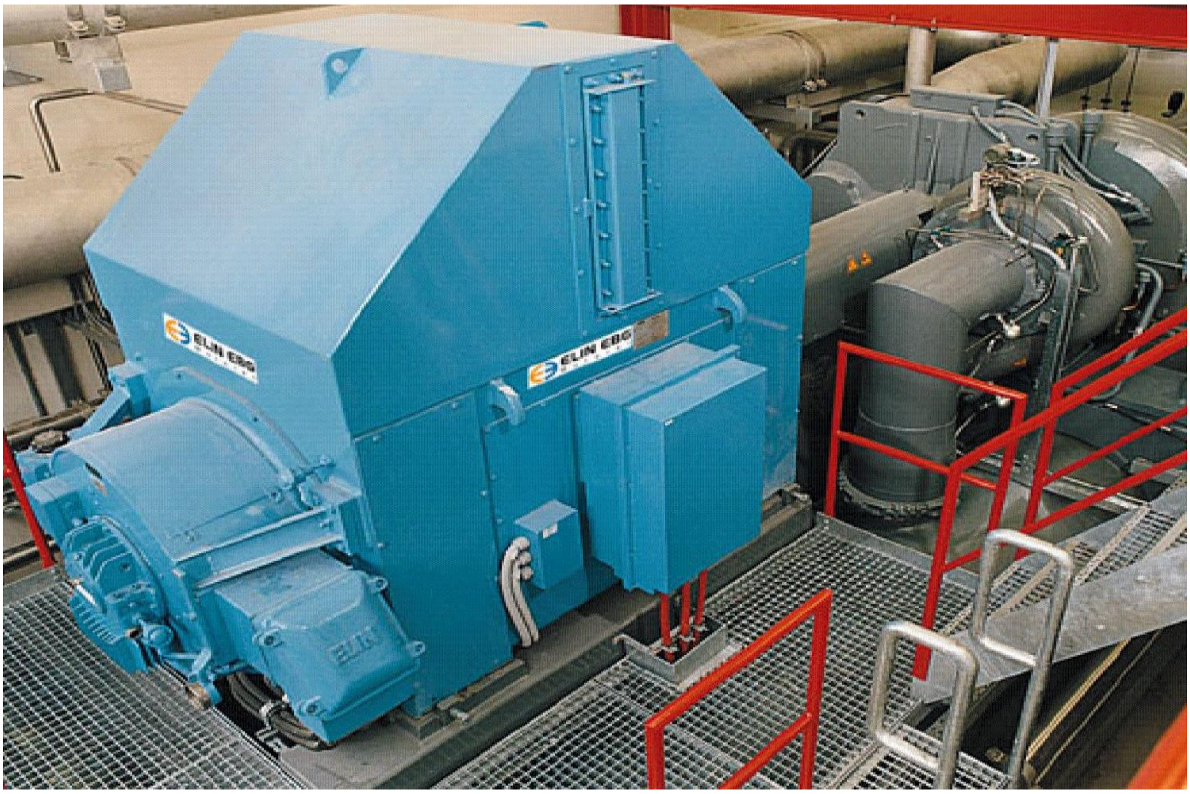
TECHNISCHE
UNIVERSITÄT
DARMSTADT

Institut für Elektrische Energiewandlung

Motor Development for Electric Drive Systems

Collection of Exercises



Source: *ELIN EBG Motoren GmbH, Weiz, Austria*

Advice:
Try to solve the test examples first by yourself only with the aid of the text book. Compare afterwards your results with the solutions given here. If you find differences compared with your way of solution, the try again by going through the solutions presented here. If there are afterward still questions to be answered, do not hesitate to contact us.

Issue SS 2017 Prof. Dr.-Ing. habil. Dr. h. c. A. Binder

1. Three-phase AC-machine

A machine has following specifications:

- 4 poles
- bore diameter: 100 mm
- the air gap fundamental field wave has a frequency of 75 Hz
- the magnetomotive force / magnetic voltage has amplitude of 755 A
- air gap width: 1 mm
- unsaturated iron with $\mu_{\mathrm{Fe}} \to \infty$

Task: Calculate the velocity v_{syn} of the air gap fundamental field wave, the rotational speed n of the rotor and the air gap flux density B_{δ}.

2. Air gap flux density in machines with permanent magnets

Task: The air gap flux density B_{δ} of a machine must be calculated.

The machine is built with permanent magnets on its rotor. The magnet material has a remanence flux density B_{R} of 1.2 T and the coercive field H_{C} equals 9 kA/cm. The magnets, which are mounted as surface magnets, have following geometrical specification:

Magnet height h_{M} = 4 mm
Air gap δ = 2 mm

The machine is operating under no load. It should be considered that the permeability of the iron parts of the machine is much higher than the permeability of air. Furthermore, the cross section of each magnet and the air gap over it is the same.

3. Torque generation in a PM-machine with block and sine wave current operation

The machine has a rated speed of 2000 rpm and will be driven by a converter with block and sine wave current operation. The converter injects current with an amplitude of 10 A into each stator phase. All three phases are symmetrical and star-connected. In both current operations, the rotor flux induces voltage with an amplitude of 250 V in the stator windings.

Task: Based on these details, the torque M_{e} generated in each current operation and the corresponding inner power P_{δ} should be calculated.

4. Three-phase 6-pole PM-machine

A three-phase 6-pole PM-machine has a rotor using surface mounted magnet technology with a pole coverage ratio α_e of 0.8. A flux density B_p of 0.7 T is generated by the permanent magnets. Star-connected AC windings are arranged in the stator (bore diameter d_{si} = 100 mm, stack length l_{Fe} = 120 mm) with 3 slots per pole and phase. The pitched coil provides a relation of $\frac{W}{\tau_p} = \frac{8}{9}$ and number of turns per phase N_s equals 40. The machine is operated at 1500 rpm as a generator under no load.

Based on these specifications, following calculations should be performed:

a) Fundamental voltage per phase: amplitude, frequency, RMS value
b) Line-to-line voltage: frequency, RMS value
c) 5th harmonic voltage: frequency, RMS value
d) Which harmonics are measured in the line-to-line voltage and the phase voltage (the ordinal number) ?

5. Sine wave operated brushless DC-machine

The machine is built with following parameters:

$2p$ = 8
n = 1000 rpm
$\hat{\Psi}_p$ = 0.36 Vs
$I_s = I_{sq}$ = 15 A
L_q = 11.1 mH
R_s = 0.25 Ω

a) Determine the parameters X_q and U_p (back-EMF per phase).
b) Calculate voltage drop $R_s I_s$ and $X_q I_s$.
c) What is the magnitude of stator voltage U_s ?
d) Draw the phasor diagram comprising current and all voltages. Use the scales: 10V/cm, 1,5A/cm. How big is power factor cos φ ?

6. Torque-speed limit of sine wave operated brushless DC machine

The 4 poles machine is designed with a rated current I_N of 10 A r.m.s. and a rated frequency f_N of 100 Hz in motor operation. Its stator resistance R_s is negligible, and the inductance L_q equals 18 mH. Magnets on the rotor generate flux linkage Ψ_p with an amplitude of 0.3 Vs.
The machine is driven by an inverter which has following specifications:

Inverter voltage limit $U_{s,max}$ = 230 V r.m.s. per phase
Inverter current limit I_{max} = 40 A r.m.s.

a) Up to which theoretical maximum speed can we drive the motor ?
b) Which maximum torque is possible to be generated ?
c) At which speed can we still generate that possible maximum torque ?
d) Draw the torque-speed limit diagram along with the rated torque-speed operating point ! Use scale: $500\,\mathrm{rpm} \mathrel{\hat{=}} 1\,\mathrm{cm}$; $5\,\mathrm{Nm} \mathrel{\hat{=}} 1\,\mathrm{cm}$

7. Torque ripple of block commutated brushless DC motor

The motor is designed with $2p = 8$. Using a shaft torque-meter the torque is measured at a speed of 20 rpm, yielding following measurement values:

- Maximum torque $M_{\max} = 107.5$ Nm
- Minimum torque $M_{\min} = 99$ Nm

a) Calculate per-unit torque ripple !
b) Which frequency does the load-dependent torque ripple have ?
c) Now the motor will be coupled to a load via an elastic coupling with a stiftness $c = 5330$ Nm/rad. The motor inertia J_M equals 0.07 kgm^2, the load inertia J_L equals 20 J_M. Calculate torsional natural frequency !
d) The load-dependent torque ripple can excite resonance at that torsional frequency. At which speed would that excitation occur ?

8. Field weakening of PM motor as a high speed spindle drive

Stator of the 4-pole motor is designed with a line-to-line voltage limit of $U_{S,LL} = U_N = 400$ V RMS. Permitted current in the stator $I_{\max}$ is 1.5 times higher than rated current, with $I_N = 65$ A. Inductances of d- and q-axis are the same with a value of $L_d = L_q = 1.38$ mH. The permanent magnets on the rotor generates flux linkage $\Psi_p = 0.245$ Vs. At load operation, the motor delivers its rated power $P_N = 30$ kW at a speed of 4240 rpm.

a) Calculate rated torque!
b) Calculate rated speed of motor!
c) At particular speed, the motor reaches the line-to-line voltage limit at a maximum torque. Calculate that speed ! (Neglect R_s!)
d) Is it still possible to drive the motor with 30 kW at 15000 rpm ?

9. Operation boundaries of flux-weakened PM-motor

A machine distributor delivers a PM-motor with following specifications:

n_N = 4240 rpm
P_N = 30 kW
U_N = 400 V RMS sine wave (line-to-line)
$\cos\varphi_N$ = 0.78
η_N = 0.85
$M_{\max}$ = 1.5 M_N → short time overload (at low speed)

For an operation with variable speed and torque, the motor has its limit in two speed intervals:

$0 \le n \le n_N$ $(I_{sd} = 0)$: limited by $M = M_N \rightarrow$ steady state thermal limit
$n_N \le n \le 2.2\, n_N$ $(I_{sd} < 0)$: limited by $P = P_N$

a) Calculate rated current I_N.
b) Calculate rated and overload torque M_N, $M_{\max}$.
c) How big is the current at overload?
d) Draw thermal limit curve of the motor for $M(n)$, $P(n)$.

e) Due to the motor capability for a short time overload, the motor shall be operated up to its maximum torque M_{max} without exceeding the rated power P_{N}. Up to which speed is this still possible ? Add the overload capability line $M_{\text{max}}(n)$ to the drawing of your thermal limit curve.

10. Single-sided linear PM-drive in tooling machine

The machine comprises:

1) A linear motor
   - Primary part with AC windings
   - Secondary part with NdFeB permanent magnets ($B_{\text{R}} = 1.1$ T, $\mu_{\text{magnet}} \cong 1.06\,\mu_0$)
2) Working piece and table

The primary part together with the working piece and table build moving part of the PM-drive, and have a mass of 1000 kg totally. The primary part has following specification:

Active surface	A_{mot}	=	0.35 m^2
Winding factor	k_{W}	=	0.93
Steady state current loading	A	=	1000 A/cm
Indirect water cooling			

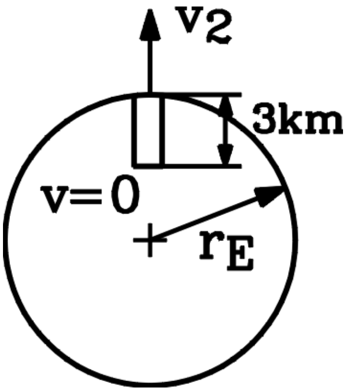
The secondary part has a length of 4 m. The magnets height is 5 mm.

Air gap of the PM-drive is $\delta = 2$ mm and equivalent pole coverage ratio α_{e} equals 0.8. The iron parts of the drive are unsaturated with $\mu_{\text{Fe}} \to \infty$.

a) Calculate fundamental flux density amplitude under no load.
b) Calculate tangential thrust and normal pull under no load.
c) The machine is operated with rated current. How much time is necessary to move the primary part from one end to the other, beginning from standstill and ending in standstill position, too?
d) Draw graph of acceleration a and velocity v of the moving part depending on its position. (Use units: $1\,\text{cm} \mathrel{\hat{=}} 0.5\,\text{m}$; $1\,\text{cm} \mathrel{\hat{=}} 10\,\text{m/s}^2$; $1\,\text{cm} \mathrel{\hat{=}} 2.5\,\text{m/s}$)

11. Linear motor as rocket propulsion

A rocket must accelerate up to a velocity of $v_2 = \sqrt{2 \cdot g \cdot r_{\text{E}}}$ in order to overcome earth gravity and therefore will be leaving earth towards space. The rocket will be accelerated by a linear motor with l = 3 km long track built in earth (see sketch).



Gravitation constant $g = 9.81\ \text{m/s}^2$
Earth radius $r_{\text{E}} = 6370$ km

a) Calculate necessary acceleration and acceleration time.
b) Considering pole pitch τ_{p} = 1 m, how big is the maximum frequency ?
c) The rocket has a mass of 5000 kg. Calculate necessary tangential thrust.

d) We assume that during the acceleration a current load of 15000 A/cm is possible at an air gap flux density of 1.5 T (with flux concentration) and a winding factor $k_W = 1$. How big is the active motor surface needed according to the thrust in point c) ? Give also your interpretation for the results.

12. Hi-torque ring motor for cylindrical mill

An inverter-fed ring-like hi-torque motor has a PM-rotor which is mounted on the mill and a stator with water-jacket cooling system. This motor will be used as driving system for the mill to pulverise ore.

The specification of the motor is:
Stator bore diameter d_{si} = 3.025 m
Iron stack length l_{Fe} = 75 mm
Current load A = 270 A/cm
Number of poles $2p$ = 128
Winding factor k_W = 1
Pole coverage ratio α_e = 1
Airgap PM flux density B_p = 0.67 T

a) Calculate fundamental air gap flux density amplitude.
b) Calculate electromagnetic torque!
c) With yoke flux density $B_y = 1.35$ T, calculate stator and rotor yoke height.
d) Determine motor frequency and rotor surface velocity at $n = 100$ rpm.

13. Modular synchronous machine

A three-phase modular synchronous machine with tooth wound coils is given with three slots per four poles.

a) Ampere turns per tooth coil equals 1800 A RMS. The machine is supplied by a sinusoidal three-phase current system. Air gap together with magnet have a total height $\delta_{res} = 9$ mm. Draw magnetic air gap flux density of stator field at time of maximum current in phase U. The iron saturation and the slot openings will be neglected.
b) The *Fourier*-analysis of stator flux density distribution is performed. Which one of the *Fourier*-harmonics is considered to generate torque with rotor permanent magnets ?

14. Transversal flux machine

Magnetic circuit of the machine is designed according to figure 1.5.3-1 in the text book. The machine has following specification:
h = 28 mm
δ = 0.8 mm
h_M = 6.5 mm
$b_p = \tau_p$ = 17.5 mm
$2p$ = 30
μ_M/μ_0 = 1.06
N_s = 22 Ring coil
I_s = 95 A Nominal current
B_R = 1.095 T Remanence flux density

a) Determine air gap flux density under no load and with $\mu_{Fe} \to \infty$.
b) Determine armature reaction (= stator field at rated current).

c) Determine no-load induced voltage as time function at a speed of 900 rpm.
d) Determine time fundamental of back EMF according to point c).

15. Transversal flux machine as vehicle drive system

A car uses transversal flux machine as motor. A battery as DC-link with a voltage of 300 V is available as power source to drive the motor. The machine has rated torque $M_N = 750$ Nm and rated power $P_N = 60$ kW. It is built with 80 poles ($2p = 80$).
The car uses direct wheel drive with wheel diameter $d_W = 0.8$ m. Maximum speed of the car equals 120 km/h.

a) Calculate maximum rotational speed of motor.
b) Sketch appropriate inverter leg of one phase between the DC-link and one phase of the motor winding. Furthermore, describe direction of voltages and currents during a block voltage operation (four step switching mode).
c) Sketch voltage per phase at maximum speed.

16. Switched reluctance machine

Following parameters are available for the machine:

3-phase, 4 poles

Q_s/Q_r	=	12/8	slot number
N_c	=	61	number of turns per coil
δ	=	0.45 mm	air gap
l_{Fe}	=	193 mm	iron stack length
b_s	=	16 mm	stator tooth width
b_r	=	b_s	rotor tooth width
d_{si}	=	122.2 mm	inner stator diameter

a) Calculate rotor and stator tooth width and slot width angles in mechanical degree.
b) Determine air gap inductance in *d*-axis with saturation neglected.
c) How much torque can be generated at a coil current of 10 A. $L_{qh} = 10$ mH and saturation is neglected.
d) Draw time function of inductance and torque per phase when current angle $\vartheta_W = \alpha$. What is the value of ϑ_W in electrical degree ?

17. Torque-speed characteristic of a switched reluctance machine

A switched reluctance machine with the following parameters is given:

$m = 4$ phases, $2p = 2$ poles

U_d	=	560 V	dc-link voltage
Q_s/Q_r	=	8/6	slot number
L_d	=	12 mH	air gap inductance in d-axis
L_q	=	1.8 mH	air gap inductance in q-axis
b_s	=	26 mm	stator tooth width
b_r	=	35 mm	rotor tooth width
d_{si}	=	197 mm	stator inner diameter

a) Calculate the period of stator unipolar current in terms of mechanical rotor angle.
b) How big is the conducting angle of the stator current, if phases do not overlap ? Sketch the stator current time function in mechanical and electrical degrees.
c) Calculate the torque at $\hat{I} = 70$ A (unsaturated).
d) Give the speed n_g , when the voltage limit is reached with $\hat{I} = \hat{I}_{max} = 70$ A. (Neglect R_s!)
e) Draw the torque limit – speed curve for $0 \le n \le 2n_g$.

18. Synchronous reluctance machine

The 3 phase motor with Y-connected stator windings has the following parameters:

Rated power	P_N	=	2.2 kW
Line-to-line voltage	U_{LL}	=	400 V
Stator frequency	f	=	50 Hz
Number of poles	$2p$	=	4
Reactance in d-axis	X_d	=	33 Ω
Reactance in q-axis	X_q	=	8 Ω

Stator resistance can be neglected ($R_s = 0$)

a) Calculate the pull-out torque M_{po} at 400 V.
b) Sketch the torque characteristic versus load angle for $-180° < \vartheta < 180°$.
c) Determine the load angle (ϑ_N) at rated motor torque and the overload capability of the motor.

19. Synchronous reluctance motor

Consider a synchronous reluctance motor with the following parameters:

$m = 3$ phases, Y-connection

Rated power	P_N	=	3.5 kW
Rated voltage	U_N	=	400 V
Stator frequency	f	=	50 Hz
Number of poles	$2p$	=	4
Inductance in d-axis	L_d	=	0.11 H
Inductance in q-axis	L_q	=	0.029 H

Stator resistance can be neglected ($R_s = 0$)

a) Calculate the reactances X_d and X_q.
b) Calculate the rated load angle (ϑ_N).
c) Draw the phasor diagram of voltage and current (use scale: $25\,\mathrm{V} \mathrel{\hat{=}} 1\,\mathrm{cm}$; $1\,\mathrm{A} \mathrel{\hat{=}} 1\,\mathrm{cm}$). Determine the stator current I_s.
d) How big is the rated power factor ($\cos\varphi$) ?

20. High speed PM synchronous motor with rotor squirrel cage for voltage-controlled inverter operation

The 4 poles, 3 phase (Y-connected) PM synchronous motor, supplied with a rated line-to-line voltage of 400 V, produces a rated mechanical power of 15 kW (rated power factor $\cos\varphi_N = 0.7$, rated efficiency $\eta_N = 0.9$) at 24000 /min rated speed.

- Stator data:
  Iron stack length l_{Fe} = 75 mm
  Stator bore diameter d_{si} = 75 mm
  Winding turns per phase N_s = 24
  Winding factor k_{ws} = 0.96

- Rotor data:
  Buried magnets
  Air gap flux density B_p = 0.7 T

a) Calculate the flux per pole at no-load Φ.
b) Determine the rated stator frequency f_s and the no-load voltage U_0.
c) Which ratio "voltage versus frequency" is necessary for rated flux operation? (Neglect influence of R_s!)
d) Calculate ESSON's number C from stator apparent power.

21. PM synchronous motor with buried magnets and squirrel cage rotor for line operation

Motor data:

m = 3 phases, Y-connection
Line-to-line voltage U_N = 130 V
Rated stator current I_N = 3.8 A
Stator frequency f_N = 50 Hz
Rated phase back EMF U_{pN} = 30 V
Number of poles $2p$ = 4
Reactance in d-axis X_d = 15.7 Ω
Reactance in q-axis X_q = 19 Ω
Stator resistance can be neglected ($R_s = 0$)
Efficiency η_N = 0.63
Power factor $\cos\varphi_N$ = 0.63

a) Calculate the absolute value of pull-out torque M_{po} and the load angle at pull-out ϑ_p.
b) Calculate rated torque.
c) Calculate overload ratio M_{po} / M_N.

22. Asynchronous start up of a PM synchronous motor with rotor squirrel cage

The 3 phase motor with Y-connected stator windings has the following specifications:

Rated power P_N = 15 kW
Rated line-to-line voltage U_N = 400 V
Number of poles $2p$ = 4
PM generated flux linkage Ψ_p = 0.045 Vs
Rated speed n_N = 24000 /min

Inductance in *d*-axis	L_d	=	0.001 H
Inductance in *q*-axis	L_q	≈	L_d
Stator resistance	R_s	=	0.35 Ω

Asynchronous starting torque is given by the KLOSS's function with break down slip $s_b = 0.2$ and break down torque $M_b = 10$ Nm.

$$\frac{M_{e,asyn}}{M_b} = \frac{2}{\frac{s}{s_b} + \frac{s_b}{s}}$$

a) Sketch the asynchronous starting torque in dependence of speed for slip values $s = 0, 0.2, 0.4, 0.6, 0.8$ and 1.
b) Calculate the speed where the maximum breaking torque $M_{p,max}$ due to permanent magnets occurs during start-up.
c) Determine maximum braking torque $M_{p,max}$.
d) Sketch braking torque in dependence of speed at slip values 0, 0.5 and 1.
e) Sketch the resulting starting torque in dependence of speed between 0 and n_{syn}.

23. Electromagnetic aircraft launch system on aircraft carrier

A linear induction motor of 103 m length as long stator configuration has to accelerate the aircraft from 0 speed to 370 km/h launch speed in 3 seconds. Secondary is aluminium cage as carriage on rollers, where the aircraft is hooked in.

Data:

- aircraft mass $m_{Aircraft} = 45$ t, motor pole pitch $\tau_p = 0.5$ m, power factor of motor $\cos\varphi_N = 0.5$, efficiency $\eta_N = 0.63$.

a) Calculate kinetic energy of moved mass at launch.
b) How big is the stator frequency at launch?
c) How big is the motor's power at launch, if frequency of motor is rising linear with time and the thrust force is constant?
d) Sketch the rise of kinetic energy during launch.
e) At 103 Hz maximum frequency, the motor line-to-line voltage reaches 10.6 kV. According to which function must voltage rise with time *t* for constant thrust force, if the motor current is constant?
f) Determine the motor current for that thrust.

24. Standard cage induction motor

A cage induction motor has the following data:

Rated voltage	$U_N = 400$ V Y
Rated current	$I_N = 44$ A
Rated power	$P_N = 22$ kW
Rated speed	$n_N = 1455\ \text{min}^{-1}$
Power factor	$\cos\varphi_N = 0.82$

No load current	$I_0 / I_N = 0.4$
Breakdown torque	$M_b / M_N = 3.4$

The motor is operated at the grid.

a) Calculate for rated operation: The slip s_N, the torque M_N, the electrical input power $P_{e,N}$, the total losses $P_{d,N}$, the efficiency η_N.
b) The stator losses are assumed to be $P_{Fe,s} = P_{d,N}/6$ and $P_{Cu,s} = P_{d,N}/2$. Calculate the numerical values of the stator losses and the airgap power P_δ.
c) Calculate the rotor cage losses $P_{Cu,r}$.
d) The additional load losses $P_{ad,1}$ are 7% of the total losses $P_{d,N}$. Calculate the friction and windage losses P_{fr+w}.
e) Calculate the stator copper losses $P_{Cu,s0}$ at no load. Assume the winding temperature to be the same as at rated operation.
f) Calculate the total no-load losses P_{d0}.
g) With P_{d0}, calculate the load losses $P_{d1,N}$ for rated operation. If you did not solve 6), please perform your calculation with $P_{d0} = 850$ W.
h) For a partial load of $M = 0.5\ M_N$, calculate the output power P_{out}, the load losses P_{d1} and the efficiency η for this load point.
i) Calculate the load point M_{opt}, where the efficiency $\eta = \eta_{max}$ is maximum. Also, calculate this efficiency η_{max}.

25. PM motor as High-speed compressor drive, Hi-Speed-Kompressor-Antrieb

A 4-pole synchronous motor with permanent magnet rotor, stator water jacket cooling and Y-connected three-phase stator winding is used to drive an air turbo-compressor at high Speed. The motor is fed by a voltage source d.c. link inverter. Maximum inverter voltage is $U_{max} = 230$ V, maximum inverter current is $I_{max} = 250$ A (fundamental phase values, r.m.s.).

Inverter data: $U_{phase,k=1,max} = 230\text{V}$, $I_{phase,k=1,max} = 250\text{A}$

Compressor data: $n_N = 24000/\text{min}$, $P_N = 65\text{kW}$
Motor data: $2p = 4$, $L_d = L_q = 0{,}169\text{mH}$, $U_p = 6.25\text{V}$ (at 50 Hz, phase value, r.m.s.)
For the following, neglect all motor losses!

1. Determine rated motor frequency!

2. Calculate at rated speed back EMF U_{pN}!

3. Evaluate motor rated current for q-current operation ($I_s = I_{sq}$, $I_{sd} = 0$)!

4. Determine stator phase voltage for rated operation according to 3)! Is inverter voltage and current limit sufficient?

5. Draw voltage and current phasor diagram for rated operation 3) (Scale: 20 V/cm, 20 A/cm). Evaluate motor apparent power and power factor! Is the motor running over- or under-excited?

Ein Synchronmotor mit Permanentmagnetläufer und einer Wassermantelkühlung soll einen Luftverdichter (Turbokompressor) mit **hoher Drehzahl („Hi-Speed")** antreiben. Der Motor wird mit einem Spannungszwischenkreisumrichter gespeist, dessen maximale Spannung $U_{\max} = 230$ V und dessen maximaler Strom $I_{\max} = 250$ A (jeweils Strangwert, Grund-schwingung, Effektivwert) beträgt.

Umrichterdaten: $U_{\mathrm{Strang,k=1,max}} = 230\mathrm{V}$, $I_{\mathrm{Strang,k=1,max}} = 250\mathrm{A}$

Kompressordaten: $n = 24000\dfrac{1}{\min}$, $P_{\mathrm{N}} = 65\mathrm{kW}$

Motordaten: $2p = 4$, $L_{\mathrm{d}} = L_{\mathrm{q}} = 0{,}169\mathrm{mH}$

$U_{\mathrm{p}} = 6{,}25\mathrm{V}$ (bei 50 Hz, Effektivwert, Strangspannung, Y-Schaltung)

Anmerkung: Im Folgenden sollen die Verluste im Motor vernachlässigt werden!

1. Mit welcher Ausgangsfrequenz muss der Umrichter den Motor mit Spannung versorgen?

2. Wie groß ist die Polradspannung bei 24000 /min?

3. Wie groß ist der erforderliche Motorstrom, wenn der Umrichter über eine Polradlagesteuerung den Strom in Phase mit der Polradspannung U_{p} einprägt ($I_{\mathrm{s}} = I_{\mathrm{sq}}$, $I_{\mathrm{sd}} = 0$)?

4. Wie groß ist zu 3. die erforderliche Strangspannung an den Klemmen des Motors? Ist der Umrichter dafür ausreichend dimensioniert?

5. Zeichnen Sie das Strom-Spannungs-Zeigerdiagramm je Phase maßstäblich (Maßstab angeben!) und berechnen Sie die Motorscheinleistung und den Leistungsfaktor. Wird der Motor über- oder untererregt betrieben?

26. Permanent magnet motor as a machine tool drive, Permanentmagnetmotor als Werkzeugmaschinenantrieb

A 6 pole *permanent magnet motor* has surface mounted magnets on the rotor with a height of $h_{\mathrm{M}} = 3.5$ mm. The stator core and winding data are:

$d_{\mathrm{si}} = 100$ mm (bore diameter)
$l = 100$ mm (iron length)
$Q = 36$ (number of stator slots)
$N_c = 20$ (number of turns per coil)
$a = 1$ (all coils series connected)

The three phases of the single-layer winding are in Y-connection. The mechanical air gap and the thickness of the non-magnetic rotor bandage sum up to an overall height of $\delta = 1.4$ mm.

Magnet data: Material NdFeB, at 20°C: $B_{\mathrm{R}} = 1.1$ T (magnetic remanence flux density)
$H_{\mathrm{CB}} = 875$ kA/m (coercive field strength)

1) How big is the magnetic flux density in the air gap at no load (stator current is zero) ? Assume infinite permeability for iron! Give a rough sketch of the air gap flux density field curve, if there are no gaps between the magnets!

2) How big is the amplitude of the fundamental flux density field wave of 1)?
3) Calculate the r.m.s. value of the fundamental harmonic of the back EMF at a stator frequency of f_s =100 Hz!
4) Verify with the magnetic data, that the rare earth magnets behave passively like air ($\mu_M = \mu_0$)!
5) How big is the unsaturated magnetizing reactance X_h ?
6) How big must be the r.m.s. phase value of the fundamental harmonic voltage U_s of the inverter output voltage at 100 Hz, so that maximum torque can be reached at a phase current of 10 A r.m.s.? Neglect R_s and assume $X_{s\sigma} = 1.4\ \Omega$.
7) Draw a voltage phasor diagram for operation point 6) with scale 25 V/cm and 2 A/cm!

Ein 6-poliger *Permanentmagnetmotor* mit den Statorblechpaket- und Wicklungs-Daten:
d_{si} = 100 mm, l = 100 mm, Q = 36, Einschichtwicklung, N_c = 20, a = 1, Y-Schaltung,
hat im Läufer aufgeklebte Magnete mit der Höhe h_M = 3.5 mm. Der mechanische Luftspalt und die amagnetische Läuferbandage ergeben zusammen δ = 1.4 mm.

<u>Magnetdaten:</u> Material NdFeB, bei 20°C gilt: B_R = 1.1 T, H_{CB} = 875 kA/m

1) Wie groß ist die magnetische Flussdichte im Luftspalt bei stromloser Ständerwicklung und wie sieht ihr räumlicher Verlauf längs des Umfangs aus, wenn keine Lücken zwischen den Magneten unterschiedlicher Polarität vorhanden sind ?

2) Wie groß ist zu 1) die Amplitude der Feldgrundwelle ?

3) Berechnen Sie den Effektivwert der Grundschwingung der Polradspannung bei einer Ständerfrequenz f_s =100 Hz !

4) Die Magnete verhalten sich passiv wie Luft! Überprüfen Sie anhand der Magnetdaten, ob dies wirklich zutrifft.

5) Wie groß ist die ungesättigte Hauptreaktanz X_h ?

6) Wie groß ist der Effektivwert der erforderlichen Grundschwingung U_s (Strangwert) der Umrichterausgangsspannung bei 100 Hz, damit der PM-Motor bei 10 A Strangstrom (Effektivwert) maximales Moment abgibt? Vernachlässigen Sie für diese Betrachtung R_s und nehmen Sie für $X_{s\sigma}$ = 1.4 Ω an.

7) Zeichnen Sie zu 5) das maßstäbliche Zeigerdiagramm und wählen Sie dafür einen geeigneten Strom- und Spannungsmaßstab!

27. Permanent magnet synchronous motor as robot drive, Roboterantrieb

An 8-pole permanent magnet synchronous machine is fed by an inverter and used as drive for a robot arm of a **welding robot**. By rotor position control the motor is operated with q-current to get maximum torque. The maximum thermal continuous current is 12 A r.m.s.. For a short time of a few seconds the motor winding can be overloaded with 4 times rated current. It was measured U_s = 90 V Y phase no-load voltage r.m.s. at f_s = 50 Hz stator frequency. The maximum inverter output phase voltage (fundamental) is U_s = 230 V r.m.s.

Motor data:

f_{sN} = 100 Hz (rated frequency), L_d = 4.5 mH (synchronous inductance)
The stator resistance is neglected.

1.) The machine is tested in the test bay of the manufacturer. It is driven as generator with another motor between 0 and 6000/min. At open stator winding terminals no-load voltage is measured. Draw the function of no-load voltage (line-to-line, r.m.s.) versus speed (Scale: abscissa: 1000/min ≙ 2 cm, ordinate: 500 V ≙ 2 cm).

