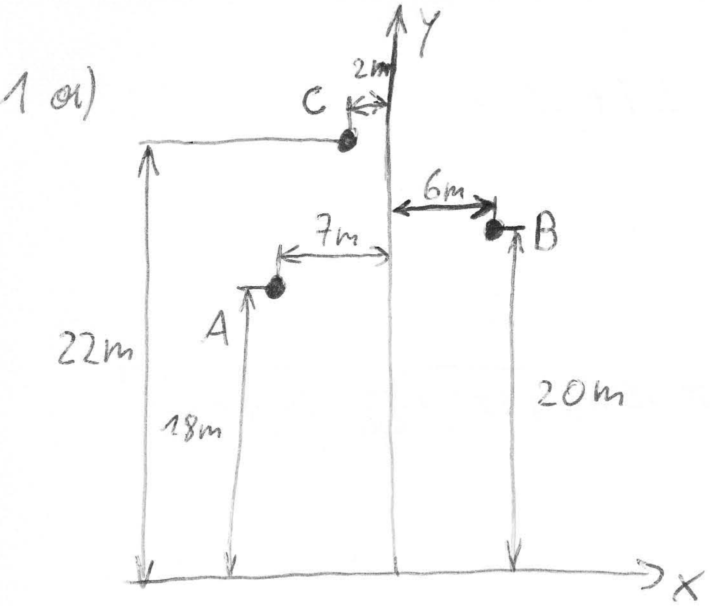
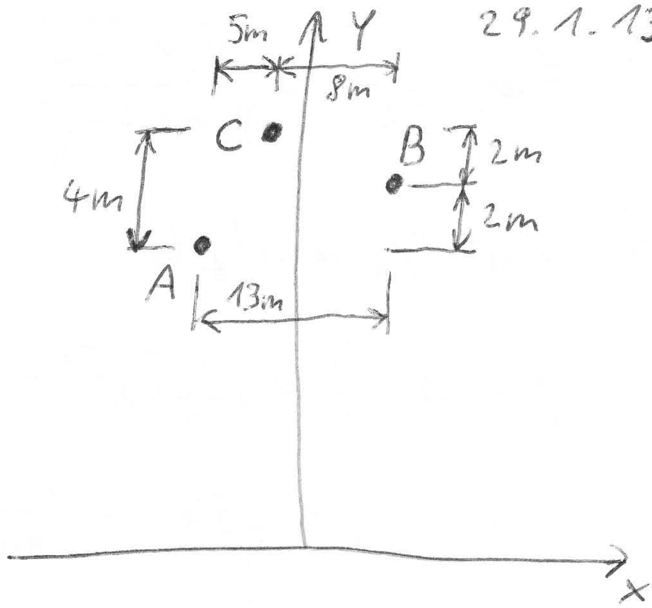
29.1.13

1 a)





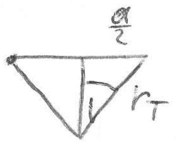
b) $D_{AB} = \sqrt{(13m)^2 + (2m)^2} = 13{,}15\,m$

$D_{BC} = \sqrt{(8m)^2 + (2m)^2} = 8{,}246\,m$

$D_{AC} = \sqrt{(5m)^2 + (4m)^2} = 6{,}403\,m$

$D = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{AC}} = \sqrt[3]{13{,}15m \cdot 8{,}246m \cdot 6{,}403m}$

$= 8{,}855\,m$



$\sin\left(\frac{\pi}{3}\right) = \frac{\frac{a}{2}}{r_T}$

$r_B = \sqrt[n]{n \cdot \sqrt{\frac{A}{\pi}} \cdot \left(\frac{a}{2\sin\left(\frac{\pi}{3}\right)}\right)^{n-1}}$

$= \sqrt[3]{3 \cdot \sqrt{\frac{187{,}233\,mm^2}{\pi}} \cdot \left(\frac{200\,mm}{2 \cdot \sin\left(\frac{\pi}{3}\right)}\right)^2} = 67{,}59\,mm$

