

The DC Machine

Laboration 3

Updated February 27, 2020

- 1. Before the lab, look through the manual and make sure you are familiar with all parts!**
- 2. Bring the course book, a pen, a notebook and this lab manual (on a printed copy, tablet or laptop, but not on a cellphone) to the lab.**
- 3. You are not allowed to do the lab if you have not submitted your home assignment for the DC Machine.**

1 Introduction

In this lab a current controller for a DC machine and a speed controller for the 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 decide in what way the CompactRIO should act is made on an interface implemented on a PC. This setup will be the same for all future labs, except that the DC machine is not always connected.

2 The equipment

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 feed 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 DC machine and brake with the PMSM by applying an external resistive load to its terminals. This means that the no load voltage of the PMSM, that is proportional to speed, will be applied to the external resistor and the braking power thus be 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 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.



Figure 3.1: The Setup Tab – Setting general parameters

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 should enter the maximum DC-link voltage, the maximum motor current, the maximum motor speed, the number of poles in the resolver and the linked flux, Ψ_m . When entering maximum DC-link voltage and maximum motor current the program tells you how the signal conditioning should scale the voltage and current.

3.8 Current control parameters

When working with power electronics it is important to not exceed the maximum allowed switching frequency, hence an over frequency protection is implemented. If for example a turn on has occurred the protection will not allow another turn on again before a certain time has elapsed. Notice that the same applies for turn offs, i.e. a turn off can occur directly after a turn on, but a subsequent turn on cannot happen until a certain time has passed. The time is based on the entered *maximum switching frequency* (See figure 3.2).

The *switching frequency* is used as frequency for the carrier wave frequency in the modulator and for calculation of the regulator parameters, as well as the motor *inductance* and *resistance*.

3.8.1 Testing

This option is not supposed to be used in the labs. It allows the user to *manually switch* the bridge legs which could be useful during tests.

3.8.2 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



Figure 3.2: The Current Control Parameters

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. 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.

3.9 Current control

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 is used in many tabs and is probably pretty self-explanatory (See figure 3.3). However it should be mentioned that the whole controller is turned on and off with the switch in the reference generator. The sampling delay box is affecting the same variable as in voltage control. It is possible to tune the controller parameters with the sliders. The dead beat parameters is calculated from the entered motor data, and a 100 % setting on the slider corresponds to this value. You can turn the anti windup protection on and off and reset the integrator with the switch and the button.

3.9.2 Tolerance band current control

This tab (See figure 3.4) is very similar to the sampled current controller tab. There are three parameters to tune, hysteresis band, hysteresis diff and maximum time between switches. Since it is a band controller it is quite obvious what the hysteresis band box corresponds to. To determine if the controller acted sufficiently when the current crossed one of the bands there are two more band outside these bands. If the current crosses one of these *outer* bands the controller knows that the output voltage change did not change the current slope in the right direction. The distance between the *inner* bands and the *outer* bands is controlled with the hysteresis diff.