2.) Is it possible to determine by measurement acc. to 1), if the magnets are properly magnetized? Do we need to know magnet temperature to draw a correct conclusion?

3.) Draw the voltage phasor diagram for rated frequency
a) at nominal current, b) at maximum current (Scale: 25 V/cm, 5 A/cm)

4.) Determine nominal speed of the motor !

5.) What is the motor torque for 3 a.) and 3 b.), if the motors losses are neglected ?

6.) Draw the *M*(*n*)-curve of the PM motor Fig. 27-1 due to current and voltage limit. Give further *M*(*n*)-curve for continuous operation (Scale: Abscissa: 100/min per cm, ordinate: 10 Nm per cm).

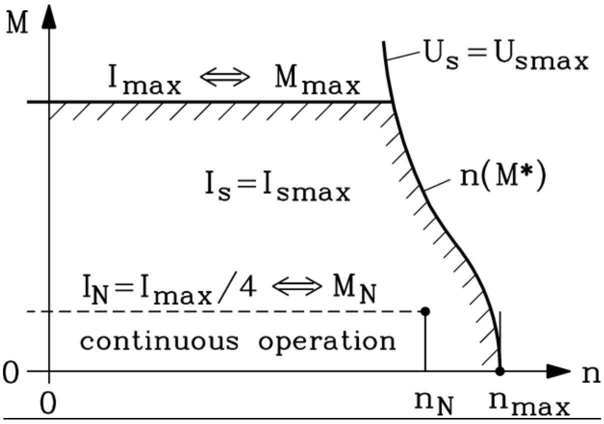


Fig. 27-1: Voltage, current and thermal limit of PM drive

Ein 8-poliger PM-Synchronmotor mit Umrichterspeisung wird als Antrieb für einen Schweißroboterarm verwendet. Mittels Polradlagegebersteuerung wird der Motor so betrieben, dass zu jedem Stromwert jeweils das maximal mögliche Drehmoment eingestellt wird. Der thermisch dauernd zulässige Nennstrom beträgt 12 A (Effektivwert). Der Motor ist kurzzeitig 4-fach überlastbar (Sekundenbereich). Die Polrad-Strangspannung (Effektivwert) beträgt 90 V bei einer Ständerfrequenz f_s = 50 Hz, die Synchroninduktivität ist L_d = 4.5 mH. Der Ständerwicklungswiderstand wird vernachlässigt.

1) Skizzieren Sie maßstäblich den Verlauf des Effektivwerts der Leerlaufspannung über der Drehzahl, wenn der Motor im Prüffeld des Herstellers zwischen 0 und 6000/min bei offenen Ständerklemmen angetrieben wird.

2) Wie kann durch die Messung von 1) auf den Zustand der Läufer-Magnete geschlossen werden? Muss die Magnettemperatur bekannt sein, um eine korrekte Aussage treffen zu können?

3) Zeichnen Sie maßstäblich das Spannungs-Strom-Zeigerdiagramm bei Nennfrequenz 100 Hz für a) Nennstrom und b) Maximalstrom (μ_U = 25 V/cm, μ_I = 5 A/cm).

4) Wie groß ist die Nenndrehzahl des Motors?

5) Wie groß ist das Drehmoment zu 3a) und 3b), wenn der Motor als verlustfrei angenommen wird?

6) Berechnen Sie den Betriebsbereich Bild 27-1deutsch des Motors im 1.Quadranten der *M(n)*-Ebene, wenn der Umrichter maximal U_s = 230 V (Effektivwert) zur Verfügung stellt. Unterscheiden Sie Kurzzeit- und Dauerbetriebsbereich!

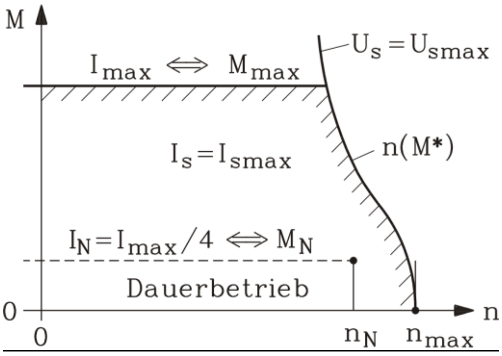


Bild 27-1deutsch: Spannung, Strom und Temperaturgrenze des PM-Motors

28. Permanent magnet motor, Permanentmagnetmotor

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 $U_{\mathrm{s},0}$ (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 ($I_\mathrm{d} = 0$, $I_\mathrm{s} = I_\mathrm{q} = I_\mathrm{N}$)? 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 $0 \le I \le I_\mathrm{N}$.

In einer Werkzeugmaschine ist ein sechspoliger Permanentmagnetmotor als Antrieb für einen Werkzeugschlitten eingesetzt.
Motordaten:

- $U_N = 400$ V Y,
- $P_N = 22$ kW,
- $n_N = 6000$ /min,
- Windungszahl je Strang $N_s = 20$,
- Wicklungsfaktor $k_w = 0.966$,
- Ständerbohrung $d_{s,i} = 100$ mm,
- Blechpaketlänge $l = 150$ mm.

Der Läufer ist mit Magneten aus Neodym-Eisen-Bor an der Oberfläche beklebt, die durch eine Kunststoffbandage fixiert sind. Der magnetisch wirksame Luftspalt δ setzt sich aus dem mechanischen Luftspalt 0.8 mm und der Bandagendicke 0.4 mm zusammen.
Magnetwerkstoffdaten bei 20 °C:

- Remanenzflussdichte $B_R = 1.2$ T,
- Koerzitivfeldstärke $H_{CB} = 900$ kA/m.
- Die Werkstoffkennlinie $B_M(H_M)$ ist im zweiten Quadranten linear und kann daher durch folgende Geradengleichung ersetzt werden: $B_M = B_R + H_M \bullet B_R/H_{CB}$.

Die Polbedeckung der Magnete beträgt 100 %. Das Eisen ist als unendlich permeabel anzunehmen. Der Einfluss der Nutöffnungen auf das Luftspaltfeld ist zu vernachlässigen.

1) Wie sieht die Verteilung des Luftspaltfelds (Radialkomponente) bei stromloser Maschine aus?
2) Wie groß muss die Magnethöhe h_M sein, damit bei stromloser Maschine und 20 °C eine Amplitude der Grundwellenflussdichte von 0.9 T entsteht?
3) Wie groß ist die Ständerfrequenz f_s bei Nenndrehzahl? Wie groß ist die induzierte Leerlaufstrangspannung $U_{s,0}$ (Effektivwert), die gemessen wird, wenn der Motor im Prüffeld des Herstellers bei offenen Klemmen angetrieben wird?
4) Wie groß ist das Drehmoment bei feldorientiertem Betrieb ($I_d = 0$, $I_s = I_q = I_N$)? Fertigen Sie eine Prinzipskizze des Spannungszeigerdiagramms im Motorbetrieb mit Berücksichtigung von R_s an. Wie verhalten sich die Beträge von Polrad- und Phasenwinkel zueinander?
5) Zeigen Sie, dass das Drehmoment im feldorientierten Betrieb nur vom Ständerstrom abhängt und diesem direkt proportional ist ("bürstenloser Gleichstrommotor"). Wie groß ist der Ständerstrom im Nennpunkt? Zeichnen Sie die $M(I)$ – Kennlinie für $0 \le I \le I_N$.

1. Three-phase AC-machine

$$\tau_{\mathrm{p}} = \frac{d_{\mathrm{si}} \cdot \pi}{2p} = \frac{100\,\mathrm{mm} \cdot \pi}{4} = 78.5\,\mathrm{mm}$$

$$v_{\mathrm{syn}} = 2 \cdot f_{\mathrm{s}} \cdot \tau_{\mathrm{p}} = 2 \cdot 75\,\mathrm{Hz} \cdot 78.5\,\mathrm{mm} = \underline{\underline{11.78}}\,\frac{\mathrm{m}}{\mathrm{s}}$$

$$n = \frac{f_{\mathrm{s}}}{p} = \frac{75\,\mathrm{Hz}}{2} = \underline{\underline{2250}}\,\mathrm{min}^{-1}$$

$$B_{\delta} = \frac{\mu_0 \cdot V}{\delta} = \frac{4\pi \cdot 10^{-7} \cdot \frac{\mathrm{Vs}}{\mathrm{Am}} \cdot 755\,\mathrm{A}}{1\,\mathrm{mm}} = \underline{\underline{0.949}}\,\mathrm{T}$$

2. Air gap flux density in machines with permanent magnets

No load :

$$B_{\mathrm{M}} = B_{\mathrm{R}} + \mu_{\mathrm{M}} \cdot H_{\mathrm{M}} \qquad (1)$$

$$\mu_{\mathrm{M}} = \frac{B_{\mathrm{R}}}{H_{\mathrm{C}}}$$

$$\left.\begin{aligned} A_{\delta} &= A_{\mathrm{M}} \\ B_{\delta} \cdot A_{\delta} &= B_{\mathrm{M}} \cdot A_{\mathrm{M}} \end{aligned}\right\} \; B_{\delta} = \mu_0 \cdot H_{\delta} = B_{\mathrm{M}} \qquad (2)$$

No load

$\downarrow$

$$\oint_C \vec{H} \cdot \mathrm{d}\vec{s} = 0 = H_{\mathrm{M}} \cdot h_{\mathrm{M}} + H_{\delta} \cdot \delta \qquad (3)$$

(2) and (3) used in (1) :

$$\mu_0 \cdot H_{\delta} = B_{\mathrm{R}} + \mu_{\mathrm{M}} \cdot \left(-H_{\delta} \cdot \frac{\delta}{h_{\mathrm{M}}} \right) \quad \Leftrightarrow \quad H_{\delta} \cdot \left(\mu_0 + \mu_{\mathrm{M}} \cdot \frac{\delta}{h_{\mathrm{M}}} \right) = B_{\mathrm{R}}$$

$$\Leftrightarrow \quad B_{\delta} = \mu_0 \cdot H_{\delta} = \frac{B_{\mathrm{R}}}{1 + \frac{\mu_{\mathrm{M}}}{\mu_0} \cdot \frac{\delta}{h_{\mathrm{M}}}}$$

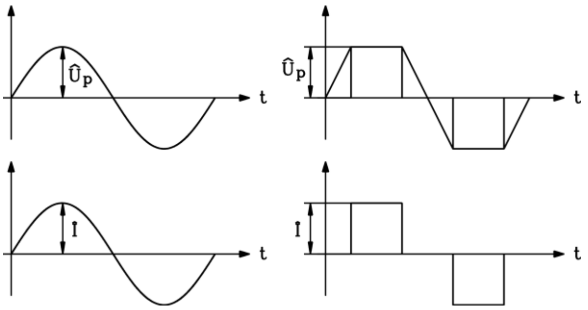
$$B_{\delta} = \frac{1.2\,\mathrm{T}}{1 + \frac{1.2\,\mathrm{T}}{9\,\mathrm{kA/cm}} \cdot \frac{10^7}{4\pi} \frac{\mathrm{Am}}{\mathrm{Vs}} \cdot \frac{2\,\mathrm{mm}}{4\,\mathrm{mm}}} = \underline{\underline{0.784}}\,\mathrm{T}$$

3. Torque generation in a PM-machine with block and sine wave current operation

Sine wave current operation :

$$M_e = \frac{3}{2}\cdot\frac{\hat{U}_p\cdot\hat{I}}{2\pi\cdot n} = \frac{3}{2}\cdot\frac{250\,\text{V}\cdot 10\,\text{A}}{2\pi\cdot 2000\,\text{min}^{-1}} = \underline{\underline{17.9}}\,\text{Nm}$$

$$P_\delta = 2\pi\cdot n\cdot M_e = 2\pi\cdot 2000\,\text{min}^{-1}\cdot 17.9\,\text{Nm} \cong$$
$$\cong \underline{\underline{3.75}}\,\text{kW}$$



Block current operation :

$$M_e = \frac{2\cdot\hat{U}_p\cdot\hat{I}}{2\pi\cdot n} = \frac{250\,\text{V}\cdot 10\,\text{A}}{\pi\cdot 2000\,\text{min}^{-1}} = \underline{\underline{23.9}}\,\text{Nm}$$

$$P_\delta = 2\pi\cdot n\cdot M_e = 2\pi\cdot 2000\,\text{min}^{-1}\cdot 23.9\,\text{Nm} \cong \underline{\underline{5}}\,\text{kW}$$

4. Three-phase 6-poles PM-machine

a)

Pole pitch $\tau_p = \frac{d_{si}\cdot\pi}{2p} = \frac{100\,\text{mm}\cdot\pi}{6} = 52.35\,\text{mm}$

Winding factor $k_{w,\mu=1} = k_{d,\mu=1}\cdot k_{p,\mu=1}$
with

$$\left.\begin{aligned} k_{d,\mu=1} &= \frac{\sin\left(\mu\cdot\frac{\pi}{2m}\right)}{q\cdot\sin\left(\mu\cdot\frac{\pi}{2mq}\right)} = \frac{\sin\left(\frac{\pi}{6}\right)}{3\cdot\sin\left(\frac{\pi}{6\cdot 3}\right)} = 0.9598 \\ k_{p,\mu=1} &= \sin\left(\mu\cdot\frac{W}{\tau_p}\cdot\frac{\pi}{2}\right) = \sin\left(1\cdot\frac{8}{9}\cdot\frac{\pi}{2}\right) = 0.9848 \end{aligned}\right\} \quad k_{w,\mu=1} = 0.945$$

Fundamental order $\mu = 1$:

$$\hat{B}_{\mu=1} = B_p\cdot\frac{4}{\pi\mu}\cdot\sin\left(\frac{\alpha_e\mu\pi}{2}\right)$$
$$= 0.7\cdot\frac{4}{\pi}\cdot\sin\left(\frac{0.8\pi}{2}\right) = 0.8476\,\text{T}$$

Flux per pole:

$$\Phi_{\mu=1} = \frac{2}{\pi} \cdot \hat{B}_{\mu=1} \cdot \tau_{\mathrm{p}} \cdot l_{\mathrm{Fe}}$$

$$= \frac{2}{\pi} \cdot 0.8476\,\mathrm{T} \cdot 52.35\,\mathrm{mm} \cdot 120\,\mathrm{mm}$$

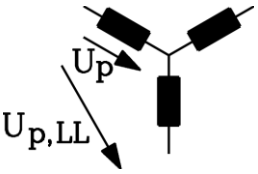
$$= 3.39\,\mathrm{mVs}$$

$$\omega = 2\pi \cdot f \qquad ; \qquad f_{\mu} = \mu \cdot n \cdot p = 1 \cdot 1500\,\mathrm{min}^{-1} \cdot 3 = \underline{\underline{75}}\,\mathrm{Hz}$$

$$\hat{U}_{\mathrm{p}} = \omega \cdot N_{\mathrm{s}} \cdot k_{ws} \cdot \Phi = 2\pi \cdot 75\,\mathrm{Hz} \cdot 40 \cdot 0.945 \cdot 3.39\,\mathrm{mVs} = \underline{\underline{60.4}}\,\mathrm{V}$$

$$U_{\mathrm{p}} = \frac{\hat{U}_{\mathrm{p}}}{\sqrt{2}} = \frac{60.4\,\mathrm{V}}{\sqrt{2}} = \underline{\underline{42.7}}\,\mathrm{V}$$

b)



Line-to-line voltage $U_{\mathrm{p,LL}} = \sqrt{3} \cdot U_{\mathrm{p}} = \sqrt{3} \cdot 42.7\,\mathrm{V} = \underline{\underline{74}}\,\mathrm{V}$

$$f = \underline{\underline{75}}\,\mathrm{Hz}$$

c)

5th harmonic:

$$B_{\delta,5} = \frac{4}{\pi \cdot 5} \cdot 0.7\ \mathrm{T} \cdot \sin\left(5 \cdot 0.8 \cdot \frac{\pi}{2}\right) = 0$$

$$\text{with} \sin\left(5 \cdot 0.8 \cdot \frac{\pi}{2}\right) = \sin(2\pi) = 0$$

$$\Phi_{\mu=5} = \frac{2}{\pi} \cdot \frac{\tau_{\mathrm{p}}}{\mu} \cdot l_{\mathrm{Fe}} \cdot B_{\delta,5} \rightarrow U_{\mathrm{p},5} = \underline{\underline{0}}$$

$$f_{\mu=5} = 5 \cdot n \cdot p = 5 \cdot 1500\,\mathrm{min}^{-1} \cdot 3 = \underline{\underline{375}}\,\mathrm{Hz}$$

d)

Ordinal number of harmonics measured in phase voltage:

μ = 1,3,5,7,9,11,13,... no even μ

Ordinal numbers of harmonics measured in line-to-line voltage:

μ = 1,5,7,11,13,... no μ dividable by 3 due to the star-connection

5. Sine wave operated brushless DC-machine

a)

$$\omega = 2\pi \cdot n \cdot p = 2\pi \cdot 1000\,\mathrm{min}^{-1} \cdot 4 = 418.9\,\mathrm{s}^{-1}$$

with $f = n \cdot p = 1000\,\mathrm{min}^{-1} \cdot 4 = 66.67\,\mathrm{Hz}$

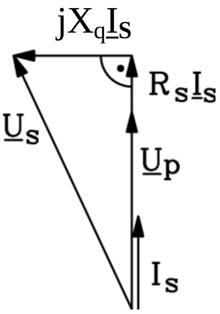
$$U_\mathrm{p} = \omega \cdot \frac{\hat{\Psi}_\mathrm{p}}{\sqrt{2}} = 418.87\,\mathrm{s}^{-1} \cdot \frac{0.36\,\mathrm{Vs}}{\sqrt{2}} = \underline{\underline{106.62}}\,\mathrm{V}$$

$$X_\mathrm{q} = \omega \cdot L_\mathrm{q} = 418.87\,\mathrm{s}^{-1} \cdot 11.1\,\mathrm{mH} = \underline{\underline{4.65}}\,\Omega$$

b)

$$R_\mathrm{s} I_\mathrm{s} = 0.25\,\Omega \cdot 15\,\mathrm{A} = \underline{\underline{3.75}}\,\mathrm{V} \qquad X_\mathrm{q} I_\mathrm{s} = 4.65\,\Omega \cdot 15\,\mathrm{A} = \underline{\underline{69.75}}\,\mathrm{V}$$

c)

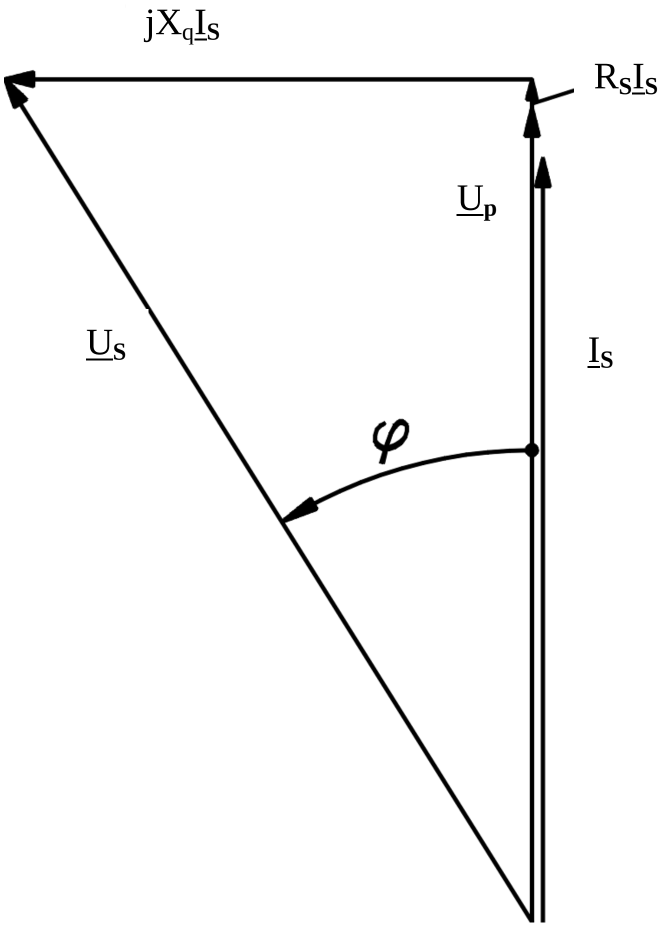


$$U_\mathrm{s} = \sqrt{(X_\mathrm{q} I_\mathrm{s})^2 + (U_\mathrm{p} + R_\mathrm{s} I_\mathrm{s})^2}$$

$$= \sqrt{(4.65\,\Omega \cdot 15\,\mathrm{A})^2 + (106.62\,\mathrm{V} + 3.75\,\mathrm{V})^2} = \underline{\underline{130.6}}\,\mathrm{V}$$

d)

scale: 10V/cm, 1,5A/cm



$$\cos\varphi = \frac{R_\mathrm{s} I_\mathrm{s} + U_\mathrm{p}}{U_\mathrm{s}} = \frac{3.75 + 106.62}{130.6} = \underline{\underline{0.845}}$$

6. Torque-speed limit of sine wave operated brushless DC machine

a)

No load : $I_s = 0:$ $U_{p,max} = U_{s,max}$

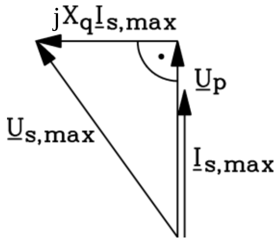
$$U_p = \omega\cdot\frac{\Psi_p}{\sqrt{2}} = 2\pi f\cdot\frac{\Psi_p}{\sqrt{2}} = 2\pi\cdot n\cdot p\cdot\frac{\Psi_p}{\sqrt{2}} = U_{s,max}$$

$$n_{max} = \frac{\sqrt{2}\cdot U_{s,max}}{2\pi\cdot p\cdot\Psi_p} = \frac{\sqrt{2}\cdot 230\,\mathrm{V}}{2\pi\cdot 2\cdot 0.3\,\mathrm{Vs}} = 86.28\,\mathrm{s}^{-1} = \underline{\underline{5177}}\,\mathrm{min}^{-1}$$

b)

$$M_{max} = \frac{3}{2}\cdot p\cdot\Psi_p\cdot\hat{I}_q = \frac{3}{2}\cdot 2\cdot 0.3\,\mathrm{Vs}\cdot\sqrt{2}\cdot 40\,\mathrm{A} = \underline{\underline{50.91}}\,\mathrm{Nm}$$

c)



$$R_s \cong 0$$

$$X_q = 2\pi\cdot n\cdot p\cdot L_q$$

$$U_{s,max}{}^2 = \left(2\pi\cdot p\cdot L_q\cdot I_{s,max}\right)^2\cdot n^2 + \left(\frac{1}{\sqrt{2}}\cdot 2\pi\cdot p\cdot\Psi_p\right)^2\cdot n^2$$

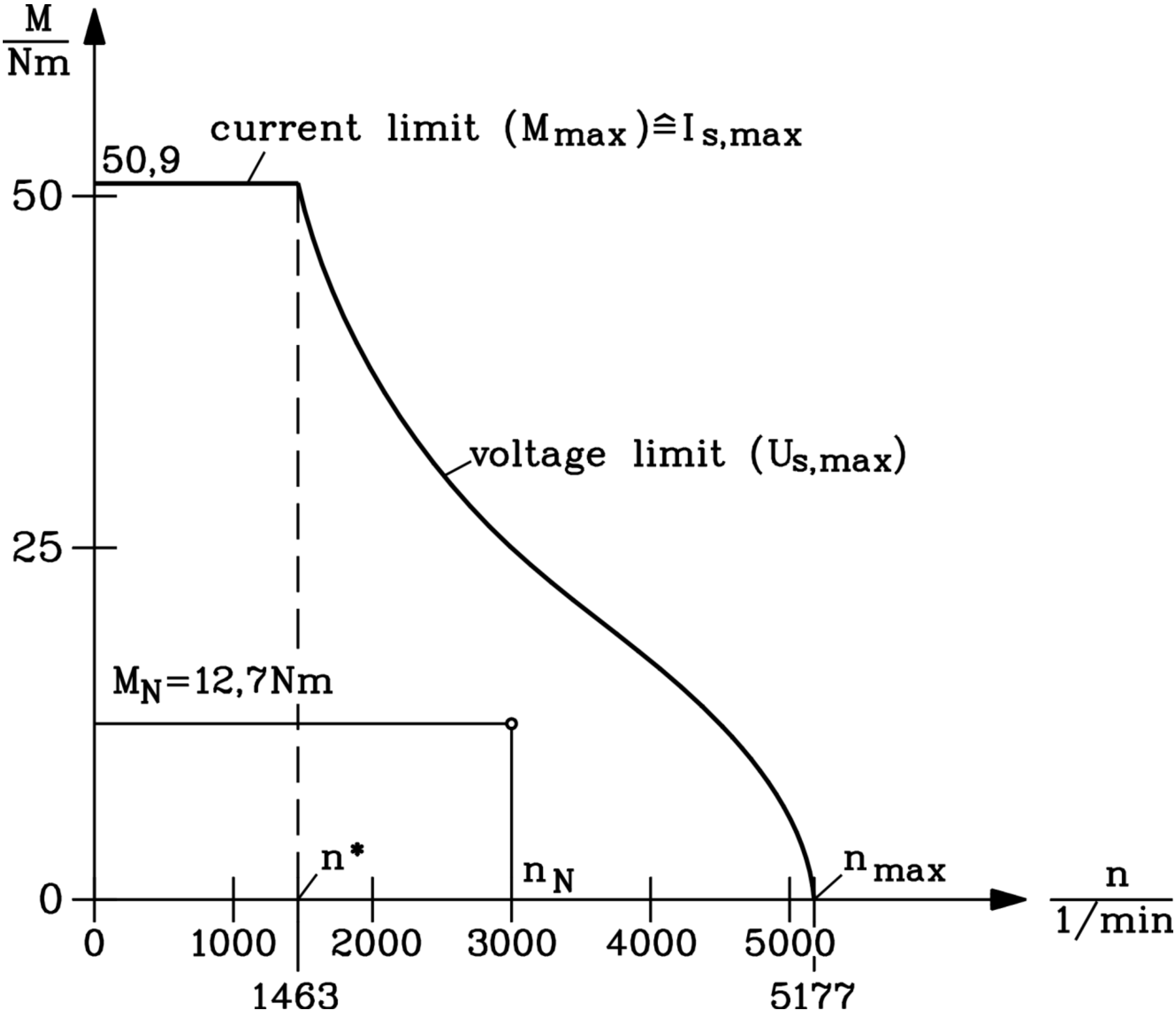
$$n = \frac{U_{s,max}}{\sqrt{\left(2\pi\cdot p\cdot L_q\cdot I_{s,max}\right)^2 + \left(\frac{2\pi\cdot p\cdot\Psi_p}{\sqrt{2}}\right)^2}} = \frac{U_{s,max}}{2\pi\cdot p}\cdot\frac{1}{\sqrt{\left(L_q I_{smax}\right)^2 + \left(\frac{\Psi_p}{\sqrt{2}}\right)^2}}$$

$$= \frac{230\,\mathrm{V}}{2\pi\cdot 2}\cdot\frac{1}{\sqrt{\left(18\,\mathrm{mH}\cdot 40\,\mathrm{A}\right)^2 + \left(\frac{0.3\,\mathrm{Vs}}{\sqrt{2}}\right)^2}} = 24.38\,\mathrm{s}^{-1} = \underline{\underline{1463}}\,\mathrm{min}^{-1} = n*$$

d)

$$M_N = \frac{3}{2}\cdot p\cdot\Psi_p\cdot\sqrt{2}\cdot I_N = \frac{3}{2}\cdot 2\cdot 0.3\,\mathrm{Vs}\cdot\sqrt{2}\cdot 10\,\mathrm{A} = \underline{\underline{12.7}}\,\mathrm{Nm}$$

$$n_N = \frac{f}{p} = \frac{100\,\mathrm{Hz}}{2} = \underline{\underline{3000}}\,\mathrm{min}^{-1}$$



Scale: $500\,\mathrm{rpm} \hat{=} 1\,\mathrm{cm}$; $5\,\mathrm{Nm} \hat{=} 1\,\mathrm{cm}$

- voltage limit curve is estimated, only the endpoints are calculated (see points a), b) and c)).

7. Torque ripple of block commutated brushless DC motor

a)

$$\hat{w}_{\mathrm{M}} = \frac{\hat{M}_{\mathrm{cog}}}{M_{\mathrm{av}}} = \frac{(M_{\max} - M_{\min})/2}{(M_{\max} + M_{\min})/2} = \frac{(107.5\ \mathrm{Nm} - 99\ \mathrm{Nm})/2}{(107.5\ \mathrm{Nm} + 99\ \mathrm{Nm})/2} = \frac{4.25}{103.25} = 4.12\,\%$$

b)

block commutation :

frequency of the torque ripple = 6 x stator frequency

$$f_{\mathrm{s}} = n \cdot p = 20\,\mathrm{min}^{-1} \cdot 4 = 1.33\ \mathrm{Hz} \quad \Rightarrow \quad f_{\mathrm{ripple}} = 6 \cdot 1.33\ \mathrm{Hz} \cong 8\ \mathrm{Hz}$$

c)

$$f_0 = \frac{1}{2\pi} \cdot \sqrt{c \cdot \frac{J_{\mathrm{L}} + J_{\mathrm{M}}}{J_{\mathrm{L}} \cdot J_{\mathrm{M}}}} = \frac{1}{2\pi} \cdot \sqrt{5330\ \mathrm{Nm/rad} \cdot \frac{21 \cdot J_{\mathrm{M}}}{20 \cdot J_{\mathrm{M}}^{2}}} = \frac{1}{2\pi} \cdot \sqrt{5330\ \mathrm{Nm/rad} \cdot \frac{21}{20 \cdot 0.07\ \mathrm{kgm}^{2}}}$$

$$= 45\ \mathrm{Hz}$$

d) At resonance : $f_{\mathrm{ripple}} = f_0 \quad \rightarrow \quad 6 f_{\mathrm{s}} = f_0 \quad \rightarrow \quad 6 \cdot n \cdot p = f_0$

$$\Leftrightarrow n = \frac{f_0}{6 \cdot p} = \frac{45\ \mathrm{Hz}}{6 \cdot 4} = 1.875\ s^{-1} = 112.5\ \mathrm{min}^{-1}$$

8. Field weakening of PM motor as a high speed spindle drive

a)

$$I_q = I_{\mathrm{N}}; \qquad M_N = mp\frac{\Psi_p}{\sqrt{2}} I_q = 3 \cdot 2 \cdot \frac{0.245}{\sqrt{2}} \cdot 65 = \underline{\underline{67.6}}\ \mathrm{Nm}$$

b)

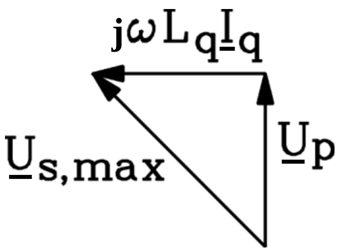
$$n_N = \frac{P_N}{2\pi M_N} = \frac{30000\ \mathrm{W}}{2\pi \cdot 67.6\ \mathrm{Nm}} = 70.66\ \mathrm{s}^{-1} = \underline{\underline{4240}}\ \mathrm{min}^{-1}$$

c)

Maximum torque: $I_{s\max} = I_q = 1.5 I_{\mathrm{N}}$

$$U_{s\max} = \frac{U_{s,LL}}{\sqrt{3}} = \frac{400\mathrm{V}}{\sqrt{3}} = 230\mathrm{V}$$

$$R_s \cong 0: \qquad \underbrace{U_p}_{2\pi n p \frac{\Psi_p}{\sqrt{2}}}^{2} + (\underbrace{\omega}_{2\pi n p} L_q I_q)^2 = U_{s\max}^2$$



$$\Rightarrow n^* = \frac{U_{s\max}}{2\pi p\sqrt{\left(\frac{\Psi_p}{\sqrt{2}}\right)^2 + L_q^2 I_{s\max}^2}} = \frac{230\ \mathrm{V}}{2\pi\cdot 2\cdot\sqrt{\left(\frac{0.245\ \mathrm{Vs}}{\sqrt{2}}\right)^2 + \left(\frac{1.38\ \mathrm{H}}{10^3}\cdot 1.5\cdot 65\ \mathrm{A}\right)^2}} =$$

$$= 83.43\ \mathrm{s}^{-1} = \underline{\underline{5006}}\ \ \mathrm{min}^{-1}$$

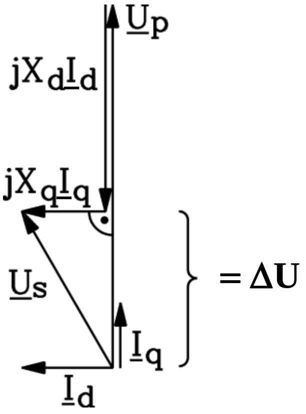
d)

$$n = 15000\ \ \mathrm{rpm}$$

$$M = M_N\cdot\frac{n_N}{n} = 67.6\ \mathrm{Nm}\cdot\frac{4240\ \mathrm{min}^{-1}}{15000\ \mathrm{min}^{-1}} = 19.1\ \mathrm{Nm}$$

$$I_q = I_N\cdot\frac{M}{M_N} = 65\ \mathrm{A}\cdot\frac{19.1\ \mathrm{Nm}}{67.6\ \mathrm{Nm}} = 18.37\ \mathrm{A}$$

$$\omega = 2\pi f,\quad f = n\cdot p = \frac{15000}{60}\ \mathrm{s}^{-1}\cdot 2 = 500\ \mathrm{Hz}$$



$$\Delta U = U_p - X_d I_d = \sqrt{U_s^{\,2} - (\omega L_q I_q)^2} =$$

$$= \sqrt{\left(\frac{400\ \mathrm{V}}{\sqrt{3}}\right)^2 - \left(2\pi\cdot 500\ \mathrm{Hz}\cdot\frac{1.38\ \mathrm{H}}{10^3}\cdot 18.37\ \mathrm{A}\right)^2} = 216.76\ \mathrm{V}$$

$$U_p = \omega\frac{\Psi_p}{\sqrt{2}} = 2\pi\cdot 500\ \mathrm{Hz}\cdot\frac{0.245\ \mathrm{Vs}}{\sqrt{2}} = 544.25\ \mathrm{V}$$

$$I_d X_d = I_d\cdot 2\pi f\cdot L_d = U_p - \Delta U = 544.25\ \mathrm{V} - 216.76\ \mathrm{V} = 327.48\ \mathrm{V}$$

$$I_d = \frac{327.48\ \mathrm{V}}{2\pi\cdot 500\ \mathrm{Hz}\cdot 1.38\cdot 10^{-3}\ \mathrm{H}} = 75.53\ \mathrm{A}$$

$$I_s = \sqrt{I_d^{\,2} + I_q^{\,2}} = \sqrt{75.53^2 + 18.37^2} = \underline{\underline{77.73}}\ \mathrm{A} < I_{inv,\mathrm{limit}} = 1.5\cdot I_N = \underline{\underline{97.5}}\ \mathrm{A}$$

Yes, it is possible to get rated power at 15000 /min, as current I_s does not exceed the inverter limit!

