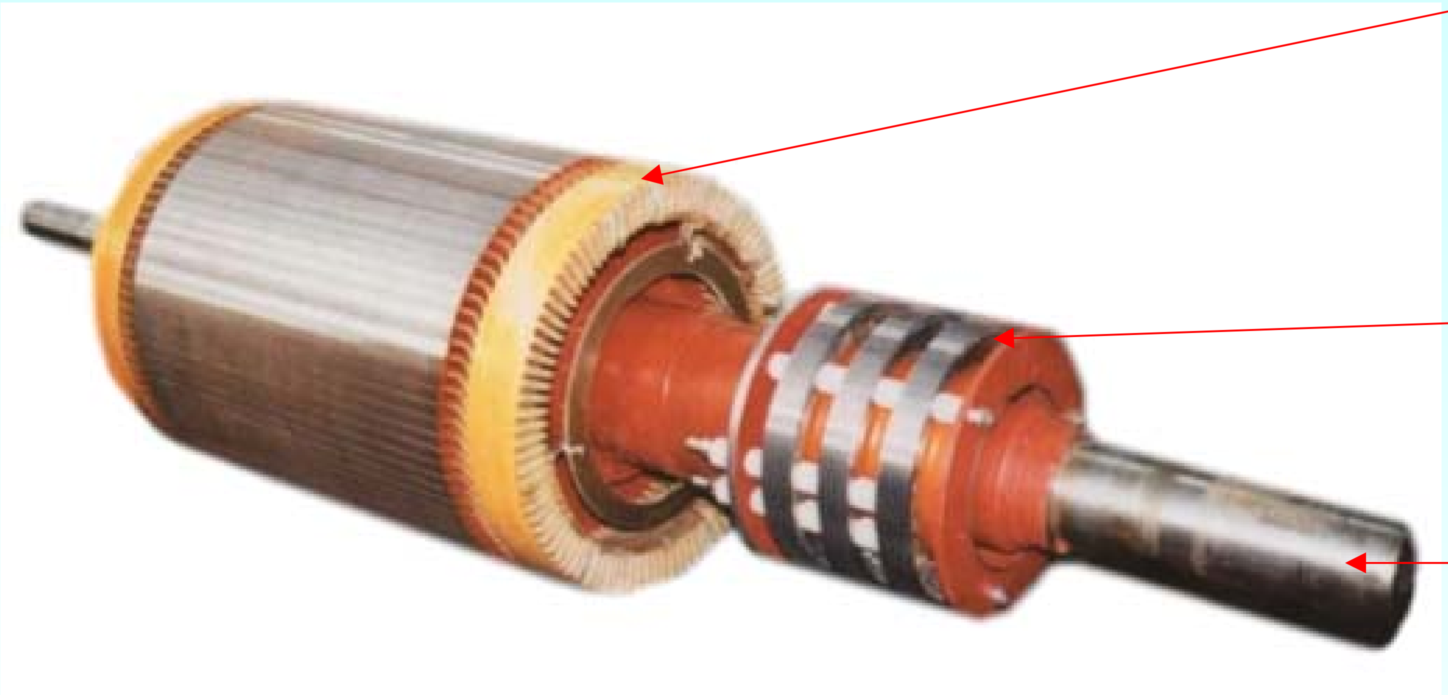
Note: $\boxed{M_{sr} = M_{rs}}$ at $m_s = m_r$!

Slip ring Induction machine

- Stator and rotor house a three phase distributed AC winding
- The three rotor phases are **short circuited**
- The 3 stator phases are fed by three phase voltage & current system (I_s, frequency f_s), and excite fundamental air gap field (amplitude $B_{\delta,s}$), which rotates with speed n_{syn} .
- If **rotor turns with $n \neq n_{syn}$** (= **ASYNCHRONOUSLY)**, then $B_{\delta,s}$ induces in rotor winding the voltage U_{rh} per phase, which drives rotor phase current $I_{c,r}$.
- Rotor phase current and stator air gap field produce via *LORENTZ*-force the **torque M_e.**



Wound rotor of slip ring induction machine



Two-layer three-phase rotor winding

Y connected

3 slip rings of the three phases

shaft end

Source:

