Supratensiuni la transformatoare

Repartizarea inițială şi finală

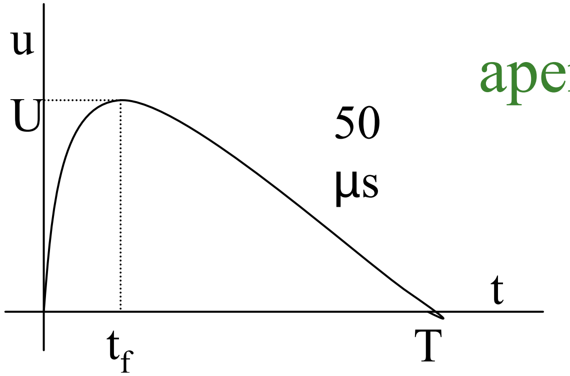
Măsuri de protecție

Formele de unde de supratensiuni

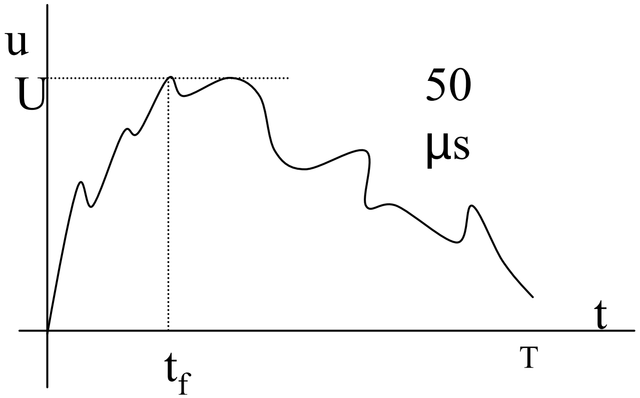
Cauzele şi formele supratensiunilor:

- atmosferice - 8….12 Un

aperiodic simplu



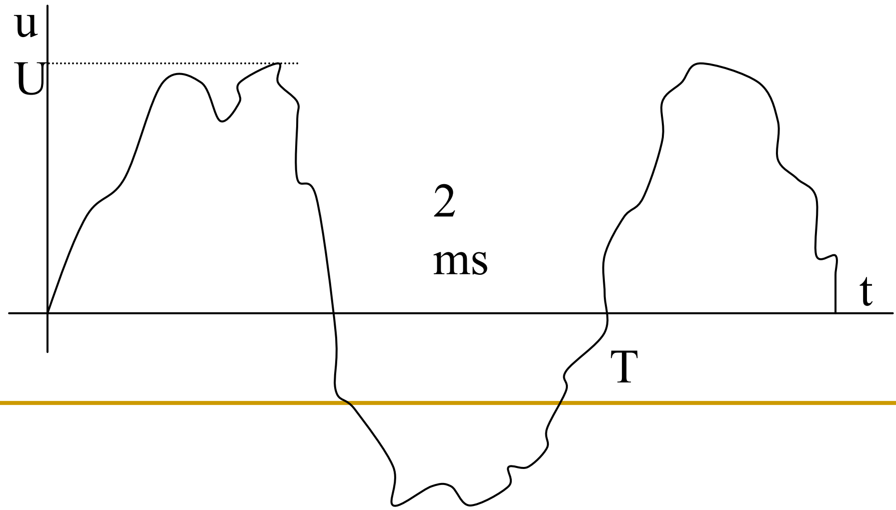
aperidic complex



- datorită avariilor - 7…..8 Un

Periodic – simplu

- complex

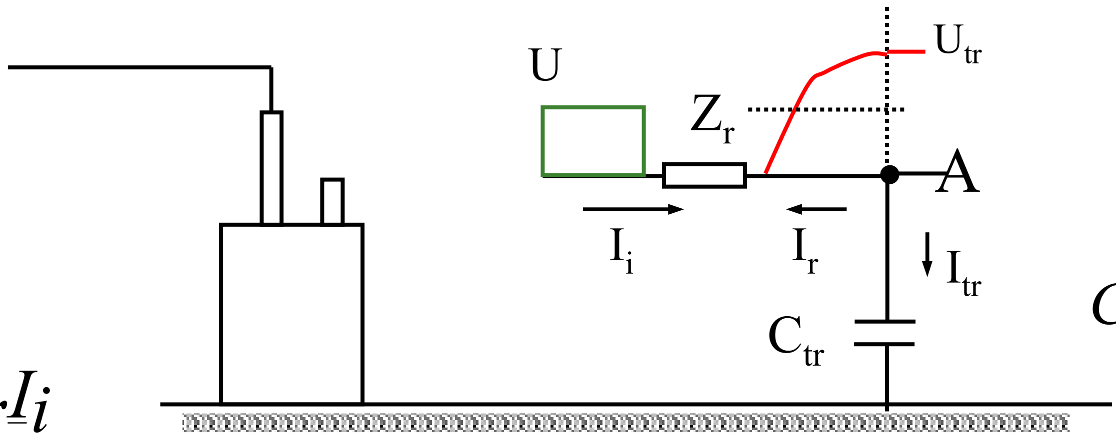


- de comutație

- 2. . . . .5 Un

periodic

Propagarea undei de supratensiuni



$Z_r \cong 500\,\Omega$

$C_{tr} \approx 0.1\,nF \div 0.1\,\mu F$

$\underline{U}_i = \underline{Z}_r \underline{I}_i$

$\underline{U}_r = \underline{Z}_r \underline{I}_r$

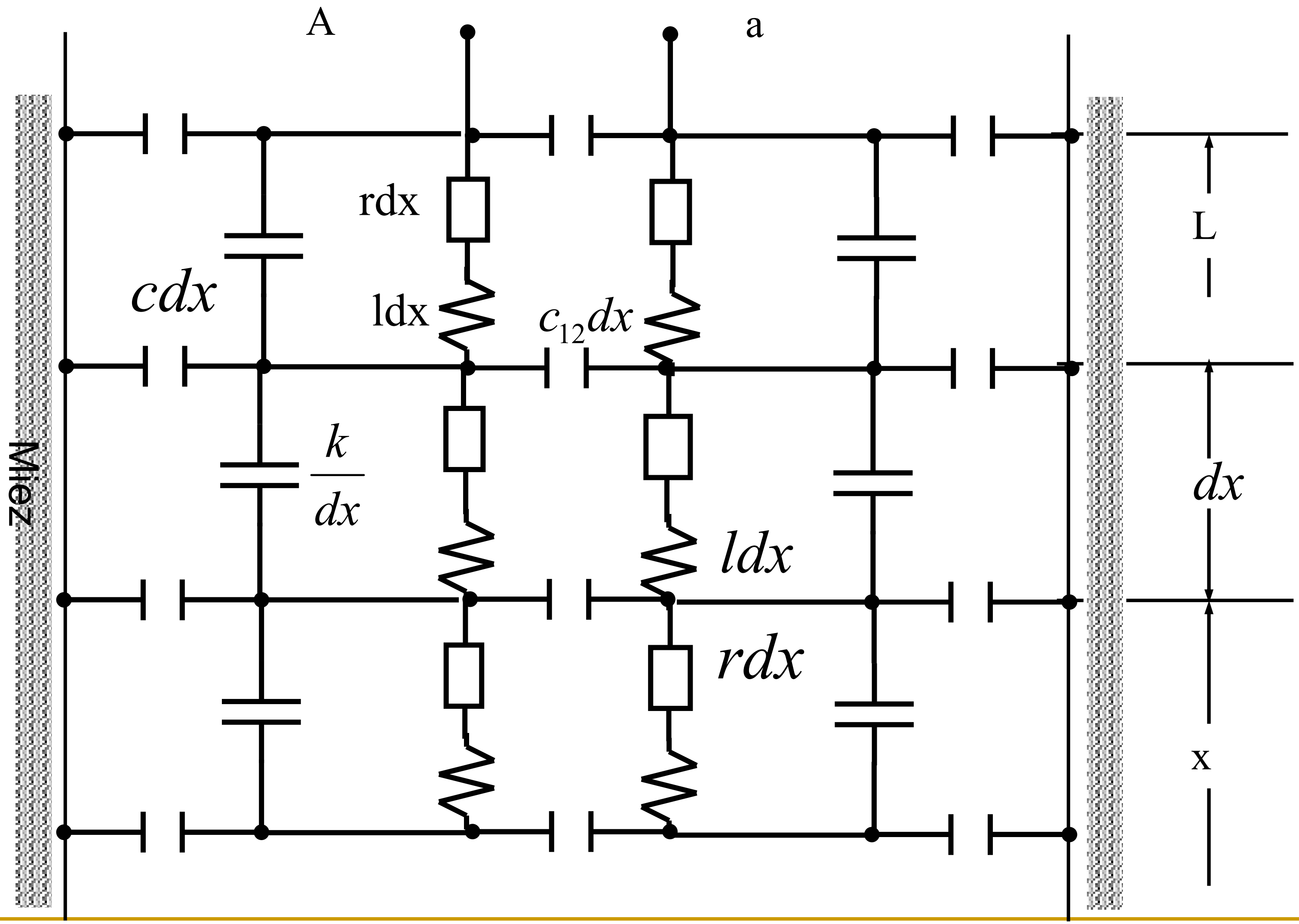
$u_{tr} = \frac{1}{C_{tr}} \int i_{tr} d$

$$u_{tr} = 2U\left(1 - e^{-\frac{t}{C_{tr} Z_r}}\right)$$

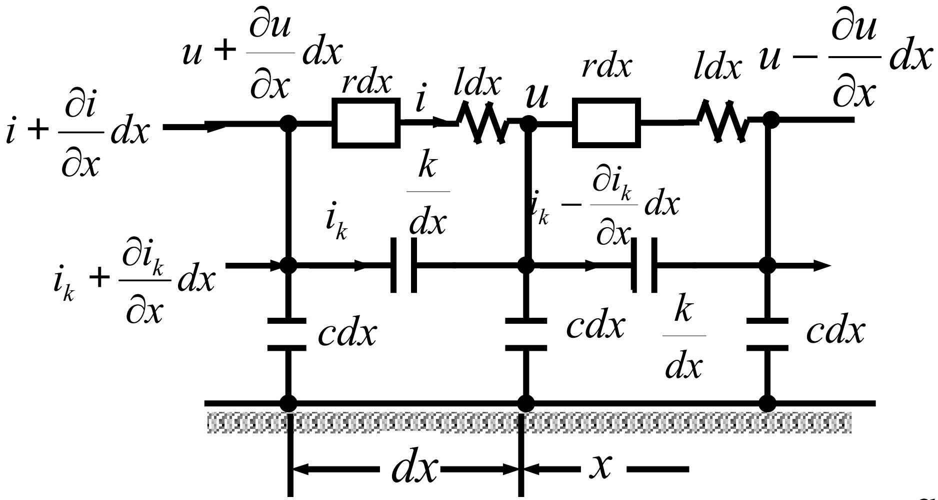
$i_t = i_i - i$

$C_{tr} \cdot Z_r \cong 0.05 \div 50\ \mu s$

Schema echivalentă a transformatorului



Ecuațiile schemei echivalente



$$\left(u+\frac{\partial u}{\partial x}dx\right)-u=rdx\cdot i+ldx\cdot\frac{\partial i}{\partial t}$$

$$\frac{\partial u}{\partial x}=r\cdot i+l\frac{\partial i}{\partial t}$$

$$\frac{1}{\frac{k}{dx}}\int i_k dt=\left(u+\frac{\partial u}{\partial x}dx\right)-u$$

$$\frac{dx}{k}\int i_k dt=\frac{\partial u}{\partial x}dx$$

$$\frac{i_k}{k}=\frac{\partial u}{\partial x\partial t}$$

$$q=u\cdot c$$

$$\sum i=\frac{\partial u}{\partial t}c$$

$$i_k-\left(i_k-\frac{\partial i_k}{\partial x}dx\right)+i-\left(i-\frac{\partial i}{\partial x}dx\right)=\frac{\partial u}{\partial t}cdx$$

$$\frac{\partial i_k}{\partial x}+\frac{\partial i}{\partial x}=\frac{\partial u}{\partial t}c$$

Deducerea ecuației generale

$$\frac{1}{k}\frac{\partial i_k}{\partial x} = \frac{\partial^3 u}{\partial x^2 \partial t} \quad \Rightarrow \quad k\frac{\partial^3 u}{\partial x^2 \partial t} + \frac{\partial i}{\partial x} = c\frac{\partial u}{\partial t} \quad \Rightarrow \quad \frac{\partial i}{\partial x} = c\frac{\partial u}{\partial t} - k\frac{\partial^3 u}{\partial x^2 \partial t}$$

$$\frac{\partial^2 u}{\partial x^2} = r\frac{\partial i}{\partial x} + l\frac{\partial^2 i}{\partial x \partial t} = r\left(c\frac{\partial u}{\partial t} - k\frac{\partial^3 u}{\partial x^2 \partial t}\right) + l\left(c\frac{\partial^2 u}{\partial t^2} - k\frac{\partial^4 u}{\partial x^2 \partial t^2}\right)$$

$$l \cdot k\frac{\partial^4 u}{\partial x^2 \partial t^2} + r \cdot k\frac{\partial^3 u}{\partial x^2 \partial t} - r \cdot c\frac{\partial u}{\partial t} + \frac{\partial^2 u}{\partial x^2} = l \cdot c\frac{\partial^2 u}{\partial t^2}$$

$$k\frac{\partial^4 u}{\partial x^2 \partial t^2} + \frac{r}{l}k\frac{\partial^3 u}{\partial x^2 \partial t} - \frac{r}{l}c\frac{\partial u}{\partial t} + \frac{1}{l}\frac{\partial^2 u}{\partial x^2} = c\frac{\partial^2 u}{\partial t^2}$$

Aplicarea transformatei Laplace

$$\frac{\partial}{\partial t} \rightarrow p \qquad\qquad u \rightarrow U$$

$$\left(k \cdot p^2 + \frac{1}{l}\right)\frac{d^2U}{dx^2} + \frac{r}{l}\left(k \cdot p \frac{d^2U}{dx^2} - c \cdot p \cdot U\right) = c \cdot p^2 \cdot U$$

$$\left(k \cdot p^2 + k\frac{r}{l}p + \frac{1}{l}\right)\frac{d^2U}{dx^2} = c\left(p^2 + \frac{r}{l}p\right)U$$

$$\frac{d^2U}{dx^2} = \alpha^2 \cdot U \qquad\qquad \alpha^2 = \frac{c \cdot p \cdot (l \cdot p + \ )}{k \cdot l \cdot p^2 + k \cdot r \cdot p + 1}$$

