Selecting the current rating for equipment

1. Rated current: the maximum continuous load current I_N
2. Short-time withstand current: thermal withstand current I_{term}

   I_{term} is given for 1s or 3s short circuit current duration (rms value)

   Equivalent 1s current stress, when Ik and time t are known:

$$W = RI^2 \cdot t \quad ; \text{ energy is the same}$$

$$\Rightarrow I_{1s}^2 \cdot 1s = I_k^2 \cdot t$$

$$\Rightarrow \underline{I_{1s} = I_k \sqrt{t/s}}$$

   If the transient components are high, the equation becomes:

$$\Rightarrow I_{1s} = I_k'' \sqrt{(m+n)\, t/s}$$

   m = the effect of DC-component

   n = the effect of decay in AC-component

   Std VDE 0102 : m = 0…0,8 n = 0,2…1

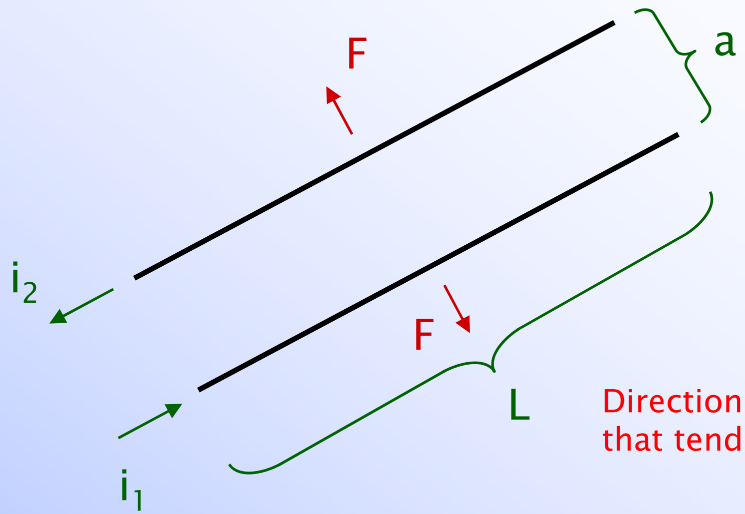
   $m \sim r/x,\ t \qquad n \sim I_k''/I_k,\ t$

3. Peak withstand current: defines the mechanical strength requirements

   $i_{dyn} = 2{,}5\ I_{term} \approx 1{,}8\ \sqrt{2}\ I_{term}$ *i_{dyn} is an instantaneous currrent value*

Mechanical stresses of a short circuit

$$F = \frac{\mu_0}{2\pi}\frac{i_1 i_2 L}{a}$$



Direction of force is such that tends to level the flux

Example: 2-phase short circuit, I_k = 10 kA
a = 1,0 m ; F/L = ?

$$\frac{F}{L} = \frac{\mu_0}{2\pi}\frac{i_1 i_2}{a} \quad ; \quad i_1 = i_2 = 2{,}5\, I_k = 25\,\mathrm{kA}$$

$$= \frac{4\pi\cdot 10^{-7}}{2\pi}\cdot 25^2\cdot 10^6 \qquad \frac{\mathrm{Vs}}{\mathrm{Am}}\mathrm{A}^2\frac{1}{\mathrm{m}} = \frac{\mathrm{VAs}}{\mathrm{m}}\cdot\frac{1}{\mathrm{m}} = \frac{\mathrm{N}}{\mathrm{m}}$$

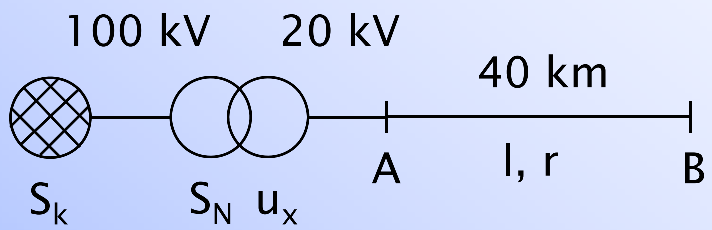
$$\left(\mathrm{VA} = \frac{\mathrm{J}}{\mathrm{s}} = \frac{\mathrm{Nm}}{\mathrm{s}}\right)$$

$$= 2\cdot 25^2\cdot 10^{-1}\,\frac{\mathrm{N}}{\mathrm{m}}$$

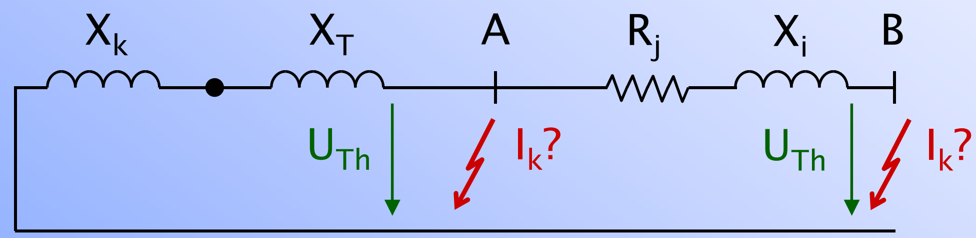
$$= \underline{\underline{125\,\frac{\mathrm{N}}{\mathrm{m}}}}$$

