5LWE0 - Control of rotating field machines - Lab report

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Abstract

The assignment for the course 'Control of rotating field machines' consists of a laboratory session and several simulation exercises for various rotating field machines.

1 Introduction

The lab consists of two assignments: implementing indirect Field Oriented Control (iFOC) and scalar control (U/f) on an induction machine. After implementation and measuring step responses, the performance of the two control implementations are compared. The main advantages of FOC over scalar control are the full torque at zero speed and the high dynamic performance such as acceleration, however it is has a higher complexity and is more expensive to implement. For both control implementations the goal is to control the rotor speed. System limitations such as maximum current are taken into account while tuning the controllers.

2 Lab setup

The setup that is used during the experiments is setup number 1 which consists of a SEW induction machine and a Siemens DC machine. Both the induction machine and DC machine are connected to a Voltage Source Inverter (VSI). Control of both the VSI's is done through a Matlab Simulink template in which the controllers are implemented. Parameters of the setup are listed below.

Parameters of the SEW induction machine:

L_m	$0.628H$	Magnetizing inductance
L_{ls}	$7.882\mu H$	Stator leakage inductance
R_s	1.72	Stator resistance
L_{lr}	$11.82mH$	Rotor leakage inductance
R_r	1.868	Rotor resistance
$I_{ph,max}$	$5.5A$	Rated per-phase RMS current
$V_{ph,max}$	$230V$	Rated phase RMS voltage
ω_{rm}	$2850rpm$	Rated rotational speed
P_{mech}	$3kW$	Rated power

Parameters of the Siemens DC machine:

R_f	561	Field winding resistance
L_f	$60.7H$	Field winding inductance
R_a	1.05	Armature winding resistance
L_a	$4.3mH$	Armature winding inductance
$I_{f,max}$	$0.48A$	Maximum field current
$V_{f,max}$	$340V$	Maximum field voltage
$I_{a,max}$	$16.4A$	Maximum armature current
$V_{a,max}$	$400V$	Maximum armature voltage
$P_{a,max}$	$5.5kW$	Rated power

Shared parameters:

J	$27.6e-6kgm^2$	Inertia
$b1$	$15.1e-4Nm/rad/s$	Friction coefficient
$b0$	$0.47Nm$	Static friction

Voltage Source Inverter (VSI) parameters:

i_{max}	$15A$	Max inverter current
v_{max}	$400V$	Max inverter voltage
T_{delay}	$187.5\mu s$	Time delay

3 Lab session

The lab consists of two parts: implement indirect FOC and scalar control. For the FOC controller first the torque control loop (inner loop) and second the speed controller (outer loop) are tested. The scalar controller is directly implemented for control of the rotor speed.

The FOC principle for the induction machine is that the dq reference frame is locked to the flux vector of the rotor. This leads to decoupling of the flux and torque which then are separately controllable through stator currents i_{ds} and i_{qs}. This is beneficial since it is now possible to control the induction machine as if it is a DC machine, resulting in better performance.

Step changes in torque (iFOC)

The torque control loop consists of two discrete PI controllers since a direct quadrature (dq) transformation is used. The reference to the PI controllers are the $I_{qs,ref}$ and $I_{ds,ref}$ signals, which are subtracted by the measured currents $I_{qs,meas}$ and $I_{ds,meas}$. The output of the PI controller are the voltage setpoints V_q and V_d for the induction machine, which are transformed to a three phase voltage V_{abc}. Tuning both current controllers is done by setting the P to 20.6 and the I to 8000 resulting in sufficient bandwidth (80 rad/s) and stability margins: PM $>$ 45 degrees, GM $>$ 6 dB.

The torque steps are executed by inserting a step reference on i_{qs} with for I_{ds} the nominal value (Figure 1) and also half (Figure 2) and double (Figure 3) this value. In these figures the measured rotor velocity, current vectors and DC machine current are shown. The DC machine is in speed control mode during the torque step with the reference speed set to $0rad/s$.

From the measurements can be concluded that the torque controller has more oscillating behavior when the value for I_{ds} is lowered. Also can be noted that the value for I_{qs} becomes larger during a step if I_{ds} is lower and vice versa, because an adjusted flux has to be compensated with a smaller or larger torque generating current.

