TECHNISCHE UNIVERSITÄT DARMSTADT

Institute of Electrical Energy Conversion
Electrical Drive Systems

Energy Converters

CAD and System Dynamics

- Tutorials -

Issue 2023/2024

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1. Switching of a choke coil (from Exercise 4.1)

A choke coil with the current-independent inductance L and resistance R is connected at the time $t = 0$ to an AC voltage source

$$u(t) = \hat{U} \cdot \sin(\omega t + \varphi)$$

The following data are given: $\hat{U} = 10\,\mathrm{V}$, $f = \omega/(2\pi) = 100\,\mathrm{Hz}$, $R = 1\ \Omega$, $X = \omega L = 1\ \Omega$.

1) Using the homogeneous and particular differential equations, calculate analytically the current in the coil and discuss the results.

2) For the two different switching moments, at $\varphi = 0$ and $\varphi = \pi/2$, give the current expressions! Analyze the special case of $R = 0$!

3) Using the method of Runge-Kutta, determine for $\varphi = 0$, by numerical integration, the current variation of the coil for the first two periods of the AC voltage source and compare the result with the analytical calculation of 1)!

2. Braking during the run-out of a rotating machine (from Exercise 4.3)

The mechanically braked run-out of a rotating machine with the inertia J is to be calculated, starting with the mechanic angular speed Ω_{m0}. The braking mechanic torque M_s has the following three different dependencies on the mechanic angular speed Ω_m:

a) $M_s(\Omega_m) = M_{s0}$

b) $M_s(\Omega_m) = M_{s0} \cdot (\Omega_m / \Omega_{m0})$

c) $M_s(\Omega_m) = M_{s0} \cdot (\Omega_m / \Omega_{m0})^2$

1) Calculate analytically the mechanic angular speed $\Omega_m(t)$ as a function of time, starting with the value Ω_{m0}, for the three braking torques a), b), c). Which one of the three braking torques gives the strongest braking?

2) Calculate numerically the mechanic angular speed $\Omega_m(t)$ as a function of time for the time range $0 \le t \le 100\,\mathrm{s}$ for the following data: $J / M_{s0} = 0.0637\,\mathrm{kgm}^2/(\mathrm{Nm})$, $n(t = 0) = 1500/\mathrm{min}$. Compare the numerical solution with the analytical one obtained from 1)!

3. Asynchronous no-load start-up of an induction machine (from Exercise 4.4)

The electromagnetic torque of a two-pole induction machine (P_N = 500 kW, U_N = 690 V Y, f_N = 50 Hz, n_N = 2982/min) with the inertia $J = 5.9\ \mathrm{kg} \cdot \mathrm{m}^2$ is described with dependence on the slip s by *Kloss* function (see EMA and EMD lecture notes, Chap. 5)

$$\frac{M_e(s)}{M_b} = \frac{2}{\frac{s}{s_b} + \frac{s_b}{s}} \quad ,$$

where $s_b = 7.5 s_N$ is the corresponding breakdown slip.

1) What simplifications are valid for the use of *Kloss*' function? Calculate the breakdown slip, the breakdown torque and the startup torque!

2) Calculate analytically the mechanical angular speed $\Omega_m(t)$ as a function of time, when the machine is uncoupled (unloaded) and starts-up from zero speed (flywheel mass start-up)!

3) Calculate numerically the mechanical angular speed $\Omega_m(t)$ as a function of time for the time range $0 \le t \le 2.0\ \mathrm{s}$! Compare the numerical solution with the analytical one, obtained from 2)!

4. Starting of a DC motor at constant voltage with starting resistors

A separately excited, four-pole DC machine is fed from a battery with a constant voltage of 460 V. In order to limit the current to a safe value during starting, a series armature resistor is used.

Machine data: P_N = 142 kW, U_N = 460 V, I_N = 320 A, n_N = 625 1/min, $k_2\phi_N$ = 6.78 Vs.
Inductances - armature: 1.5 mH, excitation: 64 H
Resistances – armature: 0.05 Ω, excitation 25 Ω
Total inertia (motor + load): J_{tot} = 150 kgm^2

1) How big is the armature current in the first moment if the rated voltage would be applied directly to the motor terminals and the motor is at stand still? How big is this current, related to the rated current?

2) How many sections of the starting resistor are used to keep the starting current within a minimum value $I_{1min} = I_N$ and a maximum value $I_{1max} = 2I_N$? Calculate the values of the resistor sections.

3) Calculate the time until disconnecting the first section of the starting resistor!

5. Starting DC Motor Directly from DC Grid (from Exercise 5.4)

A permanent-magnet excited small DC motor shall be started at a DC voltage $U = U_N$ by closing the switch S at $t = 0$ (Fig. 5.4-1)! The total rotor inertia is J.

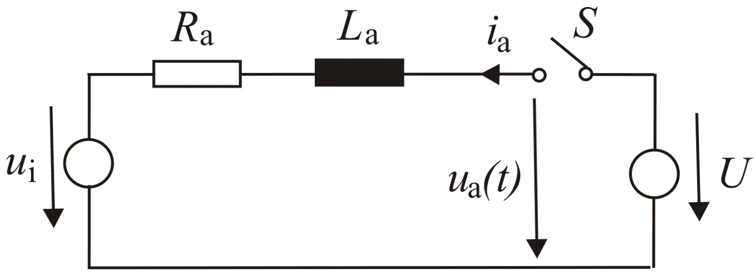

Fig. 5: Equivalent circuit of the PM excited DC machine

1) Give the formula for u_i!
2) What are the initial conditions for angular speed $\Omega_m(t)$ and armature current $i_a(t)$?
3) What basic mathematical property has the stator flux per pole with respect to time?
4) Give the qualitative graph for the armature voltage u_a(t) as a time function!
5) Give the differential equations for calculating the armature current i_a(t) and the angular speed Ω_m(t), if the load torque at the shaft is zero ($m_s = 0$)!
6) Transform the differential equations into Laplace domain and determine the current $\breve{I}_a = L\{i_a(t)\}$! [1]
7) Calculate the formula i_a(t) in the time domain during start up. Use for the calculation the fact that the DC motor's time constants T_a=10 ms, T_m = 100 ms hold the relationship $T_m > 4T_a$![2]
8) Define the time constants T_1 and T_2 and calculate them!
9) Calculate the function $\Omega_m(t)$! Sketch qualitatively the functions $i_a(t)$ and $\Omega_m(t)$ between $-\infty \le t \le +\infty$. How do the current $i_a(t)$ and $\Omega_m(t)$ behave for $t \to +\infty$ and why? Give the peak current value!

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[1] Use the DC motor's time constants in the expression of $\breve{I}_a$

[2] Give the poles of the transfer function of 6). Then, decompose the transfer function of 6) in a sum of 1st order partial functions and transform them in the time domain!

6. Small DC-motor with permanent magnet excitation and chopper controller (from Exercise 5.3)

An experimental cross-country vehicle used on *Mars* mission for surface survey should be equipped with DC-motors excited by permanent magnets. The motors serve as wheel drives similar to those in three-axis *Mars*-vehicle *Sojourner*. In a pilot survey, a DC-motor will be used with variable armature voltage generated by a MOSFET-chopper from a 48 V battery. Pulse frequency of the MOSFET-chopper equals 16 kHz. Operation with variable speed will be investigated.

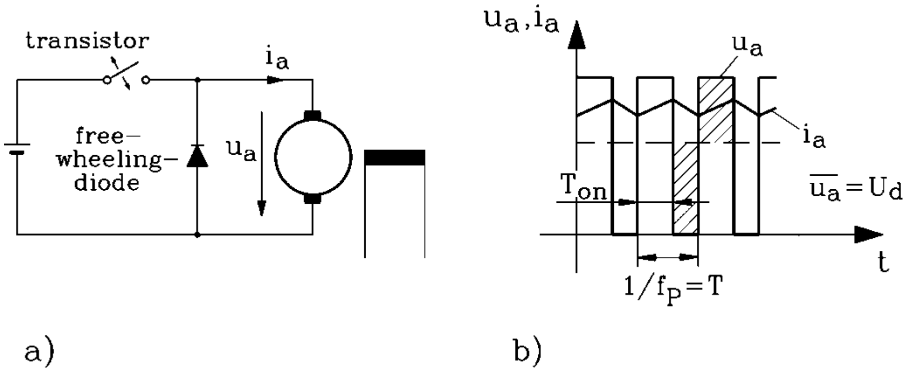

Fig. 6: **1-quadrant operation of DC-chopper: a) Basic circuit scheme, b) armature voltage pulse pattern**

Motor specification:

U_N = 48 V, I_N = 2.1 A, no-load speed n_0 = 1020/min, R_a = 5.44 Ω, L_a = 2.34 mH (Voltage drop across brushes is neglected).

1) What is electrical time constant of the armature in ms and how much is it in relation to period T of one chopper switching cycle of the battery voltage ?

2) What is the value of rated speed and efficiency of the motor (if considering only *ohmic* losses)?

3) How long is duration T_{on} of voltage pulse to operate at half of no-load speed? In this case, what is the speed at rated torque?