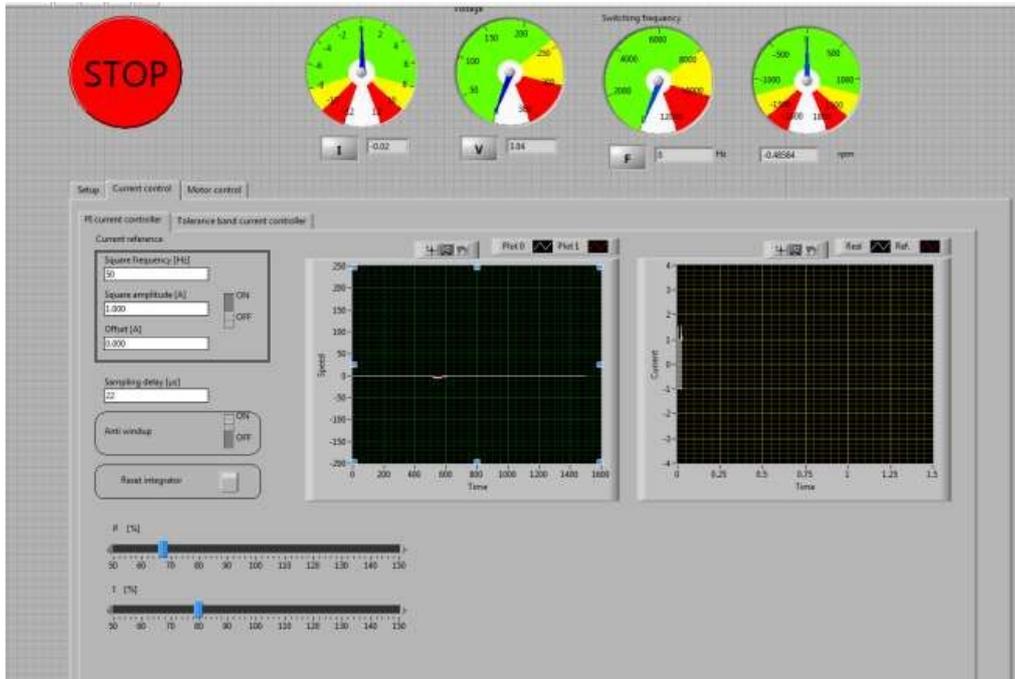


Figure 3.3: PI based current control parameters

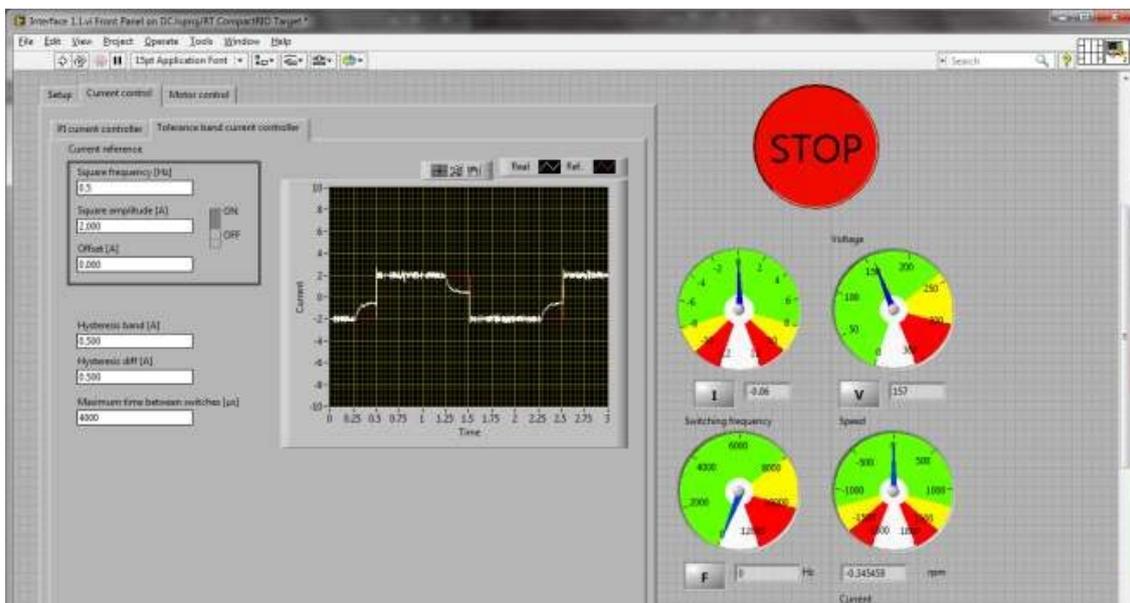


Figure 3.4: Tolerance band current control parameters

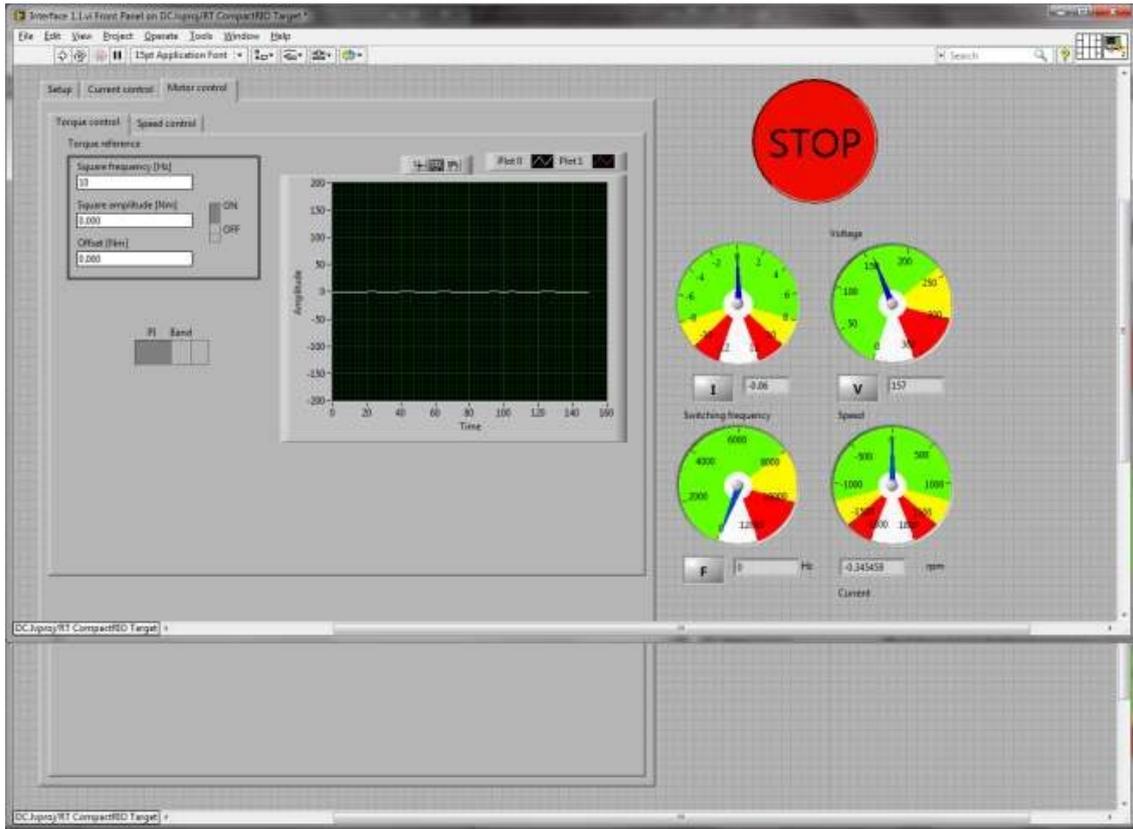


Figure 3.5: Torque controller

If the desired current is small and the inner band are on different sides of zero current there is a problem. When the voltage is turned off the current will fall to zero and the controller will get stuck since the current never reaches the negative current that will turn on the voltage again. The mean current will not be equal to the desired current. In this cases the controller uses the maximum time between switches, which is the time that the controller will wait before it force a change of output voltage to get loose again.

3.10 Motor control

Here you can choose between torque and speed controlling of the motor.

3.10.1 Torque control

