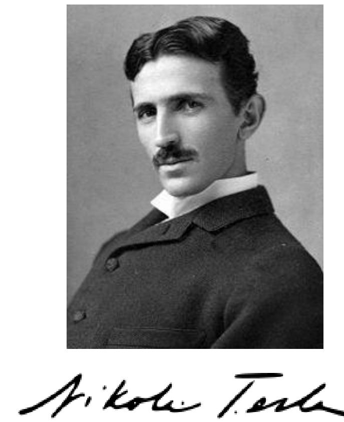
ELEKTROMOTORNI POGONI SA ASINHRONIM MOTOROM

Proučavamo samo pogone sa trofaznim motorom.

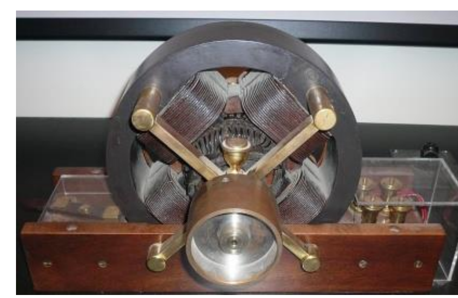
Najčešće korišćeni motor u elektromotornim pogonima.

Prednosti asinhronih motora:

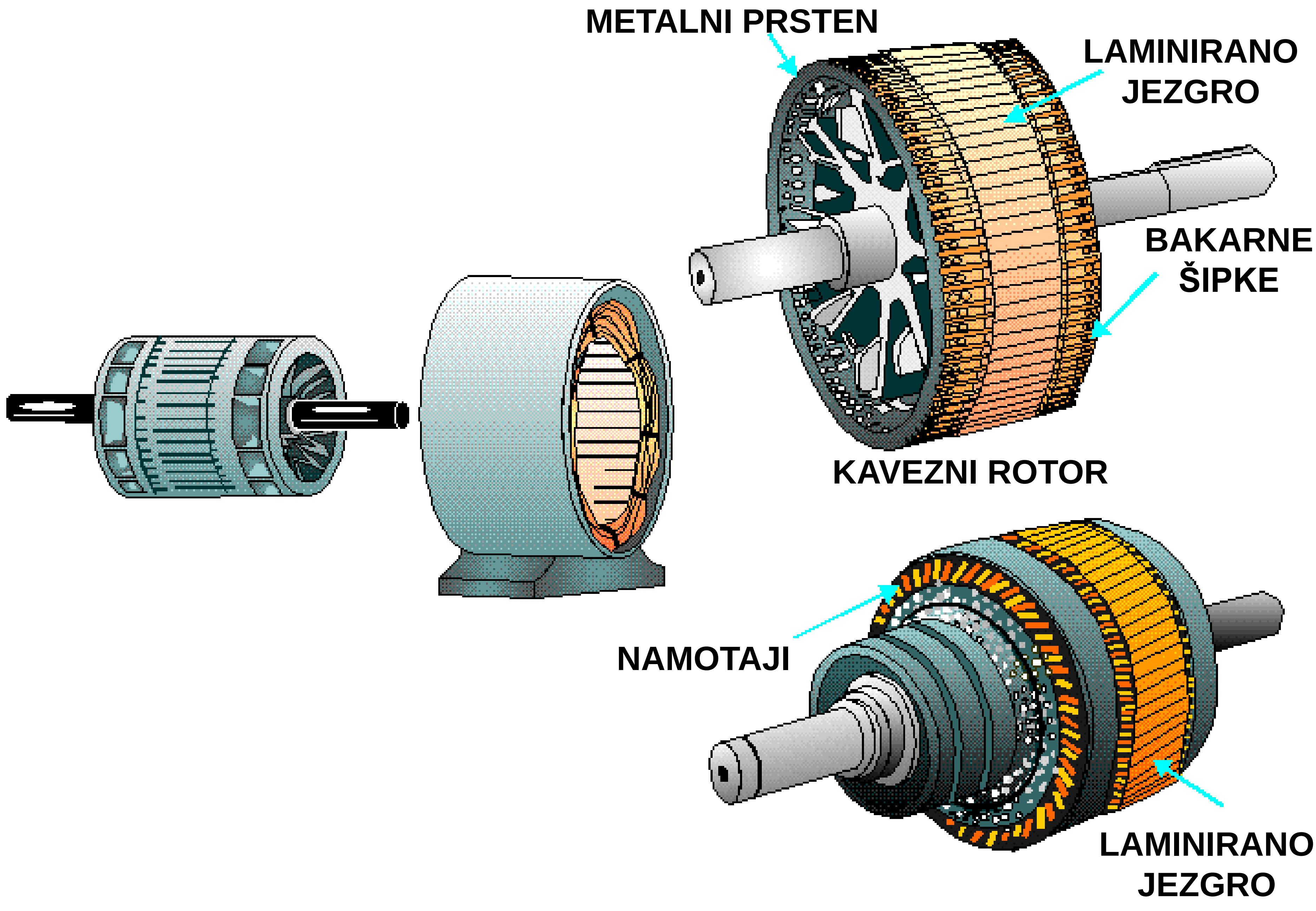
- jednostavna konstrukcija;
- mala cena;
- visoka energetska efikasnost.



