Structure of the final exam:

1. Questions : 20 Points
2. Mechanical requirements : 10 Points
3. DC Motor: 25 Points
4. SM : 25 Points
5. Power Electronics: 10 Points

8 Final example

An autonomous vehicle is to transport loads in a production hall. The following data are known for the drive task:

- Dimensions of the hall: $100\,\mathrm{m}$ x $200\,\mathrm{m}$
- Max. speed of the robot: $10\,\mathrm{km/h}$
- Weight of the vehicle m_V: $5\,\mathrm{kg}$
- Max. weight of the load m_L: $60\,\mathrm{kg}$
- 2 wheels with diameter D: $150\,\mathrm{mm}$
- One gearbox-motor system is used per wheel.
- Gear ratio: 1:10 ($i = 10$)
  - Speed of the motor = 10 · speed of the wheel
  - Torque of the motor = torque of the wheel / 10
- Only rolling resistance is considered as load force: $F_L = c_R * F_{weight}$
- Rolling resistance coefficient c_R for car tyres on concrete: 0.02
- Total moment of inertia referenced to motor shaft is $\approx J_{Tot,Mot} = \frac{1}{i^2} \cdot (m_L + m_V) * (D/2)^2$.

  $= J'_V + J_{Mot}$, $J_{Mot} \to 0$

Drive characteristic data

1. What is the maximum load torque of the motors at constant speed?
2. What is the maximum acceleration time at maximum load and starting from standstill when four-times the maximum load torque is available for the acceleration process? Calculate also the braking time.
3. If operation at maximum load and maximum speed can be assumed to be continuous and a safety factor of 2 is used, what is the rated torque and rated speed required for the drive motors?

$n_N = 3537\,\mathrm{min}^{-1} \to 3500\,\mathrm{min}^{-1} - 3600\,\mathrm{min}^{-1}$

$M_N = 2 \cdot M_{mot} = 2 \cdot 0.05\,\mathrm{Nm} = 0.1\,\mathrm{Nm}$

$v_{max} = 10\,km/h$ $m_v = 5\,kg$ $m_L = 60\,kg$ $D = 150\,mm$ $i = 2$ 2 Motors

1) $M_{Load,\,mot}$?

$$M_{Load} = F_L \cdot \frac{D}{2} = c_R \cdot (m_v + m_L) \cdot g \cdot \frac{D}{2} = 0.02 \cdot 65kg \cdot 9.8\,m/s^2 \cdot \frac{0.15m}{2} = 0.955\,Nm$$

$$\rightarrow \text{For each motor: } \frac{M_{Load}}{\#mot \cdot i} = \frac{0.955\,Nm}{2 \cdot 10} = 0.0478\,Nm \approx \underline{\underline{50\,mNm}}$$

$$i = 10 = \frac{n_{mot}}{n_{wheel}} = \frac{M_{wheel}}{M_{mot}}$$

2) $v = 0 \rightarrow 10\,km/h$ $\quad \underbrace{2 M_{mot}}_{\text{constant torque from motor and load} \neq f(n)} = 4 \cdot M_{Load}' = 4 \cdot \frac{M_{Load}}{i} \rightarrow \Delta t$?

$v = 10\,km/h \rightarrow 0$

$$M_{acc} = M_{mot} - M_{Load}' = J \cdot \frac{d\Omega_m}{dt} = J \cdot \frac{2\pi \cdot \Delta n}{\Delta t} \quad \Bigg| \quad F_{mot} - F_L = (m_L + m_v) \cdot \frac{\Delta v}{\Delta t}$$

Acceleration: $M_{acc} = M_{mot} - M_{Load}' = 4 M_{Load}' - M_{Load}' = 3 \cdot M_{Load}'$

$$v_{max} = 2\pi \frac{n_{mot}}{i} \cdot D/2 \rightarrow n_{mot} = \frac{2 \cdot i}{D} \cdot \frac{v_{max}}{2\pi} = \frac{10}{0.15m} \cdot \frac{10/3.6\,m/s}{\pi} = 58.95\,Hz$$

