AED Mini Project **Summer Semester 2021**

Operating Trajectories for the Control of Permanent Magnet Synchronous Machines
Σ 6 Points

Imagine you are working as a controls engineer in a car company and your boss tells you to program an algorithm which calculates reference currents for the controller that allow a safe and efficient operation of the traction drive.
Due to the complexity of the problem, these reference currents are usually calculated offline and stored in lookup tables (LUTs). Such operating tractories might follow the maximum torque per ampere (MTPA) trajectory in base speed operation or the maximum torque per flux (MTPF) in field weakening operation. Within this mini project the principles to calculate the current trajectories for a specific torque and varied speed taught in the lecture shall be used. For this purpose an algorithm in form of a MATLAB script shall be implemented which generates the reference current LUTs for a generic permanent magnet synchronous machine. The documentation and the answers to the following tasks shall be submitted in a two-page report.

1.1

a) Why is an operation along the MTPA trajectory in base speed operation beneficial? Why is an operation along the MTPF in field weakening desirable? Explain briefly in your own words.

b) Implement a script in MATLAB which generates the reference currents $i_{\mathrm{sd}}(T_{\mathrm{e}},\omega_{\mathrm{s}}), i_{\mathrm{sq}}(T_{\mathrm{e}},\omega_{\mathrm{s}})$ for a specific operating point $T_{\mathrm{e}},\omega_{\mathrm{s}}$ according to the principles taught in the lecture to operate a generic permanent magnet synchronous machine safe and efficient in base speed operation, basic field weakening and field weakening. Please use the following machine and system parameters as well as the respective naming conventions in your script. *Hint: Avoid redundant code and use functions instead.*

c) Describe in a few sentences your implementation, the major challenges and how you solved them.

 continued on the next page

Physical quantity	Naming in Lecture	Naming in Code
Field flux linkage	ψ_f	`Psi_f`
Stator inductance in d-axis	L_sd	`L_sd`
Stator inductance in q-axis	L_sq	`L_sq`
Maximum stator current (amplitude)	$i_\mathrm{s}^\mathrm{max}$	`i_smax`
Dc-link voltage	U_dc	`U_dc`
Maximum stator voltage	$u_\mathrm{s}^\mathrm{max}$	`u_smax`
Pole pairs	p	`p`
Stator current in d-axis (normalized on $i_\mathrm{s}^\mathrm{max}$)	i_sd (i_sd^n)	`i_sd (i_sdn)`
Stator current in q-axis (normalized on $i_\mathrm{s}^\mathrm{max}$)	i_sq (i_sd^n)	`i_sq (i_sqn)`
Short circuit current	i_s^sc	`i_sc`
Short circuit current normalized on $i_\mathrm{s}^\mathrm{max}$	$\kappa = \frac{i_\mathrm{s}^\mathrm{sc}}{i_\mathrm{s}^\mathrm{max}}$	`kappa`
Electrical torque	T_e	`T_e`
Mechanical torque	T_m	`T_m`
Electrical angular velocity	ω_s	`omega_s`
Speed in rpm	n	`n`
Saliency	$\chi = \frac{L_\mathrm{sq}-L_\mathrm{sd}}{2L_\mathrm{sd}}$	`chi`

Now your code shall be tested for a specific salient permanent magnet synchronous machine. The machine parameters and the system limits are given in the table below:

Field flux linkage	ψ_f	$= 90\,\mathrm{mVs}$
Inductance in d-axis	L_sd	$= 200\,\mu\mathrm{H}$
Inductance in q-axis	L_sq	$= 500\,\mu\mathrm{H}$
Maximum stator current (amplitude)	$i_\mathrm{s}^\mathrm{max}$	$= 500\,\mathrm{A}$
Dc-link voltage	U_dc	$= 350\,\mathrm{V}$
Maximum stator voltage	$u_\mathrm{s}^\mathrm{max}$	$= \frac{U_\mathrm{dc}}{\sqrt{3}}$
Pole pairs	p	$= 4$

1.2

a) Plot the current trajectory $i_\mathrm{sq}(i_\mathrm{sd})$ for a reference torque of $T_\mathrm{e}^* = 70\,\mathrm{Nm}$ for a speed range of $n = 0\,\mathrm{rpm} - 50\,000\,\mathrm{rpm}$ as well as the MTPA, MTPF, the maximum ampere (MA) circle and the short circuit current. Plot and label the diagram and use the scaling like in Figure 1.1.
Hints: Choose a resonable resolution for speed and torque to get accurate results. Write a separate plot script. Use e.g. the command `axis equal` to scale the axis of i_sd and i_sq.

