20.6.12

1a) $D_{AB} = \sqrt{(6m-(-7m))^2 + (25m-20m)^2} = 13,93m$

$D_{BC} = \sqrt{(-7m-(-4m))^2 + (20m-28m)^2} = 8,544m$

$D_{AC} = \sqrt{(6m-(-4m))^2 + (25m-28m)^2} = 10,44m$

$D = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{AC}} = \sqrt[3]{13,93m \cdot 8,544m \cdot 10,44m} = 10,75m$

$r_B = \sqrt[n]{n \cdot r \cdot r_T^{n-1}} = \sqrt[4]{4 \cdot \sqrt{\frac{176,714mm^2}{\pi}} \cdot \left(\frac{300mm}{\sqrt{2}}\right)^3} = 130,1mm$

$r = \sqrt{\frac{A}{\pi}} \qquad r_T = \frac{a}{\sqrt{2}}$

$L_B' = \frac{\mu_0}{2\pi}\left(\ln\left(\frac{D}{r_B}\right) + \frac{1}{4n}\right) = \frac{4\pi \cdot 10^{-7}\frac{Vs}{m}}{2\pi}\left(\ln\left(\frac{10,75m}{0,1301m}\right) + \frac{1}{4 \cdot 4}\right)$

$= 895,4\frac{nH}{m}$

b) $R' = \frac{\rho}{A} \cdot \frac{\beta}{4} = \frac{0,0269\frac{\Omega mm^2}{m}}{176,714mm^2} \cdot \frac{1,07}{4} = 40,72\ 10^{-6}\frac{\Omega}{m}$ (4 Leiter)

$\alpha \approx \frac{R'}{2}\sqrt{\frac{C'}{L'}} + 0 = \frac{40,72 \cdot 10^{-6}\frac{\Omega}{m}}{2}\sqrt{\frac{12,6\frac{pF}{m}}{895,4\frac{nH}{m}}} = 76,38 \cdot 10^{-9}\frac{1}{m}$

$\beta \approx \omega\sqrt{L'C'} = 2\pi\ 50Hz\sqrt{895,4\frac{nH}{m} \cdot 12,6\frac{pF}{m}} = 1,055 \cdot 10^{-6}\frac{1}{m}$

$\gamma = \alpha + j\beta = (76,38 \cdot 10^{-9} + j\,1,055 \cdot 10^{-6})\frac{1}{m}$

c) $\underline{Z}_W = \sqrt{\frac{R'+j\omega L'}{G'+j\omega C'}} = \sqrt{\frac{40,72 \cdot 10^{-6}\frac{\Omega}{m} + j2\pi \cdot 50Hz \cdot 895,4\frac{nH}{m}}{j2\pi 50Hz \cdot 12,6\frac{pF}{m}}} = (267,3 - j19,24)\Omega$

d) $P_{nat} = \frac{U_n^2}{|\underline{Z}_W|} = \frac{(380kV)^2}{|267,3 - j19,24|\Omega} = 538,9MW$

$\underline{I}_2 = 0$

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

$\underline{I}_1 = \frac{\underline{U}_2}{\underline{Z}_W}\sinh(\gamma \ell)$

$$\underline{Z}_1 = \frac{\underline{U}_1}{\underline{I}_1} = \underline{Z}_w \frac{\cosh(\gamma \ell)}{\sinh(\gamma \ell)}$$

$$= (267{,}3 - j\,19{,}24)\,\Omega \cdot \frac{807{,}1 + j\,27{,}12}{36{,}96 + j\,592{,}2}$$

$$= (8{,}768 - j\,364{,}6)\,\Omega$$

$$\underline{S}_1 = \frac{\underline{U}_1^2}{\underline{Z}_1^*} = \frac{(380\,kV)^2}{(8{,}768 + j\,364{,}6)\,\Omega} = (9{,}519 - 395{,}8)\,MVA$$

$$\cosh(\gamma \ell) = \cos(\beta \ell) \cdot \cosh(\alpha \ell) + j \sin(\beta \ell) \sinh(\alpha \ell)$$

$$= 807{,}1 \cdot 10^{-3} + j\,27{,}12 \cdot 10^{-3}$$

$$\sinh(\gamma \ell) = \cos(\beta \ell) \cdot \sinh(\alpha \ell) + j \sin(\beta \ell) \cosh(\alpha \ell)$$

$$= 36{,}96 \cdot 10^{-3} + j\,592{,}2 \cdot 10^{-3}$$

Da $\underline{Z}_2 = \infty > \underline{Z}_w \Rightarrow$ Überlastung $\rightarrow$ Kompensation durch Parallelinduktivität

