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KEV – MZS
Měření a zkoušení elektrických strojů
Verze pro zahraniční studenty – anglicky

KEV – MZS
Measurement and Testing of Electric Machines
Version for foreign students – English version

1 Magnetic and Electric Fields



Estimated completion time: **90 min**



After studying the topic, you will be able to:

- *characterize magnetic and electrical fields*
- *calculate field energy, force and torque*
- *describe and explain Ampere's law*
- *calculate the magnetization characteristics of the magnetic circuit*
- *analyze and design a magnetic circuit and determine the number of turns of a coil*

A question that is often raised is why practically all the motion devices make use of magnetic fields instead of electric fields. The answer lies in the amount of energy available per unit volume in the air gap separating a stator and the moving part – rotor- where the electromechanical energy conversion takes place. The typical saturation flux density of commonly used materials is 2T. The break down voltage of air is on the order 1MV/m. Using these values in the ratio of the magnetic and electric energy densities, we have

$$\frac{w_m}{w_e} = \frac{B^2}{\mu_0 \varepsilon_0 E^2} = 3{,}6x10^5 \qquad (1\text{-}1)$$

The magnetic energy density is five orders of magnitude greater than electric energy density. The above ratio clearly shows why the energy conversion through the magnetic field is preferred over an electric field.

1.1 Constituent relations

In magnetic materials, B and H are related by

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) = \mu_0\left(1 + \frac{M}{H}\right)\vec{H} = \mu_0\mu_r\vec{H} = \mu\vec{H} \qquad (1\text{-}2)$$

Where

μ	permeability of the material [H/m]
μ_r	relative permeability
μ_0	4π x 10^{-7} permeability of air [H/m]
M	magnetization density [A/m]

The constituent relation for the current density J in a coil wire is

$$J = \sigma E \ [A/m^2] \qquad (1\text{-}3)$$

1.2 Energy, forces and torque

The magnetic energy density is given by

$$w_m = \int \vec{H}.d\vec{B}\ \left[\frac{J}{m^3}\right] \tag{1-4}$$

If the permeability μ of the material is constant, B is a linear function of H, and the previous integral gives the area of a triangle of the B-H curve. Thus

$$w_m = \frac{1}{2}\vec{B}\,\vec{H} = \frac{1}{2}\mu H^2 = \frac{1}{2}\frac{B^2}{\mu} \tag{1-5}$$

By integrating the energy density over a volume, we obtain the magnetic energy stored in the volume

$$W_m = \int_V \int \vec{H}.d\vec{B}.dv\ [J] \tag{1-6}$$

For a linear medium (μ is constant), the above equation reduces to

$$W_m = \frac{\mu}{2}\int_V H^2.dv = \frac{1}{2\mu}\int_V B^2.dv\ [J] \tag{1-7}$$

We can obtain the magnetic force on a ferromagnetic body in the direction of x by

$$F = -\left(\frac{\partial W_m}{\partial x}\Big|_{\lambda=cons}\right) \tag{1-8}$$

where λ is flux linkage, which is equal to the net flux linking an N-turn coil.
The force density f is given by

$$f = \vec{J}\ x\ \vec{B}\left[\frac{N}{m^3}\right] \tag{1-9}$$

The net force on the current in a volume element is

$$\vec{F} = \int_V (\vec{J}\ x\ \vec{B})dv\ [N] \tag{1-10}$$

In a device, the current flows in a wire of uniform cross section. Thus, by integrating J over the cross section, the previous integral is reduced to (Lorentz force)

$$\vec{F} = \oint_c I\,\overrightarrow{dl}\ x\vec{B}[N] \tag{1-11}$$

Where I is the current in a wire and dl is the differential wire element.
The majority of motion devices provide rotational motion that is caused by an applied electromagnetic torque. The torque is given by

$$\vec{M} = \oint_c \vec{r}x(I\,\overrightarrow{dl}\ x\overrightarrow{B})[Nm] \tag{1-12}$$

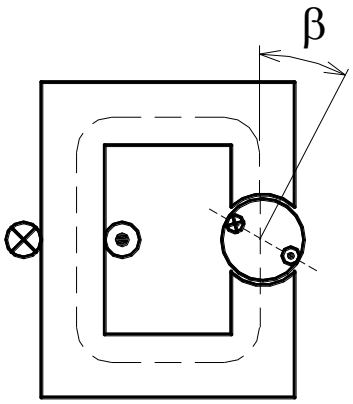
where *r* represents the length of the moment arm perpendicular to the axis of rotation and directed toward the point where the force is computed.

$$F = \frac{dW_{mg}}{dx} \tag{1-13}$$

$$W_{mg} = \frac{1}{2}Li^2 \tag{1-14}$$

For the i=const is valid relation

$$F = \frac{1}{2}i^2\frac{dL}{dx} \tag{1-15}$$



Self-inductances L_1 and L_2 are stable.

Fig.1-1. Rotary system with 2 coils and stable air gap.

Magnetic energy is

$$W_{mg} = \frac{1}{2} L_1 i_1^2 + \frac{1}{2} L_2 i_2^2 + L_{12} i_1 i_2 \tag{1-16}$$

For a stable current i_1 and i_2

$$L_{12} = L_{12m} \cos\beta \tag{1-17}$$

The torque is

$$M = \frac{\partial W_{mg}}{\partial \beta} = -L_{12m} i_1 i_2 \sin\beta \tag{1-18}$$

1.3 Ampere's law

The current is a source of a magnetic field (B and H). The relation between the current and the magnetic field is given by Ampere's law. The law in the integral form is

$$\oint_c \vec{H}\,\overrightarrow{dl} = \int_S \vec{j}\,d\vec{a} \tag{1-19}$$

The integral of $\vec{H}$ around a closed contour is equal to the net current crossing the surface by the contour.

Let us take the familiar problem of $\vec{H}$ around an infinitely long wire of a cross section A carrying a uniformly distributed current I.

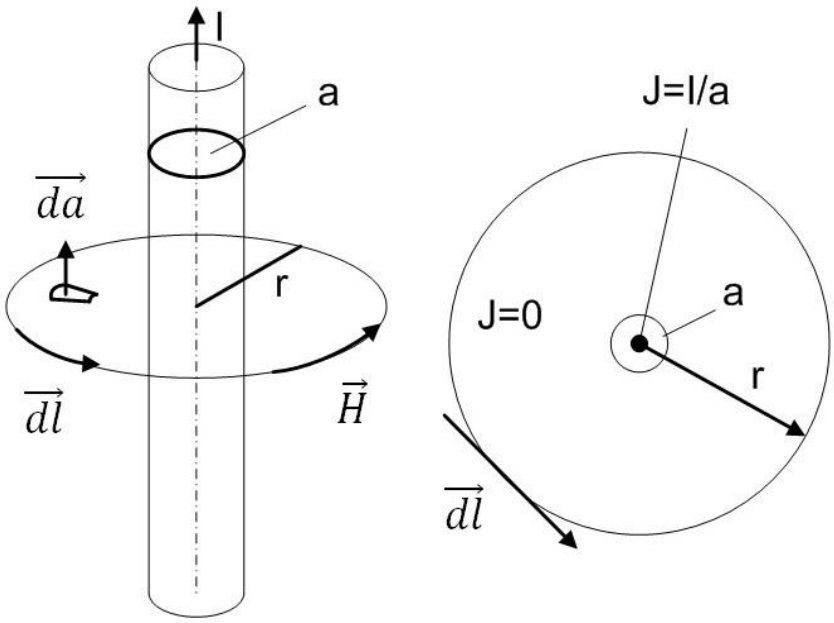


Fig.1-2. H field due to an infinitely long line current.

Let us take a circular contours of radius r concentric to the current as shown in the figure. Because of the circular cylindrical symmetry, H is constant along the path, and its direction is parallel to $\overrightarrow{dl}$ giving

$$\oint_c \vec{H}\,\overrightarrow{dl} = \int_0^{2\pi} Hr\,d\theta = 2\pi rH \tag{1-20}$$

In evaluating the surface integral $\int_S \vec{J}\,d\overrightarrow{a}$, we note that $\vec{J}$ is zero everywhere except in the wire which cuts through the surface bounded by the contour. Within the wire, J equals I/A. Now the surface integral becomes

$$\int_S \vec{J}\,d\overrightarrow{a} = I \tag{1-21}$$

In order to get a clearer picture of Ampere's law in a lumped-circuit form, let us take the toroid shown in Fig. 1-2.

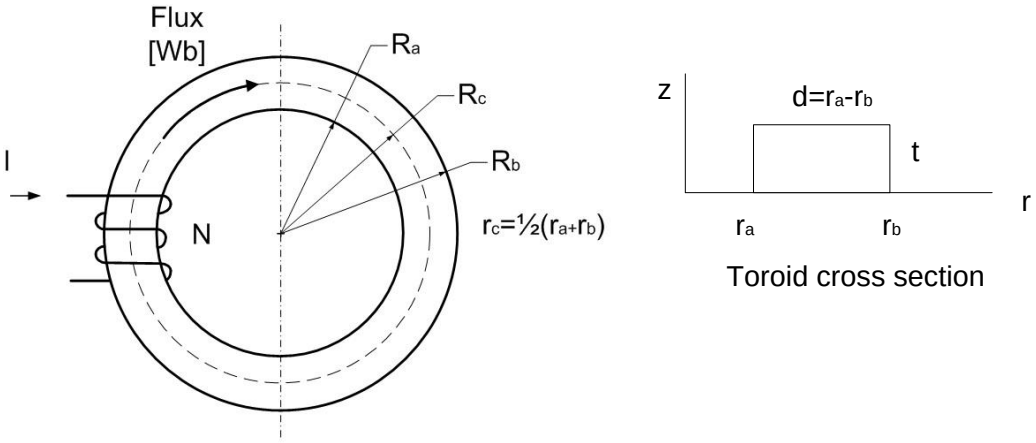


Fig.1-3. Toroid with *N* turns of wire carrying current *I*.

Because of high μ, for all practical purposes, the flux is confined within the toroid and H is circular and uniform for a given radius r. Thus

$$\oint_c \vec{H}\,\overrightarrow{dl} = \int_0^{2\pi} Hrd\theta = 2\pi rH \quad where\ r_a \le r \le r_b \tag{1-22}$$

and

$$\int_S \vec{J}\,\overrightarrow{da} = NI \tag{1-23}$$

Equating the two and solving for H, we obtain

$$H = \frac{NI}{2\pi r} \tag{1-24}$$

Thus, the flux in the toroid is

$$\Phi = \int_S \vec{B}\,\overrightarrow{da} = \int_S \overrightarrow{\mu H}\,\overrightarrow{da} = \int_{r_a}^{r_b} dr \int_0^t dz\,(\mu H) = \left(\frac{\mu}{2\pi} t \ln\frac{r_b}{r_a}\right) NI \tag{1-25}$$

Example:
Toroidal transformer has the following parameters:
Windings parameters:

Primary turns	N_1 = 640 turns	230V
Secondary turns	N_2 = 2x (32 turns bifilar)	2x 11,5 V/30,4A
U_{1n}=230V	I_{10} = 0,014A	

Core parameters:

Outer diameter	D = 106 mm
Inner diameter	d = 74 mm
Height	h = 61 mm

Calculate B – H rated parameters.

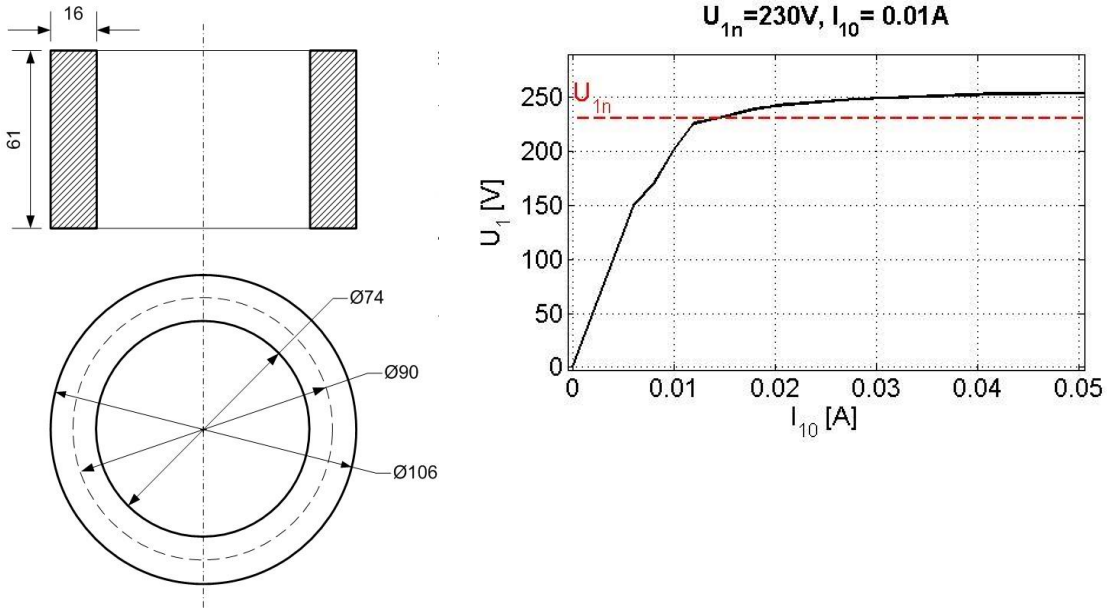


Fig.1-4. Toroidal transformer parameters and measured no-load characteristic.

Calculated parameters:

middle diameter d_{str}=0,09 m
middle length $l_{str} = \pi d_{str}$=0,2826 m
core area S_{Fe} = 0,061 x 0,016 =
976 x 10^{-6} m^2

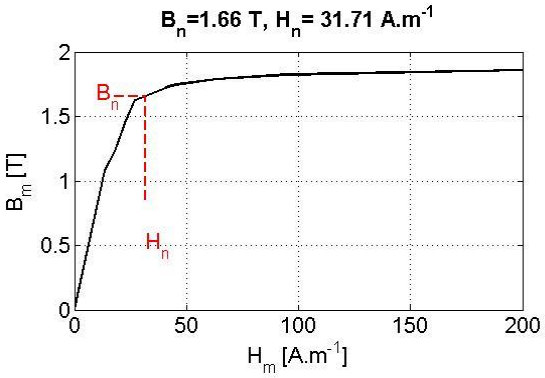


Fig.1-5. Toroid transformer B-H curve.

$$B_m = \frac{U_1}{4{,}44 N_1 S_{Fe} f} = \frac{230}{4{,}44.640.976.10^{-6}.50} = 1{,}66\ [T] \tag{1-26}$$

$$H_m = \frac{N_1 I_{10}}{l_{str}} = \frac{640\ x\ 0{,}014}{0{,}2826} = 31{,}7\ \left[\frac{A}{m}\right] \tag{1-27}$$

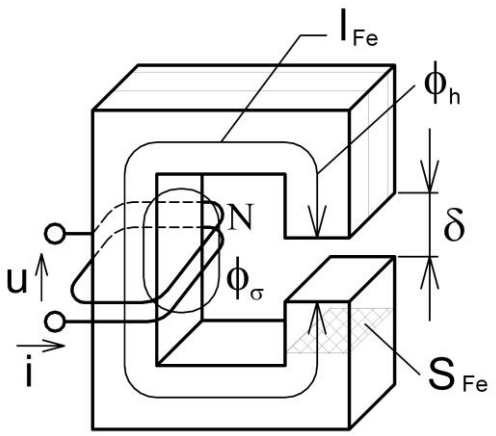


Fig.1-6. Magnetic circuit with air gap.

$$U_{mg} = H_{Fe} l_{Fe} = \frac{B_{Fe}}{\mu_{Fe}} l_{Fe} \tag{1-28}$$

$$U_{mg\delta} = H_{\delta}\delta = \frac{B_{\delta}}{\mu_0} \cdot \delta \tag{1-29}$$

$$\phi = B_{Fe} S_{Fe} \tag{1-30}$$

$$R_{mg} = \frac{l}{S\mu} = \frac{1}{\Lambda_{mg}} \tag{1-31}$$

$$\phi = \frac{U_{mg}}{R_{mg}} = \frac{Ni}{R_{mg}} = Ni\Lambda_{mg} \tag{1-32}$$

1.4 Faraday's law

When a time varying magnetic field passes through a conducting loop odd coil, a voltage is induced in the coil. Conversely, when a time varying voltage is applied to the terminals of the coil, a time varying magnetic field is generated.

$$\Psi = N\Phi \tag{1-33}$$

Where Ψ is flux linkage
N turns of coil
Φ flux linking each turn is the same

For transformer windings and coils wound around a magnetic toroid, the use of this equation is justified. However, in synchronous and induction machines, coils are distributed around a stator and rotor surface such that the flux coupling each turn is not the same!

Example:

A uniform flux density B=0,8 sin 120πt [T] is linking a 200 turn coil. The coil cross section is 10cm^2. Solve the induced voltage in the coil.

$$U_i = \mathrm{N}\frac{\partial \Phi}{\partial t} = NS\frac{\partial \mathrm{B}}{\partial t} = 200\ x\ 0{,}001\ x\ 0{,}8\ x\ 120\pi\ x \cos(120\pi\, t) = 19{,}2\pi\ x\ cos\pi t\ \ [V]$$

When flux Φ increases, the terminals A and C become positive. N_2 coils in (a) and (c) are wired in the opposite direction.

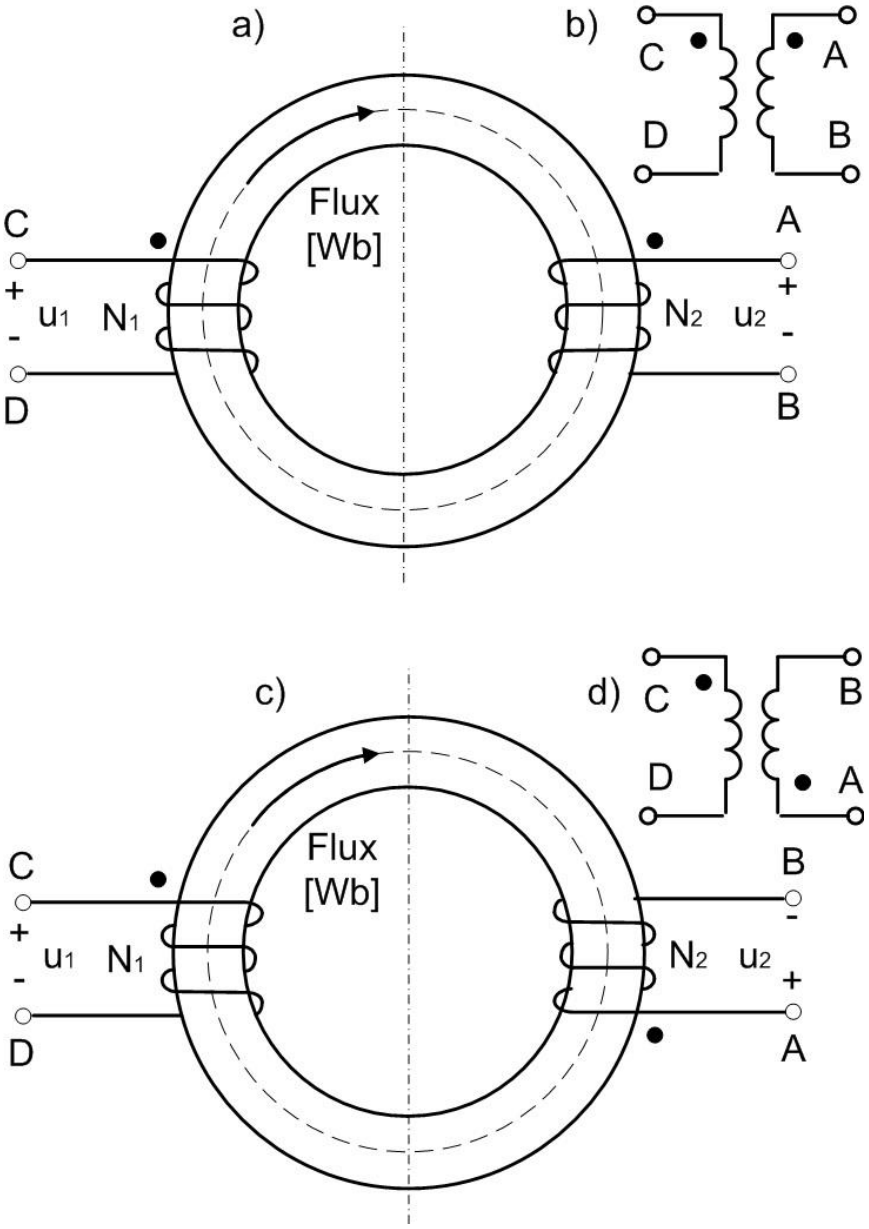


Fig.1-7. Two-coil device with electrical equivalent circuit with dot convention.

$$u_i = \frac{d\psi}{dt} \qquad (1\text{-}34)$$

$$\Psi = L \cdot i \qquad (L = N^2\ \Lambda_{mg}) \qquad (1\text{-}35)$$

$$u_i = L\frac{di}{dt} \qquad (L = konst) \qquad (1\text{-}36)$$

1.5 Inductance

II. Kirchhoff's law

$$R.i = -\frac{d\Phi}{dt} = u_i \tag{1-37}$$

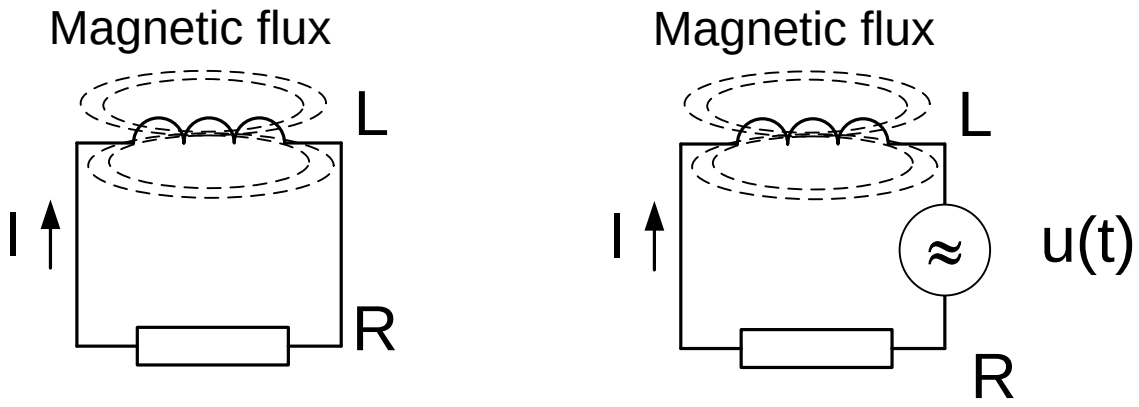


Fig.1-8. RL circuit a) without supply source b) with the supply source

Varying magnetic flux should be excited thanks to

- external source of magnetic flux
- current in the circuit, i.e., the circuit has a source of the varying voltage.

$$u(t) = R.i + \frac{d\Phi}{dt} \tag{1-38}$$

The derivation $\frac{d\Phi}{dt}$ consists of two components:

$$\Phi = f(i) \tag{1-39}$$

$$\mathrm{i} = f(t) \tag{1-40}$$

$$\frac{d\Phi}{dt} = \frac{d\Phi}{di}\frac{di}{dt} = L\frac{di(t)}{dt} \tag{1-41}$$

$$u(t) = R.i + L\frac{di}{dt} \tag{1-42}$$

1.6 Mutual inductance

The electromagnetic field in the circuit 2 can be caused by the current in the electric circuit no. 1.
Magnetic flux excited by current i_1 is labeled as Φ_{12} and this flux induces the voltage u_{i12}.

$$u_{i12} = -\frac{d\Phi_{12}}{dt} = \frac{d\Phi_{12}}{di_1}\frac{di_1}{dt} = L_{12}\frac{di_1}{dt} \tag{1-43}$$

$$u_{i21} = -\frac{d\Phi_{21}}{dt} = \frac{d\Phi_{21}}{di_2}\frac{di_2}{dt} = L_{21}\frac{di_2}{dt} \tag{1-44}$$

$$L_{21} = L_{12} = M[H] \tag{1-45}$$

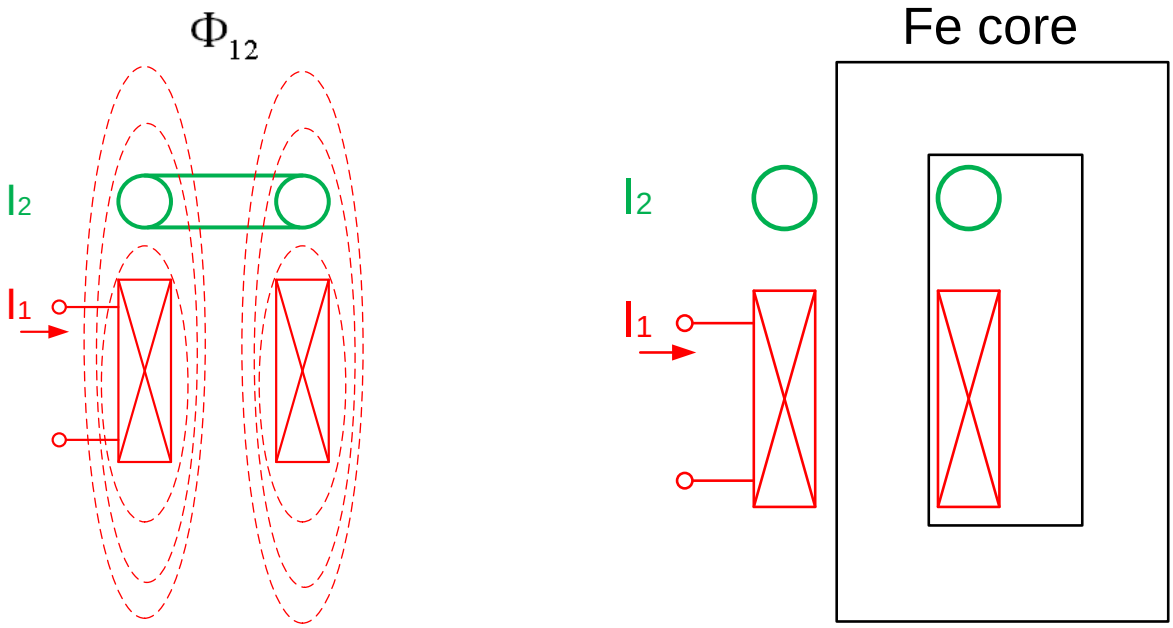


Fig.1-9. a) Mutual inductance = air cored transformer b) transformer.

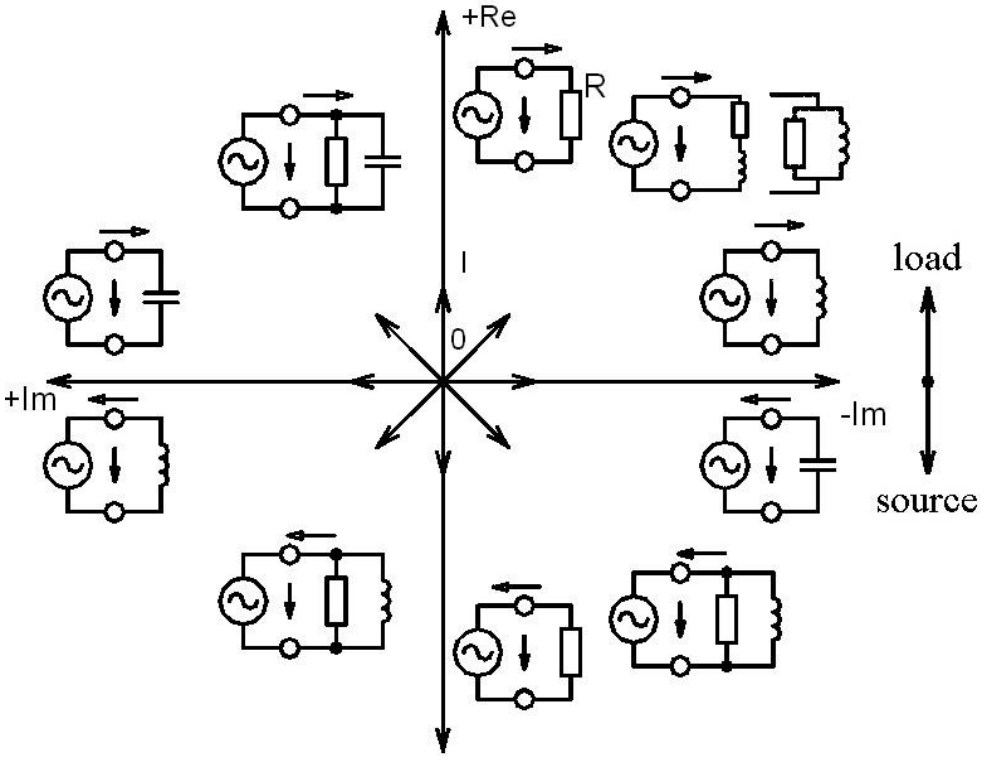


Fig.1-10. The conventional system of voltage and current for various types of loads.

1.7 Example

Determine the magnetic flux in the given magnetic circuit

a. when the $\mu_{Fe} \rightarrow \infty$

b. when the μ_{Fe} is given by the magnetization curve

The coil produces Um=200A.

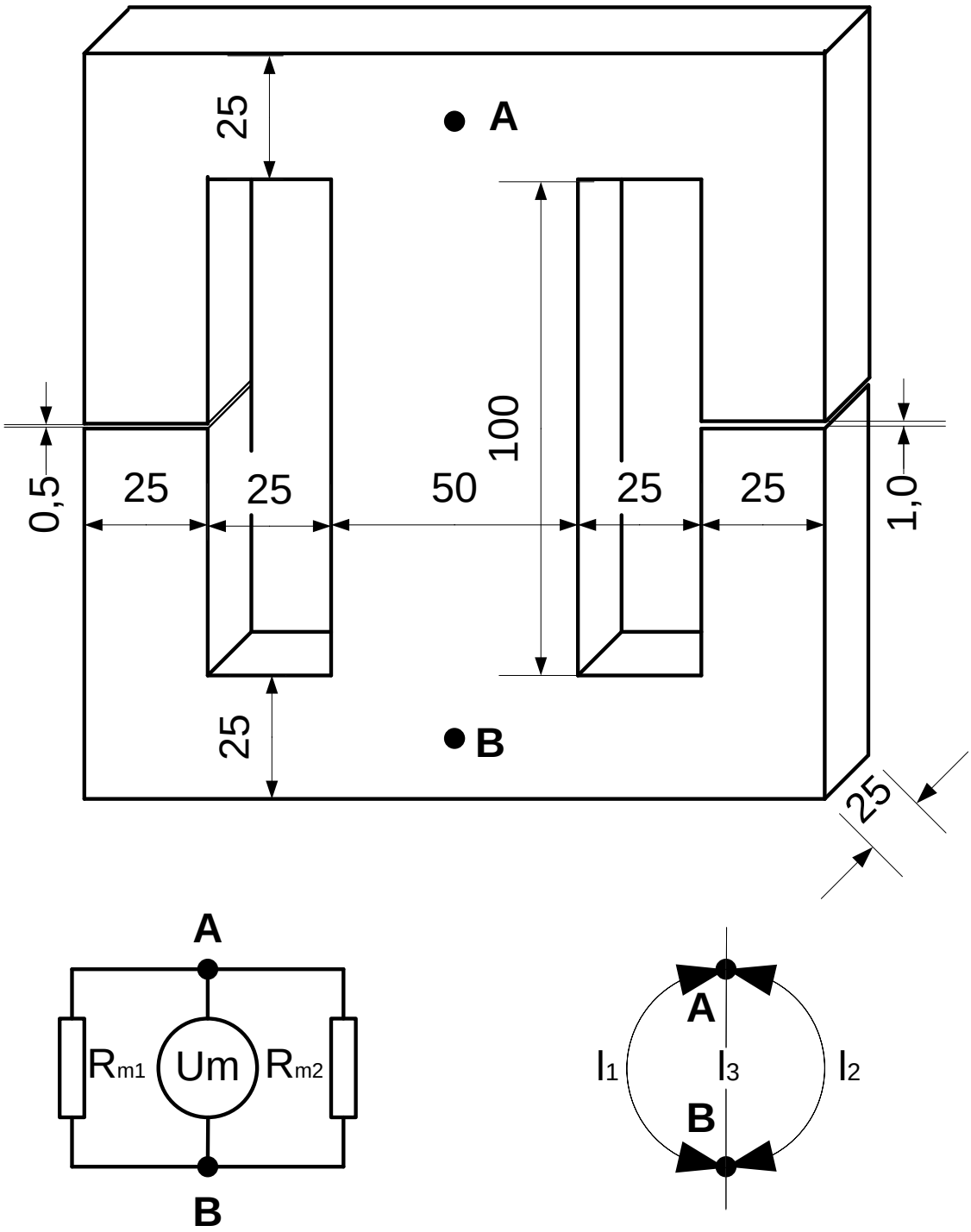


Fig.1-11. Sizes of the real magnetic circuit and equivalent circuit.

$$S_\delta = 625 \cdot 10^{-6}\ [m^2] \tag{1-46}$$

$$R_{m1} = \frac{\delta_1}{\mu_0 S_\delta} = \frac{0{,}5 \cdot 10^{-3}}{4\pi 10^{-7} \cdot 625 \cdot 10^{-6}} = 636{,}6 \cdot 10^3\ [H^{-1}] \tag{1-47}$$

$$R_{m2} = \frac{\delta_2}{\mu_0 S_\delta} = \frac{1 \cdot 10^{-3}}{4\pi 10^{-7} \cdot 625 \cdot 10^{-6}} = 1273{,}2 \cdot 10^3\ [H^{-1}] \tag{1-48}$$

$$\Phi_1 = \frac{U_m}{R_{m1}} = \frac{200}{636{,}6 \cdot 10^3} = 314{,}2 \cdot 10^{-6}\ [Wb] \tag{1-49}$$

$$\Phi_2 = \frac{U_m}{R_{m2}} = \frac{200}{1273{,}2 \cdot 10^3} = 157{,}1 \cdot 10^{-6}\ [Wb] \tag{1-50}$$

$$\Phi_3 = \Phi_1 + \Phi_2 = 471{,}3 \cdot 10^{-6}\ [Wb] \tag{1-51}$$

$$B_1 = \frac{\Phi_1}{S_\delta} = 0{,}502\ [T] \tag{1-52}$$

$$B_2 = \frac{\Phi_2}{S_\delta} = 0{,}251\ [T] \tag{1-53}$$

$$B_3 = \frac{\Phi_3}{S_3} = \frac{\Phi_3}{50.\ 10^{-3} \cdot 25.\ 10^{-3}} = 0{,}377\ [T] \tag{1-54}$$

$$l_3 = 0{,}1 + 0{,}0125 + 0{,}0125 = 0{,}125\,[m] \tag{1-55}$$

$$l_1 = l_2 = \left(50 + \frac{2\pi}{4} \cdot 0{,}0125 + 50\right) \cdot 2 = 0{,}239\ [m] \tag{1-56}$$

$${}_1B_1 = 0{,}502\ [T]\ldots\text{magnetizing curve}\ldots\ {}_1H_1 = 16\ [A.m^{-1}] \tag{1-57}$$

$${}_1B_2 = 0{,}251\ [T]\ldots\text{magnetizing curve}\ldots\ {}_1H_2 = 8\ [A.m^{-1}] \tag{1-58}$$

$${}_1B_3 = 0{,}377\ [T]\ldots\text{magnetizing curve}\ldots\ {}_1H_3 = 13\ [A.m^{-1}] \tag{1-59}$$

$${}_1U_{m1} = {}_1H_1 \cdot l_1 = 16 \cdot 0{,}239 = 3{,}8\ [A] \tag{1-60}$$

$${}_1U_{m2} = {}_1H_2 \cdot l_2 = 8 \cdot 0{,}239 = 1{,}9\ [A] \tag{1-61}$$

$${}_1U_{m3} = {}_1H_3 \cdot l_3 = 13 \cdot 0{,}125 = 1{,}6\ [A] \tag{1-62}$$

$$ {}_2B_1 = \frac{\mu_0}{\delta_1}\left(U_m - {}_1U_{m1} - {}_1U_{m3}\right) = \frac{4\pi 10^{-7}}{0{,}5.\,10^{-3}}(200 - 3{,}8 - 1{,}6) = 0{,}489\ [\mathrm{T}] \quad (1\text{-}63) $$

$$ {}_2B_2 = \frac{\mu_0}{\delta_2}\left(U_m - {}_1U_{m2} - {}_1U_{m3}\right) = \frac{4\pi 10^{-7}}{1.\,10^{-3}}(200 - 1{,}9 - 1{,}6) = 0{,}246\ [\mathrm{T}] \quad (1\text{-}64) $$

$$ {}_2\Phi_3 = {}_2B_1.S_\delta + {}_2B_2.S_\delta = (0{,}489 + 0{,}246).625.10^{-6} = 459.10^{-6}\ [Wb] \quad (1\text{-}65) $$

$$ {}_2B_3 = \frac{{}_2\Phi_3}{S_3} = \frac{459.10^{-6}}{50.\,10^{-3}.25.\,10^{-3}} = 0{,}367\ [\mathrm{T}] \quad (1\text{-}66) $$

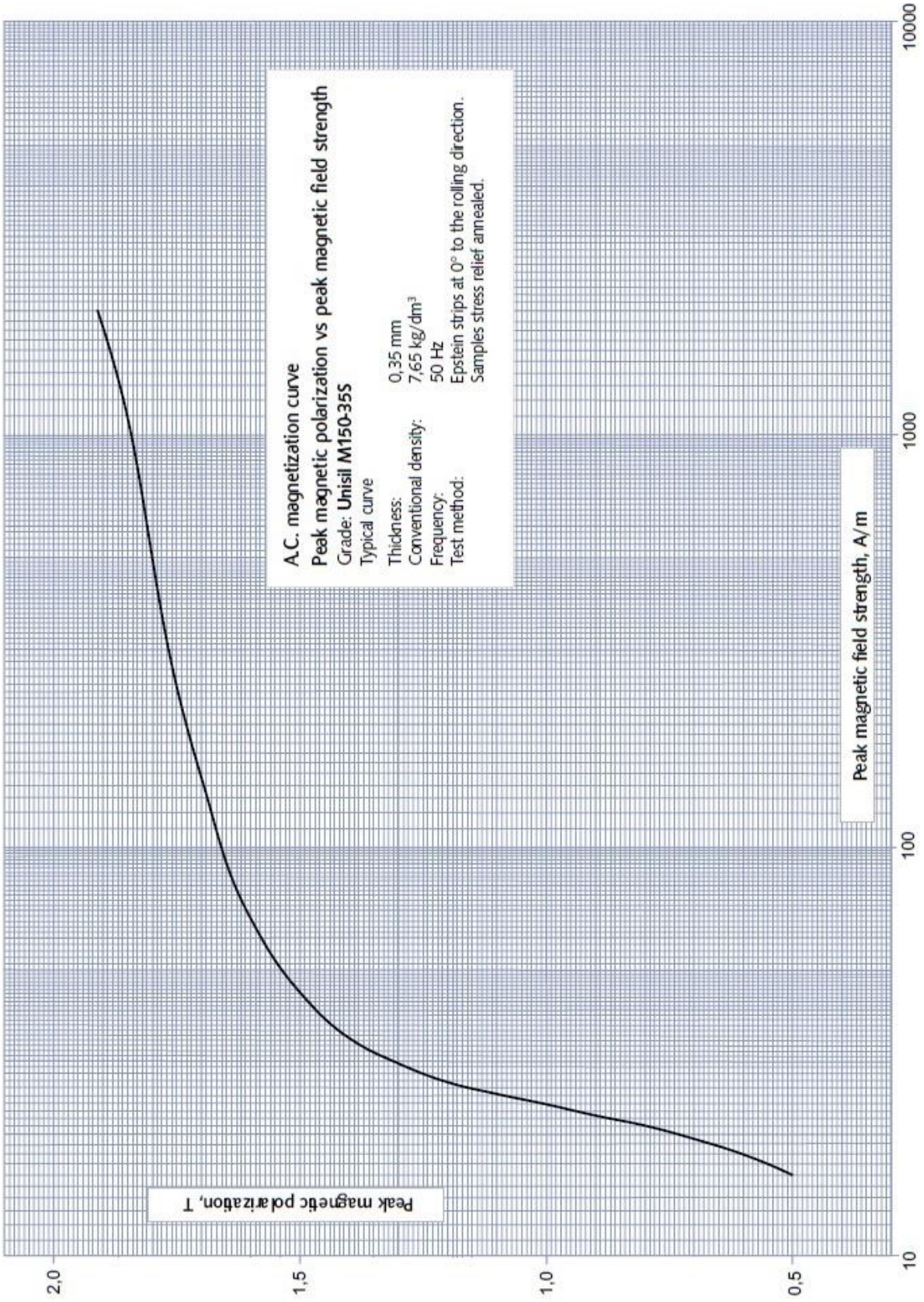


Fig.1-12. Sizes of the real magnetic circuit and equivalent circuit.
Picture taken from www.cogent-power.com, valid 08.09.2014, offering catalogue



Questions:

- *Why is inductance in Fig. 1-1 constant?*
- *What is the difference between magnetic flux Φ and Ψ in relationship 1-33?*
- *How can we create a magnetic flux in the coil (see fig. 1-8, left part) when the electrical circuit does not contain a voltage source?*
- *In Fig. 1-9 there are two coils with different magnetic coupling. Which configuration has higher mutual inductance?*



Answers

- *Why is inductance in Fig. 1-1 constant?*

Because there is a constant air gap, i.e., magnetic conductivity. This is true if we neglect the slot effect.

- *What is the difference between magnetic flux Φ and Ψ in relationship 1-33?*

The magnetic flow of Φ is a magnetic flux in the magnetic core. Magnetic flow Ψ is a so-called coupled magnetic flux with coil turns. If we do not consider leakage flux, this is the product of the flux Φ with the number of turns.

- *How can we create a magnetic flux in the coil (see fig. 1-8, left part) when the electrical circuit does not contain a voltage source?*

For example, thanks to an external electromagnet or a permanent magnet. If the flux is variable, it is the principle of the generator.

- *In Fig. 1-9 there are two coils with different magnetic coupling. Which configuration has higher mutual inductance?*

The configuration with a magnetic core.

2 Transformers



Estimated completion time: **120 min**



After studying the topic, you will be able to:

- *characterize magnetic and electrical fields*
- *draw transformer connections to transform the number of phases from 3 to 2 (Scott's connection)*
- *calculate phase voltages, currents and powers in Scott's connection*
- *draw transformer connection for 12 pulse rectifier*
- *measure the transformer clock number (vector group)*

2.1 Scott connection of the transformers

To supply the trolley wire 25kV / 50Hz from the common network caused a serious problem: the trolley is a one phase load, however the network is a 3phase system. Consequently, the loading of the 3phase network unsymmetrically caused serious problems, especially in the transformers.
The trolley is supplied from 110kV network via 1phase transformers (the Scott connection should be used).

