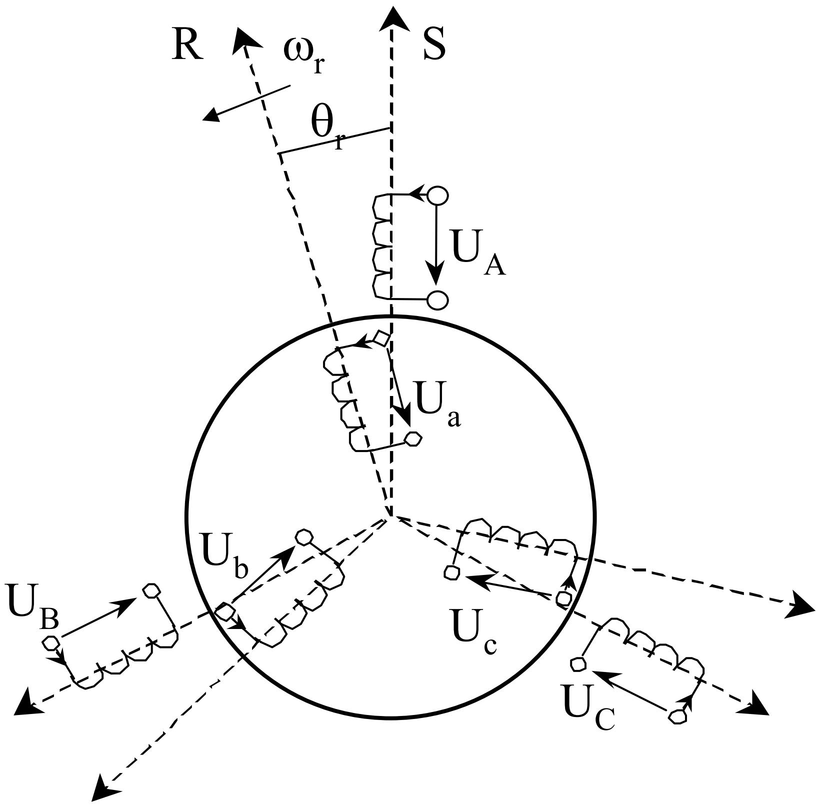
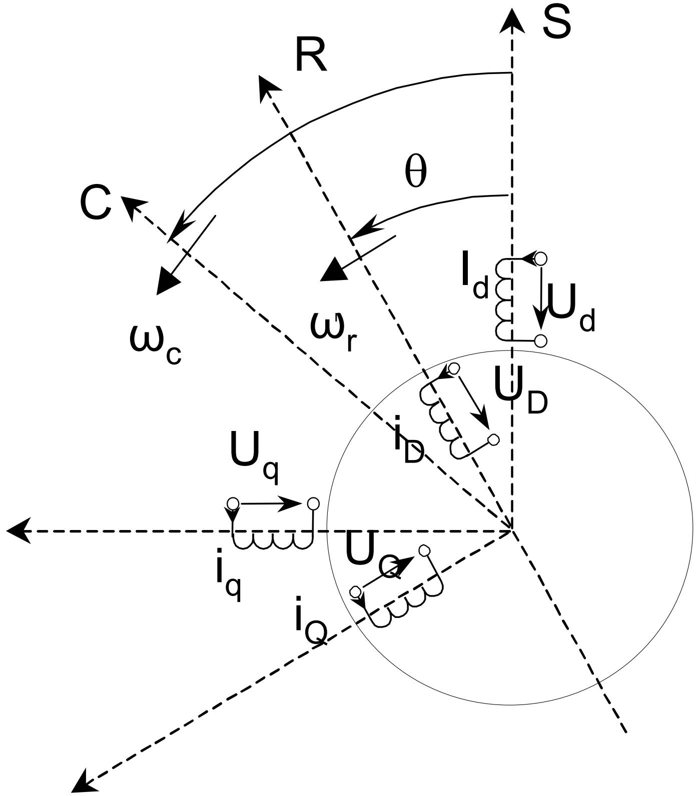
Pornirea motoarelor de inductie

Metode de pornire

Modelul masinii de inductie



Modelul de circuit trifazat



Modelul bifazat ortogonal

Ecuatiile fazoriale ale masinii de inductie

$$\underline{u}_S = R_S \cdot \underline{i}_S + \frac{d}{dt}\underline{\Psi}_S + j \cdot \omega_c \cdot \underline{\Psi}_S$$

$$0 = R_R \cdot \underline{i}_R + \frac{d}{dt}\underline{\Psi}_R + j \cdot (\omega_c - \omega) \cdot \underline{\Psi}_R$$

$$\underline{\Psi}_S = \underline{\Psi}_{S\sigma} + \underline{\Psi}_{Sm} = L_{S\sigma} \cdot \underline{i}_S + M \cdot \left(\underline{i}_S + \underline{i}_R\right)$$

$$\underline{\Psi}_R = \underline{\Psi}_{R\sigma} + \underline{\Psi}_{Rm} = L_{R\sigma} \cdot \underline{i}_R + M \cdot \left(\underline{i}_S + \underline{i}_R\right)$$

$$\underline{i}_m = \underline{i}_S + \underline{i}_R$$

$$C = p \cdot \Re e\left\{ j \cdot \underline{\Psi}_S \cdot \underline{i}_S^* \right\} = p \cdot \Re e\left\{ j \cdot \underline{\Psi}_m \cdot \underline{i}_S^* \right\} = p \cdot \Re e\left\{ j \cdot M \cdot \underline{i}_R \cdot \underline{i}_S^* \right\}$$

$$C = \frac{J}{p} \cdot \frac{d\omega}{dt} - F_v \cdot \omega - C_{sr}$$

$$\frac{d\Psi_m}{dt} = \frac{d\Psi_m}{di_m} \cdot \frac{di_m}{dt} = M_t \cdot \frac{di_m}{dt}$$

Ecuatiile modelului bifazat ortogonal

$$\underline{u}_S = u_d + j \cdot u_q$$

$$\underline{i}_S = i_d + j \cdot i_q$$

$$\underline{\Psi}_S = \Psi_d + j \cdot \Psi_q$$

$$u_d = R_S \cdot i_d + \frac{d\Psi_d}{dt} - \omega_c \cdot \Psi_q$$

$$u_q = R_S \cdot i_q + \frac{d\Psi_q}{dt} + \omega_c \cdot \Psi_d$$

$$0 = R_R \cdot i_D + \frac{d\Psi_D}{dt} - (\omega_c - \omega) \cdot \Psi_Q$$

$$0 = R_R \cdot i_Q + \frac{d\Psi_Q}{dt} + (\omega_c - \omega) \cdot \Psi_D$$

$$\Psi_d = L_{S\sigma} \cdot i_d + \Psi_{dm} = L_{S\sigma} \cdot i_d + M \cdot i_{md}$$

$$\Psi_q = L_{S\sigma} \cdot i_q + \Psi_{qm} = L_{S\sigma} \cdot i_q + M \cdot i_{mq}$$

$$\Psi_D = L_{R\sigma} \cdot i_D + \Psi_{dm} = L_{R\sigma} \cdot i_D + M \cdot i_{md}$$

$$\Psi_Q = L_{R\sigma} \cdot i_Q + \Psi_{qm} = L_{R\sigma} \cdot i_Q + M \cdot i_{mq}$$

$$C = p \cdot \left(\Psi_d \cdot i_q - \Psi_q \cdot i_d\right)$$

Expresiile curentilor

$$\underline{i}_S = \frac{L_R \cdot \underline{\Psi}_S - M \cdot \underline{\Psi}_R}{L_S \cdot L_R - M^2} \qquad \underline{i}_S = \frac{\omega_S \cdot \underline{\Psi}_S - k_R \cdot \omega_S \cdot \underline{\Psi}_R}{\omega \cdot L_S \cdot \sigma_{SR}}$$

$$\underline{i}_R = \frac{L_S \cdot \underline{\Psi}_R - M \cdot \underline{\Psi}_S}{L_S \cdot L_R - M^2} \qquad \underline{i}_R = \frac{\omega_S \cdot \underline{\Psi}_R - k_S \cdot \omega_S \cdot \underline{\Psi}_S}{\omega \cdot L_S \cdot \sigma_{SR}}$$

$$L_S \cdot L_R - M^2 = L_{S\sigma} \cdot L_{R\sigma} + M\left(L_{S\sigma} + L_{R\sigma}\right) = L_S \cdot L_R \cdot \sigma_{SR}$$

$$k_S = \frac{M}{L_S} \qquad k_R = \frac{M}{L_R}$$

$$\sigma_{SR} = 1 - \frac{M^2}{L_S \cdot L_R} = 1 - k_S \cdot k_R$$

$$s_k = \frac{R_R}{\omega_S \cdot L_S \cdot \sigma_{SR}} \qquad \varepsilon_k = \frac{R_S}{\omega_S \cdot L_S \cdot \sigma_{SR}}$$

