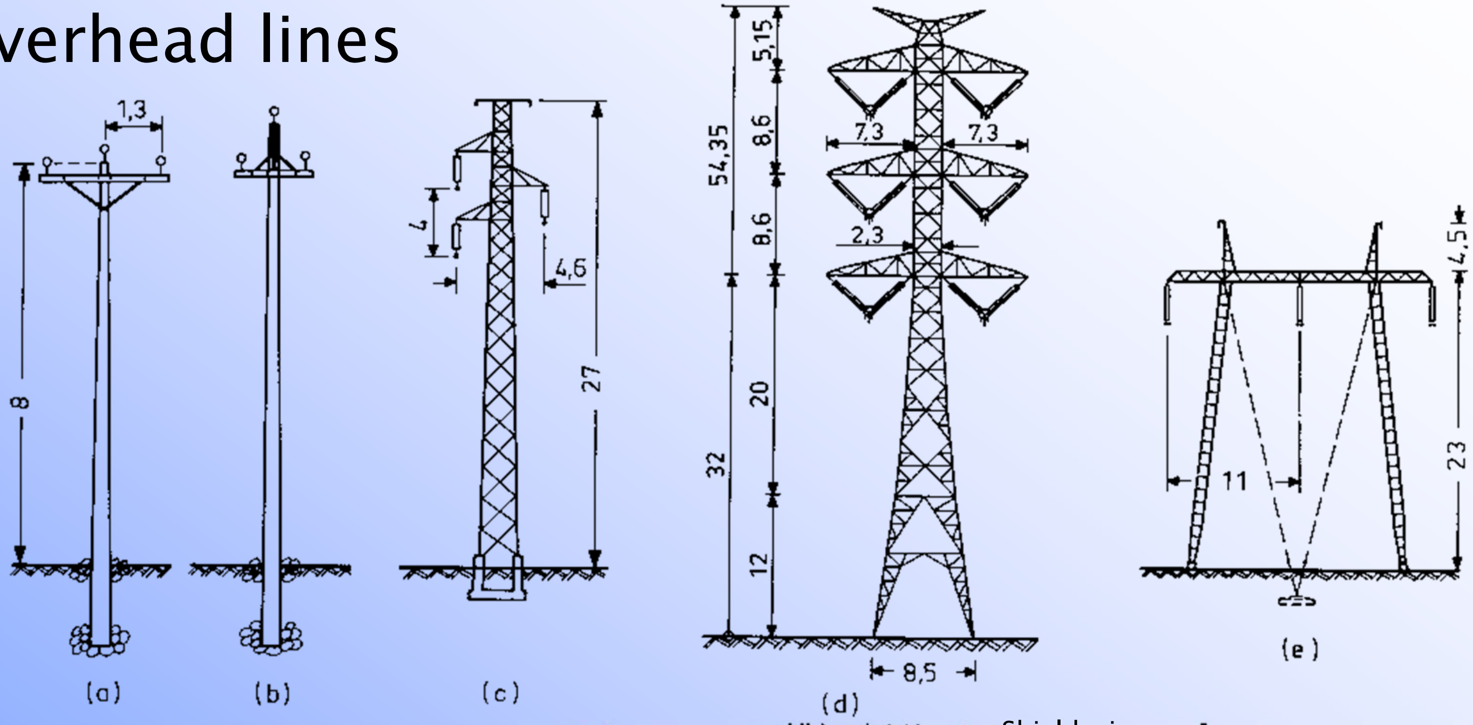
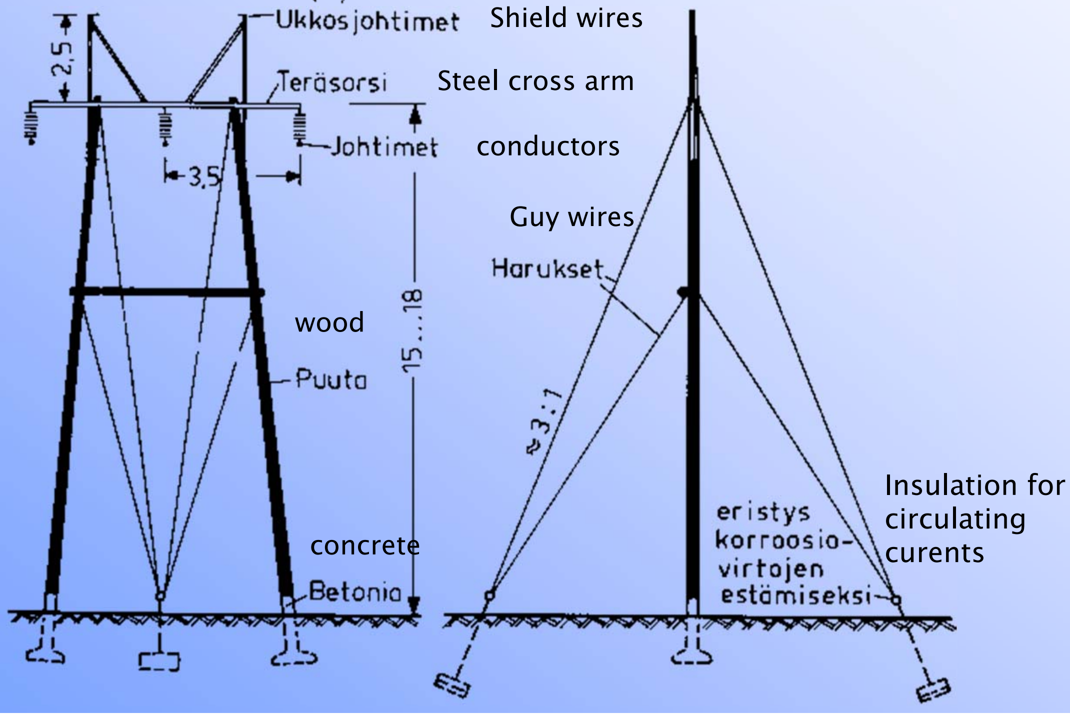
Overhead lines



a) ja b) 20 kV wood poles
c) free standing 110 kV
metal tower with I-strings
d) free standing 440 kV
metal tower with V-strings
e) 400 kV metal tower
with guy wires



110 kV wood tower with guy wires

OH line conductors

The OH conductors are made of stranded wires of Al and Fe. They are twisted in spiral form around a central wire and then compressed. In Al/Fe conductors, the steel is inner and copes for the mechanical strength.

Alternative to Al/Fe is Al alloy conductors (AlMgSi)

Some conductors are listed below:

Sparrow	34/6	(mm2 Al/Fe)
Raven	54/9	
Ostrich	152/25	
Duck	305/39	
Al 132	132 alloy	
Al 236	236 alloy	

Rated data of OH line conductors

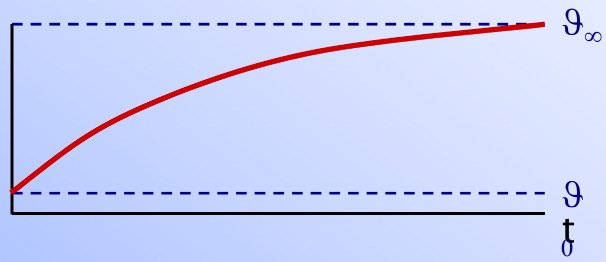
- resistance Ω/km
- nominal load carrying capacity A
- 1s thermal withstand current kA

The corresponding maximum temperatures :

	I_{nim}	I_{1s}
– copper	70 °C	170 °C
– aluminum	80 °C	130 °C
– aluminum alloy	80 °C	160 °C
– Al steel reinforced	80 °C	160 °C

Thermal time constant τ :

$$\vartheta(t) = \vartheta_0 + (1 - e^{-t/\tau})(\vartheta_\infty - \vartheta_0)$$



$\vartheta(t)$ = temperature rise at time t

ϑ_∞ = steady state temperature rise (constant load)

ϑ_0 = temperature rise in the beginning

τ = time constant

- overhead lines τ = 3…7 min
- underground cables τ = 35…60 min

Temperature rise by short circuit current

Temperature rise ϑ (°C) :

$$\vartheta = \frac{p}{mc} t = \frac{I^2 r}{mc} t \qquad (1)$$

p = heating power (per km)
I = current
r = resistance (per km)
m = conductor mass (per km)
c = heat capacity of the material

Example: 53.5° aluminum alloy :

r = 0,673 Ω/km (80°C)
m = 145 kg/km
c = 910 Ws/°C · kg
$\vartheta_{allowed}$ = 80 °C

I_{1s} = ?

