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Electric power lines

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

ZÁPADOČESKÁ UNIVERZITA V PLZNI

Electric power lines

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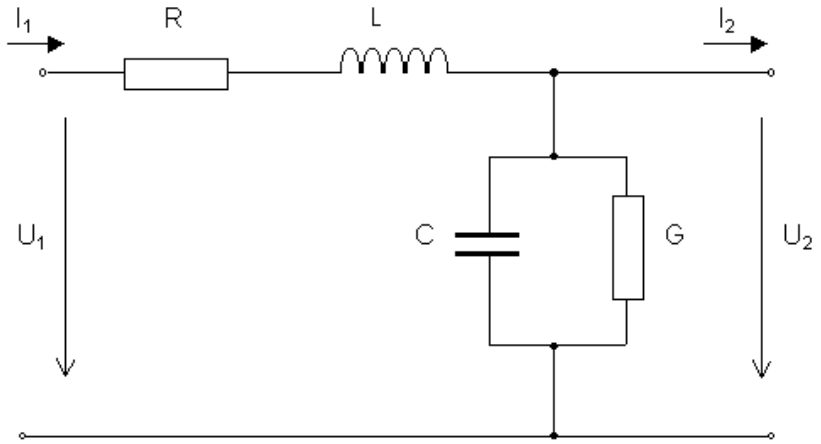
MINISTRY OF EDUCATION, YOUTH AND SPORTS

Parameters – equivalent circuits

Pasive power line parameters:

- resistance R [Ω],
- inductance L [H],
- capacity C [F],
- leakage conductivity G [S].

Γ - model



Line series impedance

$$\overline{Z} = R + j\omega L = R + jX \qquad [\Omega]$$

Line shunt admittance

$$\overline{Y} = G + j\,\omega C = G + j\,B \qquad [S]$$

Characteristic (surge/wave) impedance

ideal power line R=0 and G = 0

$$Z_V = \sqrt{\frac{\overline{Z}}{\overline{Y}}} = \sqrt{\frac{R + j\,\omega L}{G + j\,\omega C}}$$

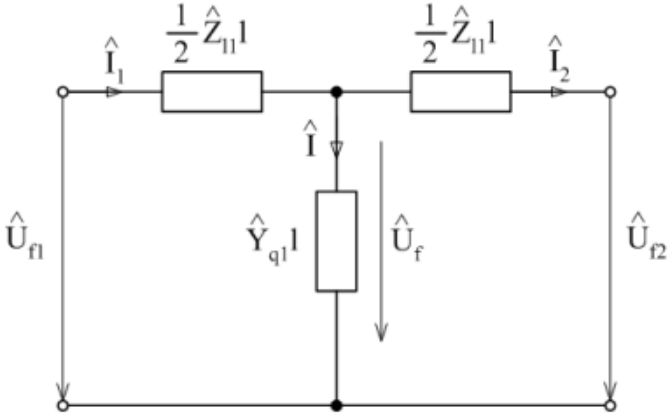
$$Z_V = \sqrt{\frac{L}{C}}$$

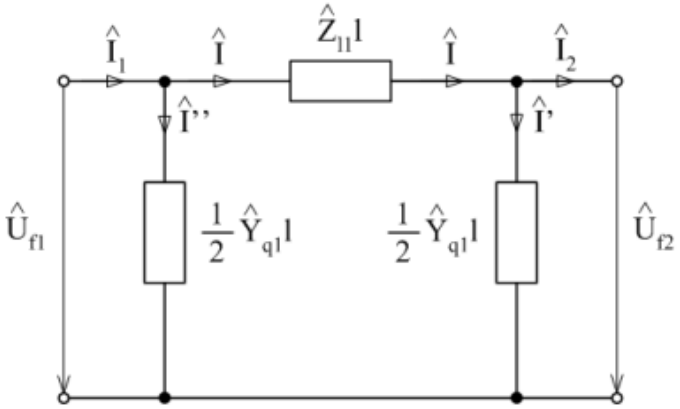
overhead lines $Z_V = 250 \div 400\ \Omega$

cables $Z_V = 35 \div 70\ \Omega$

Parameters – equivalent circuits

Other power line model /equivalent circuits
T- model a Π-model





Models for medium length lines (lines below 250 km in length)

Model simplification:

- DC lines – only R
- AC lines - LV and MV – R and X (X can be neglected for LV cables)
- AC lines - HV and EHV – all parametres, but for simple calculation and schort-circuit calculation – only R and X

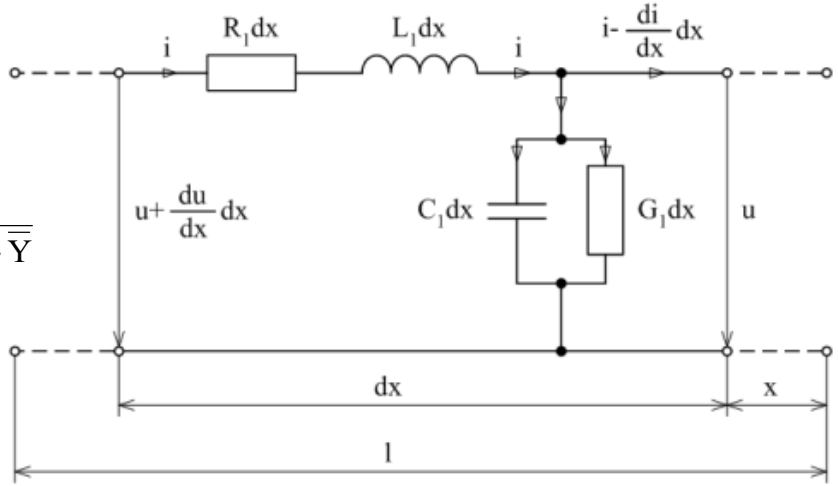
In computer simulations, Γ - model and Π-model are preferred – lower number of nodes, lower request for computation algorithms and time

Parameters – equivalent circuits

Lines above 250 km in length – long line model with distributed parameters

Characteristic (surge/wave) impedance

$$\bar{Z}_V = \sqrt{\frac{\bar{Z}_1}{\bar{Y}_1}} = \sqrt{\frac{R_1 + j\,\omega\,L_1}{G_1 + j\,\omega\,C_1}}$$



Propagation constant $\bar{\gamma} = \beta + j\alpha = \sqrt{(R + jX)\cdot(G + jB)} = \sqrt{\bar{Z}\cdot\bar{Y}}$

β ... attenuation constant

α ... phase constant

$$\hat{U}_{f1} = \hat{U}_{f2}\cosh\hat{\gamma}l + \hat{Z}_v\hat{I}_2\sinh\hat{\gamma}l$$

$$\hat{I}_1 = \frac{\hat{U}_{f2}}{\hat{Z}_v}\sinh\hat{\gamma}l + \hat{I}_2\cosh\hat{\gamma}l$$

A, B, C, D – Blondel's constants

Sending end values

$$\begin{pmatrix}\hat{U}_{f1}\\ \hat{I}_1\end{pmatrix} = \begin{pmatrix}\hat{A} & \hat{B}\\ \hat{C} & \hat{D}\end{pmatrix}\begin{pmatrix}\hat{U}_{f2}\\ \hat{I}_2\end{pmatrix}$$

Receiving end values

$$\begin{pmatrix}\hat{U}_{f2}\\ \hat{I}_2\end{pmatrix} = \begin{pmatrix}\hat{D} & -\hat{B}\\ -\hat{C} & \hat{A}\end{pmatrix}\begin{pmatrix}\hat{U}_{f1}\\ \hat{I}_1\end{pmatrix}$$

Characteristic (surge/wave) impedance

Characteristic (surge/wave) impedance

- Doe not depend on length of the power line, but it depend on power line design (conductor cross/section, conductor distance and height)

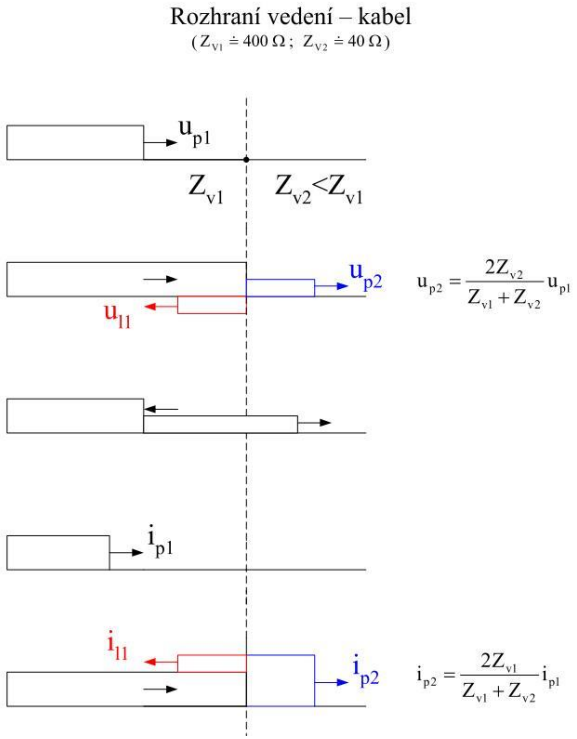
$$Z_V = \sqrt{\frac{\bar{\bar{Z}}}{\bar{\bar{Y}}}} = \sqrt{\frac{R + j\,\omega\,L}{G + j\,\omega\,C}}$$

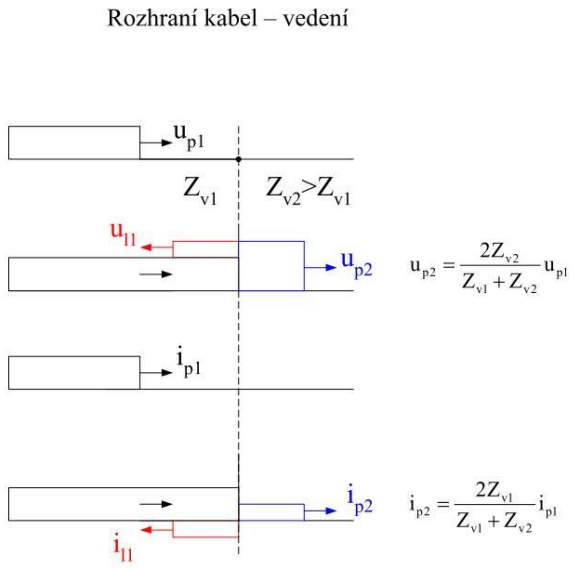
Ideal power line R=0 and G = 0

$$Z_V = \sqrt{\frac{L}{C}}$$

Overhead lines $Z_V = 250 \div 400\ \Omega$

Cables $Z_V = 35 \div 70\ \Omega$





Cable - overhead line boundary - reflected waves U and I – occurrence of overvoltages

Surge impedance loading – natural load

- Line is terminated with an impedance equal to its characteristic impedance $\bar{Z}_v \Rightarrow$ no reflected waves U and I in the line terminal
- Terminal voltage (voltage at receiving end of the line)

$$\bar{U}_{f2} = \bar{Z}_v \cdot \bar{I}_2$$

- Surge line loading – so called **natural load**

$$\hat{S}_{p2} = 3\hat{U}_{f2}\hat{I}_2^* = 3\hat{U}_{f2}\left(\frac{\hat{U}_{f2}}{\hat{Z}_v}\right)^* = \frac{U_2^2}{\hat{Z}_v^*}$$

