THEORY OF TRANSMISSION AND DISTRIBUTION OF ELECTRIC ENERGY

2nd lecture - example

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Calculation of passive line parameters

Mathematical cross-sections and diameters of rope with steel core

Nominal cross-section	Rope mathematical cross-section S [mm²] and rope diameter d [mm]							
	AlFe 8		AlFe 6		AlFe 4		AlFe 3	
[mm²]	S	d	S	d	S	d	S	d
35	*39,38*	*7,08*	40,08	8,10	*43,75*	*7,46*	47,71	9,35
50	*56,25*	*8,46*	56,29	9,60	74,39	11,20	68,71	11,22
70	*78,75*	*10,01*	77,72	11,55	94,15	12,60	96,51	13,30
95	*106,88*	*11,67*	105,02	13,35	116,24	14,00	123,28	14,40
120	*135,00*	*13,11*	143,48	15,65	147,11	15,75	167,79	16,80
150	*168,75*	*14,66*	174,27	17,25	188,96	17,85	192,62	18,00
185	*208,13*	*16,28*	215,45	19,20	227,83	19,60	245,13	20,79
210	*236,25*	*17,34*	244,85	20,20	261,54	21,00	274,63	22,02
240	*270,00*	*18,34*	276,14	21,70	298,01	22,55	317,05	23,65
300	*337,50*	*20,73*	344,35	24,20	380,91	25,65	407,17	26,25
350	*393,75*	*22,39*	*408,33*	*22,80*	426,18	27,20	461,65	27,90
450	479,00	28,67	*525,00*	*25,85*	*562,50*	*26,76*	*600,00*	*27,64*
650	755,90	36,07	*781,67*	*31,55*	*837,50*	*32,65*	*893,33*	*33,73*

Tab. 1

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Calculation of passive line parameters

For ropes apply:

$r_e = k.r$

Rope	k
AlFe 3	0,830
AlFe 4	0,826
AlFe 6	0,809
AlFe 8	0,800

Tab. 2

For calculation of induktance zero folder

$L_o = k.L$		k	
		Single line	Double line
AlFe, Cu	1 conductor per ph.	1,9	3,0
	bundle lines	2,4	3,5
Fe	1 conductor/phase	2,7	4,8
	bundle lines	3,2	5,5

Tab. 3

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Calculation of passive line parameters

Line	Insulation resistnce [MΩ/km]
nn	24
1 kV	80
10 kV	800
22 kV	1 600

Tab. 4

Line	Insulation resi-stnce of insulator [MΩ]	Insulator number per 1 km	Insulation resistnce [MΩ/km]
110 kV	1 200	5 - 10	240 - 120
220 kV	2 400	3 - 5	800 - 500
400 kV	4 800	3 - 5	1600 -1000

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Calculation of passive line parameters

Weather respecting coefficient k

Weather	Sunny	Rainy
k	1	0,8

Tab. 6

Maximum operating voltage U_{max}

U_n [kV]	22	110	220	400
$U_{max\,s}$ [kV]	24	121	245	440

Tab. 5

Weather coefficient δ

Height above sea	300	600	900	1 200
δ	0,97	0,95	0,93	0,91

Tab. 7

Surface quality coefficient m

Surface	smooth wire	weathered wire	twisted rope
m	1	0,93	0,87

Tab. 8

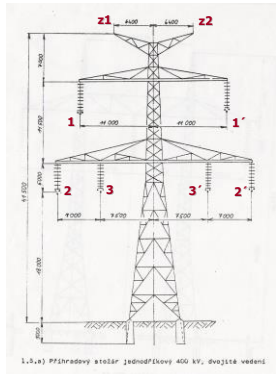
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Calculation of passive line parameters

- example for 400 kV

Task:

- conductors:
  - U_n = 400 kV
  - AlFe 8: 3 x 450 mm²
  - triplebundle (m = 500 mm)
- grounding ropes:
  - AlFe 3: 185 mm²



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Calculation of passive line parameters
- example for 400 kV lines