Ecuatiile operationale

$$\underline{U}_S = (\varepsilon \cdot \omega_S + p + j \cdot \omega_S)\underline{\Psi}_S - \varepsilon \cdot \omega_S \cdot k_R \cdot \underline{\Psi}_R$$

$$0 = -s_k \cdot \omega_S \cdot k_S \cdot \underline{\Psi}_S + (s_k \cdot \omega_S + p + j \cdot s \cdot \omega_S)\underline{\Psi}_R$$

fluxurile

$$\underline{\Psi}_S = \frac{(s_k \cdot \omega_S + p + j \cdot s \cdot \omega_S)\underline{U}_S}{(\varepsilon \cdot \omega_S + p + j \cdot \omega_S) \cdot (s_k \cdot \omega_S + p + j \cdot s \cdot \omega_S) - \varepsilon \cdot s_k \cdot k_S \cdot k_R \cdot \omega_S^2}$$

$$\underline{\Psi}_R = \frac{s_k \cdot k_S \cdot \omega_S \cdot \underline{U}_S}{(\varepsilon \cdot \omega_S + p + j \cdot \omega_S) \cdot (s_k \cdot \omega_S + p + j \cdot s \cdot \omega_S) - \varepsilon \cdot s_k \cdot k_S \cdot k_R \cdot \omega_S^2}$$

Ecuatia caracteristica

$$(\varepsilon \cdot \omega_S + p + j \cdot \omega_S) \cdot (s_k \cdot \omega_S + p + j \cdot s \cdot \omega_S) - \varepsilon \cdot s_k \cdot k_S \cdot k_R \cdot \omega_S^2 = 0$$

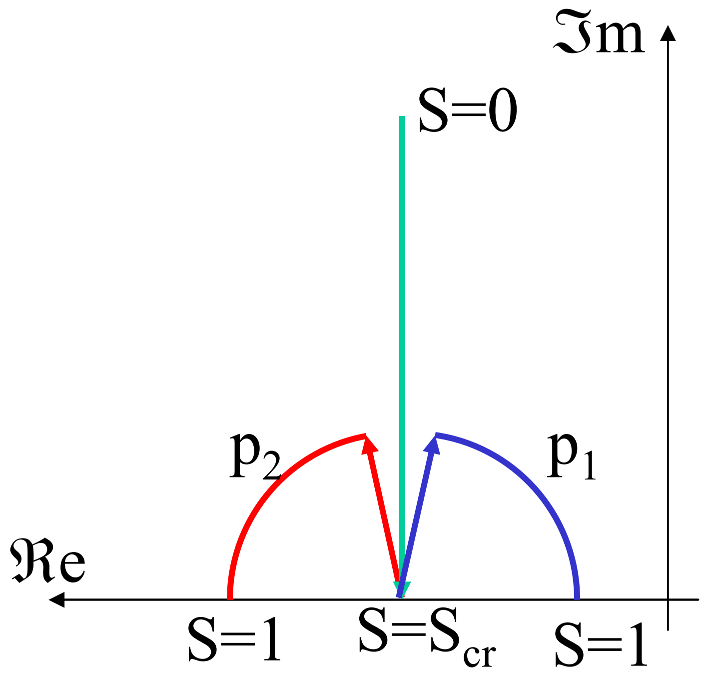
Constantele de timp si frecventele de oscilatii

Radacinile ecuatiei caracteristice:

$$p_{1,2} = \frac{\omega_S}{2}\left\{-\left[(s_k+\varepsilon)+j(1+s)\right] \pm \sqrt{\left[(s_k+\varepsilon)+j(1+s)\right]^2 - 4\cdot\left[\varepsilon\cdot s_k\cdot\sigma + j(s_k+\varepsilon\cdot s)\right]}\right\}$$

Forma generala a radacinilor

$$p_{1,2} = -\frac{1}{T(s)} \pm j\cdot\rho(s)$$



$s = s_c$ Doua radacini duble reale

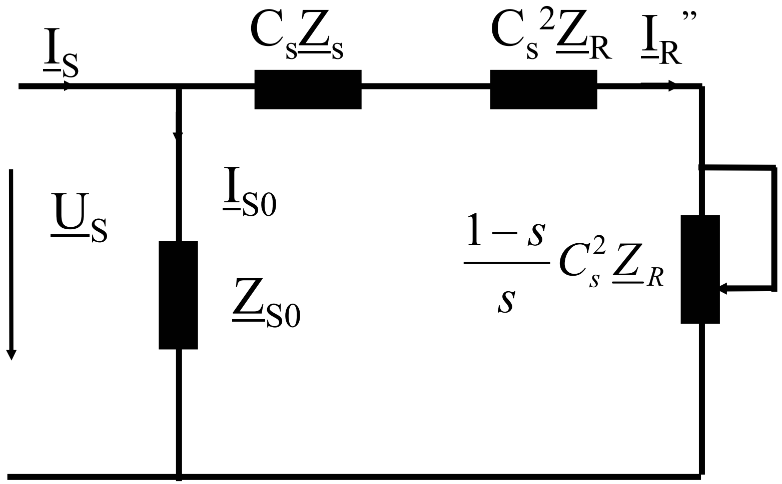
$s < s_c$ Partea reala este constanta

Pot apare oscilatii

$s > s_c$ Variaza si partea reala si imaginara

Pot apare oscilatii

Pornirea prin cuplarea directă la rețea



Regim tranzitoriu

$$i_S = i_{S0} + i_R''$$

Curentul de mers în gol:

$$i_{S0} = C_{S0} \cdot e^{-\frac{t}{T_{S0}}} + I_{S0m} \cdot \sin(\omega \cdot t + \gamma_{S0})$$

