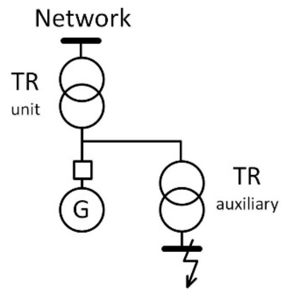
Example 1.1



Calculate an ideal symmetrical 3-phase short circuit current I''_{k3} [kA] in auxiliary 6 kV side according to the single line diagram. The generator is operated at its rated voltage $U_g = U_{gn} = 10$ kV. The network is operated at $U_n = 220$ kV. Neglect a contribution of current from motoric loads, consider HV system as an infinity bus.

Parameters:
Generator (G): $S_{gn} = 100$ MVA, $U_{gn} = 10$ kV, $x''_d = 15\%$
Unit transformer: $S_{utn} = 100$ MVA, $ratio: 10/220$ kV, $e_{kut} \approx x_{kut} = 15\%$
Auxiliary transformer: $S_{atn} = 20$ MVA, $ratio: 10/6$ kV, $e_{kat} \approx x_{kat} = 10\%$

$$S_B = S_{atn} = 20 \text{ MVA},\ U_B = 6 \text{ kV}$$

$$x_{ut} = e_{kut} \cdot \frac{S_B}{S_{utn}} . p_{at}^2 \cdot \left(\frac{U_{utpn}}{U_B}\right)^2 = 0,15 . \frac{20}{100} . \left(\frac{6}{10}\right)^2 . \left(\frac{10}{6}\right)^2 = 0,03$$

$$x_g = x''_d \cdot \frac{S_B}{S_{gn}} . p_{at}^2 \cdot \left(\frac{U_{gn}}{U_B}\right)^2 = 0,15 . \frac{20}{100} . \left(\frac{6}{10}\right)^2 . \left(\frac{10}{6}\right)^2 = 0,03$$

$$x_{ekv} = x_g \| x_{ut} + x_{at} = \frac{0,03 . 0,03}{0,03 + 0,03} + 0,1 = 0,115 = 11,5\%$$

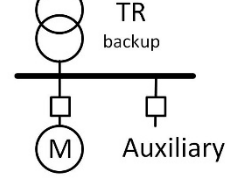
$$u_n = p_{at} . p_{ut} \cdot \frac{U_n}{U_B} = \frac{6}{10} . \frac{10}{220} . \frac{220}{6} = 1,\ u_g = p_{at} \cdot \frac{U_g}{U_B} = \frac{6}{10} . \frac{10}{6} = 1$$

$$u_{ekv} = \left(\frac{u_n}{x_{ut}} + \frac{u_g}{x_g}\right) . \left(\frac{1}{x_{ut}} + \frac{1}{x_g}\right)^{-1} = \frac{\frac{u_n}{x_{ut}} + \frac{u_g}{x_g}}{\frac{x_g + x_{ut}}{x_{ut} . x_g}} = \frac{u_n . x_g + u_g . x_{ut}}{x_g + x_{ut}} = \frac{1 . 0,3 + 1 . 0,3}{0,3 + 0,3} = 1$$

$$i_k = \frac{u_{ekv}}{x_{ekv}} = \frac{1}{0,115} = 8,696$$

$$I''_{k3} = i_k \cdot \frac{S_B}{\sqrt{3} . U_B} = 8,696 \frac{20}{\sqrt{3} . 6} = 16,74 \text{ kA}$$

Example 1.2



An auxiliary substation is fed by backup transformer as shown in the picture. Calculate auxiliary voltage U_{aux} [kV] during motor starting.
Parameters:
Network: U_n = 110 kV, infinity bus

Backup transformer: S_{nT} = 25 MVA, $e_k = 0,1$, $p = 110/10$ kV

Motor: $S_{nM} = 4$ MVA, $U_{nM} = 10$ kV, startup current: $i_{startM} = I_{startM} / I_{nM} = 4$ p.u.