$L_B' = \frac{\mu_0}{2\pi}\left(\ln\left(\frac{D}{r_B}\right) + \frac{1}{n \cdot 4}\right) = \frac{4 \cdot \pi \cdot 10^{-7}\frac{H}{m}}{2\pi}\left(\ln\left(\frac{8{,}855m}{0{,}06759m}\right) + \frac{1}{4 \cdot 3}\right)$

$= 991{,}7\,\frac{nH}{m} = 991{,}7\,\frac{\mu H}{km}$

$C_B' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{D}{r_B}\right)} = \frac{2\pi \cdot 8{,}854\frac{pF}{m}}{\ln\left(\frac{8{,}855m}{0{,}06759m}\right)} = 11{,}41\,\frac{pF}{m} = 11{,}41\,\frac{nF}{km}$

1 c) $Z_W = \sqrt{\frac{L_B'}{C_B'}} = \sqrt{\frac{991{,}7\frac{\mu H}{km}}{11{,}41\frac{nF}{km}}} = 294{,}8\,\Omega$

d) $\underline{U}_1 = \underline{U}_2 \cosh(\gamma l)$

$\gamma = j\beta = j\omega\sqrt{L_B' C_B'} = j\,2\pi\, 50\,Hz \sqrt{991{,}7\frac{\mu H}{km} \cdot 11{,}41\frac{nF}{km}}$

$= j\,1{,}057 \cdot 10^{-3} \frac{1}{km}$

$\cosh(j\beta l) = \cos(\beta l)$

$\underline{U}_2 = \frac{U_1}{\cos(\beta l)} = \frac{380kV}{\cos(1{,}057\cdot 10^{-3}\frac{1}{km} \cdot 400km)} = 416{,}7kV$

e) $S_{Therm} = \sqrt{3}\, U_{12}\, I_1 = \sqrt{3}\, U_{Nenn} \cdot 3 \cdot I_{max} = \sqrt{3} \cdot 380kV \cdot 3 \cdot 346A$

$= 683{,}2MVA$

f) $\underline{Z}_{(1)} = (35 + j35)\,\Omega$ weil es ein symmetrisches System ist

g) $\sinh(j\beta l) = j\sin(\beta l) \qquad \underline{Z}_2 = \underline{Z}_{(1)}$

$\underline{Z}_1 = \frac{\underline{U}_1}{\underline{I}_1} = \frac{\cos(\beta l)\,\underline{U}_2 + j\sin(\beta l)\frac{\underline{Z}_W}{\underline{Z}_2}\underline{U}_2}{j\sin(\beta l)\frac{\underline{U}_2}{\underline{Z}_W} + \cos(\beta l)\frac{\underline{U}_2}{\underline{Z}_2}}$

$\underline{Z}_1 = \frac{\cos(1{,}057\cdot 10^{-3}\frac{1}{km}\cdot 400km) + j\sin(1{,}057\cdot 10^{-3}\frac{1}{km}\cdot 400km)\frac{294{,}8\Omega}{(35+35j)\Omega}}{j\sin(1{,}057\cdot 10^{-3}\frac{1}{km}\cdot 400km)\frac{1}{294{,}8\Omega} + \cos(1{,}057\cdot 10^{-3}\frac{1}{km}\cdot 400km)\frac{1}{(35+j35)\Omega}}$

$= (46{,}82 + j174{,}5)\,\Omega$

2a) $E_{Pump} = \rho V_{us} g \Delta h_1 = 1000 \frac{kg}{m^3} \cdot 20 \cdot 10^6 m^3 \, 9{,}81 \frac{m}{s^2} \cdot 150 m$

$= 29{,}43 TJ$

$E_{Pump,el} = \frac{E_{Pump}}{\eta_{Pump}} = \frac{29{,}43 TJ}{0{,}85} = 34{,}62 TJ$