The torque controller (See figure 3.5) is nothing else but the current controller but with the reference scaled so that you could enter the reference in Nm instead of A. You can choose which current controller you want to use. The entered parameters from the current control tab will be used. If you want to evaluate both kinds of current controllers for torque control, make sure to tune them in the current control tab first!

3.10.2 Speed control

To control the speed of the DC machine a PI controller is used. It uses the reference created with the generator and the feedback signal from the resolver to create a torque reference. The torque

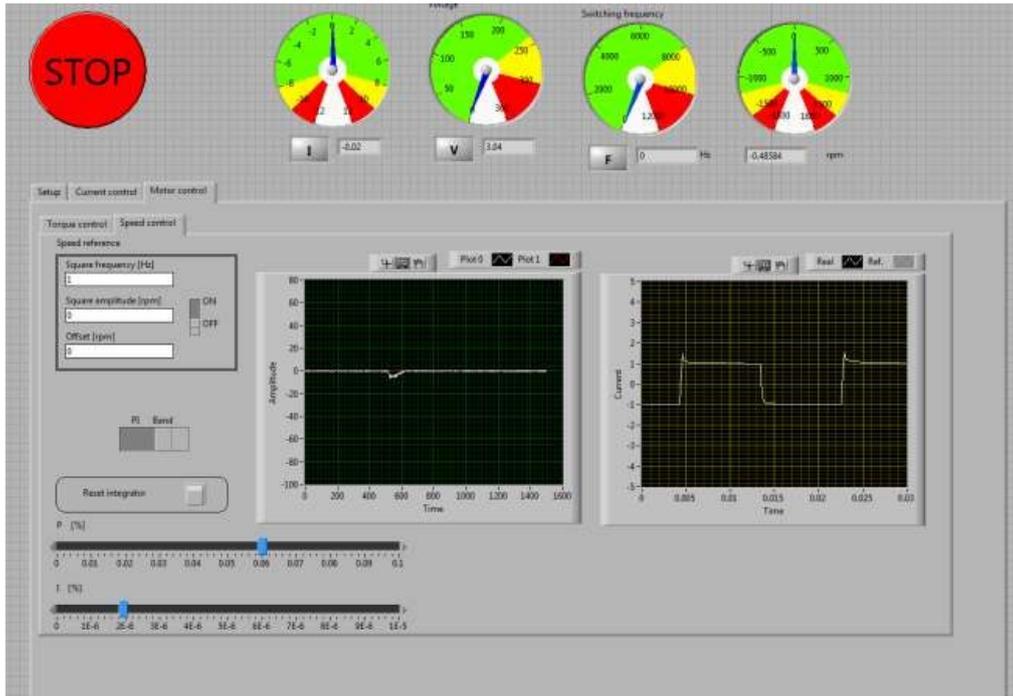


Figure 3.6: Speed controller

reference is converted to a current and feed to the current controller that you choose. If you want to evaluate both current controllers, make sure to tune them in current control first!