Auxiliary (rest): $S_{aux} = 15$ MVA, $\cos\varphi_{aux} = 0{,}8$

$U_B = 10$ kV a $S_B = 25$ MVA

$$u_n = \frac{U_n}{U_B.p} = \frac{110}{10.\frac{110}{10}} = 1, \quad x_{TR} = e_k.\frac{S_B}{S_{nT}} = 0{,}1.\frac{25}{25} = 0{,}1$$

$$Q_{nM} = i_{start}.S_{nM} = 4.4 = 16 \text{ MVAr}, \; Q_{aux} = S_{aux}\sqrt{1-\cos^2\varphi_{aux}} = 15.0{,}6 = 9 \text{ MVAr}$$

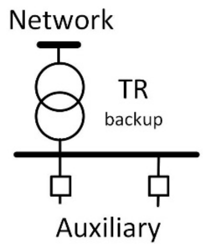
$$x_{start} = \frac{S_B}{Q_{tot}} = \frac{S_B}{Q_{aux}+Q_{nM}} = \frac{25}{9+16} = 1$$

$$u_{aux} = \frac{x_{start}}{x_{TR}+x_{start}} = \frac{1}{0{,}1+1} = 0{,}909$$

$$U_{aux} = u_{aux}.U_B = 0{,}909.10 = 9{,}09 \text{ kV}$$

Example 2.1

An auxiliary substation is fed by backup transformer as shown in the picture. Calculate auxiliary voltage U_{aux} [kV] during total auxiliary start-up.



Parameters:

Network: $U_n = 110$ kV, infinity bus

Backup transformer: $S_{nT} = 25$ MVA, $e_k = 0{,}1$, $p = 110/10$ kV

Auxiliary start-up parameters: $P_{start} = 10$ MW, $Q_{start} = 62{,}5$ MVAr

$U_B = 10$ kV a $S_B = 25$ MVA

$$u_n = \frac{U_n}{U_B.p} = \frac{110}{10.\frac{110}{10}} = 1, \quad x_{TR} = e_k.\frac{S_B}{S_{nT}} = 0{,}1.\frac{25}{25} = 0{,}1$$

$$x_{start} = \frac{S_B}{Q_{start}} = \frac{25}{62{,}5} = 0{,}4$$

$$u_{aux} = \frac{x_{start}}{x_{TR}+x_{start}} = \frac{0{,}4}{0{,}1+0{,}4} = 0{,}8$$

$$U_{aux} = u_{aux}.U_B = 0{,}8.10 = 8 \text{ kV}$$

Example 3.1

Conductors of three phase system 10,5 kV are rectangular, type Al 63x10 mm (one per phase), span length between supports is 1m and phase distance is 0,5m. Make a decision, which type of support do you select and whether a conductor use is suitable for conductor arrangement:

1) Horizontal
2) Vertical

Mounted clamp means total height elongation by 3,5 cm ($T = 0,035$ m)
Number of spans/supports: 4/5
Input data:

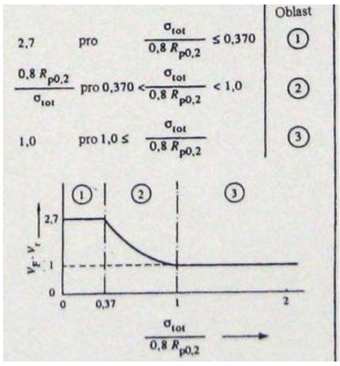
$d_m = 0,5$ m $\sigma_{0,2} = 120$ MPa

$I''_{k3} = 25$ kA $\kappa = 1,7$

(without respecting double CO)

For this case:

$V_\sigma.V_r = 1$ $V_F.V_r$



Typ nosníku a způsob upevnění			Typ		
nosník o jednom poli	A a B prosté podepření	A B	A	$\alpha_A = 0,5$ $\alpha_B = 0,5$	$\beta = 1$
	A : vetknutí B : prosté podepření	A B	B	$\alpha_A = 0,625$ $\alpha_B = 0,375$	$\beta = 0,73$
	A a B vetknutí	A B	C	$\alpha_A = 0,5$ $\alpha_B = 0,5$	$\beta = 0,5$
nosník o více polích o stejných rozpětích	2 pole	A B A	D	$\alpha_A = 0,375$ $\alpha_B = 1,25$	$\beta = 0,73$
	3 nebo více polí	A B B A	E	$\alpha_A = 0,4$ $\alpha_B = 1,1$	$\beta = 0,73$