Step changes in speed (iFOC)

For the speed control a single discrete PI controller is implemented with a P of 0.4 and an I of 5, resulting in a bandwidth of around 0.5 Hz and sufficient margins (PM $>$ 45 deg, GM $>$ 6dB). The inputs of this controller are the speed reference ω_{ref} minus ω_{meas} and the output is the torque reference T_{ref}. The torque reference is then converted to $I_{qs,ref}$ and implemented in the torque controller for $I_{qs,meas}$.

A step of 0 to 20 revolutions per second is made and the measured results are shown in Figure 4. Simulations of the iFOC controlled induction machine resulted in comparable behavior.

Scalar control

For the second lab an scalar controller is implemented that controls the induction machine using the U/f factor which is based on the

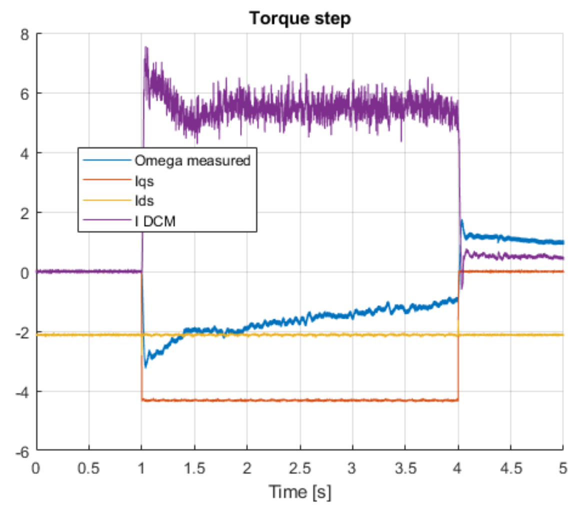

Figure 1: Torque step

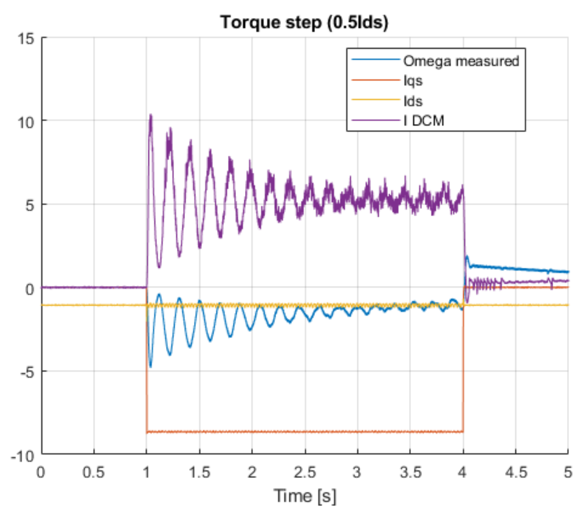

Figure 2: Torque step with $Ids \cdot 0.5$

machine parameters.

This controller is implemented and resulted in a step response from 0 to 20 revolutions per second as shown in Figure 5.

Comparing the step responses of the FOC to the scalar controller several things can be observed. First of all the FOC controller has a direct response, whereas the scalar controller needs some time to start moving thus does not have full torque at standstill. Also is the tracking performance of the scalar controlled induction machine worse, as can be concluded from the larger steady-state error.

Simulating the machine with the same parameters resulted in almost the same behavior. Compared to the measurement, the simulation had more overshoot and a faster settling time. This can be explained by the nonlinear friction of the real setup, where the simulation model has linear friction.