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

3.11 Safety

Of course you should have in mind that it is quite much power you are controlling with this equipment. Connectors, etc. is as far as possible protected against human contact, but since it is lab equipment it is not as safe as the electrical equipment you buy at the shop. **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 LM.lvproj. The Project Explorer for the DC machine control project will open.
3. In the navigation tree in the tab *Items* expand the cRIO item named PEstation2 and then the RT VIs folder.
4. To open the control interface double click on **Interface 1.1.vi**.
5. Click on the run button in the upper left corner of the toolbar.
6. If everything works the icon of the run button changes and the control system is executed in the cRIO system.
7. 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 current with a 4-quadrant bridge towards the RLE-like rotor circuit of a DC machine, both with a sampled current controller and a tolerance band controller. Study these sections of the course material before you enter the lab.
- You should in case of 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.
- Controlling Speed with a DC-machine with and without load. You shall do this both with the PI-based current control and with the tolerance band current control.

4.3 Sampled current control

First, calculate the theoretical proportional and integral gains for the Sampled current controller. The relevant values for the DC machine are found under the Setup → Current control parameters in Labview.

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- Attach a (Y-connected) resistive load to the brake machine (the PMSM) terminals and turn it to roughly halfway between min and max. It will be used to break the DC Machine in (parts of) this lab.
- Turn the red/yellow switch on the front panel of the **DCM VSC** to 1 and turn on the corresponding green switch.

- Do not** switch on the brake machine VSC. Both the green and the red/yellow switch on the front panel of the **PMSM VSC** should be set to 0 during the whole lab.
- Magnetize the DC Machine with the adjustable transformer on the rack. The magnetization current should be set to 0.8 A. When the windings get hot, the current will decrease. When this happens, turn it back up to 0.8 A.
- Connect a voltmeter to any of the DC link voltage terminals of the VSCs.
- Carefully increase the DC link voltage to 150 V with the adjustable transformer on the bench. Some of the transformers are very responsive, so take it easy. Use the voltmeter to measure the DC link voltage.
- In Labview open the Current control → PI current controller tab.
- Set the current reference to a square wave, with ± 2 A and 0.5 Hz.
- Turn on the current reference signal.
- Play around with the controller parameters (P and I) until you understand how they affect the step response.

Tip: Follow the instructions in figure 4.1 to make the graph zoom to fit the data. Remember this, you will find it useful many times during this and coming labs.

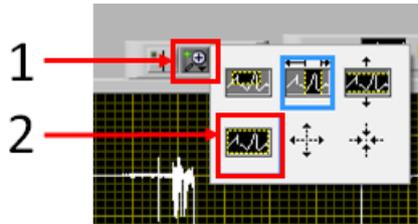


Figure 4.1: Tip for graphs in Labview

Set the controller parameters to values that give a step response you are happy with and write them down:

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- Turn off the current reference and make sure the machine has stopped.
- Disconnect the resistive load from the PMSM.

Why should you **not** disconnect the load while the machine is running?

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- Set the current reference back to the same square wave as before and reduce the frequency until the speed starts to flatten out just before the end of each square.

Look at the machine behind the bench. You will see the machine going back and forth. At what point in the current square wave is the machine turning from one direction to the other?

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- With the oscilloscope, connect one channel to look at the current ripple.
- With the other channel of the oscilloscope, look at the voltage pulses from the PWM/VSC.

How is the shape of the voltage and the current linked? Why is the duty cycle changing?

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At what duty cycle is the current ripple at its biggest? Why?

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- Reduce the square wave frequency even more, so that you can see how the speed stabilizes.

What is happening to the current and why?

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- Carefully increase the DC link voltage slightly, to roughly 160 or 170 V.

What happens to the speed? Does it make sense? Calculate the expected back emf at this speed.

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- Turn off the current reference and make sure the machine has stopped.
- Set the DC link voltage back to 150 V.

4.4 Direct current control

Calculate what tolerance band that will result in a 2 kHz switching frequency when the speed is 500 rpm at 2 A. Use the motor parameters from the Setup → General and Current control parameters tabs in your calculations.

