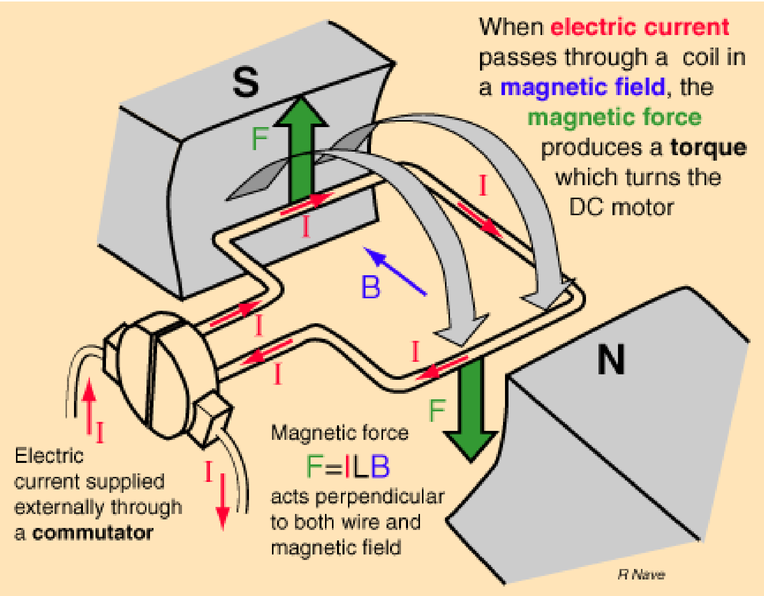
T6

Performance Characteristics of DC Motors

As the title of the lab suggests, you will measure the performance characteristics of a DC motor, both in the series and separately excited configuration. By varying the load on the motor, you will be able to extract the torque against speed curves which describe the basic operation and from which the power can be derived. The experiment itself is relatively straight forward and emphasis is on the presentation of the experimental results and the extraction of the parameters that determine motor operation.

This exercise uses high current and medium voltages which are potentially harmful. Please be thoughtful.



Schedule

Preparation time	:	3 hours
Lab time	:	3 hours

Items provided

Tools	:	n/a
Components	:	Motor
Equipment	:	Voltage and current sources and meters and leads, Tachometer
Software	:	n/a

Items to bring

Essentials. A full list is available on the Laboratory website at https://secure.ecs.soton.ac.uk/notes/ellabs/databook/essentials/

Before you come to the lab, it is essential that you read through this document and complete ***all*** of the preparation work in section 2. If possible, prepare for the lab with your usual lab partner. Only preparation which is recorded in your laboratory logbook will contribute towards your mark for this exercise. There is no objection to several students working together on preparation, as long as all understand the results of that work. Before starting your preparation, read through all sections of these notes so that you are fully aware of what you will have to do in the lab.

> **Academic Integrity** – *If you undertake the preparation jointly with other students, it is important that you acknowledge this fact in your logbook. Similarly, you may want to use sources from the internet or books to help answer some of the questions. Again, record any sources in your logbook.*

Revision History

August 10 , 2013	Mihai D Rotaru (mr)	Version 2a, Minor modifications
February 01, 2013	Kees de Groot (chdg)	Version 1, Continuation of EE4

1 Aims, Learning Outcomes and Outline

This laboratory exercise aims to:

- Give you experience of performing a range of electrical measurements on dc motor performance.

Having successfully completed the lab, you will be able to:

- Understand engineering principles and apply them to analyse key engineering processes
- Record and report laboratory work
- Use mathematical skills to analyse real problems.

As the title of the lab suggests, you will measure the performance characteristics of a DC motor, both in the series and separately excited configuration. By varying the load on the motor, you will be able to extract the torque against speed curves which describe the basic operation and from which the power can be derived. The experiment itself is relatively straight forward and emphasis is on the presentation of the experimental results and the extraction of the parameters that determine motor operation.

While you are performing a range of electrical measurements on dc motor performance, you are required to write down the measurements results in well-presented legible tables, and subsequently in graph form. This will allow you to test the theoretical models that are described in the preparation section.

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2 Preparation

Read through the course handbook statement on safety and safe working practices, and your copy of the standard operating procedure. Make sure that you understand how to work safely.