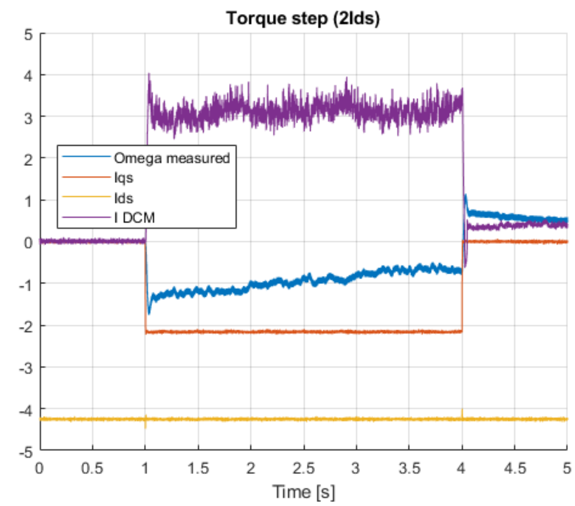

Figure 3: Torque step with $Ids \cdot 2$

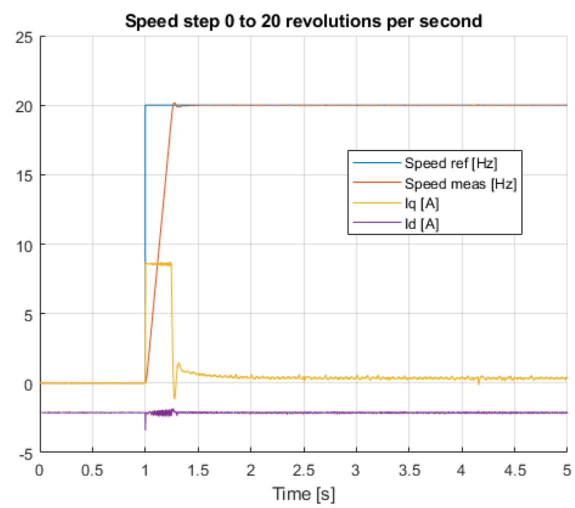

Figure 4: Speed step FOC (0 to 20 revolutions per second)

4 Simulation exercises

DC machine

During this assignment a simulation model of the DC machine is built in Matlab Simulink using the following machine parameters:

$V_{a,max}$	$420V$	maximum armature voltage
r_a	2.56	armature resistance
k_v	$1.11Nm/A$	machine constant
L_a	$43.8mH$	armature inductance
J	$134m \cdot kg \cdot m^2$	inertia
B_m	$5Nms/rad$	friction

The simulation model of the DC machine is based on the model equations given in the lecture slides, in which the input is the armature voltage and the output the rotor speed. With this simulation model, where first the armature voltage and then the load torque are varied (both from 10 to 100%). With this data the steady-state torque-speed map is obtained, as shown in Figure 6. Maximum load torque is computed by determining the maximum armature current $i_{a,max} = V_{a,max}/r_a$ and multiplying it with the torque constant k_v. From the simulated torque-speed characteristics can be concluded

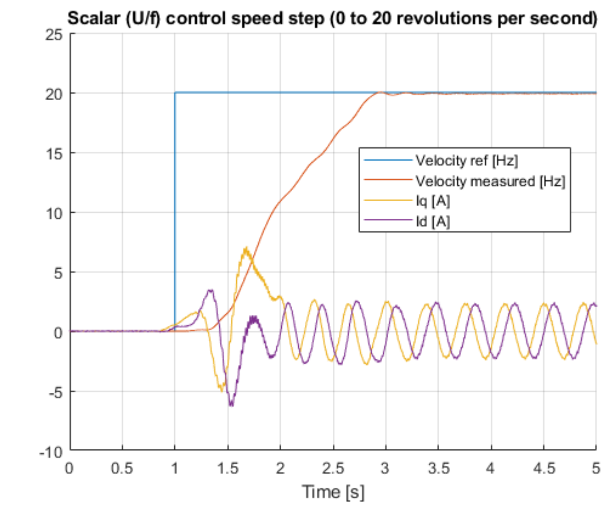

Figure 5: Step response scalar control (o to 20 revolutions per second)

that the relationship between rotor speed, load torque and armature voltage is linear.

