

# Power Plants

## A1M15ENY

### Lecture No. 4

*Jan Špetlík*

[spetlij@fel.cvut.cz](mailto:spetlij@fel.cvut.cz) - subject in e-mail „ENY”

Department of Power Engineering, Faculty of Electrical Engineering CTU, Technická 2,  
166 27 Praha 6

Calculation of the parameters:

$$X_s \cong X'_r = \frac{1}{2} \cdot \frac{\sqrt{3.U_k^2.I_k^2 - P_k^2}}{3.I_k^2} = \frac{10^3}{2} \cdot \frac{\sqrt{3.1,529^2.185^2 - 127,5^2}}{3.185^2} = 2,3 \Omega$$

$$R_s = \frac{234,5 + \vartheta}{234,5 + \vartheta_0} \cdot R_{s20} = \frac{234,5 + 80}{234,5 + 20} \cdot R_{s20} = 0,178 \Omega$$

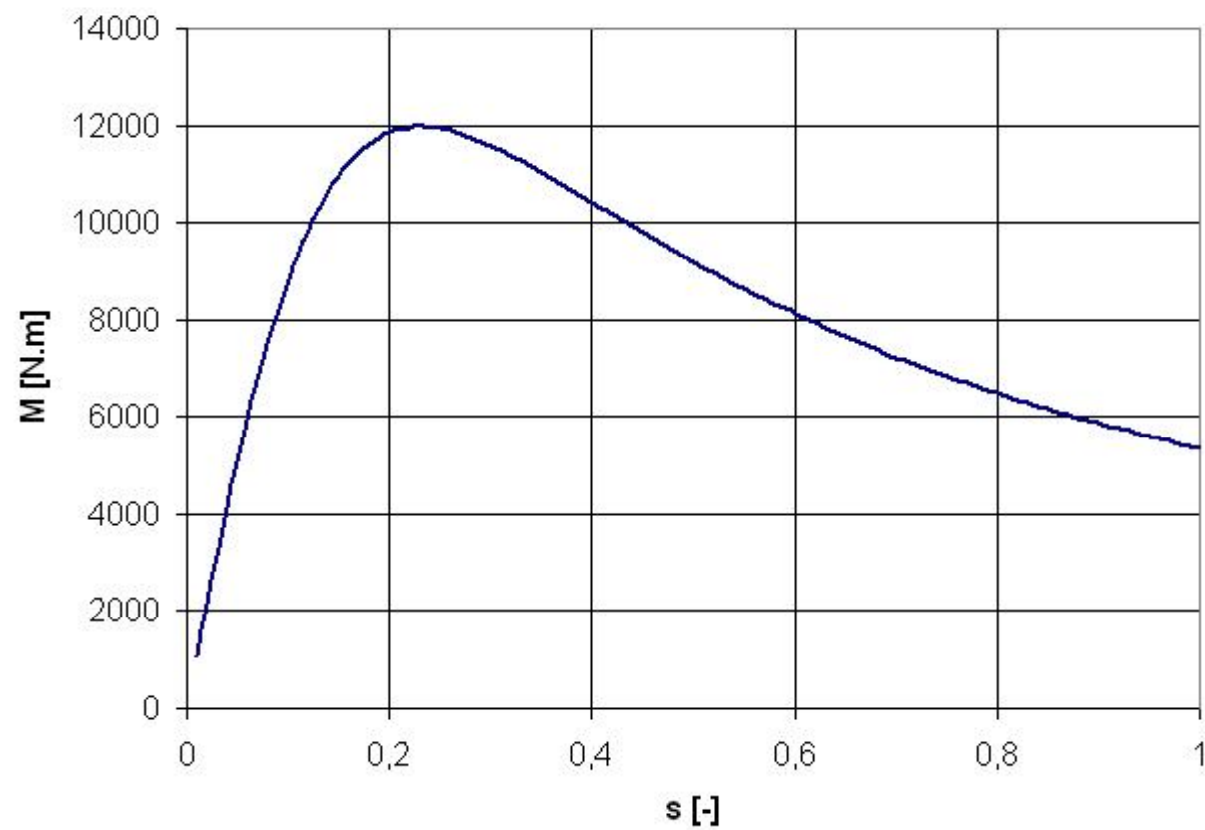
$$R'_r = \frac{P_k}{3.I_k^2} - R_s = \frac{127,5}{3.185^2} \cdot 10^3 - 0,178 = 1,064 \Omega$$

$$M = \frac{R'_r}{s \cdot \Omega_{SM}} \cdot \frac{U^2}{(X_s + X'_r)^2 + \left(R_s + \frac{R'_r}{s}\right)^2} =$$

$$= \frac{1,064}{s \cdot 100 \cdot \pi} \cdot \frac{U^2}{(2,3 + 2,3)^2 + \left(0,178 + \frac{1,064}{s}\right)^2} =$$

$$M = \frac{3,386 \cdot 10^{-3}}{s} \cdot \frac{U^2}{5,308 + \left( 0,178 + \frac{1,064}{s} \right)^2}$$

aproximace momentové charakteristiky



# Short Circuit Currents in Auxiliary

Short circuit currents are calculated according to EN 60 909-0  
Force and thermal effects are calculated according to  
EN 60 909-1 and EN 60 865-1 (IEC standard 909, 865)

