Průmyslová energetika
X15PEN

přednáška č. 7

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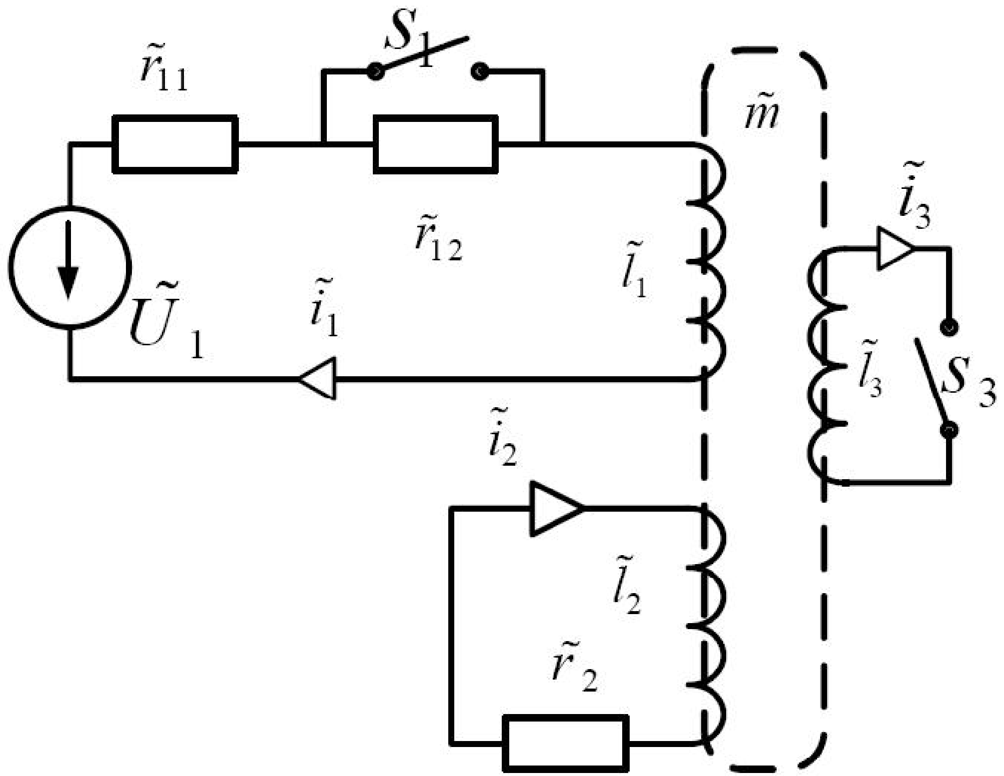
Modální analýza - příklad



$\tilde{U}_1 = 0.656;$

$\tilde{r}_{11} = \tilde{r}_{12} = 0.328 * 10^{-3}; \tilde{r} = \tilde{r}_{11} + \tilde{r}_{12} = 0.656 * 10^{-3}$

$\tilde{l}_1 = 1.03;$ $\tilde{m} = 0.85$

$\tilde{r}_2 = 0.003$ $; \tilde{l}_2 = 0.95$

$\tilde{l}_3 = 1$

Případ A

A. S_3=0, S_1=1→0

$$\tilde{i}_1(0)=\frac{\tilde{U}_1}{\tilde{r}_{11}}=\frac{0.656}{0.328*10^{-3}}=2000;\ \tilde{i}_{2u}(0)=0\ \textit{před rozpojením}$$

$$\tilde{i}_{1u}(0)=\frac{\tilde{U}_1}{\tilde{r}_1}=\frac{0.656}{0.656*10^{-3}}=1000;\ \tilde{i}_{2u}(0)=0\quad \textit{po rozpojení}$$

$$\tilde{i}_{1v0}=\tilde{i}_1(0)-\tilde{i}_{1u}(0)=2000-1000=1000$$

$$\tilde{i}_{2v0}=0$$

⇒ Případ popisovaný teoreticky v př. č. 6

⇒ Nejprve zjistíme volné proudy v t=0

Případ A

$$T_1 = \frac{\tilde{l}_1}{\omega \tilde{r}_1} = \frac{1.03}{100\pi * 0.656 * 10^{-3}} = 5 \ \ (s);$$

$$T_2 = \frac{\tilde{l}_2}{\omega \tilde{r}_2} = \frac{0.95}{100\pi * 0.003} = 1\,(s);$$

$$\sigma_{12} = 1 - \frac{\tilde{l}_{12}^2}{\tilde{l}_{11}\tilde{l}_{22}} = 1 - \frac{0.85^2}{1.03 * 0.95} = 0.262;$$

$$q = \sqrt{1 - \frac{4\sigma_{12} T_1 T_2}{(T_1 + T_2)^2}} = \sqrt{1 - \frac{4 * 0.262 * 5 * 1}{(5+1)^2}} = 0.9244;$$

přechodná →

$$T' = \frac{(1+q)(T_1 + T_2)}{2} = \frac{(1+0.9244)}{2}(5+1) = 5.773\,(s);$$

rázová →

$$T'' = T_1 + T_2 - T' = 6 - 5.772 = 0.227(s)$$

$$T_\Delta = T_1 + T_2 - 2T'' = 6 - 2 * 0.227 = 5.546\,(\mathrm{s})$$

Případ A

⇒ Výpočet koeficientů:

$$K_{11} = \frac{T_1 - T''}{T_\Delta}\tilde{i}_{v10} + \frac{\tilde{l}_{12}}{\tilde{l}_{11}} \cdot \frac{T_1}{T_\Delta}\tilde{i}_{v20} = 860.6$$