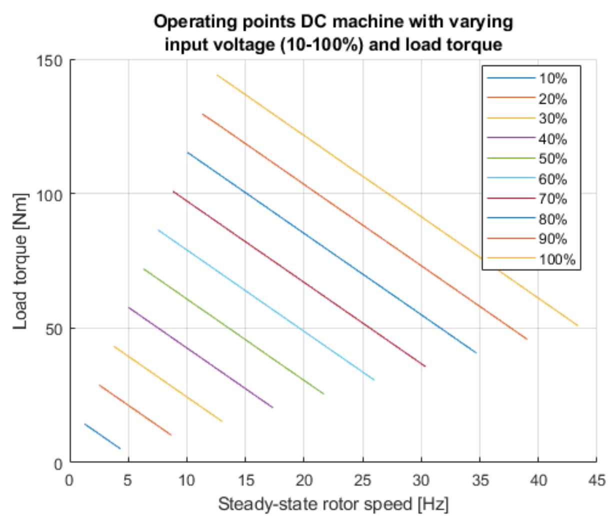

Figure 6: Torque-speed characteristics of a DC machine

Induction machine

During this assignment a simulation model of the induction machine, that is based on the equations from the lecture slides, is built in Matlab Simulink using the following machine parameters:

V_{max}	$230V$	amplitude for the phase voltage
f	$50Hz$	reference frequency
P	2	number of poles
ω	0	stator reference frame speed
r_s	2	stator resistance
$r_{r'}$	1.7	rotor resistance
L_m	$0.48H$	magnetizing inductance
L_{ls}	$8mH$	stator leakage inductance
$L_{lr'}$	$12mH$	rotor leakage inductance
J	$6.8mkg \cdot m^2$	equivalent inertia
P_m	$3kW$	rated mechanical power
I_s	$6.3A$	rated stator current
N	$2845rpm$	rated mechanical speed

The model input is the frequency setpoint and the output is the rotor velocity, where the control is done through open-loop scalar control. The reference frequency is varied from 10 to $100Hz$ and the load torque is varied between 0 and 9 Nm. This results in the steady-state operating points as shown in Figure 7. When the setpoint frequency increases, the induction machine reaches its torque limit resulting in decreased steady-state rotor velocity. This is as expected due to field weakening of the induction machine, resulting in a reduced torque.

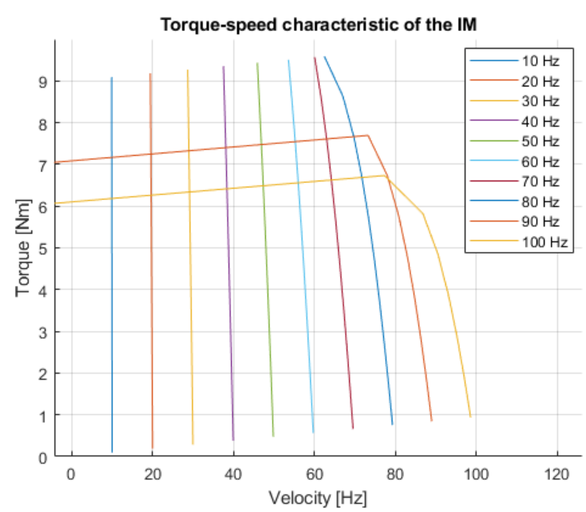

Figure 7: Induction Machine steady-state points over different reference frequencies (10-100 Hz and load torques (0-9 Nm)

PI control of DC machine

In order to control the DC machine's velocity, two control loops are implemented. The first loop is the current/torque controller, also called the inner loop since it is nested inside an second control loop. The second loop is called the outer loop and used to control the rotor speed. The inner loop is designed with a much larger bandwidth compared to the outerloop such that it does not influence the outer loop.

For designing the current controller the transfer function of the electric characteristics of the motor are used, which are:

$$H_{electric}(s) = \frac{I(s)}{V(s)} = \frac{1}{L_a s + r_a} = \frac{1}{0.0438s + 2.56} \qquad (1)$$

Now an integrator is added and also a zero to cancel the system's pole, resulting in an open-loop slope of -20dB/dec (integrator) which is needed for cancelling the steady-state error. This also results in a Phase Margin of 90 degrees since the system order is 1. The cross-over frequency of the current controller is also sufficiently large with 2700 rad/s, which is needed because it must be at least one decade higher compared to the speed loop to have no influence on that loop.