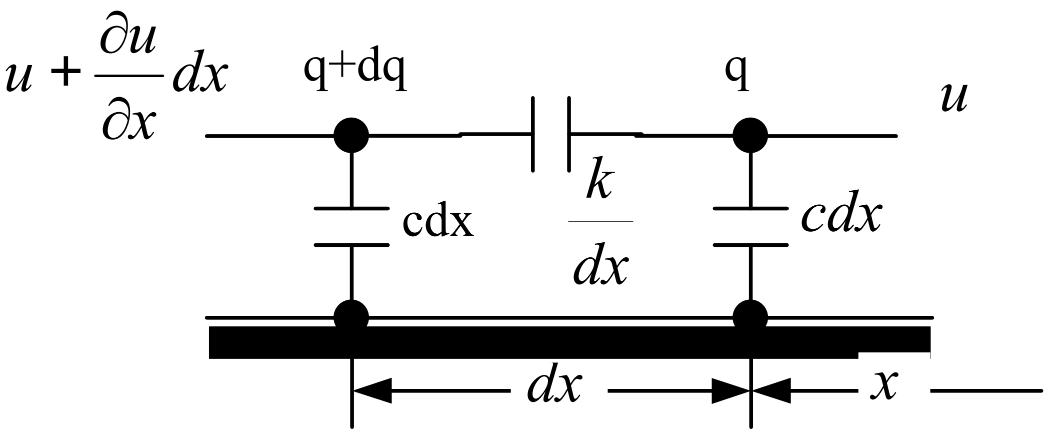
Analiza procesului

La începutul procesului $t = 0^+$ $p \rightarrow \infty$

$$\alpha^2 = \frac{c}{k}$$

Inductivitatea nu are influiență

se consideră $l \rightarrow \infty$



$$k \frac{\partial^4 u}{\partial x^2 \cdot \partial t^2} = c \frac{\partial^2 u}{\partial t^2}$$

$$\alpha = \sqrt{\frac{c}{k}}$$

Repartizarea inițială a supratensiunii

$$\frac{\partial^2 u}{\partial t^2} \rightarrow p^2 \cdot U$$

$$U = A \cdot sh(\alpha \cdot x) + B \cdot ch(\alpha \cdot x)$$

$$\frac{\partial^2 U}{\partial x^2} = \alpha^2 \cdot U$$

<u>nulul transformatorului este legat la pământ</u>

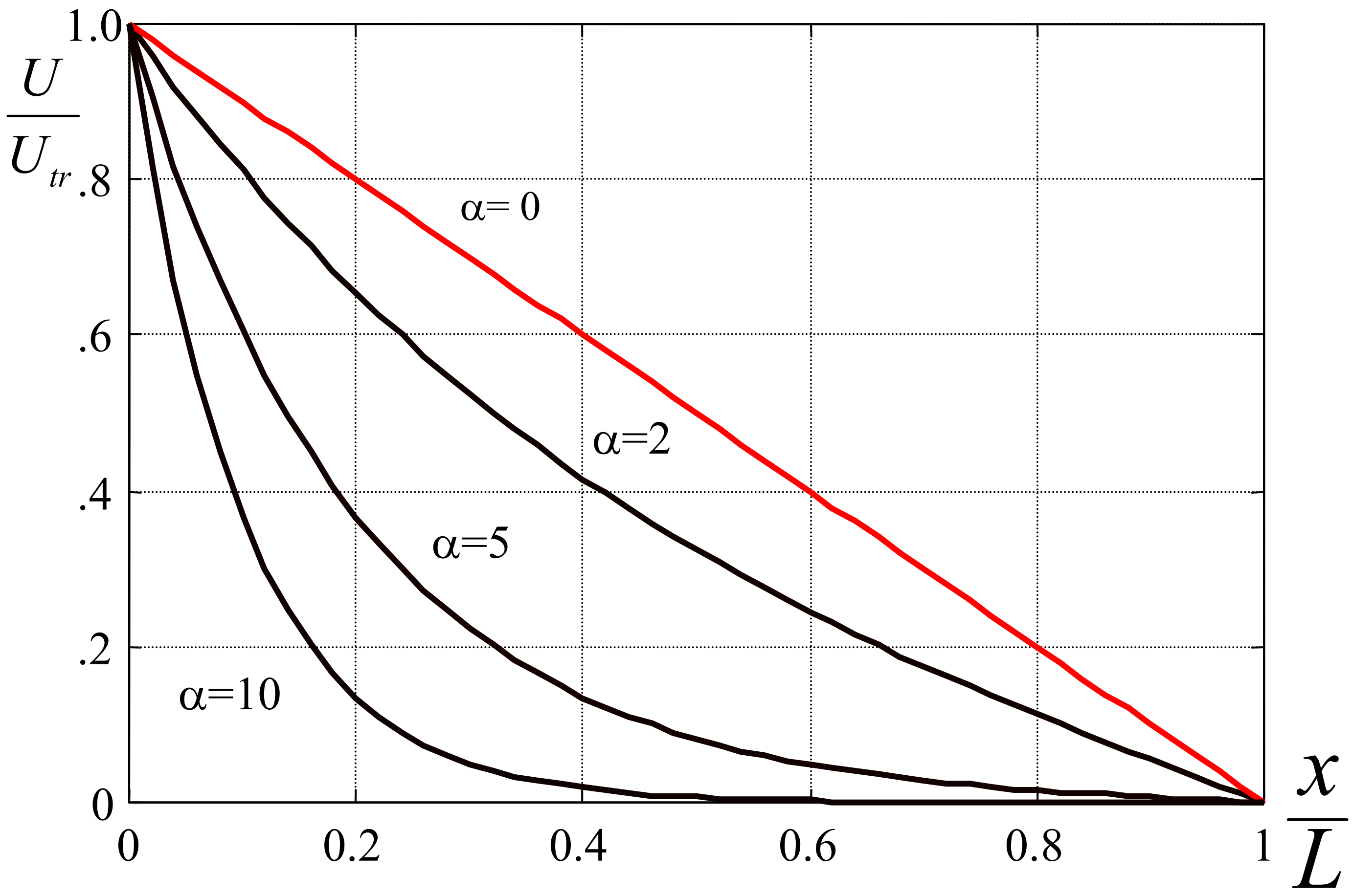
la $x=0$ (nulul) potențialul este al pământului $U = 0$

$$0 = A \cdot sh\alpha x + B \cdot ch\alpha x \quad \Longrightarrow \quad B = 0$$

la $x = L$ (borna de intrare) este tensiunea $U = U_{tr}$

Repartizarea inițială a supratensiunii

Utr = A ·sh (α·L) → $U = U_{tr}\frac{sh(\alpha \cdot x)}{sh(\alpha \cdot L)}$



Repartizarea inițială a supratensiunii

Nulul transformatorului este izolat față de pământ

$$q = \left[u - \left(u - \frac{\partial u}{\partial x} dx \right) \right] \frac{k}{dx} = k \frac{\partial u}{\partial x}$$

$q = [\ A \cdot \alpha \cdot sh\ \alpha \cdot x - B \cdot \alpha \cdot ch\ \alpha \cdot x]$ $\qquad$ $k = 0$

