A1B15EN2

Topics

- Electrical parameters of power lines and ES elements
- DC and AC power lines LV, MV
- HV power lines, substitution elements
- Meshed grids
- Electrical waves on power lines
- Short-circuits
- Ground faults
- Transmission stability
- Electrical protections
- Substations
- Grounding
- Dimensioning

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Overhead Power line Electrical Parameters

4 basic (primary) el. parameters (for each phase)

- Resistance R_1 (Ω/km)
- Operational inductance L_1 (H/km)
- Conductance G_1 (S/km)
- Operational capacity C_1 (F/km)

Secondary parameters

- inductive reactance

$$X_1 = \omega L_1 = 2\pi f L_1 \quad (\Omega / \text{km})$$

- susceptance

$$B_1 = \omega C_1 = 2\pi f C_1 \quad (\text{S} / \text{km})$$

- longitudinal impedance

$$\hat{Z}_{l1} = R_1 + jX_1 \quad (\Omega / \text{km})$$

- cross admittance

$$\hat{Y}_{q1} = G_1 + jB_1 \quad (S/km)$$

- wave impedance

$$\hat{Z}_v = \sqrt{\frac{\hat{Z}_{l1}}{\hat{Y}_{q1}}} \quad (\Omega)$$

- propagation constant

$$\hat{\gamma} = \sqrt{\hat{Z}_{l1}\hat{Y}_{q1}} = \alpha + j\beta \quad (km^{-1})$$

α – specific damping

β – specific phase shift

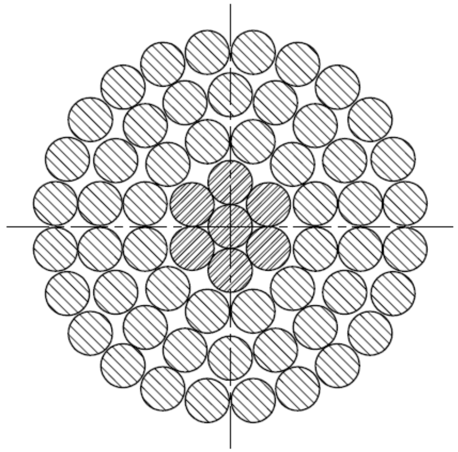
Note:

- we consider symmetrical supply and load
- networks LV – mainly R
  MV – R, L (in failures C)
  HV – R, L, G, C (distributed)

Overhead power line conductors

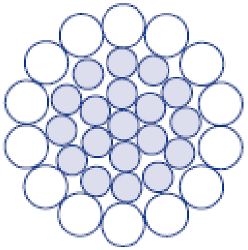
- full cross section or twist (1 or more materials)
- ropes Cu, Al, alloys, composites, optical wires, high-temperature materials
- ACSR (Aluminum Conductor Steel Reinforced) = carrying Fe core + conductive Al coat

  $$S \in (180\,;\,680)\,\mathrm{mm}^2$$

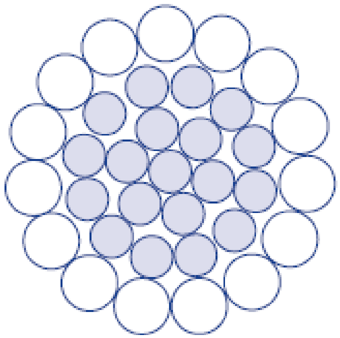


- example of labeling
  - 382-AL1/49-ST1A
  - 350AlFe4
  - AlFe450/52

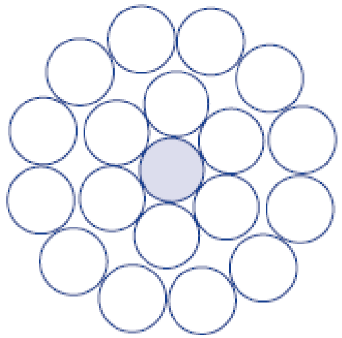
Rope	Construction	Fe				Al			Rope		
		Nb. of wires	Diameter of wire	Diameter of inner tube	Cross-section	Nb. Of wires	Diameter of wire	Cross-section	Diameter	Cross-section	R_{DC+20}
		ks	mm	mm	mm^2	ks	mm	mm^2	mm	mm^2	$\Omega\cdot km^{-1}$
350 AlFe 4	1+6+12/12+18	19	2,36	11,80	83,11	30	3,75	331,34	26,80	414,45	0,087
450 AlFe 8	3+9/18+14+20	12	2,36	9,90	52,49	18+34	1,90+3,75	426,55	28,70	479,05	0,0674
AlFe 450/52	3+9/12+18+24	12	2,36	9,81	52,49	54	3,25	447,97	29,31	500,46	0,0646
382-AL1/49-ST1A	1+6/12+18+24	7	3,00	3,00	49,48	54	3,00	381,70	27,00	431,18	0,0758
476-AL1/62-ST1A	1+6/12+18+24	7	3,35	10,05	61,70	54	3,35	475,96	30,15	537,66	0,0608