1856-1943

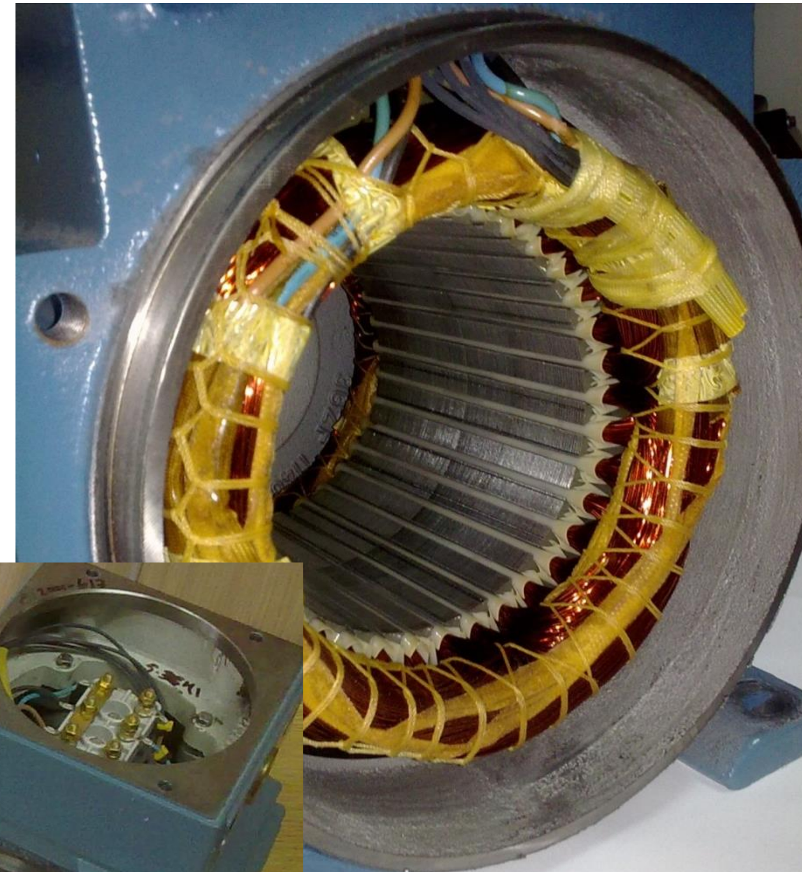


Asinhroni (indukcioni) motor
Patent iz 1888 godine

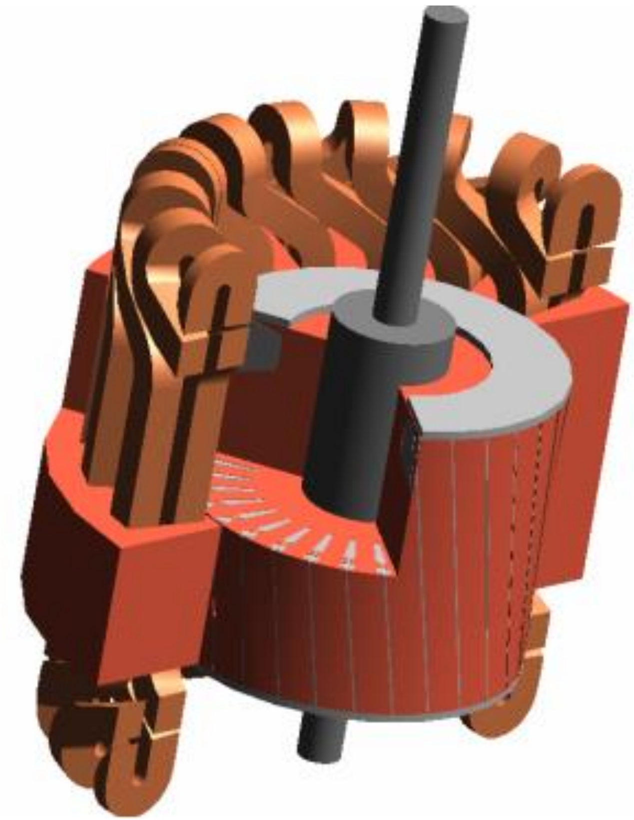

METALNI PRSTEN
LAMINIRANO JEZGRO
BAKARNE ŠIPKE
KAVEZNI ROTOR
NAMOTAJI
LAMINIRANO JEZGRO
NAMOTANI ROTOR

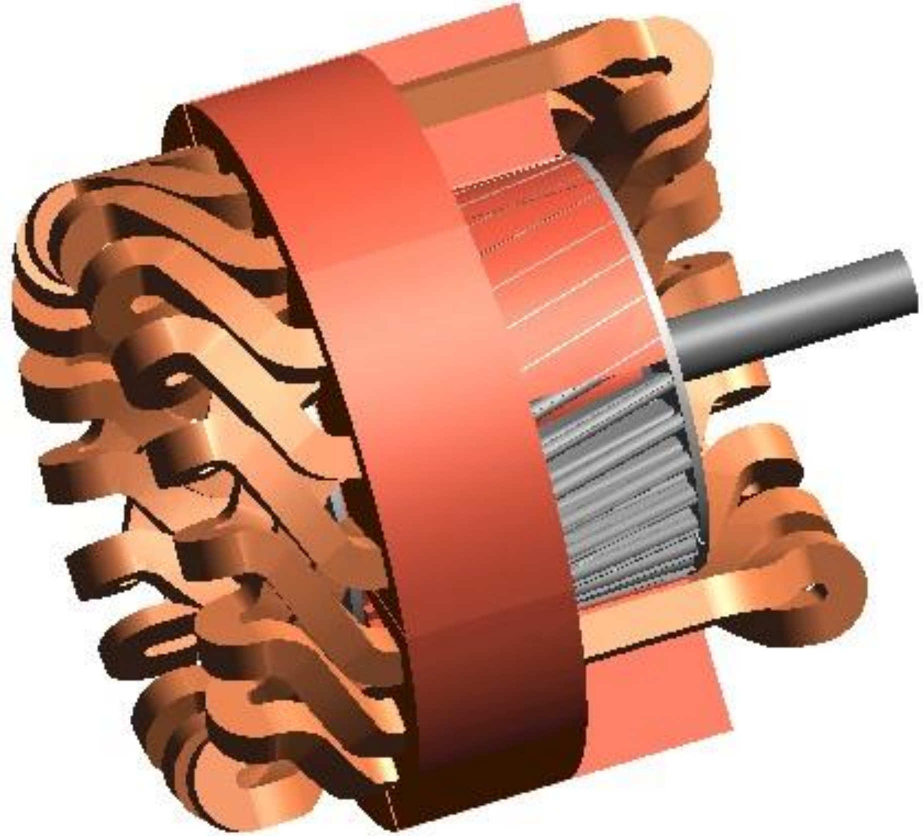
Motor sa kaveznim rotorom

Stator



Rotor



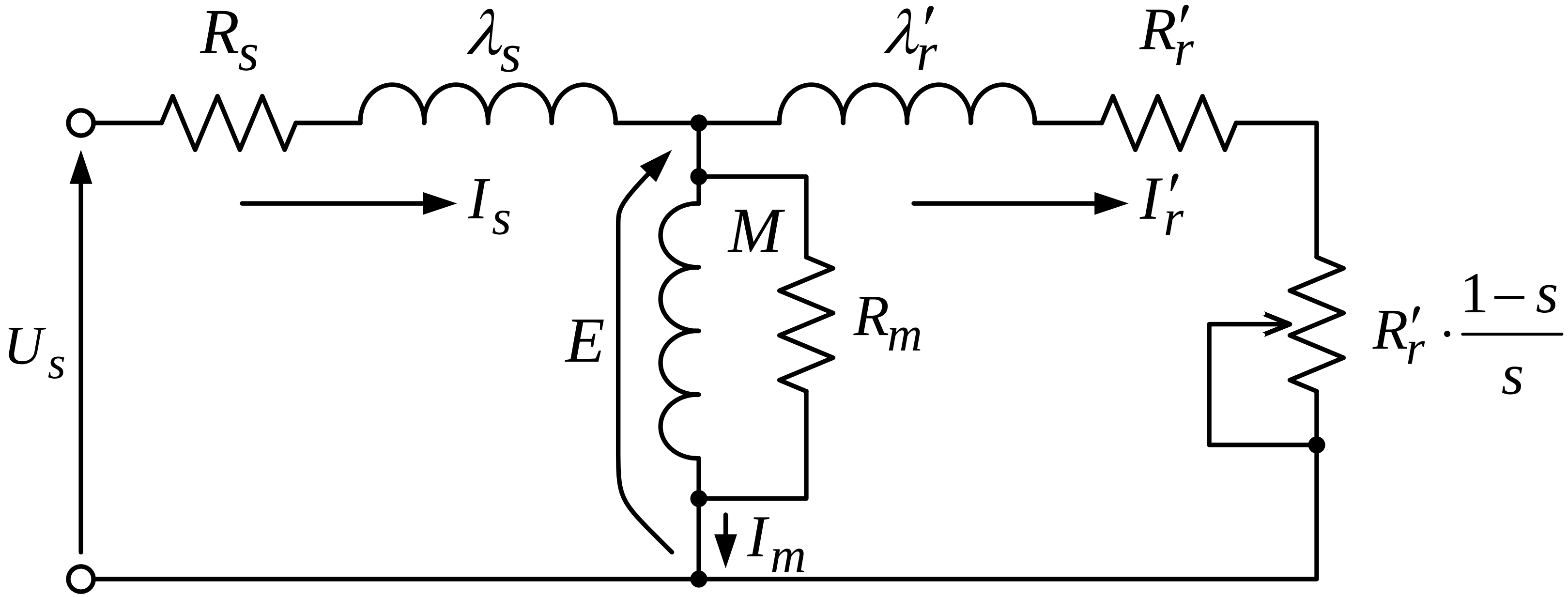


ROTOR ASINHRONOG MOTORA NAJČEŠĆE IMA ZAKOŠENE ŽLEBOVE DA BI SE MINIMIZIRALE PULSACIJE MOMENTA

POPREČNI PRESEK ASINHRONOG MOTORA

STATIKA POGONA

Ekvivalentna šema motora (po fazi).



Rotorske veličine su svedene na stator.

Ostale karakteristične veličine:

$f_s\ [\mathrm{Hz}]$ - statorska učestanost;

$f_r\ [\mathrm{Hz}]$ - rotorska učestanost;

$\omega_s = 2\pi \cdot f_s\ [\mathrm{rad.el./s}]$ - kružna učestanost statora ili električna sinhrona brzina ili brzina obrtnog polja (električna)

$\omega_r = 2\pi \cdot f_r\ [\mathrm{rad.el./s}]$ -kružna učestanost rotora;
U knjizi: apsolutno klizanje

$\omega = \omega_s - \omega_r\ [\mathrm{rad.el./s}]$ - ugaona brzina (električna);

P - broj pari polova;

$\omega_m = \omega / P\ [\mathrm{rad.meh./s} = \mathrm{rad/s}]$ - mehanička ugaona brzina;

$s = \omega_r / \omega_s = (\omega_s - \omega) / \omega_s$ - klizanje.

BAZNE VREDNOSTI

$U_b = U_{sn}$ – nominalna efektivna vrednost faznog napona

$I_b = I_{sn}$ – nominalna efektivna vrednost fazne struje

$\omega_b = 2\pi f_{sn}$ – nominalna kružna učestanost (električna)

$$Z_b = U_b / I_b$$

$$P_b = q\, U_b\, I_b = 3\, U_b\, I_b$$ q - broj faza = 3

$$M_b = P_b / (\omega_b / P)$$

TOKOVI SNAGE

$P_s = 3 \cdot U_s \cdot I_s \cdot \cos\varphi_s$ - snaga statora, snaga uzeta iz izvora;

$P_{s\,Cu} = 3 \cdot R_s \cdot I_s^2$ - snaga gubitaka u bakru statora;

$P_{Fe} = 3 \cdot E^2 / R_m$ - snaga gubitaka u gvožđu $\left(\lim\limits_{R_m \to \infty} P_{Fe} \to 0 \right)$

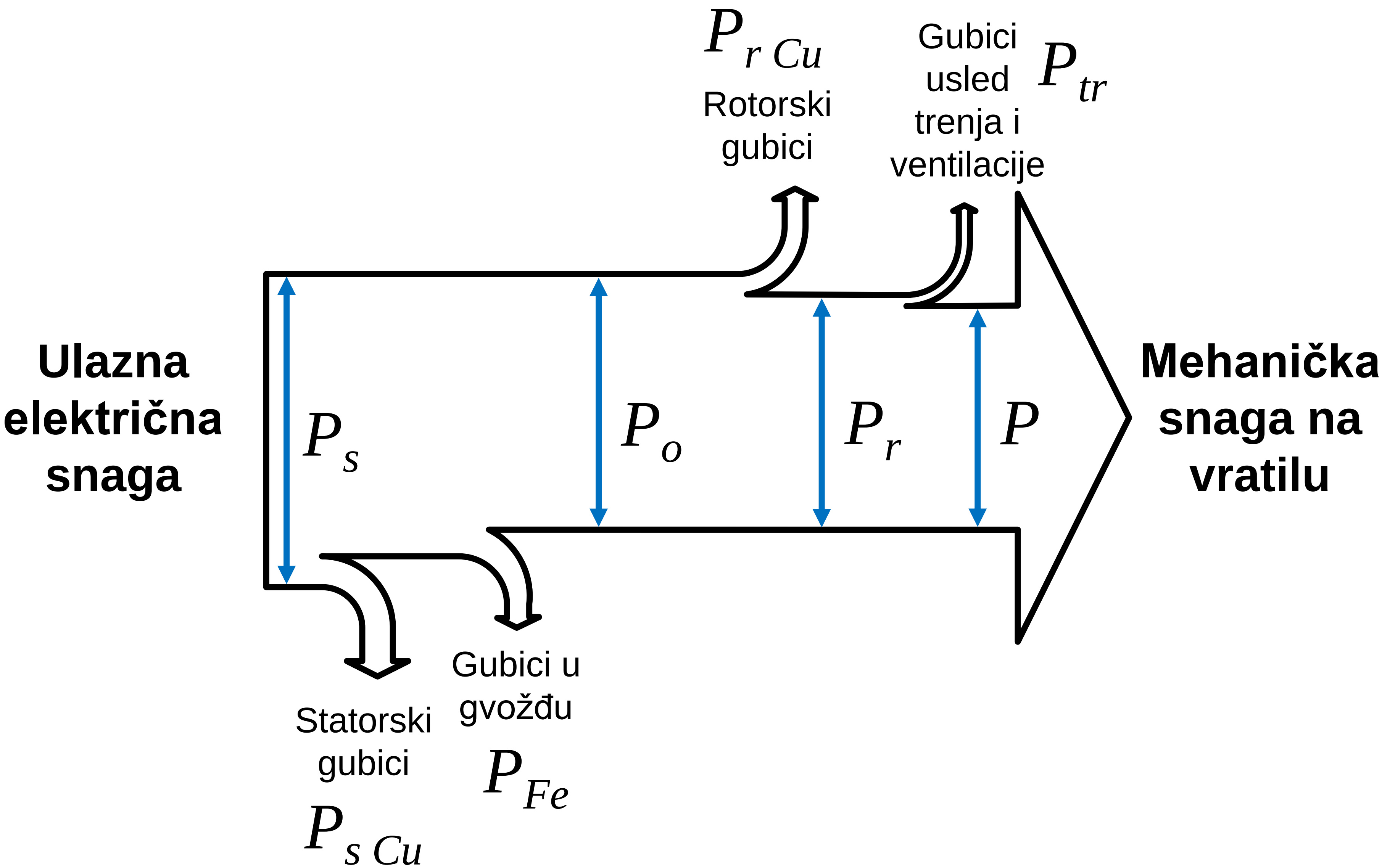
$P_o = 3 \cdot \left(R_r' / s \right) \cdot \left(I_r' \right)^2$ - snaga obrtnog magnetnog polja;

$P_{r\,Cu} = 3 \cdot R_r' \cdot \left(I_r' \right)^2 = s \cdot P_o$ - snaga gubitaka u bakru rotora;

$P_r = P_o - P_{r\,Cu} = 3 \cdot R_r' \cdot \frac{1-s}{s} \cdot \left(I_r' \right)^2 = \left(1 - s \right) \cdot P_o$ - mehanička snaga;

P_{tr} - snaga gubitaka na trenje i ventilaciju;

$P = P_r - P_{tr}$ - korisna mehanička snaga.



Napomena: Snaga P_{tr} prenosi se u opterećenje!

Elektromagnetni moment:

$$M_e = \frac{P_r}{\omega_m} = \underbrace{3 \cdot R_r' \cdot \frac{1-s}{s} \cdot \left(I_r'\right)^2}_{P_r} \cdot \frac{1}{\omega_m} =$$

$$= 3 \cdot R_r' \frac{1-s}{s} \cdot \left(I_r'\right)^2 \cdot \left(\frac{\omega_s}{\omega_s}\right) \cdot \frac{P}{\omega} =$$

$$= 3 \cdot P \cdot \frac{R_r'}{s} \cdot \frac{\left(I_r'\right)^2}{\omega_s} = 3 \cdot P \cdot R_r' \frac{\left(I_r'\right)^2}{\omega_r}$$

MEHANIČKA KARAKTERISTIKA
(statička karakteristika momenta)

U PREDSTOJEĆOJ ANALIZI PRETPOSTAVIMO DA JE $E = \text{const.}$

$$M_e = M_e(\omega)$$

$$\left|I'_r(s)\right| = \frac{|E|}{\sqrt{\left(R'_r/s\right)^2 + \left(\omega_s \cdot \lambda'_r\right)^2}}$$

$$M_e(s) = 3 \cdot P \cdot \frac{E^2}{\omega_s} \frac{R'_r/s}{\left(R'_r/s\right)^2 + \left(\omega_s \cdot \lambda'_r\right)^2}$$

$$M_e(\omega_r) = 3 \cdot P \cdot \left(\frac{E}{\omega_s}\right)^2 \frac{\omega_r \cdot R'_r}{\left(R'_r\right)^2 + \left(\omega_r \cdot \lambda'_r\right)^2}$$

Funkcija $M_e\,(s)$ ima ekstremum koji se može naći iz:

$$\frac{dM_e(s)}{ds} = 0$$

Momenat u tački ekstremuma naziva se *PREVALNI MOMENAT* (M_p),
a odgovarajuće klizanje *PREVALNO KLIZANJE* (s_p).

$$s_p = \pm \frac{R_r'}{\omega_s \cdot \lambda_r'}; \qquad M_p = \pm \frac{3 \cdot P}{2} \cdot \left(\frac{E}{\omega_s}\right)^2 \frac{1}{\lambda_r'}$$