b) Plot the torque over speed map $T_\mathrm{m}(n)$ for $n = 0\,\mathrm{rpm} - 50\,000\,\mathrm{rpm}$.

c) Until which speed (in rpm) is base speed operation along the MTPA for a reference torque of $T_\mathrm{e}^* = 70\,\mathrm{Nm}$ possible?

continued on the next page

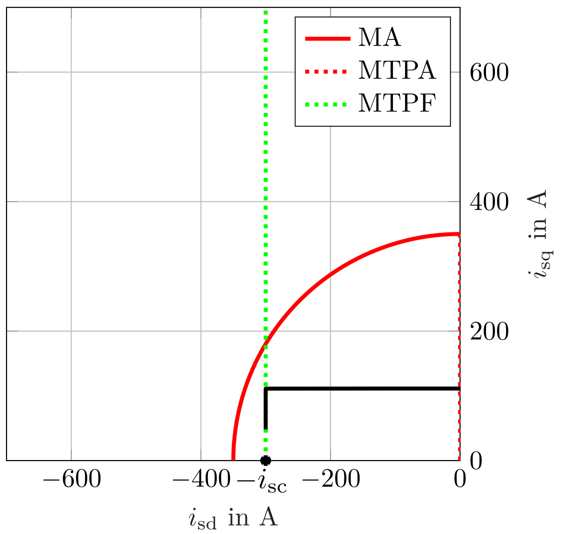

Figure 1.1: Current locus diagram for an exemplary nonsalient synchronous machine ($\psi_{\mathrm{f}} = 60\,\mathrm{mVs}$, $L_{\mathrm{sd}} = L_{\mathrm{sq}} = 200\,\mu\mathrm{H}$, $p = 4$, $i_{\mathrm{s}}^{\max} = 350\,\mathrm{A}$, $u_{\mathrm{s}}^{\max} = \frac{350}{\sqrt{3}}\mathrm{V}$) and a reference torque of $T_{\mathrm{e}}^{*} = 10\,\mathrm{Nm}$.

d) Until which speed (in rpm) can a torque of $T_{\mathrm{e}}^{*} = 70\,\mathrm{Nm}$ be delivered?

The previous inverter has been actively cooled with water. A cheaper version of this inverter is passively cooled and therefore limited to a maximum current of $i_{\mathrm{s}}^{\max} = 400\,\mathrm{A}$. Your company wants to benchmark both inverters by comparing the deliverable torque of the machine.

1.3

a) Is an operation at short circuit current safe? Explain briefly.

b) Plot the current trajectory $i_{\mathrm{sq}}(i_{\mathrm{sd}})$ for a reference torque of $T_{\mathrm{e}}^{*} = 70\,\mathrm{Nm}$ and a speed range of $n = 0\,\mathrm{rpm} - 50\,000\,\mathrm{rpm}$ as well as the MTPA, MTPF, the MA circle and the short circuit current.

c) Plot the torque speed characteristic $T_{\mathrm{m}}(n)$ for $T_{\mathrm{e}}^{*} = 70\,\mathrm{Nm}$ in the same figure as in the previous exercise. Compare both torque characteristics and discuss the deliverable torque in field weakening operation.

continued on the next page

Submission and Credit:

- We request you to submit the code in the following form:
  - The code is executable.
  - The code is self-explanatory (well commented).
  - The naming convention is followed.
  - The submitted code consists of ONE Matlab (.m) file containing all dependent, self-written functions.
  - The Matlab (.m) file is named after your group name in a format like `Code_Fixed_Group_4.m`
  - The code (and comments) contain NO personal data like your names or matriculation number.
- Every group has to submit ONE zip-file including
  - ONE Matlab script in the above requested format.
  - A two-page report including signatures of all members and an explanation how each member contributed to the project. You can write your report e.g. in Word (font size 11). For the submission, please convert the document into a PDF.
- The zip-file should be named after your group name (e.g. `Fixed_Group_4`)
- The zip-file shall be uploaded in Moodle once within your group.
- If your group mate jumps off during the working period, please inform us before you upload anything.
- The submission of the code files is mandatory to get bonus points. If they are missing, NO points will be credited.
- We will check your code for plagiarism and reserve the right to ask additional questions about the project work to the respective group(s) in case plagiarism is suspected.
- Up to 6 points (approx. 10% of the total exam points) will be added to your exam points according to the quality of the project work. Bonus points are only credited if you take the AED Exam in SS 2023 or WS 2023/24 and passed the exam.
- Deadline: June 28th 2023