- For lossless line (R=0 and G=0), natural load is purely active

$$P_{př} = S_{př} = 3 \cdot U_f \cdot I = 3 \cdot U_f \cdot \frac{U_f}{Z_v} = 3 \cdot \frac{U_f^2}{Z_v} = \frac{U_n^2}{Z_v}$$

Reactive power absorbed by the line is equal to the reactive power generated, self-compensation effect

$$\frac{1}{2} C \cdot U^2 = \frac{1}{2} L \cdot I^2$$

$$\left(\frac{U}{I}\right)^2 = Z_v^2 = \frac{L}{C} \Rightarrow Z_v = \sqrt{\frac{L}{C}}$$

Surge impedance loading – natural load

For lossless line (R=0 and G=0)
- voltage and current at any point along the line are constant in magnitude and are equal to their sending ends values $U_{1f} = U_{2f}$ (only phase shift of vectors)
- power line efficiency is equal to 1, i.e. no losses on the line

Natural load = the most optimal loading

$$P_{př} = \frac{U_n^2}{Z_v} = U_n^2 \cdot \sqrt{\frac{C}{L}}$$

Overhead lines: $Z_v \approx 250$ až 400 Ω
Cables: $Z_v \approx 35$ až 70 Ω
- cca 10x higher then for overhead lines ⇒ higher transmission capacity of cables

voltage	22 kV	110 kV	220 kV	400 kV
cables	12 MW	300 MW	1 200 MW	---------
Overhead lines	1,2 MW	30 MW	120 až 160 MW	400 až 580 MW

Example: power line 400 kV
L = 1 mH/km
C = 11,7 nF/km

$$Z_v = \sqrt{\frac{L}{C}} = \sqrt{\frac{1 \cdot 10^{-3}}{11,7 \cdot 10^{-9}}} = 292\ \Omega$$

$$S_{př} = \frac{U_n^2}{Z_v} = \frac{400^2}{292} = 548\ MVA$$

Surge impedance loading – natural load

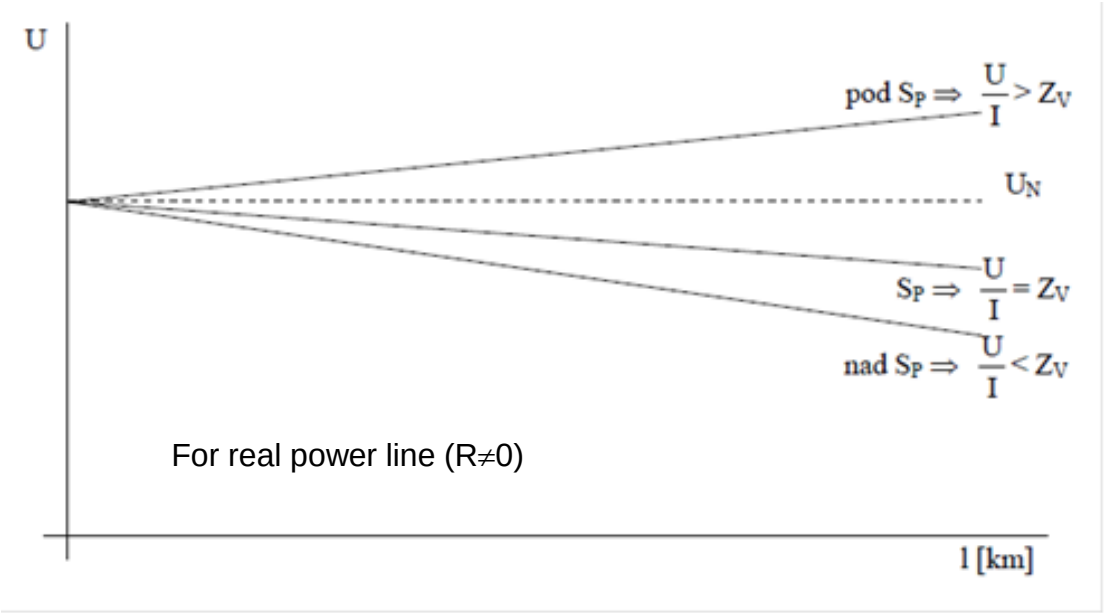
Voltage profile along a line:

$P > P_{př} \rightarrow U_1 > U_2$

$P < P_{př} \rightarrow U_1 < U_2$

$P = P_{př} \rightarrow U_1 = U_2$

$$P_{př} = \frac{U_n^2}{Z_v} = U_n^2 \cdot \sqrt{\frac{C}{L}}$$



Real natural load is complex power.

Surge impedance loading – natural load

Enhancement of natural load Ppř

- Higher voltage
- Reduction of surge impedance (tube conductors, bundle conductors, higher diameter of conductor,…)

Power line loaded by natural load Ppř:

- Lower power losses
- The best transmission stability
- Medium length lines (below 250 km): line loading > Ppř due to higher utilization of conductor cross-section
- Long length lines: line loading is similar to natural load Ppř → lower power losses, better transmission stability

Open-circuited line - Ferranti effect

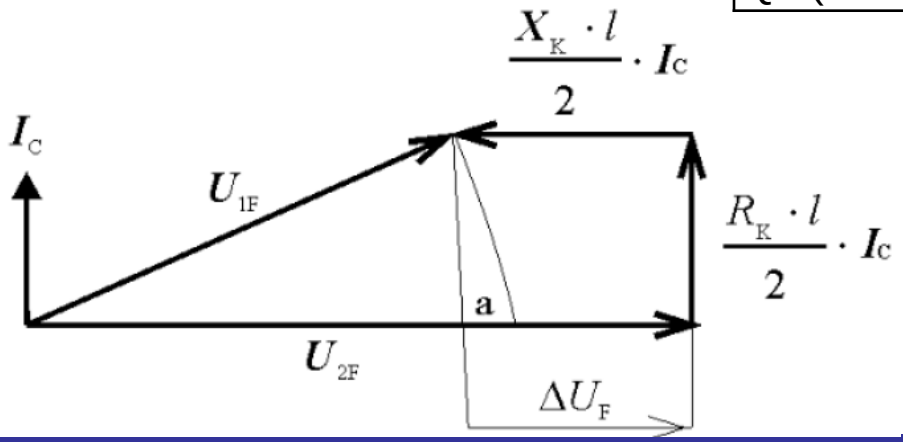
- line loading is much lower than natural load
- receiving end voltage is higher than sending end voltage (open-circuit line, lowly loaded line)
- open-circuit EHV and HV lines are loaded by huge charging current, which value positively correlates with line capacitance

$$I_c = \omega \cdot C \cdot U_f$$

- line is loaded by so called **charging power**

$$Q_c = \sqrt{3} \cdot U_n \cdot I_c = \omega \cdot C \cdot U_n^2$$

Vector diagram:



voltage	22 kV	110 kV	220 kV	400 kV
Qc (kVAr/km)	1,4	32	129	610

Open-circuited line - Ferranti effect

Example:

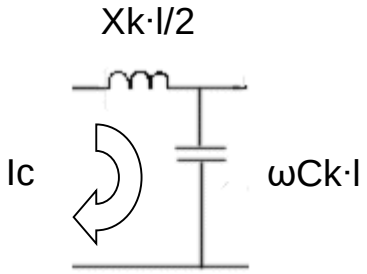
How does receiving end voltage increase if it is suddenly unloaded?
400 kV power line has length 300 km.
C_k = 11,7 nF/km; X_k = 0,314 Ω/km; R_k – neglected; G_k – neglected

The line is modeled as line with distributed parameters – Γ - models
Sending end current is charging current Ic, receiving end current is zero – open-circuited line

Uniformly distributed loading → half-length model with current Ic

$$\Delta U \approx U_{2f} - U_{1f} \approx I_c \cdot \frac{X}{2} = \frac{1}{2}\omega \cdot C_k \cdot l \cdot U_f \cdot X_k \cdot l =$$

$$= 0,5 \cdot 314 \cdot 11,7 \cdot 10^{-9} \cdot 300 \cdot \frac{400 \cdot 10^3}{\sqrt{3}} \cdot 0,314 \cdot 300 = \frac{21}{\sqrt{3}}\, kV$$



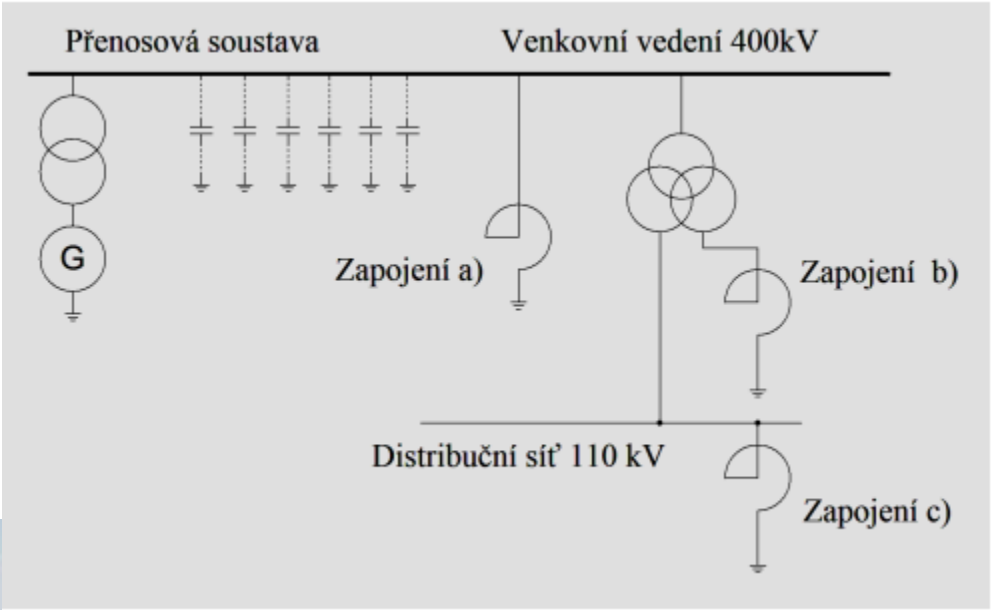
$$U_2 = U_1 + \Delta U = 400 + 21 = 421\, kV \Rightarrow$$ Overvoltage at receiving end

Supply voltage in substations is higher than Un → much higher overvoltage at receiving end.

Open-circuited line - Ferranti effect

Decompensation of charging power

- Shunt reactors/coils



Shunt reactors 90 MVAr, 10,5kV



Power transmission capability

Power handling ability of a line is limited by the thermal loading limit and the stability limit.