4) Due to the switching modulation as depicted in Fig. 6 b), the armature current $i_a(t) = I_a + \Delta i_a(t)$ comprises an average value $I_a = \bar{i}_a$ and a small ripple of $\Delta i_a(t)$. Calculate this ripple with following approximation for the operating point according to 3)!

$$u_a(t) = L_a \cdot \frac{di_a(t)}{dt} + R_a \cdot i_a(t) + U_i = L_a \cdot \frac{d\Delta i_a(t)}{dt} + R_a \cdot (I_a + \Delta i_a(t)) + U_i \approx$$

$$\approx L_a \cdot \frac{d\Delta i_a(t)}{dt} + R_a \cdot I_a + U_i$$

7. Oscillation behaviour of an uncontrolled DC drive

A separately excited, compensated four-pole DC machine is operated with a three-phase 2-quadrant full converter.

Machine data: 142 kW, 460 V, 320 A, 625 1/min
Inductances - armature: 1.5 mH, excitation: 64 H
Resistances – armature: 0.05 Ω, excitation 25 Ω
Power Grid : 400 V line-to-line AC voltage

1) Sketch the circuit of drive! Which are the operating quadrants of the motor drive?

2) Draw the momentary rectified voltage for a control of thyristors with a control angle of 30°! Ignore the line source inductance and consider an ideal commutation for the bridge thyristors.

3) How big is the control angle of the bridge thyristors for a motor operation at the rated speed? Which is the voltage margin for the voltage control?

4) At the time t = 0.2 s, the machine is loaded at the shaft with the rated torque. Is the drive oscillating during uncontrolled operation? The sum of the motor and load inertia is J_{tot} = 150 kgm^2.

5) The motor and load inertia is reduced up to J_{tot} = 15 kgm^2. The load changes suddenly and the drive is oscillating. How big are the natural frequency and period of oscillation? After how many half periods, the oscillation is reduced down to 5% of initial value?

8. Speed transients of a separately excited DC machine

A separately excited DC machine is to be used in an electric drive system, where several voltage drops at the winding armature terminals or strong disturbances of the load at the machine shaft are expected.

Machine data: P_N = 142 kW, U_N = 460 V, I_N = 320 A, n_N = 625 1/min, $k_2\phi_N$ = 6.78 Vs.
Inductances - armature: 1.5 mH, excitation: 64 H
Resistances – armature: 0.05 Ω, excitation 25 Ω
Total inertia (motor + load): J_{tot} = 150 kgm^2

1) Draw the block diagram model with transfer functions of the separately excited DC machine.

2) Use the transfer functions and determine the speed response of the DC machine when the motor drives a load at the rated torque and a suddenly drop of the input voltage of up to 20% of the rated voltage is produced.

3) Use the transfer functions and determine the speed response of the DC machine when a sudden decreases of the load of up to 50% from the rated torque is produced at the rated voltage!

4) How big is the steady-state speed deviation in the case of 2) and 3) respectively? After how long time, the machine reaches the steady state speed?

9. Cage induction generator for wind power (from Exercise 1.1)

A **three-phase 6-pole cage induction generator** for wind power has the following data:

Rated voltage: U_N = 400 V Y — Rated phase current: I_{sN} = 1095 A
Rated frequency: f_N = 50 Hz — Power factor: $\cos\varphi_s$ = 0.81 (generator)
Rated shaft power: P_N = 640 kW — Bore diameter: d_{si} = 490 mm
Number of turns per phase: N_s = 15
Amplitude of fundamental field wave: $B_{\delta,1}$ = 0.994 T
Stack length: l_{Fe} = 450 mm
The stack length l_{Fe} is assumed to be equal to the equivalent iron length l_e for simplification!

1) Calculate the induced voltage with a winding factor k_{ws1} = 0.945! How is this value called in the T-equivalent circuit?
2) Calculate the internal apparent power S_δ!
3) Determine *Esson*'s number C in $\frac{\text{VAs}}{\text{m}^3}$ and in $\frac{\text{kVAmin}}{\text{m}^3}$
   a) via S_δ,
   b) via the current loading A and the fundamental field amplitude $B_{\delta,1}$!
4) Determine with the rated current density J = 3.56 A/mm² the product $A \cdot J$ and discuss, which kind of cooling is recommended, if the stator winding temperature rise at steady state nominal operation shall not exceed $\Delta\vartheta$ = 105 K at ϑ_{amb} = 40 °C ambient temperature!
5) Determine with the product $A \cdot J$ the heat transfer coefficient α_k at nominal temperature rise according to 4)! Which kind of losses is only considered?
6) Calculate the rated apparent power S_N and the generator efficiency η_N! Is S_N bigger than S_δ and if so, why? Use the consumer reference frame and give the correct sign for the real power flow including the determination of input and output power and overall losses!
7) Determine the specific thrust for $\cos\varphi_i \cong \cos\varphi_s$ and the apparent specific thrust $\tau_{AC,app}$! Give the relationship between $\tau_{AC,app}$ and Esson's number (theoretically and calculative)!
8) Calculate the tangential force F_t and the electromagnetic torque M_e at rated operation from τ_{AC}! Assume, that M_e is equal to the shaft torque M_N and determine the speed and the slip of the generator! If we assume $M_e = M_N$, which kind of losses are neglected?

10. Cage induction motor for a pump drive (from Exercise 1.2)

A **12-pole high voltage cage induction motor** with open air ventilation is used as a pump drive in a thermal power plant. The three-phase machine has the following data:

Rated power:	P_N =1060 kW	Power factor:	$\cos\varphi_{sN}$ = 0.83
Rated voltage:	U_N = 6600 V Y	Rated frequency:	f_N = 50 Hz
Rated phase current:	I_{sN} = 117 A		

Bore diameter:	d_{si} = 830 mm
Number of stator slots:	Q_s = 72
Number of turns per phase:	N_s = 156
Coil span:	W = 5 stator slots pitches
Air gap width:	δ = 1.4 mm

The internal voltage U_h is by 5 % smaller than the stator nominal voltage with an internal power factor $\cos\varphi_i = 0.85$. For a good cooling the iron length l_{Fe} = 800 mm is separated into 20 packets with radial cooling ducts with a width of l_k = 8 mm in between.

1) Determine the slots per pole and phase q, the distribution factor k_{d1}, the pitch factor k_{p1}, and the winding factor k_{ws1} of the fundamental field wave!

2) Calculate the overall stack length L, the packet length l_1 and the equivalent iron length l_e! Give the relationship between L, l_{Fe} and l_e!

3) Evaluate the pole flux Φ of the fundamental field wave and its flux density amplitude $B_{\delta,1}$!

4) Determine the current loading A and Esson's number C with the length l_e:
   a) via the internal apparent power S_δ,
   b) via A and $B_{\delta,1}$!

5) The stator winding copper cross sections is q_{Cu} = 26.5 mm². Determine the stator current density J and the product $A \cdot J$! Is it valid for open ventilated air cooling?

6) Calculate the efficiency η_N, the total losses P_d, and the air gap power P_δ via $\cos\varphi_i$! Separate via P_δ the losses P_d into stator-side losses $P_{d,s}$ and rotor-side losses $P_{d,r}$! If rotor friction and windage losses P_{fr+w} and rotor side additional losses $P_{add,r}$ are 5 kW, how big is the slip and the speed of the rotor?

7) Calculate the specific thrust τ_{AC} and the electromagnetic torque M_e
   a) from τ_{AC},
   b) from P_δ!

11. Design of a squirrel-cage induction machine

A **squirrel-cage induction machine** is to be designed for the following rated values:

$P_N = 500$ kW $2p = 4$
$U_N = 6$ kV, Y $f_N = 50$ Hz

1) Determine the main dimensions of "bore diameter" and "length of core" with help of the design curves in the text book. According to these curves, how big ist the efficiency, the power factor, the electric loading as well as the amplitude of the fundamental wave of the magnetic air gap field?

2) Calculate with help of the values determined in 1) the so called *Esson* coefficient in units of $\mathrm{kVA\,min/m^3}$.

3) For verification calculate *Esson*'s number in units of $\mathrm{kVA\,min/m^3}$ once more, calculate the electromagnetic utilization or *Esson*'s number with the help of the electric loading and the field amplitude determined at 1). Assume that the value of the stator winding factor is $k_{ws1} = 0.91$.

4) Determine the number of turns per phase according to the fundamental wave amplitude of the magnetic field. Neglect the voltage drop across the *ohmic* resistance and the leakage reactance of the stator winding.

5) How big is the number of turns per coil if a slot number per phase and pole $q = 5$ and two layer winding with all coils per phase connected in series is chosen? Calculate the stator winding factor! Consider that the stator winding coils are connected in series and pitched by 12/15.

6) How big is the induced voltage in one coil?

12. Magnetic design of an induction motor

A four-pole **three-phase squirrel-cage induction motor** has following data:

Nominal power:	P_N = 500 kW	Nominal voltage:	U_N = 6 kV Y
Rated frequency:	f_N = 50 Hz	Power factor:	$\cos\varphi_N$ = 0.85
Efficiency:	η_N = 95.3 %	Stack length:	l_{Fe} = 0.38 m
Bore diameter:	d_{si} = 0.46 m	Air gap:	δ = 1.4 mm

The sketch (Fig. 12) shows the stator and rotor slots. The double-layer stator winding has 10 turns per coil. The stator winding coils are connected in series and pitched by 12/15. The number of stator slots is Q_s = 60 and the number of rotor slots is Q_r = 50.

