TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta mechatroniky, informatiky
a mezioborových studií

Electric drives

Lecture 6 – Induction motors

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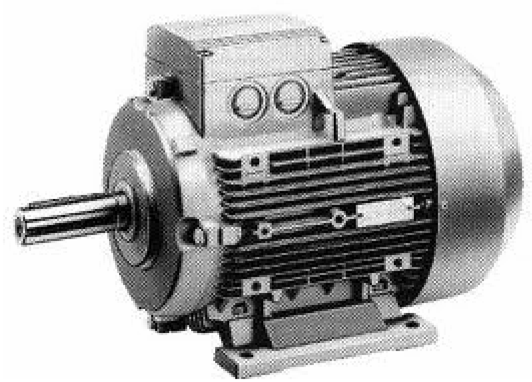


evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Projekt ESF CZ.1.07/2.2.00/28.0050
Modernizace didaktických metod
a inovace výuky technických předmětů.

Lecture focus

- Advantage, disadvantage
- Construction
- Principle
- Equivalent circuit
- Model of induction motor
- ω – M and other characteristic
- Velocity regulation

Basic description

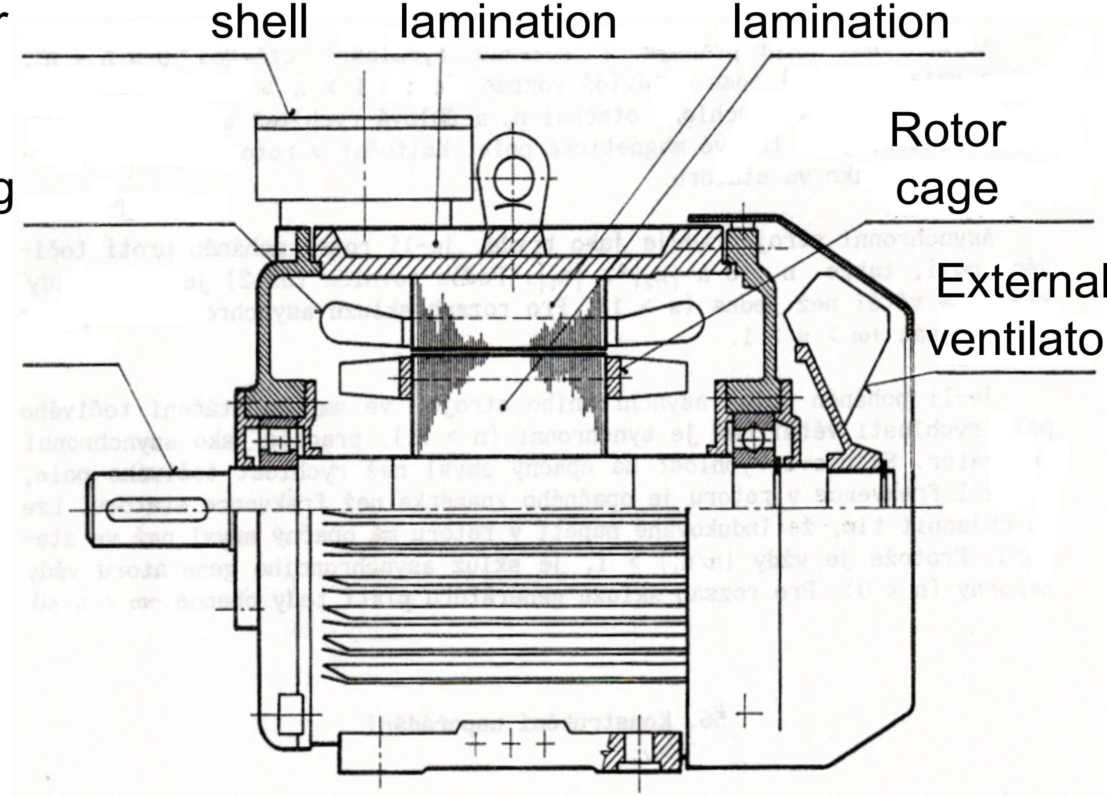
Focus
Description
Construction
Principle
Equivalent circuit
Torque
ω-M characteristic
Characteristics
Start-up
Breaking
Speed control

- The most wide-spread electic motors
- Used for aplication with the constant velocity such as :
  - pumps,
  - ventilators,
  - compressors, blowers, mining and construction machines

Basic description

- Advantages
  - Simple construction
  - Cheap
  - The highest service dependability
  - The frequent servicing is not needed
- Disadvatages
  - It is not suitable for application with the request on accurate positioning
  - Big current stroke at starting up (5 – 9) x I_n
  - Consumption of reactive current

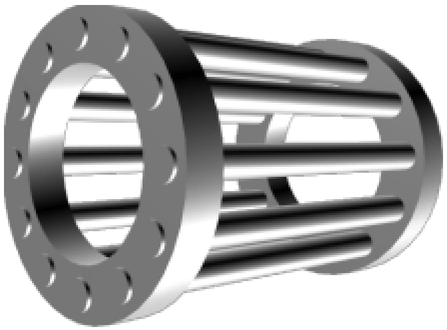
Construction



Construction

- Stator
  - magnetic core made up of punchings (laminations) – 0,1 mm to 0,5 mm thick
  - slot-embedded coils – interconnected in a certain fashion to constitute the so-called a.c. armature winding

Construction



Focus
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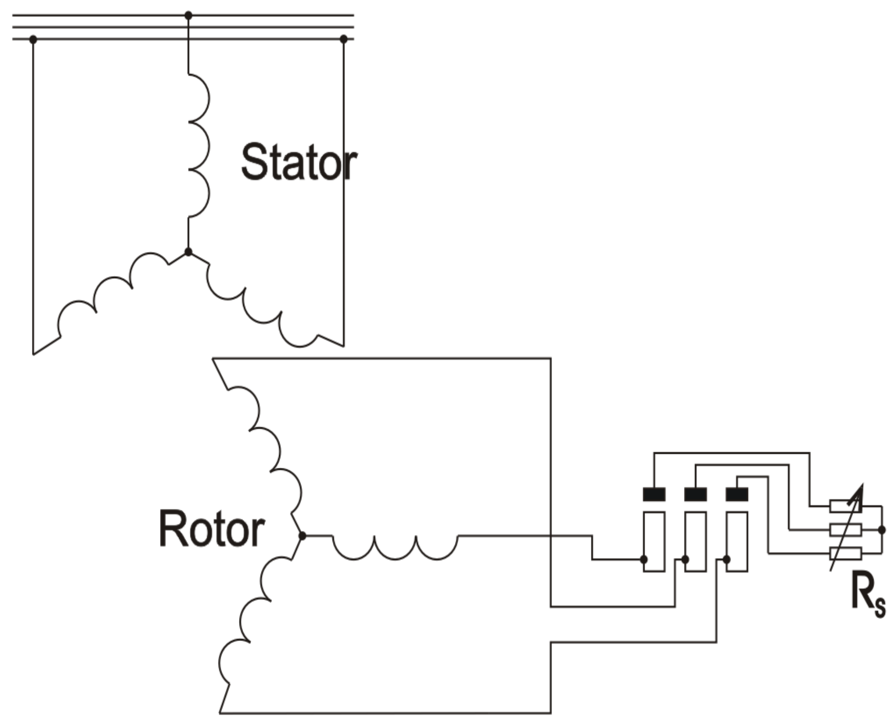
- Rotor
  - Laminated core with uniform slotting
  - Aluminum(copper) bars short-circuited by end-rings (the squirrel cage)

or

  - tree-phase winding connected to some copper ring and fixed brushes (wound rotor)