Thermal loading limit – the increase in conductor temperature stretches the conductors → increase in sag between line towers → higher temperature - irreversible stretching

Thermal limit is specified by the current-carrying capacity of the conductor (ampacity) $I_{thermal}$

Thermal loading limit

$$S_{thermal} = \sqrt{3} \cdot U_n \cdot I_{thermal}$$

Real power transferred over a lossless line

$$P = \frac{U_1 \cdot U_2}{X_v} \cdot \sin \vartheta$$

U_1, U_2 – sending end and receiving end voltages
Xv – line reactance
ϑ – power angle = phase shift between vectors of sending end and receiving end voltages

Increase in line loading → increase in ϑ

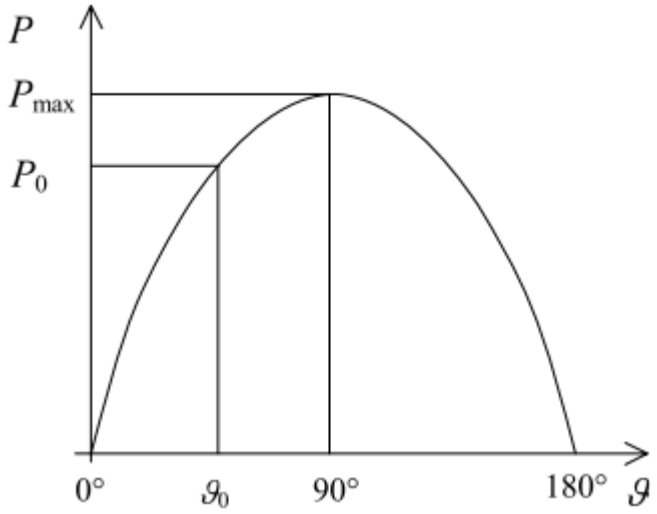
Power transmission capability

Stability limit

Maximum transmitted power under stable steady-state conditions

$\vartheta = 90°$ - steady-state stability limit

$$P = \frac{U_n^2}{X_v} \cdot \sin \vartheta$$



To assure an adequate stability margin, practical operating load angle is usually limited to 30° to 45°

Overhead lines ϑ ~ 6°per 100 km → critical length of line is about 500 km

Overhead power lines

Overhead power lines

- 400 kV, 220 kV, 110 kV networks, some 22 kV and 35 kV networks, LV networks – rural areas

Properties:

- they contain : towers/pylons/poles, insulators, conductors and other accessories (lightning protection gaps, dampers, bird protections …)
- inductive X_L (L) is higher in comparison to cables
- capacitive susceptance B (C) is lower in comparison to cables
- voltage drop ΔU and reactive losses ΔQ are higher due to higher reactance
- more failures, usually fortuitous faults due to lightning, storms, ice coating
  - 90% faults are fortuitous – autoreclosing
    - 90% faults are single-phase-to ground
- easy to locate faults

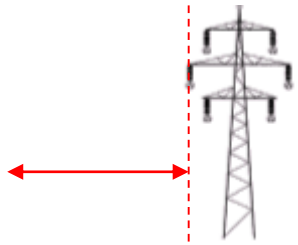
Overhead power lines

Properties:

- Less expensive for longer distances
- Maintenance intensive
- High level of expertise and specialized equipment needed for installation
- Not environment-friendly
- Bulky

Protective zone

400 kV	20 m
220kV	15 m
110 kV	12 m
22 kV a 35 kV	7 m

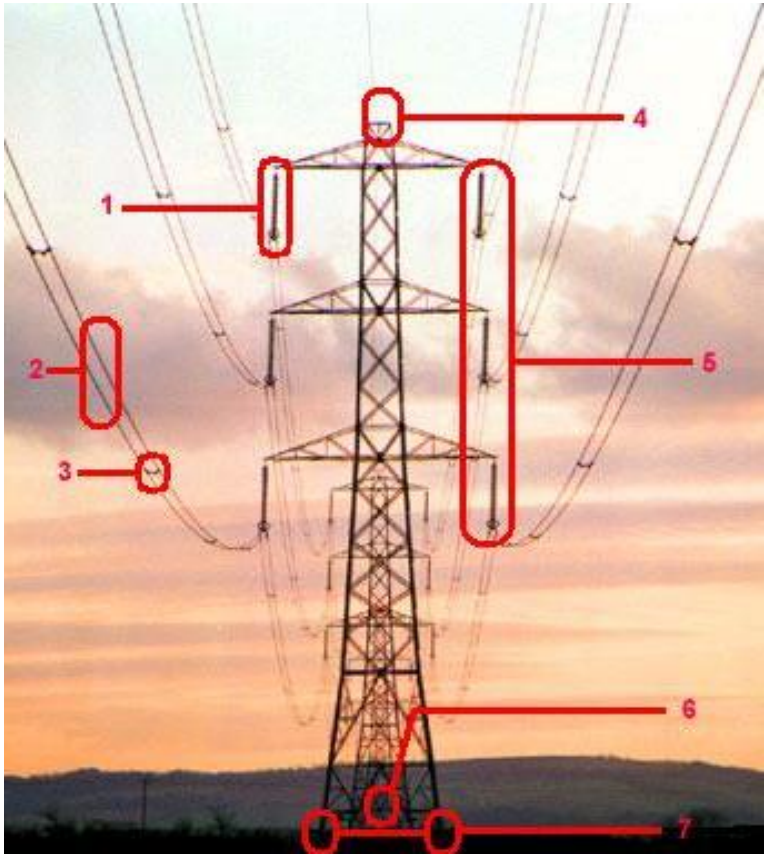




Overhead power lines

Double-circuit overhead line

1 … Insulator
2 … Bundled conductor - bundle of two conductors (some lines have 3 or 4)
3 … Spacer to hold the two conductors apart
4 … Earth wire at top of tower or pylon
5 … Three bundles on one side of the tower make up one electrical circuit. Most lines have two circuits, one each side
6 … Identity plate
7 … Tower foundantion



Conductors of overhead lines

Conductors
- cooper Cu
- aluminum Al and its alloys (ingredient Mg, Si, Fe)
- steel
- for special purposes: bronze etc.

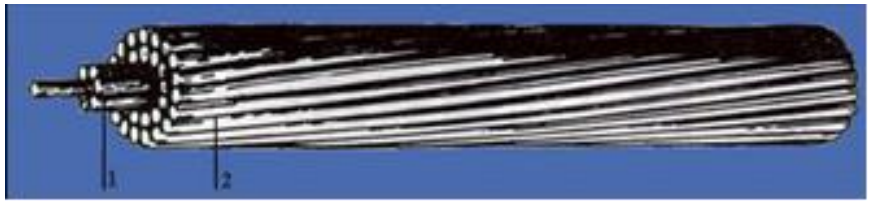
Requirements:
- Low specific weight
- Low conductor cross-section reducing wind impact and corona losses
- High mechanical/breaking strength
- resistance to chemical impacts and temperature changes
- Vibration
- Low price

$\Rightarrow$ Requirements are contradictory.

Conductors of overhead lines

wires − cooper, aluminum, steel

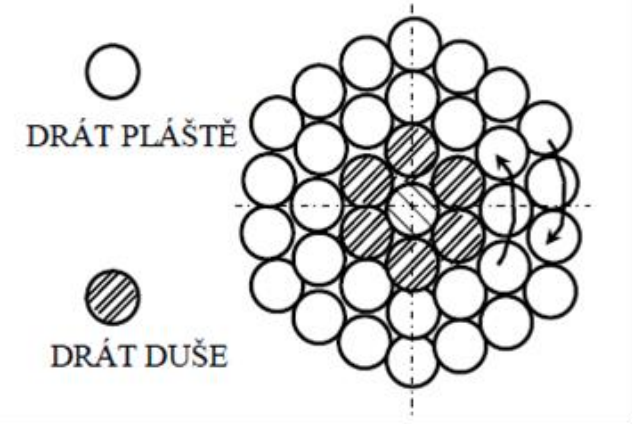
steel reinforced wires
1 – steel core
2 – Al conductor



Aluminum conductor steel reinforced (ACSR) – so called AlFe wires

steel (Fe) - mechanical strength
AlFe 6 240 : 240 … Al cross-section [mm^2]
40 mm^2 Fe cross-section
6 … rate Al / Fe
mathematical cross-section 240 + 40 = 280 mm^2

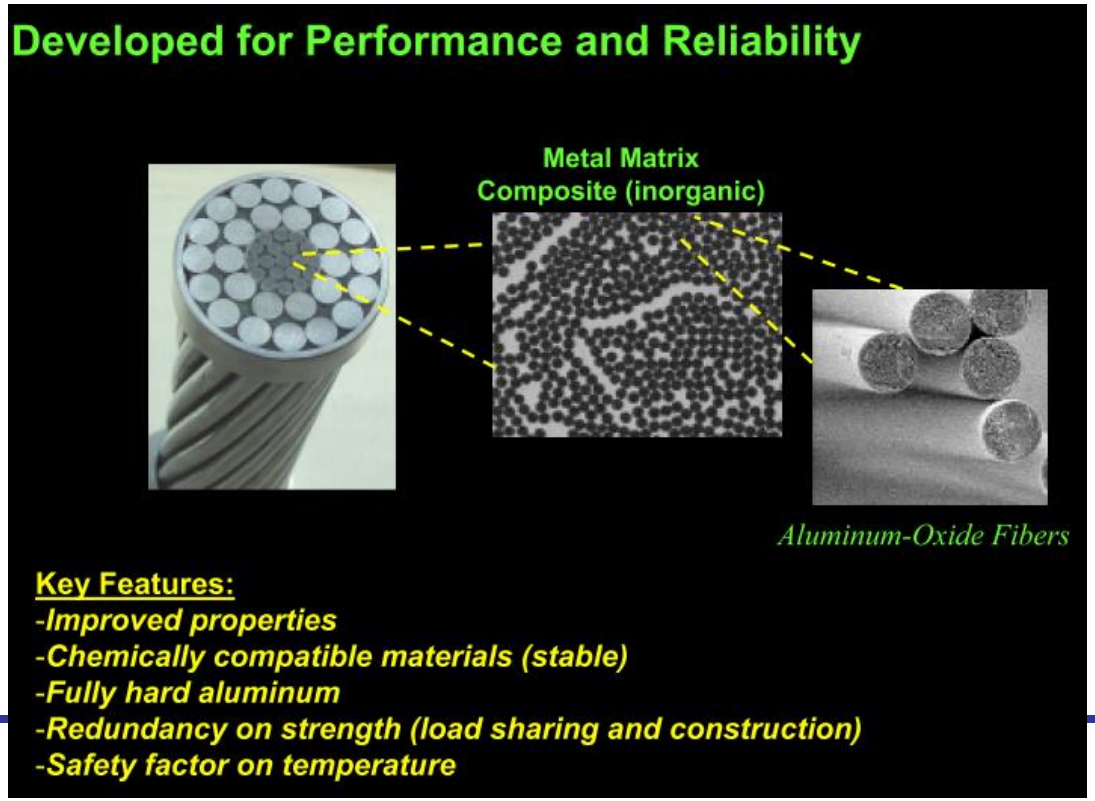
AlFe 4 – higher mechanical strength



Conductors of overhead lines

Aluminum Conductor Composite Reinforced (ACCR)

- 2x to 3x gain in ampacity - without tower and insulator replacement
- Weight of composite core (aluminum oxide) is half in comparison to steel core, mechanical strength is equal to steel core
- Higher operation temperature (up to 250°C)
- 7x more expensive than ACSR





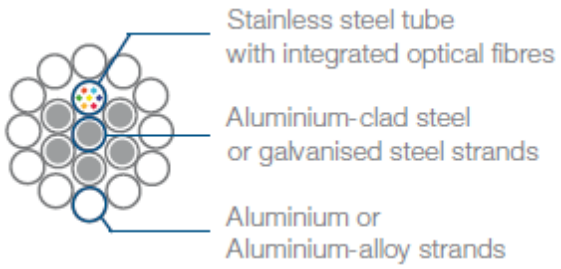
ACSR (AlFe) ACCR

Conductors of overhead lines

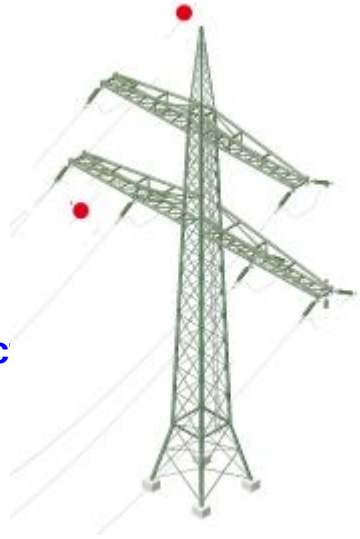


OPGW (Optical Ground Wire)