Solving I from Eq. (1) :

$$\Rightarrow \quad I^2 = \frac{\vartheta mc}{rt} = \frac{80 \cdot 145 \cdot 910}{0{,}673 \cdot 1}$$

$$= 1{,}568 \cdot 10^7 \ A^2$$

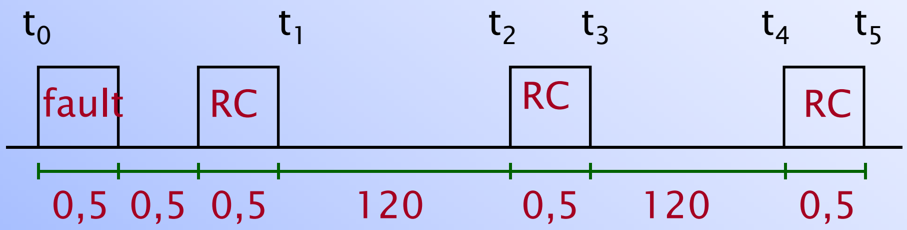
$$\Rightarrow \quad \underline{\underline{I_{1s} \approx 3{,}9 \, kA}}$$

$$\frac{°C \cdot kg/km \cdot Ws/°C\,kg}{\Omega / km \cdot s} = \frac{W}{\Omega} = \frac{VA}{V/A} = A^2$$

Temperature rise for different currents and different times:

$$\frac{\vartheta_1}{\vartheta_2} = \frac{I_1^{\,2}\, r\, t_1}{mc} : \frac{I_2^{\,2}\, r\, t_2}{mc} = \frac{I_1^{\,2}\, t_1}{I_2^{\,2}\, t_2}$$

Example: ΔT in a MV OH-line during a short circuit fault



Data :

- $I_{1s} = 3{,}9$ kA thermal 1s withstand current
- $I_k = 3{,}0$ kA fault current
- $\tau = 4$ min time constant
- $T_{max} = 80$ °C max operation temperature
- $T_{max1s} = 160$ °C max I_{1s} temperature
- $T_0 = 50$ °C initial conductor temperature
- $T_a = 20$ °C ambient temperature

One 0,5 s fault current pulse causes the temperature rise of ϑ :

$$\frac{\vartheta}{\vartheta_{1s}} = \frac{\Delta t \, R \, I_k^2}{1s \cdot R \, I_{1s}^2} = \frac{0{,}5 \cdot 3{,}0^2}{1{,}0 \cdot 3{,}9^2} = 0{,}296$$

$$\Rightarrow \quad \vartheta = 0{,}296 \cdot \vartheta_{1s} = 0{,}296\,(160 - 80)\text{°C} \approx 23{,}7\,\text{°C}$$

Temperature at time t_1
($t_1 - t_0 << \tau$; all the heat in conductor) :

$$T_1 = T_0 + 2 \cdot \vartheta = 50 + 2 \cdot 23{,}7\,\text{°C} = \underline{97{,}4\,\text{°C}}$$

Cooling in the period $t_1 - t_2$:

$$T_2 = T_a + (T_1 - T_a)\,(1 - e^{-(t_2 - t_1)/\tau})$$
$$= 20 + 77{,}4\,(1 - e^{-2/4})\,\text{°C} = \underline{50{,}5\,\text{°C}}$$

Heating by re-closing at time t_3:

$$T_3 = T_2 + \vartheta = \underline{74{,}2\,\text{°C}}$$

Cooling in the period $t_3 - t_4$:

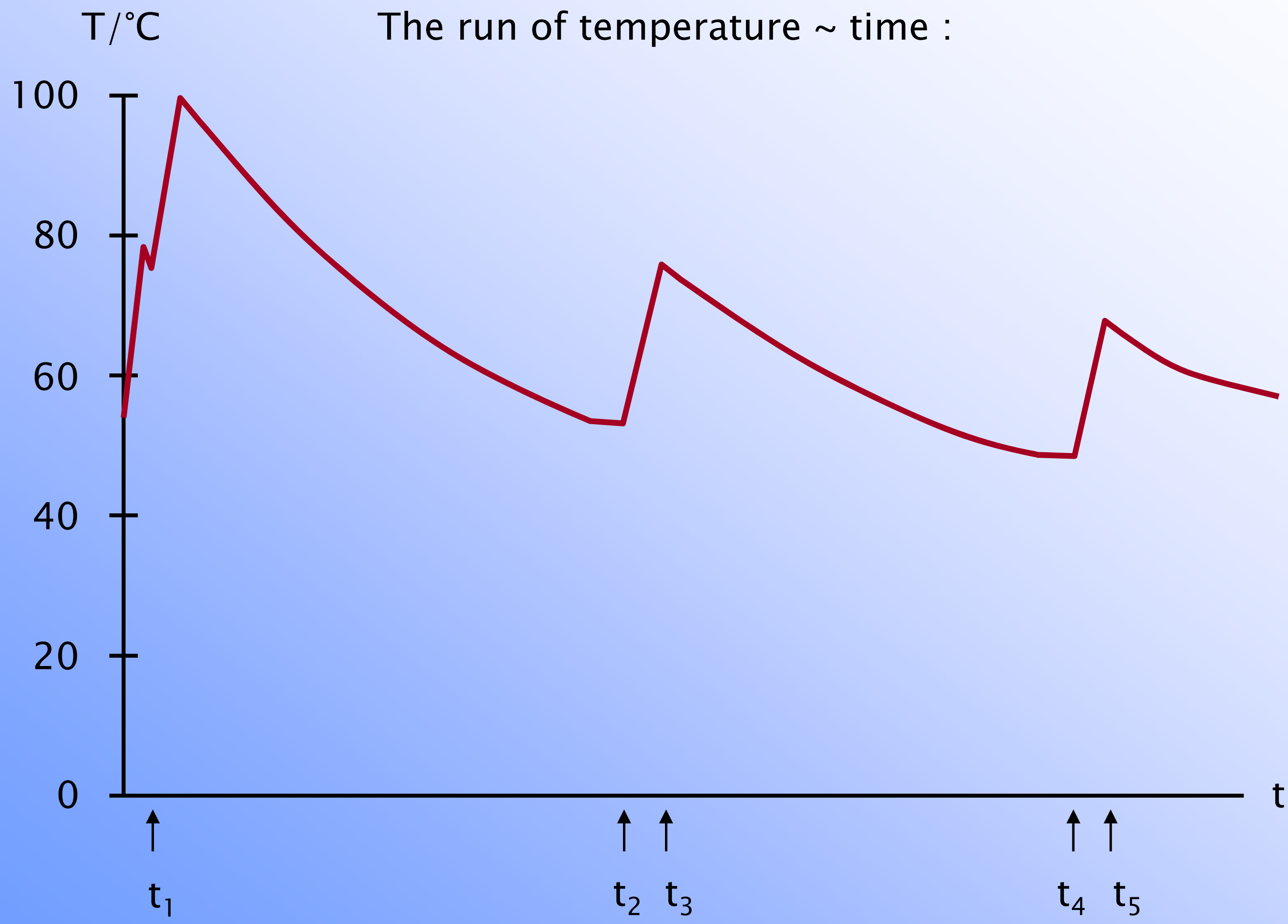
$$T_4 = T_a + (T_3 - T_a)\,(1 - e^{-(t_4 - t_3)/\tau})$$
$$= 20 + 54{,}2\,(1 - e^{-2/4}) \approx \underline{41{,}3\,\text{°C}}$$

