

The PMSM

Laboration 5

Updated February 24, 2020

1. Before the lab, look through the manual and make sure you are familiar with all parts!
2. Bring the course book to the lab.
3. You are not allowed to do the lab if you have not submitted your home assignment for the PMSM.

1 Introduction

In this 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.

2 The equipment

The data of the PMSM necessary for the torque control is presented below in table 2.1. This data is used to design the PIE current controller.

Table 2.1: The PMSM control design data

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

2.1 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.

3 The control system

3.1 The CompactRIO

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*.

3.2 The FPGA

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.

3.3 The RT

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.

3.4 The I/O's

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.

3.5 Signal conditioning

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.

3.6 The interface

The interface is mainly a tab-based interface. The idea is to save space on the control panel and to only show necessary controls, graphs, etc. Some of the control elements are always good to keep within reach, such as the stop button or the DC-link voltage. They are placed on upper part of the panel.

There are a number of boxes where you can enter variables; these are normally saved when you press enter after entering them, even if you leave the tab. However some setting, reference generators for example, are turned off when leaving a tab.

3.7 Setup

This tab (See figure 3.1) contains several sub-tabs which are not meant to be changed during the lab. Briefly the idea is to set up the controller for different signal conditioning, motors, etc., and to do some underlying tests.

Here you set the speed controller and current controller parameters, as well as a scaling factor for DC link voltage measurement.

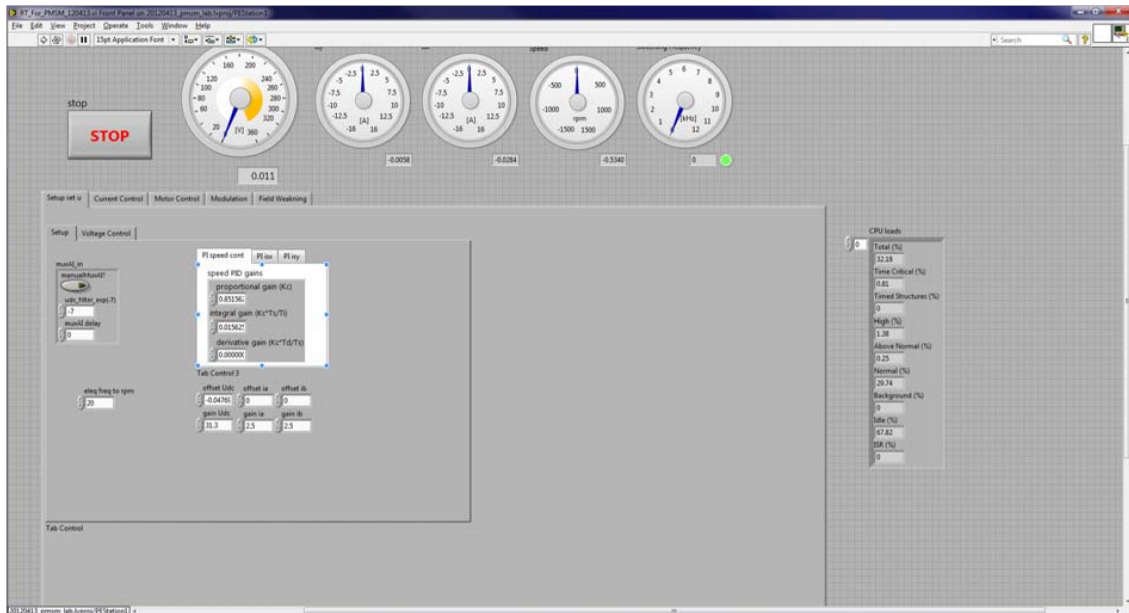


Figure 3.1: The Setup Tab – Setting general parameters (do not change there during the lab)

3.8 Voltage control

This option is not supposed to be used in the labs. It allows the user to enter a voltage reference to the modulator. It is useful during tests as you can generate a PWM signal without any feedback signals. Since the height of the carrier wave in the modulator is scaled with the DC link voltage it is possible for a disturbance to propagate in to the system this way. Hence a variable *hysteresis* band is implemented in the modulator, whose height is entered in volts in the modulator hysteresis band box, see figure 3.2. Normally the current sampling is synchronized with the turning points of the carrier wave in the modulator, but since there are delays, mainly in the power electronics, it is sometimes useful to apply a *delay* on the sampling point. This delay is entered in the sampling delay box.