$\downarrow$

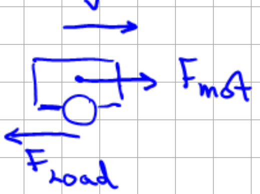
$\underline{\underline{3537\,min^{-1}}}$

$$\Delta t = \frac{J \cdot \Delta n \cdot 2\pi}{M_{acc}} = \frac{1}{i^2}(m_L + m_v) \cdot \left(\frac{D}{2}\right)^2 \cdot \frac{\Delta n \cdot 2\pi}{M_{acc}}$$

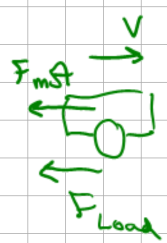
$$\Delta t = \frac{1}{10^2} \cdot (60kg + 5kg) \cdot \left(\frac{0.15m}{2}\right)^2 \cdot \frac{-58.95\,Hz \cdot 2\pi}{\underset{-5}{3} \cdot \underbrace{0.0955\,Nm}_{M_{Load}' = \frac{M_{Load}}{i}}} = \begin{matrix} 2.83\,s \\ \underline{\underline{4.73\,s}} \end{matrix}$$

Braking: $M_{Braking} = -M_{mot} - M_{Load}' = -4 M_{Load}' - M_{Load}' = -5 \cdot M_{Load}'$

Acceleration:



Braking



DC-Motor

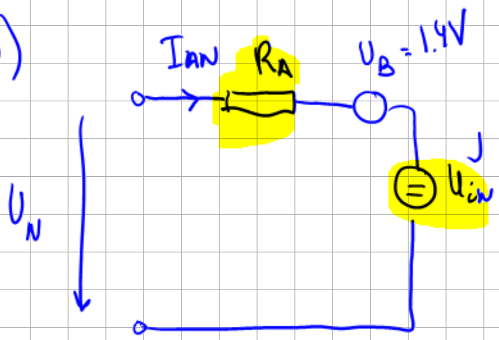
$U_N = 24V$, $I_{AN} = 2.3A$ $\quad M_N = 0.1\,Nm$ $\quad n_N = 3600\,min^{-1}$, $I_{A0} = 0.28A$ $\quad U_B = 2 \cdot 0.7V$

4) η_N?

$$\eta_N = \frac{P_{out}}{P_{in}} = \frac{M_N \cdot 2\pi n_N}{U_N \cdot I_{AN}} = \frac{0.1Nm \cdot 2\pi \cdot \frac{3600}{60} s^{-1}}{24V \cdot 2.3A} = \begin{matrix} 0.683 \\ 68.3\% \end{matrix}$$

~~0.683%~~

5)



$$U_{iN} = \frac{P_{i,mech}}{I_{AN}} = \frac{(M_N + M_{Fric}) \cdot 2\pi n_N}{I_{AN}}$$

$$M_i \sim I_A \rightarrow M_i = c\Phi_F \cdot I_A$$

constant! (PM)

No-load → I_{A0}, $M = 0Nm$

$$\frac{I_{A0}}{I_{AN}} = \frac{M_{Fric}}{M_N + M_{Fric}} \rightarrow I_{A0}(M_N + M_{Fric}) = I_{AN} \cdot M_{Fric}$$

$$I_{A0} \cdot M_N = (I_{AN} - I_{A0}) \cdot M_{Fric}$$

$$\rightarrow M_{Fric} = \frac{I_{A0}}{(I_{AN} - I_{A0})} \cdot M_N = 0.1Nm \cdot \frac{0.28A}{2.02A}$$

$$M_{Fric} = 0.014\,Nm$$

$$U_{iN} = \frac{0.114\,Nm \cdot 2\pi \cdot \frac{3600}{60} s^{-1}}{2.3A} = 18.686V$$

$$R_A = \frac{U_N - U_{iN} - U_B}{I_{AN}} = \frac{24V - 18.686V - 1.4V}{2.3A} = 1.702\Omega$$

6) $n = \frac{n_N}{2}$ $\quad U_A, I_A$?

$$M = \frac{M_N}{4}$$

$$U_i = \frac{U_{iN}}{2} \qquad (U_i = c\Phi_F \cdot 2\pi n)$$

$$(M_i = c\Phi_F \cdot I_A)$$

$$M_i = \frac{1}{4} M_N + M_{Fric} = \frac{0.1Nm}{4} + 0.014\,Nm = 0.039\,Nm$$

$$I_A = I_{AN} \cdot \frac{M_i}{M_{iN}} = 2.3A \cdot \frac{0.039\,Nm}{0.114\,Nm} = 0.787\,A$$

$$U_A = U_i + R_A \cdot I_A + U_B = 9.434V + 1.702\Omega \cdot 0.787A + 1.4V = \underline{\underline{12.173V}}$$

Motor choice

In the catalogue of a motor manufacturer [1], which specialises in automation and robotics applications, a DC motor and a synchronous motor (both with permanent magnet excitation) are available for the calculated rated torque and speed.