***KLOSS* - ova FORMULA**

$$\frac{M_e}{M_p} = \frac{2}{\frac{s}{s_p} + \frac{s_p}{s}} = \frac{2}{\frac{\omega_r}{\omega_{rp}} + \frac{\omega_{rp}}{\omega_r}}$$

Važno:

$$\omega_{rp} = \omega_s \cdot s_p = \pm \frac{R_r'}{\lambda_r'} = \text{const.}$$

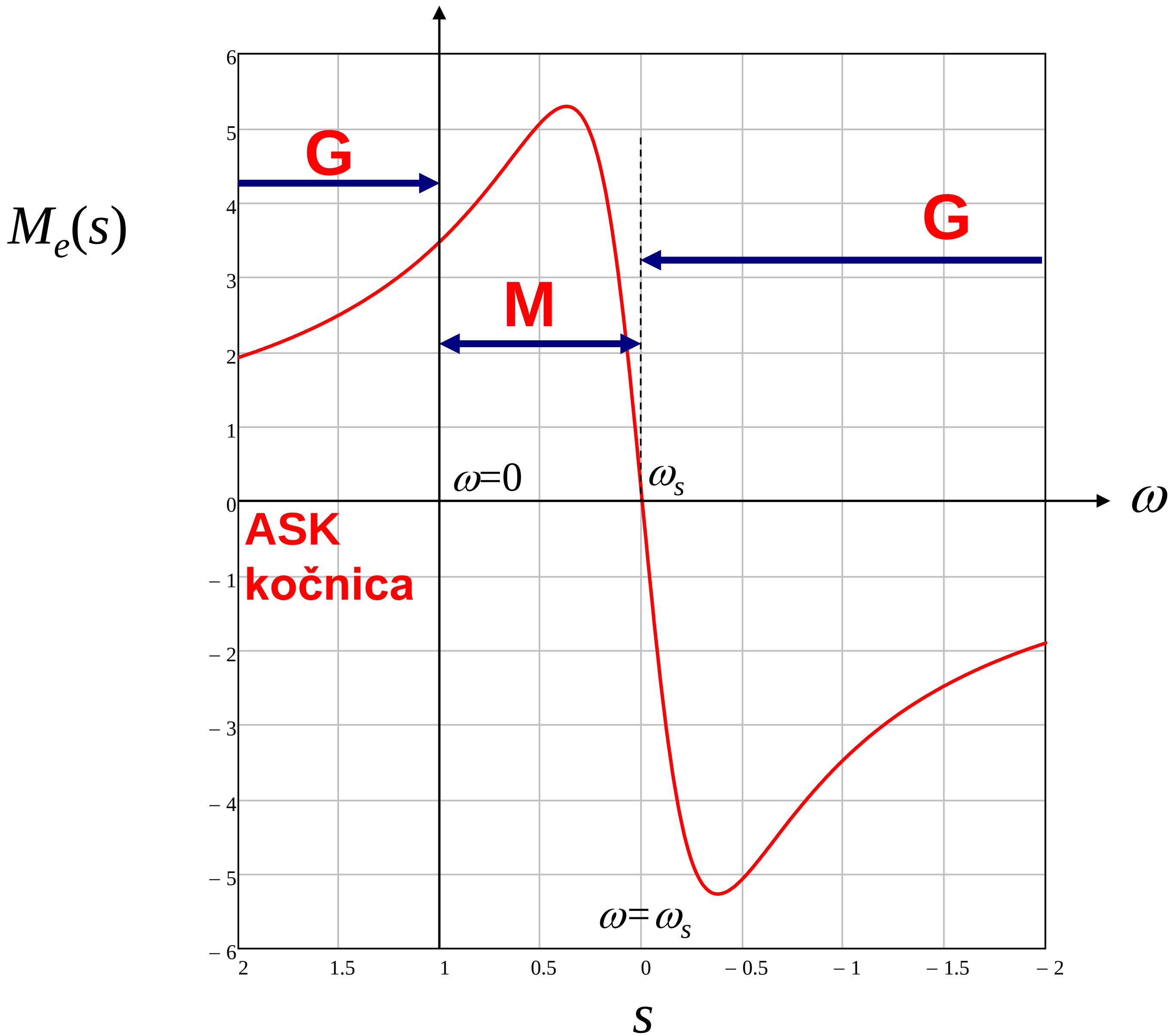
STATIČKE KARAKTERISTIKE STRUJA

$$\vec{I}_s = \vec{I}_r' + \vec{I}_m$$

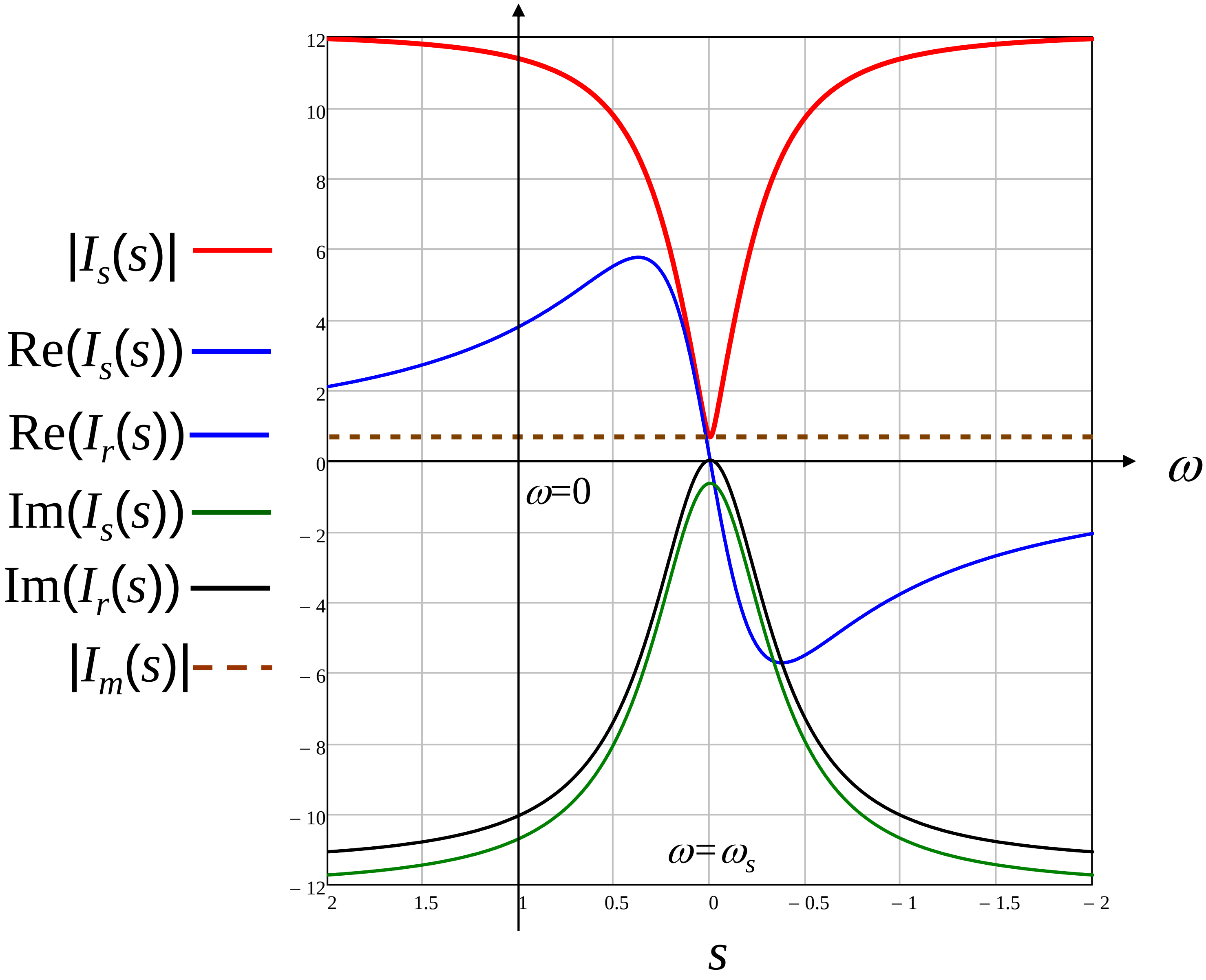
$$\vec{I}_r' = \frac{E \cdot R_r'/s}{\left(R_r'/s\right)^2 + \left(\omega_s \cdot \lambda_r'\right)^2} - j\frac{E \cdot \omega_s \cdot \lambda_r'}{\left(R_r'/s\right)^2 + \left(\omega_s \cdot \lambda_r'\right)^2} = I_{ra}' - jI_{rr}'$$

$$\vec{I}_m = -j\frac{E}{\omega_s \cdot M} \qquad \text{za} \quad P_{Fe} \approx 0 \quad \text{ili} \quad \left(R_m \to \infty\right)$$

Statička karakteristika momenta, pri E=const.



Statičke karakteristike struja, E=const.

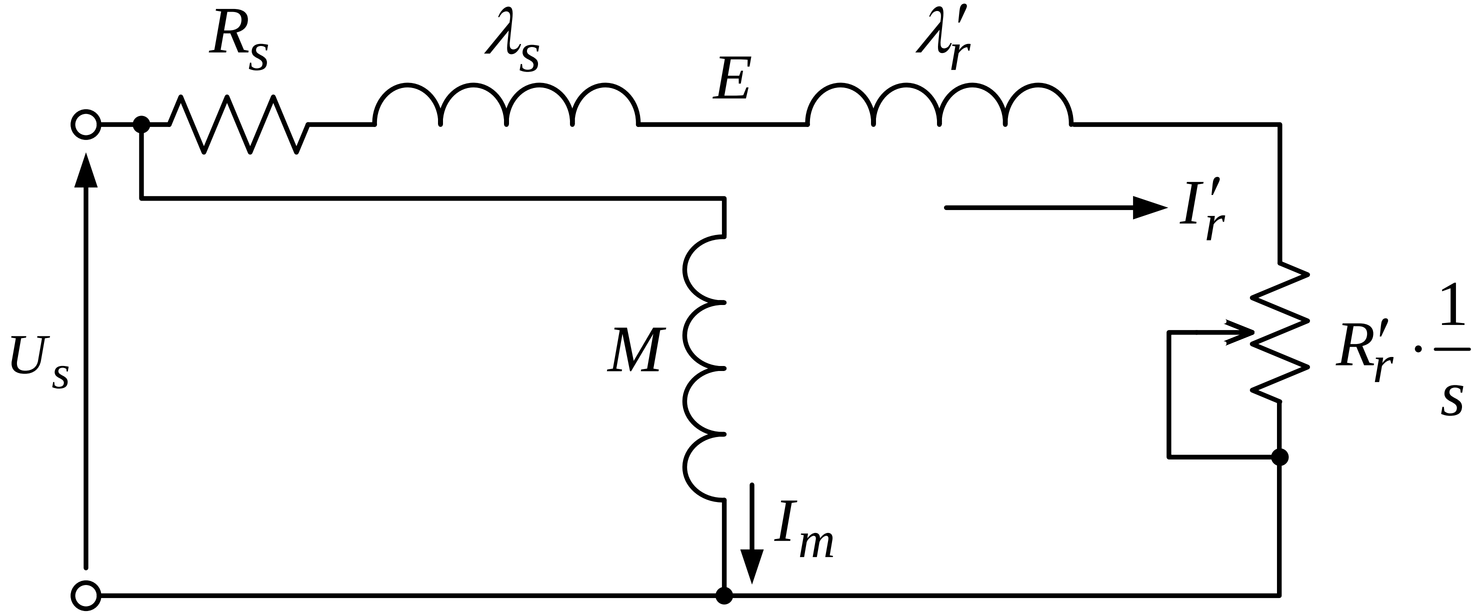


RAZMOTRIMO REALAN (realniji) SLUČAJ

$$E \neq \text{const.} \quad U_s = \text{const.}$$

Dve pretpostavke:

1. $P_{Fe} = 0 \quad \Rightarrow \quad R_m \to \infty$
2. $\omega_s^2 \cdot M^2 >> R_s^2 + \omega_s^2 \cdot \lambda_s^2$ (sasvim realna pretpostavka)