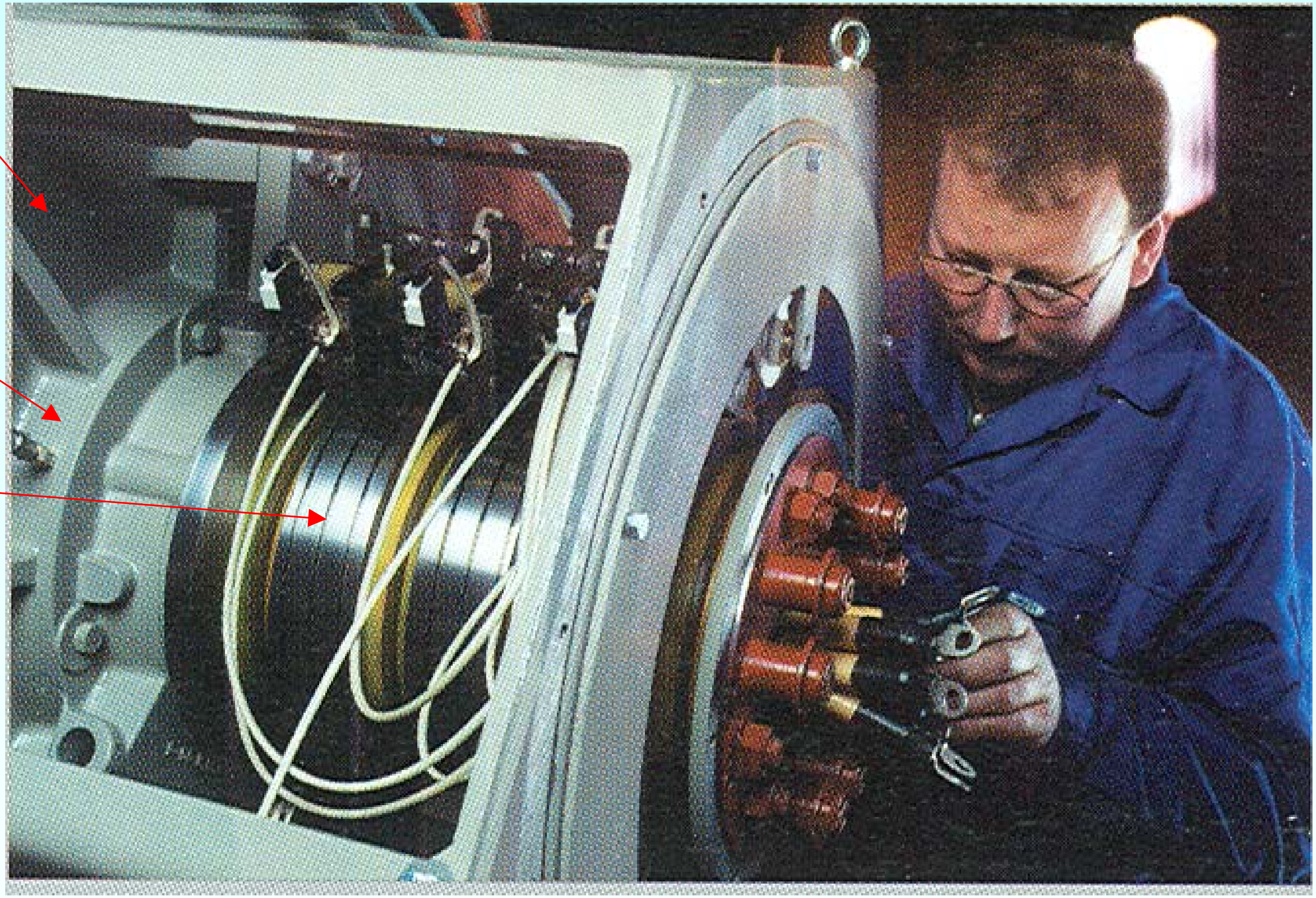
GE Wind, Germany

Slip ring Induction machine

Non-drive end shield

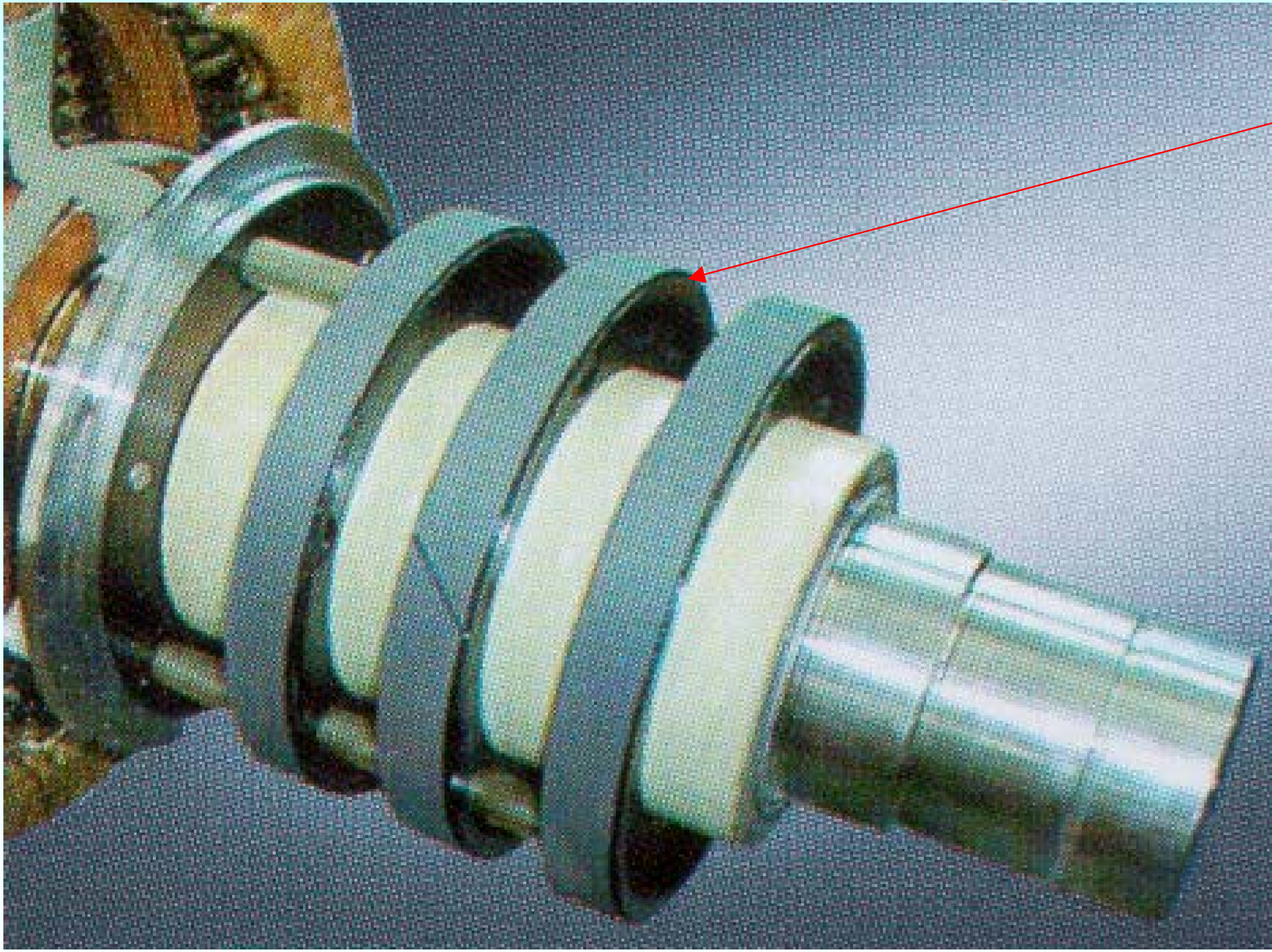
bearing seat

slip rings



Source: Winergy Germany

Carbon slip rings



Alternatively to steel slip rings nowadays also carbon slip rings are used to enhance brush life by reducing brush wear

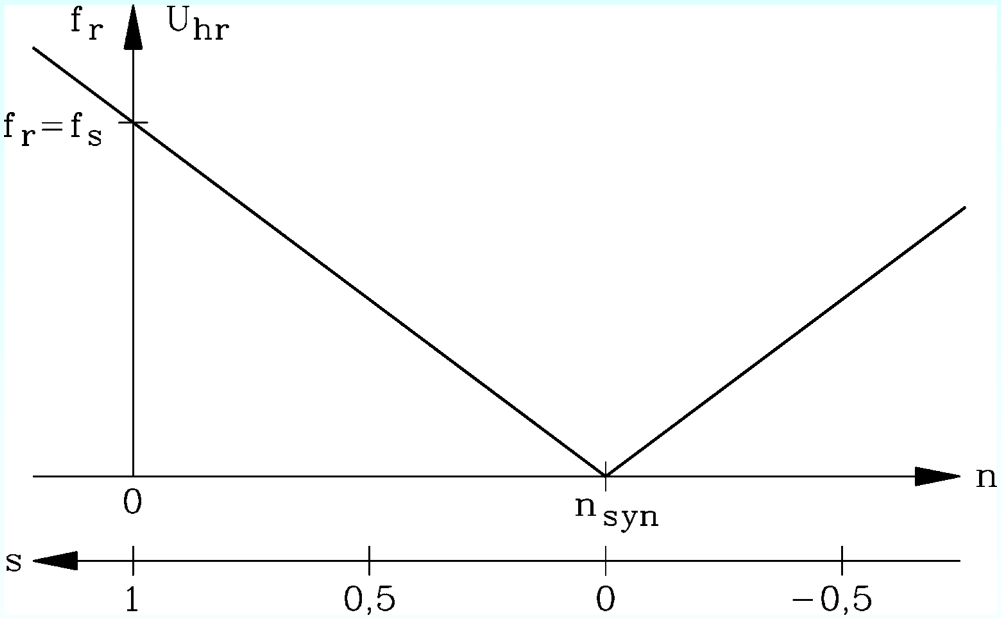
Source:

Siemens AG, Germany

Rotor frequency and slip

- In rotary transformer (n = 0) rotor voltage is phase shifted to stator voltage, depending on rotor position angle γ_r : $\underline{U}_{rh} e^{j\omega_s t} = U_{rh} \cdot e^{-j\gamma_r} \cdot e^{j\omega_s t}$
- When rotor turns with n = const. > 0, rotor position angle will increase continuously:
- $\gamma_r = p \cdot 2\pi n \cdot t + \gamma_{r0} \Rightarrow \underline{U}_{rh} e^{j\omega_r t} = U_{rh} \cdot e^{j(-2\pi \cdot n \cdot p + \omega_s)t} \cdot e^{-j\gamma_{r0}}$

Rotor frequency $\boxed{f_r = f_s - n \cdot p}$



- **Slip *s*** (Definition):

$$\boxed{f_r = s \cdot f_s}$$

$$\boxed{s = \frac{f_s / p - n}{f_s / p}}$$

$$\boxed{s = \frac{n_{syn} - n}{n_{syn}}}$$

Rotor voltage equation

- CONSTANT speed = CONSTANT frequencies = STATIONARY machine performance = only sinusoidal time functions of current and voltage = complex phasor calculus is used

$$i_s(t) = \sqrt{2} I_s \cos(\omega_s t) = \mathrm{Re}\left(\sqrt{2}\underline{I}_s e^{j\omega_s t}\right) \quad \Rightarrow \quad i_s(t) \leftrightarrow \underline{I}_s$$

- Rotor winding short circuited: $u_r = 0$: (R_r: winding resistance per rotor phase)

$$R_r \cdot i_r = u_r + u_{i,r} = u_r - d\Psi_r / dt \quad \Rightarrow \quad R_r \cdot i_r + d\Psi_r / dt = u_r = 0$$

