The DC Machine

Home Assignment 3

Updated February 28, 2020

Introduction

This assignment aims at detailed simulation of a speed controlled DC motor. In the assignment several speed and current control methods will be studied when supplying an idealized load. Finally one of the speed control methods and one of the current control methods in combination with a 4-quadrant DC converter will be used to control the speed of a DC machine. There are 3 subtasks:

1. Speed control. P- and PI controllers for speed will be used with and without a torque source model.
2. Current control. Sampled and Direct modulation and current control methods will be applied to a 2- and 4-quadrant converter.
3. Full System. Any speed controller and any current controller of your choice that works with a 4-quadrant DC converter will be simulated with a DC motor.

Note that in a real system, you need to master current control before you can control the speed of the machine, but in this simulation exercise, looking at speed control is more intuitive.

Simulink

For those of you who have not used Simulink before, there is a good introduction available from the Simulink Help menu. Start Matlab, type "Simulink" at the command prompt, and select "Help/Simulink Help" from the Simulink Menu bar. From there you will get a quick introduction to the software. Then, experiment on your own, and ask friends or any lab supervisor in the course if you run into troubles with the basics of Simulink.

Non-ideal loads

A non-ideal load is any three phase load that consumes power with anything else than a **symmetric** three phase current at **power factor of 1** (no phase lag between voltage and current) and **fundamental frequency** is non-ideal. A non-ideal load current contains at least one of the following components:

- Reactive current. Loads containing inductive or capacitive elements consume reactive current components.
- Asymmetric current. Consumed by three phase loads that are not equal in all three phases.
- Harmonics. Consumed by non-linear loads, e.g. a diode rectifier, with the result that the current is not perfectly sinusoidal.

Report requirements

- Submit via email and attach your report as a PDF-file, with **the email header starting with "`DCM_YourLastName`"**. Example: `DCM_Estenlund v1`.
- You must submit your home assignment report before your lab session starts to be allowed to do the lab. The first report does not have to be perfect, but you should have made honest attempts to complete all tasks.
- All students must send an individual report. You may cooperate when you do the simulations and discuss the problems, but your report should be written by you personally and the simulations run by yourself with your own (random) maximum torque value.
- There are no lab report for these labs, only the home assignments.
- Deadline for corrections is the week after the exam.

Other tips

- If you have problems, do not be afraid to ask us. Send an email or come by the office.
- Submitting your report a couple of days before your lab session will give you a chance to receive feedback and help to understand vital parts of the exercise, which will make you understand more of the lab itself.
- Anything that is unclear in the home assignment will be explained during the lab. After the lab, you will also get access to videos that explain the different parts of the home assignment.
- You will receive your feedback after the lab week is over. The feedback will be sent out in the same order as the home assignments are submitted, so the earlier you are with your first submission, the earlier you will receive your feedback.
- You are free to update your home assignment as many times as you like, with or without getting any feedback on the previous version. It is recommended that you update your home assignment as early as possible after you do the lab, when your new insights are fresh in your memory. If you wait for the feedback, when you already know that you can make an important improvement to your report, you risk forgetting it before receiving the feedback.
- Technically the deadline for a corrected report is the end of the semester (or a few weeks into the summer). But the longer you wait, the more you will forget and the longer you may have to wait for further feedback. If you wait until the end of the summer, you will have to redo the lab next spring to pass the home assignment.
- If you hand in your corrected report during the week of the exam, you will get the results in Ladok at the same time as the exam results.

1 Theoretical questions

Answer these two questions in your report.

1.1 Braking torque

When a machine is running at constant speed, the electrically produced torque T_{el} and the braking load torque T_l are equal (see eq 9.1 in the text book). In the lab, a braking machine with a resistance will be connected to the shaft of the DC Machine. There is a basic relation between the active power and the torque that is used to brake or accelerate a machine (eq 8.5 in the book):

$P = T\omega$

What does this say about the effect of the load resistance on the braking torque – When the resistance is smaller, will the braking torque be smaller or bigger?