Sa navedenim pretpostavkama se može napisati:

$$\left|\vec{I}_r'\right| = \frac{U_s}{\sqrt{\left(R_s + R_r'/s\right)^2 + \omega_s^2 \cdot \left(\lambda_s + \lambda_r'\right)^2}}$$

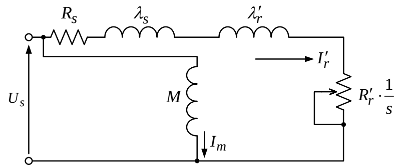
$$M_e = \frac{3 \cdot P \cdot U_s^2}{\omega_s} \frac{R_r'/s}{\left(R_s + R_r'/s\right)^2 + \omega_s^2 \cdot \left(\lambda_s + \lambda_r'\right)^2}$$

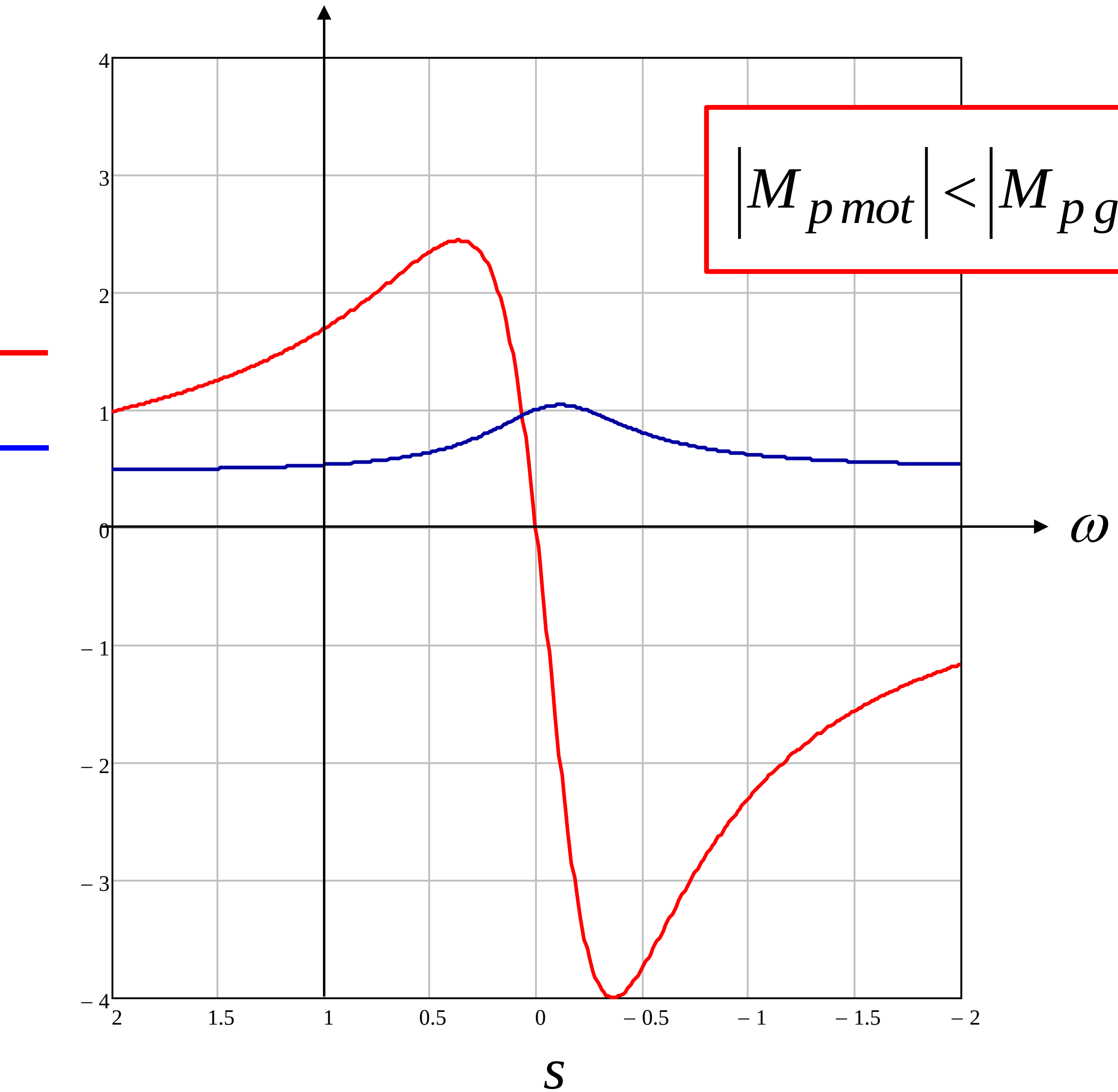
$$s_p = \pm \frac{R_r'}{\sqrt{R_s^2 + \omega_s^2 \cdot \left(\lambda_s + \lambda_r'\right)^2}} = f\left(\omega_s\right)$$

$$M_p = \pm \frac{3 \cdot P \cdot U_s^2}{2 \cdot \omega_s} \cdot \frac{1}{\sqrt{R_s^2 + \omega_s^2 \cdot \left(\lambda_s + \lambda_r'\right)^2} \pm R_s}$$

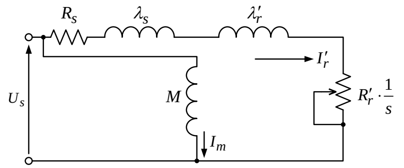
znaci: + za motorni režim;
− za generatorski režim.

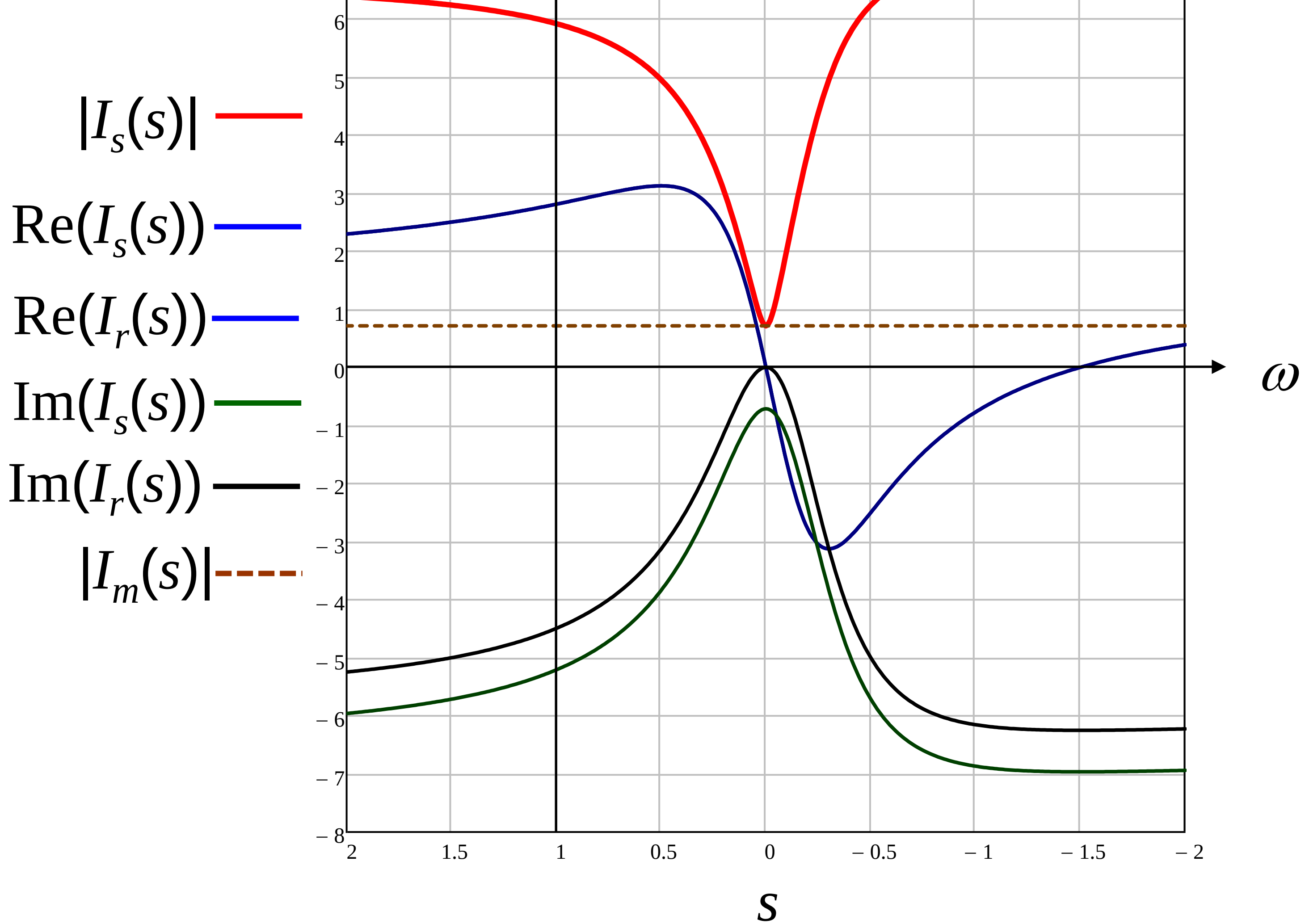
Statička karakteristika momenta, pri $E \neq$ const., $U_s = U_{sn}$ = const.





Statičke karakteristike struja, pri $E \neq$ const., $U_s = U_{sn}$ = const.

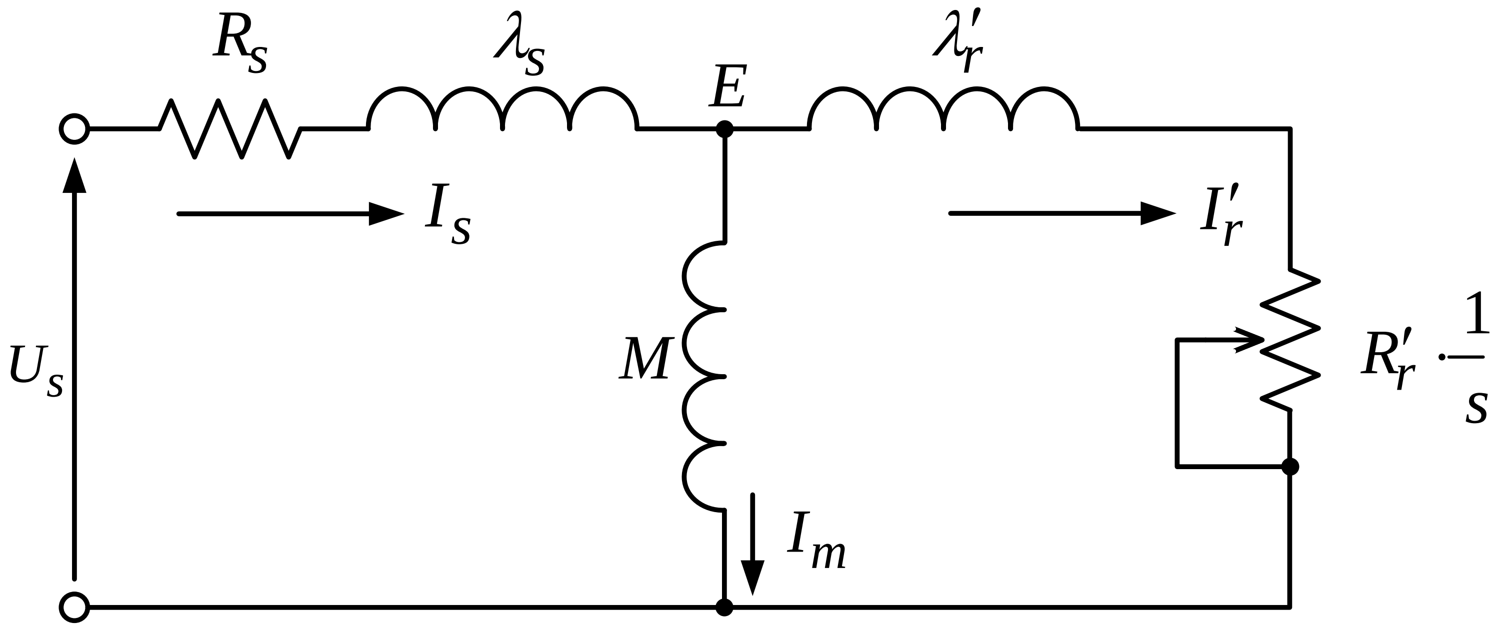




RAZMOTRIMO SLUČAJ BEZ ZANEMARENJA INDUKTIVNOSTI MAGNEĆENJA

$$E \neq \text{const.} \quad U_s = \text{const.}$$

Jedina pretpostavka: $P_{Fe} = 0 \quad \Rightarrow \quad R_m \rightarrow \infty$



$$Z_s = R_s + j \cdot \omega_s \cdot \lambda_s \qquad Z'_r(s) = R'_r / s + j \cdot \omega_s \cdot \lambda'_r$$