Ψ_r : total flux linkage of one rotor phase:

a) **Mutual induction** of **stator rotating field** into rotor winding: $j\omega_r M_{sr} \underline{I}_s$

b) **Self induction** by **rotor rotating air gap field**: Rotor AC currents per phase I_r , oscillating with rotor frequency f_r , excite rotor rotating field !

$$B_{\delta,r}(x_r, t) = \hat{B}_{\delta,r} \cos(\gamma_r - \omega_r t), \; B_{\delta,r} \sim I_r$$

and induce a voltage into rotor phase winding $j\omega_r L_{rh} \underline{I}_r$

c) **Self induction** by rotor stray field with 3 components: $\boxed{L_{r\sigma} = L_{r,\sigma Q} + L_{r,\sigma b} + \sigma_{r,o} L_{rh}}$

- **harmonic fields:** $j\omega_r \sigma_{r,o} L_{rh} \underline{I}_r$, **slot stray field** $L_{r,\sigma Q}$, **winding overhang stray field** $L_{r,\sigma b}$

$$\boxed{j\omega_r M_{sr} \underline{I}_s + j\omega_r L_{rh} \underline{I}_r + j\omega_r (\sigma_{r,o} L_{rh} + L_{r,\sigma Q} + L_{r,\sigma b}) \underline{I}_r + R_r \underline{I}_r = 0}$$

Stator voltage equation

- **Mutual induction:** Rotor field $B_{\delta,r}$ rotates relatively to stator with synchronous speed:

$$v = v_m + v_{r,syn} = 2pn\tau_p + 2f_r\tau_p = 2p \cdot n_{syn}(1-s)\cdot\tau_p + 2\cdot sf_s\cdot\tau_p$$

$$v = 2p\cdot\frac{f_s}{p}\cdot(1-s)\cdot\tau_p + 2\cdot sf_s\cdot\tau_p = 2f_s\tau_p = v_{syn}$$

Hence it induces the stator winding with stator frequency f_s: $j\omega_s M_{rs}\underline{I}_r$

- **Self induction:** Stator air gap field $B_{\delta,s} \Rightarrow$ leads to self induced stator voltage: $j\omega_s L_{sh}\underline{I}_s$
- **Self induction** by stator stray fields (3 components): $\boxed{L_{s\sigma} = L_{s,\sigma Q} + L_{s,\sigma b} + \sigma_{s,o}L_{sh}}$

  Harmonic fields: $j\omega_s\sigma_{s,o}L_{sh}\underline{I}_s$, **slot stray field** $L_{s,\sigma Q}$, **winding overhang stray field** $L_{s,\sigma b}$
- resistive voltage drop at **stator winding resistance** R_s

- Sum of all stator voltage components must balance the voltage at the winding terminals $\underline{U}_s$ (voltage per phase), which is impressed by the feeding grid !

Stator voltage equation:

$$\boxed{\underline{U}_s = j\omega_s M_{rs}\underline{I}_r + j\omega_s L_{sh}\underline{I}_s + j\omega_s(\sigma_{s,o}L_{h,s} + L_{s,\sigma Q} + L_{s,\sigma b})\underline{I}_s + R_s\underline{I}_s}$$

Transfer ratio

- **Transfer ratio *ü*** from stator to rotor winding: $\boxed{\ddot{u} = \dfrac{k_{w,s} N_s}{k_{w,r} N_r}}$

  we get with $m_r = m_s = m$ (= 3) :

$$\ddot{u}^2 L_{rh} = \left(\frac{k_{w,s} N_s}{k_{w,r} N_r} \right)^2 \cdot \mu_0 N_r^2 k_{w,r}^2 \cdot \frac{2m}{\pi^2} \frac{l \tau_p}{p\delta} = \mu_0 N_s^2 k_{w,s}^2 \cdot \frac{2m}{\pi^2} \frac{l \tau_p}{p\delta} = L_{sh}$$

$$\ddot{u} \cdot M_{sr} = \frac{k_{w,s} N_s}{k_{w,r} N_r} \cdot \mu_0 \cdot N_s k_{w,s} \cdot N_r k_{w,r} \cdot \frac{2m}{\pi^2} \frac{l \tau_p}{p\delta} = \mu_0 N_s^2 k_{w,s}^2 \cdot \frac{2m}{\pi^2} \frac{l \tau_p}{p\delta} = L_{sh}$$

$$\boxed{L_{sh} = \text{麺}_{sr} = \ddot{u}^2 L_{rh} = \underline{\underline{L_h}}}$$

Magnetizing inductance L_h $(m_r = m_s : M_{rs} = M_{sr})$

- *ü* in rotor voltage equation:

$$j\omega_r \text{麺}_{sr} \underline{I}_s + j\omega_r \ddot{u}^2 L_{r,h} \cdot (\underline{I}_r / \ddot{u}) + j\omega_r \ddot{u}^2 L_{r\sigma} \cdot (\underline{I}_r / \ddot{u}) + \ddot{u}^2 R_r \cdot (\underline{I}_r / \ddot{u}) = 0$$

$$\boxed{R'_r = \ddot{u}^2 R_r}, \boxed{L'_{r\sigma} = \ddot{u}^2 L_{r\sigma}}, \boxed{I_r / \ddot{u} = I'_r}, \boxed{\text{舦}_r = U'_r}$$

Rotor voltage equation with *ü*: $\boxed{js\omega_s L_h \underline{I}_s + js\omega_s L_h \underline{I}'_r + js\omega_s L'_{r\sigma} \underline{I}'_r + R'_r \underline{I}'_r = 0}$

$(\omega_r = s\omega_s)$

Equivalent circuit diagram

- Introducing transfer ratio *ü* in **stator voltage equation**:

$$\underline{U}_s = j\omega_s \cdot \text{麺}_{sr} \cdot (\underline{I}_r / \ddot{u}) + j\omega_s L_h \underline{I}_s + j\omega_s L_{s\sigma} \underline{I}_s + R_s \underline{I}_s$$

- $\underline{U}_s = j\omega_s L_h \underline{I}'_r + j\omega_s L_h \underline{I}_s + j\omega_s L_{s\sigma} \underline{I}_s + R_s \underline{I}_s$

$$0 = js\omega_s L_h \underline{I}_s + js\omega_s L_h \underline{I}'_r + js\omega_s L'_{r\sigma} \underline{I}'_r + R'_r \underline{I}'_r$$

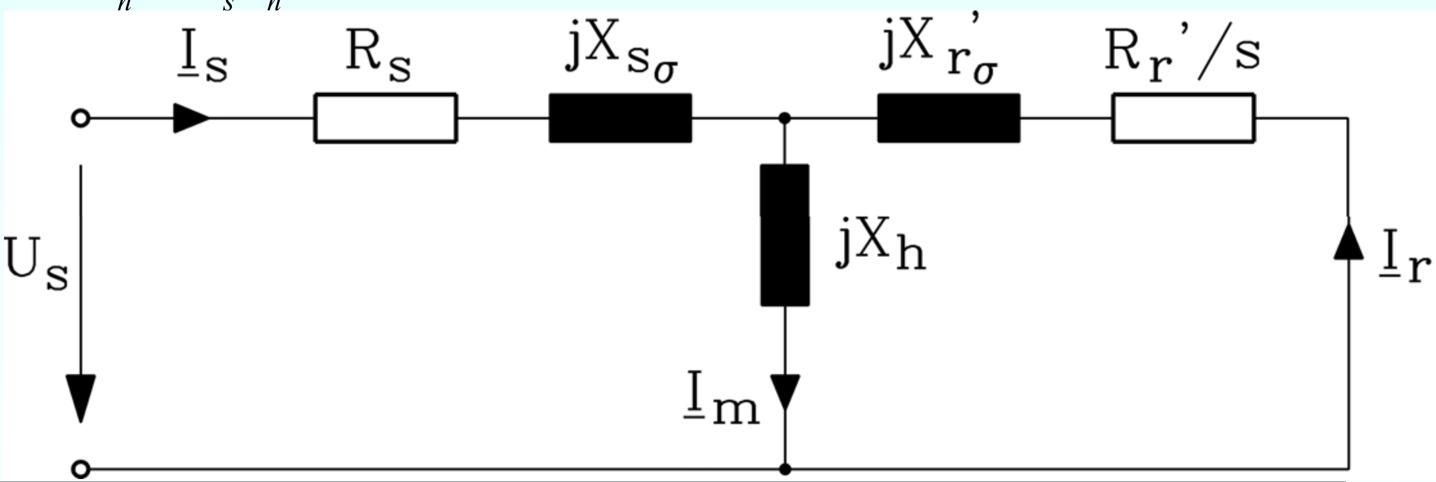
$$\boxed{\underline{U}_s = R_s \underline{I}_s + jX_{s\sigma} \underline{I}_s + jX_h (\underline{I}_s + \underline{I}'_r)}$$