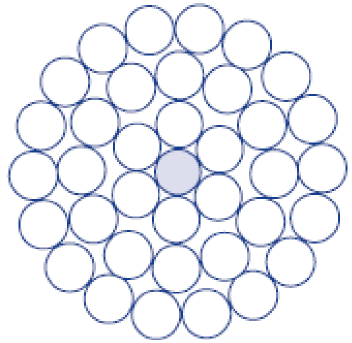
14Al/19Fe



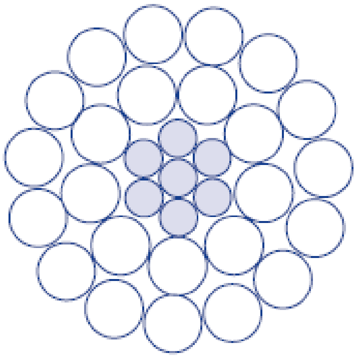
15Al/19Fe



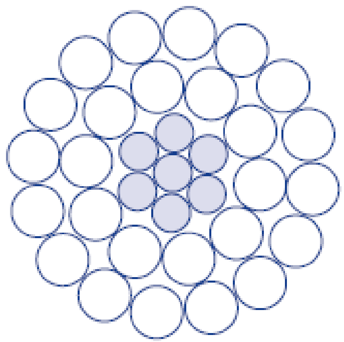
18Al/1Fe



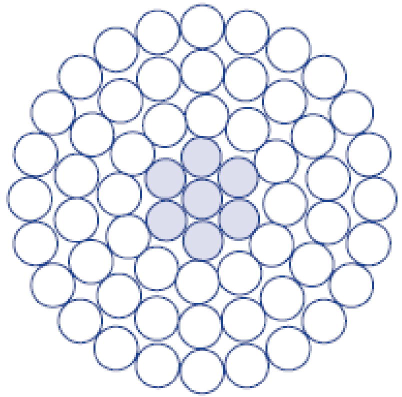
36Al/1Fe



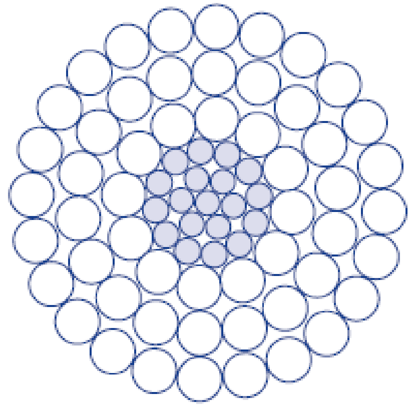
24Al/7Fe



26Al/7Fe

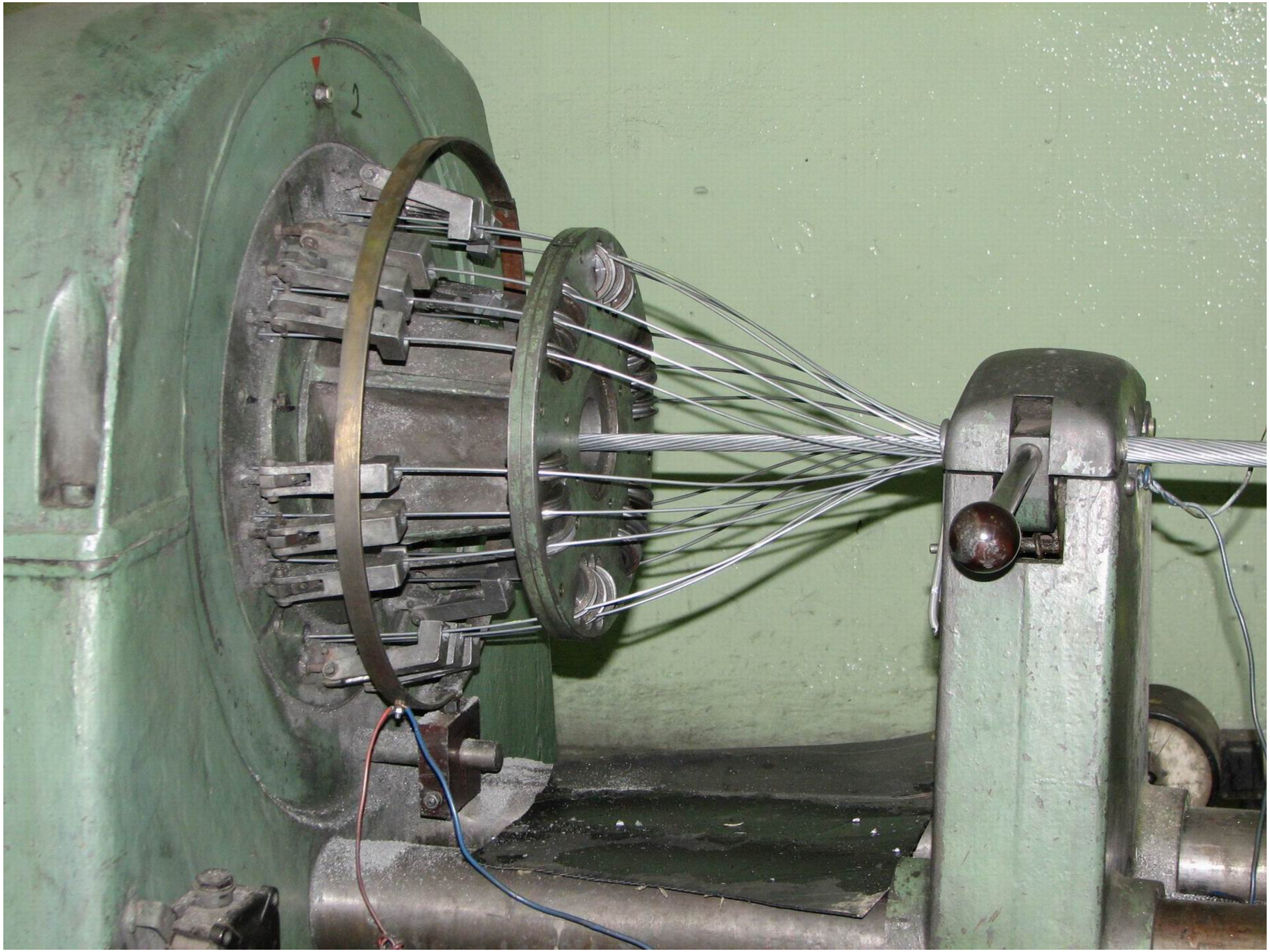


54Al/7Fe



54Al/19Fe


862



Resistance

Value influenced by:

conductor material, temperature, skin effect, elongation due to twisted wires, current density distribution along stripes, sag, unequal cross section, connections

With DC current (at 20°C)

$$R_{1dc0} = \frac{\rho_0}{S} \quad (\Omega / km)$$

Cu: $\rho_0 = 1{,}78 \cdot 10^{-8} \quad (\Omega m)$

Al: $\rho_0 = 2{,}81 \cdot 10^{-8} \quad (\Omega m)$

Fe: $\rho_0 = 12{,}8 \cdot 10^{-8} \quad (\Omega m)$

$$\rho_{AlFeDC} = \frac{\rho_{Al} \cdot S_{Al} + \rho_{Fe} \cdot S_{Fe}}{S_{Al} + S_{Fe}}$$

Temperature effect

$$k_T = 1 + \alpha(T_1 - T_0) + \beta(T_1 - T_0)^2 \quad (-)$$

Cu: $\alpha = 3{,}93 \cdot 10^{-3} \quad (K^{-1})$

Al: $\alpha = 4{,}03 \cdot 10^{-3} \quad (K^{-1})$

Fe: $\alpha = 4{,}5 \cdot 10^{-3} \quad (K^{-1})$

$\beta \approx 10^{-6}\ K^{-2}$ $\rightarrow$ under normal ΔT neglected

$$\alpha = \frac{\alpha_{Al} \cdot \alpha_{Fe}\left(\frac{\rho_{Al}}{S_{Al}} + \frac{\rho_{Fe}}{S_{Fe}}\right) + \alpha_{Al} \cdot \frac{\rho_{Fe}}{S_{Fe}} + \alpha_{Fe} \cdot \frac{\rho_{Al}}{S_{Al}}}{\frac{\rho_{Al}}{S_{Al}} + \frac{\rho_{Fe}}{S_{Fe}} + \alpha_{Al} \cdot \frac{\rho_{Al}}{S_{Al}} + \alpha_{Fe} \cdot \frac{\rho_{Fe}}{S_{Fe}}}$$

Influence of AC current, e.g.

$$k_{ac} = 1 + 0{,}0375 \cdot 10^{-12} \cdot \left[\frac{(r_2 - r_1) \cdot f}{r_2 \cdot R_{1dc0}}\right]^2 \quad \left(-;\ m,\ m,\ Hz,\ m,\ \Omega \cdot m^{-1}\right)$$

$$k_{ac} = 1{,}004 \div 1{,}3 \quad (-)$$

Empirically by the number of layers Al (Fe core 2÷3% of current)

two layers $k_{ac} = 1{,}04$

three layers $k_{ac} = 1{,}06$

four layers $k_{ac} = 1{,}05$

In catalogue usually R_{1dc0}

$$\Rightarrow R_1 = R_{1dc0} \cdot k_T \cdot k_{ac} \quad (\Omega / km)$$

$$cca\ R_{1dc0} \in (0{,}05 ; 2)\ \Omega / km$$

AlFe42 $R_{1dc0} \sim 0{,}7\ \Omega/km$

AlFe70 $R_{1dc0} \sim 0{,}4\ \Omega/km$

AlFe95 $R_{1dc0} \sim 0{,}3\ \Omega/km$

AlFe120 $R_{1dc0} \sim 0{,}2\ \Omega/km$

AlFe210 $R_{1dc0} \sim 0{,}14\ \Omega/km$

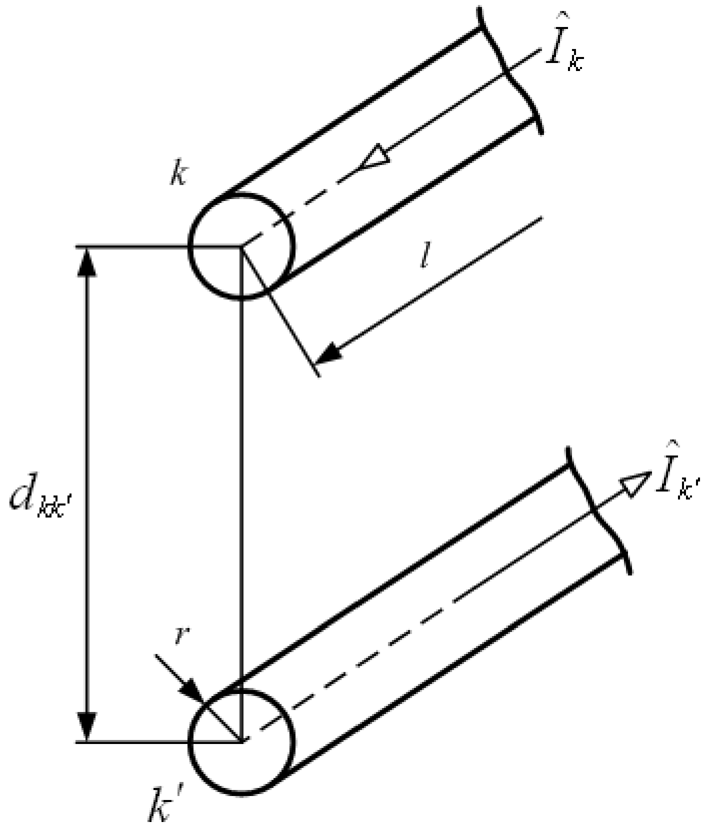
AlFe350 $R_{1dc0} \sim 0{,}09\ \Omega/km$

