University of Sheffield

FIRST YEAR DC MACHINE DRIVES LABORATORY

THIS EXPERIMENT INVOLVES VOLTAGES IN EXCESS OF 50VDC. DO NOT TOUCH ANY TERMINALS OR DISCONNECT ANY WIRING EXCEPT WHEN THE DRIVE CONTROLS HAVE BEEN ISOLATED AND THE MACHINE HAS STOPPED. IF YOU ARE IN ANY DOUBT CONSULT A DEMONSTRATOR OR SUPERVISOR.

September 2008

Department of Electronic and Electrical Engineering

University of Sheffield
Department of Electronic and Electrical Engineering

Experiment 7

DC Machine Drives

Aim

To introduce the dc machine as a controllable electromechanical energy conversion device and to investigate its more important characteristics.

Objectives

By carrying out a sequence of tests, students should be able to do the following:-

(i) Measure the steady state electrical and mechanical characteristics of a dc machine and relate these to the equivalent circuit model provided

(ii) Recognise that a dc motor and generator are essentially the same device but operated with alternative energy flow directions.

(iii) Observe the essential electromagnetic structure of the dc machine and relate this to the equivalent circuit model.

(iv) Identify the main control characteristics of torque proportional to current and induced emf proportional to speed, as the key to the specification of any controller requirements.

Assessment

(i) No written report is required for this experiment.

(ii) Your assessment will be based on your performance during the lab and your preparation for it.

(iii) You must record all results in your lab book and plot all graphs as the experiments proceed.

(iv) Marks will be awarded for: sensible recording and choice of data, graph plotting and annotation, interpretation of your results, and your general contribution to discussions with the staff or postgraduate supervisor.

DC Machine Drives

1. Introduction

1.1 The DC Machine

DC Machines consist essentially of two parts, a source of magnetic flux and its associated magnetic circuit, which mat be either an electromagnet (field winding) or a permanent magnet, and a rotating winding or armature connected to a dc supply via a commutator and brushes. These are shown schematically in figure 1.

There are two basic interactions between the armature and the field:

1) Rotation of the armature within the field produces an induced emf E.
2) The armature current I_a interacts with the field to produce torque T.

Both mechanisms occur in a motor and in a generator. As a generator, mechanical power applied to the shaft produces rotation, E is generated and the output current I_a produces torque to oppose the applied driving torque. As a motor, power flow is reversed, V is applied, and the input current produces torque and rotation. The resulting E generated opposes V and the mechanical load applied opposes the torque produced.