Construction

Electrical scheme of induction motor with wound rotor



Motor principle

- The induction motor principle is founded on the interaction of stator rotation magnetic field and currents, which are created by this field in the rotor winding
- U_s => I_s =>Rot.mag.field => U_{iR} => I_R =>F = B.I_R.l=>M=>n

Motor principle

- Slip speed
  - $n_2 = n_s - n$
    - n_s = synchronous speed
    - n = motor speed
- Slip
  - Slip is ratio of slip velocity and synchronous velocity

$$s = \frac{n_2}{n_s} = \frac{n_s - n}{n_s} = 1 - \frac{n}{n_s}$$

Motor principle

- Frequence f_2 depens on slip velocity n_2

$$n_2 = \frac{f_2}{p} = \frac{\omega_2}{2\pi p}$$

$$s = \frac{f_2}{f_1} = \frac{\omega_2}{\omega_1} = \frac{\omega_{2m}}{\omega_{1m}}$$

Induction machine works as motor for velocity $0 \leq n < n_m$

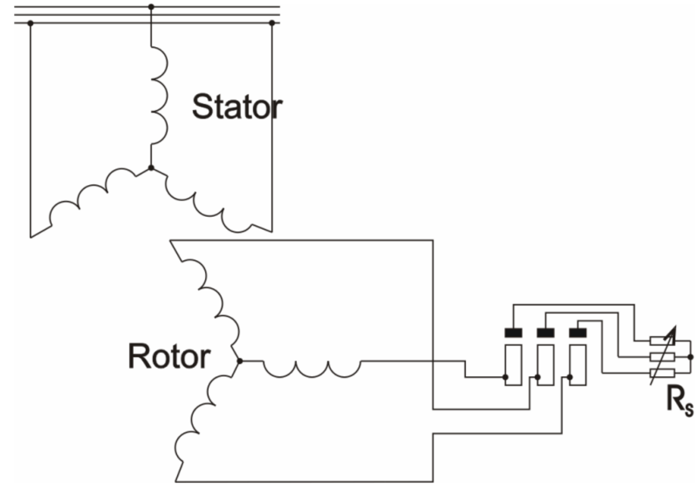
and for slip $1 > s > 0$ that meas slip is positive, n_2 and ω_{2m} has the same sense of rotation as rotating magnetic field

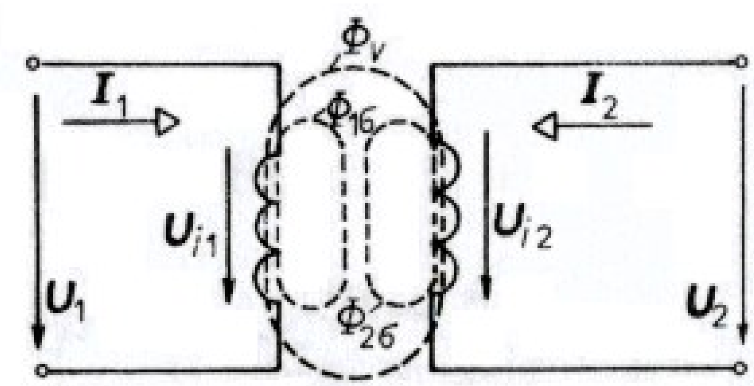
Induction machine works as brake for velocity $n < 0$ a $|n_2| > |n_1|$ and slip $+\infty > s > 1$

Induction machine works as generator when $n > n_1$ and $-\infty < s < 0$

Equivalent circuit of induction motor

- After conection symmetrical resistances to the stalled motor, we close the circuit and through the winding will pass m – phase current, which create rotating field





Equivalent circuit of induction motor

- Stator magnetic flux

$$\Phi_{1C} = \Phi_V + \Phi_{1\sigma}$$

- Rotor magnetic flux

$$\Phi_{2C} = \Phi_V + \Phi_{2\sigma}$$

Stator voltage equation

$$U_1 = R_1 I_1 + jX_{1\sigma} I_1 + U_{i1}$$

Rotor voltage equation

$$U_2 = R_2 I_2 + jsX_{2\sigma} I_2 + U_{i2}$$

Equivalent circuit of induction motor

- Recomputation rotor quantities to the stator

$$U_2' = U_2 \frac{N_1 k_{v1}}{N_2 k_{v2}} = U_2 p$$

$$I_2' = I_2 \frac{N_2 k_{v2}}{N_1 k_{v1}} = \frac{I_2}{p}$$

$$R_2' = R_2 \left(\frac{N_1 k_{v1}}{N_2 k_{v2}} \right)^2 = R_2 p^2$$

$$X'_{2\sigma} = X_{2\sigma} \left(\frac{N_1 k_{v1}}{N_2 k_{v2}} \right)^2 = X_{2\sigma} p^2$$

Equivalent circuit of induction motor

$$U_{i2} = 4{,}44\Phi_v f_2 N_2 k_{v2} = 4{,}44\Phi_v s f_1 N_2 k_{v2} \,|\cdot \frac{N_1 k_{v1}}{N_2 k_{v2}}$$

$$U_{i2} \frac{N_1 k_{v1}}{N_2 k_{v2}} = 4{,}44\Phi_v s f_1 \frac{N_2 k_{v2}}{N_2 k_{v2}} N_1 k_{v1}$$

$$U_{i2} p = s U_{i1}$$

$$U_{i2} = s \frac{U_{i1}}{p}$$

$$U_2 = R_2 I_2 + jsX_{2\sigma} I_2 + U_{i2}$$

$$U_2 = R_2 I_2 + jsX_{2\sigma} I_2 + s\frac{U_{i1}}{p} \bigg| \cdot \frac{1}{s} \cdot \frac{p^2}{p}$$

$$\frac{U_2}{s} p = U_{i1} + \frac{I_2}{p}\left(\frac{R_2 p^2}{s} + jX_{2\sigma} p^2\right)$$

$$\frac{U_2^{'}}{s} = U_{i1} + I_2^{'}\left(\frac{R_2^{'}}{s} + jX_{2\sigma}^{'}\right)$$