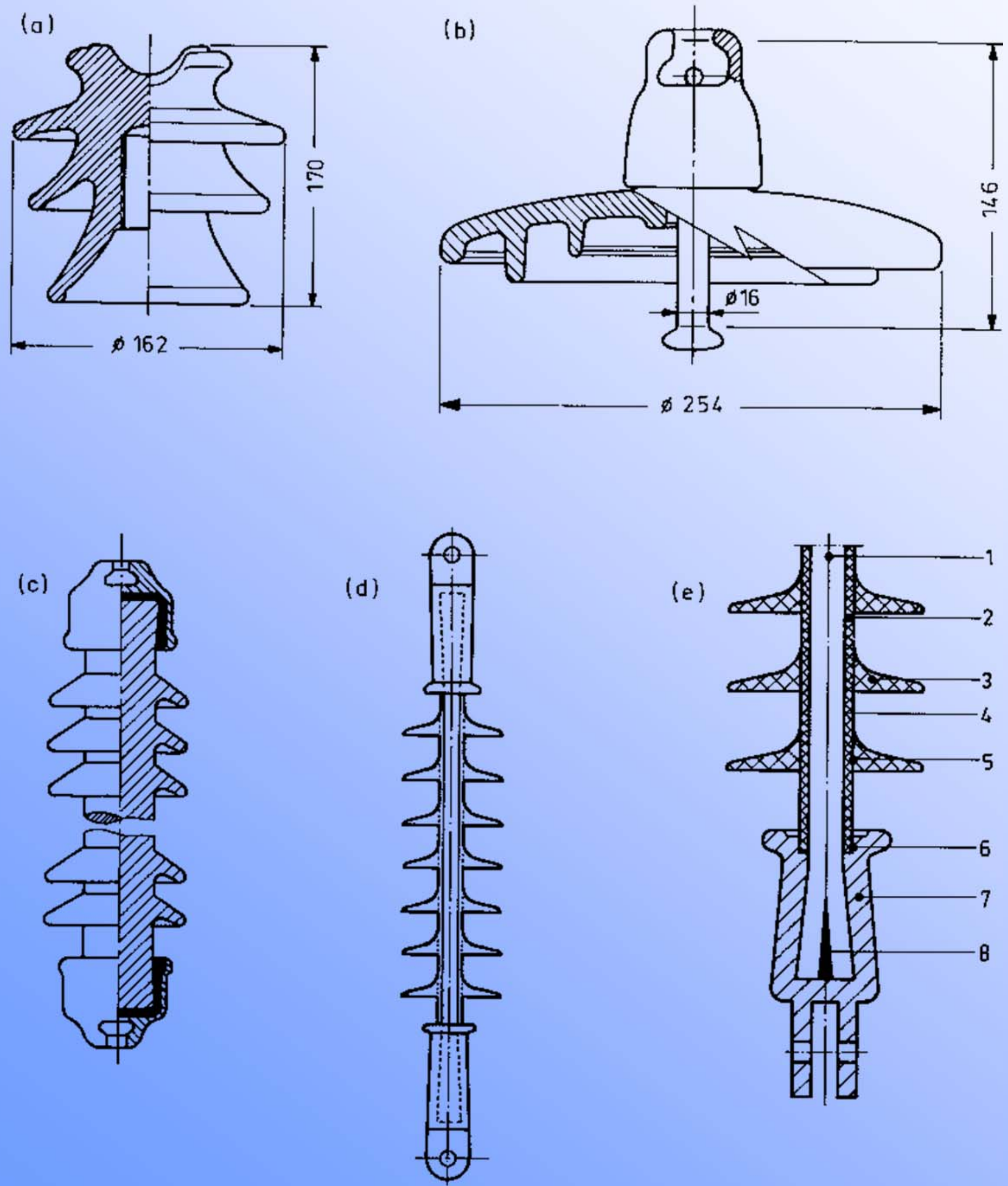
Heating by re-closing at time t_5 :