9. Operation boundaries of flux-weakened PM-motor

a)

$$I_{\mathrm{N}} = \frac{P_{\mathrm{N}}}{\sqrt{3}\cdot U_{\mathrm{N}}\cdot \cos\varphi_{\mathrm{N}}\cdot \eta_{\mathrm{N}}} = \frac{30000\ \mathrm{W}}{\sqrt{3}\cdot 400\ \ \mathrm{V}\cdot 0.78\cdot 0.85} = \underline{\underline{65.3}}\ \mathrm{A}$$

b)

$$M_N = \frac{P_N}{2\pi n_N} = \frac{30000\ \mathrm{W}}{2\pi\cdot \dfrac{4240}{60}\ \mathrm{s}^{-1}} = \underline{\underline{67.6}}\ \mathrm{Nm}$$

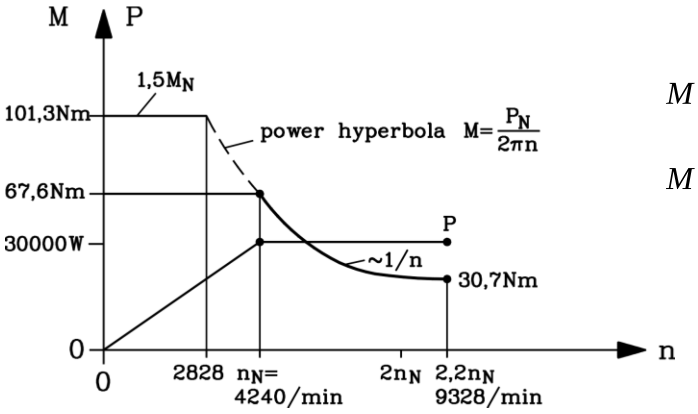
$$M_{\max} = 1.5\cdot M_N = 1.5\cdot 67.6\ \mathrm{Nm} = \underline{\underline{101.3}}\ \mathrm{Nm}$$

c)

$$I_s = I_{sq},\quad I_{sd} = 0 \quad \Rightarrow I_s = 1.5\cdot I_{sqN} = 1.5\cdot 65.3\ \mathrm{A} = \underline{\underline{97.95}}\ \mathrm{A}$$

d)

$0 \le n \le n_{\mathrm{N}}$ $(I_{\mathrm{sd}} = 0)$: limited by $M = M_{\mathrm{N}} \rightarrow$ steady state thermal limit
$n_{\mathrm{N}} \le n \le 2.2\ n_{\mathrm{N}}$ $(I_{\mathrm{sd}} < 0)$: limited by $P = P_{\mathrm{N}}$



$$M \sim \frac{1}{n},\quad n > n_N$$

$$M(n_{\max}) = \frac{1}{2.2}\cdot M_N = \frac{67.6\ \mathrm{Nm}}{2.2} = 30.7\ \mathrm{Nm}$$

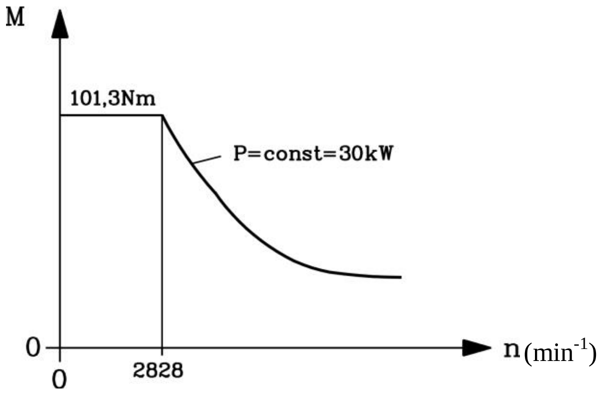
e)

Power limit:

$$P_N \ \rightarrow\quad M = \frac{P_N}{2\pi n}\ :\mathrm{hyperbola}$$

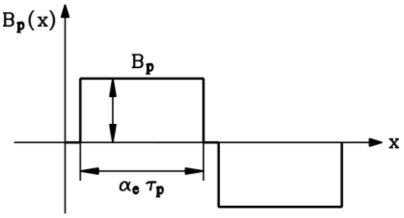
$$n^* = \frac{P_N}{2\pi\cdot M_{\max}} = \frac{30000\ \mathrm{W}}{2\pi\cdot 101.3\ \mathrm{Nm}} =$$

$$= 47.133\ \mathrm{s}^{-1} = \underline{\underline{2828}}\ \mathrm{min}^{-1}$$



10. Single-sided linear PM-drive in tooling machine

a)



$$B_p = \frac{(h_M/\mu_M)\cdot B_R}{\frac{\delta}{\mu_0}+\frac{h_M}{\mu_M}} = \frac{5\,\text{mm}/1.06}{\frac{2\,\text{mm}}{1}+\frac{5\,\text{mm}}{1.06}}\cdot 1.1\,\text{T} = 0.77\,\text{T}$$

$$\hat{B}_{\mu=1} = \frac{4}{\pi}\cdot B_p \sin\left(\alpha_e\frac{\pi}{2}\right) = \frac{4}{\pi}\cdot 0.77\,\text{T}\cdot\sin\left(0.8\frac{\pi}{2}\right) = \underline{\underline{0.935}}\,\text{T}$$

b)

$$F_t = \frac{k_w}{\sqrt{2}}\cdot A\cdot\hat{B}_1\cdot A_{mot} = \frac{0.93}{\sqrt{2}}\cdot 100000\,\frac{\text{A}}{\text{m}}\cdot 0.935\,\text{T}\cdot 0.35\,\text{m}^2 = \underline{\underline{21530}}\,\text{N}$$

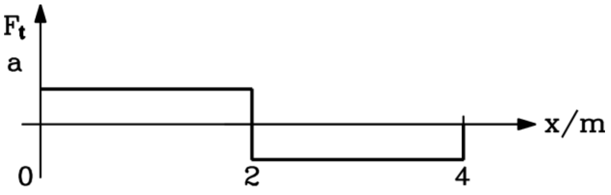
$$f_n = \frac{B_\delta^{\;2}}{2\mu_0} \quad\Rightarrow F_n = \frac{B_p^{\;2}}{2\mu_0}\cdot\alpha_e\cdot A_{mot} = \frac{0.77^2\,\text{T}^2}{2\cdot 4\pi\cdot 10^{-7}\,\frac{\text{Vs}}{\text{Am}}}\cdot 0.8\cdot 0.35\,\text{m}^2 = \underline{\underline{85785}}\,\text{N}$$

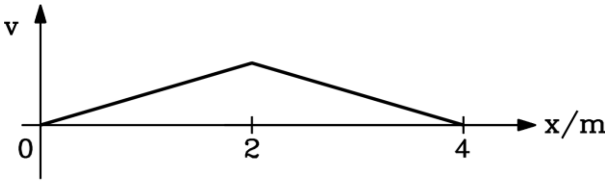
Note: For tangential force we only consider the fundamental wave for force generation. For magnetic pull at no-load, we consider the flux distribution at no-load.
Ratio $F_n/F_t = 4$!

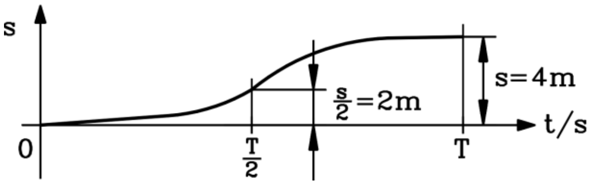
c)

Rated current → Rated current load: $A = 1000\,\text{A/cm}$.
Stand still from $x = 0$ to $x = 4$ m: acceleration at $0 \le x \le 2$ m, braking at $2\text{ m} \le x \le 4$ m.

a : acceleration
v : velocity
s : position (accumulated)







$$m\frac{d^2x}{dt^2} = m\cdot a = F_t$$

$$m\frac{dx}{dt} = F_t\cdot t + v_0,\quad v_0 = 0 = v(t_0)$$

$$m\cdot x = \frac{F_t\cdot t^2}{2} + s_0,\quad s_0 = 0 = s(t_0) = x(t_0) = 0$$

$$m\frac{s}{2} = \frac{F_t\left(\frac{T}{2}\right)^2}{2}$$

$$\to\ T = \sqrt{\frac{m\cdot s}{F_t}} = \sqrt{\frac{1000\,\text{kg}\cdot 4\,\text{m}\cdot 4}{21530\,\text{N}}} = \underline{\underline{0.862\,\text{s}}}$$

d)

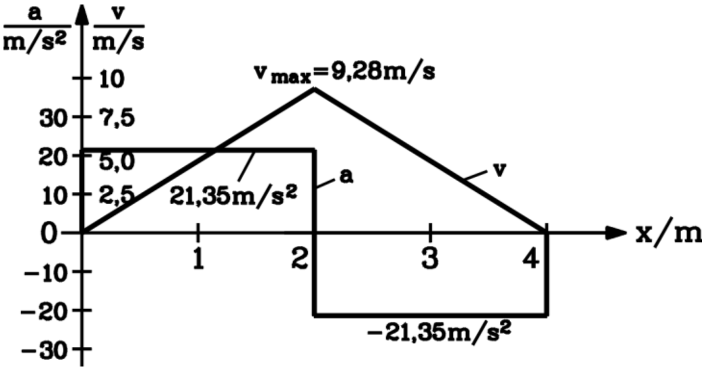
$$a = \frac{F_t}{m} = \frac{21530\ \mathrm{N}}{1000\ \mathrm{kg}} = \underline{\underline{21.53}}\,\frac{\mathrm{m}}{\mathrm{s}^2}$$

$$v_{\max} = \frac{F_t \cdot \frac{T}{2}}{m} = \frac{21530\ \mathrm{N} \cdot \frac{0.862\ \mathrm{s}}{2}}{1000\ \mathrm{kg}} = \underline{\underline{9.28}}\,\frac{\mathrm{m}}{\mathrm{s}}$$

Control of calculation:

$$T = \frac{s}{\bar{v}} = \frac{4\ \mathrm{m}}{4.64\,\frac{\mathrm{m}}{\mathrm{s}}} = \underline{\underline{0.862}}\ \mathrm{s}$$

$$\bar{v} = \frac{v_{\max}}{2} = \frac{9.28\,\frac{\mathrm{m}}{\mathrm{s}}}{2} = 4.64\,\frac{\mathrm{m}}{\mathrm{s}}$$



11. Linear motor as rocket propulsion

a)

$$\frac{dv}{dt} = a, \qquad v = a \cdot t, \qquad \int_0^T v\,dt = \int_0^T \frac{dx}{dt} \cdot dt = \int_0^l dx = l = \frac{a \cdot T^2}{2}, \qquad v_2 = aT$$

$$\rightarrow l = \frac{a}{2}\left(\frac{v_2}{a}\right)^2 \Rightarrow l = \frac{v_2^{\,2}}{2a}$$

$$a = \frac{v_2^{\,2}}{2l} = \frac{11179.4^2 \left(\frac{\mathrm{m}}{\mathrm{s}}\right)^2}{2 \cdot 3000\ \mathrm{m}} = \underline{\underline{20830}}\,\frac{\mathrm{m}}{\mathrm{s}^2}, \qquad T = \frac{v_2}{a} = \frac{11179.4\,\frac{\mathrm{m}}{\mathrm{s}}}{20830\,\frac{\mathrm{m}}{\mathrm{s}^2}} = \underline{\underline{0.54\ \mathrm{s}}}$$

$$v_2 = \sqrt{2 g r_e} = \sqrt{2 \cdot 9.81\ \mathrm{m/s}^2 \cdot 6370000\ \mathrm{m}} = 11179.4\,\frac{\mathrm{m}}{\mathrm{s}} = 40246\,\frac{\mathrm{km}}{\mathrm{h}}$$

b)

Maximum frequency of travelling field is given by $v_{\max} = v_2 = 2 f_{\max} \tau_p$

$$\rightarrow f_{\max} = \frac{v_2}{2\tau_p} = \frac{11179.4\,\frac{\mathrm{m}}{\mathrm{s}}}{2 \cdot 1\ \mathrm{m}} = \underline{\underline{5590}}\ \mathrm{Hz}$$

c)

$$F_t = m\cdot a = 5000\,\text{kg}\cdot 20830\,\frac{\text{m}}{\text{s}^2} = \underline{\underline{104150}}\,\text{kN}$$

d)

$$F_t = k_w\cdot\frac{A}{\sqrt{2}}\cdot\hat{B}\cdot A_{mot} \rightarrow A_{mot} = \frac{104150000\,\text{N}}{\frac{1}{\sqrt{2}}\cdot 1500000\,\frac{\text{A}}{\text{m}}\cdot 1.5\,\text{T}} = \underline{\underline{65.46}}\,\text{m}^2$$

Comment: Surface is too big to correspond with relatively small mass of 5000 kg. So force density has to be maximised by increasing *A* and *B* e.g. by superconducting coils or/and the linear motor has to be built longer (e.g. 20 km).

12. Hi-torque ring motor for cylindrical mill

a)

$$\hat{B}_{\mu=1} = \frac{4}{\pi}\cdot B_p \sin\left(\alpha_e\frac{\pi}{2}\right) = \frac{4}{\pi}\cdot 0.67\,\text{T}\cdot\sin\left(1\cdot\frac{\pi}{2}\right) = \underline{\underline{0.85}}\,\text{T} = B_\delta$$

b)

$$M = \frac{k_w}{\sqrt{2}}\cdot\frac{\pi}{2}\cdot A\cdot B_\delta\cdot d_{si}^{\ 2}\cdot l_{Fe} = \frac{1}{\sqrt{2}}\cdot\frac{\pi}{2}\cdot 27000\,\frac{\text{A}}{\text{m}}\cdot 0.85\,\text{T}\cdot 3.025^2\,\text{m}^2\cdot 0.075\,\text{m} = \underline{\underline{17494}}\,\text{Nm}$$

c)

Total flux per pole (no-load):

$$\Phi_p = \alpha_e\tau_p l B_p = 1\cdot 0.0742\,\text{m}\cdot 0.075\,\text{m}\cdot 0.67\,\text{T} = 3.7286\,\text{mWb}$$

$$\tau_p = \frac{d_{si}\pi}{2p} = \frac{3025\,\text{mm}\cdot\pi}{128} = 74.2\,\text{mm}$$

$$\rightarrow \Phi_y = \frac{\Phi_p}{2} \qquad B_y h_y l_{Fe} = \Phi_y \ \rightarrow\ 2B_y h_y l_{Fe} = \alpha_e\tau_p l B_p$$

$$\rightarrow\ h_y = \frac{\alpha_e\tau_p l_{Fe} B_p}{2B_y l_{Fe}} = \frac{1\cdot 74.2\,\text{mm}\cdot 0.67\,\text{T}}{2\cdot 1.35\,\text{T}} = \underline{\underline{18.4}}\,\text{mm}$$

d)

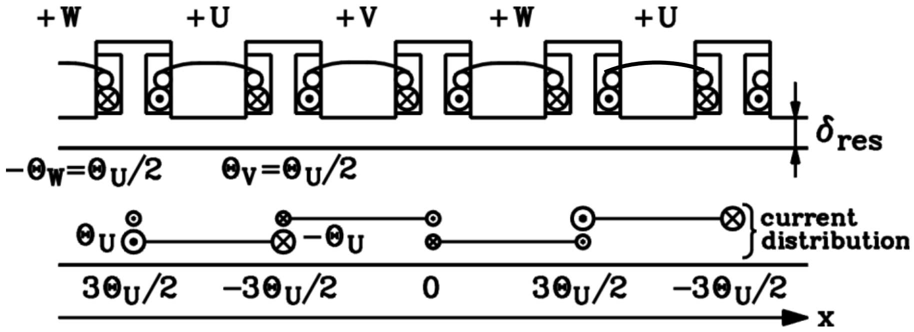
$$f = n\cdot p = \frac{100}{60}\,\text{s}^{-1}\cdot\frac{128}{2} = \underline{\underline{106.65}}\,\text{Hz}$$

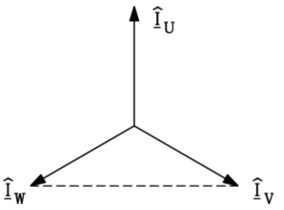
$$v = d_{ra}\pi\cdot n \cong d_{si}\pi n = 3.025\,\text{m}\cdot\pi\cdot\frac{100}{60}\,\text{s}^{-1} = \underline{\underline{15.83}}\,\frac{\text{m}}{\text{s}} = \underline{\underline{57}}\,\frac{\text{km}}{\text{h}}$$

13. Modular synchronous machine

a)

$$3\,\text{slots}/4\,\text{poles},\quad 3\,\text{phasesystem} \Rightarrow q = \frac{1}{4}\quad \text{slot per pole and phase}$$

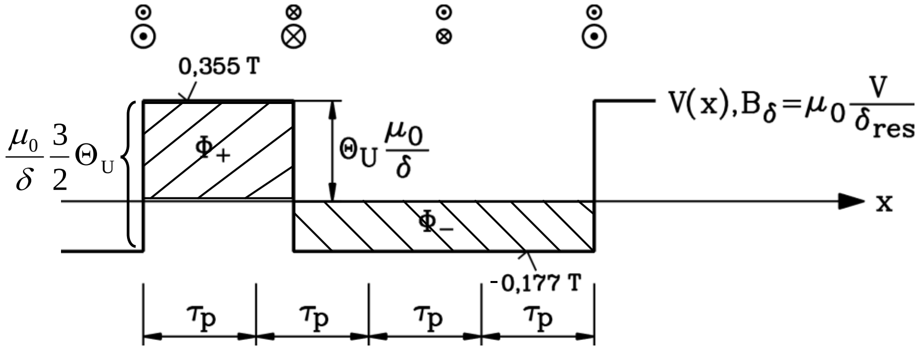




$$t = 0 : i_U = \hat{I}_U = \max$$

$$i_V = i_W = -\frac{\hat{I}_U}{2}$$

Neglected slotopenings !!



$$V = H_\delta \cdot \delta_{res}$$

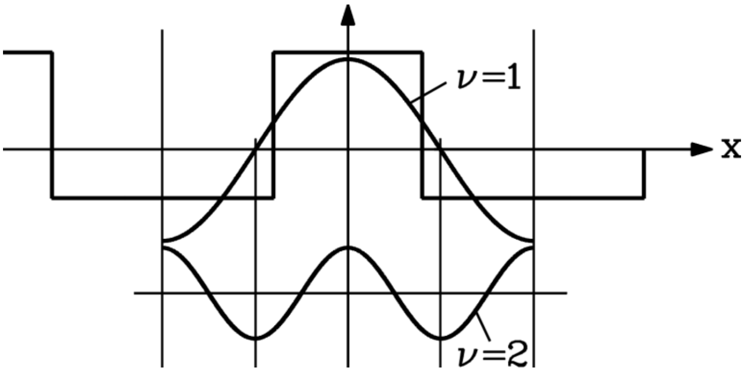
$$\Phi = \int B_\delta dx \cdot l;\qquad \Phi_+ = -\Phi_-;\qquad V_{\max} = \Theta_U$$

$$\Theta_U = \sqrt{2}\cdot\Theta_{rms} = \sqrt{2}\cdot 1800\ \text{A} = 2545\ \text{A}$$

$$B_\delta = \mu_0\frac{V}{\delta_{ges}} = 4\pi\cdot 10^{-7}\,\frac{\text{Vs}}{\text{Am}}\cdot\frac{2545\ \text{A}}{9\cdot 10^{-3}\ \text{m}} = 0.355\ \text{T}$$

b)

Qualitative analysis:



Fundamental: $\nu = 1$

Wave length: $4\tau_p$

First harmonic: $\nu = 2$

Wave length: $\underline{\underline{2\tau_p}}$

Rotor magnets fundamental: $\mu = 1$

Wave length: $\underline{\underline{2\tau_p}}$

Result: Stator first harmonic $\nu = 2$ is generating with rotor fundamental $\mu = 1$ the torque, as they have the same wave length!

14. Transversal flux machine

a)

Ampere's law:

$$2\delta \cdot H_\delta + 2h_M H_M = 0 \quad (1)$$

$$B_M A_M = B_\delta A_\delta \quad (2)$$ - no flux concentration! $A_M = A_\delta$

Magnet in second quadrant of $B_M(H_M)$-plane:

$$B_M = \mu_M H_M + B_R \quad (3)$$

$$(1)+(2): \quad B_M = B_\delta = \mu_0 H_\delta = -\frac{\mu_0 h_M}{\delta} \underset{\uparrow (3)}{H_M} = -\frac{\mu_0 h_M}{\delta} \cdot \frac{B_M - B_R}{\mu_M}$$

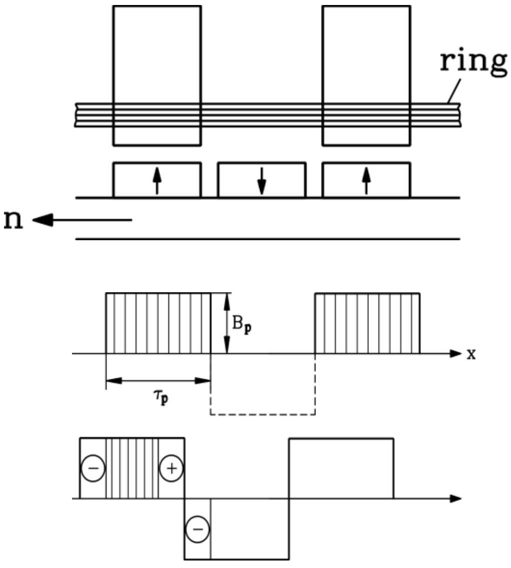
$$B_M = B_\delta = \frac{\frac{\mu_0 h_M}{\delta} \cdot \frac{B_R}{\mu_M}}{1 + \frac{h_M}{\delta} \cdot \frac{\mu_0}{\mu_M}} = \frac{\frac{1}{1.06} \cdot \frac{6.5\,\mathrm{mm}}{0.8\,\mathrm{mm}} \cdot 1.095\,\mathrm{T}}{1 + \frac{1}{1.06} \cdot \frac{6.5\,\mathrm{mm}}{0.8\,\mathrm{mm}}} = \underline{\underline{0.9686}}\,\mathrm{T} = B_p$$

b)

Ampere's law: $2\hat{H}_\delta(\delta + h_M) = N_s \hat{I}_s$

$$\hat{B}_{\delta,s} = B_s = \mu_0 H_\delta = \mu_0 \frac{N_s \hat{I}_s}{2(\delta + h_M)} = 4\pi \cdot 10^{-7} \frac{\mathrm{Vs}}{\mathrm{Am}} \cdot \frac{22 \cdot 95 \cdot \sqrt{2}\,\mathrm{A}}{2(0.8\,\mathrm{mm} + 6.5\,\mathrm{mm})} \cdot 10^3 = \underline{\underline{0.254}}\,\mathrm{T}$$

c)



per pole-pair :

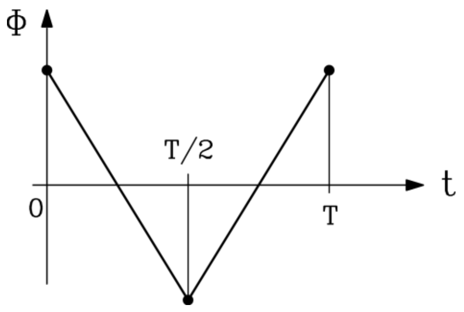
$$\Phi = \tau_p \cdot h \cdot B_p =$$

$$= 17.5\,\mathrm{mm} \cdot 28\,\mathrm{mm} \cdot 0.9686\,\mathrm{T} \cdot 10^{-6} =$$

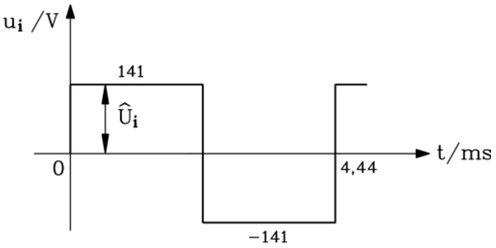
$$= 0.4746\,\mathrm{mWb}$$

linear decrease of flux with moving rotor:

$$T = \frac{1}{f} = \frac{1}{n \cdot p} = \frac{1}{\frac{900}{60}\,\mathrm{s}^{-1} \cdot 15} = 4.44 \cdot 10^{-3}\,\mathrm{s}$$



$$u_i = -N_s \frac{d\Phi}{dt}\cdot p = +N_s \frac{2\Phi}{T/2}\cdot p = 22\frac{4\cdot 0.4746\,\text{Wb}}{10^3\cdot 4.44\cdot 10^{-3}\,\text{s}}\cdot 15 = \underline{\underline{141}}\,\text{V}$$



d)

Fourier-Analysis:

$$\hat U_{i(1)} = \frac{2}{T}\int_0^T u_i(t)\sin\left(\frac{2\pi t}{T}\right)dt = \frac{2\cdot 4}{T}\int_0^{T/4}\hat U_i \sin\left(\frac{2\pi t}{T}\right)dt = \frac{2\cdot 4\hat U_i}{T}\left(-\cos\left(\frac{2\pi t}{T}\right)\right)\Bigg|_0^{T/4}\cdot\frac{T}{2\pi} =$$

$$= \frac{4}{\pi}\hat U_i\left(-\cos\frac{\pi}{2}+1\right) = \frac{4}{\pi}\hat U_i$$

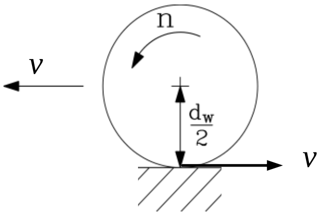
$$\hat U_{i(1)} = \frac{4}{\pi}141\,\text{V} = \underline{\underline{179.65}}\,\text{V}$$

15. Transversal flux machine as vehicle drive system

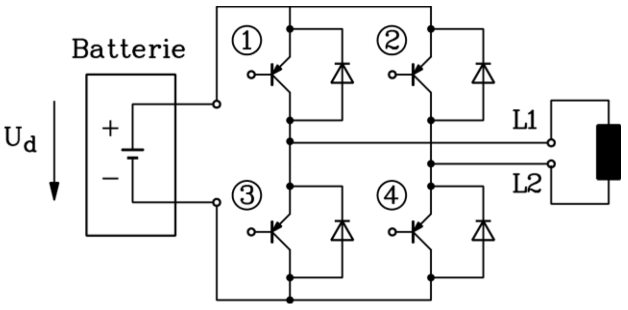
a)

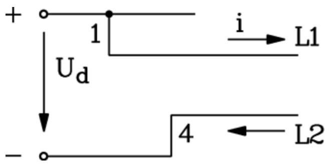
$$v_{\max} = d_w\pi\cdot n_{\max}$$

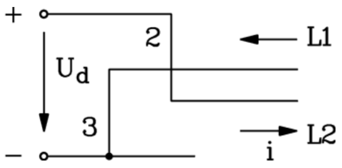
$$\rightarrow \quad n_{\max} = \frac{\frac{120}{3.6}\frac{\text{m}}{\text{s}}}{0.8\,\text{m}\cdot\pi} = 13.26\,\text{s}^{-1} = \underline{\underline{795}}\,\text{min}^{-1}$$



b)





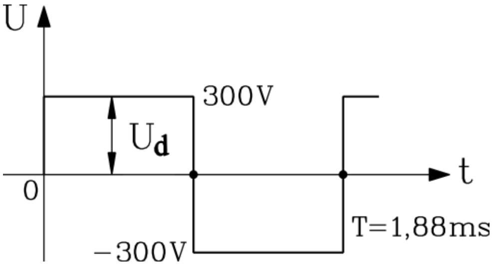


c)

$2p = 80:$

$f_{\max} = 40 \cdot 13.26\,\mathrm{s}^{-1} = 530.5\,\mathrm{Hz}$

$\rightarrow \quad T = 1.88\,\mathrm{ms}$



16. Switched reluctance machine

a)

$$\alpha_s = \frac{b_s}{d_{si}\pi}\cdot 360° = \frac{16\,\mathrm{mm}}{122.2\,\mathrm{mm}\cdot\pi}\cdot 360° = \underline{\underline{15}}°, \qquad \alpha_{sg} = \frac{360°}{Q_s} - \alpha_s = \frac{360°}{12} - 15° = \underline{\underline{15}}°$$

$$\alpha_r = \frac{b_r}{d_{si}\pi}\cdot 360° = \alpha_s = \underline{\underline{15}}°, \qquad \alpha_{rg} = \frac{360°}{Q_r} - \alpha_r = \frac{360°}{8} - 15° = \underline{\underline{30}}°$$

b)

$$L_{d_h} = 2p\cdot L_c = 2p\cdot\mu_0 N_c{}^2 \frac{b_s}{\delta}\cdot l_{Fe} = 4\cdot 4\pi\cdot 10^{-7}\,\frac{\mathrm{Vs}}{\mathrm{Am}}\cdot 61^2\,\frac{16\,\mathrm{mm}}{0.45\,\mathrm{mm}}\cdot 0.193\,\mathrm{m} = \underline{\underline{128.3}}\,\mathrm{mH}$$

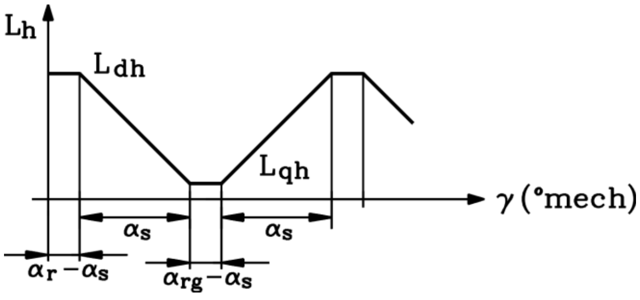
c)