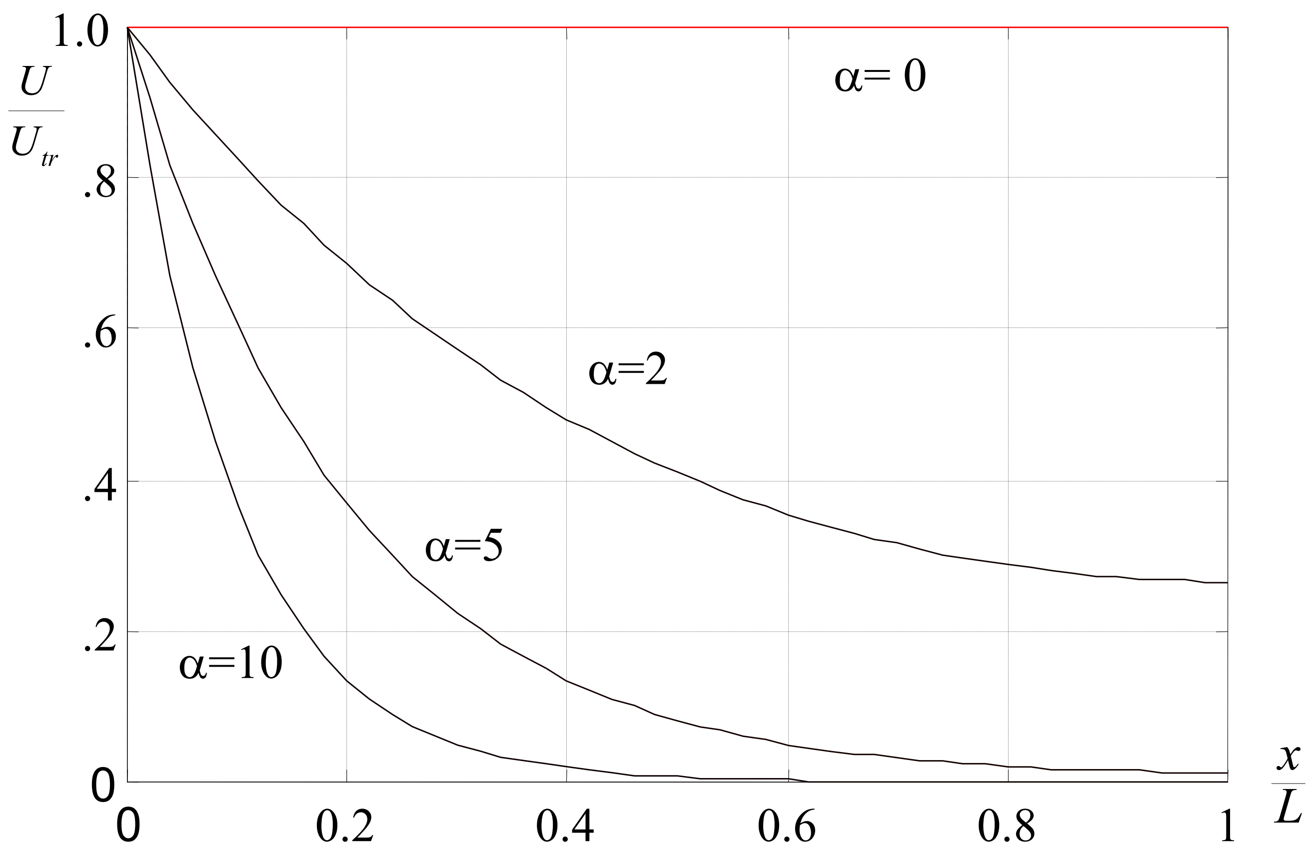
La $x = 0$ sarcinile sunt repartizate pe condensatoare iar la nul $q = 0$

$A = 0$

la $x = L$ (borna de intrare) este tensiunea $U = U_{tr}$

Repartizarea inițială a supratensiunii

$U_{tr} = B \cdot ch\, \alpha \cdot L$ ⟶ $$U = U_{tr} \frac{ch(\alpha \cdot x)}{ch(\alpha \cdot L)}$$



Repartizarea finală a supratensiunii

t → ∞ p = 0 ⇒ α = 0

Regimul tranzitoriu este determinat de rădăcinile ecuației caracteristice:

$$k \cdot l \cdot p^2 + k \cdot r \cdot p + 1 = 0$$

$$p_{1,2} = -\frac{r}{2 \cdot l} \pm \sqrt{\left(\frac{r}{2 \cdot l}\right)^2 - \frac{1}{k \cdot l}} = -\frac{1}{T} \pm \sqrt{\frac{1}{T^2} - \frac{1}{k \cdot l}}$$

Repartizarea finală a supratensiunii

$$T = \frac{2 \cdot l}{r}$$

$$T = \sqrt{k \cdot l}$$

$$p_1 = p_2 = -\frac{1}{T}$$

aperiodic

$$T \rangle \sqrt{k \cdot l}$$

$$p_1 = -\frac{1}{T_1}$$

$$p_2 = -\frac{1}{T_2}$$

aperiodic

$$T \langle \sqrt{k \cdot l}$$

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

oscilatii

Măsuri de protecție

Măsuri exterioare:

- alegerea corespunzătoare a traseului liniei electrice
- folosirea eclatoarelor şi descărcătoarelor electrice
- legarea nulului la pământ prin grup RLC în paralel

Măsuri constructive (interioare)

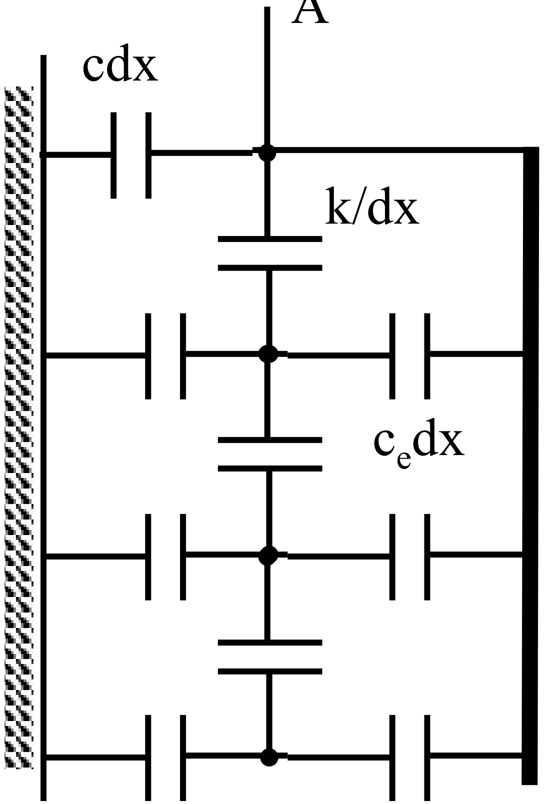
- izolarea suplimentară a primelor spire
- ecran electrostatic
- inel secționat pentru primele prize

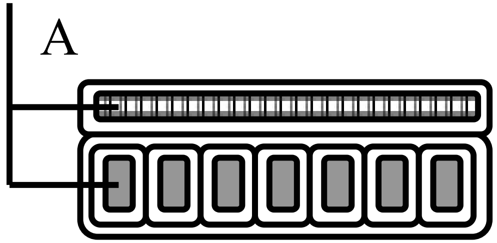
Măsuri de protecție

ecran electrostatic

$$\alpha = \sqrt{\frac{c}{k}}$$

$$\alpha \to 0$$





inel sectionat pentru primele prize

Regimurile tranzitorii la transformatoare

Cuplarea la rețea a transformatorului şi scurtcircuitul brusc.