- **Parameters of high-voltage 400 kV mast - entered:**

$h_1 = 29\,500$ mm $h_2 = h_3 = 18\,000$ mm

$d_{12} = 12\,021$ mm $d_{23} = 7\,000$ mm $d_{13} = 12\,021$ mm
$d_{11'} = 22\,000$ mm $d_{22'} = 29\,000$ mm $d_{33'} = 15\,000$ mm
$d_{12'} = 27\,973$ mm $d_{13'} = 21\,783$ mm $d_{23'} = 22\,000$ mm



$d_z = 12\,800$ mm

$d_{1Z1} = 12\,851$ mm $d_{1Z2} = 21\,137$ mm
$d_{2Z1} = 24\,857$ mm $d_{2Z2} = 31\,449$ mm
$d_{3Z1} = 23\,526$ mm $d_{3Z2} = 27\,303$ mm

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Calculation of passive line parameters
- example for 400 kV lines

- **Parameters of high voltage 400 kV mast - determined:**

Middle distance of conductors:

$$d_s = \sqrt[3]{d_{12} \cdot d_{13} \cdot d_{23}} = \sqrt[3]{12\,021 \cdot 12\,021 \cdot 7\,000} = 10\,038 \text{ mm}$$

$$d_s' = \sqrt[3]{d_{11'} \cdot d_{22'} \cdot d_{33'}} = \sqrt[3]{22\,000 \cdot 29\,000 \cdot 15\,000} = 21\,231 \text{ mm}$$

$$d_s'' = \sqrt[3]{d_{12'} \cdot d_{13'} \cdot d_{23'}} = \sqrt[3]{27\,973 \cdot 21\,783 \cdot 22\,000} = 23\,755 \text{ mm}$$

$$d_{s\,(2ved)} = \frac{d_s \cdot d_s''}{d_s'} = \frac{10038 \cdot 23755}{21231} = 11231 \text{ mm}$$

Middle distance between conductors and ground. rope:

$$d_{zzs} = \sqrt[6]{d_{1Z1} \cdot d_{1Z2} \cdot d_{2Z1} \cdot d_{2Z2} \cdot d_{3Z1} \cdot d_{3Z2}} =$$
$$= \sqrt[6]{12\,851 \cdot 24\,857 \cdot 23526 \cdot 21137 \cdot 31\,449 \cdot 27\,303} =$$
$$= 22\,688 \text{ mm}$$

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Calculation of passive line parameters
- example for 400 kV lines

- **Parameters of high voltage 400 kV mast - determined:**

Middle height of line from ground:

$$h_s = \sqrt[3]{h_1 \cdot h_2 \cdot h_3} = \sqrt[3]{29\,500 \cdot 18\,000 \cdot 18\,000} =$$
$$= 21\,222 \text{ mm}$$

Height of ground ropes above ground:

$h_z = 41\,500$ mm

Distance of grounding ropes:

$d_z = 12\,800$ mm

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Calculation of passive line parameters
- example for 400 kV lines

- **Calculation of basic line parameters:**
  - **conductors**

    AlFe 8: 450 mm² => Al : Fe = 8 : 1

    S_{math} = 479 mm²; d = 28,67 mm ⟵ **tab. 1**

    k = 0,8 ⟵ **tab. 2** - for calculation of the equivalent radius
  - **grounding ropes**

    AlFe 3: 185 mm² => Al : Fe = 3 : 1

    S_{math} = 245,13 mm²; d = 20,79 mm ⟵ **tab. 1**

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Calculation of passive line parameters
- example for 400 kV lines

- **Calculation of basic line parameters:**
  - **cross-section Fe:**

    $S_{Fe} = \frac{S}{9} = \frac{479}{9} = 53{,}2\ \text{mm}^2 \rightarrow d_{Fe} = 8{,}23\ \text{mm}$
  - **cross-section Al:**

    $S_{Al} = 8 \cdot \frac{S}{9} = 8 \cdot S_{Fe} = 8 \cdot 53{,}2 = 425{,}8\ \text{mm}^2 \rightarrow d_{Al} = 23{,}28\ \text{mm}^2$
  - **equivalent radius:**

    $r_e = k \cdot \frac{d}{2} = 0{,}8 \cdot \frac{28{,}67}{2} = 11{,}468\ \text{mm}$
  - **bundle radius:**