Select a suitable support from following list

	Minimum 50 Hz (wet) withstand [kV]	Leakage distance [mm]	Maximum working cantilever load [kN]	Section length H [mm]	Diameter D [mm]
1.	75	174	5	130	60
2.	75	187	10	130	72
3.	75	195	16	130	90

Solution:

Peak short circuit current is:

$$i_{p3} = \kappa.\sqrt{2}.I''_{k3} = 1,7.\sqrt{2}.25 = 59,9 \text{ kA}$$

Force between main conductors for both cases:

$$F_{m3}=\frac{\mu_0}{2.\pi}.\frac{\sqrt{3}}{2}.i_{p3}^2.\frac{l}{d_m}=\frac{4.\pi.10^{-7}}{2.\pi}.\frac{\sqrt{3}}{2}.59,9^2.10^6.\frac{1}{0,5}=1,242\text{ kN}$$

Factors:

$\beta=0,73 \qquad V_\sigma.V_r=1 \qquad q.\sigma_{0,2}=1,5.120=180\text{ MPa}$

Force effects on conductors:

1) Vertical arrangement

$$Z=\frac{a.b^2}{6}=\frac{0,010.0,063^2}{6}=6,615.10^{-6}\text{ m}^3$$

$$\sigma_m=V_\sigma.V_r.\beta.\frac{F_{m3}.l}{8.Z}=1.0,73.\frac{1,242.10^3.1}{8.6,615.10^{-6}}=17,1\text{ MPa}$$

Conductors are OK, because

$\sigma_{tot}<q.\sigma_{0,2}$ i.e. $17.1<180$

2) Horizontal arrangement

$$Z=\frac{0,063.0,010^2}{6}=1,05.10^{-6}\text{ m}^3$$

$$\sigma_m=V_\sigma.V_r.\beta.\frac{F_{m3}.l}{8.Z}=1.0,73.\frac{1,242.10^3.1}{8.1,05.10^{-6}}=107,9\text{ MPa}$$

Conductors are OK, because

$\sigma_{tot}<q.\sigma_{0,2}$ i.e. $107.9<180$

Force effects on supports:

1) Vertical arrangement

$$\frac{0,8.\sigma_{0,2}}{\sigma_{tot}}=\frac{0,8.120}{2,85}>2,7\Rightarrow V_F.V_r=2,7 \qquad \alpha_{crit}=\alpha_B=1,1$$

$$F_D=V_F.V_r.\alpha.F_{m3}=2,7.1,1.1,242=3,69\text{ kN}$$

$$T=0,035\text{ m}$$

$$\frac{3,69}{0,8}.\frac{0,13+0,035}{0,13}=5,85\text{ kN}<P$$

Corresponding support is 10 kN

2) Horizontal arrangement

$$\frac{0,8.\sigma_{0,2}}{\sigma_{tot}}=\frac{0,8.120}{107,9}=0,889<1\Rightarrow V_F.V_r=1 \quad \alpha_{crit}=\alpha_B=1,1$$

$F_D = V_F.V_r.\alpha.F_{m3} = 1.1,1.1,242 = 1,37$ kN

$T = 0,035$ m

$$\frac{1,37}{0,8}.\frac{0,13+0,062}{0,13} = 2,53 \text{ kN} < P$$

Corresponding support is 5 kN

Example 3.2

Calculate phase angle difference [°] between voltage on generator terminals where $U_g = 6,3$ kV and voltage on HV side of unit transformer where $U_s = 37,8$ kV. Parameters of unit transformer are:

$S_{nT} = 10$ MVA, $e_k = 0,1$, $p = 6,3 \text{ kV}/36 \text{ kV}$, Yy0

Generator power delivery shall be:

a) 0 MW
b) 8 MW

Solution:

Base voltage and apparent power:

$U_B = 6,3$ kV and $S_B = 10$ MVA

Voltages and transformer impedance in p.u.:

$$u_g = \frac{U_g}{U_B} = \frac{6,3}{6,3} = 1,\ u_s = \frac{p.U_s}{U_B} = \frac{\frac{6,3}{36}.37,8}{6,3} = 1,05,\ x_t = e_k.\frac{S_B}{S_{nT}} = 0,1.\frac{10}{10} = 0,1$$

Active power transferred through transformer:

$$p = \frac{u_g.u_s}{x_t}\sin\delta$$

a) $\frac{P}{S_V} = \frac{0}{10} = 0 = \frac{1.1,05}{0,1}\sin\delta$ and thus $\delta = 0°$

b) $\frac{P}{S_V} = \frac{8}{10} = 0,8 = \frac{1.1,05}{0,1}\sin\delta$ and thus $\delta = \arcsin\frac{0,8.0,1}{1.1,05} = \arcsin 0,0762 = 4,37°$

Example 3.3

Calculate phase angle difference [°] causing the same overcurrent as in the case of 10% voltage difference.

$S_{nT} = S_{nG}$, $u_k = 0,1$ and $x''_d = 0,15$. (Do not neglect an impedance of the unit transformer!).

Solution:

$$i''_{k(U)} = \frac{e'' - u_s}{x_t + x''_d} = \frac{\Delta u}{u_k + x''_d} = \frac{0,1}{0,1+0,15} = 0,4$$

$$i''_{k(\varphi)} = \frac{e'' - u_s}{x_t + x''_d} = \frac{2u.\sin\frac{\psi}{2}}{u_k + x''_d} = \frac{2.1.\sin\frac{\psi}{2}}{0,1 + 0,15} = 0,4$$

$$\psi = \frac{180}{\pi}.2.\arcsin\frac{0,4.0,25}{2} = 5,73°$$

Example 3.4

Generator is being synchronized to grid (system) which is assumed to be an infinity bus via unit transformer under following conditions:

$$U_G = 23 \text{ kV}, \; U_s = 410 \text{ kV}$$

Unit transformer parameters are:

$$S_{nT} = 1100 \text{ MVA}, \; e_k = 0,15, \; p = 24 \text{ kV} / 420 \text{ kV}, \text{ Ynd11}$$

Generator parameters are:

$$S_{nG} = 1100 \text{ MVA}, \; U_{nG} = 24 \text{ kV}, \; x''_d = 0,15$$

Calculate initial symmetrical overcurrent and decide whether generator is during this transient working in underexcited or overexcited regime.

Solution:

Base voltage and apparent power:

$U_B = 24 \text{ kV}$ a $S_B = 1100 \text{ MVA}$

Voltages and impedances in p.u.:

$$u_g = e'' = \frac{U_G}{U_B} = \frac{23}{24} = 0,9583, \; u_s = p.\frac{U_s}{U_B} = \frac{24}{420}.\frac{410}{24} = 0,9762,$$

$$x_g = x''_d.\frac{S_B}{S_{nG}} = 0,15.\frac{1100}{1100} = 0,15, \; x_t = e_k.\frac{S_B}{S_{nT}} = 0,15.\frac{1100}{1100} = 0,15$$

Three phase initial symmetrical overcurrent will be (source orientation):

$$\hat{i}''_k = \frac{e'' - u_s}{j.(x_t + x_g)} = \frac{0,9583 - 0,9762}{j.(0,15 + 0,15)} = -j.0,0179 \text{, and thus}$$

$$I''_k = i''_k.p.\frac{S_B}{\sqrt{3}.U_B} = 0,0179.\frac{24}{420}.\frac{1100}{\sqrt{3}.24} = 1,154 \text{ kA}$$

While reactive current has negative value respectively $e'' < u_s$, generator is working in *underexcited* regime.