$$K_{12} = \tilde{i}_{v10} - K_{11} = 1000 - 860.6 = 139.4$$

$$K_{21} = \frac{T_2 - T''}{T_\Delta}\tilde{i}_{v20} + \frac{\tilde{l}_{12}}{\tilde{l}_{2}} \cdot \frac{T_2}{T_\Delta}\tilde{i}_{v10} = 161.3$$

$$K_{22} = \tilde{i}_{v20} - K_{21} = -K_{21} = -161.3$$

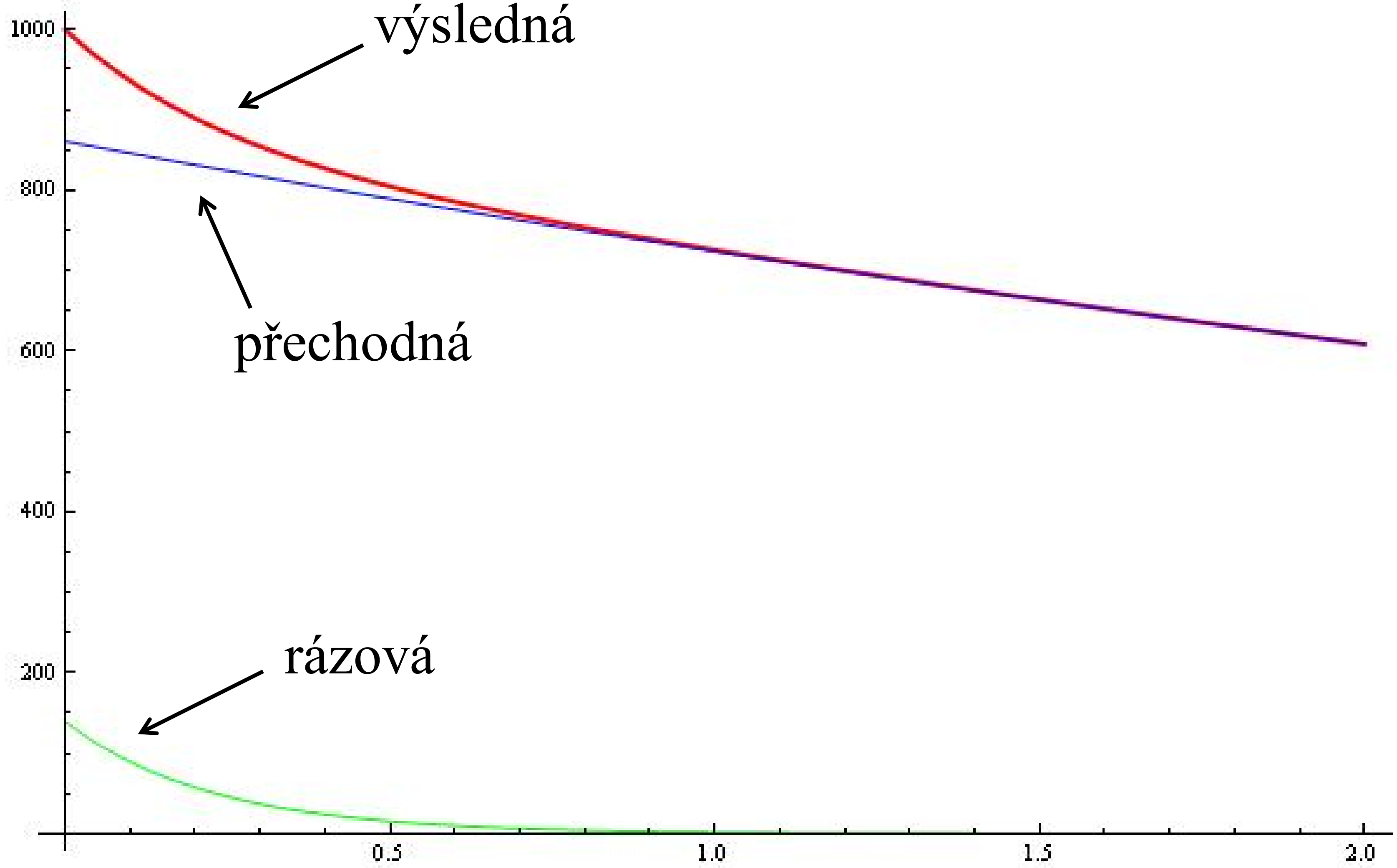
Případ A

⇒ Konečný vztah pro volné proudy systému:

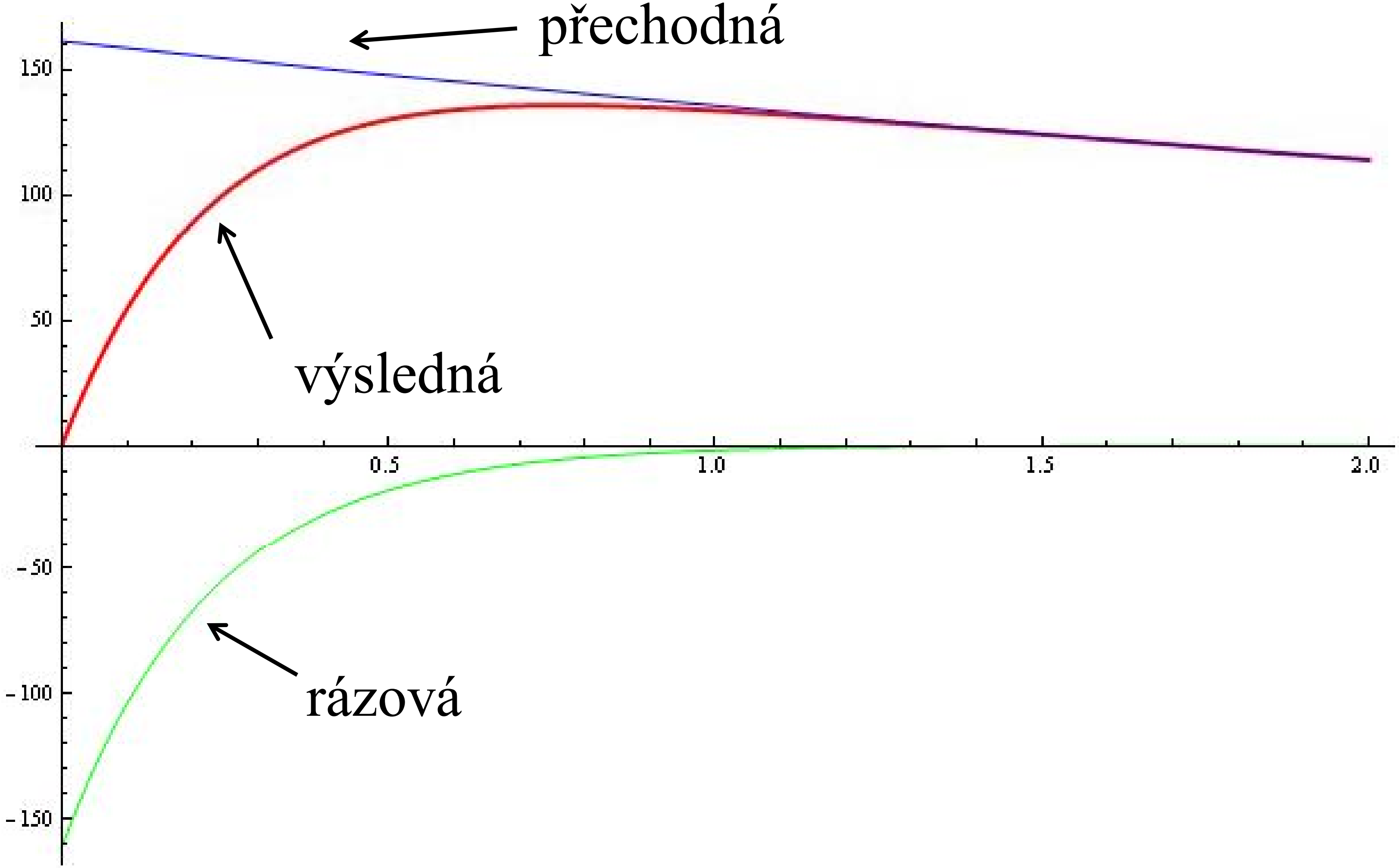
$$\begin{bmatrix} \tilde{i}_{v1} \\ \tilde{i}_{v2} \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \cdot \begin{bmatrix} e^{-\frac{t}{T'}} \\ e^{-\frac{t}{T''}} \end{bmatrix}$$

$$\begin{bmatrix} \tilde{i}_{v1} \\ \tilde{i}_{v2} \end{bmatrix} = \begin{bmatrix} 860.6 & 139.4 \\ 161.3 & -161.3 \end{bmatrix} \begin{bmatrix} e^{-\frac{t}{5.773}} \\ e^{-\frac{t}{0.227}} \end{bmatrix}$$

Případ A – *iv1(t)*



Případ A – *$i_{v2}(t)$*



Případ B

B. S_3=0;r_2=0 (supravodivý obvod)

$$\tilde{u}_1 = \tilde{r}_1 \, .\tilde{i}_1 + \tilde{l}_1 . \tilde{i}_1^{\bullet} + \tilde{m}\tilde{i}_2^{\bullet} ; \tilde{u}_2 = 0 = \tilde{l}_2 . \tilde{i}_2^{\bullet} + \tilde{m}\tilde{i}_1^{\bullet}$$

$$\tilde{i}_2^{\bullet} = -\frac{\tilde{m}}{\tilde{l}_2}\tilde{i}_1^{\bullet} ; \tilde{u}_1 = \tilde{r}_1 \, .\tilde{i}_1 + \tilde{l}_1 . \tilde{i}_1^{\bullet} - \tilde{m}^2 \frac{\tilde{i}_1^{\bullet}}{\tilde{l}_2}$$

$$\tilde{u}_1 = \tilde{r}_1 \, .\tilde{i} + \tilde{l}_1 . \tilde{i}_1^{\bullet} \left(1 - \frac{\tilde{m}^2}{\tilde{l}_1 \tilde{l}_2} \right)$$

Případ B

$$T = \frac{\tilde{l}_1}{\omega \tilde{r}_1}\sigma_{12} = 5*0.262 = 1.31(s)$$

$$\tilde{i}_1 = \tilde{u}_1/\tilde{r}_1 + K_1.e^{-\frac{t}{T_1}}$$

$$\tilde{i}_1(0) = \overbrace{\tilde{u}_1/\tilde{r}_1}^{1000} + K_1 = 2000 \rightarrow K_1 = 1000$$

$$\tilde{i}_2^{\bullet} = -\left(\tilde{m}/\tilde{l}_2\right)K_1.e^{-\frac{t}{T_1}} + K_2 \Rightarrow$$

$$\tilde{i}_2(0) = -\left(\tilde{m}/\tilde{l}_2\right)K_1 + K_2 = 0$$

$$K_2 = (0.85/0.95)*1000 = 894.7$$

$$\tilde{i}_2 = \left(\tilde{m}/\tilde{l}_2\right)K_1 * \left(1 - e^{-\frac{t}{T}}\right) = 894.7\left(1 - e^{-\frac{t}{1.31}}\right)$$