$$\underline{Z}_2 = j\omega L_2 = \frac{\underline{U}_2}{\underline{I}_2}$$

$$U_2 \leq 1{,}1 \cdot U_n = 1{,}1 \cdot U_1$$

$$\underline{U}_1 = \cosh(\gamma \ell)\, \underline{U}_2 + \underline{Z}_w \cdot \frac{\underline{U}_2}{\underline{Z}_2} \sinh(\gamma \ell)$$

$$\underline{Z}_2 = \frac{\underline{Z}_w \cdot \underline{U}_2 \sinh(\gamma \ell)}{\underline{U}_1 - \cosh(\gamma \ell)\, \underline{U}_2} \quad \text{mit } \underline{U}_2 = U_2 = 1{,}1\, U_1$$

$$\underline{Z}_2 = \frac{\underline{Z}_w \cdot 1{,}1 \sinh(\gamma \ell)}{1 - 1{,}1 \cosh(\gamma \ell)} = \frac{(267{,}3 - j\,19{,}24)\,\Omega \cdot 1{,}1 \cdot (36{,}96 + j\,592{,}2)\,10^{-3}}{1 - 1{,}1\,(807{,}1 + j\,27{,}12) \cdot 10^{-3}}$$

$$= (-188{,}9 + j\,1{,}495 \cdot 10^3)\,\Omega \approx j\,|\underline{Z}_2| = j\,1507\,\Omega$$

$$L_2 = \frac{|\underline{Z}_2|}{\omega} = \frac{1507\,\Omega}{2\pi \cdot 50\,Hz} = 4{,}797\,H$$

c) $$P_{nat} = \frac{U_n^2}{Z_w} = \frac{380\,kV^2}{|267{,}3 - j\,19{,}24|\,\Omega} = 538{,}9\,MW$$

2 a)

$$a = \frac{230 \cdot 10^6 €}{19{,}9 \cdot 10^3 kW} = 11{,}56 \frac{10^3 €}{kW}$$

$$c = \frac{0{,}06}{a} \cdot a = \frac{0{,}06}{a} \cdot 11{,}56 \frac{€}{kW} = 0{,}6936 \frac{10^3 €}{kW a}$$

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

$$T_m = \frac{110 GWh/a}{19{,}9 MW_{el}} = 5528 \frac{h}{a} \qquad b = d = 0$$

$$k = \frac{\alpha \cdot a + c}{T_m} = \frac{0{,}08581 \frac{1}{a} \cdot 11{,}56 \frac{10^3 €}{kW} + 0{,}6936 \frac{10^3 €}{kW a}}{5528 \frac{h}{a}} = 0{,}3049 \frac{€}{kWh}$$

b) $a = 650 \frac{€}{kW_{el}}$

$c = 95 \frac{€}{kW_{el} a}$

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

$d = 0{,}001 \frac{€}{kWh_{el}}$

$$k = \frac{\alpha a + c}{T_m} + b + d = \frac{0{,}08581 \frac{1}{a} \cdot 650 \frac{€}{kWh_{el}} + 95 \frac{€}{kW_{el} a}}{5528 \frac{h}{a}} + 0{,}08276 \frac{€}{kWh_{el}} + 0{,}001 \frac{€}{kWh_{el}}$$

$$= 0{,}1110 \frac{€}{kWh}$$

c) $k = \frac{\alpha \cdot a_{sol} + 0{,}06\frac{1}{a} \cdot a_{sec}}{T_m}$

$a_{sol} = \frac{k \cdot T_m}{\alpha + 0{,}06\frac{1}{a}} = \frac{0{,}111\frac{€}{kWh} \cdot 5528\frac{h}{a}}{0{,}08581\frac{1}{a} + 0{,}06\frac{1}{a}} = 4208\frac{€}{kW}$

d) $a' = \frac{(230+40)\,10^6 €}{19{,}8\,MW} = 13{,}57 \cdot 10^3 \frac{€}{kW}$

$c' = 0{,}06\frac{1}{a} \cdot a' = 0{,}06\frac{1}{a} \cdot 13{,}57 \cdot 10^3 \frac{€}{kW} = 814{,}2\frac{€}{kWa}$

$k = \frac{\alpha \cdot a' + c'}{T_m'} = \frac{0{,}08581\frac{1}{a} \cdot 13{,}51 \cdot 10^3 \frac{€}{kW} + 814{,}2\frac{€}{kWa}}{1{,}1 \cdot 5528\frac{h}{a}} = 0{,}3245\frac{€}{kWh}$

höhere Stromgestehungskosten ⇒ keine sinnvolle Investition

4) a) $Z_Q = c \cdot \frac{U_2^2}{S_{kQ}''} = 1{,}1 \frac{(30kV)^2}{4GVA} = 0{,}2475\,\Omega$