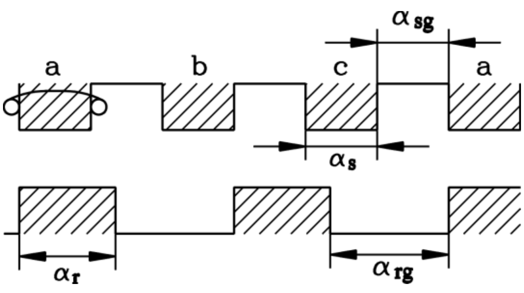
$$M = \frac{1}{2}I^2\frac{L_d - L_q}{\alpha} = \frac{1}{2}I^2\frac{L_{d_h} - L_{q_h}}{\alpha} = \frac{1}{2}\cdot 10^2\ \mathrm{A}^2\,\frac{128.3\,\mathrm{H} - 10\,\mathrm{H}}{10^3\cdot 0.262\,\mathrm{rad}}\,\mathrm{Nm} = \underline{\underline{22.5}}\,\mathrm{Nm}$$

$$L_d = L_{d_h} + L_\sigma\,, \qquad L_q = L_{q_h} + L_\sigma$$

$$\alpha = \min(\alpha_s,\alpha_r) = \min(15°,15°) = 15°\,, \qquad \alpha = \frac{15°}{360°}2\pi = 0.262\,\mathrm{rad}$$

d)

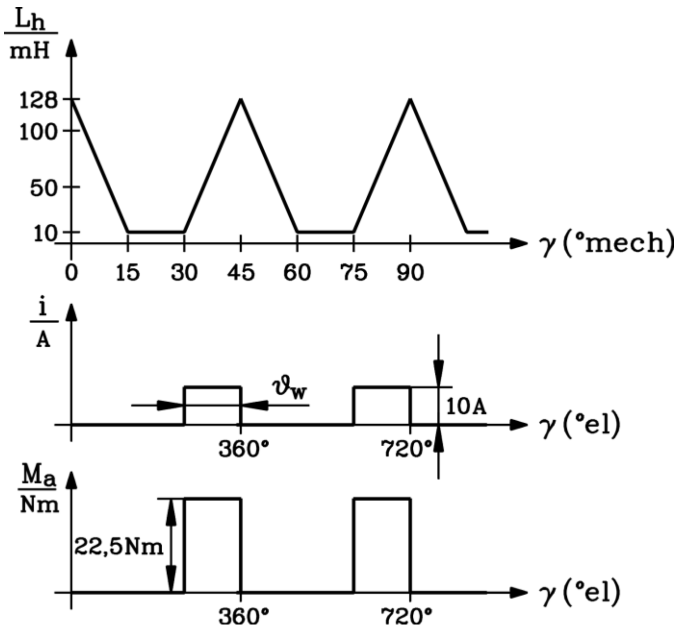




$\alpha_r = \alpha_s : \alpha_r - \alpha_s = 0°$

$\alpha_s = 15°$

$\alpha_{rg} - \alpha_s = 30° - 15° = 15°$



1 period ≙ 360°el ≙

$$\hat{=}\ \frac{2\pi}{Q_r} = \frac{360°}{8} = 45°\,\text{mech}$$

$$\vartheta_W = \underline{\underline{120°}}\ \text{el}$$

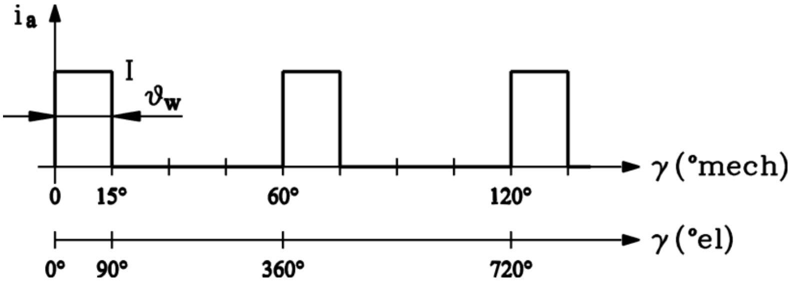
17. Torque-speed characteristic of a switched reluctance machine

a)

One period ≙ one rotor slot pitch

$\frac{360°}{Q_r} = \frac{360°}{6} = \underline{\underline{60°}}$ ≙ one period of stator phase current.

b)



No overlap ⇔ four phases ⇔ conducting angle $\vartheta_w = \frac{360°}{m} = \frac{360°}{m} = \underline{\underline{90°}}$

c)

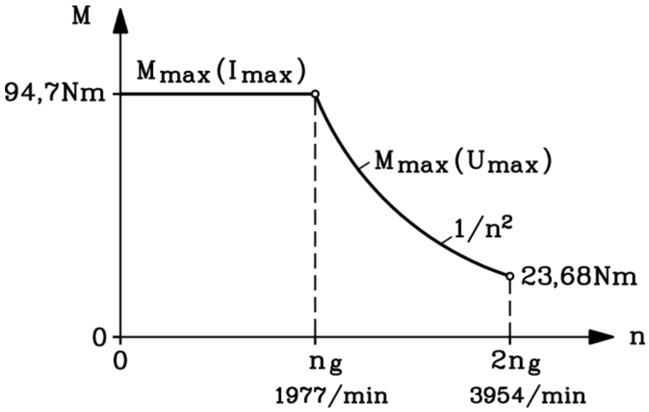
$$M = \frac{1}{2}\hat{I}^2\frac{L_d - L_q}{\alpha} = \frac{1}{2}\cdot 70^2\ \text{A}^2\,\frac{12\,\text{H} - 1.8\,\text{H}}{0.264\,\text{rad}\cdot 10^3} = \underline{\underline{94.7}}\,\text{Nm}$$

$$\alpha = \min(\alpha_s, \alpha_r) = \alpha_s\,,\quad (b_s < \text{b}_\text{r}!) \qquad \alpha_s = \frac{b_s}{d_{si}\pi}\cdot 360° = \frac{26\,\text{mm}}{197\,\text{mm}\cdot\pi}\cdot 360° = \underline{\underline{15.1}}° \,\hat{=}\, 0.264\,\text{rad}$$

d)

$$n_g = \frac{1}{2\pi}\cdot\frac{U_d}{\hat{I}_{\max}\,\frac{L_d-L_q}{\alpha}} = \frac{1}{2\pi}\cdot\frac{560\,\mathrm{V}}{70\,\mathrm{A}\cdot\frac{12\,\mathrm{H}-1.8\,\mathrm{H}}{0.264\,\mathrm{rad}\cdot 10^3}} = 32.95\,\mathrm{s}^{-1} = \underline{\underline{1977}}\,\mathrm{min}^{-1}$$

e)



$$M_e = \frac{1}{2\,\frac{L_d-L_q}{\alpha}}\cdot\left(\frac{U_d}{\Omega_m}\right)^2$$

at $2n_g$:

$$\Omega_m = 2\pi\cdot 2n_g = 2\pi\cdot 2\cdot 32.95\,\mathrm{s}^{-1} = 414\,\mathrm{s}^{-1}$$

$$M_e = 23.68\,\mathrm{Nm}$$

18. Synchronous reluctance machine

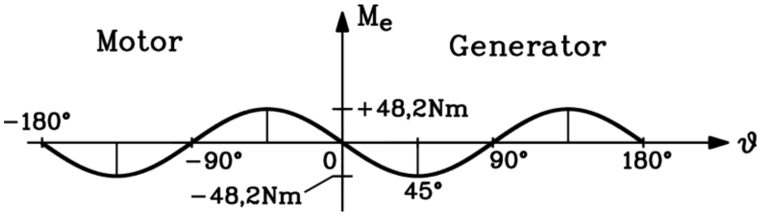
a)

$$M_{po} = \frac{pm}{\omega_s}\cdot\frac{U_s^{\,2}}{2}\left(\frac{1}{X_q}-\frac{1}{X_d}\right) = \frac{2\cdot 3}{2\pi 50\,\mathrm{Hz}}\cdot\frac{231^2\,\mathrm{V}^2}{2}\left(\frac{1}{8\,\Omega}-\frac{1}{33\,\Omega}\right) = \underline{\underline{48.2}}\,\mathrm{Nm} \qquad (\vartheta_{po} = 45°)$$

$$U_s = \frac{U_{LL}}{\sqrt{3}} = \frac{400\,\mathrm{V}}{\sqrt{3}} = 231\,\mathrm{V}$$

b)

$$M_e = -M_{po}\sin 2\vartheta$$



c)

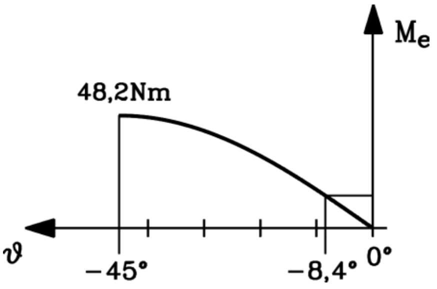
$$M_N = \frac{P_N}{2\pi n_N} = \frac{2200\,\mathrm{W}}{2\pi\cdot 25\,\mathrm{s}^{-1}} = 14\,\mathrm{Nm} \qquad M_N = -M_{po}\sin 2\vartheta_N$$

$$n_N = n_{syn} = \frac{f}{p} = \frac{50\ \mathrm{Hz}}{2} = 25\ \mathrm{s}^{-1} = 1500\ \mathrm{min}^{-1}$$

$$\vartheta_N = -\frac{1}{2}\arcsin\left(\frac{M_N}{M_{po}}\right) = -\frac{1}{2}\arcsin\left(\frac{14\ \mathrm{Nm}}{48.2\ \mathrm{Nm}}\right) =$$

$$= -0.147\ \mathrm{rad} = \underline{\underline{-8.4^\circ}}$$

$$\frac{M_{po}}{M_N} = \frac{48.2\ \mathrm{Nm}}{14\ \mathrm{Nm}} = \underline{\underline{3.44}}$$



19. Synchronous reluctance motor

a)

$$X_d = 2\pi f \cdot L_d = 2\pi 50\ Hz \cdot 0.11\ \mathrm{H} = \underline{\underline{34.6}}\ \Omega$$

$$X_q = 2\pi f \cdot L_q = 2\pi 50\ Hz \cdot 0.029\ \mathrm{H} = \underline{\underline{9.1}}\ \Omega$$

b)

$$M_N = -M_{po}\sin 2\vartheta_N$$

$$M_{po} = \frac{pm}{\omega_s}\cdot\frac{U_s^{\,2}}{2}\left(\frac{1}{X_q}-\frac{1}{X_d}\right) = \frac{2\cdot 3}{2\pi 50\ \mathrm{Hz}}\cdot\left(\frac{400}{\sqrt{3}}\right)^2 \mathrm{V}^2\cdot\frac{1}{2}\left(\frac{1}{9.1\,\Omega}-\frac{1}{34.6\,\Omega}\right) = 41.2\ \mathrm{Nm}$$

$$\vartheta_N = -\frac{1}{2}\arcsin\left(\frac{M_N}{M_{po}}\right) = -\frac{1}{2}\arcsin\left(\frac{22.3\ \mathrm{Nm}}{41.2\ \mathrm{Nm}}\right) = -0.285\ \mathrm{rad} = \underline{\underline{-16.3^\circ}}$$

$$M_N = \frac{P_N}{2\pi n_N} = \frac{3500\ \mathrm{W}}{2\pi\cdot 25\ \mathrm{s}^{-1}} = 22.3\ \mathrm{Nm}$$

$$n_N = n_{syn} = \frac{f}{p} = \frac{50\ \mathrm{Hz}}{2} = 25\ \mathrm{s}^{-1} = 1500\ \mathrm{min}^{-1}$$

c)

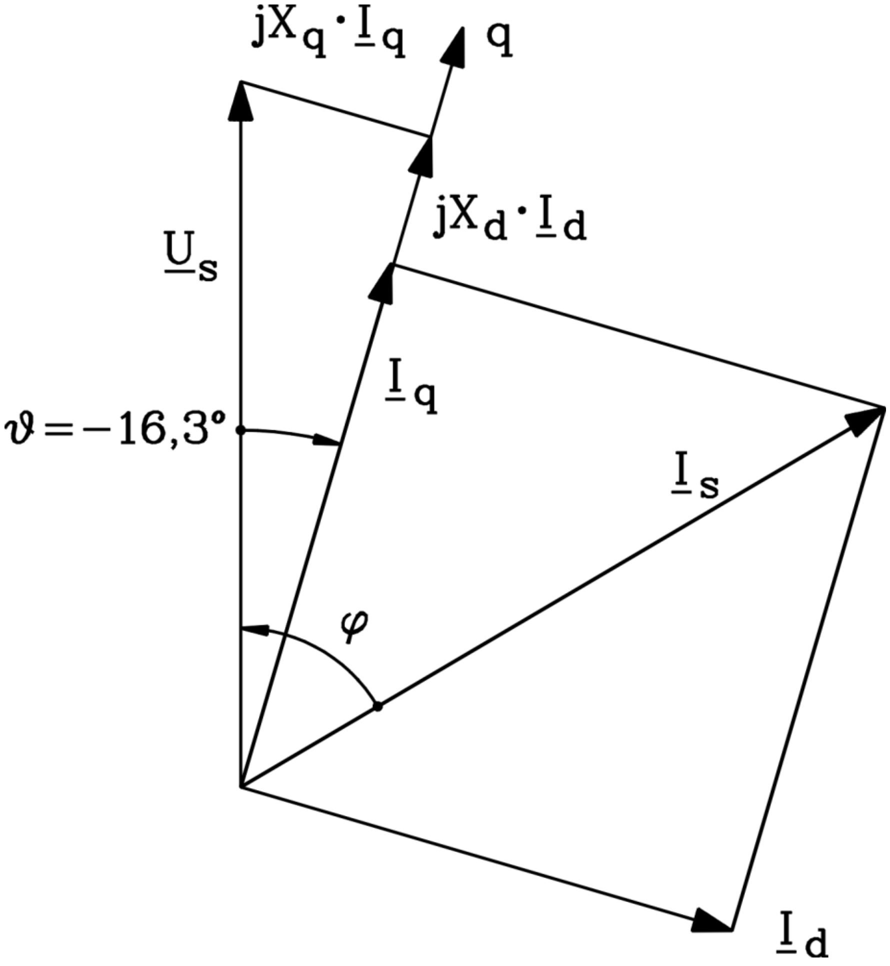
Scale: $25\ \mathrm{V} \mathrel{\hat{=}} 1\ \mathrm{cm}$; $1\ \mathrm{A} \mathrel{\hat{=}} 1\ \mathrm{cm}$

$$U_s = 231\ \mathrm{V} \mathrel{\hat{=}} 9.24\ \mathrm{cm}$$

$$X_q I_q = U_s \sin\vartheta \Rightarrow I_q = 7.13\ \mathrm{A}$$

$$X_d I_d = U_s \cos\vartheta \Rightarrow I_d = 6.7\ \mathrm{A}$$

$$I_s = \sqrt{I_d^{\,2} + I_q^{\,2}} = \sqrt{6.7^2\ \mathrm{A}^2 + 7.13^2\ \mathrm{A}^2} = \underline{\underline{9.77}}\ \mathrm{A}$$



d)

$$\cos\varphi = \frac{P_e}{3 \cdot U_s I_s} = \frac{3500\,\mathrm{W}}{3 \cdot 231\,\mathrm{V} \cdot 9.77\,\mathrm{A}} = \underline{\underline{0.51}}$$

20. High speed PM synchronous motor with rotor squirrel cage for voltage-controlled inverter operation

a)

$$\Phi = \frac{2}{\pi}\tau_p l_{Fe} B_p = \frac{2}{\pi} \cdot \frac{d_{si}\pi}{2p} \cdot l_{Fe} B_p = \frac{d_{si}}{p} \cdot l_{Fe} B_p = \frac{0.075\,\mathrm{mm}}{2} \cdot 0.075\,\mathrm{mm} \cdot 0.7\,\mathrm{T} = \underline{\underline{1.969}}\,\mathrm{mWb}$$

b)

$$f_s = n \cdot p = \frac{24000}{60}\,\mathrm{s}^{-1} \cdot 2 = \underline{\underline{800}}\,\mathrm{Hz}$$

No-load voltage:

$$U_0 = U_p = \sqrt{2}\pi f_N \cdot N_s \cdot k_{ws} \cdot \Phi_p = \sqrt{2}\pi \cdot 800\,\mathrm{Hz} \cdot 24 \cdot 0.96 \cdot 1.969 \cdot 10^{-3}\,\mathrm{Wb} = \underline{\underline{161.2}}\,\mathrm{V}$$

No-load: $I_s = 0 \rightarrow U_s = U_p = U_0$

c)

Neglecting R_s : $U_{sN} = \omega_{sN} k_{ws} N_s \cdot \Phi_{sN} \Rightarrow \dfrac{U_{sN}}{f_{sN}} \sim \Phi_{sN}$

$$\frac{U_{sN}}{f_{sN}} = \frac{400\text{ V}}{\sqrt{3}} \cdot \frac{1}{800\text{ Hz}} = \frac{1}{2\sqrt{3}} = \underline{\underline{0.288}}\,\frac{\text{V}}{\text{Hz}}$$

d)

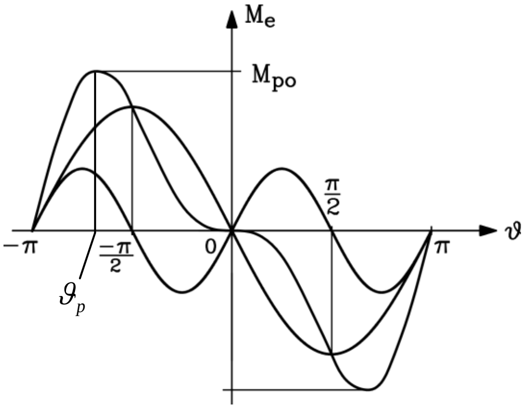
motor: $P_N = P_m = P_{out}$

$$S = \frac{P_N}{\cos\varphi_N \cdot \eta_N} = \frac{15000\text{ W}}{0.7 \cdot 0.9} = 23810\text{ VA}$$

$$\Rightarrow C = \frac{S_i}{d_{si}{}^2 l_{Fe} n} = \frac{23.810\text{ kVA}}{0.075^2\text{ m}^2 \cdot 0.075\text{ m} \cdot 24000\text{ min}^{-1}} = \underline{\underline{2.35}}\,\text{kVA}\,\frac{\text{min}}{\text{m}^3}$$

21. PM synchronous motor with buried magnets and squirrel cage rotor for line operation

a)



$$\frac{\omega_s}{p} M_e = -\frac{3U_s U_p}{X_d}\sin\vartheta - \underbrace{\frac{3U_s^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)}_{>0}\sin 2\vartheta$$

$$\frac{\omega_s}{p} M_e = -\text{A}\sin\vartheta + \text{B}\sin 2\vartheta$$

$$\frac{dM_e}{d\vartheta} = 0: \qquad \text{A}\cos\vartheta - 2\text{B}\cos 2\vartheta = 0$$

$$\cos 2\vartheta = 2\cos^2\vartheta - 1 \rightarrow \text{A}\cos\vartheta - 2\text{B}\left(2\cos^2\vartheta - 1\right) = 0$$

$$\cos\vartheta = x \rightarrow \qquad \text{A}x - 2\text{B}\left(2x^2 - 1\right) = 0$$

$$-4\text{B}x^2 + \text{A}x + 2\text{B} = 0$$

$$x^2 - \frac{\text{A}}{4\text{B}}x - \frac{1}{2} = 0$$

$$\cos\vartheta_{1,2} = x_{1,2} = +\frac{\text{A}}{8\text{B}} \pm \sqrt{\left(\frac{\text{A}}{8\text{B}}\right)^2 + \frac{1}{2}}$$

$$\left|\vartheta_p\right| > \frac{\pi}{2} \rightarrow \cos\vartheta_p < 0 \quad !!$$

$$\Rightarrow \cos\vartheta_p = +\frac{\text{A}}{8\text{B}} - \sqrt{\left(\frac{\text{A}}{8\text{B}}\right)^2 + \frac{1}{2}} \quad < 0$$

$$\frac{A}{8B}=\frac{3U_sU_p}{8X_d}\cdot\frac{1}{\frac{3U_s^{\,2}}{2}\left(\frac{1}{X_d}-\frac{1}{X_q}\right)}=\frac{U_p}{4U_s}\frac{1}{1-\frac{X_d}{X_q}}=\frac{30\text{ V}}{4\cdot 75.06\text{ V}}\frac{1}{1-\frac{15.7\,\Omega}{19\,\Omega}}=0.575$$

$$U_s=\frac{130}{\sqrt{3}}=75.06\text{ V}$$

$$\cos\vartheta_p=0.575-\sqrt{0.575^2+0.5}=-0.33626$$

$$\vartheta_p=\underline{\underline{-109.65°}}\ \text{Motor}$$

$$\vartheta_p=\underline{\underline{109.65°}}\ \text{Generator}$$

$$\left|M_p\right|=\left|-\frac{3U_sU_p}{X_d}\sin\vartheta_p+\frac{3U_s^{\,2}}{2}\left(\frac{1}{X_d}-\frac{1}{X_q}\right)\sin 2\vartheta_p\right|\frac{p}{\omega_s}$$

$$M_p=\left|-\frac{3\cdot 75.06\cdot 30}{15.7}\sin(-109.65°)+\frac{3\cdot 75.06^2}{2}\left(\frac{1}{15.7}-\frac{1}{19}\right)\cdot\sin(-2\cdot 109.65°)\right|\frac{2}{2\pi\cdot 50}=$$

$$=\left|2.5797+0.377\right|=\underline{\underline{2.956}}\text{ Nm}$$

b)

$$M_N=\frac{P_N}{2\pi\cdot n_N}=\frac{340\text{ W}}{2\pi\cdot\frac{1500}{60}\text{ s}^{-1}}=\underline{\underline{2.16}}\text{ Nm}$$

$$2p=4,\quad f=50\text{ Hz}\Rightarrow n_N=1500\text{ min}^{-1}$$

$$P_N=\sqrt{3}\cdot U_NI_N\cdot\cos\varphi_N\cdot\eta_N=\sqrt{3}\cdot 130\text{V}\cdot 3.8\text{ A}\cdot 0.63\cdot 0.63=340\text{ W}$$

c)

$$\frac{M_{po}}{M_N}=\frac{2.956\text{ Nm}}{2.16\text{ Nm}}=\underline{\underline{1.36}}$$

22. Asynchronous start up of a PM synchronous motor with rotor squirrel cage

a)

$$(1-s)=\frac{n}{n_{syn}};\qquad n_{syn}=n_N$$

$\frac{M_{e,asyn}}{M_b}=$	0	1	0.8	0.6	0.47	0.38
$s=$	0	0.2	0.4	0.6	0.8	1
$\frac{n}{\text{min}^{-1}}=$	24000	19200	14400	9600	4800	0

sketch of $M_{\text{asyn}}(n)$ see drawing at e).

b)

$$n^* = \frac{R_s}{2\pi \cdot p \cdot L_d} = \frac{0.35\,\Omega}{2\pi \cdot 2 \cdot 0.001\,\text{H}} = 27.85\,\text{s}^{-1} = \underline{\underline{1671}}\,\text{min}^{-1} \quad \hat{=} \quad s = \frac{24000 - 1671}{24000} = 0.93$$

c)

$$M_{p,\max} = \frac{3p}{2} \cdot \frac{\Psi_p^{\;2}}{2L_d} = \frac{3 \cdot 2}{2} \cdot \frac{0.045^2\,(\text{Vs})^2}{2 \cdot 0.001} = \underline{\underline{3.0}}\,\text{Nm}$$

d)

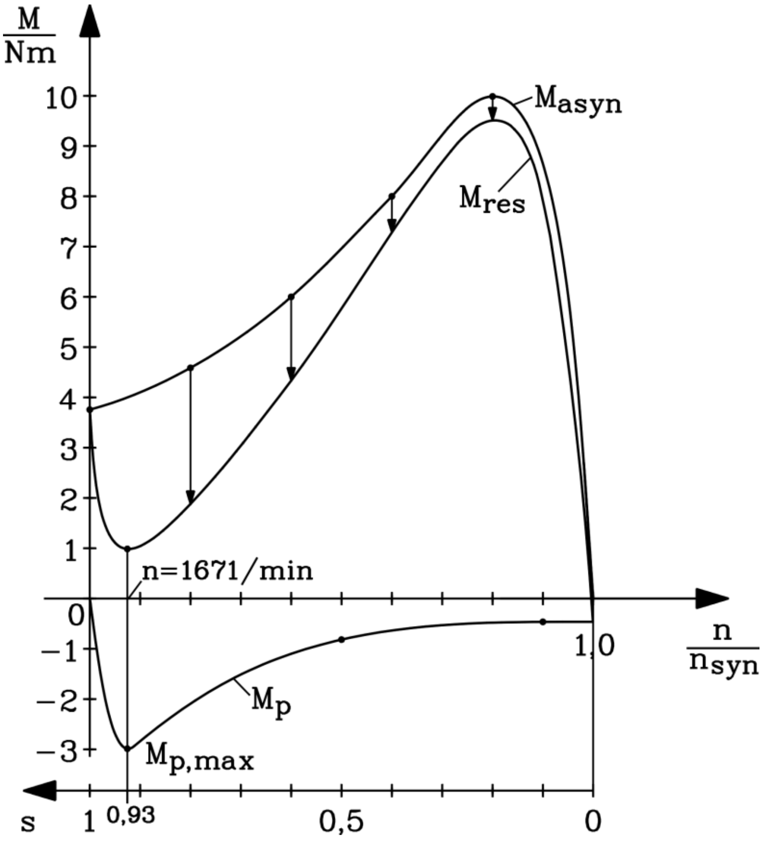
$$M_p = -\frac{3p \cdot R_s}{2} \cdot \frac{\omega \cdot \Psi_p^{\;2}}{R_s^{\;2} + \omega^2 L_d^{\;2}}$$

$$\omega = 2\pi \cdot n \cdot p$$

$$n = (1 - s)\, n_{syn}$$

$s =$	0	0.1	0.5	1
$\frac{M_p}{\text{Nm}} =$	0.42	0.47	0.83	0
$\frac{\omega}{s^{-1}} =$	5026	4523	2513	0

e)



23. Electromagnetic aircraft launch system on aircraft carrier

a)

$$W_{kin} = m_{Aircraft}\cdot\frac{v_{launch}^2}{2} = 45000\,\text{kg}\cdot\frac{1}{2}\cdot\left(\frac{370}{3.6}\right)^2\left(\frac{\text{m}}{\text{s}}\right)^2 = \underline{\underline{237.67}}\,\text{MJ}$$

b)

$$v = 2f\cdot\tau_p \qquad\Rightarrow\qquad f = \frac{v_{launch}}{2\tau_p} = \frac{\frac{370}{3.6}\frac{\text{m}}{\text{s}}}{2\cdot 0.5\,\text{m}} = \underline{\underline{103}}\,\text{Hz}$$

c)

$$P(t) = F(t)\cdot v(t) = F\cdot 2f\tau_p \sim t$$

$$m\ddot{x} = F\,,\quad \ddot{x} = a$$

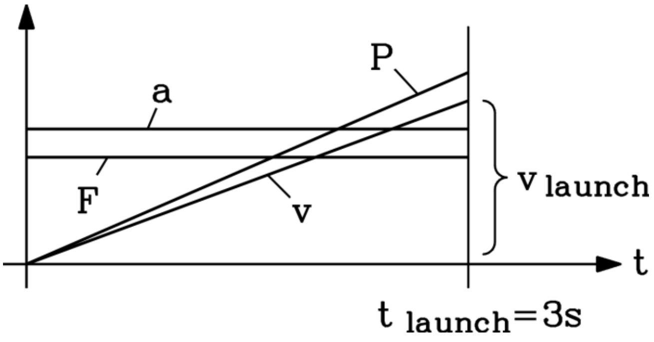
v rises linear with time $\rightarrow v \sim$ t

$$a = \frac{dv}{dt} = \text{const.}$$

$$F = m\cdot a = 45000\,\text{kg}\cdot 34.3\frac{m}{s^2} = \underline{\underline{1541.6}}\,\text{kN}$$

$$a = \frac{v_{launch}}{t_{launch}} = \frac{\frac{370}{3.6}\frac{\text{m}}{\text{s}}}{3\,\text{s}} = 34.3\frac{\text{m}}{\text{s}^2}$$

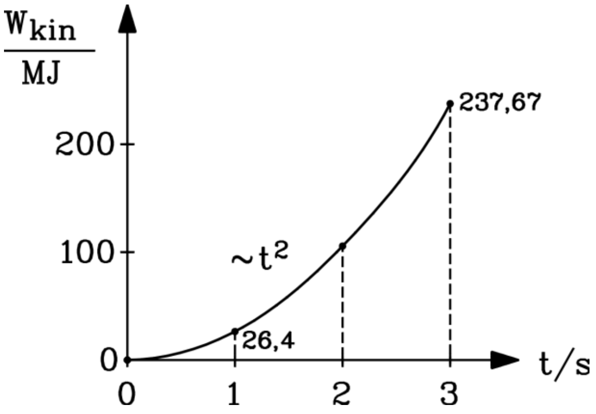
$$P_{launch} = F\cdot v_{launch} = 1541666\,\text{N}\cdot\frac{370}{3.6}\frac{m}{s} = \underline{\underline{158.5}}\,\text{MW}$$



d)

$$W_{kin} = \int_0^t P(t)dt = \int_0^t F\cdot v\,dt = \int_0^t F\cdot\frac{v_{launch}}{T}\cdot t\,dt = \frac{F}{T}v_{launch}\cdot\frac{t^2}{2}$$

Check of result: $W_{kin}(t=T) = \frac{F}{T}v_{launch}\cdot\frac{T^2}{2} = F\frac{T\cdot v_{launch}}{2} = m\cdot\underbrace{a}_{\frac{v_{launch}}{T}}\cdot T\frac{v_{launch}}{2} = m\cdot\frac{v_{launch}^2}{2}$ (see **a)**)

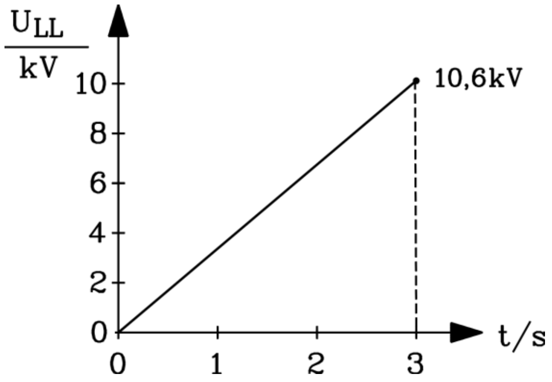


e)

Constant thrust force: $F \sim AB \sim I \cdot \Phi \qquad I = \text{const.} \quad \Rightarrow \Phi = \text{const.}$

$$\sqrt{2} \cdot U_s \cong \omega_s \Psi_s = 2\pi f_s \cdot k_{ws} \cdot N_s \cdot \Phi_s \quad \Rightarrow \underline{\underline{U_s \sim f_s}}$$

Voltage has to rise proportional with frequency, and therefore linear with time!



f)

$$\frac{P_{launch}}{\eta \cdot \cos\varphi} = \sqrt{3}\underset{10.6\ \text{kV}}{U_N} I_N \quad \Rightarrow I_N = \frac{158500000\ \text{W}}{0.8 \cdot 0.5 \cdot \sqrt{3} \cdot 10600\ \text{V}} = \underline{\underline{21582}}\ \text{A} = \underline{\underline{21.58}}\ \text{kA} \ \ \text{(!!)}$$

24. Standard cage induction motor

a)

$$s_N = \frac{n_{syn} - n_N}{n_{syn}} = \frac{45}{1500} = 0.03 = 3\%$$

$$M_N = \frac{P_N}{\Omega_N} = \frac{22\text{kW}}{2\pi \cdot \frac{1455}{60}\frac{1}{\text{s}}} = 144.4\text{Nm}$$

$$P_{e,N} = \sqrt{3} \cdot U_N \cdot I_N \cdot \cos(\varphi_N) = \sqrt{3} \cdot 400\text{V} \cdot 44\text{A} \cdot 0.82 = 25.0\text{kW}$$

$$P_{d,N} = P_{e,N} - P_N = 25.0\text{kW} - 22.0\text{kW} = 3000\text{W}$$

$$\eta_N = \frac{P_N}{P_{e,N}} = \frac{22.0\text{kW}}{25.0\text{kW}} = 0.880 = 88\%$$

b)

$$P_{d,s} = P_{Fe,s} + P_{Cu,s} = 500W + 1500W = 2000W$$

$$P_\delta = P_{e,N} - P_{d,s} = 25kW - 2kW = 23kW$$

c)

$$P_{Cu,r} = s \cdot P_\partial = 0.03 \cdot 23kW = 690W$$

d)

$$P_{fr+w} = P_\partial - P_N - P_{Cu,r} - P_{ad,1} = 23kW - 22kW - 690W - 210W = 100W$$

e)

$$P_{Cu,s0} = P_{Cu,s,N} \cdot \left(\frac{I_0}{I_N}\right)^2 = 1500W \cdot 0.16 = 240W$$

f)

$$P_{d0} = P_{Fe,s} + P_{fr+w} + P_{Cu,s0} = 500W + 100W + 240W = 840W$$

g)

$$P_{d1,N} = P_{d,N} + P_{d0} = 300W - 840W = 2160W$$

h)

$$P_{out} = P_N \cdot \left(\frac{M}{M_N}\right) = P_N \cdot 0.5 = 11kW$$

$$P_{d1} = P_{d1,N} \cdot \left(\frac{M}{M_N}\right)^2 = P_{d1,N} \cdot 0.25 = 540W$$

$$\eta = \frac{P_{out}}{P_{out} + P_{d0} + P_{d1}} = \frac{11\text{kW}}{11\text{kW} + 840\text{W} + 540\text{W}} = 88.85\%$$

i)

$$\frac{M_{opt}}{M_N} = \sqrt{\frac{P_{d0}}{P_{d1,N}}} = \sqrt{\frac{840W}{2160W}} = 0.6236 \Rightarrow M_{opt} = 90.0Nm$$

$$\eta_{\max} = \frac{0.6236 \cdot 22kW}{0.6236 \cdot 22kW + 840W + 840W} = 89.1\%$$

25. Hi-Speed-Compressor Drive, Hi-Speed-Kompressor-Antrieb

1) $f_{sN} = n_N \cdot p = (24000/60) \cdot 2 = \underline{\underline{800}}\,\text{Hz}$

2) $U_{pN} = \dfrac{f_{sN}}{f} \cdot U_p = \dfrac{800}{50} \cdot 6.25 = \underline{\underline{100}}\,\text{V}$

3) $P_{e,in} = P_{m,out} = P_N = 65000\,\text{W}$

q-current operation, no losses (Fig. 25-1): $U_{sN} \cos\varphi_N = U_{pN}$

$$P_{e,in} = 3 \cdot U_{sN} I_{sN} \cos\varphi_N = 3U_{pN} I_{sqN} \quad \Rightarrow \quad I_{sqN} = \frac{65000}{3 \cdot 100} = \underline{\underline{216.7}}\,\text{A}$$

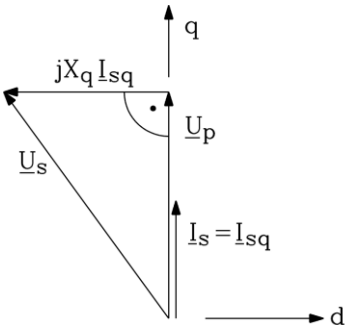


Fig. 25-1: Phasor diagram at *q*-current operation

4) Acc. to Fig. 25-2 we get:

$$U_{sN} = \sqrt{U_{pN}^2 + (2\pi \cdot f_{sN} \cdot L_q \cdot I_{sqN})^2} = \sqrt{100^2 + (2\pi \cdot 800 \cdot 0.169 \cdot 10^{-3} \cdot 216.7)^2} = \underline{\underline{209.5}}\,\text{V}$$

$$U_{sN} = 209.5V < 230V = U_{phase,k=1,\max}\,,\ I_{sN} = 216.7A < 250A = I_{phase,k=1,\max}$$

The inverter rating is sufficient for that drive purpose.