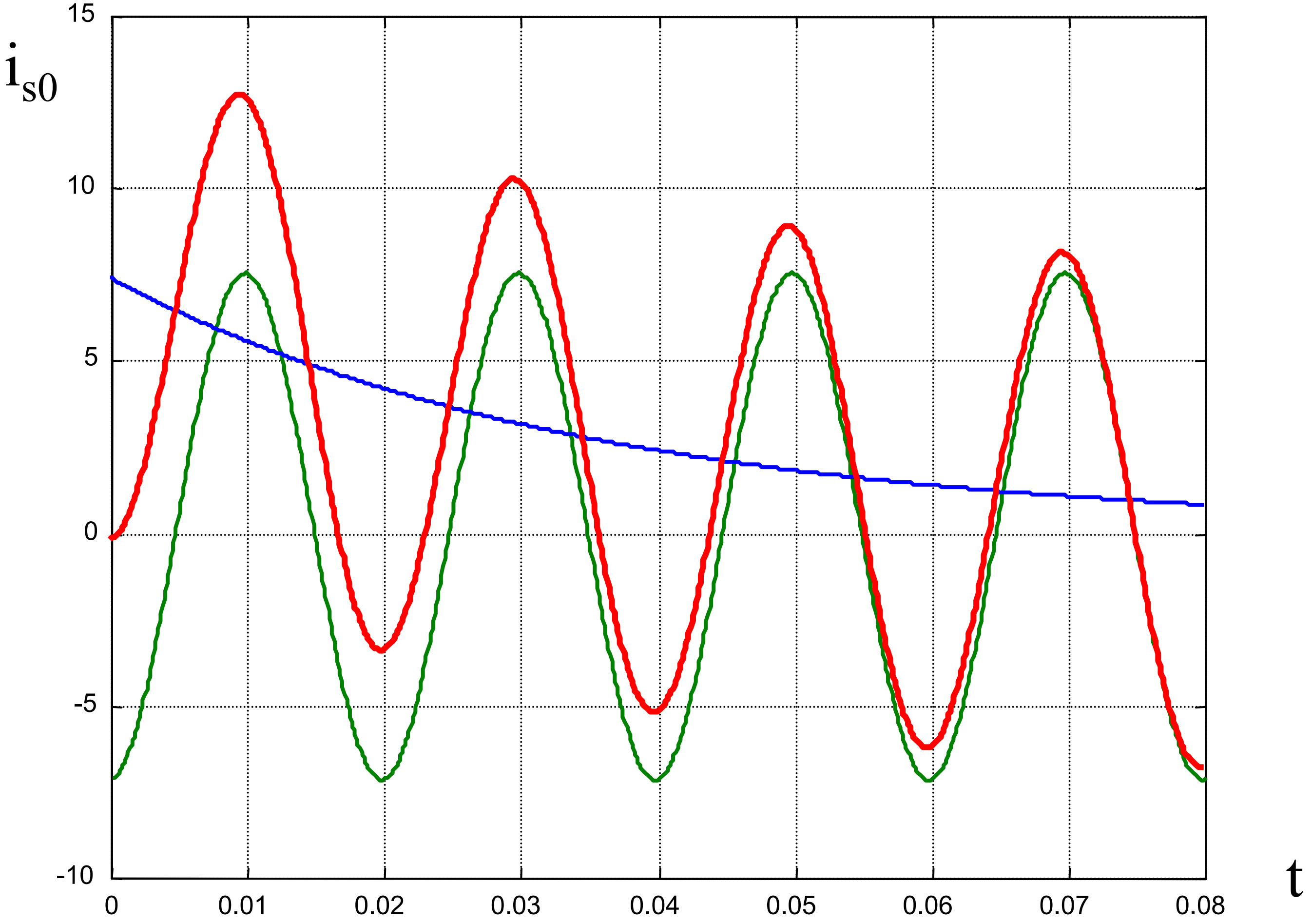
$$I_{S0m} = \frac{\sqrt{2} \cdot U_S}{Z_{S0}}$$

$$tg(\gamma_{S0} - \alpha) = -\omega \cdot T_{S0}$$

$$T_{S0} = \frac{L_{S0}}{R_{S0}}$$

$$C_{S0} = -I_{S0m} \cdot \sin \gamma_{S0}$$

Curentul de mers în gol tranzitoriu



Pornirea prin cuplarea directă la rețea

Curentul rotoric

$$i_R^{"} = C_R \cdot e^{-\frac{t}{T_{Ssc}}} + I_{Rm} \cdot \sin(\omega \cdot t + \gamma_{Ssc})$$

$$I_{Rm} = \frac{\sqrt{2} \cdot U_S}{C_S \cdot Z_{Ssc}}$$

$$tg(\gamma_{Ssc} - \alpha) = -\omega \cdot T_{Ssc}$$

$$T_{Ssc} = \frac{L_{Ssc}}{R_{Ssc}}$$

$$C_R = -I_{Rm} \cdot \sin\gamma_{Ssc}$$

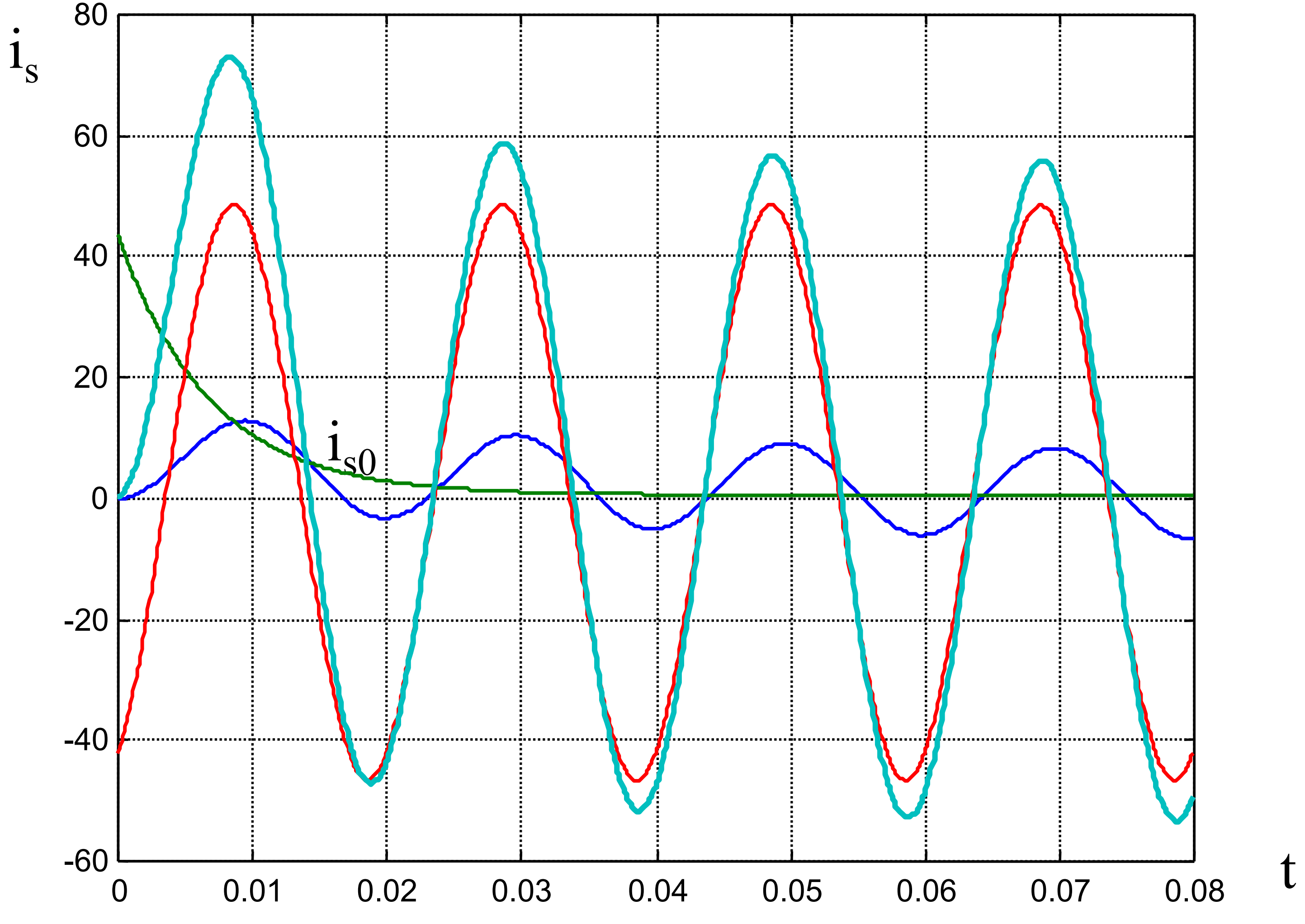
Curentul statoric de pornire

$$i_S = -I_{S0m} \cdot \sin\gamma_{S0} \cdot e^{-\frac{t}{T_{S0}}} + I_{S0m} \cdot \sin(\omega \cdot t + \gamma_{S0})$$

$$- I_{Rm} \cdot \sin\gamma_{Ssc} \cdot e^{-\frac{t}{T_{Ssc}}} + I_{Rm} \cdot \sin(\omega \cdot t + \gamma_{Ssc})$$

