THEORY OF TRANSMISSION AND DISTRIBUTION OF ELECTRIC ENERGY

2nd lecture - theory

ESF II project of the University of West Bohemia in Pilsen
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Content

- Defining of the electrical network
- Calculation of overhead line passive parameters
  - Theory
  - Types of masts
  - Procedure for calculation of passive parameters for different overhead lines

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Defining of the electrical network (1)

- In networks, calculations are performed for:
  - steady and transient processes (closer KEE/PJS)
  - symmetrical and asymmetric states
- Before the calculation it is necessary to define the network, i.e. to create a substitute schema (knowledge of branch element parameters is essential)

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Defining of the electrical network (2)

We assume:

1. *3ph networks, symmetrical passive parameters* (the same in all phases) ⇒ calculations for one phase, other recalculation (the same size + rotation by 120° and 240°)

Note.: Solution of asymmetric states → calculation again for 1ph after distributing the asymmetry into symmetrical components

2. *Sinus progress* of voltage and current → use SKM (symbolic complex method) ⇒ we consider voltages and currents in the form of phasors (given by size and angle of rotation)

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Defining of the electrical network (3)

Then:

- We convert the solved system to 1ph circuit, **where**:
  - nodes ⇔ busbar systems in electrical distribution substation equipment
  - branches ⇔ lines (outdoor, indoor), transformers, capacitors and chokes
    - Circuit shape is given by network configuration (switching elements in substations) → determines the number of nodes and branches

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Defining of the electrical network (4)

When calculating:

- we will create a *substitute schema* – currents (or power outputs) are injected (= in or out) into (from) nodes
  - EPS = multiple networks (several voltage levels) → to solve *at one voltage level* → we recalculate elements of substitude schema via transformer conversions
  - we solve:
    - *in named units* (V, A, Ω, …)
    - *with relative variables* (related to S_v and U_v)

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Defining of the electrical network (5)

Distinction of variable by font sizes:

- Capital letters - variables with named units (V, A, W, VAr, Ω, S...)
- Lowercase letters - variables with relative units (r. u.)

Other characters:

- Underline of letter - matrix or vector
- Line over letter - complex shape (phasor)

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Defining of the electrical network (6)

Resolution of variables by index:

- Nodal variables — one index specifying a node (e.g. U_i)
- Branching variables (lengthwise) — two indexes identifying the ending nodes (e.g. U_{ik})
- Branching variables (transverse) — three indexes, two identifying the ending nodes, one (**0**) determines the common pole (ground) (e.g. Y_{ik0})
- Phase variables — indexes **a, b, c, (A, B, C)** determine the individual phases
- Symmetrical components — indexes **1, 2, 0** for sequential, backward and non-rotating component system
- Indexes of basic meaning — **f** for phase voltage; **n** for nominal voltage

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Defining of the electrical network (7)

Marking used in other calculations:

$U(\bar{U})$	... size (phasor) associated voltage
U_n	... nominal voltage → always associated (see normalized series)
$U_f(\bar{U}_f)$	... phase voltage ($U = \sqrt{3}*U_f$) (between phase and ground)
$I(\bar{I})$	... size (phasor) current
ϑ	... angle between voltages ($\bar{U} = Ue^{j\vartheta}$)
φ	... angle between voltage and current
$\cos\varphi$	... power factor

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Defining of the electrical network (8)

Marking used in other calculations:

$S(\bar{S})$	... size (complex shape) of apparent power output
P	... active power output
Q	... reactive power output (usually without further marking - inductive)
ΔP	... active power losses
f	... frequency

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Defining of the electrical network (9)

Marking used in other calculations:

$Z(\bar{Z})$	... size (complex shape) of impedance
$Y(\bar{Y})$	... size (complex shape) of admittance
R	... resistence
X	... reactance
G	... conductance
B	... susceptance
L	... inductance
C	... capacity

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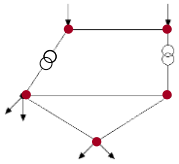
Defining of the electrical network (10)

Electrical network = electrical circuit

- ***nodes*** = electrical distribution equipment (i.e. part of a distribution station)
- ***branches*** = power lines, transformers, capacitors, chokes

In Fig.:

- nodes (energy either supplied, or subscribed)
- branches



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Defining of the electrical network (11)

Nodes:

- **consumption:** **P, Q** (input active and reactive power output → appliance connected)
- **source:** **P, U** (input active power output and voltage → connected power plant or superior system)
- **reference:** **U, $\vartheta = 0$** (1 required node, specified voltage magnitude and angle ϑ, usually marked as 1)
- **compensatory:** **Q, U** (special, reactive power output and voltage → compensating means connected = choke, capacitor)

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Defining of the electrical network (12) - nodes

Active variables in **i** node:

$\bar{U}_i, \bar{I}_i$ or $U_i, \vartheta_i, P_i, Q_i$

$$\bar{I}_i = \frac{\bar{S}_i^*}{\sqrt{3}\bar{U}_i^*} = \frac{P_i - jQ_i}{\sqrt{3}\bar{U}_i^*}$$

Basic relationships between them:

$$\bar{S}_i = P_i + jQ_i = 3\bar{U}_{if} \cdot \bar{I}_i^* = \sqrt{3}\bar{U}_i \cdot \bar{I}_i^*$$

$$\bar{U}_i = U_i e^{j\vartheta_i} \qquad \bar{U}_i^* = U_i e^{-j\vartheta_i}$$

$$P_i = \sqrt{3}U_i I_i \cos\varphi_i \qquad Q_i = \sqrt{3}U_i I_i \sin\varphi_i$$

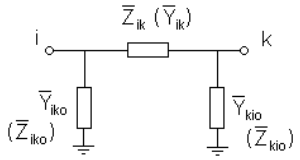
Note: When solving of circuits we perform calculations with phase voltages. Normalized series of voltages = associated voltages.

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Defining of the electrical network (13)

Branches

- Element (**line, transformer,** …) we can express it either by impedances or by admittances, i.e. to used **Π-cell** replecement.



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Defining of the electrical network (14) - branches

Active parameters are:

$\bar{I}_{ik}$ (on the **i** node side) ⇒ currents in a branch between **i, k** nodes

$\bar{I}_{ki}$ (on the **k** node side) ⇒ currents in a branch between **k, i** nodes

$\bar{U}_i - \bar{U}_k = \Delta\bar{U}_{ik}$ ... voltage difference in the **i-k** branch

$P_{ik}\,(P_{ki})$ ... active power in the **i-k** branch

$Q_{ik}\,(Q_{ki})$ ... reactive power in the **i-k** branch

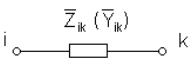
$\vartheta_{ik} = \vartheta_i - \vartheta_k$ ... angle between **i, k** node voltages

$\bar{I}_{ik0}\,(\bar{I}_{ki0})$ ... current on the transverse parameter of the **i-k** branch

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Defining of the electrical network (15) - branches

Passive parameters:



- **Longitudinal** , i.e. between **i, k** nodes
  - In general:
    - ***Impedance***:
      $\bar{Z}_{ik} = R_{ik} + jX_{ik}$
    - ***Admitance***:

$$\bar{Y}_{ik} = \frac{1}{\bar{Z}_{ik}} = \frac{1}{R_{ik} + jX_{ik}} = \frac{R_{ik} - jX_{ik}}{R_{ik}^2 + X_{ik}^2} =$$

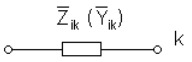
$$= \frac{R_{ik}}{R_{ik}^2 + X_{ik}^2} - j\frac{X_{ik}}{R_{ik}^2 + X_{ik}^2} = G_{ik} \oplus jB_{ik}$$

We can **choose** mark, e.g. **+**, then see next page

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Defining of the electrical network (16) - branches

- ***Admittance - cont.***:



$Y_{ik} = G_{ik} \oplus jB_{ik}$

$$G_{ik} = \frac{R_{ik}}{R_{ik}^2 + X_{ik}^2} \qquad B_{ik} = -\frac{X_{ik}}{R_{ik}^2 + X_{ik}^2}$$

Eventually. conversely -> **we choose**

$$Y_{ik} = G_{ik} \ominus jB_{ik} \Rightarrow B_{ik} = \frac{X_{ik}}{R_{ik}^2 + X_{ik}^2}$$

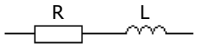
Note: Attention! G, B has different meanings!