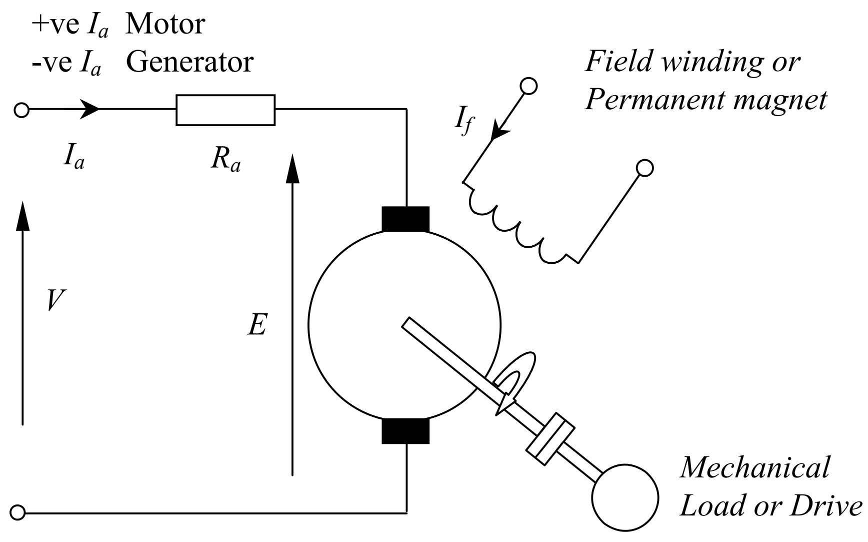


Figure 1 Schematic of DC machines

Brush type machines, as described briefly above, are produced in sizes from a few watts of output power up to several MW, with permanent magnet machines covering the smaller power ranges up to about 1kW. A recent and increasingly important development is an inverted form of permanent magnet dc machine in which the magnets rotate, the armature winding is stationary and the commutator is replaced by some form of rotor position detector and solid state switches. Such motors are then known as Brushless DC motors and can be designed to produce output and control characteristics equivalent to that of the brushed motors but eliminating the difficulties associated with the commutator and brush gear.

1.2 Emergency Stop

A RED EMERGENCY STOP BUTTON IS PROVIDED AND SHOULD BE USED TO ISOLATE AND STOP THE MACHINE SET IN AN EMERGENCY - ENSURE YOU KNOW ITS LOCATION.

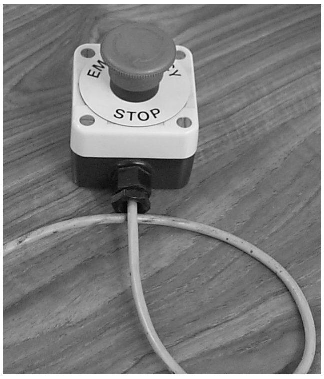


Figure 2 Emergency Stop Button – FIND IT

1.3 Description of machine and drive set

The complete machine and drive set used in this experiment consists of a DC motor, a dual shaft induction motor and a synchronous brushless permanent magnet (PM) motor mounted on an aluminium base plate, Figure 3. A torque transducer is mounted between the synchronous PM machine and the induction machine. Throughout this experiment, however, the induction machine is idle, and the DC and synchronous PM machines are used in such a manner that when one operates as a motor, the other acts as a generator. The machine set is controlled from the drive unit which include two Unidrives for the two AC machines (synchronous and induction), a 4Q2 four quadrant DC motor drive, and FX5 field controller for the regulation of the DC motor field current. On the front panel of the drive unit, an **isolation switch** and **power on**/**power off** buttons are available, Figure 4. These are only to be operated by demonstrators and supervisors, and you should **not** use them **without authorisation**.

