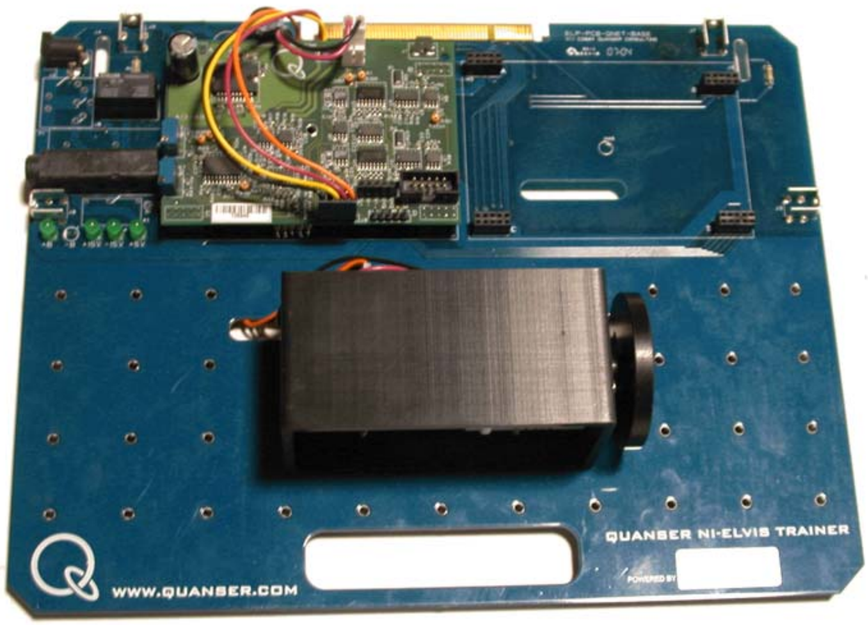
*Quanser NI-ELVIS Trainer (QNET) Series:*

# QNET Experiment #01: DC Motor Speed Control

## *DC Motor Control Trainer (DCMCT)*




# Student Manual

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# 1. Laboratory Objectives

The objective of this experiment is to design a closed-loop control system that regulates the speed of the DC motor. The mathematical model of a DC motor is reviewed and its physical parameters are identified. Once the model is verified, it is used to design a proportional-integral, or PI, controller.

# 2. References

[1] *NI-ELVIS User Manual*
[2] *DCMCT User Manual*

# 3. DCMCT Plant Presentation

## 3.1. Component Nomenclature

As a quick nomenclature, Table 1, below, provides a list of the principal elements composing the DC Motor Control Trainer (DCMCT) system. Every element is located and identified, through a unique identification (ID) number, on the DCMCT plant represented in Figure 1.

| ***ID #*** | ***Description*** | ***ID #*** | ***Description*** |
|---|---|---|---|
| **1** | DC Motor | **3** | DC Motor Case |
| **2** | Motor Encoder | **4** | Disc Load |

Table 1 DCMCT Component Nomenclature

Figure 1 DCMCT Components

## 3.2. DCMCT Plant Description

The DCMCT system consists of a DC motor equipped with a servo motor driving a disc load. The motor input is a voltage with a range of ±24V. The motor has an encoder that measures its position, a digital tachometer that measures its speed, and a current sensor to measure the actual current being fed into the motor.

It is assumed that the QNET system is properly configured as dictated in Reference [1].

# 4. Pre-Lab Assignment

**This section must be read, understood, and performed before you go to the laboratory session.**

The purpose of the experiment is to introduce concepts of control by investigating the characteristics and behaviour of a DC servo motor. As a result, it is important to become familiarized with the physical characteristics of the motor.