$$C_{current}(s) = \frac{119.7s + 6996.5}{s} \tag{2}$$

For the speed controller the mechanics of the motor are described with the following transfer function:

$$H_{mechanic}(s) = \frac{\omega(s)}{T(s)} = \frac{1}{Js + B_m} = \frac{1}{0.134s + 0.005} \tag{3}$$

The lab consists of two assignments: implementing indirect Field Oriented Control (iFOC) and scalar control (U/f) on an induction machine. After implementation and measuring step responses, the performance of the two control implementations are compared. The main advantages of FOC over scalar control are the full torque at zero speed and the high dynamic performance such as acceleration, The speed controller is also designed with an integrator and a zero to cancel the pole of the mechanics, resulting in a cross-over frequency of 9 rad/s. This resulted in the following controller:

$$C_{speed}(s) = \frac{1.2s + 0.45}{s} \tag{4}$$

Because the cross-over frequency of the speed loop is much lower, the transfer of the electric loop has no effect on it. Simulating the controller resulted in the step response shown in Figure 8, the open-loop Bode in 9, the closed-loop Bode in 10 and the disturbance rejection in 11. The step response shows that with minimal overshoot the rotor velocity goes to its setpoint velocity.

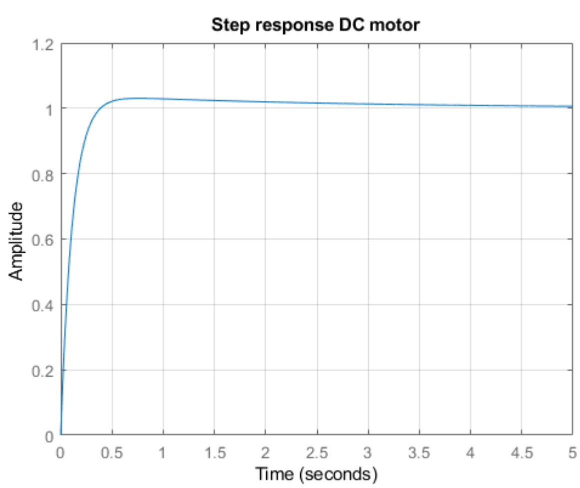

Figure 8: Controlled DC motor step response (velocity reference)

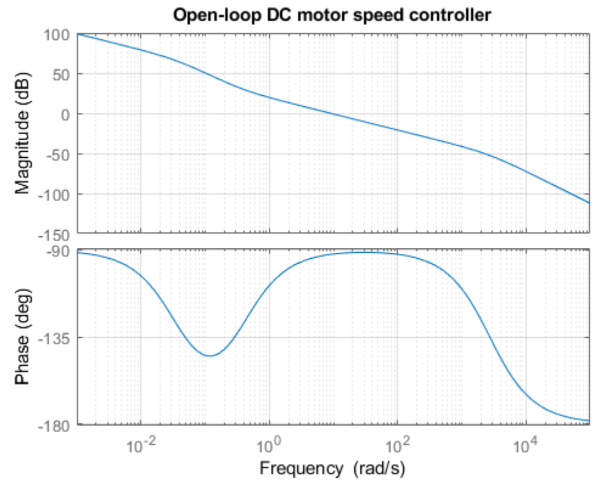

Figure 9: DC motor open-loop response

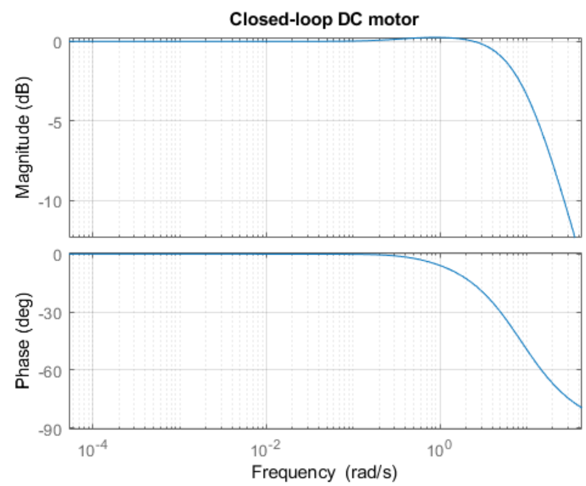

Figure 10: DC motor closed-loop response

Field Oriented Control on Induction machine

Controlling the induction machine is done in the same way as controlling the DC machine, using two controllers to control the torque/current and the rotor speed. However for the induction machine the current controller consists of two controllers since a dq-reference frame is used.