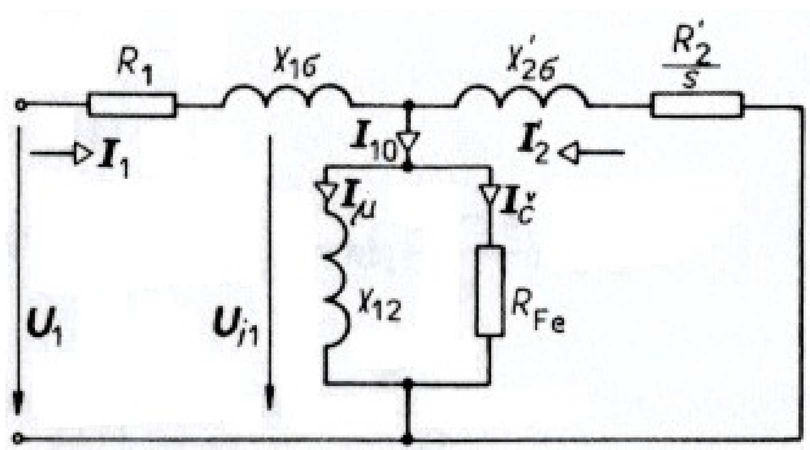
Equivalent circuit of induction motor

- For cage motor $\frac{U_2'}{s} = 0$ and we could write

$$U_{i1} + I_2'\left(\frac{R_2'}{s} + jX_{2\sigma}'\right) = 0$$

$$U_1 = R_1 I_1 + jX_{1\sigma} I_1 + U_{i1}$$

From this both equations at considering of iron influence we can draw equivalent circuit of induction motor



R_1 – stator resistance winding

$X_{1\sigma}$ – stator leakage inductance

R'_2 – rotor winding resistance

$X'_{2\sigma}$ – rotor leakage inductance

X_{12} – magnetic reactance

R_{FE} – magnetic loses resistance

Equivalent circuit of induction motor

Cross impedance

$$Z = \frac{R_{Fe}\, jX_{12}}{R_{Fe} + jX_{12}}$$

$$\mathbf{U}_{i1} = Z \cdot \mathbf{I}_{10} = Z\left(\mathbf{I}_1 + \mathbf{I}_2'\right)$$

- What is the meaning of the $\frac{R_2'}{s}$ element ?

$$\frac{R_2'}{s} = R_2' + \frac{R_2'}{s} - R_2' = R_2' + R_2'\left(\frac{1}{s} - 1\right) = R_2' + R_2'\left(\frac{1-s}{s}\right)$$

R‘$_2$ – is inherent with rotor resistance

$R_2'\left(\frac{1-s}{s}\right)$ - It is resistance which, answer to mechanical load

Why?

Energy balance and torque

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- ω-M characteristic
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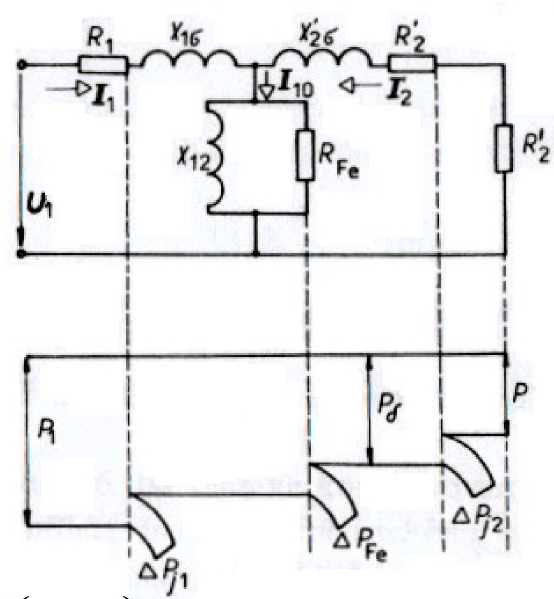


$$P_1 = m_1 U_1 I_1 \cos\varphi_1$$

$$\Delta P_{j1} = m_1 R_1 I_1^2$$

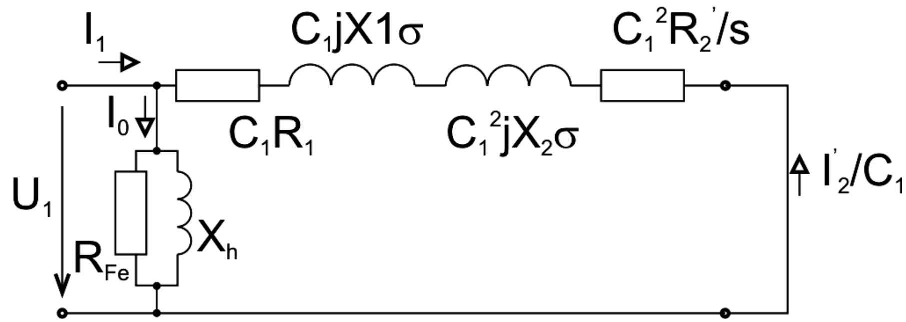
$$P_m = P_\delta - P_{j2}$$

$$P_\delta = U_{i1} I'_2 \cos\varphi = \frac{R'_2}{s} I'^2_2 = R'_2 I'^2_2 + \left(\frac{1-s}{s}\right) R'_2 I'^2_2 = \Delta P_{j2} + P_m$$

$$P = M \cdot \omega = M \cdot \omega_s (1-s)$$

$$\left(\frac{1-s}{s}\right) R'_2 I'^2_2 = M \cdot \omega_s (1-s) \Rightarrow M = \frac{m_1}{\omega_s s} R'_2 I'^2_2$$

Equivalent circuit Γ - network



changes after transformation

$$\hat{Z}_1 = R_1 + jX_{1\sigma}$$

Shunt arm has size after transformation

$$Z_{1h} = \frac{Z_0 + Z_1}{Z_0} = \dots = 1 + \frac{R_1 + jX_{1\sigma}}{Z_{1h}}$$

where $\frac{R_1 + jX_{1\sigma}}{Z_{1h}} = \hat{C}$

We can express the equation for I_1:

$$\hat{I}_1 = \frac{\hat{U}_1}{\frac{\hat{Z}_{1h} + \hat{Z}_1}{\hat{Z}_{1h}}} + \frac{\hat{U}_1}{\hat{c}_1(R_1 + jX_{1\sigma}) + \hat{c}_1^2(\frac{R_2'}{s} + jX'_{2\sigma})}$$

$$\rightarrow \frac{\hat{I}_2'}{c_1}$$

$$\rightarrow \hat{I}_0$$

Induction motor torque

- At first simplification

$\hat{c}_1$ is complex number $\hat{Z}_0 = \left|\hat{Z}_0\right| \cdot e^{-j\varphi_0}$

usually $R_{Fe} >> X_{1h}$ => φ -> $\frac{\pi}{2}$ => $\hat{c}_1$ -> $\left|\hat{c}_1\right|$ and in addition $\left|\hat{c}_1\right|$ -> 1

$X_\sigma = X_{1\sigma} + c_1 X'_{2\sigma}$ – shortcut reactance

with regard for this facts

$$\frac{I_2'}{c_1} = \frac{U_1}{c_1 R_1 + c_1^2 \frac{R_2'}{s} + c_1 jX_\sigma} \Rightarrow I_2' = \frac{U_1}{R_1 + c_1 \frac{R_2'}{s} + jX_\sigma}$$