- **G_{ik}** and **B_{ik}** here **only the designation**, does not mean a conductance and susceptance as a passive parameter of the line **!!!!**

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Defining of the electrical network (17) - branches

- Usually the longitudinal element has an inductive character, i.e. has a shape :



(In series connection)

→ at overhead lines, cables, transformers, alternators - $\bar{Z}_{ik}, \bar{Y}_{ik}$ see above

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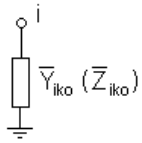
Defining of the electrical network (18) - branches

- **Transverse** (between the node and the ground)
  - index iko or kio (by node, where we consider the parameter)
  - In general:
    - ***Admitance***:

$$\bar{Y}_{iko} = G_{iko} + jB_{iko}$$

    - ***Impedance***:

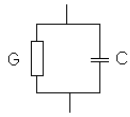
$$\bar{Z}_{iko} = \frac{1}{\bar{Y}_{iko}} = \frac{1}{G_{iko} + jB_{iko}} = \frac{G_{iko}}{G_{iko}^2 + B_{iko}^2} - j\frac{B_{iko}}{G_{iko}^2 + B_{iko}^2}$$



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Defining of the electrical network (19) - branches

- Usually (e.g. **for overhead lines and cables**) has a transverse element capacity character, parallel connection ***Admitance*** – see general solution, i.e. $\bar{Y}_{iko} = G_{iko} + jB_{iko}$



G - conductance
B = ωC - capacitive susceptance

  - ***Impedance*** - we can made it from admittance (also see general solution), it is not used very often

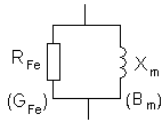
$$\bar{Z}_{iko} = \frac{1}{\bar{Y}_{iko}} = \frac{G_{iko}}{G_{iko}^2 + B_{iko}^2} - j\frac{B_{iko}}{G_{iko}^2 + B_{iko}^2}$$

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Defining of the electrical network (20) - branches

- For **transformer** – as parallel impedance connection

$$\overline{Y}_q = \frac{1}{R_{Fe}} + \frac{1}{jX_m} = \frac{1}{R_{Fe}} - j\frac{1}{X_m} = G_{Fe} - jB_m$$



R_{Fe} (G_{Fe}) – resistance (conductance) respecting no-load losses

X_m (B_m) – reaktance (susceptance) respecting the magnetizing current

- **Note:** For concrete calculations it is necessary to substitute at **transverse** elements in Π - cell **half length**.

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Passive line parameters (1) – theory

- For the study of phenomena in electric and magnetic circuits, one of the **basic tasks is the calculation of parameters**, which are **the basis for** determining **mathematical models** of individual **elements**
- Both overhead and cable lines we **replace** by two-port in shape of Π **cell**.
  - **longitudinal impedance** components are **resistance** and **inductive reactance**
  - the components of **transverse admittance** are **conductance** (usually neglected) and **capacitive susceptance**

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Passive line parameters (2) – theory

- Individual passive parameters depend on :
  - **cross section** (diameter) of conductor of one phase
  - **distance between conductors** of individual phases
  - **distances between conductors and ground**
  - **distances between conductors and grounding ropes**
  - **on the shape of a mast** (at **overhead lines**)
  - event. for construction **cable** and **insulation** type, for **profile** conductors for **shape and saving**

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Calculation of passive line parameters - target

- We want to specify for the given line:

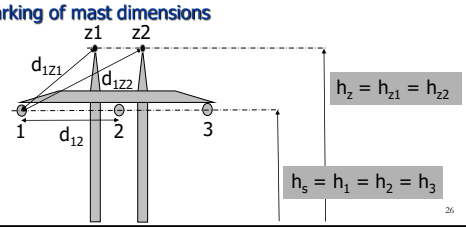
  $\underline{Z} = R + jX$ $\underline{Y} = G + jB$, i.e.