OPPC (Optical Phase Conduc
Wires with optical data transfer



Conductors of overhead lines

Bundled conductors

- each phase is bundle of several conductors
  bundle of two conductors  three conductors  four conductors 
- EHV or HV power lines
- better mechanical properties
- lower corona losses
- lower L → lower surge impedance → higher natural load → higher transmission capability

Insulated conductors or aerial bundled conductors (ABC)

- MV and LV networks
- insulation from UV resistant PE or PVC
- shorter conductor distance, lower height of towers, better electric parameters
- lower fault occurrence

1-AES



1-AYKYz



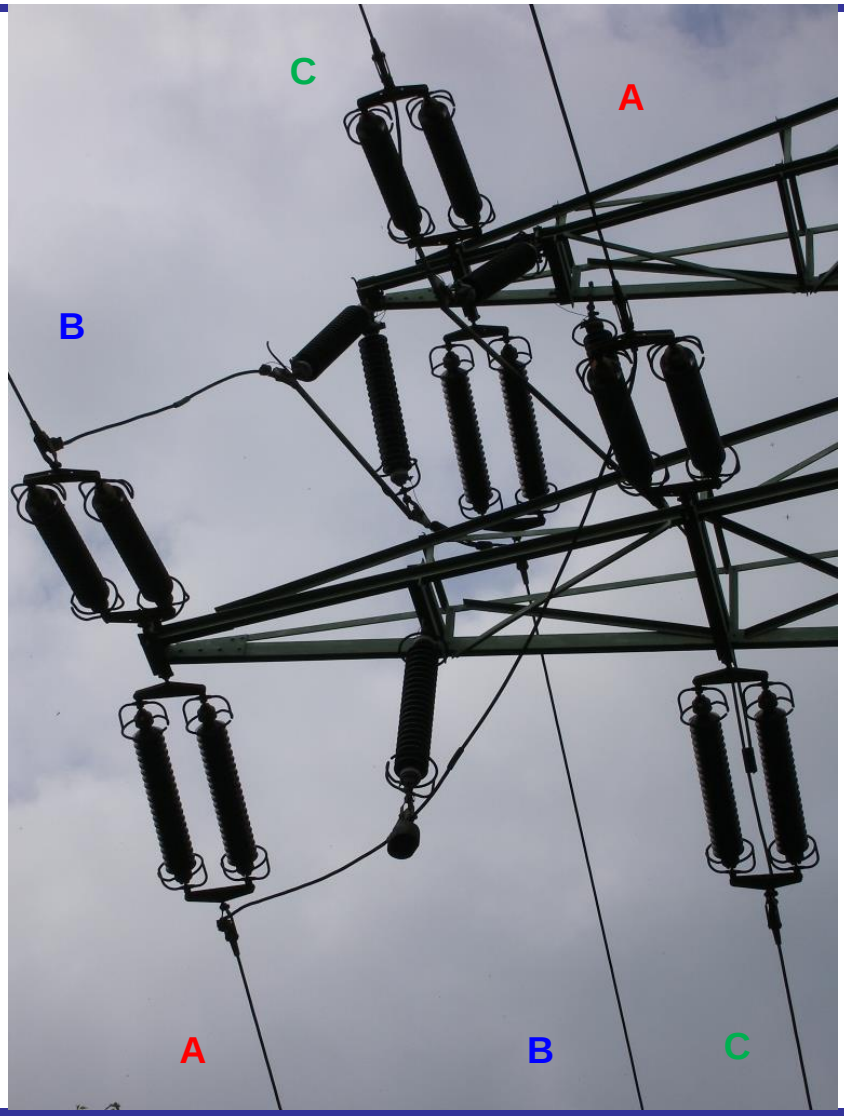
Conductors of overhead lines

Transpose line:

- interchanging the phase conductors



- Better symmetry of phase conductor parameters
- Only for HV and EHV lines
- Full interchanging - 300 km
- Special transposition towers

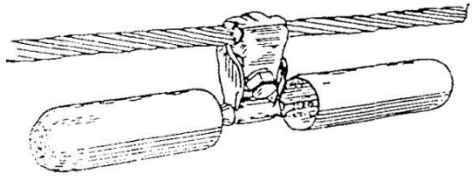


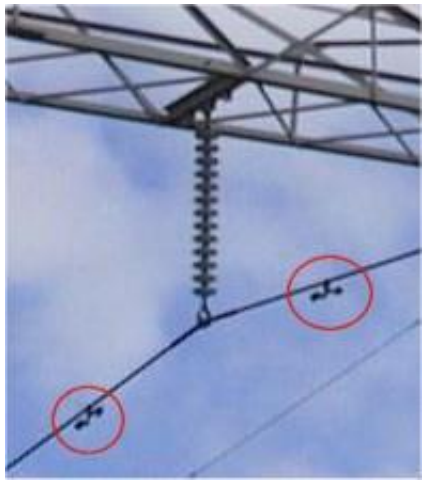
Overhead line accessories

Conductor joints

Spacers for bundle conductors

Vibration dampers
- below cross-section 120 mm^2……3 to 4 kg
- higher cross-sections ….. 8 kg







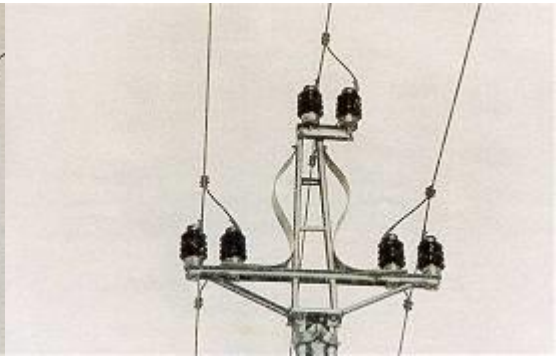
Warning balls (white-red) on conductors
- warning of helicopter and airplane pilots
- warning of birds

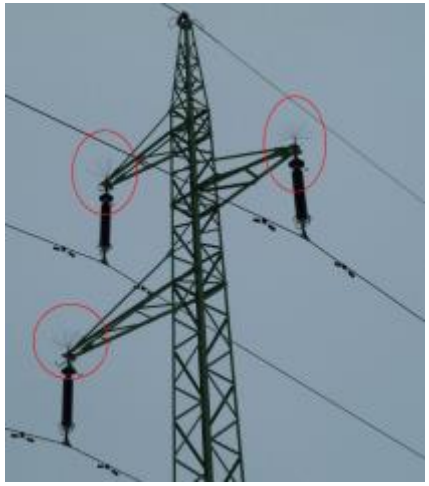
Earth wires
- protection against direct lighting stroke
- is connected to the tower that is grounded
- steel wires, ACSR, OPCC
- 110 kV - 1 earth wire, 220 kV and 400 kV – 2 earth wires)
- MV lines only in length 1 km far from substation

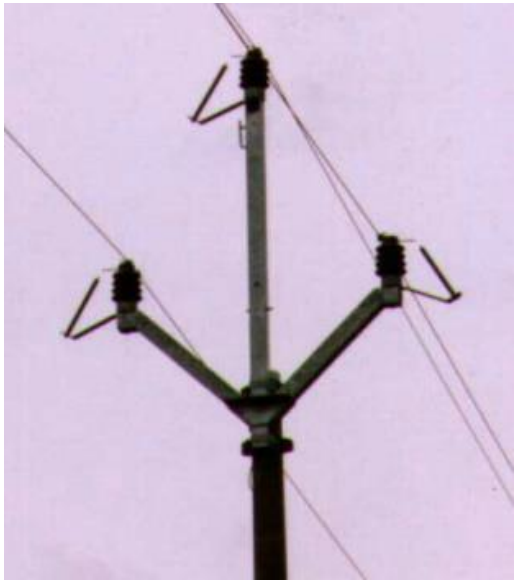


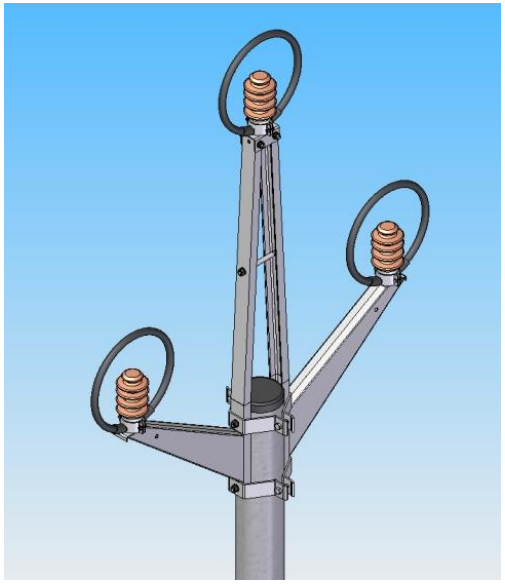
Bird protection













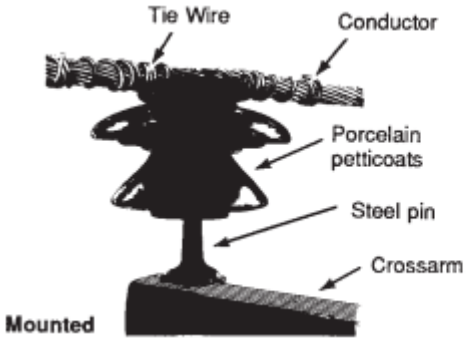


Insulators

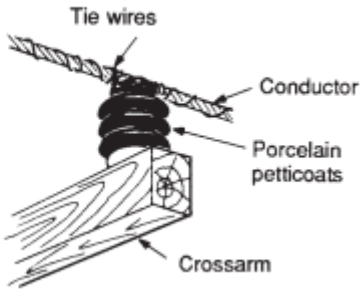
Insulator materials

- porcelain or glass
- polymer

pin-type insulator



post-type insulator



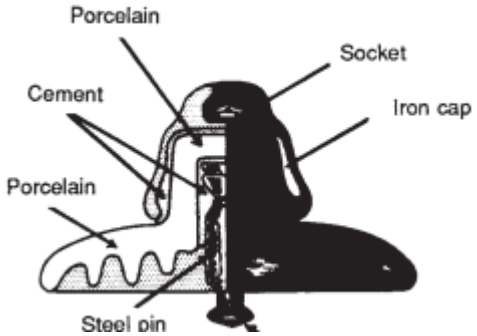
Insulator types

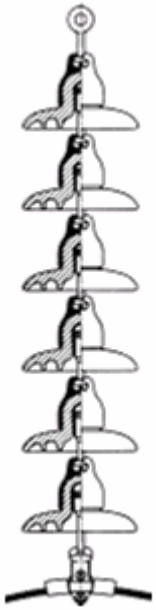
Support insulators - LV and MV lines

Suspension insulators – MV, HV and EHV lines

- long-rod insulators (MV)
- chain (disc-type) insulators







Insulator lenghts:

110 kV – 1,8 m
(7 discs)

220 kV – 2,5 m
(11-13 discs)