$$T_5 = T_4 + \vartheta = \underline{65\,\text{°C}}$$

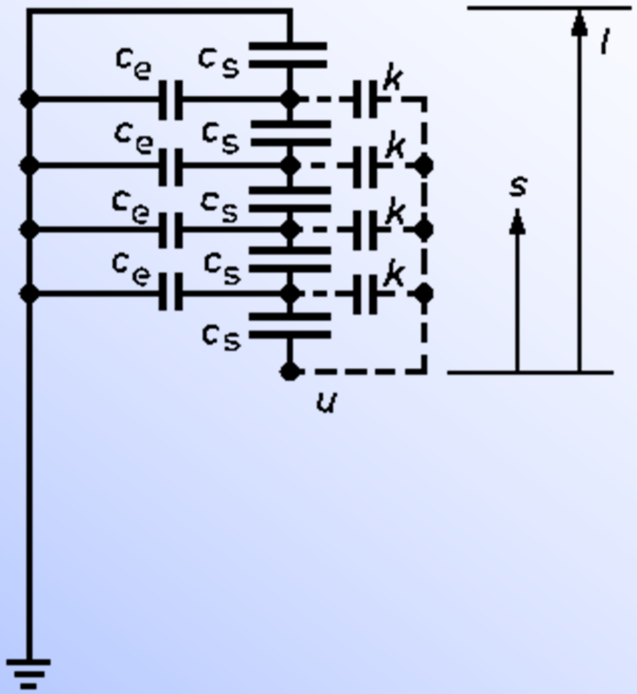
→

Example: ΔT in a MV OH-line during a short circuit fault

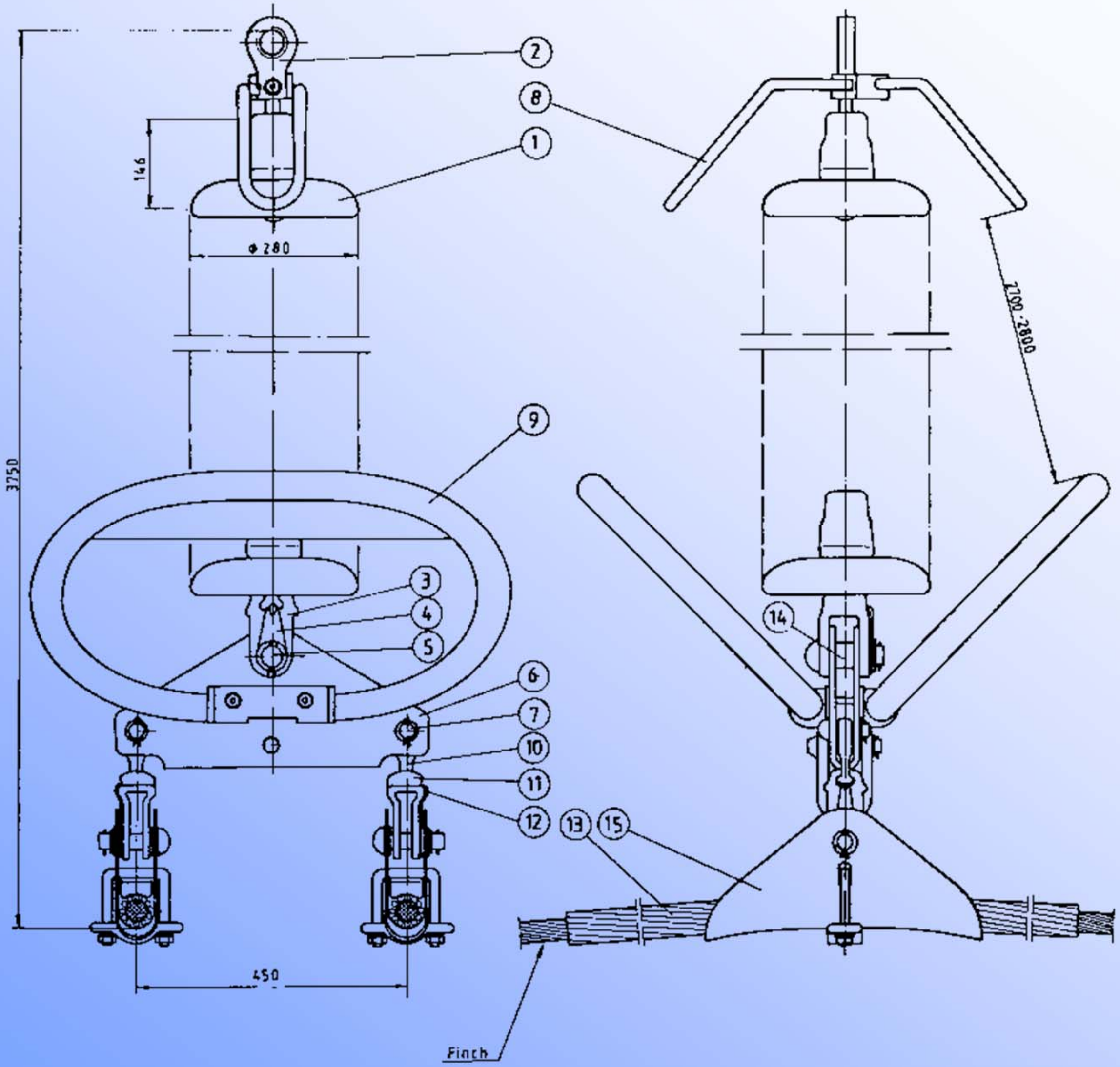




Capacitances in the chain of isolators

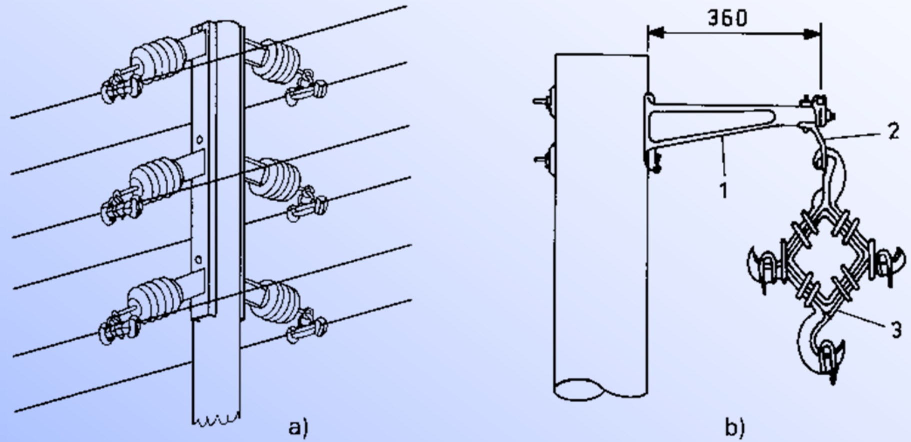


Overhead line isolators a) pin type, b) suspension type, c) long rod type, d) multi-material-type, e) and the cross-section: 1 fiber glass rod, 2 silicon plating, 3 silicon discs, 4,5,6 junctions, 7 terminal piece, 8 filling piece



400 kV chain of suspension insulators. 1 insulator, 8 upper arcing horn, 9 lower arcing horn, 13 armor rod, 15 suspending clamp

Overhead lines with covered conductors



Types of OH lines with covered conductors:
a) SAX-line (Nokia), b) SAMI-line (Sekko).
1 support, 2 spacer suspender, 3 spacer.

- narrower right of way needed
- contact of two phases $\Rightarrow$ no disturbance
- a leaning tree causes fault only after days
- detection of a broken conductor not easy

- power arc not able to move
  - risk of a broken conductor
  - clamps as arcing horns

After a possible fault the line must be checked in case a conductor has been broken !

Conductor resistance

$$R = \frac{\rho}{A} \cdot l \quad ; \quad \begin{array}{l} \rho = 0{,}0325\,\Omega\,\frac{mm^2}{m} \ (Al) \\ \rho = 0{,}0179\,\Omega\,\frac{mm^2}{m} \ (Cu) \end{array}$$

Example: 120 mm^2 copper, DC-resistance

$$R = \frac{1}{120} \cdot 1000 \cdot 0{,}0179\,\Omega/km \approx 0{,}15\,\Omega/km$$

By AC the resistance is increased due to the skin effect and in cables also due to the proximity effect

$\Rightarrow$ additional resistance ΔR, about

- 1 - 6 % for OH lines
- 3 - 18 % for cables

Resistance is given at +20°C. Temperature dependence :

$\alpha = 0{,}00393$ / °C (Cu)
$\alpha = 0{,}00403$ / °C (Al)

Total resistance :

$$R = \left[1 + \alpha\,(\vartheta - 20°C)\right](R_{20} + \Delta R)$$

Capacitances of an OH–line

r = conductor radius

h = geometric mean height

$$h = \sqrt[3]{h_1 \cdot h_2 \cdot h_3}$$

a, A : geometric mean distances

$$a = \sqrt[3]{a_{12} \cdot a_{23} \cdot a_{13}} \quad ; \quad A = \sqrt[3]{A_{12} \cdot A_{23} \cdot A_{13}}$$

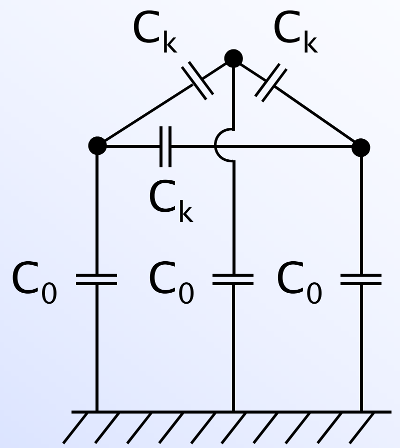
Positive sequence capacitance $C = C_0 + 3C_k$

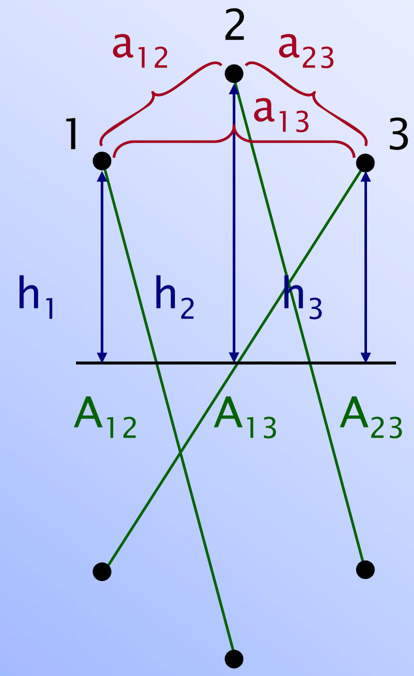
$$c = \frac{2\pi\varepsilon_0}{\ln \frac{2ha}{rA}}$$

Zero sequence capacitance C_0

$$c = \frac{2\pi\varepsilon_0}{\ln \frac{2h}{r}\left(\frac{A}{a}\right)^2}$$

ε_0 = vacuum permittivity $8{,}84 \cdot 10^{-12}$ F/m





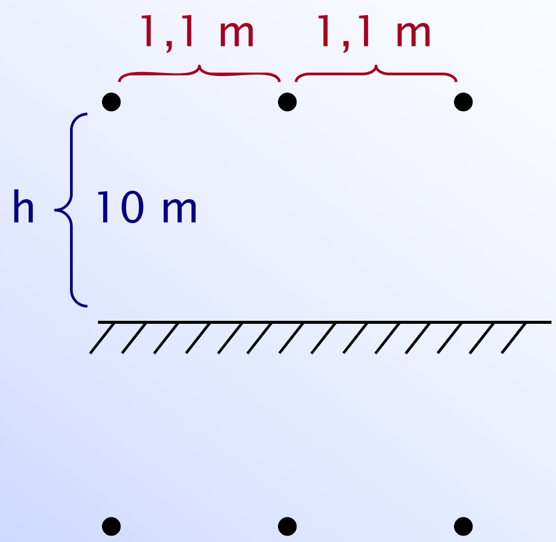
Example : 20 kV line with conductors in the same plane

$$r = 0{,}007 \text{ m}$$

$$h = 10 \text{ m}$$

$$a = \sqrt[3]{1{,}1 \cdot 1{,}1 \cdot 2{,}2} \approx 1{,}38 \text{ m}$$

$$A = \sqrt[3]{20{,}03 \cdot 20{,}03 \cdot 20{,}12} \approx 20{,}06$$



Positive sequence capacitance:

$$c = \frac{2\pi\varepsilon_0}{\ln\dfrac{2ha}{rA}} = \frac{2\pi\cdot 8{,}84\cdot 10^{-12}}{\ln\dfrac{2\cdot 10\cdot 1{,}38}{0{,}007\cdot 20.06}} \text{ F/m}$$

$$\approx 10{,}5\cdot 10^{-12}\,\frac{\text{F}}{\text{m}} = \underline{\underline{10{,}5\,\frac{\text{nF}}{\text{km}}}}$$