DC Motor with permanent magnet excitation

The following data are known from the data sheet of the permanent magnet excited DC motor:

- rated voltage $U_N = 24\,\mathrm{V}$
- rated armature current $I_{AN} = 2.3\,\mathrm{A}$
- rated torque $M_N = 0.1\,\mathrm{Nm}$
- rated speed $n_N = 3600\,\mathrm{min}^{-1}$
- no-load current $I_{A0} = 0.28\,\mathrm{A}$

The voltage drop per brush is $0.7\,\mathrm{V}$ and saturation is neglected. The frictional torque can be assumed to be constant.

4. What is the efficiency at the rated point?
5. Calculate all values of the equivalent circuit at the rated point.
6. What armature voltage and armature current are required when the motor is operated at half the rated speed and a quarter of the rated torque (vehicle with $5\,\mathrm{km/h}$ and $11\,\mathrm{kg}$ load)?

Synchronous motor with permanent magnet excitation

The following data are known from the data sheet of the permanent magnet excited synchronous motor:

- rated voltage $U_N = \frac{24}{\sqrt{2}}\mathrm{V}$ → $U_{SN} = \frac{U_N}{\sqrt{3}} = \frac{24V}{\sqrt{2}\cdot\sqrt{3}} = \frac{24V}{\sqrt{6}}$
- rated stator current $I_{SN} = 2.1\,\mathrm{A}$
- rated torque $M_N = 0.106\,\mathrm{Nm}$
- rated speed $n_N = 3610\,\mathrm{min}^{-1}$
- efficiency at rated point $\eta_N = 80\,\%$ ⇒ No friction

Only losses in the stator winding and operation with only q-current (stator current in phase with the induced voltage) are assumed.

7. Calculate all values of the equivalent circuit at the nominal point and draw the phasor diagram qualitatively.

- Trapezoidal voltages and currents
$U_{LL} = \frac{U_S}{2}$
- Sinusoidal voltages
$U_S = \frac{\hat{U}_S}{\sqrt{2}}$
$U_{LL} = \frac{\hat{U}_{LL}}{\sqrt{2}}$
$U_S = \frac{U_{LL}}{\sqrt{3}}$

Nominal voltage U_N is always line-to-line.

[1] Here, for practical reasons, slightly modified data from the catalogue of Dunkermotoren taken as a basis. Other alternatives: Wittenstein, Nidec, Maxon, Faulhaber, ...

8. What stator voltage and stator current are required if the motor is operated at half the rated speed and a quarter of the rated torque (vehicle with $5\,\mathrm{km/h}$ and $11\,\mathrm{kg}$ load)?

9. And if the motor could be operated at $2 \cdot n_N$ (or the vehicle at $20\,\mathrm{km/h}$) with the same load? In this case, the stator resistance can be neglected.

Power electronics

The power electronic motor control is fed from a DC voltage source:

10. What circuit is required for 4-quadrant operation of the DC motor? Draw the circuit with the most important components.

11. And for the synchronous motor?

12. What duty cycle (D) does the DC motor require for the operation from point 6, if the battery voltage is $U_{Bat} = 24\,\mathrm{V}$?