  - R … resistance (active resistance) [Ω/km]
  - R´ … active resistance with the influence of skin effect [Ω/km]
  - L … inductance [H/km]
  - L_0 … inductance - zero component [H/km]
  - X … inductive reaktance [Ω/km]
  - X_0 … inductive reactance - zero component [Ω/km]
  - C … capacity [F/km]
  - C_0 … capacity - zero component [F/km]
  - B … capacitive susceptance [S/km]
  - B_0 … capacitive susceptance - zero component [S/km]
  - G … conductance [S/km]

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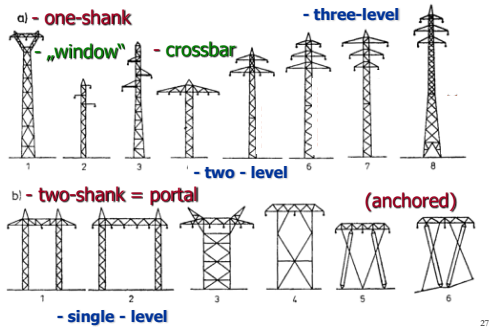
Calculation of passive line parameters

- Note:
  - we perform the calculation for one phase (see assumptions earlier)
  - R, G are not influenced by the second line
  - L, C we count with the influence of the second line
- Marking of mast dimensions



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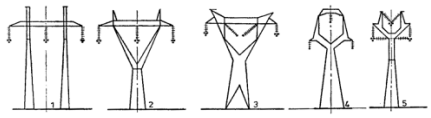
Calculation of passive line parameters - mast types



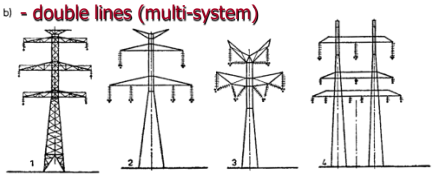
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Calculation of passive line parameters
- mast types

a) - simple line



b) - double lines (multi-system)

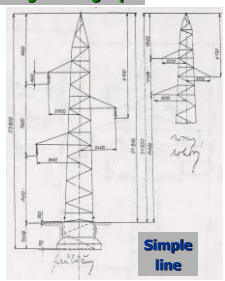


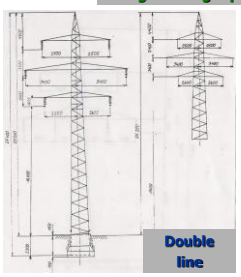
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Calculation of passive line parameters
- mast types

One grounding rope

One grounding rope





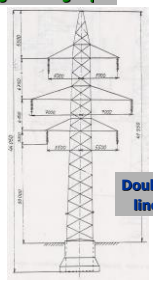
Single-bay lattice mast 110 kV

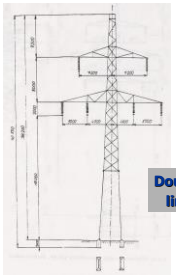
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Calculation of passive line parameters
- mast types

One grounding rope

One grounding rope



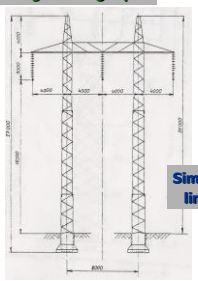


Single-bay lattice mast 220 kV

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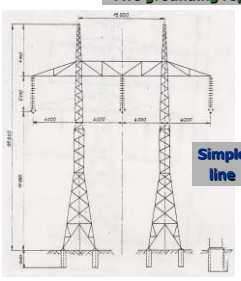
Calculation of passive line parameters
- mast types

Two grounding ropes



Simple line

Two grounding ropes



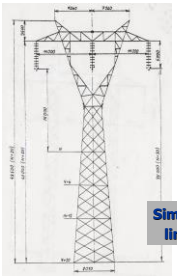
Simple line

Portal lattice mast
220 kV 400 kV

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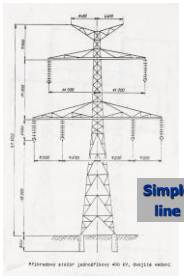
Calculation of passive line parameters
- mast types

Two grounding ropes



Simple line

Two grounding ropes



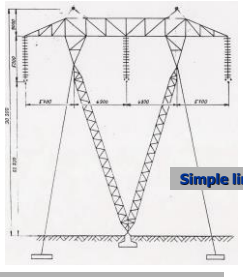
Simple line

Lattice mast 400 kV

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Calculation of passive line parameters
- mast types

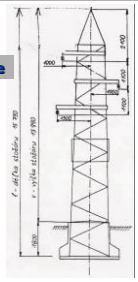
Two grounding ropes



Simple line

Without grounding rope

Simple line



Anchored lattice mast 400 kV

Lattice mast 22 kV

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Calculation of passive line parameters
- solution procedure for overhead lines