Induction motor torque

$$\left|\widehat{I}_2^{'}\right|^2 = \frac{U_1^2}{\left(R_1 + c_1^2 \frac{R_2^{'}}{s}\right)^2 + X_\sigma^2}$$

And finally, we can write the equation for induction motor torque

$$M_{(s)} = \frac{m_1}{\omega_1} \cdot \frac{R_2^{'}}{s} \frac{U_1^2}{\left(R_1 + c_1^2 \frac{R_2^{'}}{s}\right)^2 + X_\sigma^2}$$

Speed-torque characterictic

- For deduction of speed-torque characteristic we need to know M_{max}, $M_{(s=1)}$,$M_{(s=0)}$
- How to find maximum?

$$\frac{dM}{ds} = \frac{d}{ds}\left(s\left[\left(R_1 + c_1 \frac{R_2^{'}}{s} \right)^2 + X_\sigma^{\ 2} \right] \right) \stackrel{!}{=} 0$$

$$s^2 (R_1^2 + X_\sigma^2) - c_1 R_2^{'2} = 0 \Rightarrow s_{\max} = \pm \frac{c_1 R_2^{'}}{\sqrt{R_1^2 + X_\sigma^2}}$$

$$M_{\max} = \pm \frac{m_1}{\omega_1} \frac{R_2^{'}}{c_1 R_2^{'}} \frac{U_1^2 \sqrt{R_1^2 + X_{1\sigma}^2}}{R_1 + c_1 \frac{R_2^{'} \sqrt{R_1^2 + X_{1\sigma}^2}}{c_1 R_2^{'}} + X_\sigma^2} = \ldots\ldots =$$

$$= \pm \frac{m_1}{2\omega_1 c_1} \frac{U_1^2}{\left(\pm R_1 + \sqrt{R_1^2 + X_{1\sigma}^2} \right)}$$

Speed-torque characterictic

- For motors with P>10 kW

$$R_1 \doteq 0$$

$$M_{(s)} = \frac{m_1}{\omega_1} \frac{R_2^{'}}{s} \frac{U_1^2}{\left(c_1 \frac{R_2^{'}}{s}\right)^2 + X_\sigma^2}$$

$$s_{\max} = \pm \frac{c_1 R_2^{'}}{X_\sigma}$$

$$M_{\max} = \frac{m_1}{2\omega_1 c_1} \frac{U_1^2}{X_\sigma}$$

Conclusions

$M_{max}=f(U^2)$;M_{max} is influenced by R_1 and much more by X_σ

Speed-torque characterictic

- How looks like the torque of induction motor for s close to 1 and 0
- If s=1 than

$$M_{(s=1)} = \frac{m_1}{\omega_1} \cdot \frac{R_2^{'}}{1} \cdot \frac{U_1^2}{\left(R_1 + c_1 R_2^{'}\right)^2 + X_\sigma^2}$$

- For $R \overset{!}{=} 0$

$$M_{(s=1)} = \frac{m_1 R_2^{'}}{\omega_1} \cdot \frac{U_1^2}{\left(c_1 R_2^{'}\right)^2 + X_\sigma^2} \cong k_1 \frac{R_2^{'}}{s}$$

linear dependence

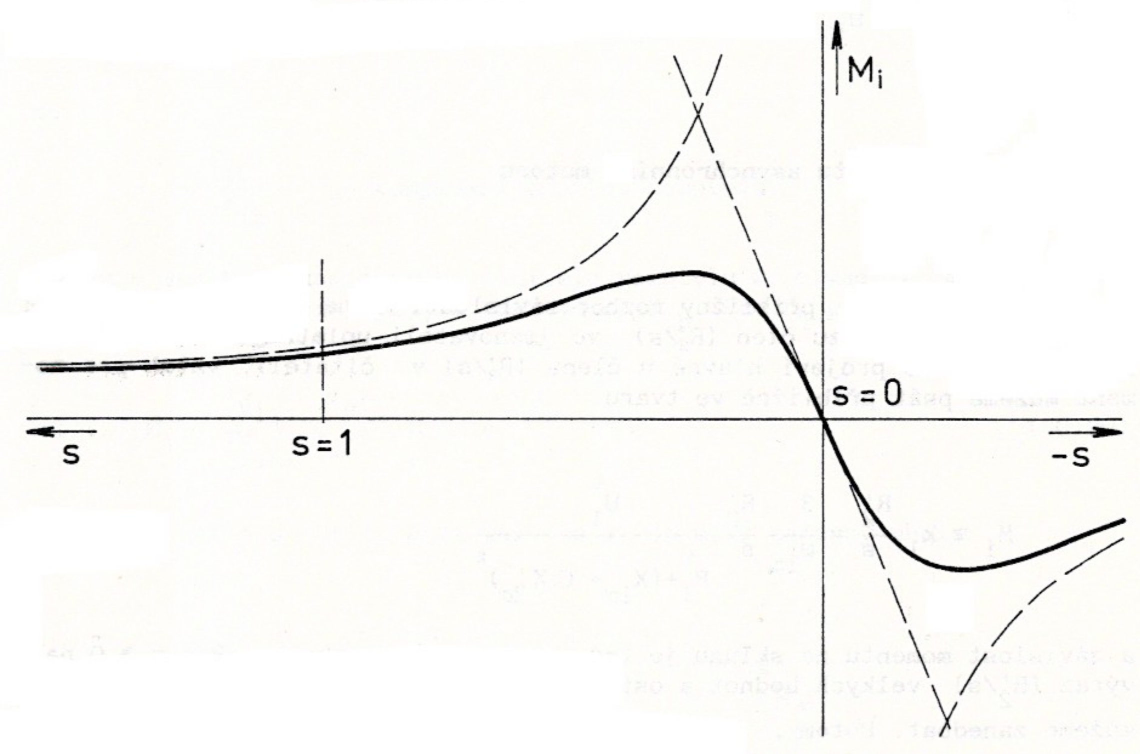
- If s=0 than

$$M = \frac{3}{\omega_{1m}} \frac{s}{R_2^{'}} U_1^2 \cong k_2 \frac{s}{R_2^{'}}$$