Note: in the case of a 3-phase fault, the forces are 15% bigger

Grid short circuit power S_k = 1200 MVA, Transformer rating S_N = 16 MVA, and reactance u_x = 10 %, secondary voltage U_N = 20 kV, line length is 40 km and resistance and inductance r = 0.3 Ω/km ja l = 1.1 mH/km. Compute a) 3-phase short circuit current in A and B, b) the dynamic current rating of busbar A, and c) the equivalent 1s current for line A-B when the fault time is 0.6 second ?.



One-line diagram:



Network impedances (in 20 kV) :

grid $$X_k = \frac{U^2}{S_k} = \frac{20^2}{1200}\Omega = 0{,}333\,\Omega$$

trafo $$X_T = u_x \frac{U^2}{S_N} = 0{,}1\frac{20^2}{16}\Omega$$

20kV line $$R_j = s \cdot r = 40 \cdot 0{,}3\,\Omega = 12\,\Omega$$

$$X_i = 2\pi f \cdot s \cdot l = 2\pi \cdot 40 \cdot 50 \cdot 1{,}1 \cdot 10^{-3}\,\Omega = 13{,}82\,\Omega$$

a) 3-phase short circuit current in points A & B :

Thevenin's method : $U_{Th} = 20/\sqrt{3}$

$$A: \quad Z_{Th} = X_k + X_T = 2{,}833\,\Omega$$

$$\Rightarrow \quad I_k = \frac{U_{Th}}{Z_{Th}} \cong \underline{\underline{4{,}075\,kA}}$$

$$B: \quad \underline{Z}_{Th} = Rj + j(X_k + X_T + X_j) = 12 + j16{,}653$$

$$\Rightarrow \quad Z_{Th} = \sqrt{12^2 + 16{,}653^2} \cong 20{,}53\,\Omega$$

$$\Rightarrow \quad I_k = \frac{U_{Th}}{Z_{Th}} \cong \underline{\underline{0{,}562\,kA}}$$

b) Dynamic rating for busbar A :

$$i_{dyn} = 2{,}5 \cdot I_{term} = 2{,}5 \cdot 4{,}075\,kA \cong \underline{\underline{10{,}2\,kA}}$$

c) Thermal rating for line A–B, when t = 0,6 s :

$$I_{k,\,max} = 4{,}075\,kA$$

$$I_s = I_{k,\,max}\sqrt{t/s}$$

$$= 4{,}075\sqrt{0{,}6}\,kA$$

$$\cong \underline{\underline{3{,}16\,kA}}$$

Note: we have to consider
The worst case = highest Ik
This is in the line beginning

Switching devices

Rated quantities :

- Rated voltages and insulation level
- Thermal 1s withstand current (Ik)
- Dynamic withstand current (Idyn = 2.5*Ik)
- Making capacity of short circuit current
  = highest fault current peak value, that the switch can close
- Breaking capacity of short circuit current

= highest fault current, that the switch can interrupt

usually given as:

- ac-component rms value, and
- dc-component %-share

1. Disconnector (isolator)

- in open-position a reliable open point
- when closed, can carry load and fault current
- no breaking or making capacity

2. Switch-disconnector

- a disconnector able to break load current & make fault current
- used e.g. in MV overhead distribution networks

Example:

U_n = 24 kV
I_n = 630 A
I_{1s} = 16 kA
I_{ma} = 40 kA (making capacity)
Capacity of disconnecting a transformer in no-load 16 A
Capacity of disconnecting an OH-line in no-load 4 A
Capacity of disconnecting an underground cable 25 A

