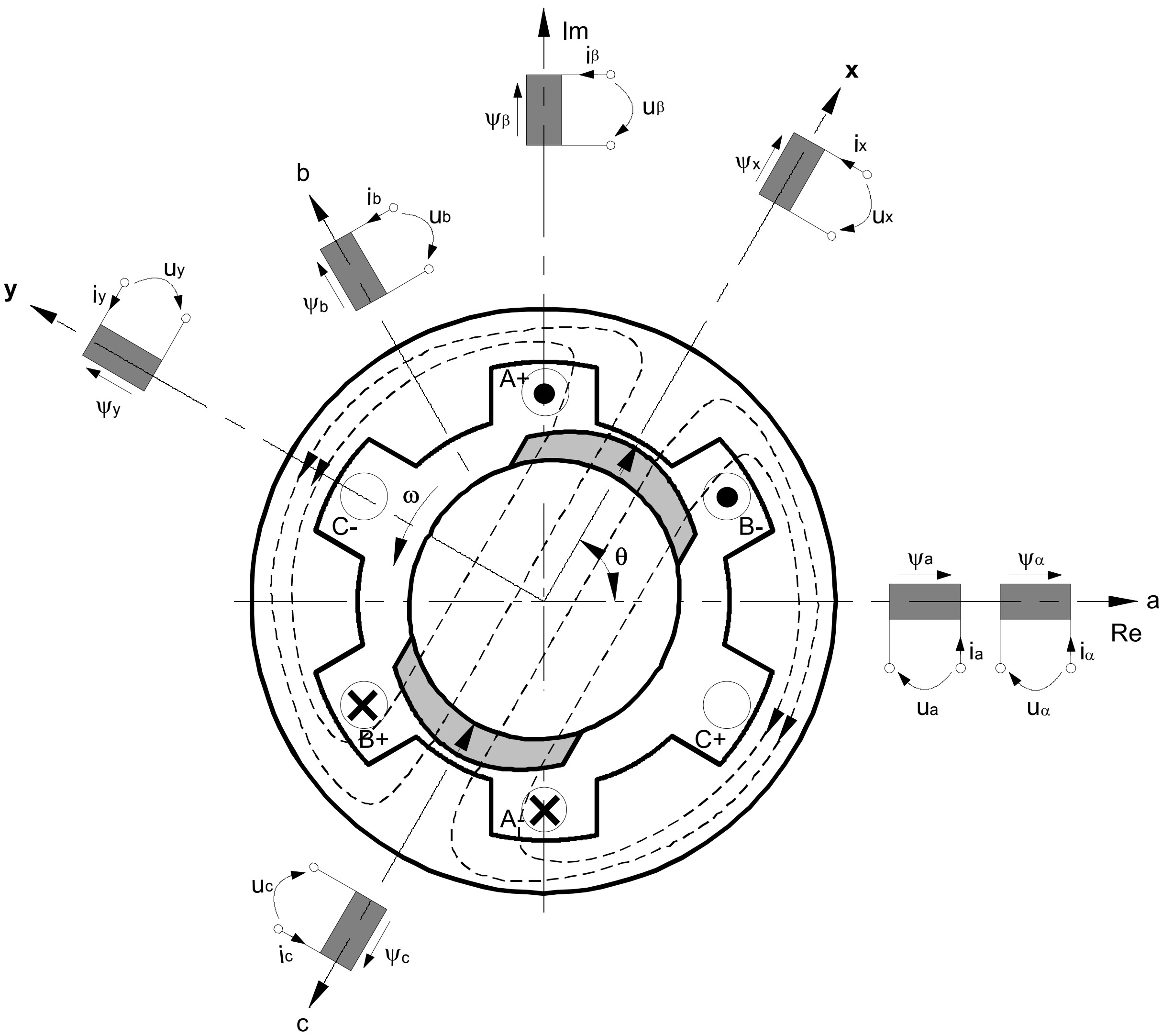
# EIE 041 Control of Electrical Drives

## Laboratory exercise 3

## Control of a Permanent Magnet Synchronous Machine



# 1. Introduction

In this lab a sampled vector current controller for a permanent magnet synchronous machine (PMSM) torque control will be studied. The control system is a Simulink block diagram-based model that is run in the dSpace real-time hardware. The scope of the laboratory work covers a comparison of some PWM modulating references that can be used for three phase PWM modulators and a vector control for PMSM including a field-weakening controller.

# 2. Laboratory Set-Up

The laboratory set-up is the same as in the first lab and it is shown in figure 2.1 below. Notice that the block set of the PMSM torque control is presented.