Regimurile tranzitorii la transformatoare

Cauzele regimurilor tranzitorii:

- modificarea bruscă a condițiilor de exploatare
    - condiții de mediu
    - condiții de funcționare
    - valorile parametrilor

Manifestarea regimului tranzitorii:

- regimuri de supracurenți
    - -cuplarea la rețea
    - -scurtcircuit brusc
- regimuri de supratensiuni

Cuplarea la rețea a transformatorului

Ipoteze:

- transformatorul este fără sarcină,
- fluxul remanent al miezului Ψ_r este redus,
- tensiunea de alimentare este sinusoidală

$$u_1 = \sqrt{2} \cdot U_1 \cdot \sin(\omega \cdot t + \alpha)$$

- conectarea se face în momentul când tensiunea are valoarea:

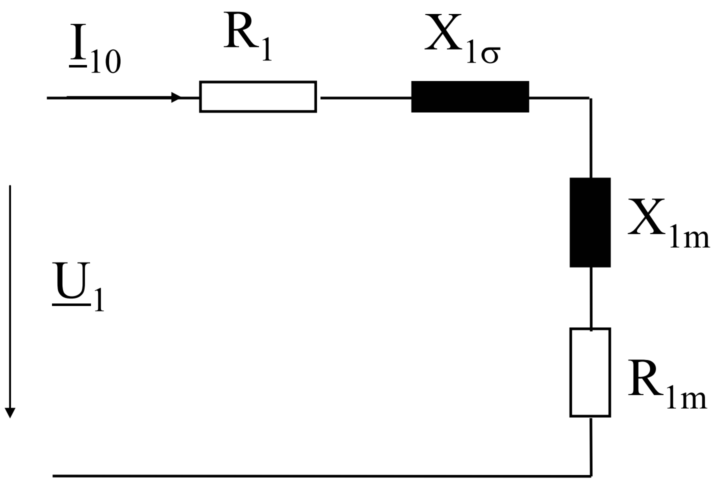
$$u_{10} = \sqrt{2} \cdot U_1 \cdot \sin(\alpha)$$

Ecuația de tensiune:

$$u_1 = R_1 \cdot i_{10} + \frac{d\Psi_1}{dt}$$

Cuplarea la rețea a transformatorului

Fluxul total la mersul în gol



$$\Psi_1 = L_1 \cdot i_{10} = \left(L_{1\sigma} + L_{1m}\right) \cdot i_{10}$$

Rezultă:

$$i_{10} = \frac{\Psi_1}{L_1}$$

$$\sqrt{2} \cdot U_1 \cdot \sin\left(\omega \cdot t + \alpha\right) = \frac{R_1}{L_1}\Psi_1 + \frac{d\Psi_1}{dt}$$

Cuplarea la rețea a transformatorului

Soluția:

$$\Psi_1 = C \cdot e^{-\frac{t}{T_1}} + \Psi_{1m} \cdot \sin(\omega \cdot t + \gamma)$$

Unde:

$$T_1 = \frac{L_1}{R_1}$$ Constanta de timp

$$\Psi_{1m} = \frac{\sqrt{2} \cdot U_1}{\sqrt{\omega^2 + \frac{1}{T_1^2}}}$$ Amplitudinea fluxului alternativ

$$tg(\gamma - \alpha) = -\omega \cdot T_1 = -\frac{X_1}{R_1}$$

Cuplarea la rețea a transformatorului

Condiții inițiale: la t = 0 $\Psi_1 = \Psi_r$

Rezultă: $$C = \Psi_r - \Psi_{1m} \cdot \sin\gamma$$

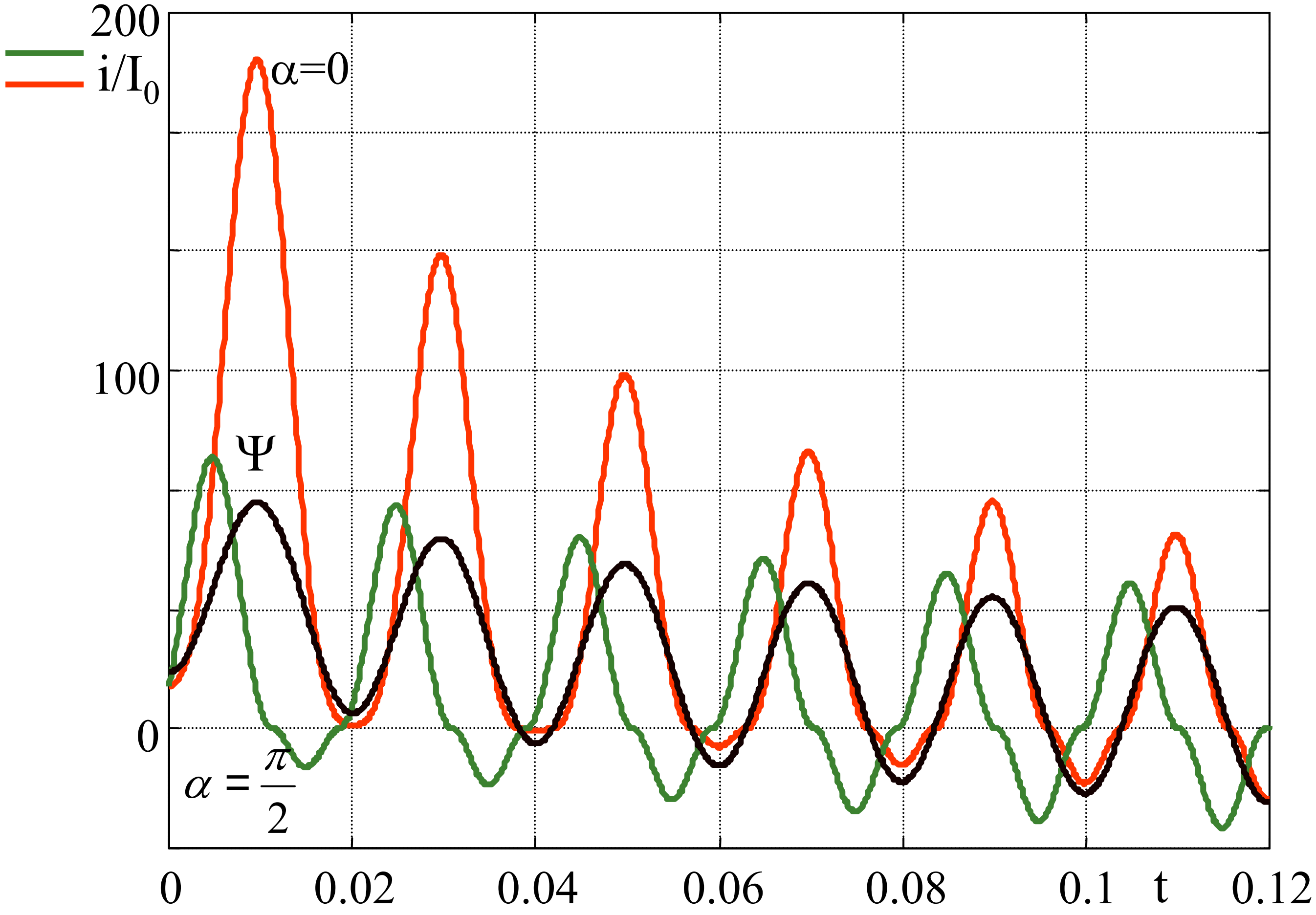
$$\Psi_1 = \Psi_{1m} \cdot \sin(\omega \cdot t + \gamma) + (\Psi_r - \Psi_{1m} \cdot \sin\gamma) \cdot e^{-\frac{t}{T_1}}$$