This type of connection consists of two transformers

- main transformer (number of turns N_1 / N_2) with the voltage tap in the middle (0,5 N_1)
- auxiliary transformer (number of turns 0,866 N_1 / N_2)

The voltage tap of the main transformer is connected to the end of the winding of the auxiliary transformer (point A1)
On the secondary side of both transformers are N_2 turns – secondary voltage is symmetrical.
Primary 3phase voltage is also symmetrical
Height of the triangular (from point A3 - above the basement B1-B3 - to the point A1=B2) is

$$\frac{\sqrt{3}}{2} U = 0{,}866\, U$$

Due to this fact the auxiliary transformer has between points A1-A3 number of turns 0,886 N1. Ration voltage to number of turns

$$U_{1t} = \frac{0{,}866\, U}{0{,}866\, N_1} = \frac{U}{N_1}$$

Magnetic flux of the auxiliary transformer has the same value as the magnetic flux of the main transformer. Consequently, both secondary voltages are the same.

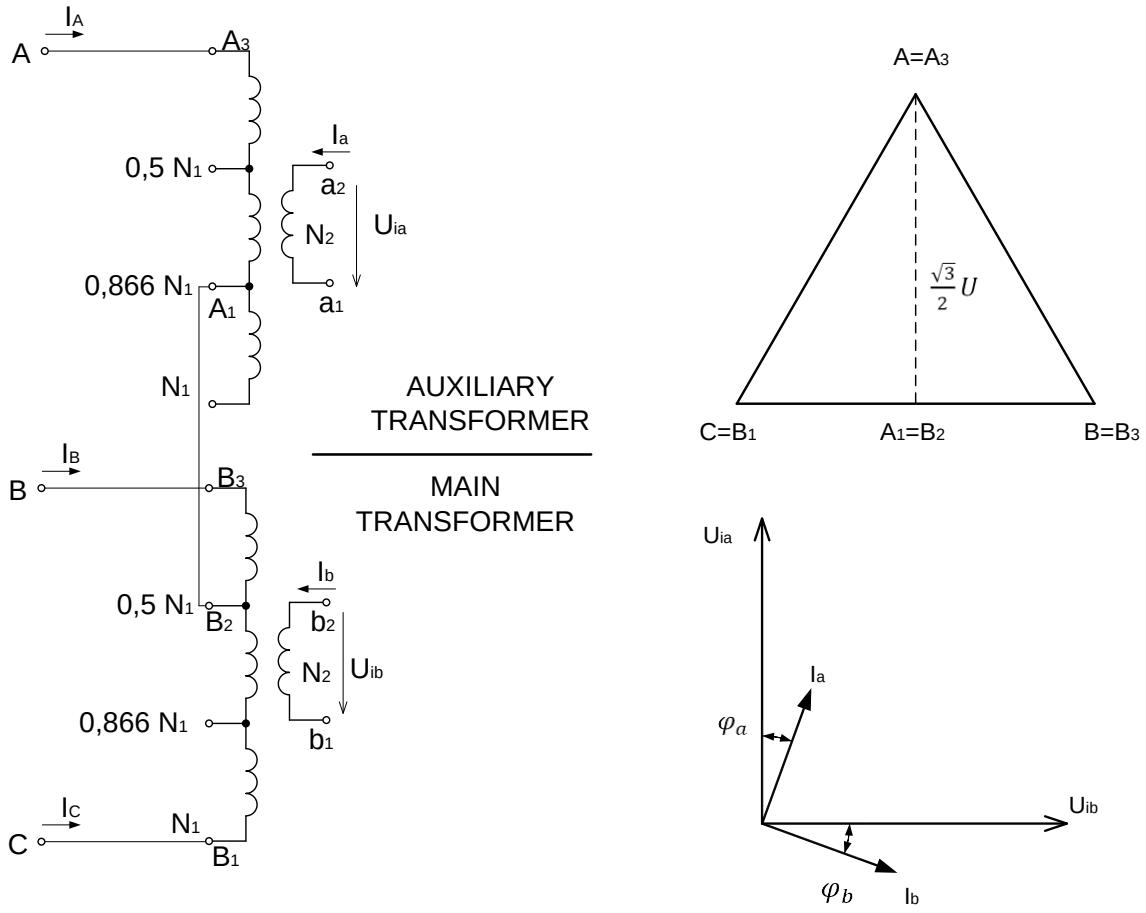


Fig.2-1. The Scott connection of transformers.

Example:

It is given the two phase supply system of a voltage 25kV. One phase has a load of P_a=4MW, PF_a=1, the second phase has a load of P_b=5MW, PF_b =0,95. The 3phase network system has a voltage of 110 kV. Determine the currents of a 2phase system (I_a, I_b) and 3phase system (I_A, I_B, I_C).

Solution:

$$I_a = \frac{P_a}{U_a} = \frac{4000000}{25000} = j160\ [A] \tag{2-1}$$

$$I_b = \frac{P_b}{U_b . cos\varphi_b} = \frac{4000000}{25000\ .0,95} = 200 - j65,7[A] = 210,5\angle -18,2^o\ [A] \tag{2-2}$$

The voltage ration of the main transformer

$$k = \frac{U_1}{U_2} = \frac{N_1}{N_2} = \frac{110000}{25000} = 4,4\ [-] \tag{2-3}$$

Primary current

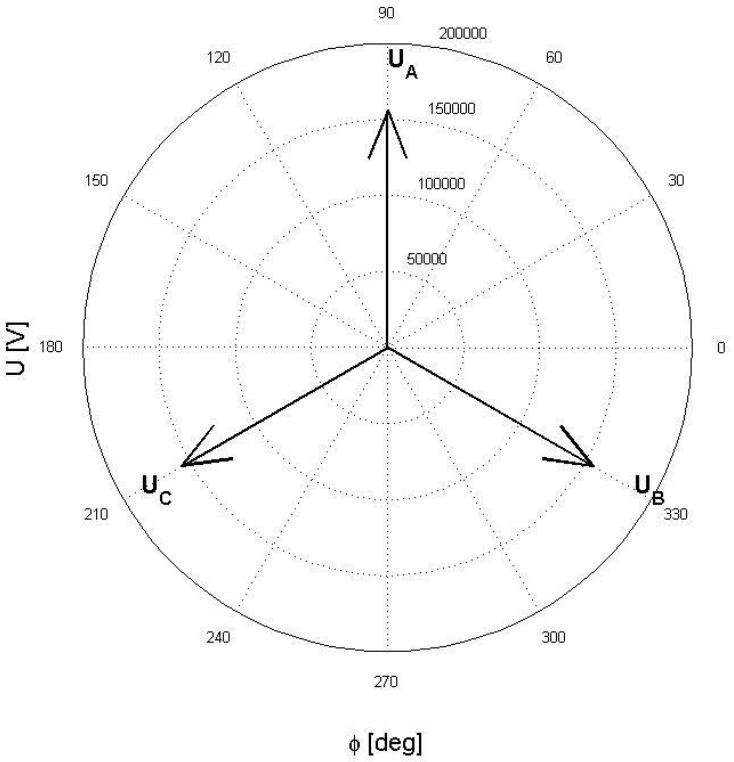
$$I_A = \frac{2}{\sqrt{3}} \frac{N_2}{N_1} I_a = \frac{2}{\sqrt{3}} \frac{1}{4,4} j160 = j42\ [A] \tag{2-4}$$

$$I_B = -\frac{I_A}{2} + I_b\frac{N_2}{N_1} = -j42 + (200 - j65{,}7)\frac{1}{4{,}4} = 45{,}4 - j35{,}9\ [A] \quad (2\text{-}5)$$

$$I_C = -\frac{I_A}{2} - I_b\frac{N_2}{N_1} = -j21 - (200 - j65{,}7)\frac{1}{4{,}4} = -45{,}4 - j6{,}1\ [A] \quad (2\text{-}6)$$

Complex plot of 3-ph system U_{ef}=110000V (Scott connection)

U_A = 0.0+155563.5i [V]
U_B = 134721.9-77781.7i [V]
U_C = -134721.9-77781.7i [V]
U_A = 155563.5 [V] ϕ= 90.0 [^{o}]
U_B = 155563.5 [V] ϕ= -30.0 [^{o}]
U_C = 155563.5 [V] ϕ= -150.0 [^{o}]



Complex plot of 3-ph system I_{Aef}=42.0A (Scott connection)

I_A = 0.0+59.4i [A]
I_B = 64.3-50.8i [A]
I_C = -64.3-8.6i [A]
I_A = 59.4 [A] ϕ= 90.0 [^{o}]
I_B = 81.9 [A] ϕ= -38.3 [^{o}]
I_C = 64.9 [A] ϕ= -172.4 [^{o}]

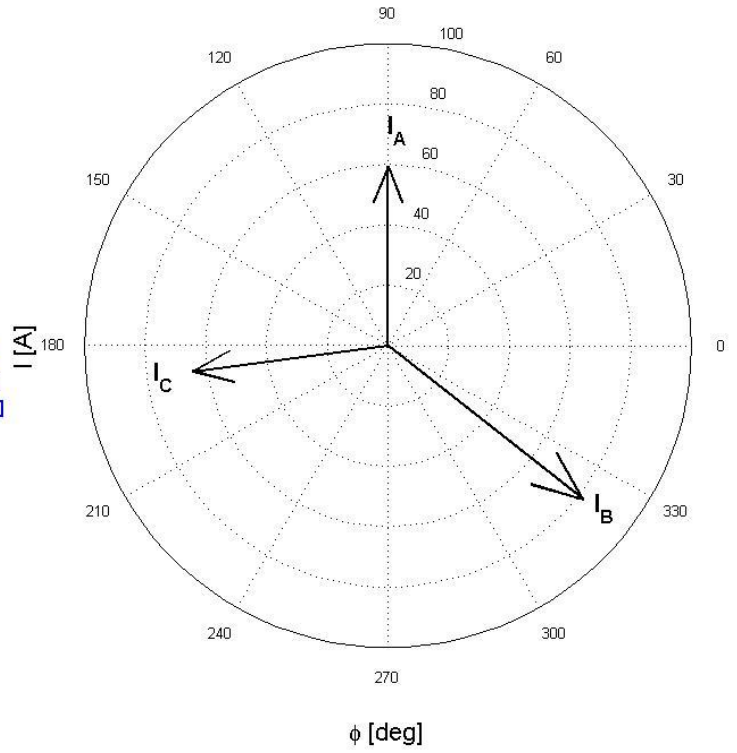
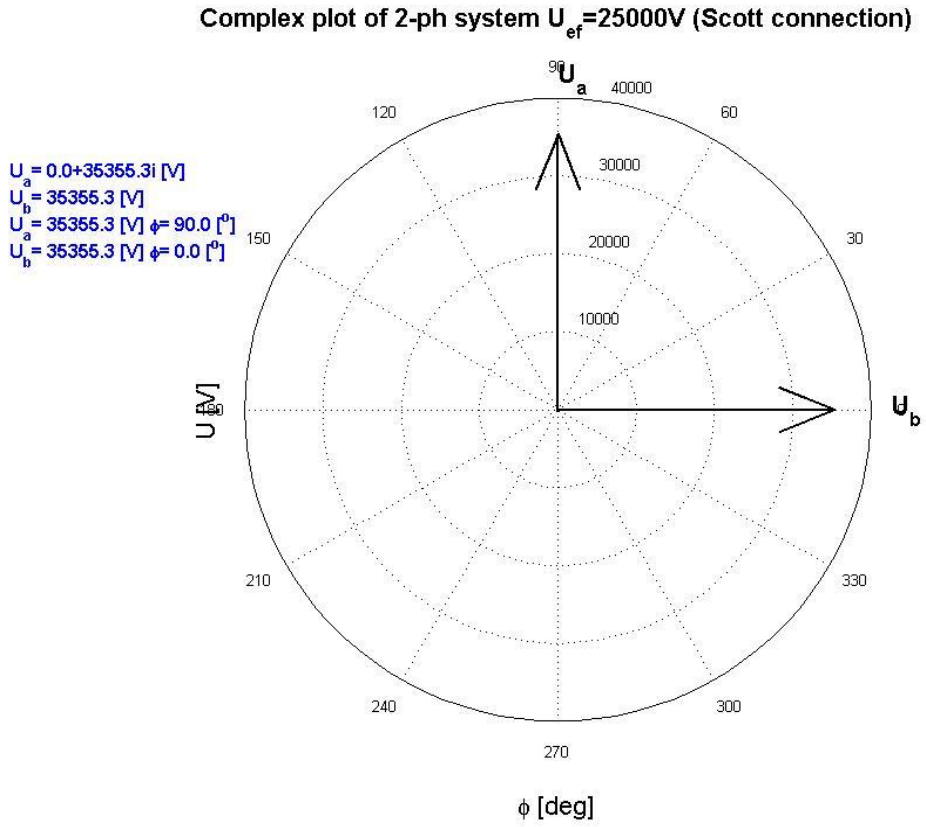


Fig.2-4. The Scott connection of transformers – 2phase supply system.



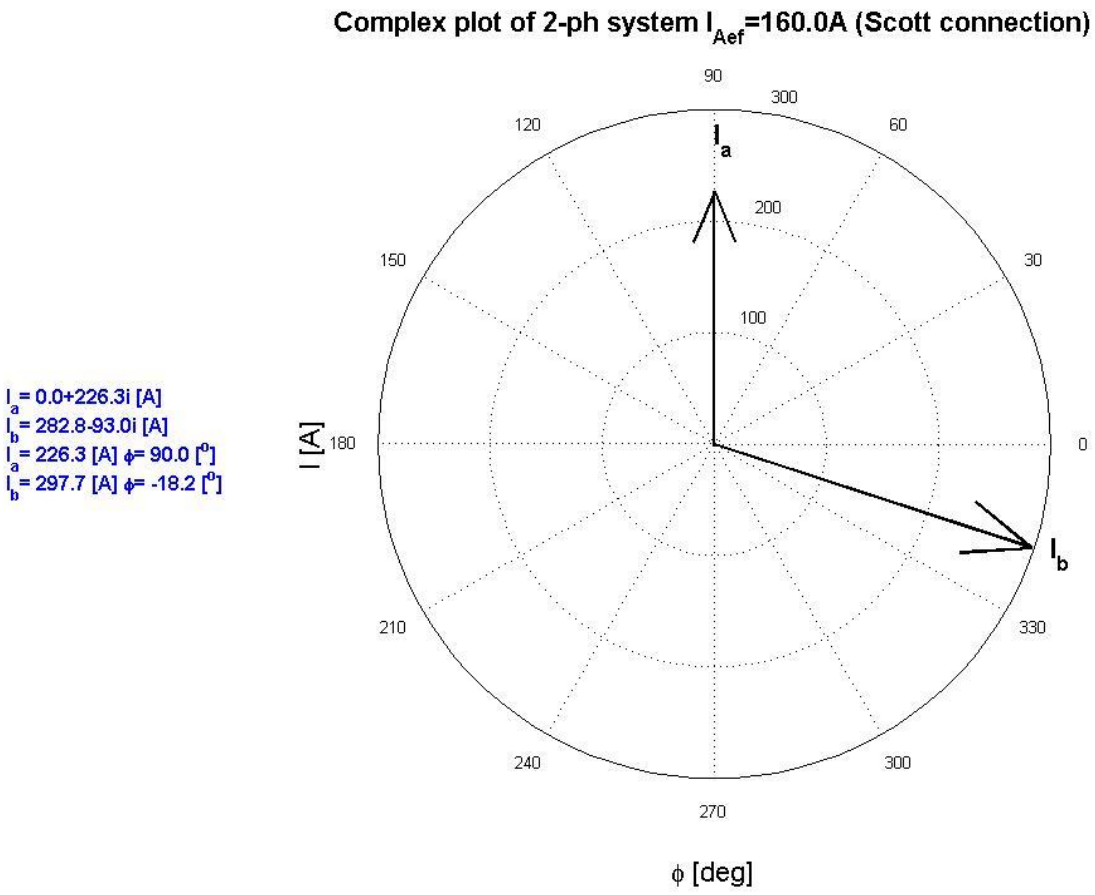


Fig.2-5. The Scott connection of transformers – 2phase supply system.

2.2 Supplying method of AC trolley

For decreasing the unsymmetrical loading of the 3ph network is each 1phase supply trolley station supplied from different phases.

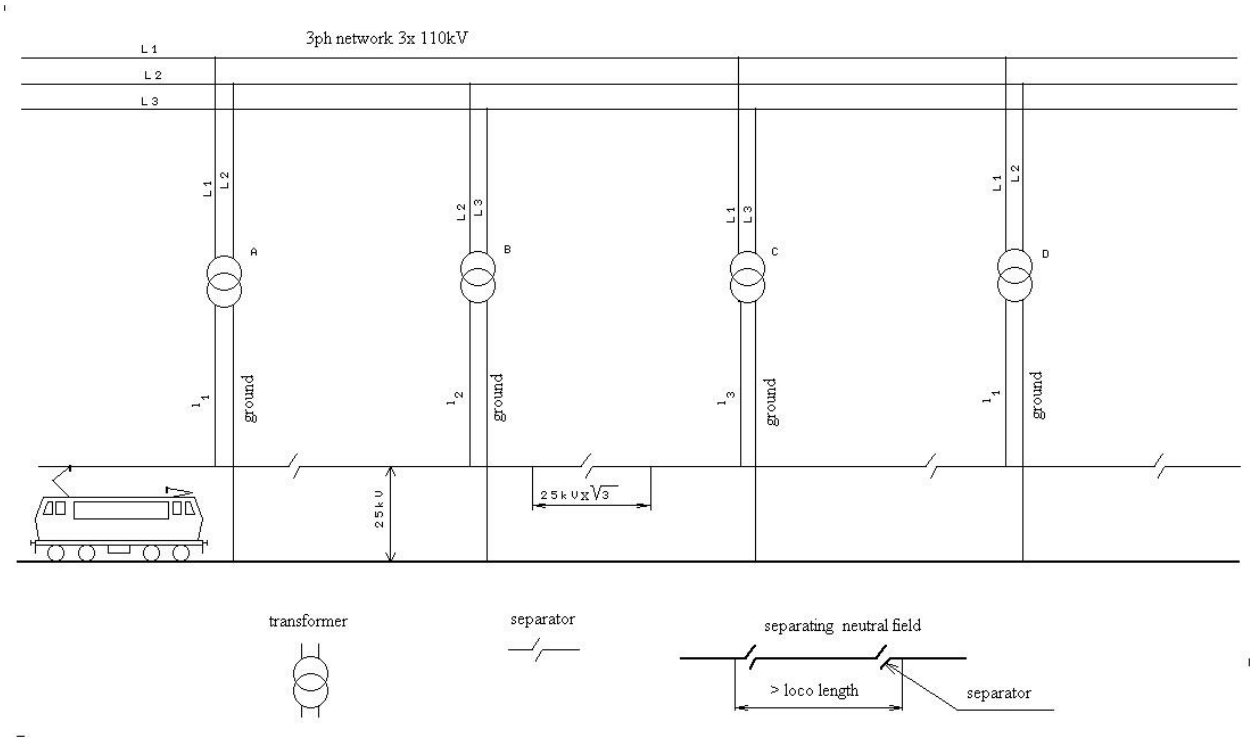


Fig.2-6. One railway line, principle of decreasing unsymmetrical load.

The trolley is supplied exclusively from one side only. Both sides supplying caused serious problems (see below).
In the previous figure the transformer is located approximately in the middle of the supplied area (which is about 30-40 km). The transformer has a rated power which is the same as the nominal power of the whole supply station.
In case of malfunction, it is necessary to place a redundant transformer in the supply station (very expensive), which is not used and serves as reserve.

In practice, we use two supply stations concentrated in one. Two transformers are located in each supply station. Each transformer has a rated power of only 50% of the nominal power of the whole supply station.
In the same emergency case (local black out of a 110kV line) it is possible to supply both trolley parts from neighboring supply stations.

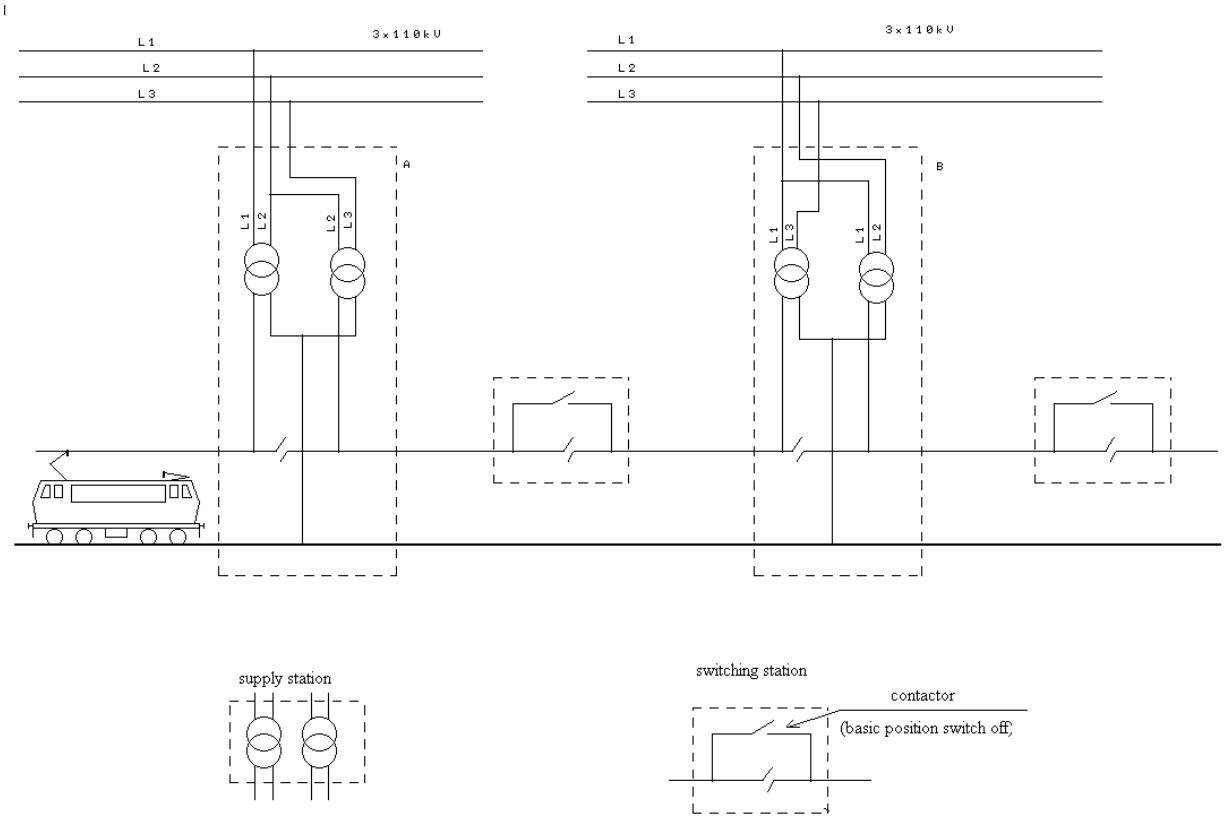


Fig.2-7. The supply stations on the one railway line.

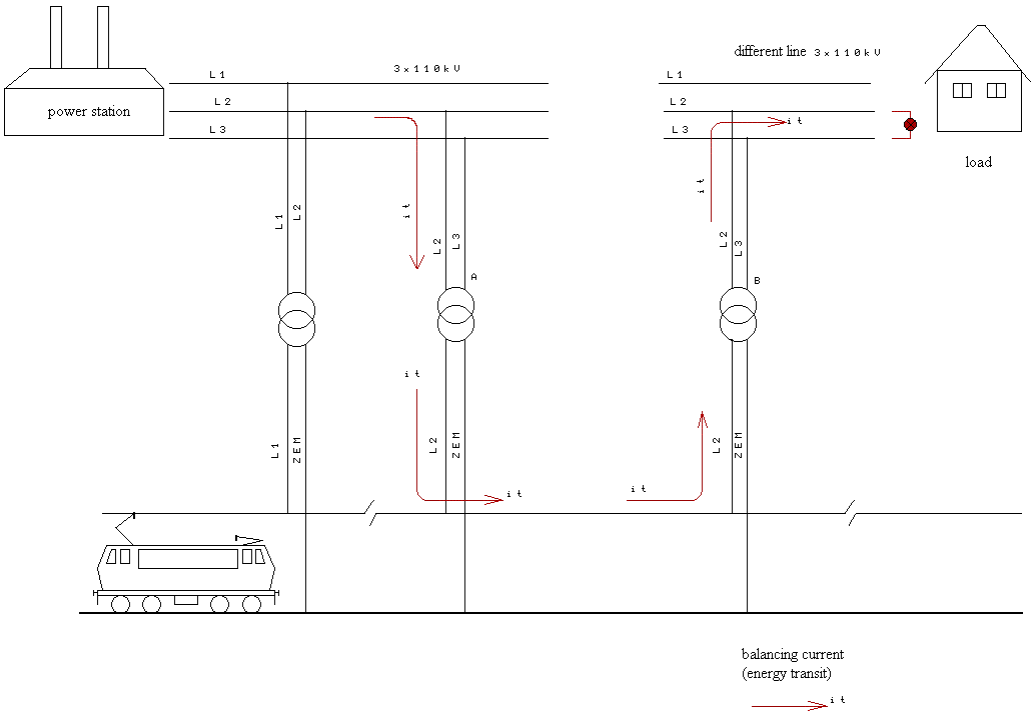


Fig.2-8. Energy transit via trolley wire (not allowable!).

2.3 Transformer for DC trolley - traction substation

Traction power supply is one of the most important parts of the transport infrastructure. It links the general AC medium voltage supply system and the DC supply line (trolley wire or third rail) of the traction vehicles.

As a contrast with the AC trolley, the DC trolley wire is supplied from both sides. This method decreases the voltage drop. In addition, both switches are coupled and in case of overcurrent both sides are disconnected simultaneously.
Traction substations are supplied by 22kV 3phase network, 2 independent cable lines.

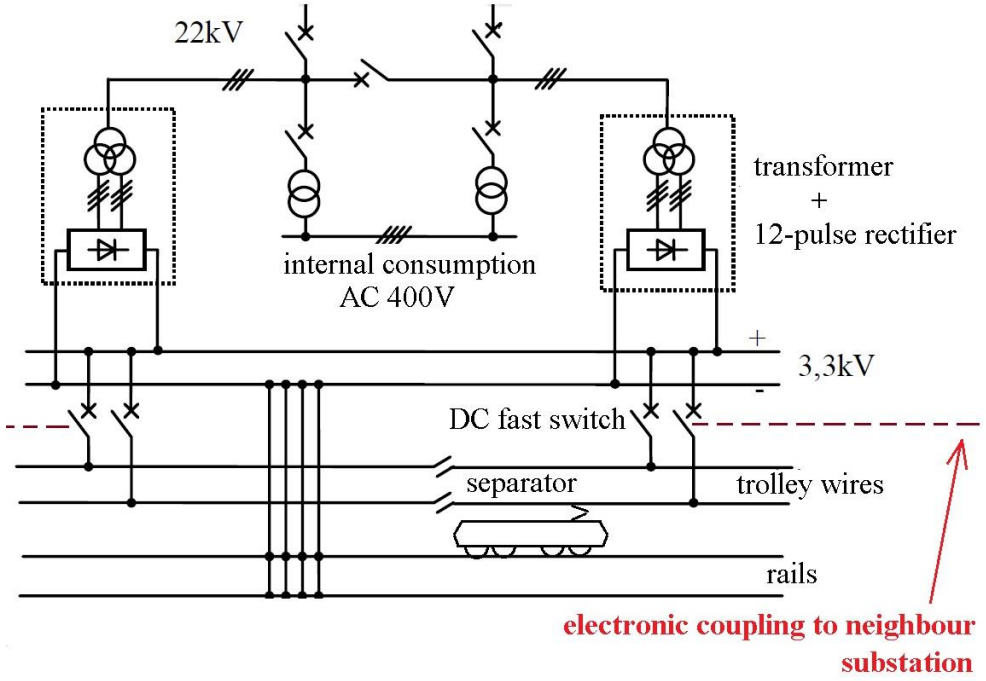


Fig.2-9. DC traction substation [15].

The rated voltage of the trolley wire is 3 kV. The DC substation has a rated voltage of 3,3kV – for voltage drop compensation purposes.

Input transformer requirements
Each rectifier always cooperates with its supply transformer [14]. This transformer provides adjustment to the Medium Voltage to the level required by the rectifier and its load. The next very important function of the input transformer is the output voltage regulation and short circuit current limitation. Both of these things depend on impedance voltage of the transformer and also on the coupling factor of secondary windings (in three winding transformers). Higher impedance voltage causes higher voltage regulation and simultaneously lower short circuit current. The correct output voltage characteristic inclination provides appropriate load sharing between rectifiers supplying the same load. The limitation of short circuit current value is demanded by: supply network, DC switchgears or by rolling stock. The input transformer must also provide appropriate overload ability, which corresponds to the overload class of the rectifier.

The rectifiers transformer family is designed for the supply of DC traction loads like urban transport systems or main-line railways in ranges of following standard output voltages:

- up to 825 V DC
- 1500-1650 V DC
- 3000-3300 V DC

To minimize the harmonic distortion the rectifier consists of two diode bridges connected in series or in parallel. Both bridges are prepared to be supplied from the two secondary windings of the transformer, this solution provides 30o phase shift and 12-pulse influence on the supply network. Two 12-pulse rectifiers supplied by two three windings transformers with +/-7.5o phase shift of primary windings create a 24-pulse rectifiers configuration. Single bridge 6-pulse rectifiers are not common.

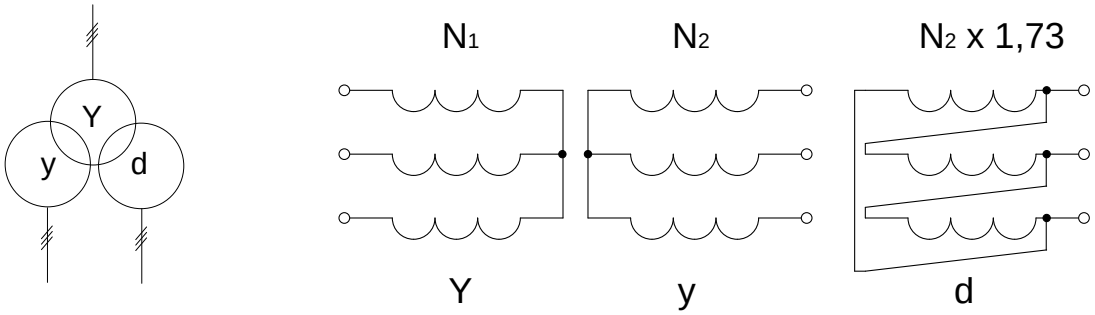


Fig.2-10. Transformer connection.

12-pulse rectifiers produce outgoing DC voltage which contains harmonics 600, 1200, 1800 Hz etc.
The input current of the 12-pulse rectifier from the 22kV network contains only 11, 13, 23 and 25 order of harmonics. Due to the low level of these harmonics the input filters are not required.

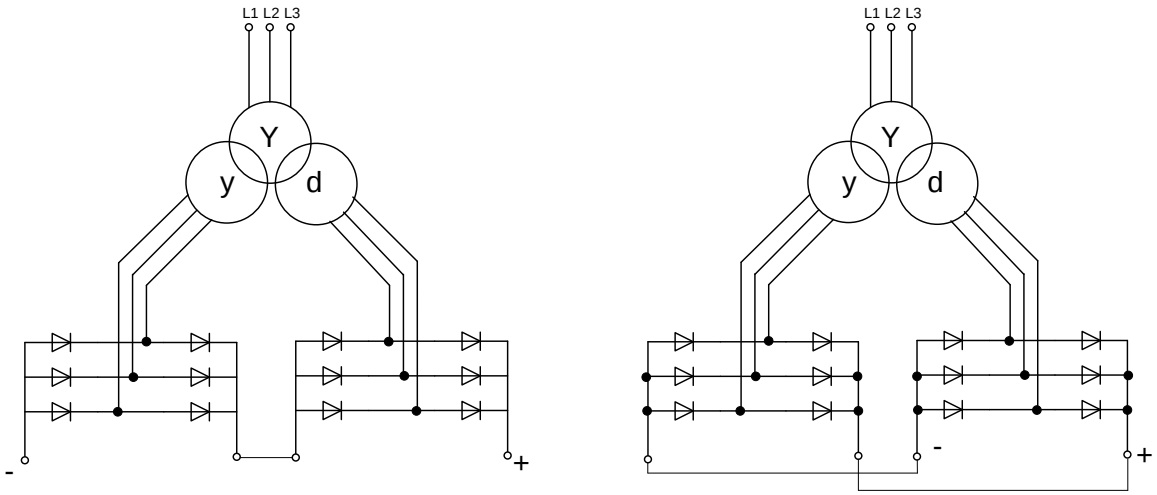


Fig.2-11. Rectifiers connection a) serial b) parallel.

The transformer shall be provided with a single primary winding and two secondary windings: one connected in star and one connected in delta. The rectifier consists of 12 diodes or thyristors.

The type of connection is Yyn0d1.

Advantages and disadvantages of serial and parallel topology
The most important advantage of parallel topology [14] is a decrease of load losses (almost two times smaller than in serial configuration). It has an impact on the rectifier dimension, number of diodes and space required to dissipate heat produced by rectifiers. However, the turn ratio unbalances between the Y- and D-windings of the converter transformer for 12-pulse converters (built up of two six-pulse bridges connected in parallel) causing discrepancies between theoretical and real harmonic levels in the supply network (especially for the 5-th, 7-th, 17-th and 19-th harmonics). To achieve the perfect balance the transformer windings connected to the rectifier bridges must generate exactly the same voltage. The number of turns should then be √3 times higher for the D-winding than for the Y-winding, but the number of turns must be an integer. Due to the low secondary voltage the number of turns must be comparatively few. Hence a turn ratio error is inevitable. The values of 5-th and 7-th harmonics are a few times higher in case of parallel than in serial topology however they do not exceed allowable levels and this difference exists mainly at low load.
The conclusion is that a 12-pulse converter built up of two parallel-connected six-pulse bridges is very sensitive to turn ratio unbalances between the Y- and D-windings of the converter transformer. A 12-pulse converter built up of two series connected six-pulse bridges is much less sensitive to this type of unbalance. The secondary windings of the transformer should be made as
decoupled to decrease this effect significantly (coupling factor < 0.2) or the output transition coil, which connects outputs of the parallel bridges, should be applied.

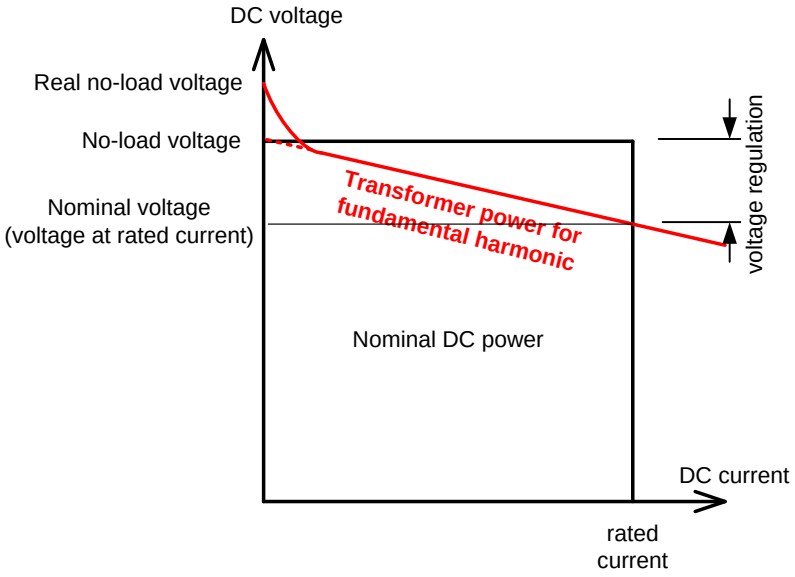


Fig.2-12. DC voltage versus current characteristic.

The international standard ČSN EN 50329 class of operation VI. Example: Transformer SEA 5300 VA for Czech railways

Loading 100%	continuously (index a)
Loading 150%	2 hours (index b)
Loading (200÷)300%	60 sec (index c)

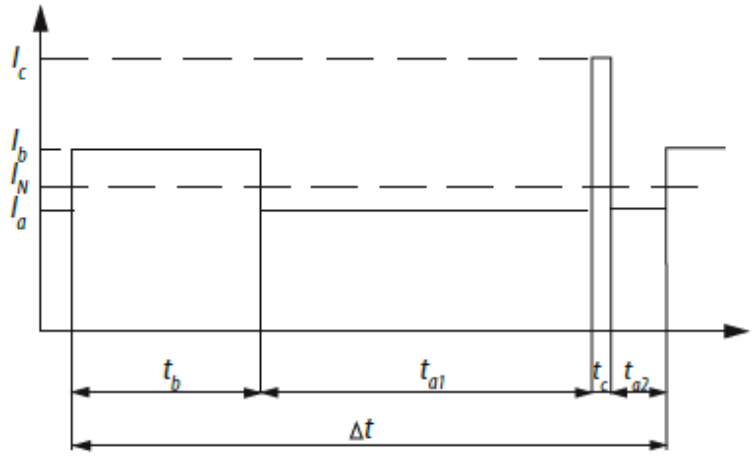


Fig.2-13. Loading cycle of the transformer.

Transformer parameters

Rated power	5300 // 2650/2650 VA
Rated frequency	50 Hz
Primary voltage	23kV, voltage taps ±2x 2,5%
Secondary voltage	2x 2500V
Dimension	2800 x 1800 x 2650 mm
Weight (oil incl.)	16 000 kg
Short circuit voltage	7,5% ± 10% tolerance
No-load losses	4 000 W
Short circuit losses	26 000W

2.4 Transformer vector group (clock hour number)

Three phase transformers consist of three sets of primary windings, one for each phase, and three sets of secondary windings wound on the same iron core.
Separate single-phase transformers can be used and externally interconnected to yield the same results as a 3-phase unit.
The primary windings are connected in one of several ways. The two most common configurations are the delta, in which the polarity end of one winding is connected to the non-polarity end of the next, and the star, in which all three non-polarity (or polarity) ends are connected together. The secondary windings are connected similarly. This means that a 3-phase transformer can have its primary and secondary windings connected the same (delta-delta or star-star), or differently (delta-star or star-delta) [16].

It's important to remember that the secondary voltage waveforms are in phase with the primary waveforms when the primary and secondary windings are connected the same way. This condition is called "***no phase shift***."

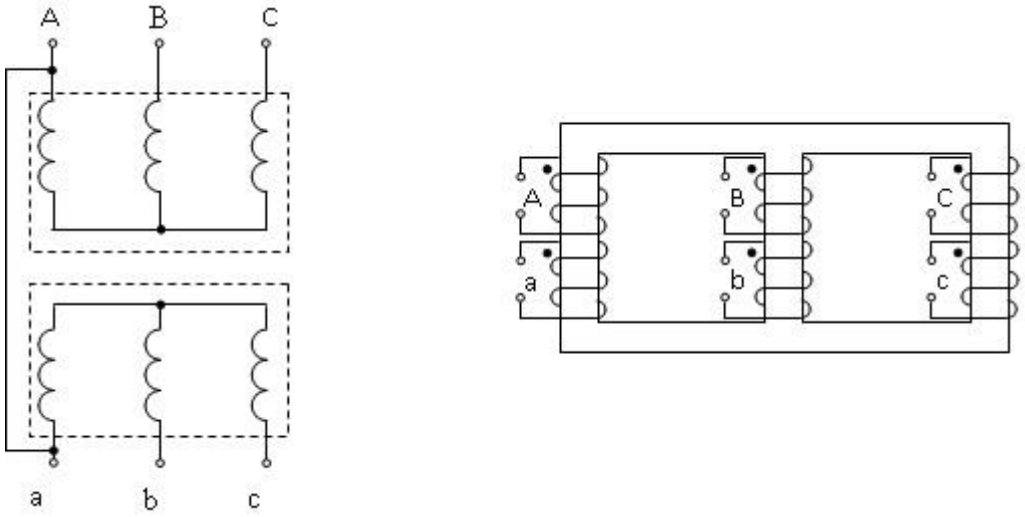


Fig.2-14. a) Measurement of the clock hour number. b) presumptions.

But when the primary and secondary windings are connected differently, the secondary voltage waveforms will differ from the corresponding primary voltage waveforms by 30 electrical degrees. This is called a 30 degree phase shift. When two transformers are connected in parallel, their phase shifts must be identical; if not, a short circuit will occur when the transformers are energized.

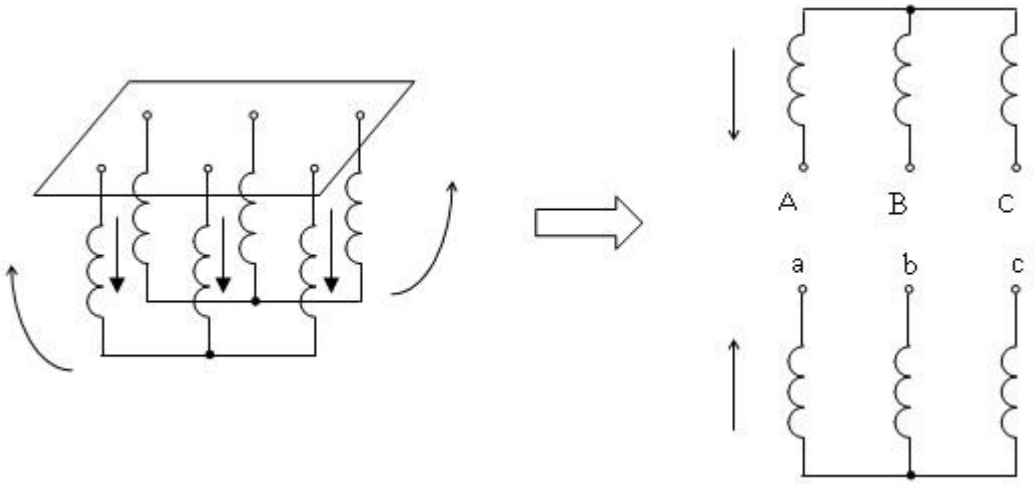


Fig.2-15. a) Transformation of 3D windings to 2D

An ac voltage applied to a coil will induce a voltage in a second coil where the two are linked by a magnetic path. The phase relationship of the two voltages depends upon which ways round the coils are connected. The voltages will either be in-phase or displaced by 180 degrees.