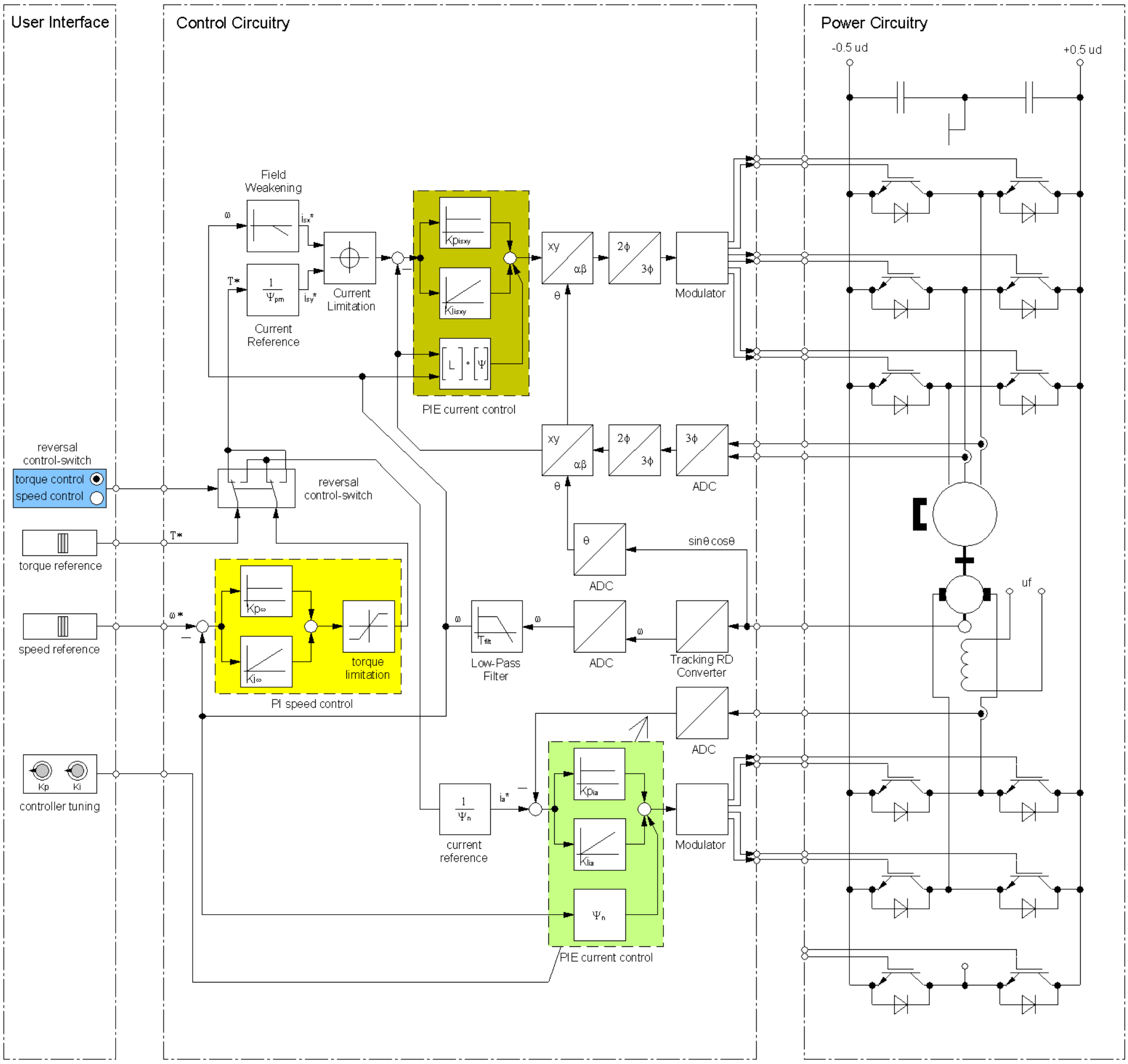



***Figure 2.1** Principal diagram of the lab system*

The power circuits are shown in the right and some inputs from the user interface in the left. The middle represents the control circuit and I/O.

The control system consists of I/O of the 3-ϕ and 2Q voltage source converters (VSC) including dc-link voltage measurement, inputs from an instantaneous angular position sensor (Resolver, Rotasyn) and a speed estimator. The control system is entirely implemented in Simulink (figure 2.2).