## Basic classification:

$I''_{k3}$  Three phase initial symmetrical short-circuit current

$I''_{k1}$  Single phase initial symmetrical short-circuit current

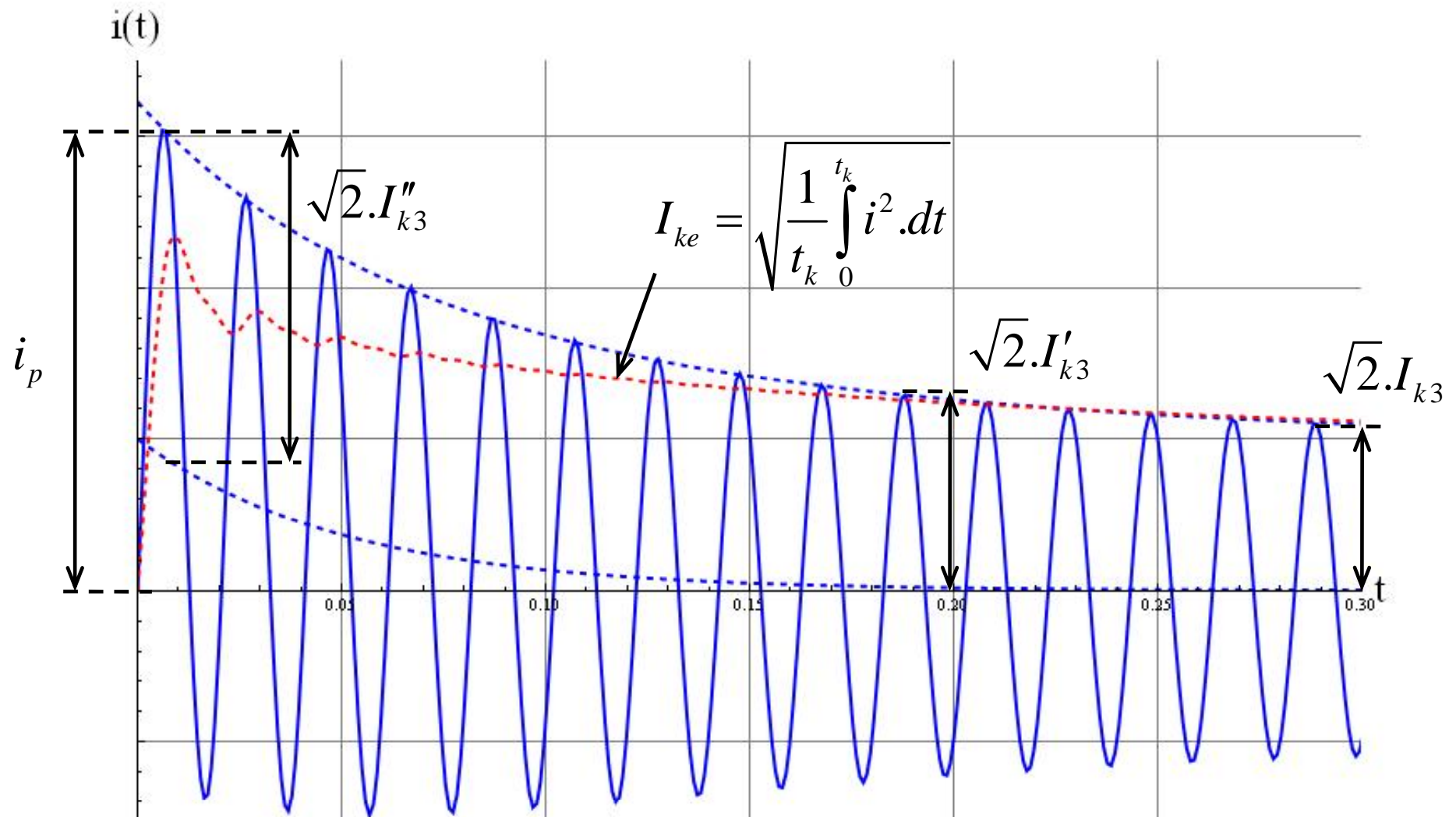
$I'_{k3}$  Three phase transient short-circuit current

$I_{k3}$  Three phase steady-state short-circuit current

$i_p$  Peak short-circuit current

$I_{ke}$  Thermal equivalent short-circuit current

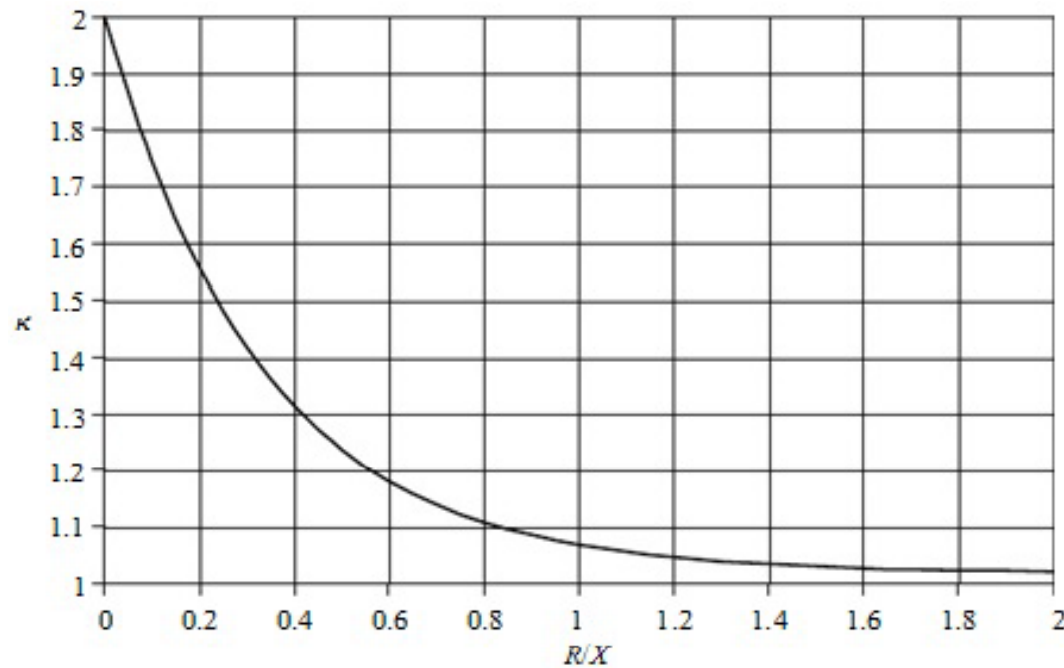
# Short Circuit Current Types



# Short Circuit Current Types

Calculation of peak short circuit current acc. to EN 60 909-0:

$$i_p = \kappa \cdot \sqrt{2} \cdot I_k'' \quad \kappa = 1,02 + 0,98 \cdot e^{-3 \cdot R/X}$$



# Short Circuit Current Types

Correction factor  $\kappa$  for impedance, overview from ČSN 33 3020:

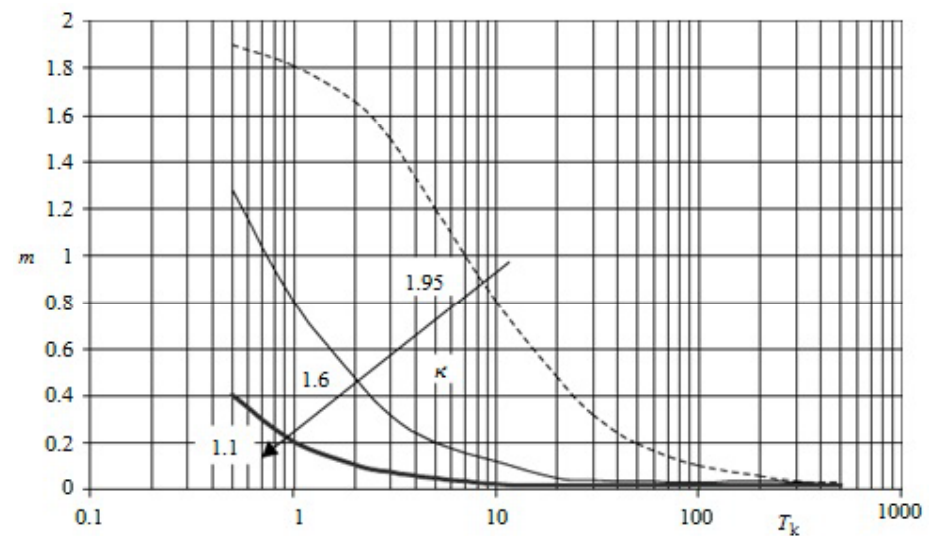
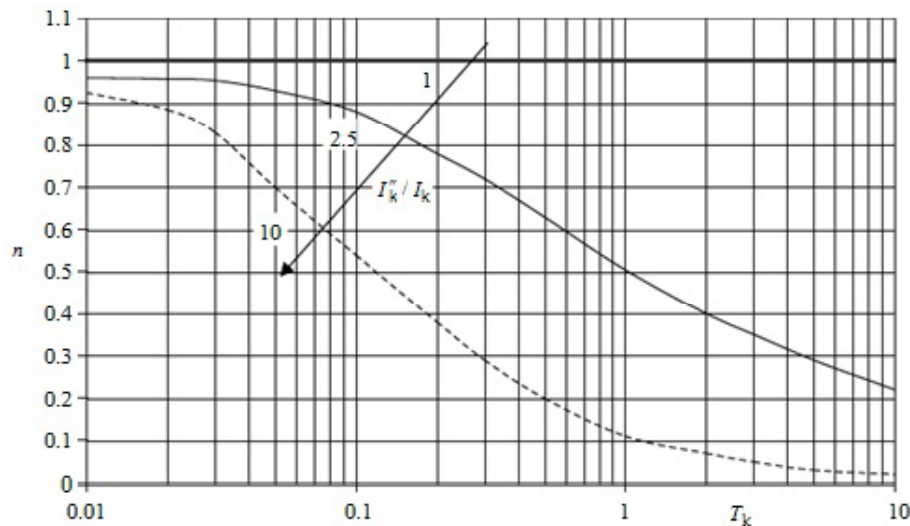
Hodnota součinitele K pro výpočet nárazového zkratového proudu		
Místo zkratu	bez asynchronních motorů	s asynchronními motory <sup>4)</sup>
za alternátorem do 55 MW <sup>1)</sup>	1,95	2,7
v soustavě vvn, zvn	1,7	-
v soustavě vn	1,6	2,4
v soustavě nn	1,4	-
v kabelovém rozvodu nn <sup>2)</sup>	1,3	1,9
za transformátory <sup>3)</sup>		
vvv/vn nebo vn/nn	1,7	2,5
vn/nn do 250 kVA včetně	1,3	1,9
do 630 kVA včetně	1,5	2,1
do 1600 kVA včetně	1,6	2,3
<sup>1)</sup> Pro zkrat v blízkosti alternátoru nebo za blokovým transformátorem <sup>2)</sup> Pro zkrat vzdálený od napájecího transformátoru i alternátoru (impedance mezi místem zkratu a napájecím transformátorem je větší než 10% ze sousledné impedance zkratového obvodu) <sup>3)</sup> Pro zkrat v blízkosti sekundární strany transformátoru (impedance mezi místem zkratu a napájecím transformátorem je do 10% sousledné impedance zkratového obvodu) <sup>4)</sup> Hodnoty součinitele K ve sloupci II slouží k orientačnímu stanovení nárazového zkratového proudu v el. rozvodu s asynchronními motory. Ve vztahu pro výpočet nárazového zkratového proudu se přitom použije hodnota počátečního rázového zkratového proudu stanovená bez příspěvku asynchronních motorů.		

# Short Circuit Current Types

Calculation of thermal equivalent short circuit current acc. to EN 60 909-0:

$$I_{ke} = k_e \cdot I_k'' \quad k_e = \sqrt{m + n}$$

Factor for thermal effects of DC component  $m$  and AC component  $n$  are present in graphs in standard EN 60 909-0





# Short Circuit Current Types

Factor  $k_e$  from ČSN 33 3020:

Součinitele $k_e$ pro výpočet ekvivalentního oteplovacího proudu bez uvažování vlivu asynchronních motorů										
Místo zkratu	$T_a$ (s)	$k_e$ pro $t_k$ (s)								
		0,02	0,035	0,05	0,08	0,1	0,2	0,5	1,0	3,0
za alternátorem do 55 MW <sup>1)</sup>	0,161	1,65	1,60	1,58	1,54	1,50	1,46	1,23	1,08	1,03
v soustavě <sup>2)</sup>										
vvn a zvn	0,03	1,44	1,32	1,24	1,16	1,13	1,07	1,03	1,01	1,00
vn	0,02	1,35	1,24	1,17	1,11	1,09	1,05	1,02	1,01	1,00
nn	0,01	1,24	1,15	1,10	1,07	1,05	1,03	1,01	1,00	1,00
v kabelovém rozvodu nn <sup>2)</sup>	0,008	1,18	1,11	1,08	1,05	1,04	1,02	1,01	1,00	1,00
za transformátory <sup>3)</sup>										
vvn/vn nebo vn/vn	0,036	1,49	1,37	1,29	1,20	1,17	1,09	1,04	1,02	1,01
vn/nn do 250 kVA včetně	0,008	1,18	1,11	1,08	1,05	1,04	1,02	1,01	1,00	1,00
do 630 kVA včetně	0,014	1,29	1,18	1,13	1,09	1,07	1,04	1,01	1,01	1,00
do 1600 kVA včetně	0,019	1,35	1,24	1,17	1,11	1,09	1,05	1,02	1,01	1,00

<sup>1)</sup> Pro zkrat v blízkosti alternátoru nebo za blokovým transformátorem  
<sup>2)</sup> Pro zkrat vzdálený od napájecího transformátoru i alternátoru (impedance mezi místem zkratu a napájecím transformátorem je větší než 10% ze sousledné impedance zkratového obvodu)  
<sup>3)</sup> Pro zkrat v blízkosti sekundární strany transformátoru (impedance mezi místem zkratu a napájecím transformátorem je do 10% sousledné impedance zkratového obvodu)

# Thermal Effects

Cross section dimensioning:

$$S \geq \frac{I_{ke} \cdot \sqrt{t_k}}{K_g} \quad K_g = \sqrt{\frac{(\vartheta_F + 20) \cdot c_{V20}}{\rho_{20}} \cdot \ln \frac{\vartheta_F + \vartheta_K}{\vartheta_F + \vartheta_1}}$$

Veličina	Význam	Dosazovaná velikost
$\vartheta_F$	Fiktivní teplota vodiče - teplotní rozdíl potřebný s změně měrného odporu vodiče o jeden $\Omega$	Cu – 234,5 °C / $\Omega$ Al – 228,0 °C / $\Omega$ Fe – 222,0 °C / $\Omega$
$\vartheta_1$	Teplota vodiče bezprostředně před vznikem zkratu	Maximální TRVALE dovolená teplota izolace
$\vartheta_K$	Teplota vodiče v době vypnutí zkratu	Maximální KRÁTKODOBĚ dovolená teplota izolace