2.1 The DC Motor

The dc motor (sometimes called the zero frequency motor, especially in old textbooks) consists of three main components: a field system, an armature and a commutator. Figure 1 shows the basic construction of a dc motor. The field system of a dc motor is usually located on its stator. The field system can be a field winding (coil) or it could be a pair (or more) of permanent magnets. As its name sugests the field system has the role of producing the main magnetic field in a DC machine. The armature coil is housed typically on the rotor of the machine, as it is in the case of the demonstration motor used in this experiment. The armature coil or armature winding is where the field existent in the machine will induce a voltage due to the movement of the armature winding with respect to the field. It should be noted that the terms field and armature refer to electrical circuits which are essential for the process of electromechanical energy conversion to be performed. The stator and the rotor refer to the stationary and rotating parts of an electromechanical device; respectively. In electrical machine terminology the armature winding refers to the winding where the voltage is induced while the field system refers to the component of the machine that produces the main magnetic field. The position of the field system and the armature windings may be reversed as it is the case of synchronous machines and brushless permanent magnet (PM) machines.

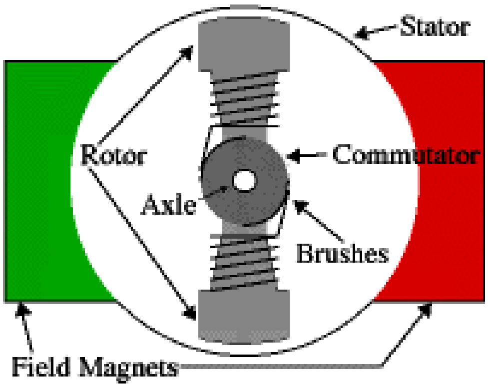

FIGURE 1: Principle of operation of a DC motor (taken from www.solarbotics.net)

The field poles project inward from the inside surface on the iron cylinder that forms the stator yoke (Figure 2). This yoke serves as a return path for the pole flux. Each iron pole consists of a narrow part, called the pole core, around which is placed the exciting winding, called a field coil. The 'coil' may consist of two or more separate windings to provide control of the field flux. A pole shoe, usually laminated, distributes the pole flux over the rotor surface. In PM motors, the pole core is made of PM material.

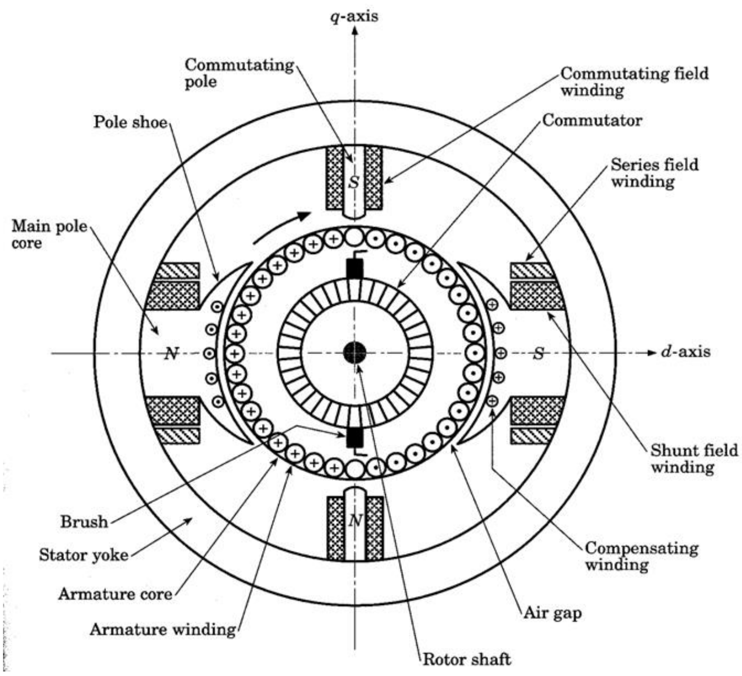

FIGURE 2: DC machine construction

The armature winding is composed of coils embedded in slots in the rotor. The rotor has a cylindrical steel core, consisting of a stack of slotted laminations. The slots in the laminations are aligned to form axial slots on the outside surface of the core, in which the armature winding is placed. In small motors, the slots are sometimes skewed to reduce acoustic noise and electromagnetic losses. The armature coils are often held in place by wood or fibre wedges.