When 3 coils are used in a 3phase transformer winding a number of options exist. The coil voltages can be in phase or displaced as above with the coils connected in star or delta and, in the case of a star winding, have the star point (neutral) brought out to an external terminal or not.

Polarity

When a pair of transformer coils have the same direction then voltage induced in both coils is

in the same direction from one end to the other. When two coils have opposite winding directions then the voltage induced in both coils is in the opposite direction.

Winding connection designations
First Symbol: for **High Voltage**: Always capital letters.
D=Delta, Y=Star, Z=zig-zag star, N=Neutral
Second Symbol: for **Low voltage**: Always Small letters.
d=Delta, y=Star, z=zig-zag star, n=Neutral.
Third Symbol: Phase displacement expressed as the clock hour number

Vector group of transformers
The transformer vector group is indicated on the name plate of the transformer by the manufacturer. The vector group indicates the phase difference between the primary and secondary sides, introduced due to that particular configuration of transformer windings connection.

Y	y d z	0 6 1 5 7 11 1 5 7 11
D	y d z	1 5 7 11 0 2 4 6 8 10 0 2 4 6 8 10

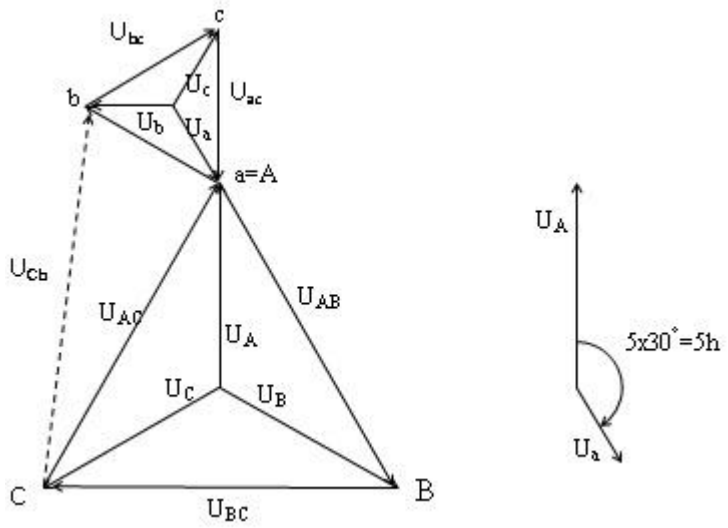


Fig.2-16. Evaluation of the measurement.



Questions:

- *Traction vehicles represent a 1phase load. Then why are we transforming the 3-phase system into a 2-phase system?*
- *What type of transformer is used for DC traction trolley-systems?*
- *From the point of view of winding connection - what conditions must the transformer meet?*
- *Why do we temporarily connect primary and secondary sides when measuring the vector group number?*



Answers

- *Traction vehicles represent a 1phase load. Then why are we transforming the 3-phase system into a 2-phase system?*

From the power sub-station, one phase is used for the left part of the railway, the second phase is used for the right part of the railway. The only exception is the power sub-stations where the traction system ends. The railway then does not continue or continues with another traction system or independent traction.

- *What type of transformer is used for DC traction trolley-systems*

A three-winding transformer is used in the Yy0d1 connection.

- *From the point of view of winding connection - what conditions must the transformer meet?*

The same winding names on one magnetic yoke, same winding direction and correct winding connection to terminal box.

- *Why do we temporarily connect primary and secondary sides when measuring the vector group number?*

The transformer galvanically separates the primary and secondary electrical circuits. However, we must measure the voltage between the terminals of the primary and secondary windings. Therefore, it is necessary to temporarily connect one terminal of the primary winding to one terminal of the secondary winding. At the end of the measurement, we must remove the connection!

3 Inductances of 3-phase Rotary Machines



Estimated completion time: **40 min**



After studying the topic, you will be able to:

- *write voltage equations of synchronous machines*
- *write equations for coupled fluxes of synchronous machines*
- *describe the characteristics of their own inductances and mutual inductances of the synchronous machine*
- *draw a graph of the dependence of inductances on the position of the rotor of the synchronous machine*

3.1 Basic equations of synchronous machine

We assume a synchronous machine with salient poles. On a stator there are three phases a, b, c. On the rotor there is excitation winding f. The further windings (for example dumper) we neglected for simplicity.

The basic voltage relations have formulas

$$u_j = R_j i_j + \frac{d\psi_j}{dt} \quad (j = a, b, c, f) \tag{3-1}$$

The relation of mutual fluxes has formulas

$$\psi_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + L_{af} i_f \tag{3-2}$$

$$\psi_b = L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + L_{bf} i_f \tag{3-3}$$

$$\psi_c = L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + L_{cf} i_f \tag{3-4}$$

$$\psi_f = L_{fa} i_a + L_{fb} i_b + L_{fc} i_c + L_{ff} i_f \tag{3-5}$$

These formulas contain

- 4 self inductances of stator and rotor
- 3 mutual inductances of the stator and rotor
- 3 mutual inductances of the stator

3.2 Inductances of synchronous machines

Self-inductance of exciting winding L_{ff} is independent of rotor position because the stator of synchronous machines has a cylindrical shape (the influence of the stator slots is neglected). Mutual inductance of rotor winding and stator winding depends on the relative position of rotor and stator phase which is taken into consideration. Mutual inductance of exciting winding f and winding of phase a is

- Positive maximal in case of zero angle between axis of exciting winding and axis of phase a,

- zero for $\vartheta = \frac{\pi}{2}$,
- negative maximal for $\vartheta = \pi$ etc. (Fig.4-1.).

This dependence can be expressed with cosines function

$$L_{af} = L_{fa} = L_{afm} cos\vartheta \qquad (3\text{-}6)$$

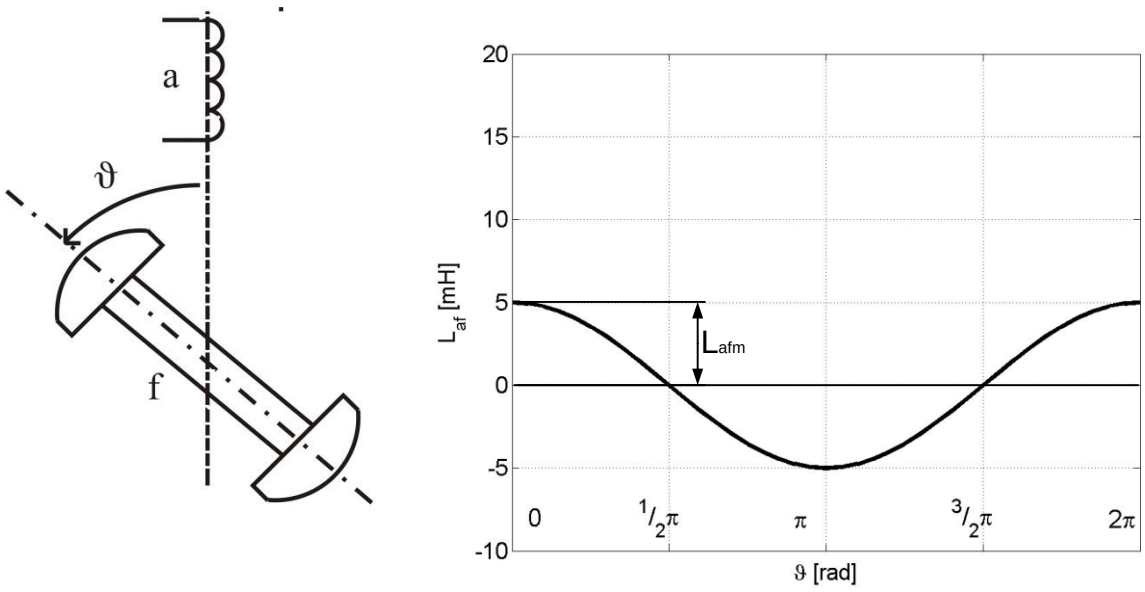


Fig.3-1. Mutual inductance of phase *a* and exciting winding *f*.

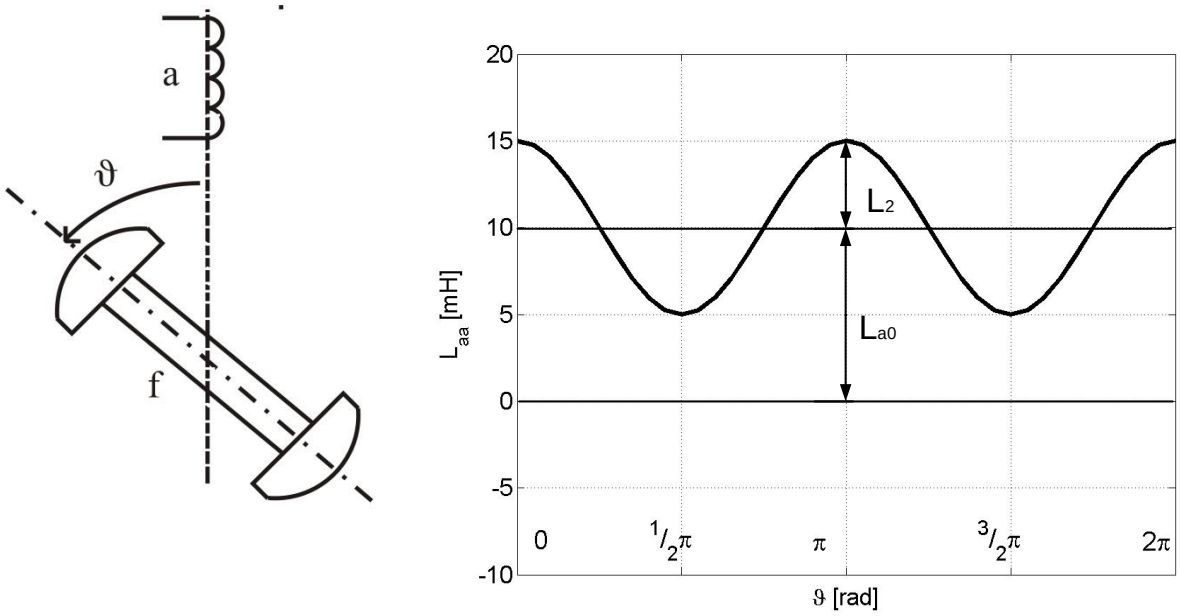


Fig.3-2. Self inductance of phase *a*.

It can be proven that this formula is valid for so-called sinus distributed winding. This winding is defined as winding, where the count of wires along the pole pitch is continuously changed according to sinus waveform. There are other formulas for the next phases, which are turned with angle $\pm\frac{2}{3}\pi$ with respect to phase a. These formulas are

$$L_{bf} = L_{fb} = L_{afm}\cos\left(\vartheta - \frac{2}{3}\pi\right) \quad (3\text{-}7)$$

$$L_{cf} = L_{fc} = L_{afm}\cos\left(\vartheta + \frac{2}{3}\pi\right) \quad (3\text{-}8)$$

Self-inductances of stator winding are the biggest when the phase axis has the same position as the salient pole axis (the biggest magnetic conductivity), and they are the smallest when the phase axis and salient pole axis have an angle equal to $\frac{\pi}{2}$ (Fig.4.2). This dependence is expressed by formula (it is valid for sinus distributed windings)

$$L_{as} = L_{a0} + L_2 cos2\vartheta \quad (3\text{-}9)$$

Similar formulas are valid for the next phases:

$$L_{bb} = L_{a0} + L_2 cos2\left(\vartheta - \frac{2}{3}\pi\right) \quad (3\text{-}10)$$

$$L_{cc} = L_{a0} + L_2 cos2\left(\vartheta + \frac{2}{3}\pi\right) \quad (3\text{-}11)$$

The value of self-inductances is not dependent on the sign of angle ϑ, the formula contains only cosine elements and the period of change of self-inductance is π, the formula contains angle multiplied by 2.

Mutual inductance of stator phases depends on angle ϑ too, because there is a change of magnetic conductivity of the magnetic circuits of two stator phases during rotor rotation. Fig.4-3 shows the rotor position for maximal and minimal mutual inductance of phase b and c, $|L_{bc}|$ is maximal for $\vartheta = \frac{\pi}{2}, \frac{3}{2}\pi$ etc. and minimal for $\vartheta = 0, \pi$ etc.

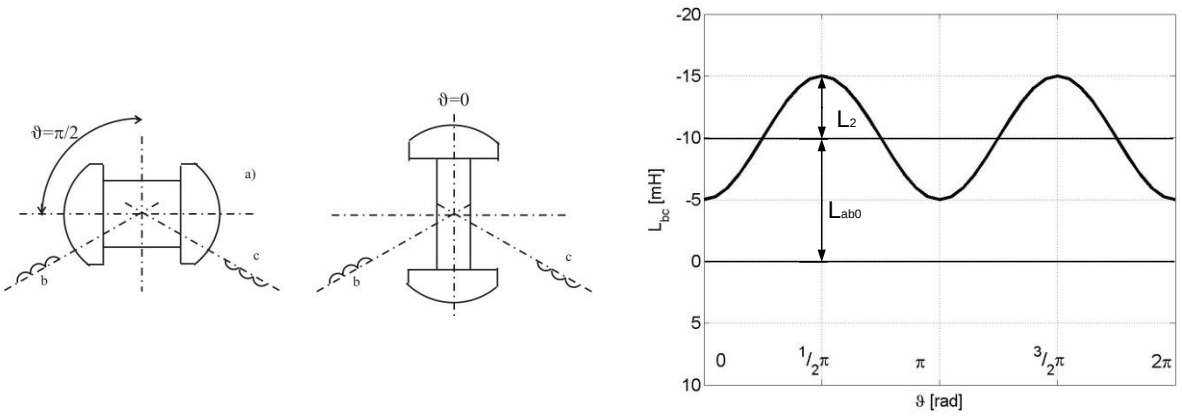


Fig.3-3. Rotor positions for maximal and minimal mutual inductance of phases b-c.

There is a negative flux of phase c if the current i_b is positive, because the angle of turning of phases is bigger than $\frac{\pi}{2}$ and smaller than $\frac{3}{2}\pi$. Therefore, mutual inductances are negative and we can express them by formulas:

$$-L_{bc} = L_{ab0} - L_2 cos2(\vartheta) \quad (3\text{-}12)$$

$$-L_{ca} = L_{ab0} - L_2 cos2\left(\vartheta - \frac{2}{3}\pi\right) = L_{ab0} - L_2 cos\left(2\vartheta + \frac{2}{3}\pi\right) \quad (3\text{-}13)$$

$$-L_{ab} = L_{ab0} - L_2 cos2\left(\vartheta + \frac{2}{3}\pi\right) = L_{ab0} - L_2 cos\left(2\vartheta - \frac{2}{3}\pi\right) \quad (3\text{-}14)$$

The formulas are accurate for sinus distributed winding and amplitudes of periodical component L_2 are the same for self and mutual inductances.



Questions:

- *How will the self-inductance of one phase of the stator change if it is a machine with a smooth rotor (turbo rotor)?*
- *Why is the mutual inductance of the two stator phases negative?*
-



Answers

- *How will the self-inductance of one phase of the stator change if it is a machine with a smooth rotor (turbo rotor)?*

The self-inductance of one phase of the stator will be constant, because even the air gap will be constant. This is valid if we neglect the effect of stator slots.

- *Why is the mutual inductance of the two stator phases negative?*

Because the phase shift of the two stator phases is 120 degrees, and the cosinus function is negative (-0.5) for this argument.

4 Insulation tests



Estimated completion time: **90 min**



After studying the topic, you will know:

- *how insulation resistance is measured*
- *how to calculate a polarizing index*
- *the components of the current when charging dielectric i.e. insulation system*
- *the definition of a disipation angle*

4.1 Insulation resistance test

Insulation resistance of the windings is a measure to assess the condition of insulation and its suitability for conducting a high-voltage test or for energizing the machine. A low reading may suggest damage to the insulation, faulty drying or impregnation or absorption of moisture.
Even during storage, the insulation resistance should be kept above the specified values. An insulation resistance test should be performed once every three months. During and immediately after measuring, the terminals must not be touched as they may carry residual dangerous voltage. Furthermore, if power cables are connected, make sure that the power supplies are clearly disconnected and there are no moving parts. After measurement, the winding must be grounded for discharging the winding.
For rated voltage below 1kV, measure with a 500V DC instrument. For rated voltage above 1kV, measure with a 5000V DC instrument.
On a new winding, where the contaminant causing low insulation resistance is generally moisture, drying the winding through the proper application of heat will normally increase the insulation resistance to an acceptable level. The following are several acceptable methods for applying heat to a winding:

- If the motor is equipped with space heaters, they can be energized to heat the winding.
- A direct current (as from a welder) can be passed through the winding. The total current should not exceed approximately 20% of the full load current. If the motor has only three leads, two must be connected to form one circuit through the winding. In this case, one phase will carry the full applied current and each of the others, one half each. If the motor has six leads (3 mains and 3 neutrals), the three phases should be connected into one series circuit.
- Heated air can be either blown directly into the motor or into a temporary enclosure surrounding the motor. The source of heated air should preferably be electrical as opposed to fueled (such as kerosene) where a malfunction of the fuel burner could result in carbon entering the motor.

Insulation resistance measurements can be made while the winding is being heated. However, they must be correctly at +40°C for evaluation since the actual insulation resistance will decrease with increasing temperature. As an approximation for a new winding, the insulation

resistance will be approximately half for each 10°C increase in insulation temperature above the dew point temperature.
Should the resistance fail to attain the specified value even after drying, careful examination should be undertaken to eliminate all other possible causes, if any.

The recommended minimum insulation resistance of the machine is obtained by the following empirical formula:

$$R_{ins} = U_{n[kV]} + 1\ [M\Omega] \qquad (5\text{-}1)$$

where

R_{ins} recommended minimum insulation resistance in MΩ of the entire machine windings, at 40°C

U_n rated machine voltage in kV

At the site, when commissioning a new or an existing motor after a long shutdown, it must have a minimum insulation level according to the above equation. An 11 kV motor, for instance, must have a minimum insulation of 12 MΩ. In normal practice, it is observed that when first measured, the resistance reading may show more than the minimum value and may mislead the operator, while the winding condition may not be adequate for a high voltage test or an actual operation.

One must therefore ensure that the winding condition is suitable before the machine is put into operation. For this purpose, the polarization index, which is determined from the insulation test data only as noted below, is a useful pointer. It must be evaluated on site while conducting the insulation test and then compared with the manufacturer's reference data for the machine to assess the condition of insulation on site and its suitability for operation.

This is usually a site test, but to establish a reference record of the machine, it is also carried out on the completed machine at the factory and test records are furnished to the user.

4.2 Effect of temperature on insulation resistance

One may argue that by measuring insulation resistance after one minute, one can diagnose the condition of the insulator. If it is less, the insulation will be considered to have been deteriorated. Unfortunately, just measuring I_R has proved to be unreliable, since it is not tenable over time. The reason is that insulation resistance is strongly dependent on temperature. A 10°C increase in temperature can reduce insulation resistance by 5 to 10 times. When readings of temperature and insulation resistance are plotted on ordinary equally divided co-ordination, a curved characteristic is obtained. On the other hand, if graph paper is used on which the insulation scale is laid out in logarithmic division, the graph becomes a straight line. Further, the effect of temperature is different for each insulation material and type of contamination. Although some temperature correction graphs and formulae are given in some books, they are acknowledged as being unreliable for extrapolation by more than 10°C. The result is that every time insulation resistance is measured at different temperatures, one gets a completely different insulation resistance. This makes it impossible to define a scientifically acceptable insulation resistance valve over a wide range of temperatures.
Insulation resistance of an induction motor with a rated voltage up to 690V (line to line value) at a cold temperature must be at least 5 MΩ. If not, the motor is impossible to connect to the network.
While the motor has a rated temperature, the insulation resistance must be better than:

Rated voltage U[V]	R ins [MΩ]
120	0,12
220	0,22
230	0,23
380	0,38
400	0,40
415	0,415
440	0,44
500	0,5
660	0,66
690	0,69

4.3 Polarization index

Polarization index is a variation of the insulation resistance test. It is the ratio of insulation resistance measured after voltage has been applied for 10 minutes (R_{10}) to the insulation resistance measured after one minute (R_1), i.e.

$$p_{1,10} = \frac{R_{10}}{R_1} \; [-] \qquad (4\text{-}1)$$

In practice, the minute polarization index is much more commonly used, when measured at 15s and 60s after the test voltage is switched on.

A low value of PI indicates that the winding may have been contaminated with oil, dirt etc. or absorbed moistures. In the test, a relatively high DC voltage is applied between the copper conductor and the stator or rotor core usually between the winding and ground (as the machine core & body are grounded). By applying Ohm's law, insulation resistance (R_t) at time t is then,

$$R_t = \frac{U}{I_t} \; [\Omega] \qquad (4\text{-}2)$$

where U … is the DC voltage applied
I_t … is the current flowing in the circuit.

The characteristics of the insulation are such that the current is not constant and varies with time. The purpose of measuring the polarization index can be understood by knowing the flow of the different currents in the insulator. There are four currents in the insulator. There are four currents that may flow when a DC voltage is applied to the winding. These four are:

- Capacitive Current (I_c)
- Conduction Current (I_R)
- Surface leakage current (I_L)
- Polarization current (I_p)

- **Capacitive Current**

An insulator behaves as a capacitor when a DC voltage is applied to a capacitor, a high charging current first flows and then it decays exponentially. The size of the capacitor and the internal resistance of the voltage supply, typically a few hundred kilo ohms, set the currents decay. In case of generator or motor windings, the current effectively decays to zero in less than 10 seconds. Since the capacitive current contains little diagnostic information, the initial insulation resistance is measured once the capacitive current has decayed. Hence the first IR measurement has been set as one minute to ensure that this current does not distort the insulation resistance calculation.

- **Conduction Current**

This current is due to the flow of electrons between the copper and the core. This is a galvanic current through ground wall. Such a current can flow if the ground wall has absorbed moisture, which can happen on the older thermoplastic insulation systems. The current may also flow if there are cracks, cuts or pinholes in the ground insulation and some contamination is present to allow the current to flow.

This current is constant with time. With modern insulation this current is usually zero (as long as there are no cracks, cuts etc.).

- **Surface leakage current**

This is a constant DC current that flows over the surface of the insulation. It is caused by conductive contamination (oil or moisture mixed with dust, dirt, insects, chemicals etc.) on the surface of the windings. This current is also constant with time.

- **Polarization current**

Electrical insulation is hygroscopic in nature and the presence of moisture will be there either in low quantity or in excess. Water molecules are very polar. When an electric field is applied the insulation starts absorbing electrons from the hydrogen molecules causing ionization of the hydrogen. In other words, the molecules constituting water align in the electric field, just as in a magnetic field. The energy required to align the molecules comes from the current in the DC test voltage supply. This current is called a polarization current. The water becomes completely polarized when the absorption of electrons from hydrogen merging with oxygen is completed. Once the molecules are all aligned, the current stops. The approximate time for complete polarization is 10 minutes. That is why the insulation resistance is measured after 10 minutes of applying voltage.

Now, the total current is the sum of all above currents, i.e.

$$I_t = I_C + I_R + I_L + I_P\,[A] \qquad (4\text{-}3)$$

As we have analyzed, after one minute, I_C is zero.

$$I_{t,1\,minute} = I_R + I_L + I_P\,[A] \qquad (4\text{-}4)$$

As we have seen, after 10 minutes, I_p is zero,

$$I_{t,10\,minutes} = I_R + I_L[A] \qquad (4\text{-}5)$$

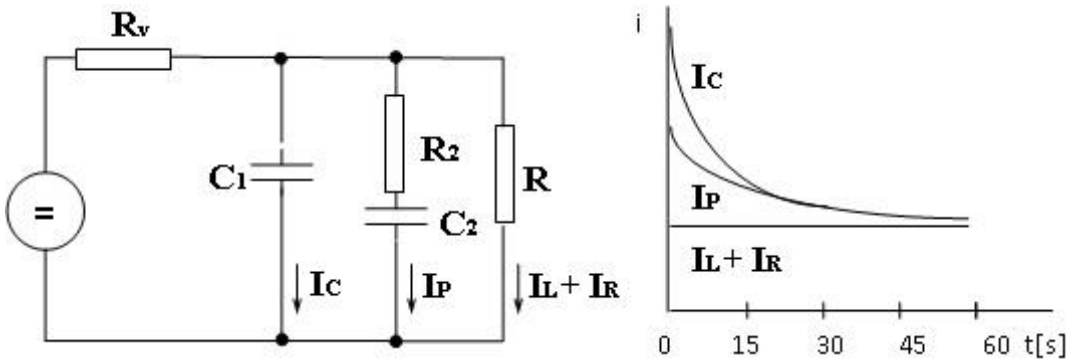


Fig.4-1. Equivalent circuit and current components.

4.4 Importance of polarization index

Polarization index was developed to make interpretation less sensitive to temperature. Polarization index is the ratio of two I_R at two different times. The temperature of the winding does not rise during the test period of 10 minutes. So, it is fairly assumed that both R_{10} and R_1 are measured at the same winding temperature. Then the temperature correction factor will be the same for both cases and will be cancelled during the calculation of the polarization index. Thus, polarization index is relatively insensitive to temperature.
Further in the formula of polarization index, the polarization current is used as a 'yard stick' to see if the leakage and conduction currents are excessive. If these later currents are much larger than the polarization current, the ratio will be about one. It is known from experience that, if the polarization index is about one, leakage and conduction currents are large enough that electrical tracking will occur. Conversely, if the leakage and conduction current are low compared to polarization currents, the polarization index will be greater than 2, and experience shows that electrical tracking problems are unlikely. Thus, during testing, if we see a decay in the total current or rise in the I_R in the interval between 1 minute and 10 minutes, then this must be due to the polarization current (since the leakage and conduction currents are constant with time) which implies that the leakage and conduction currents are low.

4.5 Test method

- Instruments

A mega-ohmmeter generates and applies a regulated DC supply. It measures the flow of a current and insulation resistance is directly read on its dial. Hand driven and motorized mega-ohmmeters are available. But for constant rotation and steady DC voltage, a motorized meter is preferred. Modern mega-ohmmeters can apply voltages exceeding 10 kV, and measure resistance higher than 100GΩ

- Test Voltage

Test voltage should be well below the rated peak line-to-ground voltage of the winding as it is not a 'high potential' test. But the voltage should be high enough to find defects such as cuts through the insulation in the windings.
If a test is carried out only on one winding of 3-phase equipment, then other windings should be grounded during the test.

Rated voltage (line to line) of the winding [V]	Test voltage (DC) [V]
< 600	500
1000 – 2500	500 – 1000
2500 – 5000	1000 – 2500
> 5000	2500 - 5000

Fig.4-2. Guidelines for DC voltage to be applied for insulation resistance test.

Polarization index	Condition of winding
< 1,0	Hazardous - Dry winding
1 – 1,5	Bad - Dry winding
1,5 – 2,0	Doubtful - Drying is recommended
2,0 – 3,0	Adequate
3,0 – 4,0	Good
> 4.0	Excellent

Fig.4-3. Interpretation of the polarization index.

4.6 Voltage test methods

Putting voltage
- DC
- AC
- Surge

Induced voltage

4.7 Dissipation factor, tan Delta

Tan Delta, also called Loss Angle or Dissipation Factor testing, is a diagnostic method of testing cables to determine the quality of the cable insulation. This is done to try to predict the remaining life expectancy and in order to prioritize cable replacement and/or injection. It is also useful for determining what other tests may be worthwhile [81].

If the insulation of winding (or cable) is free from defects, like water trees, electrical trees, moisture and air pockets, etc., the winding approaches the properties of a perfect capacitor. It is very similar to a parallel plate capacitor with the conductor and the neutral being the two plates separated by the insulation material.

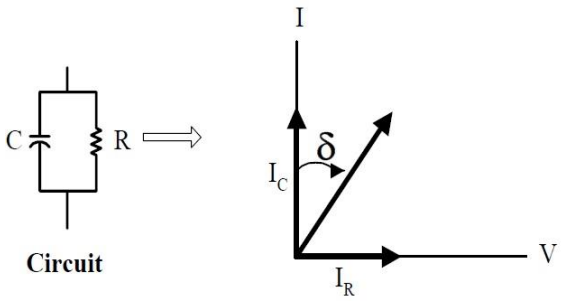


Fig.4-4. Equivalent circuit of the insulation system and current components.

In a perfect capacitor, the voltage and current are phase shifted 90 degrees and the current through the insulation is capacitive. If there are impurities in the insulation, like those mentioned above, the resistance of the insulation decreases, resulting in an increase in resistive current through the insulation. It is no longer a perfect capacitor. The current and voltage will no longer be shifted 90 degrees. It will be something less than 90 degrees. The extent to which the phase shift is less than 90 degrees is indicative of the level of insulation contamination, hence quality/reliability. This “Loss Angle” is measured and analyzed.
Below is a representation of a winding. The tangent of the angle δ is measured. This will indicate the level of resistance in the insulation. By measuring I_R/I_C (opposite over adjacent – the tangent), we can determine the quality of the insulation. In a perfect cable, the angle would be nearly zero. An increasing angle indicates an increase in the resistive current through the insulation, meaning contamination. The greater the angle, the worse the insulation.

Measurement instruments
The tan delta unit consists of a high voltage divider and a fiber optically linked measurement box. The high voltage divider measures the voltage and current input to the winding or cable, sends this information to the controller, which analyzes the voltage and current waveforms and calculates the tan delta number. A connected laptop computer displays and stores the results.
A voltage source is needed to energize the cable. What is typically used is a Very Low Frequency (VLF) AC Hipot. The VLF pictured here is a 40 kV (peak) unit that is capable of testing from 1.1 uF of cable load at 0.1 Hz, up to 5.5uF at 0.02 Hz. Other models offer an output frequency of 0.01 Hz, used to test very long cables or winding of large synchronous machines. VLF hipots are also widely used for testing newly installed and/or repaired cable before reenergizing to ensure the cable is sound and for testing critical cable runs.

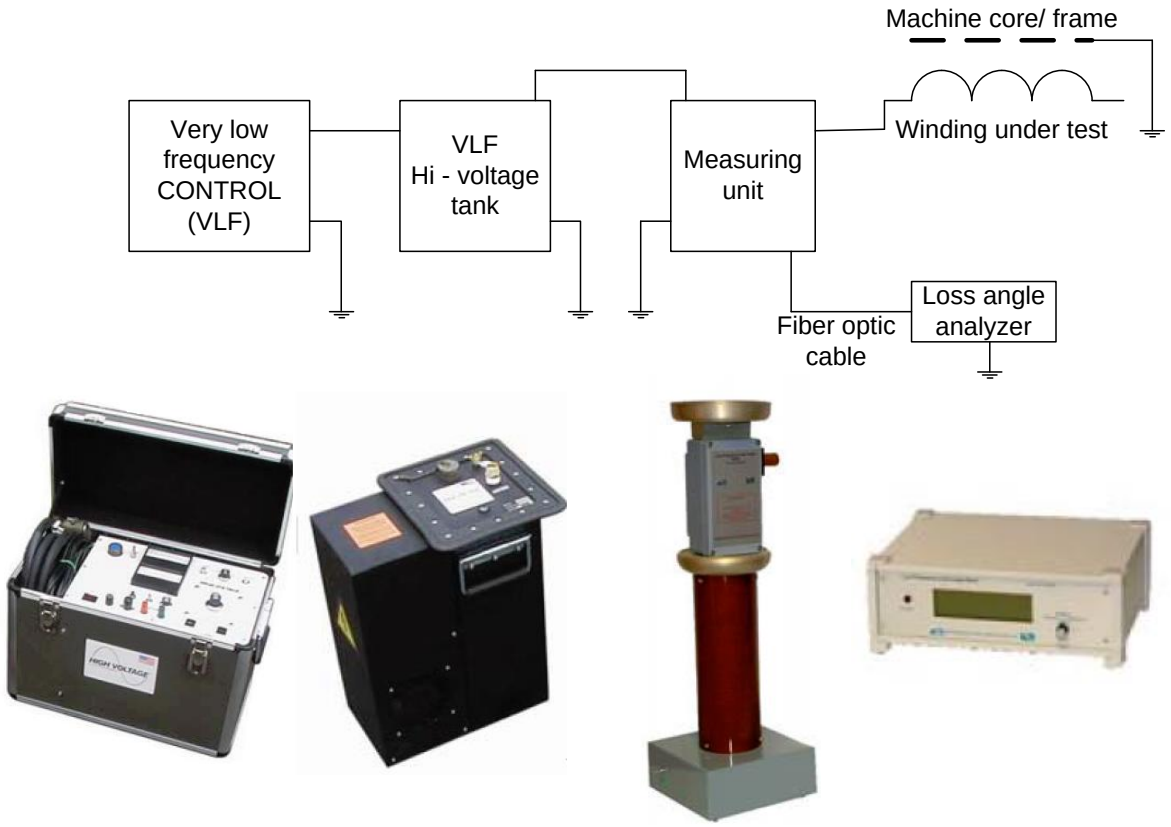


Fig.4-5. Measurement instruments.

The winding to be tested must be de-energized and each end isolated. Using a VLF AC Hipot, the test voltage is applied to the cable while the tan delta controller takes measurements. Typically, the applied test voltage is raised in steps, with measurements first taken up to 1Uo, or normal line to ground operating voltage. If the tan delta numbers indicate good insulation, the test voltage is raised up to 1,5 – 2 U_o. The tan delta numbers at the higher voltages are compared to those at lower voltages and an analysis is made.

Advantages of a low frequency

First, to test the large winding (especially a cable) with 50/60 Hz power requires a very high power supply. It is not practical, nearly impossible, to test a cable of several hundred kilometers with a 50/60 Hz supply. At a typical VLF frequency of 0.1Hz, it takes 500/600 times less power to test the same cable compared to 50/60 Hz.

Secondly, the magnitude of the tan delta numbers increases as the frequency decreases, making measurement easier. As the below equation shows, the lower the frequency (f), the higher the tan delta number.

$$\tan\delta = \frac{I_R}{I_C} = \frac{1}{2\pi f C R}\ [-; Hz, \mu F, M\Omega] \qquad (4\text{-}6)$$

Typical values of tan delta are 0,01 - 0,1.

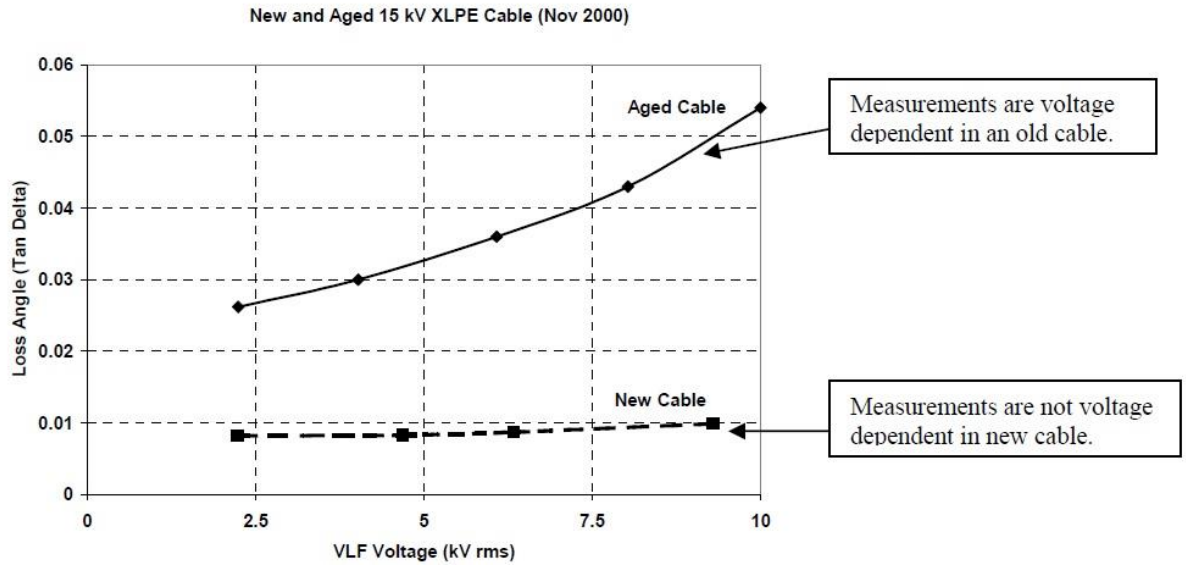


Fig.4-6. Measurement results on a cable. In case of winding, it is important to measure near to rated voltage.

Interpretation

For maintenance tests on complete windings, the initial tan delta measured is irrelevant. A typical tan delta is about 0,005 for modern epoxy and polyester impregnated insulation [82]. The tan delta can be 0,03-0,05 for asphaltic mica windings. If the tan delta is measured on a regular basis, say every few years, and if it remains constant over time, then it is an indication that there is no thermal aging or gross contamination of the winding. If there is an increase over time, then it is an indication that insulation overheating is occurring, or the winding is becoming more contaminated by moisture or partly conductive contaminants. A significant amount of deterioration has occurred if the tan delta has increased by 0,01 or more from the initial value.

If the capacitance and tan delta are measured at the same time, and if the trend in C decreases while the tan delta is increasing, this is strongly indicative of general thermal deterioration. If both C and the tan delta increase over time, then this is a powerful indicator that the winding is contaminated or has absorbed moisture.

The tan delta trend is indicative of the average condition of the insulation since it measures the total dielectric loss in a winding. The additional loss of a single seriously overheated coil in a winding, when the rest of the coils are in good condition, will be small. Thus, this test cannot detect a few deteriorated coils.

Coil manufactures sometimes use the tan delta test as a process monitor for the impregnation process. As the ground wall is impregnated, the tan delta will increase, since liquid resin has a higher tan delta than the air the resin is replacing. As the coil cures, the tan delta will decrease to its steady final level since the tan delta of liquid resin is higher than the tan delta of cured epoxy or polyester.

4.8 Drying of electric machines

If we bring the machine to the testing room from a colder environment, water droplets will form on internal surfaces inside the machine - from clotted water vapor. The water vapor contains air inside the machine. Therefore, it is necessary that the machine is in the testing room at least 24 hours before the tests and the water droplets evaporate again. If we find the

insulation to get dewy, the insulation should be dried first.

External heat source

Drying can be carried out using an external hot air source, through which we blow the machine. Every 3h we measure the polarization index and continue drying until the values of the polarizing index stabilize. Drying can take several days.

Internal heat – power losses

Winding (Joule) losses

For drying we can also use loss heat, which is generated directly in the machine. However, we must not supply the machine with rated voltage, so as not to destroy the wet insulation. We have to greatly reduce the voltage. Therefore, it is most convenient to connect the windings serially and power them with DC voltage. We choose the size so that the rated current flows through the winding. Since there are no reactances, but only active resistances, the voltage is very low. Preferably, a welding machine should be used.

Short-circuit losses

The machine can also be dryed with heat during the short circuit test. Again, we will use the reduced voltage, this time AC. If it is an asynchronous machine that does not run at short circuit test, we let it run-up once every 3hours to ventilate the machine and remove moisture.

No-load losses

If neither of the previous methods can be used, we will dry the machine via no-load losses. These are generally small even at nominal voltage. Moreover, here we must use the reduced voltage (to protect the wet insulation system), which will reduce the losses even further. Drying by this method is very time consuming and lasts for several weeks.



Questions:

- *Why does the insulation resistance have to be measured at the working temperature of the winding?*
- *What is a polarizing index?*
- *How can we dry a wet machine?*



Answers

- *Why does the insulation resistance have to be measured at the working temperature of the winding?*

The insulation resistance decreases as the temperature increases.

- *What is a polarizing index?*

Polarization index is the ratio of insulating resistors. The resistances shall be measured at a specified time after the test voltage has been switched on. Typically, this is the ratio of resistances measured in 15s to 60s or the ratio of resistances measured in 1min and 10min.

- *How can we dry a wet machine*

The damp machine can be dried by a foreign source of warm air or by its own losses.

5 Ventilation and Hydraulic Measurement



Estimated completion time: **75 min**



After studying the topic, you will:

- *know the labeling of the most common methods of cooling machines*
- *know methods of measuring air flow*
- *be able to calculate hydraulic diameter*
- *know the principles of measuring coolant flow*
- *know the heat transfer coefficient*

5.1 Cooling of the machines

All rotating electrical machines generate heat as a result of the electrical and mechanical losses inside the machine. Losses are high during starting or dynamic braking.
Also, losses usually increase with increased loading. Cooling is necessary to continuously transfer the heat to a cooling medium, such as the air.
For AC induction motors, cooling air is usually circulated internally and externally by one or more fans mounted on the rotor shaft. To allow for operation of the machine in either direction of rotation, fans are usually of the bi-directional type and made of a strong plastic material, aluminum, or steel.
In addition, the external frames of the motor are usually provided with cooling ribs to increase the surface area for heat radiation.
The most common type of AC motor is the totally enclosed fan cooled (TEFC) motor, which is provided with an external forced cooling fan mounted on the non-drive end (NDE) of the shaft, with cooling ribs running axially along the outer surface of the motor frame.
These are designed to keep the air flow close to the surface of the motor along its entire length, thus improving the cooling and self-cleaning of the ribs. An air-gap is usually left between the ribs and the fan cover for this purpose.
Internally, on smaller TEFC motors, the rotor end-rings are usually constructed with ribs to provide additional agitation of the internal air for even distribution of temperature and to allow the radiation of heat from the end shields and frame.

Special precautions need to be taken when standard TEFC induction motors are used with AC variable speed drives, powered by frequency converters. For operation at speeds below the rated frequency of 50 Hz, the shaft mounted fan cooling efficiency is lost. For constant torque loads, it is sometimes necessary to install a separately powered forced cooling fan (IC 43) to maintain adequate cooling at low speeds. On the other hand, for prolonged operation at high speeds above 50 Hz, the shaft mounted fan works well but may make excessive noise. Again, it may be advisable to fit a separately powered cooling fan.

Larger rotating machines can have more elaborate cooling systems with heat exchangers.

The system used to describe the method of cooling

- A prefix comprising the letters IC (*index of cooling*)
- A letter designating the cooling medium, this is omitted if only air is used
- Two numerals which represent:
    1. The cooling circuit layout
    2. The way in which the power is supplied to the circulation of the cooling fluid, fan, no fan, separate forced ventilation, etc.