AlFe450 $R_{1dc0} \sim 0{,}07\ \Omega/km$

AlFe680 $R_{1dc0} \sim 0{,}04\ \Omega/km$

Inductance and longitudinal impedance

Inductance and impedance in a loop



$$r \ll d \ll l \qquad d_{kk'} = d \qquad \hat{I}_k = -\hat{I}_{k'}$$

Internal inductance of a conductor (magnetic flux inside the conductor)

$$L_{ik} = \frac{\mu_0 \mu_{rv}}{8\pi} \alpha \quad (H/m; H/m, -, -)$$

$$\mu_0 = 4\pi \cdot 10^{-7} \ H \cdot m^{-1}$$

μ_{rv}....... relative permeability of conductor

α......... inequality of current distribution through cross-section

External inductance of a conductor in a loop (magnetic flux outside the conductor)

$$L_{ek} = \frac{\mu_0}{2\pi} \ln \frac{d}{r} \quad (H/m; H/m, m, m)$$

Self-inductance

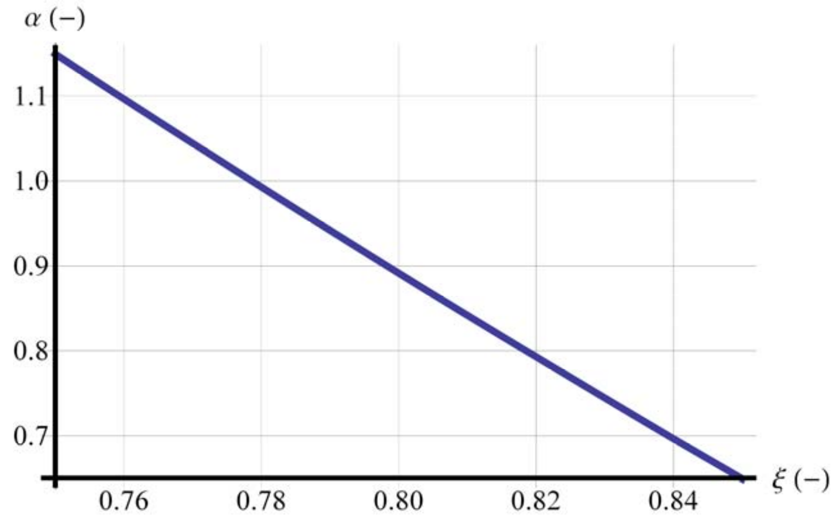
$$L_v = L_{ik} + L_{ek} = \frac{\mu_0 \mu_{rv}}{8\pi} \alpha + \frac{\mu_0}{2\pi} \ln \frac{d}{r}$$

$$L_v = 0{,}05 \mu_{rv} \alpha + 0{,}46 \log \frac{d}{r} = 0{,}46 \log \frac{d}{\xi r} \quad (mH \cdot km^{-1}; m, m)$$

ξ… coefficient of current density inequality in cross section and permeability

$$\xi = 10^{-\frac{0,05\mu_{rv}\alpha}{0,46}}$$

$\xi \in (0,809\,;\,0,826)$ for common ACSR ropes

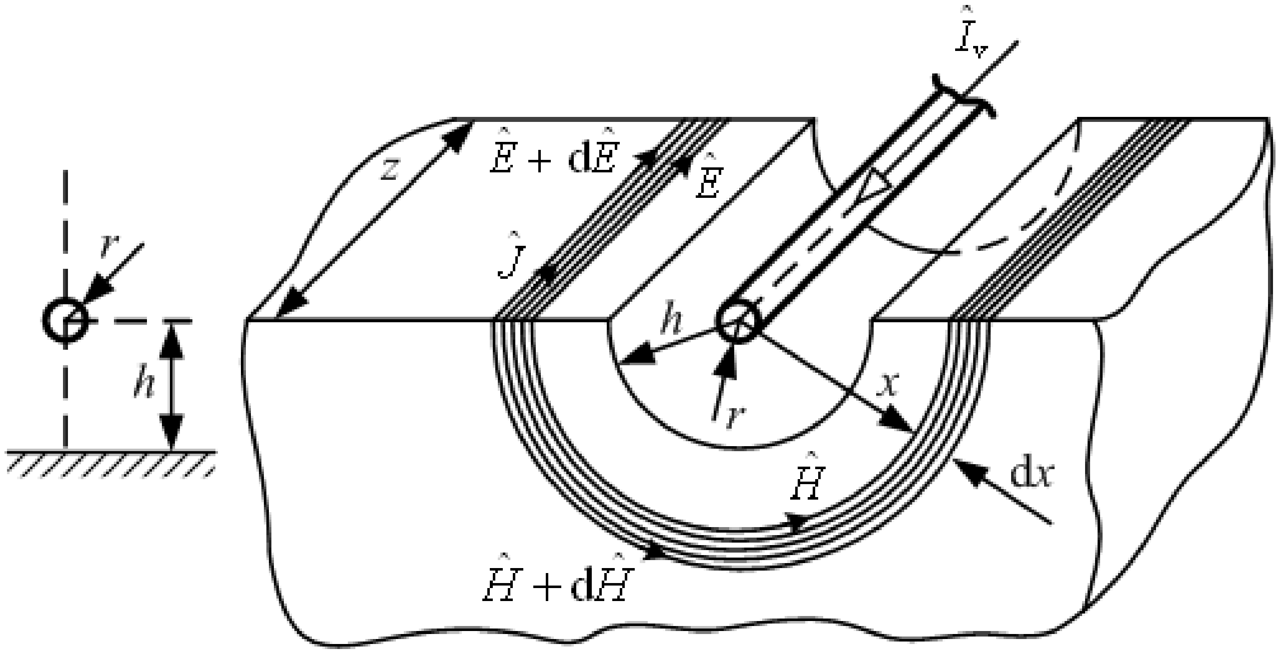


Impedance of one conductor in a loop of two conductors

$$\hat{Z}_{kv} = R_{1k} + j\omega \cdot 0,46 \cdot 10^{-6} \cdot \log \frac{d}{\xi r} \quad (\Omega \cdot m^{-1})$$

Self-impedance of a loop conductor-ground

- Ground as a conductor of stationary AC current
- Rüdenberg's conception
- Density of AC current in a ground is unequal, the maximum is under the conductor



3 components:

a) R_{1k} – resistance respecting power losses in the conductor
b) X_{1k} – reactance respecting part of magnetic flux coupled with the conductor and closed in the conductor and in the air
c) Z_{1g} – impedance respecting part of magnetic flux in the ground coupled with conductor

$$\hat{Z}_{kk} = R_{kk} + jX_{kk} = R_{1k} + jX_{1k} + R_{1g} + jX_{1g}$$

$$R_{1g} = \pi^2 f \cdot 10^{-7} \quad (\Omega \cdot m^{-1}; Hz)$$

for f = 50 Hz je $R_{1g} = 0{,}0495\,\Omega \cdot km^{-1}$

$$\hat{Z}_{kk} = R_{1k} + \pi^2 f \cdot 10^{-4} + j\omega \cdot 10^{-3} \cdot 0{,}46 \log \frac{D_g}{\xi \cdot r} \quad \left(\Omega \cdot km^{-1}\right)$$

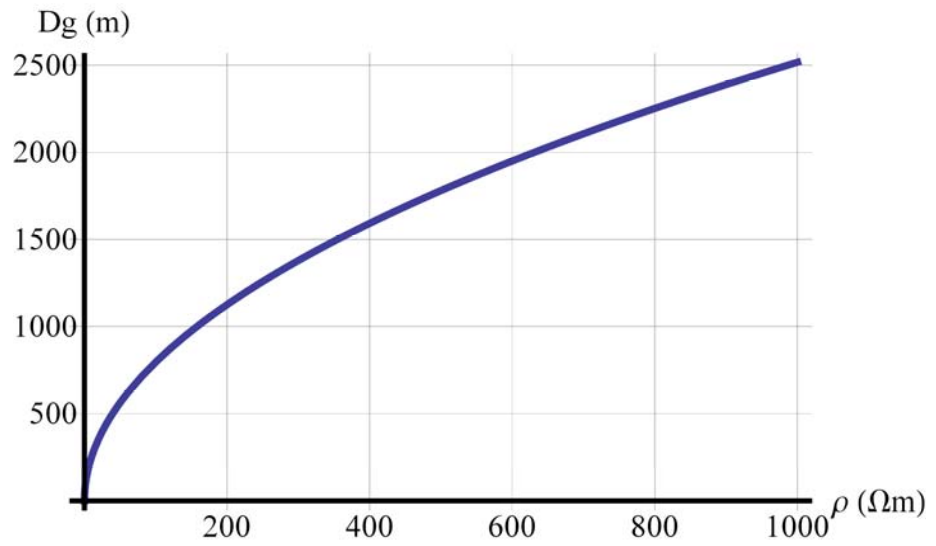
Fictitious conductor deep in the ground which has the same impacts as the real current in the ground