Zero sequence capacitance :

$$c = \frac{2\pi\varepsilon_0}{\ln\dfrac{2h}{r}\left(\dfrac{A}{a}\right)^2} = \frac{2\pi\cdot 8{,}84\cdot 10^{-12}}{\ln\dfrac{2\cdot 10}{0{,}007}\left(\dfrac{20{,}06}{1{,}38}\right)^2}\,\frac{\text{F}}{\text{m}}$$

$$\approx 4{,}17\cdot 10^{-12}\,\frac{\text{F}}{\text{m}} = \underline{\underline{4{,}17\,\frac{\text{nF}}{\text{km}}}}$$

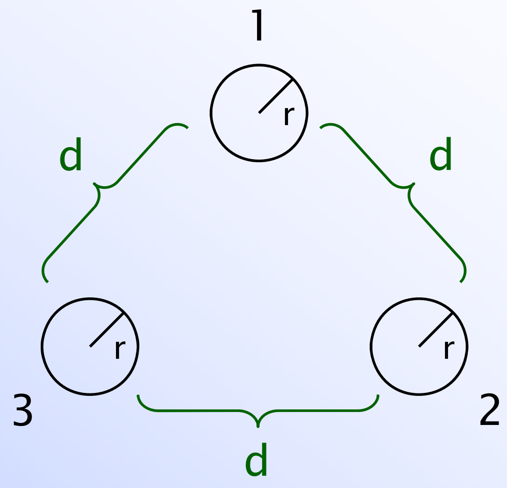
OH-line inductance

$$L = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \ln\frac{d}{r}\right]$$

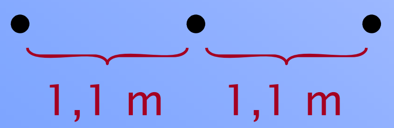
$$\mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$$

If the distances between the phases are not equal:

$$d_{eq} = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}}$$



Example: a 20 kV line with horizontal arrangement:



$150 \text{ mm}^2 \Rightarrow r \approx 7 \text{ mm}$

$$d = \sqrt[3]{1{,}1 \cdot 1{,}1 \cdot 2{,}2} \approx 1{,}39 \text{ m}$$

$$L = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \ln\frac{d_{eq}}{r}\right]$$

$$= \frac{4\pi}{2\pi} \cdot 10^{-7} \left(\frac{1}{4} + \ln\frac{1{,}39}{0{,}007}\right) \text{ H/m}$$

$$= 2 \cdot 10^{-7}(0{,}25 + 5{,}29) \text{ H/m}$$

$$\approx \underline{\underline{1{,}11 \text{ mH/km}}}$$

$$X = \omega L = 2\pi f\, L = 2\pi \cdot 50 \cdot 1{,}11 \cdot 10^{-3} \;\Omega\text{/km}$$

$$\approx \underline{\underline{0{,}35\,\Omega\text{/km}}}$$

The inductance of a multi-conductor line

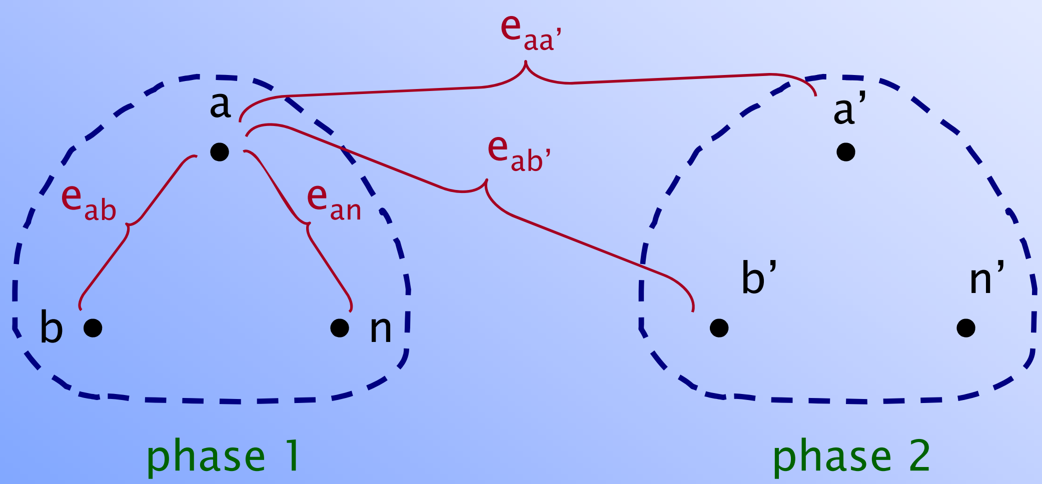
$$L = \frac{\mu_0}{2\pi}\left[\frac{1}{4n} + \ln\frac{d_e}{r_e}\right]$$

n = number of sub-conductors

$$d_e = \sqrt[3]{d_{12e} \cdot d_{23e} \cdot d_{31e}}$$

d_{12e} = equivalent distance between the phases 1 and 2

r_e = equivalent radius of one phase conductors

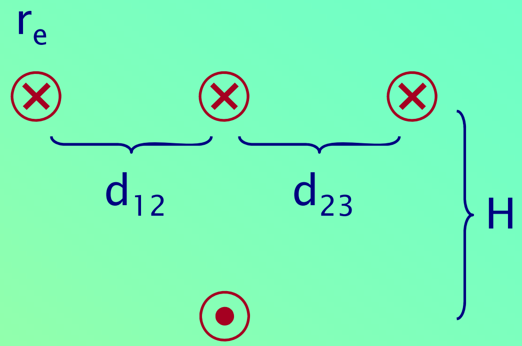


$$d_{12e} = \sqrt[n^2]{(e_{aa'} \cdot e_{ab'} \cdots e_{an'}) \cdots (e_{na'} \cdot e_{nb'} \cdots e_{nn'})}$$

$$r_e = \sqrt[n^2]{(r\, e_{ab} \cdots e_{an}) \cdots (e_{na}\ e_{nb} \cdots e_{n(n-1)} \cdot r)}$$

Zero sequence inductance of an OH-line

Inductance in a loop of 3 phase conductors and the ground return:



$$L = \frac{\mu_0}{2\pi}\left[\frac{1}{12} + \ln\frac{H}{r_{en}}\right]$$

$$r_{en} = \sqrt[3]{r_e \sqrt[3]{d_{12}^{\,2} \cdot d_{23}^{\,2} \cdot d_{13}^{\,2}}}$$

r_{en} = phase conductors equivalent radius

d_{12} = distance between phases 1 and 2

H = equivalent depth of the ground return current

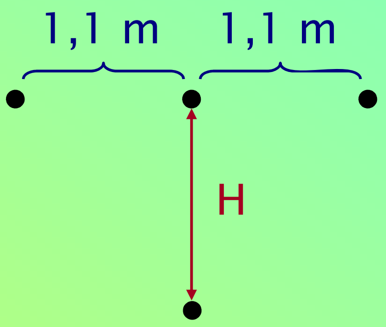
$$H = 1{,}85\sqrt{\frac{\rho_m}{\omega\mu_0}}$$