1) We determine from a known mast with dimensions:

- distance between conductors:

  d_{12}, d_{13}, d_{23}, $d_{12'}$, $d_{13'}$, $d_{23'}$, $d_{11'}$, $d_{22'}$, $d_{33'}$

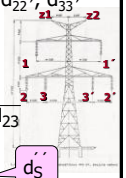
- conductor - grounding rope distance:

  d_{1Z1}, d_{2Z1}, d_{3Z1}, d_{2Z2}, d_{1Z2}, d_{3Z2}

- middle distance between conductors
  - for simple line $d_s = \sqrt[3]{d_{12} \cdot d_{13} \cdot d_{23}}$
  - for double line

$$d_s = \frac{\sqrt[3]{d_{12} \cdot d_{13} \cdot d_{23}}\sqrt[3]{d_{12}' \cdot d_{13}' \cdot d_{23}'}}{\sqrt[3]{d_{11}' \cdot d_{22}' \cdot d_{33}'}}$$

d_s'' d_s'



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Calculation of passive line parameters
- solution procedure for overhead lines

- middle distance between conductors and grounding rope
  - for one grouding rope $d_{zs} = \sqrt[3]{d_{1Z} \cdot d_{2Z} \cdot d_{3Z}}$
  - for two grounding ropes $d_{zzs} = \sqrt[6]{d_{1Z1} \cdot d_{1Z2} \cdot d_{2Z1} \cdot d_{2Z2} \cdot d_{3Z1} \cdot d_{3Z2}}$
- middle distance between conductors and ground (= middle conductor height) $h_s = \sqrt[3]{h_1 \cdot h_2 \cdot h_3}$
- height of grounding ropes above ground $h_z = \sqrt{h_{z1} \cdot h_{z2}}$
- distance between the grounding ropes d_z

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Calculation of passive line parameters
- solution procedure for overhead lines

2) using **tab. 1** we determine the mathematical cross section and the rope diameter

- if not stated in **tab. 1**, to be calculated
- nominal cross-section is specified (= cross-section Al)
- **ex.:** Alfe 6 and S = 300 mm² (it is nominal, we want a matheatical)

  Al : Fe = 6 : 1 => mathematically

  S = (300/6).7

  => we have **S** and **d** conductors [mm², mm], from which we determine:

cross-section Fe $S_{Fe} = \frac{S}{7}$

cross-section Al $S_{Al} = 6 \cdot \frac{S}{7}$

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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
- solution procedure for overhead lines

- VHV lines are often solved with bundled conductors, i.e. each phase is composed of multiple conductors.
  - radius of the doublebundle $r_{sv2} = \sqrt{r \cdot m}$
  - triplebundle $r_{sv3} = \sqrt[3]{r \cdot m^2}$
  - equivalent radius (**k ... see tab. 2**)
    $r_e = k \cdot r$ (includes internal inductance)
  - equival. radius of the double- $r_{esv2} = \sqrt{r_e \cdot m}$
    triplebundle $r_{esv3} = \sqrt[3]{r_e \cdot m^2}$

    m ... distance of wires in the sheaf

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

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Passive line parameters (3) – theory

Resistance

- Relationship for resistance in DC circuits is:

$$R_{ss} = \frac{\rho \cdot l}{S} \quad [\Omega]$$

  - where: ρ ... resistivity (usually at a temperature 20°C) [μΩm]
    ρ_{20} for Al: 0,02941 μΩm
    Cu: 0,01786 μΩm
    Fe: 0,130 μΩm
    l ... conductor length [m]
    S ... conductor cross section [mm²]
- For most calculations, this relationship is sufficiently accurate even for AC circuits.

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Passive line parameters (4) – theory

Resistance – continuation

- If the results of the calculation depend on the accuracy of the determination of resistance, then it is necessary to consider additional influences, which can be expressed by multiple coefficients:

$$R = R_{ss} \cdot k_\upsilon \cdot k_s \cdot k_e \cdot k_p$$

- k_υ - respects change R due to temperature (over 100 °C)

$$k_\upsilon = 1 + \alpha(\upsilon - \upsilon_{20}) + \beta(\upsilon - \upsilon_{20})^2$$

- k_s - respects skineffect (see below)
- k_e - respects the wires twisting in the rope (see scriptum)
- k_p - respects movement of hanging conductors (see scriptum)