$$D_g = \frac{0{,}178\sqrt{\rho \cdot 10^7}}{\sqrt{f}} \quad (m; \Omega m, Hz)$$

$D_g \sim 100x$ m, i.e. $h \ll D_g$

ρ…ground resistivity

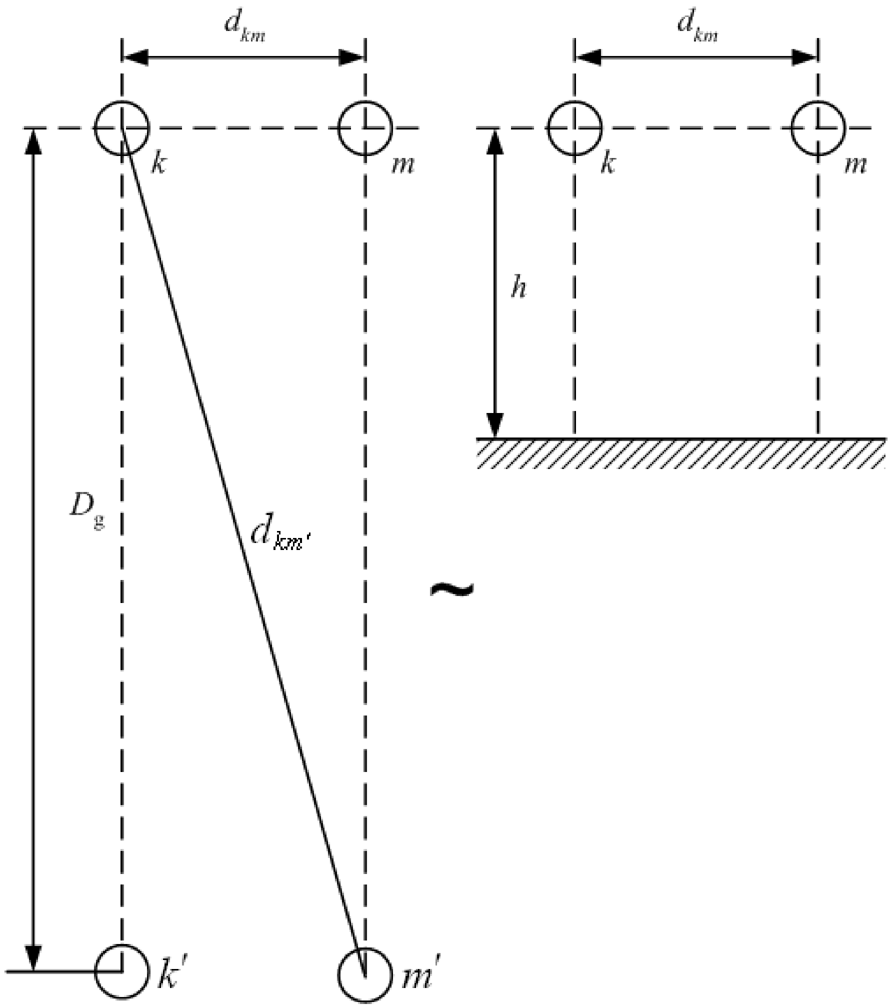
Type of soil	ρ (Ω·m)
peat	30
topsoil and clay	100
moist sand	200 - 300
dry gravel and sand	1000 - 3000
stony soil	3000 - 10000



Mutual impedance of two loops conductor-ground

- double wire one-phase power line $d_{km} \leq h$

→ return currents are compensated by each other



$D_g >> d_{km}$ → resulting electromagnetic impacts of return currents in the conductors k′, m′ on the real conductors k, m is almost zero

Impedance of one conductor in a loop

$$\Delta\hat{U}_{kv} = \hat{Z}_{kv} \cdot \hat{I}_k = \hat{Z}_{kk} \cdot \hat{I}_k + \hat{Z}_{km} \cdot \hat{I}_m$$

$$\hat{I}_k = -\hat{I}_m \Rightarrow \hat{Z}_{kv} = \hat{Z}_{kk} - \hat{Z}_{km}$$

Hence after substitutions

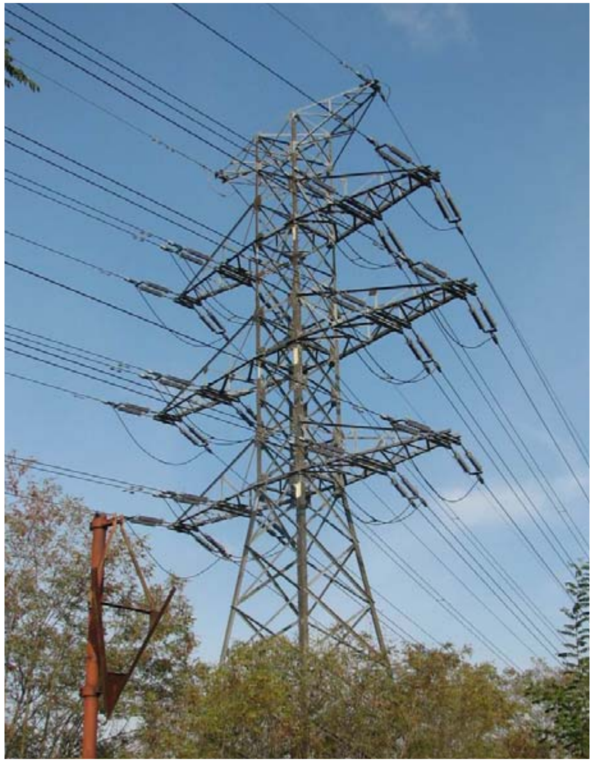
$$\hat{Z}_{kk} = R_{1k} + R_{1g} + j\omega \cdot 10^{-3} \cdot 0{,}46 \log \frac{D_g}{\xi r} \quad \left(\Omega \cdot km^{-1}\right)$$

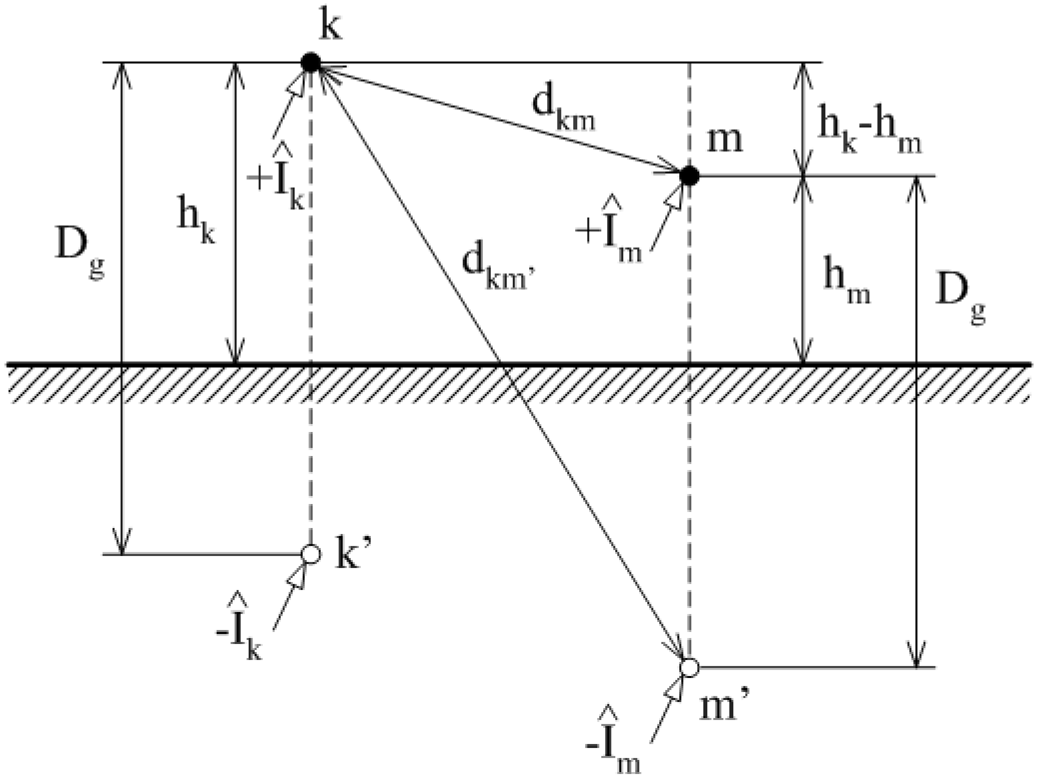
$$\hat{Z}_{kv} = R_{1k} + j\omega \cdot 0{,}46 \cdot 10^{-3} \cdot \log \frac{d_{km}}{\xi r} \quad \left(\Omega \cdot km^{-1}\right)$$

$$\hat{Z}_{km} = \hat{Z}_{kk} - \hat{Z}_{kv} = R_{1g} + j\omega \cdot 10^{-3} \cdot 0{,}46 \log \frac{D_g}{d_{km}} \quad \left(\Omega \cdot km^{-1}\right)$$

Configuration of n real conductors

Configuration of loops *n* real conductors and the ground is substituted by *n* real and *n* fictitious conductors in mutual distance D_g.