The DC motor has both electrical and mechanical properties. For the various parameters defined in Table 2, the electrical equations describing the open-loop response of the DC motor are

$$V_m(t) - R_m\, I_m(t) - E_{emf}(t) = 0 \quad [1]$$

and

$$E_{emf}(t) = K_m\, \omega_m(t) \quad [2]$$

The mechanical equations describing the torque of the motor are

$$T_m(t) = J_{eq} \left( \frac{d}{dt} \omega_m(t) \right) \quad [3]$$

and

$$T_m(t) = K_t\, I_m(t) \quad [4]$$

where $T_m$, $J_{eq}$, $\omega_m$, $K_t$, $K_m$, and $I_m$ are described in Table 2.

| ***Symbol*** | ***Description*** | ***Unit*** |
|---|---|---|
| $V_m$ | Motor terminal voltage | V |
| $R_m$ | Motor terminal resistance | Ω |
| $I_m$ | Motor armature current | A |
| $K_t$ | Motor torque constant | N.m/A |
| $K_m$ | Motor back-electromotive force constant. | V/(rad/s) |
| $\omega_m$ | Motor shaft angular velocity | rad/s |
| $T_m$ | Torque produced by the motor | N.m |
| $J_{eq}$ | Motor armature moment of inertia and load moment of inertia | kg.m$^2$ |

Table 2 DC Motor Model Parameters

## 4.1. Exercise: Open-loop Modeling

Derive the open-loop transfer function, $\omega_m(s)/V_m(s)$, representing the DC motor speed using equations [1], [2], [3], and [4].

# 5. In-Lab Session

## 5.1. System Hardware Configuration

This in-lab session is performed using the NI-ELVIS system equipped with a QNET-DCMCT board and the Quanser Virtual Instrument (VI) controller file *QNET_DCMCT_Lab_01_Speed_Control.vi*. Please refer to Reference [2] for the setup and wiring information required to carry out the present control laboratory. Reference [2] also provides the specifications and a description of the main components composing your system.

Before beginning the lab session, ensure the system is configured as follows:

QNET DC Motor Control Trainer module is connected to the ELVIS.
ELVIS Communication Switch is set to BYPASS.
DC power supply is connected to the QNET DC Motor Control Trainer module.
The 4 LEDs +B, +15V, -15V, +5V on the QNET module should be ON.

## 5.2. Experimental Procedure

The sections below correspond to the tabs in the VI, shown in Figure 2. Please follow the steps described below:

Step 1. Read through Section 5.1 and go through the setup guide in Reference [2]
Step 2. Run the VI controller *QNET_DCMCT_Lab_01_Speed_Control.vi* shown in Figure 2. The speed control VI shown in Figure 2 is the top-level VI that will guide you throughout the laboratory.