In Finland the soil resistivity typically is $\rho_m = 2300\ \Omega\text{m}$

$$\Rightarrow \quad H = 1{,}85\sqrt{\frac{2300}{2\pi \cdot 50 \cdot 4\pi \cdot 10^{-7}}}\ \text{m}$$

$$\approx 4465\ \text{m}$$

Example : a 20 kV line



$$r \;\; = 7 \text{ mm } (150°)$$

$$r_m = 2300 \; \Omega\text{m} \;\Rightarrow\; H = 4465 \text{ m}$$

$$r_{en} = \sqrt[3]{0{,}007 \; \sqrt[3]{1{,}1^2 \cdot 1{,}1^2 \cdot 2{,}2^2}}$$

$$\approx \; 0{,}238 \text{ m}$$

The zero sequence inductance for the three phases is:

$$L_a = \frac{\mu_0}{2\pi}\left[\frac{1}{12} + \ln\frac{H}{r_{en}}\right]$$

$$= \frac{4\pi \cdot 10^{-7}}{2\pi}\left[\frac{1}{12} + \ln\frac{4465}{0{,}238}\right] \text{H/m}$$

$$\approx 1{,}98 \;\; \text{mH/km}$$

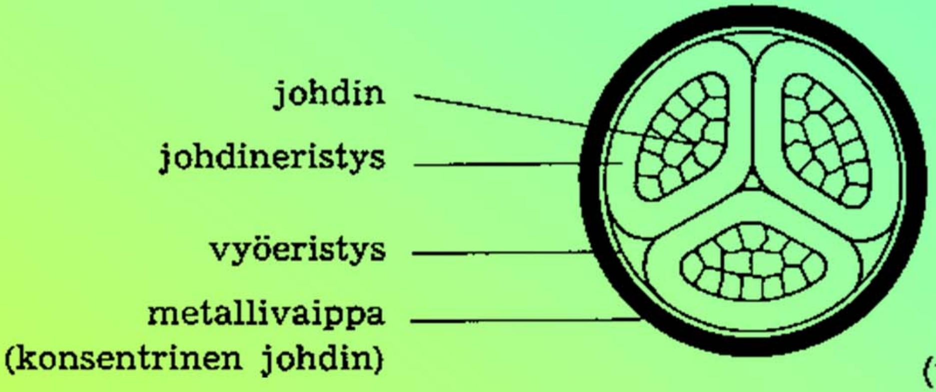
And the zero sequence inductance per phase is:

$$L_0 = 3\,L_a = \underline{5{,}94 \;\; \text{mH/km}}$$

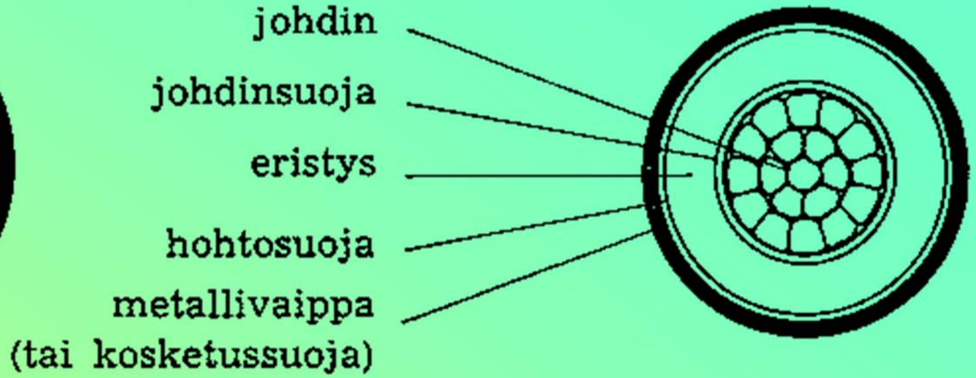
$$\Rightarrow \quad X_0 = \omega L_0 = 2\pi \cdot 50 \cdot L_0 \approx \underline{\underline{1{,}87 \;\; \Omega/\text{km}}}$$

Structures of power cables

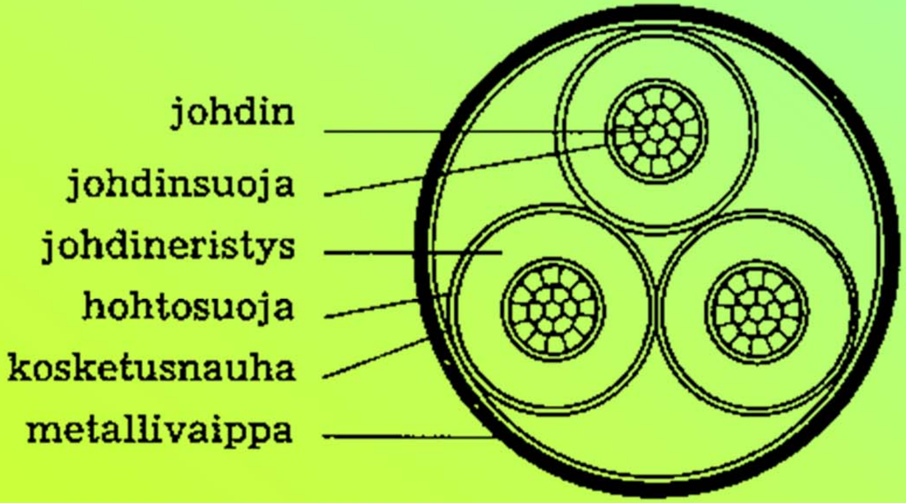
Belt type cable: ***conductor, conductor insulation, belt insulation, protection screen***



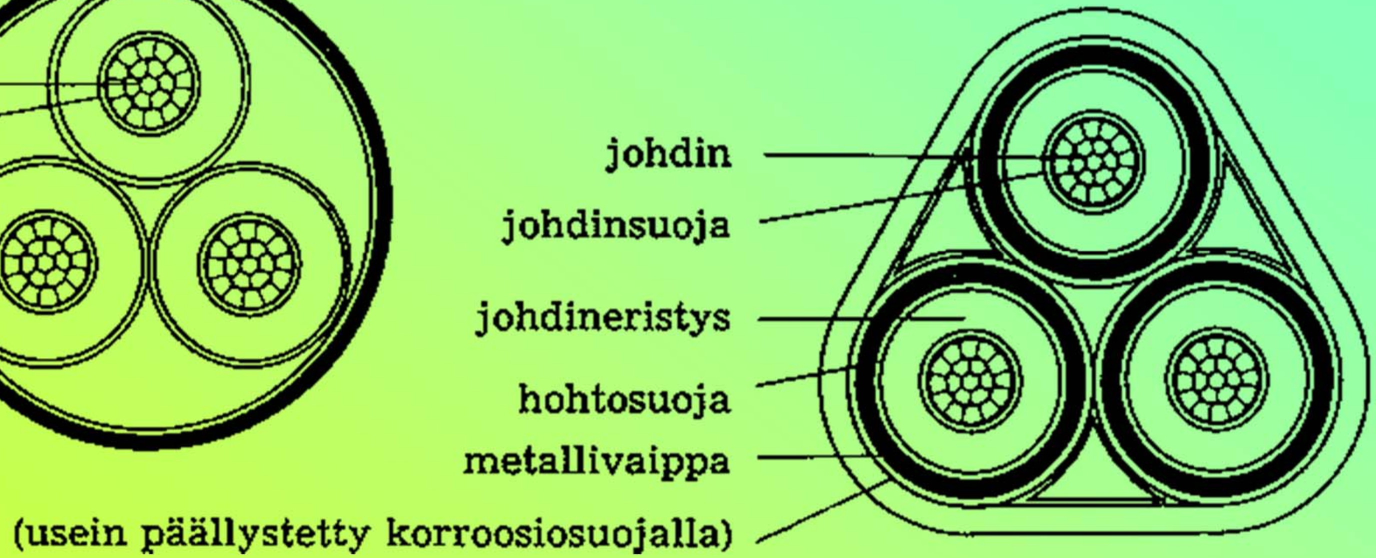
Single conductor cable: ***conductor, conductor screen, insulation, core screen, protection screen, (armoring)***



H-type cable. Composed of single conductor cables with a common protection screen



Multi-screen cable. Composed of single conductor cables with a common plastics screen.