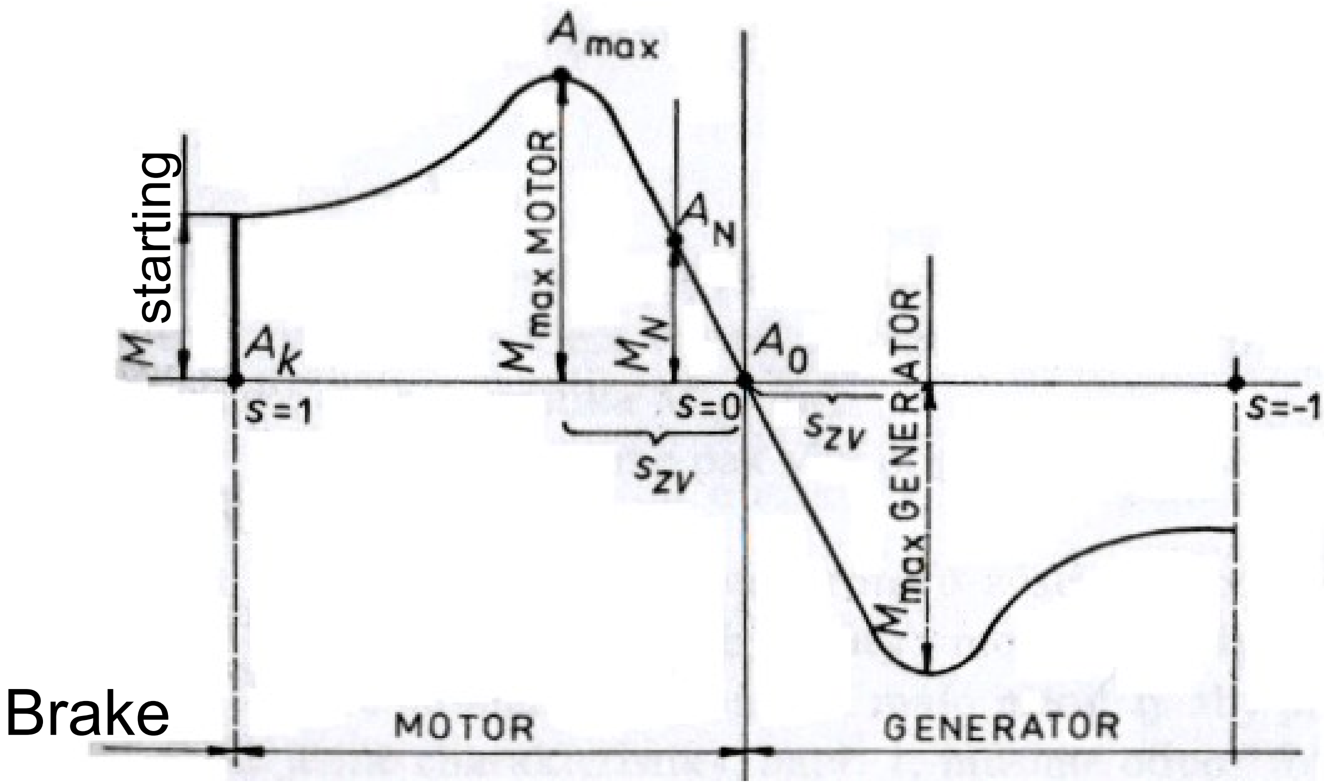
hyperbolic dependence

Speed-torque characterictic

- From Results dedused till now result in the characteristic showed on the picture



Speed-torque characterictic of induction machine



torque overload capacity $\frac{M_{max}}{M_n} = (1{,}7 - 2{,}2)$

IM - characteristics

- Focus
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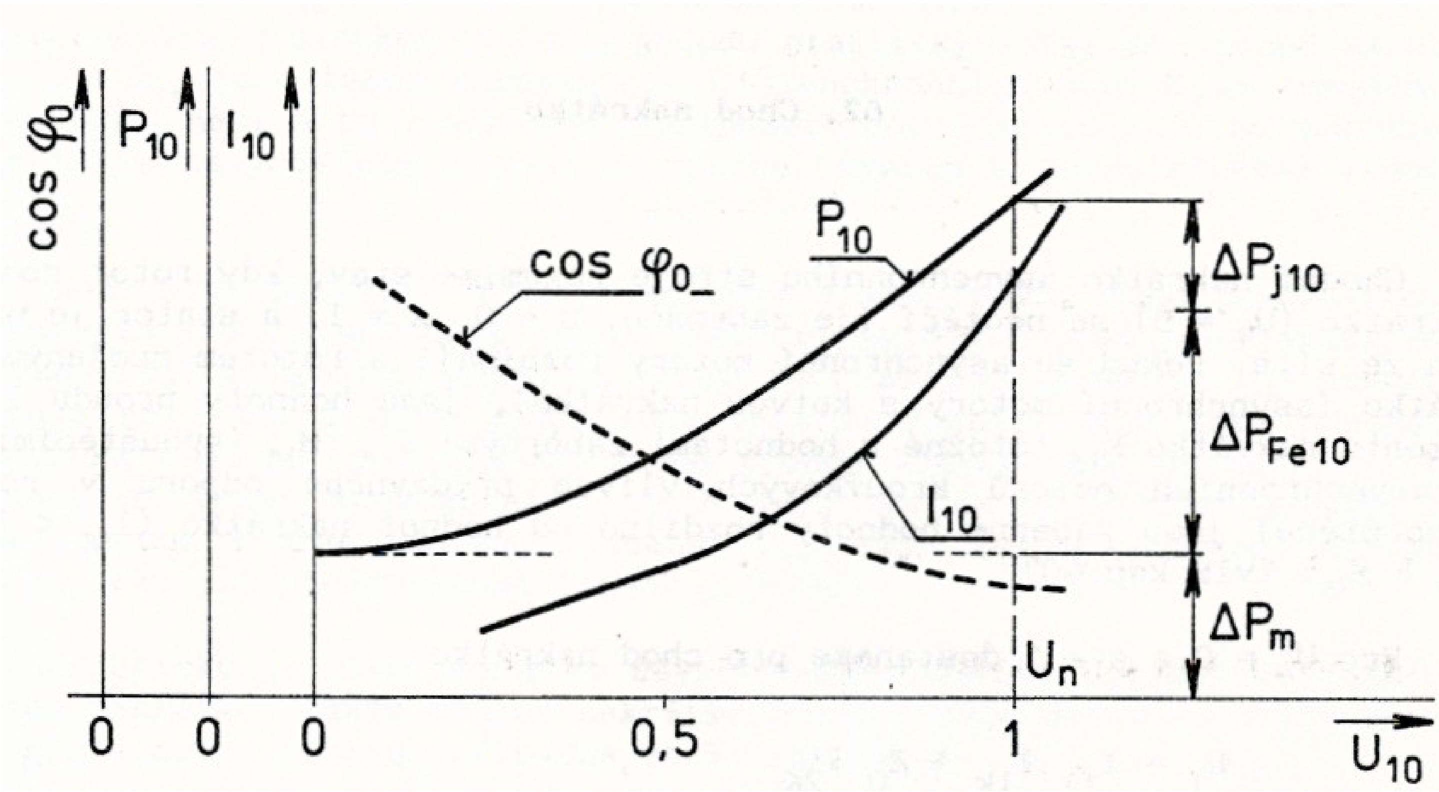
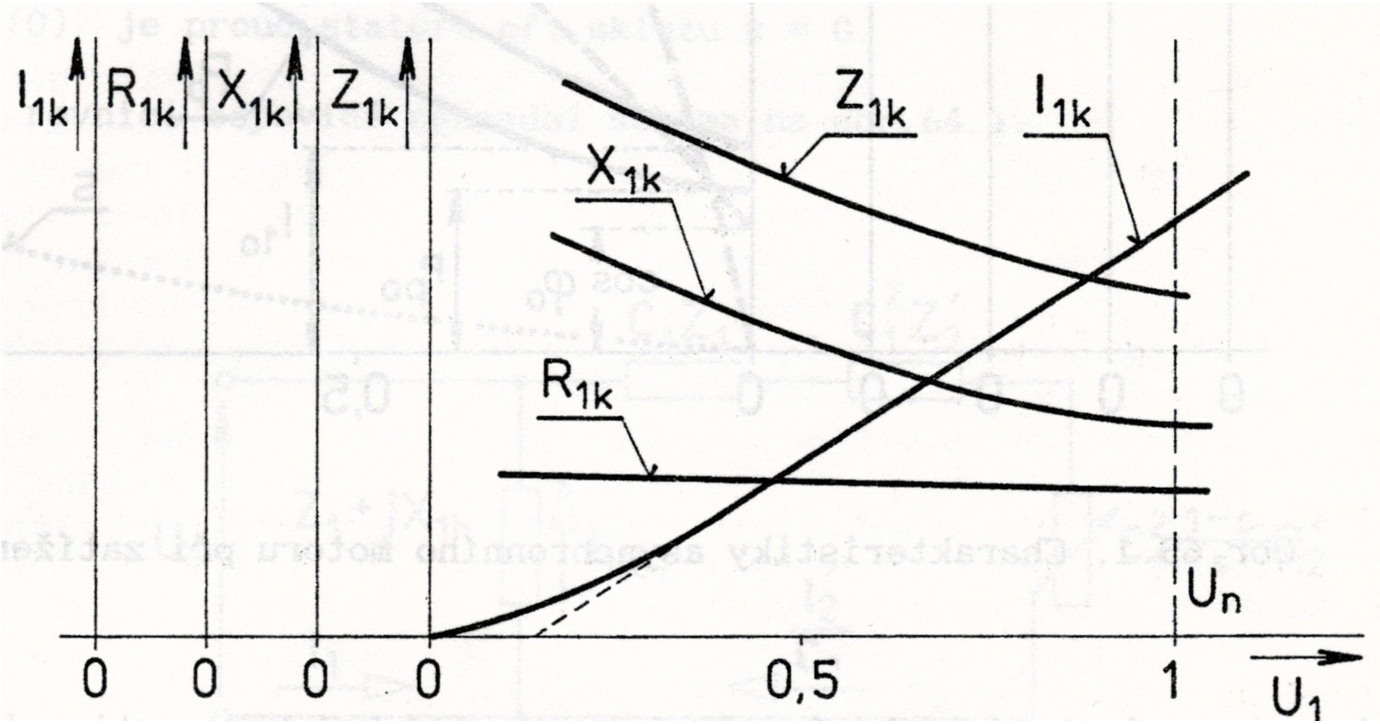
- no-load run characteristics