3. Fuse-switch-disconnector

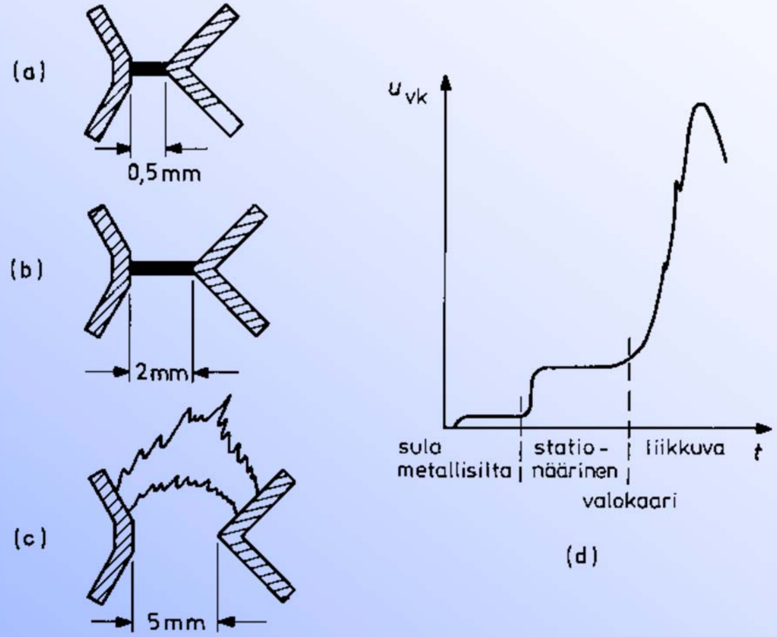
- A switch-disconnector equipped with HV fuses
- Operation of one fuse causes opening of the switch
  This is actuated by releasing a spring by blown fuse

⇒ prevents 2-phase operation

4. Circuit breaker

- switch able to break and make also the short circuit currents
- works either automatically or manually controlled
- in the case of fault, tripped by a protective relay

Operation of a circuit breaker



a) melted metal bridge
b) stationary power arc
c) moving power arc
d) the arc voltage ~ time

The breaking work $$W = \int_0^t u_{vk}(t)\, i_{vk}(t)\, dt$$

W must be kept small.

In order to help the interruption, the arc is:

- drawn longer
- divided into parts
- cooled down
- de-ionized (absorbing materials)

Some CB types

- air CB
- oil CB
- minimum oil CB
- Pressurized air CB
- SF_6 – CB
- vacuum CB

Current transformers

- The current error $$F_i = \frac{K_n I_s - I_p}{I_p} 100\,\%$$

  K_n = transformation ratio

  I_s = secondary current

  I_p = primary current

- The composite error $$\varepsilon_c = \frac{100}{I_p}\sqrt{\frac{1}{T}\int_o^T (K_n i_s - i_p)^2\,dt}\ \%$$

Measurement transformers

- Instrument security current

  = current, for which ε_c equals 10% $= F_s \cdot I_{nim}$

  - F_s = Instrument security factor
  - normal value 5 or 10

Protective transformers

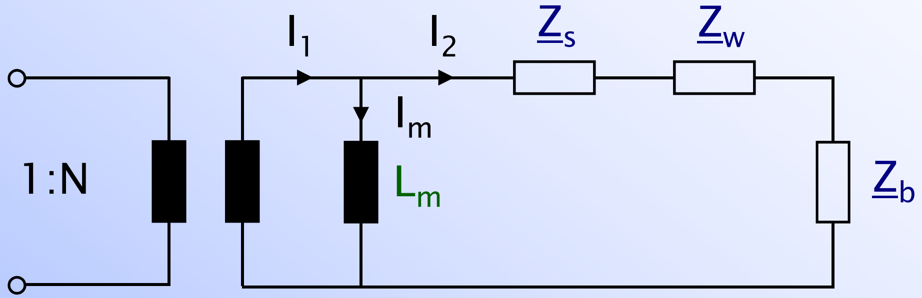
- Accuracy limit factor F_T
  - defines the current, when ε_c = 5% or 10% (5P tai 10P)
  - typical values 5,10,15,20 or 30 (times the rated current)
  - Example: 10 P 15

The accuracy classes of CT:s

Accuracy class	burden x S_N	power factor cos ϕ	Primary I x I_{pN}	I error ± %	angle error ± min	composite error %
0,1	0,25…1	0.8 ind for $S_N \geq 5$ VA otherwise 1	0,05 0,2 1,0 1,2	0,4 0,2 0,1 0,1	15 8 5 5	-
0,2			0,05 0,2 1,0 1,2	0,75 0,35 0,2 0,2	30 15 10 10	-
0,5			0,05 0,2 1,0 1,2	1,5 0,75 0,5 0,5	90 45 30 30	-
1			0,05 0,2 1,0 1,2	3,0 1,5 1,0 1,0	180 90 60 60	-
3 5	0,5…1		0,5 1,2 0,5…1,2	3 3 5	- -	- -
5 P	1		1 n	1 -	60 -	- 5
10 P			1 n	3 -	- -	- 10

Note n equals to the accuracy limit factor

Equivalent circuit for a CT



Internal burden $S_{Ns}{}^2 = Z_s \cdot I_{2N}{}^2$

Z_s = impedance of the secondary winding

Z_w = impedance of the secondary wiring

Z_b = impedance of the secondary burden (relays etc.)