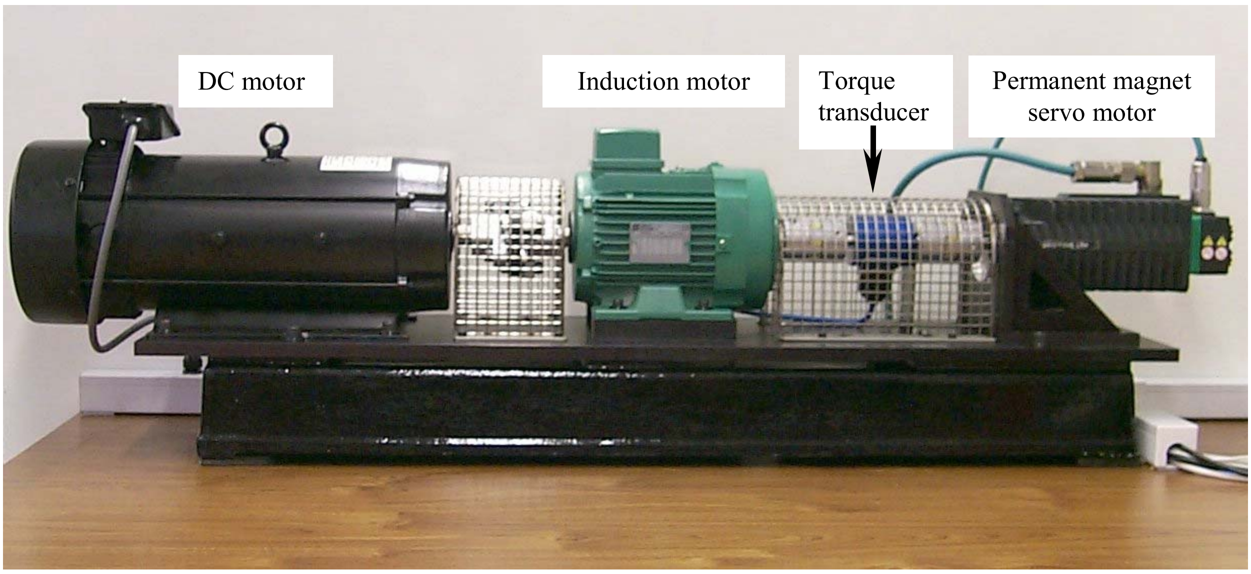


Figure 3 Experiment machine set

Figure 4 Drive control unit

The 4Q2 dc motor controller consists of two fully controlled thyristor bridges rated at 240V and 2.2 kW. The two bridges are configured to supply a single DC machine, as shown in Figure 5, so that it can operate as motor or generator in both directions of rotation. This is known as four-quadrant operation. Obviously, the logic control of the bridge must prevent simultaneous operation of both!

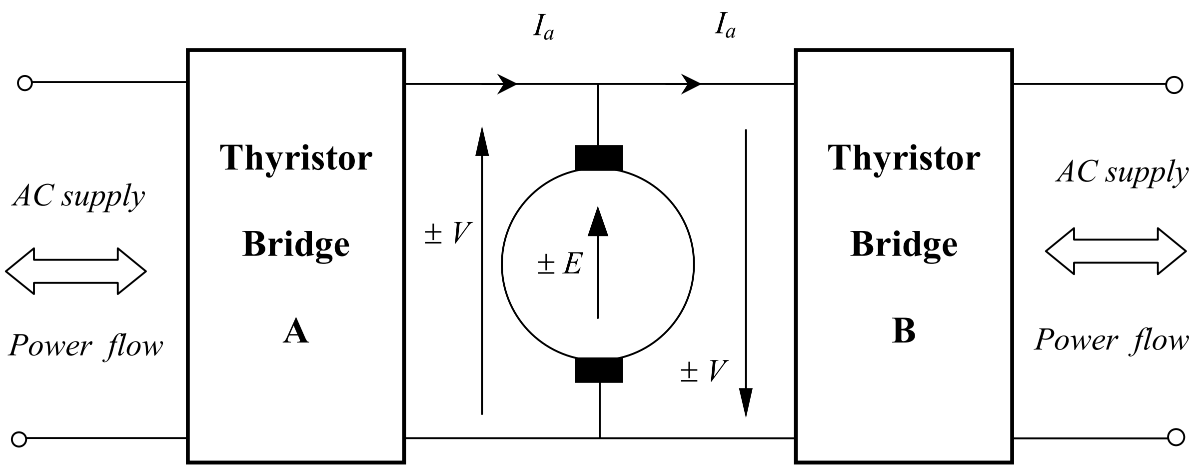


Fig. 5 Schematic of 4Q2 DC motor controller

A controller such as that describes above, plus a dc machine provides a very flexible variable speed drive. The following experiments will demonstrate that a dc machine has relatively linear control characteristics both for speed and torque, which is why it is often the first choice for closed loop speed, torque or position control systems, and why it plays a major role in the growing market and automation and robotics.

Motor specifically designed to have highly linear characteristics and usually a high torque to inertia ratio are given the name of servo motors and the complete drive is called a servo drive or servo system.

The drive unit used in this experiment is controlled by a PC via a **LabView™** based program. Figure 6. Once loaded, this program displays a Control Panel with a selection menu. An experiment task starts by clicking on a relevant menu button and a new control panel will be displayed. All necessary settings and readings except for torque reading are available on the panel. When an experimental program is running, the PC is constantly communicating with the drive unit in real-time, therefore, **you should not use PC for any other purpose**.