Self-inductance and impedance (loop k-k´)

$$M_{kk} = 0{,}46 \log \frac{D_g}{\xi r_k} \quad (\mathrm{mH/km;\ m,\ m})$$

$r_k \ldots k^{th}$ conductor radius

$$\hat{Z}_{kk} = R_{kk} + j\omega L_{kk} = R_{1k} + R_{1g} + j0{,}1445 \log \frac{D_g}{\xi \cdot r_k} \quad \left(\frac{\Omega}{\mathrm{km}}\right)$$

Mutual inductance and impedance (loop k-k´, m-m´)

$$M_{km} = 0{,}46 \log \frac{D_g}{d_{km}} = M_{mk} \quad (\mathrm{mH/km;\ m,\ m})$$

$$\hat{Z}_{km} = \hat{Z}_{mk} = R_{km} + j\omega L_{km} = R_{1g} + j0{,}1445 \log \frac{D_g}{d_{km}} \quad \left(\frac{\Omega}{\mathrm{km}}\right)$$

Voltage drop in kth conductor

$$\Delta\hat{U}_k = \sum_{m=1}^{n} \hat{Z}_{km}\hat{I}_m \quad (V/km)$$

(for $m = k$ is $d_{kk} = \xi r_k$)

Operational impedance (inductance) – for 1 single conductor, it causes the same voltage drop as in the system of n conductors (it can be a complex number, done by operating condition)

$$\Delta\hat{U}_k = \sum_{m=1}^{n} \hat{Z}_{km}\hat{I}_m = \hat{Z}_k\hat{I}_k \Rightarrow \hat{Z}_k = \frac{\sum_{m=1}^{n} \hat{Z}_{km}\hat{I}_m}{\hat{I}_k} \qquad \hat{L}_k = \frac{\sum_{m=1}^{n} M_{km}\hat{I}_m}{\hat{I}_k}$$

n-conductor system

$$[\Delta\hat{U}] = j\omega[M_{km}][\hat{I}]$$

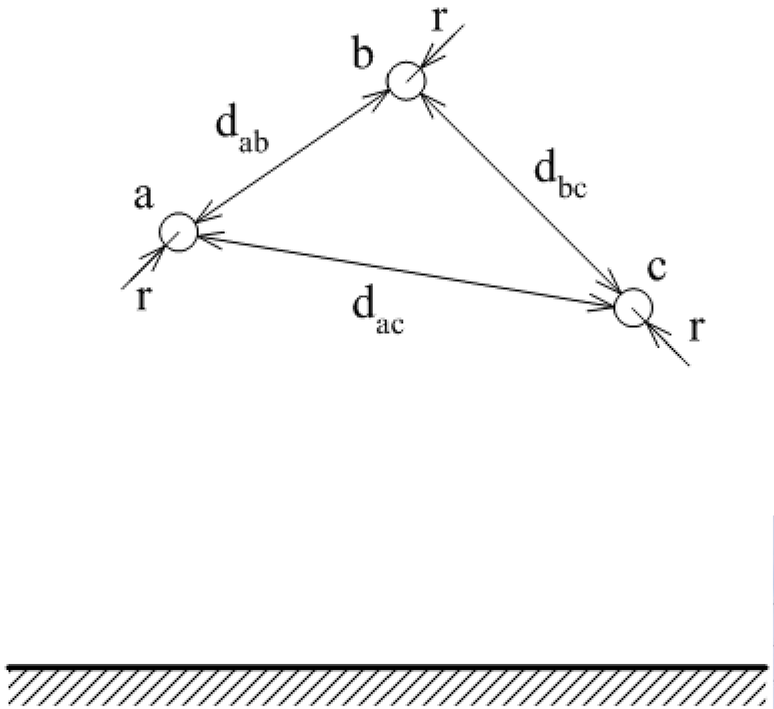
Simple (unbalanced) three-phase power line

Symmetrical loading

$$\hat{I}_a = \hat{I}_a \qquad \hat{a} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} = e^{+j\frac{2\pi}{3}}$$

$$\hat{I}_b = \hat{a}^2 \hat{I}_a \qquad \hat{a}^2 = -\frac{1}{2} - j\frac{\sqrt{3}}{2} = e^{-j\frac{2\pi}{3}}$$

$$\hat{I}_c = \hat{a}\hat{I}_a \qquad 1 + \hat{a}^2 + \hat{a} = 0$$



Operational inductances

$$\hat{L}_a = \frac{M_{aa}\hat{I}_a + M_{ab}\hat{I}_b + M_{ac}\hat{I}_c}{\hat{I}_a} = M_{aa} + \hat{a}^2 M_{ab} + \hat{a} M_{ac}$$

$$\hat{L}_b = \frac{M_{ab}\hat{I}_a + M_{bb}\hat{I}_b + M_{bc}\hat{I}_c}{\hat{I}_b} = \hat{a} M_{ab} + M_{bb} + \hat{a}^2 M_{bc}$$

$$\hat{L}_c = \frac{M_{ac}\hat{I}_a + M_{bc}\hat{I}_b + M_{cc}\hat{I}_c}{\hat{I}_c} = \hat{a}^2 M_{ac} + \hat{a} M_{bc} + M_{cc}$$

Generally

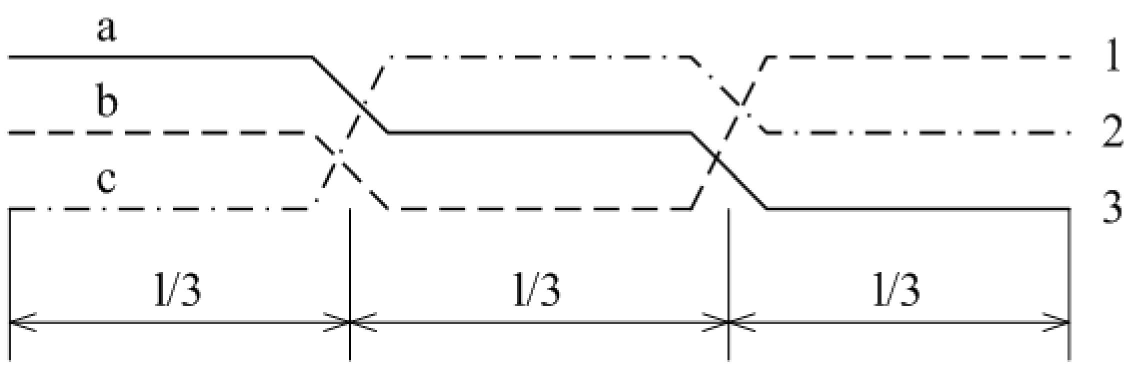
$$M_{aa} = M_{bb} = M_{cc} \qquad M_{ab} \neq M_{bc} \neq M_{ac}$$

$$\hat{L}_a \neq \hat{L}_b \neq \hat{L}_c$$

→ unequal voltage drops (magnitude and phase) → voltage unbalance, active power transfer between phases through electromagnetic coupling without further sources loading → transposition