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

Stator leakage reactance: $X_{s\sigma} = \omega_s L_{s\sigma}$, **Rotor leakage reactance:** $X'_{r\sigma} = \omega_s L'_{r\sigma}$

Magnetizing reactance: $X_h = \omega_s L_h$

- **T-equivalent circuit:**



Equivalent circuit parameters

- **Magnetizing and leakage inductance & -reactance:** $L_s = L_h + L_{s\sigma}$, $X_s = X_h + X_{s\sigma}$
  rotor side: $L'_r = L_h + L'_{r\sigma}$, $X'_r = X_h + X'_{r\sigma}$

- Leakage is quantified (*BLONDEL)* by **leakage coefficient** σ:

$$\boxed{\sigma = 1 - \frac{L_h^2}{L_s L'_r} = 1 - \frac{X_h^2}{X_s X'_r}}$$

- ***Rated data and per-unit values of parameters***: Example:
  rated voltage U_N = 400 V (line-to-line !), rated current I_N = 100 A, Star connection

Rated phase voltage $U_{ph,N} = U_N / \sqrt{3} = \underline{\underline{231}}$ V, rated phase current $I_{ph,N} = I_N = \underline{\underline{100}}$ A

Rated apparent power: $S_N = 3U_{ph,N} I_{ph,N} = 3 \cdot 231 \cdot 100 = 69.3$ kVA

Rated impedance: $Z_N = U_{ph,N} / I_{ph,N} = 231/100 = 2.31$ Ohm

Leakage coefficient σ: *shall be small*: typically 0.08 ... 0.1.

Phase resistance: *shall be small:* $r_s = R_s / Z_N$, $r_r = R_r / Z_N$: only a few percent 3 ... 6% !

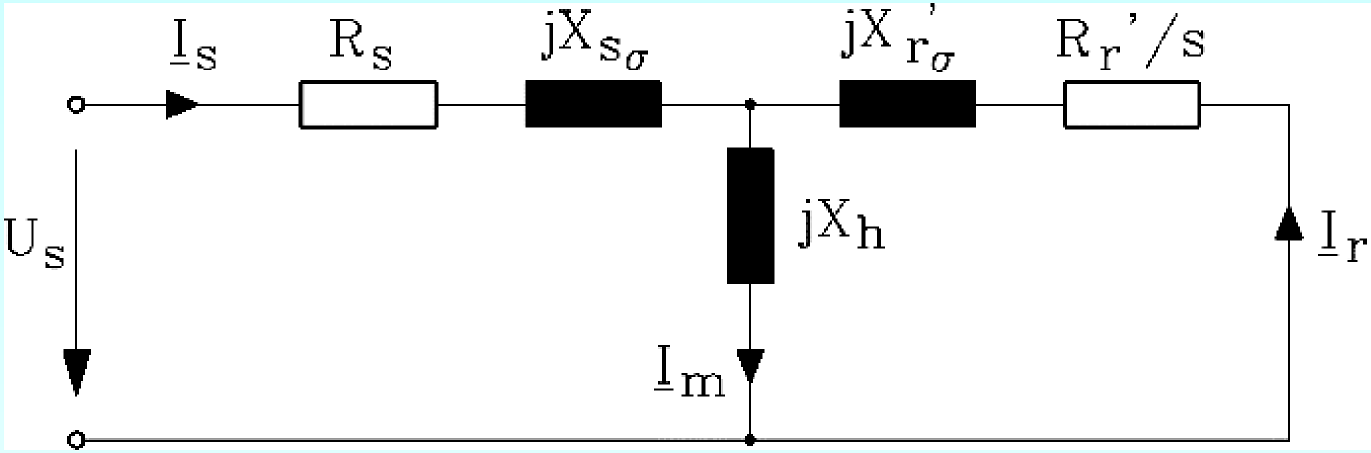
Magnetizing inductance: *shall be big* (= magnetic linkage of stator and rotor !): prop. $1/\delta$

$\Rightarrow$ SMALL air gap: mechanical lower limit ca. 0.28 mm in small motors:

$X_h / Z_N = 2.5 \ldots 3.0$ = 250% ... 300 %.

Leakage inductance: $X_{s\sigma} + X'_{r\sigma} \approx \sigma X_h \approx \sigma X_s$: $\sigma X_s / Z_N \approx (0.08 \ldots 0.1) \cdot (2.5 \ldots 3)$ = 0.2 ... 0.3.

Asynchronous energy conversion



- **Electrical input power** $P_{e,in} = 3U_s I_s \cos\varphi$
- **Resistive losses** in **stator winding:** $P_{Cu,s} = 3R_s I_s^2$
- **Air gap power:** $P_\delta = P_{e,in} - P_{Cu,s} = 3\dfrac{R'_r}{s} I'^2_r$
- **Resistive losses** in **rotor winding:** $P_{Cu,r} = 3R_r I_r^2 = 3R'_r I'^2_r = sP_\delta$
- **Mechanical output power:** $P_{m,out} = P_\delta - P_{Cu,r} = (1-s)P_\delta$
- **Electromagnetic torque** $P_{m,out} = M_e \Omega_m = (1-s)P_\delta \quad \Rightarrow \quad M_e = \dfrac{1-s}{1-s} \cdot \dfrac{P_\delta}{\Omega_{syn}} = \dfrac{P_\delta}{\Omega_{syn}}$

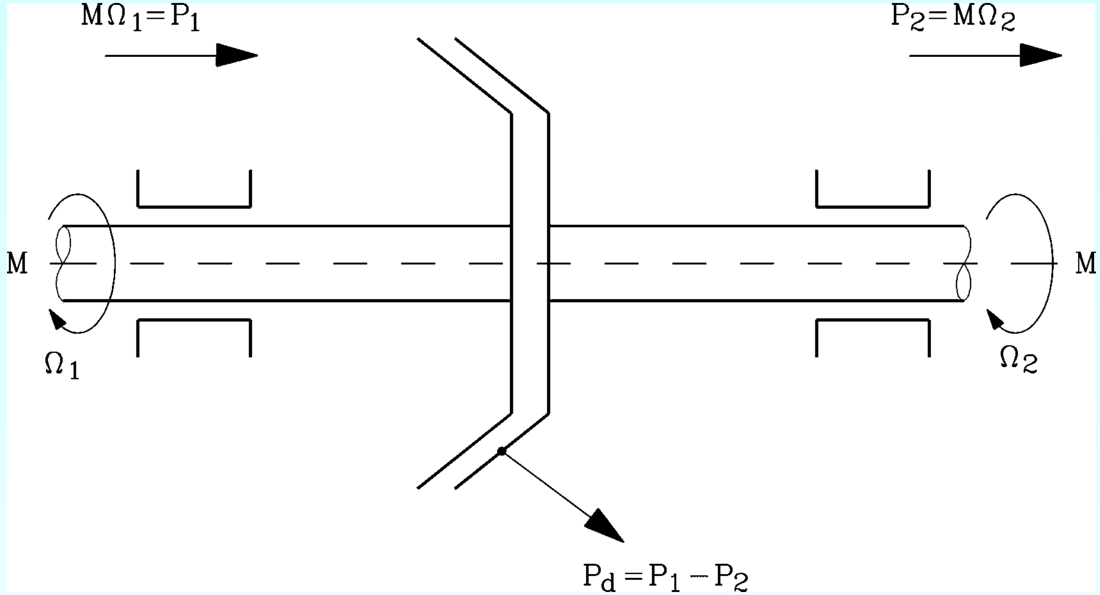
The electromagnetic torque is proportional to air gap power.

