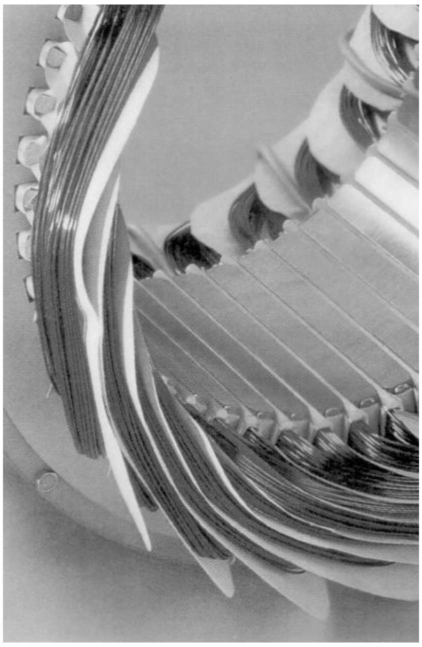
Tutorial 1 (EMD)

Rotary field winding



The unchorded two-layer three-phase winding of a small synchronous fan drive for a computer has the following parameters:

- number of slots per pole and phase $q = 1$,
- number of phases $m = 3$,
- number of turns per coil $N_c = 100$,
- number of parallel paths $a = 1$,
- number of poles $2p = 2$,
- air gap $\delta = 1$ mm.

1) Draw the current distribution for a three-phase current system

$$i_U(t) = \hat{I} \cdot \cos(\omega \cdot t),$$
$$i_V(t) = \hat{I} \cdot \cos\left(\omega \cdot t - \frac{2 \cdot \pi}{3}\right),$$
$$i_W(t) = \hat{I} \cdot \cos\left(\omega \cdot t - \frac{4 \cdot \pi}{3}\right)$$

with the r.m.s.-value of the current $I = 2.5$ A and for
a) $\omega t = 0$,
b) $\omega t = \pi/2$.

2) Draw directly underneath the current distribution the radial component of the air gap flux density $B_\delta(x)$. Neglect the influence of the slot openings on the shape of the air gap field. The iron can be treated as if it has an infinite permeability ($\mu_{Fe} \to \infty$).

3) Draw the winding diagram for one pole pair showing the arrangement of the coils. Draw the upper layer conductors using full lines, whereas the lower layer shall be represented by dashed lines. The three-phase winding shall be star-connected. Label the winding ends U-X, V-Y and W-Z.

<u>Solutions:</u>

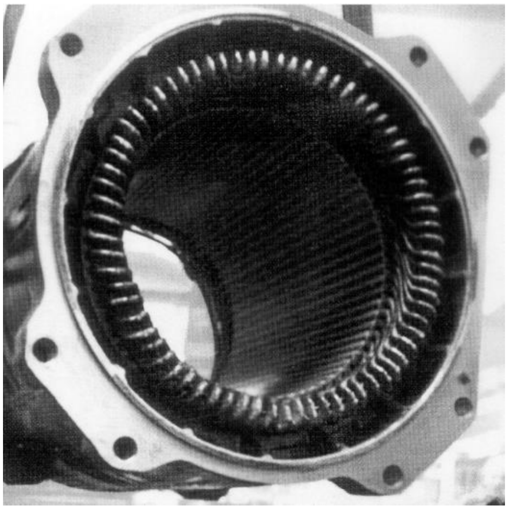
1a) $i_U(0) = \hat{I}$, $i_V(0) = -\hat{I}/2$, $i_W(0) = -\hat{I}/2$,

1b) $i_U(\pi/2) = 0$, $i_V(\pi/2) = (\sqrt{3}/2) \cdot \hat{I}$, $i_W(\pi/2) = -(\sqrt{3}/2) \cdot \hat{I}$,

2a) $B_\delta = \frac{\mu_0 \cdot V}{\delta}$, $\hat{B}_\delta = 0.89T$,

2b) $\hat{B}_\delta = 0.77T$.

Tutorial 2 (EMD)
Voltage induction into a three-phase winding



A two-layer winding of a standard induction motor, which is used as a motor drive in a Japanese lumber mill, has the following characteristics:

- number of slots per pole and phase $q = 2$,
- number of phases $m = 3$,
- number of turns per coil $N_c = 6$,
- number of parallel paths $a = 1$,
- number of poles $2p = 4$,
- short-pitching $W / \tau_p = 5/6$.

The laminated stator iron core has the following dimensions:

- stator bore diameter $d_{si} = 200$ mm,
- active iron length $l_{Fe} = 250$ mm,

Specifications of the induction machine:

- $P_N = 55$ kW,
- $U_N = 460$ V Y,
- $f_s = 60$ Hz.
- According to the design sheet the fundamental of the air gap flux density is $B_{\delta,1} = 0.9\,\text{T}$.

1) Draw the winding belt of phase U.
2) Calculate the flux Φ per pole.
3) Calculate the r.m.s.-value of the induced voltage per coil $U_{i,c}$.
4) Calculate the induced voltage of a coil group $U_{i,gr}$. Sketch the voltage phasors of a coil group.
5) How big is the induced voltage in one phase $U_{i,ph}$?
6) How big is the induced line-to-line voltage $U_{i,LL}$? Was the flux density given in the design sheet calculated correctly?

