The PMSM

Laboration 5 (Home version)

Updated April 30, 2020

This is a special home edition of the PMSM laboration, for remote education of the power electronics course. Finishing and passing the tasks of this document replaces the PMSM lab (but not the PMSM home assignment, you still have to finish that as usual).

Home version of the PMSM lab

The idea is that we go through the same tasks as in the ordinary lab - but at home, sometimes as pure theoretical questions, sometimes with the help of Simulink, and sometimes with the help of videos of the lab equipment.

The videos are filmed with my PhD student colleague (and course participant), with an narration voice added afterwards. You may have to pause, rewind or alternate the playback speed to perceive what you need, but for the most part, the important bits are either clearly shown or clarified with extra annotation in the corner. Sometimes the sound from the lab video is muted to take away chatter or other noises that would drown the narration, so if you listen to the sounds from the machine or switching, be careful not to confuse these mutes with silence from the equipment.

Just like with the home assignments, getting all the parts correct at the first attempt will be hard. You will receive more material for support later. But I want you to make an attempt to complete it on your own first, so that you don't just mechanically fill in the answers from the solution sheet and learn nothing.

This situation is new to all of us, but I hope we can find a way to learn as much as possible from this - both when it comes to power electronics (and electrical machines) but also when it comes to learning in general, and get better at teaching and studying with this new experience.

This exercise contains the following parts.

1. Introduction to the equipment, with some theoretical questions about the machine and control system.
2. The sampled current controller.
3. The direct current controller.
4. Running the machine at high speeds.
5. Investigating field weakening.
6. Using the speed controller.
7. Running the machine under load.

1 Introduction

A short introduction or reminder of the lab stations can be seen in this video:
`https://youtu.be/jo7tAL215CY`

Figure 1.1: QR-code for lab station introduction.

In the ordinary lab modulation, current control, field weakening and speed control for a PMSM machine electric drive system will be studied. The control system for the lab is implemented with a graphical programming language called LabView and is executed in a CompactRIO which controls the power electronics and sample the feedback signals. The controller settings which decides in what way the CompactRIO should act is made on an interface implemented on a PC.

The equipment

The data of the PMSM necessary for the torque control is presented below in table 1.1. This data is used to design the PIE current controller.

Table 1.1: The PMSM control design data

Measure	**Value**
Nominal flux linkage of the PMSM	$\Psi_{pm} = 0.16\,\mathrm{V\,s}$
Stator inductance of the PMSM	$L_{sx} = L_{sy} = 3\,\mathrm{mH}$
Stator resistance of the PMSM	$R_s = 0.5\,\Omega$
The nominal current of the PMSM	$I_n = 12\,\mathrm{A}$
The nominal voltage of the PMSM	$U_{Ln} = 400\,\mathrm{volt}$
Sample time	$T_s = 4 \times 10^{-4}\,\mathrm{s}$

The motor bench

All motor control labs will be made with the same motor setup. It consists of two or three motors, an externally magnetized DC Machine, a Permanent Magnetized Synchronous Machine and on some stations also an asynchronous machine. They are all mechanically coupled to the same shaft and a positive torque is always accelerating the shaft in the same direction, independent of which motor the reference is fed to.

The idea of the setup is to drive the common shaft with one of the machines and brake it with another. In this lab you will drive with the PMSM and later brake with the DC Machine by applying an external resistive load to its terminals. This means that the no load voltage of the DC Machine, that is proportional to speed, will be applied to the external resistor and the braking power thus proportional to speed squared and inversely proportional to resistance.

There is a resolver mounted on the shaft which provides the cRIO with feedback signals for instance for the vector control of the PMSM or for speed control for instance.

The control system

The CompactRIO, *cRIO*, consists basically of three parts; a Field Programmable Gate Array, *FPGA*, a Real Time system, *RT*, and the Inputs and Outputs, *I/O*.

The FPGA is a programmable electrical circuit. This means that the program that has been written to it actually is built in hardware with logical gates. From the programs point of view this means that every part of it is executed simultaneously.