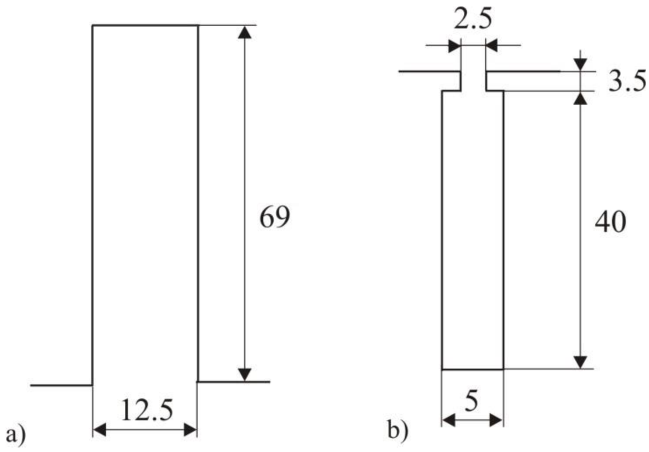

Figure 12: Dimensions of (a) stator and (b) rotor slots in millimetres

1) Calculate the nominal current I_N!

2) How big is the stator winding factor for the fundamental wave of the magnetic field?

3) How big is the amplitude of the fundamental wave of the magnetic air-gap field? Assume a stator stray coefficient of σ = 0.04 and an equivalent iron length of l_e = 0.39 m.

4) Calculate the Carter's coefficient and the equivalent air gap!

5) How big is the MMF for the air gap related to the amplitude of the field from 3)?

6) How big is the MMF for the stator and rotor tooth related to the amplitude of the field from 3)? For the magnetic material of the stator and rotor use the iron sheet type III and consider an iron stack factor k_{Fe} = 0.95. Assume that the air gap flux is completely flowing through the iron teeth.

7) How big is the degree of tooth saturation? Determine the top-flattened air-gap flux density distribution! Pay attention to the iterative determination of the degree of tooth saturation!

13. Magnetization of stator and rotor yoke

The iron stack of a 500 kW, 1480 rpm, 50 Hz, 4-pole, 3-phase, high-voltage cage-induction machine is made by iron sheets type III. The number of stator winding turns per phase is $N_s = 200$ and the stator winding factor is $k_{ws1} = 0.91$. The following data of the motor geometry are available:

Air gap:	$\delta = 1.4$ mm
Number of stator/ rotor slots:	Q_s / Q_r = 60 / 50
Length of stator/ rotor tooth:	l_{ds} / l_{dr} = 69 mm / 43.5 mm
Lamination factor:	$k_{Fe} = 0.92$
Equivalent iron length:	$l_e = 0.392$ m
Iron stack length:	l_{Fe} =0.38 m
Inner/Outer diameter of the laminated core:	d_{si}/d_{so} = 0.46 m/ 0.75 m
Shaft diameter:	$d_{sh} = 0.2$ m

1) Due to the influence of saturation, the distribution of the flux density in the air gap is flat-top. The amplitude of the air gap flux density $B_{\delta,max}$ is 0.86 T, while the amplitude of the fundamental *FOURIER*-flux density wave $B_{\delta,1}$ is 0.94 T. How big is the m.m.f. of the air gap? Consider the *Carter*'s coefficient: $k_c = 1.53$.

2) What is the value of the flux density B_{ys} in the stator yoke? The value of the stator leakage-flux has to be taken into account as $\sigma_s = 0.04$ ($\Phi_{s\sigma} = \sigma_s \cdot \Phi_h$).

3) Calculate the m.m.f. for the stator yoke!

4) What is the value of the flux density B_{yr} in the rotor yoke? Consider for the calculation of B_{yr}, a diameter of $c_2 = 30$ mm of the axial cooling ducts in the rotor yoke and the solid iron shaft with: $\mu_{sh} = 1000\mu_0$ and $\sigma_{sh} = 5$ MS/m.

5) Calculate the m.m.f. for the rotor yoke using the values of 4)!

6) Calculate the magnetizing current! How big is the magnetizing current related to the rated current $I_N = 59$ A? Assume the values of m.m.f for the stator and rotor tooth: $V_{ds} + V_{dr} = 475$ A.

7) Calculate the unsaturated and saturated magnetizing reactance!

14. Current displacement in deep-bars and wedge-bars

A rotor of a 500 kW, 6 kV, Y, 59 A, 1480/min, 94%, 50 Hz, 4-pole induction motor is equipped either with the copper deep-bar of Fig 14 a). The equivalent iron length is $l_e = 0.392$ m, the total axial length is $L = 460$ mm, the number of turns per phase is $N_s = 200$, the stator winding factor is $k_{ws1} = 0.91$ and the number of rotor slots is $Q_r = 50$.

1) Calculate the resistance per bar for the deep-bars at no load operation (slip $s = 0$) and 20°C.

2) Perform the same calculation done in 1) at stand-still.

3) How big are the bar current densities and the *ohmic* losses per bar at the rated slip and stand-still? Assume that the starting current is 5.5 times higher than the rated current.

4) The deep-bar of Fig. 14-a) is replaced with the wedge-bar of Fig 14-b). How big is the wedge-bar resistance at stand-still?

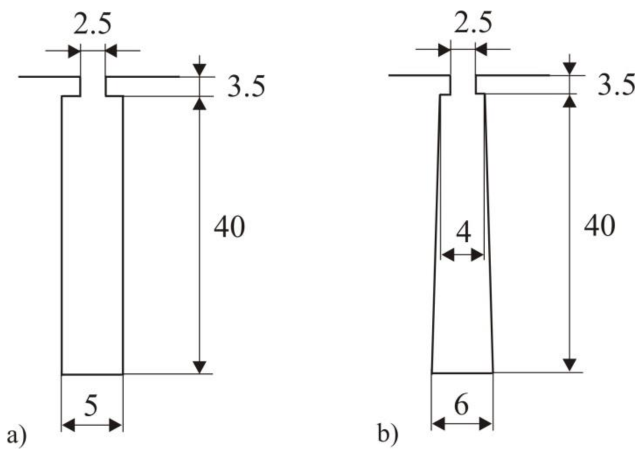

Figure 14: Dimensions of a) deep-bar and b) wedge-bar rotor slots in millimetres:

15. Calculation of stator and rotor slot leakage inductances

The cross sections of the stator and rotor slots of a 500 kW, 6kV, 4-pole cage induction machine are presented in Fig. 15.1 and 15.2. The number of stator/rotor slots is Q_s / Q_r = 60 / 50, the double-layer stator winding has 10 turns per coil and the stator winding coils are connected in series and pitched by 12/15. The insulations of the stator winding are given in Table 15.

Table 15: High voltage insulations for the stator winding

Inter-turn insulation:		0.3 mm
Conductor insulation	$d_{ic} = 2 \cdot 0.2$	= 0.4 mm
Main insulation	$2 \cdot 2.2$	= 4.4 mm
Inter-layer insulation:	Z	= 4.0 mm
Slot-lining (3 times in vertical direction):	$3 \cdot 0.15$	= 0.45 mm
Wedge:		4.5 mm
Top and Bottom lining:	$2 \cdot 0.4$	= 0.8 mm
Cond. height	h_L	= 1.80 mm
Conductor width	b_L	= 7.1 mm
Slot height	h_Q	= 69.0 mm
Slot width	b_Q	= 12.5 mm

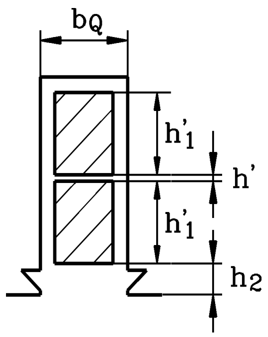

Fig. 15.1: Cross section in the stator slot; the upper and lower layer of the stator winding coils

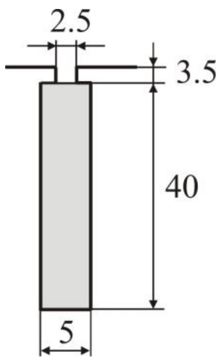

Fig. 15.2: Cross section in the deep rotor bar (dimensions in mm)

1) For 2 poles, sketch the position of the coils of the three-phase double layer winding!

2) Determine the dimensions of Fig. 15.1 and calculate the stator slot leakage inductance! Consider an equivalent iron length l_e = 0.392 m.

3) Calculate the rotor slot leakage inductance at rated slip s_N = 1.33% and stand-still! The conductivity of the copper bar is σ_{Cu} = 57 MS/m.

16. "Re-winding" of an induction machine

Deep-bar squirrel-cage induction motor:

Rated data:

$P_N = 500$ kW
$U_N = 6$ kV Y
$I_N = 59.5$ A
$n_N = 1482$ min^{-1}
$f_N = 50$ Hz

Stator winding data:

Winding type:	double-layer winding
Number of turns per coil and layer:	$N_c = 10$
Number of stator slots:	$Q_s = 60$

All coils per phase are connected into series!

Equivalent circuit parameters

The following data of the equivalent circuit diagram are known:

$$R_s = 0.74\ \Omega;\ X_{s\sigma} = 6.69\ \Omega;\ X_h = 150.5\ \Omega,$$

At $s = 1$ (current displacement!): $R_r' = 1.52\ \Omega$; $X_{r\sigma}' = 3.534\ \Omega$.

1) Calculate the stationary current at $s = 1$! How many times is it bigger than the rated current?