$$Z_m = j \cdot \omega_s \cdot M$$

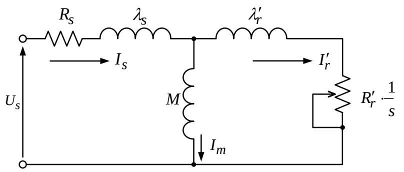
$$Z_e(s) = Z_s + Z_m \,||\, Z'_r(s)$$

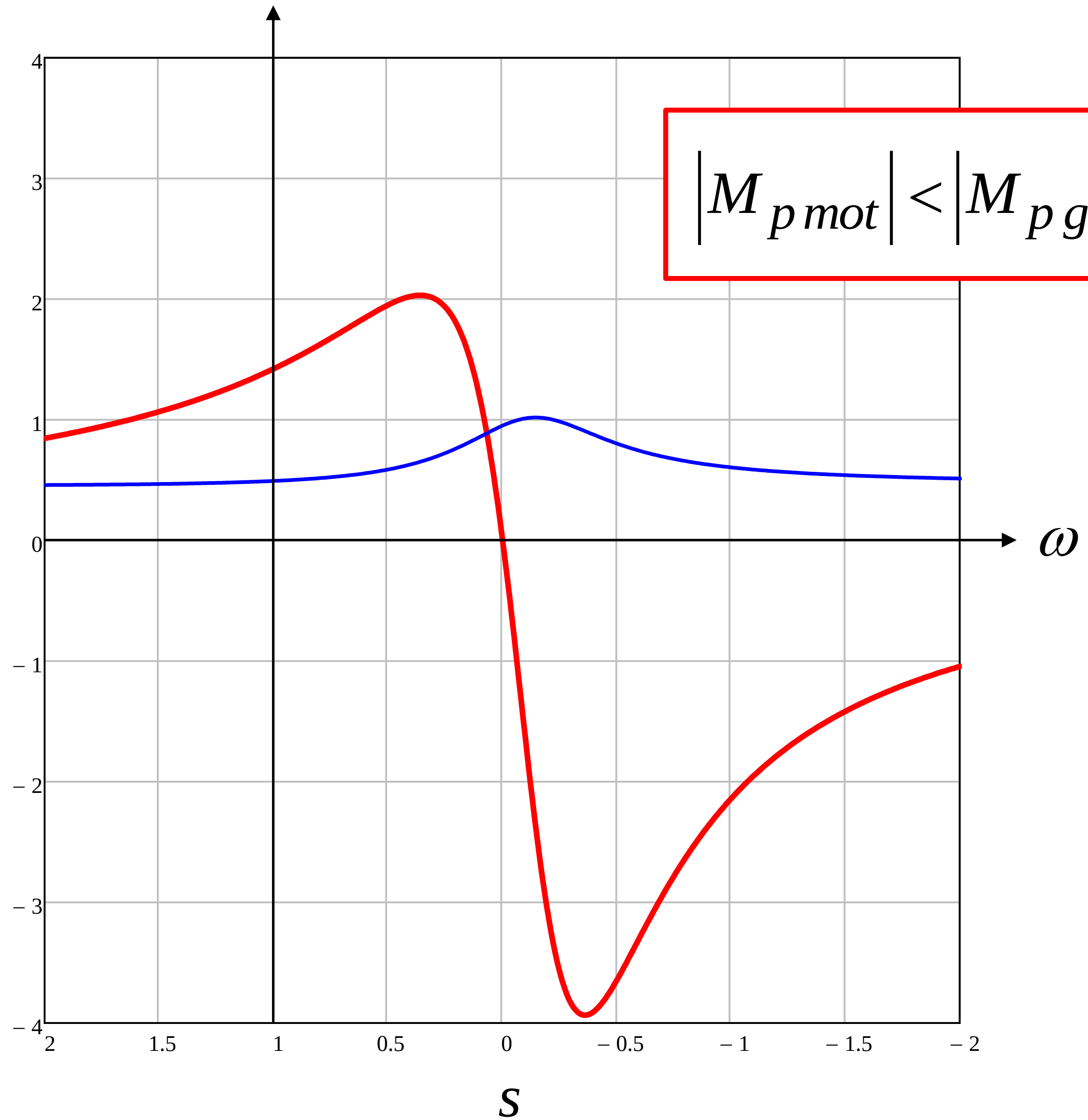
$$\vec{U}_s = U_s + j \cdot 0 = U_s \qquad \vec{I}_s(s) = \frac{U_s}{Z_e(s)} \qquad \vec{E}(s) = U_s - Z_s \cdot \vec{I}_s$$

$$\vec{I}_m(s) = \frac{\vec{E}(s)}{Z_m} \qquad \vec{I}'_r(s) = \frac{\vec{E}(s)}{Z'_r(s)} = \vec{I}_s(s) - \vec{I}_m(s)$$

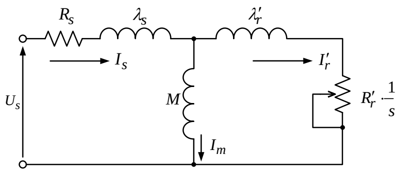
$$M_e = \frac{P_r}{\omega_m} = 3 \cdot P \cdot \frac{R'_r}{s} \cdot \frac{\left|\vec{I}'_r\right|^2}{\omega_s} = 3 \cdot P \cdot R'_r \frac{\left|\vec{I}'_r\right|^2}{\omega_r}$$

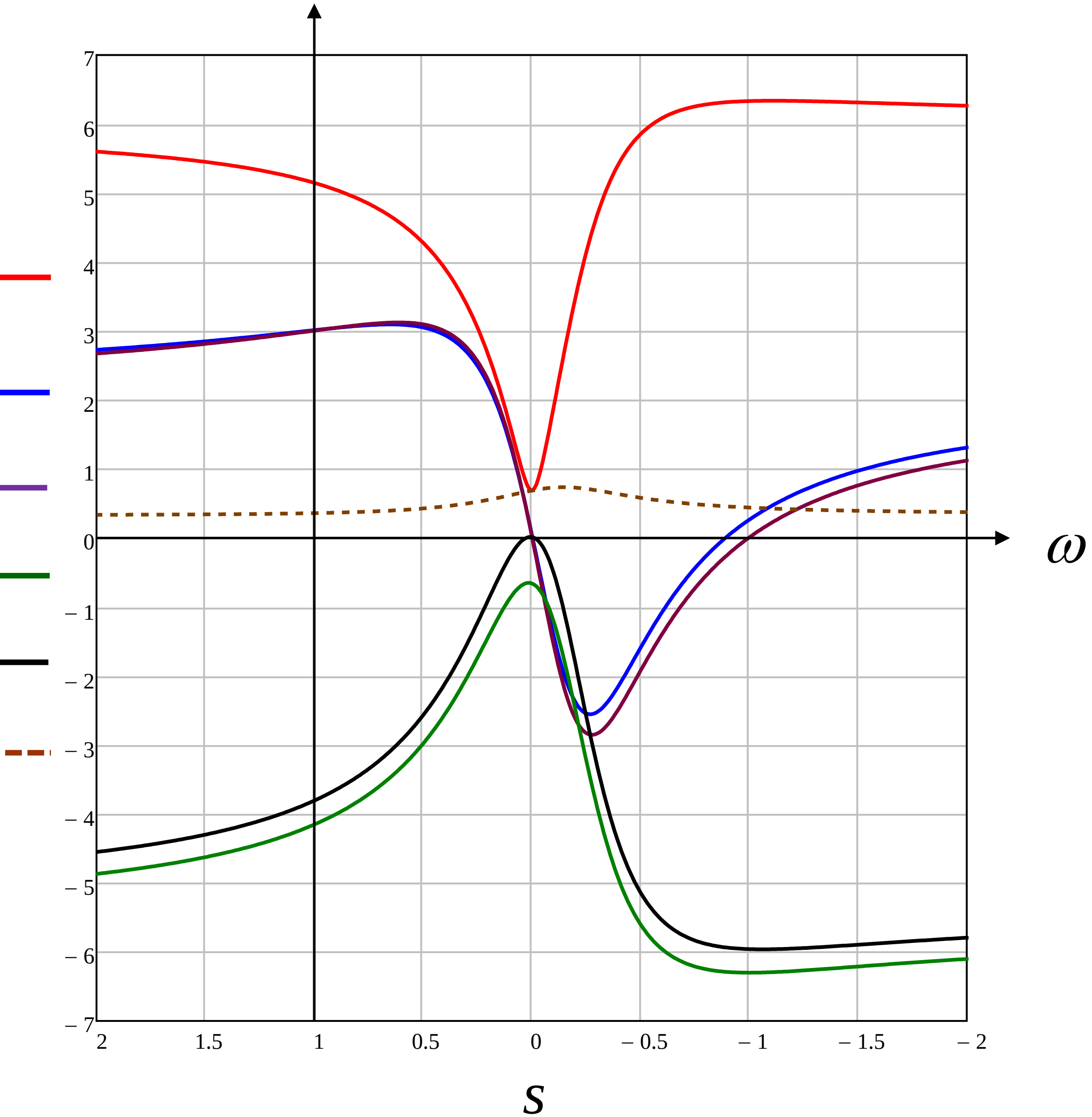
Statička karakteristika momenta, pri $E \neq \text{const.}$, $U_s = U_{sn} = \text{const.}$





Statičke karakteristike struja, pri $E \neq$ const., $U_s = U_{sn}$ = const.