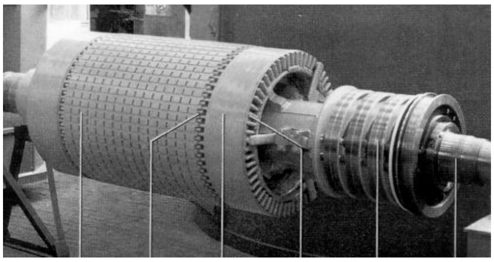
<u>Solutions:</u>

2) $\Phi = 0.0225$ Wb,
3) $U_{i,c} = 34.76$ V,
4) $U_{i,gr} = 67.15$ V,
5) $U_{i,ph} = 268.6$ V,
6) $U_{i,LL} = 465.2$ V. The flux density given in the design sheet is too big, as the induced line-to-line voltage is bigger than the actual grid voltage. In fact, the induced voltage of induction machines in motor operation is always a little bit smaller than the grid voltage.

Tutorial 3 (EMD)

Slip-ring rotor induction machine as rotary transformer

A four-pole slipring rotor induction machine shall be converted into a rotary transformer to be used in a test laboratory.



Machine data:
- P_N = 600 kW,
- U_N = 6.3 kV Y,
- f_s = 50 Hz.

Stator/rotor winding specifications:
- two-layer winding in stator and rotor,
- slots per pole and phase $q_s = 2$, $q_r = 3$,
- number of phases $m_s = m_r = 3$,
- number of turns per coil $N_{c,s} = 14$, $N_{c,r} = 2$,
- number of parallel paths $a_s = a_r = 1$,
- short pitching $W_s / \tau_p = 5/6$, $W_r / \tau_p = 7/9$,
- stator bore diameter $d_{s,i}$ = 500 mm,
- iron length l = 600 mm,
- air gap δ = 2.5 mm,
- ohmic stator phase resistance $R_s = 1\ \Omega$,
- stator phase leakage inductance $L_{s,\sigma}$ = 0.02 H

Both stator and rotor winding are Y-connected. Neglect the influence of the slot openings in the following calculations. The iron can be assumed to be unsaturated, and therefore it has an infinite permeability μ_{Fe}.

1) Calculate the number of turns per phase of both stator and rotor winding N_s, N_r and the winding factors for the fundamental wave $k_{w,s}$ and $k_{w,r}$.
2) Determine the three-phase self-inductance of the stator winding $L_{s,h}$.
3) Determine the three-phase mutual inductance M_{sr}.
4) Determine the three-phase self-inductance of the rotor winding $L_{r,h}$. Show, that introducing a transformation ratio $\ddot{u} = \dfrac{N_s \cdot k_{w,s}}{N_r \cdot k_{w,r}}$ will reduce the T equivalent circuit of the induction machine, neglecting all resistances and leakage fluxes, to only one inductance, namely the magnetising inductance L_h – which represents the influence of $L_{s,h}$, M_{sr} and $L_{r,h}$.
5) The so-called locked-rotor voltage can be measured between the rotor sliprings, if the rotor is locked and the stator winding is connected to the grid. Calculate the locked-rotor voltage $U_{r,0,LL}$.
6) Sketch the wiring of stator and rotor windings for rotary transformer operation.

<u>Solutions:</u>

1) $N_s = 112$, $N_r = 24$, $k_{w,s} = 0.933$, $k_{w,r} = 0.9019$,
2) $L_{s,h}$ = 0.3932 H,
3) M_{sr} = 0.0814 H,
4) $L_{r,h}$ = 16.87 mH, L_h = 0.3932 H,
5) $U_{r,0,LL}$ = 1242 V.

Tutorial 4 (EMD)

Grid-operated induction machine

A centrifugal pump in a ground water pump station in the Rhine Valley shall be equipped with an induction machine. The project engineer has determined the following drive specifications:

57.2 kW, four-pole machine, 50 Hz, rated slip 3%. A 400V grid is available. He chose a motor from a catalogue that is as close as possible to the specifications he determined. This motor has been designed to operate on a 230 V D / 400 V Y grid. He contacts the motor manufacturer to ask for the no-load current, the rated current and the maximum torque. Assume, you were the motor manufacturer and your motor design software determined the following equivalent circuit parameters per phase:

- Phase resistances: R_s = 0.06 Ω, R_r' = 0.07 Ω,
- Leakage reactances $X_{s,\sigma}$ = 0.17 Ω, $X_{r,\sigma}'$ = 0.4 Ω,
- Magnetising reactance X_h = 8.65 Ω,

1) Draw the equivalent circuit per phase. How big is the applied phase voltage?
2) Calculate the no-load speed n_0, the rated speed n_N and the rated torque M_N of this motor.
3) Calculate the absolute value of the rated current $\underline{I}_{s,N}$ and the real and imaginary current components, if the voltage phasor is assumed to be in phase with the real axis.
4) Calculate the no-load current $\underline{I}_{s,0}$ in the same way.
5) Draw the phasor diagram for both current and voltage according to 3) and 4) with the following scale factors: μ_U = 25 V/cm, μ_I = 10 A/cm.
6) Calculate the breakdown torque in generator and motor mode and compare it to the approximated value for R_s = 0. What is the breakdown torque given by *KLOSS'* formula for this simplification? Draw a simplified *M(n)* curve using the *KLOSS'* formula in a slip range of 0...1.5 n_{syn}.