The leads from the armature coils are connected to the commutator. The commutator, which is always mounted on, but insulated from, the shaft of the rotor at the non-drive end, consists of radial copper segments, separated from each other. Current is conducted to the armature by carbon brushes that are held against the cylindrical surface of the commutator by the force of springs fitted in the brush-holders. Current is carried into the brush by a 'pigtail', which is a very flexible wire embedded in the brush material and connected to the brush holder. Brushes must be inspected regularly and replaced as necessary as they are worn away. Most dc machines are like ac machines in that they have ac voltages and currents within them – dc machines have a dc output because the commutator converts the internal ac voltage to dc voltage at their terminals. The commutator and bushes perform inversion (from dc to ac) in the case of a motor.

2.2 Principle of Operation

A mechanical force is produced on a current carrying conductor placed in a magnetic field according the Fleming's left-hand rule as illustrated in Figure 3. Reversing the direction of current reverses the direction of the force. The magnitude of the (Lorentz) force is given by $F=L.IxB$, where **B** is the magnetic flux density in T, I is the electrical current in A, L is the effective length of the conductor in m and **F** is the force in N.

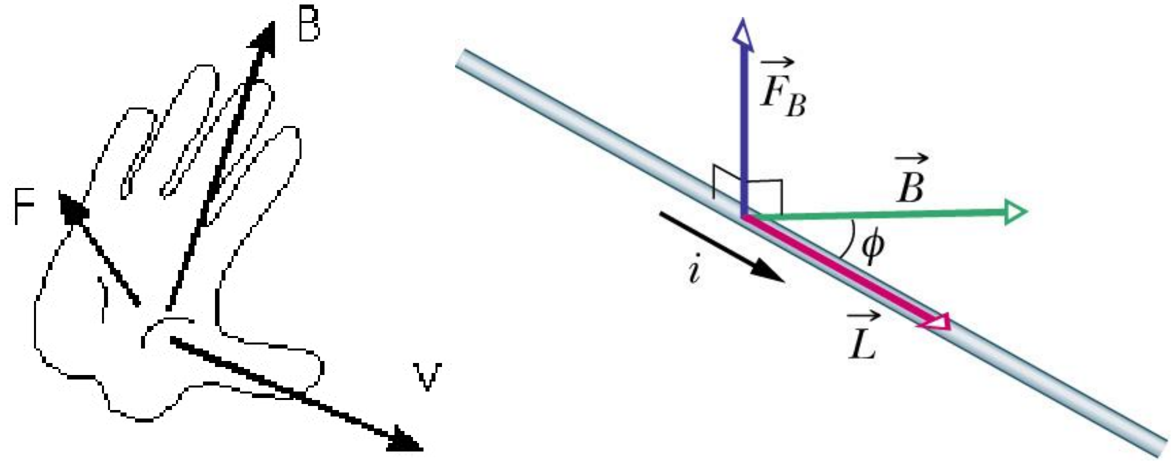

FIGURE 3: Flemming's Right-Hand Rule

Figure 4 illustrates the principle of operation of a single coil dc motor. Here there are two long conductors that run parallel to the rotation axis and two short conductors that run perpendicular, called coil-ends. The latter are in parallel to the field and produce no useful force. The magnitude of the force acting on each of the two long conductor is given by the Lorentz Force. The forces on the two conductors act in opposite directions. As the coil rotates, the direction of the current in the coil must be reversed to ensure that the produced torque is always in the same direction. This is achieved by the action of the commutator and brushes.