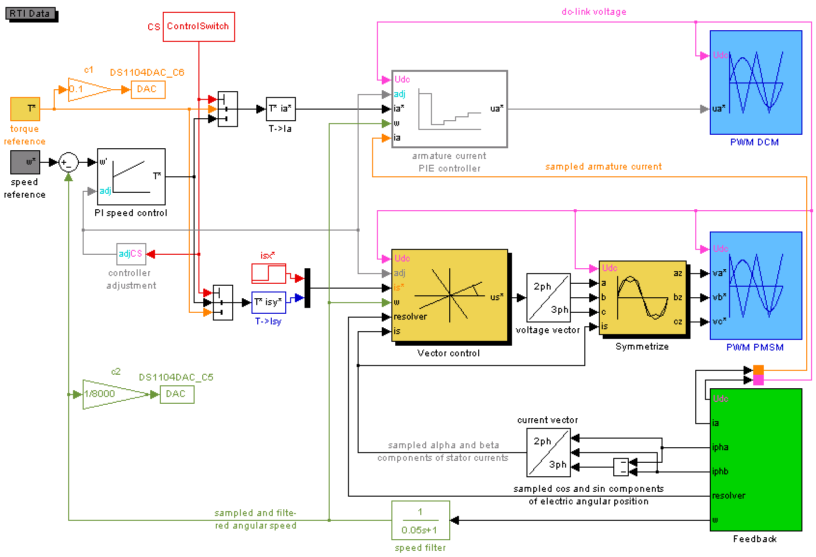



***Figure 2.2** Control system implemented in Simulink RT-model*

Different modulating signals can be studied for the 3-ϕ converter. The 3-ϕ reference potentials are calculated according to the sinusoidal, symmetrized or reduced switching modulation technique. The (2-ϕ) voltage references representing the voltage space vector are calculated by a current (vector) control and the current references are given from the torque reference / the speed controller and the field weakening controller.

Note that the DC machine and the PMSM share the same shaft. Both have the same reference direction for torque, i.e. a positive torque on either of the machines accelerates the shaft in the same direction. Stationary operation thus requires that the torque contributions from the two machines are of equal size, but with opposite signs. The reversal control-switch specifies the control task and links the torque controller of one machine directly to the torque reference, and the torque controller of the other machine to the output of the speed controller.

# 3. System Data

The data of the PMSM necessary for the torque control is presented below in table 3.1. This data is used to design the PIE current controller and can be applied for the field-weakening controller.

***Table 3.1** The PMSM control design data*

| ***Measure*** | ***Symbol*** | ***Value*** | ***Unit*** |
|---|---|---|---|
| Nominal flux linkage of the PMSM | $\Psi_{pm}$ | 0.16 | Vs |
| Stator inductance of the PMSM | $L_{sx} = L_{sy}$ | 3 | mH |
| Stator resistance of the PMSM | $R_s$ | 0.5 | Ω |
| The nominal current of the PMSM | $I_n$ | 12 | A |
| The nominal voltage of the PMSM | $U_{Ln}$ | 400 | V |
| Sample time | $T_s$ | 2e-4 | s |

The necessary files are in the work directory: ***C:/SED_Lab/pmsm/***

- The RT Simulink model setup and the model – ***pmsm_setup.m, pmsm_lab.mdl***;
- The dSpace experiment and the user interface – ***pmsm_exp.cdx***;

If necessary, refer to the first lab handout for the details on opening files and using the software.

System I/O is summarized in the table below:

**Table 3.2** System Input/Output

| **Input** | **dSpace Interface** | **symbol** | **source/measurement** |
|---|---|---|---|
| dc-link voltage | ADC1 | Udc | C&V measurement card |
| Armature current | ADC2 | ia | C&V measurement card |
| Mechanical speed | ADC3 | w | Flux linkage estimator |
| Stator current phase a | ADC5 | ipha | C&V measurement card |
| Stator current phase b | ADC6 | iphb | C&V measurement card |
| Resolver position (cos) | ADC7 | cos | Resolver & Sin/Cos card |
| Resolver position (sin) | ADC8 | sin | Resolver & Sin/Cos card |
| **Output** | **dSpace Interface** | **symbol** | **source/measurement** |
| 2φ PWM | PWM1<br>PWM2 | va<br>vb | DS1104SL_DSP_PWM |
| 3φ PWM | PWM1<br>PWM2<br>PWM3 | va<br>vb<br>vc | DS1104SL_DSP_PWM3 |
| Reference current on direct/quadrature axis* | DAC1 | ixy* | RT Simulink model |
| Feedback current on direct/quadrature axis | DAC2 | ixy | RT Simulink model |
| Predicted current on direct/quadrature axis | DAC3 | ixy^ | RT Simulink model |
| Reference voltage on direct/quadrature axis | DAC4 | uxy* | RT Simulink model |
| Filtered speed# | DAC5 | w | RT Simulink model |

* The axis of the rotating xy-frame can be selected in vector control block.

# An extra measurement cable is connected for filtered speed measurements.

# 4. 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 converter output and a current ripple at the different 3-ϕ modulating references;
3. Adjusting the sampled vector current controller for the PMSM;
4. Investigating a voltage and a current limit for the PMSM and the 3-ϕ converter;
5. Implementing the field-weakening control;

## *4.1. Induced Voltage*

In this first part of the lab, the PMSM must be disconnected from the 3-ϕ VSC (Disconnect the red/yellow switch on the front panel). The speed controlled DC machine (from lab 1) keeps the rotation speed of the shaft so that the induced voltage of the PMSM can be investigated.