<u>Solutions:</u>

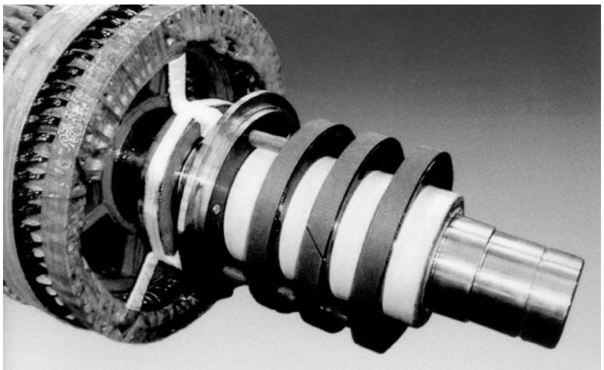
1) $U_{s,ph}$ = 230 V,
2) $n_0 = n_{syn}$ = 1500 /min, n_N = 1455 /min, M_N = 375.5 Nm,
3) $I_{s,N}$ = 99.2 A, $\underline{I}_{s,N}$ = 88.05 A – j45.63 A,
4) $I_{s,0}$ =26.08 A = 26.3 % of the rated current, $\underline{I}_{s,0}$ = 0.18 A – j26.08 A,
5) $\cos\varphi_N$ = 0.887, $\cos\varphi_0$ = 0.0069.
6) s_b = ± 0.1228, for R_s = 0 s_b = ± 0.1236, M_b = ± 819.1 Nm.

Tutorial 5 (EMD)

Current circle diagram of the induction machine

A slipring induction machine is investigated in the manufacturer test bay. It has the following characteristics:

- P_N = 55 kW,
- U_N = 400 V Y,
- f_s = 50 Hz,
- four poles.



The following measured values are available:

- P_0: $s = 0$, I_{s0} = 26.0 A, $\cos\varphi_0 = 0$, P_0: no-load point
- P_N: $s = s_N$, I_{sN} = 96.0 A, $\cos\varphi_N = 0.89$, P_N: rated load point
- P_1: $s = 1$, I_{s1} = 404.0 A, $\cos\varphi_1 = 0.218$, P_1: locked rotor
- Hysteresis and eddy-current losses: P_{Fe} = 870 W,
- Friction losses: P_R = 250 W.
- At $s = 1$ the resistive stator and rotor losses are identical: $P_{Cu,s} = P_{Cu,r}$ ($s = 1$).

1) What is the simplified OSSANNA-circle ?
2) Construct the OSSANNA-circle using the three measured points P_0, P_N and P_1. Use of the following scale factors: μ_U = 25 V/cm, μ_I = 15 A/cm. Label the real and the imaginary axis according to the text book.
3) Add the torque and the power line and label the slip using the slip line. How big are rated and breakdown slip for motor operation?
4) Plot the $M(n)$-curve, using s = 1, 0.6, 0.4, 0.2, s_b, 0.1, s_N, 0, $-s_N$, -0.1, $-s_b$, -0.2, -0.4 as sampling points.

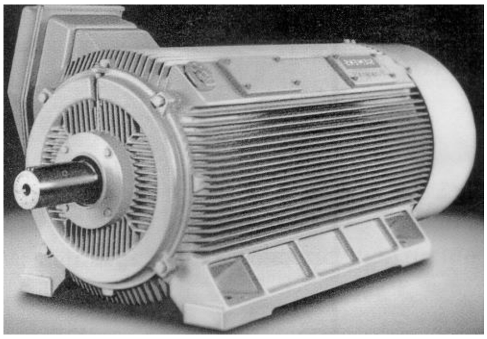
Supplementary question: When using the current locus diagram according to 2), hysteresis and eddy-current losses are not considered. Those losses can be approximately included into the diagram by simulating them as resistive losses per phase, described by a resistor in parallel to the input of the T equivalent circuit. This will lead to an additional real component of the current, which will shift the centre of the circle diagram in vertical direction. How big is this displacement and in which direction does the circle diagram need to be shifted?

<u>Solutions:</u>

1) For the simplified OSSANNA-circle the centre of the diagram is put to the x-axis, while the point representing $s = \infty$ remains above the x-axis.
3) $s_N = 0.03$, $s_b = 0.13$,
4) M_b = 766 Nm (motor operation),
5) additional active current 1.62 A/phase.
As these losses are incorporated in the measured data, but not included in the OSSANNA-diagram, the additional active current needs to be subtracted from the measured data. Therefore, the whole circle diagram needs to be shifted to the negative real axis by the value of this additional active current.

Tutorial 6 (EMD)

Squirrel-cage induction machine with deep-bar rotor



A four-pole induction machine with round rotor bars is specified by the following data:

- P_N = 55 kW,
- U_N = 230 V Δ / 400 V Y,
- f_s = 50 Hz
- Rated slip s_N = 3 %
- Phase resistance $R_s \approx 0$, R_r' = 0.07 Ω,
- Leakage reactance $X_{s,\sigma}$ = 0.17 Ω, $X_{r,\sigma}'$ = 0.4 Ω,
- Magnetising reactance X_h = 8.65 Ω

The motor drives a fan in a sugar factory. As sugar factories are not operating between January and October, the bearings got so filthy that they blocked the rotor and the motor starting torque was not able to start the motor anymore. Therefore, the rotor shall be replaced by a deep-bar rotor to increase the starting torque. The deep-bar slot has the following dimensions:

- bar width 10 mm,
- bar height 40 mm.
- the leakage reactance in the slot area amounts to 60 % of the total rotor leakage reactance.