A CT keeps its accuracy class when $\underline{Z}_w + \underline{Z}_b$ is smaller than the rated burden $\underline{Z}_N$ impedance defined by $S_N = Z_N \cdot I_{2N}{}^2$

Example : 100/1 A 10 P 15 current transformer

Internal burden	0.5 VA
Rated burden	10 VA
Secondary cabling	2 Ω

If the burden by relays is 10 VA, what is the effect of cabling impedance to the accuracy limit current ?

The burden of secondary cabling at rated current:

$$S_w = RI_{2N}^{\;2} = 2\,VA$$

$$F_T' = F_T \left| \frac{\underline{S}_{NS} + \underline{S}_N}{\underline{S}_{NS} + \underline{S}_w + \underline{S}_N} \right|$$

The burdens are resistive:

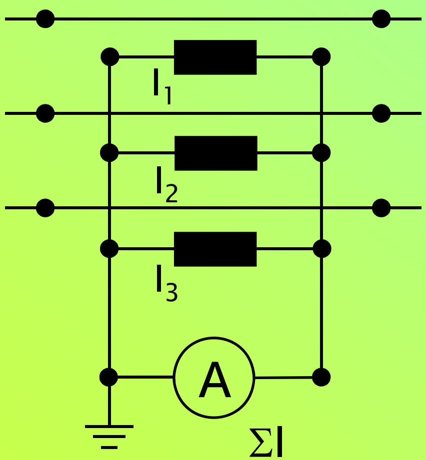
$$\Rightarrow F_T' = \frac{0.5+10}{0.5+2+10} \cdot 15 = 12.6$$

$\Rightarrow$ the accuracy limit current = $F_T' \cdot I_N$ = 1,26 kA

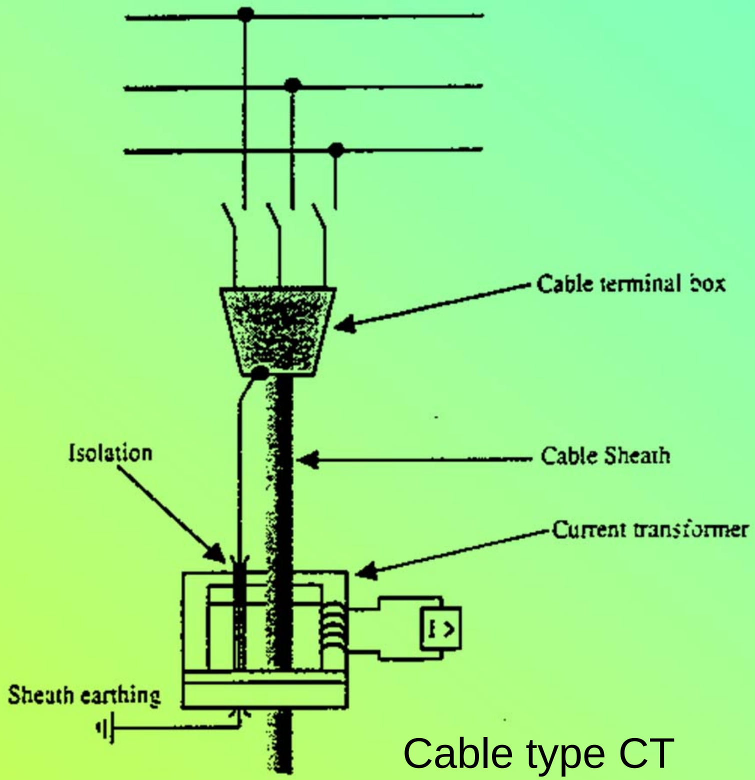
Measurement of zero sequence current

Sum connection :

- Large load currents cause measurement errors
- Short circuit currents and unequal saturation
  ⇒ apparent sum current created
  cable type CT: even 0.5 A currents detected



Sum connection



Cable type CT

Voltage transformers (VT)

- the rated voltage factor k_N = maximum operating frequency voltage, that the VT must tolerate for a given time ($U_{rated} \cdot k_N$)
- protective transformer (3 P or 6 P) must keep its accuracy up to the voltage $k_N \cdot U_{rated}$