2) The number of turns per coil will be decreased from 10 to 9. Decreasing the number of turns per coil allows to increase the cross-section of copper (The fill factor of a stator slot remains unchanged). How do the motor impedances change? How do the starting torque and current vary in comparison to the given data?

3) Does the total leakage coefficient and the breakdown slip change? In case of changes, what is the percentage of the changes?

4) How do the air-gap induction, the primary current at rated slip and the electric loading change?

17. Magnetic design of an induction motor (from Exercise 2.1)

A four pole **three-phase squirrel-cage induction motor** (tapered deep-bar cage rotor) has following data:

Nominal power:	P_N =55 kW	Nominal voltage:	U_N =380 V/ 220 V Y/Δ
Rated frequency:	f_N =50 Hz	Power factor:	$\cos\varphi_N$ = 0.885
Efficiency:	η_N = 90.8 %	Stack length:	l_{Fe} = 220 mm
Bore diameter:	d_{si} = 270 mm	Air gap:	δ = 0.7 mm
Specific iron losses:	v_{10} = 2.3 W/kg	Sheet thickness:	b_{sh} = 0.5 mm
Iron stack factor:	k_{Fe} = 0.94		

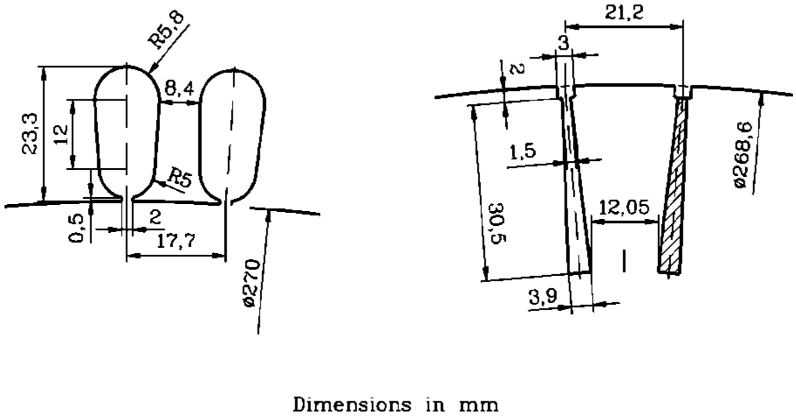

Fig. 17: Stator and rotor iron lamination geometry

The sketch shows the stator and rotor lamination in the slot region. The double-layer stator winding has 11 turns per coil and layer, and four parallel branches. Coils are pitched by 5/6.

1) Calculate the nominal current I_N as well as the stator and rotor slot number.

2) How big is the number of turns per phase and the winding factor for the fundamental wave of the magnetic field?

3) How big is the amplitude of the fundamental wave of the magnetic air-gap field in motor idle operation? The voltage drop across the *ohmic* resistance and the leakage reactance in the stator winding is to be neglected.

4) How big is the m.m.f. for the air gap related to the amplitude of the field from 3)?

5) How big is the m.m.f. for the stator tooth related to the amplitude of the field from 3)? Consider only the parallel sided part of the tooth and neglect the magnetic flux through the slot.

6) As shown in the sketch, the rotor tooth is considerably broader than the stator tooth, so that its influence on saturation – as well as the influence of the rather low yoke flux density – can be neglected. How big is the magnetizing current referred to the rated current in percent?

18. Hysteresis and eddy-current losses in the stator core (from Exercise 2.5)

The drawing below shows the cut out of stator lamination. It was made for the stator of a four pole induction motor. The rated power P_N of the motor at 50 Hz is 55 kW. Further data of the motor:

Number of stator slots:	$Q_s = 48$
Lamination factor:	$k_{Fe} = 0.95$
Length of core:	$l_{Fe} = 220$ mm
inner/outer diameter of the laminated core:	$d_{sa}/d_{si} = 400$ mm / 270 mm

The coefficients for the calculation of the hysteresis and eddy current losses of the sheet steel

at 1 T and 50 Hz are: $\sigma_{Hy} = 1.3$ W/kg, $\sigma_{Ft} = 0.4$ W/kg

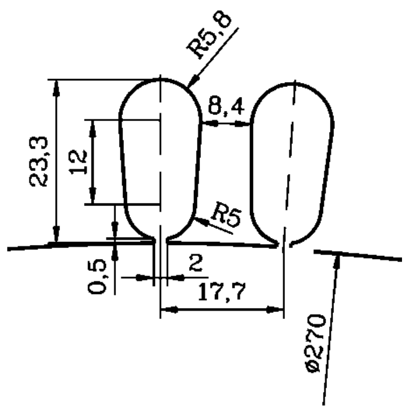

Fig. 18: Stator iron lamination geometry

1) Due to the influence of saturation, the distribution of the flux density in the air gap is flat-top. The amplitude of the air gap flux density $B_{\delta,max}$ is 0.8 T, while the amplitude of the fundamental FOURIER-wave $B_{\delta,1}$ is 0.85 T. What is the value of the main flux Φ_h? For calculating Φ_h make use of the value for the flux density of the fundamental wave.

2) What is the value for the apparent induction B'_{ds} in the teeth and the induction B_{ys} in the yoke. The value of the stator leakage-flux has to be taken into account as $\sigma_s = 0.04$ ($\Phi_{s\sigma} = \sigma_s \cdot \Phi_h$).

3) Calculate the value for the specific iron loss v_{10} of the magnetic sheet steel for the frequencies of 50 Hz and 100 Hz in the *Epstein* frame!

4) Under influence of higher harmonics and by stamping the magnetic sheet steel, the loss coefficients for the iron increases compared to *Epstein* frame values. The eddy-current and hysteresis losses in the teeth are 80 % and in the yoke 50 % higher than according to *Epstein* frame. Recalculate the hysteresis and eddy-current losses for 50 and 100 Hz !
***Advice*:** For simplification make use of B'_{ds} instead of B_{ds}!

19. Heating of a three-phase winding (from Exercise 3.1)

A three-phase a.c. motor has stator coils according to the drawing of the slot as shown below (all conductors are connected in series). The dimensions of the bright shaped wire are 7.1 mm×1.8 mm. The active iron length l_{Fe} is 380 mm, the inner stator diameter d_{si} is 460 mm and the number of stator slots Q_s is 60. Further data of the motor are given.

Data:

$P_N = 500$ kW
$U_N = 6$ kV
$I_N = 59$ A
$n_N = 1460$/min

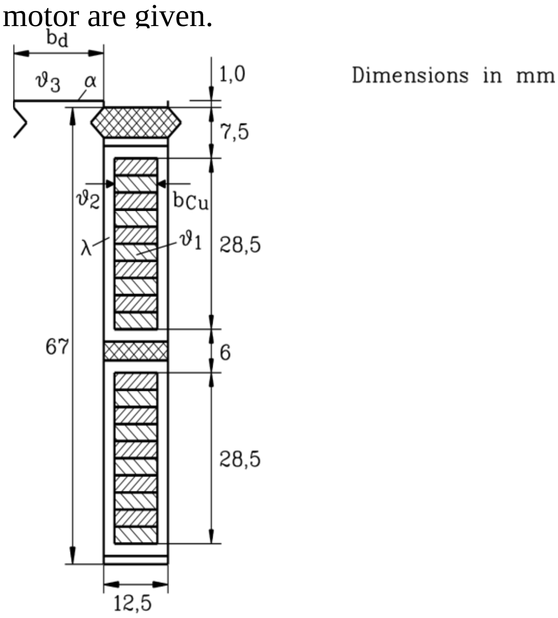

Fig. 19: Stator slot geometry

1) Calculate the *ohmic* losses per slot and the current density in the conductor at an ambient temperature of 30 °C. Make sure that the temperature-rise limit for a winding of thermal class B is fully utilized!

2) Compute the temperature difference between the copper wire and the stator core, if the heat conductivity of the slot insulation λ is 0.2 W/(m·K). The heat flow via the slot wedge shall be neglected.

3) Calculate the temperature difference between tooth tip (surface along b_d) and the air in the air gap. Assume, that half of the *ohmic* losses is flowing as heat flow directly to the housing via the stator core.
The heat transfer coefficient α (W/(m^2·K) at the surface of the core assembly is depending on the circumference speed of the rotor v_u as the following equation shows:

$$\alpha = 30 \cdot \sqrt{0.75 \cdot v_u} - 20 \quad (v_u \text{ in m/s})$$

What is the temperature difference between the copper of the winding and the cooling air at the air gap, when the temperature gradient of the iron along the tooth is neglected?