Materiál	$c_{V0} [J / cm^3 \cdot K]$ $[J / mm^2 \cdot m \cdot K]$	$\rho_{20} [\mu \cdot \Omega \cdot m]$ $[\Omega \cdot mm^2 / m]$
Cu	3.500	0.0179
Al	2.417	0.0294
Fe	3.770	0.1430

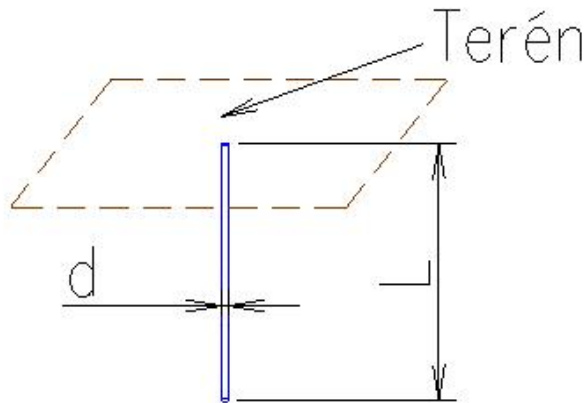
Attention! In addition to that, cross section dimensioning must respect voltage increments, operation currents and/or economy of losses

# Earthing and Touch Voltage

Dimensioning of system earthing must correspond the short circuit:

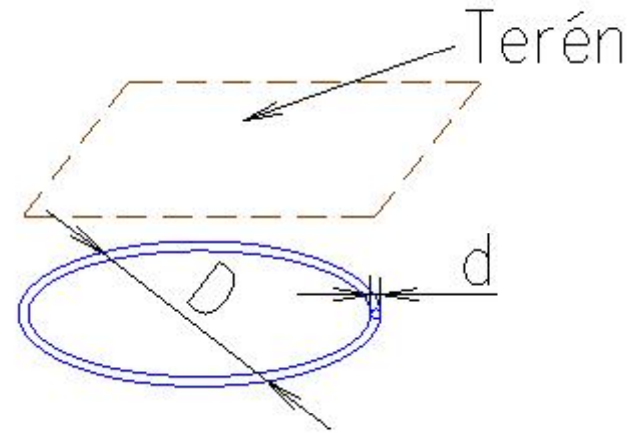
I. Calculation of earthing resistance:

a) Earth rod



$$R_E = \frac{\rho_E}{2\pi \cdot L} \cdot \ln \frac{4 \cdot L}{d}$$

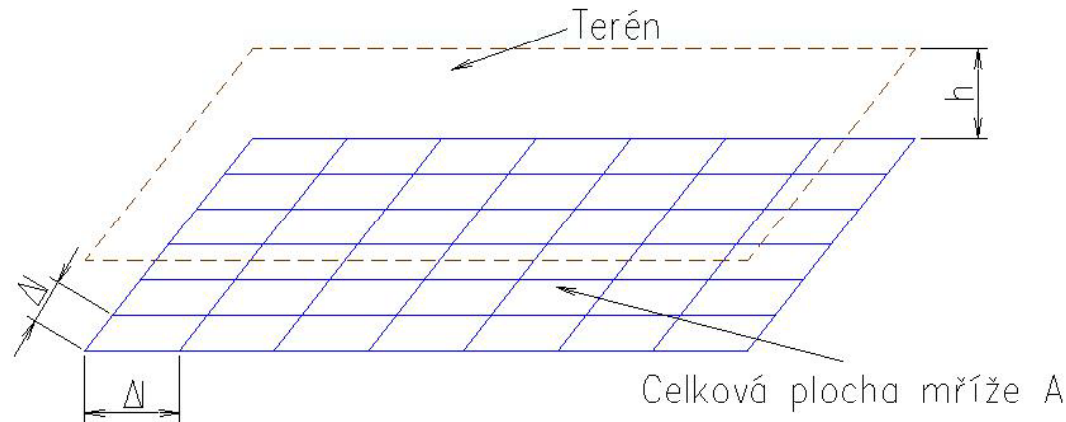
b) Circular earth electrode



$$R_E = \frac{\rho_E}{\pi^2 \cdot D} \cdot \ln \frac{2 \cdot \pi \cdot D}{d}$$

# Earthing and Touch Voltage

## c) Earthing mesh



Acc. to EN 50522:

$$R_E = \frac{\rho_E}{2.D} = \frac{\rho_E}{4} \sqrt{\frac{\pi}{A}}$$

(Dwight's formula)

A formula acc. to std. IEEE respecting earthing conductor length:  
(Laurent-Niemahn's formula):

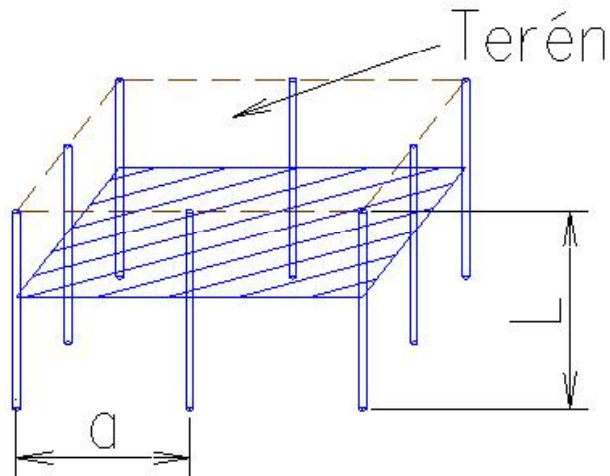
$$R_E = \rho_E \cdot \left[ \frac{1}{4} \sqrt{\frac{\pi}{A}} + \frac{1}{L} \right] \cong \rho_E \cdot \left[ \frac{1}{4} \sqrt{\frac{\pi}{A}} + \frac{1}{2 \cdot (N + \sqrt{N}) \cdot \Delta l} \right]$$

A formula respecting depth of the mesh:

$$R_E = \rho_E \cdot \left[ \frac{1}{4} \sqrt{\frac{\pi}{A}} + \frac{1}{2 \cdot N \cdot \Delta l} \left( \frac{1}{\sqrt{2} \cdot \pi} \ln \frac{0,165 \cdot \Delta l \cdot \sqrt{\pi}}{2 \cdot \sqrt{S_{FeZn}}} \right) \right] \left( 1 - 1,128 \cdot \frac{2 \cdot h}{\sqrt{A}} \right)$$