$Z_Q = \sqrt{R_Q^2 + X_Q^2} = X_Q \sqrt{0{,}3^2+1^2}$

$X_Q = \frac{Z_Q}{\sqrt{0{,}3^2+1}} = \frac{0{,}2475\,\Omega}{\sqrt{0{,}3^2+1}} = 0{,}2371\,\Omega$

$R_Q = 0{,}3 \cdot X_Q = 0{,}3 \cdot 0{,}2371\,\Omega = 0{,}07113\,\Omega$

b) $Z_T = u_k \frac{U_2^2}{S_N} = 0{,}12 \frac{(30kV)^2}{40MVA} = 2{,}7\,\Omega$

$R_T = \frac{P_k}{S_N} \cdot \frac{U_2^2}{S_N} = \frac{430kW \cdot (30kV)^2}{(40MVA)^2} = 0{,}2419\,\Omega$

$X_T = \sqrt{Z_T^2 - R_T^2} = \sqrt{(2{,}7\Omega)^2 - (0{,}2419\Omega)^2} = 2{,}689\,\Omega$

c) $R_L = R' \cdot l = 0{,}15 \frac{\Omega}{km} \cdot 50km = 7{,}5\Omega$

$X_L = \omega L' \cdot l = 2\pi \cdot 50Hz \cdot 1 \frac{mH}{km} \cdot 50km = 15{,}71\,\Omega$

d) $Z_G = (R_Q + R_T + R_L) + j(X_Q + X_T + X_L) =$

$= 0{,}07113\,\Omega + 0{,}2419\Omega + 7{,}5\Omega + j(0{,}2371 + 2{,}689 + 15{,}71)\Omega =$

$= (7{,}813 + j\,18{,}64)\,\Omega$

e) $I_{k3p}'' = c \frac{U_2}{\sqrt{3}\,Z_G} = \frac{1{,}1 \cdot 30kV}{\sqrt{3} \cdot |7{,}813 + j18{,}64|\,\Omega} = 942{,}7A$

f) $i_p = \sqrt{2}\left(1 + e^{-t \cdot R_G \frac{\omega}{X_G}}\right) I_{k3p}'' = \sqrt{2}\left(1 + e^{-10ms \cdot 7{,}813\Omega \cdot \frac{2\pi 50Hz}{18{,}64\Omega}}\right) \cdot$

$\cdot 942{,}7A$

$= 1{,}690kA$

4g) $Z_{Q'} = c \cdot \frac{U_1^2}{S_{kQ}''} = 1{,}1 \frac{(110kV)^2}{4GVA} = 3{,}328\Omega$

$$I_{k3p}'' = c \cdot \frac{U_1}{\sqrt{3}\, Z_{Q'}} = 1{,}1 \frac{110kV}{\sqrt{3} \cdot 3{,}328\Omega} = 20{,}99kA$$

5a) $E = \rho \cdot V \cdot g \cdot \Delta h = 1000 \frac{kg}{m^3} \cdot 0{,}4 \cdot 60 \cdot 10^6 m^3 \cdot 9{,}81 \frac{m}{s^2} \cdot 231m$

$= 54{,}39TJ$

b) $E = m \cdot c_p \cdot \Delta T \Rightarrow \Delta T = \frac{E}{m \cdot c_p} = \frac{54{,}39 \cdot 10^{12} J}{0{,}75 \cdot 1000 \frac{kg}{m^3} \cdot 20 \cdot 10^6 m^3 \cdot 4{,}18 \cdot 10^3 \frac{J}{kgK}}$

$= 0{,}8675K$

c) $P_{el} = \eta_H \cdot \eta_T \cdot \eta_{el} \cdot (1-\varepsilon) \cdot \rho \cdot Q_N \cdot g \cdot \Delta h =$

$= 0{,}94 \cdot 0{,}9 \cdot 0{,}96 \cdot (1-0{,}02) \cdot 1000 \frac{kg}{m^3} \cdot 110 \frac{m^3}{s} \cdot 9{,}81 \frac{m}{s^2} \cdot 231m =$

$= 198{,}4MW$

d) $0{,}4 \cdot V_{OS} = 0{,}4 \cdot 60 \cdot 10^6 m^3 = 24 \cdot 10^6 m^3$

$(1-0{,}75) \cdot V_{OS} = (1-0{,}75) \cdot 20 \cdot 10^6 m^3 = 5 \cdot 10^6 m^3$ ← ist weniger

$t = \frac{0{,}25 \cdot V_{OS}}{Q_N} = \frac{5 \cdot 10^6 m^3}{110 \frac{m^3}{s}} = 12{,}63h$

e) $E = P_{el} \cdot t = 198{,}4MW \cdot 12{,}63h = 2{,}506GWh$