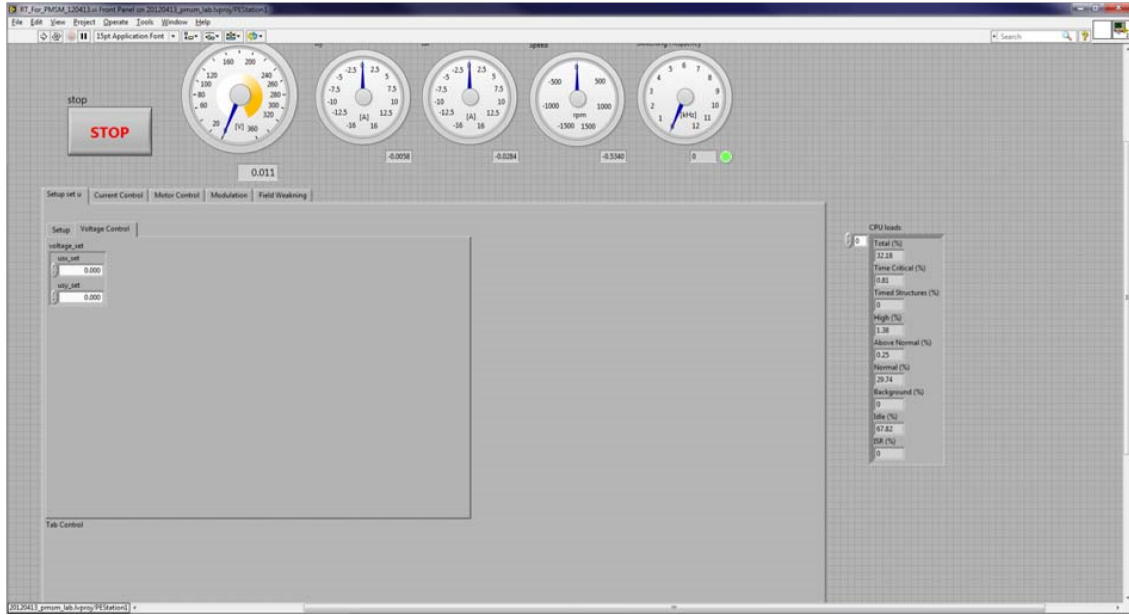


Figure 3.2: Tab to set output Voltage

3.9 Current control parameters

Here you can choose if you want to tune the PI current controller or the tolerance band current controller.

3.9.1 PI current control

The reference generator enables you to set a constant, sine or square wave reference with offset (See figure 3.3). The dead beat parameters are calculated from the entered motor data, and a 1.0 setting on the slider GAINS corresponds to those values (in the Setup tab, figure 3.1).