(Do not forget that the voltage over the braking resistance is generated by the braking machine and thus proportional to the speed of it.)

1.2 Produced torque

The converter output is connected to the armature voltage of the DC Machine. Look at the mathematical model in the chapter about the DC Machine in the text book. How can the converter control the electrically produced torque in the machine?

2 Speed control

Open the Speed.mdl. The model contains all the elements you need to simulate some different speed control systems. On the top level you see the systems in the figure below.

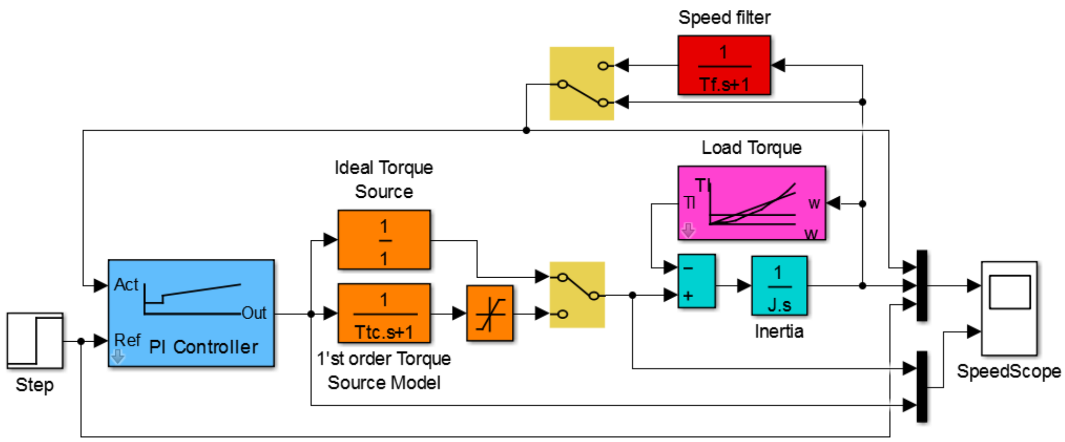

Figure 2.1: The topmost level of the Speed Control System.

This is the **PI-controller**. This *Speed Controller* can be of P- or PI-type. An output limitation can be introduced; including an Anti Windup function that stops the Integration part of the Controller Output from exceeding the limits. All these settings are done by double clicking on the PI controller block.

This is the **Torque Source model**. The *Torque Source* can be ideal or represented by a 1'st order time constant and a maximum torque limitation. You choose between ideal and the more realistic model by flipping the switch after the models.

With these **switches** you can select if the Torque Source model and/or the Speed Filter should be engaged.

This is the **Speed filter**. It reduces the dynamic performance of the measured speed signal.

This is the **Load torque model**. The *Load Torque* is set by double clicking the load torque block and selecting the characteristic. It can be set to either a constant load torque or a load torque that is linearly or quadratically proportional to speed. In this lab only the constant setting will be used. Note that the speed setting is irrelevant in the constant case.

These two blocks make up the **Mechanical load**, with inertia and load torque.

The parameters you will need during the simulation are: (Copy and insert into Matlab console)

```
>> J = 0.034;    % The inertia of the DC machine
>> La = 0.02;    % The inductance of the DC machine
>> Ra = 2.5;     % The resistance of the DC machine
>> Udc = 250;    % The DC link voltage we are going to use in the
                 % lab
>> Ts = 0.001;   % The sampling time of the control system (Ts)
>> Ttc = 0.001;  % This is the time constant of the torque source
                 % dynamics (Ttc), which in this case is the same as
                 % the sampling time of the control system (Ts)
>> Tf = 0.05;    % Filter time constant
>> Tmax = 16+round(rand*40)/10; % This is the maximum torque the
                 % torque source is able to produce. You will get
                 % your personal value between 16 and 20.
>> Psi = 1.36;   % The flux from the rotor excitation
```

Run all of the cases below and present the following for each of them:

- A screenshot of the SpeedScope window (Tip: in Microsoft Windows, Alt+PrtScr screenshots the currently selected window. Cmd+Shift+4 and then Space lets you select a part of the screen in OS X).
- Your choice of controller parameters with motivation.
- Comment the results by answering these questions:
  - How does the speed step response look? Is it stable? Remaining error?
  - How does the torque reference and actual torque look?
  - How do you connect the results to your choice of PI parameters?
- The system starts with an ideal case and then gets more functionality/limitations added for each case. What can you say about the system in each case? What is added and why?