400 kV – 3,5 m
(22 discs)

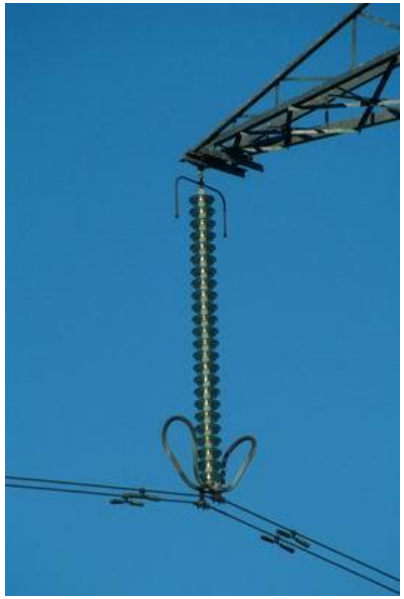
Insulator accessories

Lightning protection gap

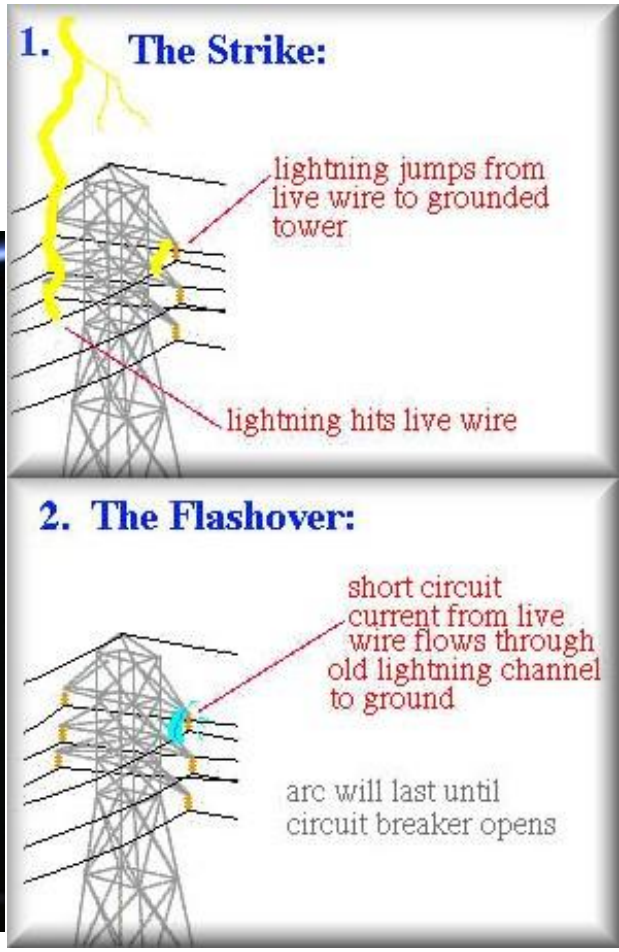
- protection against damage cased by flashover
- flashover → short circuit fault → autoreclosing

Lightning arresters – MV, LV, sometimes HV









Insulator accessories

Grading / corona ring (HV, EHV)

- suppression of corona (exorbitant surface field density not only generate corona discharge, affect line electromagnetic environment, produce audible sound pollution, but also cause strong electric erosion, causing further insulator aging)

- reduction of the potential gradient along the insulator, preventing premature electrical breakdown of insulators (potential distribution along insulator without corona ring is greatly uneven)







Power line poles and towers

Tower types

Straight-line towers

span length: HV, EHV 300 - 500 m (110 kV - 300 m)