The torque reading can be obtained from the E302 instrument panel, Figure 7, which also includes a digital zero button. This can be used to reset the zero torque reference to reduce the effect of drafting due to temperature and other environmental factors

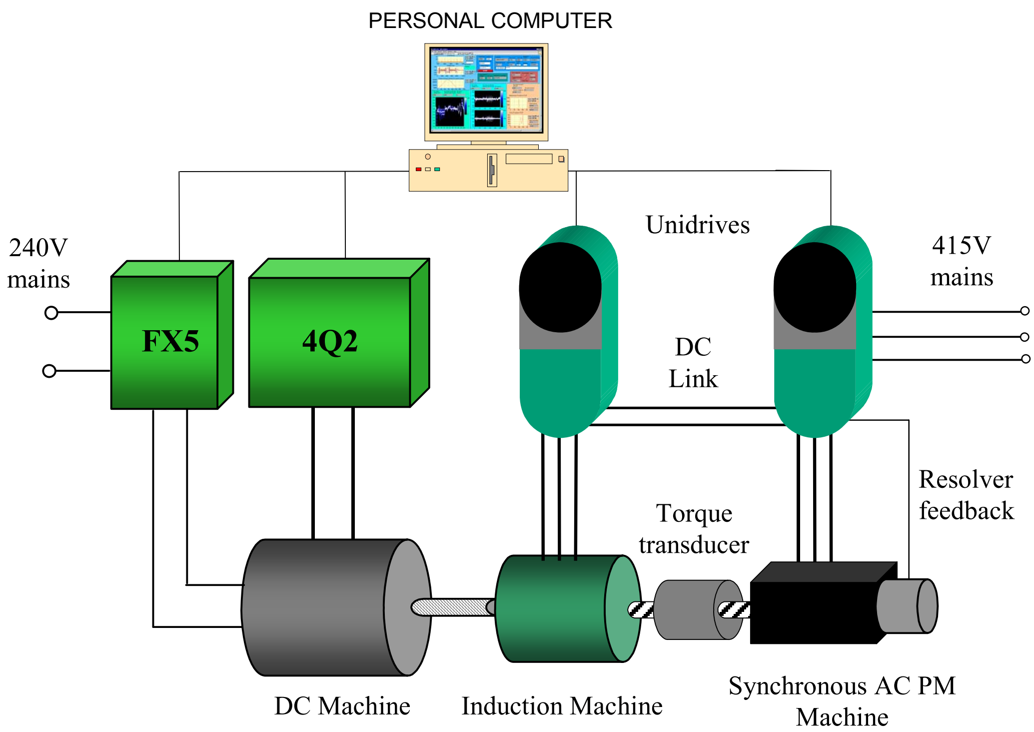


Figure 6 Drive control unit

Figure 7 Torque instrument panel

2. DC Machine theory

1) The flux Φ in a wound field machine is produced by a field current I_f and, because of the air gap between field and armature, the relationship between Φ and I_f is largely linear.

$\therefore \Phi = f(I_f)$ in Webers

However, there is a small amount of remnant magnetism at zero I_f and saturation at high levels of I_f so the linear relationship is only approximate, i.e.

$$\Phi = K_f I_f \tag{1}$$

2) Faradays law states that the induced emf is proportional to the rate of change of flux linkages. Hence the emf induced in the armature windings is given by:

$$E \propto \mathit{flux}\,\Phi \times \mathit{speed}\,\omega[\mathit{rad}\,s^{-1}]\ \mathit{Volts} \tag{2}$$

and $E = k\omega$ Volts for a constant flux Φ. (3)

The relationship between E and I_f from equations (1) and (2) contains all the non-linearities mentioned above and whilst these are important in self-excited generators, they are minimised in servo-motors to give good linear control characteristics. The relationship is called the open circuit (or magnetisation) characteristic of the machine.

Experiments 1 and 2 can now be carried out to verify the above relationships and the extent of any non-linearities. Do this before continuing with the theory.