Case	Controller	Torque source	Load Torque	Speed filter
2.1	P-controller (*Do not forget to choose parameters!*) No Limit / Anti Windup	Ideal	$T_l = 0$ Nm	No
2.2	P-controller No Limit / Anti Windup	Delayed and limited. T_{tc}, T_{max}		
2.3	P-controller No Limit / Anti Windup		$T_l = 10$ Nm, constant.	
2.4	PI-controller No Limit / Anti Windup			
2.5	PI-controller Limit / Anti Windup!			
2.6	PI-controller Limit / Anti Windup!			Yes, T_f

The simulation time is set to 1 second. In the last case you may need to extend it to 2 seconds. This is done in the toolbar at the top of the window.

3 Current Control

Open the files "Current2Q" and "Current4Q". You are going to investigate two current control methods (Sampled and Direct) in two different converters (2-quadrant and 4-quadrant). Below you can see one of the converters (4Q) with some descriptions:

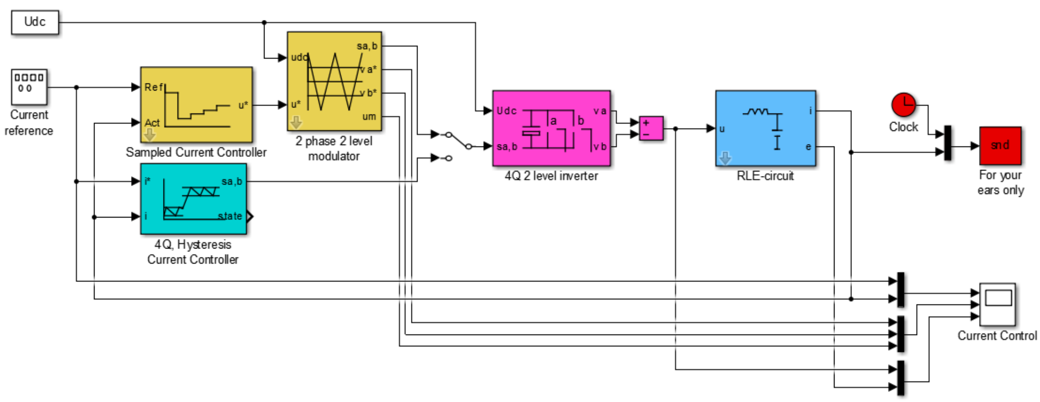

Figure 3.1: The topmost level of the 4Q converter.

These blocks are the **Sampled Current Controller** and the Modulator. The switch to the right of the blocks decide which method is used.

- In the controller block, the controller parameters are set along with a lot of other values. **DO NOT FORGET** to look under the mask to see how the controller equation (look up dead beat control in chapter 3.4 in the text book!) is implemented, so you know how your controller parameters are used.
- In the modulator block, the modulation method (Symmetric or Minswitch) can be chosen as well as the frequency (fixed or random).

The **Direct Current Controller** uses a hysteresis band set by *di* to choose the switching states for the inverter. Before you start the simulation you must give *di* a value, start by setting it to
```
>> di=5;
```

This is the **inverter**, which has either one or two output voltages (depending on if you look at the 2Q or 4Q inverter).

This is the **load**, modelling the DC Machine as just a resistance, an inductance and a constant induced back emf that is preset to 40 V.

These blocks create a vector so that you can listen to the inverter switching via the "Playsound.m" file. This is optional! See more info at the end of the task (after the Case table).

For each case, present the following:

- A screenshot of the plots.
- (When applicable:) Your choice of controller parameters (both P and I) with motivation.
- Your comments about response time, stability, current ripple size and frequency.