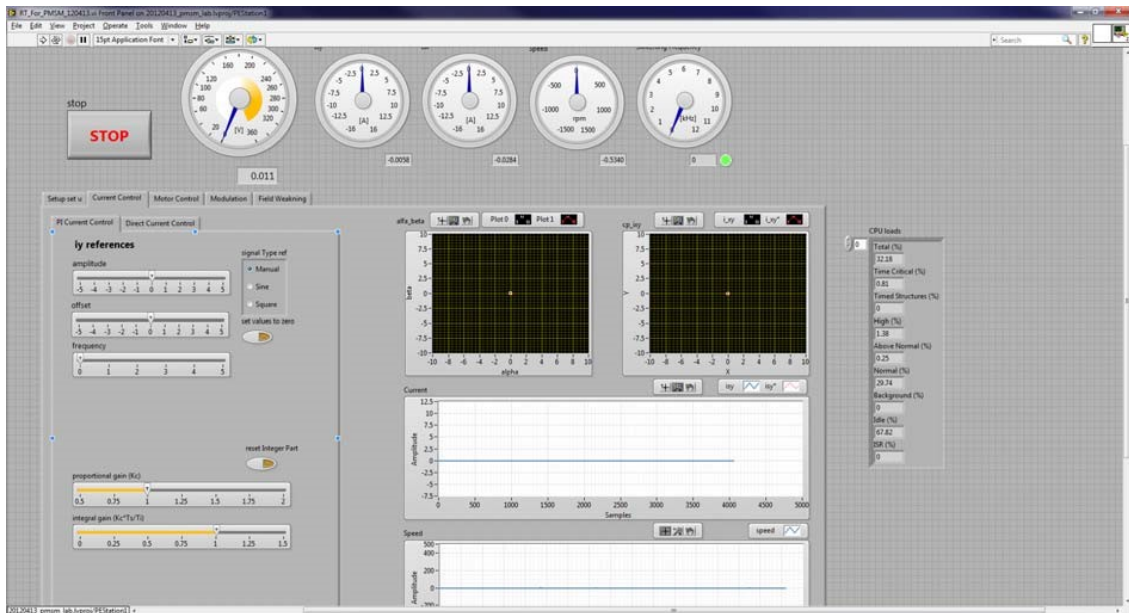


Figure 3.3: PI based current control parameters

3.9.2 Tolerance band current control

This tab (figure 3.4) is very similar to the sampled current controller tab. There are two parameters to tune, the inner and outer hysteresis bands as illustrated.

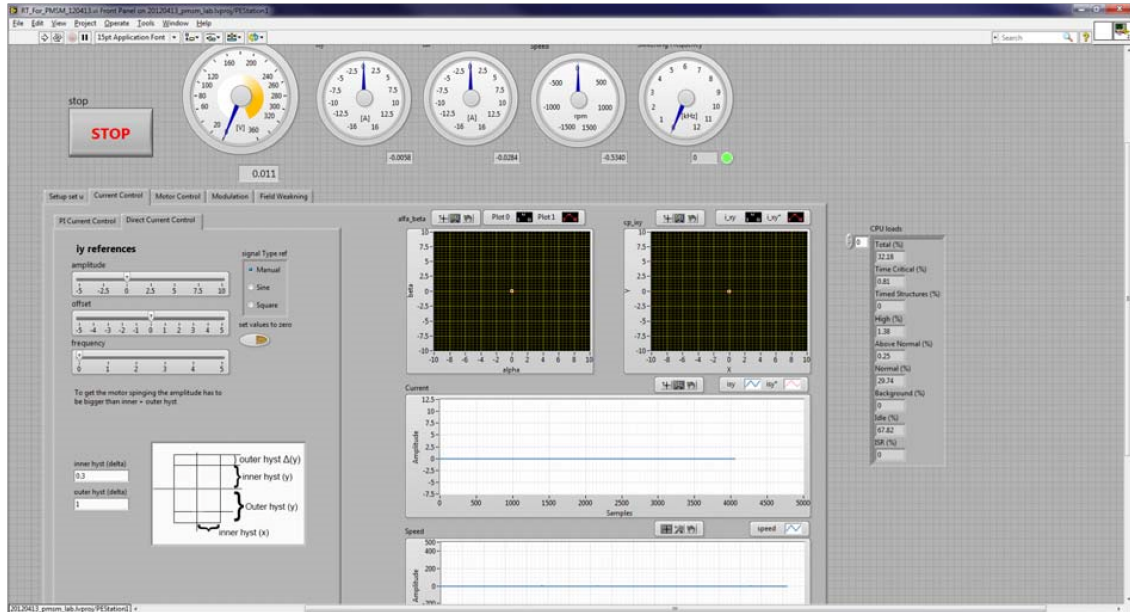


Figure 3.4: Tolerance band current control parameters

3.10 Modulation

In this tab (figure 3.5) you can try out the three different variants of modulation that are taught in the course.