1) Calculate the absolute value, the real and the imaginary part of the stator current $\underline{I}_{s,1}$ of the round-bar rotor for starting conditions (s = 1), assuming the phase voltage to be in phase with the real axis.
2) How big is the corresponding starting torque M_1 and the ratio M_1/M_N ?
3) Determine the current displacement factors k_R and k_L for the deep-bar for slip s = 1 ($\kappa_{Cu}(20°) = 57 \cdot 10^6$ S/m). How do the parameters of the equivalent circuit change?
4) Calculate the absolute value, the real and the imaginary part of the stator current $\underline{I}_{s,1}$ of the deep-bar rotor for starting conditions (s = 1), assuming the phase voltage to be in phase with the real axis. How big is the corresponding starting torque M_1?
5) Supplementary question: Usually, the big main reactance can be neglected when calculating the starting currents. Why? Calculate the starting currents of 1) and 4) again using this simplification. Is this simplification permitted?

<u>Solution:</u>

1) $I_{s,1}$ = 413.3 A, $\underline{I}_{s,1}$ = 47.46 A – j410.6 A,
2) M_1 = 208 Nm = 58 % of the rated torque,
3) k_R = 4.24, k_L = 0.354,
4) $I_{s,1}$ = 457.4 A, $\underline{I}_{s,1}$ = 254.1 A – j380.7 A, M_1 = 1116.2 Nm = 309 % of the rated torque,
5) round bar: $\underline{I}_{s,1}$ = 48.8 A – j397.5 A,
   deep bar: $\underline{I}_{s,1}$ = 262.0 A – j367.3 A.

Tutorial 7 (EMD)

Starting of an induction machine

A squirrel-cage induction machine with a shaft height of AH = 560 mm is employed to propel a sugar centrifuge. Motor data:

- U_N = 400 V Δ / 690 V Y,
- I_N = 540 A Δ / 310 A Y,
- P_N = 280 kW,
- $\cos\varphi_N$ = 0.82,
- f_s = 50 Hz,
- n_N = 740 /min,
- starting torque: $M_1/M_N = 1$,
- breakdown torque: $M_b/M_N = 2$,
- starting current: $I_1/I_N = 5$.

1) The moment of inertia of the motor J_M = 24.5 kgm² is considerably smaller than the one of the sugar centrifuge J_Z = 1800 kgm². Why? How big is the acceleration time from 0 to n_N, if the average torque $M_{e,av}$ is estimated to be $0.5\bullet(M_1 + M_b)$?
2) How big is the total energy that is converted into heat inside the rotor during start-up?
3) Give an estimation about how much the rotor losses during start-up will be bigger than during rated operation (<u>Assumption:</u> rotor losses = $s \cdot P_\delta \approx s \cdot P_{in}$).
4) How big is the starting current drawn from the grid, if the motor is operated in Δ-connection at 400 V?
5) Star-Delta starting at a 400 V grid: How big is the starting current I_1 which is drawn from the grid and the acceleration time t_a? Do the rotor losses change?

<u>Solutions:</u>

1) The outer diameter of the sugar centrifuge is much bigger than the outer diameter of the induction machine rotor. Due to centrifugal forces all the sugar concentrates at the outer circumference. Therefore, the moment of inertia of the centrifuge is much bigger than the one of the machine rotor.
t_a = 26 s,
2) $W_{thermal} = W_r$ = 5.48 MJ,
3) $\overline{P}_{Cu,r} = 210.7\,\text{kW},\ \overline{P}_{Cu,r} / P_{Cu,r,N} = 51.7$,
4) I_1 = 2700 A,
5) I_1 = 900 A, t_a = 78 s.
The thermal energy consumed inside the rotor during start-up does not change.

Tutorial 8 (EMD)

Inverter-fed induction machine

In tutorial 7 a mains-operated squirrel-cage induction machine was deployed to operate a sugar centrifuge:

- U_N = 690 V Y,
- I_N =310 A Y,
- P_N = 280 kW,
- $\cos\varphi_N$ = 0.82,
- f_S = 50 Hz,
- n_N = 740 /min,
- starting torque: M_1/M_N = 1,
- breakdown torque: M_b/M_N = 2,
- breakdown slip s_b = 0.27,
- motor moment of inertia: J_M = 24.5 kgm²,
- centrifuge moment of inertia: J_Z = 1800 kgm².

Because of the high starting current due to the high inertia starting, the system shall be equipped with an inverter. The stator resistance R_s can be neglected in the following considerations.

1) A voltage-source inverter with a dc link voltage of 690 V is used in order to be able to operate the machine in Y-connection. Why is it beneficial to operate an inverter-fed machine in Y-connection?
2) The sugar centrifuge is operated at three times its rated speed, which we assume is possible. Why is an increase of rotational speed advantageous for the operation of a centrifuge? How big is the maximum output frequency the inverter has to provide to the motor? What does the U/f-characteristic look like (sketch!)? Which areas of operation can be distinguished?
3) Sketch the $M(n)$-characteristics for the following stator frequencies using KLOSS' formula: f_s = 25, 50, 150 Hz.
4) How big must the stator frequency be to ensure motor starting with rated torque? How big is the starting time t_a from 0 to rated speed n_N?
5) The inverter has a line-side B6 diode rectifier, ensuring that current and voltage on the grid side are in phase. As an approximation, you can assume the input current to be sinusoidal. How big is the current drawn from the grid during starting? Sketch the r.m.s. value of the grid current I_{grid} between 0 and n_N.