    $r_{sv3} = \sqrt[3]{r \cdot m^2} = \sqrt[3]{14{,}335 \cdot 500^2} = 153\ \text{mm}$
  - **equivalent radius of the triplebundle:**

    $r_{esv3} = \sqrt[3]{r_e \cdot m^2} = \sqrt[3]{11{,}468 \cdot 500^2} = 142\ \text{mm}$

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Calculation of passive line parameters
- example for 400 kV lines

- **Calculation of resistance:**
  - resistance of iron: $R_{Fe} = \frac{\rho_{Fe} \cdot l}{S_{Fe}} = \frac{0{,}13 \cdot 1000}{53{,}2} = 2{,}44\ \Omega/\text{km}$
  - aluminum resistance: $R_{Al} = \frac{\rho_{Al} \cdot l}{S_{Al}} = \frac{0{,}02941 \cdot 1000}{425{,}8} = 0{,}069\ \Omega/\text{km}$
  - total resistance of 1 conductor without considering the effect of skineffect.:

    $R = \frac{1}{\frac{1}{R_{Al}} + \frac{1}{R_{Fe}}} = \frac{1}{\frac{1}{0{,}069} + \frac{1}{2{,}44}} = 0{,}067\ \Omega/\text{km}$
  - resistance of 1 ph (bunch): $R_{sv3} = \frac{R}{3} = \frac{0{,}067}{3} = 0{,}022\ \Omega/\text{km}$

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Calculation of passive line parameters
- example for 400 kV lines

- **Resistance calculation including skineffect:**
  - iron resistance with a skineffect:

$$m = \frac{\pi \cdot d_{Fe}}{10}\sqrt{\frac{2 \cdot f \cdot \mu_r}{\rho_{Fe} \cdot 10^9}} = \frac{\pi \cdot 8{,}23}{10}\sqrt{\frac{2 \cdot 50 \cdot 1000}{0{,}13 \cdot 10^9}} = 0{,}0717$$

$$k = 1 + \frac{1}{12}\left(\frac{m}{2}\right)^4 - \frac{1}{180}\left(\frac{m}{2}\right)^8 = 1 + \frac{1}{12}\left(\frac{0{,}0717}{2}\right)^4 - \frac{1}{180}\left(\frac{0{,}0717}{2}\right)^8 = 1{,}000000138$$

$$R'_{Fe} = k \cdot R_{Fe} = 1 \cdot 2{,}44 = 2{,}44\ \Omega/\text{km}$$

  - aluminium resistance with a skineffect:

$$k = 1 + 7{,}5 \cdot f^2 \cdot d^4 \cdot 10^{-11} = 1 + 7{,}5 \cdot 50^2 \cdot 23{,}28^4 \cdot 10^{-11} = 1{,}055$$

$$R'_{Al} = k \cdot R_{Al} = 1{,}055 \cdot 0{,}069 = 0{,}0728\ \Omega/\text{km}$$

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Calculation of passive line parameters
- example for 400 kV lines

- **Resistance calculation including skineffect - cont.:**
  - total resistance, considering the skineffect:

$$R' = \frac{1}{\frac{1}{R'_{Al}} + \frac{1}{R'_{Fe}}} = \frac{1}{\frac{1}{0{,}0728} + \frac{1}{2{,}44}} = 0{,}071\ \Omega\ /\text{km}$$

  - triplebundle resistance (three equal wires in parallel):

$$R'_{sv3} = \frac{R'}{3} = \frac{0{,}071}{3} = 0{,}024\ \Omega/\text{km}$$

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Calculation of passive line parameters
- example for 400 kV lines

- **Inductance calculation:**
  - operating inductance:

$$L_p = 0{,}46 \cdot \log\frac{d_s}{r_e} = 0{,}46 \cdot \log\frac{11\,231}{142} = 0{,}873 \cdot 10^{-3}\ \text{H/km}$$

  - zero folder for line with grounding rope:

$$L_0 = k \cdot L = \underset{\text{from tab. 3}}{3{,}5} \cdot 0{,}873 \cdot 10^{-3} = 3{,}056 \cdot 10^{-3}\ \text{H/km}$$