Set dc-link voltage to 150 V, do not forget external magnetisation while you are working with the dc-machine and set the speed reference to about 100rad/s. Connect a high voltage probe between the outputs of the PMSM VSC and measure the induced voltage.

The interface layout used for the electric drive system – interface is shown in figure 4.1.

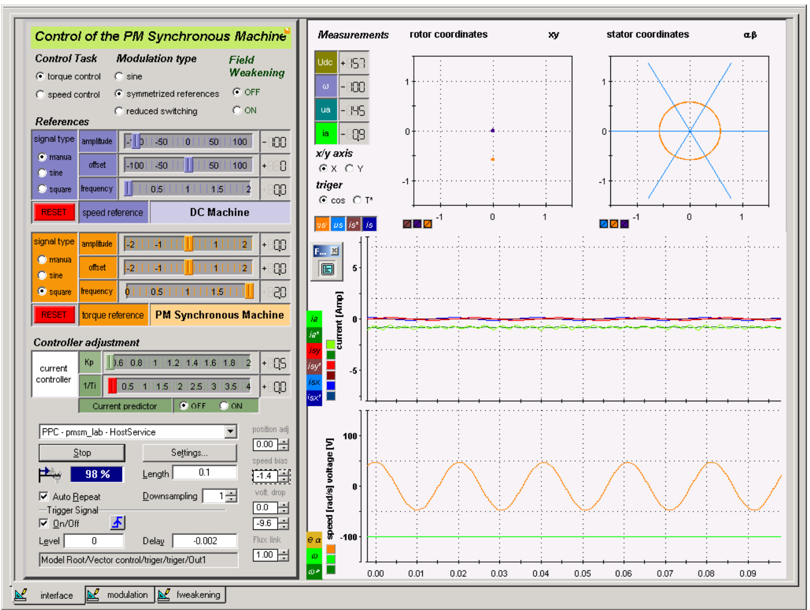



**Figure 4.1** *Control Desk layout for the electrical drive system*

How does the induced voltage waveform of the PMSM look like? Draw the induced voltage waveform and the corresponding space vector at “position 0”. Indicate the rotation direction, the flux vector and the position of the rotating xy-frame at the position 0.

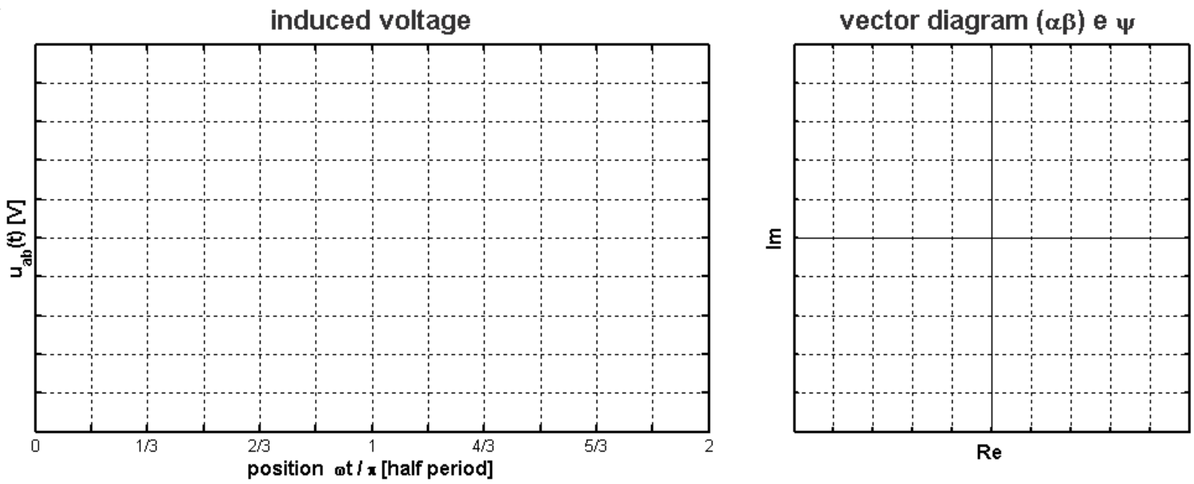



**Figure 4.2** *Induced voltage waveform and the corresponding xy frame at "position 0"*

What is the magnitude of the flux linkage vector $\boldsymbol{\Psi}_{pm}$? Note that the PMSM has 6 poles. Does your calculated value coincide the value shown on the table 3.1?

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What is the nominal <u>mechanical</u> torque, based on the nominal stator current?

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What is the necessary minimal value for the dc-link voltage if the torque reference is 1.0 Nm and the rotation speed is lower than 100rad/s, with no field weakening used?