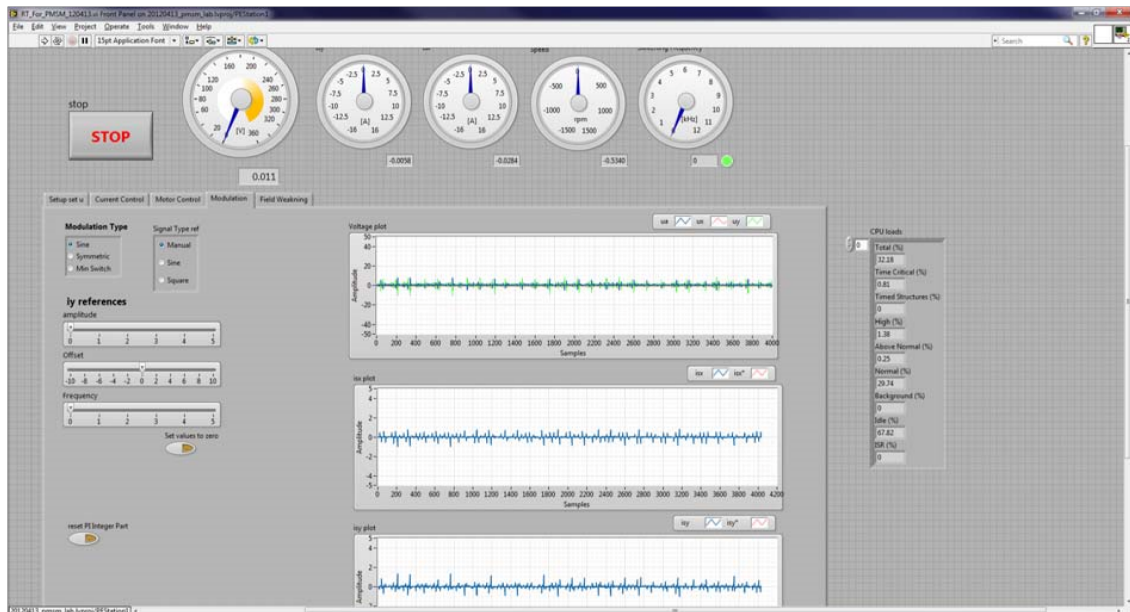


Figure 3.5: The Modulation tab

3.11 Field Weakening

In this tab (figure 3.6) you can try out the effect of introducing a negative i_{sx} current as a field weakening effort.