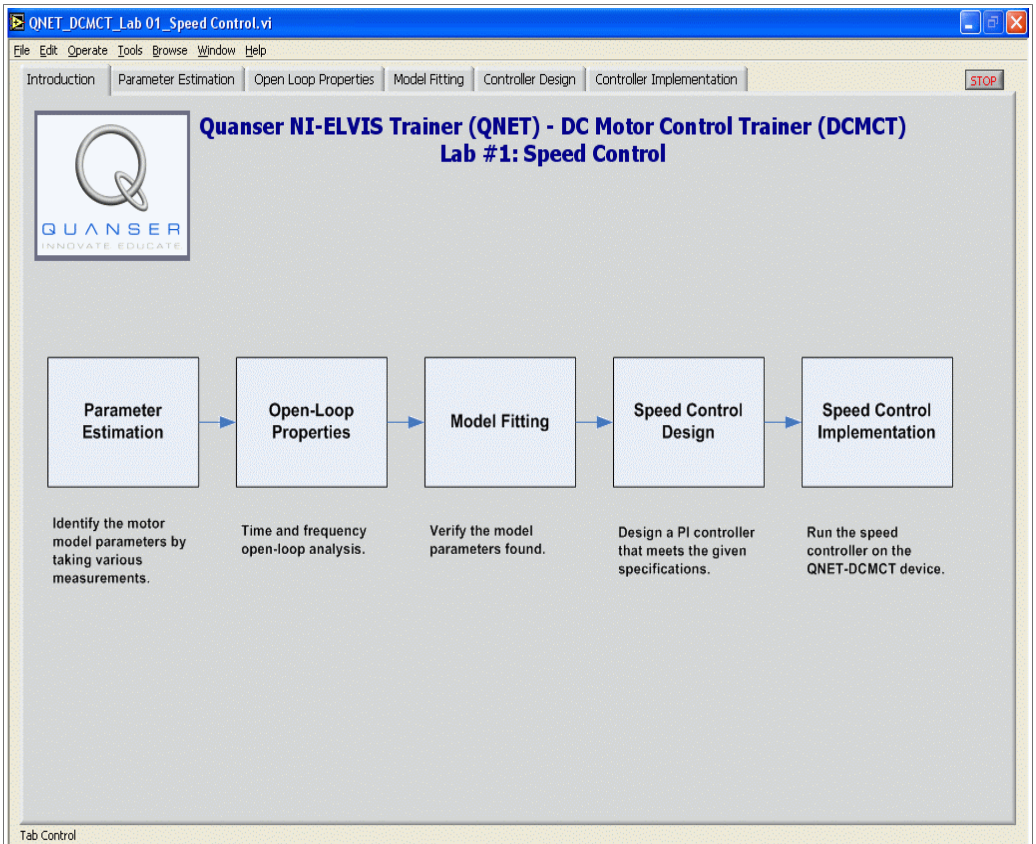


Figure 2 Overview of QNET-DCMCT Speed Control Laboratory VI

Step 3. As discovered in the pre-lab there are three characteristics that determine the operation and behaviour of a DC servo motor:
(1) **Motor Electrical Resistance ($R_m$) –** An electrical property of a motor. It describes the motor's response to a given voltage and determines the amount of current able to flow through the motor.
(2) **Motor Torque Constant ($K_t$) –** Describes the torque a motor generates and is directly proportional to the current going through the motor. Note that the electromotive force constant, $K_m$, is equal to the motor torque constant $K_t$.
(3) **Moment of Inertia ($J_{eq}$)** – The moment of inertia of the disc load and the motor shaft.
These three open-loop model parameters will be identified.

Step 4. Select the *Parameter Estimation* tab that opens the sub-VI shown in Figure 3.