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## *4.2. Modulation Types and Output of the Three-Phase Converter*

In this 2'nd part of the lab, the PMSM VS-converter must be connected to the 3-ϕ machine. The different 3-ϕ modulating references are under the study. Let the DC machine give a constant speed. Measure the stator current given by an (analogue) coordinate transformation block. Look at the quantities $\boldsymbol{i}_{sx}$ and $\boldsymbol{i}_{sy}$ as a function of time and a vector. Consider the differences in modulation by looking in the book, and make sure that you understand the cause of the current plot in the (x,y)-frame.

Assume the rotor position, the induced voltage vector and the corresponding active vectors of the VSC so that you can draw the current on the direct (x) and quadrature (y) axis over one switching cycle (carrier period). Draw the time functions and the corresponding vector plot for sinusoidal, symmetrized and reduced switching modulation (figure 4.3 – 4.5).

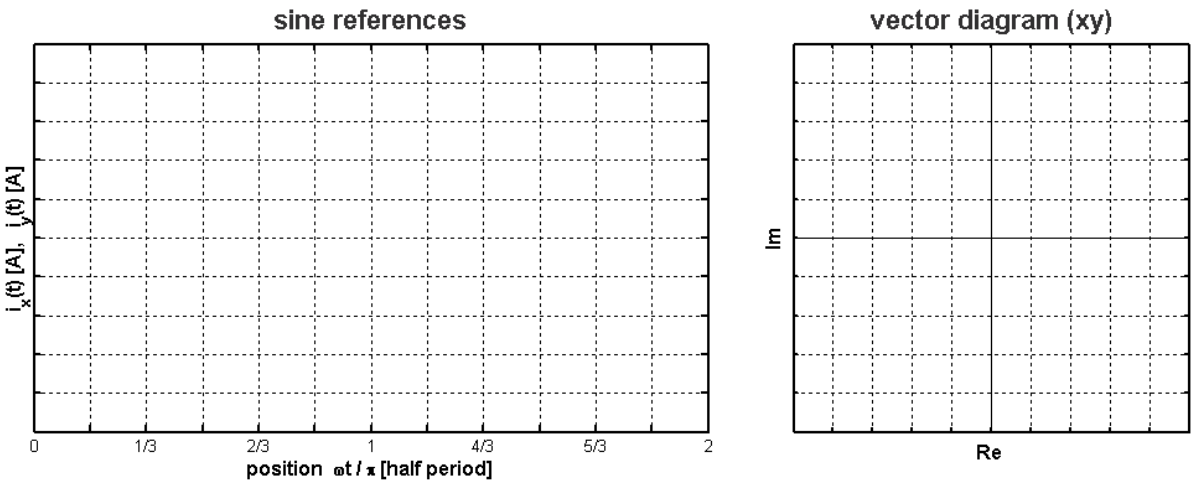