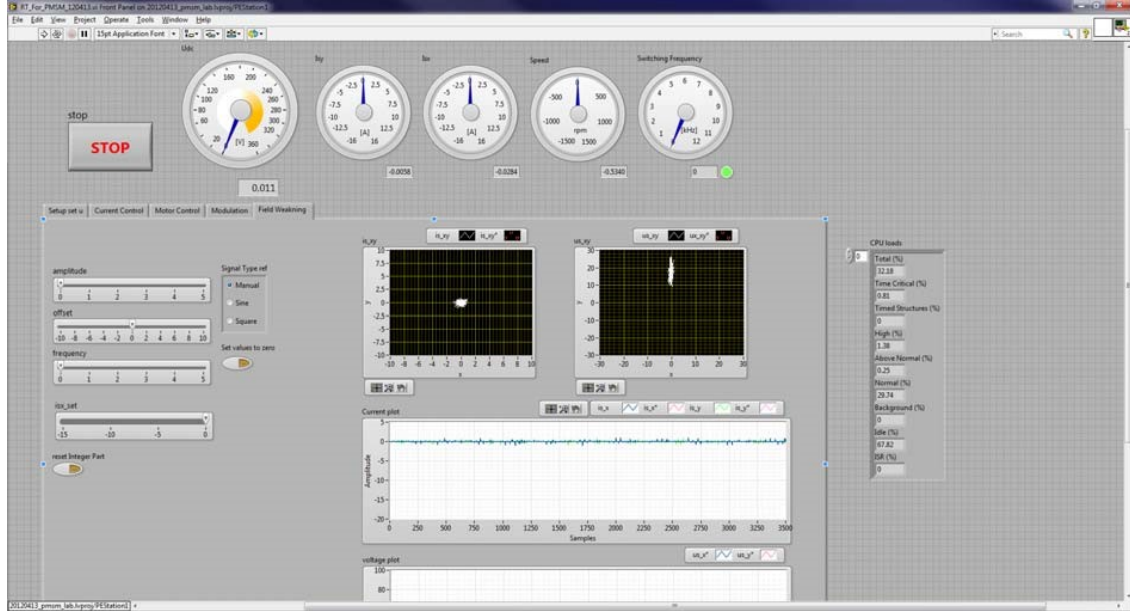


Figure 3.6: The Field Weakening tab

3.12 Motor/Speed control

To control the speed of the DC machine a PI controller is used (see figure 3.7). It uses the reference created with the generator and the feedback signal from the resolver to create a torque reference. The torque reference is converted to a i_{sy} current reference and fed to the current controller that you choose.

The PI control parameters are tuned with the sliders and the integrator could be reset with the reset button.

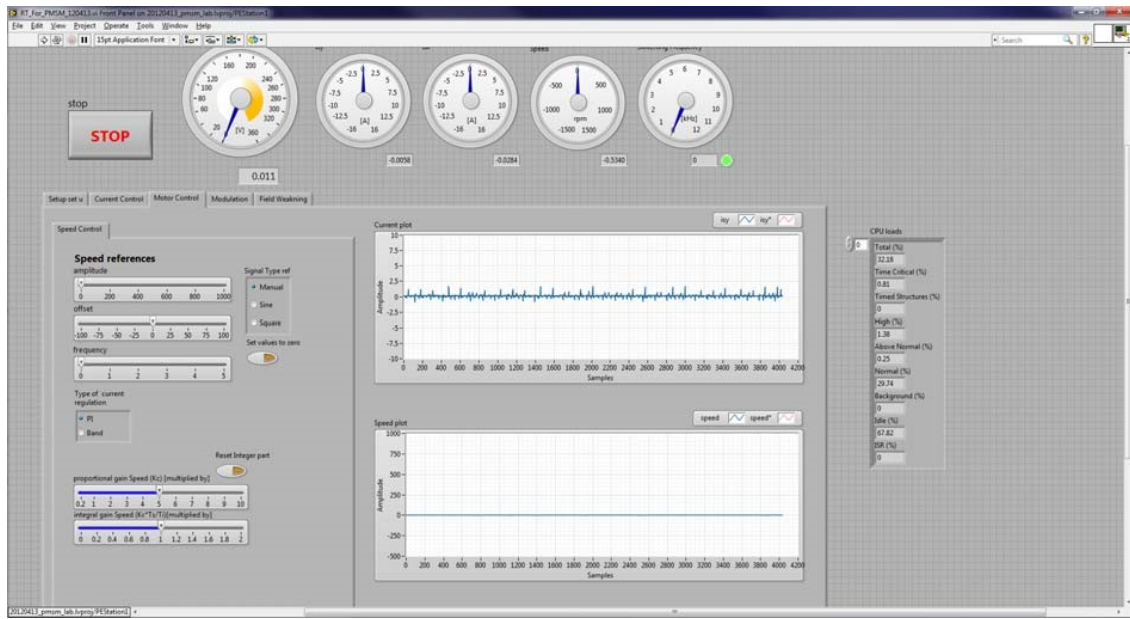


Figure 3.7: Speed Controller

3.13 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.