Rated voltage factors of VT:s

rated voltage factor kN	time	Primary connection and system earthing
1,2	continuous	in general between the phases and between the star point and earth
1,2	continuous	between phase and earth in solid earthed systems
1,5	30 s	
1,2	continuous	between phase and earth in other systems
1,9	30 s	if automatic earth fault tripping
1,2	continuous	between phase and earth in unearthed and compensated
1,9	8 h	neutral systems, if no earth fault tripping

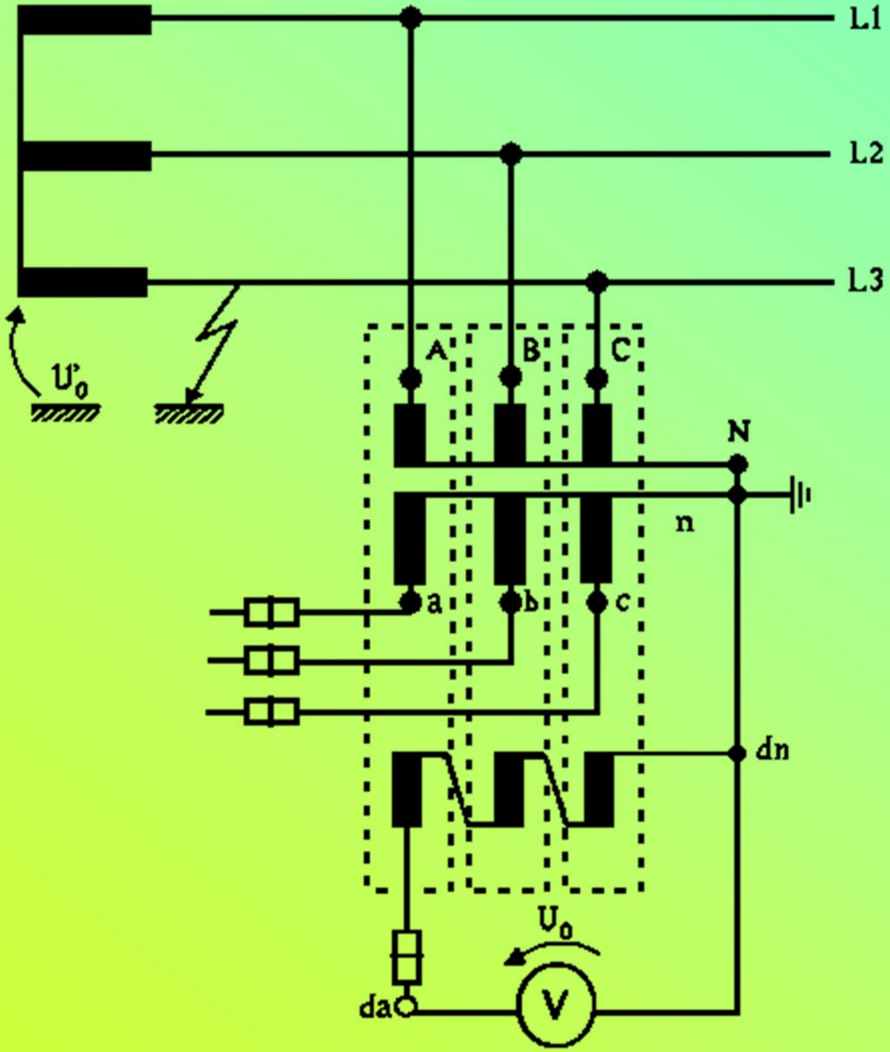
The maximum errors allowed for VT:s in general

class	voltage error %	angle error min
0,1	0,1	5
0,2	0,2	10
0,5	0,5	20
1	1,0	40
3	3,0	-

Additional requirements for protective VT:s

class	voltage error %	angle error min
3 P	3,0	120
6 P	6,0	240

The measurement of zero sequence voltage



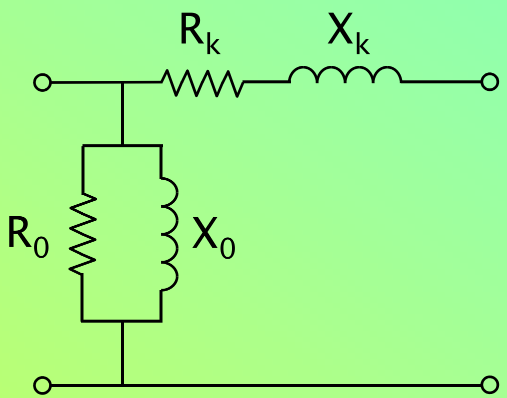
$$\underline{U}_d = \underline{U}_{L1} + \underline{U}_{L2} + \underline{U}_{L3}$$
$$= (1 + \underline{a} + \underline{a}^2)(\underline{U}_1 + \underline{U}_2) + 3\underline{U}_0$$
$$= 3\underline{U}_0$$