Span (guyed) towers

- tower with higher mechanical strength
- strain insulators

span length of span towers

cca 3 km for single conductors

up to 5 km for bundled conductors

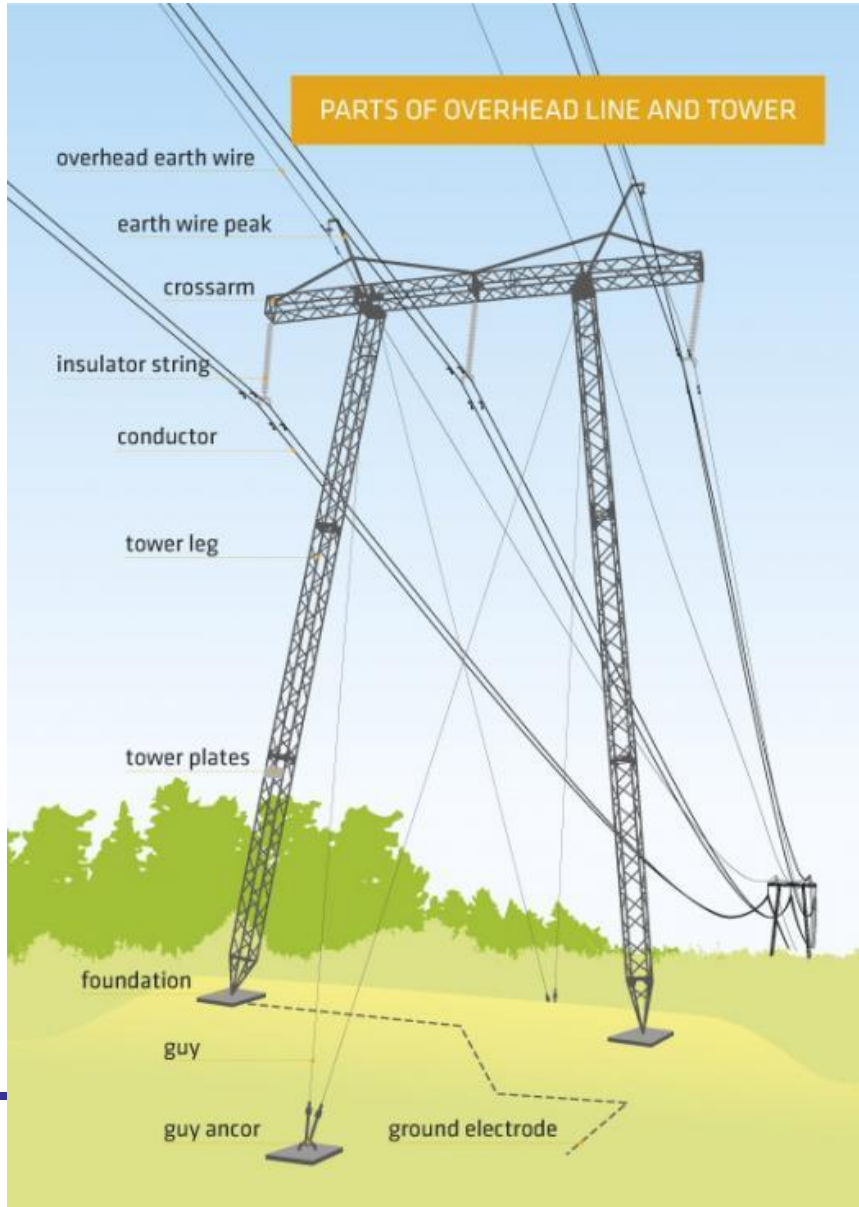
Angle or branch towers

Terminal towers

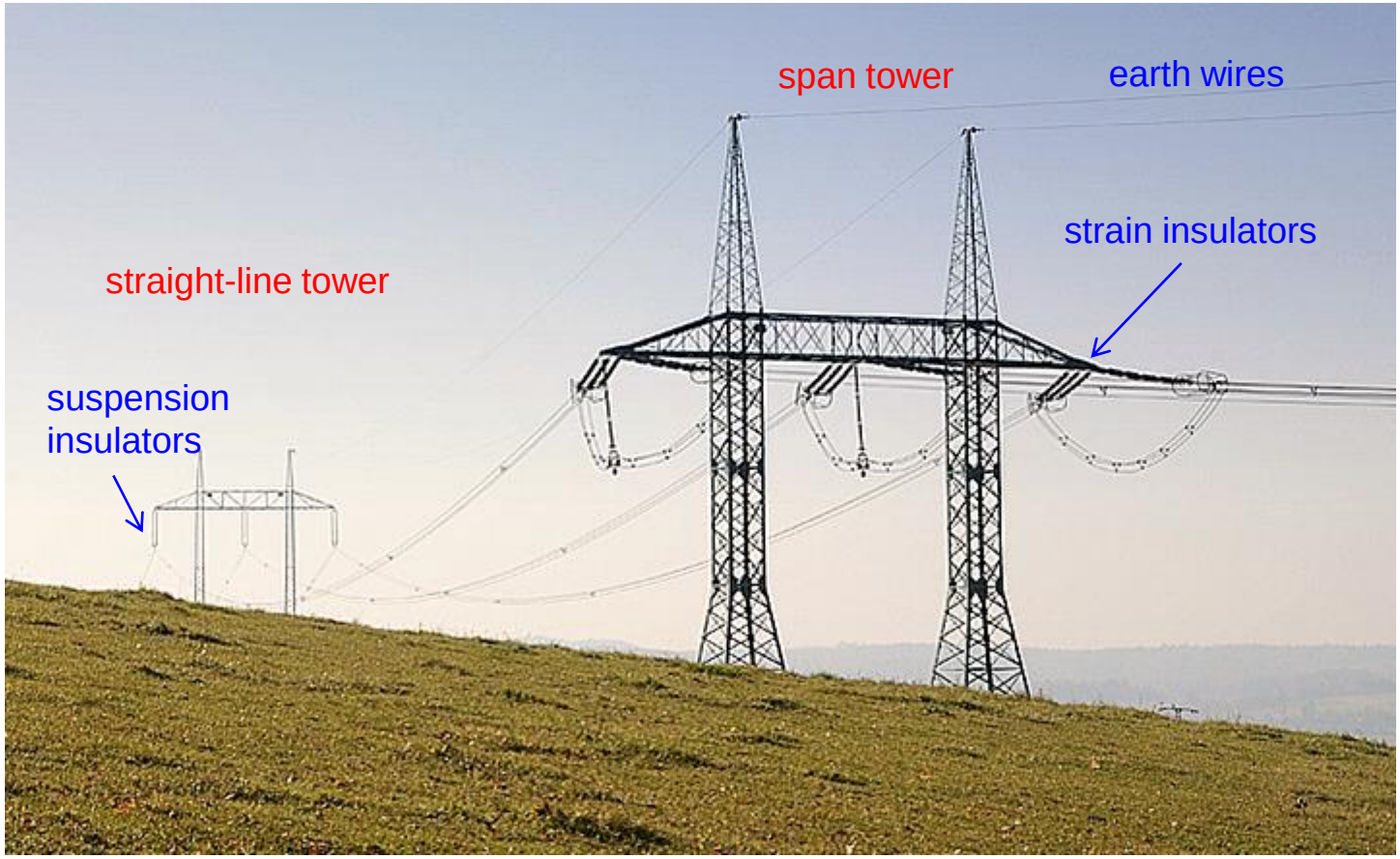
– entering to a substation

The highest san length of tower in the world

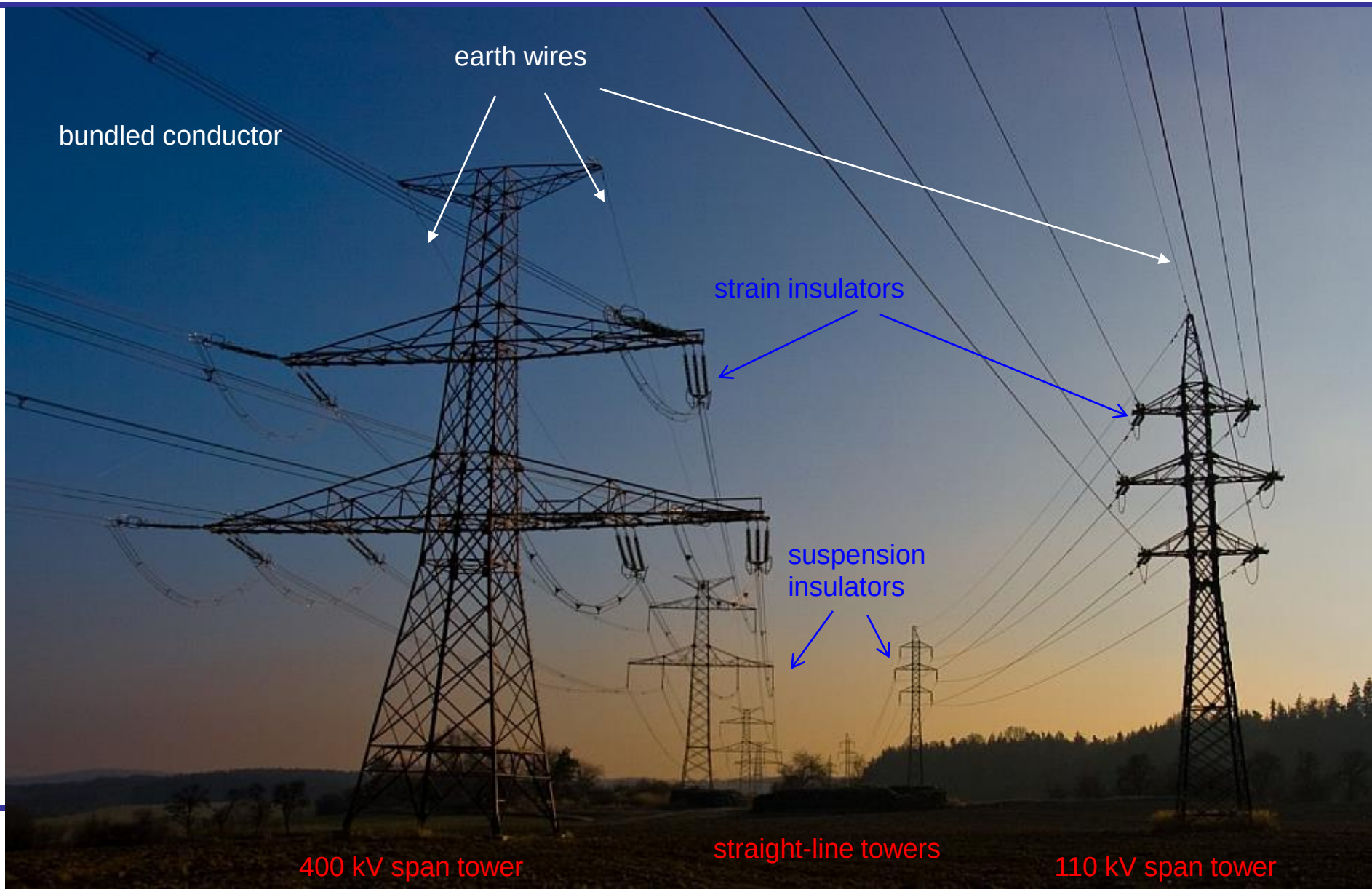
5374 m overarching fjord Ameralik in Greenland, 132 kV overhead power line (1993)



Power line poles and towers



Power line poles and towers



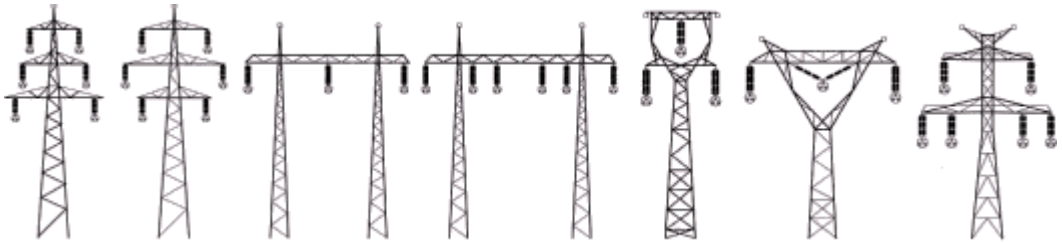
Power line poles and towers

Material: steel, concrete, reinforced concrete, wood

Wood poles
rot proofing – preservation, concrete footing

Concrete poles
- steel cross-arm with support insulators
- LV or MV lines

Steel towers
- steel lattice towers, tube towers, tubular towers
- corrosion prevention (paint or zinc coat, atmofix (special steel)

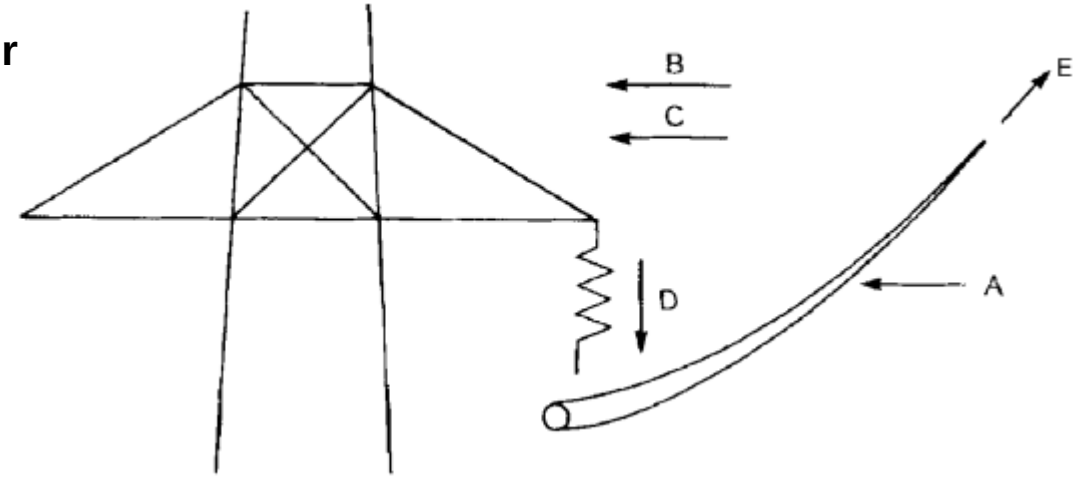




Height of EHV and HV towers - 20 to 40 m according to kind of tower and terrain profile

Power line poles and towers

Forces on overhead line tower



A = horizontal conductor wind load, wind span × wind pressure

B = horizontal structure wind load

C = component of wind loading due to direction of wind and effective structure area normal to the wind

D = vertical conductor weight span × conductor weight, including weight of insulator strings and fixings

E = longitudinal loads due to conductor tension. This will occur under uneven loading, such as for broken wire conditions or at a terminal tower with a slack span on one side of the tower entering to a substation gantry

Overhead line building





Overhead line failures



Obr.1 „Klasicky“ rozlomený dřevěný, patkovaný stožár



Obr.2 Zlomený betonový sloup, celkový pohled



Emma storm 2008

Overhead line failures



Obr.4 Havárie dvojitého vedení 22 kV, celkový pohled

Emma storm 2008



Overhead line failures





Kyril storm 2004

Overhead line failures



Ice-coating calamity 12/2014

Overhead line failures



400 kV overhead line

Ice rain 2014 - Slovenia



freeze-up on 110 kV overhead line

Overhead line failures







110 kV overhead line

Cables

Cable power lines

- LV and MV networks in cities and industrial areas, rarely HV and EHV cables

Properties:

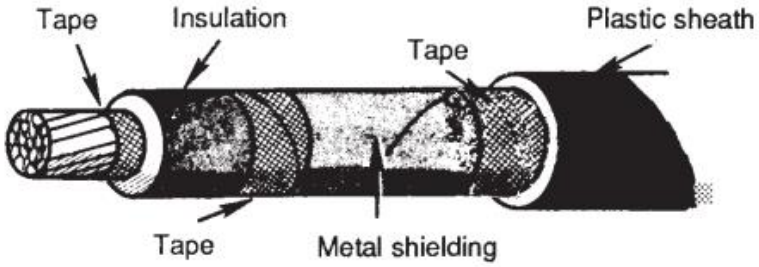
- insulated single-core or multiple-core conductors and accessories (cable terminals, grommets and joints)
- inductive X_L (L) is lower in comparison to
- capacitive susceptance B (C) is higher in comparison to overhead lines (cca 30 x)
- voltage drop ΔU and reactive losses ΔQ are lower due to lower reactance
- less failures, usually permanent faults

  - more multiphase faults – single-phase faults pass tomultiphase ones
- more expensive distances (MV, HV, EHV)
- cables are preferred in residential areas
- space saving

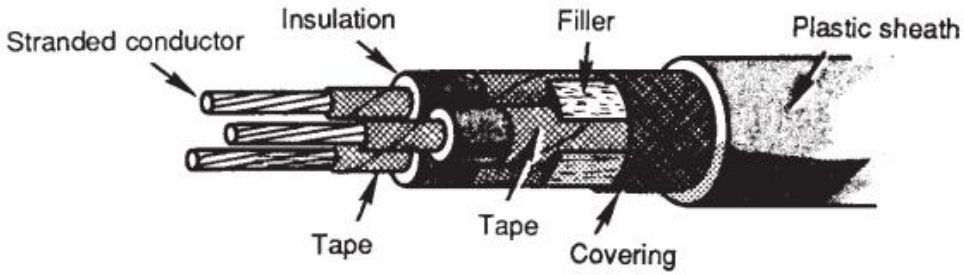
Protective zone	above 110kV	3 m
	below 110 kV	1 m
	loading limit: 6 tons	

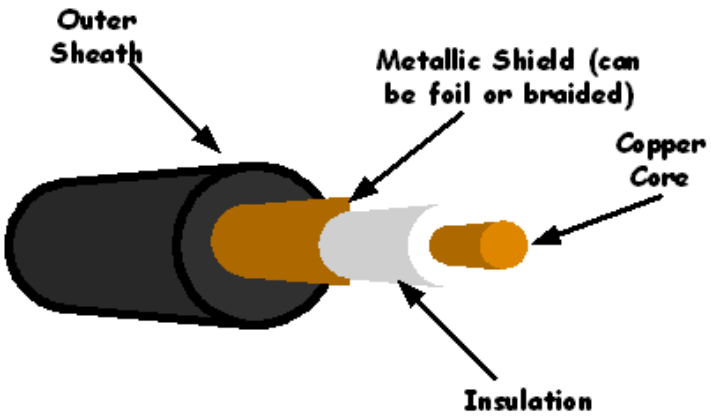
Cables


PVC Outer Jacket
Braided Shield
Dielectric
Foil Shield
Solid Center Conductor


Tape
Insulation
Tape
Plastic sheath
Tape
Metal shielding

(a)


Stranded conductor
Insulation
Filler
Plastic sheath
Tape
Tape
Covering


Outer Sheath
Metallic Shield (can be foil or braided)
Copper Core
Insulation

Cables

Material of conductors - Cu or Al

With the same resistance:

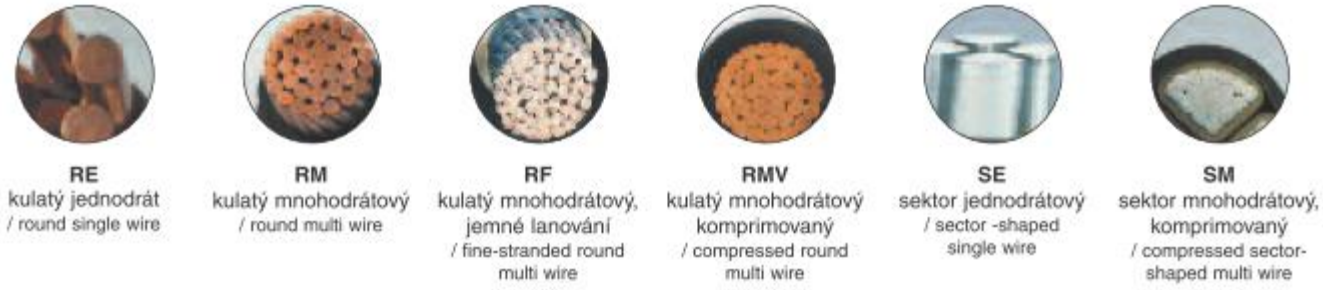
- cross-section: Al/Cu = 1,64/1
- weigth: Al/Cu = 1/2
- tensile strength: Al/Cu = 0,7/1

AL conductors – so called cold flow → to tighten screw joints
- more cracky
- oxide surface film

Joints of Cu and Al conductors – electrolytic destruction
→ special clamps -between AL a Cu conductors - bimetal plate



Construction of cable cores



Cables

Insulation

PVC (polyvinyl chloride) – LV and MV cables (70°C) CYKY.., AYKY…

- during burning it liberates hydrogen chloride HCl

1 kg PVC liberates 180 liters HCl → dangerous to health, corrosive effects



XE (cross-linked polyethylene) – MV and HV cables (90°C) AXEXCY…

- higher mechanical and thermal strength
- lower dielectric losses, low charging currents
- flammable material

Rubber – trailing cables

Silicone rubber – high flexibility, operational temperature (-55°C to 180°C)

Oil-impregnated paper – old-fashioned technology

Special insulations – HFFR (Halogen-Free Fire-Resistant), fire-resistant or flame-retarding (glass/mica tape, ceramics-forming) insulation

Overhead or self-supporting cables - LV



Cable designation - Europe

Number of cores	Ground	Neutral	Phase 1	Phase 2	Phase 3
Bipolar	--			--	--
Bipolar with ground				--	--
Tripolar without ground (with neutral)	--				--
Tripolar without ground (without neutral)	--	--			
Quadripolar with ground (without neutral)		--			
Quadripolar with ground (with neutral)					--
Quadripolar without ground	--				
Pentapolar					

Cable letter marking

0	-	1	2	3	4		5	(6)	x	7

0 rated voltage in kV, e.g. 1, 6, 22, 110

1 conductor material

Cu……..C		Cu waterproof…….CV	
Al……..A		Al waterproof ……..AV	

2 Insulation material

rubber	G
PVC	Y
cross-linked PE	XE
paper	N

3 cable type

power cable	K

4 other layers – shield, material and protection of sheath

Cu metal shield	C	waterproof protection	V
armouring of steel tapes	P	PVC	Y
armouring of steel wires	D	PE	E

5 (6) number of cores in cable, colour of cores

7 nominal cross-section of conductors

Examples: 1-AYKCY, 22-AXEKVCE

Cable joints and terminals

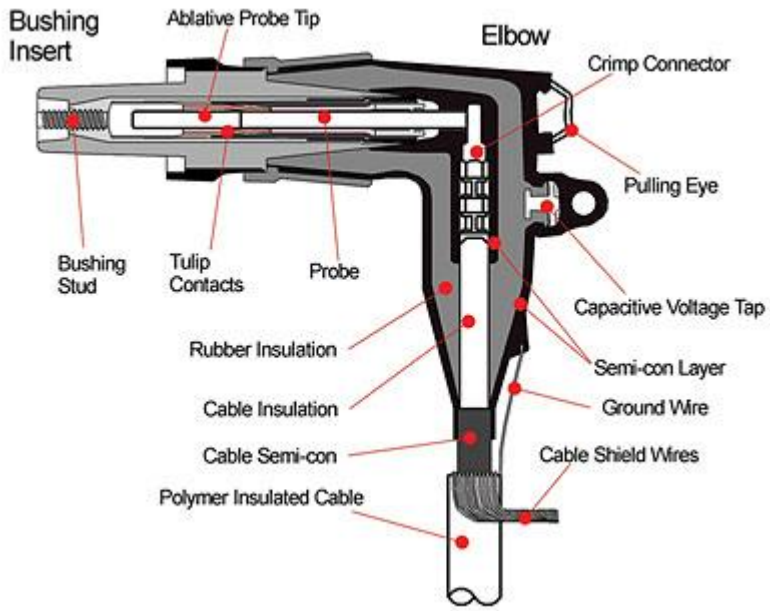
Terminals:
- indoor
- outdoor





Connectors:
- cable connection to switchboard

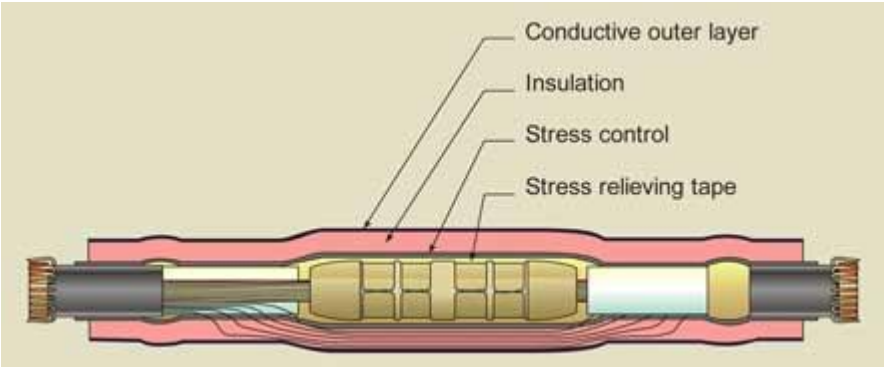


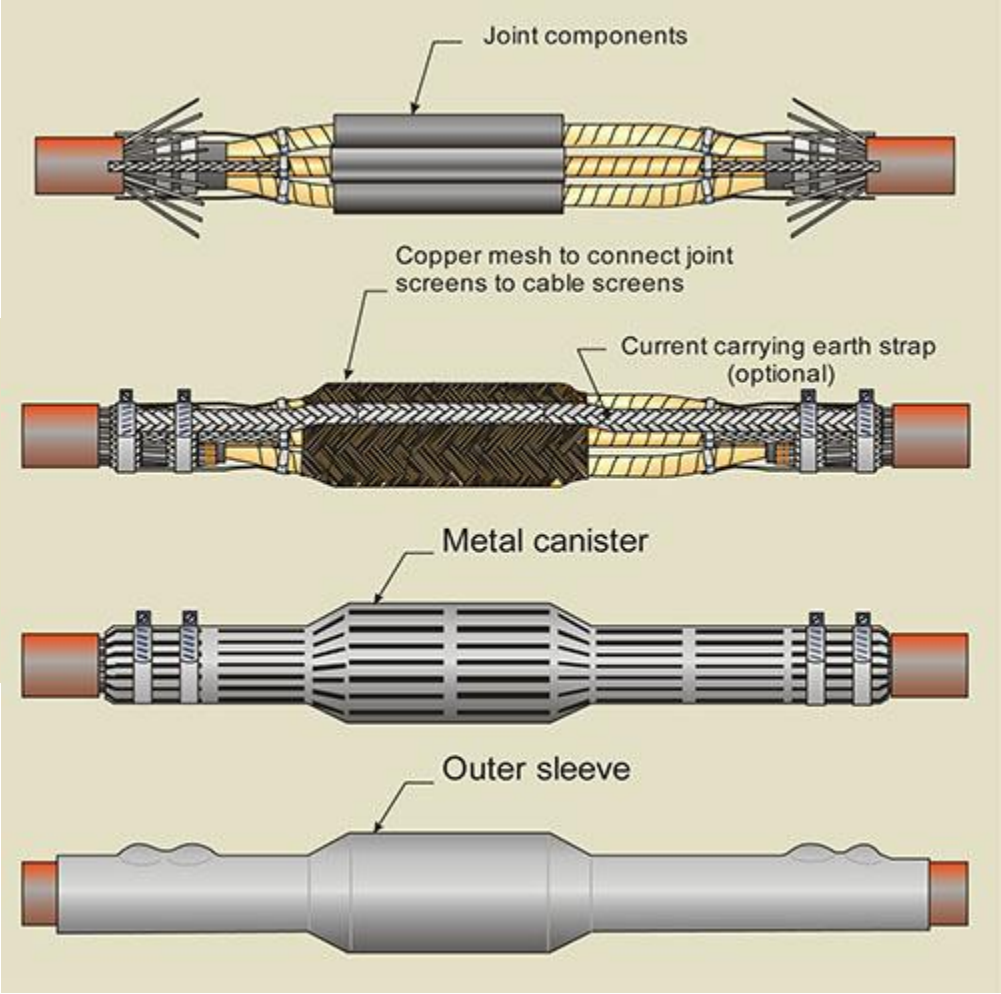


Cable joints and terminals

Cable joints:

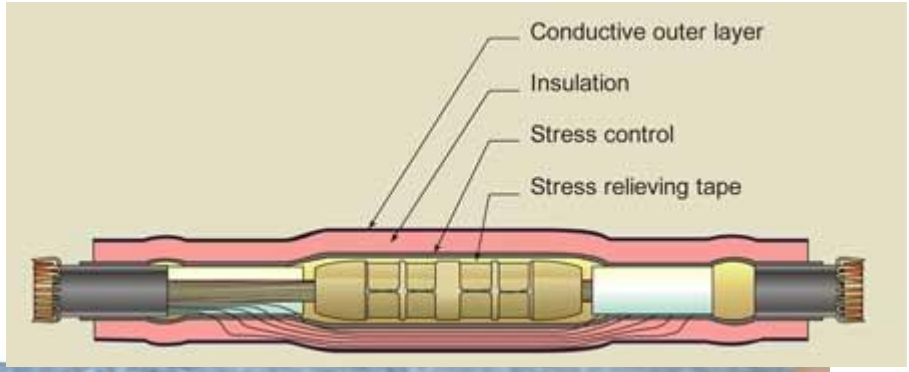
- straight, branch, repair





Cable joints and terminals

Heat shrink cable joint



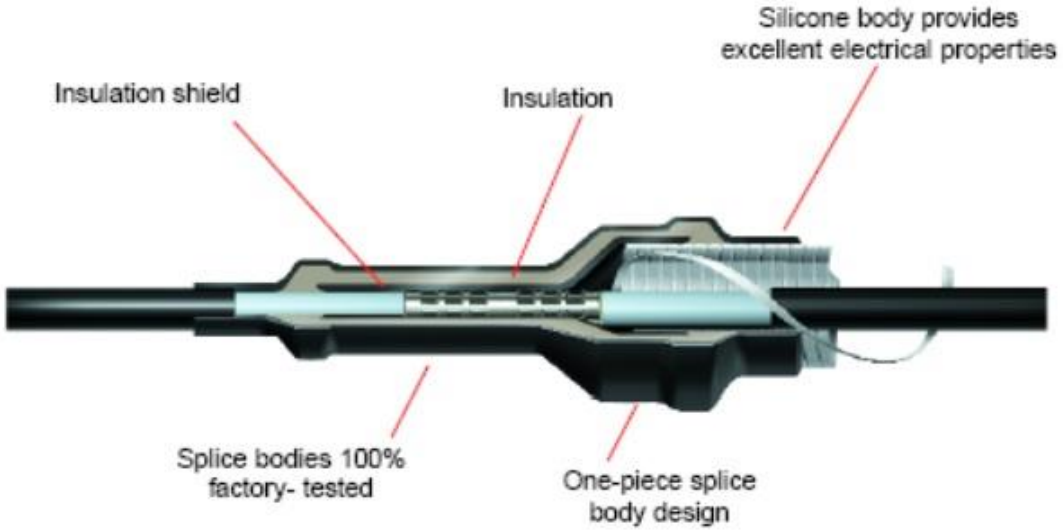






Cable joints and terminals

Cold shrink cable joint



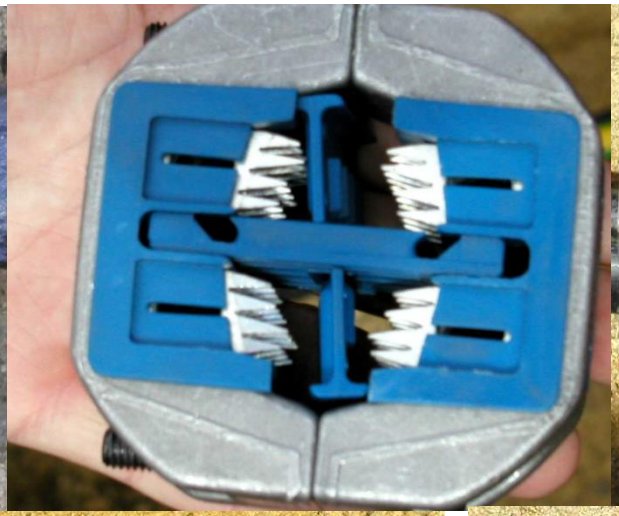


Nasazení vnitřní trubice | Vytažení spirály | Smrštění vnější ochranné trubice

Cable joints and terminals

Resin filled branch cable joint











Cable installation

Cable installation :

- directly in the ground
- in cable ducts, manholes
- on wall, into wall, on cable tray
- on steel support rope
- **in collectors** (along with other pipelines)





Cable installation

In the ground









Cable installation





Cable + earting wire

Cable installation







Cable installation

In cable ducts, manholes

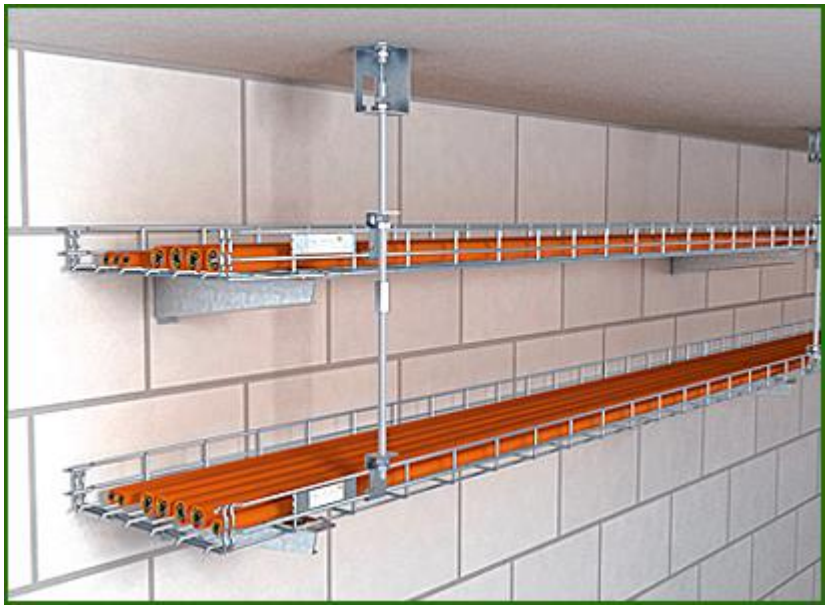


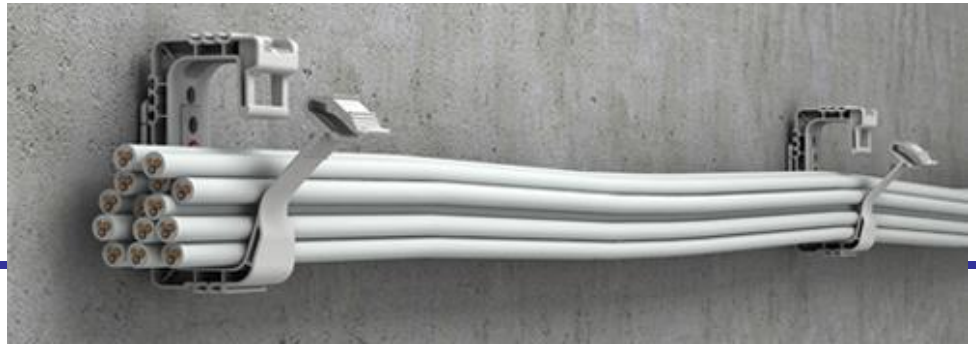


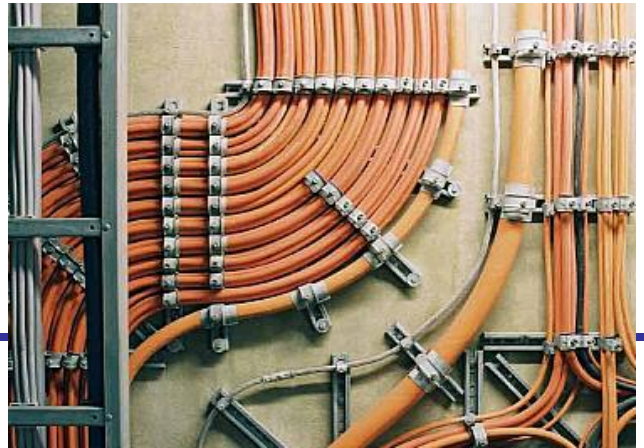
Cable installation

On wall, into wall, on cable trays









Trends – superconducting cables

HTS (High Temperature Superconducting) cables

- conductor – brittle ceramic material
- 1st generation materials: BSCCO (BiSrCaCuO) conductors
  - critical temperature Tc ≈ 110K, critical current density 1 to 5x 10^4 A/cm^2
- 2nd generation materials : YBCO (YBiCuO) conductors
  - critical temperature Tc ≈ 70K, critical current density on order of 10^6 A/cm^2
- cooling medium – liquid nitrogen N2 (boiling temperature 77 K)

- conductor thickness several tenths mm, superconductive layer 1 or more μm is laid on flexible band
- cross-section of HTS conductor can be 100 x lower in comparison to conventional conductor
- mostly single-core cables, length cca 100 to 200 m

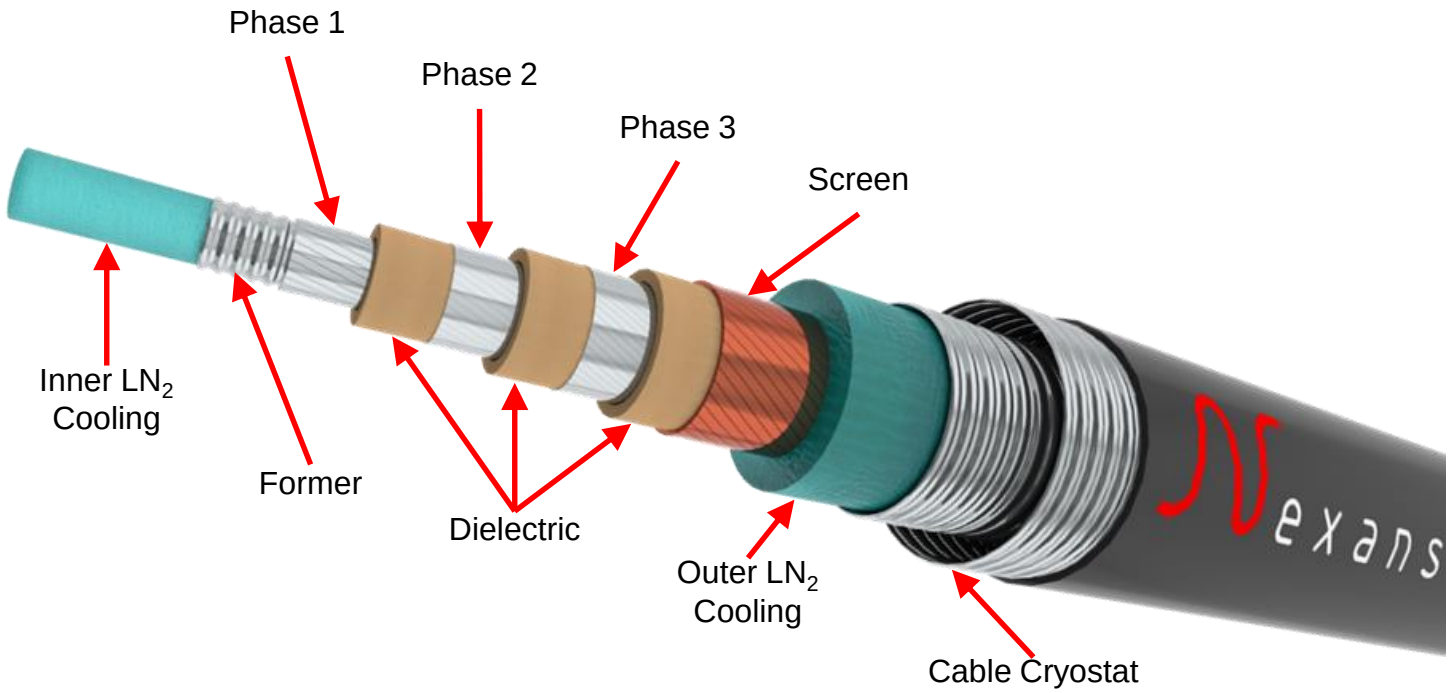


Trends – superconducting cables

HTS (High Temperature Superconducting) cables

the first HTS cable – May 2001 Copenhagen, single-phase cable with warm insulation, 30 kV, 2 kA, 30 m

HTS cable with cold insulation, 10 kV, 40 MVA, Essen, Germany



Cable sizing

Rating according operational temperature

Permissible load

$$I_z = k_1.k_2....k_i.I_N \quad \geq \quad I_p$$

I_N - nominal current (rated current ampacity) determined by the producer (in catalogue, in standards)

I_{NV} – in air, ambient air temperature of 30 °C,

I_{NZ} - in ground or in ducts, air temperature of 20 °C

k_1 , k_2 , ... k_i - derating factors for non-standard conditions (ambient temperature, kind of laying)

Permissible load I_Z must be higher than load current $I_{p.}$

Permissible voltage drop

$$\Delta u_{\%} = \frac{\sqrt{3} \cdot (R.I_p.\cos\varphi + X.I_p.\sin\varphi)}{U_n} \cdot 100 \ \leq \ 5\%$$

Short circuit rating – thermal effect

$$S_{\min} = \frac{I_{th} \cdot \sqrt{t_k}}{K} \leq S$$