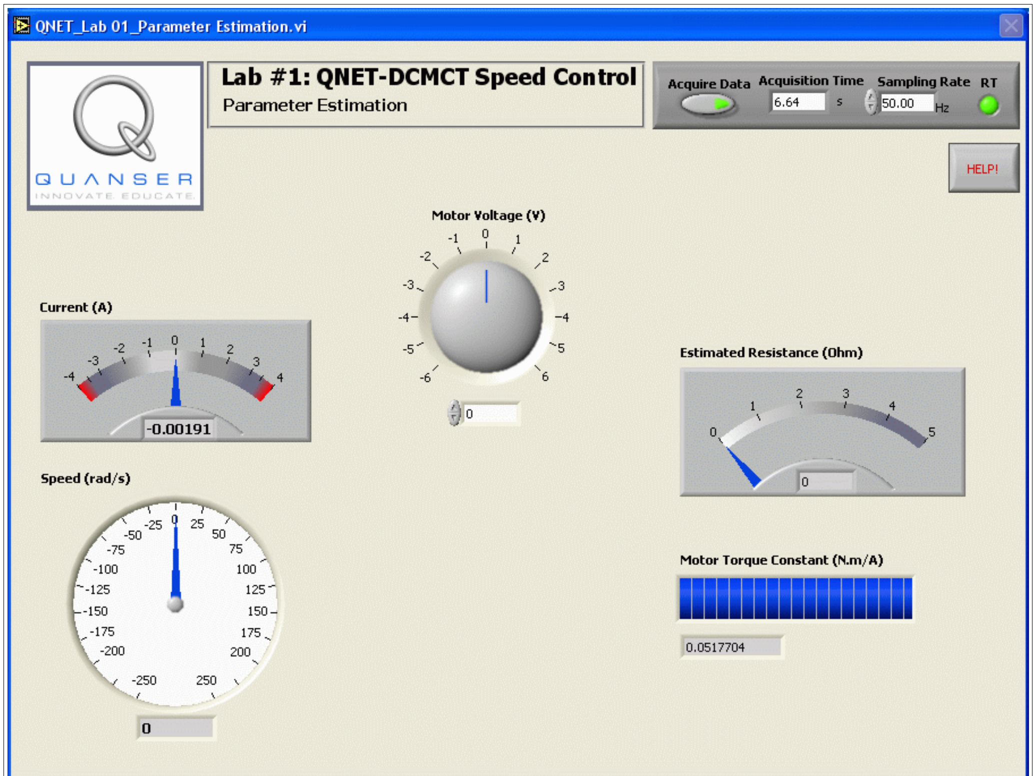


Figure 3 Parameter Estimation

Step 5. The current running through the motor armature, the speed of the motor shaft, the motor terminal resistance, and the torque constant are measured using the tachometer and the current sensor. They are displayed through the various gauges shown in Figure 3. The input voltage of the motor, $V_m$, is controlled using the knob in the top-center of the VI. The top-right panel contains an *Acquire Data* button that stops the VI when pressed. Additionally, the panel contains an *Acquisition Time* indicator that displays the running simulation time of the VI, a control that can change the rate at which the analog controller are sampled, and an LED that indicates whether the controller is maintaining real-time. Real-time is maintained when the VI does not loose any samples from the sensors.

**If the LED is red or flickers, it implies that there is insufficient computational power for the VI to keep up with the sensors.** In this case, decrease the sampling rate and restart the VI by clicking on the *Acquire Data* button to close the VI and selecting the *Parameter Estimation* tab to reload this VI.

Step 6. Increment the voltage of the motor in steps of 1V starting at -5V to +5V. At each step, measure the motor speed, motor current, and stall current. The stall current is measured by holding the load such that the motor is no longer spinning (i.e. stall the motor). Record your results in Table 3.

| ***Motor Voltage (V)*** | ***Motor Speed (rad/s)*** | ***Motor Current (A)*** | ***Stall Current (A)*** |
|---:|---|---|---|
| -5 | | | |
| -4 | | | |
| -3 | | | |
| -2 | | | |
| -1 | | | |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |

Table 3 Parameter Estimation Measurements

Step 7. Click on *Acquire Data* after all the measurements are taken to proceed with the laboratory.

Step 8. These measurements are used to identify the physical parameters of your particular motor. Later, the mathematical model being developed is used to design a controller. Ensure the same system used to develop the model is also used when implementing the control system. As discussed earlier, there are three model parameters to be identified – electrical resistance, motor torque constant, and the equivalent moment of inertia.

Step 9. Recall that the The DC motor's electrical equations are

$$V_m(t) - R_m\, I_m(t) - E_{emf}(t) = 0 \qquad [5]$$

and

$$E_{emf}(t) = K_m\, \omega_m(t) \qquad [6]$$

As captured in equation [6], if the motor is not allowed to spin (i.e. motor stalled) there is no back-emf voltage. Therefore if $E_{emf}$ = 0V when I = $I_{stall}$, equation [5] becomes

$$R_m = \frac{V_m(t)}{I_{stall}(t)} \quad [7]$$

Step 10. The motor resistance can be estimated by copying your stall current measurements from Table 3 into Table 5 and calculating $R_m$ at each voltage step using the expression in [7]. The estimate of the motor resistance can then be found by taking the average over the ten measurements.

| ***Motor Voltage (V)*** | ***Stall Current (A)*** | ***Estimated Resistance (Ω)*** |
|---|---|---|
| -5 | | |
| -4 | | |
| -3 | | |
| -2 | | |
| -1 | | |
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| **Average Electrical Resistance ($R_m$):** | | |

Table 4 Electrical Resistance Estimation

Step 11. The second model parameter to be found is the motor torque constant, denoted by $K_t$. Given that in SI units $K_t = K_m$, combining equations [5] and [6] and solving for the torque constant gives

$$K_t = \frac{V_m(t) - R_m I_m(t)}{\omega_m(t)} \quad [8]$$

The torque constant can be calculated at each voltage step using the motor speed and the current recorded in Table 3, along with the estimated electrical resistance in Table 4. The final estimate of the motor torque constant is found by taking the average of the ten torque constants. Complete Table 5.