Case	Circuit	Controller	Controller setting	More settings/comments
3.1	2-quadrant (Default controller setting: Fixed frequency)	Sampled	Fast computer	Use deadbeat gain.
3.2			Slow computer	Use a gain that gives a stable step response.
3.3			Slow with Smith Predictor	Use deadbeat gain.
3.4			Slow with Smith Predictor, Random modulation	
3.5		Direct	N/A	Select a *di* that gives the roughly same current ripple as with the sampled controller.
3.6		Sampled or Direct	Any	Set the back emf to 0 V. **Why does the current not become negative?**
3.7	4-quadrant (Default controller setting: Fixed frequency and Symmetric)	Sampled	Fast computer	Reset 40 V back emf before you proceed. Use deadbeat gain.
3.8			Slow computer	Select a gain that gives a stable step response.
3.9			Slow with Smith Predictor	Use deadbeat gain.
3.10			Slow with Smith Predictor, Random modulation	
3.11		Direct	N/A	Select a *di* that gives the same current ripple as with the sampled controller.
3.12		Sampled or Direct	Any	Set the back emf to 0 V. Why does the current become negative?

If you want to, you are free to play with the modulation and sound aspects. The best sound impression is made if you set the current reference constant, e.g. zero, and uses the "Playsound" command after a simulation according to:

```
>> Playsound(snd(:,1),snd(:,2))
```

Try out the sound of a fixed frequency, and of random modulation. Think of what you prefer. The fixed frequency has a "penetrating" pitch and can be annoying, but on the other hand it is clear and "clean". The random modulation gives a "crunchy" sound that is easier to disregard in an otherwise noisy environment, but sound like "sand in the gearbox" which may be annoying to an engineering ear.

4 Full system

Now, you have experimented with the speed control and current control of a DC Machine. But the DC Machine has only been modeled a first order torque source, a RL-circuit and a constant back emf.

Your task is now to put together a new model for a speed control system, which contains the DC Machine model and the necessary power electronic control system. You are free to do it as you prefer, but here are some advices:

1. Use the "Speed"-program, and save it under another name, like "FullSpeed" or whatever you like.
2. Select the torque source model, the torque summation point and the inertia model and use the menu-command "Create Subsystem".
3. Open the new subsystem. It contains two input nodes (torque reference and load torque) and two output nodes (torque and speed). Delete the contents except for the input and output nodes. Rename the inputs and outputs to names you understand (like "T*" or "Torque ref").
4. Copy all the contents of the "Current4Q" model and paste it into the empty subsystem you just have created.
5. Delete the RLE Load model and copy and paste the "DCM"-motor from "DCM.mdl" into the place where the load model was.
6. Connect all the input and output nodes to the proper places. Most connections should be intuitive, but to turn the torque reference signal into a current reference signal, you have to insert a Gain block (Library Browser → Math operations) and multiply/divide with the correct kind of unit.
7. Voila – you now have a torque source and mechanical dynamics model representing the real control system in very good detail.

Run the following cases and present the following:

- A screenshot of your full system Simulink model AND notes of what the gains or other values in the added blocks are set to.
- Controller parameters chosen.
- Screenshot of plots.
- In Case 4.1, you only have to see that the speed and torque references are reasonably well followed by the actual values.
- In Case 4.2, try to answer the following questions:
  - Why does the machine not reach the reference speed?
  - Before the current/torque is lost completely, a phenomenon occurs:
    - If you use Sampled current control: Why is the ripple thickest in the middle of the acceleration?
    - If you use Direct current control: Why is the switching frequency higher in the middle of the acceleration?

Case	Controllers	Torque Source	Load Torque	Speed filter	Comment
4.1	**Speed Controller**: PI with Limit / Anti Windup. **Current Controller** of your choice.	Full	No	Yes, T_f	Run everything like Case 2.6, but without load torque, just to check that your solution works.
4.2	**Speed Controller** PI with Limit / Anti Windup. **Current Controller** of your choice.	Full	No	Yes, T_f	Set the speed reference to a step to 400 rad/s.