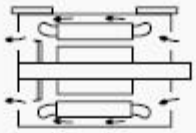
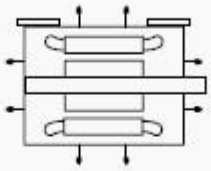
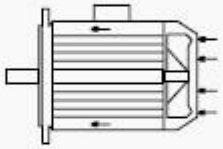
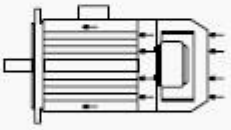
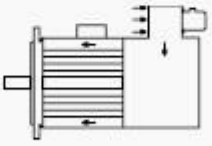
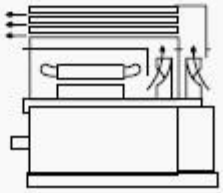
Code	Description	Drawing
IC 01	- Open machine - Fan mounted on shaft - Often called 'drip-proof' motor	
IC 410	- Enclosed machine - Surface cooled by natural convection and radiation - No external fan	
IC 411	- Enclosed machine - Smooth or finned casing - External shaft-mounted fan - Often called TEFC motor	
IC 416A	- Enclosed machine - Smooth or finned casing - External motorized Axial fan supplied with machine	
IC 416R	- Enclosed machine - Smooth or finned casing - External motorized Radial fan supplied with machine	
IC 610	- Enclosed machine - Heat Exchanger fitted - Two separate air circuits - Shaft-mounted Fans - Often called CacA motor	

Fig.5-1. Designation of the most common methods of cooling.

5.2 Measuring air flow

A. Measuring with rotating vane anemometer

For highly accurate quick measurement, the rotating vane anemometer is the best way to measure airflow. Vane anemometers have several advantages over any other method. The primary advantages are speed, accuracy, and ease of use. Vane anemometers do not require air density compensation due to air temperature, humidity, or atmospheric pressure. The mini vane allows for a full duct traverse with an automatic calculation of the CFM in the duct if the dimensions are input into the instrument before the measurement is taken. It is imperative that the ducting attached to the appliance, and the base pan, if side returned is used, is sealed. A large vane can be used at the registers to proportional balance the system or for accurately measuring airflow at the return

B. Measuring airflow with the Pitot tube

Pitot tubes (called Prandtl tubes) are well suited for mid to high velocity airflow measurement, and are considered the standard by which all other airflow devices are compared. Accurate measurement requires density correction and a careful traverse. Because the accuracy is dictated by the pressure measurement device attached to the Pitot tube, there are often more economical ways (hot wire and vane) to measure airflow in low flow applications. For high flow or high temperature applications the Pitot tube is ideal.

A Pitot tube measures total pressure and static pressure to determine the velocity pressure from which air velocity can be derived. The Pitot tube is inserted into the duct with the tip pointed toward the airflow. The positive port of the manometer is connected to the total pressure port (Pt) and the negative to the static pressure port (Ps). The manometer will then display velocity pressure which can be converted to velocity.

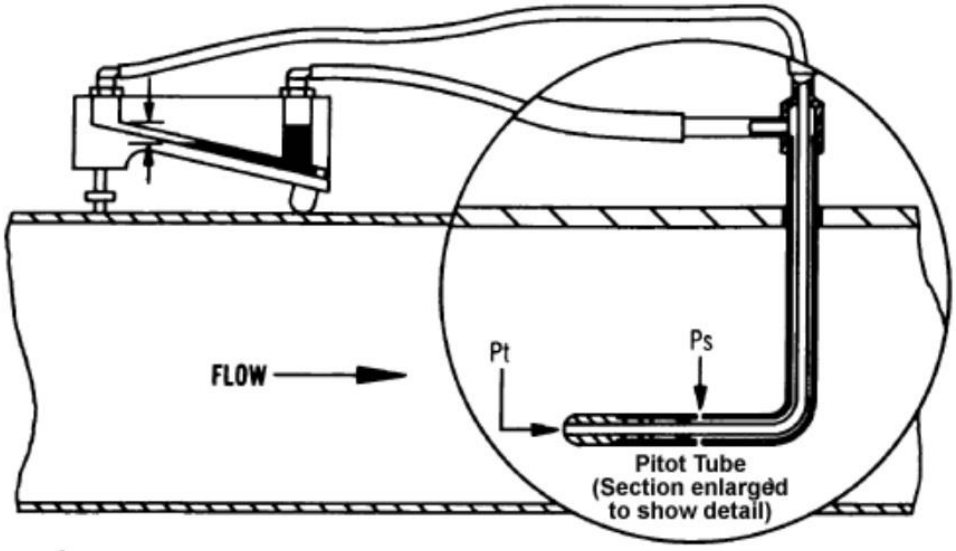


Fig.5-2. Pitot (Prandtl) tube principle.

Bernouli's equation

$$p_{total} = p_{static} + p_{dynamic} = h\varrho g + \frac{1}{2}\varrho v^2 \qquad (5\text{-}1)$$

where
h is deep under the fluid / liquid surface level
ρ density of a fluid / liquid
g gravity acceleration
v speed of the flow

From this we can derive the speed relation as formula

$$v = \sqrt{\frac{2(p_{total} - p_{static})}{\varrho}} [m.s^{-1}; Pa, kg.m^{-3}] \quad (5\text{-}2)$$

There are some practical limitations to the use of a pitot-static tube:

- If the velocity is low, the difference in pressures is very small and hard to accurately measure with the transducer. Errors in the instrument could be greater than the measurement! So, pitot-static tubes don't work very well for very low velocities.
- If the velocity is very high (supersonic), we have violated the assumptions of Bernoulli's equation and the measurement is wrong again. At the front of the tube, a shock wave appears that will change the total pressure. There are corrections for the shock wave that can be applied to allow us to use pitot-static tubes for high-speed aircraft.
- If the tubes become clogged or pinched, the resulting pressures at the transducer are not the total and static pressures of the external flow. The transducer output is then used to calculate a velocity that is not the actual velocity of the flow. Several years ago, there were reports of icing problems occurring on airliner pitot-static probes. Output from the probes was used as part of the auto-pilot and flight control system. The solution to the icing problem was to install heaters on the probes to ensure that the probe was not clogged by ice build-up.

C. Measuring air flow by pressure drop

An easy way to quickly estimate airflow is to measure the static pressure drop across the evaporator coil, for example;

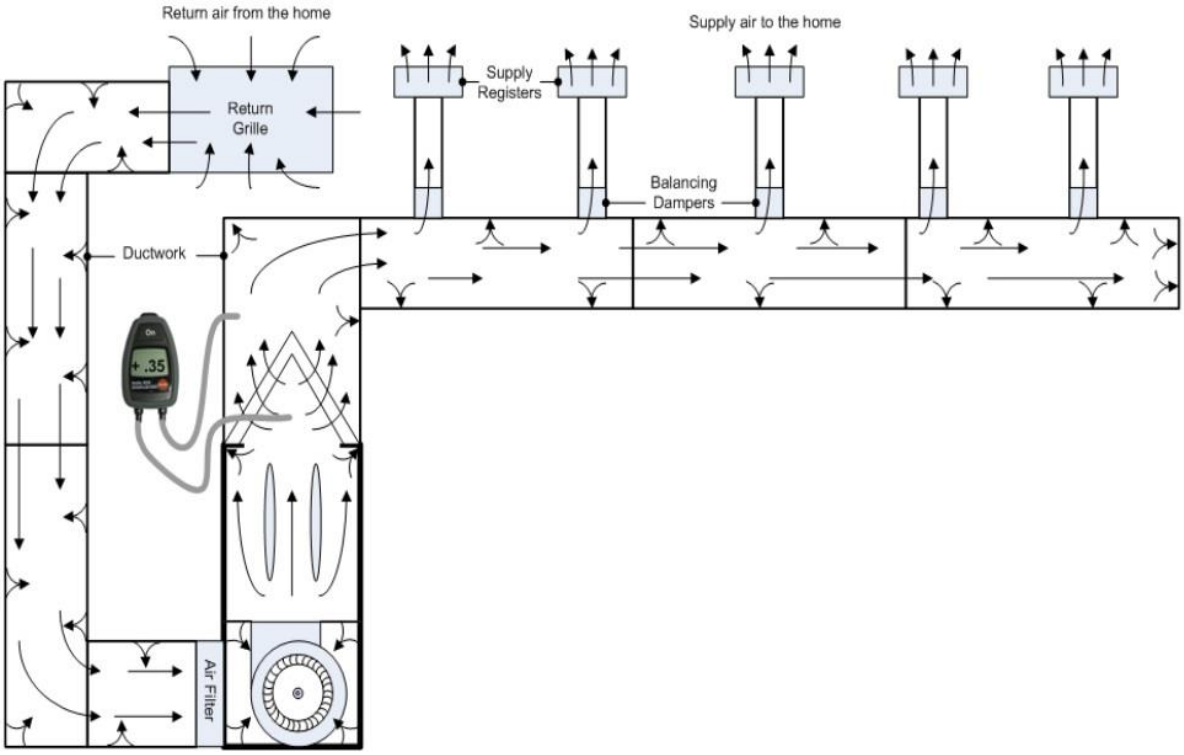


Fig.5-3. Measuring air flow by pressure drop.

The positive probe should be inserted ahead of the air entering the evaporator and the negative probe immediately downstream of the evaporator. The reading obtained will be the pressure drop in Pascal. While this measurement is accurate enough for setting up equipment, it is not accurate enough to make a field measurement of the system capacity.

D. Measuring air flow with a hot wire anemometer

The principal of a hot wire anemometer is based on a heated element from which heat is extracted by the colder impact airflow. The temperature of the hot wire is kept constant via a regulating switch, and the current (amp draw measured internally) is directly proportional to the air velocity. When using a hot wire in turbulent air streams the measured results can be impacted by turbulent airflow striking the measurement sensor from multiple directions. This could indicate a higher measured value than a vane probe. This characteristic is typically prevalent in ducts where turbulent airflow can occur even at very low velocities.

All measurements should be made in a straight section of duct if possible. In an ideal location the duct will have a minimum of 10 diameters before the measuring spot and at least 4 diameters after before making a transition of turn. The airflow should not be inferred by dampers.

5.3 Hydraulic diameter

Hydraulic diameter is defined by the formula

$$D_n = \frac{4S}{O} \qquad (5\text{-}3)$$

Where S … cross section of the channel
O … circumference of the channel

The anemometer must be negligible with respect to the hydraulic diameter, i.e., the anemometer's diameter must be at worst 1/6 of the hydraulic diameter. In other cases, the measurement has an impact on the original air flow.

5.4 Measuring liquid flow

Liquid flow measurement such as lubricating oil or cooling medium (water) is very often required.

A. Ultrasonic Doppler flowmeters

An ultrasonic flowmeter (non-intrusive Doppler flow meters) is a volumetric flow meter which requires particulates or bubbles in the flow. Ultrasonic flowmeters are ideal for wastewater applications or any dirty liquid which is conductive, or water based. Ultrasonic flowmeters will generally not work with distilled water or drinking water. Aerations would be required in the clean liquid applications. Ultrasonic flowmeters are also ideal for applications where low pressure drops, chemical compatibility, and low maintenance are required.

The basic principle of operation employs the frequency shift (Doppler Effect) of an ultrasonic signal when it is reflected by suspended particles or gas bubbles (discontinuities) in motion. This metering technique utilizes the physical phenomenon of a sound wave that changes frequency when it is reflected by moving discontinuities in a flowing liquid. Ultrasonic sound is transmitted into a pipe with flowing liquids, and the discontinuities reflect the ultrasonic wave with a slightly different frequency that is directly proportional to the rate of flow of the liquid. Current technology requires that the liquid contain at least 100 parts per million (PPM) of 100 micron or larger suspended particles or bubbles.

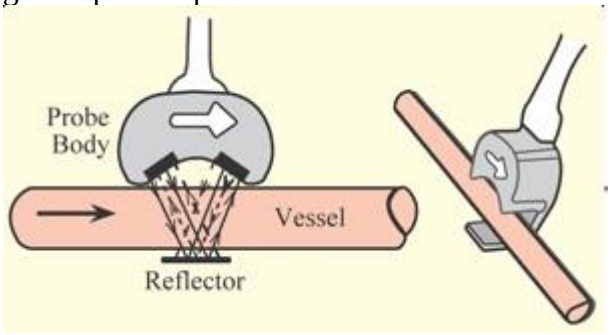


Fig.5-4. Measuring liquid flow by ultrasonic flow meter. [84]

Clamp-on ultrasonic flow meters come in either single or dual-sensor versions. In the single-sensor version, the transmit and receive crystals are potted into the same sensor body, which is clamped onto a single point of the pipe surface. A coupling compound is used to ultrasonically connect the sensor to the pipe. In the dual sensor version, the transmitting crystal is in one sensor body, while the receiving crystal is in another. Clamp-on Doppler flowmeters are subject to interference from the pipe wall itself, as well as from any air space between the sensor and the wall. If the pipe wall is made of stainless steel, it might conduct the transmit signal far enough so that the returning echo will be shifted enough to interfere with the reading. There are also built-in acoustic discontinuities in copper, concrete-lined, plastic-lined, and fiberglass-reinforced pipes. These are significant enough to either completely scatter the transmitted signal or attenuate the return signal. This dramatically decreases flowmeter accuracy (to within only ±20%), and, in most cases, clamp-on meters will not work at all if the pipe is lined.

B. Turbine meter

These instruments operate linearly with respect to the volume flow rate. Because there is no square-root relationship (as with differential pressure devices), their range ability is greater. Velocity meters have minimum sensitivity to viscosity changes when used at Reynolds numbers above 10,000. Most velocity-type meter housings are equipped with flanges or fittings to permit them to be connected directly into pipelines.

Turbine meters have found widespread use for accurate liquid measurement applications. The unit consists of a multiple-bladed rotor mounted with a pipe, perpendicular to the liquid flow.

The rotor spins as the liquid passes through the blades. The rotational speed is a direct function of flow rate and can be sensed by magnetic pick-up, photoelectric cell, or gears. Electrical pulses can be counted and totalized.

The number of electrical pulses counted for a given period of time is directly proportional to flow volume. A tachometer can be added to measure the turbine's rotational speed and to determine the liquid flow rate. Turbine meters, when properly specified and installed, have good accuracy, particularly with low-viscosity liquids.

A major concern with turbine meters is bearing wear. A "bearing less" design has been developed to avoid this problem. Liquid entering the meter travels through the spiraling vanes of a stator that imparts rotation to the liquid stream. The stream acts on a sphere, causing it to orbit in the space between the first stator and a similarly spiraled second stator. The orbiting movement of the sphere is detected electronically. The frequency of the resulting pulse output is proportional to flow rate.

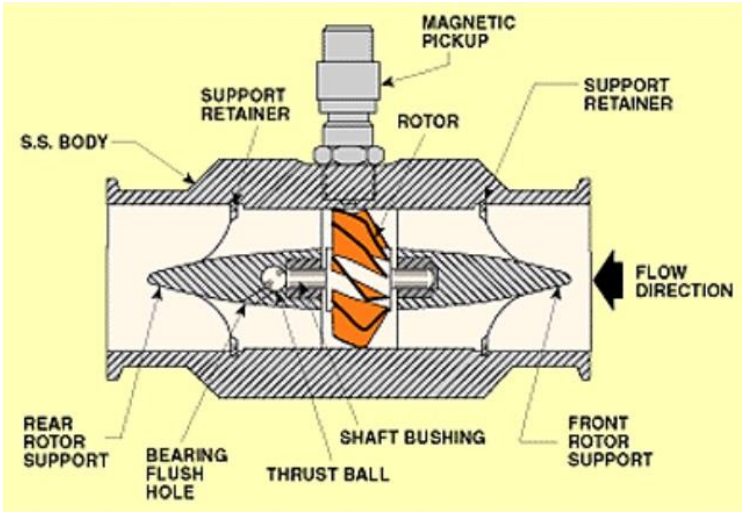


Fig.5-5. Measuring liquid speed of flow by turbine meter. [85]

5.5 Thomas tube

Very precisely measure the air flow rate. The internal surface has a thermal insulation.

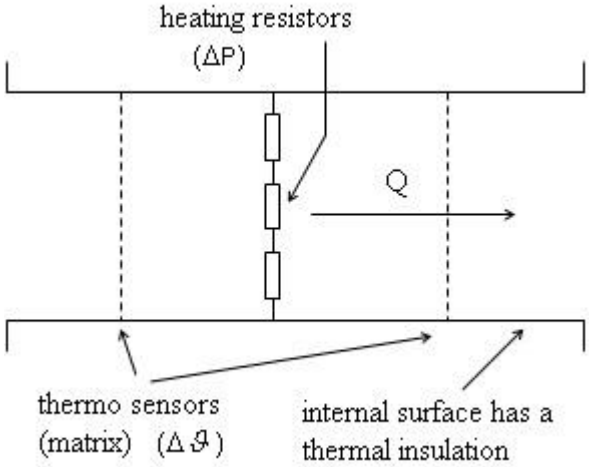


Fig.5-6. Thomas tube.

$$Q = \frac{\Delta P}{\varrho \,.\, c_p \Delta v} \qquad (5\text{-}4)$$

Where (for air) $c_p = 1000\ J.kg^{-1}\ .\ K^{-1}$
$\rho = 1{,}2\ kg.m^{-3}$

5.6 Heat transfer coefficient

Heat transfer coefficient $\alpha[W/m^2/K]$ from the material surface to coolant depends on

- Speed of the flowing
- Cooler arrangement

Based on the heat transfer coefficient we can make a decision about switching boar cooling etc. The main part of the α-meter is a small plate with the well-known thickness (b) and thermal conductivity (λ). On the surface of this plate there are two groups of thermo sensors. The α-meter works on the basis of the heat sharing Q.

$$Q = \lambda \frac{S \,.\, \Delta v_\varepsilon}{b} \qquad (5\text{-}5)$$

$$\alpha = \frac{Q}{S \Delta v_\alpha} = \lambda \frac{\Delta v_\varepsilon}{\Delta v_\alpha . b} \qquad (5\text{-}6)$$

Where Q … shared heat
Δv_α … temperature difference between the surface and coolant
Δv_ε … temperature difference on the α-meter

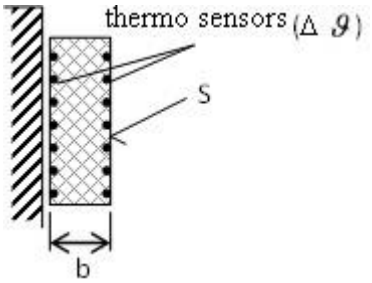


Fig.5-7. The α-meter, principle of operation.

5.7 Hydraulic resistivity

Labeled as K $[Pa.m^6]$. The following formula is valid

$$\Delta p = K Q^2 \qquad (5\text{-}7)$$

This means that pressure difference depends on the square of the flow rate. The hydraulic resistivity depends on

- Channel cross section
- Channel shape
- Wall roughness of the channel
- Curves and bending
- Narrowing and widening etc.

On the testing machine the pressure differences are usually very small and the hydraulic resistivity determination will be inaccurate. Do to this fact we have to use the air-conditioning measurement system.

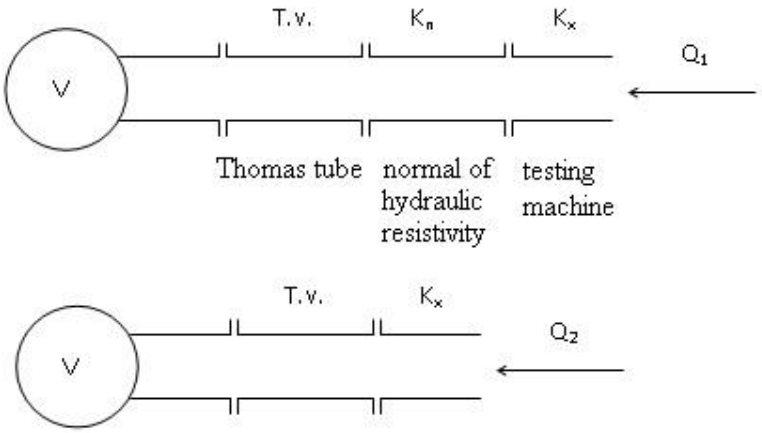


Fig.5-8. The air conditioning measurement system.

For the first version the valid formula is...

$$p = (K_T + K_n + K_x)Q_1^2 \tag{5-8}$$

In the second version the valid formula is...

$$p = (K_T + K_x)Q_1^2 \tag{5-9}$$

Both measurements have the same value of pressure, i.e., the fan must be regulated with the speed. The testing machine has the hydraulic resistivity

$$K_x = \frac{K_n}{\left(\frac{Q_2}{Q_1}\right)^2 - 1} \tag{5-10}$$



Questions:

- *Which is the cooling type of the most widely used asynchronous machine?*
- *How can the speed of airflow be measured?*
- *How can the liquid flow be measured?*
- *Which unit has a heat transfer coefficient*
- *Which physical principle is the pitot tube working on?*



Answers

- *Which is the cooling type of the most widely used asynchronous machine?*

The most common type of AC motor is the totally enclosed fan cooled (TEFC) motor, which is provided with an external forced cooling fan mounted on the non-drive end (NDE) of the shaft, with cooling ribs running axially along the outer surface of the motor frame.

- *How can the speed of airflow be measured?*

The air speed can be measured by pitot tube or anemometer (vane or hot-wire). It is also possible to use a principle of pressure-drop.

- *How can the liquid flow be measured?*

Thanks to ultrasonic Doppler flowmeter, turbine meter or Thomas tube.

- *Which unit has a heat transfer coefficient?*

Heat transfer coefficient α has a unit [W/m^2/K].

- *Which physical principle is the Pitot's (or Prandtl's) tube working on?*

It works on the principle of the difference between dynamic and static pressure that comes from the Bernoulli equation.

6 Thermal Performance and Test



Estimated completion time: **75 min**

After studying the topic, you will:

- *be able to define the conditions to be fulfilled for the warming test*
- *know how to measure the temperature of the machine and its parts*
- *be able to determine the machine's winding temperature*
- *be able to correct the winding temperature and its extrapolation to the machine stopping time*
- *know temperature and warming limit values*
- *be able to calculate the thermal time constant of the machine*

6.1 Thermal class

A thermal class shall be assigned to the insulation systems used in machines. It is the responsibility of the manufacturer of the machine to interpret the results obtained by thermal endurance testing.

6.2 Conditions of thermal tests

Electrical supply
During thermal testing of an AC machine the HVF of the supply shall not exceed 0,015 and the negative-sequence component of the system of voltages shall be less than 0,5 % of the positive-sequence component, the influence of the zero-sequence component being eliminated.
By agreement, the negative-sequence component of the system of currents may be measured instead of the negative-sequence component of the system of voltages. The negative sequence component of the system of currents shall not exceed 2,5 % of the positive sequence component.

AC motors rated for use on a power supply of fixed frequency, supplied from an AC generator (whether local or via a supply network) shall be suitable for operation on a supply voltage having a harmonic voltage factor (*HVF*) not exceeding:
– 0,02 for single-phase motors and 3-phase motors, including synchronous motors but excluding motors of design N (see IEC 60034-12), unless the manufacturer declares otherwise.
– 0,03 for design N motors.
The *HVF* shall be computed by using the following formula:

$$HVF = \sqrt{\sum_{n=2}^{k} \frac{u_n^2}{u_N^2}} \quad (6\text{-}1)$$

where

u_n is the ratio of the harmonic voltage Un to the rated voltage U_N;

n is the order of harmonic (not divisible by three in the case of three-phase AC motors);

k = 13

Temperature of machine before test

If the temperature of a winding is to be determined from the increase of resistance, the initial winding temperature shall not differ from the coolant by more than 2 K. When a machine is to be tested on a short-time rating (duty type S2) its temperature at the beginning of the thermal test shall be within 5 K of the temperature of the coolant.

Temperature of coolant

A machine may be tested at any convenient value of coolant temperature.

Measurement of coolant temperature during test

The value to be adopted for the temperature of a coolant during a test shall be the mean of the readings of the temperature detectors taken at equal intervals of time during the last quarter of the duration of the test. To reduce errors due to the time lag of the change of temperature of large machines following variations in the temperature of the coolant, all reasonable precautions shall be taken to minimize such variations.

- Closed machines without heat exchangers (cooled by surrounding ambient air or gas)

The temperature of the ambient air or gas shall be measured by means of several detectors placed at different points around and halfway up the machine at 1 m to 2 m from it. Each detector shall be protected from radiant heat and draughts.

- Open machines and machines cooled by air or gas from a remote source through ventilation ducts and machines with separately mounted heat exchangers

The temperature of the primary coolant shall be measured where it enters the machine.

- Closed machines with machine-mounted or internal heat exchangers.

The temperature of the primary coolant shall be measured where it enters the machine. The temperature of the secondary coolant shall be measured where it enters the heat exchanger.

6.3 Temperature rise of a part of a machine

The temperature rise, $\Delta\Theta_1$, of a part of a machine is the difference between the temperature of that part measured by the appropriate method in accordance with the following paragraph, and the temperature of the coolant.

For comparison with the limits of temperature rise or of temperature, when possible, the temperature shall be measured immediately before the machine is shut down at the end of the thermal test.

When this is not possible, for example, when using the direct measurement of resistance method, a correction for stopping time is needed. For machines tested on actual periodic duty (duty types S3 to S8) the temperature at the end of the test shall be taken as that at the middle of the rise period causing the greatest heating in the last cycle of operation.

6.4 Methods of measurement of temperature

Three methods of measuring the temperature of windings and other parts are recognized:
- − resistance method
- − embedded temperature detector (ETD) method
- − thermometer method

Different methods shall not be used as a check upon one another.

- Resistance method

The temperature of the windings is determined from the increase of the resistance of the windings.

- Embedded temperature detector (ETD) method

The temperature is determined by means of temperature detectors (e.g., resistance thermometers, thermocouples or semi-conductor negative coefficient detectors) built into the machine during construction, at points which are inaccessible after the machine is completed.

- Thermometer method

The temperature is determined by thermometers applied to accessible surfaces of the completed machine. The term 'thermometer' includes not only bulb-thermometers, but also non-embedded thermocouples and resistance thermometers. When bulb-thermometers are used in places where there is a strong varying or moving magnetic field, alcohol thermometers shall be used in preference to mercury thermometers.

6.5 Determination of winding temperature

Choice of method

In general, for measuring the temperature of the windings of a machine, the resistance method shall be applied.

For AC stator windings of machines having a rated output of 5 000 kW (or kVA) or more the ETD method shall be used.

For AC machines having a rated output less than 5 000 kW (or kVA) but greater than 200 kW (or kVA) the manufacturer shall choose either the resistance or the ETD method, unless otherwise agreed.

For AC machines having a rated output less than or equal to 200 kW (or kVA) the manufacturer shall choose the direct measurement version or the superposition version of the resistance method, unless otherwise agreed (but see also below).

For machines having a rated output less than or equal to 600 W (or VA), when the windings are non-uniform or severe complications are involved in making the necessary connections, the temperature may be determined by means of thermometers. Temperature rise limits in accordance with “Limits of temperature rise”, item 1d for resistance method shall apply.

The thermometer method is recognized in the following cases:

a) when it is not practical to determine the temperature rise by the resistance method as, for example, with low-resistance commutating coils and compensating windings and, in general, in the case of low-resistance windings, especially when the resistance of joints and connections forms a considerable proportion of the total resistance;

b) single layer windings, rotating or stationary;

c) during routine tests on machines manufactured in large numbers. For AC stator windings having only one coil-side per slot, the ETD method shall not be used for verifying compliance with this standard: the resistance method shall be used.

For checking the temperature of such windings in service, an embedded detector at the bottom

of the slot is of little value because it gives mainly the temperature of the iron core. A detector placed between the coil and the wedge will follow the temperature of the winding much more closely and is, therefore, better for checks in service. Because the temperature there may be rather low, the relation between it and the temperature measured by the resistance method should be determined by a thermal test.

For other windings having one coil-side per slot and for end windings, the ETD method shall not be used for verifying compliance with this standard.
For windings of armatures having commutators and for field windings, the resistance method and the thermometer method are recognized. The resistance method is preferred, but for stationary field windings of DC machines having more than one layer the ETD method may be used.

Determination by resistance method
One of the following methods shall be used:

- direct measurement at the beginning and the end of the test, using an instrument having a suitable range
- measurement by DC current/voltage in DC windings, by measuring the current in and the voltage across the winding, using instruments having suitable ranges
- measurement by DC current/voltage in AC windings, by injecting a direct current into the winding when de-energized.

The temperature rise, $\Theta_2 - \Theta_a$, may be obtained from the equation:

$$\frac{\Theta_2 + k}{\Theta_1 + k} = \frac{R_2}{R_1} \qquad (6\text{-}2)$$

where

Θ_1 is the temperature (°C) of the winding (cold) at the moment of the initial resistance measurement;

$\Theta_2$is the temperature (°C) of the winding at the end of the thermal test;

Θ_a is the temperature (°C) of the coolant at the end of the thermal test;

$R_1$is the resistance of the winding at temperature Θ_1 (cold);

$R_2$is the resistance of the winding at the end of the thermal test;

k is the reciprocal of the temperature coefficient of resistance at 0 °C of the conductor material

for copper k = 235

for aluminum k = 225 unless specified otherwise.

For practical purposes, the following alternative formula may be found convenient:

$$\Theta_2 - \Theta_a = \frac{R_2 - R_1}{R_1}(k + \Theta_1) + \Theta_1 - \Theta_a \qquad (6\text{-}3)$$

Correction for stopping time
The measurement of temperatures at the end of the thermal test by the direct measurement resistance method requires a quick shutdown. A carefully planned procedure and an adequate number of people are required.

- Short stopping time

If the initial resistance reading is obtained within the time interval specified in the following

table, that reading shall be accepted for the temperature measurement.

Rated output Pn [kW],[kVA]	Time interval after switching off power [s]
Pn ≤ 50	30
50 < Pn ≤ 200	90
200 < Pn ≤ 5000	120
5000 < Pn	by agreement

- Extended stopping time

If a resistance reading cannot be made in the time interval specified in the table above, it shall be made as soon as possible but not after more than twice the interval specified in the table above, and additional readings shall be taken at intervals of approximately 1 min until these readings have begun a distinct decline from their maximum value. A curve of these readings shall be plotted as a function of time and extrapolated to the appropriate time interval in the table above for the rated output of the machine. A semi-logarithmic plot is recommended where temperature or resistance is plotted on the logarithmic scale. The value of temperature thus obtained shall be considered as the temperature at shutdown. If successive measurements show increasing temperatures after shutdown the highest value shall be taken.
If a resistance reading cannot be made until after twice the time interval specified in the table above, this method of correction shall only be used by agreement.

- Windings with one coil-side per slot

For machines with one coil-side per slot, the resistance method by direct measurement may be used if the machine comes to rest within the time interval specified in the table above. If the machine takes more than 90 seconds to come to rest after switching off the power, the superposition method may be used if previously agreed.

Determination by ETD method

The detectors shall be suitably distributed throughout the winding and the number of detectors installed shall be not less than six.
All reasonable efforts, consistent with safety, shall be made to place the detectors at the points where the highest temperatures are likely to occur, in such a manner that they are effectively protected against contact with the primary coolant.
The highest reading from the ETD elements shall be used to determine the temperature of the winding.
ETD elements or their connections may fail and give incorrect readings. Therefore, if one or more readings are shown to be erratic, after investigation they should be eliminated.

- Two or more coil-sides per slot

The detectors shall be located between the insulated coil-sides within the slot in positions at which the highest temperatures are likely to occur.

- One coil-side per slot

The detectors shall be located between the wedge and the outside of the winding insulation in positions at which the highest temperatures are likely to occur.

- End windings

The temperature detectors shall be located between two adjacent coil-sides within the end windings in positions where the highest temperatures are likely to occur. The sensing point of each detector shall be in close contact with the surface of a coil-side and be adequately protected against the influence of the coolant.

When placing an ETD in the end windings of high voltage machines, care must be taken that the stress grading of the insulation isn't compromised and that the difference of potential along the winding overhang doesn't cause problems. In addition, the ground of the measuring system is thus directly capacitive coupled to the HV system. Disconnection of the measurement ground will in this case immediately lead to over voltages on the measuring system. Measures have to be taken to prevent consequential damage up to lethal injuries.

If the stator winding is a direct liquid cooled bar type, an ETD installed in the nozzle area of each bar monitoring water outlet temperature can give an indication of conductor strand cooling passage blocking.

Determination by thermometer method
All reasonable efforts, consistent with safety, shall be made to place thermometers at the point, or points where the highest temperatures are likely to occur (e.g., in the end windings close to the iron core) in such a manner that they are effectively protected against contact with the primary coolant and are in good thermal contact with the winding or other part of the machine.
The highest reading from any thermometer shall be taken to be the temperature of the winding or other part of the machine.

6.6 Duration of thermal test

- Rating for continuous running duty

The test shall be continued until thermal equilibrium has been reached.

- Rating for short-time duty

The duration of the test shall be the time given in the rating.

- Rating for periodic duty

Normally the rating for equivalent loading assigned by the manufacturer shall be applied until thermal equilibrium has been reached. If a test on the actual duty is agreed, the load cycle specified shall be applied and continued until practically identical temperature cycles are obtained. The criterion for this shall be that a straight line between the corresponding points of successive duty cycles on a temperature plot has a gradient of less than 2 K per hour. If necessary, measurements shall be taken at reasonable intervals over a period of time.

- Ratings for non-periodic duty and for duty with discrete constant loads

The rating for equivalent loading assigned by the manufacturer shall be applied until thermal equilibrium has been reached.

6.7 Measurement of bearing temperature

Either the thermometer method or the ETD method may be used. The thermal resistance between the temperature detector and the object whose temperature is to be measured shall be minimized; for example, air gaps shall be packed with thermally conducting paste.

6.8 Limits of temperature and of temperature rise

Limits are given for operation under site operating conditions and at rating for continuous running duty (reference conditions), followed by rules for the adjustment of those limits when operating at site under other conditions and on other ratings. Further rules give adjustments to the limits during thermal testing when conditions at the test site differ from those at the operating site.

Thermal class		130 (B)			155 (F)			180 (H)			200 (N)		
Method of measurement Th = Thermometer, R = Resistance, ETD = Embedded temperature detector		Th K	R K	ETD K	Th K	R K	ETD K	Th K	R K	ETD K	Th K	R K	ETD K
Item	Part of machine												
1a)	AC windings of machines having outputs of 5 000 kW (or kVA) or more	–	80	85 [a]	–	105	110 [a]	–	125	130 [a]	–	145	150 [a]
1b)	AC windings of machines having outputs above 200 kW (or kVA), but less than 5 000 kW (or kVA)	–	80	90 [a]	–	105	115 [a]	–	125	135 [a]	–	145	155 [a]
1c)	AC windings of machines having outputs of 200 kW (or kVA) or less, other than those in items 1d) or 1e) [b]	–	80	–	–	105	–	–	125	–	–	145	–
1d)	AC windings of machines having rated outputs of less than 600 W (or VA) [b]	–	85	–	–	110	–	–	130	–	–	150	–
1e)	AC windings which are self-cooled without a fan (IC 40) and/or with encapsulated windings [b]	–	85	–	–	110	–	–	130	–	–	150	–
2	Windings of armatures having commutators	70	80	–	85	105	–	105	125	–	125	145	–
3	Field windings of a.c. and d.c. machines other than those in item 4	70	80	–	85	105	–	105	125	–	125	145	–
4a)	Field windings of synchronous machines with cylindrical rotors having a d.c. excitation winding embedded in slots, except synchronous induction motors	–	90	–	–	110	–	–	135	–	–	155	–
4b)	Insulated stationary field windings of d.c. machines having more than one layer	70	80	90	85	105	110	105	125	135	125	145	155
4c)	Low-resistance field windings of d.c. machines having more than one layer and compensating windings of d.c. machines	80	80	–	100	100	–	125	125	–	145	145	–
4d)	Single-layer windings of a.c. and d.c. machines with exposed bare or varnished metal surfaces [c]	90	90	–	110	110	–	135	135	–	155	155	–

[a] For adjustment for high-voltage a.c. windings, see item 4 of Table 9.

[b] With the application of the superposition test method to windings of machines rated at 200 kW (or kVA) or less with thermal classes 130 (B) and 155 (F), the limits of temperature rise given for the resistance method may be exceeded by 5 K.

[c] Also includes multiple layer windings, provided that the under layers are each in contact with the circulating primary coolant.

Fig.7-1. Limits of temperature rise of windings indirectly cooled by air.

It is understood that the temperature of the hottest point of each winding under reference conditions generally does not exceed the agreed thermal class temperature of the insulation system.

The limits are stated relative to the reference coolant specified in the following table.

Thermal class		130 (B)			155 (F)		
Method of measurement		Thermo-meter °C	Resistance °C	ETD °C	Thermo-meter °C	Resistance °C	ETD °C
Item	Part of the machine						
1	Coolant at the outlet of direct-cooled a.c. windings. These temperatures are preferred to the values given in item 2 as the basis of rating.						
1a)	Gas (air, hydrogen, helium, etc.)	110	–	–	130	–	–
1b)	Water	90	–	–	90	–	–
2	AC windings						
2a) 2b)	Gas cooled / Liquid cooled	–	–	120 [a]	–	–	145 [a]
3	Field windings of turbine type machines						
3a)	Cooled by gas leaving the rotor through the following number of outlet regions [b]						
	1 and 2	–	100	–	–	115	–
	3 and 4	–	105	–	–	120	–
	5 and 6	–	110	–	–	125	–
	7 to 14	–	115	–	–	130	–
	above 14	–	120	–	–	135	–
3b)	Liquid cooled	Observance of the maximum coolant temperature given in item 1b) will ensure that the hotspot temperature of the winding is not excessive					
4	Field windings of a.c. and d.c. machines having d.c. excitation other than in item 3.						
4a)	Gas cooled	–	130	–	–	150	–
4b)	Liquid cooled	Observance of the maximum coolant temperature given in item 1b) will ensure that the hotspot temperature of the winding is not excessive					

[a] No adjustment in the case of high-voltage a.c. windings is applicable to these items, see Table 13, item 2.

[b] The rotor ventilation is classified by the number of radial outlet regions on the total length of the rotor. Special outlet regions for the coolant of the end windings are included as one outlet for each end. The common outlet region of two axially opposed flows is to be counted as two regions.

Fig.7-2. Limits of temperature of directly cooled windings and their coolants.

6.9 Thermal time constant

The thermal time constant of the machine is the time during which the temperature drops (or rises) to 1/e of its initial value.
The situation is illustrated in the following figure. The initial temperature was 155K. The drop to 1/e is a drop to approximately 36% of the original temperature, i.e., to 56K. This temperature was measured at a time of about 57min from the beginning of the transient phenomena. The time constant of the machine is therefore approximately 57 minutes.

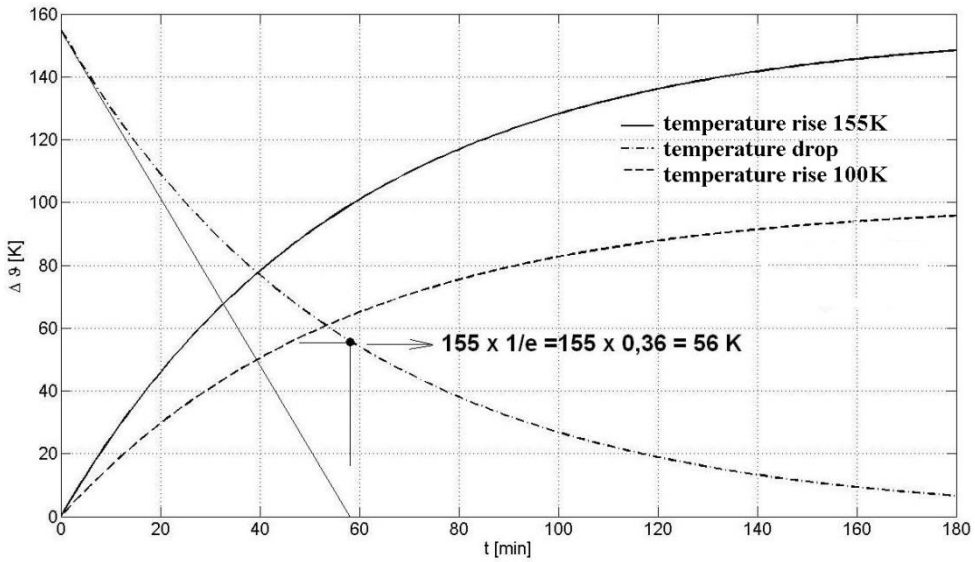


Fig.7-3. Thermal time constant determination.

6.10 Low ambient temperature, self-cooling and forced cooling effect of IM

The induction motor of a wastewater pump was operating in duty S4 (intermittent periodic duty with starting), i.e., the running was being interrupted, however, irregularly. During the running, the motor was loaded with 130% of its rated power. The wastewater pump was located in the concrete dungeon, almost completely under the surface. The motor ambient temperature was relatively low, 10-15 ^{o}C all the year. Due to this fact the cooling is relatively intensive.

Type of IM

The motor has a squirrel cage rotor. The motor was class efficiency 2 (improved efficiency), type 1LG4 310-4AA, duty S1 (continuous operation). Temperature class 155 (F), used according to class 130 (B) for altitudes up to 1000m and ambient temperatures from -20 to +40^{o}C.

Parameter	Motor	Overload to
Rated power	110 kW	143 kW
Rated speed	1488 rpm	1482 rpm
Rated stator current	198 A	257 A
Rated stator voltage	400 V $_{D}$	400 V $_{D}$
Rated torque	706 Nm	918 Nm
Rated efficiency	0,946	-
Rated power factor	0,85	0,85

Weight	730 kg	-
Frequency	50 Hz	-
Producer	Siemens	-

The heating and cooling time constant

Based on the basic motor dimensions (length *l*=0.527m and frame diameter *d*=0.610m) we can calculate the surface area. The rib area (blowing by fan) has a higher heat transfer coefficient. Due to this fact, as well as the mass and thermal capacity, we can calculate time constant as:

$$\tau_{run} = \frac{cm}{\alpha S} = \frac{400\left[\frac{Ws}{kg}\right].730[kg]}{40\left[\frac{W}{^{o}Cm^{2}}\right].3{,}133[m^{2}]} = 39\,\text{min} \tag{6-4}$$

and similarly, for a motor at rest (no blowing) $\tau_0 = 194\,\text{min}$.

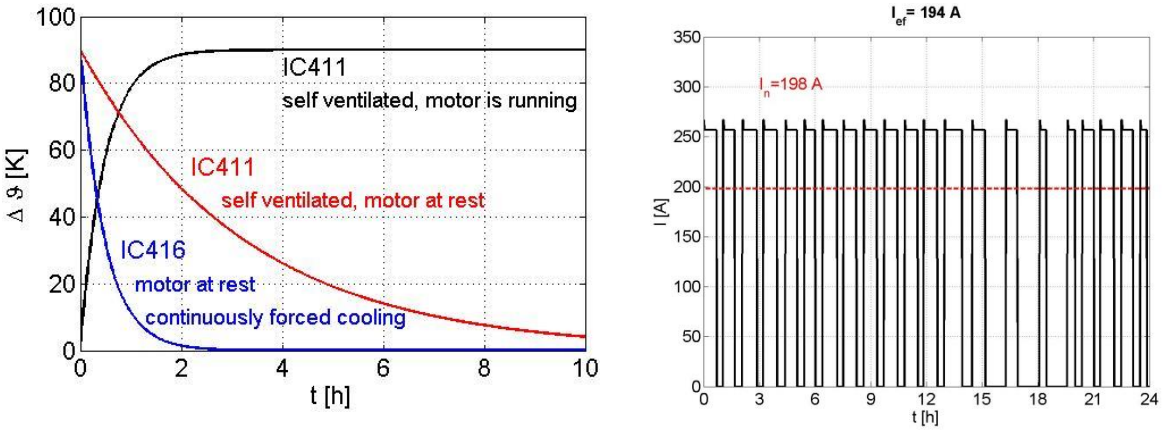


Fig.7-4. Thermal time constant as dependent on the various type of cooling system.