20. Thermal Heating of a Totally Enclosed, Fan Cooled Cage Induction Motor (from Exercise 3.4)

A totally enclosed, fan cooled, cage induction motor has the following losses and thermal resistances according to Fig. 20:

- Rotor-end ring via air to end shield: R_{th1} = 167 mK/W
- End shield via housing to ambient air: R_{th2} =50 mK/W
- Rotor surface via air gap to stator iron: R_{th3} = 79 mK/W
- Stator winding via insulation to stator teeth: R_{th4} = 21 mK/W
- Stator teeth to stator yoke: R_{th5}= 12 mK/W
- Stator yoke via housing to ambient air R_{th6} = 20 mK/W
- Rotor cage losses, including additional losses and friction losses: $P_r = P_{cu,r} + P_{ad} + P_{fr+w}$ =1300 W
- Stator winding losses: $P_{Cu,s}$ = 1200 W
- Stator iron losses in teeth $P_{Fe,ds}$ = 200 W
- Stator iron losses in the yoke $P_{Fe,ys}$ = 400 W

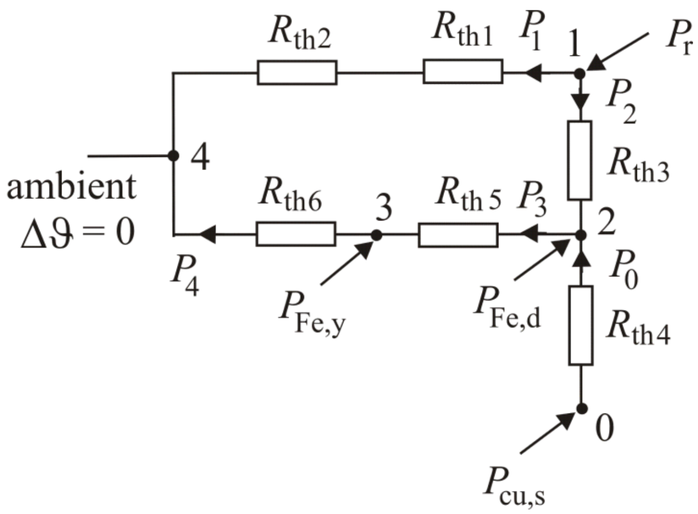

Fig. 20: Losses and heat sources plot

1) Determine the temperature rise $\Delta\vartheta_{20}$ between stator winding and stator iron!
2) Determine the motor efficiency for an output power of P_{out} = 60 kW!
3) Determine the heat flow P_0!
4) Determine the heat flow P_1, P_2, P_3, P_4! [3] Give the power flow as a graph like in Fig. 20.
5) Determine the temperature rise $\Delta\vartheta_1$ in the cage (node 1), $\Delta\vartheta_2$ of the stator iron teeth (node 2) and $\Delta\vartheta_3$ of the stator iron yoke (node 3)!
6) Where is the hot spot in the machine?

[3] Use the Kirchhoff's circuit laws!

21. Different operation modes of a.c. machines (from Exercise 3.2)

A **500 kW three-phase asynchronous motor**, with shaft-mounted fan, thermally utilized in accordance with Thermal Class H, with an efficiency of 94.7 %, has a thermal time constant T_ϑ = 1 h with rotating rotor (fan turns) and a time constant $T_{\vartheta\mathrm{St}}$ = 1.5 h with locked rotor (fan is not moving).

1) How big is the admissible maximum temperature rise of the stator winding? How big are the losses, which the motor at continuous operation may have?

2) How big are the admissible total losses and the output power of the motor in the S2-Operation (30 min. operating time)?

3) How long is the operating time, how big are the admissible total losses and the output power of the machine in the S3-Operation (60 % ON-time, duty cycle time 20 min.)?

4) Which temperature (°C) and temperature rise (K) are reached within the motor winding at an ambient temperature of 20 °C, if the machine is operated continuously with the admissible output power according to 3)? To what extent is the life span shortening of the used insulation system with this mode of operation?

22. Heating up of an asynchronous machine with blocked rotor (from Exercise 3.3)

A **three-phase asynchronous motor with squirrel-cage rotor** (wedge-bars in the rotor) and following rated data

P_N = 55 kW; U_N = 400 V Y; f_N = 50 Hz; $\cos\varphi_N$ = 0,86, η_N = 0.9

will be connected to the mains. Due to a defect in the coupled load machine the motor cannot run up; the rotor is **blocked**. From the calculation sheet of the manufacturer, the following data of the equivalent circuit diagram are known:

R_s = 0.06 Ω; $X_{s\sigma}$ = 0.17 Ω; X_h = 8.63 Ω,
At s = 1 (current displacement!): R_r' = 0.17 Ω; $X_{r\sigma}'$ = 0.24 Ω.

Answer the following questions:

1.) How big is the stationary current in the stator winding?

2.) How many times is it bigger than the rated current?

3.) How big are the copper losses in the stator winding at s = 1 compared to the rated operation?

4.) The mass of the stator winding amounts to 22.9 kg. Determine the final temperature of the stator winding with an ambient temperature (coolant temperature) of ϑ_{amb} = 25°C, if the protection switch disconnects the motor from the mains after 20 s. Neglect due to this short operating time the heat transfer from the winding to the ambient (heat transfer coefficient $\alpha \cong 0$: "adiabatic heating"); specific thermal capacity of copper c_{Cu} = 386 Ws/(kg·K).

5.) The thermal time constant $T_{\vartheta,st}$ of the machine at stand still (n = 0) amounts to 40 min. How big is the winding temperature ϑ_{Cu} at the time 25 min after switching the motor off?

23. Transient temperature rise in a motor stator (from Exercise 3.6)

The temperature rise in the stator iron stack and stator copper winding of a 4-pole 11 kW squirrel cage induction motor for 400 V Y, 50 Hz, has to be calculated for rated steady state operation after turning on the cold machine. The air-cooled motor is totally enclosed with a shaft-mounted radial fan (TEFC). The thermal resistance between the stator iron stack in the housing and the outside air is determined by the cooling fins as R_{th1} = 0.072 K/W, and that of the electrical insulation between the stator winding in the slots as R_{th2} = 0.047 K/W. The stator winding copper mass and specific heat capacity are m_{Cu} = 4.8 kg, c_{Cu} = 388.5 Ws/(kgK); the corresponding values for the stator iron stack are m_{Fe} = 22.5 kg, c_{Fe} = 502 Ws/(kgK). The losses in the stator winding and stator iron stack are constant as P_{Cu} = 554 W, P_{Fe} = 260 W. Use in the following the simplified thermal equivalent network of Fig. 23. The masses of the housing and of the end shields and the corresponding heat flow are neglected as well as the rotor copper, friction and additional losses!

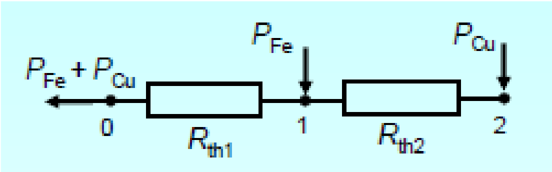

Fig. 23: Thermal equivalent network of the stator iron stack and stator copper winding

1) Give the set of differential equations for the temperature rise of the iron stack $\Delta\vartheta_{Fe}$ in node 1 and of the stator copper winding $\Delta\vartheta_{Cu}$ in node 2 for general functions $P_{Cu}(t)$, $P_{Fe}(t)$. Assume the temperature rise in node 0 (housing surface) over the air coolant temperature to be zero: $\Delta\vartheta = 0$.
2) Give for the system of Fig. 23 one resulting differential equation a) for $\Delta\vartheta_{Cu}$, b) for $\Delta\vartheta_{Fe}$. Comment the result!
3) Give the relevant thermal time constants.
4) Determine the temperature rise $\Delta\vartheta_{Cu}(t)$ and $\Delta\vartheta_{Fe}(t)$ as general formulas for the initial condition $\Delta\vartheta_{Cu}(0) = 0$, $\Delta\vartheta_{Fe}(0) = 0$ and constant losses P_{Cu} = const., P_{Fe} = const.
5) Give the steady state values $\Delta\vartheta_{Cu}(t \to \infty) = 0$, $\Delta\vartheta_{Fe}(t \to \infty)$.
6) Give the graph $\Delta\vartheta_{Cu}(t)$ and $\Delta\vartheta_{Fe}(t)$ for $0 \le t \le T$ (with T at least as three times the longest time constant of the system).

24. Space vector representation of an induction machine

A three-phase 110.8 kW, 380 V Y, 212 A, 50 Hz, 2 pole pairs induction machine with a power factor cos φ =0.85, efficiency of 93.4% and a motor inertia of J = 2.8 kgm^2 has the following parameters of the equivalent circuit:

R_s = 25 mΩ, R_r' = 20 mΩ, L_s = 9.71 mH, L_r' = 9.55 mH, L_h = 9.17 mH

1) Find the *quadrature*-, *direct*-, and *zero*-axis components of voltage in an arbitrary reference frame, if the following phase voltages are supplied to the stator winding terminals:

$$u_R(\omega t) = 220\sqrt{2} \cdot \cos(\omega t)$$
$$u_S(\omega t) = 220\sqrt{2} \cdot \cos\left(\omega t - \frac{2\pi}{3}\right)$$
$$u_T(\omega t) = 220\sqrt{2} \cdot \cos\left(\omega t - \frac{4\pi}{3}\right)$$

2) Write the stator and rotor equations in a reference frame which rotates at an arbitrary angular speed ω_k. Draw the space vector model of the machine.

3) The reference system of 2) rotating at the speed ω_k is set to the stator reference frame. Use the *quadrature*-, and *direct*- axis and give the equivalent circuit of the machine on the two axes!

4) Determine the machine data for the p.u. calculation!

5) Neglect the stator and rotor resistances and calculate the no-load current and starting current in p.u.

6) The machine is running at no-load speed at steady-state. At a time $\tau = 0$ the motor is disconnected from the power grid. Calculate in p.u. the space vector of the decaying stator voltage which is induced by the decaying rotor flux. During the transient process the speed can be assumed constant and the stator resistance can be neglected. Chose for this calculation a reference frame which is oriented to the rotating field $\omega_k = \omega_{syn}$.

