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EEI 413: DC Motor Speed Control

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List of Abbreviations

Abbreviation	Meaning
ECSA	Engineering council of South Africa

ELO	Exit level outcome
emf	Electromotive force
dc	Direct current
ac	Alternating current
PI	Proportional and integral
PD	Proportional and derivative
PID	Proportional, integral and derivative
%error	Percentage error
PWM	Pulse width modulation

Executive Summary

The purpose of this report is to document evidence that ELO 2 and 4 are met throughout the experiment. This report documents the process to design a mechanism to control the speed of a dc motor.

The impact of the variance of the NWU's heavy current laboratory direct current (dc) motor parameters and the variance of power electronic converter design on the accuracy of dc motor speed control is assessed. A dc-dc switch mode converter is controlled by a microcontroller with Pulse width modulation (PWM) to control the dc motor speed with switching of the dc-dc converter. The assessment is done through research, experimental design, simulation and data analysis.

To design the controller, the dc motor characteristics had to be determined. The dc motors in the heavy current laboratory of the NWU were tested. The dc motor parameters were determined using the following tests; short-circuit test, open-circuit test, run-down test and the run-up test. The dc motor characteristics are calculated from the results of these tests. A model of the dc motor is simulated with Simulink® using the dc motor characteristics as determined. Thereafter the controller had to be simulated in Simulink® for several tests to ensure its correct operation.

1 Introduction

The experimental aim is to assess the impact on the accuracy of dc motor speed control as a result of the variance in direct current (dc) motor parameters and power electronic converter design. To simulate the dc motor speed control, a dc motor model must first be derived from an actual dc motor. The simulation is used to assess the dc motor speed control.

In order to accurately and efficiently control the speed of a dc motor a few steps need to be completed. Firstly, the dc motor needs to be characterised to ascertain the necessary dc motor parameters required for the modelling and simulation of the motor. Once an accurate model for the motor is created and simulated the design of a PI-controller will start. A PI-controller will be designed and then implemented in simulation with the motor simulation in order to validate the accuracy of the controller model. When established that the PI-controller model has the desired effect on the dc motor model. Finally, the PI-controller will be constructed, implemented and tested with the dc-motor to ensure all models and simulations where accurate.

2 Literature background

2.1 Background to system (dc motors, power electronics and associated control system) being investigated

2.1.1 DC Motor

A section view of the major components of a dc machine can be seen in Figure 1 [1] below. A dc machine may describe either a dc motor or a dc generator. In a dc motor electrical energy is converted to mechanical energy while in a dc generator mechanical energy is converted to electrical energy. The dc machine consists of the following main components, the stator, shaft, brush, commutator, pigtail, pole, armature windings, end-turns and end bell [1].

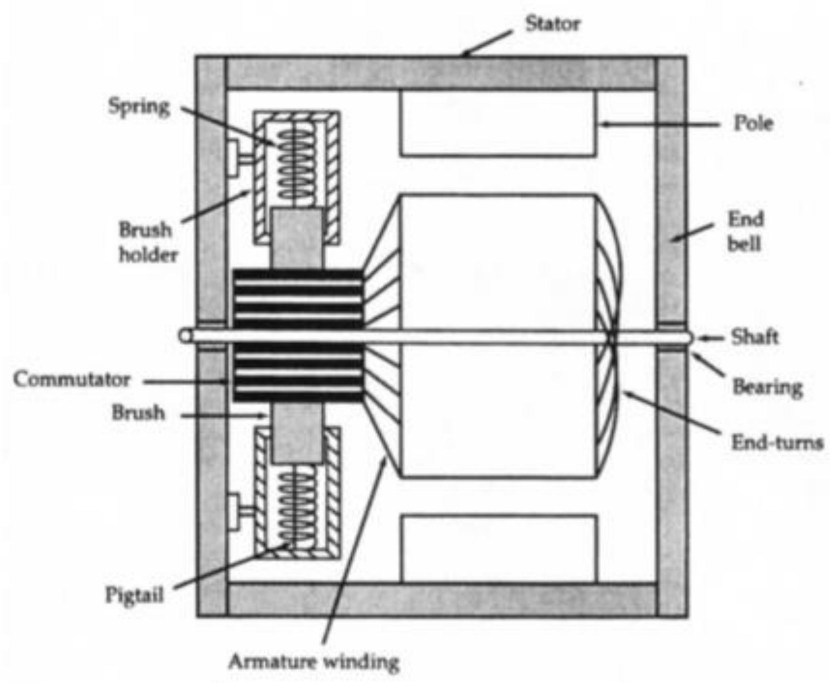

Figure 1: DC Machine section view [1]

This report will solely deal with a dc motor. There are three general types of dc motor namely shunt, series and compound. The dc motor type investigated in this report is a shunt dc motor. A shunt motor is self-excited and in a shunt motor's configuration the armature windings and field windings are connected in parallel as can be seen in Figure 2 below.

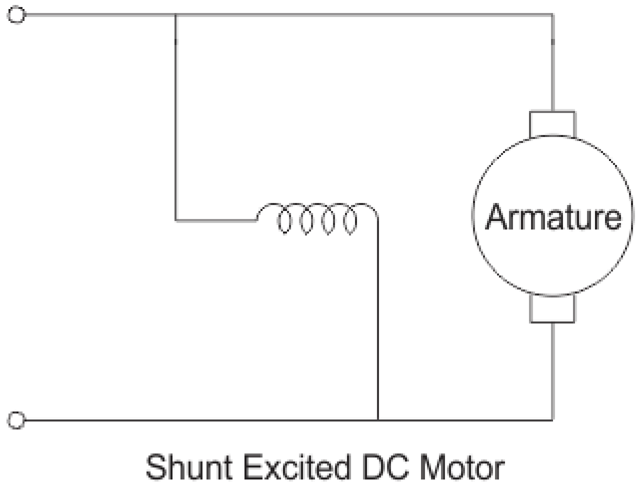

Figure 2 DC shunt motor circuit diagram [2]

The operation of a shunt dc motor is similar to other types of dc motors [2]. The stator is the stationary part of the dc motor and therefore the stator windings is the shunt field windings, which is generally referred to as the field windings. The field windings have a small diameter and many windings turns. The Rotor is also known as the armature, which is the rotating section that carries the shaft load. The armature windings have a large diameter and fewer windings turns. The commutator and brush connect the stator and the armature to conduct the current produced by the windings' magnetic field and the armature, from the field windings to the armature windings [3].

The following aspects control the torque generated by the dc motor: the armature winding and field windings. The torque produced by the dc motor is proportional to the armature current, therefore the current applied to the armature windings should be far higher than the current applied to the field windings in order to produce a high torque. The torque is also proportional to the flux linkage between the armature and field windings. The flux linkage is increased by increased turns of the field windings. Therefore, the armature windings and field windings' effect on the characteristics have to be taken into account in the design of a shunt dc motor. To produce a higher current on the armature windings than on the field windings, the resistance in the field windings are increased. The resistance in the field windings is decreased by reducing the diameter of the field windings in respect to the diameter of the armature windings. The flux linkage is increased by increasing the number of winding turns of the field windings relative to the armature windings. When starting a motor, it is important not to start the motor at rated voltage as the starting current in the armature will be extremely high and damage the armature windings permanently [1].

2.1.2 Power electronics

Power electronics is the technology that acts as an interface between an electrical source and electrical load as shown in Figure 3 below [4]. Knowledge of power electronics is necessary as the electrical source and load often have different frequencies, voltages or number of phases, and power electronics deals with switching electronic circuits in order to control the flow of electrical energy. With power electronic technology it is possible to convert voltage and current of the source from one form to another for the load. Applications for power electronics are often used in renewable energy. Some applications are [4]:

- Storage of energy in batteries and flywheels
- Improved transmission efficiency
- Improved efficiency of electricity consumption in motor driven systems

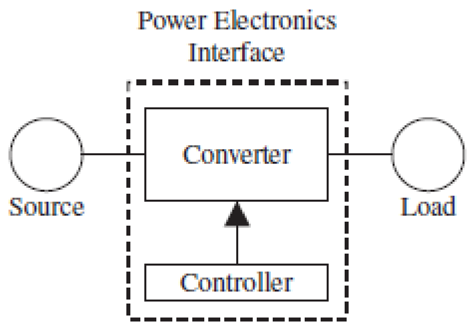

Figure 3: Power electronics interface between the electrical source and the electrical load [4]

Power electronics mostly consists of high-speed switching done with semiconductors such as diodes and transistors. The power electronics switch AC to DC, DC to AC, DC to DC and AC to AC as required by the system.

2.1.3 Associated control systems

The speed of a dc motor can be controlled either with field control, that is by varying the current supply to the stator or armature resistance control, by varying the current control to the stator [1]. However, the speed of a dc motor can also be controlled with a controller such as a type of PID controller. To determine the control of the dc motor a mathematical model is derived with a transfer function to approximate the motor. The converter controls the speed of the dc motor by controlling the voltage output to the dc motor. The converter output is dependent on the duty cycle which is supplied by the PI controller PWM.

2.1.3.1 Field control

During field control the speed of a dc motor is controlled by controlling the flux in the motor through the control of the field current. The field control method is more economical than the armature resistance control, as the field current is a small part of the current intake and therefore the power dissipation is small. A decrease in the flux results in an increase in armature current and therefore an increase in the motor speed [1].

2.1.3.2 Armature resistance control

The speed of a dc motor is controlled by placing a resistance R_c in the armature circuit to decrease the back electromotive force (emf) for the required armature current. The decrease in back emf decreases the motor speed as the motor torque is dependent on the armature current [1].

2.1.3.3 Controller

In the industry Proportional integral and derivative (PID) controllers are often used to control different processes. There are three other forms of this controller namely proportional (P) controllers, Proportional integral (PI) controllers and proportional derivative (PD) controllers [5].

In P controllers the controller multiplies the Error with the proportional gain to obtain the output. The only way to change the outcome of a P controller is thus to change the proportional gain. A PI controller is one of the most common types, as it is less complex than a PID controller but still very effective in control. The PI controller is used to eliminate the steady state error created by the P controller. A weakness of the PI controller is that it has an effect on the speed of the response of the system and is unable to predict future errors.

The PD controller predicts the future error of the response and therefore increases the stability of the system. PID controllers are optimal as they combine both the advantages of the PI controller and the PD controller [5].

The PI controller is used in this experiment to control the speed of the DC motor as it is not as complex as the PID controller, but the elimination of the steady state error is sufficient to control the dc motor speed.

In order to design a PI controller for the control of the dc motor speed a model of the dc motor must be constructed. The dc motor model may be reduced as follow in Figure 4 below [6]. The model will be used in the experimental design.

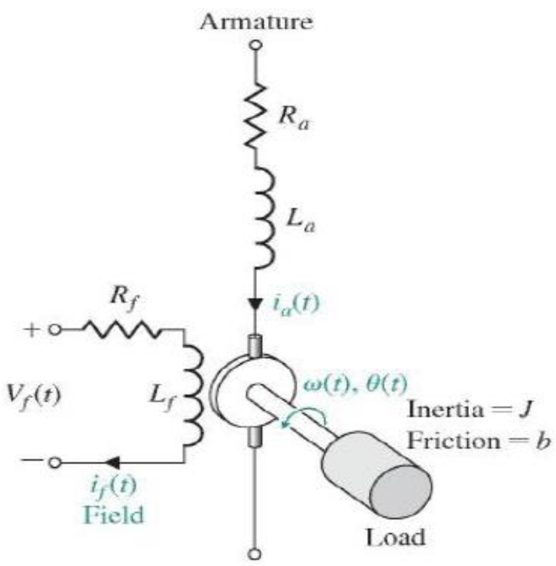

Figure 4: Mathematical model electrical diagram of dc motor [6]

2.2 Background to experiment design

In order to successfully obtain results from experimental design the following steps must be followed [7]:

1. Set objectives
2. Select process variables
3. Select an experimental design
4. Execute the selected experimental design

5. Check the obtained data to ensure that it is consistent with the experimental assumptions
6. Analyse and interpret the results obtained from the experiment
7. Use or present the results obtained from the analysis and interpretation of the results.

Experimental design differs from field to field. Therefore, though the general process of experimental design is similar, the experimental design model varies greatly. Engineering experimental design is similar in the mechanical and electrical fields, but differs substantially from chemical engineering experimental design. For the experiments in this report electrical engineering experimental design will be applied. These are principles of experimental designs [8]:

- Randomization designs
- Crossover Design (Repeat Measures Design)
- Factorial Design
- Blocking principle

2.2.1 Description of Types of experimental designs

2.2.1.1 Factorial Design

Factorial design consists of two or more factors with discrete independent variables manipulated to investigate the effect on the dependent variable [9].