	V_{OS}	V_{US}
Anfang	leer	voll
Ende	voll	leer

b) $E_{Turb,el} = (\eta_{Turb1} \cdot V_{OS} \cdot \Delta h_1 + \eta_{Turb2} \cdot V_{US} \cdot \Delta h_2) \rho g$

$= (0{,}93 \cdot 20 \cdot 10^6 m^3 \cdot 150 m + 0{,}9 \cdot 20 \cdot 10^6 m^3 \cdot 564 m) 1000 \frac{kg}{m^3} \, 9{,}81 \frac{m}{s^2}$

$= 127{,}0 TJ$

	V_{OS}	V_{US}
Anfang	voll	voll
Ende	leer	leer

c) $E_{Verluste} = E_{Pump,el} - E_{Pump} + (1 - \eta_{Turb1}) \rho V_{OS} g \Delta h_1$

$= 34{,}62 TJ - 29{,}43 TJ + (1 - 0{,}93) \cdot 1000 \frac{kg}{m^3} \cdot 20 \cdot 10^6 m^3 \cdot$

$\cdot 9{,}81 \frac{m}{s^2} \cdot 150 m$

$= 7{,}254 TJ$

d) $t_{Pump} = \frac{V_{US}}{Q_{N1}} = \frac{20 \cdot 10^6 m^3}{25 \frac{m^3}{s}} = 222{,}2 h$

e) $t_{Turb} = \frac{V_{OS}}{Q_{N1}} + \frac{V_{US}}{Q_{N2}} = \frac{20 \cdot 10^6 m^3}{25 m^3/s} + \frac{20 \cdot 10^6 m^3}{35 m^3/s} = 381{,}0 h$

3a) $a = \frac{230 \cdot 10^6 €}{19{,}9\,MW_{el}} = 11{,}56 \frac{€}{W_{el}} = 11{,}56 \cdot 10^3 \frac{€}{kW_{el}}$

$T_m = \frac{110 \frac{GWh}{a}}{19{,}9\,MW_{el}} = 5528 \frac{h}{a}$

$\alpha = \frac{(q-1) \cdot q^n}{q^n - 1} = \frac{(1{,}07-1) \cdot 1{,}07^{25}}{1{,}07^{25} - 1} = 0{,}08581 \frac{1}{a}$

$k = \frac{\alpha a + c}{T_m} + \underbrace{b + d}_{0} = \frac{0{,}08581 \frac{1}{a} \cdot 11{,}56 \cdot 10^3 \frac{€}{kW_{el}} + 0{,}06 \frac{1}{a} \cdot 11{,}56 \cdot 10^3 \frac{€}{kW_{el}}}{5528 \frac{h}{a}}$

$= 0{,}3049 \frac{€}{kW_{el}h}$

b) $b = \frac{0{,}40 \frac{€}{m^3} \cdot 3{,}6 \frac{MJ}{kWh}}{0{,}58 \cdot 30 \frac{MJ}{m^3}} = 0{,}08276 \frac{€}{kW_{el}h}$

$k = \frac{\alpha a + c}{T_m} + b + d = \frac{0{,}08581 \frac{1}{a} \cdot 650 \frac{€}{kW_{el}} + 95 \frac{€}{kW_{el}a}}{5528 \frac{h}{a}} + 0{,}08276 \frac{€}{kW_{el}h} +$

$+ 0{,}001 \frac{€}{kW_{el}h}$

$= 0{,}1110 \frac{€}{kW_{el}h}$

c) $k_{GuD} = \frac{(\alpha + 0{,}06 \frac{1}{a}) \cdot a_{Gema}}{T_m}$

$a_{Gema} = \frac{k_{GuD} \cdot T_m}{\alpha + 0{,}06 \frac{1}{a}} = \frac{0{,}1110 \frac{€}{kW_{el}h} \cdot 5528 \frac{h}{a}}{0{,}08581 \frac{1}{a} + 0{,}06 \frac{1}{a}} = 4208 \frac{€}{kW_{el}}$