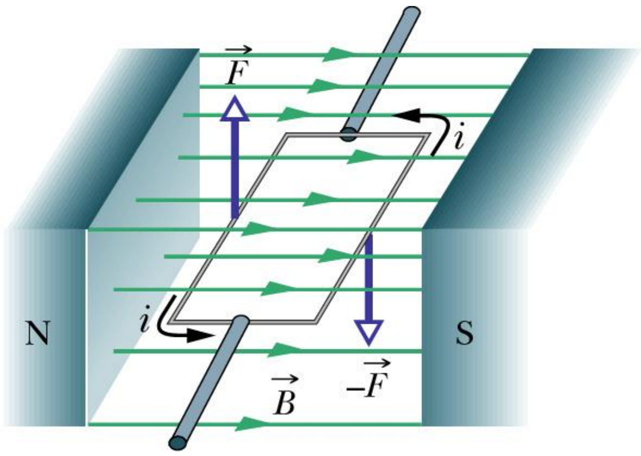

FIGURE 4: Forces on a coil in a magnetic field

In a practical motor multiple coils are used, and the action of the commutator is to ensure that the current distribution in the armature is fixed relative to the stationary field poles and does not rotate with the rotor; i.e. the current in the conductors under the north pole is always in the same direction (opposite to the direction of current in the conductors under the south pole) regardless of rotor rotation as shown in Figure 5. When a conductor moves from the north pole to the south pole, the commutator changes the direction of current in this conductor.

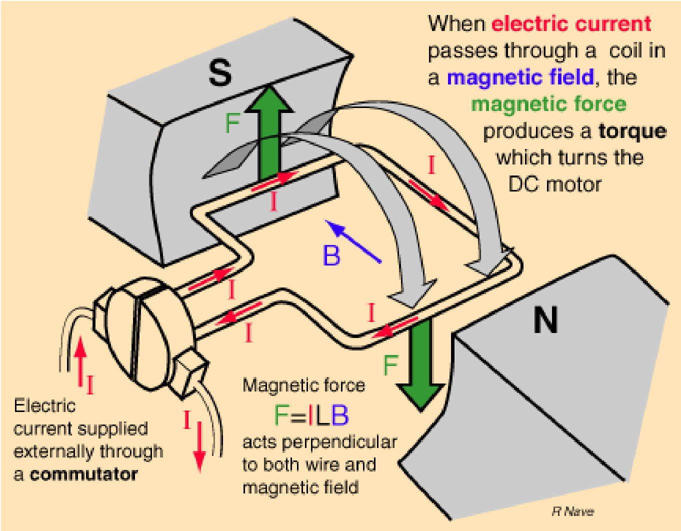

FIGURE 5: Schematic of a simple DC Motor

The dc motor can be represented by simple equivalent circuits as shown in Figure 6, for steady state conditions. There are two circuits, one for the armature winding and one for the field winding. The field winding may be connected in *series* or in *parallel* to the armature winding, or it is separately excited, as in Figure 6. The field winding is not present in a PM motor.

In a separately excited motor, both the field and the armature windings are supplied from different power supplies. The field voltage is usually held constant and therefore the field current and flux remain approximately constant (there are slight variation due to the change of the field resistance with temperature). The PM and the shunt (parallel) connected motors also have approximately constant field current and flux and their characteristics are similar to the separately excited motor.

In the series connected motor, the field and the armature are connected in series and hence the field and the armature current are the same. This produces a very different set of performance characteristics. The most notable feature of the series motor is the very high starting torque making it ideal for starting heavy loads from rest as in traction applications such as trains and hoists.

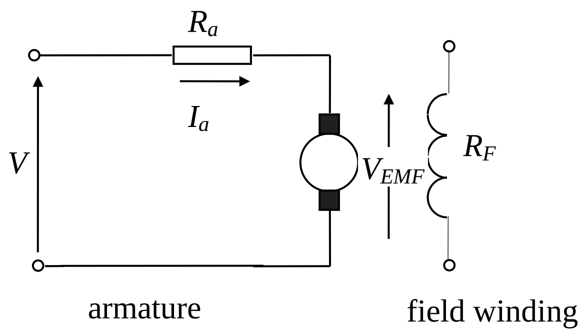

FIGURE 6: Equivalent circuit of a dc motor

2.3 Theory of Operation

The torque of a motor T is related to the armature current I_A through the torque constant K_T. The mechanical power generated by this motor P_{out} is equal to the torque multiplied by the angular velocity or speed ω. The rotating motor will induce a back emf V_{EMF} on the armature winding through Faraday's law of induction with K_V the back emf constant. The input motor power P_{in} is simply given by the current times voltage.