Slip coupling – mechanical analogy to induction machine

- Driving input torque M at shat no. 1 = output torque at second shaft no.2.
- Transmission of torque only possible, if **friction disc 2** has a certain slip with respect to friction disc 1.

Hence output speed Ω_2 is smaller by the **slip *s*** than speed Ω_1 of input shaft.

$$\Omega_2 = (1 - s)\Omega_1.$$



- Output power:

$P_2 = M\Omega_2$ is smaller by slip losses $P_d = s\Omega_1 M$ than input power $P_1 = M\Omega_1$.

Induction machine	Slip coupling
Ω_{syn} , Ω_m	Ω_1 , Ω_2
P_δ , $P_{Cu,r}$, P_m	P_1 , P_d , P_2
M_e	M

Stator and rotor current

- **Solution of the two linear equations** of T-equivalent circuit: Unknowns $\underline{I}_s, \underline{I}'_r$

$$\underline{U}_s = R_s \underline{I}_s + jX_s \underline{I}_s + jX_h \underline{I}'_r \qquad 0 = \frac{R_r}{s}\underline{I}'_r + jX'_r \underline{I}'_r + jX_h \underline{I}_s$$

$$\boxed{\underline{I}_s = \underline{U}_s \frac{R'_r + jsX'_r}{(R_s R'_r - s\cdot\sigma\cdot X_s X'_r) + j(s\cdot R_s X'_r + X_s R'_r)}} \qquad \boxed{\underline{I}'_r = -\underline{I}_s \frac{jX_h}{\frac{R'_r}{s} + jX'_r}}$$

- **Solution for R_s = 0:**

$$\underline{I}_s = \frac{\underline{U}_s}{jX_s}\cdot\frac{R'_r + js\cdot X'_r}{R'_r + js\cdot\sigma X'_r} \qquad \underline{I}'_r = -\frac{\underline{U}_s}{X_s}\cdot\frac{s\cdot X_h}{R'_r + js\cdot\sigma X'_r}$$

- Derivation of electromagnetic **torque at R_s = 0:**

$$M_e = \frac{P_\delta}{\Omega_{syn}} = \frac{m_s R'_r I'^2_r}{s\cdot\Omega_{syn}} = m_s \frac{p}{\omega_s} U_s^2 \frac{X_h^2}{X_s^2} \frac{sR'_r}{R'^2_r + (s\sigma X'_r)^2}$$

$$\boxed{M_e = m_s \frac{p}{\omega_s} U_s^2 \frac{1-\sigma}{X_s} \frac{sR'_r X'_r}{R'^2_r + (s\sigma X'_r)^2}}$$

KLOSS formula for torque (at $R_s = 0$)

- **Breakdown torque:** Maximum of electromagnetic torque: $dM_e / ds = 0$

Breakdown slip s_b

$$R_s = 0: \boxed{s_b = \pm \frac{R_r'}{\sigma X_r'}}$$

Breakdown torque:

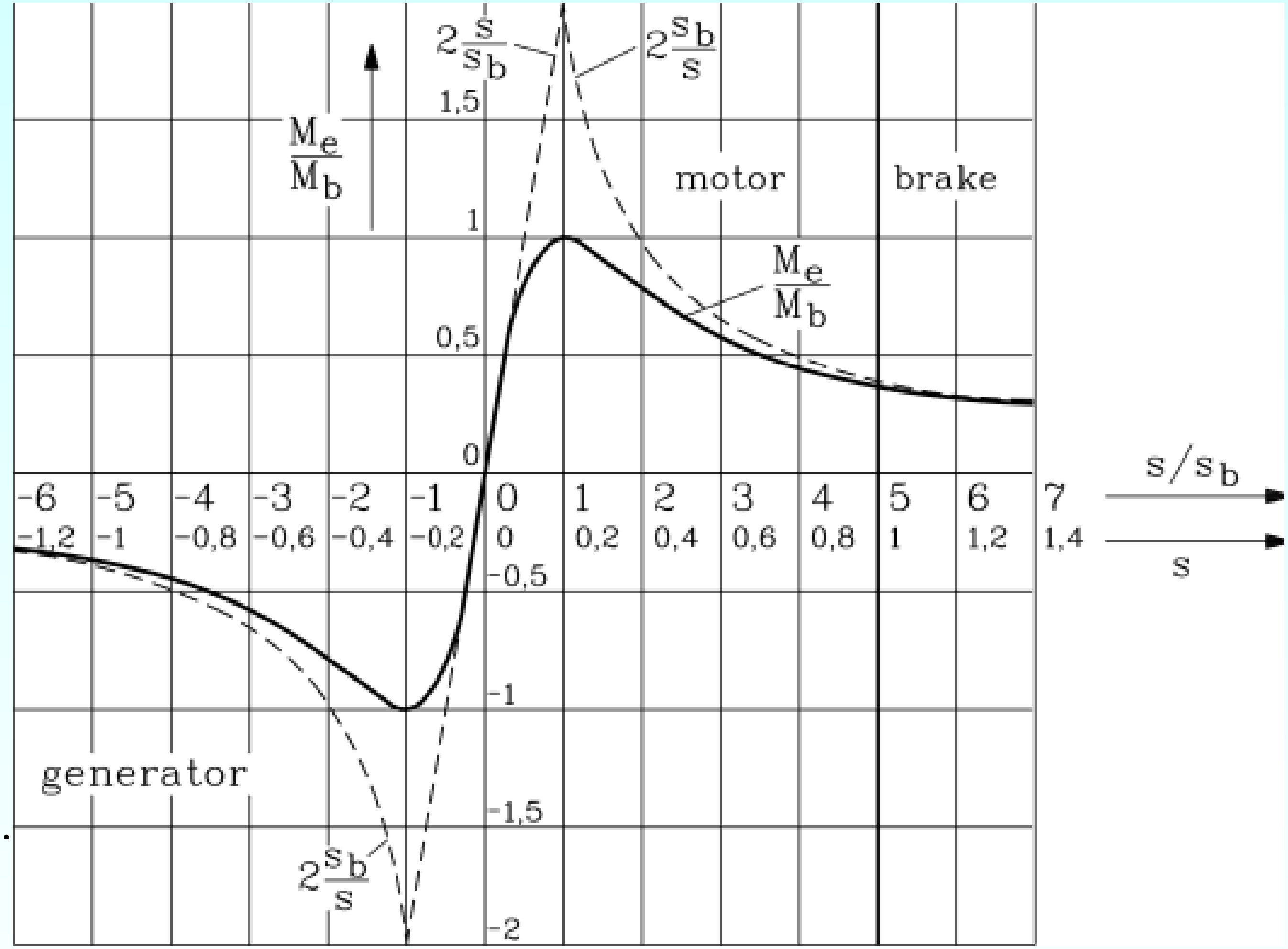
$$\boxed{M_b = \pm \frac{m_s}{2} \frac{p}{\omega_s} U_s^2 \frac{1-\sigma}{\sigma X_s}}$$