Solutions:

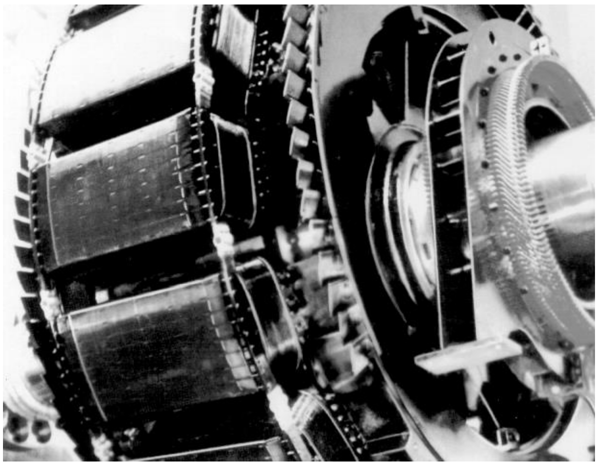
1) Y-connection is advantageous as voltage harmonics with ordinal numbers 3*k* (*k* = 1,2,3,...) do not cause current harmonics.
2) Increasing the speed will increase the centrifugal forces with n^2.
   $f_{s,max}$ = 150 Hz
   0...50 Hz: base speed operation with rated flux,
   50...150 Hz: field weakening range, flux reduced proportional to $1/f_S$.
3)

25 Hz	50 Hz	150 Hz
690/2 V = 345 V	690 V	690 V
M_b/M_N = 2	M_b/M_N = 2	M_b/M_N = 2/9 = 0.22
n_{syn} = 375 /min	n_{syn} = 750 /min	n_{syn} = 2250 /min

4) f_S = 0.67 Hz, t_a = 39.1 s
5) I_{grid} rises (almost) linear from 0 to 135 A with increasing the speed from 0 to n_N.

Tutorial 9 (EMD)

Synchronous machine in motor and generator operation



The pump-storage power station in *Grimsel* (*Switzerland*) is equipped with motor-generators (salient-pole synchronous machines). For simplification we consider the machines as round-rotor machines. In generator operation each machine is propelled by a *Francis* turbine, whereas in motor operation a shaft-coupled single-stage pump is used to pump water into the reservoir.

- U_N = 13.5 kV Y,
- f_s = 50 Hz,
- efficiency $\eta \approx 1$,
- n_N = 750 /min,
- x_d = 1.2 p.u.,
- generator operation at rated current: 100 MVA, $\cos\varphi$ = 0.75, overexcited,
- motor operation at rated current: 90 MW, $\cos\varphi$ = 0.9, overexcited,

Use the load reference arrow system.

1) How big is the number of poles of the machines? How big is the rated current and the synchronous reactance X_d in Ω ?
2) Draw the phasor diagram of the voltages and the stator current for motor and generator operation and read off the load angle ϑ, the phase angle φ and the synchronous generated voltage (back e.m.f.) U_p (Scales: μ_U = 800 V/cm, μ_I = 800 A/cm).
3) Determine the rated torque and the pull-out torque as well as the corresponding active power for generator operation.
4) Illustrate the characteristic $P(\vartheta)$ for generator operation in a range of 0...180° and specify the rated and pull-out points.

<u>Solutions:</u>

1) $2p = 8$, I_N = 4277 A, X_d = 2.187 Ω.

2)

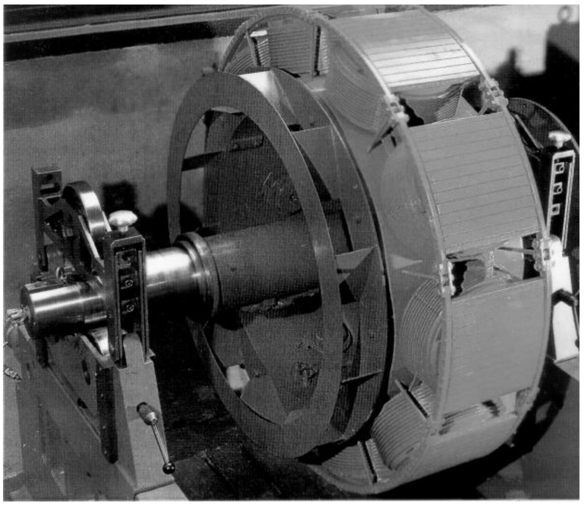
generator	motor
U_p = 15641 V	U_p = 14552 V
ϑ = 26.6 °	ϑ = - 35.4 °
φ = - 138.6 °	φ = - 25.8 °

3)

generator	load angle ϑ	torque M	active power P
rated operation	26.6 °	-953.3 kNm	-75 MW
pull-out point	90 °	-2129.1 kNm	-167.2 MW

Tutorial 10 (EMD)

Salient-pole synchronous machine



An electrically excited salient-pole synchronous motor is used as a fan drive in a furnace.
Motor data:

- P_N = 510 kW,
- U_N = 400 V Y,
- f_s = 50 Hz,
- $\cos\varphi$ = 0.85, overexcited,
- $2p$ = 8.