4 Lab assignments

4.1 Getting started

1. Start the program National Instruments LabVIEW 2010. A *Getting Started* window will open.
2. Open the file C:\Labview\pmsm lab\20130213_pmsm_lab.lvproj. The Project Explorer for the 20130213_pmsm_lab project will open.
3. To open the control interface double click on PC_For_PMSM130226.vi.
4. Click on the run button in the upper left corner of the toolbar.
5. If everything works the icon of the run button changes and the control system is executed in the cRIO system.
6. Make sure that everything else, such as the signal conditioning and the control system in the power electronics is running.

4.2 Goal

The ambition with this lab is that you shall get “hands on” experience of the following:

- Controlling the three phase current with a 3-phase bridge towards the RLE-like rotor circuit of a PMSM, both with a sampled current controller and a tolerance band controller. Study these sections of the course material before you enter the lab.
- When working with the sampled current controller be aware of how
 - I) the controller parameter settings affect the response,
 - II) how the voltage limitation affects the response and finally,
 - III) how “Anti Windup” helps in giving a stable control response with a limited output voltage.
- Evaluating Field Weakening with the AC-machine.
- Controlling Speed with the AC-machine.

4.3 The Laboratory Exercises

The content of the laboratory exercises are divided into five parts:

1. Measuring the induced voltage of the PMSM and calculating the corresponding flux linkage.
2. Studying the different 3- ϕ modulating references.
3. Adjusting the sampled vector current controller and the direct current controller for the PMSM.
4. Investigating field weakening.
5. Using Speed Control.

4.4 Induced Voltage

In this first part of the lab you will use the DC Machine to run the PMSM. This means the PMSM must be disconnected from the 3- ϕ VSC.

- ☐ Make sure the red/yellow switch on the front panel of the PMSM VSC is set to 0.

- ☐ Connect the voltmeter to the DC link voltage input on the VSC.
- ☐ Make sure the DC link voltage to minimum with the adjustable transformer on the table (The output from the basement generator will not be exactly 0).
- ☐ Connect the DC Machine Drive to the DC link using two short lab cables. The DC Machine VSC should be turned off (with both the green switch and the red/yellow switch) through the whole task. You will feed the DC Machine directly with the DC link voltage.
- ☐ Magnetize the DC Machine with the adjustable transformer on the rack.
- ☐ Measure the DC link voltage with the voltmeter and slowly increase until the machines reach a speed you think is sufficient (sw. "lagom"). A DC Link voltage between 80 V and 120 volts should be fine.
- ☐ Connect a voltage probe from the oscilloscope between the outputs of phases *a* and *b* of the PMSM VSC and measure the induced voltage over the stator windings.

Note: The indicators and numbers in the top of the Labview window are inaccurate. Therefore, always measure important values, that need to be accurate, with other instruments (like voltmeter or oscilloscope).

What does the induced voltage waveform of the PMSM look like?

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Calculate Ψ_{pm} , with the measured values from the oscilloscope. Note the power invariant transformation, $u_q = \sqrt{\frac{3}{2}} \cdot \hat{u}_{ph}$. Does your calculated value match the value shown in table 2.1?

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What is the nominal mechanical torque, based on the nominal stator current?

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What is the necessary minimum value for the DC-link voltage if the torque reference is 1.0 Nm and the rotation speed is lower than 100 rad/s, with no field weakening used? (Remember that the PMSM has 6 poles)

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- ☐ Reduce the DC link voltage to minimum.
 - ☐ Disconnect the two wires you used to connect the DC link voltage to the DC Machine.

4.5 Modulation Types and Output of the Three-Phase Converter

In this second part of the lab, the PMSM-converter **must be connected to the 3- ϕ machine** and the DC Machine must be disconnected from the DC link voltage. The different 3- ϕ modulating references are under the study.

- ☐ Open the Modulation tab in Labview.
- ☐ Turn on the green switch and the Red/Yellow switch on the PMSM VSC.
- ☐ Increase the DC link voltage to 150 V.
- ☐ Read the entire next step before starting.
- ☐ Increase the y-stator current **to maximum for a short moment, then quickly down to around 1 A** and adjust it until the machine is running at a medium speed forward. This procedure is to overcome the friction when acceleration from stand still. Depending on which station you use, the final adjusted current will be somewhere between 1 A and 2.5 A. Repeat if necessary.