The controller for the current loop is first tuned based on the system's transfer function for the current, which is:

$$H_{current,IM}(s) = \frac{1}{L_s' s + r_s} \tag{5}$$

Resulting in the following stable controller with the transfer function:

$$C_{current,IM}(s) = \frac{50}{s} \tag{6}$$

Then the controller for the speed loop was designed based on the following transfer function:

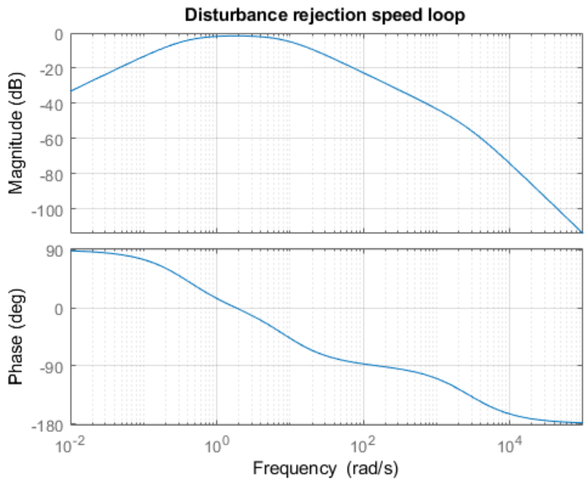

Figure 11: DC motor disturbance rejection

$$H_{speed,IM}(s) = \frac{1}{Js + B_m} \tag{7}$$

Resulting in the following controller:

$$C_{speed,IM}(s) = \frac{0.166}{s} \tag{8}$$

Permanent Magnet AC machine

For this assignment a simulation model of a Permanent Magnet AC machine is built in Matlab Simulink using the model equations from the lecture slides and the following machine parameters:

$\omega_{m,nom}$	$60,000 \cdot (2\pi/60) rad/s$	nominal rotor speed
V_{max}	$24V$	peak voltage
L_{ls}	$7.2\mu H$	leakage inductance
L_m	$64.8\mu H$	magnetizing inductance
L_q	$= L_d = L_{ls} + L_m$	stator inductance
r_s	1.3	stator resistance
P_l	$30W$	load power
B_m	$P_l / w_{m,norm} Nms/rad$	load coefficient
J	$25.5 nkg \cdot m^2$	inertia
λ_m	$3.49 mWb/turns$	PM flux linkage
P	2	Number of poles

There was no instruction given on what to simulate with the model, so for verification the start-up behavior of the motor is simulated as shown in Figure 12.

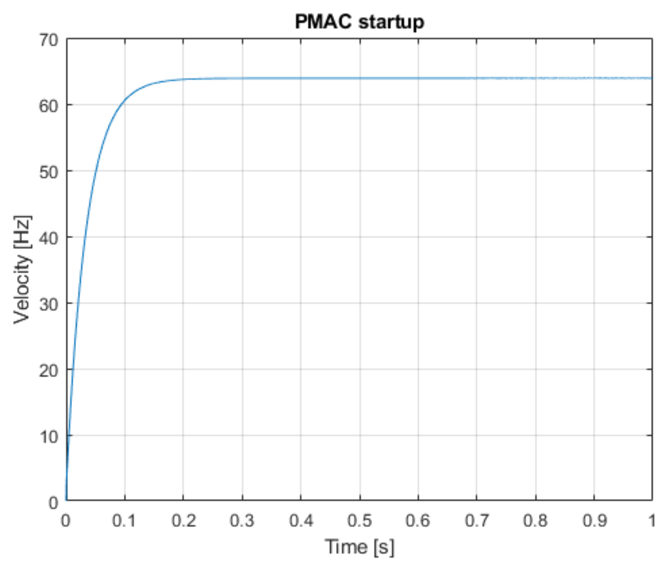

Figure 12: PMAC startup behavior