2.2.1.2 Randomization Design

Randomization design can be categorized to the following randomization designs:

- Simple
- Unequal allocation
- Stratified
- Blocked
- Black box

Randomization design is used to eliminate bias during experimentation, as the factors of the experiment are randomly assigned to groups in the experiment.

2.2.1.3 Crossover Design (Repeat Measures Design)

Multiple measurements are made of the same variables under different conditions or over several time periods [9].

2.2.1.4 Blocking principle

There are two factors in a block design namely the variables of primary interest and nuisance variables [10]. A homogeneous block is created to make nuisance variables constant and free variables.

2.2.1.5 *Black Box method*

The black box is a system that can be viewed in terms of its inputs and outputs without knowledge of the internal workings. Therefore, in the case of experimentation discrete input are applied to a system and the output of the system is measured. From the controlled input and measured output a model is derived to link the input and output of the system.

2.2.2 Selected Experimental design

The crossover design and the black box method is used during the experimental design. The crossover experimental design will be used in order to measure some of the basic characteristics of the dc motor during the experiment. The crossover experimental design is selected as the fixed variables are known and the factors will be calculated from the variables as a function of time for several repetitions. However, the black box method will be used for the more complex experiments in order to determine the characteristics of the dc motor and create the dc motor model. The black box method is used in essence to determine the transfer function for the dc motor model.

3 Full details of the experiment design.

3.1 Problem statement

A controller must be designed to control the speed of a dc motor in the heavy current laboratory of the NWU. The steps to attain this goal is to design a PI controller to control the speed of a dc motor. A prerequisite of this design is to characterise the dc motor. This characterization will be used to derive at an experimental equation to model the dc motor for the controller design.

3.2 Experimental parameters

The dc motor's transfer function may be approximated from an actual dc motor [5]. The dc motor is reduced to the motor electrical diagram shown in Figure 4 in the background. From the background of a dc motor it is clear that the speed of the dc motor may be varied either by changing the armature current or the field flux linkage. The air gap flux $\phi(t)$ is proportional to the field current $i_f(t)$ and may be defined as [6],

$$\phi(t) = K_f i_f(t) \tag{1}$$

The torque of the motor $T_m(t)$ is dependent on the flux and the armature current as stated in the background. The armature current $i_t(t)$ and flux and motor torque are related as follows [6],

$$T_m(t) = \phi(t) K_1 i_a(t) = K_1 K_f i_f(t) i_a(t) \tag{2}$$

It is therefore clear that one current must remain constant and the other varied to have a linear system [6]. In the experiment the armature current will be controlled therefore and the field current is kept constant, therefore the motor torque in Laplace transform notation is equal to [6],

$$T_m(s) = K_1 K_f I_f I_a(s) = K_m I_a(s) \tag{3}$$

Where $K_m$is the permeability of the magnetic material [6]. The armature voltage is related to the armature current as follow [6],

$$V_a(s) = (R_a + L_a s) I_a(s) + V_b(s) \tag{4}$$

Where $V_b(s)$ is the back emf voltage [6],

$$V_b(s) = K_b \omega(s) \tag{5}$$

And the motor speed $\omega(s)$ is [6],

$$\omega(s) = s\theta(s) \tag{6}$$

The armature current is [6],

$$I_a(s) = \frac{V_a(s) - K_b\omega(s)}{R_a + L_a s} \tag{7}$$

The motor torque is equal to the load torque $T_L(s)$ plus the delivered torque$T_d(s)$. The load torque is for rotating inertia is [6],

$$T_L(s) = Js^2\theta(s) + bs\theta(s) \tag{8}$$

Taking $T_d(s)$ as zero the transfer function of the armature-controlled dc motor is obtained [6],

$$G(s) = \frac{\theta(s)}{V_a(s)} \tag{9}$$

Equal to [6],

$$G(s) = \frac{K_m}{s[(R_a + L_a s)(Js + b) + K_b K_m]} \tag{10}$$

Which is also equal to [6],

$$G(s) = \frac{K_m}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)} \tag{11}$$

The armature time constant $\tau_a = \frac{L_a}{R_a}$ for a dc motor is negligible therefore the transfer function is reduced as follow,

$$G(s) = \frac{K_m}{s[R_a(Js + b) + K_b K_m]} \tag{12}$$

Which is equal to,

$$G(s) = \frac{\frac{K_m}{(R_a b + K_b K_m)}}{s(\tau s + 1)} \tag{13}$$

Therefore, the equivalent time constant τ is the mechanical time constant as the electrical time constant is negligible. The equivalent time constant is,

$$\tau = m = \frac{R_a J}{R_a b + K_b K_m} \tag{14}$$

The motor is taken to operate at steady state and the rotor resistance is negligible. Under steady state conditions,

$$K_b\omega(t)i_a(t) = T(t)\omega(t) \tag{15}$$

Therefore as $T_m(t) = K_m i_a(t)$ we determine,

$$K_b = K_m \tag{16}$$

To derive a model of the dc motor the following parameters in Table 1 will be calculated to characterize the dc motor. These characteristics influence way the dc motor operates and therefore will be required to derive an accurate model of the dc motor.

Table 1: dc motor parameters to be calculated

Symbol	Parameter	Unit
R_a	Armature resistance	Ohm
L_a	Armature inductance	Henry
R_f	Field resistance	Ohm
L_f	Field inductance	Henry
J	Moment of inertia	kg/m^2
b	Frictional coefficient of the rotor	-
T_s	Settling time	s

The section contains a description of the experiments done to calculate the parameters of the dc motor. The field resistance, field current, field voltage and armature voltage are measured directly on the dc motor.

The experiments are briefly described below and details of the experiments are shown in Appendix A.

3.2.1 Field Voltage

The field voltage is measured in order to determine the armature resistance of the dc motor. The field voltage is measured directly on the dc motor and documented in the results section 4. The field resistance is measured at different voltages while the armature current is measured simultaneously. Similarly, the field resistance is measured at the same set of voltages and then the armature voltage is measured simultaneously. These values are tabled in Table 13 in appendix B in order that the armature current and the armature voltage at the corresponding field voltage can be used to determine the armature resistance.

3.2.2 Settling time

The mechanical time constant *m* is a critical part of the motor transfer function.

$$G_p(s) = \frac{K}{sm + b} \tag{17}$$

The motor transfer function is used to create the dc motor model in Simulink®. In order to determine the mechanical time constant (m), the settling time must be determined as, the mechanical time constant is calculated as follows,

$$T_s = 4m \quad (18)$$

Only the mechanical time constant is taken into account and not the electrical time constant as the effect of the electrical constant is minimal that it is negligible. The settling time is determined in terms of the run-up-test by measuring the time taken by the dc motor to accelerate from standstill to maximum rated speed. The run-up-test measurements are used to determine the settling time. The run-up-test graph of the dc motor speed as a function of time measured from stand still up to rated speed of 1500 RPM is used to determine the time it takes for the dc motor speed to settle at 1500 RPM

3.2.3 Experiment 1: Armature resistance

The armature of a dc motor is the rotating part where the voltage is induced and power transfer occurs between mechanical and electrical systems [11]. The armature resistance must be calculated in order to create a model of the dc motor as the armature resistance is used to calculate the armature inductance as shown in appendix A experiment 2. The armature resistance R_a is calculated with ohm's law [1],

$$R_a = \frac{E_a}{I_a} \quad (19)$$

where the armature current and voltage is measured during an open and short circuit test of the dc machine operated as a motor with a synchronous motor as a source. The open-circuit test is used to determine the armature voltage. The open-circuit test is also known as the no load test therefore the load current is zero while the speed is held constant. The induced emf is measured as a function of the excitation current [12]. The short circuit test is used to determine the armature current. From the short circuit test the short circuit current (the armature current) can be plotted as a function of the excitation current. In the short circuit test an ammeter is used to short circuit the armature of the dc motor [12]. The speed is held constant during the short circuit test and an extremely small field current is applied to the field. These measurements are taken with the field voltage and then paired at the same field voltage, as stated in section 3.2.1. Field Voltage.

3.2.4 Experiment 2: Armature inductance

The armature windings affect the armature inductance of the dc motor [13]. The armature inductance is proportional to the square of the number of turns of the armature windings [13]. The armature inductance must be calculated in order to derive a model of the dc motor. The induction of the armature is calculated by operating the dc machine as an ac motor, as a low ac voltage is applied to the armature windings. This is due to the inductance being proportional to the reactance and the source frequency. The reactance is calculated as the square root of the square impedance minus the square armature resistance. The armature resistance is determined in experiment 1. The armature impedance is equal to the armature voltage divided by the armature current. When a low ac voltage is applied to the armature, the measurements are taken at incremental speed increases. Therefore, it is a form of a run-up test where the dc motor is operated as an ac motor.

3.2.5 Experiment 3: Moment of inertia

The moment of inertia (J) is important for good speed control characteristics and the effect of stops and starts during the control of a dc motor. Therefore, the moment of inertia is determined through experimentation as it is a parameter required to derive the model of the dc motor. The moment of inertia is calculated with the run-down test or retardation test. The run-down test works on the principle that the dc motor will decelerate until it stops once the motor is switched off. The angular velocity at any speed is proportional to the torque and inversely proportional to the inertia as the dc motor decelerates [12] as shown below,

$$T = \frac{P}{\omega} = J\frac{d\omega}{dt} \tag{20}$$

where $\frac{d\omega}{dt}$ is the run-down slope. The moment of inertia can therefore be calculated from the run-down test [12].

3.2.6 Experiment 4: Frictional coefficient of the rotor

The frictional coefficient (b) of the rotor forms part of the motor transfer function as shown in (1) used to derive the model of the dc motor. It thus has to be calculated to derive the dc motor model. The frictional coefficient depends on the back emf K_b, rotor speed and the armature current. Therefore, the frictional coefficient is calculated with the following equation [14],

$$b = \frac{I_a K_b}{\omega} \tag{21}$$

Consequently, the back emf must first be calculated. The back emf is equal to the slope of the armature voltage versus the speed of the rotor. The run-up test is analysed with a graph where the armature voltage is plotted as a function of the rotor speed on a scatter plot as the measurements are not exact. The scatter plot can be linearized in order to determine the approximate run-up test, armature voltage vs speed gradient as depicted in section 4.2. The back emf is equal to the gradient, therefore the gradient is then used to determine the frictional coefficient with (5).

4 Details of the experiments conducted

The detailed raw results are displayed in Appendix B.

4.1 Open circuit and Short circuit test

From the short circuit and open circuit test the armature resistance is calculated using ohms law and the armature voltage and current. The measured data shown in Appendix B. From the data the average armature resistance is calculated as,

$$R_a = 10.46088\Omega$$

4.2 Run up test

The run-up test data is displayed in Appendix B Table 15 and graphed in Figure 15. From the run-up graph the regression line is calculated as follows by using the built in Excel function to linearize the scatter plot as can be seen in Figure 15,

$$y = 2.2002x - 16.14 \tag{22}$$

From the relationship between the armature voltage and speed the gradient K_b is calculated as,

$$K_b = 2.2002$$

Therefore, the coefficient of friction can also be calculated,

$$b = \frac{I_a K_b}{\omega}$$

For the selected armature current the shaft speed is taken as follows,

$$b = \frac{(0.6795)2.2002}{23.24779}$$

Therefore,

$$b = 0{,}064308732$$

4.3 Run down test

From the run-down test the relationship between the dc motor shaft speed and time can be seen in Figure 13 in Appendix B. From the rundown test the gradient is determined with the selected points in the linear section of the rundown graph shown in Table 14 in appendix B. The gradient is calculated as,

$$\frac{d\omega}{dt} = -60.44264044$$

It is assumed that the dc motor is at steady state for the conducted experiments. Therefore, K_m is equal to K_b,

$$K_m = 2.2002$$

The inertia of a dc machine is equal to,

$$J = \frac{K_m I_a}{-\frac{d\omega}{dt}} \quad (23)$$

Therefore, the inertia of the dc machine is calculated as,

$$J = \frac{2.2002(3)}{60.44264044}$$

$$J = 0.109204362\ kg/m^2$$

4.4 Final results

From the dc motor measurements of speed against time depicted in Table 2 in appendix B the following parameters are attained, as can be seen in Table 2 below.