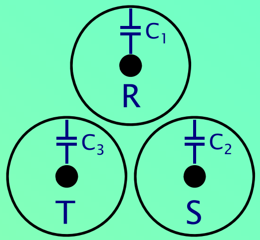


Cable capacitances

1. Cables with cylindrical field :

$$C_1 = C_2 = C_3$$

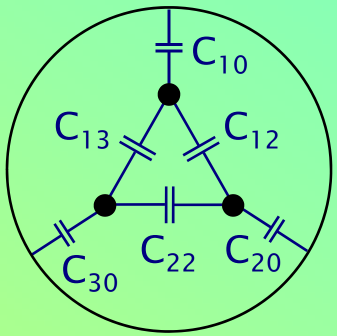
Positive sequence C = zero sequence C = C_1



2. Belt type cable :

$$C_{12} = C_{13} = C_{23}$$

$$C_{10} = C_{20} = C_{30}$$



Positive sequence C :

$$C = C_{10} + 3C_{12}$$

Zero sequence C = C_{10}

The usually given rated data for cables includes :

· operational (pos.seq.) capacitance $\mu F/km$ (C)

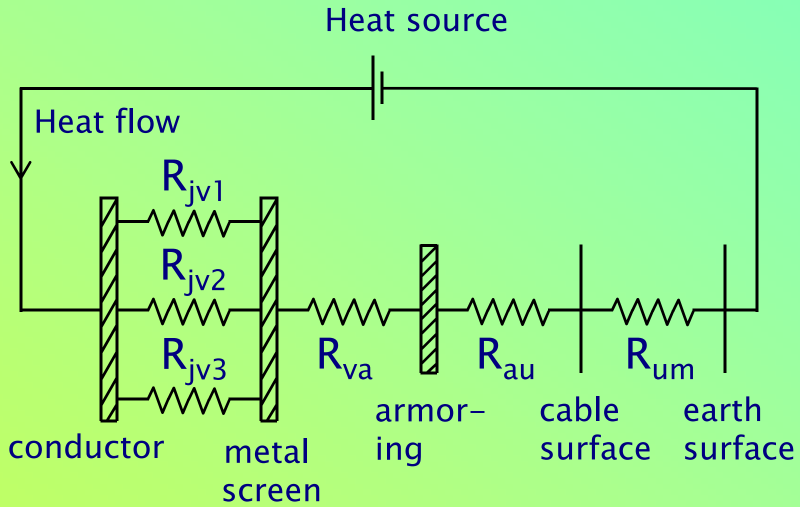
· charging current A/km $(U_v \cdot \omega C)$

· earth fault current A/km $(3U_v \cdot \omega C_0)$

The data is given in tables according to the type and cross-section

The load carrying capacity of power cables

The thermal circuit :



Thermal resistances :

- R_{jv} conductor – screen
- R_{va} screen – armoring
- R_{au} armoring – cable surface
- R_{um} cable surface – earth surface

Maximum load depends on the allowed insulation temperature :

MV-cables normally:		(during fault)
· PVC :	65 °C	(135)
· paper:	65 °C	(250)
· PE :	65 °C	(150)
· PEX :	90 °C in air	(250)
	65 °C in soil	

Power cable load carrying capacity

Maximum load currents are given in standard conditions:

- in soil : 1 cable in 70 cm depth, soil temperature +15°C and soil resistivity 1 Km/W
- in air : ambient temperature +25°C, free air flow around the cable

The differences to the standard conditions are taken into account by correction coefficients k_i :

- impact of adjacent cables
- effect of burial depth
- difference in soil thermal resistivity
- soil ambient temperature

The final loading is the product of std-loading and the correction coefficients.

The effect of adjacent cables in the soil to the ampacity of cables

number of adjacent cables correction factor when the free distance between cables is	2	3	4	5	6	8	10
a) 0 mm	0,79	0,69	0,63	0,58	0,55	0,50	0,46
b) 70 mm	0,85	0,75	0,68	0,64	0,60	0,56	0,53
c) 250 mm	0,87	0,79	0,75	0,72	0,69	0,66	0,64

The effect of burial depth in soil

depth in soil m	rated voltage 0,6/1 kV	6/10…40/69 kV
0,5…0,7	1,0	1,0
0,71…0,9	0,97	0,99
0,91…1,1	0,95	0,98
1,1…1,3	0,93	0,96
1,31…1,5	0,92	0,95

The effect of soil thermal resistivity

Soil thermal resistivity Km/W	0,7	1,0	1,2	1,5	2,0	2,5	3,0
0,6/1 kV							
up to 25 mm	1,11	1	0,94	0,87	0,78	0,72	0,67
35…95 mm^2	1,13	1	0,93	0,86	0,76	0,70	0,64
120…500 mm^2	1,14	1	0,92	0,85	0,75	0,69	0,63
6/10 kV							
up to 25 mm	1,09	1	0,95	0,88	0,80	0,74	0,69
25…95 mm^2	1,11	1	0,94	0,87	0,78	0,72	0,66
120…500 mm^2	1,12	1	0,93	0,86	0,77	0,70	0,65
12/20 kV							
up to 25 mm	1,08	1	0,96	0,90	0,81	0,75	0,70
35…95 mm^2	1,10	1	0,95	0,89	0,79	0,73	0,67
120…500 mm^2	1,11	1	0,94	0,88	0,78	0,72	0,66
18/30-34,6/60 kV							
up to 95 mm	1,08	1	0,95	0,90	0,82	0,76	0,71
120…500 mm^2	1,09	1	0,95	0,89	0,80	0,74	0,69

Examples of the soil thermal resistivities

Dry sand (water content 0 %)	3,0 Km/W
Dry gravel and clay	1,5 "
Half dry gravel and sand (water content 10 %)	1,2 "
Half dry clay and wet gravel	1,0 "
Wet clay and sand (water content 25 %)	0,7 "

The effect of soil ambient temperature

Soil temperature C	5	10	15	20	25	30
90°C conductor temp.	1,06	1,03	1,0	0,96	0,93	0,89
80°C "	1,07	1,04	1,0	0,96	0,92	0,88
70°C "	1,09	1,04	1,0	0,95	0,90	0,85
65°C "	1,10	1,05	1,0	0,95	0,89	0,84

Example:

Three cables APAKM 3 · 185° 0,6/1,0 kV
with 7 cm distances in soil:

- in 90 cm depth
- half dry gravel soil
- soil temperature +10°C
- std-loading 350 A / cable

Correction coefficients :

- 3 cables $\Rightarrow$ $k_1 = 0{,}75$
- 90 cm $\Rightarrow$ $k_2 = 0{,}97$
- soil resistivity $\Rightarrow$ $k_3 = 0{,}92$
- soil temperature $\Rightarrow$ $k_3 = 1{,}04$

$\Rightarrow$ Maximum allowed load current is

$$I_n \cdot \mathrm{k}_1 \cdot \mathrm{k}_2 \cdot \mathrm{k}_3 \cdot \mathrm{k}_4$$