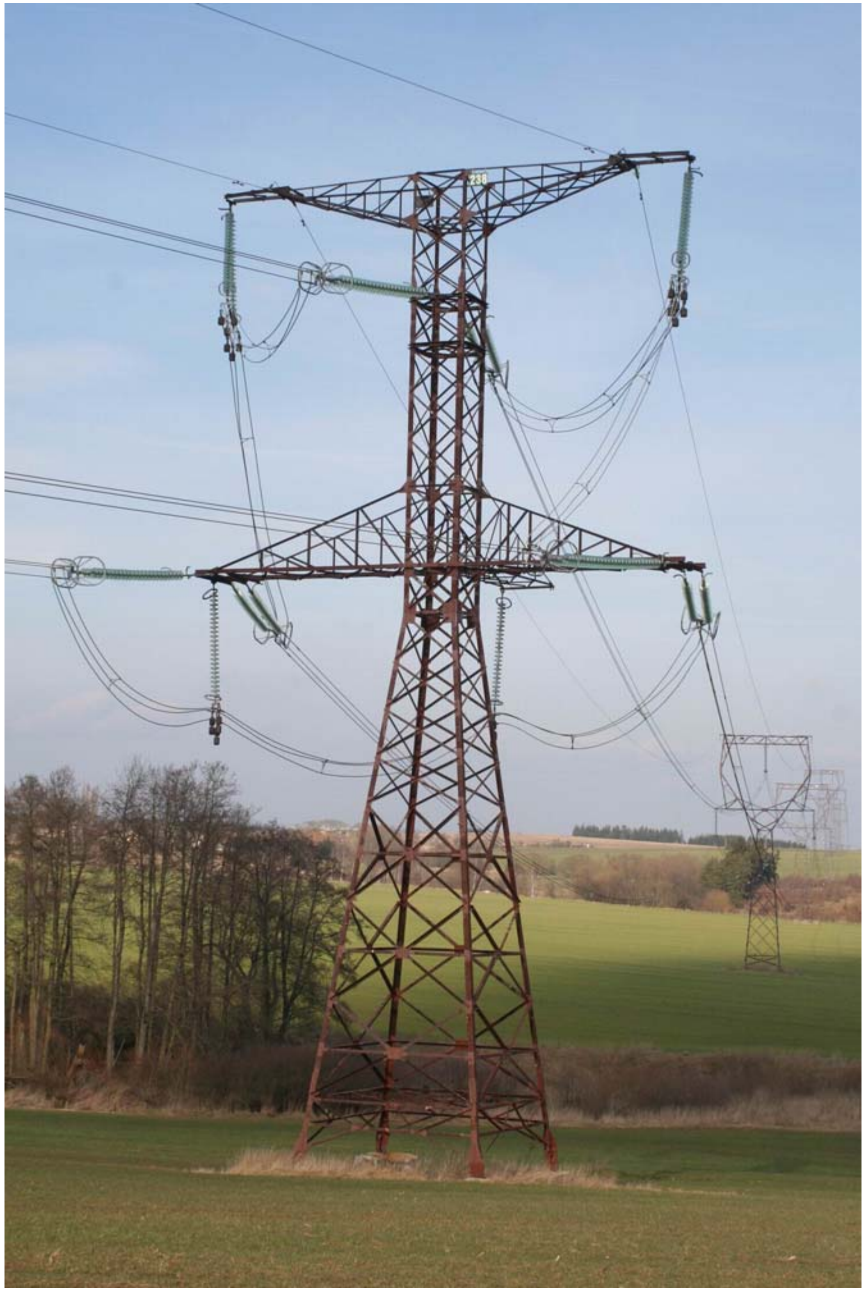
Transposition of three-phase power line

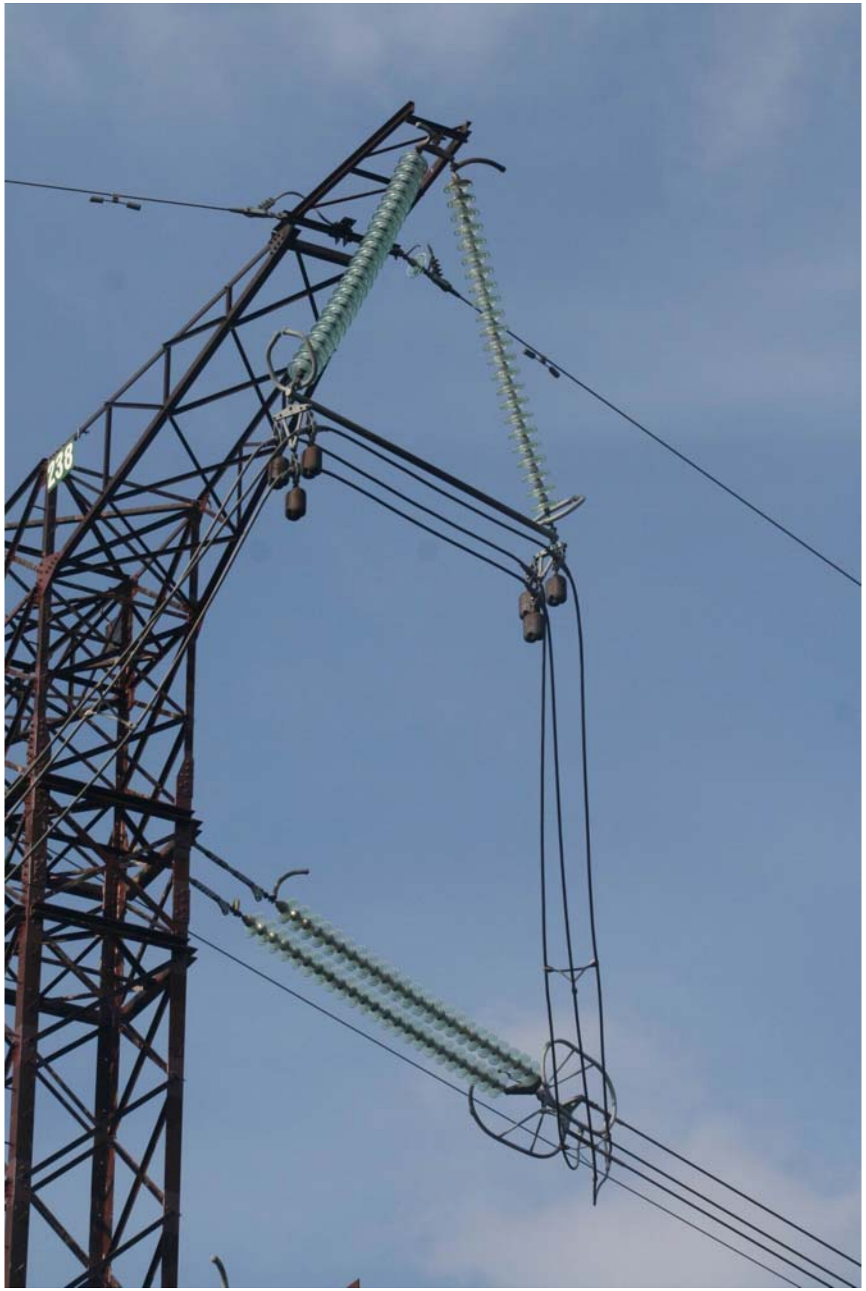
= conductors position exchange so that each one is in a definite position for 1/3 length



Voltage drops

$$\begin{pmatrix} \Delta\hat{U}_a \\ \Delta\hat{U}_b \\ \Delta\hat{U}_c \end{pmatrix} = \frac{1}{3} j\omega \left\{ \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{pmatrix} + \begin{pmatrix} M_{33} & M_{13} & M_{23} \\ M_{13} & M_{11} & M_{12} \\ M_{23} & M_{12} & M_{22} \end{pmatrix} + \begin{pmatrix} M_{22} & M_{23} & M_{12} \\ M_{23} & M_{33} & M_{13} \\ M_{12} & M_{13} & M_{11} \end{pmatrix} \right\} \begin{pmatrix} \hat{I}_a \\ \hat{I}_b \\ \hat{I}_c \end{pmatrix}$$

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Let’s mark

$$M = \frac{1}{3}(M_{11} + M_{22} + M_{33})$$

$$M' = \frac{1}{3}(M_{12} + M_{13} + M_{23})$$

Then

$$\begin{pmatrix} \Delta\hat{U}_a \\ \Delta\hat{U}_b \\ \Delta\hat{U}_c \end{pmatrix} = j\omega \begin{pmatrix} M & M' & M' \\ M' & M & M' \\ M' & M' & M \end{pmatrix} \begin{pmatrix} \hat{I}_a \\ \hat{a}^2\hat{I}_a \\ \hat{a}\hat{I}_a \end{pmatrix}$$

Phase operational inductances at transposed and symmetrically loaded power line are equal and real:

$$L_a = M + \hat{a}^2 M' + \hat{a} M'$$

$$L_a = L_b = L_c = M - M'$$

After substitution

$$M = 0{,}46\log\frac{D_g}{\xi r} \quad (\mathrm{mH/km})$$

$$M' = 0{,}46\log\frac{D_g}{d} \quad (\mathrm{mH/km})$$

mean geometrical distance

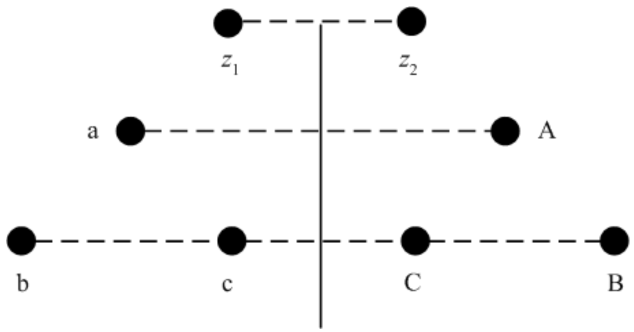
$$d = \sqrt[3]{d_{12}d_{13}d_{23}}$$

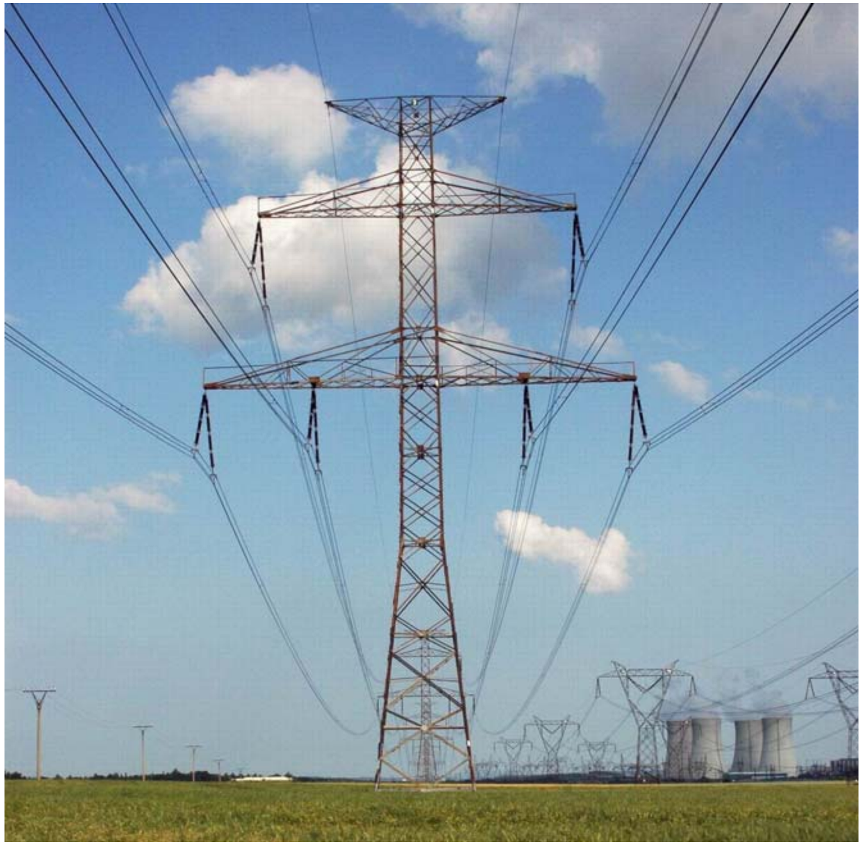
Finally

$$L_1 = L_a = L_b = L_c = 0{,}46\log\frac{d}{\xi r} \quad (\mathrm{mH/km})$$

$$\hat{Z}_1 = \hat{Z} - \hat{Z}' = R_1 + j0{,}1445\log\frac{d}{\xi \cdot r} \quad \left(\frac{\Omega}{\mathrm{km}}\right)$$

Double power lines with two ground wires





$$
\begin{pmatrix} \Delta\hat{U}_a \\ \Delta\hat{U}_b \\ \Delta\hat{U}_c \\ \Delta\hat{U}_A \\ \Delta\hat{U}_B \\ \Delta\hat{U}_C \\ \Delta\hat{U}_{z1} \\ \Delta\hat{U}_{z2} \end{pmatrix} =
\begin{pmatrix}
\hat{Z}_{aa} & \hat{Z}_{ab} & \hat{Z}_{ac} & \hat{Z}_{aA} & \hat{Z}_{aB} & \hat{Z}_{aC} & \hat{Z}_{az1} & \hat{Z}_{az2} \\
\hat{Z}_{ba} & \hat{Z}_{bb} & \hat{Z}_{bc} & \hat{Z}_{bA} & \hat{Z}_{bB} & \hat{Z}_{bC} & \hat{Z}_{bz1} & \hat{Z}_{bz2} \\
\hat{Z}_{ca} & \hat{Z}_{cb} & \hat{Z}_{cc} & \hat{Z}_{cA} & \hat{Z}_{cB} & \hat{Z}_{cC} & \hat{Z}_{cz1} & \hat{Z}_{cz2} \\
\hat{Z}_{Aa} & \hat{Z}_{Ab} & \hat{Z}_{Ac} & \hat{Z}_{AA} & \hat{Z}_{AB} & \hat{Z}_{AC} & \hat{Z}_{Az1} & \hat{Z}_{Az2} \\
\hat{Z}_{Ba} & \hat{Z}_{Bb} & \hat{Z}_{Bc} & \hat{Z}_{BA} & \hat{Z}_{BB} & \hat{Z}_{BC} & \hat{Z}_{Bz1} & \hat{Z}_{Bz2} \\
\hat{Z}_{Ca} & \hat{Z}_{Cb} & \hat{Z}_{Cc} & \hat{Z}_{CA} & \hat{Z}_{CB} & \hat{Z}_{CC} & \hat{Z}_{Cz1} & \hat{Z}_{Cz2} \\
\hat{Z}_{z1a} & \hat{Z}_{z1b} & \hat{Z}_{z1c} & \hat{Z}_{z1A} & \hat{Z}_{z1B} & \hat{Z}_{z1C} & \hat{Z}_{z1z1} & \hat{Z}_{z1z2} \\
\hat{Z}_{z2a} & \hat{Z}_{z2b} & \hat{Z}_{z2c} & \hat{Z}_{z2A} & \hat{Z}_{z2B} & \hat{Z}_{z2C} & \hat{Z}_{z2z1} & \hat{Z}_{z2z2}
\end{pmatrix}
\begin{pmatrix} \hat{I}_a \\ \hat{I}_b \\ \hat{I}_c \\ \hat{I}_A \\ \hat{I}_B \\ \hat{I}_C \\ \hat{I}_{z1} \\ \hat{I}_{z2} \end{pmatrix}
$$

After modifications it can be written (assumption of continuous grounding of ground wires)

$$
\left(\Delta\hat{U}_v\right) = \left(\hat{Z}_{vv}\right)\left(\hat{I}_v\right) + \left(\hat{Z}_{vV}\right)\left(\hat{I}_V\right) + \left(\hat{Z}_{vz}\right)\left(\hat{I}_z\right)
$$

$$
\left(\Delta\hat{U}_V\right) = \left(\hat{Z}_{Vv}\right)\left(\hat{I}_v\right) + \left(\hat{Z}_{VV}\right)\left(\hat{I}_V\right) + \left(\hat{Z}_{Vz}\right)\left(\hat{I}_z\right)
$$

$$
0 = \left(\Delta\hat{U}_z\right) = \left(\hat{Z}_{zv}\right)\left(\hat{I}_v\right) + \left(\hat{Z}_{zV}\right)\left(\hat{I}_V\right) + \left(\hat{Z}_{zz}\right)\left(\hat{I}_z\right)
$$

$\Rightarrow$ currents in ground wires

$$\left(\hat{I}_{z}\right) = -\left(\hat{Z}_{zz}\right)^{-1}\left[\left(\hat{Z}_{zv}\right)\left(\hat{I}_{v}\right) + \left(\hat{Z}_{zV}\right)\left(\hat{I}_{V}\right)\right]$$

For modified power line

$$\left(\Delta\hat{U}_{v}\right) = \left[\left(\hat{Z}_{vv}\right) - \left(\hat{Z}_{vz}\right)\left(\hat{Z}_{zz}\right)^{-1}\left(\hat{Z}_{zv}\right)\right]\left(\hat{I}_{v}\right) + \left[\left(\hat{Z}_{vV}\right) - \left(\hat{Z}_{vz}\right)\left(\hat{Z}_{zz}\right)^{-1}\left(\hat{Z}_{zV}\right)\right]\left(\hat{I}_{V}\right)$$

$$\left(\Delta\hat{U}_{V}\right) = \left[\left(\hat{Z}_{Vv}\right) - \left(\hat{Z}_{Vz}\right)\left(\hat{Z}_{zz}\right)^{-1}\left(\hat{Z}_{zv}\right)\right]\left(\hat{I}_{v}\right) + \left[\left(\hat{Z}_{VV}\right) - \left(\hat{Z}_{Vz}\right)\left(\hat{Z}_{zz}\right)^{-1}\left(\hat{Z}_{zV}\right)\right]\left(\hat{I}_{V}\right)$$

- it is an imaginary power line without ground wires which would act as a real power line with ground wires
- for impedances transfer to symmetrical components system