Table 2: dc motor measurements speed vs time parameters

Parameter	Value	Unit
T_{start}	1.897	s
T_{settle}	2.453	s
T_s	0.556	s
ω_{max}	1782.95	rad/s
$P.O.$	0.188633	%

From the time to steady state the mechanical time constant is calculated as follows,

$$m = 0.139s$$

The motor parameters determined from the experimental results are as follows in Table 3 below as determined in Appendix B.

Table 3: Experimental results

Symbol	Value	Unit
R_a	10.46088	Ω
R_f	1429	Ω
J	0.109204362	kg/m^2
b	0,064308732	-
T_s	0.556	s

$\boldsymbol{m}$	0.139	s
$\boldsymbol{K_b}$	2.2002	-
$\boldsymbol{K_m}$	2.2002	-
$\boldsymbol{\omega}$	157.07963267949	rad/s

From the experimental results the dc motor model the motor transfer function is determined.

5 Analog control system design

5.1 Purpose

The purpose is to design a PI controller to control the speed of the dc motor. The PI controller should meet the following requirements [14]:

1. Speed control with 1% of set point in steady state
2. Speed transient during load transition between 50 % load and full load of ±10 % with a settling time of less than 2 s.

The PI controller is simulated to confirm that the design requirements are met.

5.2 Procedure

The transfer function for a PI controller [6],

$$G_c(s) = K_P + \frac{K_I}{s} \tag{24}$$

where K_P is the proportional control term and K_I is the integration term. For the control a first order transfer function will be determined for the Figure 5 below.

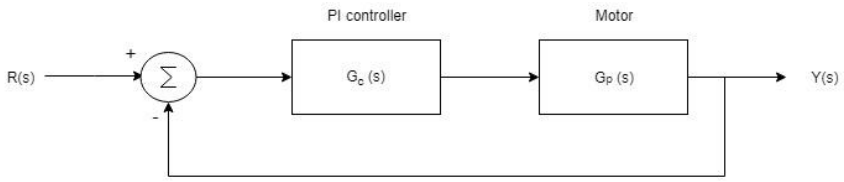

Figure 5: Control system diagram

The motor transfer function,

$$G_p(s) = \frac{\omega\ (s)}{V_a(s)} = \frac{K}{sm + b} \tag{25}$$

The controller function is,

$$G_c(s) = K_p + \frac{K_I}{s} \tag{26}$$

The PI control for the time domain.

$$PI(t) = K_{pe}(t) + \ K_I \int_0^t e(t)dt \tag{27}$$

The closed loop transfer function loop for the control system can be seen below [6],

$$T(s) = \frac{Y(s)}{R(s)} \tag{28}$$

From the control system in Figure 5 above the transfer function becomes,

$$T(s) = \frac{G_c(s)\, G_p(s)}{1 + G_c(s)\, G_p(s)} \quad (29)$$

From the motor control function and the PI controller function the transfer function becomes,

$$T(s) = \frac{\left(K_p + \frac{K_I}{s}\right) \frac{K}{sm + b}}{1 + \left(K_p + \frac{K_I}{s}\right) \frac{K}{sm + b}} \quad (30)$$

Reducing to,

$$T(s) = \frac{\left(K_p + \frac{K_I}{s}\right) K}{(sm + b) + \left(K_p + \frac{K_I}{s}\right)\, K}$$

Therefore,

$$T(s) = \frac{K\,(K_p s + K_I)}{ms^2 + \left(b + K_p K\right)s + K_I K}$$

The general characteristic equation is as follows [6],

$$q(s) = s^2 + 2\xi\omega_n s + {\omega_n}^2 = 0 \quad (31)$$

Where the percentage overshoot P.O. is calculated with

$$P.O. = 100 \frac{Max\ speed - nominal\ speed}{nominal\ speed} \quad (32)$$

From the percentage overshoot,

$$P.O. = 100\, e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \quad (33)$$

The percentage overshoot for this practical is ±10%. The settling time equation is,

$$T_s = \frac{4}{\xi\omega_n} \quad (34)$$

From (9) and (8) we can then determine K_p and K_I with (12),

$$s^2 + \frac{\left(b + K_p K\right)}{m} s + \frac{K_I K}{m} = s^2 + 2\xi\omega_n s + {\omega_n}^2 \quad (35)$$

From (12) the following two equations can be derived,

$$\frac{\left(b + K_p K\right)}{m} = 2\xi\omega_n \quad (36)$$

Reducing to

$$K_p = \frac{2\zeta\omega_n m - 1}{K} \quad (37)$$

And,

$$\frac{K_I K}{m} = {\omega_n}^2 \tag{38}$$

Reducing to,

$$K_I = \frac{\omega_n^2 m}{K} \tag{39}$$

Therefore, the transfer function is determined. The percentage error is determined to calculate the gain (K).

$$\%error = 100 \times \left| \frac{|accepted\ value| - |experimental\ value|}{|accepted\ value|} \right| \tag{40}$$

The K is selected randomly until the percentage error is acceptable.

Table 4: K and percentage error

K	Measurement [RPM]	Simulation [RPM]	% error [%]
1.009	1514.17	1512.51576301865	0.1093

The PI controller system parameters are shown in the following Table 5 below.

Table 5: PI controller parameters

Parameter	Value	SI Unit
$\boldsymbol{P.O}$	8	%
$\boldsymbol{T_s}$	0.556	s
m	0.139	s
$\boldsymbol{\zeta}$	0.626577	-
$\boldsymbol{\omega_n}$	11.4818	rad/s
$\boldsymbol{K_P}$	18.161214	-
$\boldsymbol{K_I}$	0.99107675	-
$\boldsymbol{K}$	1.009	-

5.3 Controller Simulation

From the experimental results the dc motor model the motor transfer function is determined,

$$G_p(s) = \frac{K}{ms + b} \tag{41}$$

Therefore, from the calculated parameters in Table 3 the transfer function is,

$$G_p(s) = \frac{1.009}{0.139s + 0.064308732} \quad (42)$$

And the controller function,

$$G_c(s) = \frac{2\zeta\omega_n m - 1}{K} + \frac{\frac{\omega_n^2 m}{K}}{s}$$

Therefore,

$$G_c(s) = \frac{18.161214s + 0.99107675}{s}$$

Which can be written as,

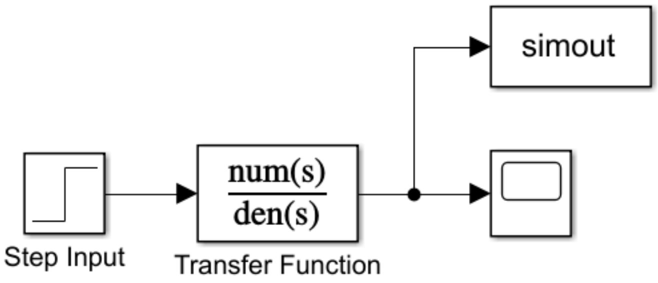

Figure 6: Simulink® simulation transfer function

With K equal to 1.009 and a percentage error of 0.109% the simulated and measured results of the dc motor can be seen in Figure 7 below.

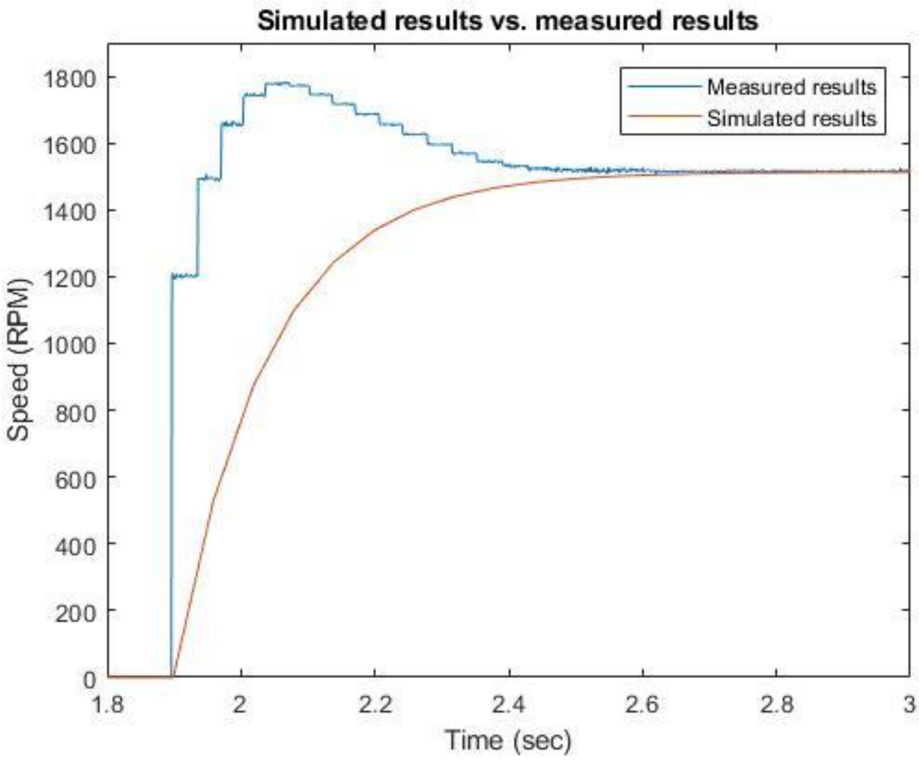

Figure 7:Simulated results vs measured motor results

For the PI controller and the DC motor simulation in Simulink the following model was used as shown in Figure 8.

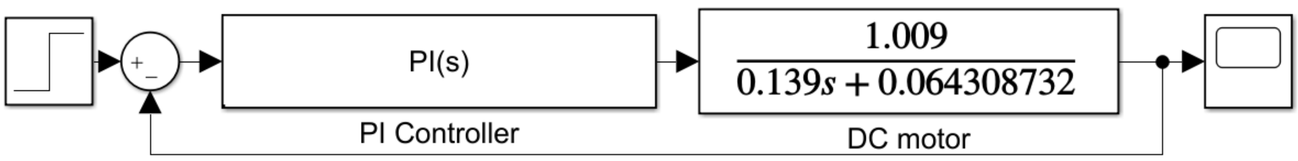

Figure 8: Basic Simulink model for measured dc motor parameters

The output of the Basic Simulink model start-up can be seen in Figure 17 in Appendix B. From this the percentage overshoot was calculated as 0.277%. This is a very desirable percentage overshoot, therefore the PI controller controls the dc motor model derived from the experimentation sufficiently. In order to determine if the PI controller percentage over shoot remains small enough for other dc motor that may have some variation in parameter values. Therefore simulations of the PI controller are conducted for the averages of all the student data, therefore an average of the dc motors in the NWU laboratory is represented.

6 Simulation of system

6.1 Static load simulation of the model

For the simulation in Simulink the static load was used. The Simulink model shown in Figure 16 in Appendix B was used to simulate the transfer functions for the following motor conditions:

- From 50% to full speed
- From full speed back to 50%

The simulation output for 50% speed to full speed is graphed in Figure 18 in appendix B. The full speed to half speed simulation output is graphed in Figure 19 in appendix B. For the full to half speed test the percentage overshoot was calculated as 0.2948% and for half speed to full speed the percentage overshoot was calculated as 0.3022%.

6.2 Impact of the dc motor parameters on the model

The averages of the static analysis of the different dc motor in the heavy current laboratory was used to create the following models below. The analysis of the data is documented in section 7. The averages of the dc motor parameters used to determine the transfer functions below, are the averages without the outliers in the data set.

There are three models for the dc motor parameter data of all the students, to show the range of the models that are acceptable. Therefore, the average data, average minus one standard deviation and the average plus one standard deviation is used to assess the data. From the statistical analysis done in Section 0 the following functions for the students' motor parameters are derived.

6.2.1 Average without outliers

The average of the data set, without the outliers is used to derive the motor transfer function,

$$G_p(s) = \frac{0.415918}{0.296s + 0.047} \tag{43}$$

Ideally the design of the designed PI controller should be able to accurately control the speed of this dc motor model.

6.2.2 Average without outliers minus one standard deviation

Average minus one standard deviation results in the following motor transfer function,

$$G_p(s) = \frac{0.494965}{0.171s + 0.04} \tag{44}$$

6.2.3 Average without outliers plus one standard deviation

Average plus one standard deviation results in the following motor transfer function,

$$G_p(s) = \frac{0.358515}{0.421s + 0.054} \quad (45)$$

6.2.4 Simulation

The results of the Simulink simulation can be seen in Appendix B 11.4. These simulations are compared to the base line data in Section 5. All the above-named transfer functions are simulated for the following motor conditions:

- From 50% to full speed
- From full speed back to 50%

The Simulink model shown in Figure 9 was used to simulate the output for the 50% speed to full speed of the dc motor as shown in the graph depicted in Figure 20 in appendix B section11.4.