Případ C

C. S_3=1,

$$\tilde{r}_1.\tilde{i}_1+\tilde{l}_1\tilde{i}_1^{\bullet}+\tilde{m}\left(\tilde{i}_2^{\bullet}+\tilde{i}_3^{\bullet}\right)=\tilde{u}_1$$

$$\tilde{r}_2.\tilde{i}_2+\tilde{l}_2\tilde{i}_2^{\bullet}+\tilde{m}\left(\tilde{i}_1^{\bullet}+\tilde{i}_3^{\bullet}\right)=0$$

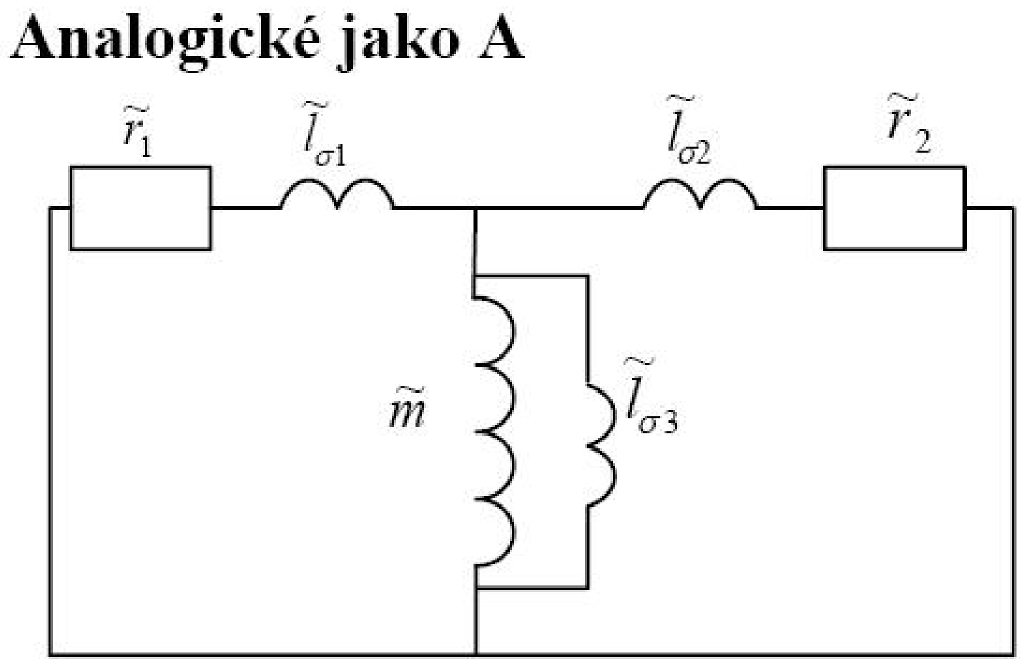
$$\tilde{l}_3\tilde{i}_3^{\bullet}+\tilde{m}\left(\tilde{i}_2^{\bullet}+\tilde{i}_1^{\bullet}\right)=0\Rightarrow\tilde{i}_3^{\bullet}=-\tilde{m}\left(\tilde{i}_2^{\bullet}+\tilde{i}_1^{\bullet}\right)/\tilde{l}_3$$

$$\tilde{r}_1.\tilde{i}_1+\overbrace{\left(\tilde{l}_1-\tilde{m}^2/\tilde{l}_3\right)}^{l_1'}\tilde{i}_1^{\bullet}+\overbrace{\tilde{m}\left(\frac{\tilde{l}_3-\tilde{m}}{\tilde{l}_3}\right)}^{m'}\tilde{i}_2^{\bullet}=\tilde{u}_1$$

$$\tilde{r}_2.\tilde{i}_2+\underbrace{\left(\tilde{l}_2-\tilde{m}^2/\tilde{l}_3\right)}_{l_2'}\tilde{i}_2^{\bullet}+\tilde{m}\left(\frac{\tilde{l}_3-\tilde{m}}{\tilde{l}_3}\right)\tilde{i}_1^{\bullet}=0$$

Případ C

$\Rightarrow$ Řešíme jako případ A, rozdíl je v hlavní reaktanci:



Případ D

D. **Vliv rozptylu**

$$\sigma_{12} \to 0 \Rightarrow T'' \to 0; \qquad T' \to T_1 + T_2 = 5 + 1 = 6$$

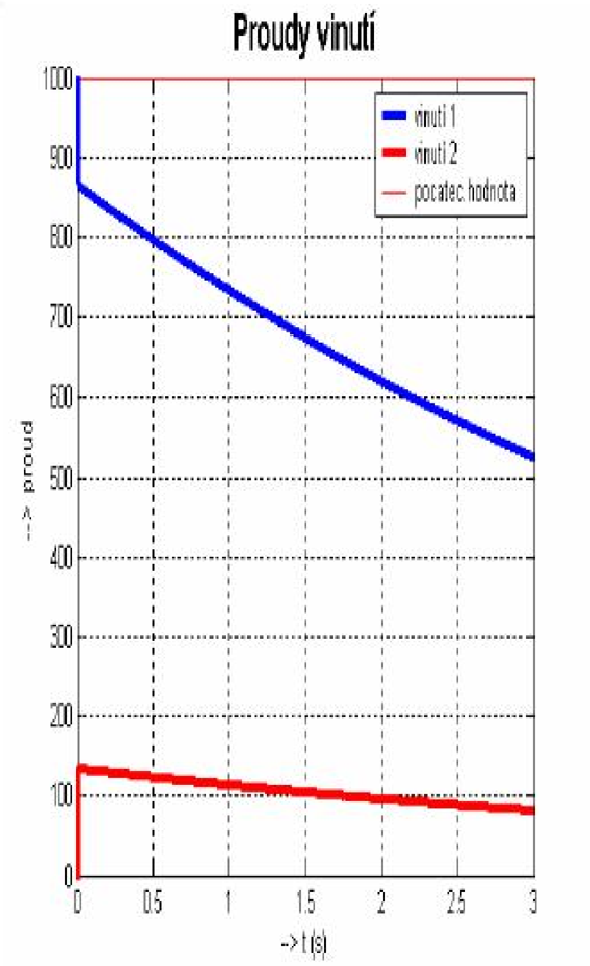
$$i_{v1} = K_{11}.e^{-\frac{t}{T'}}; \qquad i_{v2} = K_{21}.e^{-\frac{t}{T'}}$$

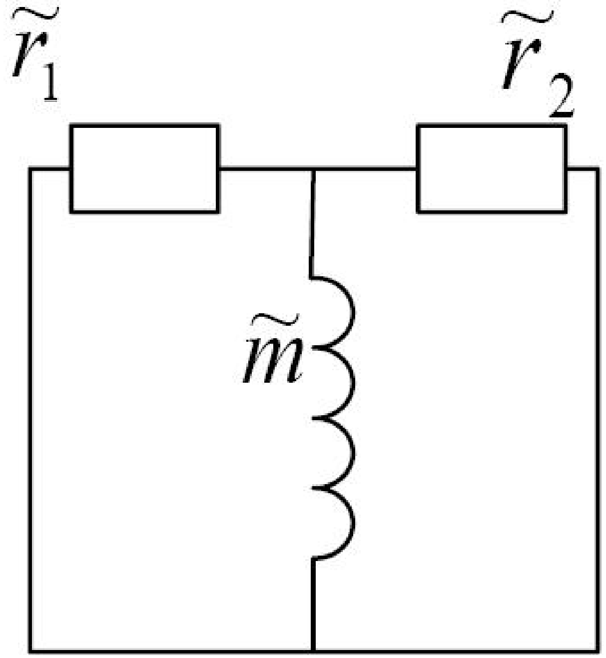
$$K_{11} = \frac{T_1}{T_1 + T_2}\left(i_{v10} + i_{v20}\right) = \frac{5}{6}\left(1000 + 0\right) = 833.334;;$$

$$K_{21} = \frac{T_2}{T_1 + T_2}\left(i_{v10} + i_{v20}\right) = \frac{1}{6}\left(1000\right) = 166.666$$

Případ D

závěr: $T'' \Leftrightarrow \sigma, \quad T' \Leftrightarrow společný\ tok\ \psi_{12}$





Modální analýza synchr. stroje

$\Rightarrow$ Příklad:

Vypočtěte poměrné parametry .

Parametry stroje: (Dukovany)

S_n	259	MVA	T_J	9.89	s
cosφ	0.85	-			
Un	15.75	kV			
x_d	1.926	p.u.			
x'_d	0.267	p.u.	T'_d	0.84	s
x''_d	0.199	p.u.	T''_d	0.03	s
x_q	1.36	p.u.			
x''_q	0.204	p.u.	T''_q	0.03	s
x_σ	0.166	p.u.	T_a	0.37	s

$$x_{ex} = 0.2(p.u)$$

Modální analýza synchr. stroje

$$\text{Vstupy}: S_n, U_n, \cos\varphi, x_d, x'_d, x''_d, x_q, x''_q, x_\sigma, T_J$$

$$Z_n = \frac{U_n^2}{S_n} = \frac{15.75^2}{259} =$$

$$x_{ad} = x_d - x_\sigma = 1.926 - 0.166 = 1.76 \quad ,$$

1) $x_{aq} = x_q - x_\sigma = 1.836 - 0.166 = 1.67$

2) $x_f = x_{f\sigma} + x_{ad}; x'_d = x_\sigma + \left(\frac{1}{x_{ad}} + \frac{1}{x_{f\sigma}}\right)^{-1} \Rightarrow$

$$x_{f\sigma} = \left(\frac{1}{x'_d - x_\sigma} - \frac{1}{x_{ad}}\right)^{-1} = \left(\frac{1}{0.267 - 0.166} - \frac{1}{1.76}\right)^{-1} = 0.107$$

$$x_f = x_{f\sigma} + x_{ad} = 0.107 + 1.76 = 1.867$$

Modální analýza synchr. stroje

$$3)\quad x_d'' = x_\sigma + \left(\frac{1}{x_{ad}} + \frac{1}{x_{f\sigma}} + \frac{1}{x_{D\sigma}}\right)^{-1} \Rightarrow$$

$$\Rightarrow x_{D\sigma} = \left(\frac{1}{x_d'' - x_\sigma} - \frac{1}{x_{ad}} - \frac{1}{x_{f\sigma}}\right)^{-1}$$

$$\Rightarrow x_{D\sigma} = \left(\frac{1}{0.199 - 0.166} - \frac{1}{1.76} - \frac{1}{0.107}\right)^{-1} = 0.049$$

$$4)\quad x_d'' = x_\sigma + \left(\frac{1}{x_{aq}} + \frac{1}{x_{Q\sigma}}\right)^{-1} \Rightarrow x_{Q\sigma} = \left(\frac{1}{x_q'' - x_\sigma} - \frac{1}{x_{aq}}\right)^{-1}$$