Effective torque and current

For intermittent periodic duty, including the starting phase, we can calculate the so called "effective current" and "effective torque". Thanks to these parameters we can check the motor dimensioning.

$$I_{ef} = \sqrt{\frac{\sum_i I_i^2 t_i}{\sum_i t_i}} = \sqrt{\frac{256.7*797+0*603}{797+603}} = 193.7A \tag{6-5}$$

$$T_{ef} = \sqrt{\frac{\sum_i T_i^2 t_i}{\sum_i t_i}} = \sqrt{\frac{918.2*797+0*603}{797+603}} = 692.8Nm \tag{6-6}$$

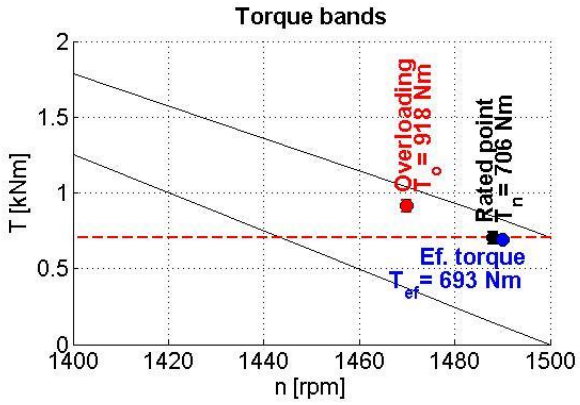


Fig.7-5. Rated point, effective torque and overloading torque.

The stator resistivity

The resistivity is dependent on the temperature of the winding

$$R_{130} = R_{20}(1+\alpha\Delta\upsilon) = 0.0351(1+0.004\cdot 110) = 0.0505\,\Omega \qquad (7\text{-}1)$$

Hence the RI^2 winding losses depend on temperature as well.

The following figures are simulations for rated power and self-cooling IC411, duty S4.

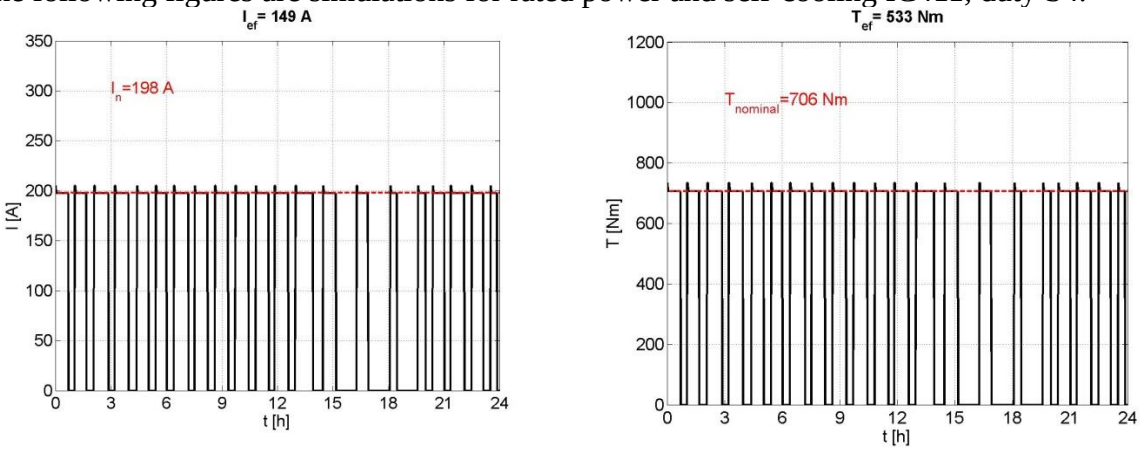


Fig.7-6. Current and torque.

The following figures are simulations for

- Left column - ambient temperature +40°C
- right column - ambient temperature +10°C

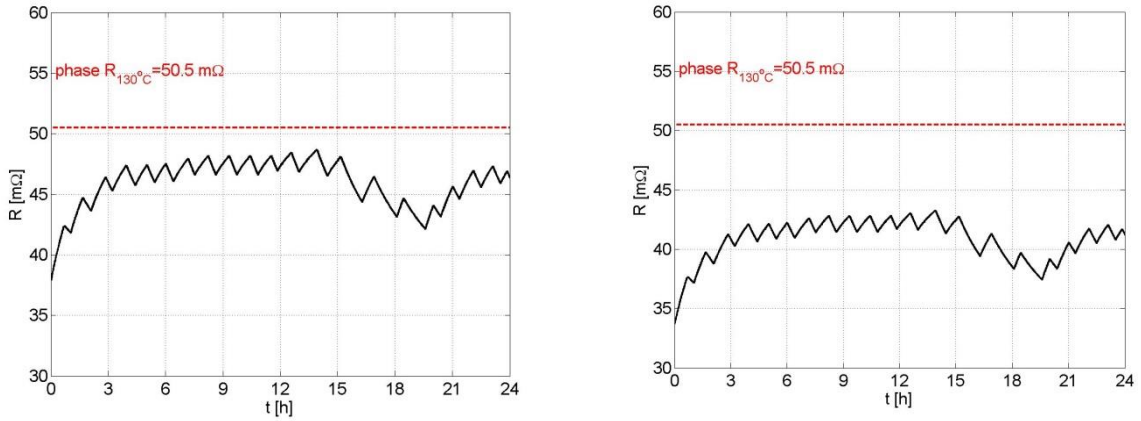


Fig.7-7. Phase winding resistivity.

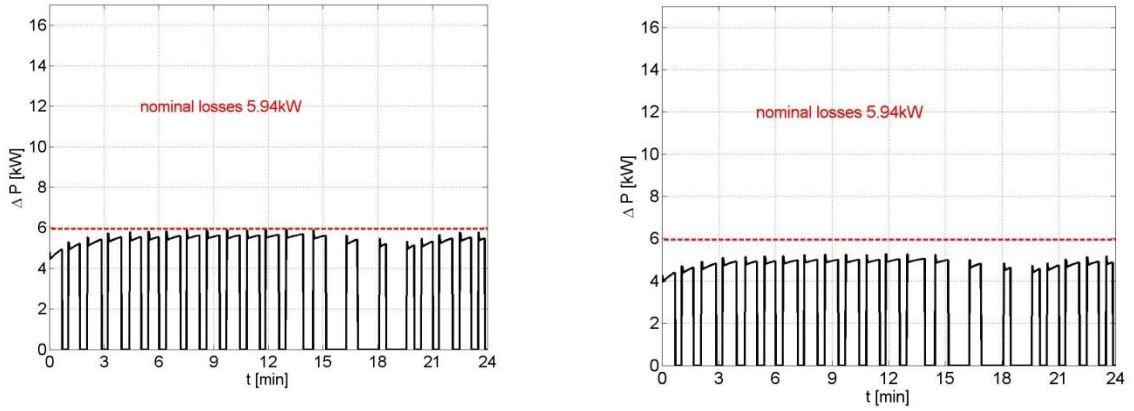


Fig.7-8. Power losses of the IM.

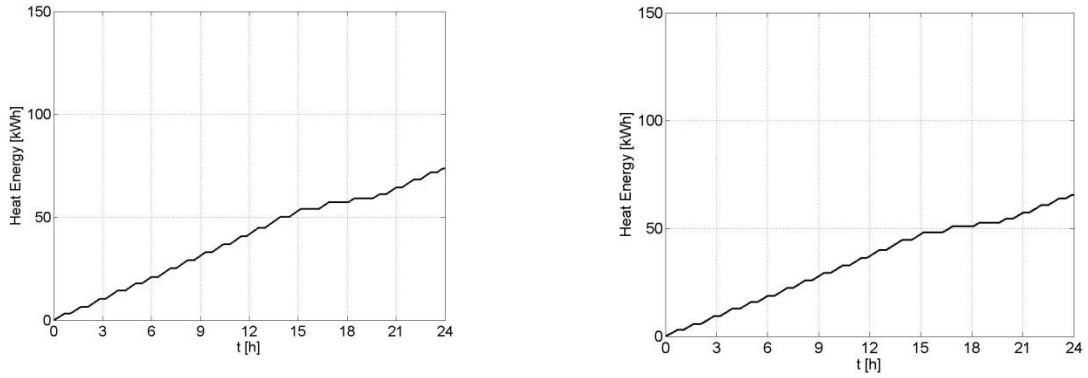


Fig.7-9. Losses – heat energy.

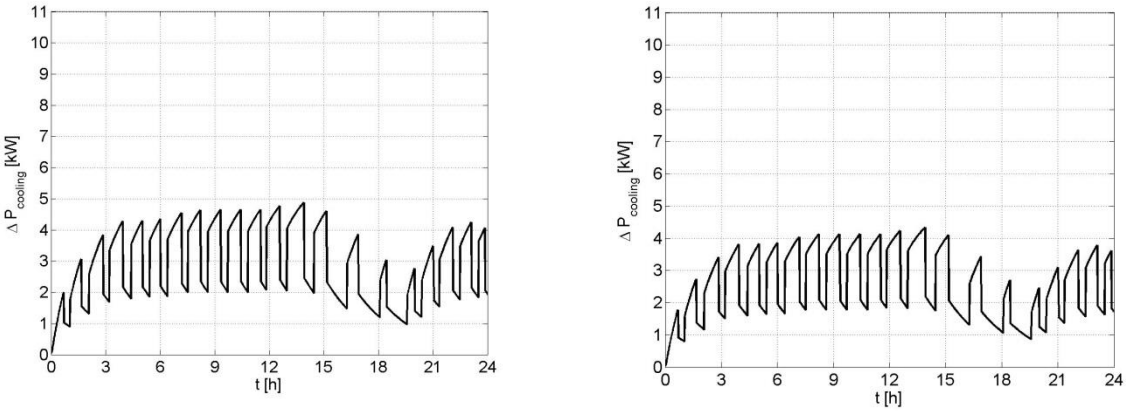


Fig.7-10. Cooling power transferred to vicinity.

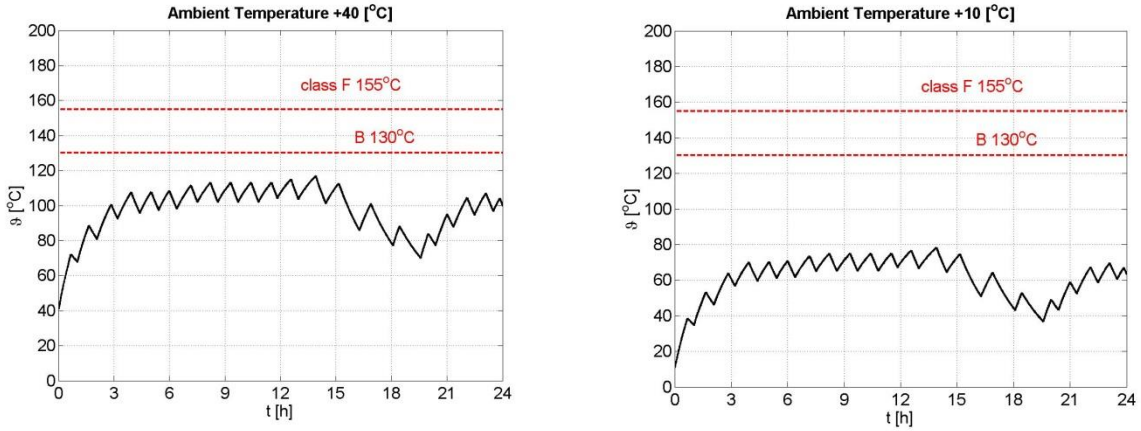


Fig.7-11. Winding average temperature.

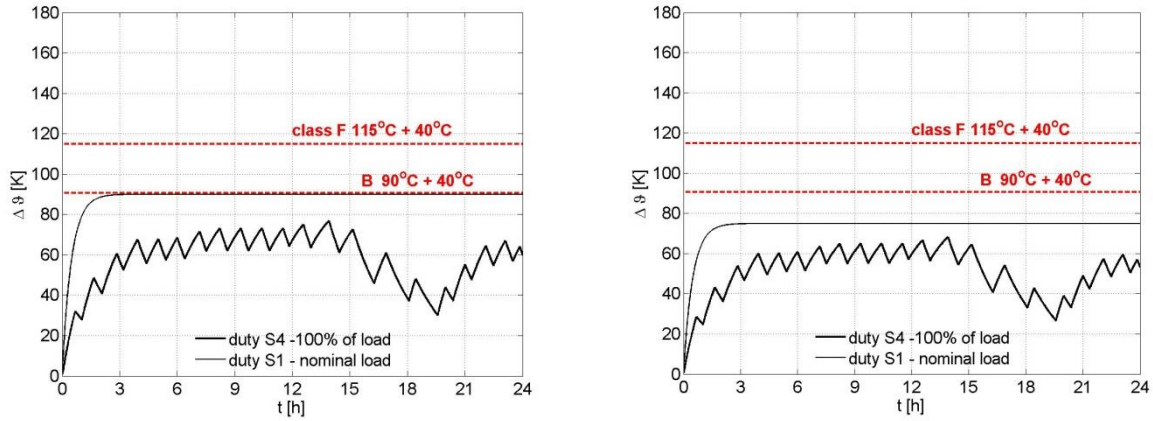


Fig.7-12. Winding temperature rise, average value.

The following figures are simulations for overloading by 130% of a rated power and ambient temperature +10°C, duty S4.

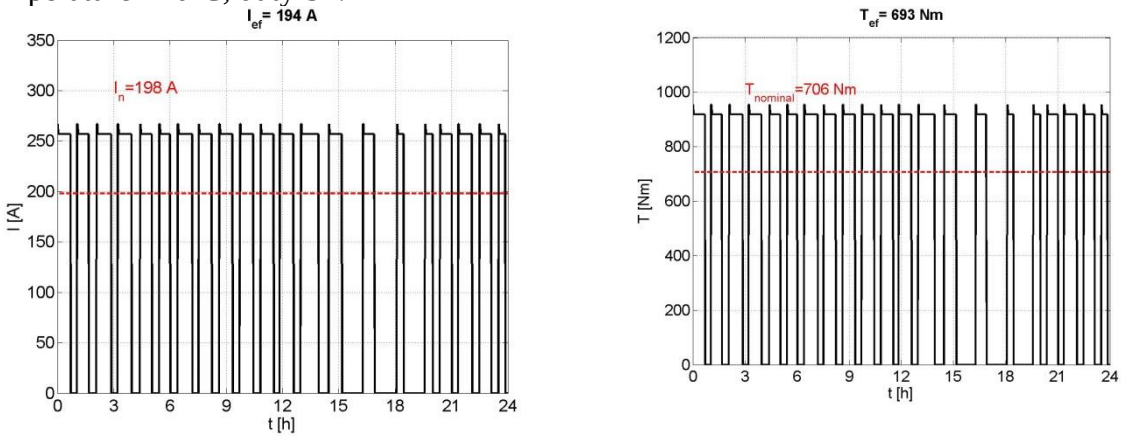


Fig.7-13. Current and torque.

The following figures are simulations for

- Left column – self cooling method IC411
- right column – forced cooling method IC416

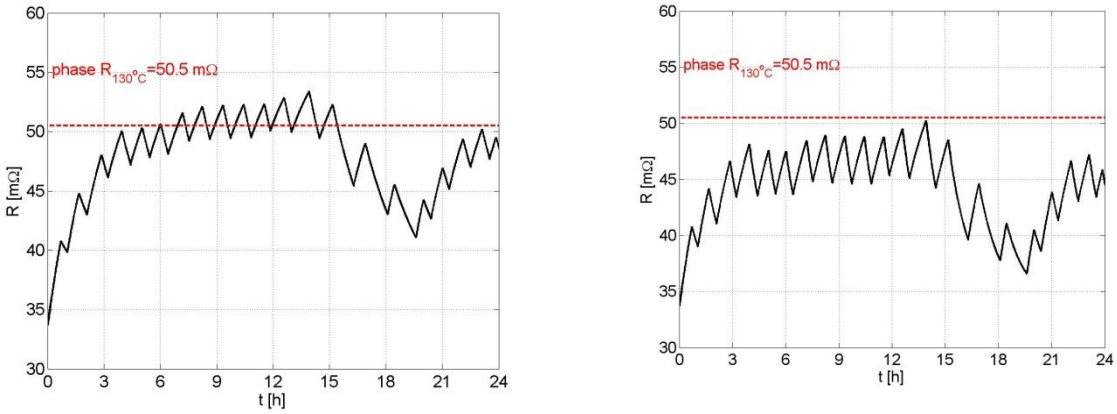


Fig.7-1. Phase winding resistivity.

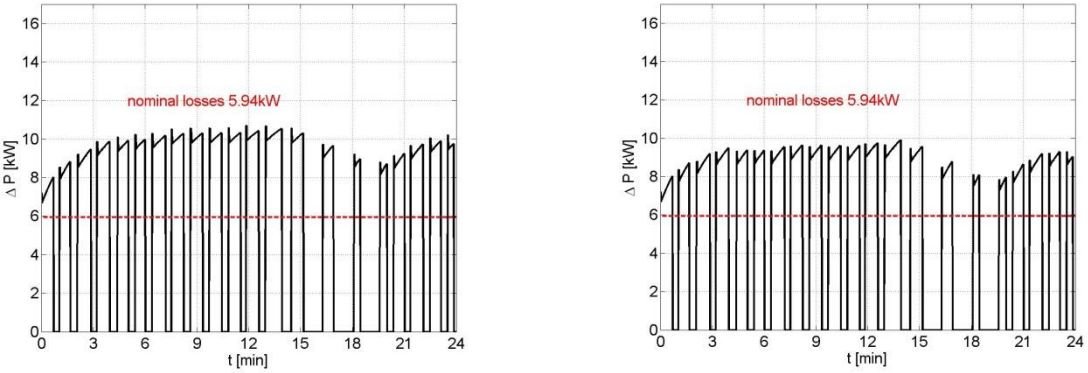


Fig.7-2. Power losses of the IM.

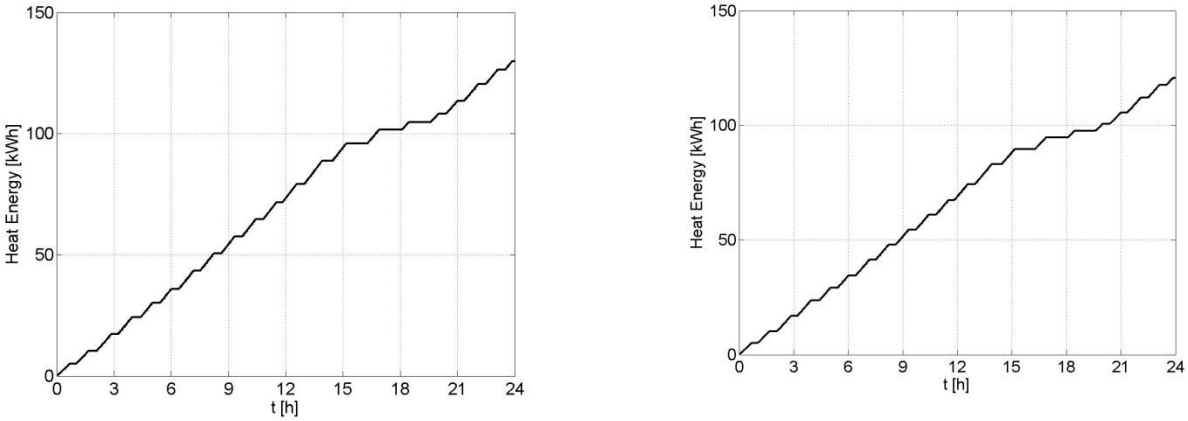


Fig.7-3. Losses – heat energy.

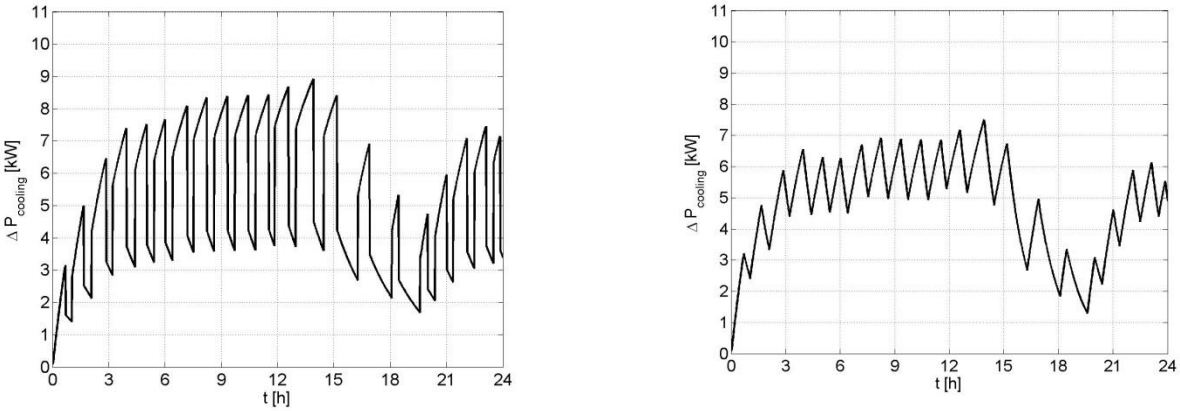
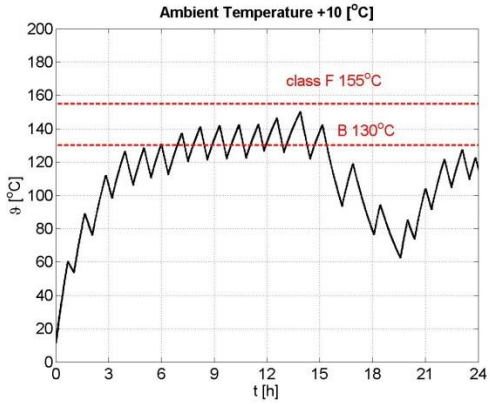


Fig.7-4. Cooling power transferred to vicinity.



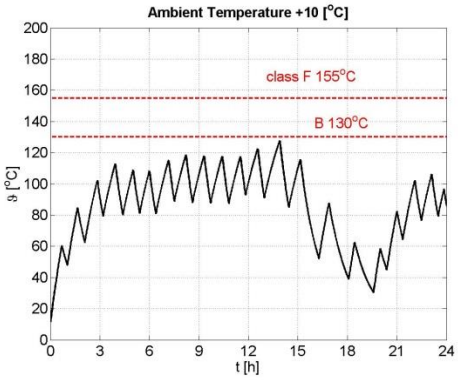
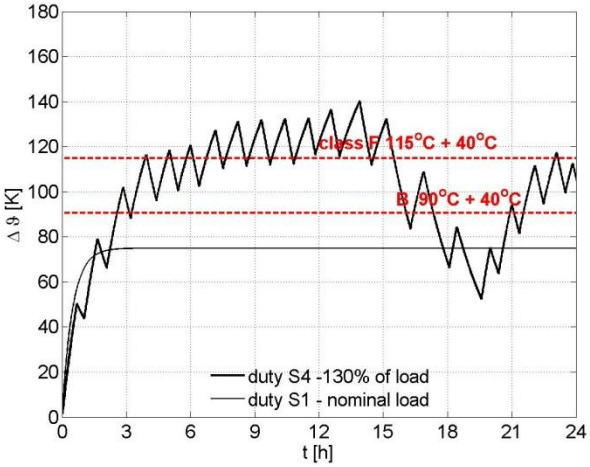


Fig.7-5. Winding average temperature.



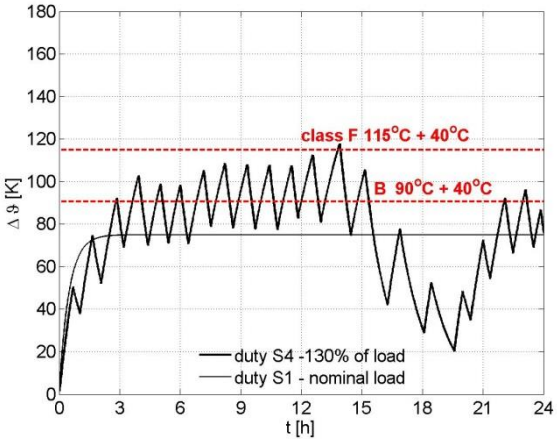


Fig.7-6. Winding temperature rise, average value.

Please note that the temperature rise is on the figures calculated from +10°C, not from assumed ambient temperature +40°C. Due to the fact the temperature is in allowed limits and temperature rise not.

Questions:



- *Why must the test machine be placed in the test room at a steady temperature of at least 24h before the warming test?*
- *Is it necessary to measure the ambient temperature during the warming test?*
- *Which method for determining the temperature of the winding is recommended to use?*
- *How long does the warming test take for machines with a load of S1?*
- *How is the time warm constant determined for warming?*



Answers

- *Why must the test machine be placed in the test room at a steady temperature of at least 24h before the warming test?*

The temperature of the winding must be stabilized, i.e., it must not differ by more than 2K from the surrounding area. This is valid for air-cooled machines.

- *Is it necessary to measure the ambient temperature during the warming test?*

Yes, we have to measure the ambient temperature, because the test can take several hours and the temperature in the test room may change due to the heat released from the testing machine.

- *Which method for determining the temperature of the winding is recommended to use?*

In general, for measuring the temperature of the windings of a machine, the resistance method shall be applied.

- *How long does the warming test take for machines with a load of S1?*

The test shall be continued until thermal equilibrium has been reached.

- *How is the time warm constant determined for warming?*

Analogous to cooling, we use a stable end temperature instead of the initial temperature. We determine the time when the temperature rises from the initial value to its 1/e of steady state temperature.

7 Measurement of Hysteresis Losses in the Rotor of Induction Machines



Estimated completion time: **45 min**



After studying the topic, you will:

- *know the physical principle of loss in rotor IM*
- *understand why IM also has a non-zero moment in synchronism*
- *learn to measure hysteresis losses in the IM rotor*
- *learn to calculate synchronous moment of IM*

7.1 Physical principle

The magnetic core of the rotor of an induction machine has the losses given by the following formula:

$$\Delta P_{Fe2} = \Delta P_{Fe2H} + \Delta P_{Fe2V} \qquad (7\text{-}1)$$

where is ΔP_{Fe2H} … hysteresis losses
ΔP_{Fe2V} … losses by eddy currents

The induction motor creates the constant torque which is proportional to the ΔP_{Fe2H}. This torque M_H is constant even for

- open rotor winding (in case of wound rotor)
- fixed shaft, i.e. speed is zero

This torque is

- $M_H > 0$ for slip $s > 0$
- $M_H < 0$ for slip $s < 0$

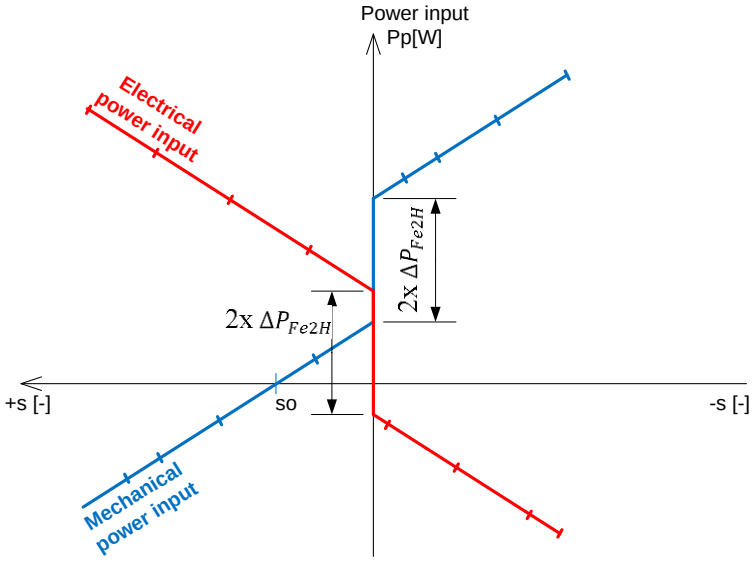


Fig.7-1. Changing the sign of the hysteresis torque

$$\mathrm{M}_H = \frac{\Delta P_{Fe2H}}{\omega_1} = \frac{\Delta P_{Fe2H}}{\frac{\pi n_1}{30}} \tag{7-2}$$

where is n_1 … synchronous speed

7.2 Principle of measurement

The tested induction machine must be coupled mechanically with the driven machine. The driven machine shall be a small power, however the small power of a motor mode and generator mode of operation must be possible.
The tested machine is not loaded, i.e. is at no-load state. The driven machine has slowly increasing power input until we reach the synchronous speed of the tested induction machine. Then we performed 3-4 measurement points at a slip s>0 and further 3-4 measurement points at a slip s<0. The voltage and frequency of the tested induction machine must be at rated values.

$$\Delta P_{2H} \approx B^2 \approx U^2 \tag{7-3}$$

$$\Delta P_{2H} \approx f \tag{7-4}$$

The measurement is performed at no-load state. During the no-load test there are mechanical power losses and power losses caused by slots harmonic components only.

$$(1-s)P_\delta = \Delta P_m + \Delta P_{vf} \tag{7-5}$$

Because the slip is negligible, we can write

$$P_\delta = \Delta P_m + \Delta P_{vf} \tag{7-6}$$

Power losses in the rotor are

$$sP_\delta = \Delta P_{j2} + \Delta P_{Fe2s} \tag{7-7}$$

$$P_\delta = \frac{\Delta P_{j2}}{s} + \frac{\Delta P_{Fe2s}}{s} \tag{7-8}$$

where ΔP_{Fe2s} is.. power losses in the rotor core, depending on the slip
These losses consist of two components, as was established above.

$$P_\delta = \frac{\Delta P_{j2}}{s} + \frac{\Delta P_{Fe2s}}{s} = \frac{\Delta P_{j2}}{s} + \Delta P_{2H} + s\Delta P_{2V} \tag{7-9}$$

The hysteresis losses are independent on the machine loading, i.e. independent on the slip.

$$\Delta P_m + \Delta P_{vf} = \frac{\Delta P_{j2}}{s} + \Delta P_{p2H} \tag{7-10}$$

The component of eddy current losses can be neglected, because the slip is almost zero.

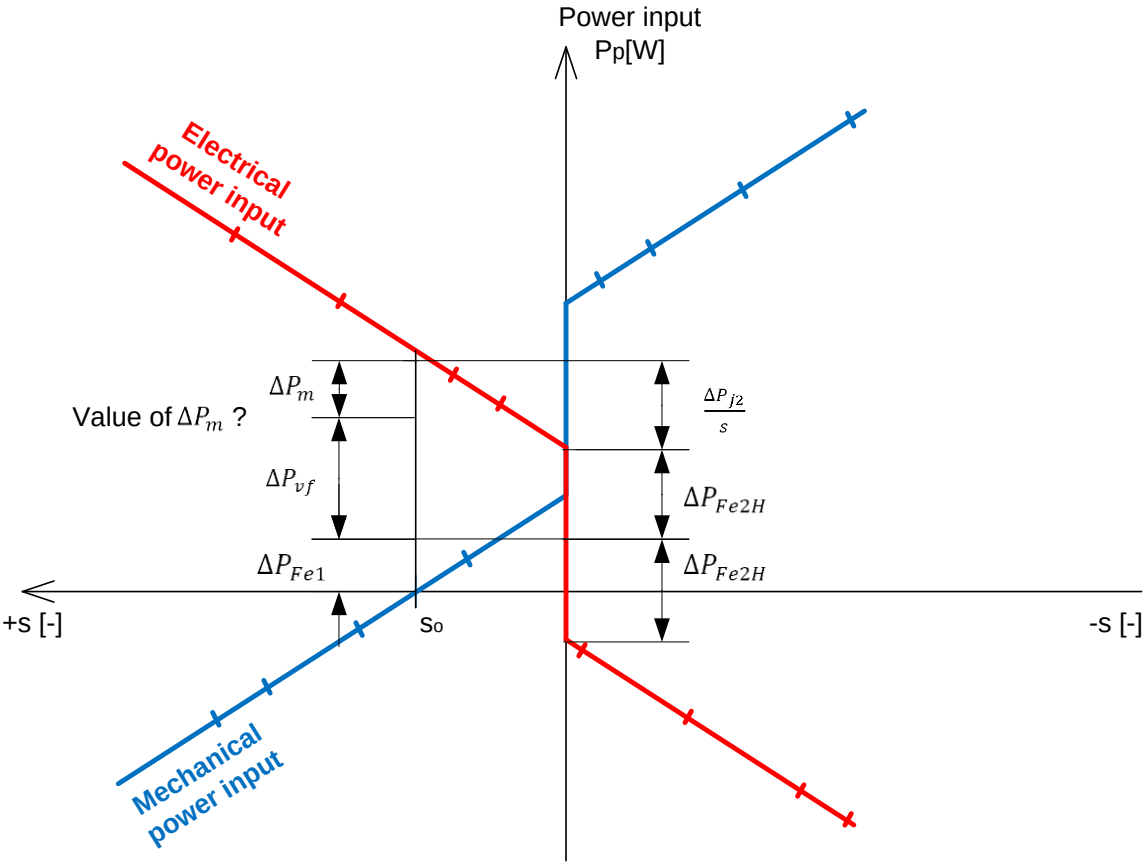


Fig.7-2. The sizes of power losses.

The mechanical power losses are not defined by this measurement. However, the additional measurements (for example no-load test) help to determine this value.

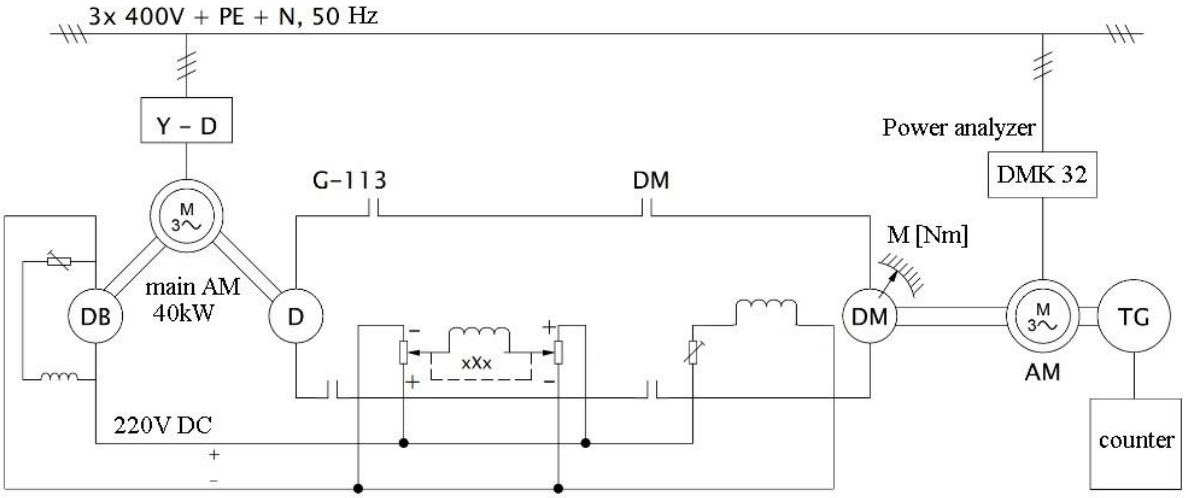


Fig.7-3. Scheme of connection.

7.3 Example of results of measurement

Name plate of the induction motor

Rated power	3,5 kW
Rated voltage	380V D
Rated current	7,1A
Rated speed	2950 rpm

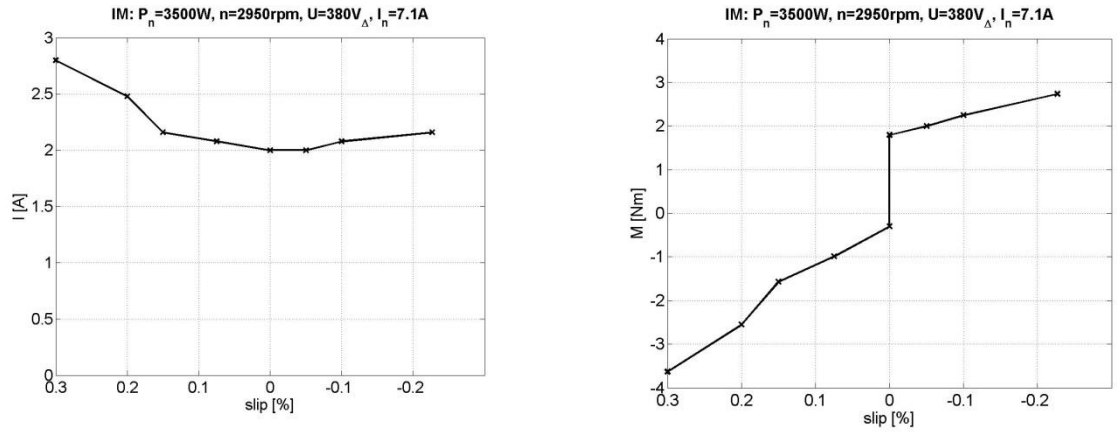


Fig.7-4. The current a torque versus slip.

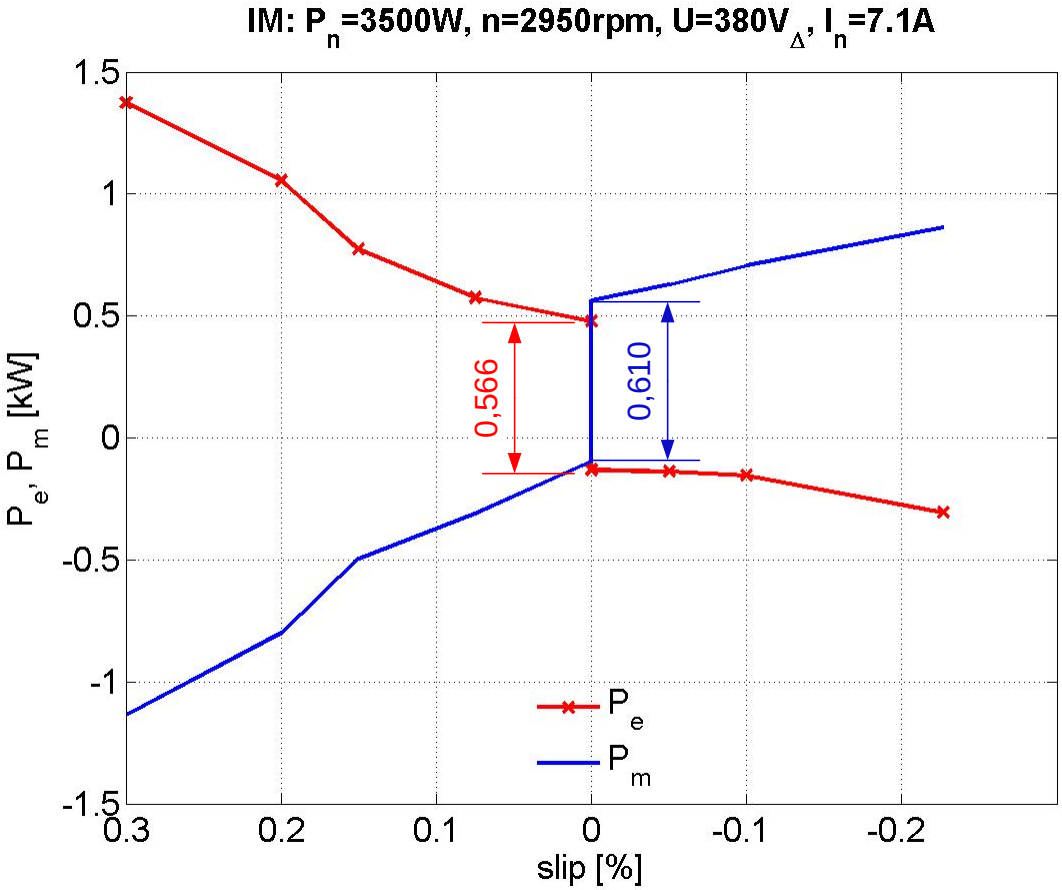


Fig.7-5. Power inputs (mechanical, electrical) versus slip and results.



Questions:

- *Does the size of hysteresis losses depend on the size of the machine's supply voltage?*
- *How much power do we have to deliver to the machine being tested by a power tool (dynamometer) to achieve synchronism?*
- *Why does the IM operating at zero-slip not have a zero current?*
- *Why is the change (step) in electrical power different from the change of mechanical power?*



Answers

- *Does the size of hysteresis losses depend on the size of the machine's supply voltage?*

Yes, addiction is quadratic.

- *How much power do we have to deliver to the machine being tested by a driven machine (dynamometer) to achieve synchronism?*

We have to supply power to cover losses in the machine, i.e. mechanical, Joule and magnetic circuit losses.

- *Why does the IM operating at zero-slip not have a zero current?*

The machine needs a magnetization current, i.e. reactive power is taken from the supply network.

- *Why is the change (step) in electrical power different from the change of mechanical power?*

On the physical principle, the jump is just identical. The reason for the difference of a mechanical and electrical jump is the different accuracy of the measuring instruments.

8 Loading of Induction Machines



Estimated completion time: **90 min**

After studying the topic, you will:



- *be able to determine the working mode operation of the induction machine based on its speed or slip*
- *be able to characterize various types of mechanical load as dependent on speed*
- *know the IM working characteristics*
- *be able to brake the IM*
- *be able to characterize the working characteristics of self-operated induction generators*

8.1 Introduction

The induction machine can be loaded in the mode of operation

- Motor (slip 0<s<1)
- Generator (slip s<0)
- Brake (slip s>1 or DC supply voltage)
- Self operated generator (work without supply mains)

Motor is usually loaded by mechanical load (pump, fan, gear box with belt conveyor). For laboratory purposes and testing the mechanical load is replaced by

- brake (change the mechanical energy on the motor shaft to the heat)
- dynamometer (recuperation of energy back to the network)

Asynchronous generator is usually powered by water or wind turbine (sometimes also by combustion engine). The electric energy is sent to the network. Sometimes the generator mode is used for recuperation of kinetic energy of the mechanical load and the mechanical load is braking (drilling machine, trolley bus, locomotive, tube, subway, etc.).
When the generator is connected directly to the network, the speed is higher than synchronous speed (hyper synchronous speed). When the generator is supplied by frequency convertor, the supply frequency is lower than the corresponding frequency and the actual speed.
For laboratory purposes and testing, the dynamometer is used very often.