5) $S_N = 3 \cdot U_{sN} \cdot I_{sN} = 3 \cdot 209.5 \cdot 216.7 = \underline{\underline{136.2}}\,\text{kVA}$

$\cos\varphi_N = P_N / S_N = 65000/136200 = \underline{\underline{0.477}}$

Motor current is lagging; motor is inductive consumer = under-excited operation.

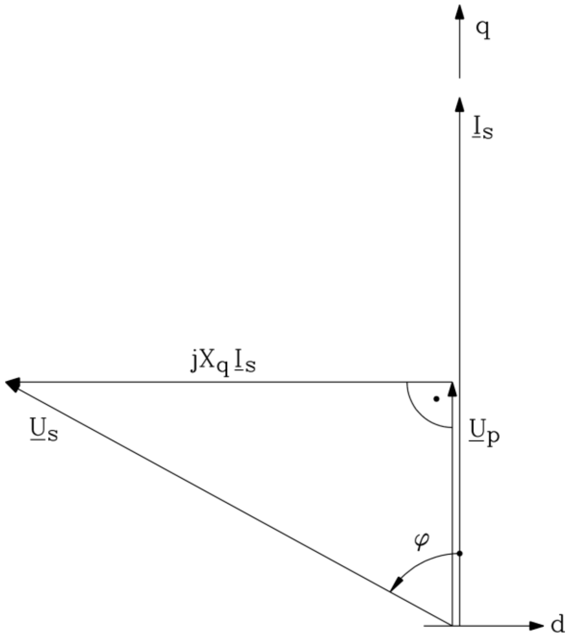


Fig. 25-2: Voltage and phasor diagram of PM motor at rated load and speed

1) $f_{sN} = n_N \cdot p = (24000/60) \cdot 2 = \underline{\underline{800}}\,\text{Hz}$

2) $U_{pN} = \dfrac{f_{sN}}{f} \cdot U_p = \dfrac{800}{50} \cdot 6.25 = \underline{\underline{100}}\,\text{V}$

3) $P_{e,in} = P_{m,out} = P_N = 65000\text{W}$

q-Strombetrieb, keine Verluste berücksichtigt (Bild 25-1deutsch): $U_{sN}\cos\varphi_N = U_{pN}$

$$P_{e,in} = 3 \cdot U_{sN} I_{sN} \cos\varphi_N = 3U_{pN} I_{sqN} \quad \Rightarrow \quad I_{sqN} = \frac{65000}{3 \cdot 100} = \underline{\underline{216.7}}\,\text{A}$$

4) Gemäß Bild 25-2deutsch erhalten wir:

$$U_{sN} = \sqrt{U_{pN}^2 + (2\pi \cdot f_{sN} \cdot L_q \cdot I_{sqN})^2} = \sqrt{100^2 + (2\pi \cdot 800 \cdot 0.169 \cdot 10^{-3} \cdot 216.7)^2} = \underline{\underline{209.5}}\,\text{V}$$

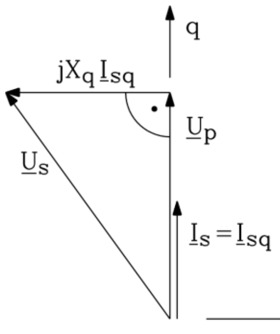
$U_{sN} = 209.5V < 230V = U_{phase,k=1,\max}$, $I_{sN} = 216.7A < 250A = I_{phase,k=1,\max}$

Der Umrichter ist für den Antrieb ausreichend bemessen.

5) $S_N = 3 \cdot U_{sN} \cdot I_{sN} = 3 \cdot 209.5 \cdot 216.7 = \underline{\underline{136.2}}\,\text{kVA}$

$\cos\varphi_N = P_N / S_N = 65000/136200 = \underline{\underline{0.477}}$

Der Motorstrom eilt der Spannung nach; der Motor ist ein induktiver Verbraucher = untererregter Betrieb.



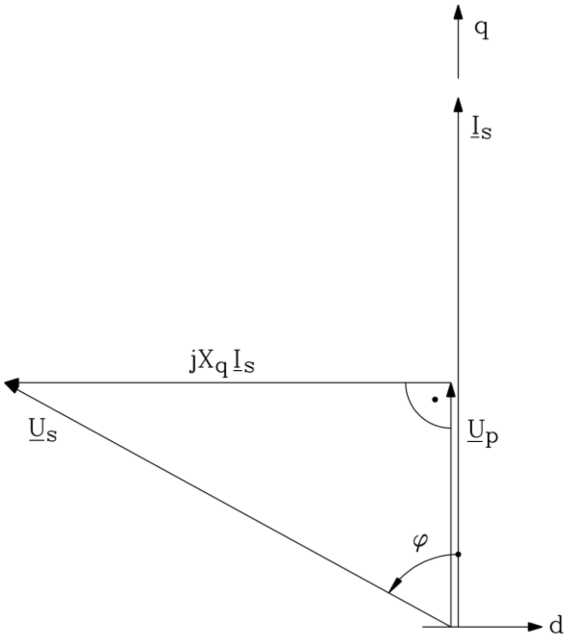


Bild 25-1deutsch: Zeigerdiagramm bei q-Strombetrieb

Bild 25-2deutsch: Spannung- und Stromzeiger des PM-Motors bei Nenndrehzahl und -drehmoment

26. Permanent magnet motor as a machine tool drive, Permanentmagnetmotor als Werkzeugmaschinenantrieb

1)

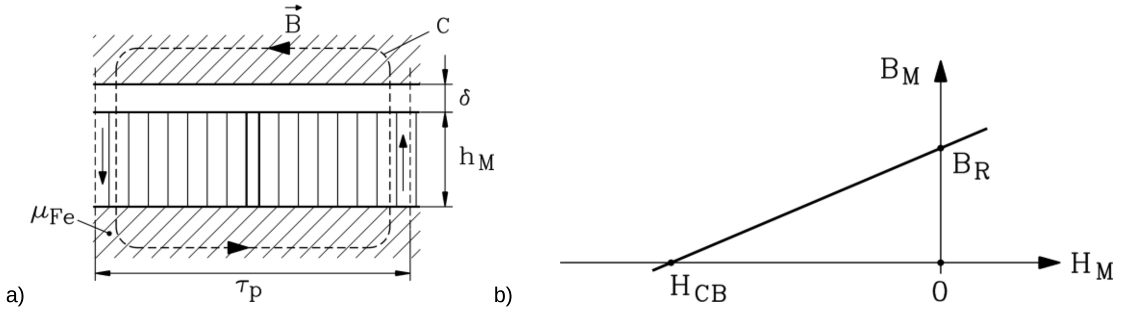


Fig. 26-1: a) *Ampere´s* law at no-load for surface mounted permanent magnets, b) Permanent magnet characteristic

$$\oint_l \vec{H} \bullet d\vec{s} = 2 \cdot H_\delta \cdot \delta + 2 \cdot H_M \cdot h_M = \Theta = 0$$ (infinite iron permeability: $H_{Fe} = 0$)

$$\Rightarrow B_\delta = \mu_0 \cdot H_\delta = -\frac{h_M}{\delta} \cdot \mu_0 \cdot H_M$$

Permanent magnet characteristic in second quadrant of $B_M(H_M)$-plane: $B_M = \mu_M \cdot H_M + B_R$ (Fig. 26-1)

$$\mu_M = \frac{B_R}{H_{CB}} = \frac{1.1}{875000} = 12.57 \cdot 10^{-6} \cong 4 \cdot \pi \cdot 10^{-7} Vs/(Am) = \mu_0$$

Constant magnetic flux: $\Phi_M = \Phi_\delta$: $B_M = B_\delta$:

$$\Rightarrow B_\delta = B_\mathrm{M} = \mu_\mathrm{M} \cdot H_\mathrm{M} + B_\mathrm{R} = \mu_\mathrm{M} \cdot \left(-\frac{\delta}{\mu_0 \cdot h_\mathrm{M}}\right) \cdot B_\delta + B_\mathrm{R}$$

$$B_\delta = \frac{B_R}{1+\frac{\mu_M \cdot \delta}{\mu_0 \cdot h_M}} = \frac{1.1}{1+\frac{1.4}{3.5}} = \underline{\underline{0.786T}} = B_p$$

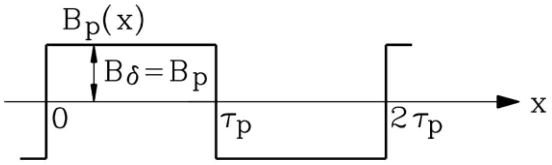


Fig. 26-2: No-load permanent magnet air gap flux density curve at 100% pole coverage ratio of magnets

2) *FOURIER* analysis leads to fundamental harmonic of a rectangular field curve of Fig. 26-2:

$$B_{\delta,\mu=1} = B_\delta \cdot \frac{4}{\pi} \cdot \sin\left(\frac{\pi}{2}\right) = 0.786 \cdot \frac{4}{\pi}\,\mathrm{T} = \underline{\underline{1.0\,\mathrm{T}}}$$

3) With following motor data:

$$2p = 6,\ m = 3,\ q = \frac{Q}{2\cdot p\cdot m} = \frac{36}{6\cdot 3} = \underline{2},\ N_\mathrm{s} = p\cdot q\cdot \frac{N_\mathrm{c}}{a} = 2\cdot 3\cdot \frac{20}{1} = \underline{120}$$

$$\tau_\mathrm{p} = \frac{d_\mathrm{si}\cdot\pi}{2\cdot p} = \frac{100\cdot\pi}{6}\,\mathrm{mm} = \underline{52.4\,\mathrm{mm}},\ f_\mathrm{s} = 100\ \mathrm{Hz},$$

fundamental winding factor: $k_{\mathrm{w},1} = k_{\mathrm{d},1}\cdot k_{\mathrm{p},1}$

single layer winding has full-pitched coils: $k_{\mathrm{p},1} = 1$

$$k_{\mathrm{d},1} = \frac{\sin\left(\frac{\pi}{2\cdot m}\right)}{q\cdot\sin\left(\frac{\pi}{2\cdot m\cdot q}\right)} = \frac{\sin\left(\frac{\pi}{6}\right)}{2\cdot\sin\left(\frac{\pi}{6\cdot 2}\right)} = \underline{0.9659} = k_{\mathrm{w},1}$$

we get:

$$U_{\mathrm{p},1} = \sqrt{2}\cdot\pi\cdot f_s\cdot N_s k_{w,1}\cdot\frac{2}{\pi}\cdot\tau_p\cdot l\cdot B_{\delta,\mu=1} = 2\pi\cdot 100\cdot 120\cdot 0.9659\cdot\frac{2}{\pi}\cdot 0.0524\cdot 0.1\cdot 1.0 = \underline{\underline{171.5\,\mathrm{V}}}$$

4) Permeability of magnets:

$$\mu_\mathrm{M} = \frac{B_\mathrm{R}}{H_\mathrm{CB}} = \frac{1.1}{875000} = 12.57\cdot 10^{-6} \cong 4\cdot\pi\cdot 10^{-7}\,Vs/(Am) = \mu_0$$

Rare earth permanent magnets have the same permeability as air.

5)

$$X_{\mathrm{h},\nu=1} = 2\cdot\pi\cdot f_\mathrm{s}\cdot\mu_0\cdot N_\mathrm{s}^2\cdot k_{w,1}^2\cdot\frac{2\cdot m}{\pi^2}\cdot\frac{l\cdot\tau_\mathrm{p}}{p\cdot(\delta+h_\mathrm{M})} =$$

$$= 2\cdot\pi\cdot 100\cdot 4\cdot\pi\cdot 10^{-7}\cdot 120^2\cdot 0.9659^2\cdot\frac{2\cdot 3}{\pi^2}\cdot\frac{0.1\cdot 0.0524}{3\cdot(1.4+3.5)\cdot 10^{-3}} = \underline{\underline{2.3\,\Omega}}$$

$\mu_\mathrm{M} \approx \mu_0 \quad \Rightarrow$ resulting magnetic effective air gap is $\delta + h_\mathrm{M}$.

6) Maximum torque at given current is reached, if stator current is only q-axis current: $I_\mathrm{s} = I_\mathrm{q}$

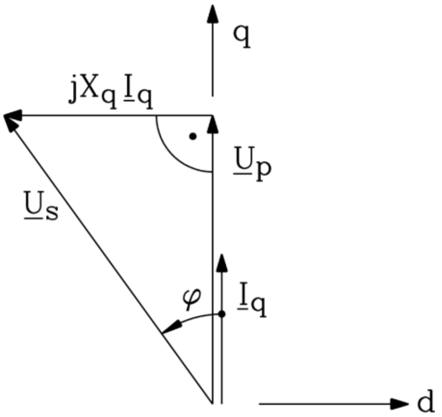


Fig. 26-3: Voltage diagram for q-current, motor operation, R_s neglected

Due to constant air gap and neglected iron saturation it is $X_d = X_q$.
With $X_{s\sigma} = 1.4\,\Omega$, $R_s \cong 0$, we get acc. to Fig. 26-3:

$$U_s^2 = (X_q \cdot I_q)^2 + U_p^2, \quad I_q = 10\text{ A}, \quad X_q = X_{s\sigma} + X_h = (1.4 + 2.3)\,\Omega = \underline{3.7\,\Omega}$$

$$\Rightarrow \quad U_s = \sqrt{(X_q \cdot I_q)^2 + U_p^2} = \sqrt{(3.7 \cdot 10)^2 + 171.5^2}\text{ V} = \underline{\underline{175.4\text{ V}}}$$

7) Voltage phasor diagram acc. to Fig. 26-3 is given in Fig. 26-4.

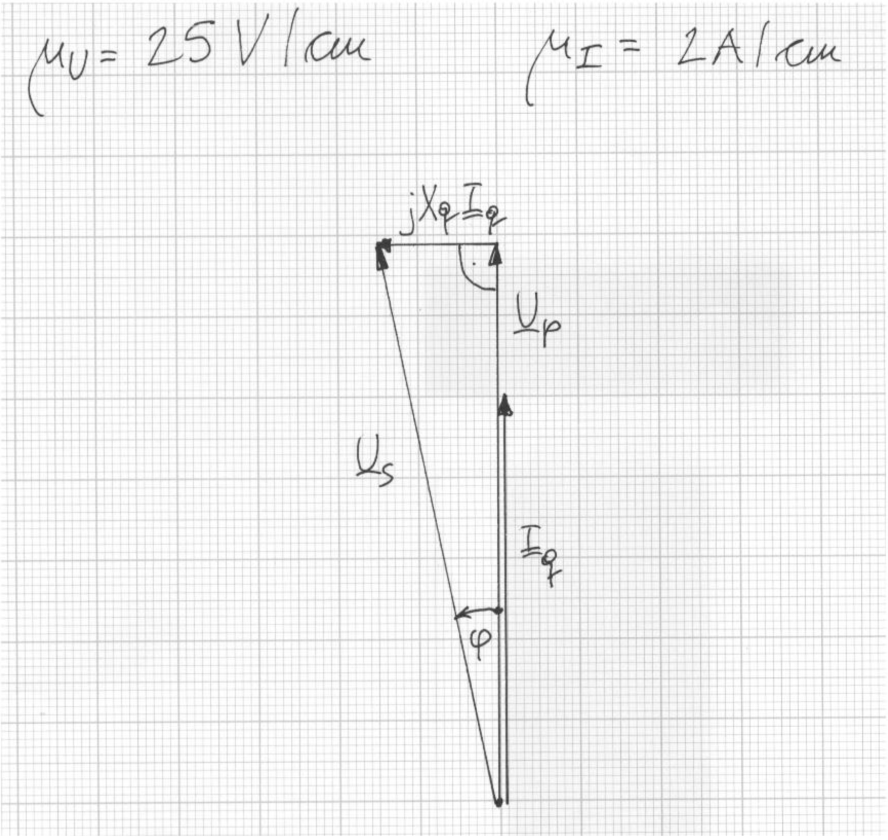


Fig. 26-4: Voltage diagram for q-current, motor operation, R_s neglected

1)

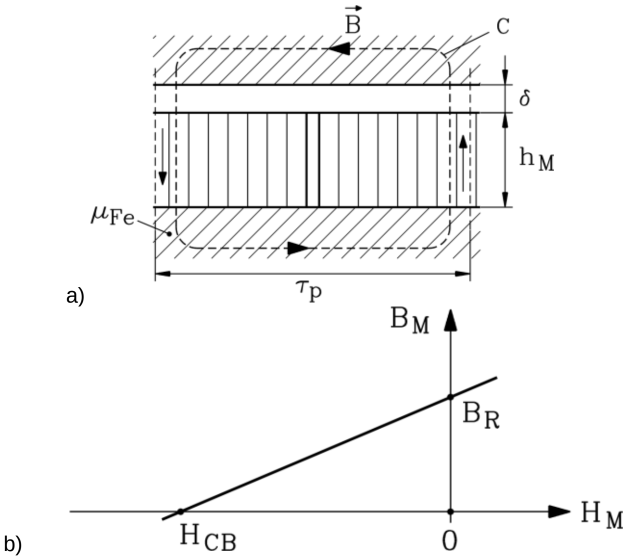


Bild 26-1deutsch: a) *Ampere*sches Gesetz bei Leerlauf für Oberflächenmagnete, b) Permanentmagnet-Kennlinie

$$\oint_l \vec{H} \bullet d\vec{s} = 2\cdot H_\delta \cdot \delta + 2\cdot H_\mathrm{M} \cdot h_\mathrm{M} = \Theta = 0$$

(Unendlich große Eisenpermeabilität: $H_\mathrm{Fe} = 0$)

$$\Rightarrow B_\delta = \mu_0 \cdot H_\delta = -\frac{h_\mathrm{M}}{\delta} \cdot \mu_0 \cdot H_\mathrm{M}$$

Permanentmagnetkennlinie im zweiten Quadranten der $B_\mathrm{M}(H_\mathrm{M})$-Ebene: $B_\mathrm{M} = \mu_\mathrm{M} \cdot H_\mathrm{M} + B_\mathrm{R}$

$$\mu_\mathrm{M} = \frac{B_\mathrm{R}}{H_\mathrm{CB}} = \frac{1.1}{875000} = 12.57\cdot 10^{-6} \cong 4\cdot\pi\cdot 10^{-7} Vs/(Am) = \mu_0$$

Konstanter Fluss: $\Phi_\mathrm{M} = \Phi_\delta$: $B_\mathrm{M} = B_\delta$:

$$\Rightarrow B_\delta = B_\mathrm{M} = \mu_\mathrm{M} \cdot H_\mathrm{M} + B_\mathrm{R} = \mu_\mathrm{M} \cdot \left(-\frac{\delta}{\mu_0 \cdot h_\mathrm{M}} \right) \cdot B_\delta + B_\mathrm{R}$$

$$B_\delta = \frac{B_R}{1 + \dfrac{\mu_M \cdot \delta}{\mu_0 \cdot h_M}} = \frac{1.1}{1 + \dfrac{1.4}{3.5}} = \underline{\underline{0.786T}} = B_p$$

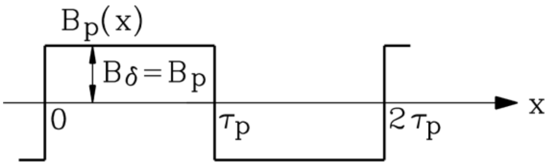


Bild 26-2deutsch: Leerlaufflussdichte im Luftspalt für Permanentmagneten bei 100% Polbedeckung der Magnete

2) *FOURIER*-analyse führt zur Grundwelle der rechteckförmigen Feldkurve in Bild 26-2deutsch:

$$B_{\delta,\mu=1} = B_\delta \cdot \frac{4}{\pi} \cdot \sin\left(\frac{\pi}{2}\right) = 0.786 \cdot \frac{4}{\pi}\,\mathrm{T} = \underline{\underline{1.0\,\mathrm{T}}}$$

3) Mit den Motordaten:

$$2p = 6,\ m = 3,\ q = \frac{Q}{2\cdot p\cdot m} = \frac{36}{6\cdot 3} = \underline{2},\ N_\mathrm{s} = p\cdot q\cdot\frac{N_\mathrm{c}}{a} = 2\cdot 3\cdot\frac{20}{1} = \underline{120}$$

$\tau_\mathrm{p} = \dfrac{d_\mathrm{si} \cdot \pi}{2 \cdot p} = \dfrac{100 \cdot \pi}{6}\,\mathrm{mm} = \underline{52{,}4\mathrm{mm}}$, $f_\mathrm{s} = 100$ Hz,

Grundwickelfaktor: $k_\mathrm{w,1} = k_\mathrm{d,1} \cdot k_\mathrm{p,1}$

Einschichtwicklung ungesehnt: $k_\mathrm{p,1} = 1$

$$k_\mathrm{d,1} = \frac{\sin\left(\dfrac{\pi}{2 \cdot m}\right)}{q \cdot \sin\left(\dfrac{\pi}{2 \cdot m \cdot q}\right)} = \frac{\sin\left(\dfrac{\pi}{6}\right)}{2 \cdot \sin\left(\dfrac{\pi}{6 \cdot 2}\right)} = \underline{0{,}9659} = k_\mathrm{w,1}$$

erhält man:

$$U_\mathrm{p,1} = \sqrt{2} \cdot \pi \cdot f_s \cdot N_s k_{w,1} \cdot \frac{2}{\pi} \cdot \tau_p \cdot l \cdot B_{\delta,\mu=1} = 2\pi \cdot 100 \cdot 120 \cdot 0.9659 \cdot \frac{2}{\pi} \cdot 0.0524 \cdot 0.1 \cdot 1.0 = \underline{\underline{171.5\mathrm{V}}}$$

4) Permeabilität der Magnete:

$$\mu_\mathrm{M} = \frac{B_\mathrm{R}}{H_\mathrm{CB}} = \frac{1.1}{875000} = 12.57 \cdot 10^{-6} \cong 4 \cdot \pi \cdot 10^{-7} Vs/(Am) = \mu_0$$

Seltenerd-Magnete haben annähernd dieselbe Permeabilität wie Luft.

5) $X_{\mathrm{h},\nu=1} = 2 \cdot \pi \cdot f_\mathrm{s} \cdot \mu_0 \cdot N_\mathrm{s}^2 \cdot k_{w,1}^2 \cdot \dfrac{2 \cdot m}{\pi^2} \cdot \dfrac{l \cdot \tau_\mathrm{p}}{p \cdot (\delta + h_\mathrm{M})} =$

$$= 2 \cdot \pi \cdot 100 \cdot 4 \cdot \pi \cdot 10^{-7} \cdot 120^2 \cdot 0.9659^2 \cdot \frac{2 \cdot 3}{\pi^2} \cdot \frac{0.1 \cdot 0.0524}{3 \cdot (1.4 + 3.5) \cdot 10^{-3}} = \underline{\underline{2.3\,\Omega}}$$

$\mu_\mathrm{M} \approx \mu_0 \quad \Rightarrow \quad$ Resultierender magnetisch wirksamer Luftspalt ist $\delta + h_\mathrm{M}$.

6) Maximales Moment bei gegebenem Strom wird erreicht, wenn $I_\mathrm{s} = I_\mathrm{q}$.

Wegen des konstanten Luftspalts und vernachlässigter Eisensättigung gilt $X_\mathrm{d} = X_\mathrm{q}$.
Mit $X_{\mathrm{s}\sigma} = 1.4\,\Omega$, $R_\mathrm{s} \cong 0$, ergibt sich nach Bild 26-3deutsch:

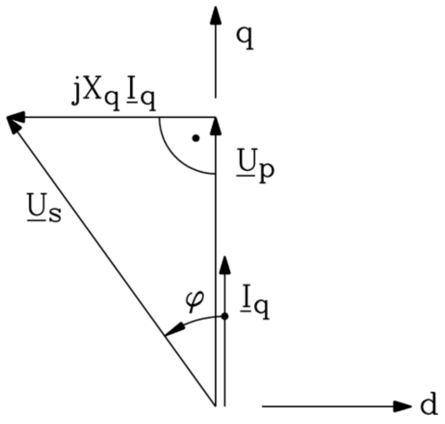


Bild 26-3deutsch: Spannungszeigerdiagramm für q-Strom, Motorbetrieb, R_s vernachlässigt

$$U_\mathrm{s}^2 = (X_\mathrm{q} \cdot I_\mathrm{q})^2 + U_\mathrm{p}^2, \quad I_\mathrm{q} = 10\,\mathrm{A}, \quad X_\mathrm{q} = X_{\mathrm{s}\sigma} + X_\mathrm{h} = (1.4 + 2.3)\,\Omega = \underline{3.7\,\Omega}$$

$$\Rightarrow \quad U_\mathrm{s} = \sqrt{(X_\mathrm{q} \cdot I_\mathrm{q})^2 + U_\mathrm{p}^2} = \sqrt{(3.7 \cdot 10)^2 + 171.5^2}\ \mathrm{V} = \underline{\underline{175.4\mathrm{V}}}$$

7) Spannungszeigerdiagramm gemäß Bild 26-3deutsch ist in Bild 26-4deutsch zu sehen.

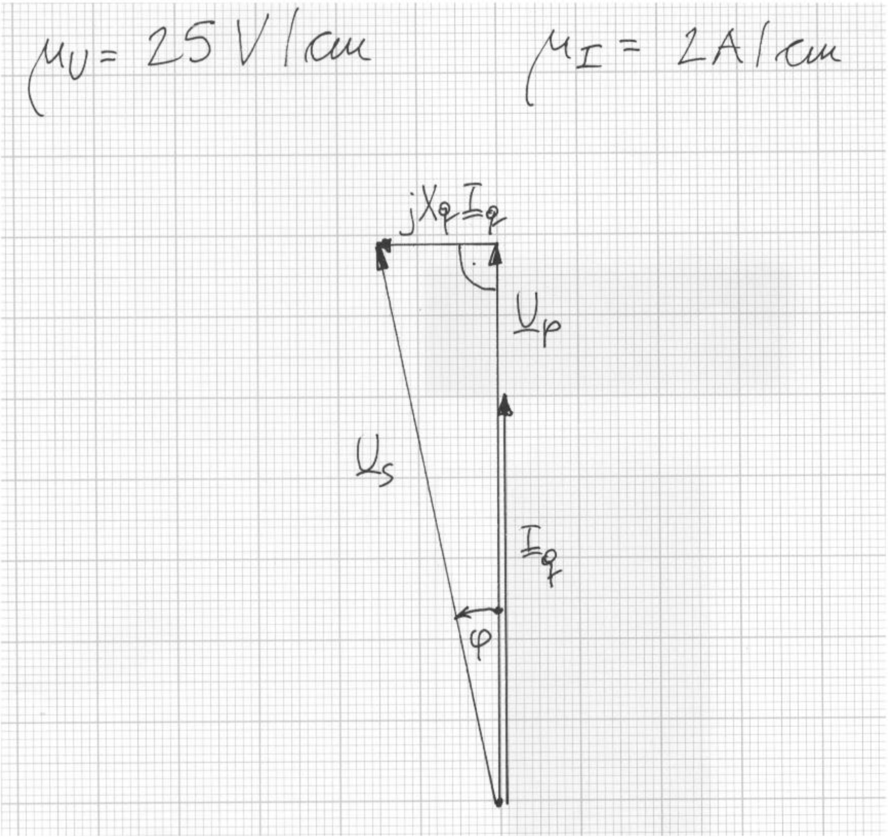


Bild 26-4deutsch: Spannungszeigerdiagramm für q-Strom, Motorbetrieb, R_s vernachlässigt

27. Permanent magnet synchronous motor as robot drive, Roboterantrieb

1.) $U_p = 90$ V, $f_s = 50$ Hz, $n = f_s / p = 50 / 4 = 12.5$ /s = 750 / min

$U_p = \omega_s \cdot \Psi_p / \sqrt{2} = 2 \cdot \pi \cdot f_s \cdot \Psi_p / \sqrt{2} = 2 \cdot \pi \cdot n \cdot p \cdot \Psi_p / \sqrt{2} => \quad U_p \sim n \cdot \Psi_p$

Open circuit no-load phase voltage = back EMF:

$$U_{p,\max} = \frac{n_{\max}}{n} \cdot U_p = \frac{6000}{750} \cdot 90 = 720\,\text{V},$$

Line-to-line voltage (Y): $U_{p,LL} = \sqrt{3} \cdot 720 = 1247$ V ... Diagram $U_{p,LL}(n)$: Fig. 27-2

2.) U_p is proportional to speed and permanent magnet flux $U_p \sim \Psi_p$

Due to $\Psi_p = N \cdot k_w \frac{2}{\pi} \cdot \tau_p \cdot l \cdot B_{p,\mu=1}$, $B_{p,\mu=1} = \frac{4}{\pi} \cdot B_p$ and $B_p = \dfrac{B_R}{1 + \dfrac{\mu_M}{\mu_0} \cdot \dfrac{\delta}{h_M}}$ the back EMF is directly proportional to remanence flux density B_R. Therefore it is possible to determine by back EMF measurement, if the magnets are properly magnetized. For that, the magnet temperature must be known, as remanence depends on temperature: $B_R = B_R(\vartheta)$!