**Figure 4.3** *Sinusoidal 3φ references and the corresponding current ripple*

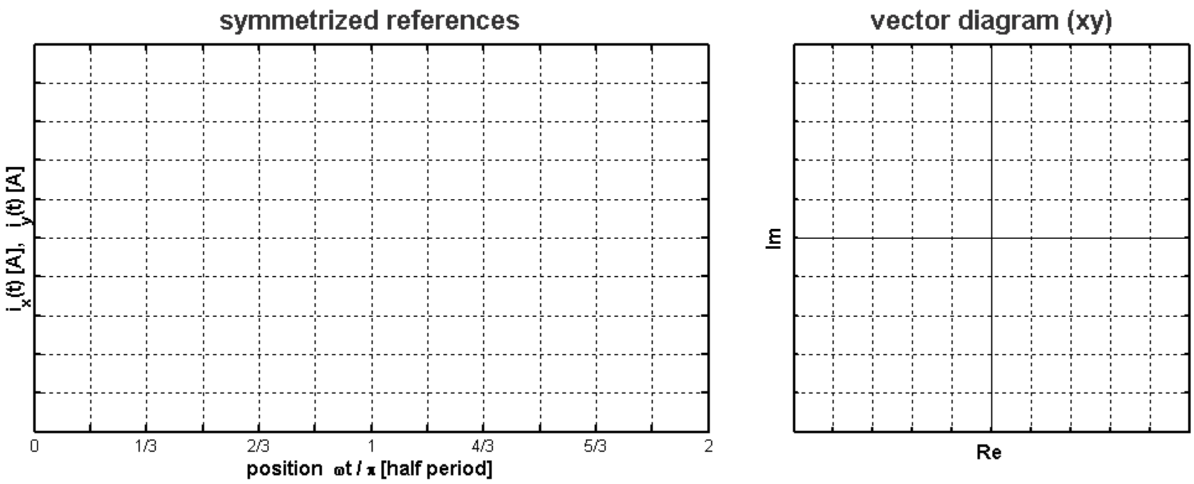


**Figure 4.4** *Symmetrized 3φ references and the corresponding current ripple*

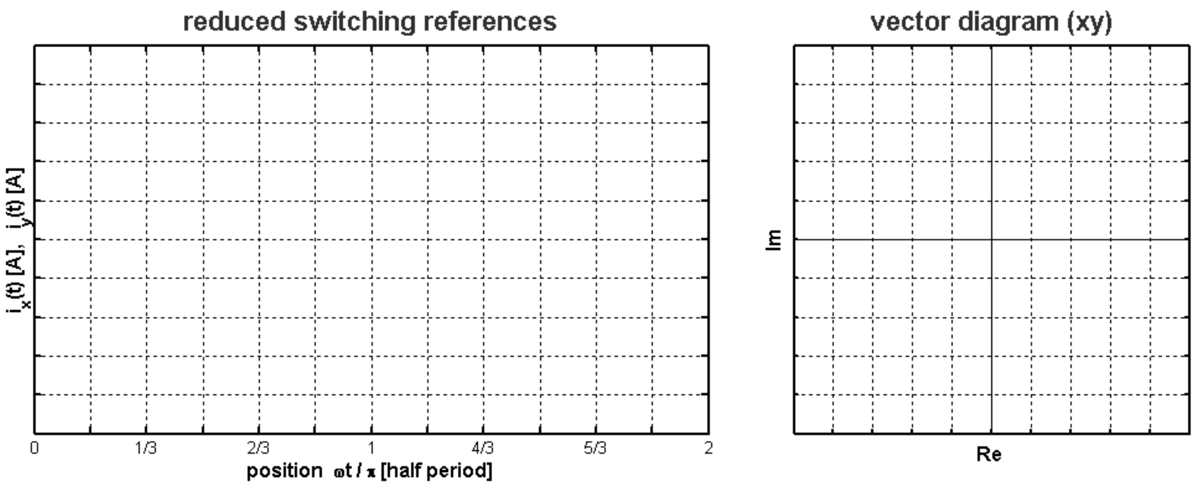


**Figure 4.5** *Reduced switching 3φ references and the corresponding current ripple*

## 4.3. *Torque Control*

The third lab exercise is about to study the sampled vector current controller for the torque control of the PMSM. The content of the sampled vector current control is shown in figure 4.6. Apart from the PIE current controller and field weakening reference block the system contains blocks necessary for system I/O.

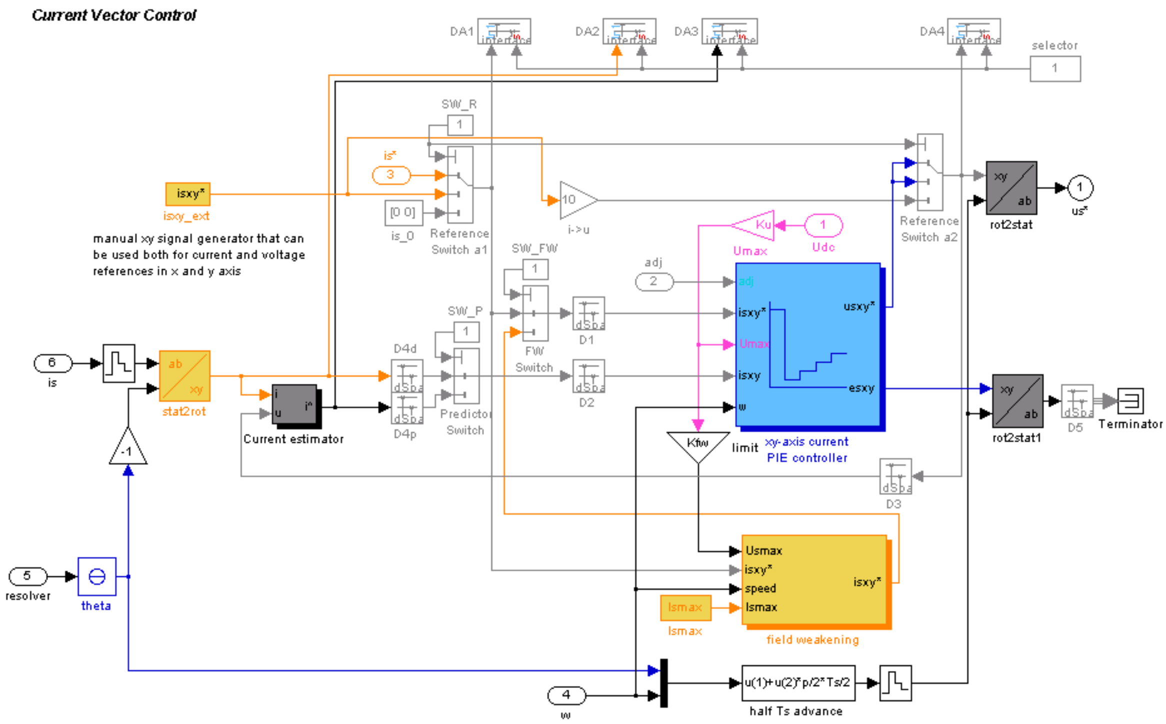


**Figure 4.6** *The vector control block*

Disconnect the dc-machine. Now there is no machine keeping the speed reference while the PMSM is torque controlled. Set the torque reference to square (e.g. ±1 Nm, 0.5 Hz) so that the motor runs back and forth without reaching to the voltage limitation which is set by the dc-link voltage Udc=120V.