3) The dc machine armature has a finite resistance and inductance such that in general the terminal voltage is given by.

$$V = i_a R_a + L\frac{di_a}{dt} + e$$

Under steady state conditions $\frac{di_a}{dt} = 0$ and as can be seen from Figure 8 then

$$V = \pm I_a R_a + E \tag{4}$$

Where $+ I_a \equiv$ motor operations and $- I_a \equiv$ generator operation. Thus it can be seen that a dc machine can either be a motor or a generator simply by reversing the direction of current flow and consequently the flow of power.

4) The power flow corresponds to the conversion of electrical to mechanical energy or vice-versa.

From equation (4), multiplying through by $\pm I_a$ gives:-

$\pm VI_a$	$=$	$I_a^2 R$	$\pm$	EI_a
Electrical Power		Heat loss		Mechanical power

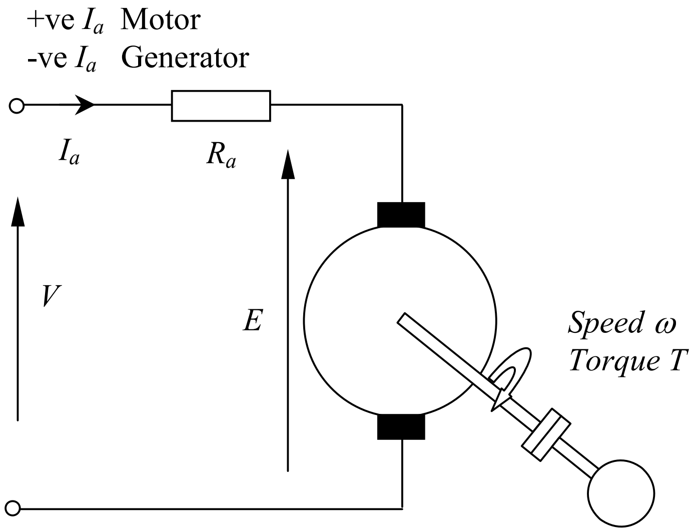


Figure 8 Schematic of DC machine operation

In motor operation electrical power input is converted to an output mechanical torque and speed and in generator operation an applied mechanical torque and speed is converted to electrical power output.

In both cases Mechanical power = Torque (Nm) x Speed (rad s^{-1})

Thus $EI_a = T\omega$

Or $\frac{E}{\omega} = \frac{T}{I_a} = K$

and $T = KI_a$

In some literature, E/ω is defined as back-emf constant K_E, and T/I_a as torque constant K_T. For an ideal DC machine therefore, we have:

$$K_E = \frac{E}{\omega} = \frac{T}{I_a} = K_T = K$$

Your results from experiments 2 and 4 should confirm these relationships.

Note also that in many practical systems, the speed is measured in revolutions per minute (rpm) denoted as *n*. Thus the relationship between ω (rad/s) and *n*(rpm) is given by:

$$\omega = \frac{2\pi n}{60}$$

Experiment 1 — Measurement of open circuit characteristic

In this experiment, the DC machine is driven by the PM motor at a constant speed of 2400 rpm, and its armature is in open-circuit. The emf (open circuit armature voltage) as a function of field current is measured.

1. From the main computer menu, press the button labelled "**Run Back-emf vs. If test**";
2. Click on the "**Drives Run**" button. An information window "The brushed machine is now going to be driven up to a speed of 2400 rpm" appears. If you are ready for the experiment, click **OK.** The DC machine speed is now controlled at 2400 rpm.
3. Increase I_f in steps up to a maximum 0.65A. Click on "**Add point**" in each step and record I_f and the induced emf, E. A graph of back-emf vs. I_f will be displayed as each point is added. **Do not allow I_f to fall back during this process**.
4. Take readings of E as I_f is gradually decreased to its minimum value. **Do not allow I_f to rise during this process**.