Inductive reactance:

$$X_p = \omega L_p = 2\pi f \cdot L_p = 2 \cdot 3{,}14 \cdot 50 \cdot 0{,}873 \cdot 10^{-3} = 0{,}27\ \Omega/\text{km}$$

$$X_0 = \omega L_0 = 2\pi f \cdot L_0 = 2 \cdot 3{,}14 \cdot 50 \cdot 3{,}056 \cdot 10^{-3} = 0{,}96\ \Omega/\text{km}$$

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Calculation of passive line parameters
- example for 400 kV lines

- **Capacity calculation**:
  - operating capacity

$$C_p = \frac{1}{D - D'}$$

  - for double line $D = D_I + D_{I,II}$, $D' = D_I' + D_{I,II}'$
    - D_I , D_I' ... as for simple line
    - $D_{I,II}$, $D_{I,II}'$ ... ensures the influence of the 2nd line

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Calculation of passive line parameters
- example for 400 kV lines

$$D_I = 41{,}3 \cdot 10^6 \log \frac{2h_s}{r_{sv}} = 41{,}3 \cdot 10^6 \log \frac{2 \cdot 21222}{153} = 100{,}09 \cdot 10^6 \text{ km/F}$$

$$D_I' = 41{,}3 \cdot 10^6 \log \frac{\sqrt{4h_s^2 + d_s^2}}{d_s} = 41{,}3 \cdot 10^6 \log \frac{\sqrt{4 \cdot 21\,222^2 + 11\,231^2}}{11\,231} =$$

$$= 24{,}45 \cdot 10^6 \text{ km/F}$$

$$D_{I,II} = 41{,}3 \cdot 10^6 \cdot \log \frac{\sqrt{4h_s^2 + d_s'^2}}{d_s'} = 41{,}3 \cdot 10^6 \log \frac{\sqrt{4 \cdot 21\,222^2 + 21\,231^2}}{21\,231} =$$

$$= 14{,}43 \cdot 10^6 \text{ km/F}$$

$$D_{I,II}' = 41{,}3 \cdot 10^6 \cdot \log \frac{\sqrt{4h_s^2 + d_s''^2}}{d_s''} = 41{,}3 \cdot 10^6 \cdot \log \frac{\sqrt{4 \cdot 21\,222^2 + 23\,755^2}}{23\,755}$$

$$= 12{,}85 \cdot 10^6 \text{ km/F}$$

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Calculation of passive line parameters
- example for 400 kV lines

$$D = D_I + D_{I,II} = (100{,}09 + 14{,}43) \cdot 10^6 = 115{,}33 \cdot 10^6 \text{ km/F}$$

$$D' = D_I' + D_{I,II}' = (24{,}45 + 12{,}85) \cdot 10^6 = 37{,}3 \cdot 10^6 \text{ km/F}$$

$$C_p = \frac{1}{D - D'} = \frac{1}{115{,}33 \cdot 10^6 - 37{,}3 \cdot 10^6} = 13 \cdot 10^{-9} \text{ F/km}$$

- zero folder of capacity

$$C_0 = \frac{1}{D + 2D' - 3D_r} \quad , \quad \text{where:} \quad D_r = \frac{2 \cdot D_{vz}'^2}{D_{zz} + D_z}$$

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Calculation of passive line parameters - example for 400 kV lines

$$D'_{vz} = 41{,}3 \cdot 10^6 \log \frac{\sqrt{4h_s \cdot h_z + d_{zzs}^2}}{d_{zzs}} =$$

$$= 41{,}3 \cdot 10^6 \log \frac{\sqrt{4 \cdot 21222 \cdot 41500 + 22688^2}}{22688} = 18{,}52 \cdot 10^6 \text{ km/F}$$

$$D_z = 41{,}3 \cdot 10^6 \log \frac{\sqrt{4h_z^2 + d_z^2}}{d_z} = 41{,}3 \cdot 10^6 \log \frac{\sqrt{4 \cdot 41500^2 + 12800^2}}{12800} =$$