Look at the y-axis current response at the screen and with the oscilloscope. The y-axis current reference is available at the analogue output DA1 (table 3.2). A switch defined on a control desk layout can switch between the quantities on the x and y axis. The real (not sampled) y-axis current is available at an analogue coordinate transformation card. Adjust the controller gain and integration constant until you are happy with the performance. Compare the gain with the theoretical.

$$\begin{cases} u_{sx} = R_s \cdot i_{sx} + \dfrac{d\psi_{sx}}{dt} - \omega \cdot \psi_{sy} \\ u_{sy} = R_s \cdot i_{sy} + \dfrac{d\psi_{sy}}{dt} + \omega \cdot \psi_{sx} \end{cases} \qquad \begin{cases} \psi_{sx} = L_{sx} \cdot i_{sx} + \psi_{pm} \\ \psi_{sy} = L_{sy} \cdot i_{sy} \end{cases}$$

$$T = \vec{\psi}_s \times \vec{i}_s = \psi_{sx} \cdot i_{sy} - \psi_{sy} \cdot i_{sx} = \psi_{pm} \cdot i_{sy} + (L_{sx} - L_{sy}) \cdot i_{sx} \cdot i_{sy} = \frac{J}{p} \cdot \frac{d\omega}{dt} + T_{load}$$

***Equation 4.1*** *The mathematic model of the PMSM*

## 4.4. 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. The field weakening controller, which sets the level of the demagnetising current $-i_{sx}^*$, and the stator current modulus limitation block are shown in figure 4.7.

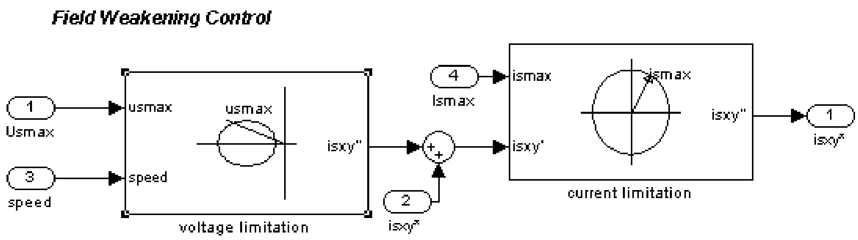


**Figure 4.7** *The field weakening reference block*

Continue the study of the torque controlled PMSM. Increase the reference period so that the machine hits the voltage limitation. What did happen with the motor if the reference voltage hits the limit? Implement your field-weakening controller to the vector control so that the motor can be run at the higher speed. Measure the speed and compare how the maximum speed is depending on the field-weakening. The corresponding Control Desk layout is shown in figure 4.8.

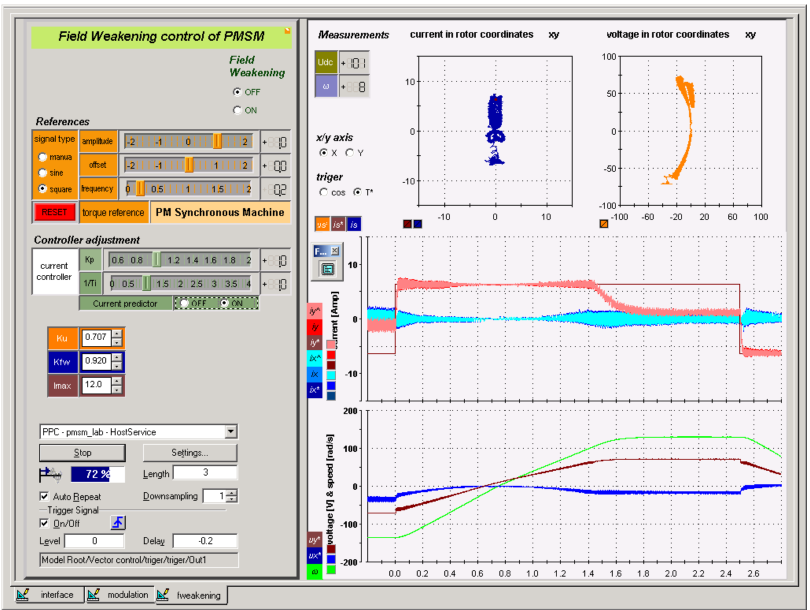


**Figure 4.8** *The layout for the field weakening experimentation*

What is the relationship between the maximum speed for the field-weakening and no field-weakening? What is the corresponding value of the maximum voltage (the base speed) for the field-weakening controller? What will happen if the limitation is set to be smaller? Look at the current vector can you distinguish the field-weakening and current limitation control? Compare the experiments with your simulations.