- ***KLOSS* formula:**

$$R_s = 0: \boxed{\frac{M_e}{M_b} = \frac{2}{\frac{s_b}{s} + \frac{s}{s_b}}}$$

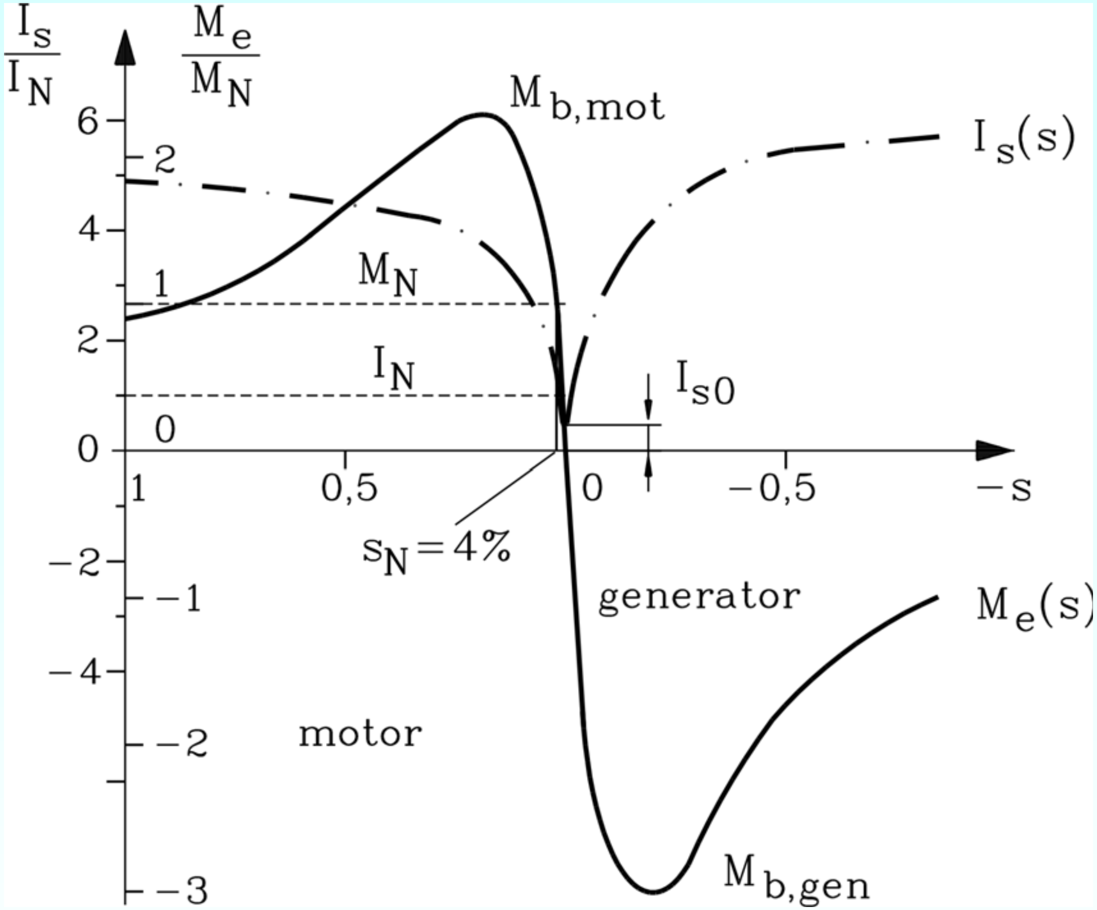
Example:

Breakdown slip $s_b = \pm 0.2$.

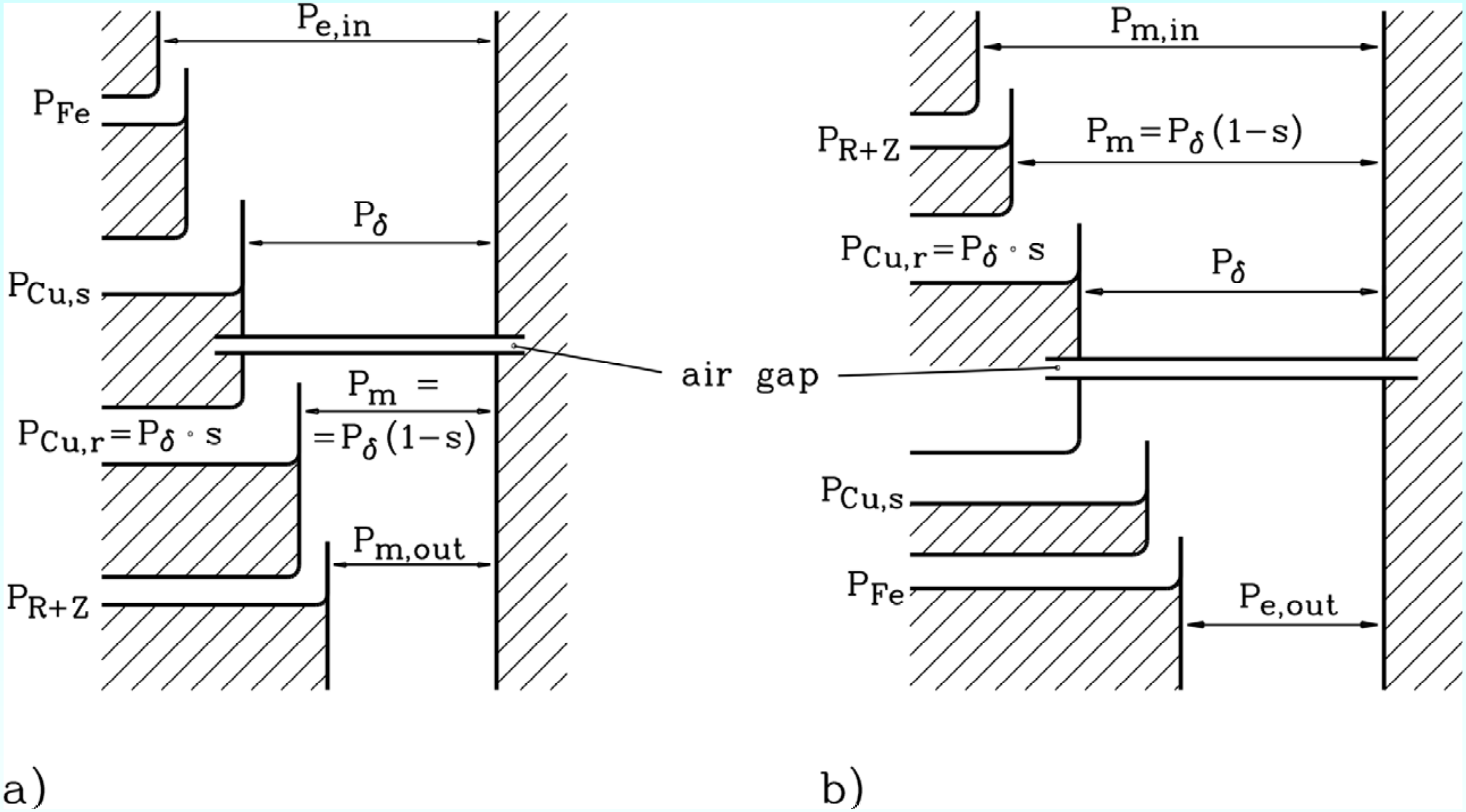


Torque-speed and current-speed characteristic

- Due to $n = (1-s)\cdot f_s/p$: M_e and I_s can be described in dependence of s as well as of n !
- Example: R_s/X_s =1/100, R_r/X_r = 1.3/100, σ = 0.067, $X_s = X'_r = 3Z_N$, $Z_N = U_{ph,N}/I_{ph,N}$



Power flow in (a) motor- and (b) generator mode



- **Efficiency** of induction machine: motor: $\eta = \dfrac{P_{m,out}}{P_{e,in}}$, generator: $\eta = \dfrac{P_{e,out}}{P_{m,in}}$

Air cooled slip ring induction generator

Air inlet fan

Air cooled doubly fed induction generator

2 MW, 4 poles, 600 V,

60 Hz, 1800/min +/-30%

Air-air heat exchanger

Source:

ELIN EBG Motors, Austria

Air cooled slip ring induction generator

Air-air heat exchanger

Slip ring terminal box

Stator winding terminal box

Source:

GE Wind, Germany

VEM Motors, Germany

Air cooled slip ring induction generator

Scirocco centrifugal fan for Air-air heat exchanger

Generator drive end side

Source:

GE Wind, Germany

VEM Motors, Germany

Air cooled slip ring induction generator

Air-air heat exchanger

Air inlet fan

Drive end side

Source:

GE Wind, Germany

Winergy, Germany

Statot terminal box

Rotor terminal box

Air cooled slip ring induction generator

View into air-air heat exchanger

Many parallel tubes for external air flow give big surface for heat exchange

Internal air flow around those tubes allows heat transfer to external cooling air

Source:

GE Wind, Germany

Winergy, Germany

Stator current magnitude of induction motors (1)

- **No-load:** No-load speed is synchronous speed: Slip is ZERO.

$$\underline{I}_s(s=0)=\frac{\underline{U}_s}{R_s+jX_s}\approx -j\frac{\underline{U}_s}{X_s} \qquad \frac{\underline{I}_s}{I_N}(s=0)\approx -j\frac{\underline{U}_s/U_N}{X_s/Z_N}=-j\frac{1}{x_s}$$

Example:

$x_s = x_h + x_{s\sigma} \cong 3.0+0.15=3.15:\ I_S/I_N \cong 1/X_S \cong 1/3$ **No-load current:** ca. 1/3 of rated current. At 100 A rated current the no-load current is ca. 33 A.