d) $k = \frac{\alpha a' + c'}{T_m'} = \frac{(0{,}08581 \frac{1}{a} + 0{,}06 \frac{1}{a}) \cdot \left(\frac{(230+25) \cdot 10^6 €}{19{,}9\,MW_{el}}\right)}{1{,}15 \cdot 5528 \frac{h}{a}} = 0{,}2939 \frac{€}{kW_{el}}$

niedrigere Stromgestehungskosten $\Rightarrow$ sinnvoll

5a) $Z_Q = c \cdot \frac{U_2^2}{S''_{kQ}} = 1{,}1 \cdot \frac{(30kV)^2}{4{,}5GVA} = 0{,}220\,\Omega$

$$Z_Q = \sqrt{R_Q^2 + X_Q^2} = X_Q \sqrt{(0{,}5)^2 + 1^2}$$

$$X_Q = \frac{Z_Q}{\sqrt{0{,}5^2+1}} = \frac{0{,}220\,\Omega}{\sqrt{0{,}5^2+1}} = 0{,}1968\,\Omega$$

$$R_Q = 0{,}5\,X_Q = 0{,}5 \cdot 0{,}1968\,\Omega = 0{,}09840\,\Omega$$

$$\underline{Z}_Q = (0{,}09840 + j\,0{,}1968)\,\Omega$$

b) $Z_T = u_k \frac{U_2^2}{S_N} = 0{,}16 \cdot \frac{(30kV)^2}{40MVA} = 3{,}6\,\Omega$

$$R_T = P_K \frac{U_2^2}{S_N^2} = 500kW \frac{(30kV)^2}{(40MVA)^2} = 0{,}2813\,\Omega$$

$$X_T = \sqrt{Z_T^2 - R_T^2} = \sqrt{(3{,}6\,\Omega)^2 - (0{,}2813\,\Omega)^2} = 3{,}589\,\Omega$$

$$\underline{Z}_T = (0{,}2813 + j\,3{,}589)\,\Omega$$

c) $R_L = R' \cdot l = 0{,}24\,\frac{\Omega}{km} \cdot 50km = 12\,\Omega$

$$X_L = \omega \cdot L' l = 2\pi \cdot 50Hz \cdot 1{,}145\,\frac{mH}{km} \cdot 50km = 17{,}99\,\Omega$$

$$\underline{Z}_L = (12 + j\,17{,}99)\,\Omega$$

d) $\underline{I}_{a,F} = 0$

$$\underline{U}_{bN,F} = \underline{U}_{cN,F}$$

$$\underline{I}_{b,F} + \underline{I}_{c,F} = 0$$

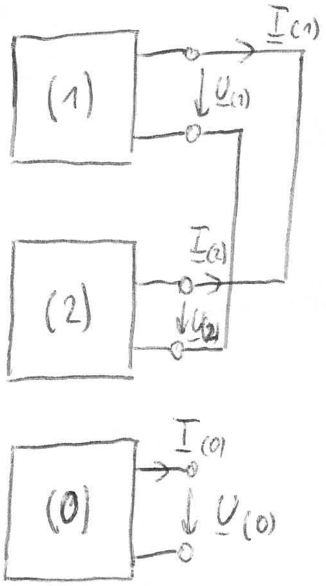
$$\Rightarrow \underline{I}_{(0)} = \frac{1}{3}(\underline{I}_{a,F} + \underline{I}_{b,F} + \underline{I}_{c,F}) = 0$$