Kod velikih mašina može se smatrati: $R_s \approx 0 \quad M \gg \left(\lambda_s,\, \lambda_r'\right)$

Sada je:

$$M_e \approx \frac{3 \cdot P \cdot U_s^2}{\omega_s} \cdot \frac{R_r'/s}{\left(R_r'/s\right)^2 + \omega_s^2 \cdot \left(\lambda_s + \lambda_r'\right)^2}$$

Analitički izraz momenta za Γ šemu

$$s_p = \pm \frac{R_r'}{\omega_s \cdot \left(\lambda_s + \lambda_r'\right)} \qquad \omega_s \cdot s_p = \omega_{rp} = \pm \frac{R_r'}{\left(\lambda_s + \lambda_r'\right)}$$

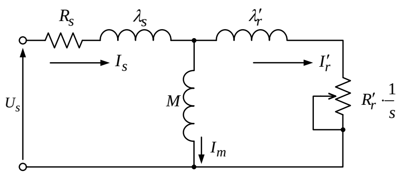
$$M_p = \pm \frac{3 \cdot P}{2} \cdot \left(\frac{U_s}{\omega_s}\right)^2 \cdot \frac{1}{\lambda_s + \lambda_r'}$$

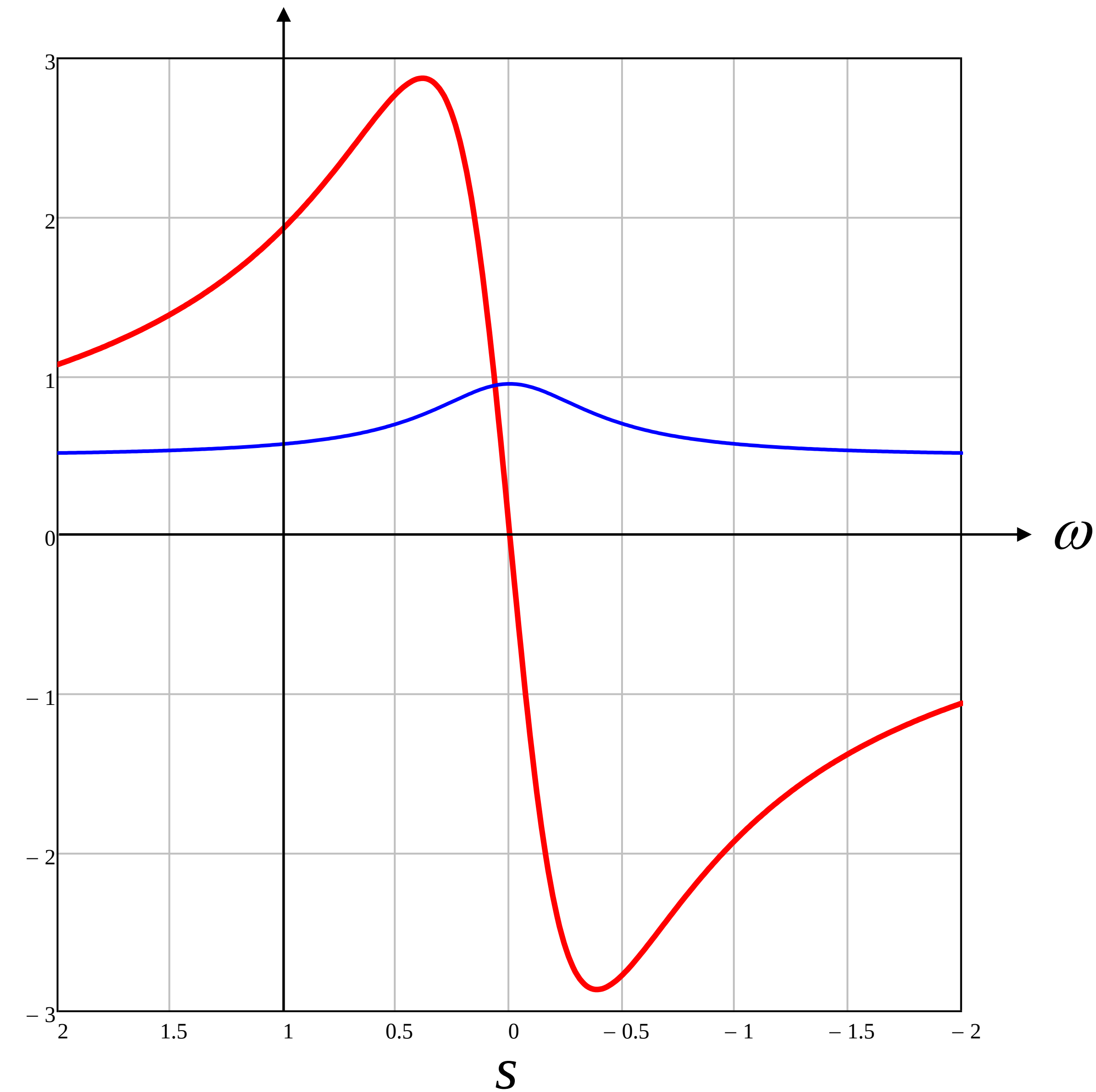
Veoma slično kao kod E=const. Može se izvesti *KLOSS* - ova formula.

$$\frac{M_e}{M_p} = \frac{2}{\frac{s}{s_p} + \frac{s_p}{s}} = \frac{2}{\frac{\omega_r}{\omega_{rp}} + \frac{\omega_{rp}}{\omega_r}}$$

Statička karakteristika momenta, pri $E \neq \text{const.}$, $U_s = U_{sn} = \text{const.}$

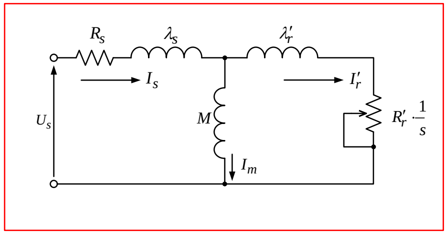
$R_s=0$

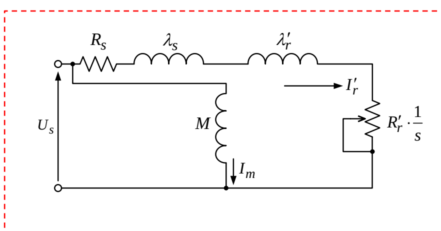




Statička karakteristika momenta, pri $E \neq \text{const.}$, $U_s = U_{sn} = \text{const.}$

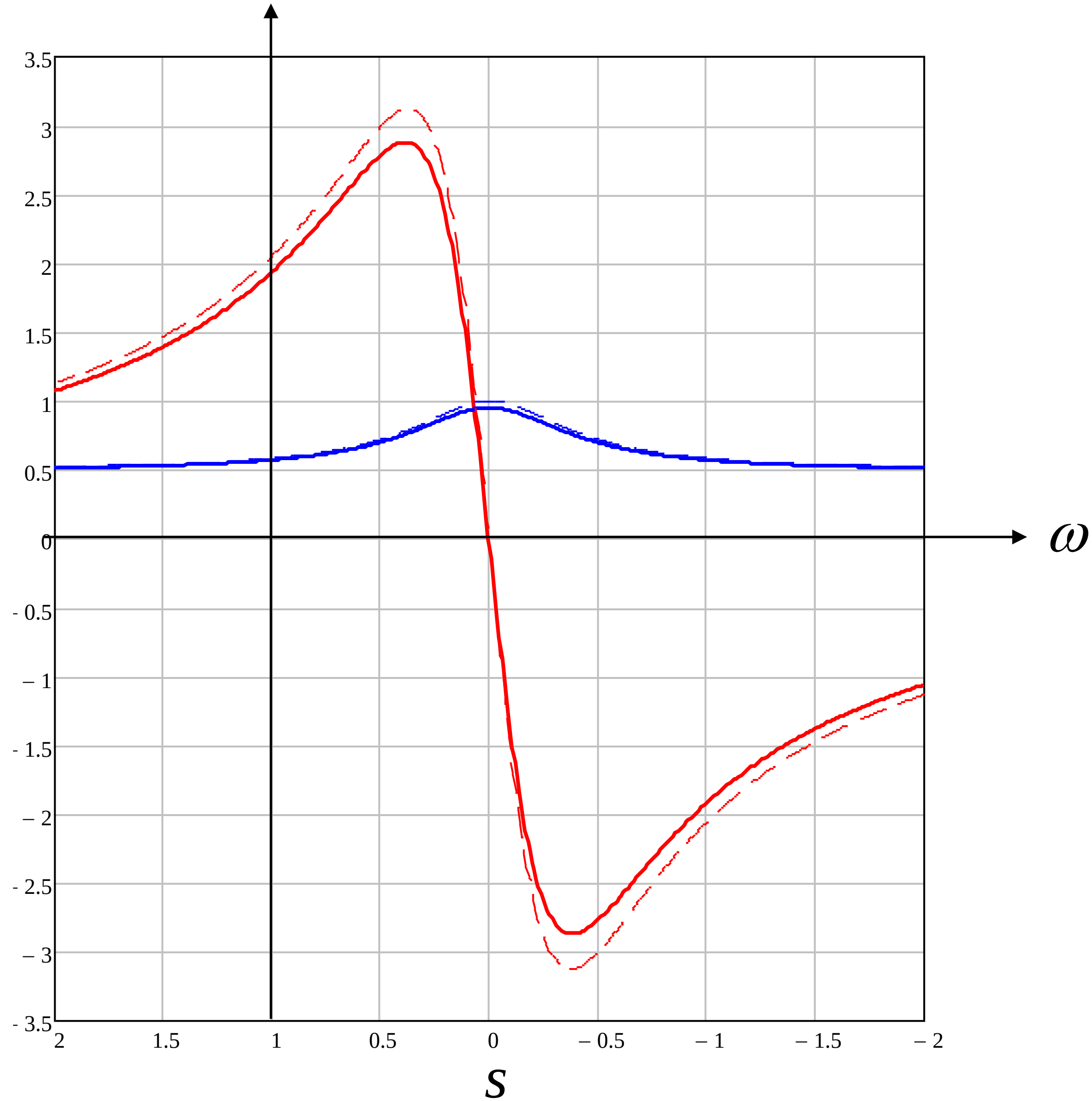
$R_s = 0$





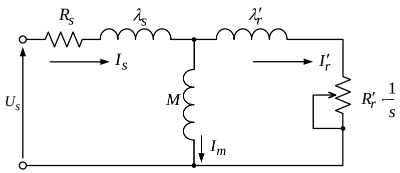
$M_e(s)$

$|E(s)|$

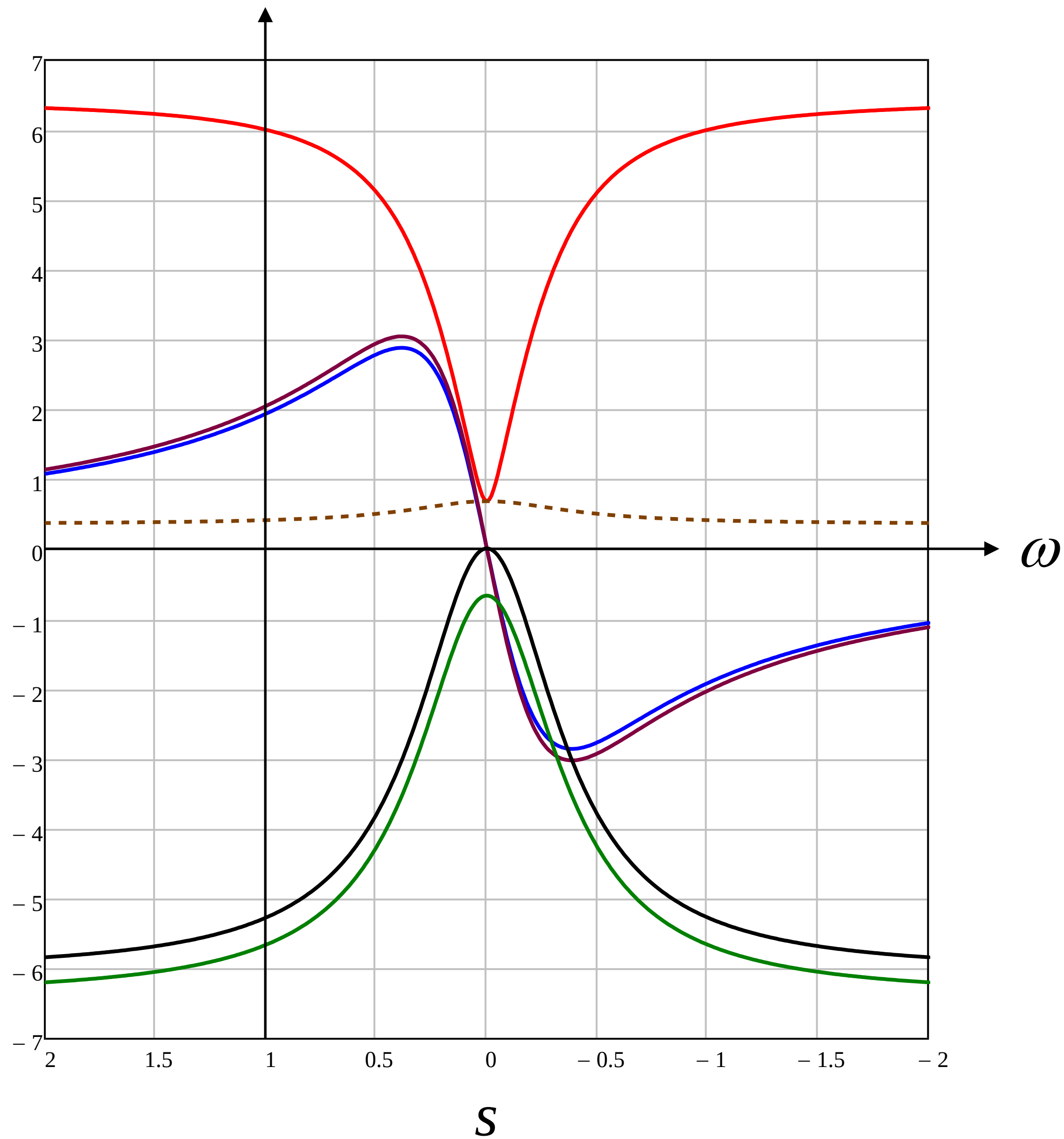


Statičke karakteristike struja, pri $E \neq$ const., $U_s = U_{sn} =$ const.