From the manufacturer test certificate we know:

Open circuit characteristic (line-to-line values):

U_0 / U_N	0.2	0.4	0.6	0.8	1.0	1.1	1.2	1.3	1.4
I_f / A	11	23	36	51	70	82	97	114	135

Short circuit characteristic (line-to-line values):

I_k / I_N	0.3	0.7	1.1
I_f / A	30	70	110

- X_d/X_q = 1/0.6,
- $x_{s,\sigma}$ = 0.26 p.u.
- The influence of the stator resistance can be neglected.

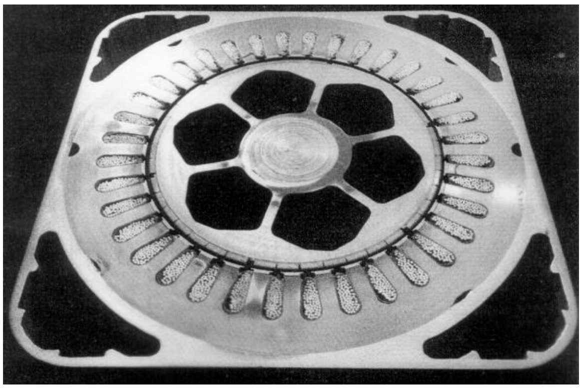
1) Draw the characteristics $U_0/U_N = u(I_f)$ and $I_k/I_N = i(I_f)$ into one diagram. Determine the short-circuit ratio k_k, the synchronous direct-axis reactance x_d (in p.u.), the corresponding value X_d in Ω as well as the value of the stator leakage reactance $X_{s,\sigma}$ in Ω.
2) Draw the phasor diagram for rated operation (scales: μ_U = 50 V/cm, μ_I = 200 A/cm) and read off the phase angle φ, the load angle ϑ, the magnitude of the internal voltage U_h, the synchronous generated voltage (back e.m.f.) U_p as well as the *d*- and *q*-components of the stator current.
3) The open circuit characteristic $U_{s,0}$ is the characteristic of the induced voltage U_i (= internal voltage U_h). Add the value of the internal voltage derived in 2) to the open circuit diagram and determine the level of saturation (= deviation from linearity, reference value is the tangent to the open circuit curve in the origin).
4) Calculate both rated torque M_N and pull-out torque M_b of the involved synchronous and reluctance torque. Sketch the characteristics of the load angle in a range of -180° ... 0° and determine the resultant characteristic of the motor torque. Assign the rated operating point.

Solutions:

1) k_k = 0.7, x_d = 1.43 p.u., X_d = 0.38 Ω, $X_{s,\sigma}$ = 0.07 Ω,
2) φ = -31.8 °, ϑ = 27 °, U_h = 262.5 V, U_p = 485 V, $I_{s,d}$ = -720 A, $I_{s,q}$ = 480 A,
3) Level of saturation: 1.44,
4) M_N = 6494 Nm, pull-out torque components: synchronous torque 11261 Nm (ϑ = -90°),
reluctance torque 1788 Nm (ϑ = -45°).

Tutorial 11 (EMD)

Permanent magnet motor



In a tooling machine a six pole permanent magnet motor is used to move the tool slide.
Motor data:

- U_N = 400 V Y,
- P_N = 22 kW,
- n_N = 6000 /min,
- number of windings per phase N_s = 20,
- winding factor k_w = 0.966,
- stator bore diameter $d_{s,i}$ = 100 mm,
- iron length l = 150 mm.

Permanent magnets made from neodymium iron boron are glued to the rotor surface and are mechanically fixed by a carbon fibre bandage. The magnetically active air gap δ consists of the mechanical air gap 0.8 mm and the thickness of the bandage 0.4 mm.

Magnet data at 20°C:

- remanence flux density B_R = 1.2 T,
- coercive field strength H_{CB} = 900 kA/m.
- The material characteristic $B_M(H_M)$ is linear in the 2nd quadrant and can therefore be expressed by the following linear equation: $B_M = B_R + H_M \cdot B_R/H_{CB}$.

The pole pitch of the magnets is 100%. The iron can be assumed to have an infinite permeability. The influence of the slot openings on the air gap flux density distribution can be neglected.

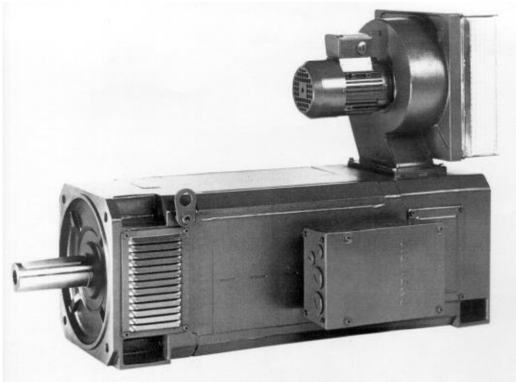
1) How does the air gap flux density distribution (radial component) of the machine under no-load conditions look like?
2) How big do we have to choose the magnet height h_M to obtain a fundamental wave of the air gap flux density of 0.9 T at 20°C under no-load conditions?
3) How big is the stator frequency f_s at rated speed? How big is the induced no-load voltage per phase $U_{s,0}$ (r.m.s.-value), which can be measured between the open terminals, if the motor is driven by a second machine in the manufacturer's test laboratory?
4) How big is the torque in field oriented operation ($I_d = 0$, $I_s = I_q = I_N$)? Draw a sketch of the voltage phasors for motor operation with consideration of R_s. What is the relation of the absolute values of phase angle and load angle?
5) Prove, that in field oriented operation the torque only depends on the stator current and is directly proportional to it ("brushless dc drive"). How big is the rated stator current? Plot the $M(I)$-characteristic for $0 \le I \le I_N$.