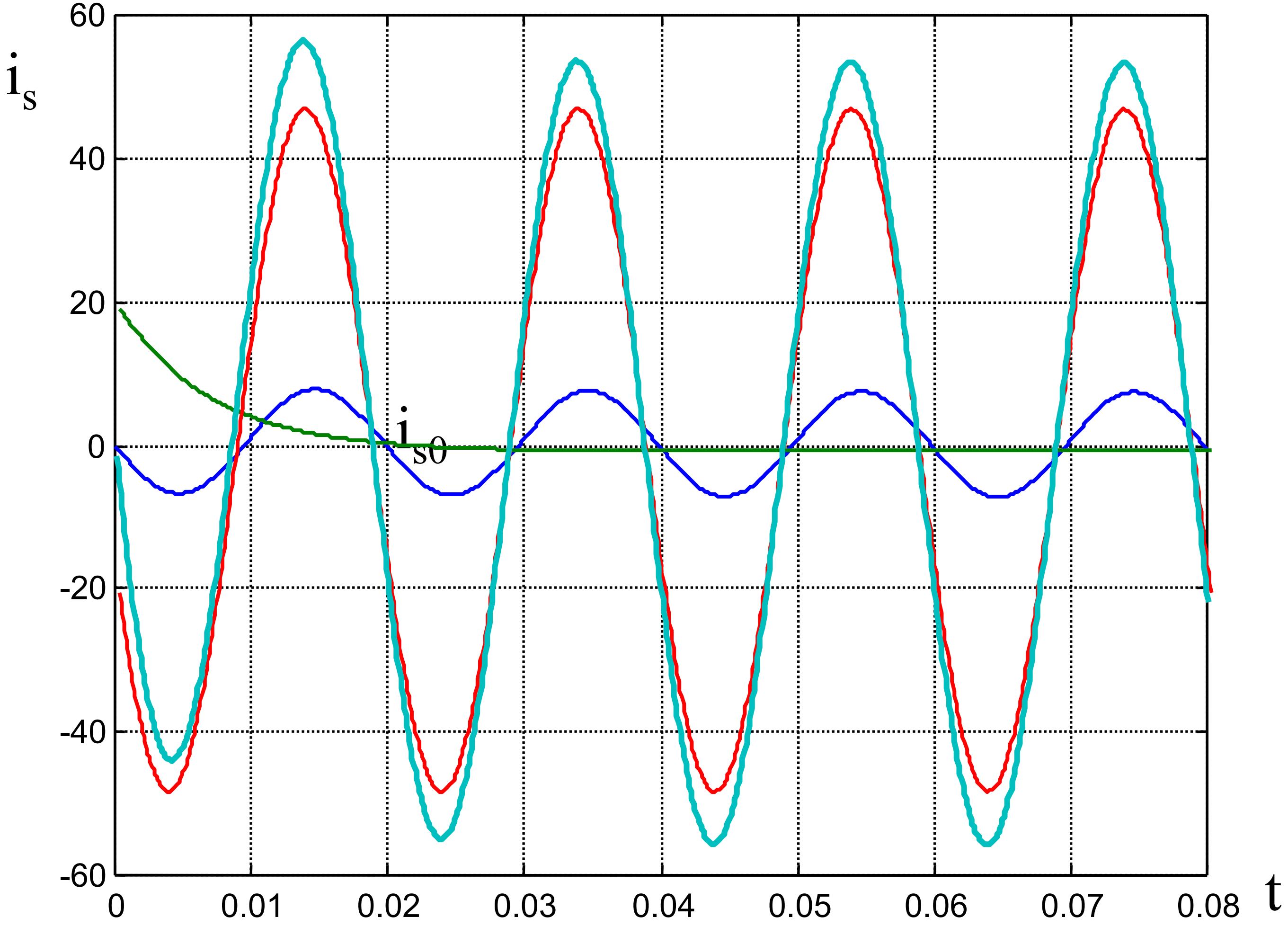
Curentul statoric tranzitoriu

$\alpha = 0$

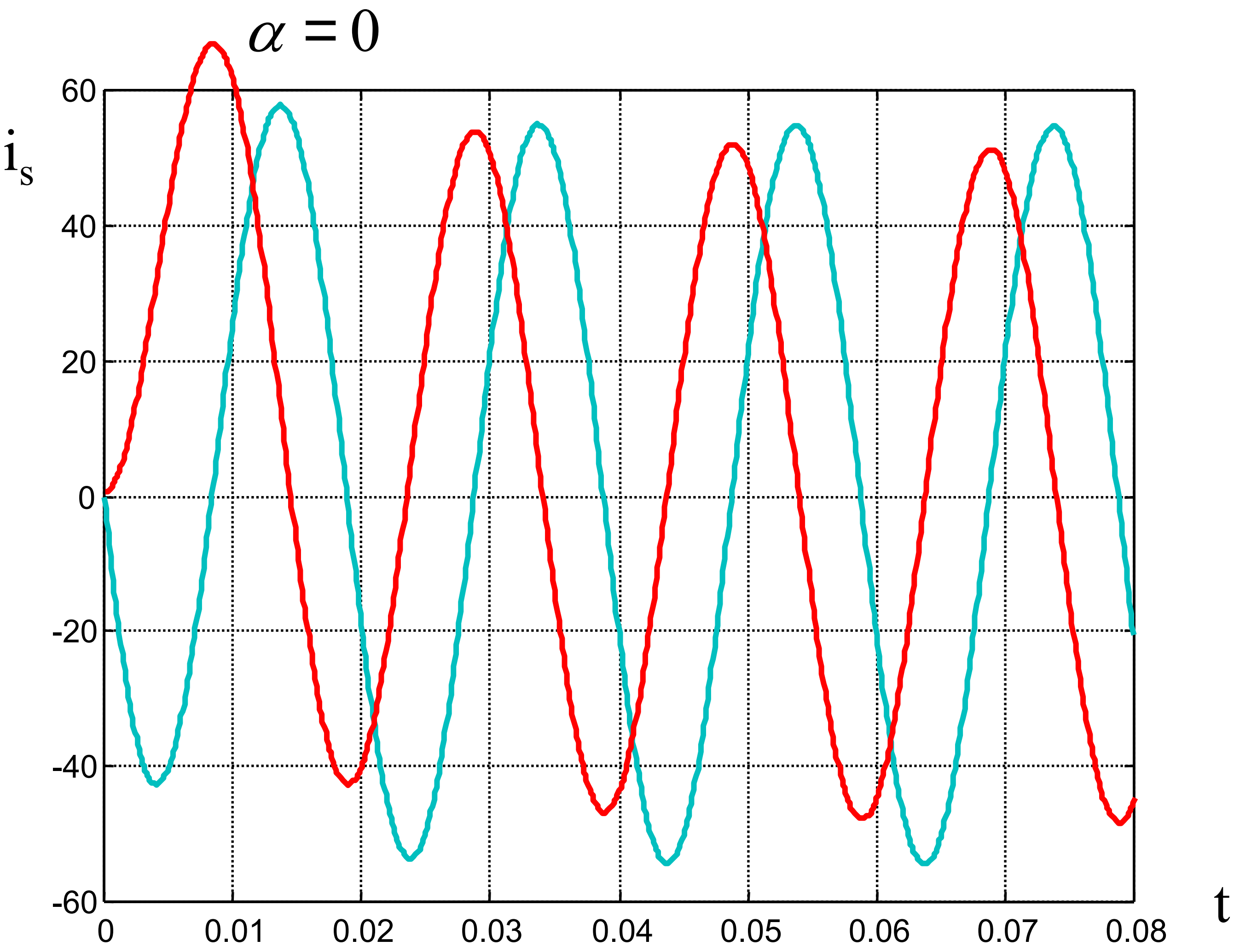


Curentul statoric tranzitoriu

$$\alpha = \frac{\pi}{2}$$



Curentul statoric tranzitoriu



Cuplul de pornire

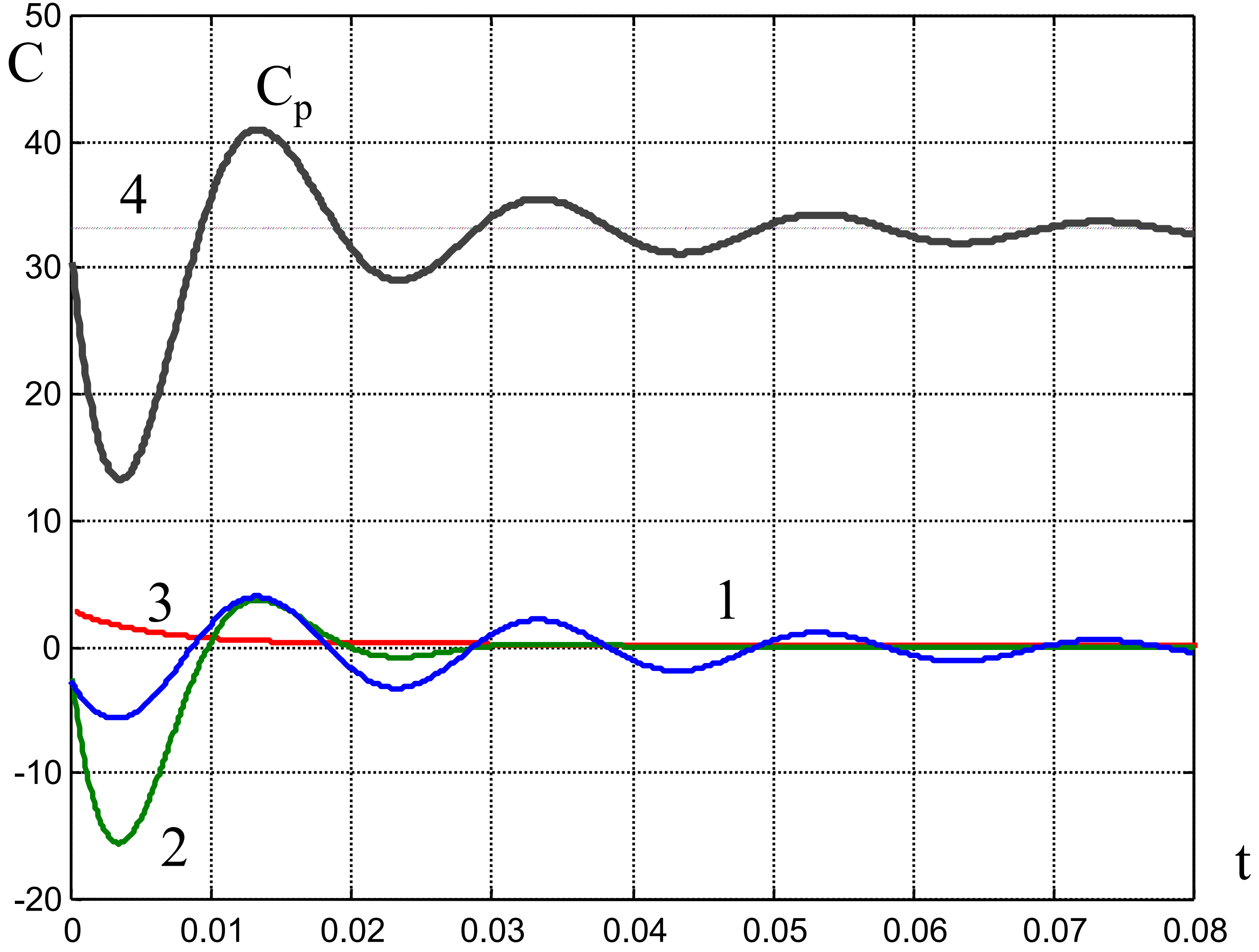
Cuplul este proporțional cu produsul curenților

$$i_{S0} = C_{S0} \cdot e^{-\frac{t}{T_{S0}}} + I_{S0m} \cdot \sin(\omega \cdot t + \gamma_{S0})$$

$$T_1 \cdot e^{-\frac{t}{T_{S0}}} \cdot \sin(\omega \cdot t + \gamma_1) \qquad T_2 \cdot e^{-\frac{t}{T_{Rsc}}} \cdot \sin(\omega \cdot t + \gamma_2) \qquad T_3 \cdot e^{-\left(\frac{t}{T_{S0}} + \frac{t}{T_{Rsc}}\right)} \qquad T_4$$

$$i_R'' = C_R \cdot e^{-\frac{t}{T_{Ssc}}} + I_{Rm} \cdot \sin(\omega \cdot t + \gamma_{Ssc})$$

Cuplul de pornire



Pornirea prin cuplarea directă la rețea

Curentul de pornire.

Alunecarea s = 1 regim staționar

$$\underline{I}_{Sp} = \underline{U}_S \cdot \left(\frac{1}{\underline{Z}_{Sm}} + \frac{1}{\underline{C}_S \cdot \underline{Z}_{Ssc}} \right) = I_{Rp} \cdot e^{-j\cdot\varphi_{sc}} \cdot \left(\frac{Z_{Ssc}}{Z_{Sm}} e^{-j\cdot\varphi_{0sc}} + 1 \right)$$