3.) $L_d = 4.5mH$, $R_s \cong 0$, Due to constant magnetic air-gap and neglected iron saturation we may assume: $L_d = L_q$

$$X_{dN} = \omega_{sN} \cdot L_d = 2\pi \cdot f_{sN} \cdot L_d = 2\pi \cdot 100 \cdot 4.5 \cdot 10^{-3} = 2.83\Omega$$

a.) $I_q = I_s = 12A = I_N \quad : X_{dN} \cdot I_N = 2.83 \cdot 12 = 33.9V = X_{qN} \cdot I_N$

b.) $I_q = I_s = 4 \cdot I_N = 48A \quad : X_{dN} \cdot 4 \cdot I_N = 4 \cdot 33.9 = 135.7V = X_{qN} \cdot 4 \cdot I_N$

$$U_{pN} = \frac{f_{sN}}{f_s} \cdot U_p = \frac{100}{50} \cdot 90 = 180\,\mathrm{V}$$

a.) $U_s = \sqrt{U_p^2 + (X_{qN} \cdot I_N)^2} = \sqrt{180^2 + 33.9^2} = 183.2V$

b.) $U_s = \sqrt{U_p^2 + (X_{qN} \cdot 4I_N)^2} = \sqrt{180^2 + 135.7^2} = 225.4V$

Voltage phasor diagram Fig. 27-3.

4) $n_N = \frac{f_{sN}}{p} = \frac{100}{4} = 25/s = \underline{\underline{1500/\min}}$

5) No losses considered: $\eta = 1: P_{out} = P_m = P_{in} = P_e \Rightarrow \quad P_e = 3 \cdot U_s \cdot I_s \cdot \cos\varphi = 3 \cdot U_p \cdot I_s$

$$U_s \cdot \cos\varphi = U_p,\ M_e \cdot \Omega_{syn} = P_m \Rightarrow \quad M_e = \frac{3 \cdot U_p \cdot I_s}{\Omega_{syn}},\ \Omega_{syn} = 2\pi \cdot \frac{f_{sN}}{p} = 2\pi \cdot 25 = 157.1/\mathrm{s}$$

a.) $M_e = \frac{3 \cdot U_p \cdot I_s}{\Omega_{syn}} = \frac{3 \cdot 180 \cdot 12}{157.1} = \underline{\underline{41.25Nm}}$, b.) $M_e = \frac{3 \cdot U_p \cdot I_s}{\Omega_{syn}} = \frac{3 \cdot 180 \cdot 48}{157.1} = \underline{\underline{165Nm}}$

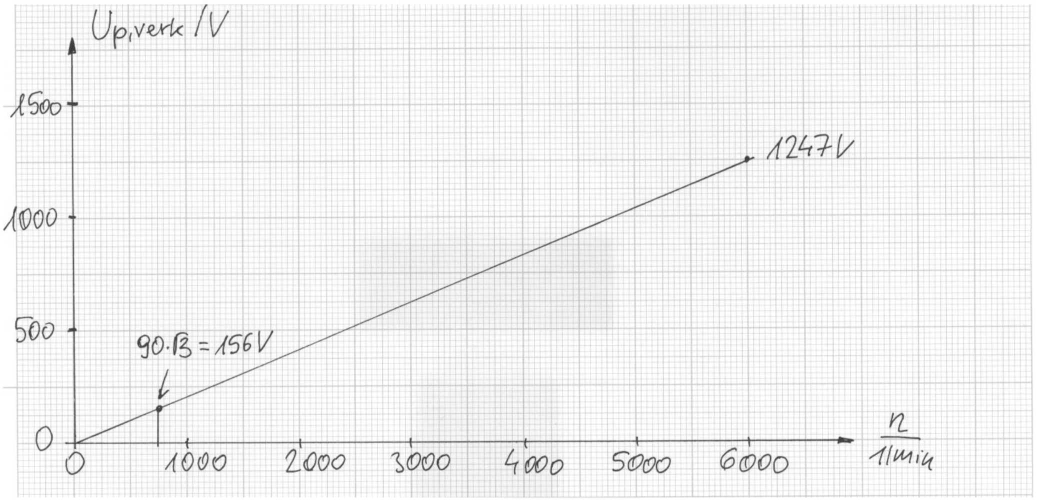


Fig. 27-2: Back EMF (r.m.s., line-to-line) versus speed, measured at open circuit, no-load generator operation

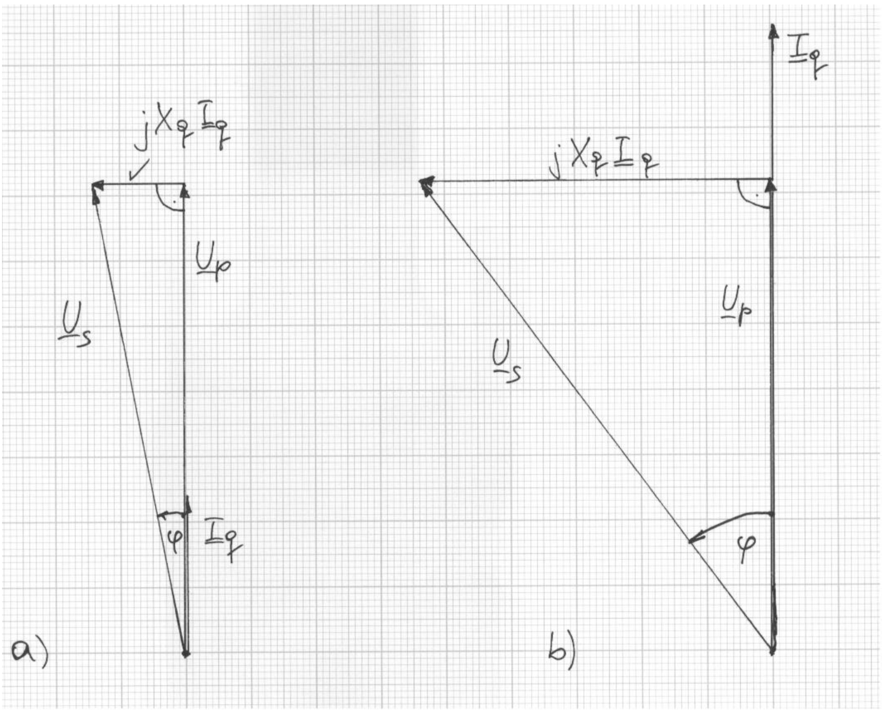


Fig. 27-3: Voltage phasor diagram for q-current operation: a) rated current, b) 4 times overload

6.) a) Voltage limit: $U_{s,max}$ = 230V : $U_{s\max}^2 = \left(\frac{n}{n_N}\cdot X_{qN}\cdot I_q\right)^2 + \left(\frac{n}{n_N}\right)^2 \cdot U_{pN}^2$

n_N = 1500/min, X_{qN} = 2.83 Ω, U_{pN} = 180V

Speed ratio: $\frac{n}{n_N} = \nu : \; I_q = \frac{\sqrt{U_{s\max}^2 - \nu^2 \cdot U_{pN}^2}}{\nu \cdot X_{qN}} = I_s^*$

Maximum speed: $n_{\max}$: $I_q = 0$: ideal motor no load,

$$n_{\max} = n_N \cdot \frac{U_{s\max}}{U_{pN}} = 1500 \cdot \frac{230}{180} = 1917/\min$$

$$M_e = \frac{3 \cdot U_p \cdot I_q}{2\pi \cdot n} = \frac{3 \cdot 2\pi(p \cdot n) \cdot \Psi_p \cdot I_q}{2\pi \cdot n \cdot \sqrt{2}} = \frac{3 \cdot p \cdot \Psi_p \cdot I_q}{\sqrt{2}}, \quad \Psi_p = \sqrt{2} \cdot \frac{U_p}{\omega_s} = \frac{\sqrt{2} \cdot 180}{2\pi \cdot 100} = 0.405 Vs$$

$\nu = n/n_N$	I_s^*	n	M^*
	A	1/min	Nm
1.2780	0	1917	0
1.16	28.5	1750	98
1	50.8	1500	174.6
0.9	64.3	1350	221

Table 27-1: Operation data at the voltage limit

b) Current limit: $I_{s,\max}$ = 48 A: $M_{\max}$ = 165 Nm
c) Thermal limit: I_N = 12 A: M_N = 41.25 Nm

Diagram of voltage, current and thermal limit for *M(n)* is given in Fig. 27-4.

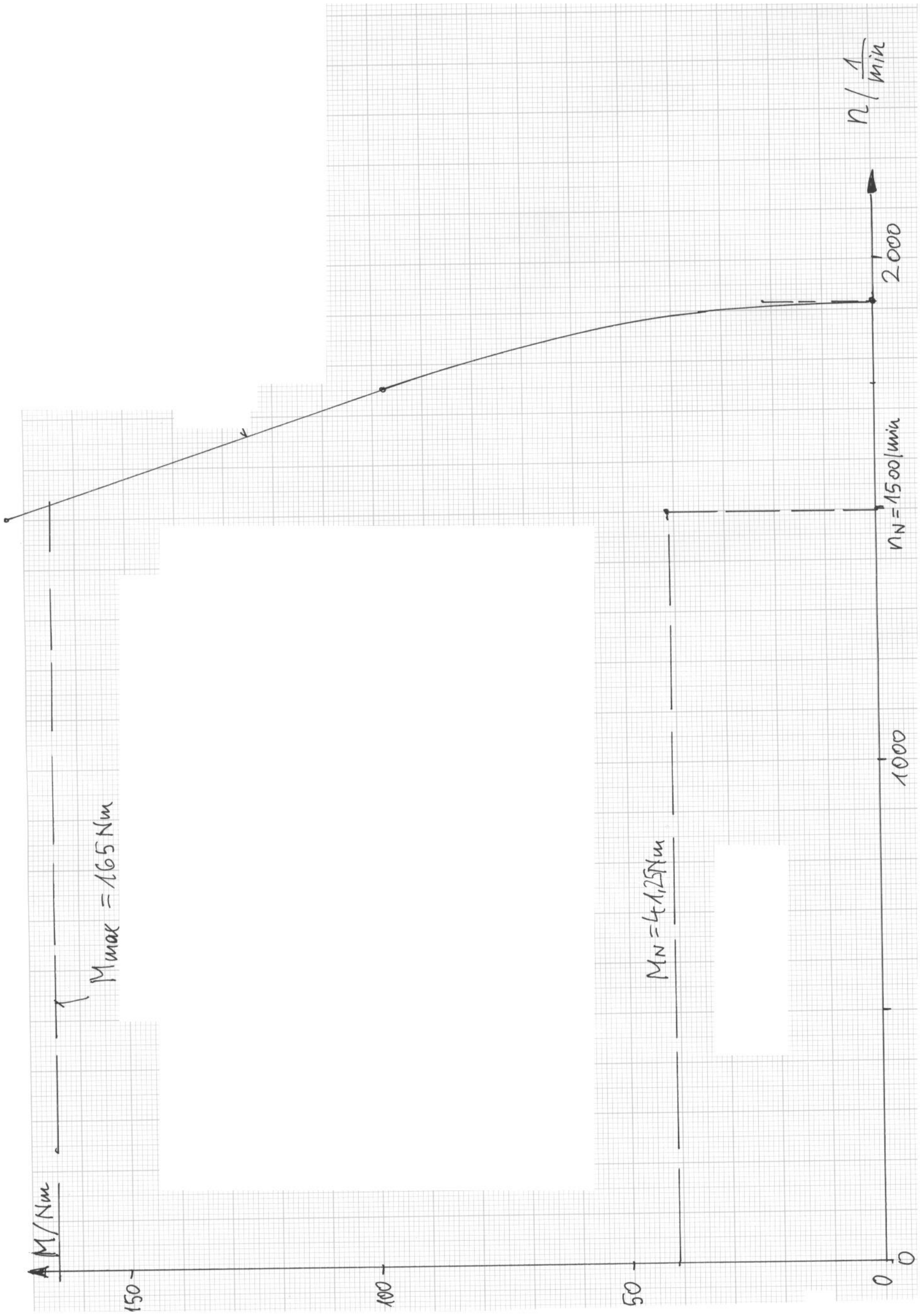


Fig. 27-4: Voltage, current and thermal limit according to Fig. 27-1

1) U_p = 90 V, f_s = 50 Hz, $n = f_s / p$ = 50 / 4 = 12.5 /s = 750 / min

$$U_p = \omega_s \cdot \Psi_p / \sqrt{2} = 2\cdot\pi\cdot f_s \cdot \Psi_p / \sqrt{2} = 2\cdot\pi\cdot n\cdot p\cdot \Psi_p / \sqrt{2} \Rightarrow \quad U_p \sim n\cdot\Psi_p$$

Leerlauf-Strangspannung = Polradspannung: $U_{p,\max} = \frac{n_{\max}}{n}\cdot U_p = \frac{6000}{750}\cdot 90 = 720\,\mathrm{V}$,

Verkettete Spannung (Y): $U_{p,LL} = \sqrt{3}\cdot 720 = 1247\,\mathrm{V}$ Diagramm $U_{p,LL}(n)$: Bild 27-2deutsch

2) U_p ist proportional zur Drehzahl und zur Permanentmagnet-Flussverkettung $U_p \sim \Psi_p$

Wegen $\Psi_p = N\cdot k_w \frac{2}{\pi}\cdot\tau_p\cdot l\cdot B_{p,\mu=1}$, $B_{p,\mu=1} = \frac{4}{\pi}\cdot B_p$ und $B_p = \dfrac{B_R}{1+\frac{\mu_M}{\mu_0}\cdot\frac{\delta}{h_M}}$ kann von der gemessenen Leerlauf-Polradspannung direkt auf die Remanenzflussdichte geschlossen werden. Die Magnettemperatur muss dabei bekannt sein, da $B_R = B_R(\vartheta)$!

3) $L_d = 4.5\,mH$, $R_s \cong 0$. Wegen des konstanten magnetisch wirksamen Luftspaltes und vernachlässigter Eisensättigung kann angenommen werden, dass $L_d = L_q$.

$X_{dN} = \omega_{sN}\cdot L_d = 2\pi\cdot f_{sN}\cdot L_d = 2\pi\cdot 100\cdot 4.5\cdot 10^{-3} = 2.83\,\Omega$

a) $I_q = I_s = 12\,\mathrm{A} = I_N$: $X_{dN}\cdot I_N = 2.83\cdot 12 = 33.9\,\mathrm{V} = X_{qN}\cdot I_N$

b) $I_q = I_s = 4\cdot I_N = 48\,\mathrm{A}$: $X_{dN}\cdot 4\cdot I_N = 4\cdot 33.9 = 135.7\,\mathrm{V} = X_{qN}\cdot 4\cdot I_N$

$U_{pN} = \frac{f_{sN}}{f_s}\cdot U_p = \frac{100}{50}\cdot 90 = 180\,\mathrm{V}$, Spannungszeigerdiagramm in Bild 27-3deutsch.

a) $U_s = \sqrt{U_p^2 + (X_{qN}\cdot I_N)^2} = \sqrt{180^2 + 33.9^2} = 183.2\,\mathrm{V}$

b) $U_s = \sqrt{U_p^2 + (X_{qN}\cdot 4I_N)^2} = \sqrt{180^2 + 135.7^2} = 225.4\,\mathrm{V}$

4) $n_N = \frac{f_{sN}}{p} = \frac{100}{4} = 25/\mathrm{s} = \underline{\underline{1500/\min}}$

5) Keine Verluste berücksichtigt:

$\eta = 1$: $P_{out} = P_m = P_{in} = P_e \Rightarrow \quad P_e = 3\cdot U_s\cdot I_s\cdot\cos\varphi = 3\cdot U_p\cdot I_s$

$U_s\cdot\cos\varphi = U_p$, $M_e\cdot\Omega_{syn} = P_m \Rightarrow \quad M_e = \frac{3\cdot U_p\cdot I_s}{\Omega_{syn}}$, $\quad \Omega_{syn} = 2\pi\cdot\frac{f_{sN}}{p} = 2\pi\cdot 25 = 157.1/\mathrm{s}$

a) $M_e = \frac{3\cdot U_p\cdot I_s}{\Omega_{syn}} = \frac{3\cdot 180\cdot 12}{157.1} = \underline{\underline{41.25\,\mathrm{Nm}}}$, b) $M_e = \frac{3\cdot U_p\cdot I_s}{\Omega_{syn}} = \frac{3\cdot 180\cdot 48}{157.1} = \underline{\underline{165\,\mathrm{Nm}}}$

6) a) Spannungsgrenze: $U_{s,max}$ = 230V : $U_{s\max}^2 = \left(\frac{n}{n_N}\cdot X_{qN}\cdot I_q\right)^2 + \left(\frac{n}{n_N}\right)^2\cdot U_{pN}^2$

n_N = 1500/min, X_{qN} = 2.83 Ω, U_{pN} = 180V

Drehzahlverhältnis: $\frac{n}{n_N} = \nu$: $I_q = \frac{\sqrt{U_{s\max}^2 - \nu^2\cdot U_{pN}^2}}{\nu\cdot X_{qN}} = I_s^*$

Maximaldrehzahl: $n_{\max}$: I_q = 0: idealer Leerlauf, $n_{\max} = n_N\cdot\frac{U_{s\max}}{U_{pN}} = 1500\cdot\frac{230}{180} = 1917/\min$

$$M_e = \frac{3\cdot U_p\cdot I_q}{2\pi\cdot n} = \frac{3\cdot 2\pi(p\cdot n)\cdot\Psi_p\cdot I_q}{2\pi\cdot n\cdot\sqrt{2}} = \frac{3\cdot p\cdot\Psi_p\cdot I_q}{\sqrt{2}}, \quad \Psi_p = \sqrt{2}\cdot\frac{U_p}{\omega_s} = \frac{\sqrt{2}\cdot 180}{2\pi\cdot 100} = 0.405\,\mathrm{Vs}$$

$\nu = n/n_N$	I_s^*	n	M^*
	A	1/min	Nm
1.2780	0	1917	0
1.16	28.5	1750	98
1	50.8	1500	174.6
0.9	64.3	1350	221

b) Stromgrenze: $I_{s,\max}$ = 48 A: $M_{\max}$ = 165 Nm
c) Temperaturgrenze: I_N = 12 A: M_N = 41.25 Nm

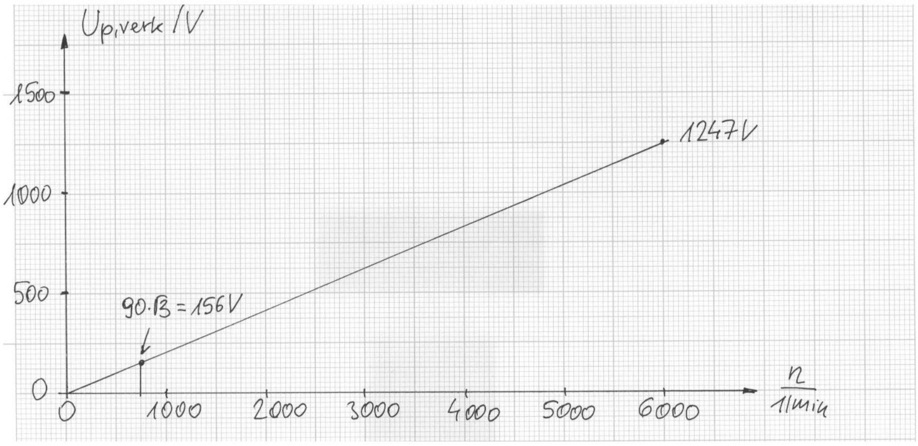


Bild 27-2deutsch: Polradspannung (Effektivwert, verkettet) gegen Drehzahl, gemessen im Generatorbetrieb bei Leerlauf

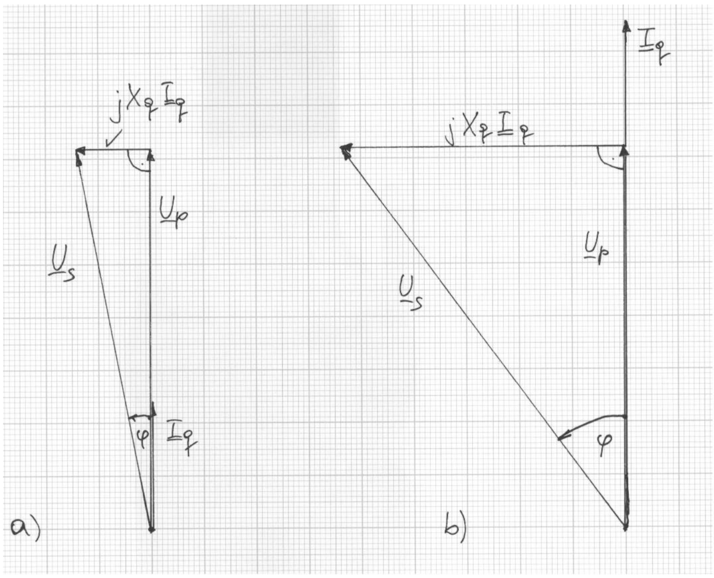
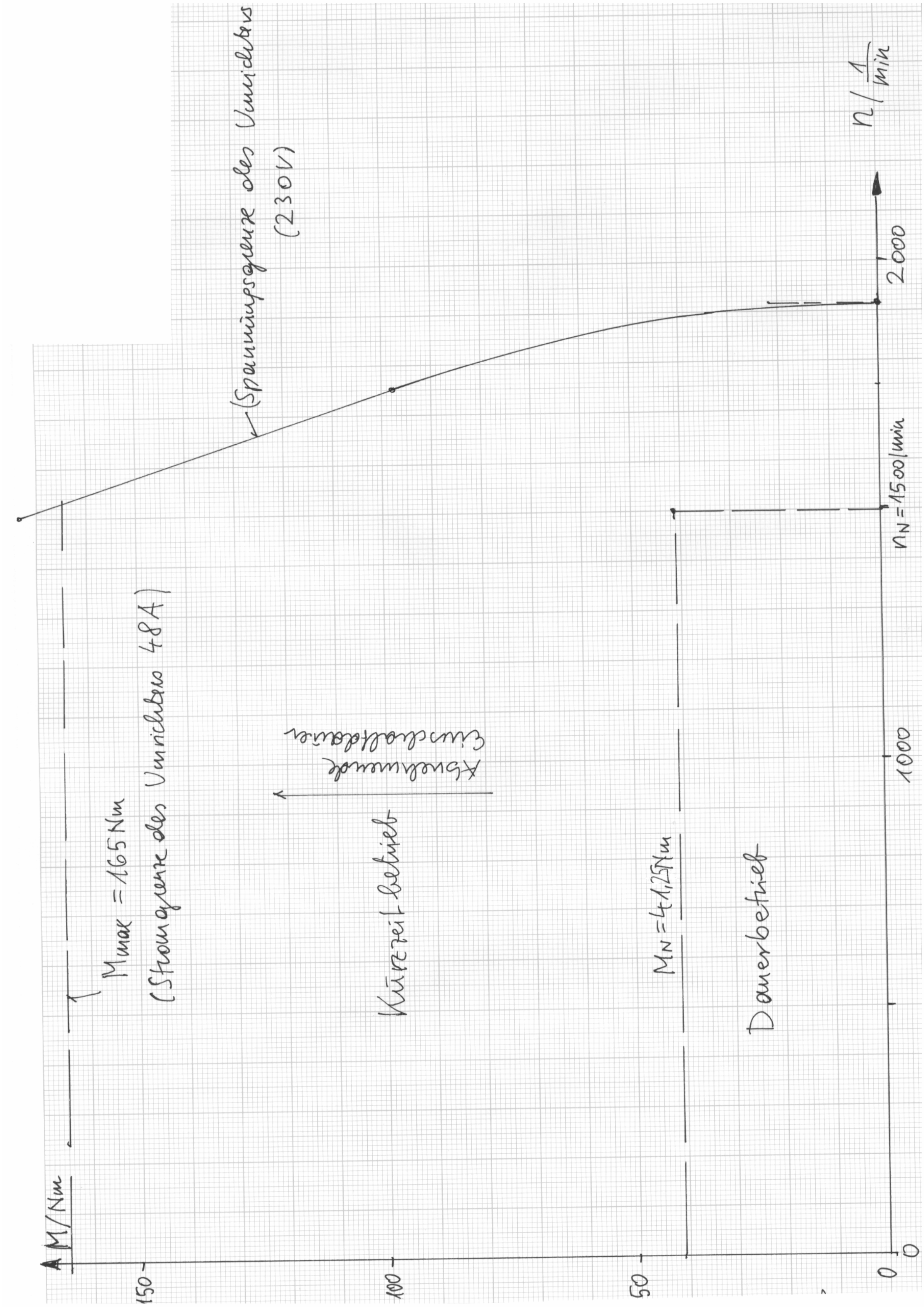


Bild 27-3deutsch: Spannungszeigerdiagramm für Betrieb mit q-Strom: a) Nennstrom, b) 4-fache Überlastung



<u>Bild 27-4deutsch:</u> Spannung, Strom und Temperaturgrenze gemäß Bild 27-1deutsch

28. Permanent magnet motor, Permanentmagnetmotor

Solutions:

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.

Lösungen:

1) Die Luftspaltfeldverteilung ist rechteckförmig.
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.

Preparation for Examination

Examination is in writing, where your ability to calculate some problems, is examined, and where your understanding of theory is checked.

We recommend preparation for examination in the following way: Calculate the examples, given in the Collection of Exercises, and test yourself by comparing your solutions with those given in the Collection. The problems at the test in writing are very similar to those. For theory part of examination only those questions, which you find hereafter included, will be asked. Thus the content for learning is exactly defined.

Please note, that the text book contains much more information about motors, than you will need for examination. We advice you to prepare the collection of questions, when you are learning for exam, and try to find the answers from the text book. If you have difficulties in answering the questions, do not hesitate to consult us.

If you have any further questions concerning examination, either theory or method of calculation, do not hesitate to contact us.

Yours sincerely

A. Binder Darmstadt, 18.7.2014

Theoretical part of the examination of the lecture „Motor Development for Electric Drive Systems“

Examination questions:

Rotating permanent magnet drives - synchronous servo-drives:

1) How is the magnetic operating point of the motor determined at no-load operation? How will this operating point be shifted at load and by temperature change?
2) Draw some typical $B(H)$-characteristics of permanent magnets and explain them.
3) Sketch and describe the operating characteristics of the PM synchronous motor with rotor position control.
4) How can field weakening be realized for PM machines?
5) Explain the operating mode of block-current commutated PM synchronous machines! Why is this motor type called “brushless DC”-drive?
6) Explain the sinus-commutated operating mode of PM synchronous machines! Name the differences to block-commutation and indicate some advantages and disadvantages!
7) Explain the structure of rotors with surface mounted and buried magnets! What does flux concentration mean? How is it realized?
8) Describe the structure of a position-controlled PM servo drive. Name some application domains.
9) What does “*q*-current operation” mean? Explain it with help of the phasor diagram. How does the torque generation at this operation mode look like (Explain it with the air gap field)?
10) Describe the danger of demagnetization of permanent magnets through the stator field at load / overload!
11) Which electromagnetic and mechanic parameters are essential for design of high-speed drives with high utilization of active mass?

PM-linear drives:

1) How are PM linear drives built? Give an overview of the variety of different configurations.
2) Discuss the tangential and normal force density of PM linear motors and give some typical numerical values, depending on type of motor cooling!
3) Name typical values for the acceleration, the speed, the movement distances of PM linear machines! Why is the efficiency of linear machines lower than the efficiency of rotating machines?
4) Name the basic components of a typical PM linear drive. Sketch the structure of the complete drive system!

PM high-torque drives:

1) What characteristics do synchronous machines with high pole count have and when are they used?
2) Why is the active mass of PM synchronous machines with high pole count relatively smaller for a given torque, compared with machines with low pole count (e.g. 2 pole machine)?
3) Describe the basic ideas of modular synchronous machines. What is a tooth wound armature winding?
4) Which are the advantages and disadvantages of modular synchronous machines? Where are they used?
5) How does the transversal flux machine operate in principle? For which application domains is it well suitable?
6) Describe the basic characteristics of the transversal flux machine. Which loss components are most dominant?
7) Sketch different structures of transversal flux machines and name the advantages and disadvantages of them!

Switched reluctance drives:

1) Describe the motor and inverter design, and the operation modes of switched reluctance drives!
2) What are the advantages and disadvantages of the switched reluctance drive, compared to traditional rotating field machines?
3) Explain the torque generation of the switched reluctance machine on the basis of the variation of phase inductance at rotor rotation!
4) Sketch the “maximum torque vs. speed”-curve of the switched reluctance drive and explain the particular speed sections!
5) Why is for switched reluctance machines a high saturation aimed to get high machine utilization? Explain the principle by means of the “flux linkage –current”-characteristic for different rotor positions!
6) Explain the causes of torque ripple generated by switched reluctance machines!
7) Why do switched reluctance machines tend to generate electromagnetically excited acoustic noise? Describe the mechanism of this effect! With which dominant frequency does this noise generation occur?
8) Name typical application domains for switched reluctance drives, and the reasons why they are used.

Synchronous reluctance motors:

1) Describe the stator and rotor design and the operation modes of synchronous reluctance motors! Which parameters are significant for torque generation?
2) Draw the phasor diagram of the synchronous reluctance machine in motor operation! Explain the main parameter load angle, phase angle, voltage and current!
3) The synchronous reluctance machine is supplied by fixed stator voltage and frequency: Sketch the torque’s dependency on load angle ϑ at neglected stator resistance and give the formula. How does the stator resistance change the torque curve?
4) Sketch rotor structures of the synchronous reluctance motor for increased ratio X_d/X_q!
5) Name typical application domains for synchronous reluctance motors, and the reasons why they are used. Why are synchronous reluctance motors built and used only in lower power range?

PM synchronous motors with rotor cage:

1) Describe the stator and rotor design of a PM synchronous machine with rotor cage. Give applications, where these motors are used!
2) Explain the flux concentration effect and sketch possible rotor configurations! What is the concentration factor?
3) Give the characteristic “torque vs. load angle” for grid-operated PM synchronous machines with buried rotor magnets! Which condition is necessary for minimum magnet strength?
4) Discuss the peculiarities of the starting characteristic “torque vs. speed” of grid-operated PM synchronous machines with rotor cage!
5) Describe the synchronization process of the line-started PM synchronous machine with rotor cage! What is the critical slip?

Grid-operated asynchronous machines with squirrel-cage rotor – standard motors:

1) Explain the dependence of motor efficiency and the efficiency maximum at variable load!
2) Name the basic components of standard asynchronous motors! What is “standardized” at these motors and up to which shaft height?
3) Sketch the speed-torque characteristic of squirrel-cage asynchronous motors by mains supply with fixed voltage and frequency! What are “torque classifications”?
4) What are the main loss groups in line-operated squirrel-cage asynchronous machines? How do they influence the operational behaviour?

5) Explain the physical nature of asynchronous space harmonic torque! How is this additional torque component generated? How it is influencing motor performance?
6) What are space harmonics of air gap flux density? Give an overview on ordinal numbers (formula) of stator and rotor field harmonics in squirrel-cage asynchronous machines!
7) Why do cage rotors of grid-operated asynchronous machines have skewed bars?
8) Explain the appearance of inter-bar currents and inter-bar current losses in cage rotors. How do these losses depend on inter-bar resistance and slot number ratio Q_s/Q_r ?
9) How are rotor time harmonic currents generated in line-fed asynchronous machines? How do they contribute to so-called additional losses?
10) Why do synchronous space harmonic torque components appear? How does this additional torque component change the speed-torque characteristic of the asynchronous machine?
11) Explain the generation of magnetic noise in asynchronous machines at line-operation! Explain the physical background step by step from the magnetic air gap field to the sound pressure waves in air!
12) What are “slot harmonic” flux density waves? Give an example! Why do different slot number ratios Q_s/Q_r have significant influence on the stimulation of magnetic noise?

Inverter-fed standard induction machines:

1) Explain the operational behaviour (maximum torque-speed curve, voltage speed-curve, power-speed curve) of inverter-fed standard- induction machines without and with influence of the stator winding resistance!
2) Sketch the steady state torque-speed characteristic (thermal limit of motor winding) of the variable-speed asynchronous drive with shaft-mounted fan cooling! Explain the particular speed sections!
3) Discuss the operational mode (maximum torque-speed curve, voltage speed-curve, power-speed curve) of standard induction machines with “steep” and “flat” voltage-frequency characteristic! Explain, why the same motor with flat characteristic can deliver a higher power (how many times?)!
4) Explain the field-weakening operation of inverter-fed asynchronous machines! How is the field-weakening realized? Why is the field-weakening used? What natural limitations in torque-speed range exist at field-weakening?
5) Name the loss components in inverter-fed asynchronous machine with shaft-mounted fan! How do they change with variable stator frequency? What effect has the variable speed (variable loss) on the steady state torque-speed characteristic concerning thermal limits?