Example 4.1

Calculate total cooling water mass flow $[kg/s]$ in circulation cooling circuit and raw water mass flow $[kg/s]$ needed for supplying cooling circuit. Emission steam from turbine LP part outlet is injected to condenser as a saturated vapor (ideally dry) at mass flow rate $\dot{m}_e = 25 \text{ kg.s}^{-1}$, where is condensing at 40 °C. Cooling water condenser has inlet temperature $T_{cool\,IN} = 20°C$ and outlet temperature

$T_{cool\,OUT} = 35°C$. Cooling water is (partly) evaporated in cooling tower at $T_{evap} = 25°C$. In addition to that, blow-out losses are 0,1%. Heat capacity of water is $c_w = 4{,}18 \frac{kJ}{kg.K}$

Turbine emission steam parameters: $T_e = 40$ °C, $s_e = 8{,}675$ kJ.kg^{-1}.K^{-1}, $i_e = 2575$ kJ.kg^{-1}

Condensate parameters: $T_k = 40$ °C, $s_k = 0{,}527$ kJ.kg^{-1}.K^{-1}, $i_k = 167{,}5$ kJ.kg^{-1}

Water at 25 °C: $s_{v25} = 0{,}367$ kJ.kg^{-1}.K^{-1}, $i_{v25} = 104{,}8$ kJ.kg^{-1}

Saturated steam at 25 °C: $s_{p25} = 8{,}556$ kJ.kg^{-1}.K^{-1}, $i_{p25} = 2547$ kJ.kg^{-1}

Solution:

$$\dot{m}_{cool\,IN} = \frac{\dot{m}_e.(i_e - i_k)}{c_w.(T_{cool\,OUT} - T_{cool\,IN})} = \frac{25.(2575 - 167{,}5)}{4{,}18.(35 - 20)} = 960\ kg/s$$

$$\dot{m}_{cool\,SUP} = \left(0{,}001 + \frac{c_w.(T_{cool\,OUT} - T_{cool\,IN})}{i_{p25} - i_{v25}}\right).\dot{m}_{cool\,IN} = \left(0{,}001 + \frac{4{,}18.(35 - 20)}{2547 - 104{,}8}\right).960 = 25{,}6\ kg/s$$

Example 4.2

Calculate total efficiency of CCGT cycle:

Gas cycle efficiency	$\eta_g = 0{,}4$
Total heat exchanger losses	$\xi_e = 0{,}1$
Steam cycle efficiency	$\eta_s = 0{,}35$

Solution:

$$\eta_{CCGT} = \eta_g + (1 - \xi_e).(1 - \eta_g).\eta_s = 0{,}4 + (1 - 0{,}1).(1 - 0{,}4).0{,}35 = 0{,}589$$

Example 4.3

Calculate total efficiency of CHP (combined heat + power generation) consisting of back pressure turbine + district heat system:

Back pressure turbine efficiency	$\eta_{BP} = 0{,}25$
Total district heat system losses	$\xi_H = 0{,}15$

Solution:

$$\eta_{CHP} = \eta_{BP} + (1 - \xi_H).(1 - \eta_{BP}) = 0{,}25 + (1 - 0{,}15).(1 - 0{,}25) = 0{,}8875$$

Example 4.4

Calculate volume of air [m^3.kg^{-1}] needed for an ideal combustion of 1 kg of anthracite with ash content $A^r = 10$ % and carbon content $C^r = 90$ %. Excess of air factor shall be $\lambda = 1{,}3$ for this case (boiler). Water content (fuel, air) is negligible.

(The air contains 21% of oxygen, molar volume of oxygen at normal temperature and pressure is $22{,}4\ \text{dm}^3.\text{mol}^{-1}$ and carbon molecular weight is $M(C) = 12\ \text{g.mol}^{-1}$)

Solution:

$$V_{vzs} = 1{,}3.\frac{22{,}4}{0{,}21}.\frac{0{,}9}{12} = 10{,}4\ \text{m}^3.\text{kg}^{-1}$$

Example 4.5

Calculate excess of oxygen ω_{O_2} [%] (vol.) in flue gas outlet from boiler. Flue gas is assumed to be ideally dry. Volume of combustion air $\approx$ volume of flue gas ($\dot{V}_{vz} \approx \dot{V}_{sn}$). Excess of air factor shall be $\lambda = 1{,}2$ for this case (boiler).