$$I_{Rp} = \frac{U_S}{C_S \cdot Z_{Ssc}}$$

$$\underline{k}_p = \left(\frac{Z_{Ssc}}{Z_{Sm}} e^{-j\cdot\varphi_{0sc}} + 1 \right) \cdot e^{-j\cdot\varphi_{sc}}$$

$$\underline{I}_{Sp} = I_{Rp} \cdot \underline{k}_p$$

Curentul de pornire la cuplarea directă

$$\underline{Z}_{Ssc} = 2.5 + j5.4$$

$$\underline{Z}_{m} = 2.8 + j39.8$$

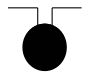
$$\underline{k}_{p} = 0.4310 + j1.0613$$

$$\underline{k}_{p} = 1.1455 \cdot e^{-j1.185}$$

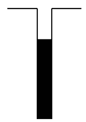
$$I_{Rp} = \frac{U_S}{C_S \cdot Z_{Ssc}} = 33.6421 \quad A$$

$$I_{Sp} = I_{Rp} \cdot \left|\underline{k}_{p}\right| = 38.537 \quad A$$

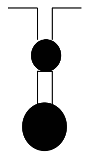
1.185 rad = 67,9^0



$6 \div 8$



$4 \div 6$



$3 \div 4$

Curentul de pornire raportat

$$i_p = \frac{I_{Sp}}{I_{SN}}$$

Pornirea prin cuplarea directă la rețea

Cuplul de pornire

$$C_p = \frac{2 \cdot C_k \cdot (1+\varepsilon)}{\frac{1}{s_k} + \frac{s_k}{1} + \varepsilon} = 2 \cdot C_k \frac{(1+\varepsilon) \cdot s_k}{1 + \varepsilon \cdot s_k + s_k^2}$$