$$\underline{a} = 1\angle 120^\circ$$

Voltage transformer ferroresonance

- initiated by some switching action
- is stopped, when more lines are connected
- phase voltages strongly distorted
- may cause high overvoltages
- damping using 50 – 60 Ω resistor in open delta

Equivalent circuit for a power transformer



Öljyeristeiset 110 kV, 10...63 MVA tehomuuntajat

TAULUKKO 12.3c. Tekniset arvot

Käämit	Teho MVA	P_0 kW	P_k kW	Z_k %	S_0 %	Jäähd. tapa	P_j kW	Painot Kok. kg	Painot Öljy kg	Painot Kulj. kg
Al	10	11,2	61	10,0	0,60	ONAN	–	29000	10000	24500
Al	16	16,1	88	10,0	0,50	ONAN	–	38000	12200	31500
Cu	(20)	16,8	106	10,0	0,45	ONAN	–	40500	12000	33500
Al	25	21,8	121	10,0	0,45	ONAN	–	49000	16300	40300
Cu	(31,5)	24,5	136	10,0	0,40	ONAN/ONAF	2,5	53000	15200	48000
Al	40	33,5	178	12,0	0,44	ONAN/ONAF	5,0	64500	21000	56000
Cu	(50)	32,7	212	12,0	0,35	ONAN/ONAF	5,0	68000	19500	58000
Cu	63	38,0	260	12,0	0,30	ONAN/ONAF	5,0	83000	21000	71500

ONAN/ONAF-jäähdytteisissä muuntajissa on öljynlämpömittarin ohjaamat tuulettimet. Näillä muuntajilla saavutetaan nimelliskuormitettavuus ONAF-jäähdytyksellä ja noin 70 % kuormitettavuus ONAN-jäähdytyksellä.

TAULUKKO 12.3d. Muuntajien jännitteet ja kytkentä

Jännitteet	110±9x1,67%/21 kV, 110±9x1,67%/10,5 kV tai 110±9x1,67%/6,3 kV
Kytkentä	YNd11 tai YNyn0

Example: A 16 MVA transformer

$$X_0 = \frac{U^2}{S_0} = \frac{21^2}{0{,}005 \cdot 16}\,\Omega = \underline{5{,}5\,\mathrm{k\Omega}}$$

$$R_0 = \frac{U^2}{P_0} = \frac{21^2}{0{,}0161}\,\Omega = \underline{27{,}4\,\mathrm{k\Omega}}$$