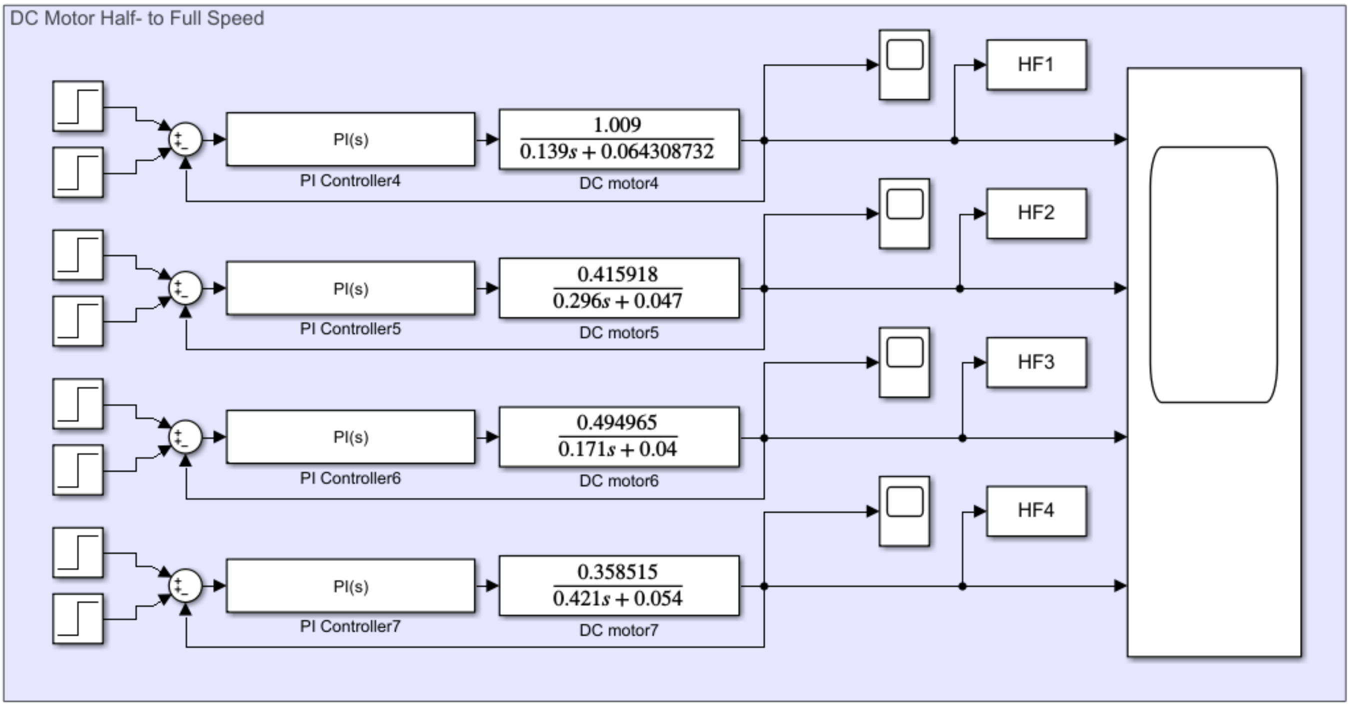

Figure 9: DC motor half to full speed Simulink model

The Simulink model shown in Figure 10 was used to simulate the output for the full speed to half speed of the dc motor as shown in the graph depicted in Figure 21 in appendix B section11.4.

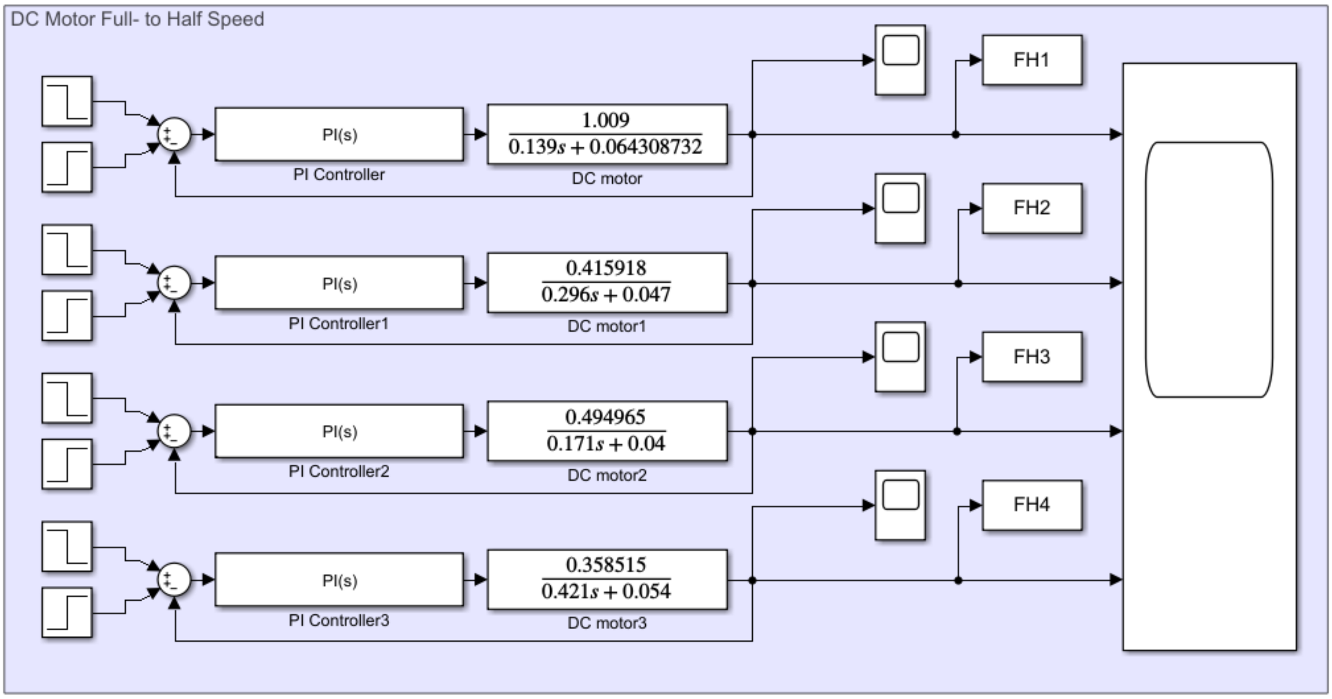

Figure 10 DC motor full to half speed Simulink model

6.3 Evaluation of Simulations

For these models in Figure 9 and Figure 10 the percentage overshoot was calculated as shown in Table 6 below.

Table 6 Percentage overshoot for models

Analysed data Model	Percentage Overshoot [%]
Full speed to 50% speed	
Average without outliers	0.3868
Average minus one standard deviation without outliers	0.3227
Average plus one standard deviation without outliers	0.4523
50% speed to full speed	
Average without outliers	0.3766
Average minus one standard deviation without outliers	0.3256

Average plus one standard deviation without outliers	0.4865

The percentage overshoot for the PI controller design is required to be less than 10%. To determine the difference between the experimental model outputs and the model derived from the average of all the student's dc motor parameters (details shown in section 7) the percentage overshoot is compared for the different data. The percentage overshoot is calculated for the model from full speed to 50% speed as well as 50% speed to full speed. The intention is to assess the effect of the model's change in speed on the percentage overshoot.

The model is created in MATLAB® using Simulink®. Therefore, the percentage overshoot for each scenario is calculated with a function in MATLAB® code. The models' in Figure 9 and Figure 10 output is plotted as the speed of the motor as a function of time in Appendix B. The model output for the full speed to 50% speed and 50% speed to full speed is plotted on the same axis using MATLAB® as can be seen in Figure 20 and Figure 21 respectively. From these figures it is clear that the experimental model has the lowest percentage overshoot and is the closest to a block waveform. The percentage overshoot is low compared to the required less than approximately 10%. This would not have been possible if the data set was not filtered to remove the outliers. The outliers would have caused the dc motor model to be to deviant from the experimental results and therefore the PI controller would not have been able to keep the percentage overshoot so low. The data set had many outliers that had to be filtered out in order to determine in accurate average representation of the dc motor parameters. In order to ensure that such deviations in the data set does not occur, each student should conduct the same experiment, therefore it is a type of repeat measure experimental design for all the student data.

In the Table 6 above the models derived from the data of all the student's measurements are displayed. Comparing the full speed to 50% speed and 50% speed to full speed, the percentage overshoot for 50% speed to full speed is larger than the percentage overshoot of the motor speed change from full speed to 50% speed. The difference in percentage overshoot is between the start up to 50% speed and the 50% to rated speed is very small. Therefore, the effect of 50% to full speed of the dc motor does not have much of an effect on the percentage overshoot compared to, 50% speed to rated speed.

For both full to 50% speed and 50% to full speed, the average without outliers plus one standard deviation reflects the highest percentage overshoot. The average minus one standard deviation without the outlier data of all the students shows the lowest overshoot of the student parameter data models. However, the experimental model still has a lower percentage overshoot. This is due to the PI controller having been designed for the experimental model, the deviation between the experimental model and the average value model effect the efficiency of the control of the PI controller.

7 Statistical analysis of motor parameters as provided:

In section 7 the data is based on the results of all the students as provided. The outliers are removed from the data before the analysis is completed in order to prevent errors in the data sets to present in inaccurate average of the dc motor parameters. Removing the outliers has a clear impact on the data as can be seen in Table 7 below when comparing the average to the average without the outliers.

7.1 Data filtering

The data of dc motor characteristics calculated by all the students is analysed and filtered to prevent student data errors to impact the data. The data is filtered in two ways, namely with the trim function and the average without the outliers. The average of the trimmed data is calculated with the average function in excel. The trim however does not provide an accurate enough data set from which the average can be calculated. The average without the outliers is calculated by removing the outliers from the data set and then using the average function to determine the average of that data set. The outliers are taken as data that is above the upper limit and below the lower limit. The upper limit and lower limit are defined in the section below.

Therefore, the average without the outliers is calculated. The average is determined as follow,

$$Average = \frac{\sum elements}{nuber\ of\ elements} \tag{46}$$

The standard deviation is calculated with the excel function DSTDEV().The maximum and minimum outliers can be seen with the maximum and minimum values. The maximum and minimum values are determined using the MIN() and MAX() function in Excel. The outliers are taken as the values above the upper limit and lower than the lower limit. In order to calculate the upper and lower limit the median, Q1, Q3 and IQR must be calculated. The median is calculated with the MEDIAN function in excel. Q1 and Q3 are the quartiles which are calculated with QUARTILE.INC function in excel. The inter quartile range IQR is calculated,

$$IQR = Q_3 - Q_1 \tag{47}$$

The lower and upper limit is calculated,

$$lower\ limit = mean - 1.5\ IQR \tag{48}$$

And,

$$Upper\ limit = mean + 1.5\ IQR \tag{49}$$

The outliers are filtered out of the data set in excel. In the Table 7 below the *Tau* represents the mechanical time constant *m* in the experiment.

Table 7: DC motor parameters analysis

DC Motor Tests						
analysis	***Km***	***b***	***Kb***	***Tau (m)***	***Ra***	***J***
Average	1.971	0.052	1.998	0.296	20.550	0.094
Standard deviation	1.010	0.042	1.003	0.125	21.958	0.077
Min	0.040	0.000	0.040	0.025	7.629	0.000
Max	5.080	0.273	5.080	0.610	88.640	0.265
Median	2.009	0.046	2.010	0.325	13.000	0.086
Q1	1.882	0.043	1.883	0.223	11.710	0.021
Q3	2.388	0.053	2.388	0.386	13.670	0.141
IQR	0.506	0.010	0.505	0.163	1.960	0.120
lower limit	1.123	0.029	1.126	-0.022	8.770	-0.159
Upper limit	3.147	0.067	3.145	0.630	16.610	0.322
% Trim	0.250	0.250	0.250	0.250	0.250	0.250
Average without outliers	2.151	0.047	2.092	0.296	12.631	0.091
Standard deviation	0.363	0.007	0.363	0.125	1.262	0.077
Without outliers – 1 standard deviation	1.760	0.040	1.760	0.171	11.369	0.018
Without outliers + 1 standard deviation	2.487	0.054	2.487	0.421	13.893	0.172
Average after trim	1.958	0.046	1.992	0.307	13.511	0.090
Own calculations	2.2002	0.064308732	2.2002	0.139	10.46088	0.109204362

7.2 Analysis of results

In order to analyse whether the experimental dc motor parameters are an accurate representation of the dc motor parameters the experimental data is compared to the data collected by all the other students. However, there may be some errors in the student data therefore the upper and lower outliers are removed from the data set and the new average is determined. This average excluding the outliers is compared to the data collected in this experiment. Firstly, the Km determined in the experiments 2.2002 which is similar to the average without the outliers of 2.151. It is well within one standard deviation of the average. The Km is equal to Kb, the average however differs as some students did not provide a Kb or did not take Km equal to Kb thereby creating the discrepancy.