$$s_k = \frac{R_R}{\sqrt{R_S^2 + X_{Ssc}^2}} \cong \frac{R_R}{Z_{Ssc}}$$

$$\varepsilon = \frac{R_S \cdot s_k}{R_R} \cong \frac{R_S}{Z_{Ssc}}$$

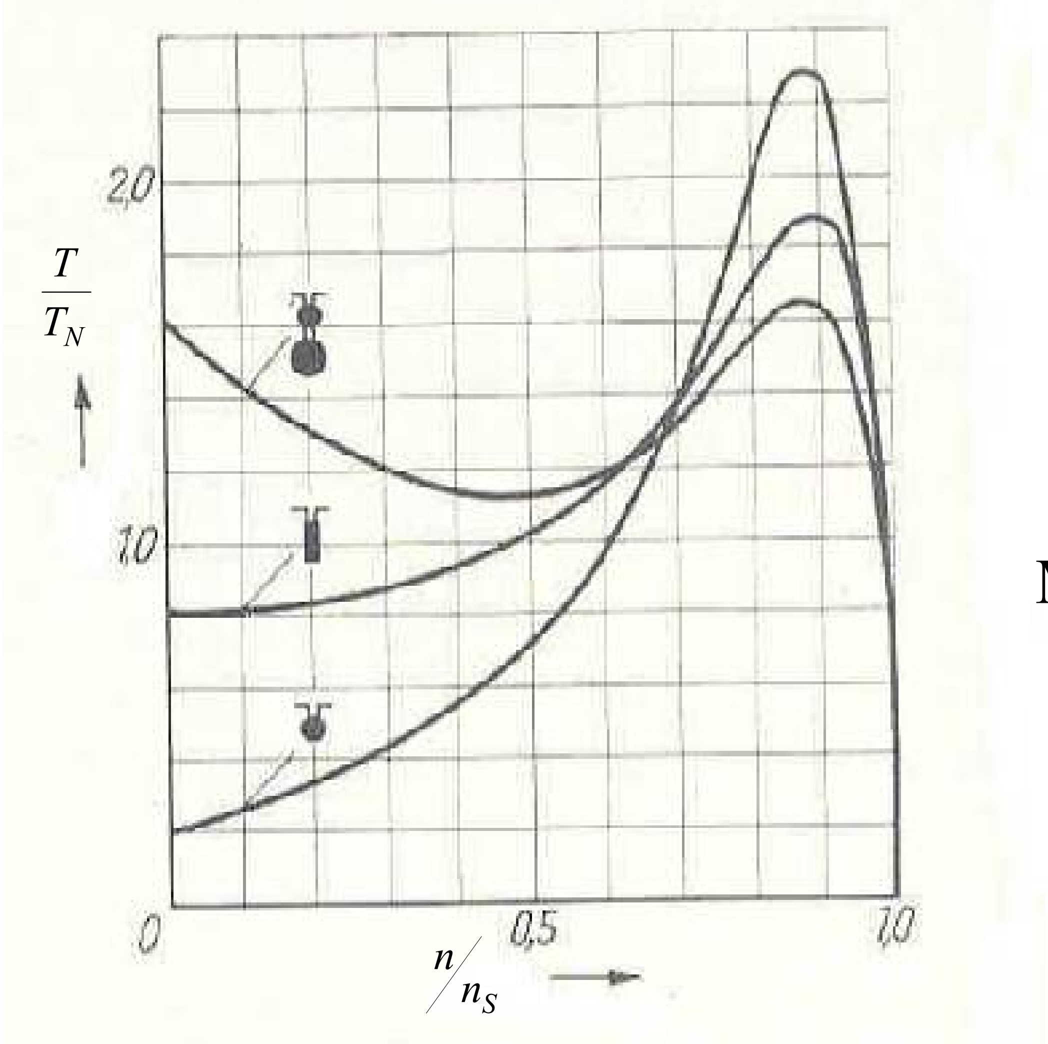
$$C_k = \frac{p \cdot m_S}{\omega_S} \frac{U_S^2}{2 \cdot c_S} \frac{1}{R_S \pm \sqrt{R_S^2 + \left(X_{S\sigma} + c_S \cdot X'_{R\sigma}\right)^2}}$$

$$C_k \cong \frac{p \cdot m_S}{\omega_S} \frac{U_S^2}{2 \cdot c_S} \frac{1}{R_S \pm Z_{Ssc}} \approx k_c \cdot \frac{U_S^2}{Z_{Ssc}} \frac{1}{\varepsilon \pm 1}$$

$$k_c = \frac{m_s}{2} \frac{p}{\omega_s}$$

Cuplul de pornire la cuplarea directă

Cuplul de pornire



$0.2 \div 0.8$

$0.8 \div 1.4$

$1.4 \div 2$

Modulul curentului rotoric

$$I_{Rp} = \frac{(\varepsilon + 1) \cdot C_k}{k_c \cdot c_S \cdot U_S}$$

Metode de pornire

$$\underline{I}_{Sp} = \frac{U_S}{C_S \cdot Z_{Ssc}} \underline{k}_p$$

Reducerea tensiunii de alimentare

- comutator stea triunghi
- autotransformator

Marirea impedantei de scurtcircuit

- reactante in circuitul statoric
- rezistente in circutul rotoric

Pornire cu comutator stea- triunghi

Metoda se poate aplica numai în cazul motoarelor care în mod normal funcționeaza în conexiunea triunghi.

Curentul de pornire în cazul cuplării directe în conexiunea triunghi:

$$\underline{I}_{p\Delta} = \sqrt{3} \cdot \frac{U_S}{Z_{Ssc}} \underline{k}_p \cdot e^{-j\frac{\pi}{3}}$$

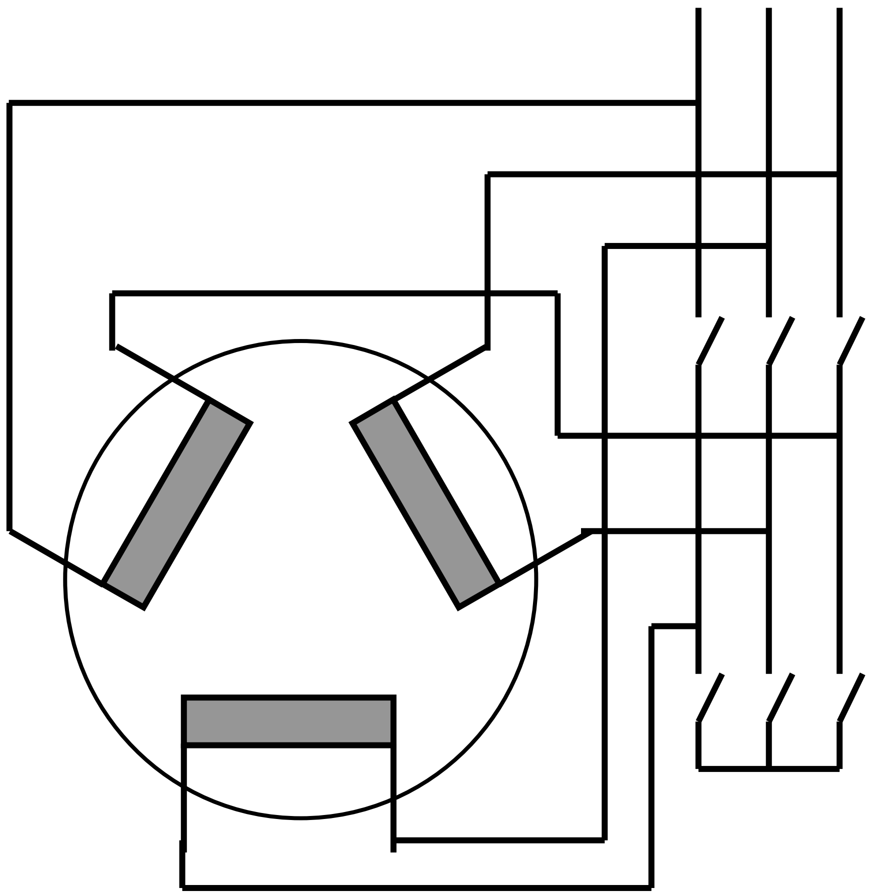
La conectarea în stea a înfăşurărilor se reduce tensiunea