| *Motor Voltage (V)* | *Motor Speed (rad/s)* | *Motor Current (A)* | *Estimated Motor Torque Constant (N·m/A)* |
|---|---|---|---|
| -5 | | | |
| -4 | | | |
| -3 | | | |
| -2 | | | |
| -1 | | | |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| **Average Motor Torque Constant ($K_t$):** | | | |

Table 5 Motor Torque Constant Estimation

Step 12. The final parameter needed to be calculated is the moment of inertia. In the case of the QNET module, there is a disc load fastened to the motor shaft. The moment of inertia of a disc rotating about its center is

$$J_l = \frac{m\,r^2}{2} \quad [9]$$

The moment of inertia of the disc used in the QNET systems is 0.000015 kg m$^2$. The motor shaft also adds to the moment of inertia of the system and varies with each QNET module. The total equivalent moment of inertia, $J_{eq}$, will be found by *fitting* the model to the actual system later.

Step 13. Click on the *Open-Loop Properties* tab and the VI shown in Figure 4 should be loaded.

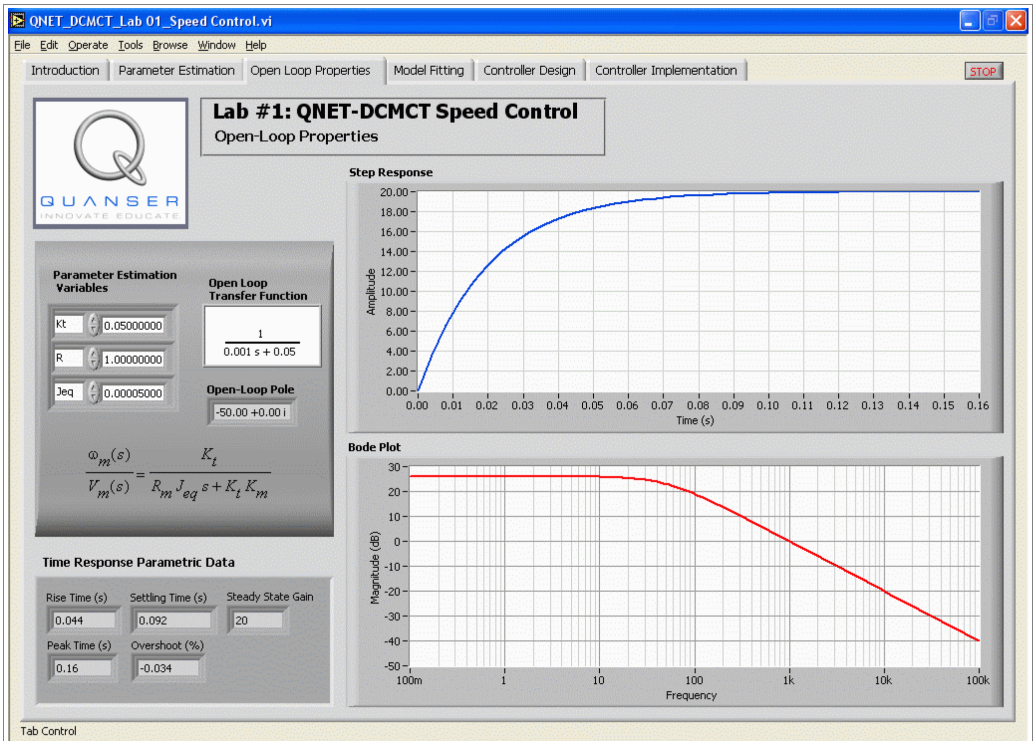

Figure 4 Open-Loop System Properties

Step 14. Enter the estimated values of $R_m$, $K_t$, and $J_{eq}$. The response should change accordingly.

Step 15. The motor's step response is the response of the motor speed when subject to a 1V unit step. The bode plot maps the motor speed response to a given input frequency. Note that the magnitude is in dB and decreases at higher frequencies. Take this opportunity to investigate the model of the system by varying the three model parameters and how each effects the step response, bode plot, and transfer function. For instance, observe how the *peak time* rises and the *settling time* decreases when the motor inertia $J_{eq}$ increases.

Step 16. After the open-loop properties have been investigated, make sure the parameters are set back to those originally identified. Select the *Model Fitting* tab that load the VI shown in Figure 5 and continue with the laboratory.