Valoarea maximă pentru: $\gamma = -\frac{\pi}{2}$ $\omega \cdot t + \gamma = \frac{\pi}{2}$

Rezultă: $t = \frac{\pi}{\omega}$ $\alpha = \lambda + arctg\left(\frac{X_1}{R_1}\right) \approx 0$

$$\Psi_{1\max} = \Psi_{1m} + (\Psi_r + \Psi_{1m}) \cdot e^{-\frac{\pi}{\omega \cdot T_1}}$$

Cuplarea la rețea a transformatorului



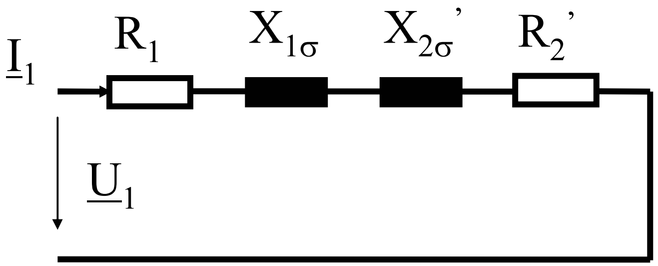
Scurtcircuitul brusc

Ipoteze:

- funcționează în sarcină având curentul I_0

- la apariția scurtcircuitului tensiunea are valoarea

$$u_1 = \sqrt{2} \cdot U_1 \cdot \sin(\alpha)$$



$$Z_{1sc} = \sqrt{R_{1sc}^2 + X_{1sc}^2}$$

$$T_{1sc} = \frac{L_{1sc}}{R_{1sc}}$$

Scurtcircuitul brusc

$$\sqrt{2}\cdot U_1\cdot\sin(\omega\cdot t+\alpha)=R_{1sc}\cdot i_{1sc}+L_{1sc}\frac{di_{1sc}}{dt}$$

Soluția:

$$i_{1sc}=I_{1msc}\cdot\sin(\omega\cdot t+\gamma_{sc})+C\cdot e^{-\frac{t}{T_{1sc}}}$$

Curentul inițial I_0

$$I_0=I_{1msc}\cdot\sin(\gamma_{sc})+C$$

$$I_{1msc}=\frac{\sqrt{2}\cdot U_1}{Z_{1sc}}\qquad tg(\gamma_{sc}-\alpha)=-\omega\cdot T_{1sc}$$

$$i_{1sc}=\frac{\sqrt{2}\cdot U_1}{Z_{1sc}}\sin(\omega\cdot t+\gamma_{sc})+\left(I_0-\frac{\sqrt{2}\cdot U_1}{Z_{1sc}}\sin\gamma_{sc}\right)\cdot e^{-\frac{t}{T_{1sc}}}$$

Scurtcircuitul brusc

Valoarea maximă la

$$\omega \cdot t + \gamma_{sc} = \frac{\pi}{2} \qquad \gamma_{sc} = -\frac{\pi}{2}$$

$$t = \frac{\pi}{\omega}$$

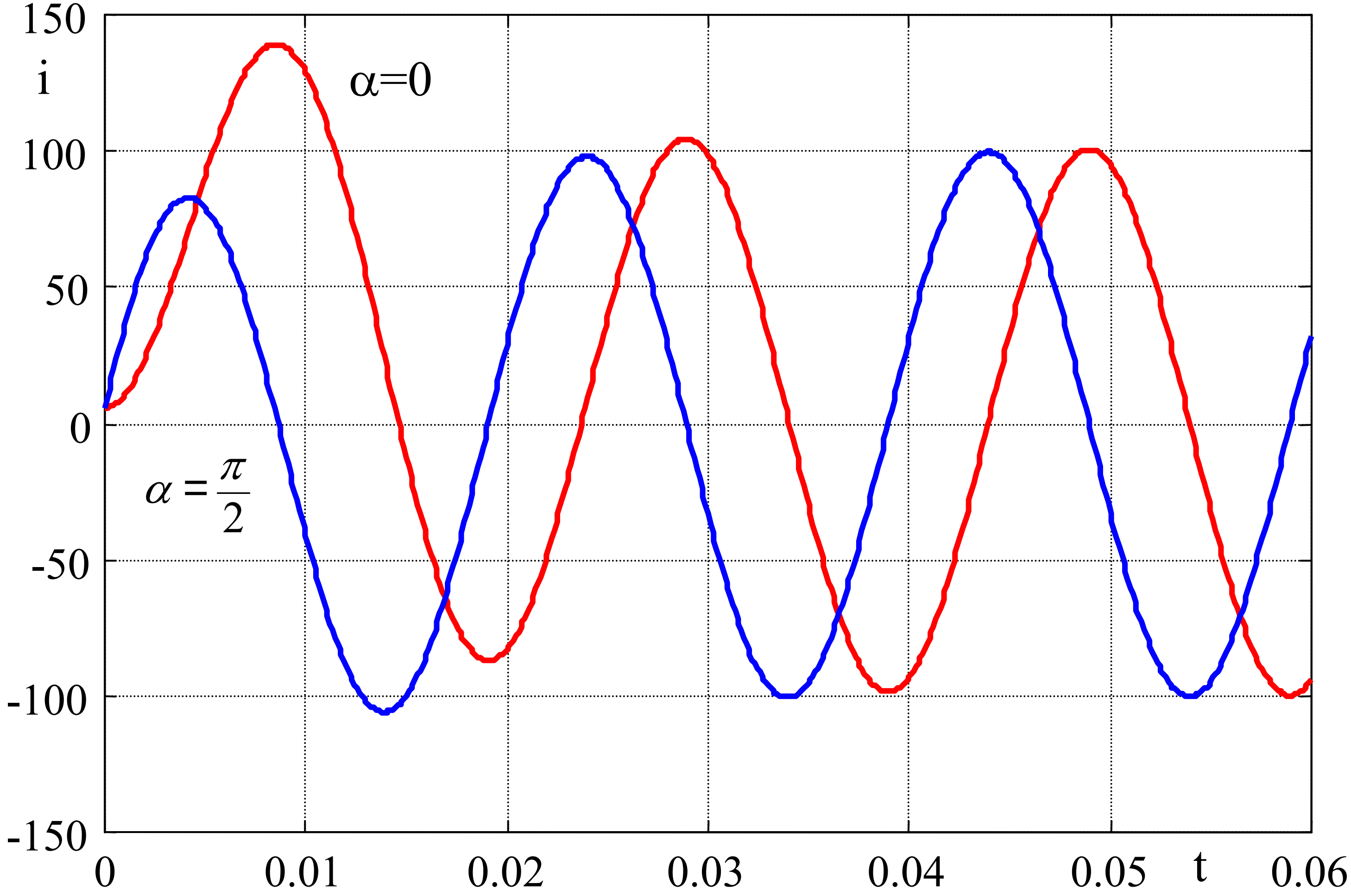
$$i_{1sc\max} = \frac{\sqrt{2} \cdot U_1}{Z_{1sc}} \left(1 + e^{-\frac{\pi}{\omega \cdot T_{1sc}}} \right) + I_0 \cdot e^{-\frac{\pi}{\omega \cdot T_{1sc}}}$$