$$\underline{I}_{pY} = \frac{U_S}{\sqrt{3} \cdot Z_{Ssc}} \underline{k}_p$$

Raportul curenților de pornire, considerând neglijabilă saturația

$$\underline{r}_{i\Delta Y} = 3 \cdot e^{-j \cdot \frac{\pi}{3}}$$

Pornire cu comutator stea triunghi

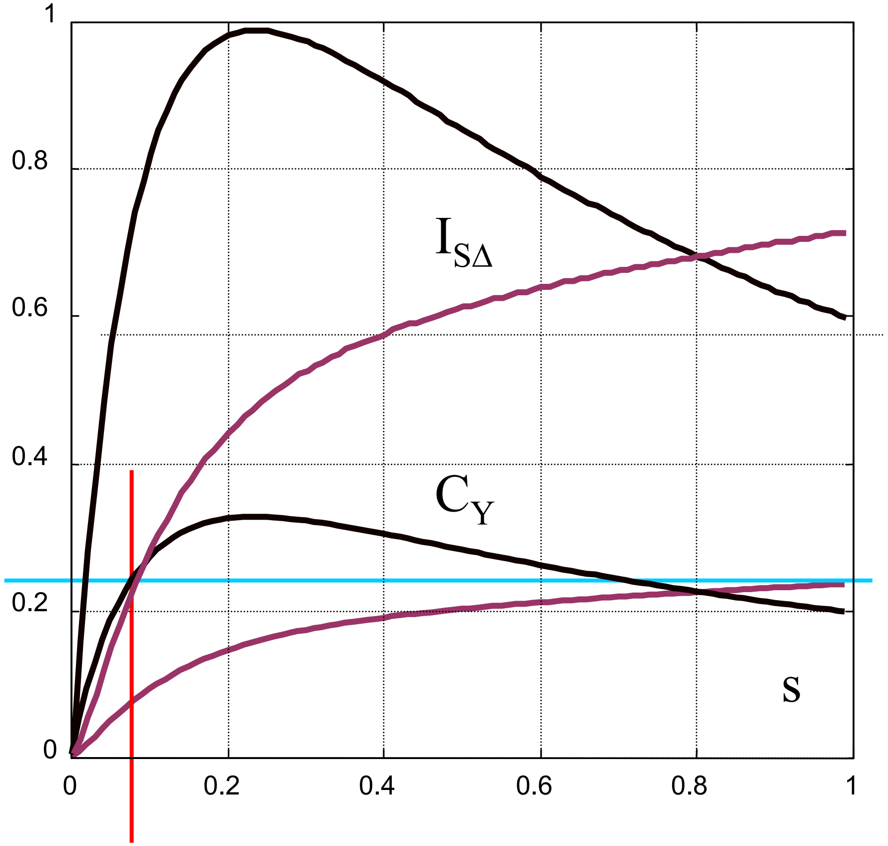


Cuplul de pornire se reduce proporțional cu pătratul tensiunii, deci:

$$r_{C\Delta Y} = \left(\frac{U_S}{\frac{U_S}{\sqrt{3}}} \right)^2 = 3$$

$$C_p = 2 \cdot k_c \cdot U_S^2 \frac{R_R}{Z_{Ssc}^2 + R_S \cdot R_R + R_R^2}$$

Pornire cu comutator stea triunghi

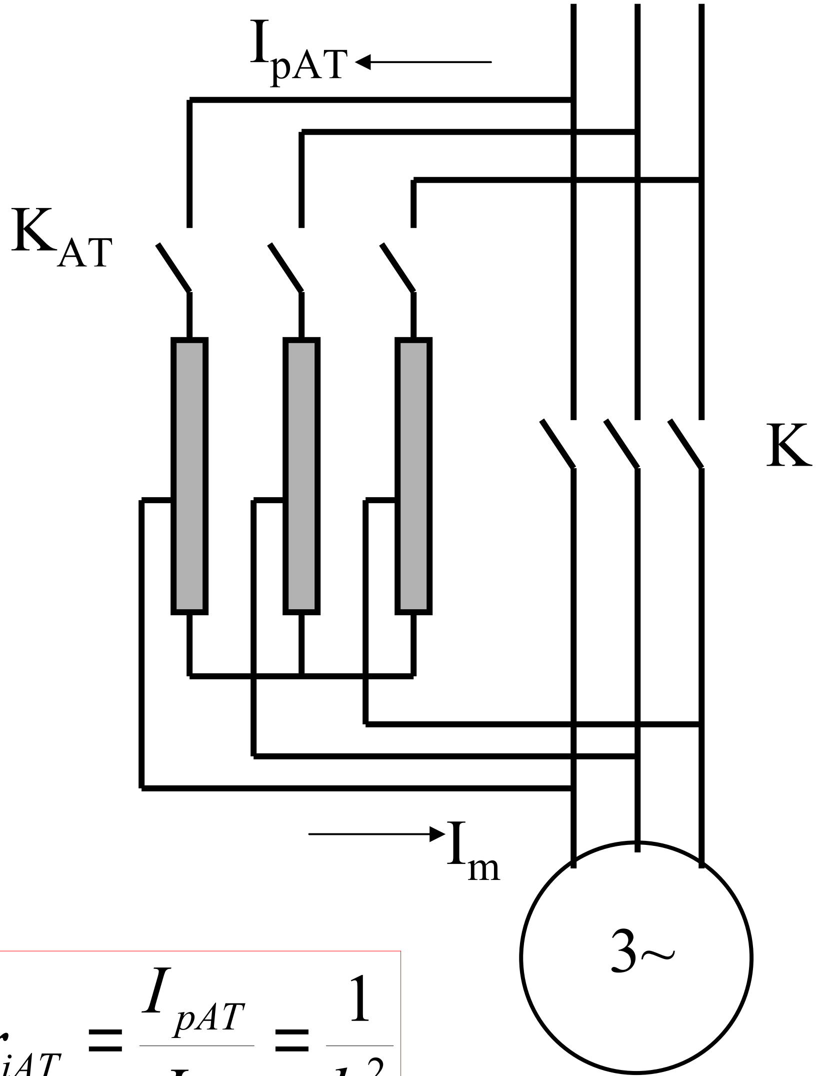


Schimbarea conexiunii. alunecarea trebuie să fie mai mică decât valoarea din figură

Curentul la schimbarea conexiunii nu trebuie să depăşească curentul de pornire.

Valabil la oricare metodă de pornire.

Pornire cu autotransformator



$$r_{iAT} = \frac{I_{pAT}}{I_{Sp}} = \frac{1}{k_T^2}$$

Tensiunea aplicată motorului

$$U_m = \frac{U_S}{k_T}$$

Curentul prin motor

$$\underline{I}_m = \frac{I_{Rp}}{k_T}\underline{k}_p$$

Curentul de pornire curentul în primarul autotransformatorului

$$\underline{I}_{pAT} = \frac{\underline{I}_m}{k_T} = \frac{1}{k_T^2}\underline{I}_{Sp}$$

Pornire cu autotransformator

Cuplul de pornire

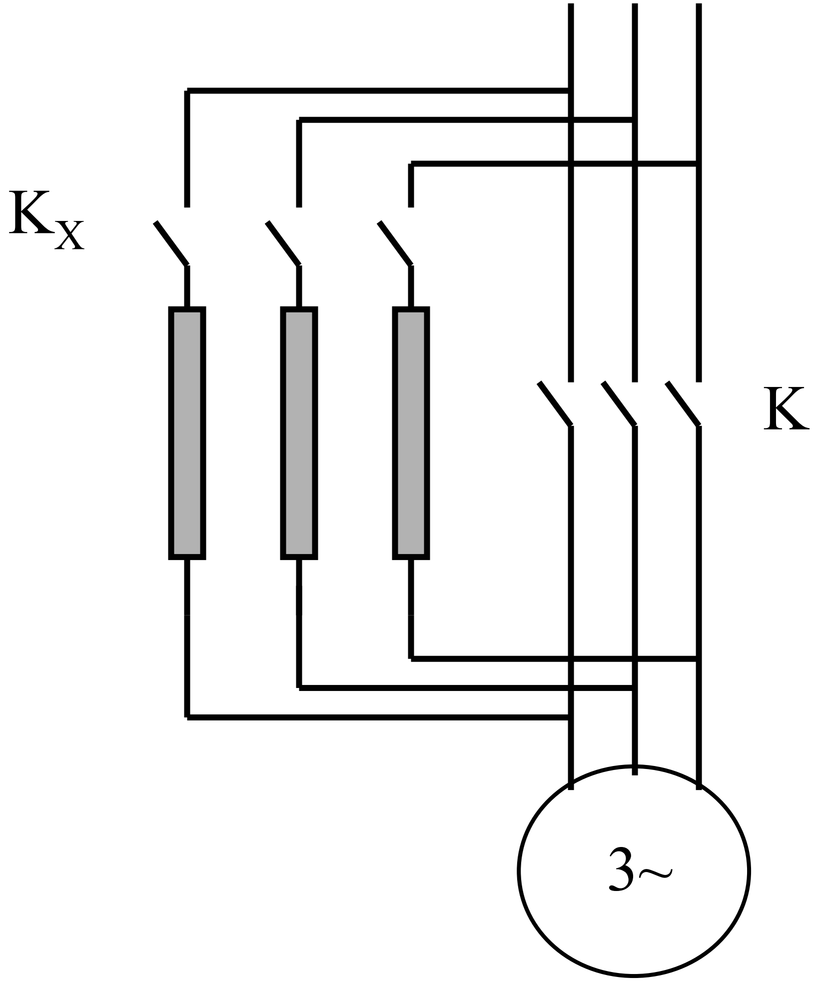
$$C_{pAT} = 2 \cdot k_c \cdot \left(\frac{U_S}{k_T}\right)^2 \frac{R_R}{\left|\underline{Z}_{AT} + \underline{Z}_{Ssc}\right|^2 + \left(R_S + R_{AT}\right) \cdot R_R + R_R^2}$$