The coefficient of friction (b) of the experiment is 0.064308732 is not within one standard deviation of the average without the outliers. The coefficient of friction is dependent on the speed gradient Kb. The experimental speed gradient is quite similar to the average value therefore the speed gradient is not the cause of the discrepancy between the experimental data and the average. The coefficient of friction is also related to the armature current and the shaft speed. The shaft speed measurements may be inaccurate or the armature current measurements may be inaccurate. Possible reasons are human error during measurement, faulty test benches in the heavy current laboratory or inconsistencies between the test benches.

The mechanical time constant Tau or as it is referred to in this experiment *m* is close to the average mechanical time constant. There are some discrepancies in the mechanical time constant data even after the outliers are removed from the data set. This is clearl when comparing the average and the average minus or plus one standard deviation. The mechanical time constant depends on the settling time. This may vary substantially between the different dc machines. Therefore, the mechanical time constant determined in this experiment may be taken as a reasonably accurate representation of the dc motor parameter.

The armature resistance calculated in this experiment is more than one standard deviation smaller than the average armature resistance of all the students without the outlier. The armature resistance is calculated from the open circuit test and short circuit test. Incorrect values may be recorded during the measurement as both the open and short circuit test require manual measurement. The armature voltage and current are then paired based on the field voltage, this is very imprecise and may account for the large armature resistance. The armature resistance may also be high due to damage to the dc motor.

The inertia of the rotor of the dc machine calculated in this experiment is 0.109 [kg/m^2] and the average of all the students without the outliers is 0.091 [kg/m^2], it is clear that the inertia calculated from the experiment conducted is close to the average inertia of the students, it is also with in one standard deviation of the average. The inertia is dependent on the Km, armature current and dω/dt. As the inertia of the experiment is similar to the average inertia and it is dependent on the armature current, we can assume that the discrepancy between the experimental coefficient of friction and the average coefficient of friction is not as a result of the armature current but the rotor speed. Therefore, it is most likely that the rotor speed measurements taken were in accurate.

The K values calculated from the analysed data are tabulated in Table 8 below.

Table 8: K value for all students

Analysed data	K
Average without outliers	0.415918
Average – one standard deviation	0.494965
Average + one standard deviation	0.358515

The K values where used to calculate the transfer functions for the three averages of the analysed data as shown in section 6 of the report.

The data set of the dc motor parameters is also analysed using the box and whisker diagram. In the following Figure 11 and Figure 12 below the box and whisker diagram of the data of all the student dc motor parameters provided in the DC motor parameters excel file.

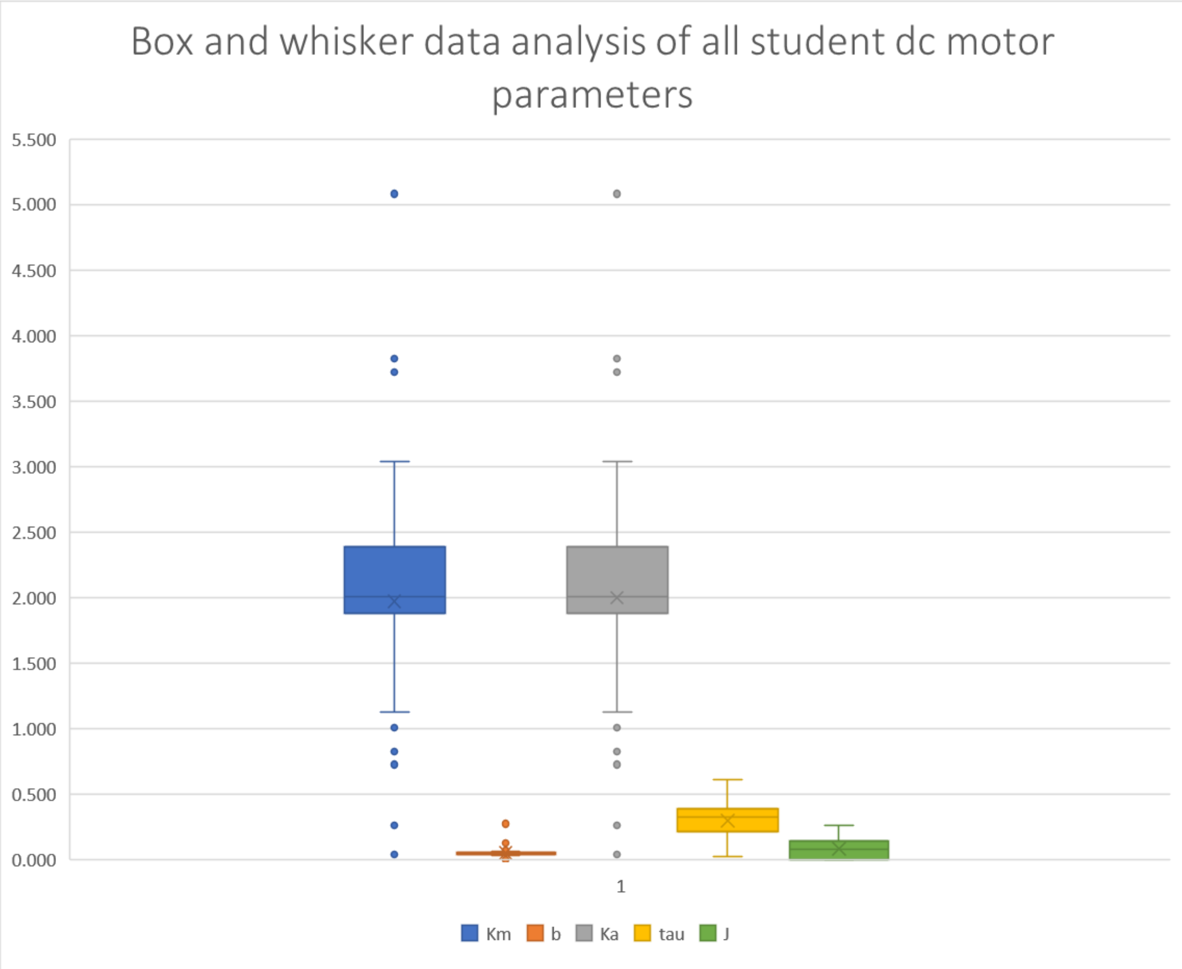

Figure 11: Box and whisker plot data analysis of data from all student dc motor parameters

The box and whisker diagram show clearly how many outliers there were in the data set. These outliers are not only many but also far above and below the limits. Therefore, it is clear that these outliers would affect the data analysis and must be removed in order to have an accurate representation of the dc motor parameters. The armature resistance data is shown in Figure 12 because the armature current is too large for the graph in Figure 11.

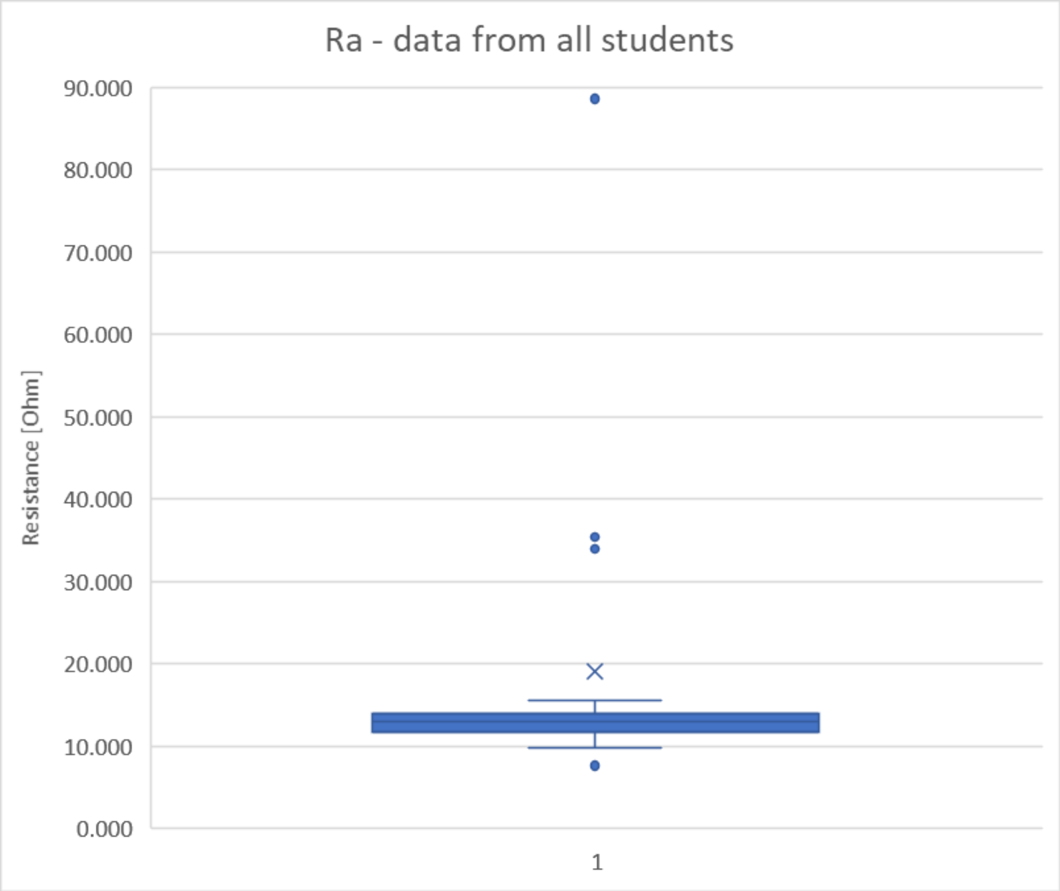

Figure 12: Box and whisker diagram of armature resistance data of all student data

The armature resistance box and whisker are plotted separately in order that the data distribution is shown more clearly. From the data distribution it is clear that most of the armature resistance in the data set are spread close together with the exception of a few extreme outliers that would affect the average. These outliers clearly do not represent the average dc motor in the heavy current laboratory.

8 ELO Requirements

8.1 ELO 2

Exit level outcome 2 is the application of knowledge of mathematics, natural science, engineering fundamentals and an engineering speciality to solve complex engineering problems [15].

- The fundamentals of engineering were used throughout the experiment and documentation of the report. Proof of this can be seen throughout the report as the experiment purpose, procedure and results are documented thoroughly. The experimental procedure was created using engineering fundamentals.
- The experiments in Appendix A and section 5 displays the application of mathematical and scientific knowledge to solve the engineering problem.
- Application of numerical analysis and the application of programming and informational technology are shown in the following aspects. The Simulink simulation where used to create models of the dc motor and simulate the effect of the PI controller on the dc motor. The calculations for the dc motor model where done using Matlab. While the data of all the students' measurements of the dc motor parameter were analysed using Excel.
- The theory-based solution using engineering fundamentals was displayed the study of dc motor characterization and control as well as PI controller theory in order to design and simulate the PI controller and dc motor models.

8.2 ELO 4

Exit level outcome 4 is the investigation of broadly-defined problems through research of literature, designing and conducting experiments, analysing and interpreting results to provide a valid conclusion [15].

- In this report the control of a dc motor speed with controller was investigated. In order to solve this broadly defined problem dc motors were investigated to determine how the speed may be controlled. Different types of controllers were investigated as well in order to determine what type of controller should be used to solve the problem. This can be seen in section 2 of the report.
- From the investigation the PI controller for the control of the dc motor was designed using engineering fundamentals of science and mathematics to calculate the parameters of the model designed. The parameters used during the calculations were gathered through the experiments documented in appendix A.
- Data analysis was done of the dc motor parameter data collected from all the students the data was analysed in section 7. This data was then used to create models of the averages

as documented and compared to the data collected during the experiments conducted to calculate the parameters in this report.