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Calculation of passive line parameters
- solution procedure for overhead lines

3) calculation of individual passive parameters

- **Resistance** [Ω/km]
  - $R_{Al} = \frac{\rho_{Al} \cdot l}{S_{Al}}$ ρ_{Al} = 0,02941 μΩm, l = 1000 m
  - $R_{Fe} = \frac{\rho_{Fe} \cdot l}{S_{Fe}}$ ρ_{Fe} = 0,13 μΩm

connected in parallel Al and Fe

  - $R = \frac{1}{\frac{1}{R_{Fe}} + \frac{1}{R_{Al}}}$ ... for a simple conductor (for bundle => the number of wires in parallel) !!!

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Calculation of passive line parameters
- solution procedure for overhead lines

- Influence of skineffect (there is no need to count for our networks)
  - $R'_{Fe} = k \,.\, R_{Fe}$
    - where: $k = 1 + \frac{1}{12}\left(\frac{m}{2}\right)^4 - \frac{1}{180}\left(\frac{m}{2}\right)^8 + \ldots$

$$m = \frac{\pi \cdot d_{Fe}}{10}\sqrt{\frac{2 \cdot f \cdot \mu_r}{\rho_{Fe} \cdot 10^9}}$$; f = 50Hz ; μ_r = 1000

  - $R'_{Al} = k \,.\, R_{Al}$
    - where: $k = 1 + 7{,}5 \,.\, f^2 \,.\, d_{Al}^4 \,.\, 10^{-11}$ d [mm]

$$R' = \frac{1}{\frac{1}{R'_{Fe}} + \frac{1}{R'_{Al}}}$$

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Passive line parameters (5) – theory

Inductance

- Wire inductance is composed of **self** and **mutual** inductance
- Self inductance contains both **internal** and **external** inductance
- Considering the equally loaded transposed line, we can assume the same inductance in all phases. This inductance, called **"operating"**, is based on the average of the inductances of the individual phases

$$L_p = \frac{1}{3}(L_1 + L_2 + L_3)$$

- The derivation of the following relationships is indicated in the scriptum

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Calculation of passive line parameters
- solution procedure for overhead lines

- **Inductance**
  - Operating induktance (for symmetrical state)

$$L = 0{,}46 \cdot \log \frac{d_s}{r_{e(sv)}} \qquad [\text{mH/km , mm}]$$

    - in asymmetric state it is a phrase. and back folder
  - Zero folder
    - to keep the ground. rope $L_0 = k \,.\, L$, **k ... see tab. 3**
    - without grounding rope

$$L_0 = 0{,}46 \cdot \log \frac{h_s^3}{d_s^2 \cdot r_{e(sv)}}$$

- **Inductive reactance**

$X = \omega \cdot L$; $X_0 = \omega \cdot L_0$ [Ω/km] $\omega = 2\pi f$

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Calculation of passive line parameters
- solution procedure for overhead lines

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. č. 3

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Passive line parameters (6) – theory

Capacity

- To calculate the so-called **operating capacity** the same assumptions apply as for **operating inductance**, i.e. symmetrical line with symetrical load.
- Capacity calculation is based on the determination of potential coefficients **D** and **D´**, which are for symmetrically loaded symmetrical lines the average of the potential coefficients of the individual phases.

$$D = \frac{1}{3}(D_{11} + D_{22} + D_{33}) \qquad D' = \frac{1}{3}(D_{12} + D_{13} + D_{23})$$

- The derivation of the following relationships is again indicated in the scriptum for KEE/TPR subject.

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Calculation of passive line parameters
- solution procedure for overhead lines

- **Capacity**
  - Operational (sequential, reverse folder)

$$C = \frac{1}{D - D'} \quad [F/km]$$

  - Zero folder
    - line with grounding rope $C_0 = \frac{1}{D + 2D' - 3D_r}$ [F/km]
    - without grounding rope $C_0 = \frac{1}{D + 2D'}$ [F/km]
- **Capacitive susceptance**

$B = \omega \cdot C$; $B_0 = \omega \cdot C_0$ [S/km]

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Calculation of passive line parameters
- solution procedure for overhead lines