- **"Locked rotor" (Stand still):** Slip is 1: ("**Locked rotor current, starting current**"):

$$\underline{I}_s(s=1)\approx -j\underline{U}_s\frac{1}{\sigma\cdot X_s} \qquad \frac{\underline{I}_s}{I_N}(s=1)\approx -j\frac{\underline{U}_s/U_N}{\sigma X_s/Z_N}=-j\frac{1}{\sigma\cdot x_s}$$

Example:

$\sigma = 0.08$, $x_s = 2.6$: $i(s=1) = 1/(2.6\cdot 0.08) = \underline{4.8}$: **starting current** is 4.8-times rated current. Bigger motors have smaller leakage flux, so bigger starting current: typically 5 ... 7-times rated current.

Stator current magnitude of induction motors (2)

- **Rated operation:**

Rated slip s_N: **Rated current (Thermal continuous duty):**

We get rated torque !

Example:

Four-pole machine, 50 Hz: No-load speed n_{syn} = 1500/min, Rated speed n_N = 1450/min, Rated slip s_N = 0.033 = 3.3%.

- **"Balance" of stator and rotor ampere turns:**

Rotor current nearly in opposite phase to stator current.

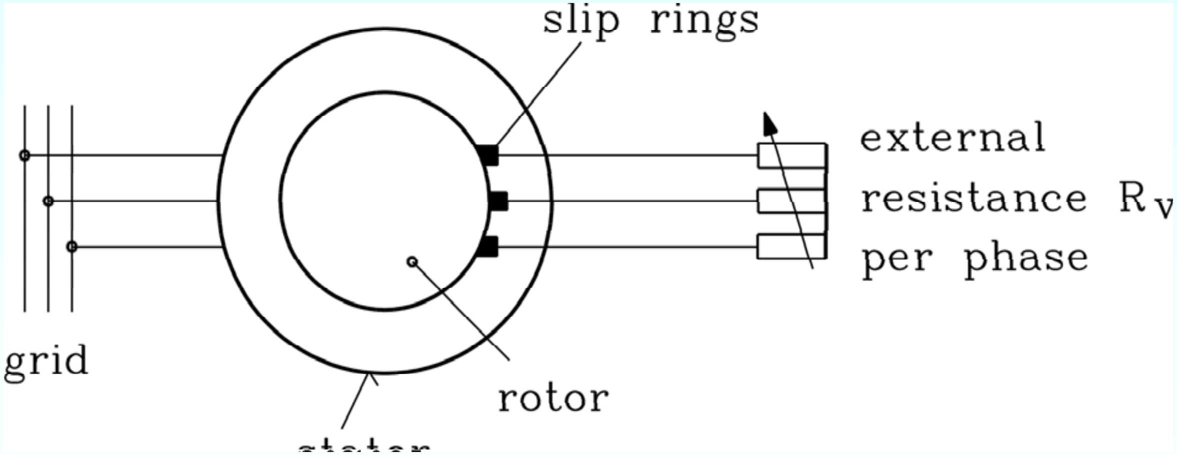
Starting of slip-ring induction machine with external rotor resistance

- External **resistance per phase are** connected to rotor phase via slip rings and carbon brush contacts. Hence rotor total resistance is increased. By that also the starting torque is increased. Maximum starting torque is motor breakdown torque. Starting slip s = 1 is then also breakdown slip. Starting current is reduced to breakdown current.

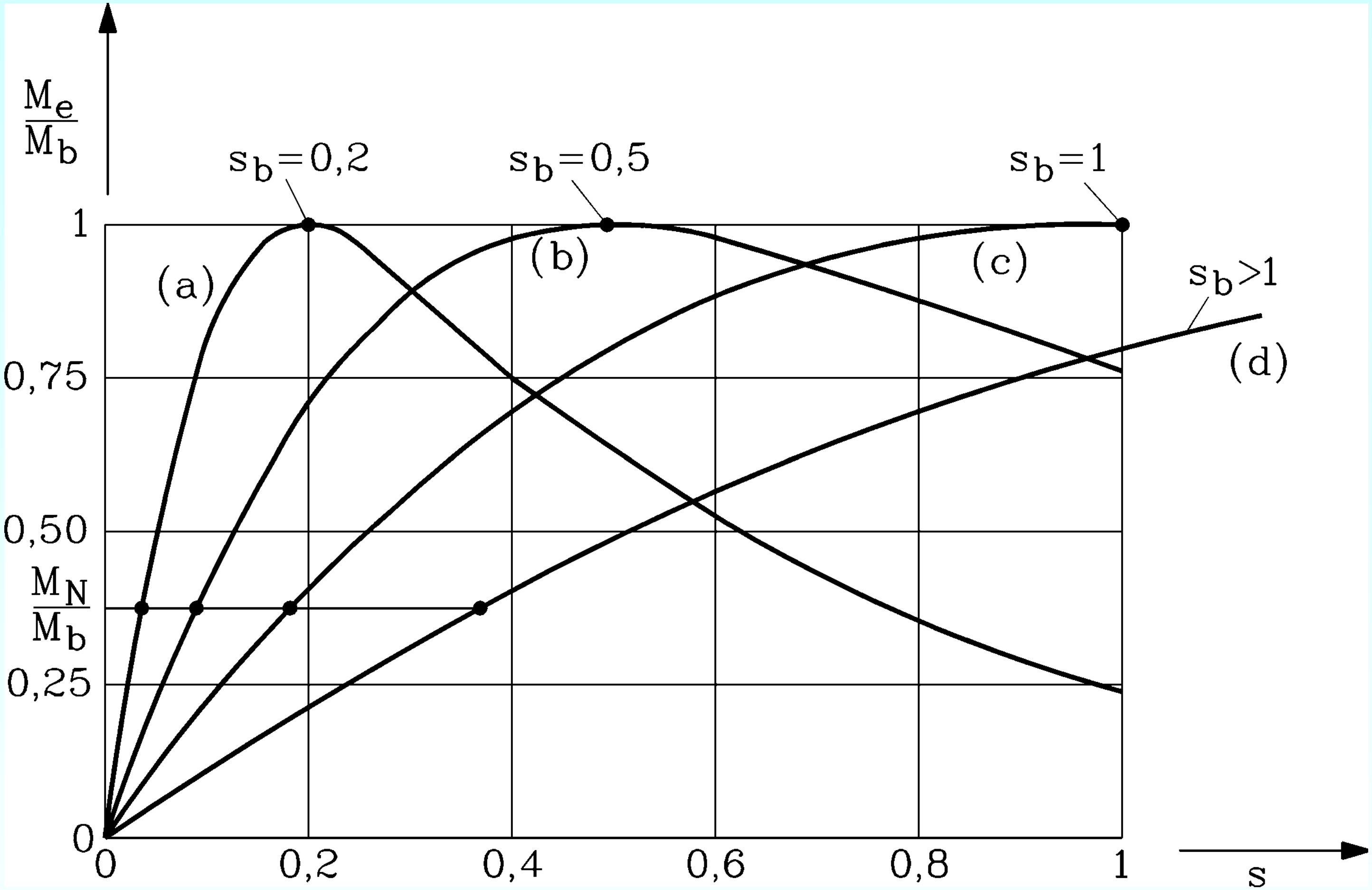
- By keeping $R_r' / s = const.$, the parameters of the equivalent circuit remain unchanged. .