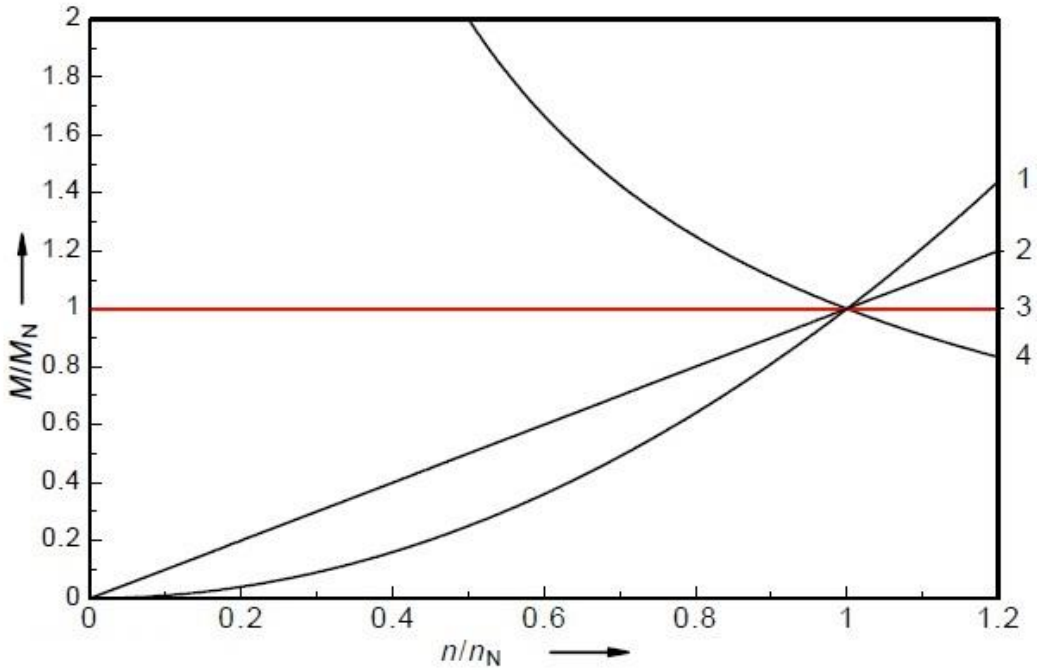
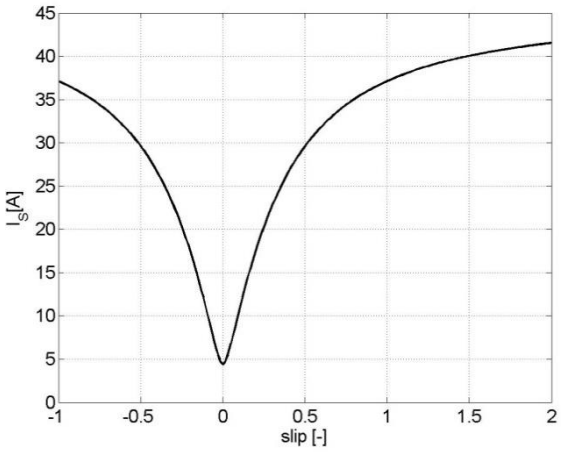


Fig.8-1. Typical torque-speed characteristic curves of driven machinery. 1 – square (pumps, fans), 2 – linear (calendars, sheet rollers) 3 – constant (elevator, conveyors, overcoming friction and gravitation), 4 – inverse (coil winders, machine tools).

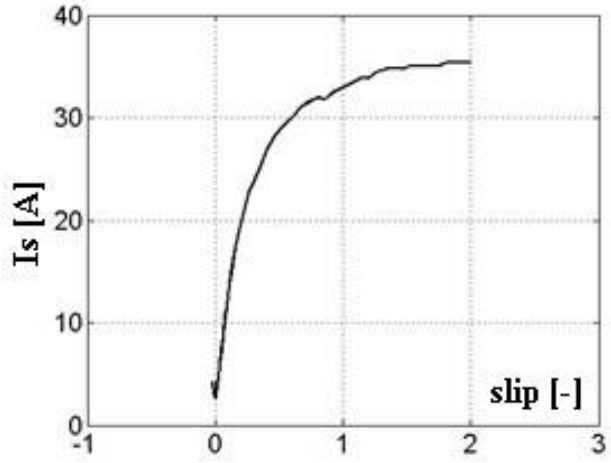
8.2 Motor

Simulation loading characteristics for a machine with rated parameters:

P_n [kW]	3
U Y/D [V]	400 / 230
I Y/D [A]	6,5 / 11,4
cos φ [-]	0,81
J [kg.m^2]	0,0065
M_n [Nm]	20,25
n_n [rpm]	1415
efficiency [%]	81,5
Starting torque / rated torque [-]	2,6
Starting current / rated current [-]	6,1
Max torque / rated torque [-]	2,8
Stator resistance (one phase), short circuit test [Ω]	1,99
Stator resistance (one phase), Ohm‘s method [Ω]	1,9
Magnetizing inductivity [mH]	153
Leakage inductivity stator / recalculated to stator [mH]	7,9 / 13,1
R_{Fe} [Ω]	544
Mechanical losses [W]	20
Joule losses (no-load test) [W]	126
Core losses (no-load test) [W]	275

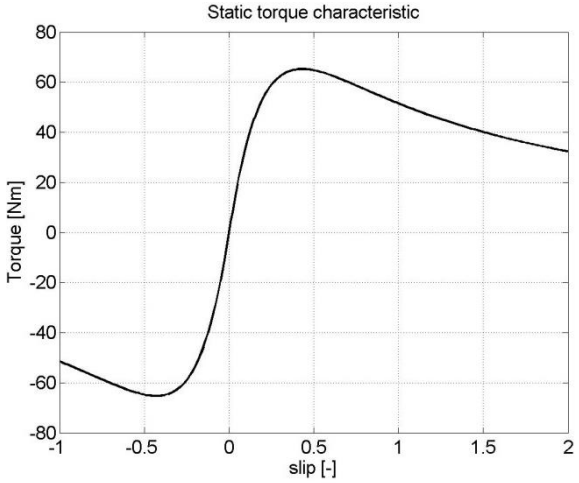


a)

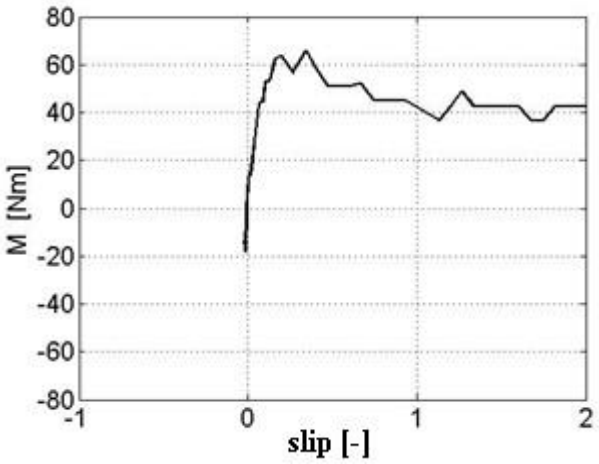


b)

Fig.8-2. Stator current a) simulation b) measurement.

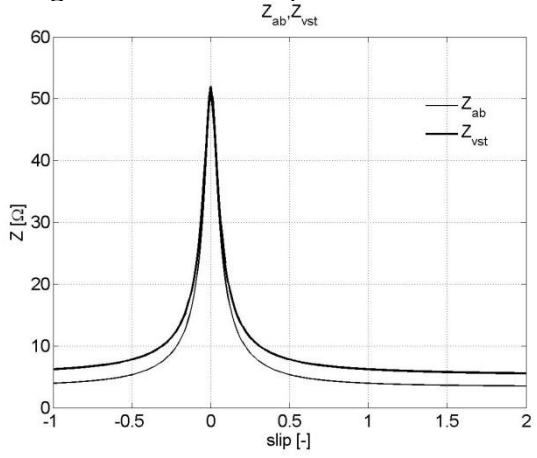


a)

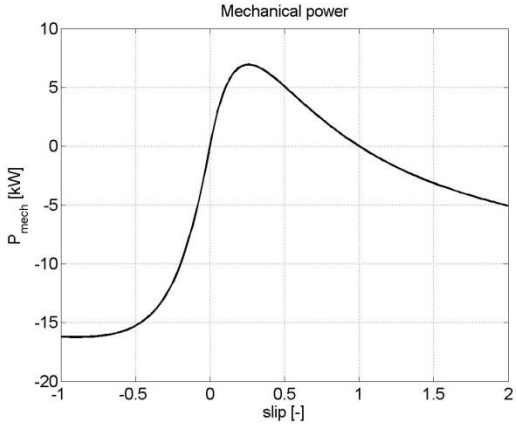


b)

Fig.8-3. Static torque characteristics a) simulation b) measurement.



a)



b)

Fig.8-4. a) Equivalent circuit impedance b) mechanical power.

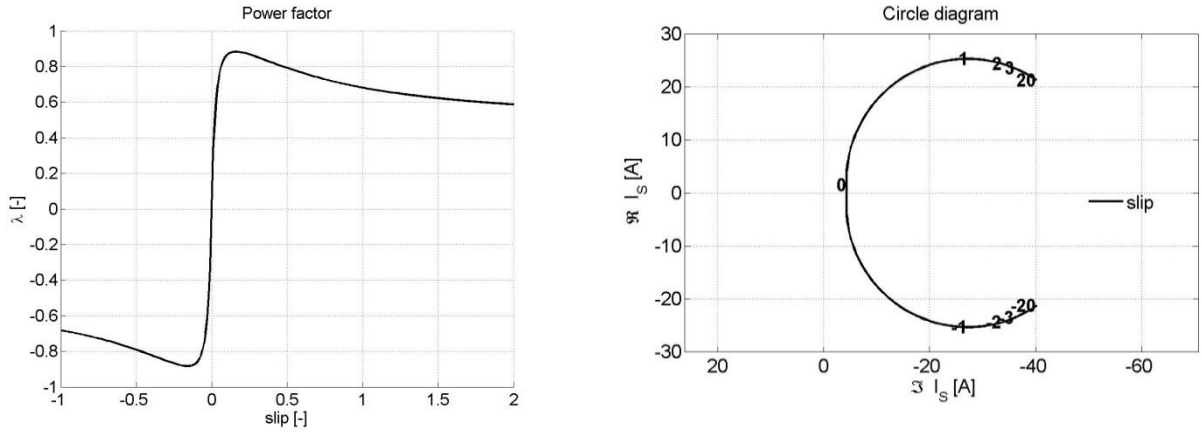


Fig.8-5. a) Power factor b) circle diagram.

8.3 Generator

The regenerative torque characteristic curve, when working in hyper synchronous range, will be almost a mirror image of the normal speed of rotation. However, the regenerative breakdown torque will be significantly greater than the breakdown torque when motoring. Although the shock load of changing from a higher to a lower speed can cause faults, in the lowering mode the high braking generator - even with a two-wire connection (that is to say, even if the breakdown torque were drastically reduced to 50% of a three phase connection), the braking torque would be sufficient to lower the load safely without undue rise in speed.

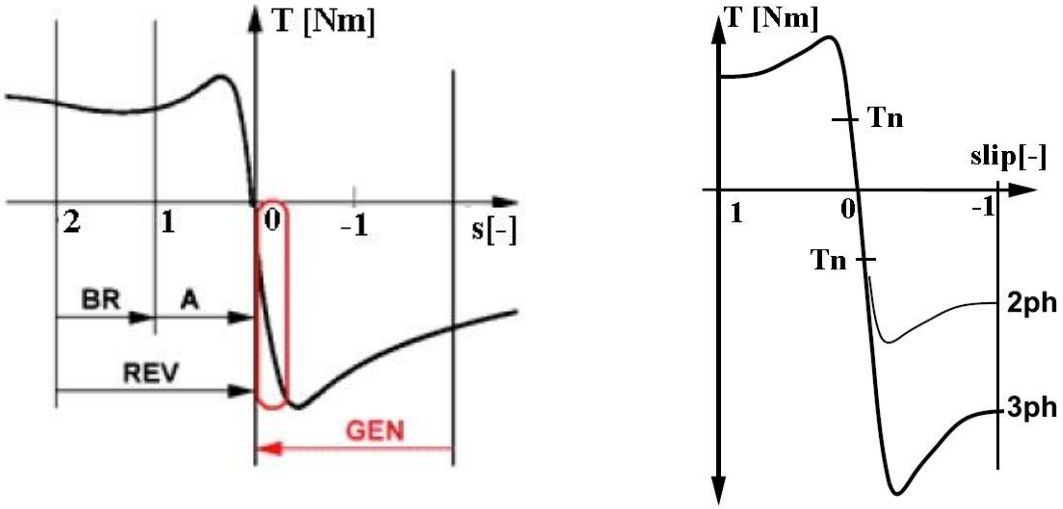


Fig.8-6. Torque characteristics. Lowering a load (Tn) in hyper synchronous generating mode with a 3-phase connection (3ph) and a 2-phase connection ("phase failure" 2ph).

8.4 Practical measurement on dynamometer, rated parameters

The squirrel cage IM of a rated power 3,5kW was tested on the dynamometer on motor mode and generator mode of operation. The results are in the following graphs. The left side is the generator mode, the right side is the motor mode.
The horizontal axis has a per unit value – relative power. Negative relative power = generator mode of operation. The machine was slightly overloaded in both modes of operation.

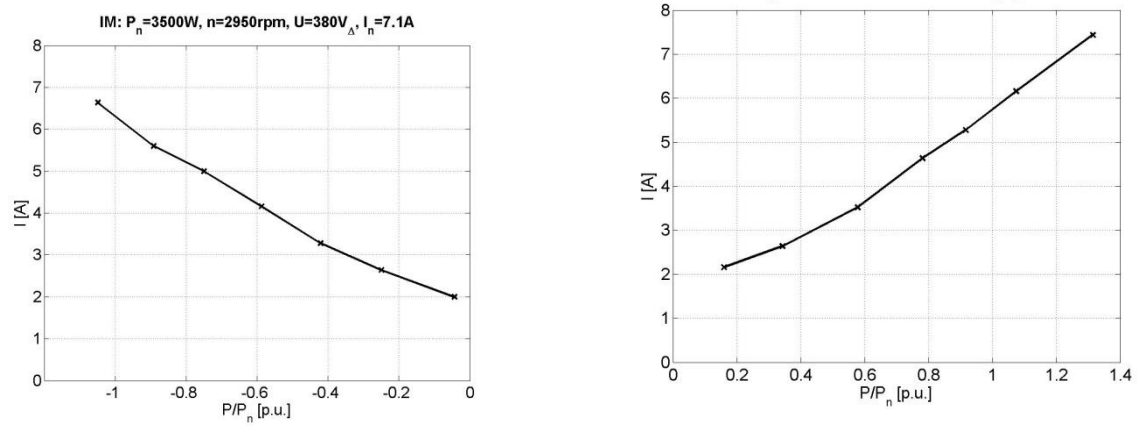


Fig.8-7. The stator current, average value of 3ph.

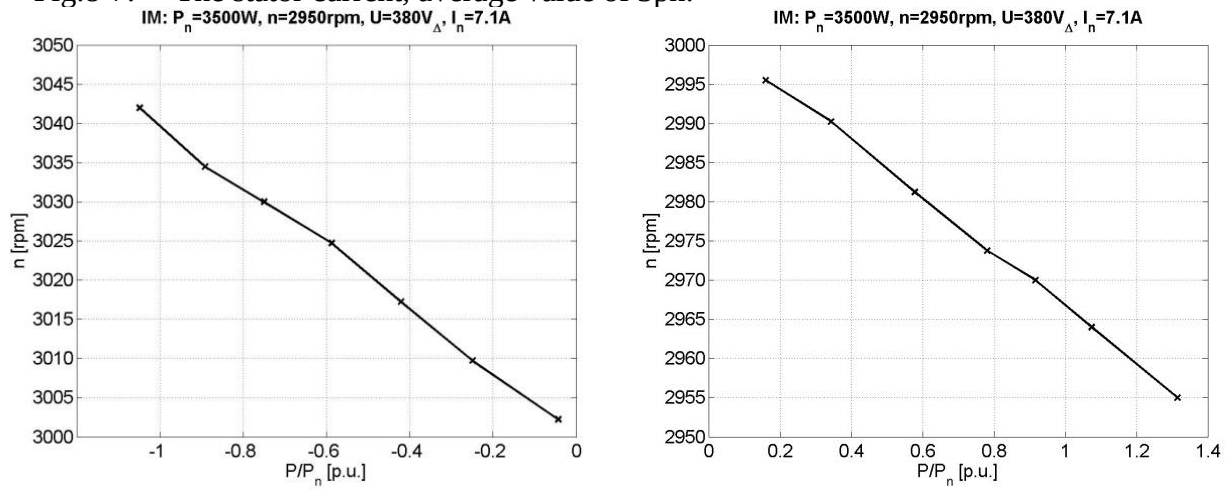


Fig.8-8. Rotor speed.

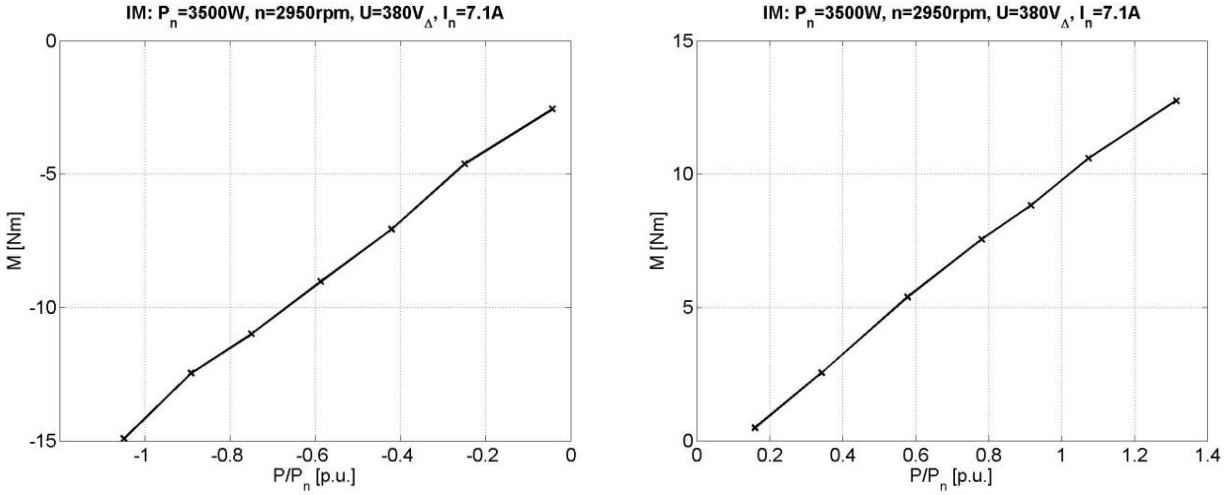
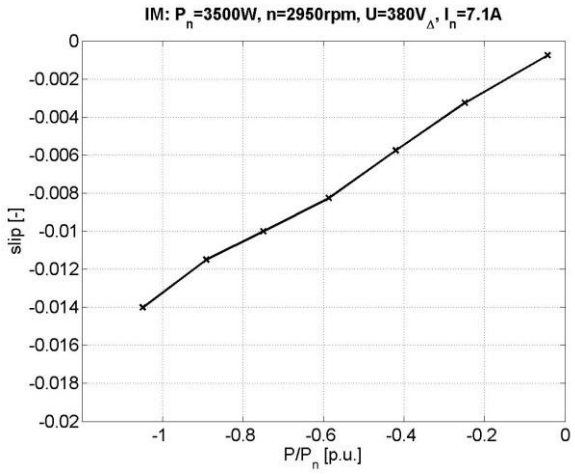


Fig.8-9. The mechanical torque.



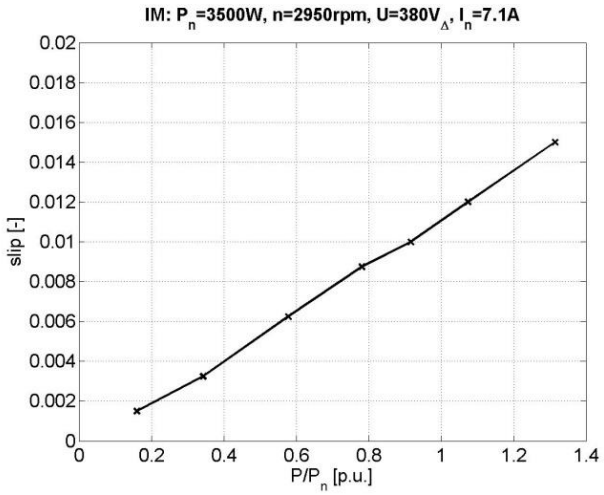
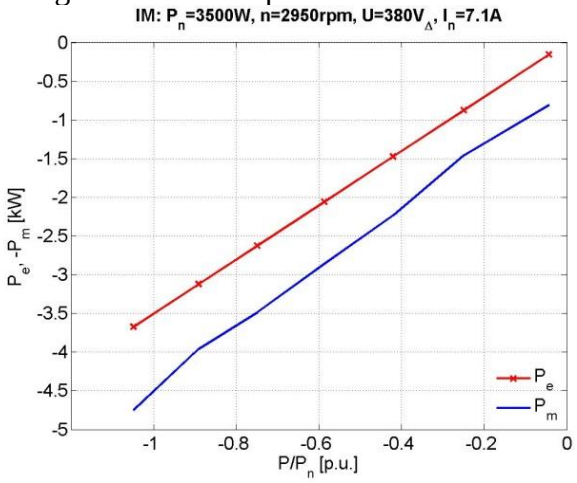


Fig.8-10. The slip.



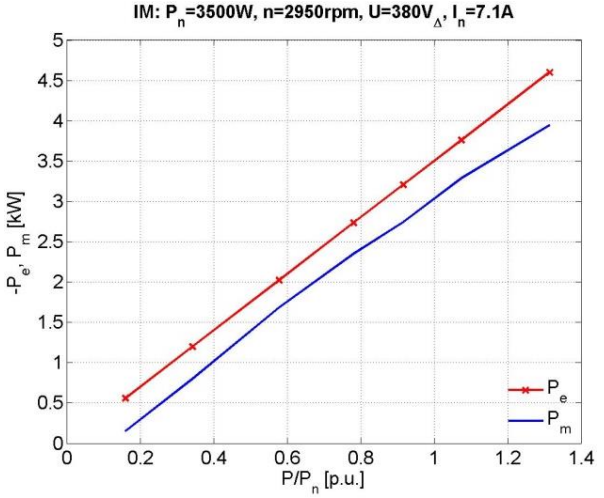
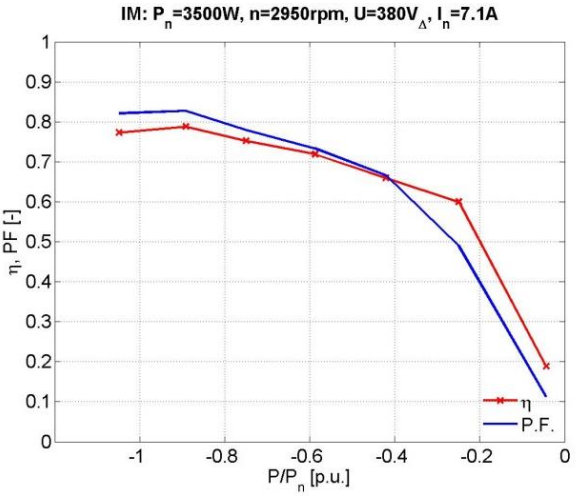


Fig.8-11. Mechanical power input and electrical power input (negative input = output).



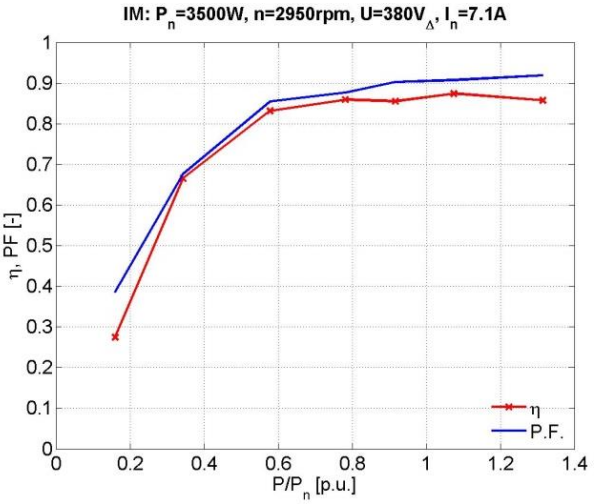


Fig.8-12. Efficiency and power factor.

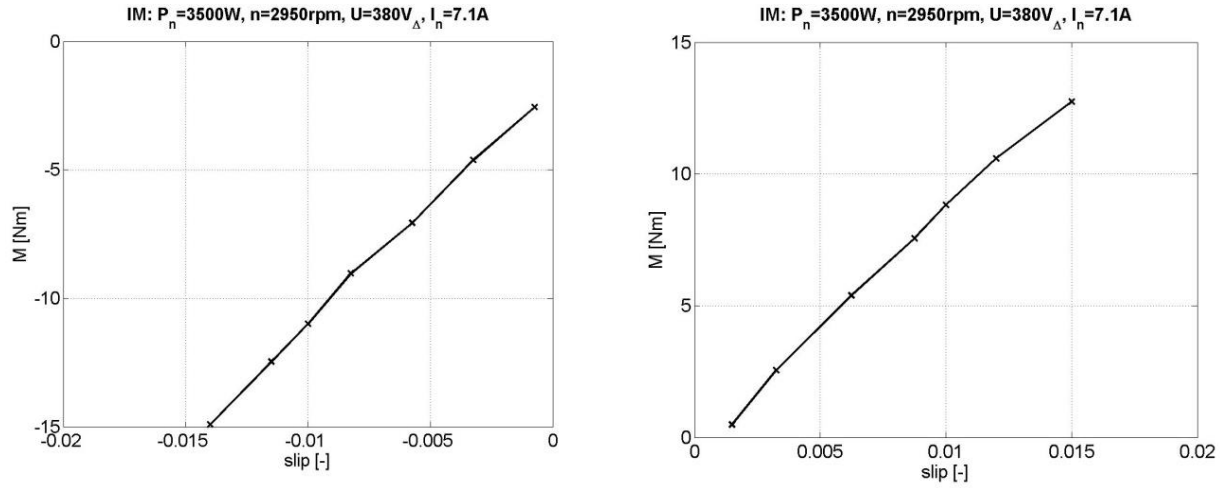


Fig.8-13. Torque characteristic versus slip.

8.5 Practical measurement on dynamometer, overloading

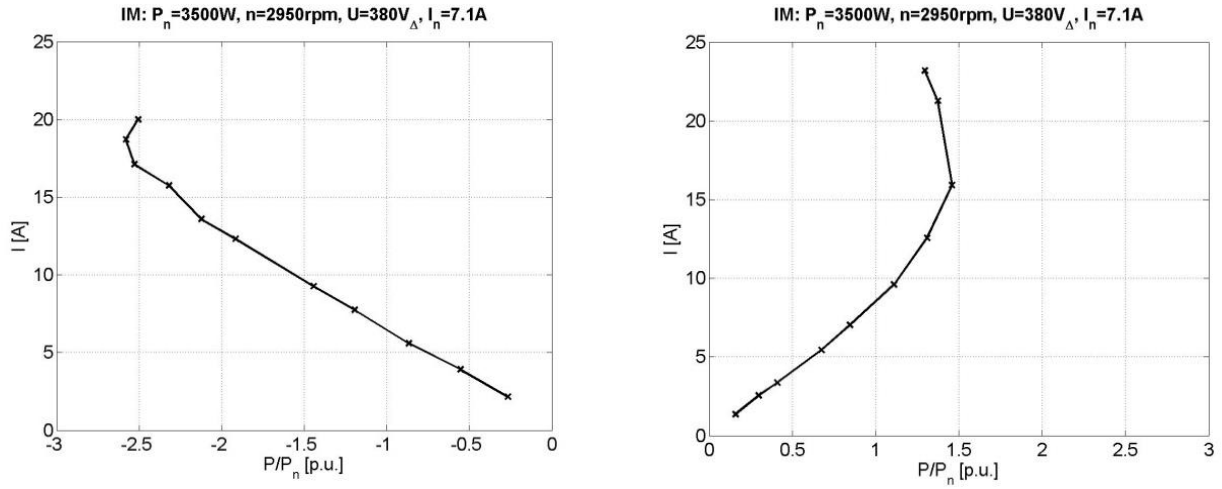


Fig.8-14. The stator current, average value of 3ph.

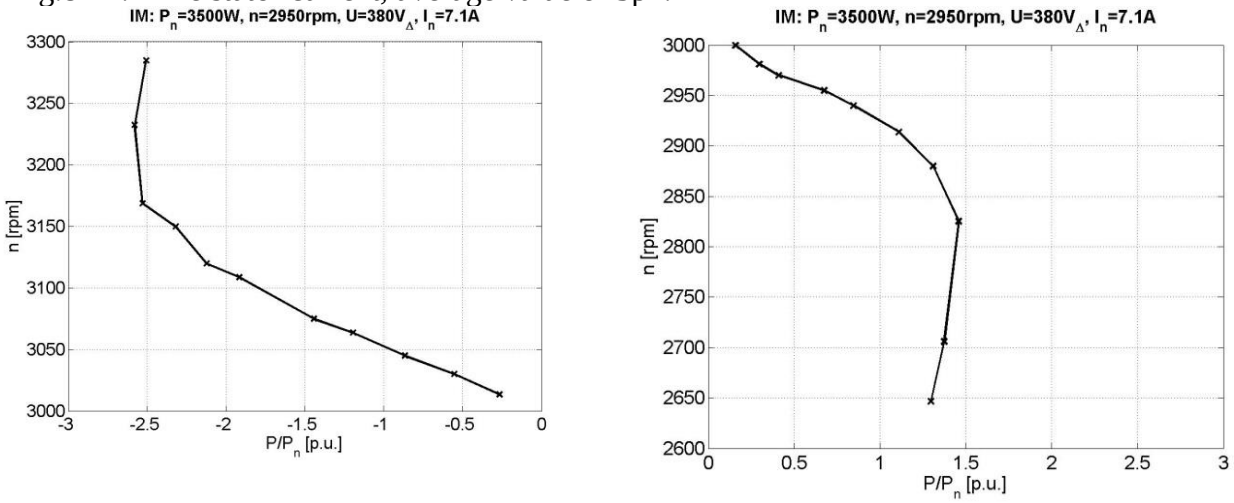
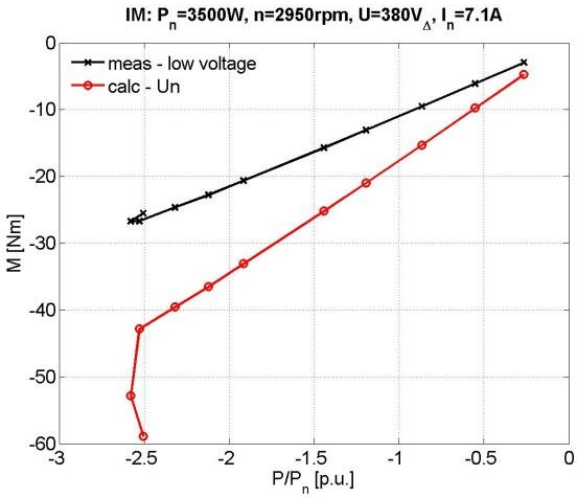


Fig.8-15. Rotor speed.



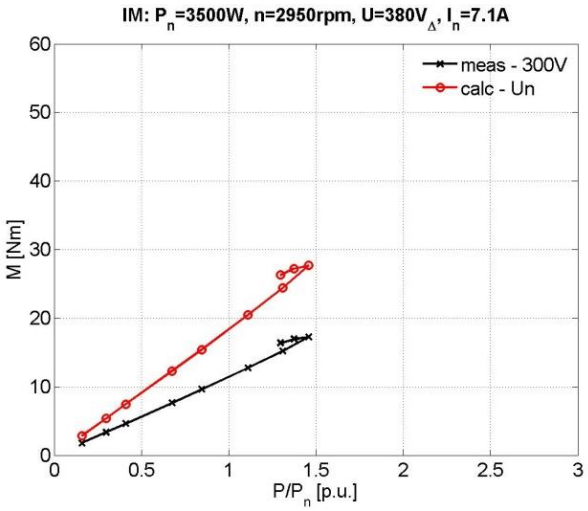
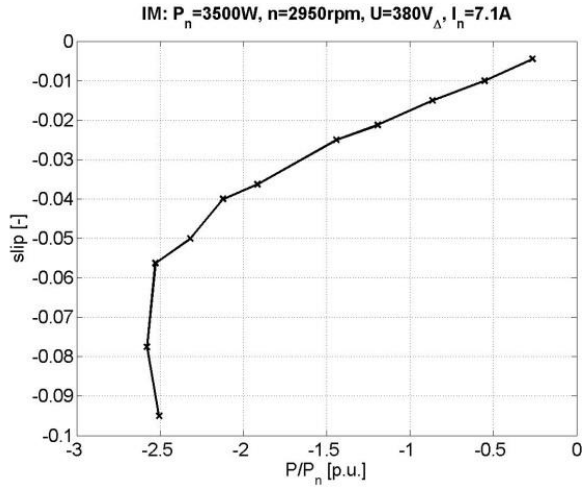


Fig.8-16. The mechanical torque.



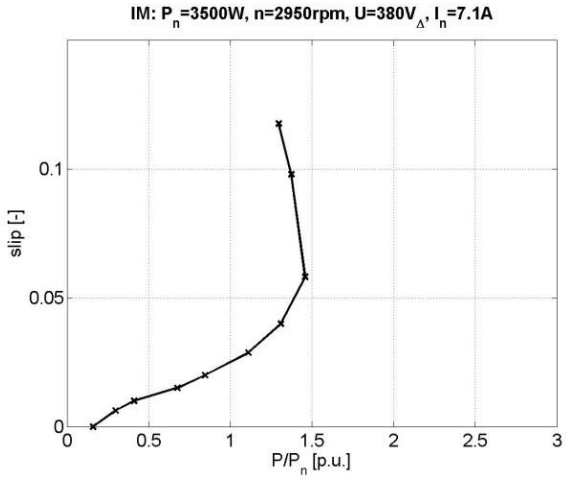
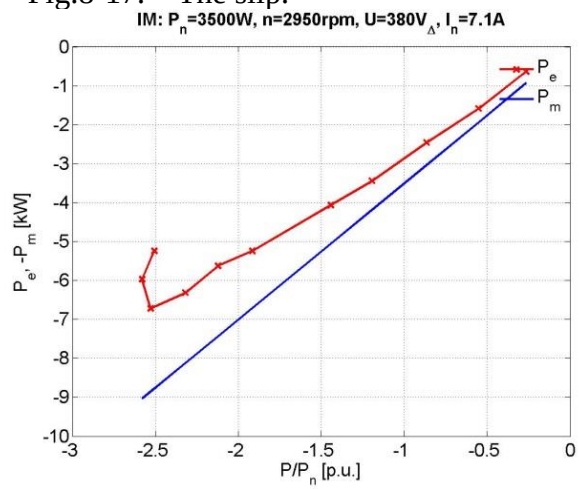


Fig.8-17. The slip.



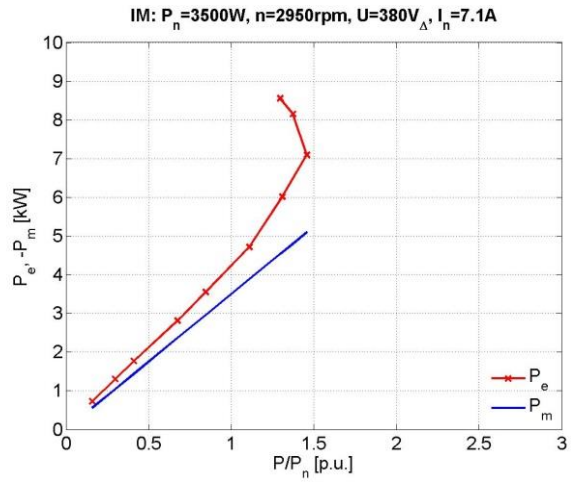


Fig.8-18. Mechanical power input and electrical power input (negative input = output).

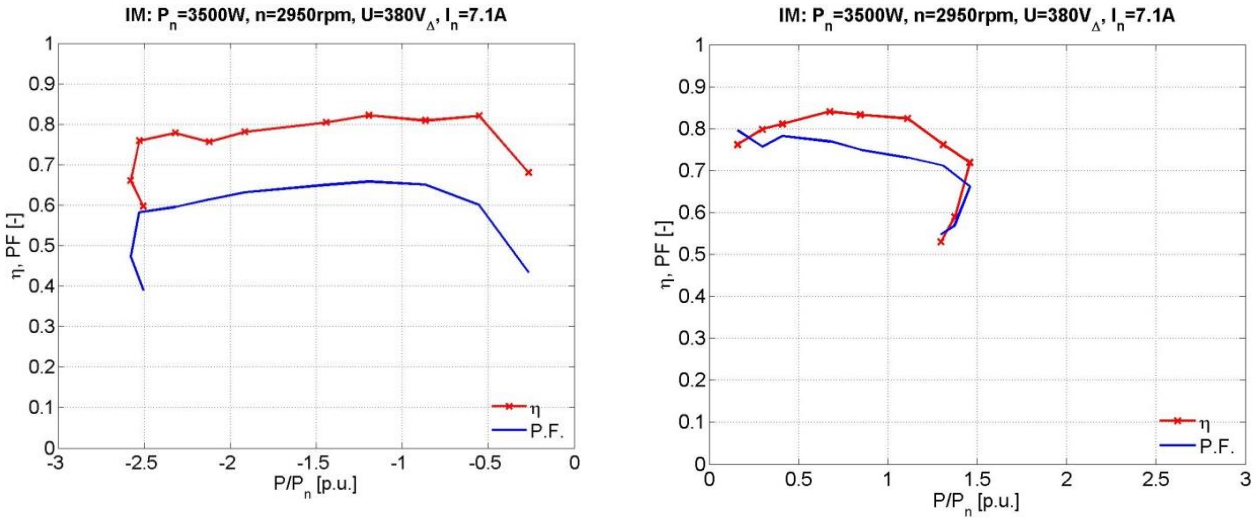


Fig.8-19. Efficiency and power factor.

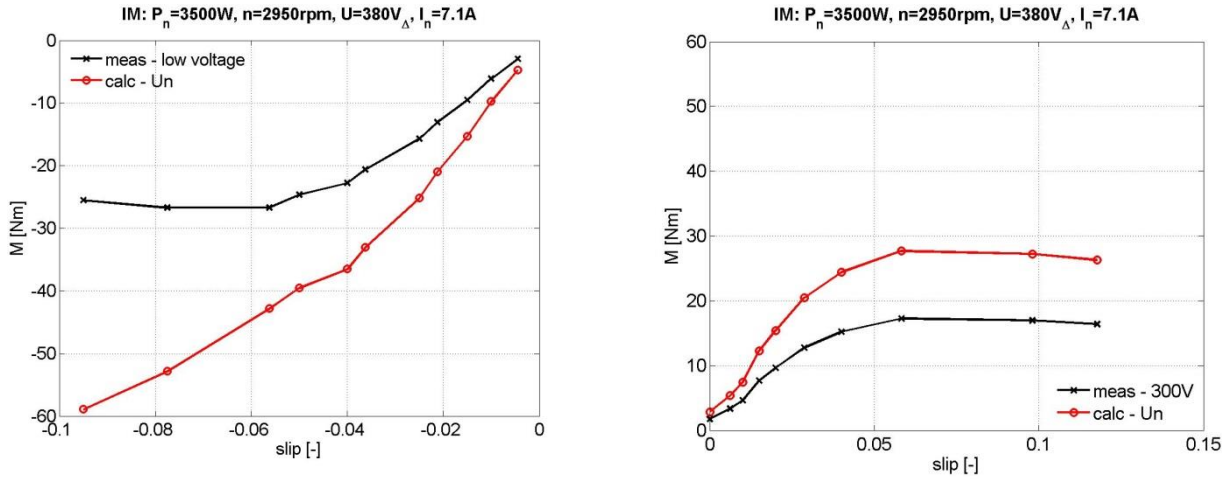


Fig.8-20. Torque characteristic versus slip.

8.6 Brake (reverse phase sequence)

In the braking operation (reverse field braking), the mass moment of inertia of the drive is decelerated to a stop in the same way as in the first part of a reversing operation. As the speed change passes through zero, the braking contactor is opened by a braking monitor (zero speed switch) to prevent the driving motor from re-starting in the reverse direction.
Although braking would appear to be simple, both in effect and in its circuitry, in practice there are two important limitations:

- The mechanical shock load can be unacceptably high, particularly where the transmission components have some lost motion or backlash (such as chain drives and claw couplings)
- The difficulties of opening the braking contactor at exactly zero speed becomes greater as the braking time is shortened. The timer cannot register the effect of different loads and the mass moment of inertia and speed sensor will involve increased costs and longevity of a machine.

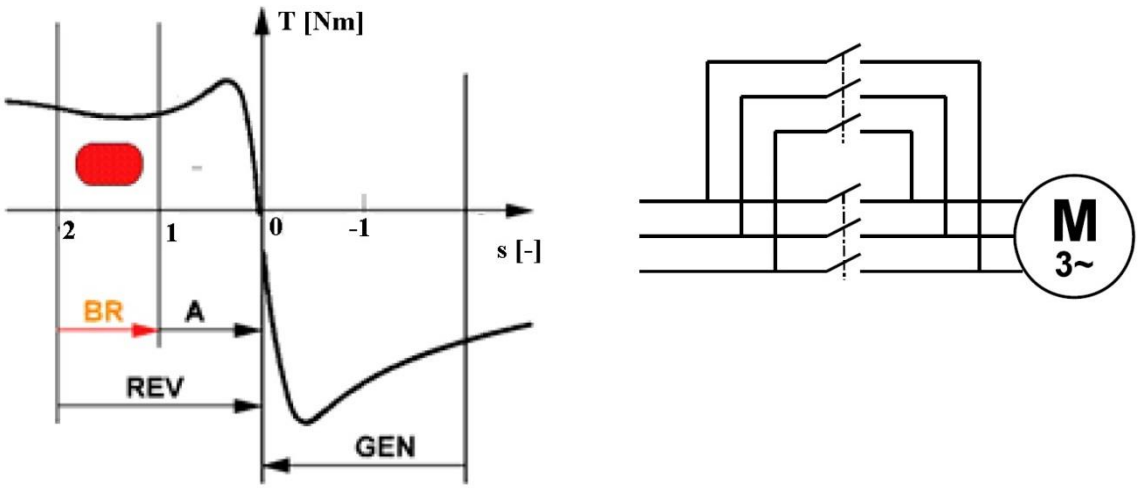
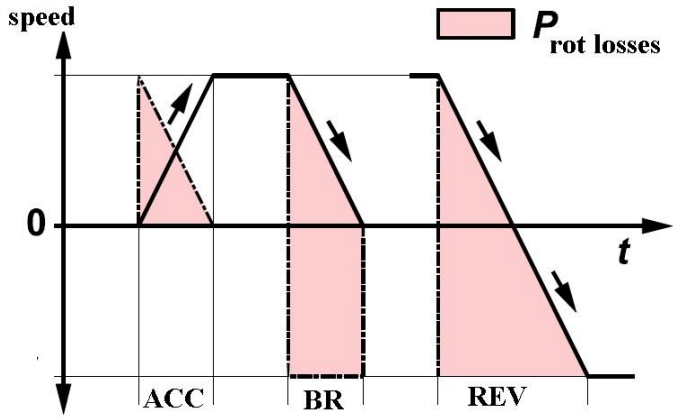


Fig.8-21. Torque characteristics and basic circuit diagram for braking (and reversing as well).