Induction machines, designed especially for inverter operation:

1) How can field weakening range (= constant power range) be extended by serial and parallel switching of the windings?
2) What methods of creating a wide field weakening range do you know? What typical field weakening range (= constant power range) is possible? Name applications!
3) How is the shaft-height defined? With which methods can a significant increase of power per shaft-height be obtained in inverter-fed special induction machines, compared to standard induction machines?
4) Sketch maximum torque-speed curve, voltage speed-curve, power-speed curve of an inverter-fed induction motor with external fan cooling!
5) What is the difference between “field-oriented control” and operation with “U/f- characteristic”?
6) Name some special features of induction machines, which are designed especially for inverter-operation! In which way do they differ from the standard induction machines?

Effects in asynchronous machines, caused by inverter-operation:

1) Why do additional time harmonic currents occur both in stator and rotor winding in asynchronous machines at inverter supply? Which are the dominating frequencies, if the inverter is operated with pulse-width modulated inverter output voltage?
2) Explain the reasons for additional losses in asynchronous machines at inverter supply!
3) How is a “pulsating torque” component generated in asynchronous machines at inverter supply? Name the dominant frequency! Why may this oscillating torque be harmful in some application cases?
4) Why are space harmonic additional torque components (asynchronous and synchronous harmonic torque) generally insignificant at inverter supply?
5) Why does inverter supply lead to an additional electromagnetic noise generation? Which frequency and pulsation mode of the motor housing are dominating?
6) Why can the time harmonic content of current in asynchronous machines be obviously reduced with fast-switching IGBT voltage DC link converter?
7) Which parasitic effects occur due to fast-switching IGBT voltage DC link converter in asynchronous machines and in the motor cables?
8) Explain the appearance of an increased motor terminal voltage at inverter supply, caused by voltage wave reflections!
9) Why will the “first” coil of each motor phase be the most highly charged with voltage stress at inverter supply with fast-switching IGBTs?

Rotor balancing:

1) What is “unbalance” of a rotor defined? How is this unbalance disturbing motor operation ? How is its effect encountered by the balancing procedure in principle?
2) Define the static and dynamic unbalance by means of a simple rotor model and give the formulas for their definition! How do both unbalance modes manifest at motor operation?
3) What is meant by “rigid body balancing”? Describe the configuration of a balancing machine and its function!
4) Describe the difference between a rigid and an elastic rotor! Explain the natural bending frequencies and their influence on the oscillatory behaviour of rotor and on the balancing process?
5) How can be estimated the magnitude of unbalance by a vibration measurement of an (electrical) machine?
6) Give a quantitative measure which describes the quality of balancing of a rotor? How is it defined? Give examples (numerical values) for different applications!

DARMSTADT UNIVERSITY OF TECHNOLOGY

Department of Electrical Energy Conversion

Motor Development for Electric Drive Systems

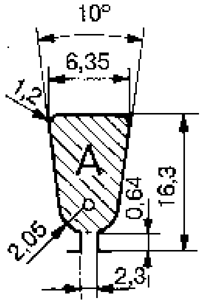
Tutorial 1

Permanent magnet excited synchronous motor with position encoder and surface magnets

A four-pole permanent magnet synchronous motor shall provide 30 kW continuous power at a speed of 24000 rpm. It is supplied by an inverter, which uses a filter to provide approximately sinusoidal voltages. By interpreting the signals of a position encoder, the inverter can align the current phasor with the back EMF E_0. The cooling of the machine is realised using a water jacket cooling of the stator housing. The main dimensions of the machine are as follows:

Stator outer/inner diameter 150 mm/90 mm; core length 90 mm; number of stator slots 36; slot dimension according to the drawing.

Two layer winding; short-pitching 7/9 to reduce the influence of higher harmonics armature reaction; number of turns per coil 4;
number of parallel paths 2; Y-connection;
diameter of copper wires 0.85 mm; number of conductor elements 7;
magnet material Sm_2Co_{17}; magnet height 3.5 mm; pole-pitch factor 87 %;
mechanical air gap 0.7 mm; thickness of bandage 2.8 mm;
end connector length 115 mm



B_R	T	1.07	1.03
$_BH_C$	kA/m	720	650
Temp.	°C	20	150

1) Calculate the number of turns per phase, the phase resistance at 20°C and 145°C (temperature class F with 40°C water inlet temperature) and the leakage impedance. Take into account the slot and end winding leakage. Due to the large active air gap, the high order harmonics leakage is too small and can be neglected, therefore, like the large synchronous generators, the tooth-top leakage is dominating.

2) Calculate the magnetic operating point under no-load conditions and 150°C magnet temperature (worst case) and the back EMF E_0.

3) Estimate the efficiency to be 95% and determine the current consumption and the required stator voltage for 30kW output power. What is the current density inside the copper conductors?

4) Determine the maximum possible magnitude of the sudden short circuit current. Are the magnets protected against permanent demagnetisation?

DARMSTADT UNIVERSITY OF TECHNOLOGY

Department of Electrical Energy Conversion

Motor Development For Electric Drive Systems

Tutorial 2

Permanent magnet synchronous machine with surface magnets

A permanent magnet synchronous machine with 30 kW rated power at 24000 rpm shall be designed with a commercial motor design software. Use the motor calculated in tutorial 1 as benchmark.

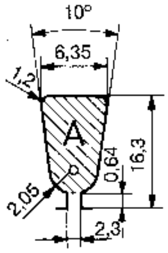
The most relevant data from tutorial 1 are listed below:

Main dimensions:

Stator outer/inner diameter	150 mm/90 mm
Stator iron length	90 mm
Number of stator slots	36
Mechanical air gap	0.7 mm
Bandage thickness	2.8 mm
Pole-pitch factor	87%

Slot dimensions:

See drawing



Slot height	15.66 mm
Slot opening	2.3 mm
Tooth height	0.64 mm
Tooth width	4.15 mm

Magnet data: (20°C)

Magnet height	3.5 mm
Remanent flux density B_R	1.07 T
Coercive field strength H_C	720 kA/m
Material	Sm_2Co_{17}

Winding data:

Y-connection

Number of turns per coil	4
Number of parallel paths	2
Copper wire diameter	0.85 mm
Number of conductor elements	7

The data for the permanent magnets and the characteristics for the core stack are already prepared and can be found in the files **RECOMA 28** and **V 250 35**.

Page 2 shows the labelling of the motor parameters as used by the SPEED software. Fig. 1 shows the geometry of the whole motor, Fig. 2 depicts the rotor parameters and Fig. 3 shows the slot parameters.

Labelling of the motor parameters as used by **SPEED PC-BDC**

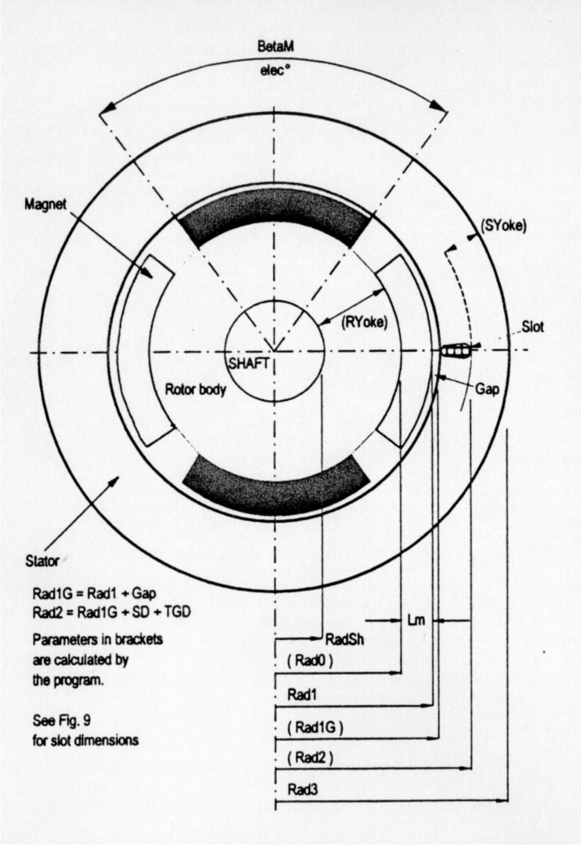


Fig. 1 Motor dimensions

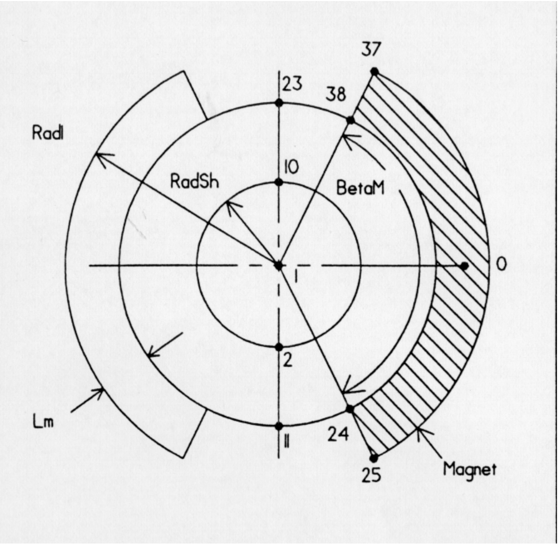


Fig. 2 Rotor dimensions

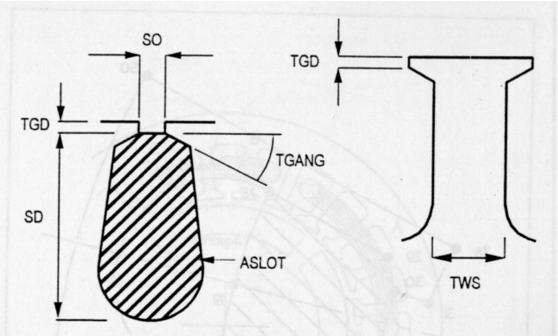


Fig.3 Slot dimensions

Results of tutorial 2

After a brief introduction to the SPEED motor design software, an automatic design suggestion created by SPEED was investigated and improved in some further steps.

1. Calculation of the motor parameters based on a coarse design suggestion obtained from SPEED.

Starting values for the automatic design suggestion:

1. Input data required from the SPEED software:

1. Aspired torque	[Nm]
2. Ratio of torque / rotor volume	$\left[\frac{\text{kNm}}{\text{m}^3}\right]$
3. Ratio of rotor length / rotor diameter	$\frac{L}{D}$
4. Number of poles	
5. Number of slots	
6. Supply voltage	[V]
7. Rated speed	[min^{-1}]
8. Rotor type (external-, internal rotor,...)	

According to exercise 1 the input data was chosen to be:

$$M = \frac{30\,kW}{2\cdot\pi\cdot\frac{24000}{60}s^{-1}} = 11.9\,Nm$$

$$T_{RV} = \frac{11{,}9\cdot10^{-3}}{5{,}22\cdot10^{-4}} = 22{,}8\frac{kNm}{m^3} \quad ; \quad V_{ROTOR} = 0{,}09mm\cdot\pi\cdot\left(\frac{0.086}{2}\right)^2 = 5{,}22\cdot10^{-4}\,m^3$$

$$\frac{L}{D} = \frac{0.09\,mm}{0.086\,mm} = 1{,}05$$

$p = 4$

$N = 36$

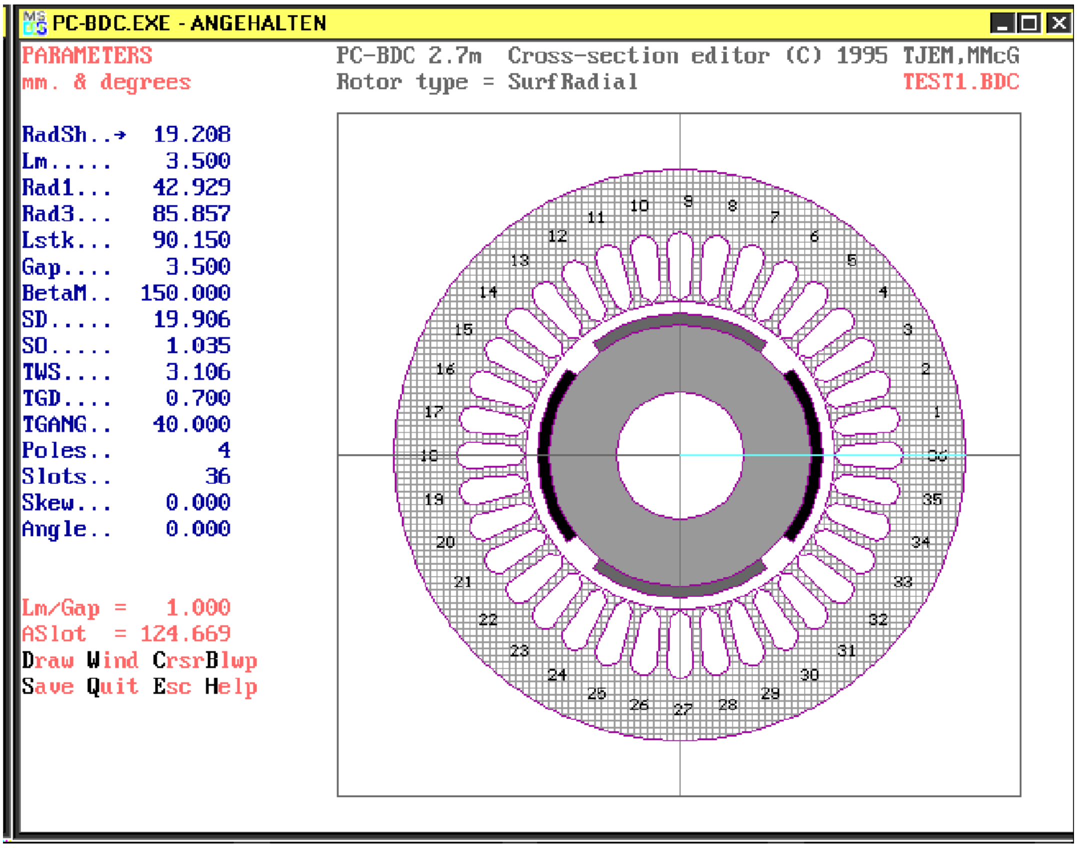
$V_{DC} = 400$ V

$N = 24000$ min^{-1}

$Rotor_{TYP} = 1$

The calculation result is a valid machine, but some assumptions have to be corrected manually (e.g. no bandage is employed, etc.)

This leads to a machine which is very close to the machine designed in the PhD project of Mrs. Greiffenstein, which is operating in the machine laboratory of the department.

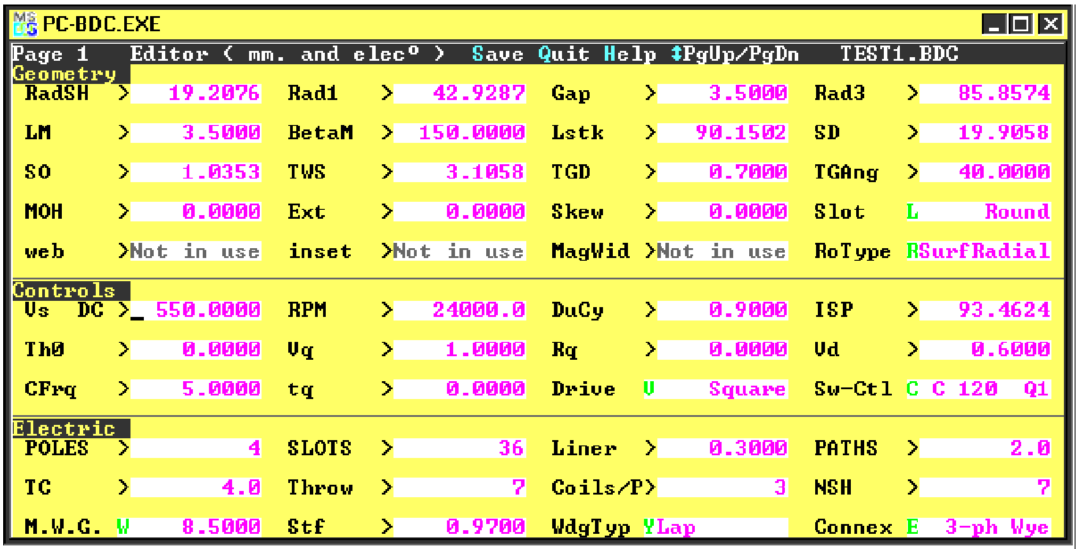


```
PC-BDC.EXE - ANGEHALTEN
PARAMETERS             PC-BDC 2.7m  Cross-section editor (C) 1995 TJEM,MMcG
mm. & degrees          Rotor type = SurfRadial                 TEST1.BDC

RadSh..→   19.208
Lm.....     3.500
Rad1...    42.929
Rad3...    85.857
Lstk...    90.150
Gap....     3.500
BetaM..   150.000
SD.....    19.906
SO.....     1.035
TWS....     3.106
TGD....     0.700
TGANG..    40.000
Poles..         4
Slots..        36
Skew...     0.000
Angle..     0.000

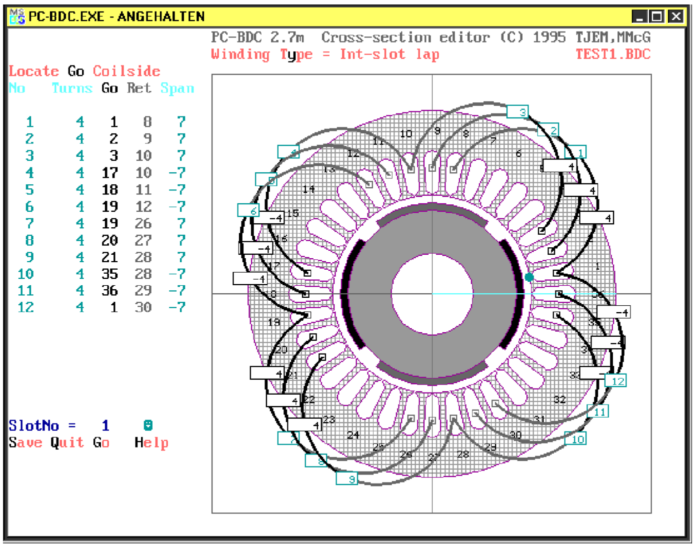

Lm/Gap =    1.000
ASlot  = 124.669
Draw Wind CrsrBlwp
Save Quit Esc Help
```

Fig. 4 Cross section of the adjusted motor design



```
PC-BDC.EXE
Page 1    Editor ( mm. and elec° )  Save Quit Help ⇕PgUp/PgDn    TEST1.BDC
Geometry
 RadSH    >   19.2076  Rad1     >   42.9287  Gap      >    3.5000  Rad3     >   85.8574
 LM       >    3.5000  BetaM    >  150.0000  Lstk     >   90.1502  SD       >   19.9058
 SO       >    1.0353  TWS      >    3.1058  TGD      >    0.7000  TGAng    >   40.0000
 MOH      >    0.0000  Ext      >    0.0000  Skew     >    0.0000  Slot     L     Round
 web      >Not in use  inset    >Not in use  MagWid   >Not in use  RoType   RSurfRadial
Controls
 Vs   DC  >_ 550.0000  RPM      >   24000.0  DuCy     >    0.9000  ISP      >   93.4624
 Th0      >    0.0000  Vq       >    1.0000  Rq       >    0.0000  Vd       >    0.6000
 CFrq     >    5.0000  tq       >    0.0000  Drive    V    Square  Sw-Ctl   C C 120  Q1
Electric
 POLES    >         4  SLOTS    >        36  Liner    >    0.3000  PATHS    >       2.0
 TC       >       4.0  Throw    >         7  Coils/P>           3  NSH      >         7
 M.W.G. W      8.5000  Stf      >    0.9700  WdgTyp   YLap         Connex   E 3-ph Wye
```

Fig. 5 Input data for the adjusted motor design



```
PC-BDC 2.7m  Cross-section editor (C) 1995 TJEM,MMcG
Winding Type = Int-slot lap                TEST1.BDC
```

No	Turns	Go	Ret	Span
1	4	1	8	7
2	4	2	9	7
3	4	3	10	7
4	4	17	10	-7
5	4	18	11	-7
6	4	19	12	-7
7	4	19	26	7
8	4	20	27	7
9	4	21	28	7
10	4	35	28	-7
11	4	36	29	-7
12	4	1	30	-7

Fig. 6 Winding arrangement of one phase

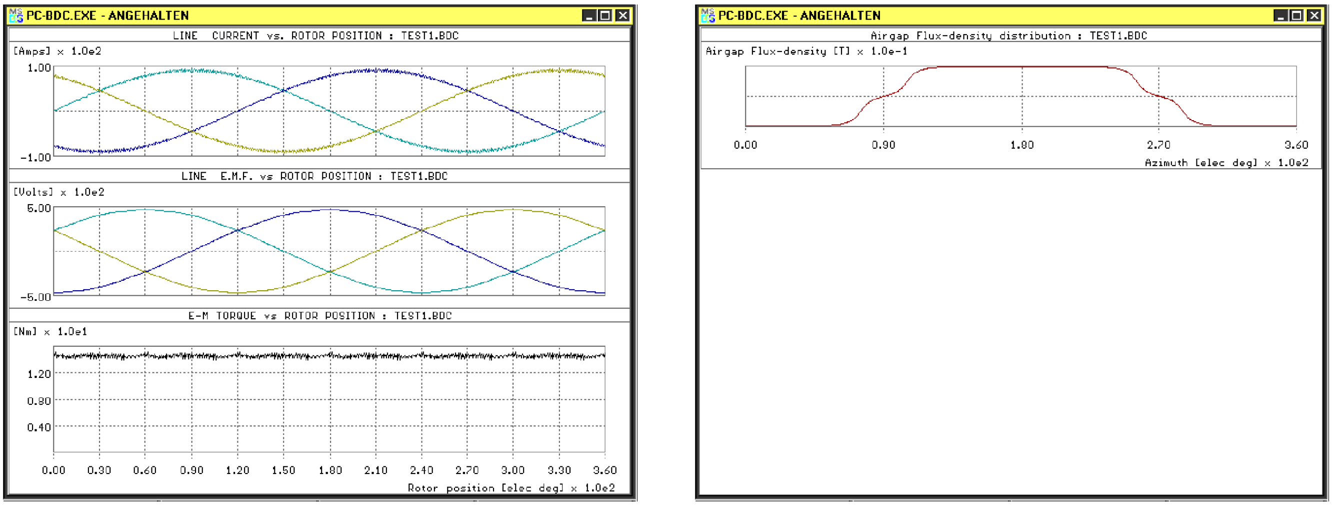


Fig. 7 Simulation results for sinusoidal current supply

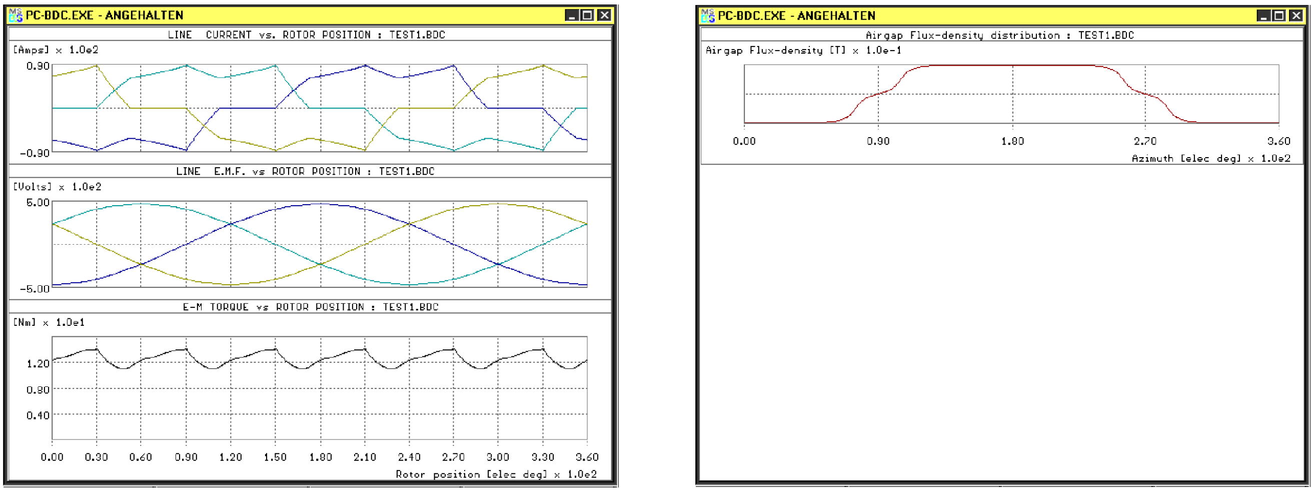


Fig. 8 Simulation results for block voltage supply

Here is a detailed list of all parameters calculated by SPEED

```
PCBDC 2.7m           TECHNICAL UN OF DARMSTADT
21st Jan 1999 13:08   TEST1.BDC

PCBDC Main Title
PCBDC Subtitle

1. DIMENSIONS ( mm )[.. =  input parameter]

Configuration :  Surface magnet [radial]; Interior rotor; Normal slotting

Rotor RadSh..   19.208   Rad1..        42.929   Gap..          3.500
Magnet Lm..      3.500   BetaM..[Edeg]  150.000   Poles..        4.000
Stator Rad2     67.034   Rad3..        85.857   Slots..       36.000
Slot opening..   1.035   Slot Depth..   19.906   Tooth width..   3.106
Tang depth..     0.700   TgAng..[Mdeg]  40.000   Ext..           0.000
SYoke         18.823   RYoke         20.221   Skew..[slots]   0.000
LStk..        90.150   Stack factor..  0.970   Magnet O/hang..  0.000

2. MAGNET DATA RotorType..  SurfRadial

Magnet..     Recoma 28
MuRec..        1.064   Br(20C) [T]..    1.070   Hc (20C)[kA/m].  800.000
TC(Br)[%/C]..   0.035   TC(Hc)[%/C]..    0.035   Dens [kg/m3].. 8300.000
Am(hp)  [mm2] 2429.675   Rg(hp)[kA/Wb] 1060.423   Pm0  [uWb/At]    0.928

3. CONTROL DATA Drive..       SINEWAVE

Vs..     [V]  550.000   Sw_Ctl..     ISP/AltH   RPM..        24000.000
ISP..    [A]  93.462   gamma..[Edeg]    0.000   Hys.band.. [%]    6.250
DuCy..           NA   CFrq.. [kHz]    5.000   TOL..    [1/]      64
Vq..     [V]    1.000   Rq..   [Ohm]    0.000   ISLA..   [1/]       8
Vd..     [V]    1.000   tq..   [us]    0.000   dq0..            Off


4. WINDING DATA Slot..      RoundBottom

Integralslot lap  : equal turns/coil  [type 3]   Phases..           3
Turns/coil..    4.000   Coils/pole..    3.000   No. str/cond..   7.000
Turns/ser/ph    24.000   Pll paths..    2.000   Slots/pole/ph    3.000
Layers          2.000   Coilsides/ph       24   Connection..      WYE
MLT    [mm]  393.206   Lgth o/ends    157.920   Throw..[slots]   7.000
M.W.G...        8.500   Bare WDia[mm]    0.800   InsThk.. [mm]    0.000
ACond   [mm2]    3.519   Liner.. [mm]    0.3000   L_Liner  [mm]   47.504
ASlot  [mm2]  124.669   ASlotLL[mm2]  110.418   WdgTemp..       25.000
SFillbare Cu    0.226   SFill LL      0.325   Rph     [ohm]   0.024

Inductances...
Lph   [mH/ph]    0.174   Mph   [mH/ph]   0.066   XL..           1.000
```

```
Lg    [mH/ph]    0.123   Lslot [mH/ph]    0.032   Lendt  [mH/ph]    0.019
Mg       [mH]   0.058   Mslot     [mH]   0.008   Ldiff  [mH/ph]    0.004
Lgg      [mH]    0.238   Mgg       [mH]   0.113   PCSlot           2.236
LLmin    [mH]    0.483   LLmax     [mH]    0.480   L_LL     [mH]    0.482
Lg0   [mH/ph]    0.119   Lg2   [mH/ph]    0.001   Laa_min   [mH]    0.175
Ld    [mH/ph]    0.242   Lq    [mH/ph]    0.240   Laa_max   [mH]    0.174
Xd   [ohm/ph]    1.215   Xq   [ohm/ph]    1.206   Lsigma [mH/ph]    0.056
Gd              0.516   Gq              0.511   Msigma [mH/ph]   0.007
kw1             0.902   Xm0  [ohm/ph]    1.746   Xsigma[ohm/ph]    0.313
ks1            1.000   kp1            0.940   kd1            0.960
ksg            0.971   fz             1.078   Nse           27.560

5. MAGNETIC DESIGN

MagTemp.. [C]   25.000   BrT      [T]    1.068   HcT     [kA/m]  801.400
Bg_av(OC) [T]    0.483   Bm(OC)    [T]    0.551   Hm(OC)  [kA/m] 386.459
Bg1(OC)   [T]    0.591   PhiM1    [mWb]    2.380   Leakage f_LKG     0.950
Bstpk(OC) [T]    1.246   PhiG     [mWb]    2.546   prl             0.053
Bsypk(OC) [T]    0.773   Brypk(OC) [T]    0.698   PC              1.135
eLLpk    [V]  471.979   Z    [conds]     288   Ag(hp)   [mm2] 2636.186
kT    [Nm/A]    0.161   kE  [Vs/rad]    0.188
Bg1 (Load)[T]    0.621   Bm  (Load)[T]    0.551   Bma        [T]   0.000


6. STATIC DESIGN  (Phasor diagram)    Motoring

MechPower[kW]   36.307   ElecPower[kW]   37.697   Machine Effcy%   96.313
Torque  [Nm]   14.446   PF       [lag]    0.918   sigma [kN/m^ 2]   13.911
Eq1       [V]  183.125   Vph1      [V]  201.152   VLL1   [Vrms]  348.405
IL    pk [A]   93.462   IL mean  [A]   59.500   IL rms    [A]   66.088
IW    pk [A]   93.462   IW mean  [A]   59.500   IW rms    [A]   66.088
delta.. [deg]   23.346   gamma    [deg]    0.000   phi     [deg]   23.346
Vq1       [V]  184.683   Vd1       [V]   79.713
Iq1       [A]   66.088   Id1       [A]    0.000   Fda1  [At/gap]    0.000
Losses...
W(Cu)    [W]  308.878   W(Iron) [We] 1081.101   W(w/f)    [W]    0.000
W(total) [W] 1389.978   Temp rise [C]    0.000   Jrms [A/mm2]    9.391
Max VLLrms available  :  (6step)  [V]  428.833   Linear PWM [V]  336.805

7. DYNAMIC DESIGN (timestepping simulation)    Motoring

Torque  [Nm]   14.515   MechPower[kW]   36.480   Machine Effcy%   96.380
W(Cu)    [W]  288.914   W(Iron) [We] 1081.101   W(w/f)    [W]    0.000
W(Can)   [W]    0.000   W(Magnet)[W]    0.000   W(shaft)  [W]    0.000
W(total) [W] 1370.015   Temp rise [C]    0.000   Jrms [A/mm2]    9.083
IW    pk [A]   93.466   IW mean  [A]   57.521   IW rms    [A]   63.917
IL    pk [A]   93.466   IL mean  [A]   57.521   IL rms    [A]   63.917
IQchop pk [A]   93.791   IQch mean [A]   20.030   IQchop rms [A]   38.085
```

```
IQcomm pk [A]   93.791   IQcm mean [A]   20.030   IQcomm rms [A]   38.085
IDchop pk [A]   93.629   IDch mean [A]    8.737   IDchop rms [A]   24.343
IDcomm pk [A]   93.629   IDcm mean [A]    8.737   IDcomm rms [A]   24.343
DC [wfm]  [A]    0.000   W (Conv)  [W]  151.636   Eff DC/shaft %   95.996

8. MISC. PARAMETERS

Wt Cu    [kg]    1.771   Wt Iron  [kg]   10.278   Wt Magnet [kg]    0.565
Total wt [kg]   12.613   RotJ  [kgm2] 3.38E03   Ironloss[W/kg]  105.191
Int Step.[Ed]    0.063   DC [pball][A]   69.093   DegC/W..          0.000
Ax1    [Mdeg]   55.000   Fund.Freq[Hz]  800.000   Chop.Freq[kHz]  443.200
XFe..            1.000   Xrl..            1.000   CFrq..  [kHz]     5.000
XET.             1.000   Carter coefft    1.004   BmHm   [kJ/m3]  213.097
NWFT.            2.000   XBtpk..          1.000   TFRho             1.020
EMF :              BLV   Mag. Fringing :     ON   XFringe..         1.000

Sinewound parameters     CPhi           0.922   1+Pm0*Rg          1.984
Cd               0.516   Cq             0.511   k1                0.000
k1ad             0.992   k1aq           0.674   kAlphad           0.000

9. CORE LOSS ANALYSIS      V250 35

Wt teeth [kg]    1.852   Wt yoke  [kg]    5.914   Wt troots[kg]    0.688

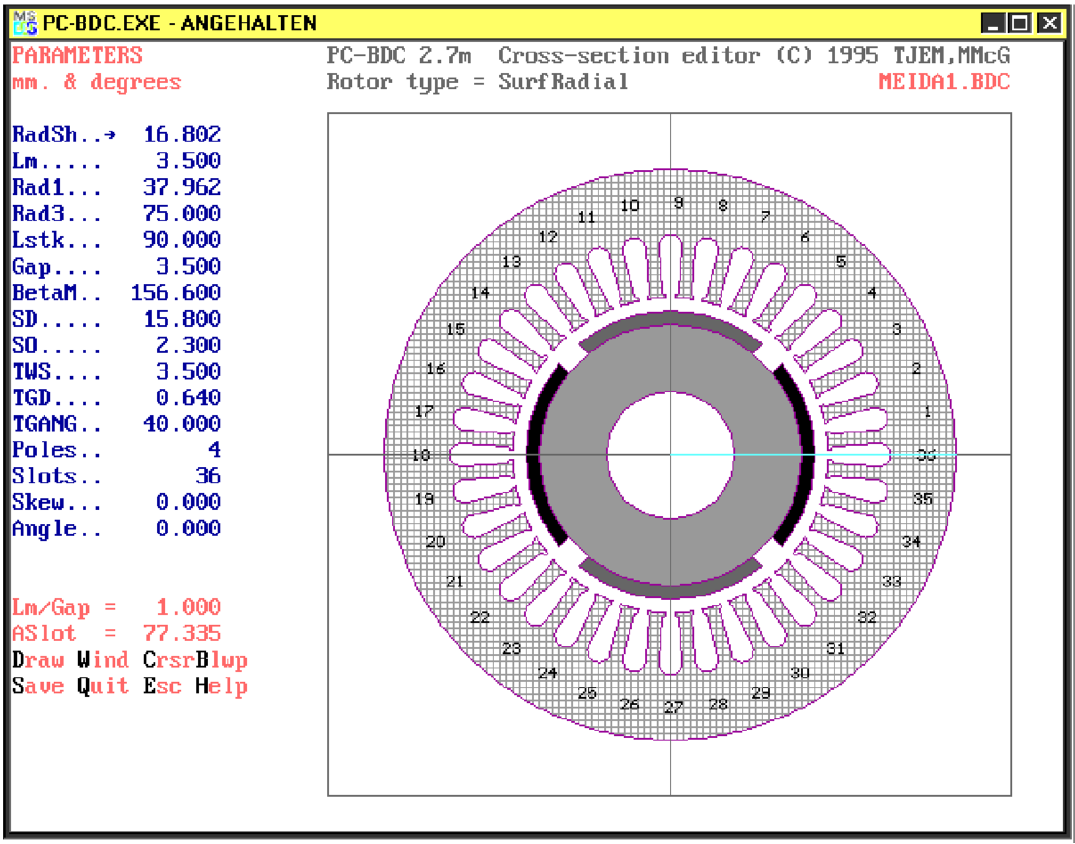
Teeth eddy[W]  784.494   Teeth hyst[W]   55.718   Teeth total[W]  840.212
      [W/kg]   308.853          [W/kg]   21.936          [W/kg]   330.789
Yoke eddy [W]  187.010   Yoke hyst [W]   53.879   Yoke total [W]  240.889
      [W/kg]    31.622          [W/kg]    9.111          [W/kg]    40.732

EC50Hz [W/kg]    0.478   Hys50Hz[W/kg]    1.951   WFe50Hz [W/kg]    2.429

End of DesignRefNo 980224
```

2. Calculation of a machine according to tutorial 1

In a second machine design a motor according to the one investigated in tutorial 1 is designed using the input data editor.