25. Stator space vectors of an induction machine with removed rotor

The three-phase stator winding of an induction motor is tested during manufacturing with removed rotor. The stator winding is connected in star to the three-phase AC system at reduced voltage (u = 0.2 p.u):

$$u_R(\tau) = u \cdot \cos(\tau)\,, \quad u_S(\tau) = u \cdot \cos\left(\tau - \frac{2\pi}{3}\right), \quad u_T(\tau) = u \cdot \cos\left(\tau - \frac{4\pi}{3}\right)$$

Due to the removed rotor (air gap = half stator bore diameter) the impedance x_s is rather small, containing only the stator stray flux and the small stator bore field: x_s = 0.2 p.u. The stator resistance is neglected.

1) Calculate the voltage space vector $\underline{u}(\tau)$!

(**Note**: Use the formula $\cos x = (e^{jx} + e^{-jx})/2$)

2) Calculate the current space vector $\underline{i}(\tau)$ in steady state operation and draw the trajectory of $\underline{i}(\tau)$ in a diagram.

3) Due to a failure, the phase connection W of the induction machine breaks (Fig. 25.1). Calculate the space vector $\underline{i}(\tau)$ in p.u. after failure and draw the vector $\underline{i}(\tau)$ in a diagram.

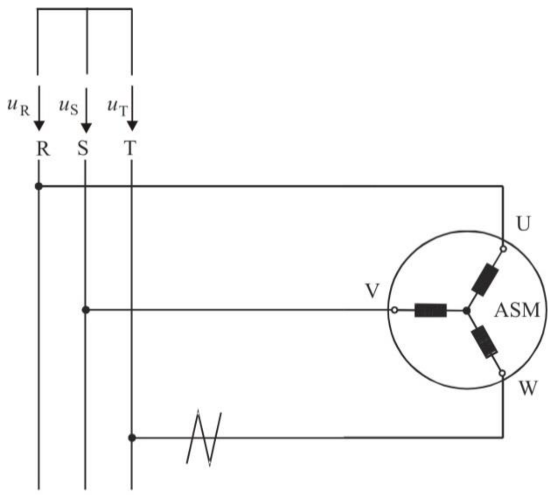

Fig. 25.1: Electric circuit with broken W connection

26. Current space vector of a power synchronous drive

A synchronous motor used in a petrochemical factory is supplied by a current-source inverter. The phase currents in the stator winding and the phase voltages are given in Fig. 26.1 and Fig. 26.2 respectively.

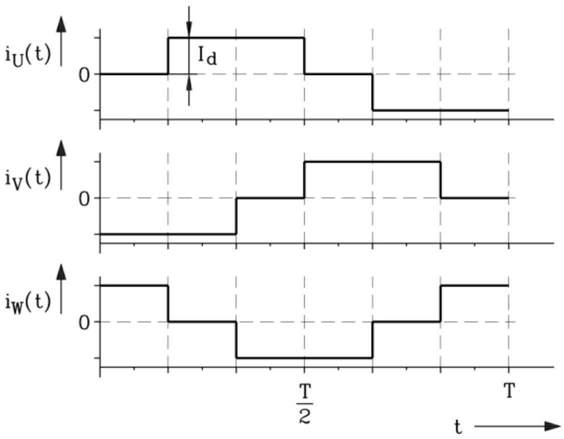

Fig 26.1: Phase currents function of time

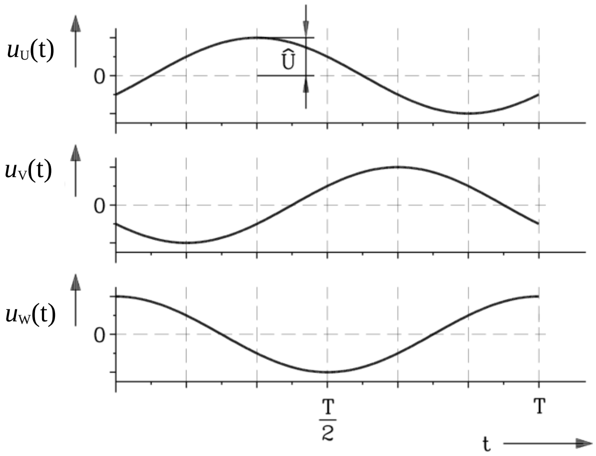

Fig. 26.2: Phase voltages function of time

1) With which power factor is the motor operated (see Fig. 26.1 and 26.2)?

2) Calculate the current space vector in A, for an inverter DC-link current of I_d = 1850 A, at the following instants of time:

   a) $t = T/12$ and b) $t = T/4$.

3) Draw the current space vectors $\underline{i}$(T/12), $\underline{i}$(T/4) of 2) in the complex reference frame (Scale: 200 A/cm). How big is the angle between the two vectors?

27. Voltage space vector of an inverter-synchronous machine drive system

A permanent magnet synchronous machine without damper cage, which is controlled by a rotor position encoder, is fed by an inverter for a six step voltage operation in field oriented control.

1) Draw the electric circuit of the inverter with the star connected stator winding!

2) Which transistors must conduct to get the stator voltage space vector $\underline{u}_s = 0.85 \cdot e^{j \cdot 240°}$, when the machine is supplied from two phases of the inverter?

28. Sudden short circuit of induction motor after no-load operation (in script 7.6-2.)

An induction motor is operating at no load, rated voltage, at the grid and is short-circuited in all three phases between grid fuses and motor terminals. Grid fuses blow, disconnecting short-circuited machine from grid. Magnetic energy of main flux is dissipated in stator and rotor ohmic losses by the big short circuit current flow. The decay of short-circuit current happens due to $\omega_m = 1$ with electric short-circuit time constant (7.6-21) rather quickly, so speed does not change significantly, and assumption of constant speed is justified.

Motor data	4 pole motor, 50 Hz operation	
Rated power	110.8 kW	
Rated voltage	380 V Y	$u_s = 1$
Rated current	212 A	$i_s = 1$
Rated speed	1470/min	
Rated torque	720 Nm	$M_B = 888.3$ Nm
J	2.8 kgm^2	$\tau_J = 155.5$
R_s	25 mΩ	0.024 p.u.
R_r'	20 mΩ	0.019 p.u.
L_s	9.71 mH	2.95 p.u.
L_r'	9.55 mH	2.90 p.u.
L_h	9.17 mH	2.78 p.u.
σ	0.094	

1) Derive the formulas of the stator $\underline{i}_s(\tau)$ and the rotor current $\underline{i}'_r(\tau)$ in the time domain after short-circuit.

2) Solve the stator and the rotor current space vectors for the non-damped short circuit case ($r_s = r_r' = 0$). Give the maximum short circuit U-phase current (peak) when short-circuit occurred a) at voltage zero crossing and b) at maximum voltage.

29. Sudden short circuit of an induction machine (from Exercise 7.2)

A **3-phase induction motor** is running at no-load connected to a 60 Hz grid.

Motor specification: U_N = 460 V Y, 60 Hz, rated current 22 A, no-load current 9 A, *Blondel's* leakage coefficient σ = 0.07. Measurement of resistance between two stator terminals results in $0.4\ \Omega$ (rotor open-circuit time constant $\tau_r = x'_r / r'_r = 70$).

Calculate

1) the rated impedance and per-unit value of the stator resistance.

2) the primary reactance X_s, its per-unit value x_s and corresponding inductance L_s.

3) the space vector of stator and rotor flux linkage in rotating-field oriented reference frame. Assume that $x_s = x'_r$!

4) A short-circuit occurs at the terminals suddenly. How big is the maximum value of the sudden short circuit current in the worst case, when neglecting any damping of current? The short circuit current decays to the steady state value. What is the value of this steady state level? With which typical time constant does associated short-circuit alternating torque decay and to which steady state value? How much time is needed approximately to reach this steady state value?

30. Starting of an induction machine (from Exercise 7.3)

A wedge bar cage induction machine with the following nameplate data is given:

Frame size 250 mm, 55 kW, 220V/380V, Δ/Y, 178 A/103 A, 50 Hz, 1455/min, $\cos\varphi = 0.885$, continuous duty, Thermal Class B, mounting IM B3

From the catalogue additional details are given: starting current 4.4-times, starting torque 1.55-times, break down torque 1.94-times, inertia 0.9 kgm^2, machine mass 440 kg

From the calculation sheet of the manufacturer there are the addition data available:
Break down slip 13.3 %, at 75° according to Thermal Class B, stator resistance $R_s = 0.06\ \Omega$, rotor resistance $R'_r = 0.0643\ \Omega$, stator reactance $X_s = 8.8\ \Omega$,
rotor reactance $X'_r = 9.03\ \Omega$, leakage coefficient $\sigma = 0.067$.

Calculate:

1.) the nominal torque, breakdown torque, starting torque in Nm, starting current at Δ- and Y- connection and the motor efficiency,

2.) the nominal impedance and the motor equivalent circuit parameters for rated slip in per unit (p.u.). Calculate also in p.u.: the nominal torque, the nominal voltage (peak value), the nominal current (peak value), the nominal frequency, the nominal apparent power, the nominal power,

3.) the start-up time constant in seconds and in p.u.

4.) The motor is starting with no load. Is the static break down torque reached? If not, please calculate the maximum occurring torque. In a second test the machine starts up with no load at half of the nominal voltage. Is static break down torque reached?