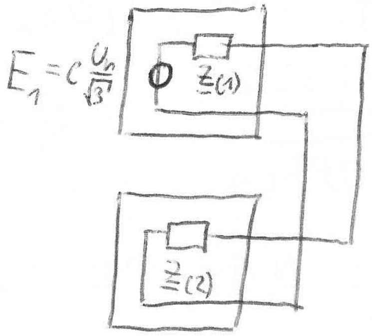
$$\underline{I}_{(1)} = \frac{1}{3}(\underline{I}_{a,F} + \underline{a}\,\underline{I}_{b,F} + \underline{a}^2\underline{I}_{c,F}) = \frac{1}{3}(\underline{a}\,\underline{I}_{b,F} - \underline{a}^2\underline{I}_{b,F})$$

$$\underline{I}_{(2)} = \frac{1}{3}(\underline{I}_{a,F} + \underline{a}^2\underline{I}_{b,F} + \underline{a}\,\underline{I}_{c,F}) = \frac{1}{3}(\underline{a}^2\underline{I}_{b,F} - \underline{a}\,\underline{I}_{b,F}) = -\underline{I}_{(1)}$$

$$\underline{U}_{(1)} = \frac{1}{3}\left(\underline{U}_{aN,F} + \underline{a}\,\underline{U}_{bN,F} + \underline{a}^2\,\underline{U}_{cN,F}\right) = \frac{1}{3}\left(\underline{U}_{aN,F} + \underline{a}\,\underline{U}_{bN,F} + \underline{a}^2\,\underline{U}_{bN,F}\right)$$

$$\underline{U}_{(2)} = \frac{1}{3}\left(\underline{U}_{aN,F} + \underline{a}^2\,\underline{U}_{bN,F} + \underline{a}\,\underline{U}_{cN,F}\right) = \frac{1}{3}\left(\underline{U}_{aN,F} + \underline{a}^2\,\underline{U}_{bN,F} + \underline{a}\,\underline{U}_{bN,F}\right) = \underline{U}_{(1)}$$





Symmetrisches System bis Kurzschluss

$$\Rightarrow \underline{Z}_{(1)} = \underline{Z}_{(2)} = R_Q + R_T + R_L + j(X_Q + X_T + X_L)$$

$$= (0{,}09840 + 0{,}2813 + 12 + j(0{,}1968 + 3{,}589 + 17{,}99))\,\Omega$$

$$= (12{,}38 + j\,21{,}78)\,\Omega$$

$$\underline{Z}_k = \underline{Z}_{(1)} + \underline{Z}_{(2)} = 2\cdot(12{,}38 + j\,21{,}78)\,\Omega$$

$$= (24{,}76 + j\,43{,}56)\,\Omega$$

e) $$I_{(1)} = \frac{E_1}{|\underline{Z}_{(1)} + \underline{Z}_{(2)}|} = \frac{1{,}1\cdot 30\,\mathrm{kV}}{\sqrt{3}\cdot|30\,\Omega + j\,40\,\Omega|} = 381{,}1\,\mathrm{A}$$

$$I''_{k2p} = |\underline{I}_b| = |\underline{I}_{(0)} + \underline{a}^2\,\underline{I}_{(1)} + \underline{a}\,\underline{I}_{(2)}| = |\underline{a}^2 - \underline{a}|\cdot|\underline{I}_{(1)}| =$$

$$= |-j\sqrt{3}|\cdot 381{,}1\,\mathrm{A} = 660{,}1\,\mathrm{A}$$

f) $$Z_Q = c\,\frac{U_{nQ}^2}{S_{kQ}} = 1{,}1\cdot\frac{(110\,\mathrm{kV})^2}{4{,}5\,\mathrm{GVA}} = 2{,}958\,\Omega$$

$$I''_{k2p,Prim} = \sqrt{3}\,\frac{E_1}{|\underline{Z}_{(1)} + \underline{Z}_{(2)}|} = \frac{\sqrt{3}\cdot 1{,}1\cdot 110\,\mathrm{kV}}{\sqrt{3}\cdot 2\cdot 2{,}958\,\Omega} = 20{,}45\,\mathrm{kA}$$

5 g) $i_p = \sqrt{2}\left(1 + e^{-t\frac{R}{L}}\right) I''_{k3p} =$

$$= \sqrt{2}\left(1 + e^{-10ms \cdot \frac{15\Omega \cdot 2\pi \cdot 50Hz}{20\Omega}}\right) \cdot 0{,}95kA = 1{,}471kA$$