The FPGA is connected to both the RT system and the I/O-modules. It therefore acts as the bridge between the I/O- modules and the RT system. It can also make some or all of the signal processing, which will be utilized in this setup. Since the space on the FPGA is limited it is important to choose what to implement on it. The characteristics of things that should be implemented on the FPGA is that they need to execute fast, often and/or in parallel.

The real time system consists of an industry PC and a Real Time operating system. Programs on the RT system make things that do not have high demands on speed or tasks that are typical for a computer like read and write to files, talk over ethernet, display information and so on.

The cRIO is flexible unit where you can insert different I/O-modules, the cRIO used in the labs can take up to eight different modules. For example an eight channel TTL I/O is used to control the power electronics and a fast, simultaneously sampling four channel AD module is used to sample time critical signals, such as the current and the resolver signals.

Normally the I/O modules is intended to work with small signals, ie small voltages and currents. Since the power electronics is working with larger signals it is necessary to have some signal conditioning between them. This is done by a unit placed between the cRIO and the power electronics. The same unit also excites and interprets the resolver and provides some useful measuring points.

Safety

~~Remember that the lab equipment involves voltage levels that are dangerous, especially at the different terminals of the power electronic converter.~~ ~~**Be careful!**~~

~~The DC link voltage should always be the last thing to turn up during start up and always the first thing to turn down during turn off.~~

1.1 Introduction exercise: Induced Voltage

If we set the DC machine to turn at a set speed and measure the induced voltage between two phases of the synchronous machine, the oscilloscope could show something like Figure 1.1. Answer the following questions in your report.

Note the power invariant transformation, $u_q = \sqrt{\frac{3}{2}} \cdot \hat{u}_{ph}$ and the pole number (6) of the PMSM. Also note (here, and for the rest of the lab exercise) that the specs can vary between the individual machines of the different stations, and is not necessarily exactly the same as in the data of Table 1.1.

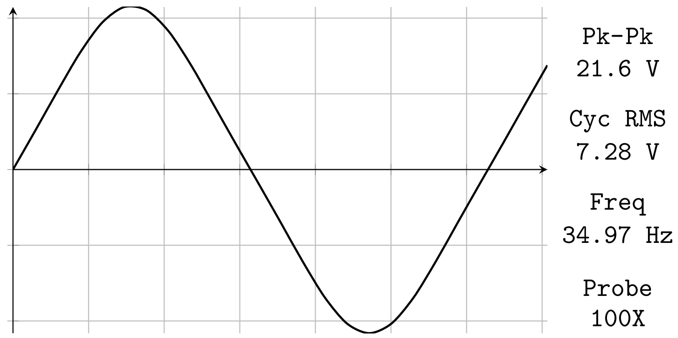

Figure 1.2: Induced voltage of the synchronous machine. The differential probe attenuation is set to 500X.

a) What is the mechanical speed [rpm]?

b) What is the magnetic flux [Vs], Ψ, of the synchronous machine?

c) What is the necessary minimum DC-link voltage needed to deliver a torque of 1.0 Nm at 100 rad/s, without over-modulation and with no field weakening used?

1.2 Introduction exercise: Modulation Types and Output of the Three-Phase Converter

Three different types of modulations can be used in the control system. The first one is using pure sine waves as the **phase potential reference waveform** (u_a^*, u_b^*, u_c^*). Answer the following questions about the other two waveforms in your report.

If you need to, use the previously provided Simulink models to simulate and find clues to the following questions.

a) What is the main advantage with *symmetric modulation* and how do the phase potential reference waveforms contribute to that?

b) What is the main advantage with *minswitch modulation* and how do the phase potential reference waveforms contribute to that?

2 The sampled current Controller

A short video of the sampled current controller in action can be seen in this video:
`https://youtu.be/x_no5FryEsE`

Figure 2.1: QR-code for sampled current controller video.