Speed (rpm)								
I_f (A) rising								
E (V)								
I_f (A) falling								
E (V)								

5. Click on the "**Drives Stop**" button.
6. Plot E against I_f in **Graph 1**
7. Click on the "**Stop VI**" button to return to the main menu.

Graph 1

Summarise the factors influencing these characteristics and also their significance.

Experiment 2 — Measurement of open circuit speed emf

Similar to Experiment 1, the DC machine is in open-circuit and driven by the PM motor at different speeds. The emf as a function of speed and field current is measured.

1. From the main computer menu, press the button labelled "**Run Back-emf vs. w test**";
2. Click on the "**Drives Run**" button.
3. Adjust the DC machine field current I_f to 0.35 A.
4. Increase the servo machine controls speed in steps from 0 to 2000 rpm. Click on "**Add point**" in each step, and record the speed and the induced emf, E. A graph of back-emf vs. ω will be displayed as each point is added.
5. Click on "**Add series**".
6. Repeat step 4, with I_f set to 0.57 A.

I_f (A)									
Speed (rpm)									
E (V)									
I_f (A)									
Speed (rpm)									
E (V)									

7. Click on the "**Drives Stop**" button.
8. Click on the "**Stop VI**" button to return to the main menu.
9. Plot the results of steps 4 and 6 (E against ω) in **Graph 2**. Calculate the speed-emf constant $K_E = E/\omega$.

Graph 2

Experiments 1 and 2 give you the basic open circuit characteristics measured with the DC machine operating as a generator. The same induced emf occurs when operating as a motor, where the induced emf E now opposes the applied voltage V.

Read the remaining theory before continuing the experiment

Experiment 3 — Separately Excited Generator on Load

This experiment corresponds to the conversion of mechanical power to electrical power and you should note the direction of the power flow.

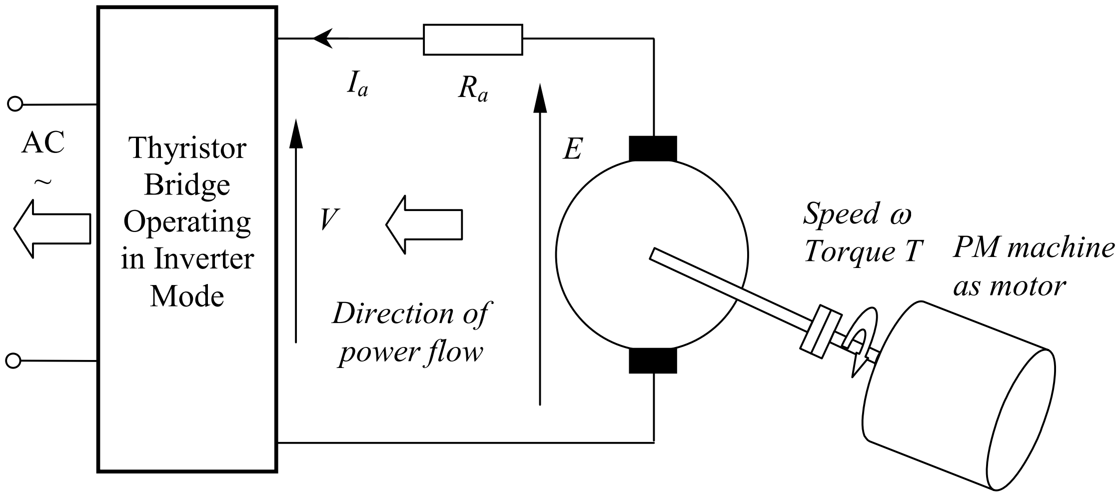


Figure 9 DC generator operation

1. From the main computer menu, press the button labelled "**Run Generator on load**";
2. Click on the "**Drives Run**" button.
3. Zero the torque reading by press the "zero" button on the torque instrument panel.
4. Set the servo machine controls speed to 2000 rpm, record the field current I_f
5. Increase the generator load in steps from 0 to −40%. Click on "**Add point**" in each step, and record voltage, current and torque. A graph of output voltage against current will be displayed as each point is added. **Note that in order to generate the electric power to AC mains, thyristor bridge B needs to be activated. If bridge A is initially activated then because of the hysteresis it may be necessary to apply a sufficient amount of load (e.g. −30%) to activate bridge B. Once this has been done, you can set the load back to zero, and start to increase it in steps.**