31. Current feeding of a locked rotor induction machine (from Exercise 6.2)

A locked rotor induction machine is fed by a current controlled inverter. At time t = 0 the de-energized machine is abruptly fed by a stator current space vector $\underline{i}_s(\tau) = i_s \cdot e^{j0°}$, $i_s = 1\,\text{p.u.}$

Motor data: (p.u. values, phase values, star-connected stator winding)

Stator resistance: $r_s = 0.04\,\text{p.u.}$
Stator inductance: $x_s = 3.0\,\text{p.u.}$
Rotor inductance: $x_r' = 3.0\,\text{p.u.}$
Rotor open-circuit time constant: $\tau_r = \dfrac{x_r'}{r_r'} = 60$
Blondel's leakage coefficient: $\sigma = 0.07$

1.) Draw the circuit state of the inverter and the current path through the machine for the given current space vector.

2.) Calculate the time characteristic of the rotor flux linkage space vector after the current step and draw the time function of the current. Use the stator reference frame!

32. Synchronous machine at the three-phase sinusoidal symmetrical grid

The time functions of the three-phase sinusoidal voltages in p.u.:

$$u_{sU}(\tau) = u_s \cdot \cos(\omega_s \tau)\,, \quad u_{sV}(\tau) = u_s \cdot \cos(\omega_s \tau - \frac{2\pi}{3})\,, \quad u_{sW}(\tau) = u_s \cdot \cos(\omega_s \tau - \frac{4\pi}{3})$$

result in a stator space vector $\underline{u}_s$ in the stator reference frame as: $\underline{u}_{s(S)} = u_s \cdot e^{j\omega_s \tau}$.

1) Give the stator space vector $\underline{u}_s$ in the rotor d-q-reference frame. The rotor rotates with $\omega_m = \omega_s = \text{const}$. At $\tau = 0$, the rotor position is $\gamma_0 = 0$.

2) Draw the equivalent circuit of the synchronous machine in the d-q-rotor reference frame and give the complete set of dynamic equations!

3) Give the voltage and flux linkage equation of the synchronous machine with field and damper winding for steady state condition in the rotor reference frame. Neglect the stator resistance! Calculate the damper and field current for $u_f = 1$ p.u. and $r_f = 0.707$ p.u. How big is the back EMF u_p for $x_d = x_f = 1.2$ p.u. and $x_{dh} = x_{qh} = 1$ p.u at $\omega_m = \omega_s = 1$ p.u.?

4) Calculate the u_d, u_q, i_d, i_q and give the phasor diagram for the voltage and current space vector $\underline{u}_s$ and $\underline{i}_s$ in the d-q-rotor reference frame for $\underline{u}_{s(R)} = \underline{u}_s = 1 \cdot e^{j \cdot \frac{\pi}{4}}$. Sketch u_p in the d-q-reference frame and determine the load angle ϑ. Is the synchronous machine a generator or motor? Over- or under-excited?

33. Synchronous servomotor for a machine tool drive (Brushless DC motor) (from Exercise 8.4)

A **permanent magnet excited synchronous motor** is operated from voltage source inverter. Rotor position is measured by an encoder and controls phase angle of stator voltage (field oriented control = brushless DC drive). No damper cage is needed in the rotor.

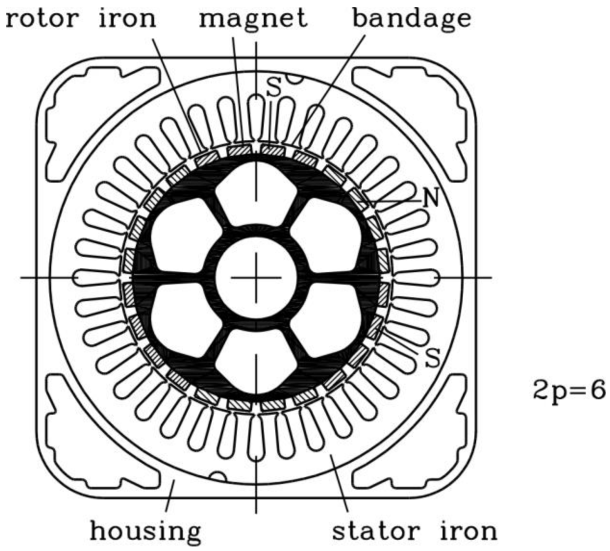

Fig. 33: Axial section of a permanent magnet synchronous machine without damper cage

Given: x_d = 0.35 p.u., $r_s \approx 0$, back EMF u_p = 0.71 p.u. at nominal speed.

1) Indicate the dynamic set of equations of the machine.

2) Draw the space vector diagram for stationary operation in rotor reference frame for rated speed. With which angular position relative to q-axis the stator current space vector has to be operated, so that the machine develops maximum torque?

3) Indicate for the results of 2) the space vector diagram for rated current and speed in rotor reference frame. How big is the amplitude of the stator voltage space vector?

4) How big is the maximum torque for field-oriented control operation in accordance with 2) for rated speed, if the inverter maximum voltage U_{max} is rated voltage U_N?

34. Locked Rotor Synchronous Drive (from Exercise 8.5)

A 6-pole permanent magnet synchronous machine without damper cage, which is controlled by a rotor position encoder, is fed by a converter in field oriented operation. In locked rotor operation the machine is supplied from two phases of the converter with a voltage space vector $\underline{u}_s = u_s \cdot e^{j \cdot 120°}$.

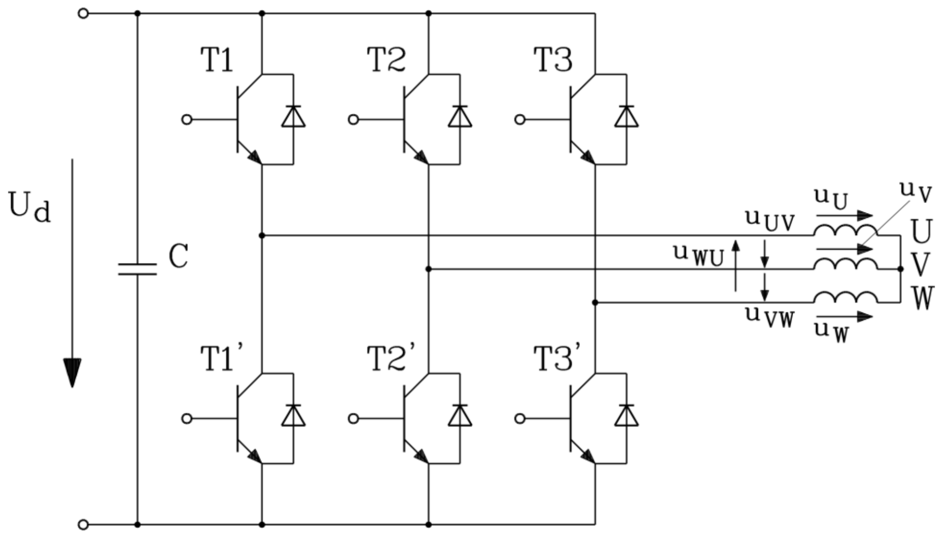

Fig. 34: The electric circuit of the inverter with the star connected stator winding

Motor parameters: stator winding star connection, r_s = 0.05 p.u., x_d = 0.3 p.u., rated voltage 231 V, rated current: 10 A (r.m.s.), rated speed 3000/min. The six-pole rotor has surface mounted permanent magnets, so the direct and the quadrature axis inductance are identical: $x_d = x_q$.

1) Which transistors must conduct in Fig. 34 to get the wanted position of the stator voltage space vector? Describe the corresponding current flow!

2) Compute and draw for 1) the time function of current in the phase W (in Ampere), if the current was zero at the beginning. Since *d*- and *q*-axis are identical and the machine is not rotating (no rotation voltage is induced by the permanent magnets), you can use the asynchronous machine system of equations without secondary (no damper) e. g. in synchronous reference frame. The dc link voltage is U_d = 489 V. Is this point of operation admissible for the drive system?

3) Give the six switching states of the inverter and the corresponding positions of the stator voltage space vector for voltage six-step operation.

35. Sudden short circuit of a marine generator (from Exercise 8.7)

On a cruise ship with electric propulsion the power supply is provided by 3 diesel-powered on-board generators with 32 MVA each. Data of each of the synchronous generators:
U_N = 10.5 kV Y, S_N = 32 MVA, $\cos\varphi_N$ = 0.8, overexcited, f_N = 50 Hz, reactances: x_d = 1.1 p.u., $x''_d = 0.18$ p.u.. The stator resistance is neglected.

1) One of the generators, which was operating at no-load ("stand-by"), suffers from a sudden terminal short circuit after a system failure. The short circuit happens during the zero-crossing of phase V. How big is the peak value of the sudden short circuit current in phase V, if a decay rate of the dc-component of 0.8 is assumed?

2) How big is the amplitude of the steady-state short circuit current, after all transient currents have vanished, if this current is not switched off immediately by a power switch?

3) The generator needs to be sent back to the manufacturer to be repaired. After successful recovery, the generator shall be asynchronously started in the manufacturer test bay via the damper cage. How big is the stator current per phase assuming a direct connection of the machine to the grid in the worst case?

4) To limit the asynchronous starting current according to 3) a series inductor shall be dimensioned. How big must this inductance be to reduce the starting current to 70 %?