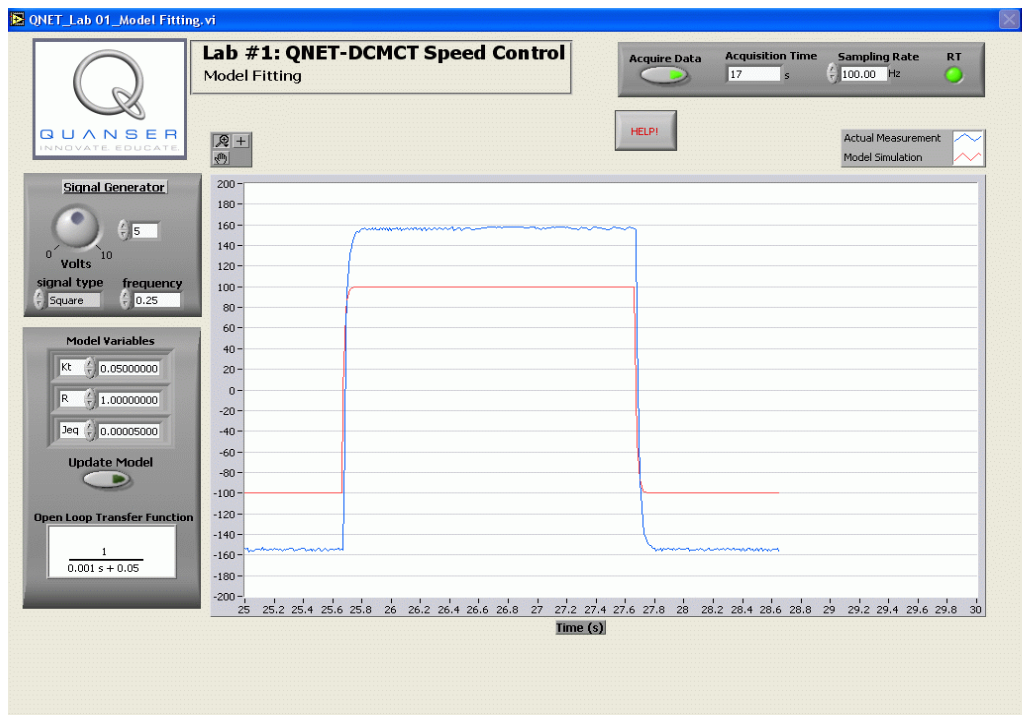

Figure 5 Model Fitting

Step 17. As depicted in Figure 5, the scope displays the simulation of the motor speed response, generated using the mathematical model developed, and the actual motor speed response, measured using the tachometer sensor. The QNET motor is being driven by the signal generator.

Step 18. Enter the estimated parameters $R_m$ and $K_t$ are into the model variables. Select the *Update Model* button and notice that the simulation on the plot changes because it is simulating the system using the model with new parameters.

Step 19. Adjust the inertia parameter $J_{eq}$ until the simulated response begins to match the actual response. As mentioned earlier, the inertia of the disc load is known but the inertia of the motor shaft is not.

**Remember to click on the *Update Model* button after changing a model parameter for the changes to take effect in the simulation.**

Step 20. Additionally, the motor torque constant, $K_t$, and the motor resistance, $R_m$, can be adjusted to fine-tune the model fitting. Once the simulation matches the actual response well, record the final $J_{eq}$, $K_t$, and $R_m$ used and click on the *Acquire Data* button to proceed to the control design. **Record these parameters for use in the next session, *DCMCT Laboratory #2 – Position Control*.**

| ***Model Fitted Parameter*** | ***Measured Value*** | ***Unit*** |
|---|---|---|
| $R_m$ | | Ω |
| $K_t$ | | N·m/A |
| $J_{eq}$ | | kg·m$^2$ |

Table 6 Model Fitted Parameters

Step 21. The *Controller Design* tab should now be selected. As shown in Figure 6, the *Motor Model* block is the transfer function representing the open-loop system and the *PI Controller* block is the control system to be designed. Both blocks are in a negative feedback loop, hence making this system a closed loop control system. By default, the reference input signal is a step of a 100 `deg/s`. The control system should output a voltage to the motor that ensures the actual motor speed achieves the desired speed.