(The air contains 21% of oxygen)

Solution:

$$\omega_{O_2} = \frac{\lambda - 1}{\lambda}.\omega_{O_2 air} = \frac{1{,}2 - 1}{1{,}2}.0{,}21 = 3{,}5\ \%$$

Example 5.1

Calculate volume of flue gas exhausted from the stack of power plant per one kg of fuel $[\text{m}^3.\text{kg}^{-1}]$. The boiler is fired by anthracite with following composition: ash content $A^r = 15\ \%$ and carbon content $C^r = 85\ \%$. Excess of air factor shall be $\lambda = 1{,}25$ for this case (boiler). Water content (in fuel / inlet air) is negligible.

(The air contains 21% of oxygen, 79% of nitrogen, carbon molecular weight is $M(C) = 12\ \text{g.mol}^{-1}$, for normal temperature and pressure: molar volume of oxygen is $V_m(O_2) = 22{,}4\ \text{dm}^3.\text{mol}^{-1}$, carbon dioxide is $V_m(CO_2) = 22{,}3\ \text{dm}^3.\text{mol}^{-1}$)

$$V_{vzst} = \frac{22{,}4}{0{,}21}.\frac{0{,}85}{12} = 7{,}56\ \text{m}^3.\text{kg}^{-1}$$

$$V_{sns} = 22{,}3.\frac{0{,}85}{12} + 0{,}79.7{,}56 + (1{,}25 - 1).7{,}56 = 1{,}58 + 5{,}97 + 1{,}89 = 9{,}44\ \text{m}^3.\text{kg}^{-1}$$

Example 5.2

Calculate limestone ($CaCO_3$) consumption $[\text{kg.s}^{-1}]$ in flue gas desulphurization (FGD) unit working with efficiency of 96%. Flue gas volume flow is $\dot{V}_{sn} = 200\ \text{m}^3.\text{s}^{-1}$. Concentration of SO_2 in the inlet flue gas reaches $c(SO_2) = 5000\ \text{mg.m}^{-3}$.

(limestone molecular weight is $M(CaCO_3)=100$ g.mol^{-1}, sulphur dioxide molecular weight is $M(SO_2)=64$ g.mol^{-1}, assume an ideal reactivity of limestone)

$$\dot{m}_{\Delta SO_2} = 0{,}96.5.10^{-3}.200 = 0{,}96 \text{ kg.s}^{-1}$$

$$\dot{n}_{\Delta SO_2} = \dot{n}_{CaCO_3} = \frac{0{,}96}{0{,}064} = 15 \text{ mol.s}^{-1}$$

$$\dot{m}_{CaCO_3} = 15.0{,}100 = 1{,}5 \text{ kg.s}^{-1}$$

Example 5.3

In the stack inlet it has been measured: Sulphur dioxide concentration $c_{SO_2 measured} = 220 \text{ mg.m}^{-3}$ and excess of oxygen $\omega_{O_2 measured} = 4\%$ (vol.). Environmental limits are $c_{\text{limit}SO_2} = 200 \text{ mg.m}^{-3}$ at reference value excess of oxygen $\omega_{O_2 ref} = 6\%$ (vol.).
Decide whether environmental limits for SO_2 are met.

(The air contains 21% of oxygen)

$$c_{SO_2 ref} = c_{SO_2 measured} \cdot \frac{\lambda_{measured}}{\lambda_{ref}} = c_{SO_2 measured} \cdot \frac{\dfrac{\omega_{O_2 air}}{\omega_{O_2 air} - \omega_{O_2 measured}}}{\dfrac{\omega_{O_2 air}}{\omega_{O_2 air} - \omega_{O_2 ref}}} =$$

$$= c_{SO_2 measured} \cdot \frac{\omega_{O_2 air} - \omega_{O_2 ref}}{\omega_{O_2 air} - \omega_{O_2 measured}} = 220.\frac{0{,}21-0{,}06}{0{,}21-0{,}04} = 194 \text{ mg.m}^{-3}$$

$c_{\text{limit}SO_2} > c_{SO_2 ref}$, the boiler is operated under environmental limits.