$$r_k = \frac{P_k}{S_N} = \frac{0{,}088}{16} = 0{,}0055\,\mathrm{p.u.}$$

$$(S_N = \sqrt{3}\,U_N\,I_N \quad \& \quad P_k = \sqrt{3}\,U_{hr}\,I_N)$$

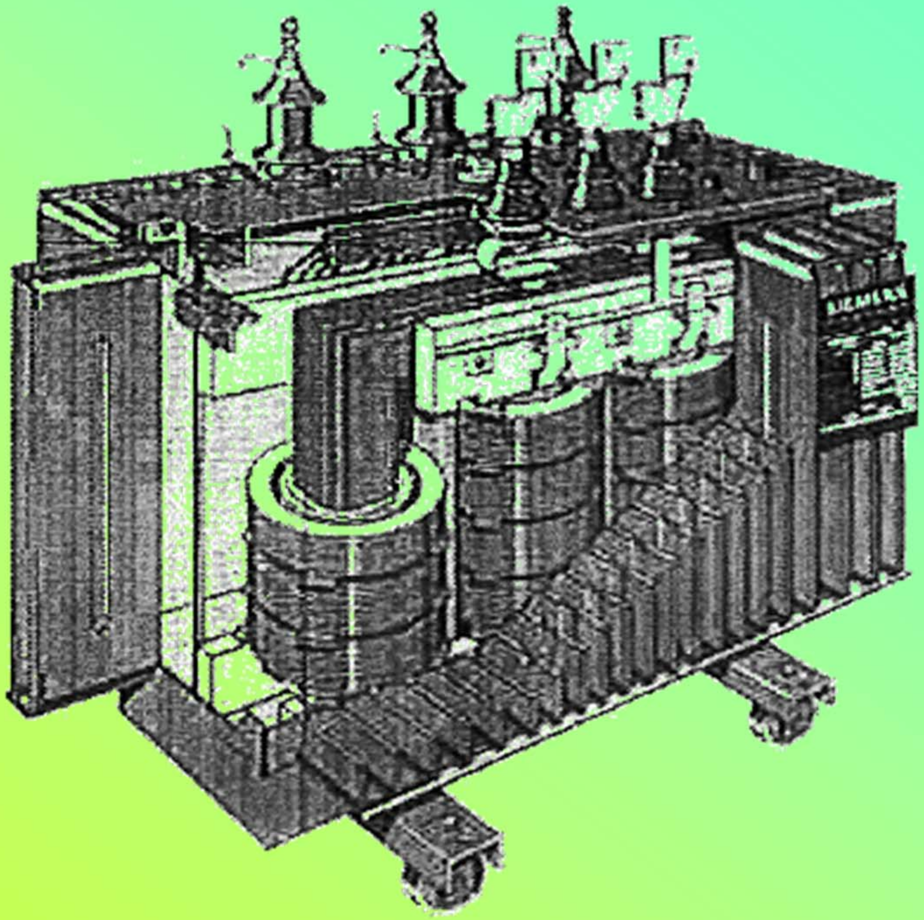
$$z_k = \sqrt{x_k^{\ 2} + r_k^{\ 2}} = 0{,}1\,\mathrm{p.u.}$$

$$\Rightarrow \quad x_k = \sqrt{z_k^{\ 2} - r_k^{\ 2}} = 0{,}09985 \approx 0{,}1\,\mathrm{p.u.}$$

$$R_k = r_k \frac{U^2}{S_N} = 0{,}0055\,\frac{21^2}{16}\,\Omega = \underline{0{,}15\,\Omega}$$

$$X_k = x_k \frac{U^2}{S_N} = 0{,}1\,\frac{21^2}{16}\,\Omega = \underline{2{,}76\,\Omega}$$

The ampacity of a power transformer

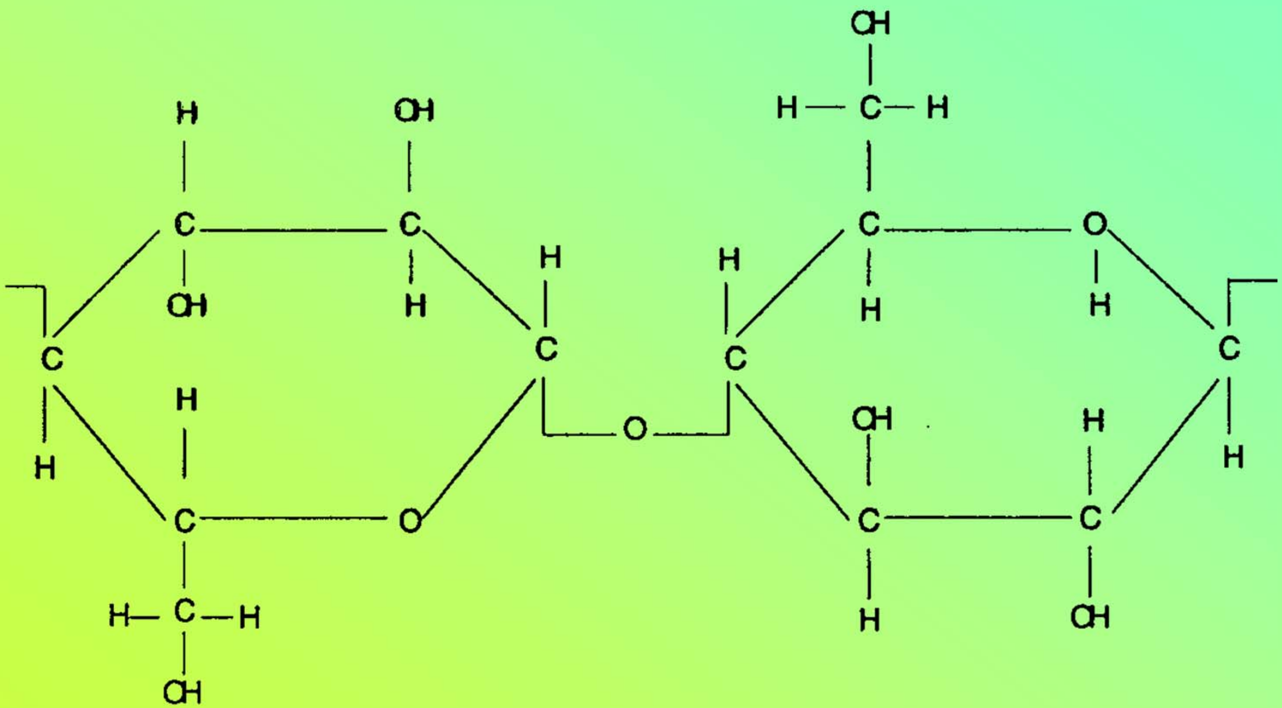


The load capacity (Ampacity)