5) Which further advantages are obtained by using a starting-transformer, which feeds with its secondary winding the stator winding, with a transfer ratio $ü$ = 2? Calculate the AC starting current on grid and secondary side, if the primary and secondary leakage reactances are $x_{1\sigma} = x'_{2\sigma}$ = 0.03 p.u. and the rated primary voltage is 10.5 kV, and the rated transformer power is 6.5 MVA!

36. Sudden short-circuit of an hydro-electric synchronous salient pole generator (from Exercise 8.1)

The machine has following specifications:
20 poles, 32.2 MVA, 11 kV, $\cos\varphi$ = 0.9, bore diameter = 3.8 m, X_{dh} = 3.42 Ω, $X_{qh} = 0.6 \cdot X_{dh}$, $X_{s\sigma}$ = 0.52 Ω, $X_{f\sigma}$ = 0.484 Ω, $X_{D\sigma}$ = 1.73 Ω, $X_{Q\sigma}$ = 0.56 Ω, R_s = 15.2 mΩ, R_f = 0.002 Ω, R_D = 0.31 Ω, R_Q = 0.08 Ω.
The reactances and resistances are already converted to the stator side at 50 Hz and 75°C (Thermal Class B).

Note: Above rotor values are already converted with the respective transformation ratio to the stator side. The "true", measurable value of the ohmic resistance of the field winding is for example R_f = 0.23 Ω. For this reason the converted values of the field winding are smaller than those of the damper winding, because the transformation ratio "stator- to- field" is very small ($\ddot{u} \sim N_s/N_f$, N_f is large, since all 20 poles are connected in series: N_s = 96, N_f = 20 x 55 =1100).

Calculate

1) rated current, rated impedance and per-unit value of above resistances and reactances.

2) the reactances: direct-axis X_d, quadrature-axis X_q, transient X'_d, direct-axis subtransient X''_d and quadrature-axis subtransient X''_q in per-unit value. Is the machine "subtransient symmetrical"?

3) the time constants: open-circuit field T_f, direct-axis open-circuit damper T_D, quadrature-axis open-circuit damper T_Q, armature time constant T_a, transient T'_d and subtransient time constants T''_d.

4) The worst case of sudden short-circuit at the generator terminals shall be calculated! Use the formula indicated in the lecture notes for the calculation of the sudden short-circuit current in phase U in case, when the short circuit happens at zero voltage. How much smaller/bigger is the value compared to the simplified relation $\hat{i}_{sc} = 0.8 \cdot \dfrac{2 \cdot \sqrt{2}}{x''_d} \cdot I_N$?

<u>37. Sudden short-circuit of a cylindrical-rotor generator (Turbine generator) (from Exercise 8.2)</u>

A two-pole turbine generator in a steam power station with the data: 400 MVA, 21 kV, Y, 60 Hz, $\cos\varphi = 0.75$, $x_d = 2.2$ p.u., $x_q \approx x_d$, $x''_d = x''_q = 0.17\,\text{p.u.}$, $x'_d = 0.28\,\text{p.u.}$, $T''_d = 0.2\,\text{s}$, $T'_d = 1.1\,\text{s}$, $T_a = 0.3\,\text{s}$
suffers a sudden terminal short-circuit, after having been operated at rated conditions.

At rated operation the internal voltage U_h - induced by air gap flux - is 1.1-fold of rated voltage. This voltage feeds on the short-circuit.

1) How big is the sudden short-circuit current in phase U
   a) in case the short-circuit happens at voltage maximum,
   b) in case the short-circuit happens at voltage zero ?

2) Calculate and draw the time function of short-circuit torque neglecting damping.

38. Steady state operation and transient stability of a synchronous motor (from Exercise 8.9)

A 2-pole 20 MW synchronous motor with cylindrical rotor is used for a pipe-line compressor drive. The main motor data are $x_{S\sigma} = 0.1$, $x_{dh} = x_{qh} = 1.5$, $x_{f\sigma} = 0.15$. The stator winding resistance is neglected $r_s \cong 0$.

1) Give the *p.u.* steady state voltage (u_d, u_q), flux linkage (ψ_d, ψ_q) and torque (m_s) equations as a special case of the general dynamic equation in the *d-q*-reference frame.
2) The motor is operated at rated torque $m_s = 1$ and rated speed $\omega_m = 1$, with $i_f = 1.5$ at under-voltage $u_s = 0.9$ and $u_q > 0$. Determine u_d, u_q, i_d, i_q ! Is the motor current exceeding the rated value $i_s = 1$?
3) Give the phasor diagram, scale 0.1 *p.u.* = 0.5 cm for phase voltage, phase current, the back EMF $x_{dh} \cdot i_f$ and the self-induced voltage $x_d \cdot i_s$. Introduce a complex coordinate system (Re-axis = d-axis, Im-axis = q-axis) and give the correct complex phasors in the diagram. Show the load angle ϑ and phase angle φ in the diagram. Discuss the result.
4) Give the power equation $p_e(\vartheta)$ at transient condition as a formula in *p.u.*!
5) Determine x'_d and u'_p and give the graph $p_e(\vartheta)$ for motor operation in the load angle range $-\pi \leq \vartheta \leq 0$! Determine the values $p_e(\vartheta)$ for $\vartheta = -\pi, -3\pi/4, -5\pi/8, -\pi/2, -\pi/4$, and 0.
6) How big is the transient motor overload capability (= transient pull-out power) in *p.u.* and in terms of the electrical real power! You can do this either graphically or analytically!

39. Exercise from [1] (16.6-1):

Calculate the stationary and the dynamic (transient) break-down power, which belongs to the same excitation, for an over-excited cylindrical-rotor generator with the p.u. data: $u_s = 1$, $i_s = 1$, $\vartheta_N = 45°$, $x_d = 1$, $x'_d = 0.3$, $r_s \approx 0$.

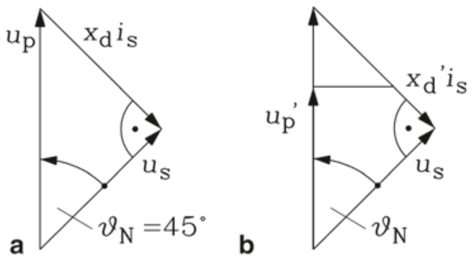

Fig. 39.1: Voltage phasor diagram for **a** stationary and **b** transient operating mode with the rated load angle $\vartheta_N = 45°$, the rated voltage and the rated current for an over-excited synchronous generator with cylindrical-rotor: $X'_q = X_q = X_d$, $X'_d < X_d$, ($R_s = 0$)

[1] A. Binder, *Elektrische Maschinen und Antriebe* [Electrical machines and drives] (in German). Heidelberg, Germany: Springer, 2012.

40. Exercise from [1] (16.7-1):

Calculate the critical clarification time of a two-pole turbine generator in a thermal power plant with the following generator data:
Rated apparent power S_N = 850 MVA, 50 Hz; starting time constant T_J = 5.4 s; power factor for rated operation: $\cos\varphi_s = \cos\varphi_N = -0.9$; reactances: x_d = 1.85 p.u.; x'_d = 0.29 p.u.

The short-circuit reactance of the block transformer is x_{sc} = 0.16 p.u.

1. Calculate for steady-state operation at the rated point the induced voltage u_p, the load angles $\vartheta = \vartheta_N$ and $\vartheta_T = \vartheta_{TN}$ and the grid voltage u_{grid} on the transformer secondary side with the help of the phasor diagram!
2. Determine the transient induced voltage u'_p and the numerical value equation for the transient torque $m_e(\vartheta_T)$!
3. Determine according to Fig. 40.1 and with the results of 1) and 2) the load angles ϑ_{T1krit} and ϑ_{T2} and from that the critical clarification time t_{crit} for safe self-synchronization after reconnection of the generator to the grid after previous short-circuit at the secondary side transformer grid terminals!

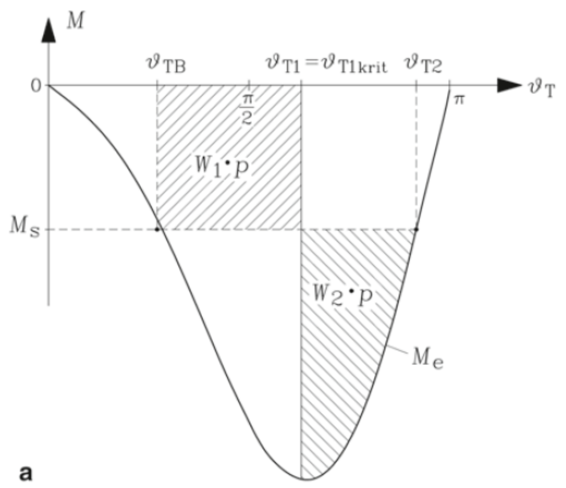

Fig. 40.1: Transient electromagnetic torque M_e in dependence of the load angle ϑ_T in generator mode of a cylindrical-rotor synchronous machine.
The work W_1, produced by the shaft-torque M_s for accelerating the rotating masses, is shown as the shaded area $W_1 \cdot p$ and leads to an increasing of the load angle from ϑ_{TB} to ϑ_{T1}. The stationary operating point ϑ_{TB} is located on the transient and on the stationary torque characteristic

[1] A. Binder, *Elektrische Maschinen und Antriebe* [Electrical machines and drives] (in German). Heidelberg, Germany: Springer, 2012.