$$r_{CAT} = \frac{C_{pAT}}{C_p} = \frac{1}{k_T^2} \frac{Z_{Ssc}^2 + R_S \cdot R_R + R_R^2}{\left|\underline{Z}_{AT} + \underline{Z}_{Ssc}\right|^2 + \left(R_S + R_{AT}\right) \cdot R_R + R_R^2}$$

Se reduce ceva mai mult decât proporțional cu k_T^2

$$\frac{Z_{AT}}{Z_{Ssc}} = \frac{u_{scAT}}{\cos\varphi_S} \frac{S_{Nmotor}}{S_{NAT}} \qquad \frac{Z_{AT}}{Z_{Ssc}} = \frac{0.06}{0.9} < 0.1$$

Pornire cu reactanță înseriată



Se modifică Z_{Ssc}

$$\underline{Z}_{Ssc} \Rightarrow \underline{Z}_{Ssc} + j \cdot X$$

Se modifică φ_{sc} si $\underline{k}_p$

$$\varphi^*_{sc} = arctg \frac{R_{sc}}{X_{sc} + X}$$

$$\underline{k}_p = \left(\frac{(\underline{Z}_{Ssc} + jX)}{\underline{Z}_{Sm}} + 1 \right) \cdot e^{-j \cdot \varphi^*_{sc}}$$

Curentul se reduce dependent de X

$$I_{Rp} = \frac{U_S}{C_S \cdot \left| \underline{Z}_{Ssc} + jX \right|}$$

Pornire cu reactanță înseriată

$$r_{iB}=\frac{Z_{Ssc}}{\left|\underline{Z}_{Ssc}+jX\right|}\left|1+\frac{\underline{Z}_{Ssc}+jX}{\underline{Z}_{Sm}}\right|$$

Cuplul se reduce dependent de X

$$C_{pB}=2\cdot k_c\cdot U_S{}^2\frac{R_R}{\left|jX+\underline{Z}_{Ssc}\right|^2+R_S\cdot R_R+R_R^2}$$

$$r_{CB}=\frac{C_{pB}}{C_p}=\frac{Z_{Ssc}^2+R_S\cdot R_R+R_R^2}{\left|jX+\underline{Z}_{Ssc}\right|^2+\left(R_S+R_B\right)\cdot R_R+R_R^2}$$

Pornire cu rezistență în rotor

Numai la motoare cu rotor bobinat

$$\underline{Z}_{Ssc}^{*} \Rightarrow \left(R_{Ssc} + R_p\right) + j \cdot X_{Ssc}$$

Se modifică $\underline{k}_p$ si φ_{sc}

$$\varphi_{sc}^{*} = arctg \frac{R_{sc} + R}{X_{sc}}$$

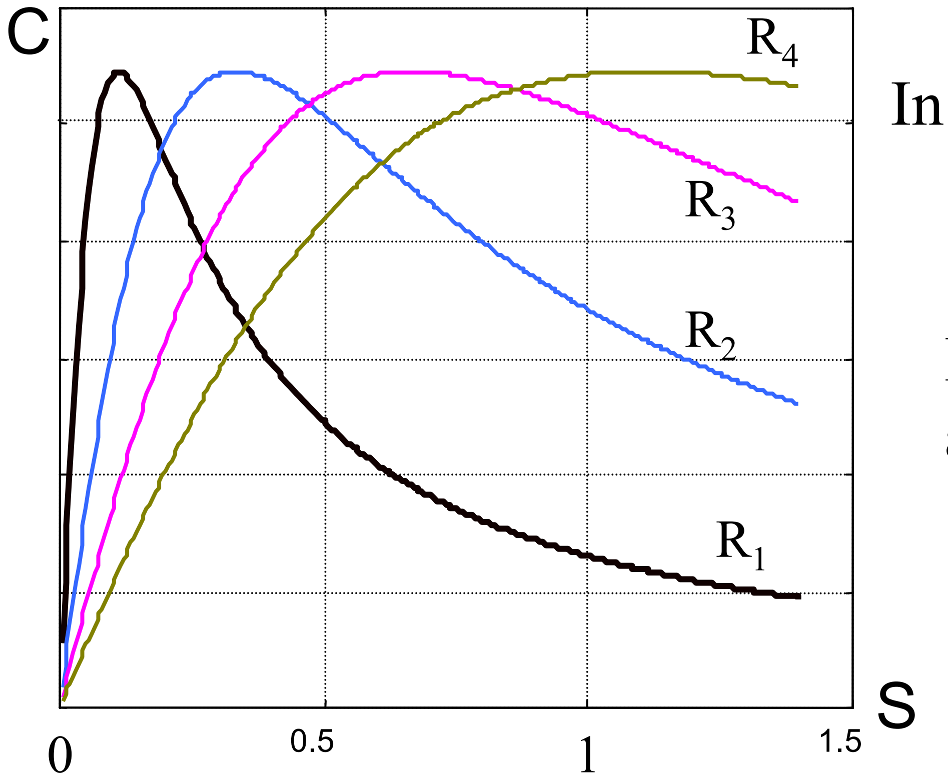
$$\underline{k}_p = \left(\frac{\left(\underline{Z}_{Ssc} + R\right)}{\underline{Z}_{Sm}} + 1 \right) \cdot e^{-j \cdot \varphi_{sc}^{*}}$$

Se reduce curentul de ponire

$$I_{Rp} = \frac{U_S}{C_S \cdot \left|\underline{Z}_{Ssc} + R\right|}$$

$$r_{iR} = \frac{Z_{Ssc}}{\left|\underline{Z}_{Ssc} + R\right|} \left| 1 + \frac{\underline{Z}_{Ssc} + R}{\underline{Z}_{Sm}} \right|$$

Pornire cu rezistență în rotor



In expresia cuplului $R^*_R \Rightarrow R_R + R_p$

La început cuplul creşte,
atinge maxim la $R_R + R_p = Z_{Ssc}$

$$C_{pR} = 2 \cdot k_c \cdot U_S^{\ 2} \frac{R_R^*}{\left(Z_{Ssc}^*\right)^2 + R_S \cdot R_R^* + R_R^{*2}}$$

$$r_{CR} = \frac{C_{pR}}{C_p} = \frac{Z_{Ssc}^2 + R_S \cdot R_R + R_R^2}{\left|R + \underline{Z}_{Ssc}\right|^2 + \left(R_R + R_B\right) \cdot R_S + \left(R + R_R\right)^2} \frac{R_R + R}{R_R}$$

Reducerea cuplului şi curentului la pornire cu reactanţă şi rezistenţă