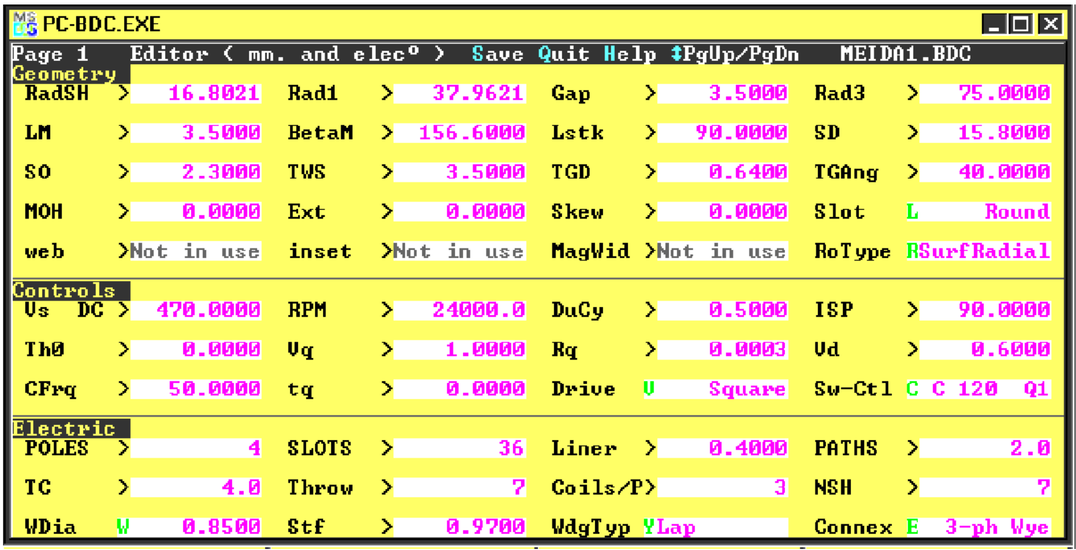


```
PARAMETERS          PC-BDC 2.7m  Cross-section editor (C) 1995 TJEM,MMcG
mm. & degrees       Rotor type = SurfRadial                   MEIDA1.BDC

RadSh..→   16.802
Lm.....     3.500
Rad1...    37.962
Rad3...    75.000
Lstk...    90.000
Gap....     3.500
BetaM..   156.600
SD.....    15.800
SO.....     2.300
TWS....     3.500
TGD....     0.640
TGANG..    40.000
Poles..         4
Slots..        36
Skew...     0.000
Angle..     0.000


Lm/Gap =    1.000
ASlot  =   77.335
Draw Wind CrsrBlup
Save Quit Esc Help
```

Fig. 9 Motor cross section according to tutorial 1



```
Page 1    Editor ( mm. and elec° )  Save Quit Help ‡PgUp/PgDn    MEIDA1.BDC
Geometry
 RadSH   >   16.8021  Rad1    >   37.9621  Gap     >    3.5000  Rad3    >   75.0000

 LM      >    3.5000  BetaM   >  156.6000  Lstk    >   90.0000  SD      >   15.8000

 SO      >    2.3000  TWS     >    3.5000  TGD     >    0.6400  TGAng   >   40.0000

 MOH     >    0.0000  Ext     >    0.0000  Skew    >    0.0000  Slot    L     Round

 web     >Not in use  inset   >Not in use  MagWid  >Not in use  RoType  RSurfRadial

Controls
 Vs   DC >  470.0000  RPM     >   24000.0  DuCy    >    0.5000  ISP     >   90.0000

 Th0     >    0.0000  Vq      >    1.0000  Rq      >    0.0003  Vd      >    0.6000

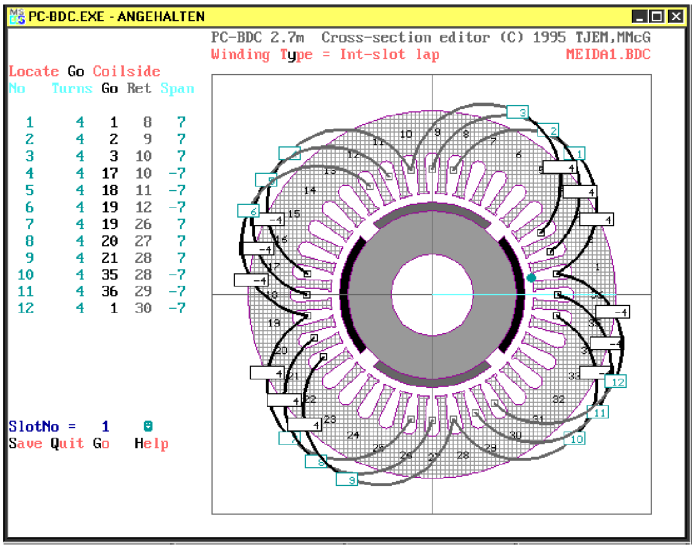
 CFrq    >   50.0000  tq      >    0.0000  Drive   V    Square  Sw-Ctl  C C 120  Q1

Electric
 POLES   >         4  SLOTS   >        36  Liner   >    0.4000  PATHS   >       2.0

 TC      >       4.0  Throw   >         7  Coils/P>         3  NSH     >         7

 WDia    W    0.8500  Stf     >    0.9700  WdgTyp  YLap         Connex  E  3-ph Wye
```

Fig. 10 Input data according to tutorial 1



```
PC-BDC 2.7m  Cross-section editor (C) 1995 TJEM,MMcG
Winding Type = Int-slot lap                 MEIDA1.BDC

No   Turns Go Ret Span

 1     4    1   8   7
 2     4    2   9   7
 3     4    3  10   7
 4     4   17  10  -7
 5     4   18  11  -7
 6     4   19  12  -7
 7     4   19  26   7
 8     4   20  27   7
 9     4   21  28   7
10     4   35  28  -7
11     4   36  29  -7
12     4    1  30  -7
```

Fig. 11 Winding arrangement of one phase

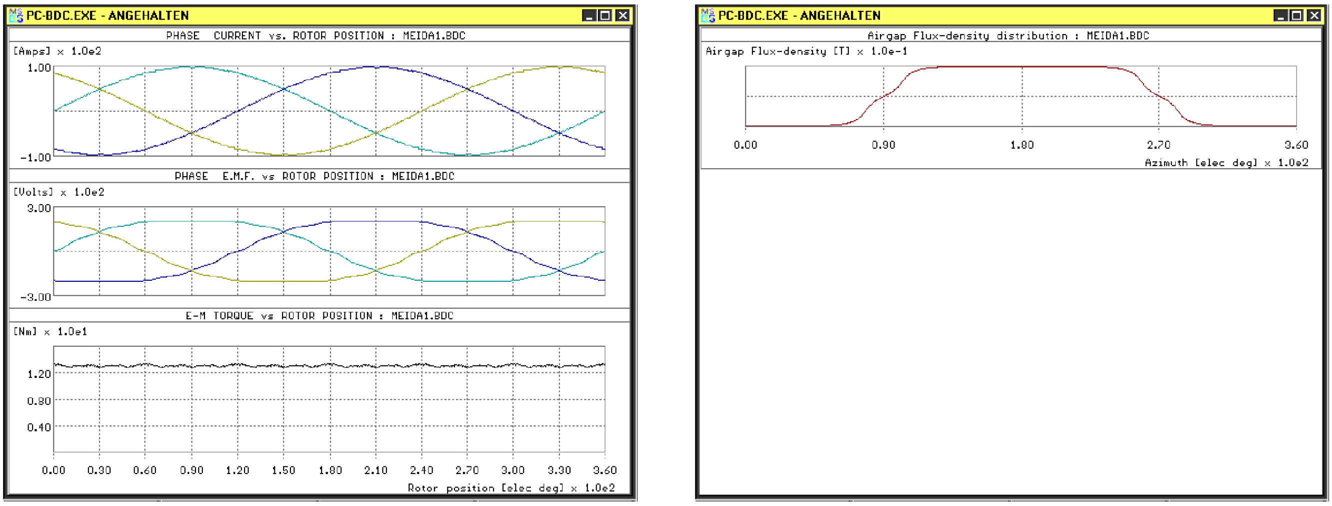


Fig. 12 Simulation results for sinusoidal current supply

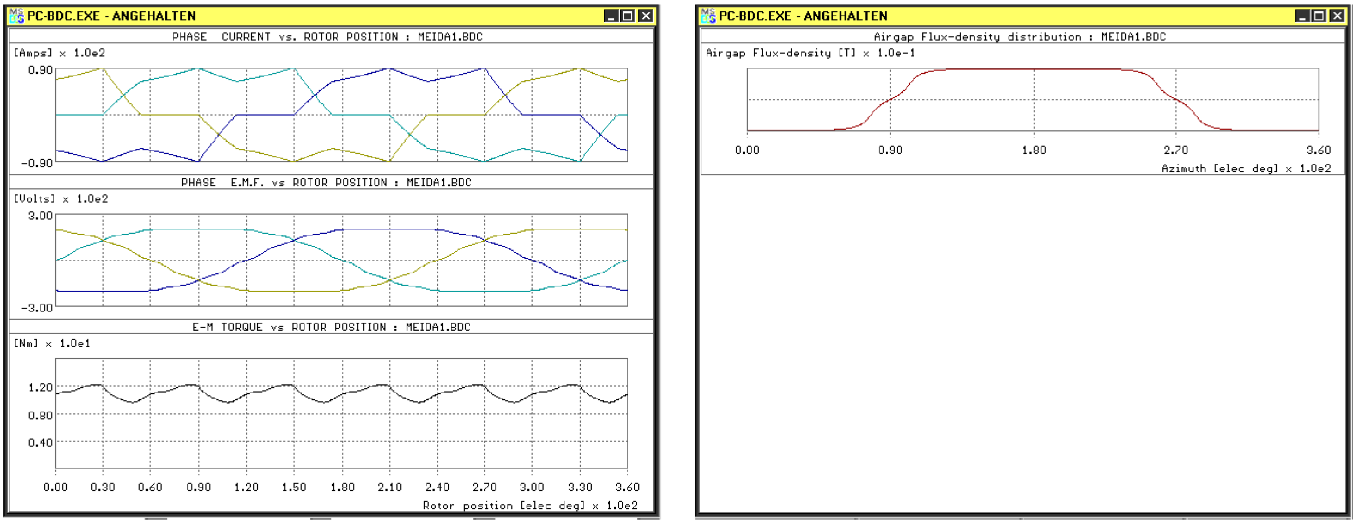


Fig. 13 Simulation results for block voltage supply

```
PCBDC 2.7m          TECHNICAL UN OF DARMSTADT
21st Jan 1999 15:20   MEIDA1.BDC

PCBDC Main Title
PCBDC Subtitle

1. DIMENSIONS ( mm )[.. =  input parameter]

Configuration :  Surface magnet [radial]; Interior rotor; Normal slotting

Rotor RadSh..   16.802   Rad1..         37.962   Gap..          3.500
Magnet Lm..      3.500   BetaM..[Edeg]  156.600   Poles..         4.000
Stator Rad2     57.902   Rad3..         75.000   Slots..        36.000
Slot opening..   2.300   Slot Depth..    15.800   Tooth width..    3.500
Tang depth..     0.640   TgAng..[Mdeg]   40.000   Ext..            0.000
SYoke          17.098   RYoke          17.660   Skew..[slots]    0.000
LStk..         90.000   Stack factor..   0.970   Magnet O/hang..  0.000

2. MAGNET DATA RotorType..  SurfRadial

Magnet..     Recoma 28
MuRec..         1.064   Br(20C) [T]..    1.070   Hc(20C)[kA/m].  800.000
TC(Br)[%/C]..   0.035   TC(Hc)[%/C]..    0.035   Dens [kg/m3].. 8300.000
Am(hp)  [mm2] 2226.921   Rg(hp)[kA/Wb] 1163.269   Pm0  [uWb/At]    0.851

3. CONTROL DATA Drive..      SQUAREWAVE

Vs..     [V]  470.000   Sw_Ctl..     C 120  Q1   RPM..        24000.000
ISP..    [A]   90.000   Th0..  [Edeg]    0.000   Hysband.. [%]    0.391
DuCy..          0.500   CFrq..  [kHz]   50.000   TOL..     [1/]      2
Vq..     [V]    1.000   Rq..    [Ohm]    0.000   ISLA..    [1/]     32
Vd..     [V]    1.000   tq..    [us]     0.000   dq0..            Off
R_s..   [ohm]   0.000

4. WINDING DATA Slot..      RoundBottom

Integralslot lap  : equal turns/coil  [type 3]   Phases..          3
Turns/coil..    4.000   Coils/pole..    3.000   No. str/cond..   7.000
Turns/ser/ph   24.000   Pll paths..     2.000   Slots/pole/ph    3.000
Layers          2.000   Coilsides/ph      24   Connection..      WYE
MLT     [mm]  370.477   Lgth o/ends    150.631   Throw..[slots]   7.000
WDia..  [mm]    0.850   Bare WDia[mm]    0.850   InsThk..  [mm]   0.000
ACond   [mm2]   3.972   Liner..  [mm]   0.4000   L_Liner  [mm]   38.251
ASlot   [mm2]  77.335   ASlotLL [mm2]   62.034   WdgTemp..       25.000
SFillbare Cu    0.411   SFill LL        0.652   Rph     [ohm]    0.020

Inductances...
Lph   [mH/ph]   0.151   Mph   [mH/ph]   0.058   XL..            1.000
```

```
Lg    [mH/ph]   0.108   Lslot [mH/ph]   0.027   Lendt  [mH/ph]   0.016
Mg      [mH]   0.051   Mslot    [mH]   0.007   Ldiff  [mH/ph]   0.004
Lgg     [mH]   0.208   Mgg      [mH]  0.098   PCSlot          1.854
LLmin   [mH]   0.420   LLmax   [mH]   0.417   L_LL     [mH]   0.418
Lg0   [mH/ph]   0.105   Lg2   [mH/ph]   0.000   Laa_min   [mH]   0.152
Ld    [mH/ph]   0.210   Lq    [mH/ph]   0.209   Laa_max  [mH]   0.151
Xd   [ohm/ph]   1.054   Xq   [ohm/ph]   1.048   Lsigma [mH/ph]   0.046
Gd              0.520   Gq              0.516   Msigma [mH/ph]  0.006
kw1             0.902   Xm0  [ohm/ph]   1.525   Xsigma[ohm/ph]   0.261
ks1            1.000   kp1            0.940   kd1             0.960
ksg            0.971   fz             1.078   Nse           27.560
```

5. MAGNETIC DESIGN

```
MagTemp.. [C]  25.000   BrT     [T]   1.068   HcT    [kA/m]  801.400
Bg_av(OC) [T]   0.477   Bm(OC)    [T]   0.550   Hm(OC)  [kA/m] 387.411
Bg1(OC)  [T]   0.595   PhiM1   [mWb]   2.126   Leakage f_LKG    0.950
Bstpk(TFW)[T]   0.958   PhiG    [mWb]   2.328   prl             0.053
Bsypk(TFW)[T]   0.758   Brypk(OC) [T]   0.732   PC              1.130
eLLpk   [V]  395.964   Z    [conds]     288   Ag(hp)   [mm2] 2442.160
kT    [Nm/A]   0.148   kE [Vs/rad]   0.158   Noload kRPM     30.332
I(Bk)   [A]  233.001   Bk..     [T]   0.000   Hk     [kA/m]  798.86
I(LR) ~  [A]11685.632   Bm (LR)  [T]  27.075   Hm (LR) [kA/m]2.10E+04
I(C180)~  [A]21572.585   Bm (C180) [T]  50.448   Hm(C180)[kA/m]3.85E+04
```

6. STATIC DESIGN   Motoring

```
MechPower[kW]  33.470   ElecPower[kW]  34.269   Machine Effcy%   97.668
Torque  [Nm]  13.317                        sigma [kN/m^ 2]  13.447
IL    pk [A]  90.000   IL mean  [A]  60.000   IL rms    [A]  73.485
IW    pk [A]  90.000   IW mean  [A]  60.000   IW rms    [A]  73.485
Losses...
W(Cu)    [W]  318.728   W(Iron) [We]  480.376   W(w/f)    [W]   0.000
W(Can)   [W]   0.000   W(Magnet)[W]   0.000   W(shaft)  [W]   0.000
W(total) [W]  799.104   Temp rise [C]   0.000   J rms  [A/mm2]   9.250
IQchop pk [A]   90.000   IQch mean [A]   25.274   IQchop rms [A]   47.694
IQcomm pk [A]   90.000   IQcm mean [A]   30.000   IQcomm rms [A]   51.962
IDchop pk [A]   90.000   IDch mean [A]    4.726   IDchop rms [A]   20.623
IDcomm pk [A]   90.000   IDcm mean [A]    0.000   IDcomm rms [A]    0.000
DC [wfm]  [A]   75.823   W(Conv)  [W]  179.553   Req'd voltage   395.964
```

7. DYNAMIC DESIGN (timestepping simulation)   Motoring

```
Torque  [Nm]   10.946   MechPower[kW]   27.511   Machine Effcy%   97.522
W(Cu)    [W]  218.578   W(Iron) [We]  480.376   W(w/f)    [W]   0.000
W(Can)   [W]   0.000   W(Magnet)[W]   0.000   W(shaft)  [W]   0.000
W(total) [W]  698.954   Temp rise [C]   0.000   J rms  [A/mm2]   7.660
```

```
IW     pk [A]   89.955   IW mean  [A]   51.145   IW rms    [A]   60.854
IL     pk [A]   89.955   IL mean  [A]   51.145   IL rms    [A]   60.854
IQchop pk [A]   90.006   IQch mean [A]   22.567   IQchop rms [A]   40.863
IQcomm pk [A]   90.006   IQcm mean [A]   22.770   IQcomm rms [A]   41.085
IDchop pk [A]   90.006   IDch mean [A]    3.004   IDchop rms [A]   13.474
IDcomm pk [A]   89.933   IDcm mean [A]    2.802   IDcomm rms [A]   12.781
DC [wfm]  [A]   59.295   W(Conv)  [W]  149.986   Eff DC/shaft %   97.007

8. MISC. PARAMETERS

Wt Cu    [kg]    1.884   Wt Iron  [kg]    8.075   Wt Magnet [kg]    0.518
Total wt [kg]   10.477   RotJ  [kgm2] 2.09E03   Ironloss[W/kg]   59.488
Int Step.[Ed]    0.016   DC [pball][A]   60.341   DegC/W..          0.000
Ax1    [Mdeg]   55.000   Fund.Freq[Hz]  800.000   Chop.Freq[kHz]   28.800
XFe..            1.000   Xrl..            1.000   CFrq..  [kHz]   50.000
XET..            1.000   Carter coefft    1.020   BmHm   [kJ/m3]  213.128
NWFT..           2.000   XBtpk..          1.000   TFRho             1.020
EMF : Constructed  wfm   Mag. Fringing :     ON   XFringe..         1.000
                         ET_rms   [mV] 1662.151   EY_rms    [mV] 3798.642

9. CORE LOSS ANALYSIS      V250 35

Wt teeth [kg]    1.499   Wt yoke  [kg]    4.662   Wt troots[kg]    0.703

Teeth eddy[W]  280.461   Teeth hyst[W]   29.498   Teeth total[W]  309.958
      [W/kg]  127.364          [W/kg]    13.396          [W/kg]  140.759
Yoke eddy [W]  129.947   Yoke hyst [W]   40.471   Yoke total [W]  170.417
      [W/kg]   27.875          [W/kg]     8.681          [W/kg]   36.556

EC50Hz [W/kg]    0.478   Hys50Hz[W/kg]    1.951   WFe50Hz [W/kg]    2.429

End of DesignRefNo 980224
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DARMSTADT UNIVERSITY OF TECHNOLOGY

Department of Electrical Energy Conversion

Motor Development For Electric Drive Systems

Tutorial 3

Linear motors: generation and characteristics of moving magnetic fields

1) Perform a qualitative comparison of the field excitation (m.m.f.) curve *V(x,t)* of both a linear moving and a rotating magnetic field with the following data: q = 1, m = 3, unchorded two-layer winding, sinusoidal three-phase system at time t with $i_U = 0$, $i_V = -i_W = \sqrt{3}/2 \cdot \hat{I}$. Check the compliance with the third *MAXWELL* equation ($div\vec{B} = 0$)!
   a) Draw 2 poles of the rotating field.
   b) Generate the linear moving field by "cutting" a four-pole rotating field winding, so that the end poles only consist of upper or lower layer conductors. How many poles does this moving field winding span? What do the end-pole m.m.f. curves look like, compared to the interior field curves?

2) Fundamental harmonic analysis for task 1): Assume the electric loading *A(x,t)* to be sinusoidally distributed and calculate, neglecting iron saturation and slot opening effects
   a) the rotating air gap field $B_\delta(x,t)$,
   b) the linear moving air gap field $B_\delta(x,t)$. Take into account that the electric loading is reduced to its half at the end of the winding. Divide the winding zone into the end sections I and III and the middle section II. What special characteristic occurs in the field of the end zones I and III ?

3) Plot the rotating and the linear moving air gap flux density from 2) for three different times $\omega t = 0$, $\omega t = \pi/2$, $\omega t = \pi$.

4) Assume the secondary to be a linear squirrel-cage armature (linear induction machine), moving with v_m, whereas the primary, carrying the linear winding, stands still. Is there any tangential force on the armature if slip $s = 0$? If so, why is that and how does this force act?

5) Like 4), but with a permanent magnet synchronous armature. Does the armature experience any tangential force? If so, why and which way does this force act?

Motor Development For Electric Drive Systems

Tutorial 4

Linear motors with tooth-wound coils

A permanent magnet linear motor can also be designed using tooth-wound coils (see also "modular synchronous machine", "fractional slot windings"):

In this tutorial we consider a tooth wound linear motor with the following specification:

number of slots per pole and phase	$q = 2/7$
air gap	$\delta = 2$ mm
rated current	$I_r = 13$ A
maximum current	$I_{max} = 40$ A
rated speed	$v_r = 2$ m/s
number of turns per coil	$N_C = 150$
number of parallel paths	$a = 2$
wire cross section	0.83 mm
number of poles	$2p = 14$
magnet height	$h_m = 5$ mm
magnet width	11 mm (2 magnets per pole)
remanence flux density	$B_R = 1.2$ T
relative magnet permeability	$\mu_r = 1.05$
pole pitch factor	$\alpha_e = 100$ %
slot-/pole pitch:	26.8/23 mm
open rectangular slots:	
slot width:	11.8 mm
slot height:	23 mm

stator slots skewed by one slot pitch.

water jacket cooling

1) Calculate the winding factor of the fundamental harmonic.

2) Calculate the rated normal force and the rated thrust.

3) Calculate the ohmic losses and the efficiency at rated speed v_r. Is the motor protected against permanent demagnetisation if maximum current is employed?

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Tutorial 5

Switched Reluctance Machines

A four-pole, three phase switched reluctance motor with 7.5 kW rated output power at 1500 rpm (3000 rpm maximum speed) has a rated current of 12 A (rms-value) per phase for temperature class B. The maximum inverter output current is 30 A, the supply voltage is 400 V at 50 Hz. The motor is fan-cooled with a ribbed housing like a standard inverter motor. The following main dimensions have been chosen:

Stator outer/inner diameter 209.5 mm/120.9 mm; stator core length 193 mm; air gap $\delta = 0.45$ mm; number of stator/rotor teeth 12/8; stator/rotor tooth width 16.0/16.7 mm; stator/rotor tooth height 30.5/19 mm; number of turns per coil 61; series connection of all coils; round wire diameter 1.8 mm; coil width/height 9/22.5 mm.

1) Calculate the ratio of peak to r.m.s. current at 120° current flow duration and ideal block current shape.

2) Calculate the coil resistance at 20°C and at maximum temperature for temperature class B, according to VDE 0530/1. The end winding length is 43 mm.

3) Determine the direct- and quatrature-axis inductivity for the non-saturated machine using the *CARTER*-model.

4) Calculate the internal torque at low speed with 120° block current supply from the change of the magnetic coenergy, if the flux linkage of the *d*-axis of the saturated machine has the following charateristic: 5A/0.69Vs, 10A/1.1Vs, 15A/1.25Vs, 24A/1.38Vs, 30A/1.43Vs. Use the data for 15A/1.25Vs and 30A/1.43Vs to linearize the characteristic. In the highly saturated area *d*- and *q*-axis flux linkage shall be parallel to each other. Use this data to determine the internal torque at maximum inverter output current and at rated motor current.

5) Check the results from 4) for rated speed (1500 /min), if the measured total losses are 1220 W and if temperature class B is fully exploited. Calculate the electric loading ("current layer") A, the current density J and the product $A \cdot J$ and compare it with that of standard induction motors of similar size, temperature class and number of poles (electric loading ca. 300 A/cm, current density ca. 7.5 A/mm^2).

6) Estimate the current rise time and assess the maximum speed for pulse control operation. (guide value: current flow time > 10 times the current rise time)

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Tutorial 6

Effects of high order harmonics on the grid connected induction motor

An induction motor has the following dimensions:

Rated voltage U_N = 690 V Y, rated current I_N = 60 A, rated speed n_N = 960 /min, rated frequency f_N = 50 Hz, efficiency $\eta = 0.9$, power factor $\cos \varphi_N = 0.87$.
Measured no-load current: I_0 = 20 A.

Winding data:
Number of turns per coil $N_c = 5$, chorded two-layer winding $w/\tau_p = 7/9$
Series connection of all coils per phase: $a = 1$, number of pole pairs $2p = 6$.

Dimensions:
Stator inner diameter: D_i = 250 mm, length of laminated core l_{Fe} =250 mm
Number of Stator / Rotor slots $Q_s/Q_r = 54/42$, air gap δ = 1 mm

Calculate

1) the rated motor power P_N, the rated slip s_N, the number of turns per phase N_{Ph}, the pole pitch τ_p, the number of stator slots per pole and phase q, the synchronous rotational speed n_{syn} and the synchronous speed of the fundamental harmonic v_{syn}.
2) the ordinal numbers under no-load conditions of the field waves up to the first slot harmonics pair, the corresponding chording-, distribution- and winding-factors and the magnitudes of the field waves, if saturation of iron is neglected.
3) the slip s_ν of the ν^{th}-harmonic with respect the rotating armature in general and for the 5th harmonic.
4) the slip s of the rotor with respect to the synchronous speed, if the rotor runs synchronously with the ν^{th} harmonic, in general and for the 5th harmonic.
5) the slip condition for the generation of synchronous harmonic torque. Which are the major synchronous harmonic torque slips for this non-saturated induction machine?
6) the ordinal numbers of the force wave and the excited frequencies generated by the sinusoidally distributed forces around the surface that are generated by the air gap harmonics and by the magnetic pull.
7) the ordinal numbers of the force wave and the exited frequencies for the induction motor described above, assuming no eccentricity and draw the corresponding deformation of the stator lamination.

Motor Development For Electric Drive Systems

Tutorial 7

Induction motor, fed by a voltage source inverter

For an electric vehicle application, an induction motor with a voltage source inverter has to be designed. The battery delivers 120 V and 200 A. The motor is connected to a single-stage gear box and shall provide 14 kW rated power at 1600 min^{-1}. Temporary (2 min.) 20 kW output power is requested. The motor shall operate in constant power mode between 1600 min^{-1} and 5500 min^{-1}.

The following motor with water jacket cooling has been chosen:
Stator outer/inner diameter: 180/114.5 mm, length of stator iron core: 165 mm, number of poles: 4, single layer winding, number of stator/rotor slots 36/28, aluminium diecast cage, stator slot fill factor: 42%, stator slot cross section: 80 mm^2, air gap 0.5 mm, *Blondel* leakage coefficient $\sigma = 0.1$.

1) At its voltage limit, the inverter operates with block shape voltages to provide a maximum possible fundamental harmonic. What is the number of turns per phase if the air gap flux density (fundamental wave) is aspired to be 0.9 T at rated speed?

2) Determine the rated and maximum torque at rated speed. What is the apparent inverter output power? (Estimate reasonable values for both efficiency and fundamental harmonic power factor) Is the maximum battery current sufficient for maximum torque at rated speed?

3) Calculate the *ESSON* coefficient of this motor. What are the values of current layer and current density for this motor? Are these values permitted for water jacket cooled motors?

4) Determine the magnetizing inductance L_h, the leakage inductance L_σ and the breakdown torque M_b at rated speed. (Assume that the total magnetization is 1.5 times that of the air gap magnetization!)

5) What is the maximum speed for constant power operation with 20 kW and 14 kW? Draw the $P(n)$-diagram for rated power within a speed range of 0..5500 min^{-1}.

6) Estimate the harmonic currents up to the 13th harmonic. Neglect the influence of ohmic resistance, take only inductances into consideration. What are the additional ohmic losses in the stator compared to the ohmic losses of the fundamental current?