IM - characteristics

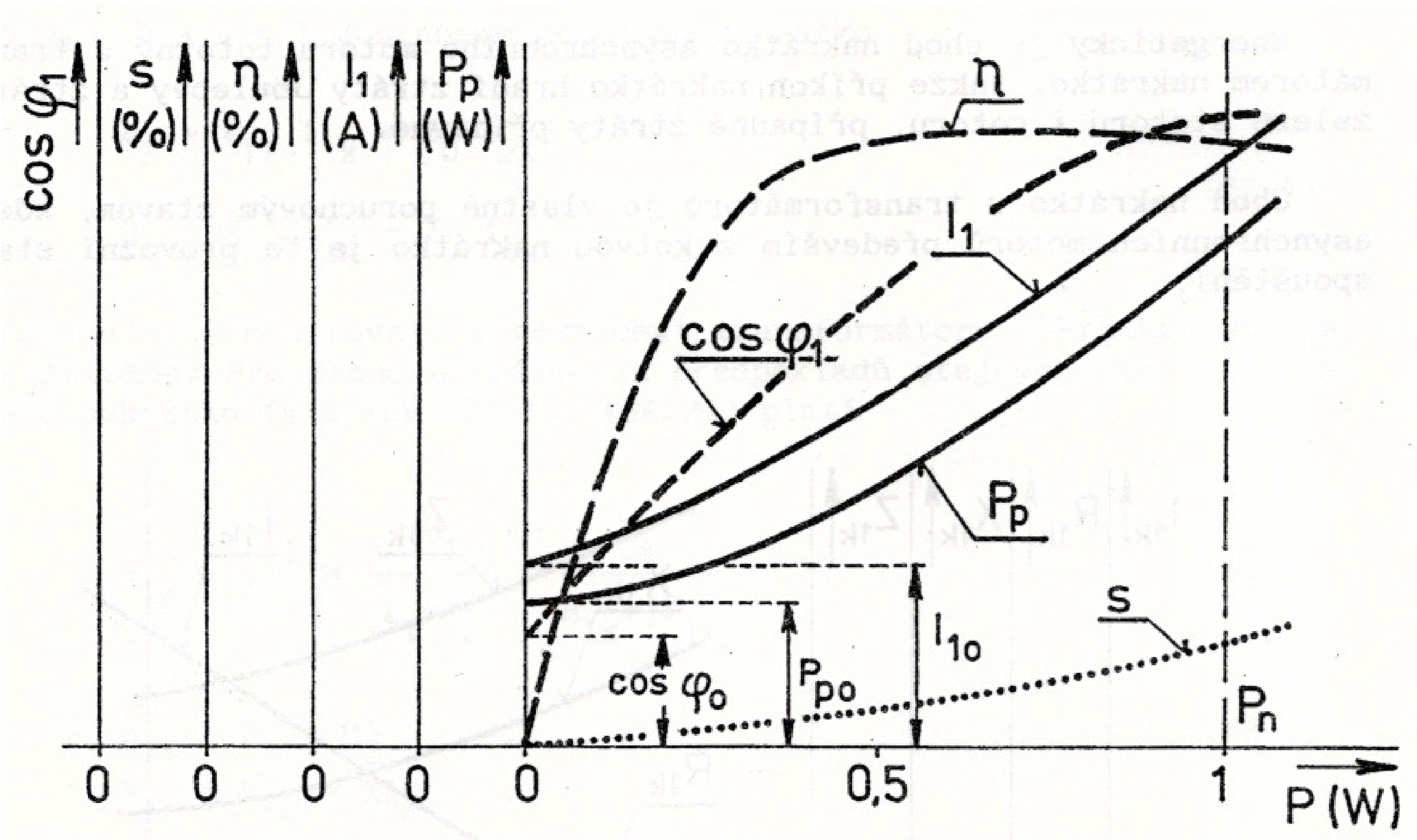
- Short-circuit run



- $I_{1k} = 4 – 7\ I_n$

IM - characteristics

- Load run



IM Startup

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- Direct connection – to the 3 - 5 - 7 kW

  (depends on short-circuit net capability)