# Earthing and Touch Voltage

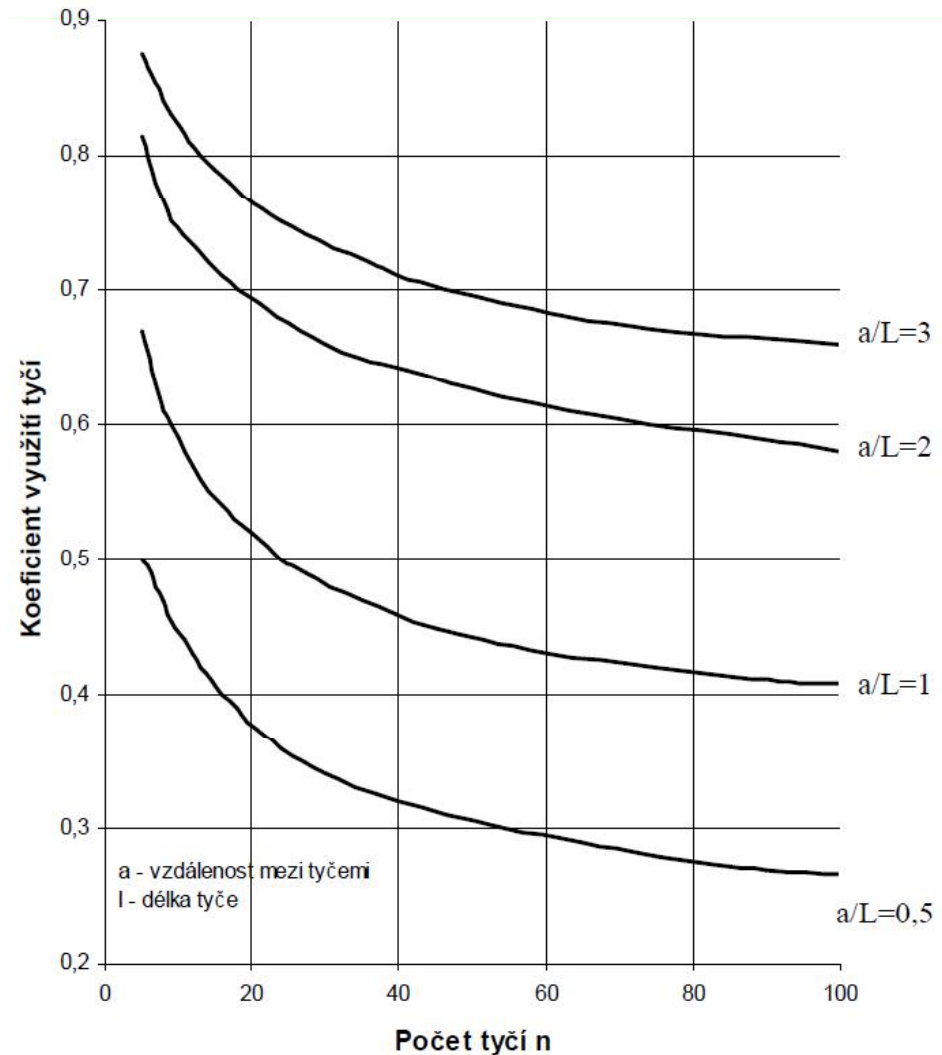
## d) Combination mesh + rod



Detailed formula:

$$R_E = \frac{1}{\frac{1}{R_{E1}} + \frac{\eta_{E2} \cdot n}{R_{E2}}} \cdot \frac{1}{0,9}$$

Koeficient využití tyčových zemničů v závislosti na poměru vzdálenosti mezi tyčemi a jejich délky



# Earthing and Touch Voltage

## II. Current dimensioning of earthing conductors and electrodes

### a) Current duration less than 5 s

$$S_{\min} = \frac{I_{ke}}{K} \cdot \sqrt{\frac{t_k}{\ln \frac{g_K + g_F}{g_1 + g_F}}}$$

Materiál	$\beta$	K
Al	228	148
Cu	234,5	226
Fe	202	78

Rem. Acc. to EN 50522 is the initial temperature 20°C and final 300°C

Example of current dimensioning of FeZn conductors for final

temperature 300°C:

t [s]	Dovolený proud [A]		
	30x4 mm	40x4 mm	20x5 mm
0,1	26700	35600	22200
0,2	18900	25200	15700
0,3	15400	20500	12800
0,4	13300	17800	11100
0,5	11900	15900	9960
0,6	10900	14500	9090
0,7	10100	13400	8420
0,8	9450	12600	7870
0,9	8910	11800	7420
1	8450	11200	7040

# Earthing and Touch Voltage

b) Current duration more than 5 s

- From the graphs in EN 50522, attach. C

Continuous permitted current for FeZn conductors (temp. 300°C)

Profil	Dovolený trvalý proud [A]
pásek 30x4	420
pásek 40x4	540
pásek 20x5	330
Drát průměr 10 mm	220

Re-computation to other final temperature:

Konečná teplota ve °C	Přepočítací činitel
400	1,2
350	1,1
300	1,0
250	0,9
200	0,8
150	0,7
100	0,6

# Earthing and Touch Voltage

## III. Touch voltage and earth potential rise

Earth potential rise  $U_E$  means voltage between selected point and reference (remote) earth within corresponding short circuit level and location.

$$U_E = R_E \cdot I_E$$

where  $I_E$  is current to earth

TT network with low impedance neutral earthing

$$I_E = r \cdot I''_{k1}$$

IT network with resonant impedance earthing

$$I_E = r \cdot \sqrt{I_{Res}^2 + I_L^2}$$

IT(r) network with resistance neutral earthing

$$I_E = r \cdot I_R \nearrow$$

residual earth fault current, maximum 10%  $I_C$

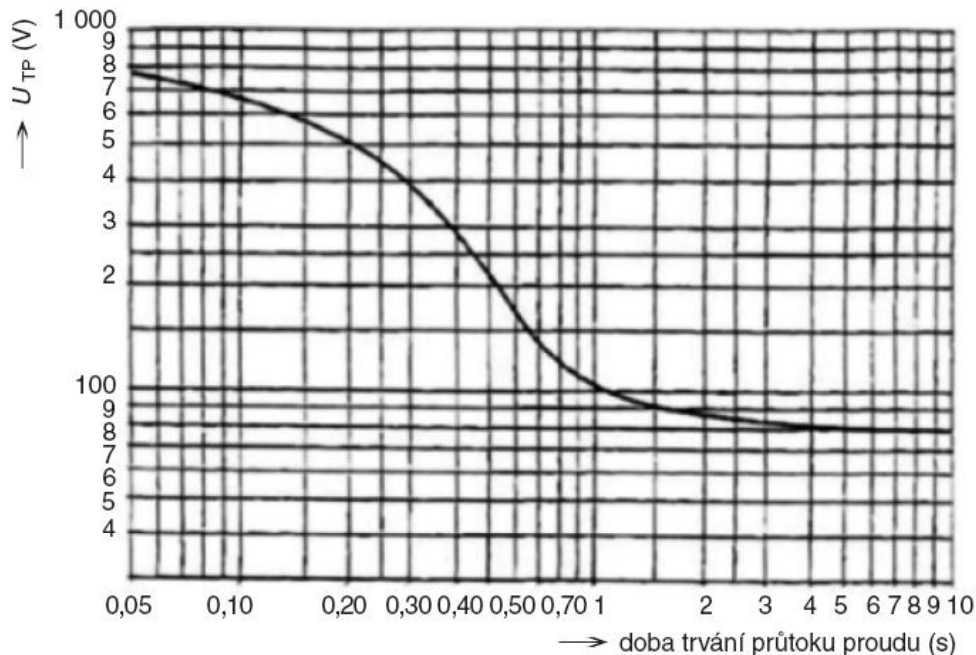
Reduction factor  $r$  is respecting partial outlet of short circuit current or earth fault current through ground cables, cable shieldings or transformer neutral. Reduction factor is thus defined as

$$r = \frac{I_E}{3 \cdot I_0}$$



# Earthing and Touch Voltage

Touch voltage  $U_{Tp}$  is potential between conductive parts, which can be touched by human or animal. Real touch voltage level is significantly influenced by human (animal) body impedance.