9 Conclusions

A PI controller model to control the speed of a dc motor was designed and simulated in this report. To design the dc motor model proper, experimental design was implemented in order to determine the dc motor characteristics necessary to design the PI controller. The repeated measurement process was used in this practical to measure the basic parameters such as the field voltage. To derive the dc motor model transfer function however, the black box method was followed. With the black box method, the experiments where conducted by applying controlled inputs and measuring the outputs. Therefore, the dc motor transfer function could be derived without knowing the exact inner workings. In order to ensure that an experiment has a high probability of success the following steps must be taken during the experiment. The first is to select objectives and then determine variables from the objectives. Next an appropriate experimental design must then be selected and executed. The data from the experiment must then be compared with the experimental assumptions to ensure that they are consistent. These results must then be analysed and interpreted in order to be used or presented appropriately.

Four experiments where conducted in order to determine the characteristics of the dc motor. The four experiments were executed to determine the, armature resistance, armature inductance, moment of inertia and frictional coefficient of the rotor respectively. The dc motor parameters determined during the experimentation is used to derive a transfer function model of the dc motor. The dc motor model simulation of the start-up to rated speed is compared to the measured speed. The percentage error of the dc motor model simulation and the measured results of the dc motor is 0.109%. Therefore, the model is an accurate representation of the measured dc motor.

The experimental results are compared to the data set of the parameters determined by all of the other students. This is done in section 7, by analysing the other student's dc motor parameter data. To ensure that incorrect parameters calculated by some of the other students does not influence the analysis of the average parameters, the outliers are removed from the data set. If the outliers are not removed from the data set before the dc motor model is derived an inaccurate representation of the dc motor in the heavy current laboratory would be derived. Therefore, the PI controller would not be able to limit the percentage overshoot as accurately. Once the outliers are removed from the data set, the students' average values of the dc motor parameters can be compared to the experimental parameters determined in this report.

To accurately compare the average parameter value with the experimental value the standard deviation of the students' average parameters without the outliers must be calculated. The average plus one standard deviation is determined as well as the average minus one standard deviation, this provides a reasonable range for the dc motor parameters.

The comparing the experimental and student values are simplified by checking if the experimental value is within one standard deviation of the average of the student's data.

From this comparison done in section 7 it is clear that most of the parameters determined during the experiment are reasonably close to the average of all the student's parameters. With the exclusion of the armature resistor and the coefficient of friction which are slightly outside one standard deviation from the average of all the students' calculated parameters. The discrepancy may have been caused by human error during measurement or faulty dc motors or machinery. The armature resistance is determined with the open and short circuit test, these tests require taking measurements by hand and comparing measurements at the same field voltage, therefore incorrect measurements could easily have been documented. The coefficient of friction is dependent on the armature current and the shaft speed, therefore either the armature current measurement is incorrect or the shaft speed is incorrect.

A PI controller is designed to control the speed of the dc motor. The PI controller was selected to control the dc motor speed as it is only required that the percentage overshoot is controlled and the controller is not required to be predictive therefore a PID controller is not required even though it would result in more effective control of the dc motor speed.

The model of the dc motor and PI controller is simulated with MATLAB®'s Simulink®. From the PI controller and dc motor model simulation of the start up to rated speed of 1500 RPM the percentage overshoot is calculated as 0.277%. The model is thither simulated for the full speed to 50% speed and for 50% speed to full speed. For the full to half speed the percentage overshoot was calculated as 0.2948% and for half speed to full speed the percentage overshoot was calculated as 0.3022% which is significantly below the maximum percentage overshoot of 10% required.

The average dc motor model was derived from the average parameters of the data set. The average dc motor is represented by three model namely, the average without the outliers, the average without the outliers minus one standard deviation and the average without the outliers plus one standard deviation. Therefore, there is a range for the average dc motor. These models where simulated in Simulink with the PI controller. From these models the percentage overshoot was determined for full speed to half speed and for half speed to full speed. The maximum percentage overshoot calculated for these simulations where smaller than 0.5% overshoot. The percentage overshoot for other dc motors is therefore greater than that of the percentage overshoot for the dc motor that the PI controller was designed for. Therefore, the PI controller will not be as effective on dc motor with very different characteristics than the dc motor analysed in this experiment. However, the PI controller is effective on the average dc motor of the NWU heavy current laboratory.

The ELO requirements for this practical is ELO 2 and 4. ELO 2 is the application of mathematical, scientific and engineering knowledge. Proof of this outcome can be seen in the calculations and design of the controller and low side switch as knowledge of these subjects are required for the appropriate design. ELO 4 is the design and conduction of experiments and analysis of the data. Proof of ELO 4 can be seen in section 2 where the aspects of the project are investigated. It can thither be seen from the experimental designs devised in Appendix A. Data analysis and interpretation is shown in section 4 where the results of the experiments are analysed.

10 Appendix A

Experiment 1: Determine the armature resistance of a dc motor

Purpose

The intention is to control the speed of a dc motor in the heavy current laboratory at NWU Engineering campus. A common method to control the speed of a dc motor is by applying a constant voltage to the field winding and adjusting the voltage applied to the armature winding.

In order to control the speed of the motor, two components are required: a dc-dc converter to adjust the applied voltage and a controller to control the converter to supply the correct voltage. The load applied to a dc motor results in a reduction in speed, thus requiring a closed-loop controller to maintain constant speed irrespective of the system supply voltage and motor loading condition.

It is known from section 2 that the following parameters affect the efficiency and accuracy of a dc motor speed controller, R_a, L_a, R_f, L_f, J, b. It is necessary to characterise the motor for these parameters.

The aim of Experiment 1 is to determine the armature resistance of the dc motor.

Variables

Table 9: Experiment 1 parameter

Parameter Name	**Symbol**
Armature resistance	R_a
Armature voltage	V_a
Armature current	I_a
Field voltage	V_f
Motor speed	ω

Objective

For this experiment, a three-phase induction motor is used to drive the dc motor, which then acts as a generator. A range of field voltages are applied in two sets of tests where the armature voltage and current are measured respectively vs. the same field voltage. These armature voltage and current measurements are then used to calculate the armature resistance using Ohm's law.

Procedure

The test will be performed at one of the test benches of the heavy current laboratory. The following steps are used to determine the armature resistance:

1. Connect an ammeter in series with the dc motor armature winding to measure the short-circuit current when the dc motor is being turned by the induction motor.
2. Connect the three-phase induction motor on the test bench to rotate the dc motor at rated speed of 1800 rpm.
3. Apply a low dc voltage to the field of the dc motor.
4. Record the field voltage and the armature short-circuit current.
5. Adjust the field voltage in small steps until the dc motor rated current flows through the ammeter. Record both the field voltage and armature short-circuit current at each step.
6. Switch off field voltage applied to the dc motor as well as the induction motor.
7. Remove the ammeter and connect a voltmeter across the armature winding terminals.
8. Energise the induction motor again to rotate the dc motor at rated speed.
9. Starting at a low dc voltage, repeat the same field voltage steps used in steps 4 and 5. Record both the field voltage and armature voltage at each step.
10. Switch off field voltage applied to the dc motor as well as the induction motor.

Analyse and interpret the results

In order to determine the armature resistance some tests need to be completed first these are the short circuit and open circuit tests. An external synchronous motor is used to rotate the dc motor rotor. Proceeding then to suppling the field windings with a voltage and measuring the field voltage for different input voltages. The open circuit test will then give us the armature voltage while the short circuit test will be used to get the armature current.

The armature resistance is calculated from the correlated armature voltage and current data sets using Ohm's law as given by equation (1):

$$R_a(k) = \frac{V_a\left(V_f(k)\right)}{I_a\left(V_f(k)\right)}$$

where k = 1 to K

and K is the number of tests done.

The average of the $R_a(k)$ values calculated is used as the representative armature resistance value.

Experiment 2: Determine the armature inductance of a dc motor

Purpose

The purpose of the practical is to control the speed of the dc motor in the NWU heavy current laboratory of the Engineering campus. The dc motor speed is controlled by controlling the armature voltage. To control the dc motor speed accurately the R_a, R_f, L_f, J, b parameters are required and therefore they must be characterized.

The aim of Experiment 2 is to determine the armature induction L_f of the dc motor.

Variables

Table 10: Experiment 2 parameter

Parameter Name	Symbol
Back EMF	K_b
Armature impedance	Z_a
Armature reactance	X_a
Friction coefficient of the rotor	b
Armature induction	L_a

Objective

The dc motor is connected for this experiment, where the field voltage and current are constant and the armature voltage varies to control the speed of the dc motor. The speed is slowly increased for a run-up test.

Procedure

The run-up test is performed at one of the test benches of the heavy current laboratory of the NWU on the engineering campus. the following steps are used to determine the armature inductance:

1. Connect the dc motor armature and shunt to two electrical benches dc sources.
2. Connect a multimeter over the shunt and armature independently.
3. Set the field voltage and field current to a specific value.
4. Measure speed of the shaft with a tachometer
5. Increase armature voltage until the shafts speed is 100RPM.
6. Record armature voltage and current at 100 RPM
7. Repeat step 5 and 6 in increments until 1500 RPM is reached.

Analyse and interpret the results

The back emf is calculated from the run-up test from the armature voltage vs speed graph.

$$K_b = \frac{E_{a2} - E_{a1}}{\omega_2 - \omega_1} \tag{50}$$

Where the shaft speed is in rad/s. the armature impedance is calculated with,

$$Z_a = \frac{E_a}{I_a} \tag{51}$$

The armature reactance of the dc motor is calculated as follows,

$$X_a = \sqrt{{Z_a}^2 - {R_a}^2} \tag{52}$$

The armature inductance is calculated with,

$$L_a = \frac{X_a}{2\pi f} \tag{53}$$

The frequency is assumed as 50 Hz.

Experiment 3: Determine the inertia of a dc motor

Purpose

The purpose of the practical is to control the speed of the dc motor in the NWU heavy current laboratory of the Engineering campus. The dc motor speed is controlled by controlling the armature voltage. To control the dc motor speed accurately the R_a, R_f, L_f, J, b parameters are required and therefore they must be characterized.

The aim of Experiment 3 is to determine the inertia J of the dc motor.

Variables

Table 11: Experiment 2 parameter

Parameter Name	**Symbol**
Inertia	J
Gradient	$\frac{d\omega}{dt}$
Armature current	I_a
Field voltage	V_f
Motor speed	Ω

Objective

For this experiment, the dc motor is connected and operated at maximum speed. The field voltage and current is constant while the armature voltage is changed to set the speed. Once the dc motor runs at maximum speed the rundown time is measured by disconnecting the armature supply voltage and measuring the time taken by the motor to become stationary.

Procedure

The run-down test is performed at one of the test benches of the heavy current laboratory of the NWU. The following steps are followed to determine the Inertia of the dc motor:

1. The dc motor is connected to the electrical bench with the shunt and the armature.
2. A multi meter is connected over the armature and the shunt of the DC motor.
3. The field voltage is set to 380 V.
4. The speed of the shaft is measured suing a tachometer
5. The electrical source connected to the armature is slowly increased until the tachometer measures 1500 RPM.
6. Once 1500 RPM is reached the armature is quickly disconnected and the time it takes the shaft to go from 1500 RPM to 0 RPM is recorded.

7. A plot of speed vs time is graphed from the run-down test.

Analyse and interpret the results

The inertia of the dc motor is calculated with [6],

$$J = \frac{-K_m I_a}{\frac{d\omega}{dt}} \tag{54}$$

Where the gradient is the speed as a function of time calculated from the run-down test. Therefore, from the experiment it is calculated with,

$$\frac{d\omega}{dt} = \frac{\omega_2 - \omega_1}{t_2 - t_1} \tag{55}$$

Where I_a is the armature current of the run-down test.

Experiment 4: Determine the friction of a dc motor

Purpose

The purpose of the practical is to control the speed of the dc motor in the NWU heavy current laboratory of the Engineering campus. The dc motor speed is controlled by controlling the armature voltage. To control the dc motor speed accurately the R_a, R_f, L_f, J, b parameters are required and therefore they must be characterized.

The aim of experiment 4 is to determine the frictional coefficient of the dc motor.

Variables

Table 12: Experiment 4 variables

Parameter Name	**Symbol**
Back EMF	K_b
Armature impedance	Z_a
Armature reactance	X_a
Friction coefficient of the rotor	b

Objective

The frictional coefficient of the dc motor is determined by measuring the armature voltage, current and dc motor speed, when only the dc motor is connected. The field voltage and current remain constant while the armature voltage is varied.