From 6 $\rightarrow$ $U_2 = \cancel{12.568V}$ $12.173V$

$U_1 = 24V$

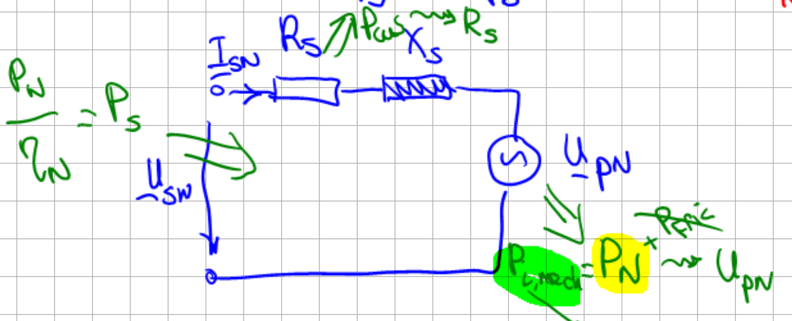
$$U_2 = (2D-1) \cdot U_1$$

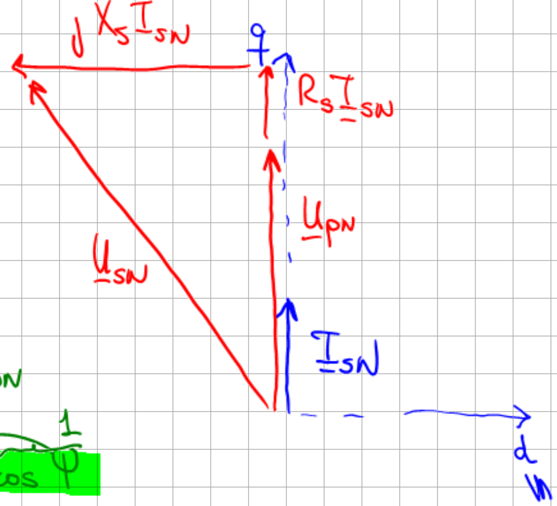
$$D = \left(\frac{U_2}{U_1} + 1\right) \cdot 0.5 = \left(\frac{\cancel{12.568V}\ 12.173V}{24V} + 1\right) \cdot 0.5 = \cancel{0.762}\ 0.754$$

SM

$U_N = \frac{24}{\sqrt{2}}V \qquad I_{SN} = 2.1A, \quad M_N = 0.106\,Nm, \quad n_N = 3610\,min^{-1}, \quad \eta_N = 80\%$

7 $\quad U_{SN} = \frac{U_N}{\sqrt{3}} = \frac{24V}{\sqrt{6}}$





direction of the rotor flux Φ_F

$$P_N = M_N \cdot 2\pi n_N = 3 \cdot U_{pN} \cdot I_{SN} \cdot \underbrace{\cos\varphi}_{1}$$

$$U_{pN} = \frac{M_N \cdot 2\pi n_N}{3 \cdot I_{SN}} = \frac{2\pi \cdot 0.106Nm \cdot 3610/60\,s^{-1}}{3 \cdot 2.1A} = 6.361V$$

$$\eta_N = \frac{P_{out}}{P_{in}} = \frac{P_N}{P_S} \rightarrow P_S = \frac{P_N}{\eta_N}$$

$$3R_SI_{SN}^2 = P_S - P_N = P_N\left(\frac{1}{\eta_N} - 1\right)$$

$$R_S = \frac{P_N}{3I_{SN}^2} \cdot \left(\frac{1}{\eta_N} - 1\right) = \frac{2\pi \cdot 0.106Nm \cdot 3610/60\,s^{-1}}{3 \cdot (2.1A)^2} \cdot \left(\frac{1}{0.8} - 1\right)$$

$$R_S = 0.757\Omega$$

$$U_{SN}^2 = (U_{pN} + R_S \cdot I_{SN})^2 + (X_SI_{SN})^2$$

$$X_S = \frac{1}{I_{SN}}\sqrt{-(U_{pN} + R_SI_{SN})^2 + U_{SN}^2} = \frac{1}{2.1A}\sqrt{\underbrace{\left(\frac{24V}{\sqrt{6}}\right)}_{9.797V}^2 - (6.361V + 0.757\Omega \cdot 2.1A)^2}$$

$$X_S = 2.726\Omega$$

8) $M = \frac{1}{4} M_N$, $n = \frac{1}{2} n_N$ $\rightarrow$ U_s, I_s?