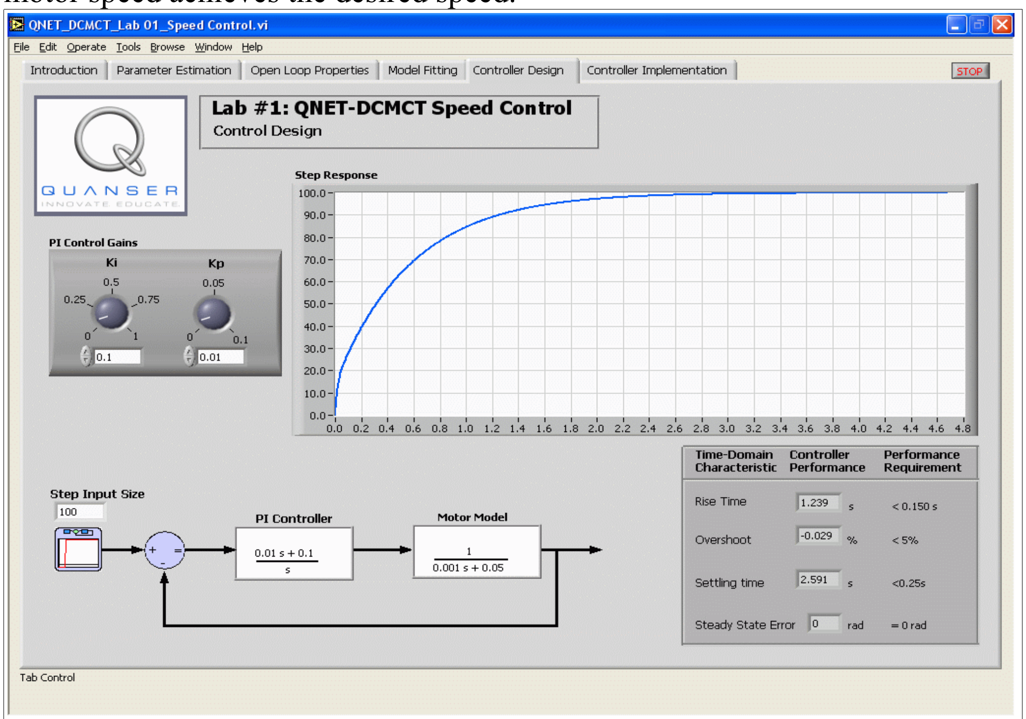

Figure 6 Controller Design

Step 22. The two control knobs in Figure 6 change the proportional gain, $K_p$, and the integral gain, $K_i$, of the controller. Vary the gains $K_p$ and $K_i$ as listed in Table 7 and record the resulting step response changes and *Controller Performance* changes.

| $K_p$ (V/rad) | $K_i$ (V/rad.s) | Rise Time (s) | Max. Overshoot (%) | Setting Time (s) | Steady-State Error (%) |
|---|---|---|---|---|---|
| 0.00 | 0.50 | | | | |
| 0.03 | 0.50 | | | | |
| 0.05 | 0.50 | | | | |
| 0.08 | 0.50 | | | | |
| 0.10 | 0.50 | | | | |
| 0.05 | 0.00 | | | | |
| 0.05 | 0.25 | | | | |
| 0.05 | 0.50 | | | | |
| 0.05 | 0.75 | | | | |
| 0.05 | 1.00 | | | | |
| | | | | | |

Table 7 Controller Performance

Step 23. In general, the type of specification and performance required by a control system varies depending on the need of the overall system and the physical limitations of the system. Find controller gains $K_p$ and $K_i$ that best meet the following requirements for the DCMCT system:

(1) Maximum *rise time* of **0.15** s.

(2) *Overshoot* should be less than **5** %.

(3) *Settling time* less than **0.25** s.

(4) *Steady-state error* of **0** % (i.e. measured motor speed should eventually reach the speed command).