$R_s = 0$



$|I_s(s)|$
$\mathrm{Re}(I_s(s))$
$\mathrm{Re}(I_r(s))$
$\mathrm{Im}(I_s(s))$
$\mathrm{Im}(I_r(s))$
$|I_m(s)|$

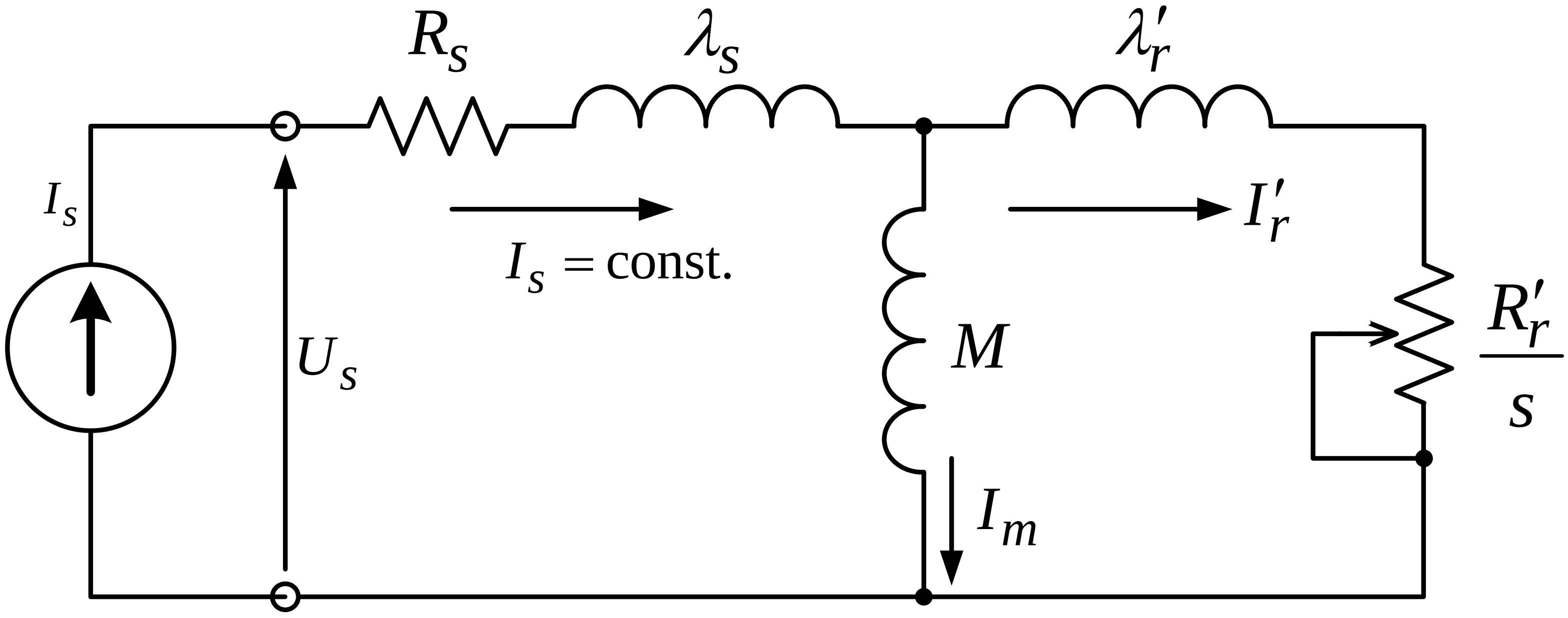


STRUJNO NAPAJANJE ASINHRONOG MOTORA

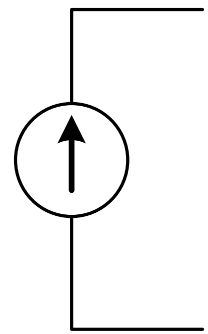
$$I_s = \text{const.}$$

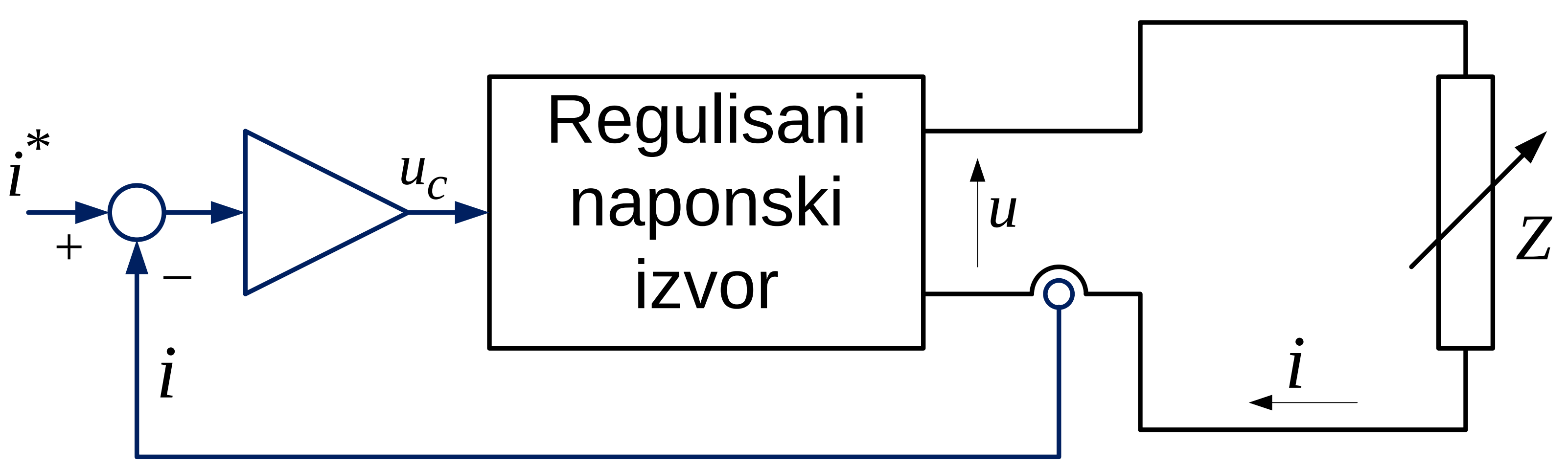
Ovakav način napajanja pruža nove mogućnosti kod napajanja iz invertora.

U analizi zanemarujemo gubitke u gvožđu. $P_{Fe} = 0$



Praktična realizacija strujnog generatora





Statička karakteristika momenta se izvodi iz:

$$\vec{I}_s = \vec{I}_m + \vec{I}_r' \qquad \vec{I}_m \cdot Z_m = \vec{I}_r' \cdot Z_r$$

$$\vec{I}_r' = \frac{Z_m}{Z_r' + Z_m} \cdot \vec{I}_s = \frac{j \cdot \omega_s \cdot M}{R_r'/s + j \cdot \omega_s \cdot \left(M + \lambda_r'\right)} \cdot \vec{I}_s$$

$$\left|\vec{I}_r'\right|^2 = \frac{\left(\omega_s \cdot M\right)^2}{\left(R_r'/s\right)^2 + \omega_s^2 \cdot \left(M + \lambda_r'\right)^2} \cdot \left|\vec{I}_s\right|^2 = \frac{\left(\omega_r \cdot M\right)^2}{\left(R_r'\right)^2 + \omega_r^2 \cdot \left(M + \lambda_r'\right)^2} \cdot \left|\vec{I}_s\right|^2$$

$$M_e = 3 \cdot P \cdot \frac{R_r'}{s} \frac{\omega_s \cdot M^2}{\left(\frac{R_r'}{s}\right)^2 + \omega_s^2 \cdot \left(M + \lambda_r'\right)^2} \cdot \left|\vec{I}_s\right|^2 =$$

$$= 3 \cdot P \cdot \frac{\omega_r \cdot R_r' \cdot M^2}{\left(R_r'\right)^2 + \omega_r^2 \cdot \left(M + \lambda_r'\right)^2} \cdot \left|\vec{I}_s\right|^2 = f\left(\omega_r, I_s\right)$$

Funkcija $M_e(s)$ ima ekstremum koji se može naći iz: $$\frac{dM_e(s)}{ds} = 0$$

Vrednosti prevalnog momenta i klizanja pri strujnom napajanju su:

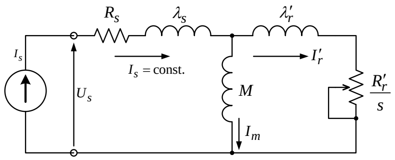
$$M_p = \pm \frac{3 \cdot P}{2} \cdot \left|\vec{I}_s\right|^2 \cdot \frac{M^2}{M + \lambda_r'} \qquad s_p = \pm \frac{R_r'}{\omega_s \cdot \left(M + \lambda_r'\right)}$$

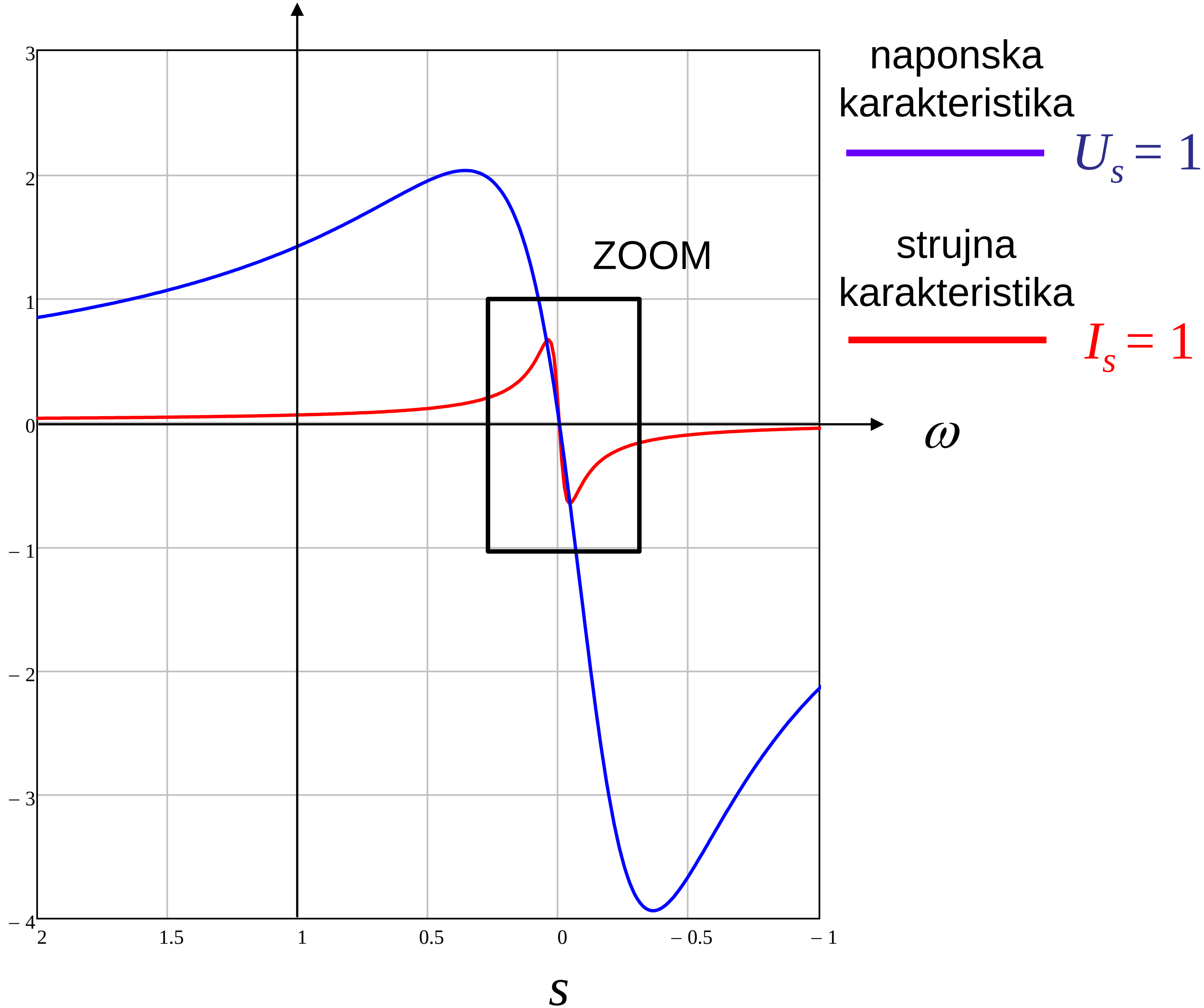
Pomoću ovih prevalnih vrednosti može se izvesti odgovarajuća *KLOSS*-ova formula.