- Potential factors (coeficients)
  - for simple power line
    - **own**

$$D = 41{,}3 \cdot 10^6 \cdot \log \frac{2h_s}{r_{(sv)}} \quad [km/F]$$

    - **mutual**

$$D' = 41{,}3 \cdot 10^6 \cdot \log \frac{\sqrt{4h_s^2 + d_s^2}}{d_s} \quad [km/F]$$

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Calculation of passive line parameters
- solution procedure for overhead lines

- for double power line

$$D = D_I + D_{I,II}$$

$$D' = D_I' + D_{I,II}'$$

- D_I, D_I' ... we determine as D, D´for simple line
- $D_{I,II}$, $D_{I,II}'$ ... ensure the influence of the 2nd line

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

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

$$d_s = \frac{\sqrt[3]{d_{12} \cdot d_{13} \cdot d_{23}}\sqrt[3]{d_{12}' \cdot d_{13}' \cdot d_{23}'}}{\sqrt[3]{d_{11}' \cdot d_{22}' \cdot d_{33}'}}$$

d_s'' ← d_s ; d_s' ← d_s'

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Calculation of passive line parameters
- solution procedure for overhead lines

- respecting the grounding rope
  - at **C** does not apply because the resultant $\mathbf{D_v = D - D_r}$ and $\mathbf{D_v' = D' - D_r}$

$$C = \frac{1}{D_v - D_v'} = \frac{1}{D - D_r - D' + D_r} = \frac{1}{D - D'}$$

  - at only $\mathbf{C_0}$ (see formulas for zero folder with ground. rope)

$$D_r = \frac{D_{vz}^2}{D_{zz}}$$ ... ensures the influence of the ground. ropes (one rope)

$$D_{vz} = 41{,}3 \cdot 10^6 \cdot \log \frac{\sqrt{4h_s h_z + d_{zs}^2}}{d_{zs}}$$

$$D_{zz} = 41{,}3 \cdot 10^6 \cdot \log \frac{2h_z}{r_z}$$

r_z ... the radius of the grounding rope

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Calculation of passive line parameters
- solution procedure for overhead lines

- $D_r = \frac{2D_{vz}'^2}{D_{zz} + D_z}$ ... for 2 grounding ropes

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

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

d_z ... distance grouding ropes apart

D_{zz} ... see calculation with one ground. rope

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Passive line parameters (7) – theory

Conductance

- Conductance is caused both by **imperfect insulation** and by **corona**
- In the calculation of current and voltage conditions in networks in normal and obnormal states the conductance is **usually neglected**

What influences the conductance size :

- **Conductance by imperfect insulation** - insulator shape, insulator material, air humidity, insulator purity, conductor spacing
- **Conductance by corona** - atmospheric conditions, maximum electric field gradient (operating voltage, distance between conductors, conductor radius, conductor surface irregularities)

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Calculation of passive line parameters
- solution procedure for overhead lines

- **Conductance**
  - At overhead lines are usually neglected because is about 3 orders smaller than **B**
  - **by imperfect insulation**

$$G = \frac{1}{R_i} \quad [S/km]$$

R_i ... insulation resistance (**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

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

Tab. 4

  - **losses**

$$\Delta P = U_s^2 \cdot G \quad [W/km]$$

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Calculation of passive line parameters
- solution procedure for overhead lines

- **by corona**
  - we calculate **from losses** by corona (e.g.: Peek 's formula)

$$\Delta P = 3 \cdot 2{,}44 \frac{f + 25}{\delta} \sqrt{\frac{r}{d_s}} \left(U_{max\ fáz} - k \cdot U_p\right)^2 \quad [W/km]$$

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

  - at first we calculate

$$U_p = 4{,}92 \cdot m \cdot r \cdot \delta \cdot \log \frac{d_s}{r} \quad [kV, mm]$$

    - where:

m = 0,87 ... twisting ropes (**tab. 8**)

U_p ... initial voltage of the corona

  - $U_p > U_{max\ fáz}$ (recalculate from **tab. 5**) => the corona does not arise

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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} [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
- solution procedure for overhead lines

- Corona conductance - cont.
  - $G = \frac{\Delta P}{U_s^2}$ [S/km]
  - for bundle conductors we do not count G by corona acording to Peek 's formula, the result would be very inaccurate (we prefer a table value)
  - for HV the corona does not count

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Next time

- Transformers
  - substitute schema and procedure of calculation of two-winding transformer passive parameters

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