<u>Solutions:</u>

1) The air gap flux density distribution has a rectangular shape.
2) h_M = 1.83 mm,
3) $f_{s,N}$ = 300 Hz , $U_{s,0}$ = 115.8 V,
4) M_N = 35 Nm, $|\vartheta| = |\varphi|$,
5) $M = 3 \cdot p \cdot \frac{\Psi_p}{\sqrt{2}} \cdot I_{s,q}$, $I_{s,N}$ = 63.3 A.

Tutorial 12 (EMD)

Shunt-wound dc machine



A four-pole shunt-wound dc machine with interpole and compensation windings and a wave winding inside the armature shall be used in a wire drawing machine. Motor data:

- U_N = 500 V,
- P_N = 40 kW,
- I_N = 87.4 A,
- variable speed operation: n = 0..3000 /min with rated torque,
  n = 3000...4500 /min with rated power.

The machine is operated with open terminals at n = 1000 /min in the manufacturer's test bay. The field current I_f is varied and the open-circuit voltage U_0 is measured.

U_0 / V	5	50	100	150	162.5	175	188	200	208
I_f / A	0	0.28	0.6	1	1.25	1.75	2.7	3.9	4.6

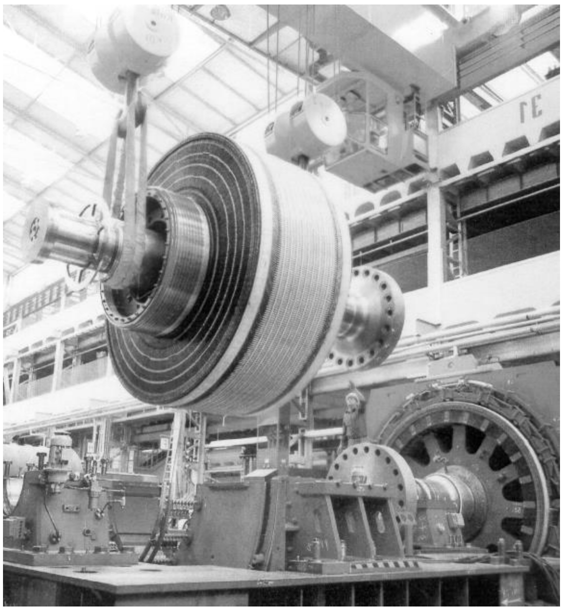
1) In the test bay, the motor is operated by a rotary converter with a dc generator (rated voltage 500 V). Sketch the connection circuit of the motor including starting resistor in the armature circuit and field resistor R_V in the field circuit. Make use of standardised terminal markings for the different winding parts.
2) How big is the rated motor torque?
3) Which components of resistance comprise to the total armature resistance R_a? How big is the armature resistance R_a? How big is the efficiency η of the motor without consideration of field winding losses? (Neglect all losses, e.g. iron and friction losses, except for the resistive losses in the armature winding.)
4) Plot the generator open-circuit characteristic $U_0(I_f)$ to scale at rated speed n_N = 3000 / min. How big is the rated field current $I_{f,N}$? How big is therefore the total field circuit resistance $R_f + R_V$?
5) Using field weakening, the speed shall be increased to n = 4500 /min at rated current and 500 V armature voltage. To which value does the field current I_f need to be adjusted?
6) What are the corresponding no-load speeds n_0 to the field currents I_f in 4) and 5)? Plot the associated $n(M)$ characteristics for $0 \le I_a \le I_N$. Label the current limit $I_a = I_N$ in the diagram.
Information: "power hyperbola" = constant power: $P = 2\pi \cdot n \cdot M \approx U_a \cdot I_a =$ constant

Solutions:

2) M_N = 127.3 Nm,
3) Components of the armature resistance: armature winding, interpole winding, compensation winding, brush contact resistance; R_a = 0.484 Ω, η = 91.5 %,
4) $I_{f,N}$ = 1.05 A, $R_f + R_V$ = 476.2 Ω,
5) I_f^* = 0.61 A,
6) $n_0(I_{f,N})$ = 3277 /min, $n_0(I_f^*)$ = 4916 /min.
The slope of the $n(M)$ - characteristic increases in the field weakening region.

Tutorial 13 (EMD)

Large rolling-mill motor



In a steel factory in *Linz/Austria* a large, separately excited, variable speed dc motor is used to drive the 2,7 m long roll stand via a gearbox. The motor is supplied with a dc voltage of max. 1300 V by a controlled thyristor bridge.

- Motor data:

P / kW	684	6840	6840
n / min^{-1}	5	50	100
U / V	130	1300	1300

- $\eta(n_N = 50$ /min) = 95 %,
- excitation losses 2 kW/Pole.

The motor is compensated.

- winding data:
  - simplex lap winding,
  - 1 winding/coil,
  - coil sides per slot and layer $u = 3$,
  - slot number $Q = 477$,
- maximum air gap flux density at n_N $B_{\delta,max} = 1.05$ T.