For substations above  
1 kV AC:

$$U_E \leq 2.U_{Tp}$$

Or:

$$U_E \leq 4.U_{Tp}$$

+ implementation of special  
measures acc. to EN 50522  
(non-conductive asphalt belt,  
equipotential grading etc.)

In this case it is necessary to isolate earthing system of substation  
(power plant) from public earthing systems (min. 20 m)!

# Force Effects – Rigid Conductors

For correct dimensioning is decisive :

- a) Bending stress of a conductor
- b) Bending forces on supports

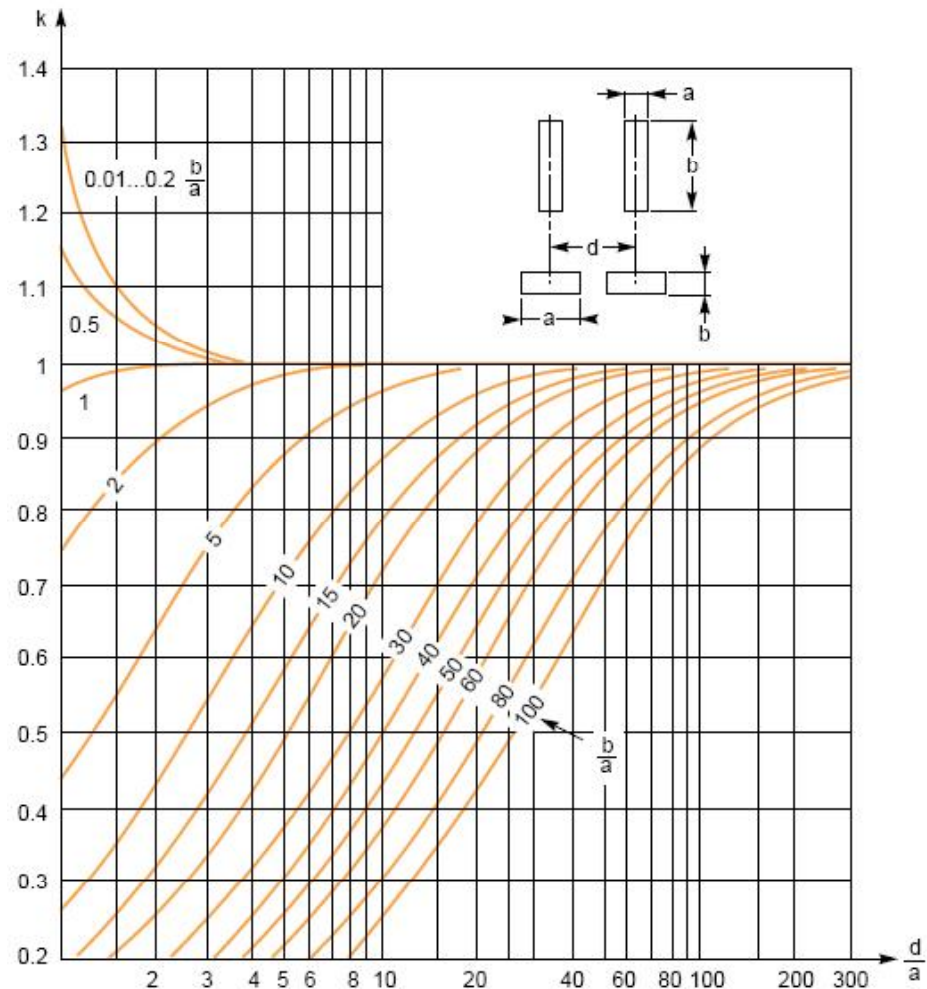
Force on central conductor is:

$$F_{m3} = \frac{\mu_0}{2\pi} \cdot \frac{\sqrt{3}}{2} \cdot i_{p3}^2 \cdot \frac{l}{d_m}$$

effective distance

$$d_m = \frac{d}{k}$$

For rectangular shaped conductors:  
(IEC 865-1 / EN 60865-1)



# Force Effects – Rigid Conductors

a) Bending stress on a conductor:

$$\sigma_m = \frac{M_o}{Z} = V_\sigma \cdot V_r \cdot \beta \cdot \frac{F_{m3} \cdot l}{8 \cdot Z}$$

Dyn. and stat. force ratio factor:

$V_\sigma$

Factor respecting double C-O operation:

$V_r$

Factor respecting an arrangement of support:  $\beta$

Section modulus:

$$Z = \frac{I}{\frac{b}{2}}$$

Requirement:

$$\sigma_m < q \cdot \sigma_{0,2}$$

Stress yield point:

Conventional, what  $\sigma$  causes elongation by 0,2%

$$\sigma_{0,2AlMgSi} = 120 - 180 \text{ MPa} \quad \sigma_{0,2Cu} = 80 \text{ MPa}$$

$q$  – factor of plasticity.

Moment of inertia:

$$I = \int_S r^2 \cdot dS$$

Rectangular shape:

$$I = \frac{a \cdot b^3}{12}$$

Circular shape:

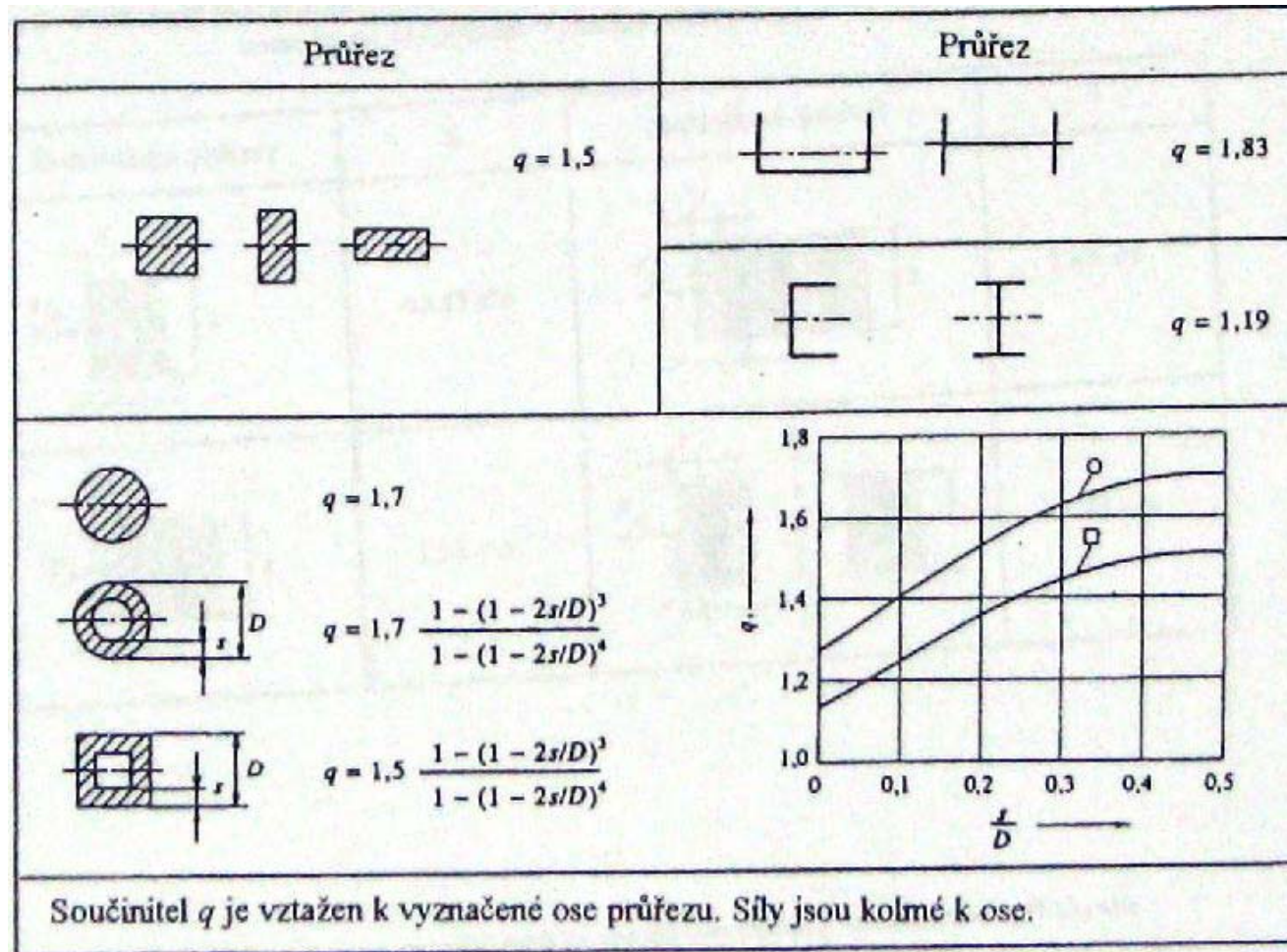
$$I = \frac{\pi}{4} r^4$$

Tubular shape:

$$I = \frac{\pi}{4} (r_1^4 - r_2^4)$$

# Force Effects – Rigid Conductors

Factor of plasticity  $q$



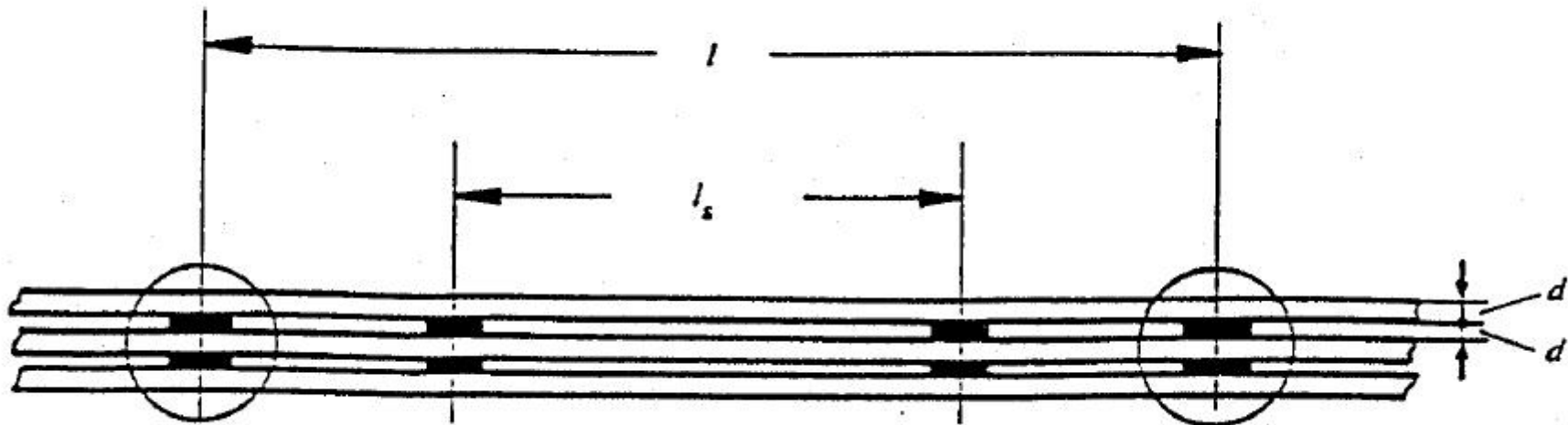
# Force Effects – Rigid Conductors

If there is more than one conductor per phase, it is necessary to add stress induced by single phase conductors:

$$F_s = \frac{\mu_0}{2\pi} \cdot \left( \frac{i_{p3}}{n} \right)^2 \cdot \frac{l_s}{d_{ms}} \quad \sigma_s = V_\sigma \cdot V_r \cdot \frac{F_s \cdot l_s}{16 \cdot Z} \quad \sigma_{tot} = \sigma_m + \sigma_s$$

Requirement:

$$\sigma_{tot} < q \cdot \sigma_{0,2}$$



# Force Effects – Rigid Conductors

## b) Bending forces on supports

Force on support:

$$F_D = V_F \cdot V_r \cdot \alpha \cdot F_{m3}$$

Dyn. and stat. force ratio factor:

$V_F$

$$V_F = \min 1; \frac{0,8 \cdot \sigma_{0,2}}{\sigma_{tot}}; \max 2,7$$

Factor respecting double C-O operation:

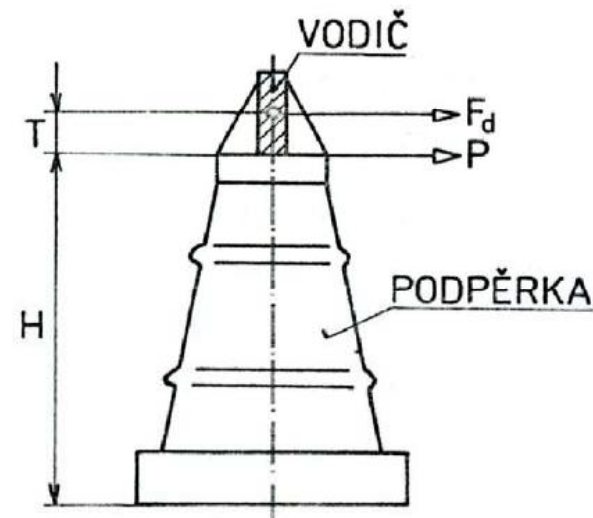
$V_r$

Factor respecting an arrangement of support:  $\alpha$

Requirement:

$$F_D < F_d = 0,8 \cdot P \cdot \frac{H}{H + T}$$

Where  $P$  is mechanical endurance of support





# Force Effects – Rigid Conductors

Factors  $V_F, V_r, V_\sigma$ : from the fig:  
or

For more accurate calculation it is possible to compute natural frequency of the arrangement:

$$f_c = \frac{\gamma}{l^2} \cdot \sqrt{\frac{E \cdot I}{m'}}$$

$\gamma$  Factor (conductor plasticity)

$E$  Young's modulus

$m'$  Mass per length

Rem.: Conductor behavior will be the same, if a natural frequency is more than 10xf network.

The worst results we obtain for circa 1-2xf network

/supporting arrangement should avoid resonance/

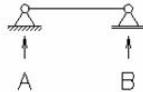
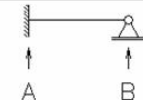
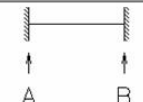
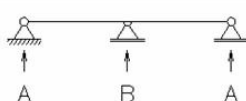
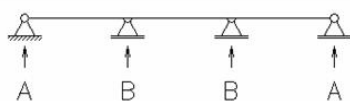
Druh zkratu	System		
	Bez trojfázového OZ	S trojfázovým OZ	S a bez trojfázového OZ
	$V_\sigma V_r V_\sigma V_r$	$V_\sigma V_r V_\sigma V_r$	$V_F V_r$
mezi dvěma vodiči	1,0	1,8	<div> <div> <div>2,0 pro <math>\frac{\sigma_{tot}}{0,8 R_{p0,2}} \leq 0,5</math></div> <div> <math>\frac{0,8 R_{p0,2}}{\sigma_{tot}}</math> pro <math>0,5 &lt; \frac{\sigma_{tot}}{0,8 R_{p0,2}} &lt; 1,0</math> </div> <div>1,0 pro <math>1,0 \leq \frac{\sigma_{tot}}{0,8 R_{p0,2}}</math></div> </div> <div> <div>Oblast ①</div> <div>Oblast ②</div> <div>Oblast ③</div> </div> </div>
trojfázový	1,0	1,8	<div> <div>2,7 pro <math>\frac{\sigma_{tot}}{0,8 R_{p0,2}} \leq 0,370</math></div> <div> <math>\frac{0,8 R_{p0,2}}{\sigma_{tot}}</math> pro <math>0,370 &lt; \frac{\sigma_{tot}}{0,8 R_{p0,2}} &lt; 1,0</math> </div> <div>1,0 pro <math>1,0 \leq \frac{\sigma_{tot}}{0,8 R_{p0,2}}</math></div> </div> <div> <div>Oblast ①</div> <div>Oblast ②</div> <div>Oblast ③</div> </div>

# Force Effects – Rigid Conductors

Factors  $\alpha, \beta, \gamma$ :

Typ nosníku a způsob upevnění

Typ

nosník o jednom poli	A a B prosté podepření		A	$\alpha_A = 0,5$ $\alpha_B = 0,5$	$\beta = 1$	$\gamma = 1,57$
	A : vetknutí B : prosté podepření		B	$\alpha_A = 0,625$ $\alpha_B = 0,375$	$\beta = 0,73$	$\gamma = 2,45$
	A a B vetknutí		C	$\alpha_A = 0,5$ $\alpha_B = 0,5$	$\beta = 0,5$	$\gamma = 3,56$
nosník o více polích o stejných rozpětích	2 pole		D	$\alpha_A = 0,375$ $\alpha_B = 1,25$	$\beta = 0,73$	$\gamma = 2,45$
	3 nebo více polí		E	$\alpha_A = 0,4$ $\alpha_B = 1,1$	$\beta = 0,73$	$\gamma = 3,56$



# Force Effects – Cable Conductors

Force effects on hanged cable conductors:

Force per length on cable conductor:

$$F_{/l} = \frac{\mu_0}{2\pi} \cdot \frac{3}{4} \cdot \frac{I_{k3}^2}{d_m} \cdot \frac{l_c}{l}$$

Detailed computation in IEC 865-1

Limitations:

- Short circuit tensile force  $F_t$
- Drop force after short circuit  $F_f$
- Minimum conductors' distance during swing out of the span  $a_{\min}$
- Horizontal displacement during swing out of the span  $b_h$
- Pinch force in the case of bundled conductors  $F_{pi}$

# Addendum to 4th Lecture

Rigid conductor arrangement:

Example:

Conductors of three phase system 10,5 kV are rectangular, type Al 63x10 mm (one per phase), span length between supports is 1m and phase distance is 0,5m. Make a decision, which type of support do you select and whether a conductor use is suitable for conductor arrangement:

- 1) Horizontal
- 2) Vertical

Mounted clamp means total height elongation by 2 cm

Number of spans/supports: 4/5

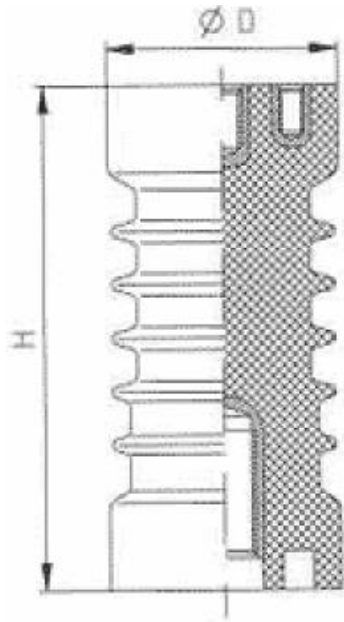
Input data:

$$d_m = 0,5 \text{ m} \quad \sigma_{0,2} = 120 \text{ MPa}$$

$$I''_{k3} = 25 \text{ kA} \quad \kappa = 1,7 \quad (\text{without respecting double CO})$$

# Addendum to 4th Lecture

Select a suitable support from following list



	Minimum 50 Hz (wet) withstand [kV]	Leakage distance [mm]	Maximum working cantilever load [kN]	Section length H [mm]	Diameter D [mm]
1.	75	174	5	130	60
2.	75	187	10	130	72
3.	75	195	16	130	90