I_f (A) =				Speed (rpm) =					
Current I_a (A)									
Voltage V (V)									
Torque (Nm)									
Input power (W)									
Output power (W)									
Efficiency									

6. Click on the "**Drives Stop**" button.
7. Click on the "**Stop VI**" button to return to the main menu.

From your results calculate the input and output power of the DC machine and hence its conversion efficiency. What are the main loss mechanisms in this system.

Experiment 4 — Separately Excited motor on Load

The next experiments use the DC machine as a motor and the drive modules are switched around so that drive A now supplies the DC motor with electrical power whilst the servo machine operates as a generator and hence applies a mechanical load on the DC machines.

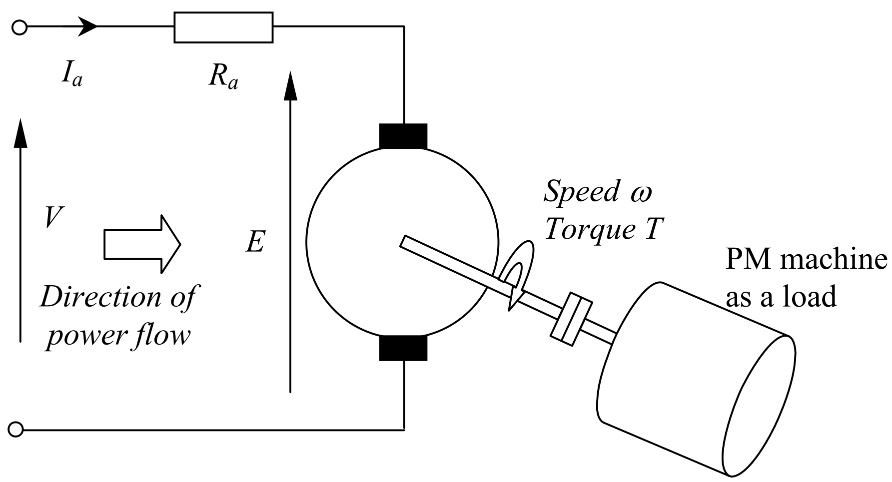


Figure 10 DC motor operation

1. From the main computer menu, press the button labelled "**Run motor on load test**";
2. Click on the "**Drives Run**" button.
3. Zero the torque reading by press the "zero" button on the torque instrument panel.
4. Record the field current I_f.
5. Set the DC motor armature voltage to 150V
6. Increase the servo machine controls torque in steps from 0 to -50%. Click on "**Add point**" in each step, and record current, torque and speed. A graph of the motor torque against current will be displayed as each point is added.
7. Set torque back to zero and click on "**Add series**"
8. Repeat step 6 for an armature voltage of 180V

I_f (A) = Armature voltage (V) =									
Current I_a (A)									
Torque (Nm)									
Speed (rpm)									
I_f (A) = Armature voltage (V) =									
Current I_a (A)									
Torque (Nm)									
Speed (rpm)									

9. Click on the "**Drives Stop**" button.
10. Click on the "**Stop VI**" button to return to the main menu.
11. Plot T against I_a for each armature voltage setting in **Graph 3**. Calculate the torque constant $K_T = T/I_a$.

Graph 3

Can you use your observation to show that the power flow has reversed?

Use the results of this experiment for I_f = 0.57A and experiment 2 to compare the values of K_E and K_T. Explain the significance of your results and any inferences you may have made in order to reconcile these with the theory.