- Reduced voltage – delta – start connection

  $$(U \rightarrow \frac{U}{\sqrt{3}} \rightarrow \frac{M}{3} \rightarrow P = M \cdot \omega \rightarrow \frac{P}{3})$$

  - Autotransformer
  - Soft start – obr. 9.10

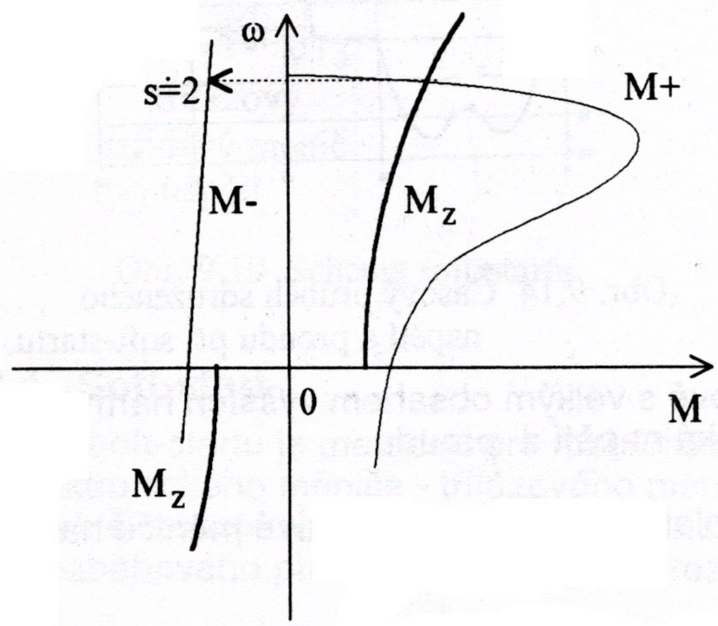
- Change of rotor resistance

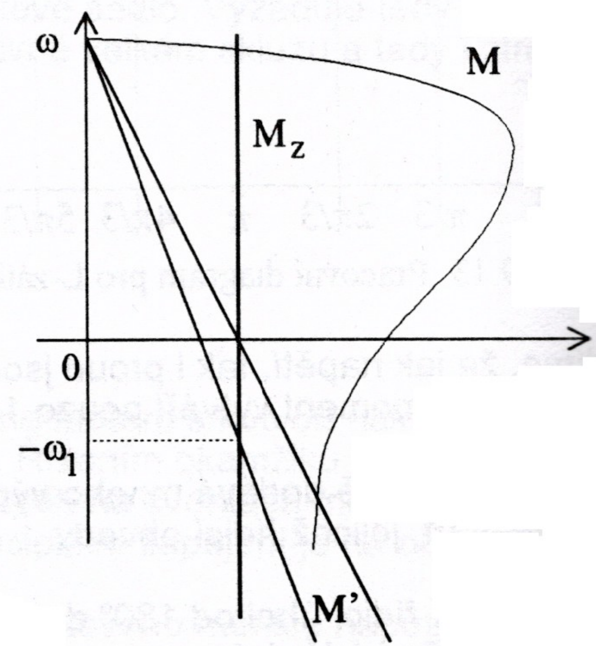
  (possible only at slip - ring rotor)

- Double squirrel cage rotor
- Vortex cage

IM Braking

- 1) Countercurrent s>1
  (Braking torque is lower than starting torque, great current surge)





IM Braking

- 2) DC current

  (DC source necessary, unequal load of phases, ineffective at low revolutions)

- 3) Rekuperative braking

  (cross from motor run to the generator run at active torque or wind, water station, we have to supply by reaktive power)

IM speed control

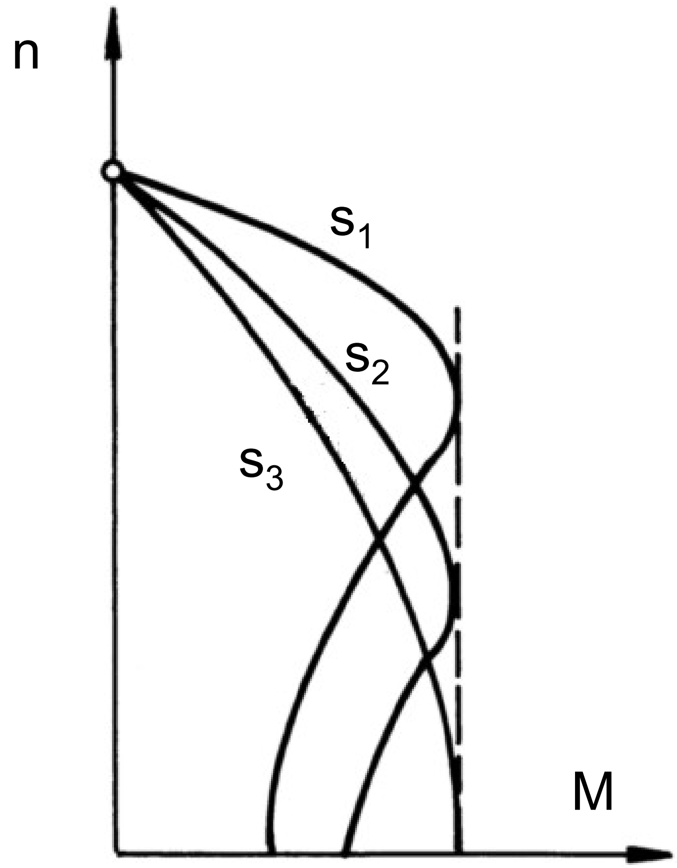
$$n = n_s(1-s) = \frac{60f}{p}(1-s)$$

1) Poles switching

(n_s change (3000 – 750), motor efficiency falls off, because utilizing of motor is lower, the motor has max. 2 speeds)