$$T = K_T I_A \tag{1}$$

$$P_{out} = T\omega \tag{2}$$

$$V_{EMF} = K_V \omega \tag{3}$$

$$P_{in} = V_{EMF} I_A \tag{4}$$

If we assume that there are no losses in the motor (internal efficiency 100%), it is necessary that the output power equals the input power. Re-arranging Equations 1 to 4 it can be shown that:

$$K_V = K_T = K \tag{5}$$

The same equality between torque constant and back emf constant can also be derived by calculating torque, and back emf from the Lorentz Force, and Faraday's law of induction, respectively. The maximum of both constant is equal to the magnetic flux Φ of each winding N, which is the magnetic flux density **B** times the area *A*. From the definition of inductance, we can relate the flux to the inductance of the magnetic coil L_F and the current through the coil I_F.

$$K_{\max} = N\Phi = NBA = L_F I_F \tag{6}$$

Derive the maximum torque using the Lorentz force

Derive the maximum back emf using Faraday's law of induction

We can now express the torque of the motor using the control parameters and the speed of the motor only. The speed of the motor is dependent on the load on it. For the series motor, both currents are of course identical giving a quadratic relation with current while for the separately excited motor the current is proportional to each current individually. Please note that in this derivation, we have neglected many aspects such as the exact geometry of the motor and any friction. The equation below is hence an idealised expression.

$$T = L_F I_F I_A = L_F I_F \frac{V_A - L_F I_F \omega}{R_A} \tag{7}$$

What do you expect to happen in the experiment in Section 3.1.1 when you reverse both magnet current and armature current?

Explain which type of DC motor you would choose for:

a) a machine tool spindle drive with a constant voltage supply

b) an urban electric car

Sketch the expected graphs of Torque against speed, and torque against armature current for both series and separately excited motors

3 Laboratory Work

This exercise uses high current and medium voltages which are potentially harmful. Please be thoughtful. Do not connect short wires together in such a way that the leads are exposed. Do not modify the circuit without switching of the power supply first

3.1 Separately Excited Motor Characteristics

Connect up the circuit as shown in Figure 7. Supply A provides the power for the armature, supply B provides the power for the electro-magnet, and supply C regulates the load. Set all the supplies to zero.

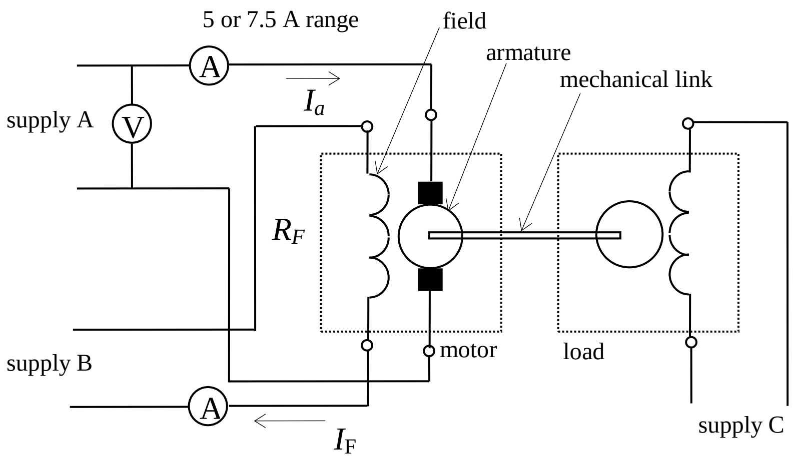

FIGURE 7: Connection for the separately excited motor tests

3.1.1 Direction of Rotation

Switch on and adjust the magnetic field current I_F to 2 A. Adjust the armature voltage V_A to 30V. Measure the speed and direction of rotation with the tachometer. Reduce V_A **and then** I_F to zero and switch off. Reverse the connections of supply A and re-measure speed and direction of rotation. Switch the supplies off again before measure the two other permutations of current direction as well (supply B only reversed, both supplies reversed).

Present your measurements in a table in matrix format. Explain the results.

Why do you think the armature current should be switched off first?

3.1.2 Constant Voltage Characteristics

Maintain the wiring of the previous test with the direction of rotation such that the torque meter (dynamometer) is functional. Keep the shaft load as regulated by supply C at zero for the moment. Switch on the supplies and set the field current I_F to 3A. Set V_A to 50 V. Under these conditions the motor ought to be running at about 100 rad/s.