In the video you can see how the sampled current controller reacts to a q-axis square wave reference current with some different PI-parameters. **But what does that current reference signal look like in the α/β- and in the d/q-frames and how does it move in those frames during one period?** Explain and illustrate this in both the vector frames (α vs β and d vs q) and in the time frame (α&β vs time and d&q vs time) in your report. Assume that the rotor position $\theta = 0$ when the d and α axes are aligned.

3 The direct current controller

A short video of the direct current controller can be seen in this video:
`https://youtu.be/M6WhkywFtBY`

Figure 3.1: QR-code for direct current controller video.

In the video you can see how the current looks with the direct current controller and how it is affected by the tolerance band(s). In the time-frame, the current ripples within a band size determined with the hysteresis. **But what does the tolerance band(s) look like in the α/β- and in the d/q-frame?** Explain or illustrate this in your report.

4 High speeds

A short video of the DC link voltage speed limitation can be seen in this video:
`https://youtu.be/dfmJPD6Vz30`

Figure 4.1: QR-code for high speeds video.

a) In the video you can see how the current is affected when the machine hits the maximum speed limited by the back-emf. **What does the actual current look like in the α/β- and in the d/q-frame and how does it change in those frames during one period?** Explain or illustrate this in your report.

b) You can also see in the video that $d\omega/dt$ varies while the speed changes from $-\max(\omega)$ to $+\max(\omega)$. **Why is that?**

5 Field weakening

A short video of field weakening in action can be seen in this video:
`https://youtu.be/XZ1n4n9kA4c`

Figure 5.1: QR-code for field weakening video.

a) What speeds did you expect the machine to reach at $i_d = 0$ and $i_d = -5$ A respectively?

b) In the video, you can see that the machine will not reach the expected maximum speed at $i_d = 0$ A. This is because the control system limits the amplitude of the phase potential references with a certain factor. **What factor?** (Meaning, what is the maximum voltage allowed compared to the maximum voltage that can be reached without this limitation?) (Note: Use the flux you derived in task 1.1.)

c) Why do you think the control system limits the phase potential reference amplitudes?

d) Within the range of tested d-axis currents, the maximum speed is increased by ~ 15 % at $i_d = -5$ A. Does that correlate with the expected increase of speed at this level of field weakening (with the previous mentioned factor taken into account)? If not, the inductance of the machine used may vary from the data in Table 1.1. What do you think the actual inductance of the machine used is instead?

e) Other machines, with a different DC link voltage, current range, rotor flux or inductance, can use field weakening to extend the speed range by several hundred percents. But even with a current that the VSC, cables and machine windings can handle, extending the speed range this much can pose a great risk for the inverter. **Why?**

6 Speed control

A short video of the speed controller in action can be seen in this video:
`https://youtu.be/eXCmUhJN95E`

Figure 6.1: QR-code for speed control video.

None one of the combinations of PI-parameters makes any noticeable difference on the time it takes to reach the speed reference at the step. **Why?**

7 Load resistance

A short video of the machine running with a load resistor can be seen in this video:
`https://youtu.be/Vt1N-ZPl100`

Figure 7.1: QR-code for load resistor video.

Why does the reestablishing of the integral part **not** remove the stationary error?

Follow the instructions to finish your obligations in home lab exercise and as a citizen.

- ☐ ~~Set values to zero.~~

- ☐ ~~Check with supervisor that you are done.~~
- ☐ ~~Turn off the Red/Yellow switch, then the green switch of the PMSM VSC.~~
- ☐ ~~Disconnect the load resistance.~~
- ☐ ~~Turn U_{dc} down to minimum.~~
- ☐ ~~Turn off the DC machine magnetizing current.~~
- ☐ Answer all the questions in an individual report and submit to the supervisor.
- ☐ Await feedback and/or comments.
- ☐ Adjust the report if needed.
- ☐ Avoid direct contact with other people as much as possible, especially older people.
- ☐ Wash your hands.

Good job, you're done!