- geometry:
  - stator bore diameter $d_{si} = 4.45$ m,
  - length of iron core $l = 930$ mm,
  - number of poles $2p = 18$,
  - equivalent pole coverage ratio $\alpha_e = 0.7$.

1) Calculate the torque M for the given speeds. How big is the corresponding motor current I_a? Determine the flux per pole Φ at rated operation.
2) Draw the quantities P_m, U_a, I_a, M, Φ as a function of the speed n both for the base speed (n = 5...50 min^{-1}) and for the field weakening region (n = 50...100 min^{-1}), ($R_a \approx 0$, $M_e \cong M_s$).
3) How big is the induced voltage U_i at rated speed?
4) How big is the total armature resistance?
5) Sketch the $M(n)$ – characteristic for rated voltage and rated excitation in the range of $M = 0 ... M_N$. How big is the no-load speed n_0 (neglect the voltage drop across the brushes)?
6) How big are the resistive losses $P_{Cu,a}$ and the sum of the iron, friction and additional losses P_{R+Fe+Z}?
7) How big is the average voltage between two segments $U_{s,av}$ at rated speed? Is it in the permissible range (give the limit value)?

Solutions:

1)

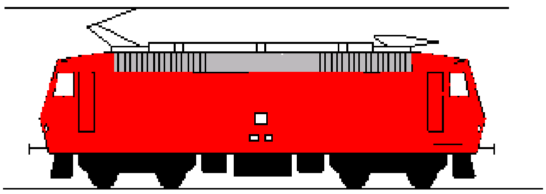
n / min^{-1}	5	50	100
M / kNm	1306.3	1306.3	653.15
I / A	5511	5511	5511
Φ / Wb	0.53	0.53	0.265

3) $U_i = 1264$ V,
4) $R_a = 6.53$ mΩ,
5) $n_0 = 51.4$ /min,

6) $P_{Cu,a} = 198.3$ kW, $P_{R+Fe+Z} = 125.7$ kW,
7) $U_{s,av} = 16.35$ V < 18...20 V
(segment voltage is sufficiently small).

Tutorial 14 (EMD)

Single-phase series-wound commutator machine



Electrical locomotive

Four single-phase series-wound commutator motors (per wheel set one motor with P_N = 1 MW, n_N/n_{max} = 1000/1490/min, U_{aN} = 465 V, I_{aN} = 2400 A (r,s-values at 16.7 Hz), $\cos\varphi_N$ = 0.985, are the drive motors of a 80 ton heavy electric loco for freight trains. Motor geometry: Bore diameter d_{si} = 896 mm, stack length l_{Fe} = 330 mm, pole count 14, commutator diameter d_C = 690 mm, brush width b_b = 12.5 mm. The motors are equipped with a simplex lap winding with N_c = 1 turns per coil, L_C = 7.5 μH coil inductance, an armature slot number Q = 175 and u = 3 coil sides per slot and layer. The rated air gap flux density beneath the pole centre is 0.75 T, and the pole coverage ratio α_e = 0.7.

1) Determine the rated motor torque M_N and the rated motor efficiency!

2) The motors are fed via the loco transformer and the step-down switch with a variable AC armature voltage amplitude at 16.7 Hz. Draw the torque-speed-characteristic $n(M)$ for U_N = 465V and 300 V in the range of $0 \le M \le M_N$, $0 \le n \le n_{max}$ for $\cos\varphi \approx 1$ at assumed constant iron saturation (flux per pole $\Phi = L' \cdot I_a$).

3) The loco wheel diameters are 1.1 m and the loco maximum velocity 150 km/h. Calculate the transmission ratio of the single stage gear between motor shaft and loco wheel set axle!

4) Is it possible for the locomotive to accelerate a train load of 520 tons at a track inclination of 2% and dry tracks (friction coefficient μ = 0.4 between wheel and track) without exceeding the rated armature current? Is this acceleration also possible at wet tracks (friction coefficient μ = 0.15)?

5) Determine the voltage U_{Tr}, which is induced at rated current operation at stand-still (v = 0) into the commutating armature coil via the AC main flux! Note that this coil is short circuited via the brushes! Compare the voltage value with the admissible limit ($U_{Tr,lim}$ = 3V, rms)!

6) Calculate at rated speed and current the back EMF U_i, the average torque value M_{av}, the torque AC amplitude $M_\sim$ and its frequency f_M! Give a sketch of $M(t)$ to scale!

7) Determine the reactance voltage of commutation U_R (rms) at rated operation! Compare this value with the admissible voltage limit!

Solutions:

1) M_N = 9550 Nm, η_N = 91.1%

2) $2\pi k_1 L' = U_N^2/(M \cdot n^2) = 0.08151\,(\mathrm{Vs})^2/\mathrm{Nm}$, M(1490/min, 465V) = 4302Nm, M(1490/min, 300V) = 1790 Nm

3) i = 2.06

4) $M(n = 0)$ = 7857 Nm < M_N. The loco can accelerate with $I_a < I_N$, also at wet tracks, but the friction force is at its limits!

5) U_{Tr} = 2.58 V (admissible max. 3 V)

6) U_i = 431 V, $M_\sim = M_{av}$ = 9869 Nm, f_M = 33.4 Hz

7) U_R = 7.4 V < 10V