For a range of 6 loads (set each by adjusting the supply C) from no load to a load corresponding to I_A = 4 A, take a set of readings of speed, torque and armature current. Ensure that the field current and armature voltage remain constant for all the readings. Reduce the load (supply C) to zero, then reduce V_A to zero and finally reduce I_B to zero. Switch off all supplies. For the calculations, use a distance to the pivot of 10cm.

Plot the following graphs:

(i) Torque against speed

(ii) Torque against armature current.

◇ *Explain the shape of each curve using the equations that were given or derived by you in the preparation section*

◇ *Extract the value of the torque constant K from the torque against armature current graph*

3.2 Series Motor Characteristics

Connect up the circuit as shown in Figure 8. Supply A provides the power for the armature and for the electro-magnet, and supply C regulates the load. Set all the supplies to zero.

Never run the series motor without a load and always keep the speed below 1500 r/min.

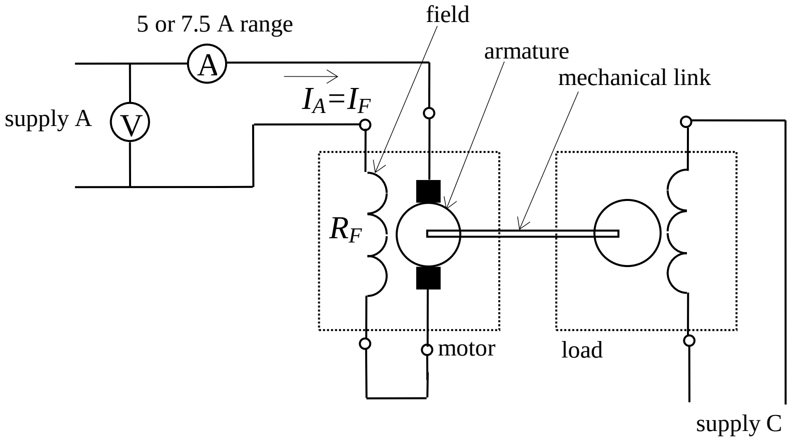

FIGURE 8: Connection for the series motor tests

Switch on and apply a small load by setting supply C to dial reading 10. Set the armature voltage V_A (supply A) to 50V and regulate supply C so that I_A = 1 A. As V_A is an unregulated power supply, you might need to adjust it to keep it at 50V. Take readings of voltage V_A, torque and speed.

Keeping V_A = 50 V, increase the load successively to increase the armature current I_A to 1.5 A, 2.0 A, 2.5 A, 3.0 A and 3.5 A, taking readings of torque and speed at each step. Ensure that V_A is kept constant during the experiment. At the end of the experiment, reduce the load to approximately half. Reduce V_A to zero and then reduce the load to zero. Switch off.

Plot the following graphs (the same as in the previous paragraph). Use the same scale as in the previous graphs, or ideally plot them in the same graphs.

(i) Torque against speed

(ii) Torque against armature current.

◇ *Why is it detrimental to run a series motor without a load while we can do this without trouble in a separately excited motor?*

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4 Optional Additional Work

<u>Marks will only be awarded for this section if you have already completed all of Section 3 to an excellent standard and with excellent understanding.</u>

4.1 Theoretical Analysis

Measure the resistance of the armature circuit (R_A) and the magnetic field circuit (R_F).

Calculate for the separately excited motors the power supplied to the system $P_{sup}=I_A V_A$, the effective power for the motor rotation, $P_{in}=I_A V_{EMF}=I_A(V_A-I_A R_A)$, and the output power P_{out}.

Plot all three values for power against speed in the same graph

Discuss the efficiency of the motor.

Do the same for the series motor!

Appendices

Some of the Figures are taken from the book “Fundamentals of Physics” by Haliday, Resnick, and Walker (Wiley). The following books can be found in the library; please consult at least one of them (or any other relevant text book on machines) before the lab session.

1. McPherson, G, *An Introduction to Electrical Machines and Transformers*, John Wiley and Sons, 1981.
2. Wildi, T, *Electrical Machines, Drives and Power Systems*, Prentice Hall, 1991.
3. Kenjo, T and Nagamori, S, *Permanent-Magnet and Brushless DC Motors*, Oxford: Clarendon Press, 1985.

The original laboratory exercise EE4 DC Motors was designed and implemented by Barry Bailey and Dr Suleiman Abu Sharkh.