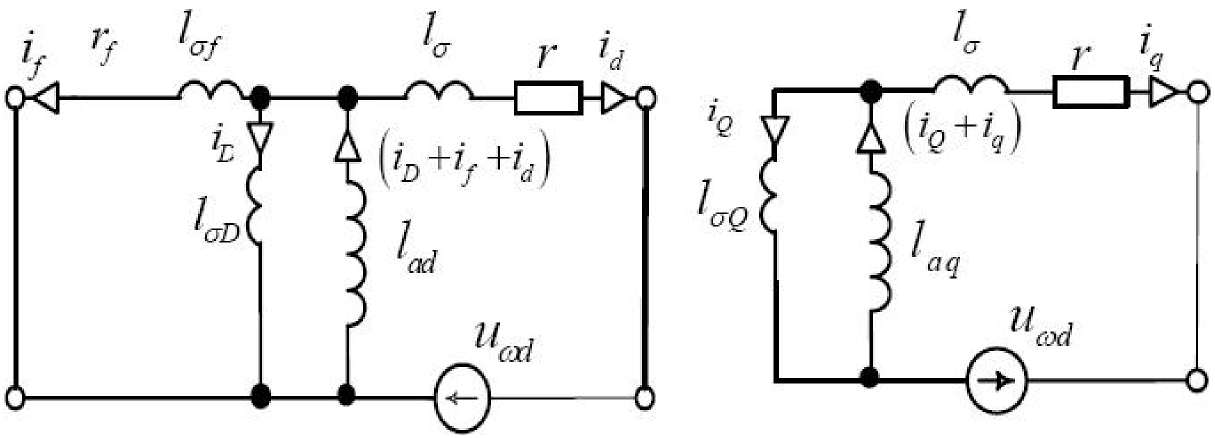
$$x_{Q\sigma} = \left(\frac{1}{0.204 - 0.166} - \frac{1}{1.67}\right)^{-1} = 0.039$$

$$x_Q = x_{Q\sigma} + x_{aq} = 0.039 + 1.67 = 1.709$$

Modální analýza synchr. stroje

5) časové konstanty statoru T_a, T'_d, T''_d, T''_q

$$u_{\omega d} = \omega \Psi_q = i_q x''_q - e''_d, \quad u_{\omega q} = \omega \Psi_d = i_d x''_d - e''_q$$



dif. rovnice volných proudů:

$$0 = -r \cdot i_{qv} - x''_q \frac{di_{qv}}{dt} + x''_d i_{dv}, \qquad 0 = -r \cdot i_{dv} - x''_d \frac{di_{dv}}{dt} - x''_q i_{qv}$$

Modální analýza synchr. stroje

$$\begin{bmatrix} -\frac{r}{x''_d} - s & -\frac{x''_q}{x''_d} \\ \frac{x''_d}{x''_q} & -\frac{r}{x''_q} - s \end{bmatrix} \cdot \begin{bmatrix} i_{dv} \\ i_{qv} \end{bmatrix} = 0$$

charakteristické rovnice :

$$\left(\frac{r}{x''_d} + s\right)\left(\frac{r}{x''_q} + s\right) + 1 = 0 \Rightarrow$$

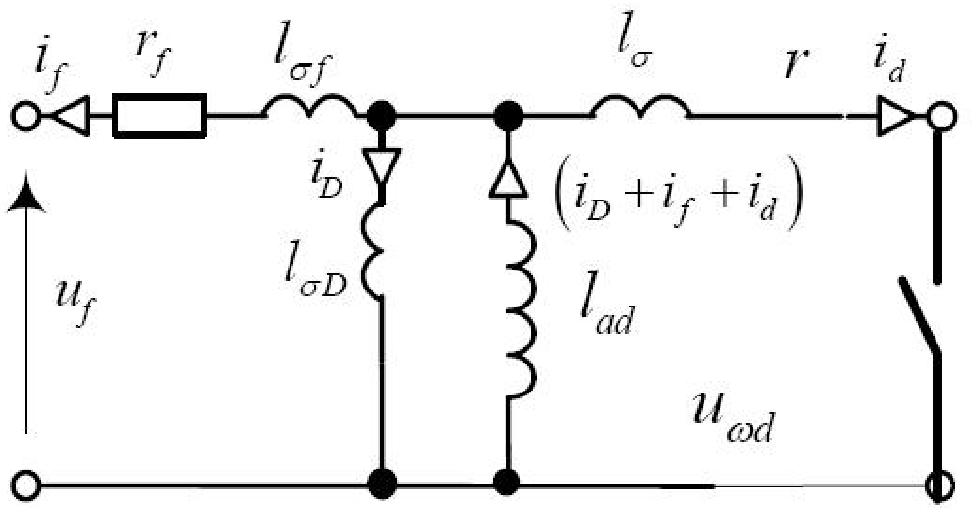
$$\Rightarrow s^2 + s \cdot r\left(\frac{1}{x''_d} + \frac{1}{x''_q}\right) + \frac{r^2}{x''_d x''_q} + 1 = 0$$

$$\lambda_{1,2} = \frac{-r\left(\frac{1}{x''_d} + \frac{1}{x''_q}\right) \pm \sqrt{r^2\left(\frac{1}{x''_d} + \frac{1}{x''_q}\right)^2 - 4\left(1 + \frac{r^2}{x''_d x''_q}\right)}}{2}$$