- External resistance R_v per phase: We get the same stator current at slip s as in case of $R_v = 0$ at s^*:

$$\frac{R_r + R_v}{s} = \frac{R_r}{s^*} = konst.$$



Torque-speed characteristic of slip-ring induction motor with external rotor resistance (M_b/M_N = 2.65)



Example: External rotor resistance $R_v = 4R_r$: Starting torque = Breakdown torque *(case c)*.

How to define value of external rotor resistance ?

- *Demand:* Starting torque (at s = 1) shall be breakdown torque:

$$\frac{R_r + R_v}{1} = \frac{R_r}{s_b} \quad \Rightarrow \quad R_v = R_r\left(\frac{1}{s_b} - 1\right)$$

Example:

Slip-ring induction machine: Data: M_b/M_N = 2.65, Breakdown slip 0.2

- Without external rotor resistance we get: Starting torque $M_1 = 0.65M_N = 0.24M_b$ (case *a*).

$$R_v = R_r\left(\frac{1}{0.2} - 1\right) = 4R_r$$

- At $R_v/R_r = 4$ starting torque is breakdown torque ! (case *c*).

- **"Shear"** (linear dilation by R_v) **of $M(n)$- resp. $M(s)$-characteristic.** The torque value M_e at slip s^* (and R_v = 0) occurs at the new slip s !
- ***Result:*** Improved (quicker) starting due to increased torque and decreased current, BUT additional losses in external resistance. ***Advantage:*** These losses occur OUTSIDE of machine, hence they do not heat up the rotor winding.

Variable speed operation of slip-ring induction machines

- By changing the external rotor resistance, the M(n)-characteristic changes and allows variable speed operation of slip-ring induction machine.

- *Example :*

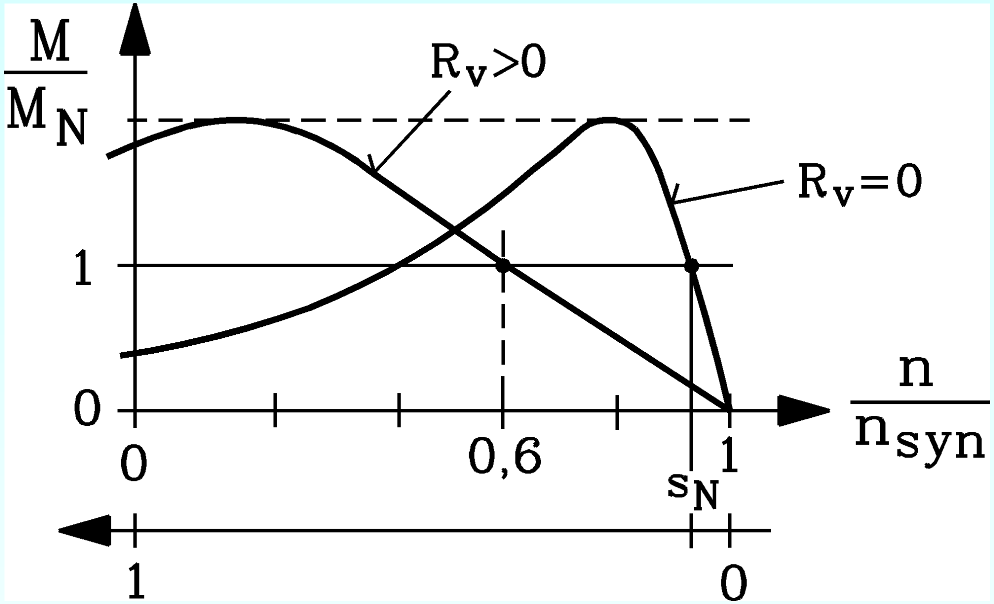
Compare ” Motor for *elevator hoist*" and ” Motor for *pump*":

Demand: Reducing of speed from n_{syn} (100%) down to 60% !

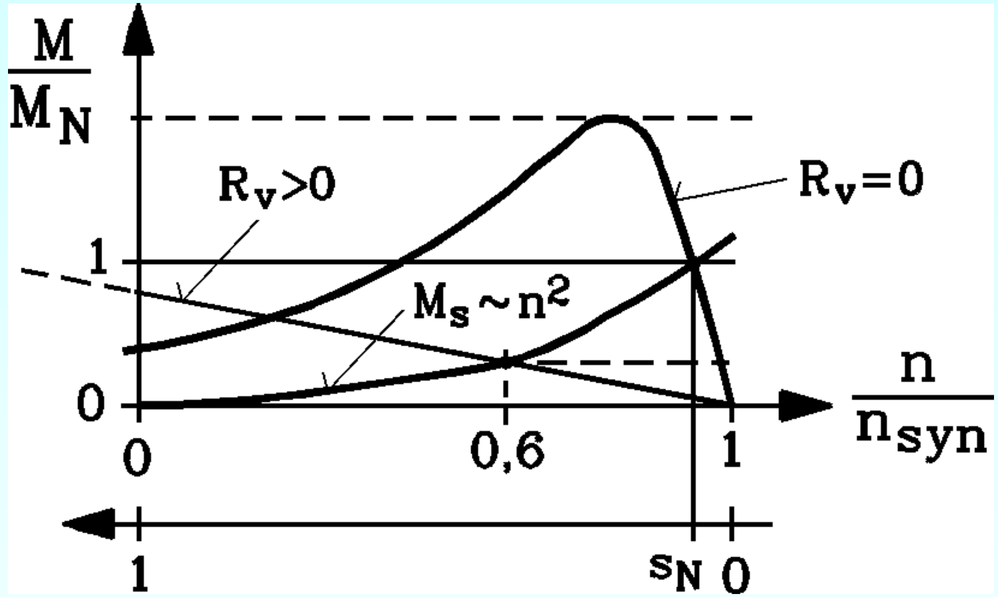
Motor power balance (when neglecting stator resistive losses $3I^2R_s$ and iron losses P_{Fe}):

$$P_{e,in} \cong P_\delta = \Omega_{syn} M_e = P_{Cu,r} + 3R_v I_r^2 + P_m \qquad P_m = 2\pi n M_e \qquad P_\delta = 2\pi n_{syn} M_e$$

M(*n*)-characteristic of variable speed slip-ring induction machine



a)



b)

a) Constant load torque: ***(e.g. elevator):*** big losses in motor: NOT USEFUL !

b) quadratic load torque: ***(e.g. pump):*** small motor losses: USEFUL SOLUTION !

Variable speed operation of slip-ring induction machines

	Elevator	Pump
Load torque	$M_s = M_N = konst.$	$M_s = (n/n_{syn})^2 \cdot M_N$
Load torque at $n/n_{syn} = 0.6$	$M_s = M_N$	$M_s = 0.36 \cdot M_N$
$P_\delta(n)/P_{\delta N} = P_\delta(n)/(2\pi n_{syn} M_N)$	1	0.36
$P_m(n)/P_{\delta N}$	0.6	0.22
$(P_{Cu,r} + 3R_v I_r^2)/P_{\delta N}$	**0.4 (! BIG)**	**0.14 (SMALL)**

- *Elevator: Constant load torque: Reduction of speed by 40% = at the cost of rotor losses of 40% of P_N = BIG LOSSES = NOT USEFUL !*
- *Pump: Quadratic load torque: Reduction of speed of 40 % = at the cost of only 14% of P_N = RATHER LOW LOSSES = USEFUL SOLUTION !*

- *Still better: Inverter-fed induction machine: much lower losses*