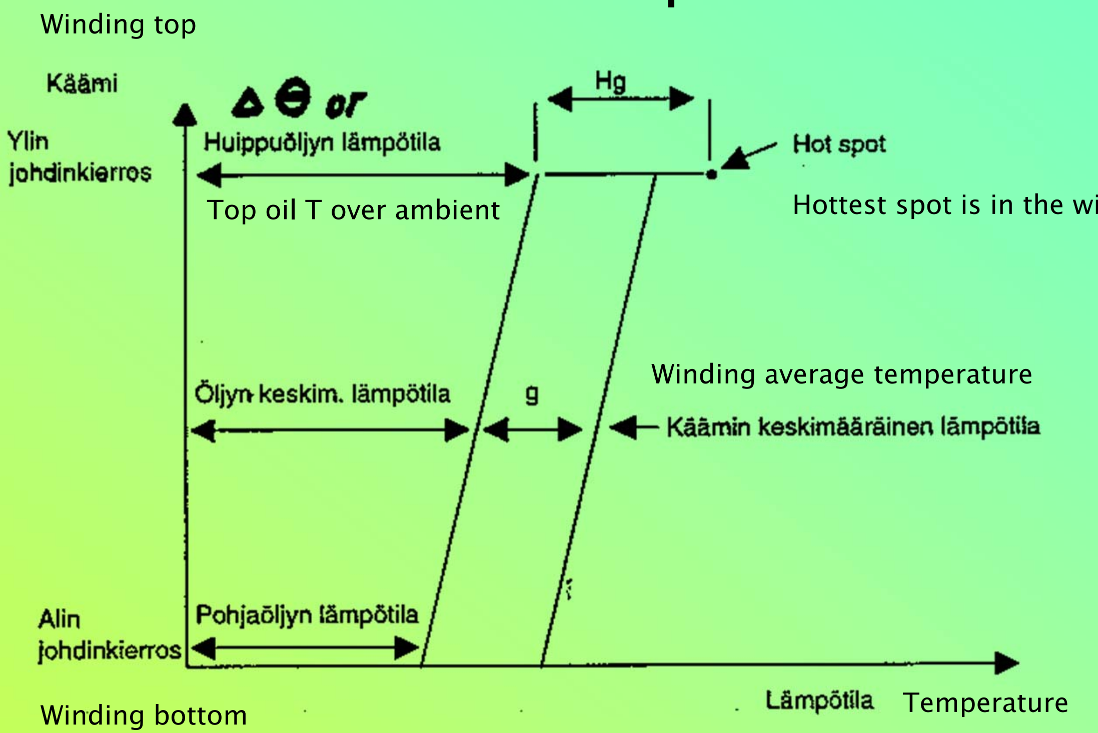
- The momentary loading. The break down risk of insulation gives the maximum limit.
- Normal loading; objective is to optimize the life time of the device.
- Life time is defined by the electrical strength of the insulation material (paper)

Cellulose fiber

- Composed of chains of molecules
- Electrical strength depends on the length of the chain
- Chains are broken by oxygen water and heat



Temperature distribution



At rated load:

θ_a = ambient temperature

$\Delta\theta_{or}$ = 55°C

Hg_r = 23°C

The rate of life time decay (IEC 354)

- the winding hot-spot temperature $$\theta_h = \theta_a + \Delta\theta_{or}\left[\frac{1+RK^2}{1+R}\right]^x + Hg_r\, K^y$$
- the relative rate of life time decay $$V = 2^{(\theta_h - 98)/6}$$

$$K = I / I_n \qquad y = 1{,}6$$

$$R = P_{kn} / P_0 \qquad x = 0{,}8$$

Overload capacity (IEC 354)

Normal cyclic load	
current	1,5
hot-spot temperature	140
top-oil temperature	105
Long term overload capacity	
current	1,8
hot-spot temperature	150
top-oil temperature	115
Short term overload capacity	
current	2
hot-spot temperature	*
top-oil temperature	*

The rate of life time decay ~ load current