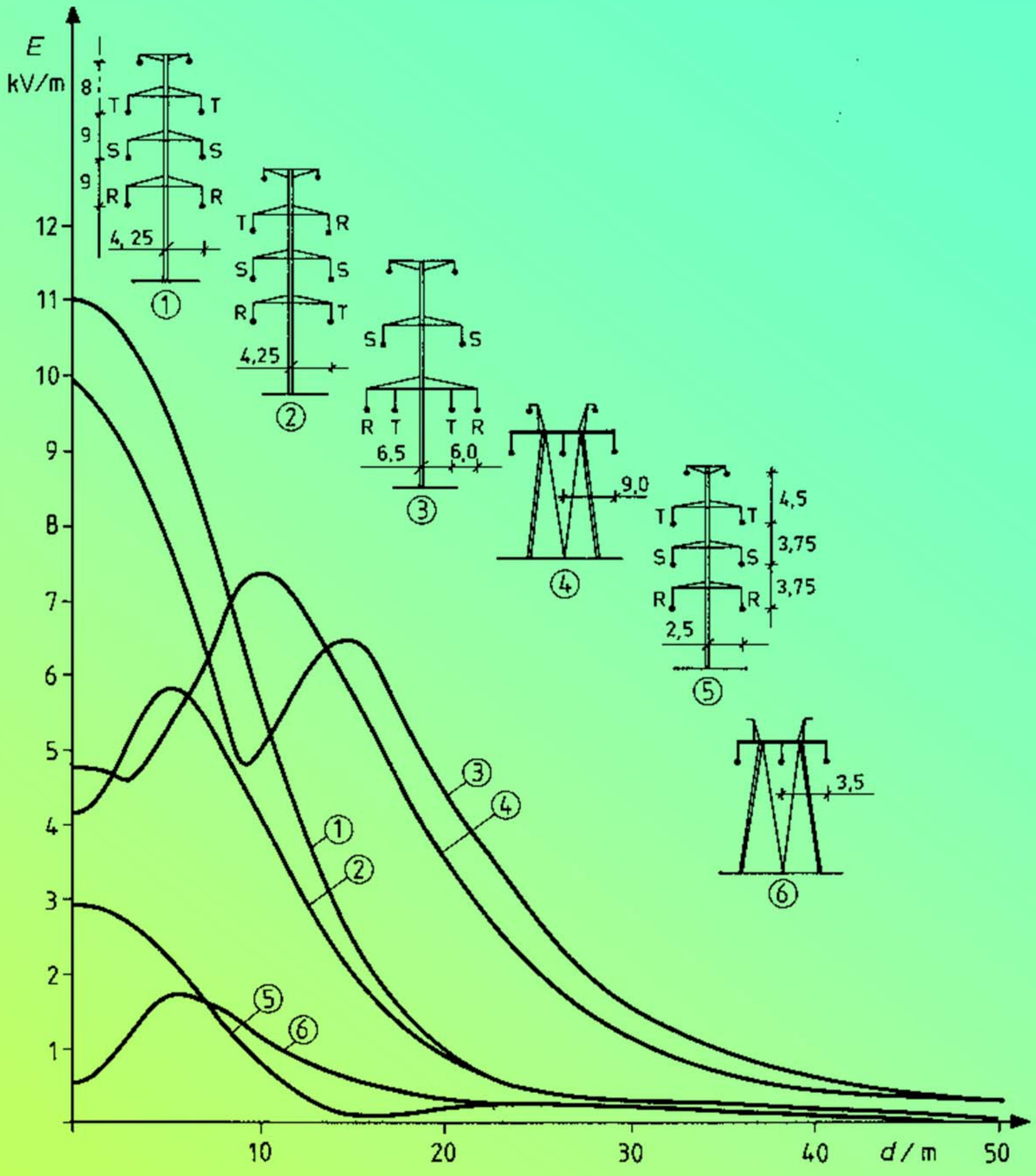
$$= 350 \cdot 0.75 \cdot 0.97 \cdot 0.92 \cdot 1.04 \text{ A}$$

$$\underline{\underline{\approx 244 \text{ A}}}$$

Power line electrical fields and health risks

- WHO v. -82 : safe limit is 20 kV/m
- exception : users of artificial pacemaker (heart)
- 110 kV lines: maximum value in practice about 2…3 kV/m
- 400 kV double lines ~10 kV/m, can be reduced by a proper phase location.

EU Comission recommendation 519 year 1999:
-5 kV/m for longer duration
-15 kV/m temporarily

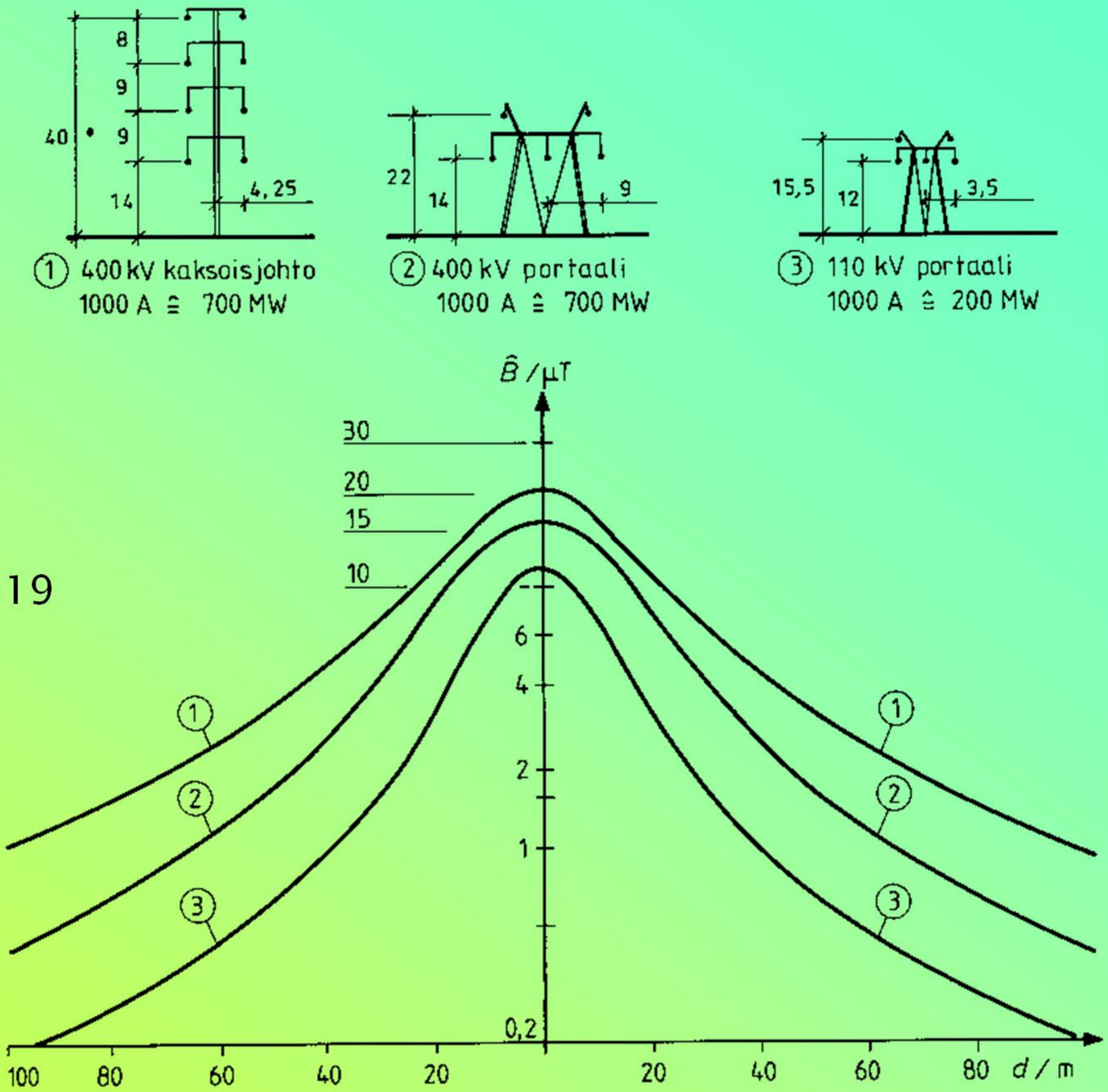


Electrical field strength at the earth level in the vicinity of power lines.
1)…4) 400 kV, lowest conductors 10 m from earth
5) , 6) 110 kV, lowest conductors 8 m from earth
1) , 5) phase conductors located symmetrically
2) phase order reversed in the other pole
3) phase order reversed in other sub-conductor
4) poles with guy wires, d = distance from center

Magnetic fields and health risks

- WHO v. -82 : safe limit 0,3 mT
- risk of cancer when 0,3 μT ?
- compare with the earth magnetic field~20 μT
- under an overhead line max value 10...40 μT
  - at 30 m distance attenuated to 10 %
  - at 100 m distance 0,2...1 μT
  - Buildings do not attenuate !

EU Comission recommendation 519
-100 uT for longer time
-500 uT temporarily



Magnetic fields of overhead lines at the earth surface level

1) , 2) 400 kV, 1000 A / circuit
3) 110 kV, 1000 A
1) double lone
2) , 3) towers, d = distance from the center