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- Switch to the tolerance band/direct current control tab.
- Apply the calculated tolerance band in LabView. Note, there is a “Hysteresis diff” to set as well. This is the width of the outer band in the “double walled” hysteresis band used in the hysteresis controller for a 4-quadrant converter. Set this to a higher value than the tolerance band.
- Set the current reference to a square with ± 2 A and 0.5 Hz.
- Turn on the reference signal.

Do your calculations seem to be somewhat right?

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- Play around with the hysteresis band width while you listen to the sound and look at the current response.

Why is the switching frequency varying?

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- Set the current reference square frequency to a value that makes the controller loose control of the current just before the reference changes.

Draw the shape of the speed and the pitch of the sound during a whole period of the current square wave into figure 4.2.

- Turn off the references and make sure the machine has stopped.

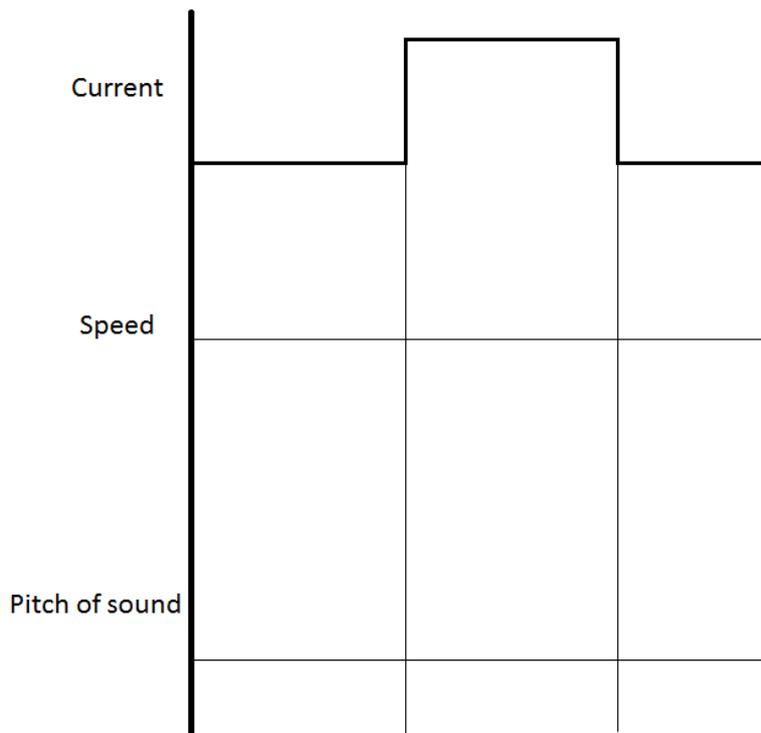


Figure 4.2: Direct current controller

4.5 Speed control

Now that we have learned current control, we can start to use it to control the speed of the machine.

- Switch back to the PI current control tab and make sure the parameter values you picked before are set.

For speed control, calculate the proportional and integral gains that are used in the controller, assuming NO speed filter, using Symmetric Optimum and a first order approximation of the torque response. Use $J = 0.034 \text{ kg m}^2$.

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- Switch to the Motor control → Speed control tab.
- Apply a square wave of $\pm 250 \text{ rpm}$ with a frequency that lets the speed controller to stabilize before the end of the step.
- Play around with the PI settings of the speed controller until you understand how they affect

the step response.

Not that it might take a second or two before Labview updates the speed graph. Set the controller parameters to values that give a step response you are happy with and write them down:

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Look at the current. Do you understand the relationship between the current plot and the speed plot?

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- Make sure the resistive load is disconnected. Stop the machine if you have to disconnect it!
- Set the speed step amplitude to 0 rpm and the speed reference to offset 750 rpm.
- Set the Integral part of the speed controller to zero.
- Press the Reset integrator button.

Do you get any stationary error? How big?

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How big is the current?

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- Turn off the speed reference and make sure the machine has stopped.
- Reconnect the resistive load and adjust it for a high load (low R).
- Turn the speed reference back on.

How big is the stationary error now?

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- Reestablish the Integral part of the speed controller

Do you still have a stationary error?

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How big is the current now? Can you explain the difference?

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- Turn off the speed reference.
- Check with supervisor that you are done.
- Turn off the Red/Yellow switch, then the green switch of the DCM VSC.
- Disconnect the load resistance and return the cables.
- Turn U_{dc} down to minimum.
- Turn off the DC machine magnetization current.

Good job! If you're happy with the comments you've gotten on the lab and your home assignment, you're done! (You are free to refine and re-submit your home assignments before you receive your individual feedback if you already know what you can improve)