$$= 33{,}74 \cdot 10^6 \text{ km/F}$$

$$D_{zz} = 41{,}3 \cdot 10^6 \log \frac{2h_z}{r_z} = 41{,}3 \cdot 10^6 \log \frac{2 \cdot 41500}{10{,}395} = 161{,}16 \cdot 10^6 \text{ km/F}$$

$$D_r = \frac{2 \cdot D'^2_{vz}}{D_{zz} + D_z} = \frac{2 \cdot \left(18{,}52 \cdot 10^6\right)^2}{161{,}16 \cdot 10^6 + 33{,}74 \cdot 10^6} = 3{,}52 \cdot 10^6 \text{ km/F}$$

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Calculation of passive line parameters - example for 400 kV lines

$$C_0 = \frac{1}{D + 2D' - 3D_r} = \frac{1}{115{,}33.10^6 + 2 \cdot 37{,}3 \cdot 10^6 - 3 \cdot 3{,}52 \cdot 10^6} =$$

$$= 5{,}58 \cdot 10^{-9} \text{ F/km}$$

Capacitive susceptance

$$B = \omega C = 2 \cdot 50 \cdot 3{,}14 \cdot 0{,}013 \cdot 10^{-6} = 4{,}08 \cdot 10^{-6} \text{ S/km}$$

$$B_0 = \omega C_0 = 2 \cdot 50 \cdot 3{,}14 \cdot 5{,}58 \cdot 10^{-9} = 1{,}75 \cdot 10^{-6} \text{ S/km}$$

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Calculation of passive line parameters - example for 400 kV lines

- **Determination of conductance:**
  - imperfect insulation :

$$G = \frac{1}{R_i} = \frac{1}{1300 \cdot 10^6} = 7{,}69 \cdot 10^{-10} \text{ S/km}$$

midlle value subtracted **from tab. 4**

  - losses

$$\Delta P = U_s^2 \cdot G = 400^2 \cdot 10^6 \cdot 7{,}69 \cdot 10^{-10} = 123 \text{ W/km}$$

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Calculation of passive line parameters - example for 400 kV lines

- **Determination of conductance :**
  - by corona (here only for illustration – for bundled conductors it is inappropriate solution)
    - first **consider corona formation**

$$U_{max\,f} = \frac{U_{max}}{\sqrt{3}} = \frac{440}{\sqrt{3}} = 254\ kV$$

U_{max} deducted **from tab. 5**

$$U_p = 4{,}92 \cdot m \cdot r \cdot \delta \cdot \log\frac{d_s}{r} = 4{,}92 \cdot 0{,}87 \cdot 153 \cdot 0{,}97 \cdot \log\frac{11\,231}{153} =$$

$$= 1185{,}21\ kV$$

m, δ deductive **from tab. 7, 8**

- If it is $U_p > U_{max\,f}$ ⟶ **corona not arise, we do not count corona conductance**

Calculation of passive line parameters - example for 400 kV lines

- If it is $U_p < U_{max\,f}$ ⟶ , e.g. 250 kV, we continue with **corona loss calculation** (Peek formula)

$$\Delta P = 3 \cdot 2{,}44 \cdot \frac{f+25}{\delta}\sqrt{\frac{r}{d_s}} \cdot (U_{max\,f} - k \cdot U_p)^2 =$$

$$= 3 \cdot 2{,}44 \cdot \frac{50+25}{0{,}97}\sqrt{\frac{153}{11231}} \cdot (254 - 0{,}8 \cdot 250) =$$

$$= 3567{,}23\ kW/km$$

- where:
  - r … 1 wire radius
  - d_s … middle distance between conductors
  - δ … **from tab. 7** (for Pilsen 300 m/sea)
  - k … respects the weather (for rain from **tab. 6**)

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Calculation of passive line parameters - example for 400 kV lines

- **Corona conductance calculation**

$$G = \frac{\Delta P}{U_s^2} = \frac{3567{,}23 \cdot 10^3}{400^2 \cdot 10^6} = 22{,}30 \cdot 10^{-6}\ S/km$$

- for bundle conductors we do not count corona G like above, the result does not correspond to reality (we prefer to consider some table value)

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