Procedure

The run-down test is performed at one of the test benches of the heavy current laboratory of the NWU. The following steps are followed to determine the frictional coefficient of the dc motor:

1. The dc motor is connected to the electrical bench with the shunt and the armature.
2. A multi meter is connected over the armature and the shunt of the DC motor.
3. The field voltage is set to 380 V.
4. The speed of the shaft is measured suing a tachometer
5. The electrical source connected to the armature is slowly increased until the tachometer measures 1500 RPM.
6. Once 1500 RPM is reached the armature is quickly disconnected and the time it takes the shaft to go from 1500 RPM to 0 RPM is recorded.
7. A plot of speed vs time is graphed from the run-down test.

Analyse and interpret the results

By making use of the rated current and speed of a motor with its motor constant (mechanical constant) it is possible to calculate the friction constant of the dc motor.

The frictional coefficient is calculated with [6],

$$b = \frac{I_a K_b}{\omega} \tag{56}$$

Where K_b is equal to the mechanical constant.

11 Appendix B: Detail results of the experiments conducted

11.1 Armature resistance data

Table 13: Armature resistance data

Vf	V_a	I_a	R_a
2	19.1	1.9	10.05263
4	23.03	2.252	10.22647
8	26.19	2.5795	10.15313
12	29.82	2.821	10.57072
16	34.16	3.133	10.90329
20	37.67	3.469	10.85904

11.2 Run-down test data

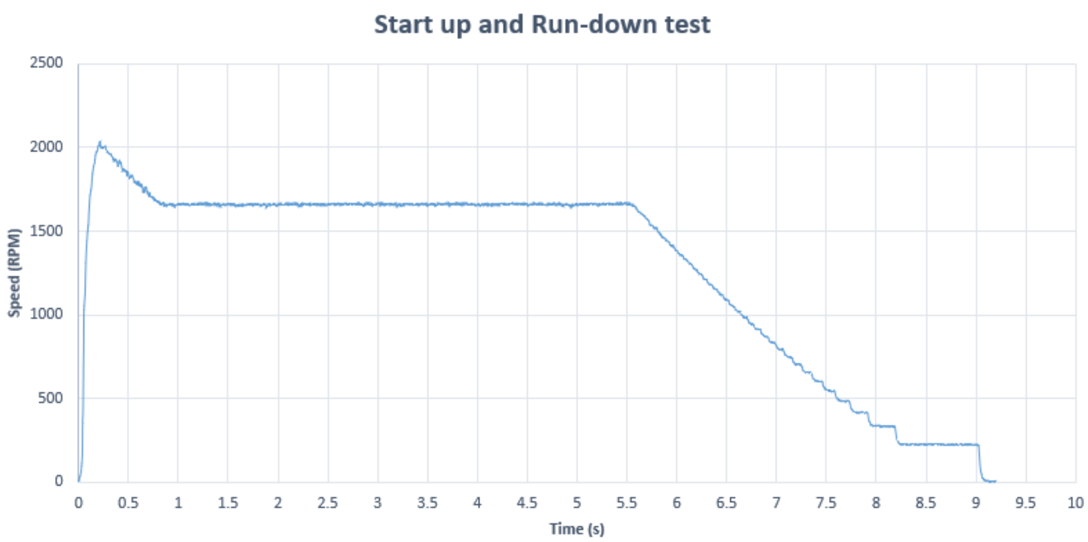

Figure 13: Start-up and run-down test

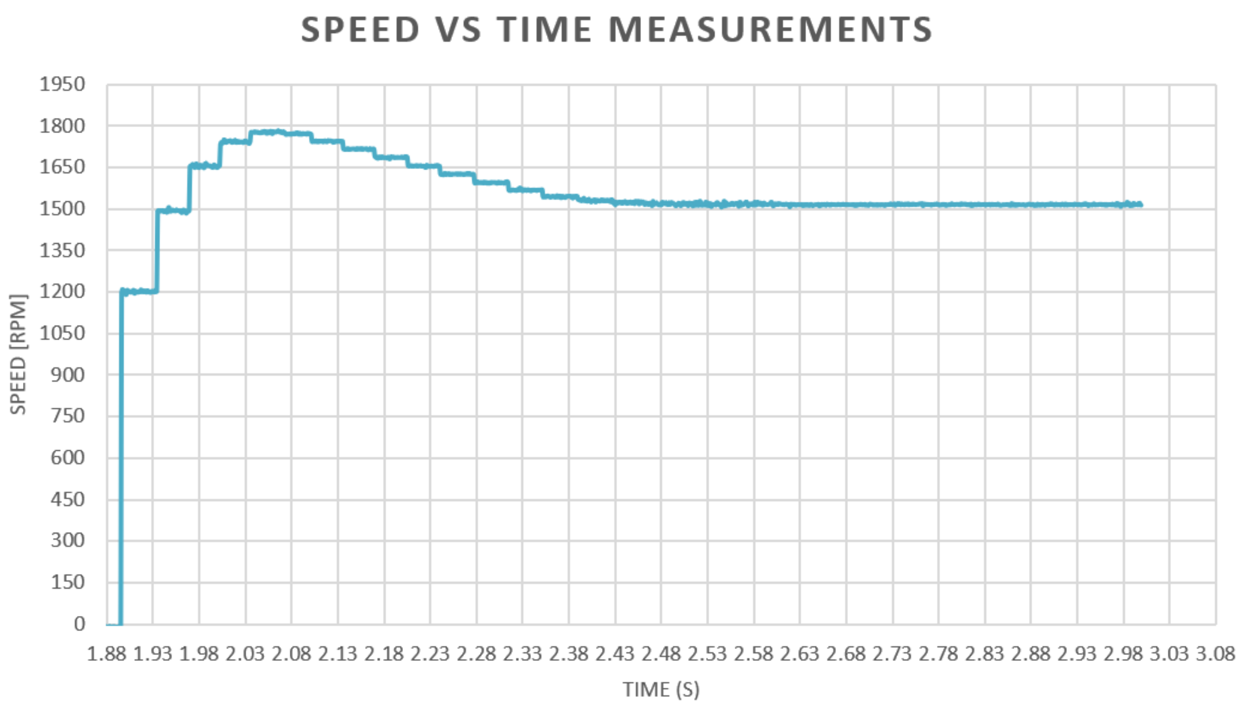

Figure 14: Speed vs time measurement of dc motor

Table 14: run down test selected data

Run-down test	
t	**rpm**
6	1385.859
7	808.6741

11.3 Run up test

Table 15: Run-up test data

Va	ω(Rpm)	ω(Rad/s)
0	0	0
25.2	222	23.24779
50.3	335	35.08112
75.3	422.8	44.27551
100.6	498.2	52.17138
125.33	613.3	64.22463
150.1	704.8	73.80648
175.1	833.6	87.29439
200.3	936.1	98.02816
225.4	1029.6	107.8195
250.1	1152.2	120.6581
275	1269	132.8894
300.8	1368.2	143.2776
328.4	1500	157.0796