Modální analýza synchr. stroje

$$\lambda_{1,2} \doteq -\frac{r}{\frac{2\cdot x''_d x''_q}{\left(x''_d + x''_q\right)}} \pm j \Rightarrow T_a = \frac{2\cdot x''_d x''_q}{\omega \cdot r \cdot \left(x''_d + x''_q\right)}$$

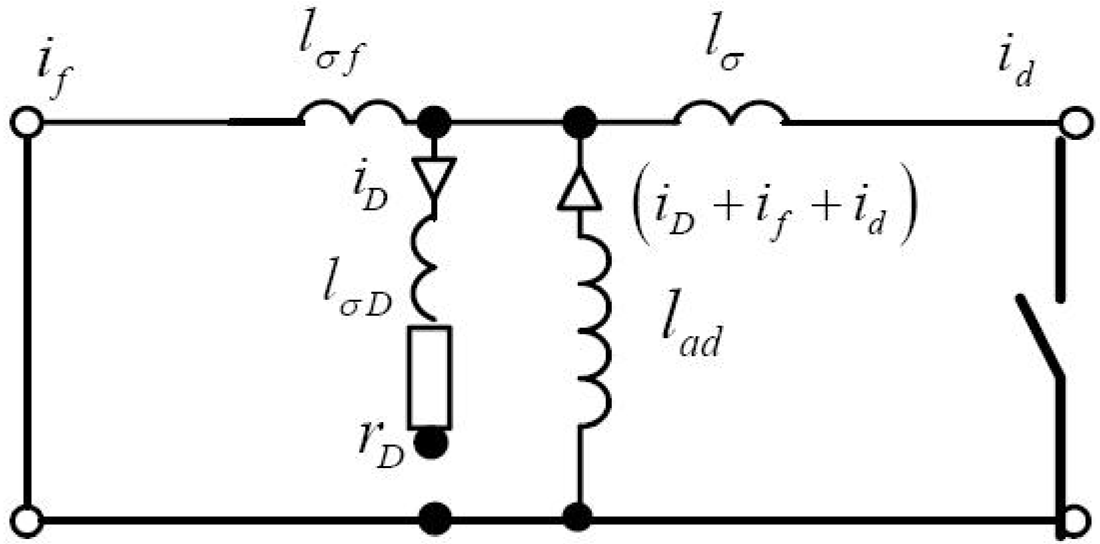
Časové konstanty rotoru



$$T_f = \frac{x_f}{\omega \cdot r_f} \quad , \quad T_D = \frac{x_D}{\omega \cdot r_D}$$

časové konstanty pro stator naprázdno

Modální analýza synchr. stroje



Modální analýza synchr. stroje

$$\sigma_{fD} = 1 - \frac{x_{ad}^2}{x_f x_D}$$

$$T'_{d0} + T''_{d0} = T_f + T_D$$

$$\underbrace{T'_{d0} \cdot T''_{d0} = \sigma_{fD} \cdot T_f \cdot T_D}_{\text{kvadratická rovnice pro } T'_{d0},\, T''_{d0}}$$

$$T'_f = \frac{x'_f}{\omega \cdot r_f} \quad , \quad T'_D = \frac{x'_D}{\omega \cdot r_D} \qquad \text{stator nakrátko}$$

$$x'_{ad} = x_{ad} \| x_\sigma \qquad x'_f = x_{f\sigma} + x'_{ad} \qquad x'_D = x_{D\sigma} + x'_{ad}$$

Modální analýza synchr. stroje

$$T'_f = \frac{x'_f}{\omega \cdot r_f} \quad , \quad T'_D = \frac{x'_D}{\omega \cdot r_D} \qquad \text{stator nakrátko}$$

$$x'_{ad} = x_{ad} \| x_\sigma \qquad x'_f = x_{f\sigma} + x'_{ad} \qquad x'_D = x_{D\sigma} + x'_{ad}$$

$$\sigma'_{fD} = 1 - \frac{x'^2_{ad}}{x'_f x'_D}$$

$$T'_f + T'_D = T'_d + T''_d$$

$$\underbrace{T'_{fD} \cdot T'_f \cdot T'_D = T'_d \cdot T''_d}_{\text{kvadratická rovnice pro } T'_d, T''_d}$$

Modální analýza synchr. stroje

$$r_f = \frac{x'_f}{\omega \cdot T'_f} \quad r_D = \frac{x'_D}{\omega \cdot T'_D} \quad r_Q = \frac{x'_Q}{\omega \cdot T'_Q - T''_q}$$

$$x'_Q = x_{\sigma Q} + \frac{x_\sigma \cdot x_{aq}}{x_\sigma + x_{aq}}$$

Přehled bázových hodnot.

$$L_{\mu d} = L_d - L_\sigma, \qquad \psi_{\mu d} = L_{\mu d} I_b = kM_f . I_{fb} = kM_D I_{Db}$$