ACC – acceleration
BR – braking
REV – reversing

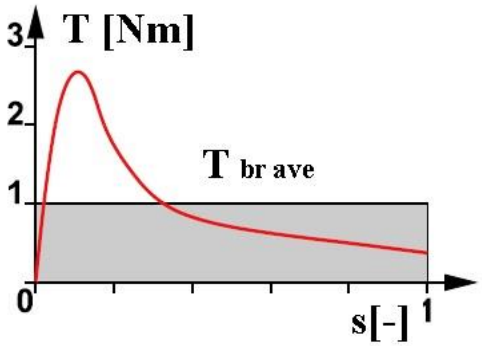
Rotor losses

Fig.8-22. Rotor losses during the acceleration, braking and reversing.

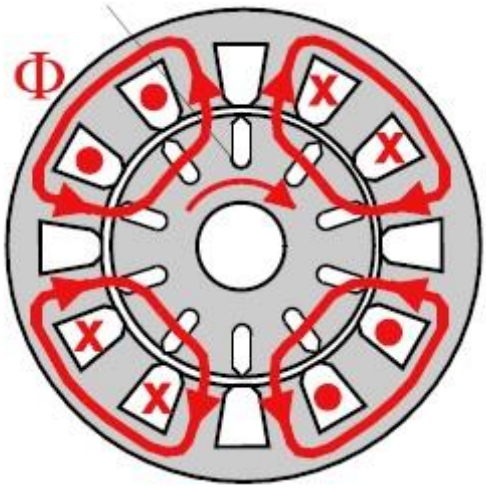
There are, however, areas of application where braking is very common. It is frequently used, for instance, for roller table drives since this method requires no additional equipment costs.

8.7 Brake (DC supply voltage)

If the 3-phase winding of the stator is fed with a direct current, a stationary magnetic field will be set up in the stator bore causing the voltage to be induced in the bars of the cage as long as the rotor is in motion.



a)

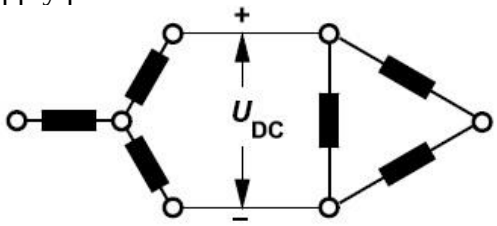


b)

Fig.8-23. a) Effectiveness of DC injection braking during retardation of speed. Instantaneous braking torque T and $T_{br\ ave}$ … average value of the braking torque. b) The field developed by DC supply to a 4pole 3-phase stator winding in a star connection.

Since the electrical resistance of the rotor cage is very low, even a small induced voltage can create a high rotor current. This current will produce a strong braking effect on the bars and hence on the rotor. As the speed falls, the frequency of the induced voltage falls and with it the inductive impedance. The ohmic resistance of the rotor gradually becomes dominant and so increases the braking effect as the speed comes down. The braking torque is therefore not suitable for actually holding a load at rest. On the other hand, the initially gentle but increasingly powerful effect of this method of braking makes it virtually ideal for almost any retardation process.

The most effective retardation is obtained by connecting the DC supply voltage to two phases in the case of a motor in a star configuration or by connecting a DC supply to two of the 3-phase terminals in the case of a motor in a delta configuration. Other possible methods of supply produce a lower retardation effect.



a)

Fig.8-24. Stator winding configuration for connection to DC voltage.

The average braking torque is approximately equal to the rated motor torque when the braking current I_{DC} is approximately 200-250% of the rated motor current I_n, i.e. when

$$I_{DC} \approx 2{,}5\, I_N \qquad (9\text{-}1)$$

The DC voltage to be applied should be sufficient to cause this braking current to flow for a given winding resistance. Rectifiers in a single-phase bridge configuration are the most suitable means of transforming the AC mains into a DC current. Silicone diodes must be protected against the expected inductive voltage spikes.

8.8 Self operated generator

The dynamometer DM was used as a drive. Rated parameters of asynchronous generator AG are summarized in the table.

Rated power	4 kW	Stator resistence	1,2 Ω
Rated voltage	Y 380 V / D 220 V	$L_{\sigma s}$	7,64 mH
Rated current	Y 8,6 A / D 14,8 A	L_{μ}	220 mH
Machine type	R55+2-06 HO 2	Moment of inertia (whole unit)	0,35 kg.m^2
		ΔP_m (n=3000 rpm)	120 W

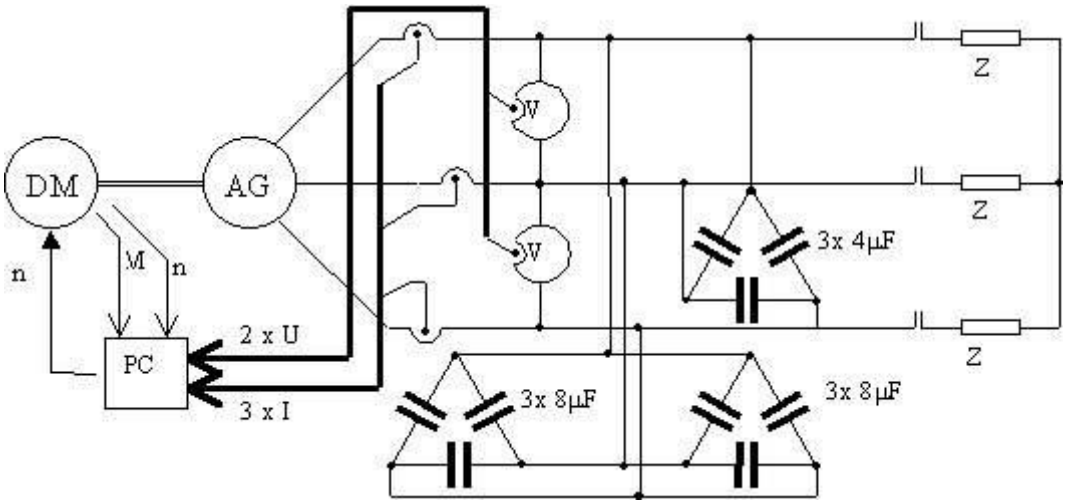
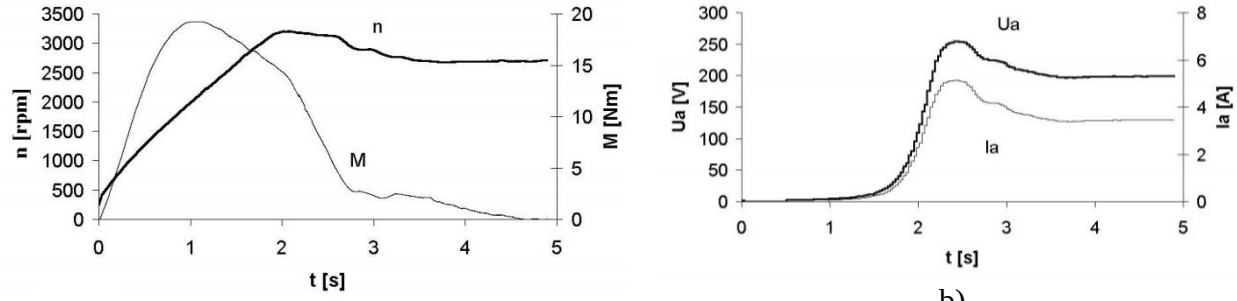
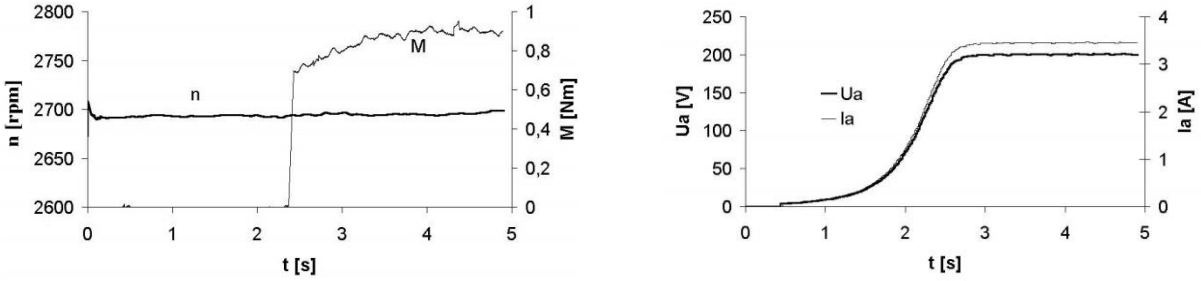


Fig.8-25. Scheme of connection for testing.



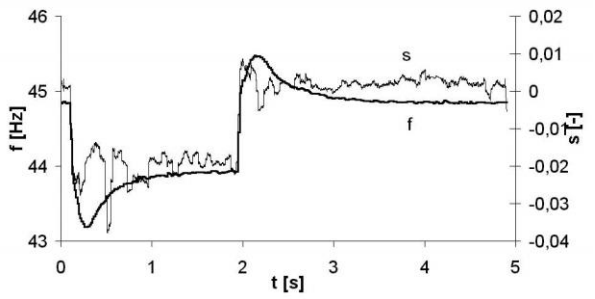
a) b)

Fig.8-26. a) Run up b) excitation of the generator.



a) b)

Fig.8-27. a) Running generator b) connection of the running machine to capacitors.



The frequency of the generated voltage is well known. The speed was also measured. Thanks to the slip definition it is possible to calculate the slip. At no load state the excited generator has a small negative slip. Frequency depends on speed and load of the generator.

Fig.8-28. Connection and disconnection of the load R=50 Ohm. Slip and frequency.

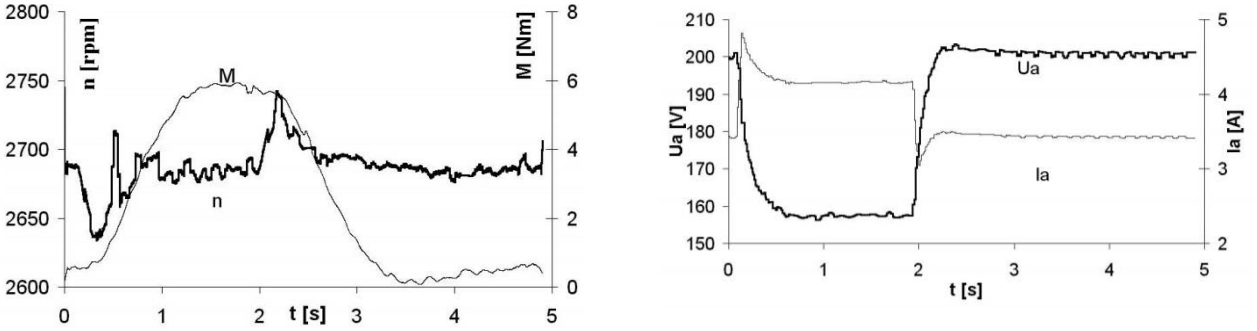


Fig.8-29. Connection and disconnection of the load R=50 Ohm (without voltage regulator).

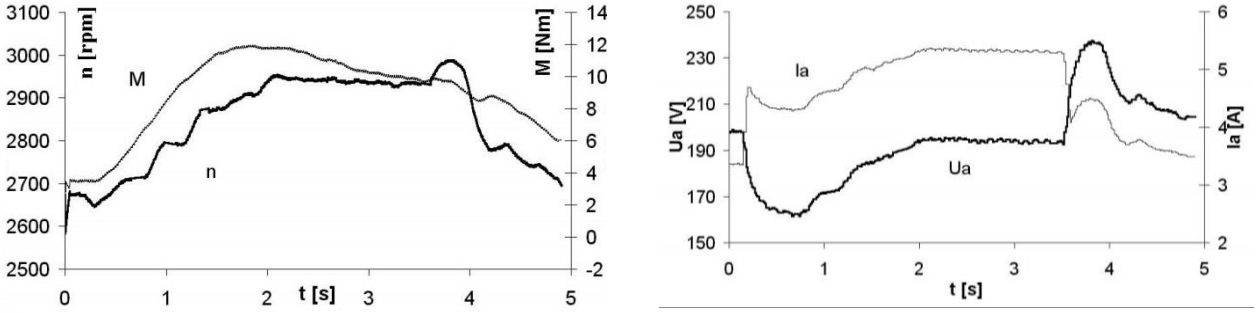


Fig.8-30. Connection and disconnection of the load R=50 Ohm. The voltage regulator increases the speed.

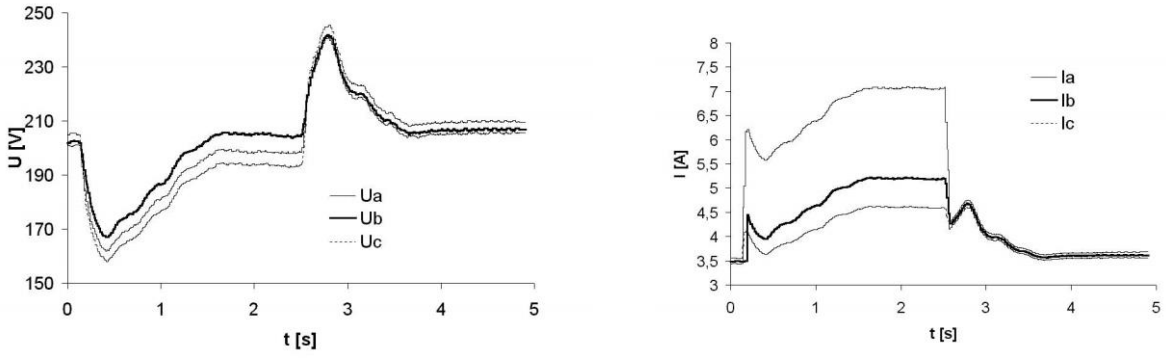
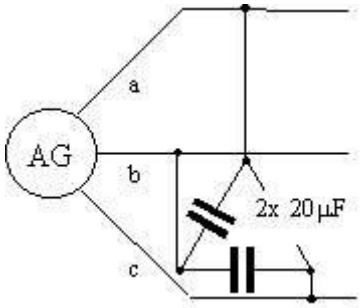


Fig.8-31. Unsymmetrical load R=25, 50, 100 Ohm (speed increases by voltage regulator).



In a state of emergency (one capacitor malfunctioning) it is impossible to load the generator via rated current. However, it is possible to load the generator by the lower power.

Fig.8-32. Emergency state – one capacitor malfunctioning and its disconnection.

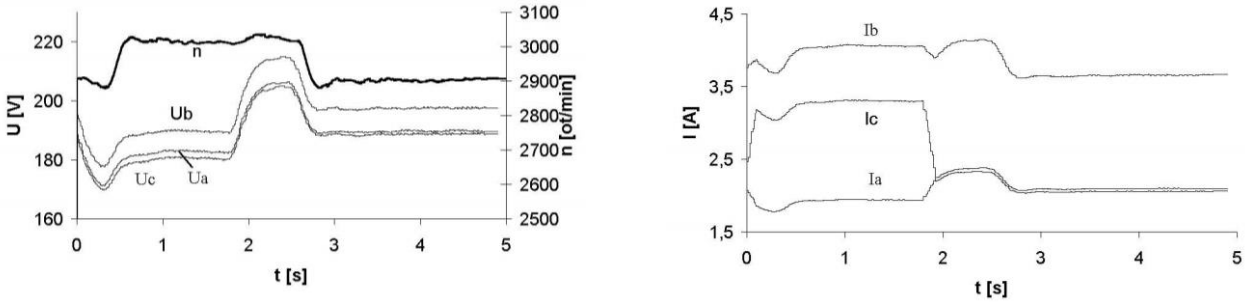
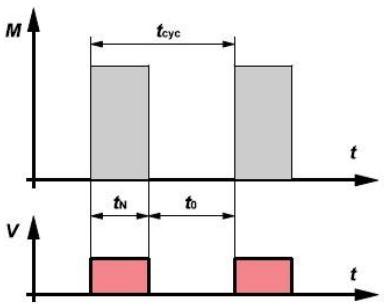


Fig.8-33. Connection and disconnection of the symmetrical load R=100 Ohm.

8.9 Thermal rating of switching duty

If the switching frequency exceeds a normal value (approximately 60 starting operations / hour as a guide), the additional thermal and mechanical load (depending on the type of power transmission) must be taken in the design of a drive.
Special abbreviated codes are used in EN 60034-1 to designate the switching duty. Duty type S3 designates no switching duty; it is used in the comparison to make a distinction from duty type S4.



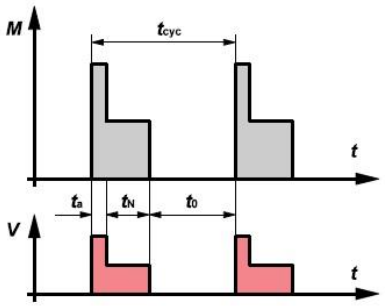
M	Load
V	Electrical losses
t	Time
t_{cyc}	Period of one cycle
t_N	Operation at constant load
t_0	Time at rest with de-energized windings

S3

Duty type S3 - Intermittent periodic duty
A sequence of identical duty cycles, each including a period of operation at constant load and a rest and de-energized period. In this duty, the cycle is such that the starting current does not significantly affect the temperature rise. The designation is S3, supplemented by the cyclic duration factor.

For example: S3 25 %

Fig.8-34. Duty type S3.



M	Load
V	Electrical losses
t	Time
t_{cyc}	Period of one cycle
t_N	Operating hours at constant load
t_0	Time at rest with de-energized windings
t_a	Run-up time

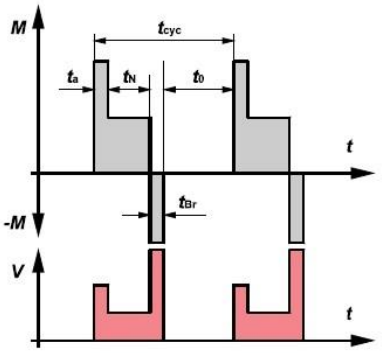
Cyclic duration factor
$= (t_a + t_N)/t_{cyc}$

S4

Duty type S4 - Intermittent periodic duty with starting

A sequence of identical duty cycles, each cycle including a significant period of starting, a period of operation at constant load and a rest and de-energized period. The corresponding designation is S4, supplemented by the cyclic duration factor, the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine, (J_{ext}), both in relation to the motor shaft.
For example:
S4 25 % $J_M = 0.15\ kgm^2$
$J_{ext} = 0.7\ kgm^2$

Fig.8-35. Duty type S4.



M	Load
V	Electrical losses
t	Time
t_{cyc}	Period of one cycle
t_N	Operating hours at constant load
t_0	Time at rest with de-energized windings
t_{Br}	Time with electrical braking

Cyclic duration factor
$= (t_a + t_N + t_{Br})/t_{cyc}$

S5

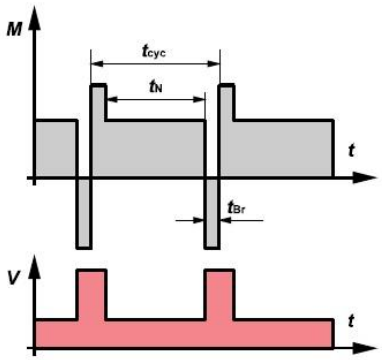
Duty type S5 - Intermittent period duty with electric braking

A sequence of identical duty cycles, each cycle consisting of a period of starting, a period of operation at constant load, a period of rapid electric braking and a rest and de=energized period.

The corresponding designation is S4, supplemented by the cyclic duration factor, the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine, (J_{ext}), both in relation to the motor shaft.

For example: S5 25% $J_M = 0.15\ kgm^2$ $J_{ext} = 0.7\ kgm^2$

Fig.8-36. Duty type S5.



M Load
V Electrical losses
t Time
t_{cyc} Period of one cycle
t_N Operating hours at constant load
t_0 Time at rest with de-energized windings
t_{Br} Time with electrical braking

Cyclic duration factor = 1

S7

Duty type S7 - Continuous-operation periodic duty with electric braking
A sequence of identical duty cycles, each cycle consisting of a period of starting, a period of operation at constant load and a period of electric braking. There is no rest and de-energized period. The corresponding designation is S7, supplemented by the mass moment of inertia of the motor (J_M) and the mass moment of inertia of the loading machine, (J_{ext}), both in relation to the motor shaft.

For example: S7 $J_M = 0.4\ kgm^2$
$J_{ext} = 7.5\ kgm^2$

Fig.8-37. Duty type S7.

Questions:



- *When does an IM start to operate as a generator on a network?*
- *Which relation "torque as depends on speed" has a fan or centrifugal pump?*
- *How can we change the dependencies in fig. 8-20 if we re-connect the IM from a delta to a star connection and network voltage has the same value?*
- *Compare the power losses (i.e., pink area, see fig. 8-22) during run-up, braking and reversing of an IM.*



Answers

- *When does an IM start to operate as a generator on a network?*

When the real part of the current starts to become negative, i.e., active power is sent back to the network.

- *Which relation "torque as depends on speed" has a fan or centrifugal pump?*

The relation is a relation of parabolic curve, i.e., $T=f(n^2)$.

- *How can we change the dependencies in fig. 8-20 if we re-connect the IM from a delta to a star connection and network voltage has the same value?*

The new dependencies have the same shape; however, the scale will be 3 times less.

- *Compare the power losses (i.e., area) during run-up, braking and reversing of an IM.*

When we assume the run-up (acceleration) power losses as 100%, then braking has a power loss of 300% and reversing 400%.

9 Torque Measurement



Estimated completion time: **90 min**

After studying the topic, you will be able to:

- *describe various types of torque sensors*
- *describe the inductive torsion sensor and sensors based on FSR*
- *describe the principle of operation of a rotary contactless accelerometer and its utilization for a dynamic torque measurement*
- *calculate the torque based on the current and flux measurement*
- *choose the suitable mechanical coupling*

Torque measurement is generally a very demanding task. The complexity lies both in the financial aspect and in the technical aspect.
Small machines are loaded at full power during the type test. The load shall be carried out by means of dynamometers or brakes, which operate on an eddy current principle.

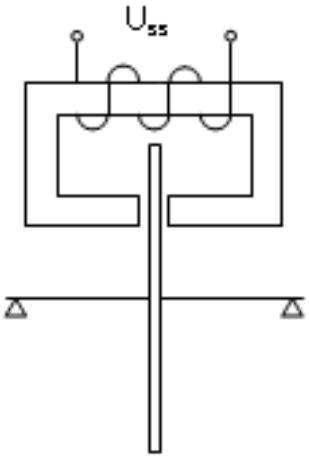


Fig. 9-1 Principle of eddy current brake.

A dynamometer can be used for single measurements. We connect the machine to a mechanical coupling with a dynamometer and thus we can drive or brake the machine, usually in both directions of rotation. We'll measure all four quadrants. The dynamometer can be a DC or AC machine. The measurement is suitable only for static torque characteristics, i.e., for steady states of the machine unit.

Next, we'll look at the torque torsion sensors. The machine to be tested shall be mechanically connected to the machine unit with the drive or braking machine. A torque torsion sensor is inserted between their couplings. This means two essential things: 1. extension of the installation length by inserted sensor and couplings, or even Cardan‘s shafts 2. Change (usually a decrease) of torsional stiffness of the machine unit with respect to a state when the machine unit is assembled without an inserted torsion sensor.

9.1 Inductive torque sensor

It is a contactless sensor operating on the principle of torsion dynamometer.

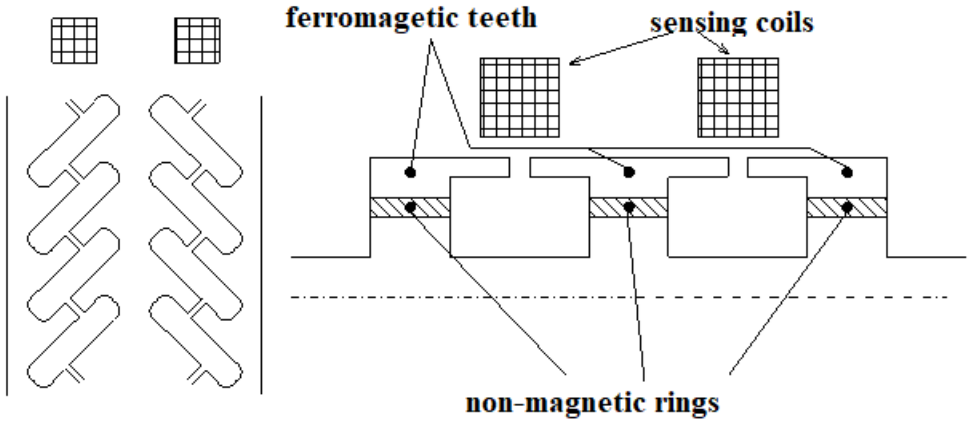


Fig. 9-2 Inductive torque sensor.

Rings are formed on the torsional stressed parts, which are fitted with non-magnetic material. On this non-magnetic insert, special tooth elements are attached. A pair of coils is located on the stator. These coils are enclosed in a ferromagnetic housing. If we feed the coils, the sleeve (not drawn) and the teeth flow the magnetic flux.

When the torsion part is stressed by torque, the air gap between the teeth changes (on one side increases and decreases on the other side), thus changing the inductance of the coils. The coils are connected to the bridge. This principle can be used up to about 4000 rpm.

The advantage of this type of sensor is the contactless transmission of torque information from the rotor to the stator. The disadvantage is the lower stiffness of the whole machine unit, due to the inserted torsion torque sensor. The sensor will be damaged in case of overloading more than 200% of the rated torque. Due to this fact we have to carefully measure transient phenomena and we should use a sensor with a high range. Likewise, the low torque in a steady state forces us to use a sensor with a low range because the sensitivity is better. As usual, the real range is a compromise.

9.2 Torque measurement by force sensitive resistors

Force sensitive resistors (FSR) may also be used to measure torque. They are fundamentally involved in bridges or half-bridges. In the extreme case, even a single force sensitive resistor can be used, connecting the "quarter-bridge".
Rings can be used to transfer contact information from rotor to stator. However, telemetry transmission is more modern and thus problems with powering the device on the rotating part are resolved.

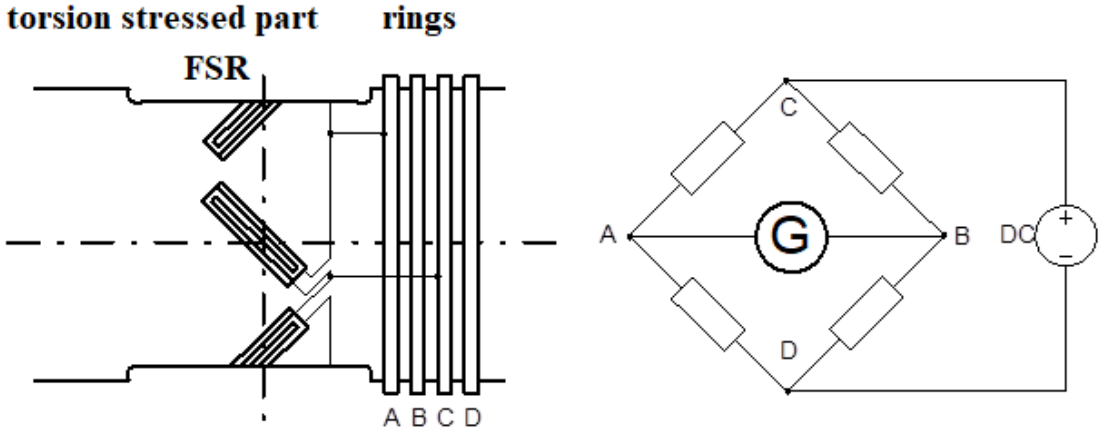


Fig. 9-3 Torque measurement by FSR.

A certain advantage of FSRs is the possibility of placing them on almost any part of the shaft. This does not change the torsional hardness of the machine unit. In the case of an inserted torsion sensor, the sensor is usually the least stiff part and this will affect the behavior of the machine (frequency of torsional oscillation), especially in transient states.

9.3 Torque measurement by rotary accelerometer

If we are satisfied with torque measurement only in transient states, a contactless rotary accelerometer can be used.

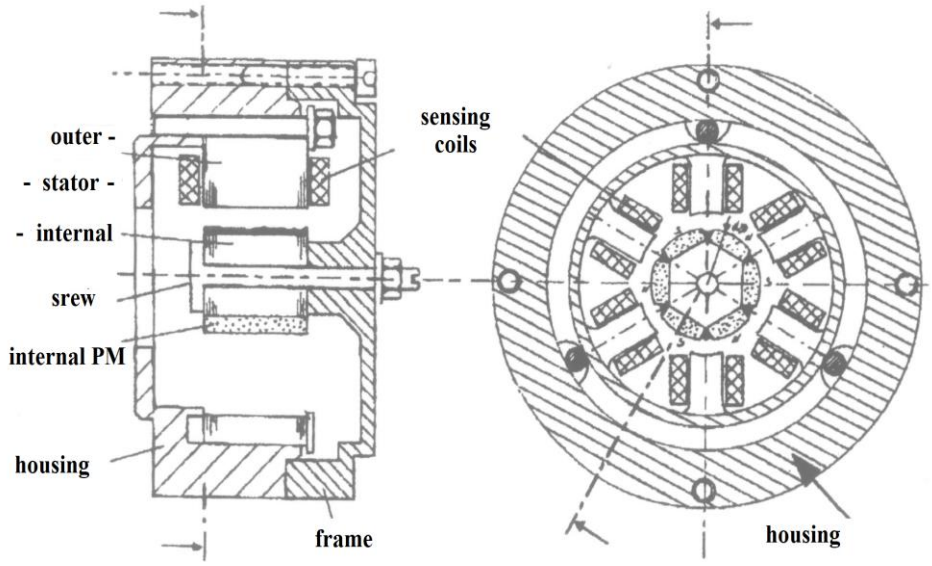


Fig. 9-4 Contact-less accelerometer.

The principle of operation of the accelerometer is simple. There are permanent magnets on the stator, which are the source of static magnetic flow. This is closed through an air gap in which the aluminium (brass) rotor rotates. The rotor is only a cylindrical shell, so its weight and moment of inertia are negligible. Eddy currents are induced in the rotor. These currents create a field that passes through stator sensing coils. If the rotor speed is constant, the size of the eddy currents are constant and no signal is induced into the sensing coils. However, when the rotor speed changes, the eddy currents change as well and the voltage is induced into the sensing coils on the stator. The signal is proportional to the acceleration of the rotor.

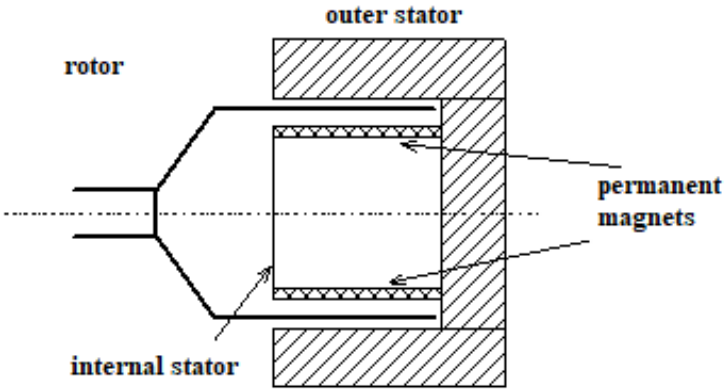


Fig. 9-5 Contact-less rotary accelerometer.

The rotor shall be mounted without bearings so that the measurement is a mirror image of the rotor's behavior and is not disturbed by a vibration, e.g., its own

bearing. When designing an accelerometer, it is necessary to look for a compromise between many, often conflicting, requirements.
If the moment of inertia on the measured shaft is known, it is possible to directly determine the torque from the acceleration according to the relation

$$M = J\frac{d\omega}{dt}. \tag{9.1}$$

The main advantage of this measurement with respect to the method described in chapter 9.1 are unlimited torque, unlimited moment of inertia (i.e., size of the machine) and almost unlimited speed. The disadvantage is impossible torque measurement at a steady state. Nevertheless, thanks to suitable arrangements we can also minimize disadvantages.

9.4 Torque determination based on mutual flux

The moment can also be determined based on the relation

$$M_e = \frac{2}{3\sqrt{3}}[\psi_a(i_b - i_c) + \psi_b(i_c - i_a) + \psi_c(i_a - i_b)], \tag{9.2}$$

Where ψ … coupled magnetic flux
i … phase current

The measurement of phase currents usually does not cause serious problems. However, determining the coupled flux may be more difficult.
The flux can be approximately determined by, for example, integrating the terminal voltage. Moreover, if we can determine the voltage drop on the resistance of the winding from the passing current, we will receive relatively good results.
The advantage is usability on any machine, without additional modifications.
Special measuring coils, located in slots as close as possible to the air gap, allow us for more precise flow determination.

9.5 Mechanical coupling for torsion sensors

In particular, torsion torque sensors must not be stressed by anything other than the torsion forces. Any other stress would result in lower measurement accuracy or, as a worst case, permanent damage to the sensor. It can be used to compensate for small misalignments of connected shafts with the advantage of special flexible couplings. However, these couplings, despite their elasticity, must have a high torsional strength to avoid interference of the measurement.
Flexible couplings consist of two hugs and a flexible member. Couplings tolerate shaft misalignment in different directions. The flexible member is realized as a wavy cell, membranes or as a polyurethane star.

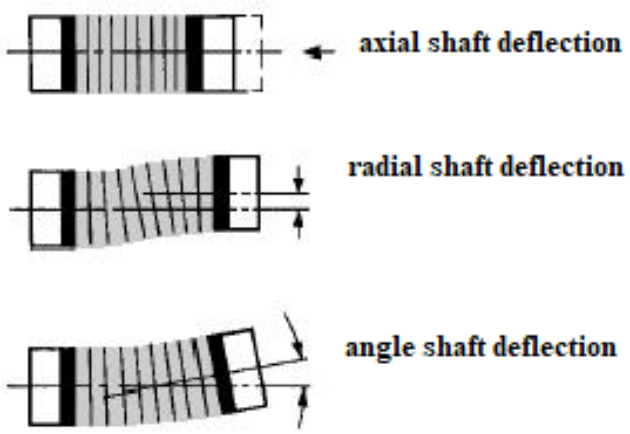


Fig.9-6 Possible types of shaft misalignments. Can be different in both vertical and horizontal directions.

Rated torque [Nm]		5	60	450
Wavy cell coupling	Radial [mm]	0,15	0,20	0,30
	Axial [mm]	1	1,5	2,5
	angle [°]	-	-	-
Coupling with polyurethane star	Radial [mm]	0,08	0,12	0,20
	Axial [mm]	1	2	2
	angle [°]	1	1	1

Fig. 9-7 Examples of allowed misalignments.

The wavy coupling is made of stainless steel forming. It's welded to the hugs. The diameter of the wavy belly affects the transmitted moment. By selecting its length, you can select torsional stiffness and influence the self frequency of the coupling with the attached moment of inertia. The wavy coupling can deform in length, angle and laterally, so it compensates for misalignment in all directions up to the limit tolerances. Miniature couplings are used to connect small motors and incremental position sensors. Large couplings up to 5kNm compensate for the static uncertainty of the connection.

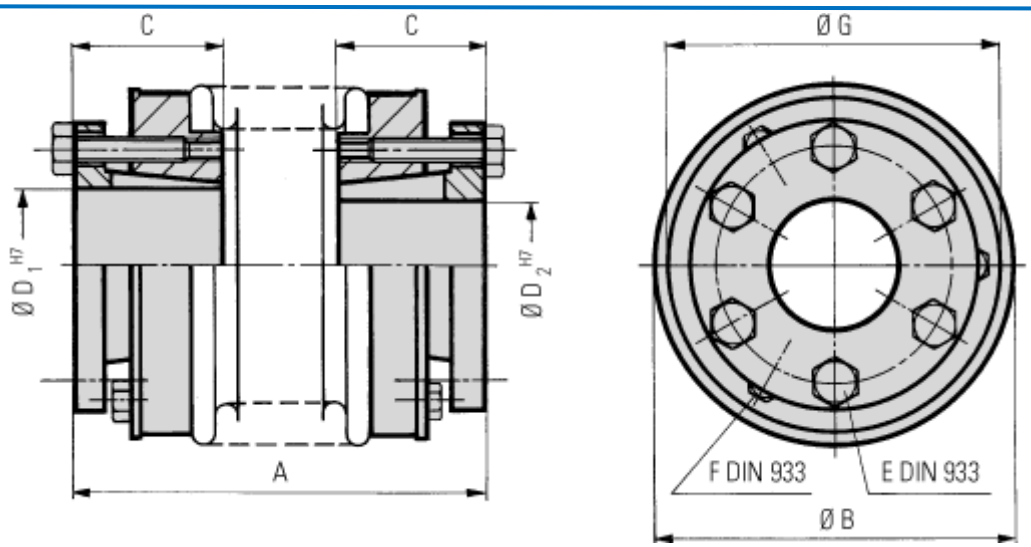


Fig. 9-8 Flexible wavy-coupling with tapered shaft seal.

The polyurethane star is squeezed between the shoulders of the straps with its shoulders. The hardness of the polyurethane associated with the strength reduces the transmitted torque. By selecting hardness, torsional solidity can be selected and the actual frequency of the joint with the attached inertia can be influenced. The star can deform in length, angle and laterally, so it compensates for misalignment in all directions up to the limit tolerances. However, it does not hold the hugs in the axial position. The hugs can be assembled out of the star or reassembled during installation.

The star is deformed during torsion surges and fits by squeezing the length of the arms. The arms are pressed radially inwards to the axis by the adjacent sides of the hugs, so the torsional hardness also depends on the design and cross-section of the inner ring of the star. The deformation energy of the star causes shock absorption, which can be used to optimize the stability of the drive control loop.

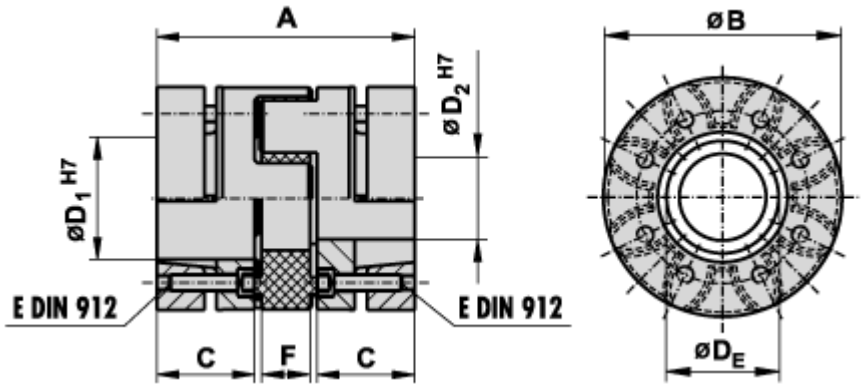


Fig. 9-9 Flexible coupling with polyurethane star.

The clamps of small couplings from the outer diameter of 10 mm are fixed to the shaft by set screws, larger ones are radially and axially cut and are tightened with a

tangential screw. The 500 Nm largest torque drawers have conical cut ends that are pulled to the shaft by a changing ring with axial screws.

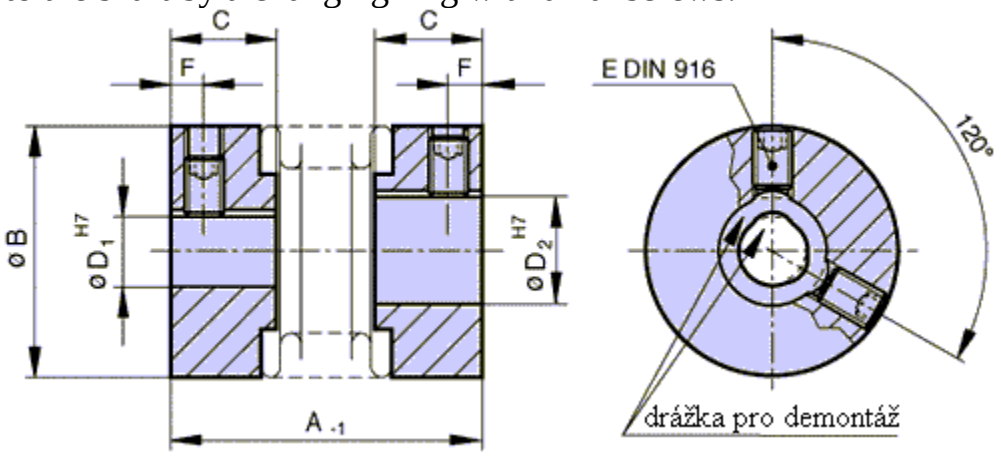


Fig. 9-10 Flexible miniature coupling with set screws for incremental sensors.

Couplings are recommended especially for "fine design elements", e.g. incremental rotor position sensors. Such a sensor shall not be stressed either by the hardness or weight of the connection cable. The permissible radial stress of the sensor shall is several Newtons. However, even at a weight of only a few hundred grams of the sensor's own, these forces are achieved at very low misalignment. It depends, of course, on the rated speed of the machine.

Questions:

- *What type of machine is the dynamometer?*
- *Is it recommended to recuperate the energy back to the network during machine loading?*
- *Which typical overloading has a torsion torque sensor?*
- *Which material is suitable for a rotor of rotary accelerometer?*

Answers

- *What type of machine is the dynamometer?*

The dynamometer is an AC or DC machine.

- *Is it recommended to recuperate the energy back to the network during machine loading?*

Energy recuperation is highly recommended, especially for large machines.

- *Which typical overloading has a torsion torque sensor?*

Typically about 200%, then permanent distortion occurs.