Switch between the modulation methods (sinusoidal, symmetrized and reduced switching modulation). As you do this consider the possible differences in speed, switching frequency, voltage reference wave form and stator current ripple.

Fill out table 4.1 with how the variables change when you switch modulation method.

Table 4.1: Modulation types

Parameter	Sinusoidal	Symmetrized	Minswitch
ω			
f_{sw}			
u^* wave form			
i_s ripple pk-pk			

Explain the differences and similarities.

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- ☐ Push “Set values to zero” in the Modulation tab.

4.6 Current Control

The third lab exercise is about studying the Sampled Vector Current Controller and the Direct Current Controller for the PMSM. There is no machine keeping the speed reference while the PMSM is current controlled.

- ☐ Switch to the PI Current Control tab within the Current Control tab.
- ☐ Set the i_{sy} reference to square
- ☐ Set the square frequency to 0.5 Hz
- ☐ Set an amplitude that makes the motor runs back and forth, somewhere around 3 A.
- ☐ Make sure that $U_{dc} = 150$ V.

Look at the y-axis current response at the screen. Experiment carefully with the controller gain and integration constant until you have understood how the parameters affect the step response. Then set the parameters to a step response you think look good.

Which PI parameter values did you find best for the lab equipment?

(Optional) What are the theoretical values of the gain and integral time constant with this PM drive, given the technical data in table 2.1? How are they compared to the values you choose in Labview?

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- ☐ Set values to zero and switch to the Direct Current Control Tab.
 - ☐ Again set the i_{sy} reference to square, 0.5 Hz and an amplitude somewhere around 3 A.

What shape does the current ripple in the x-y-graph (top right) have and how is it affected by the hysteresis band when you change its values?

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- ☐ Set values to zero.

4.7 Field Weakening

As the back-emf increases with the motor speed, the maximum speed is limited by the voltage supply. In order to exceed the operating speed above the base speed the flux has to be decreased.

- ☐ Switch back to the PI Controller tab.
- ☐ Decrease the DC link voltage to 100 V.
- ☐ Set the y-stator current reference to square wave with frequency 0.1 Hz and amplitude 5 A.

What happens with the i_{sy} -current and to the shape of the $\alpha\beta$ -current when the reference voltage hits the limit? Why? Which speed does the motor reach?

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- ☐ Set values to zero.
- ☐ Switch to the Field Weakening tab and set the same square wave as before (0.1 Hz, 5 A).
- ☐ Adjust the x-axis stator current in steps of -1 A, from 0 to -5 A.

For each step: Which new speed does the machine reach?

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How much where you able to increase the speed?

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Are there any risks for the converter when using field weakening?

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- ☐ Set values to zero.

4.8 Speed control

(Optional) Use Symmetric Optimum to calculate the proportional and integral gains for the speed controller, assuming no speed filter.

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- ☐ Turn to the Motor Control tab.
- ☐ Apply a ± 250 rpm speed step as a square wave with a suitable frequency.
- ☐ Adjust the P and I parameters in Simulink until you understand how they affect the speed step response and then set them to values you find appropriate.

What values did you choose? (Optional: Compare to the calculated values).

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- ☐ Increase the speed reference to ± 400 rpm, and adjust the frequency if you need to.
- ☐ Set the Integral part to zero.

Focus on the stationary speed error. How big is it?

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- ☐ Set the speed reference to zero
- ☐ Connect the resistive load to the DC Machine. Make sure it is adjusted to high load (minimum R value). The three integrated resistances should be coupled in series.
- ☐ Set speed reference back to ± 400 rpm.

How big is the stationary speed error now?

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- ☐ Reestablish the Integral part of the speed controller.

How big is the stationary error now? What explanation can you find to the speed limitation?

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- ☐ 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.

Good job, you're done!