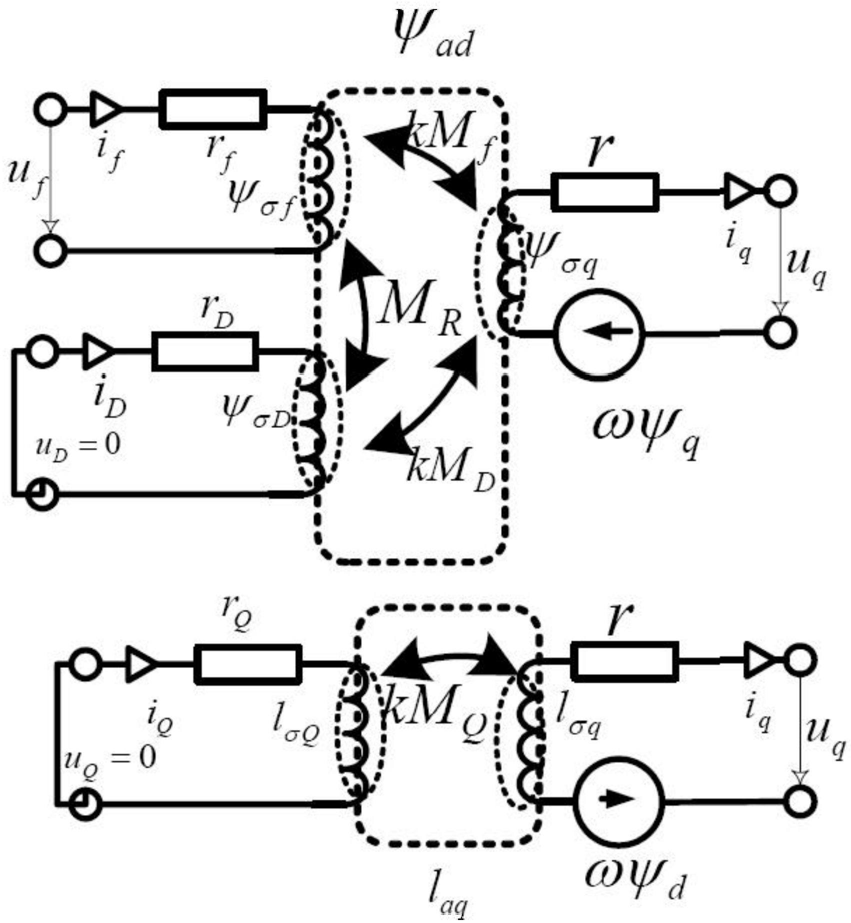
$$L_{\mu q} = L_q - L_\sigma, \qquad \psi_{\mu q} = L_{\mu q} I_b = kM_Q I_{Qb}$$

$$L_{\mu f} = L_f - L_{\sigma f}, \qquad \psi_{\mu f} = L_{\mu f} I_{fb} = kM_f . I_{fb} = M_R I_{Db}$$

$$L_{\mu Q} = L_Q - L_{\sigma Q}, \qquad \psi_{\mu Q} = L_{\mu Q} I_{Qb} = kM_Q I_b$$

$$L_{\mu D} = L_D - L_{\sigma D}, \qquad \psi_{\mu D} = L_{\mu D} I_{Db} = M_R . I_{fb} = kM_D I_b$$

Modální analýza synchr. stroje



Modální analýza synchr. stroje

Rovnost magnetomotorických sil

$$L_{\mu d} I_b^2 = L_{\mu f} I_{fb}^2 = L_{\mu D} I_{Db}^2 = kM_f I_b I_{fb} = kM_D I_b I_{Db} = M_R I_{Db} I_{fb}$$

$$L_{\mu q} I_b^2 = L_{\mu Q} I_{Qb}^2 = kM_Q I_b I_{Qb}$$

Transformační převody

$$\varepsilon_f = \frac{U_{fb}}{U_b} = \frac{I_b}{I_{fb}} = \left(\frac{L_{\mu f}}{L_{\mu d}}\right)^{1/2} = \frac{kM_f}{L_{\mu d}} = \frac{L_{\mu f}}{kM_f} = \frac{M_R}{kM_D}$$

$$\varepsilon_D = \frac{U_{Db}}{U_b} = \frac{I_b}{I_{Db}} = \left(\frac{L_{\mu D}}{L_{\mu d}}\right)^{1/2} = \frac{kM_D}{L_{\mu d}} = \frac{L_{\mu D}}{kM_D} = \frac{M_R}{kM_f}$$

$$\varepsilon_Q = \frac{U_{Qb}}{U_b} = \frac{I_b}{I_{Qb}} = \left(\frac{L_{\mu Q}}{L_{\mu q}}\right)^{1/2} = \frac{kM_Q}{L_{\mu q}} = \frac{L_{\mu q}}{kM_Q}$$

Modální analýza synchr. stroje

Přepočet.

$$R_{fb} = \varepsilon_f^2 R_b; \qquad R_{Db} = \varepsilon_D^2 R_b; \qquad R_{Qb} = \varepsilon_Q^2 R_b;$$

$$L_{fb} = \varepsilon_f^2 L_b; \qquad L_{Db} = \varepsilon_D^2 L_b; \qquad L_{Qb} = \varepsilon_Q^2 L_b;$$

$$M_{fb} = \varepsilon_f L_{b,} \qquad M_{Db} = \varepsilon_D L_{b,} \qquad M_{Qb} = \varepsilon_Q L_{b,}$$

$$M_{Rb} = \varepsilon_D \varepsilon_f L_{b,}$$

Poměrné hodnoty

$$\tilde{r} = R/R_b;$$

$$\tilde{l}_d = \tilde{x}_d = L_d/L_b \qquad \tilde{l}_q = \tilde{x}_q = L_q/L_b$$