Factorul de scurtcircuit

$$k_{sc} = 1 + e^{-\frac{\pi}{\omega \cdot T_{1sc}}} \qquad 1.2 \ldots 1.85$$

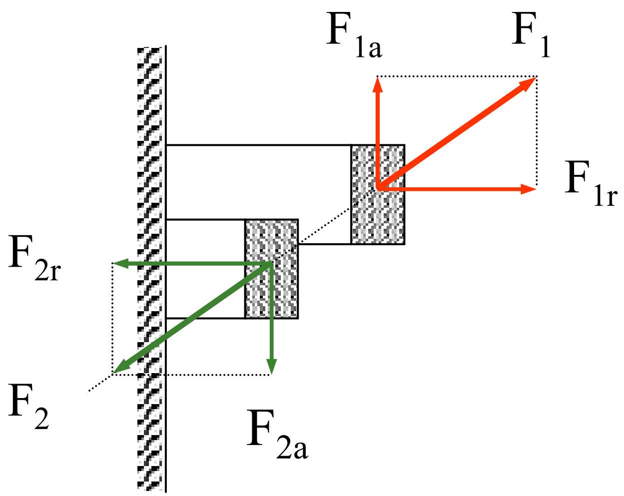
$$i_{1sc\max} = \frac{1}{u_{sc}} \cdot k_{sc} \cdot \sqrt{2} \cdot I_{1N} \qquad 20 \ldots 50$$

Scurtcircuitul brusc



Scurtcircuitul brusc

Forțe electrodinamice



$$F_r = \left(\frac{\partial W_{m\sigma}}{\partial a}\right)_{i=ct.}$$

$$F_a = \left(\frac{\partial W_{m\sigma}}{\partial h}\right)_{i=ct.}$$

Scurtcircuitul brusc

$$w_{m\sigma} = \frac{1}{2} \cdot L_{sc} \cdot i_{1sc}^2$$

$$L_{sc} = \frac{\mu_0}{\omega} \cdot \pi \cdot D_m \cdot K_R \cdot w^2 \cdot \frac{a}{h}$$

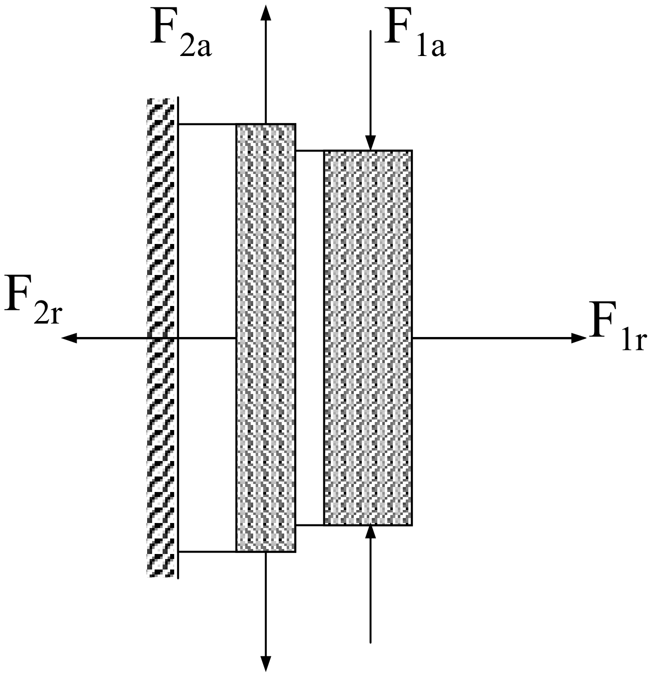
$$K_f = \frac{1}{2} \frac{\mu_0}{\omega} \cdot \pi \cdot D_m \cdot K_R \cdot w^2 \cdot i_{sc}^2$$

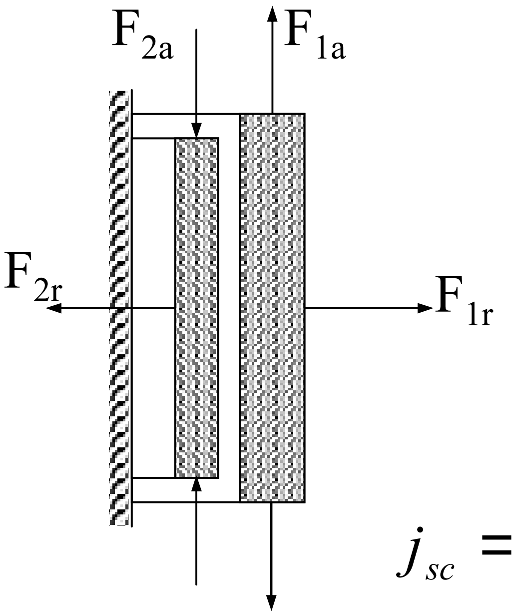
$$F_r = K_f \frac{1}{h}$$

$$K_a = -K_f \frac{a}{h^2} \qquad \Rightarrow \frac{F_a}{F} = \frac{a}{h}$$

Scurtcircuitul brusc

Solicitarea termică





$$\frac{d\theta}{dt} = k_\theta \cdot j_{sc}^2$$

$$j_{sc} = \frac{k_{sc}}{u_{sc}} \cdot j$$

$$k_\theta = 6.2 \cdot 10^{-15} \left[m^4 \cdot {}^o C / A^2 / s \right]$$

Exemplu

Transformator de putere in ulei

$Sn:=630$	kVA	$pfe:=1850$	W
$U1n:=15$	kV	$pb:=9900$	W
$U2n:=0.4$	kV	$i0:=4.9$	%
conexiune	Dy-11	$usc:=6$	%

Calculul parametrilor schemei echivalente

Exemplu

tensiuni si curenti de faza nominali

$$U1f := U1n \qquad U1f = 15 \quad kV$$

$$U2f := \frac{U2n}{\sqrt{3}} \qquad U2f = 0.231 \quad kV$$

$$I1f := \frac{Sn}{3 \cdot U1f} \qquad I1f = 14 \quad A$$

$$I2f := \frac{Sn}{3.U2f} \qquad I2f = 909.327 \quad A$$

$$I10 := \frac{i0}{100} \cdot I1f \qquad I10 = 0.686 \quad A$$

$$U1sc := \frac{usc}{100} \cdot U1f \qquad U1sc = 0.9 \quad kv$$

Exemplu

Impedantele

$$Z10 := \frac{U1f}{I10} \qquad Z10 = 21.866 \quad k\Omega$$

$$R10 := \frac{pfe \cdot 10^{-3}}{3 \cdot I10^2} \qquad R10 = 1.31 \quad k\Omega$$

$$X10 := \sqrt{Z10^2 - R10^2} \qquad X10 = 21.827 \quad k\Omega$$

$$Z1sc := \frac{U1sc \cdot 10^3}{I1f} \qquad Z1sc = 64.286 \quad \Omega$$

$$R1sc := \frac{pb}{3 \cdot I1f^2} \qquad R1sc = 16.837 \quad \Omega$$

$$X1sc := \sqrt{Z1sc^2 - R1sc^2} \qquad X1sc = 62.042 \quad \Omega$$

Exemplu

se considera : $R1 := 1.1 \cdot R2$

rezulta :