Experiment 5 — Speed control of a DC motor

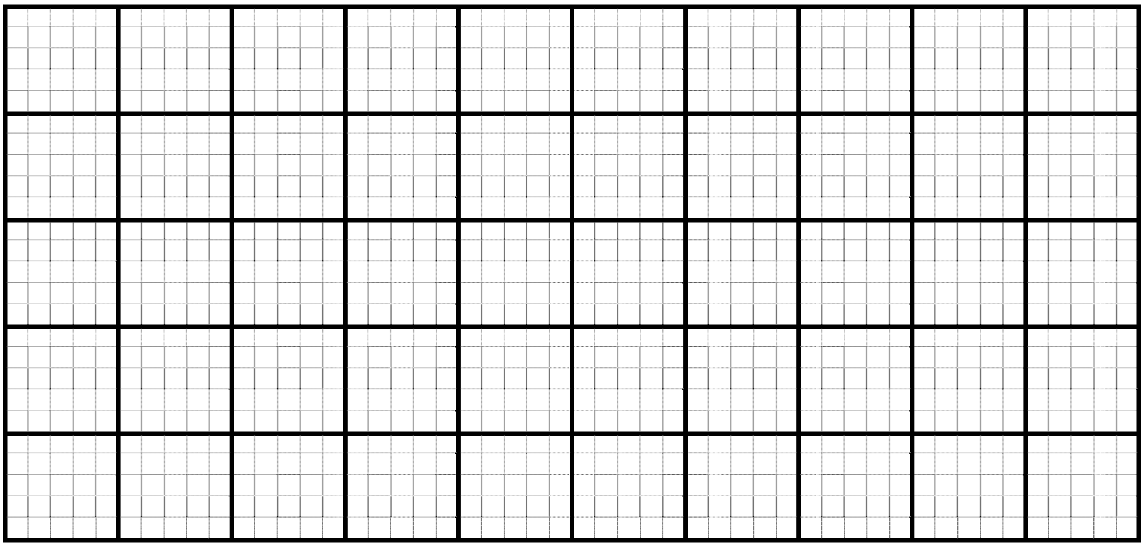
The experiment should demonstrate the principles for a variable speed drive system using DC machines.

1. From the main computer menu, press the button labelled "**Run speed control**";
2. Click on the "**Drives Run**" button.
3. Zero the torque reading by press the "zero" button on the torque instrument panel.
4. Set the field current I_f to 0.57A.
5. Set the DC motor armature voltage to 100V
6. Increase the servo machine controls torque in steps from 0 to 50%. Click on "**Add point**" in each step, and record speed, current and torque. A graph of the motor torque against speed will be displayed as each point is added.
7. Set torque back to zero and click on "**Add series**"
8. Repeat step 6 for an armature voltage of 180V.
9. Reduce I_f to 0.45A and repeat step 6 with an armature voltage of 180V.

I_f (A) = Armature voltage (V) =									
Speed (rpm)									
Current I_a (A)									
Torque (Nm)									
I_f (A) = Armature voltage (V) =									
Speed (rpm)									
Current I_a (A)									
Torque (Nm)									
I_f (A) = Armature voltage (V) =									
Speed (rpm)									
Current I_a (A)									
Torque (Nm)									

12. Click on the "**Drives Stop**" button.
13. Click on the "**Stop VI**" button to return to the main menu.
14. Plot *Torque vs. speed curves* for steps 6, 8 and 9 in **Graph 4**.

Graph 4



Explain how these characteristics can be used to demonstrate how the speed of the machine can be controlled.
Justify the shape of these graphs from the model and theory given.

DC Drive Design and Closed Loop Control

1. The test machine has an armature resistance R_a of 6Ω. You are asked to design a power electronic controller capable of driving the machine at a speed of 1200rpm when connected to a load torque of 2 Nm. Form the data you have collected on this machine can you specify the current and voltage which the controller will need to supply?

2. The controller in experiment 4 had to automatically keep the speed constant as the torque was increased, can you explain how this was achieved?