Mehanička karakteristika kod strujnog napajanja ima isti oblik kao i kod naponskog napajanja, ali se karakteristične vrednosti razlikuju.

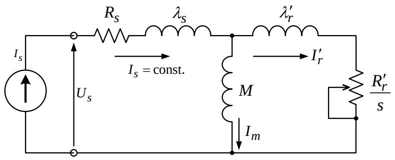
$$\left.\begin{array}{l} s_{p\,nap.} > s_{p\,str.} \\ \\ M_{p\,nap.} > M_{p\,str.} \end{array}\right\} \quad \text{jer je} \quad M >> \lambda_s + \lambda_r'$$

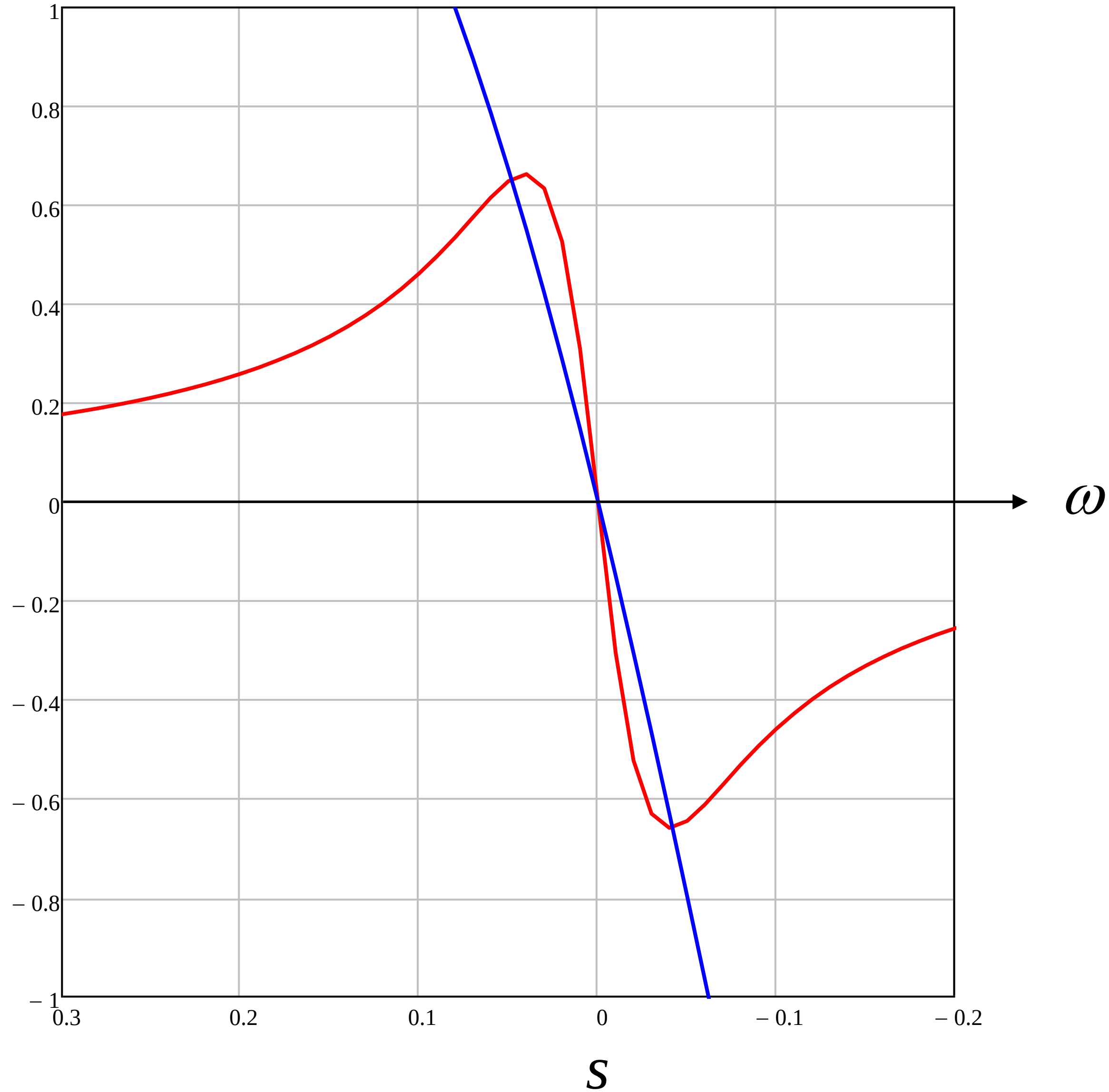
Statička karakteristika momenta, pri strujnom napajanju $I_s = I_{sn}$



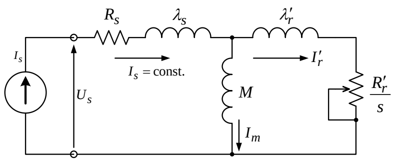


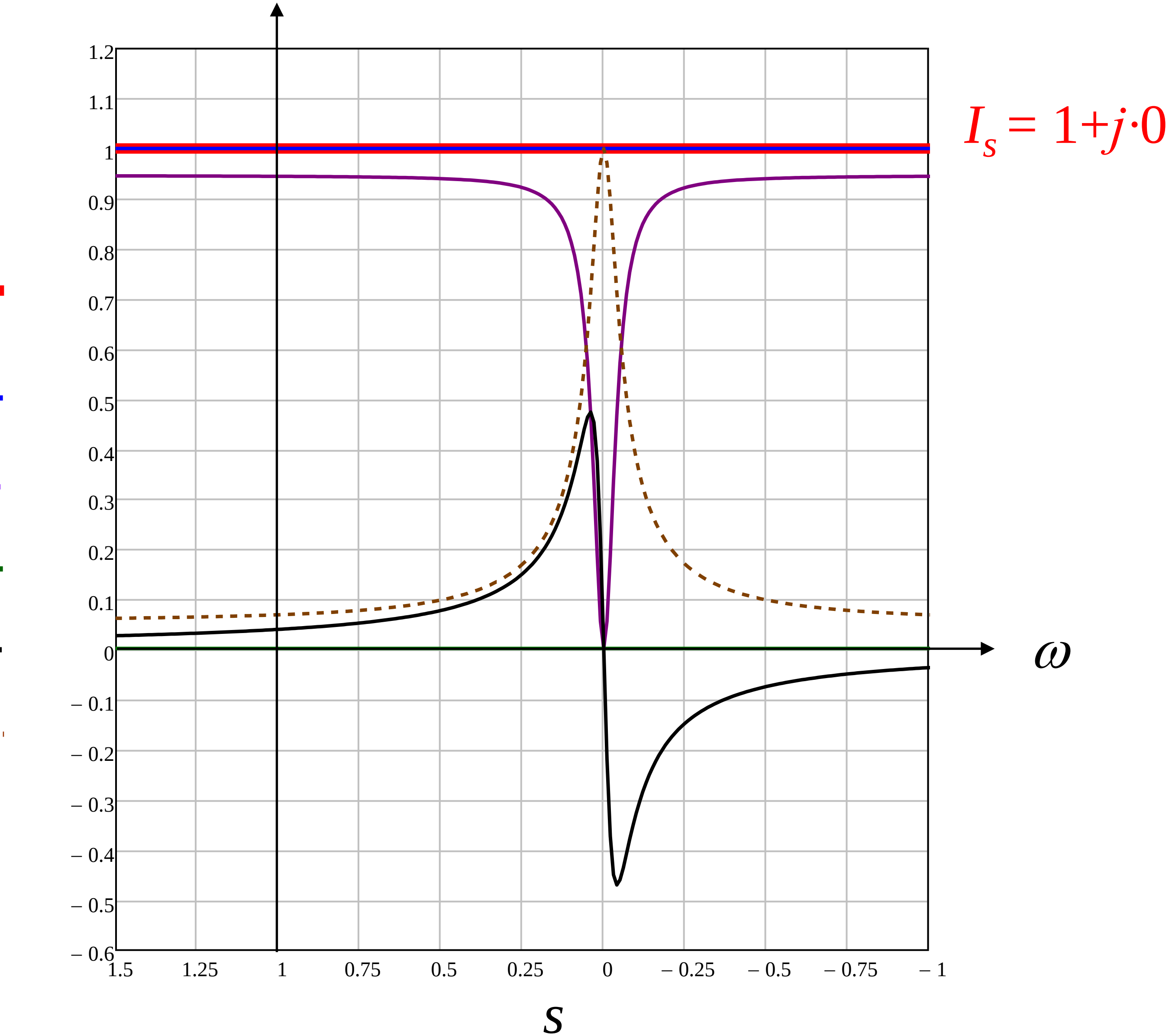
Statička karakteristika momenta, pri strujnom napajanju $I_s = I_{sn}$





Statičke karakteristike struja, pri strujnom napajanju $I_s = I_{sn}$





STATIČKA KARAKTERISTIKA NAPONA

$$\vec{U}_s(s) = \vec{I}_s \cdot Z_{ekv}(s)$$

$$Z_{ekv}(s) = Z_s + Z_m \,||\, Z_r'(s) =$$

$$= R_s + j \cdot \omega_s \cdot \lambda_s + \frac{j \cdot \omega_s \cdot M \cdot \left[\left(R_r'/s \right) + j \cdot \omega_s \cdot \lambda_r' \right]}{\left(R_r'/s \right) + j \cdot \omega_s \cdot \left(M + \lambda_r' \right)}$$

Uz uvažavanje $\lambda_r' \ll M \quad \Rightarrow \quad M - \lambda_r' \approx M$ može se napisati:

$$Z_{ekv}(s) = R_s + \frac{s \cdot \omega_s^2 \cdot M^2 \cdot R_r'}{\left(R_r' \right)^2 + s^2 \cdot \left(\omega_s \cdot M \right)^2} + j \cdot \omega_s \cdot \left(\lambda_s + \frac{s^2 \cdot \omega_s^2 \cdot \lambda_r' \cdot M^2 + M \cdot \left(R_r' \right)^2}{\left(R_r' \right)^2 + s^2 \left(\omega_s \cdot M \right)^2} \right)$$

$$\lim_{s \to 0} Z_{ekv} = R_s + j \cdot \omega_s \cdot \left(\lambda_s + M \right)$$

$$\lim_{s \to 1} Z_{ekv} \approx R_s + R_r' + j \cdot \omega_s \cdot \left(\lambda_s + \lambda_r' \right)$$

jer je: $R_r' << \omega_s \cdot M$

$$\left(R_r' \right)^2 << \left(\omega_s \cdot M \right)^2$$

Statička karakteristika napona statora kod strujno napajanog asinhronog motora pri nominalnoj struji