$$R2 := \frac{R1sc}{2.1} \qquad R2 = 8.017 \quad \Omega$$

$$R1 := 1.1 \cdot R2 \qquad R1 = 8.819 \quad \Omega$$

$$X2 := \frac{X1sc}{2.1} \qquad X2 = 29.544 \quad \Omega$$

$$X1 := 1.1 \cdot X2 \qquad X1 = 32.498 \quad \Omega$$

constantele de timp

$$T10 := \frac{X10}{100 \cdot \pi \cdot R10} \qquad T10 = 0.053 \quad s$$

$$Tsc := \frac{X1sc}{100 \cdot \pi \cdot R1sc} \qquad Tsc = 0.012 \quad s$$

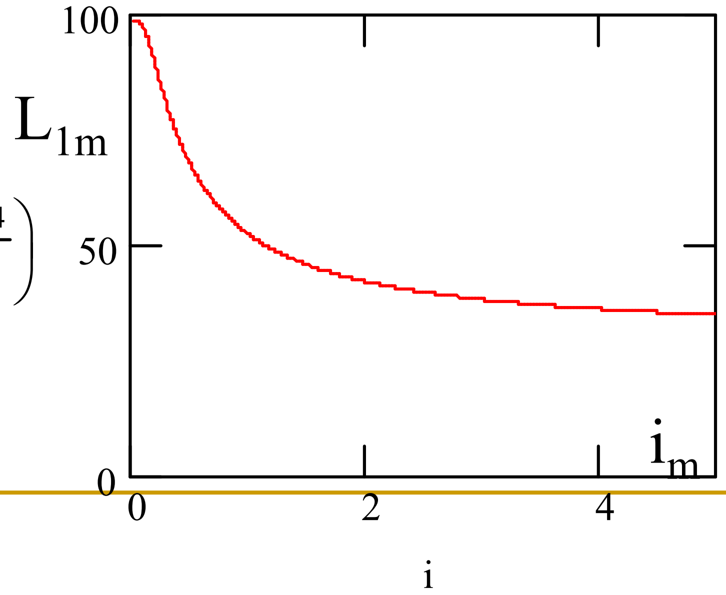
inductivitate de magnetizare

$$L1m := \frac{X10 \cdot 10^3}{100 \cdot \pi} \qquad L1m = 69.476 \quad H$$

considerand variatia in functie de curent de forma:

$$l1m := L1m \cdot \left(1 - 0.9 \cdot e^{\frac{-0.6}{i}}\right)$$

$$L1m \sqrt{2} \cdot \left(1 - 0.7 \cdot e^{\frac{-0.4}{i}}\right)$$



Exemplu

fluxul remanent $\Psi r := 5$ Wb

amplitudinea fluxului $\alpha := 0$

$$\Psi 1m := \sqrt{2} \cdot \frac{U1f \cdot 10^3}{\sqrt{(100 \cdot \pi)^2 + \frac{1}{T10^2}}}$$

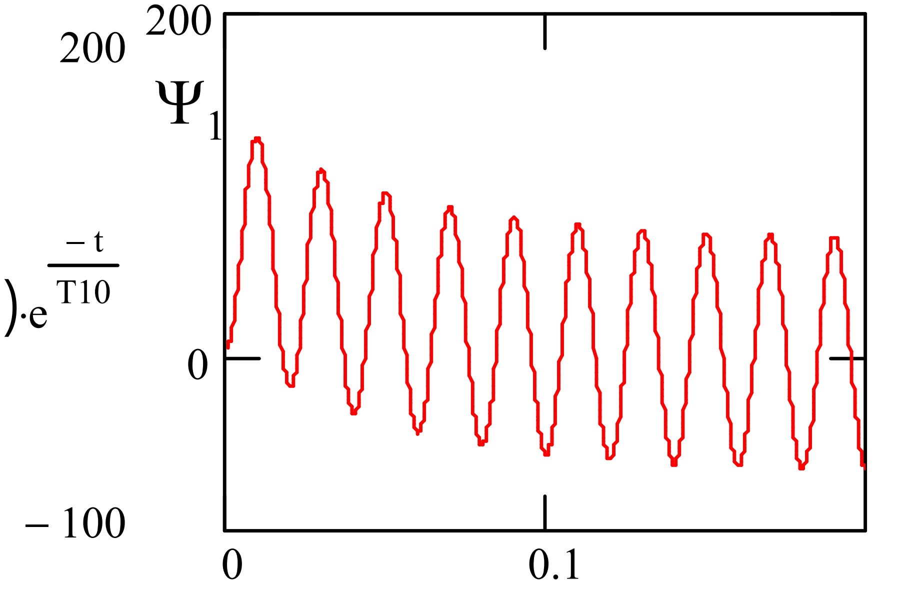
$\Psi 1m = 67.402$ Wb

$$\gamma := \alpha - \operatorname{atan}(100 \cdot \pi \cdot T10)$$

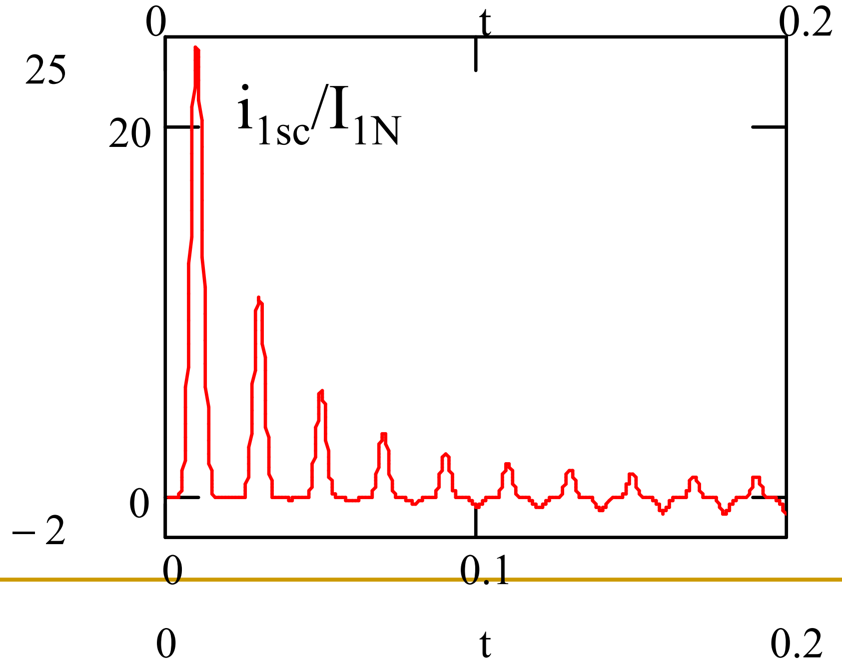
$\gamma = -1.511$ rad

$\pi / 2 = 1.507$ rad

$$\Psi 1m\sin(100\pi \cdot t+\gamma)+(\Psi r-\Psi 1m\sin(\gamma))\cdot e^{\frac{-t}{T10}}$$



$\alpha = 0$



$\alpha = \pi/2$

$$\Psi 1m\sin(100\pi \cdot t+\gamma)+(\Psi r-\Psi 1m\sin(\gamma))\cdot e^{\frac{-t}{T10}}$$