- *Which material is suitable for a rotor of rotary accelerometer?*

Extremely homogenous brass or aluminum, without any cracks.

10 Speed Measurement



Estimated completion time: **75 min**

After studying the topic, you will:

- *know the difference between the tachodynamo and tachogenerator*
- *know methods of measuring rotary speed*
- *be able to describe the principles of incremental encoders and absolute encoders*
- *be able to generate the Gray-code*
- *know the principles of resolvers*
- *know the hand tachometer features*

In the field of electric machines, it is necessary to measure not only the speed of the rotor, but sometimes also its position. In the case of linear machines, it is necessary to measure the linear speed of movement instead of the speed of rotation. Similarly, it is necessary to measure the linear position of linear rotors.
The methods described below will focus on rotational speed. However, they can be adapted and used for linear speed and position measurements as well.

10.1 Tachodynamo

The tachodynamo is a direct-type velocity transducer. It is essentially the opposite of an electric motor since its input is a rotating shaft and its output is a voltage U_o proportional to the input angular velocity ω_s:

$$U_0 = k_t . \omega_s \qquad (10\text{-}1)$$

The constant of proportionality k_t is generally linear within a large dynamic range but does vary in relation to:

- load current
- maximum input velocity
- temperature

These variations are usually amply documented in the manufacturer data sheets and do not present a problem. The following figure shows a typical relationship between U_o and ω_s for different load resistors, i.e., internal resistivity of V-meters.

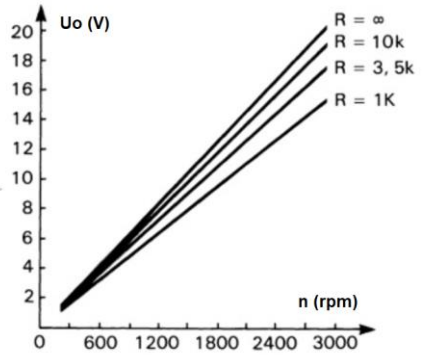


Fig.10-1. Typical transfer characteristic of tachodynamo.

Direct proportionality is ensured by excitation by a permanent magnet. For example, the tachodynamo constant is given as 20V/1000 rpm.
The tachodynamo must be mechanically connected with the machine being measured in such a way that the rubber tip of its shaft does not slip through the recess on the shaft of the measured machine.
The voltage output of a tachodynamo shall not be loaded with a higher current than 20 mA. Robust tachodynams are used in heavy industrial plants (rolling mills, smelters) to be resistant to rough handling.

10.2 Tachogenerator

The tachogenerator operates on a similar principle to tachodynamos but does not have an output commutator so its output is AC voltage. The frequency is proportional to the speed. The voltage is also proportional to the speed.

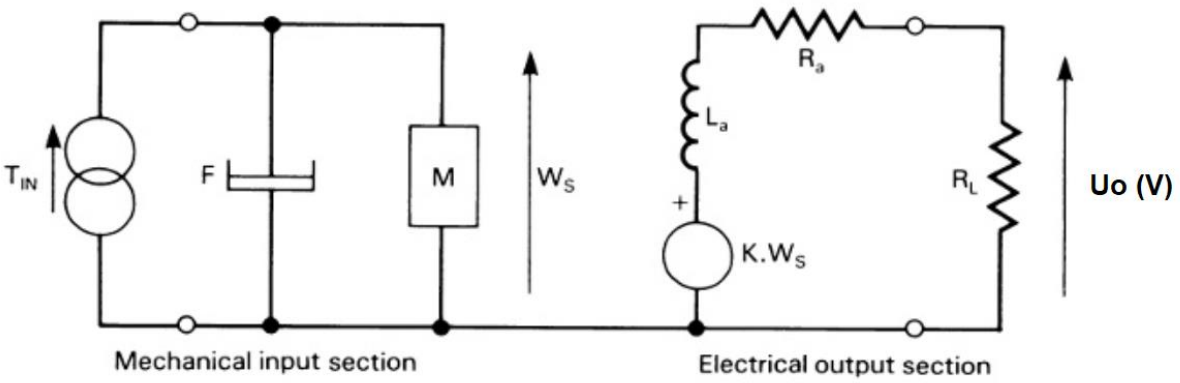


Fig.10-2. Typical transfer characteristics of a tachodynamo.

As we can see on the equivalent chart, the output section contains the inductor. The inductor has a reactance

$$X_L = L_a.\omega \quad = L_a.2\pi f \qquad (10\text{-}1)$$

Although the load current is very small, the voltage drop on the reactance will change with the frequency. Therefore, it is preferable to measure the output frequency by the counter than to have a voltmeter at the tachogenerator output and measure the voltage.

Please note that the counter input must have a voltage range adapted to the voltage corresponding to the highest possible speed.

10.3 Incremental rotary sensor

The incremental rotary encoders IRC with an LED as the light source in the standard industrial version converts rotary motion to electrical signals by the photoelectronic scanning of rasters onto two glass elements [stator and rotor]. Electrical signals provide information about the bilateral position of two mechanical parts, angle turn or rotary motion. Common use of the IRC encoders is in connection with display units or numerical control systems on machine tools or robots. They are excellent for applications in other equipment where measuring accuracy and reliability are required.

The number of impulses per rotation are usually 100, 200, 250, 360, 500, 512, 1000, 1024, 1250, 1500, 2048, 2500, 3600, 4096, 5000 and 6000 with one zero impulse per rotation. For reasons of possible FFT transformation, it is advantageous to have the number of pulses equal to the power of two.

Of the incremental type, there are three phase outputs of A-phase, B-phase, and Z-phase, and the A-phase and the B-phase create the output pulses that accompany rotation like
"H(High) → L(Low) → H→L→…".
It is possible to discriminate the direction of rotation of the phase difference between the A and B phases, and the number of pulse counting enables for the calculation of the rotation amount.
That is to say, this is a method of counting the relative movement amount from a certain position, and to define the position "0" which is the starting point of the count, the Z-phase is used with outputs once per each rotation.

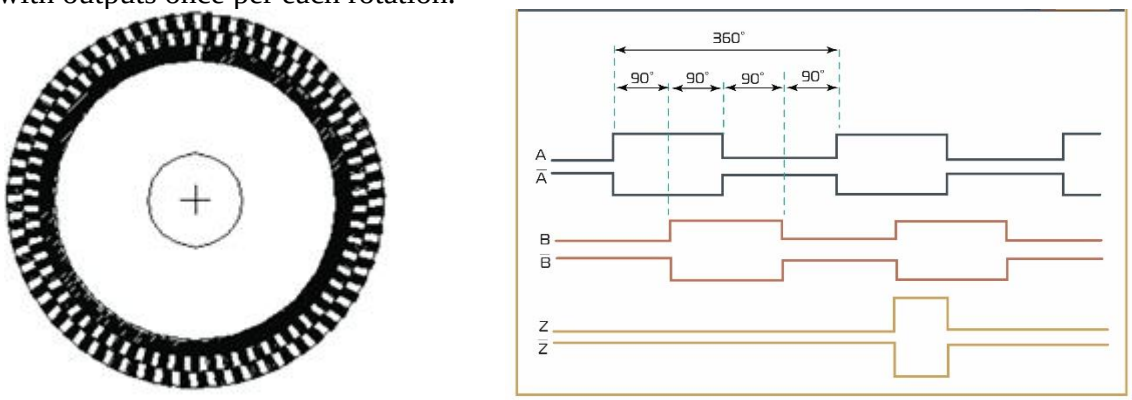


Fig.10-3. Incremental encoder with three output channels. The additional three negative channels $\bar{A}, \bar{B}, \bar{Z}$ are useful.

Advantages

- Low cost compared to the absolute type
- The simple signal processing composed of the rotation direction discrimination and the counters
- Easy to handle as it is compatible with different makers' incremental encoder

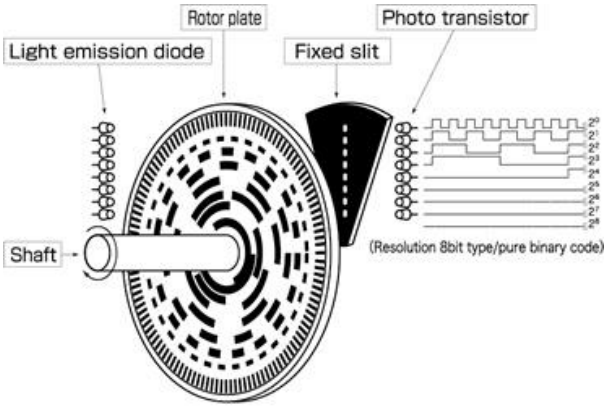
Disadvantages

- When starting up the equipment, one must always perform the zero-return action of the encoder

- If the succeeding equipment miscounts due to noise or the like, the count value cannot be corrected AND the positional data will remain incorrect

10.4 Absolute encoder

An absolute type outputs the absolute position of the rotation angle. Therefore, the reset action task was not required at the machine startup and the angular position can quickly be detected automatically. Also, even if the shaft of the absolute encoder has rotated during the time that the equipment was turned off, the angular position is detected correctly when the power is turned on again.



Digital Output

0000000000
0000000001
0000000010
-
-
1111111101
1111111110
1111111111

Fig.10-4. Absolute encoder simplified structure and its digital output.

The absolute type has the following advantages / disadvantages.

Advantages

- Because of the detection of the absolute position of the rotation angle, the machine can be started immediately without any reset actions as needed with the incremental type
- Even if there are measurement errors that occur as caused by things such as outer noise, angle reading error does not accumulate because of the detection of the absolute position and therefore the reliable angle position can be detected

Disadvantages

- Because of its complicated structure in comparison to the incremental encoder, the price of the absolute encoder is higher than that of an incremental encoder

10.5 Gray code

Gray code is also known as reflected binary code because the first (n/2) values compare with those of the last (n/2) values, but in reverse order.

This code has also come to be known as mirror code. Both of these names, reflected binary code and mirror code, stem from its mirror-reflection property. The main features of the Gray code are:

• It is a binary code just like the conventional binary code
• The code can be constructed using its mirror-reflecting property
• Adjacent numbers of the code differ in one bit-position only. This is illustrated in Table 10-1, which shows entries of decimal numbers 0 to 4, and their equivalents in the conventional binary and the Gray-code binary. In columns 2 and 3 of Table 10-1, we have highlighted the

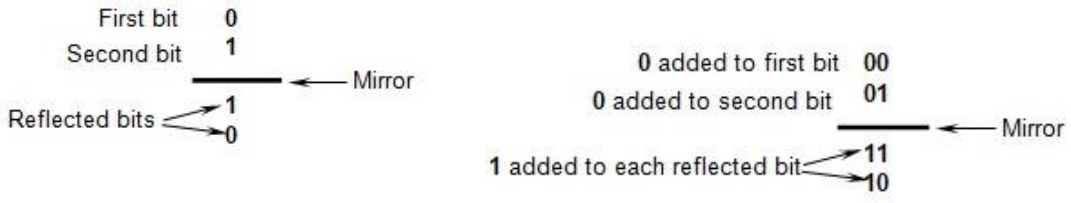
positions in which adjacent numbers differ from each other using bold fonts. It can be seen from column 2 that adjacent numbers in conventional binary may differ from each other in one or more one bit-positions. For example, 0011 (= 3) and 0100 (= 4) differ from each other in three bit-positions.
Now, inspection of column 3 of Table 10-1 shows that adjacent numbers in the Gray code differ from each other only in one bit-position. For example, 0010 (= 3) and 0110 (= 4) differ from each other only in the second bit-position from the left. This important property of the Gray code has many practical applications. The foremost among these is its use in logic simplification using the K-map and Quine-Mccluskey methods. It also finds extensive use in error-detection and correction codes.

Tab. 10-1 Decimal, conventional binary and Gray-code numbers.

Decimal number	Conventional binary equivalent	Gray-code equivalent
0	000**0**	0000
1	000**1**	000**1**
2	00**10**	00**1**1
3	001**1**	00**1**0
4	0**100**	0**1**10

Construction of the Gray code

The Gray code can be constructed by its mirror-reflection property. For example, a two-bit Gray code can be constructed as illustrated below. First we write 0 and then immediately below it write 1. Then we draw a horizontal line below bit 1 and then write the bits 1 and 0 below this line in that order, assuming the horizontal line to act as a mirror. Thus, we get the structure shown in Fig. 10-5a.
Now, add one 0 each to the bits above the mirror-line and one 1 each to the bits below the mirror-line as demonstrated in Fig. 10-5b. Table 10-2 shows the 2-bit Gray code after removal of the mirror.



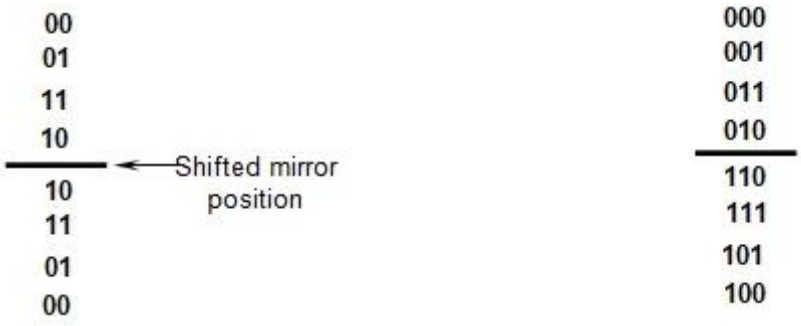
a) b)

Fig.10-5. a) Preliminary step b) Final construction of two bit Gray-code.

Tab. 10-2 Two-bit Gray -code.

Decimal number	Conventional binary equivalent	Gray-code equivalent
0	0**0**	00
1	0**1**	0**1**
2	**10**	**11**
3	1**1**	1**0**

The principles used in the construction of a 2-bit Gray code may be extended to get any n-bit (where n is a power of 2) Gray code. Figure 10-6(a) and (b) show the construction of a 3-bit Gray code. As in the 2-bit case, in the case of a 3-bit Gray code, we shift the mirror to the new position below 10 and write the reflected code words below the mirror as shown in Fig. 10-6(a). After writing the reflected code words, as in the previous case, we add one 0 to each of the code words above the mirror one 1 to each of the code words below the mirror as shown in Fig. 10-6(b). Table 10-3 shows the actual form of the 3-bit Gray code, after the removal of the mirror. Extending the principles, we draw the 4-bit Gray code as shown in Table 10-4. It may be noted that the Gray code is not a weighted code. But it finds applications because of its third feature. This reduces the risk of hazardous effects in electronic switch circuits.



a) b)

Fig.10-6. a) Mirror shifted to new position b) 0s added above and 1s added below the mirror.

Tab. 10-3 Three-bit Gray -code.

Decimal number	Conventional binary equivalent	Gray-code equivalent
0	000	000
1	001	001
2	010	011
3	011	010
4	100	110
5	101	111
6	110	101
7	111	100

Tab. 10-4 Four-bit Gray -code.

Decimal number	Conventional binary equivalent	Conventional hexadecimal code	Gray-code equivalent
0	000**0**	0	0000
1	000**1**	1	0001
2	00**10**	2	0011
3	001**1**	3	0010
4	**0100**	4	0110
5	0101	5	0111
6	0110	6	0101
7	0111	7	0100

8	1000	8	1000
9	1001	9	1001
10	1010	A	1011
11	1011	B	1010
12	1100	C	1110
13	1101	D	1111
14	1110	E	1101
15	1111	F	1100

10.6 Resolver

The resolver is a rotary transformer used for conversion of the angular position of the shaft into Cartesian coordinates. It is an analogue device which has a digital counterpart. The output of the transducer has two signals, one is proportional to the sine of the angle and the other is proportional to the cosine of the angle.
A resolver uses the same basic physical principles as an electrical transformer. Resolvers typically use copper windings in its stator and a machined metal rotor. Their construction is similar to the two phase two pole wound induction motor. The inductive coupling between the windings varies according to the angular position of the rotor.
For the position evaluation, Resolver-to-Digital Converters are commonly used. They convert sine and cosine signals to binary signals (10 to 16 bits wide) that can more easily be used by the controller. Basic resolvers are two-pole resolvers, meaning that the angular information is the mechanical angle of the stator.

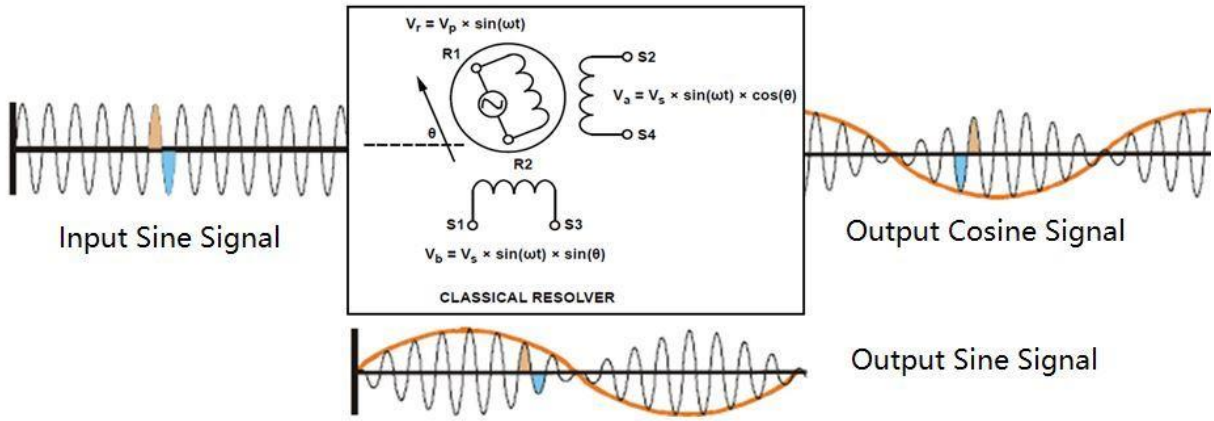


Fig.10-7. Principle of resolver internal connection.

10.7 Hand digital photo tachometer

A hand tachometer is an instrument for temporary measurement of the rotational speed. It should be equipped with a laser pointer. An IR or photo diode is used as a speed sensor. Aside from the rotation speed, it is possible to measure the liner speed and length (distance).

Typical features:
No contact
Wide range from 2,5 rpm to 100 000 rpm

High resolution 0,1 rpm or 1 rpm
Record max, min, last value
Measuring distance 50-500mm



Fig.10-8. Combination of contact and non-contact tachometers.

Contact rpm is used to measure the speed of rotating motors, shafts, pulleys, gears, etc. Non-contact rpm is used if contact measurement is not possible due to access space restriction, safety concerns etc. Linear speed and length is used for moving surfaces, such as conveyor belts, printed materials, webs of fabric or paper, etc.

Questions:

- *What is the speed of the motor when the tachodynamo has a terminal voltage of 30VDC and its constant is 20V/1000rpm?*
- *What is the speed of the motor when the tachogenerator has a number of pole-pairs p=8 and its voltage frequency is f=400Hz?*
- *If an incremental sensor has 1024 pulses/rev, what is the rotor speed when the measured output frequency is 50 kHz on channel $\bar{B}$?*
- *If an incremental sensor has 1024 pulses/rev, what is the rotor speed when the measured output frequency is 500 Hz on channel $\bar{Z}$?*
- *When the control unit of an absolute encoder loses the power supply voltage, must the drive make an initial revolution?*
- *What is the benefit of the Gray-code?*
- *What are non-weighted binary codes?*

Answers

- *What is the speed of the motor when the tachodynamo has a terminal voltage of 30VDC and its constant is 20V/1000rpm?*

The motor speed is n=30V / 20V x 1000rpm = 1500 rpm.

- *What is the speed of the motor when the tachogenerator has a number of pole-pairs p=8 and its voltage frequency is f=400Hz?*

Mechanical rotating frequency is 8 times lower than the electrical frequency, i.e., f_{mech}=400 / 8

= 50 Hz. Angular mechanical frequency $\omega=2\pi f_{mech}=314$ rad.s^{-1}. Speed n=30 x ω / π = 3000 rpm.

- *If an incremental sensor has 1024 pulses/rev, what is the rotor speed when the measured output frequency is 50 kHz on channel $\bar{B}$?*

The mechanical rotating frequency is 1024 times lower than the electrical frequency, i.e., f_{mech}=50 000 / 1024 = 48,82 Hz. Angular mechanical frequency $\omega=2\pi f_{mech}=306,64$ rad.s^{-1}. Speed n=30 x ω / π = 2928 rpm.

- *If an incremental sensor has 1024 pulses/rev, what is the rotor speed when the measured output frequency is 500 Hz on channel $\bar{Z}$?*

Channel "Z" has 1 pulse per revolution, independently on the number of pulses on channel A or B. Mechanical rotating frequency is equal to the electrical frequency, i.e. f_{mech}=500 Hz. Angular mechanical frequency $\omega=2\pi f_{mech}=3141,5$ rad.s^{-1}. Speed n=30 x ω / π = 30 000 rpm.

- *When the control unit of an absolute encoder loses the power supply voltage, must the drive make an initial revolution?*

No, it is not necessary. The absolute encoder has actual data of rotor position on its output.

- *What is the benefit of the Gray-code?*

Low risk of hazards in counters. Only one bit is changing between two steps of position.

- *What are non-weighted binary codes?*

In these codes each decimal digit is represented by a group of four bits. In this type of binary code, the positional weights are not assigned. Examples of non-weighted codes are Excess-3 code and Gray code. The Excess-3 code is also called as XS-3 code.

11 Quenching Choke Testing



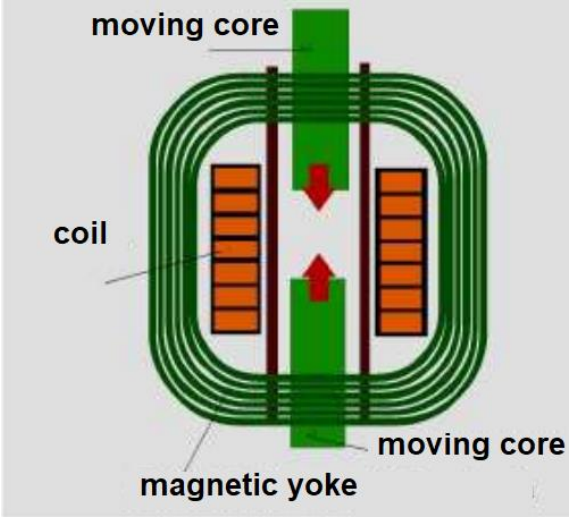
Estimated completion time: **90 min**

After studying the topic, you will be able to:

- *describe quenching choke construction and operation*
- *describe the quenching choke internal connection*
- *specify the name plate parameters*
- *describe the first and second test*
- *describe the regulation measurement*
- *describe the dielectric test*
- *describe the noise measurement*
- *describe the winding insulation resistance measurement*

11.1 Principle of operation

The quenching choke is a coil with adjustable inductance, it connects to the neutral distribution network node.
It is used to compensate for capacitive currents during ground connection. The quenching choke allows compensation for the capacitive current of the ground connection so that the fault point only passes a small residual current.



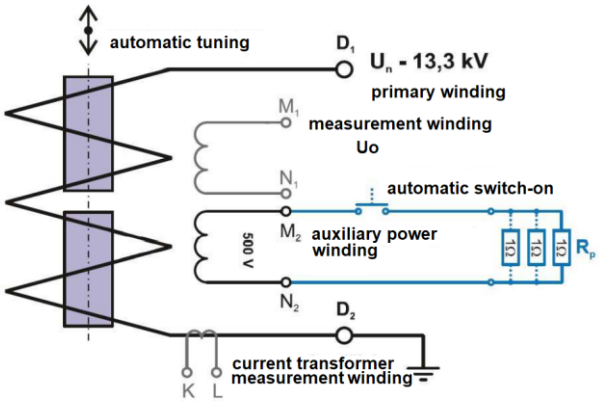


Fig. 10-1 Principle of quenching choke and its internal connection. [11]



Fig. 10-2 Quenching choke overview. [11]

11.2 Name plate parameters

A label must be located on the surface of each choke, visibly placed and containing the following data.

- Choke type
- Indoor / outdoor location
- Number of the part of international standard IEC 60076
- Name of producer
- Serial number
- Year of production
- Insulation level
- Number of phases
- Rated frequency
- Highest voltage for equipment
- Rated continuous current (if possible)
- Rated thermal short circuit current (if possible)
- Rated mechanical short circuit current (if possible)
- Rated short-time current and its duration or duty cycle (if possible)
- Impedance under rated continuous current for a 1ph and 3ph excitation (if possible)
- Impedance under rated short-circuit current, calculated or measured value
- Cooling type
- Total mass
- Mass of active parts
- Mass of insulation liquid
- Type of insulation liquid
- Scheme of connection with taps and instrument transformers

11.3 First test – active part only

This test is performed without oil. This test consists of:

- Checking the instrument transformers voltage / current
- Checking current joint
- Visual checking
- Regulation characteristic measurement – from minimum to maximum current under rated voltage in several steps of regulation range. It is measured:
  - the size of air gap
  - current
  - current of the instrument transformer (check the transformer precision)
  - power losses
  - voltage and its tolerance M1, N1 (V)
  - voltage and its tolerance M2, N2 (V)
  - level of acoustic pressure (dB)

11.4 Winding resistance

It is measured by DC current, 4-wires Ohms method for small resistances. The temperature is also measured.

11.5 Parameters measurement during the whole regulation range

This is a second test, which is already performed with oil. The whole choke must be filled with all accessories as will be used in the industry. This test measures:

- voltage on the main winding
- current of the main winding. The current is measured by two instruments- one is testing a calibrated voltmeter and the second is located directly inside the oil tank
- Voltage on the auxiliary winding
- Voltage on the measurement winding
- Power losses
- Output of the potentiometer as depends on the current value setting

All chokes are continuously adjustable inductances. In the regulatory test, the current in the choke is therefore measured at the rated voltage and frequency, this measurement must be carried out in at least five positions on a regular basis throughout the choke range. The potentiometer also stores the value at each position. First, the value of the entire range of the potentiometer is measured.

During the regulatory test, both pathways of the resistance of the potentiometer values are measured and then written to the output protocol.

- Voltage ratio measurement between main and auxiliary winding and main and secondary winding
  - Voltage ratio between the main and auxiliary winding – the helping winding is usually designed to 500V and a tolerance of +/-10% is allowed
  - Voltage ratio between the main and measurement/secondary winding – this winding is usually designed to 100 or 110V and a tolerance of +/-10% is allowed

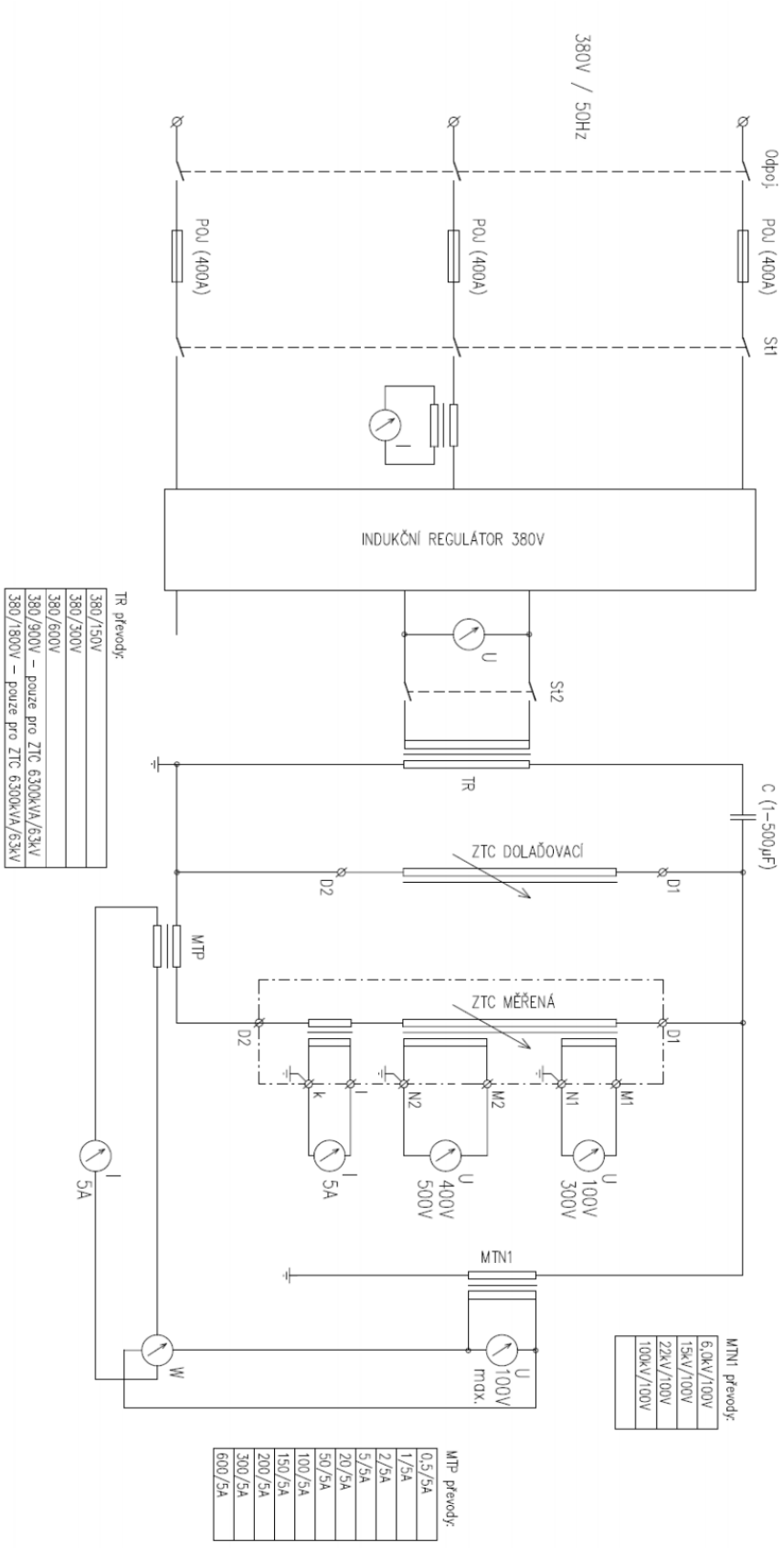


Fig. 11-1 Chart of connection during the choke test. [11]

- Power losses are measured at rated continuous current and rated frequency and reference ambient temperature. Measurement should be done at any current. Recalculation of rated value is done by multiplication of the ratio of the square rated current and testing current. All accessories must be mounted.

11.6 Dielectric tests

- Winding test by applying AC voltage (1 minute)

The test shall be carried out by a single-phase AC voltage, preferably with a perfect sine wave shape and not less than 80% of the rated frequency. The test shall begin at a voltage not more than one third of the prescribed test value test voltage and voltage must be increased to the test value as quickly as possible with respect of the measurement instrument. Before switching off, the voltage must be reduced to less than one third of the testing voltage. The voltage level during the test, accompanied by the alternating endurance voltage, is determined by the insulation level of the zero-point terminal, i.e., on the winding with reduction of insulation, the value of the control test voltage according to the insulating level of the outlet insulator D2. The phase terminals are then tested by AC endurance voltage.

The full test voltage must be applied to the main winding for a period of 60 seconds. The main winding D1, i.e., the phase terminal and the N terminal are connected. Other terminals - auxiliary and measuring coils and current transformer – are connected and grounded.

The test shall be considered successful if the test voltage does not fall down to zero.

- Winding test by induced AC voltage (1 minute)

This test is relevant for reduced winding insulation, where the insulating level of the outlet insulator D1 is dimensioned to a different value than the outlet insulator D2.

The winding cannot be tested with the full AC voltage applied. This test cannot verify the full insulating strength of all parts of the choke against the ground potential. However, turn to turn insulation is tested.

During the test, secondary auxiliary winding is supplied by sine wave voltage with the frequency up to 220Hz. The magnetizing current at the prescribed test voltage is not greater than the no-load current at the operating frequency. The required test voltage is then measured on the terminals of the main winding. According to the standard, the test time is set at 60 seconds. The frequency is less than twice of the operating frequency. If the test frequency exceeds twice the nominal frequency, the test frequency shall be timed in seconds, recalculated by the relationship:

$$\text{Time(s)} = 120.(f_n/f_{test}), \text{ min } 15\text{s.} \qquad (11.1)$$

For example, when we take a testing frequency 200Hz, the time of the test is 30s.

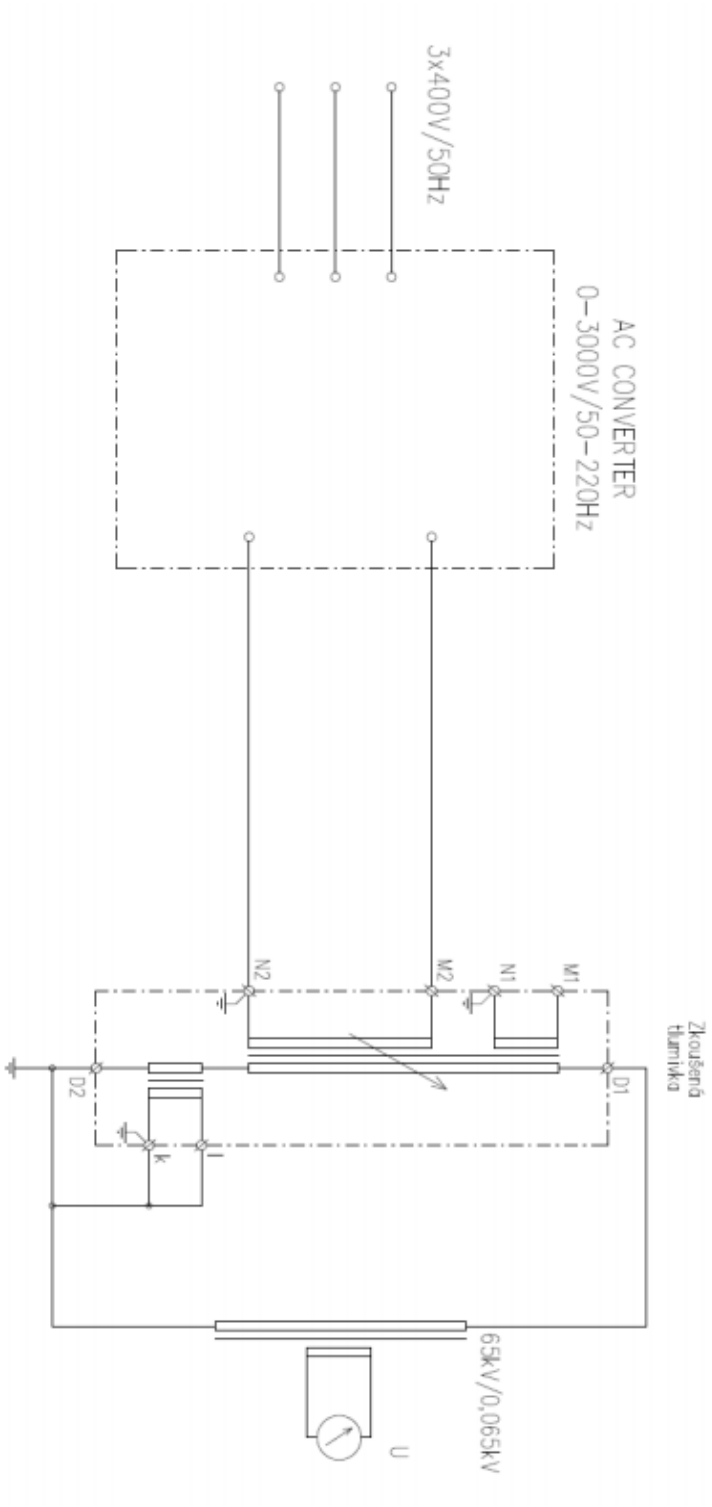


Fig. 11-2 Chart of connection during the choke test. [11]

11.7 Dielectric strength of oil

Sampling is carried out according to the CSN EN ISO 60247, CSN EN 60567 and CSN 656005 standards. After running about 3 liters of oil we put a representative sample of oil directly into the measuring vessel with electrodes. A quantity between 0.25-1.5 liters is taken. The container must be clean, rinsed several times by the tested oil, and sampling must be carried out as quickly as possible. When collecting, let the oil flow down on the wall of the vessel, it must not foam and displace the air, fill the containers to the brim with the oil pollution. The temperature of the oil tested is about 20 +/- 4 °C.

- Voltage breakdown of oil

The electrode distance is 2,5mm. We let the sample rest about 20 minutes. Then we perform the test 6 times at time intervals of 6 minutes with an oil temperature of 20 °C. From the 6 values of voltage breakdown value we calculate the average value.

- Water content

The determination of the water content of the oil is carried out by a modified method of titration according to K. Fischer on a coulometric device WTK according to ČSN EN 60814. To measure, remove a sample of oil at the same time as the sampling for measuring electrical strength in the quantity of 2 ml. After specifying the weight of the sample, the apparatus shall directly evaluate the water content of the g/t oil.

Parameter	Unit	Value
cleanness	(-)	Crystal clear
Density at 20°C	Kg/m^3	Max. 895
No. of acidity	mgKOH/g	Max 0,03
Dielectric breakdown voltage	kV/2,5mm	Min.30
Losses coefficient at 90°C	mN/m	Min. 48
Water content	g/t	Max. 30

Fig. 11-3 New oil parameters (worst case).

11.8 Level of noise

This measurement is carried out according to ČSN EN 60076-10. This standard is the Czech version of the European standard EN 60076-10:2001 and sets out a method for measuring the noise level on the measuring surface surrounding the

noise source, in conditions prevailing in the free area on one or more reflective planes.

Noise measurements according to this standard should be carried out on a flat outdoor area or in the case of a testing laboratory which fulfills background noise conditions and test environment conditions. During the measurement, the ambient temperature must not be changed by more than +/-10 K and relative humidity by +/-15%.
The LT Luxtron SL-4011 noise meter is suitable for measurement in the testing room. The noise meters must be calibrated and tested every two years by a laboratory carrying out calibration in accordance with current standards.

The measuring plane is given by the standard. This is valid for a quenching choke only. This plane is 0.3 m from the choke surface. If the choke has a maximum high of less than 2,5m, the horizontal plane is in the middle high of the container. In the choke with a height ≥2.5 m, two horizontal planes are at one third and two-thirds of the height of the choke.
Microphones must be placed on the measuring plane at approximately the same distances. The maximal distance between two adjacent microphones should not be more than 1 m. There must be at least 6 microphone stations.

11.9 Winding insulation resistance

Before operation, and especially before testing applied endurance AC voltage, its insulating resistance is measured. This verifies that the winding insulation is not damaged and the choke is not wet. The measured insulation resistance is only an informative value, highly dependent on temperature and humidity. It cannot be used to make a conclusion about the perfect state of insulation. This insulation must be verified by the voltage-apply test. Insulation resistance depends on a number of factors, e.g., machine size, type of insulation used, etc.

The insulation resistance is measured between the following terminals:

- Between main winding $D_1 – D_2$ and measurement winding $M_1 – N_1$
- Between main winding $D_1 – D_2$ and auxiliary winding $M_2 – N_2$
- Between main winding $D_1 – D_2$ and auxiliary winding of current transformer k – l
- Between main winding $D_1 – D_2$ and case
- Between measurement winding $M_1 – N_1$ and case
- Between measurement winding $M_2 – N_2$ and case
- Between auxiliary winding of current transformer k – l and case

Testing voltage level is 5 kV DC. Measurement resistance is typically several GΩ.

11.10 Apply voltage test on secondary winding

This test is carried out by a 3 kV source of AC voltage. This voltage is put to all secondary circuits of the quenching choke for a period of 60 seconds.
The test is considered to be successful if the test voltage does not fall to zero during the test.

11.11 Apply voltage test on control circuits

The control circuit insulation test is carried out by an authorized person during preparation of the choke before the regulation test. A testing voltage of 2 kV is applied to each terminal of choke for a duration of 60 seconds. Special care should be taken for connected devices that are not dimensioned on the testing voltage level of 2 kV. These circuits must be disconnected before the test. The test is considered successful if the test voltage does not fall to zero.

11.12 Test of proper operation of the equipped instruments - check the wiring and functionality

The test of the correct operation of the fitted instruments shall be carried out by an authorized person during preparation of the choke before connecting to the regulation test. In the case of quenching chokes, this is a test of the functionality of the Buchholz relay, oil level indicator and thermometer. All of these devices simulate operating conditions, which causes switching on their output contacts.

11.13 Pressurized test

A fully assembled choke filled with transformer oil is connected to the pressure gauge - manometer. The choke is pressurized by air to 50kPa (0.5 atm). The test duration is 24 hours. After that, follow an evaluation of the pressure test. For the duration of the test, the air pressure must not decrease by more than 10%. Otherwise, after a failed pressure test, we detect the leak point. The detected leak is repaired. After repair, we repeat the pressure test at the same range.

11.13 Surface varnish measurement

The thickness of the paint is measured according to standards of ČSN ISO 2178 and ČSN ISO 2360. The measurement is carried out using a digital micrometer that operates on the principle of magnetic induction for magnetic metal surfaces or on the principle of whirling currents for non-magnetic metal surfaces.
Measurement procedure: we select a 1 dm^2 reference area according to the size of the measured object.
On the cap cover we choose at least 2 areas, tank at least 8 areas, conservatory at least 3 reference areas. It is necessary to pay special attention to the tank-underframe connections, the surroundings of the oil-taps, cable fixing screws, ground block, etc. On each reference surface we make 10 measurements according to CSN EN ISO 2063.

According to the "90 to 10" method, the varnish thickness must necessarily correspond to the minimum required varnish thickness from 90% of the measured points, the remaining 10% of the measured points can be within a tolerance of not more than 10 µm below the desired varnish thickness. In the event that this tolerance is not observed, the paint must be repaired.

11.14 Typical parameters

Type	ASR 1.6 V
Rated network voltage	10kV
Maximal network voltage	12kV
Insulation level	LI 75 AC35/AC3
Choke rated voltage	5,77kV
Min current	21A
Rated current	208A
Rated power	1200kVA

Rated voltage of the measurement winding	100 V
Rated current of the measurement winding	3A
Rated voltage of the auxiliary power winding	500V
Rated current of the auxiliary power winding	350V
Current ratio of current transformer (CT)	250/1
Rated power of CT	15VA
Class of accuracy	1FS5
Noise @100A	75 dB



Questions:

- *How is the quenching choke connected?*
- *How is the winding resistance measured?*
- *Why do we use a higher frequency than rated frequency for induced voltage tests?*



Answers

- *How is the quenching choke connected?*

The choke is connected to a neutral point of the transformer network.

- *How is the winding resistance measured?*

  The four-wires Ohms method is used for the winding resistance measurement.

- *Why do we use a higher frequency than rated frequency for induced voltage tests?*

  The test needs higher than rated voltage, to avoid the oversaturation of the magnetic core we use a higher frequency.