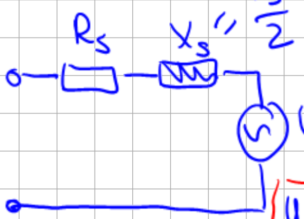
only for $n \le n_W$
In general: $M_i \sim I_{sq}$

$n < n_N \rightarrow \underline{U}_p \parallel \underline{I}_s \rightarrow \boxed{k_{M,PSM} = \frac{M_i}{I_s} = \text{constant}} \rightarrow I_s = \frac{1}{4} I_{sN}$

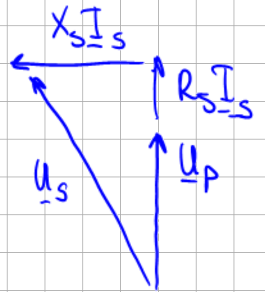
$(M \sim I_s \rightarrow I_s = \frac{1}{4} I_{sN})$

$\parallel$

$I_s = 0.525\,A$



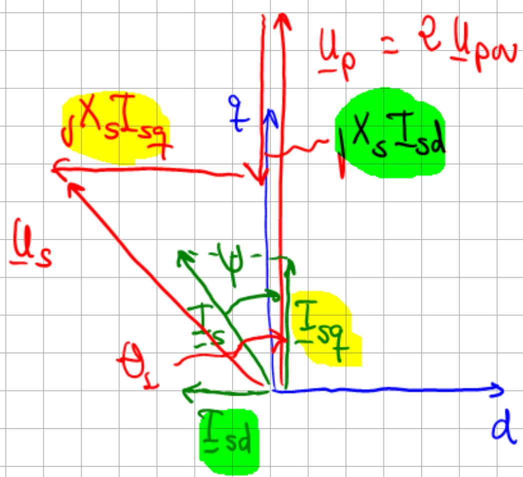
$\boxed{\begin{array}{l} U_p \sim n \\ X_s \sim f_s \sim n \end{array}}$ for $n < n_N$ and $n \geq n_N$ Always!



$$U_s = \sqrt{(U_p + R_s I_s)^2 + (X_s I_s)^2} = \sqrt{(3.181V + 0.757\Omega \cdot 0.525A)^2 + (1.363\Omega \cdot 0.525A)^2} = 3.649V$$

9) $M = \frac{1}{4} M_N$, $\underbrace{n = 2 \cdot n_N}$, U_s, I_s? $R_s \to 0$

Field-weakening $\Rightarrow$ $U_s = U_{sN} = \frac{24V}{\sqrt{6}} = 9.797V$



$P_{mech} = P_{U_p}$

$= 3 \cdot U_p \cdot \underbrace{I_s \cdot \cos\psi}_{I_{sq}}$

$M \sim I_{sq} \rightarrow I_{sq} = \frac{1}{4} I_{sN} = \frac{1}{4} \cdot 2.1A = 0.525A$

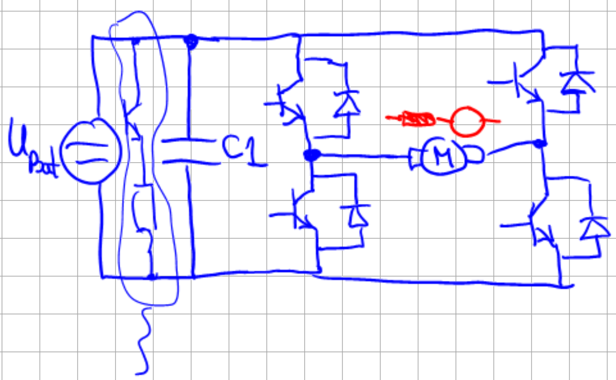
$$\underset{U_{sN}}{U_s^2} = (\underset{2U_{pN}}{U_p} - \underset{2X_s}{X_s}\cdot \underbrace{I_{sd}}_{?})^2 + (\underset{2X_s}{X_s}\underbrace{I_{sq}}_{I_{sN}/4})^2$$

$$I_{sd} = \frac{1}{X_s}\left(U_p - \sqrt{U_s^2 - (X_s I_{sq})^2}\right) = \frac{1}{5.452\Omega}\cdot\left(12.722V - \sqrt{(9.797V)^2 - (5.452\Omega \cdot 0.525A)^2}\right)$$

$$I_{sd} = 0.615\,A$$

$$I_s = \sqrt{I_{sd}^2 + I_{sq}^2} = \sqrt{(0.615A)^2 + (0.525A)^2} = 0.809\,A$$

10) Circuit 4-quadrant DC-controller → Full bridge



Only needed, if the battery cannot be charged. Not always necessary!

11) SM? Half-Bridge per phase + modulation for sinusoidal voltages and currents