IM speed control

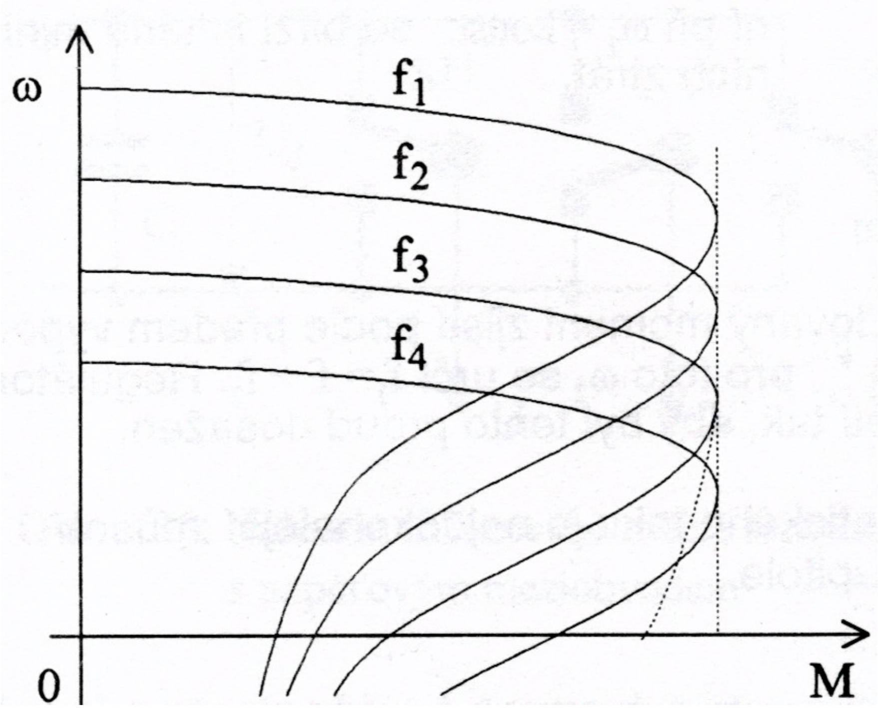
- 2) Slip increasing, changing by R'_2



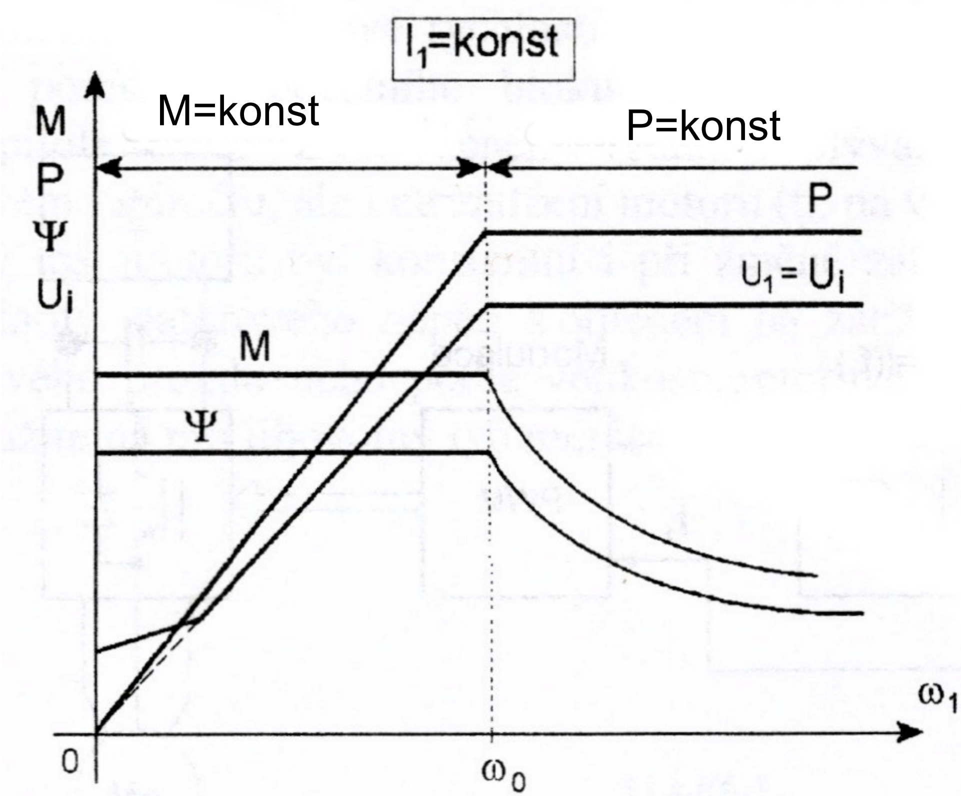
IM speed control

- variable frequence

$$M_{\max} = \frac{m_1}{2c_1\omega_1} \cdot \frac{U_1^2}{X_{1K}} = \frac{m_1}{2c_1 \cdot \pi \cdot f_1} \cdot \frac{U_1^2}{2\pi f_1 \cdot L_1} \Rightarrow M = \mathrm{f}\left(\frac{U_1^2}{f_1^2}\right) \Rightarrow \frac{U_1}{f_1} \cong konst.$$



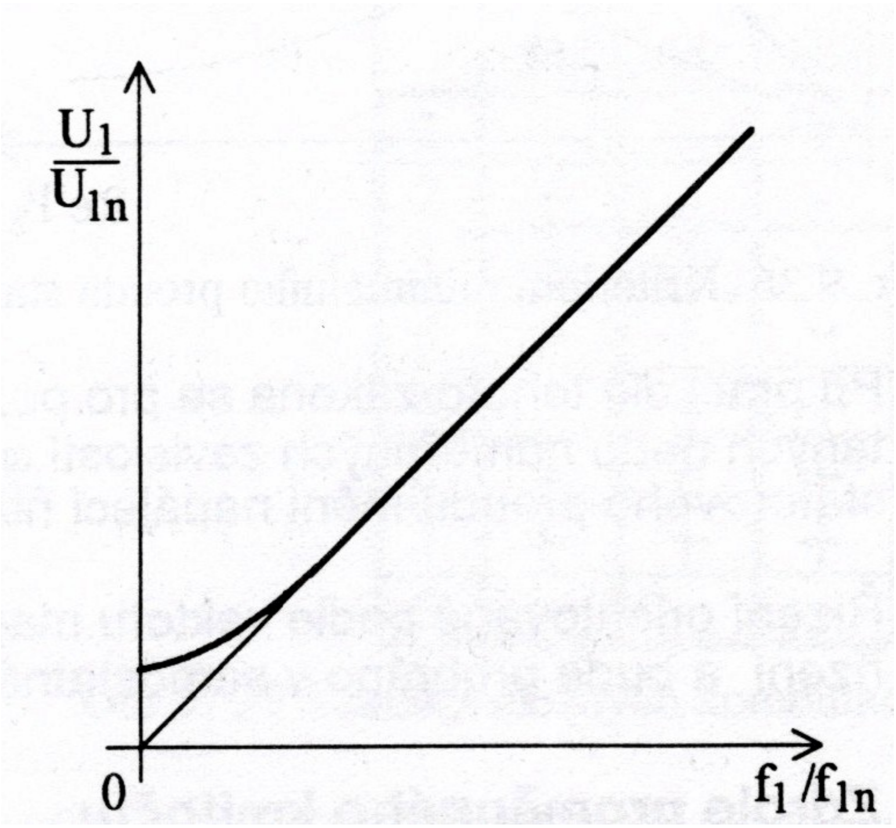
IM speed control



For $n > n_s$, $U = U_n$, => IM is de-excitated, => motor torque diminishes, starting torgue as well

IM speed control

- Influence compensation of stator resistance



IM speed control

- Vector control
  - It uses mathematical model and works not only with sizes of U and I, but with the vector directions too
  - Suitable for dynamical processes with surge load
  - It uses the principle of speed control at DC machine with separate extitation
  - There are separately controled flux and torque
  - The converters for vector speed control are more expensive, but I get the co-ordinate drive with DC-motor with external excitation with speed sensor

Thank you for yours attention

Tento materiál vznikl v rámci projektu ESF CZ.1.07/2.2.00/28.0050
Modernizace didaktických metod a inovace výuky technických předmětů,
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