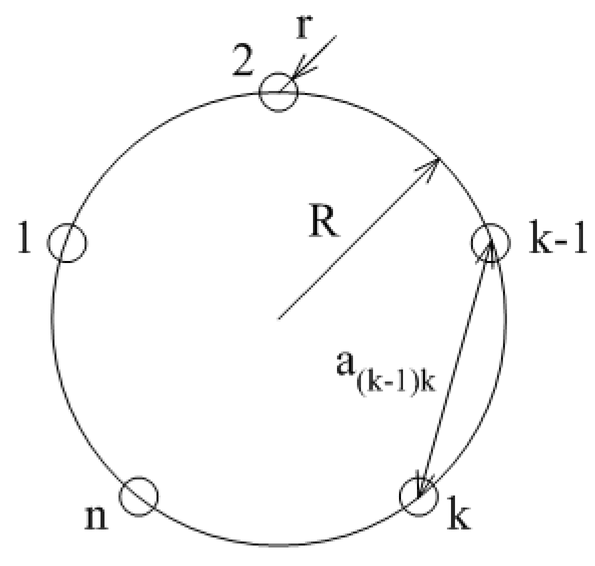
Power line with bundle conductors

Bundle conductor

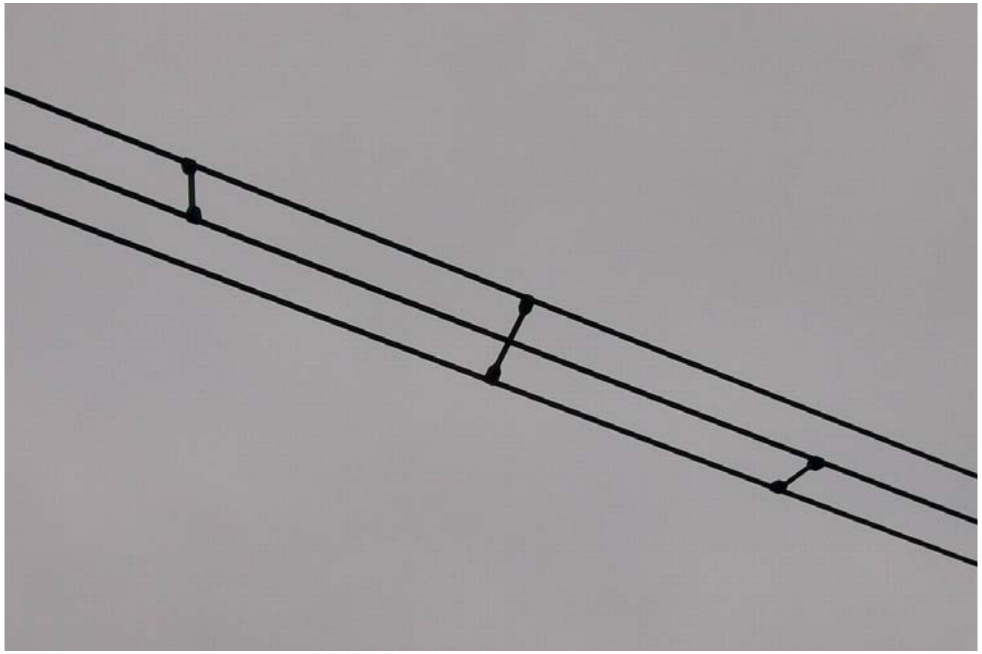
- each phase composed of *n* partial conductors connected in parallel
- arranged in regular *n*-polygon
- increases initial corona voltage
- from voltage 400 kV higher

U (kV)	400	750	1150	1800
n	3	4	8	16

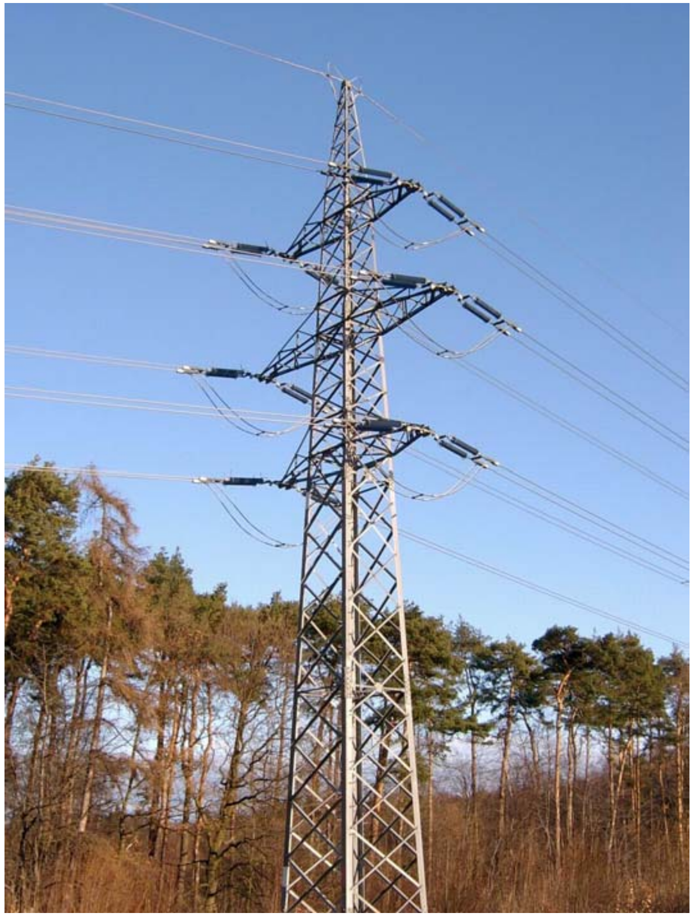
- $a_{400kV} = 40$ cm

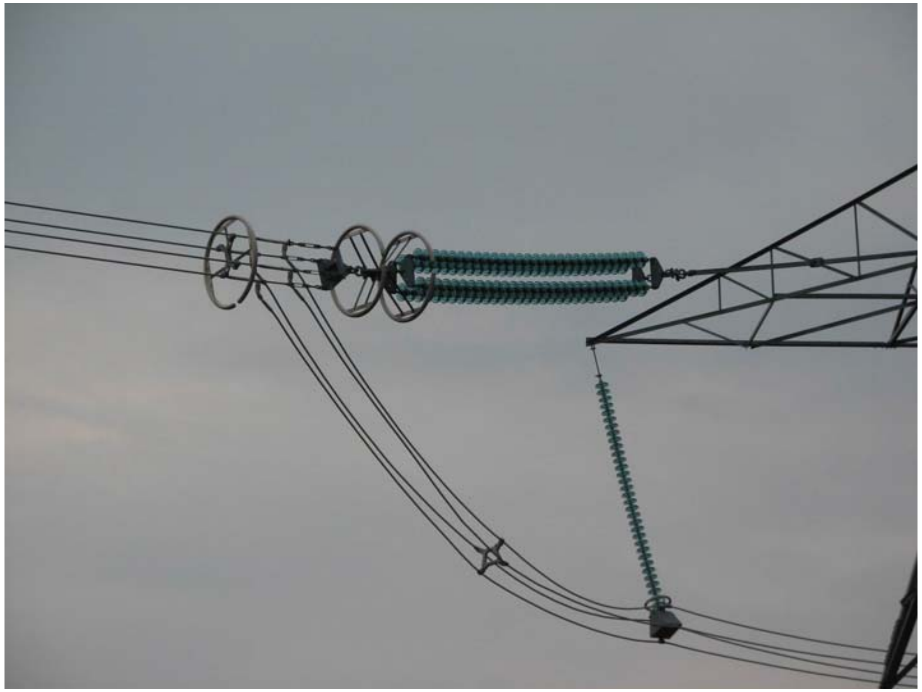


Czech Republic: 400 kV – triple-bundle conductor



Kladno (CR) 110 kV (2), Canada 750 kV (4), China 1000 kV (8)





UHV conductor

Operational inductance

$$L_1 = 0{,}46 \log \frac{d}{\xi_e r_e} \quad (\mathrm{mH/km})$$

equivalent bundle radius

$$r_e = R \sqrt[n]{r \frac{n}{R}}$$

equivalent coefficient

$$\xi_e = \sqrt[n]{\xi}$$

→ bundle conductor decreases L, R (conductors in parallel), increases C

22 kV	X ~ 0,35 Ω/km
110 kV	X ~ 0,35÷0,4 Ω/km
220 kV	X ~ 0,4 Ω/km
400 kV	X ~ 0,3 Ω/km
750 kV	X ~ 0,25 Ω/km

Zero sequence reactance

- Fe grounding wires - $X_0 \sim (3,5 \div 5,5) X_1$
- ACSR grounding wires - $X_0 \sim (2 \div 4) X_1$

Conductance

It causes active power losses by the conductance to the ground (through insulators, corona – dominant at overhead power lines). It depends on voltage, climatic conditions (p, T, humidity), conductors. Less dependant on loading.

Calculation from corona losses

$$P_S = 3U_f I_S = 3G_1 U_f^2 = G_1 U^2 \quad \left(W \cdot km^{-1}\right)$$

$$G_1 = \frac{P_S}{U^2} \quad (S/km;\ W/km,\ V)$$

$$G_1 \approx 10^{-8}\ S \cdot km^{-1} \quad x \quad B_1 \approx 10^{-6}\ S \cdot km^{-1}$$

U (kV)	G_1 (S/km)	U (kV)	G_1 (S/km)
110	$(3,6 \div 5) \cdot 10^{-8}$	750	$(1,3 \div 2,5) \cdot 10^{-8}$
220	$(2,5 \div 3,6) \cdot 10^{-8}$	1150	$(1,0 \div 2) \cdot 10^{-8}$
400	$(1,4 \div 2) \cdot 10^{-8}$		