Step 24. Once the controller gains yield a closed-loop response that meets the required specifications, enter the $K_p$ and $K_i$ gains used in the last row of Table 7 along with the resulting response time-domain properties.

Step 25. Select the *Controller Implementation* tab to load the VI shown in Figure 7. The controller designed is now to be implemented on the actual QNET DC motor system. The scope in *Controller Implementation* VI, as shown in Figure 7, plots the simulated motor speed from the mathematical model developed and the actual closed-loop speed of the motor measured by the tachometer.

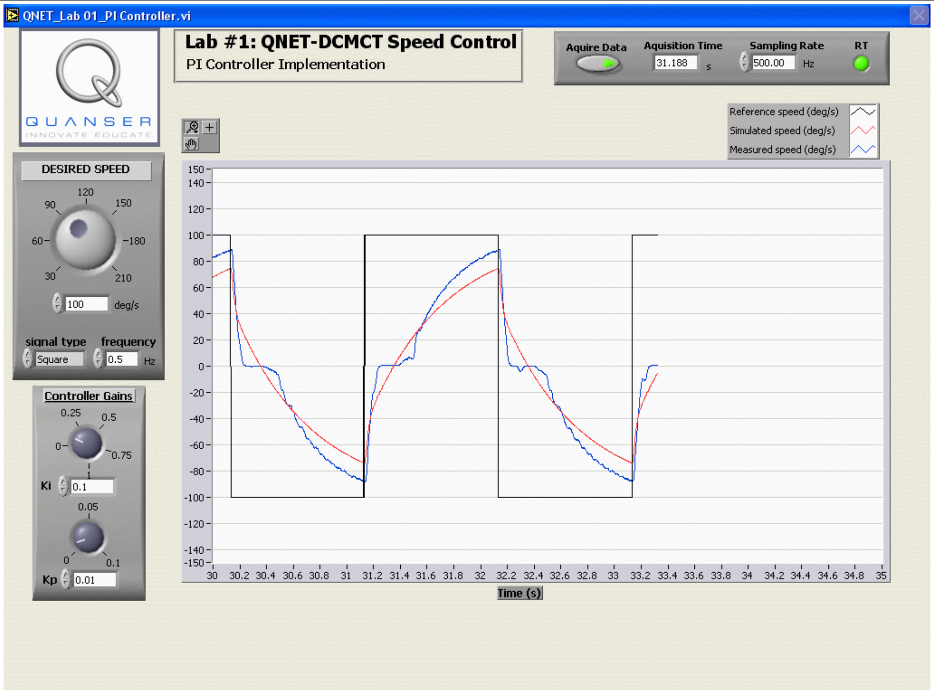


Figure 7 PI Controller Implementation

Step 26. Ensure the proportional and integral gains designed to meet the specifications are set in the *Controller Gains* panel shown in Figure 7. The function generator in the *Desired Speed* panel is used to generate the reference speed. Set the commanded speed signal to a square signal with an amplitude of 100 degrees per second.

**Implement the controller for the same system on which the model was obtained. This ensures the controller is not based on a model that may not represent your motor.**

Step 27. If the simulated or actual closed-loop response no longer meet the requirements, tune the controller in the *Controller Gains* panel. Record the final $K_p$ and $K_i$ used and the resulting control performance properties of the closed-loop response – rise time, overshoot, settling time, and steady-state error in Table 8.

| Specification | Measured Value | Unit |
|---|---|---|
| $K_p$ | | V/rad |
| $K_i$ | | V/(rad.s) |
| Rise time | | s |
| Overshoot | | % |
| Settling time | | s |
| Steady-state error | | deg/s |

Table 8 Actual Closed-Loop Performance

Step 28. Change the amplitude, frequency, and/or type of reference signal (sine, sawtooth, and square) and observe the behaviour of the responses.

Step 29. Stop the controller implementation by clicking on the *Acquire Data* button and this will send you to the *Mathematical Model* tab. Shut off the PROTOTYPING POWER BOARD switch and the SYSTEM POWER switch at the back of the ELVIS unit. Unplug the module AC cord. Finally, end the laboratory session by selecting the *Stop* button on the VI.