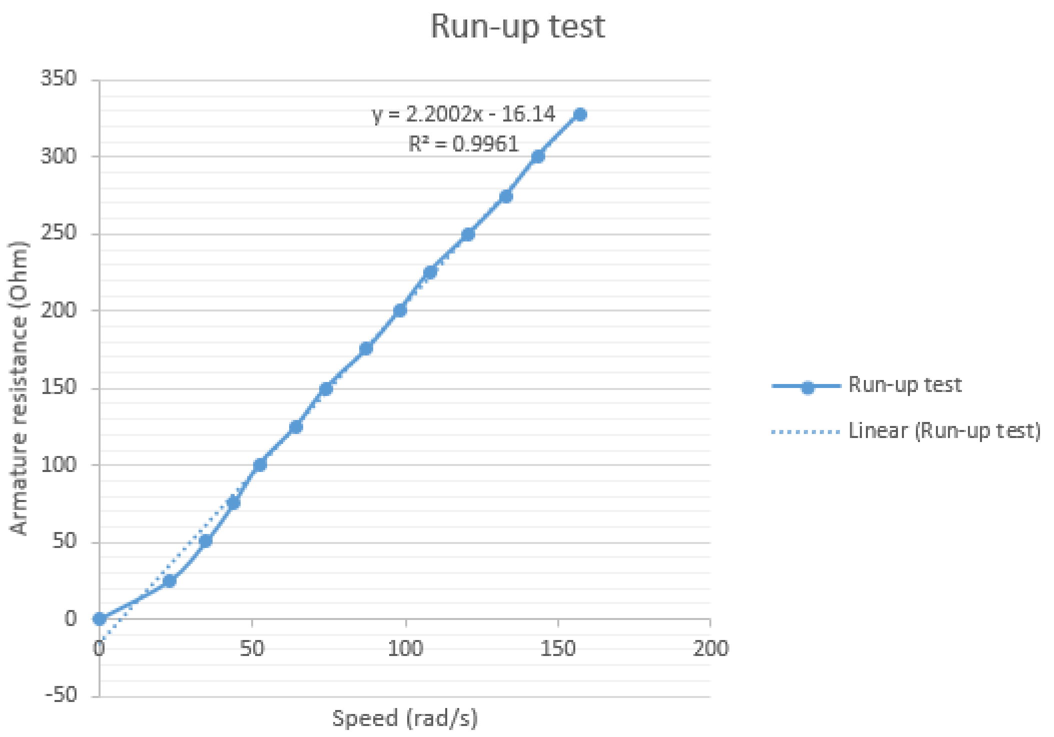

Figure 15: Run-up test graph

11.4 Simulink simulation

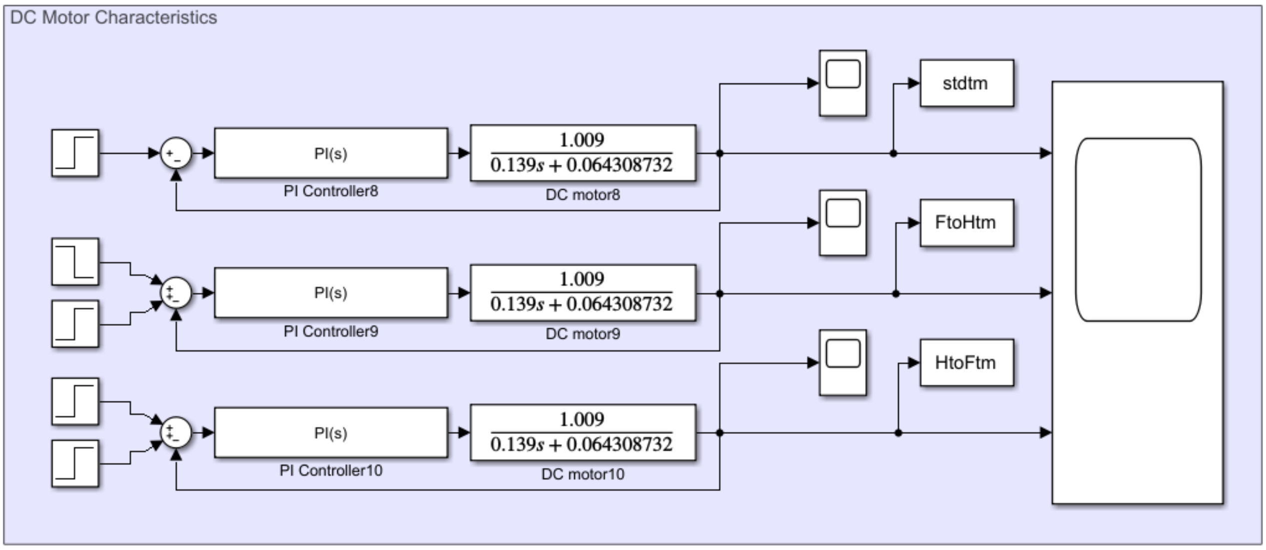

Figure 16: Simulink model of DC motor for measured values

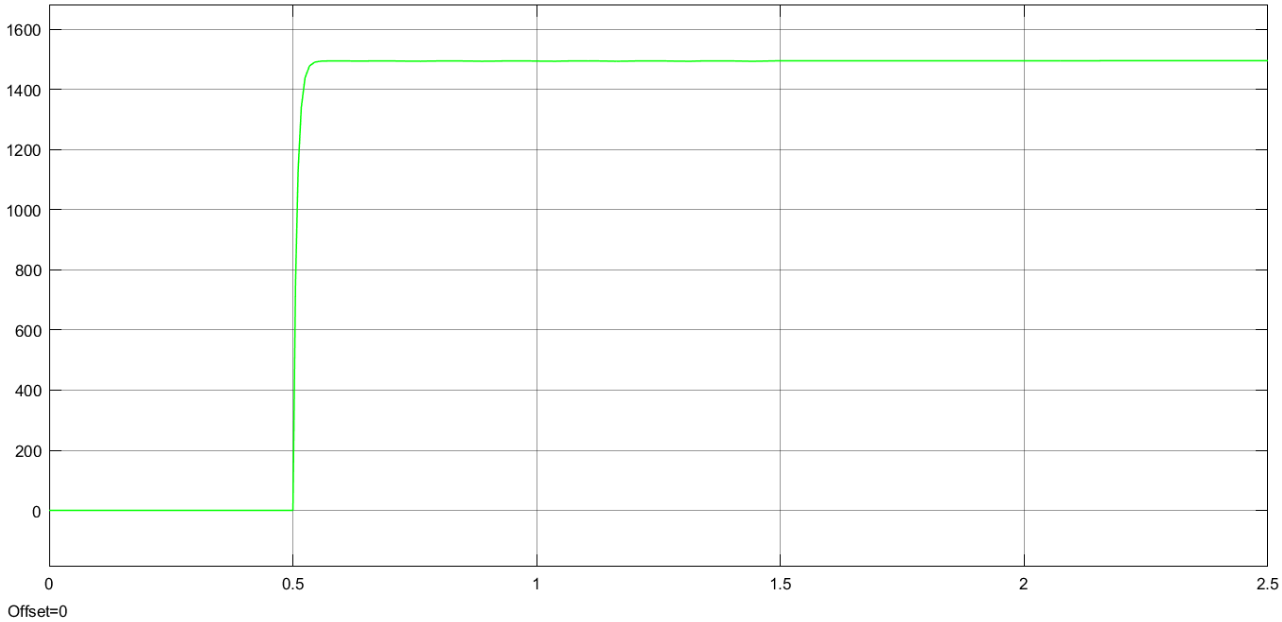

Figure 17: Simulink Simulation start-up graph for measured data

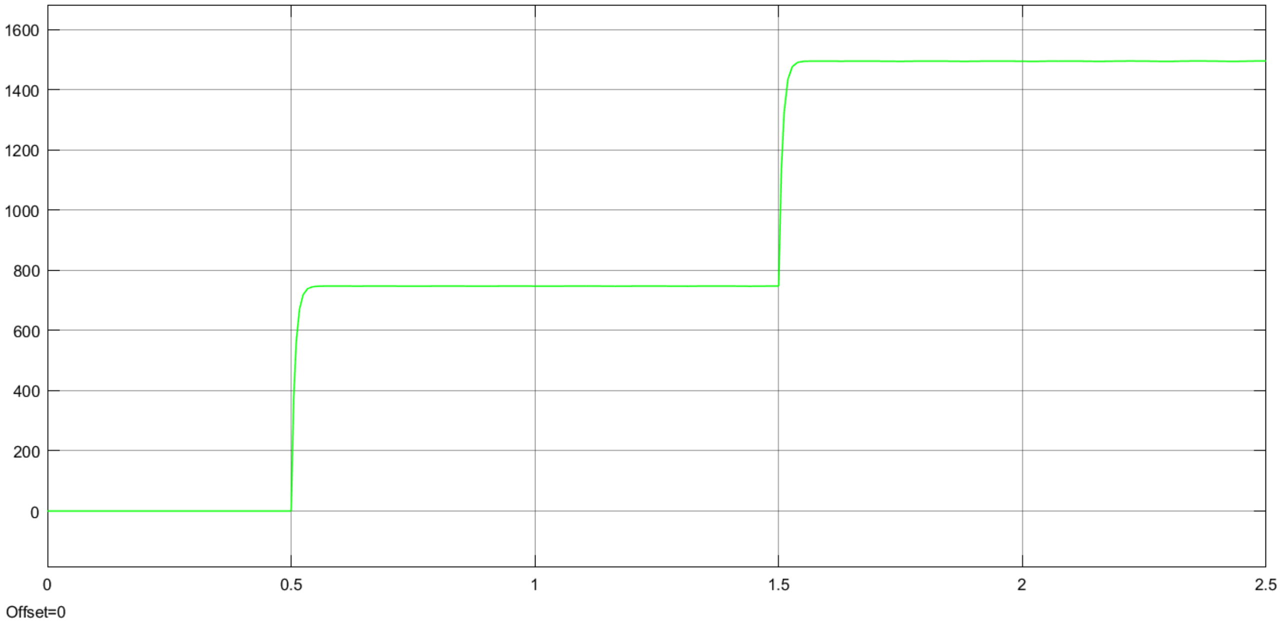

Figure 18: Simulink simulation Half speed to full speed for measured data

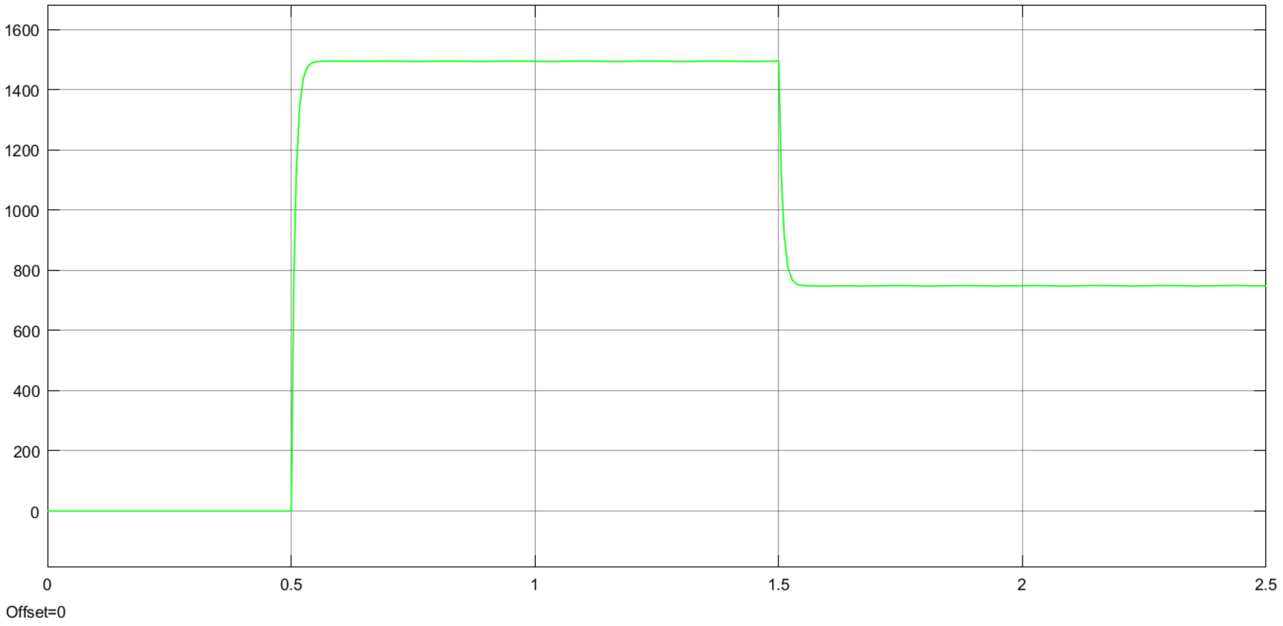

Figure 19: Simulink simulation full speed to half speed for measured data

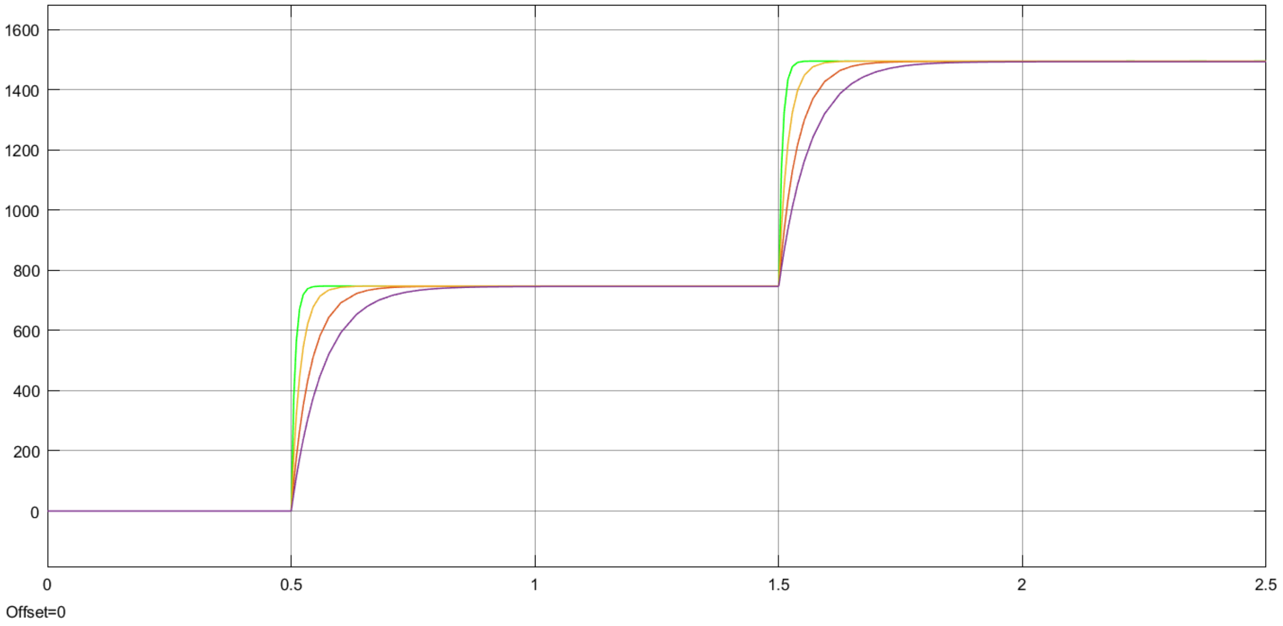

Figure 20:Individual vs statistical data for 50% peed to full speed

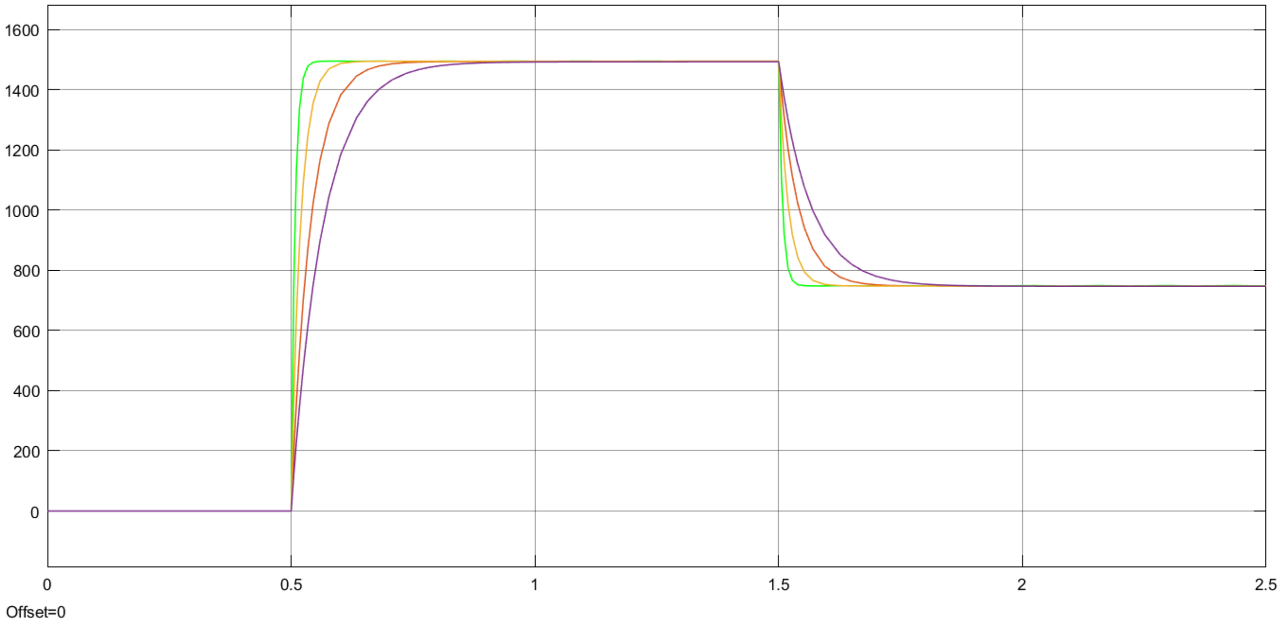

Figure 21: Individual vs statistical data for full speed to 50% speed

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