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Draw one period of the free acceleration including the field-weakening control. Distinguish the acceleration, the field weakening and the current limitation regions and draw the corresponding space voltage and current vector.

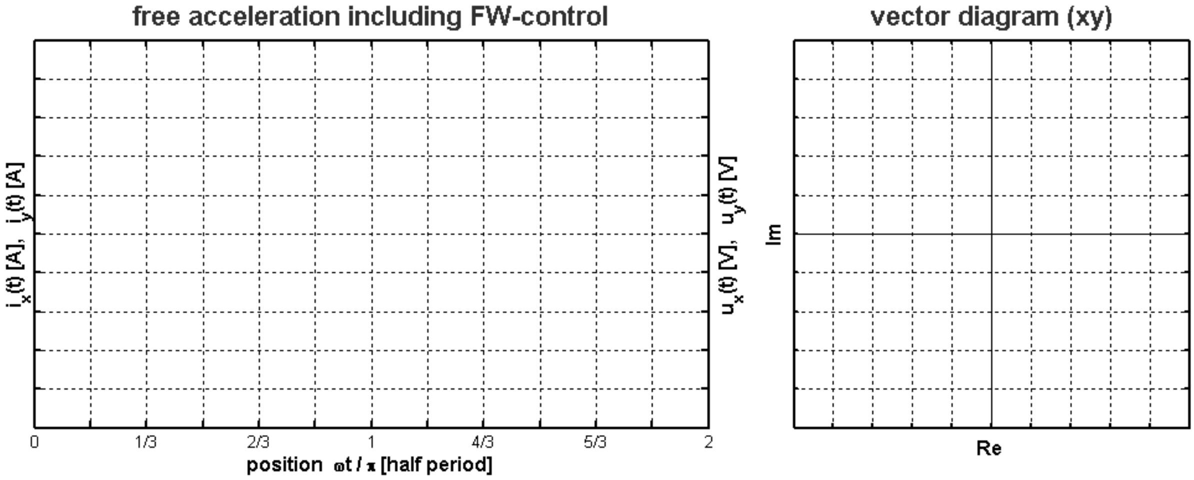


**Figure 4.9** *Free acceleration, field-weakening and current limitation*

For the sake comparison, a simulation of the field weakening and current limitation control is show in figure 4.10 (Udc=150V & Usmax=90V at T*=2Nm).

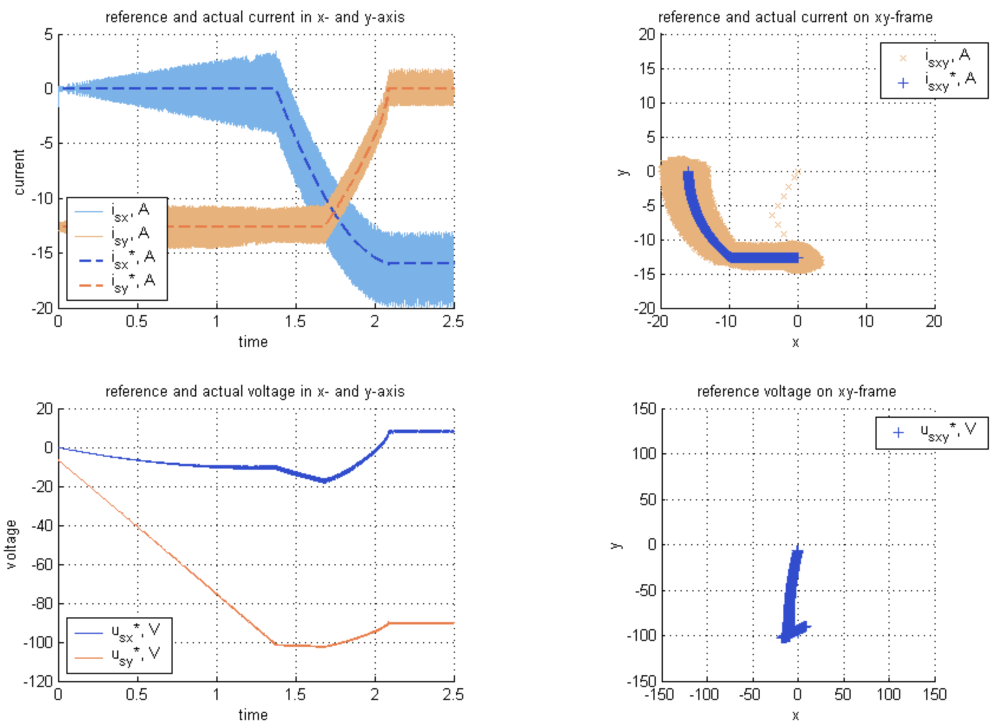


**Figure 4.10** *The field-weakening control for PMSM*