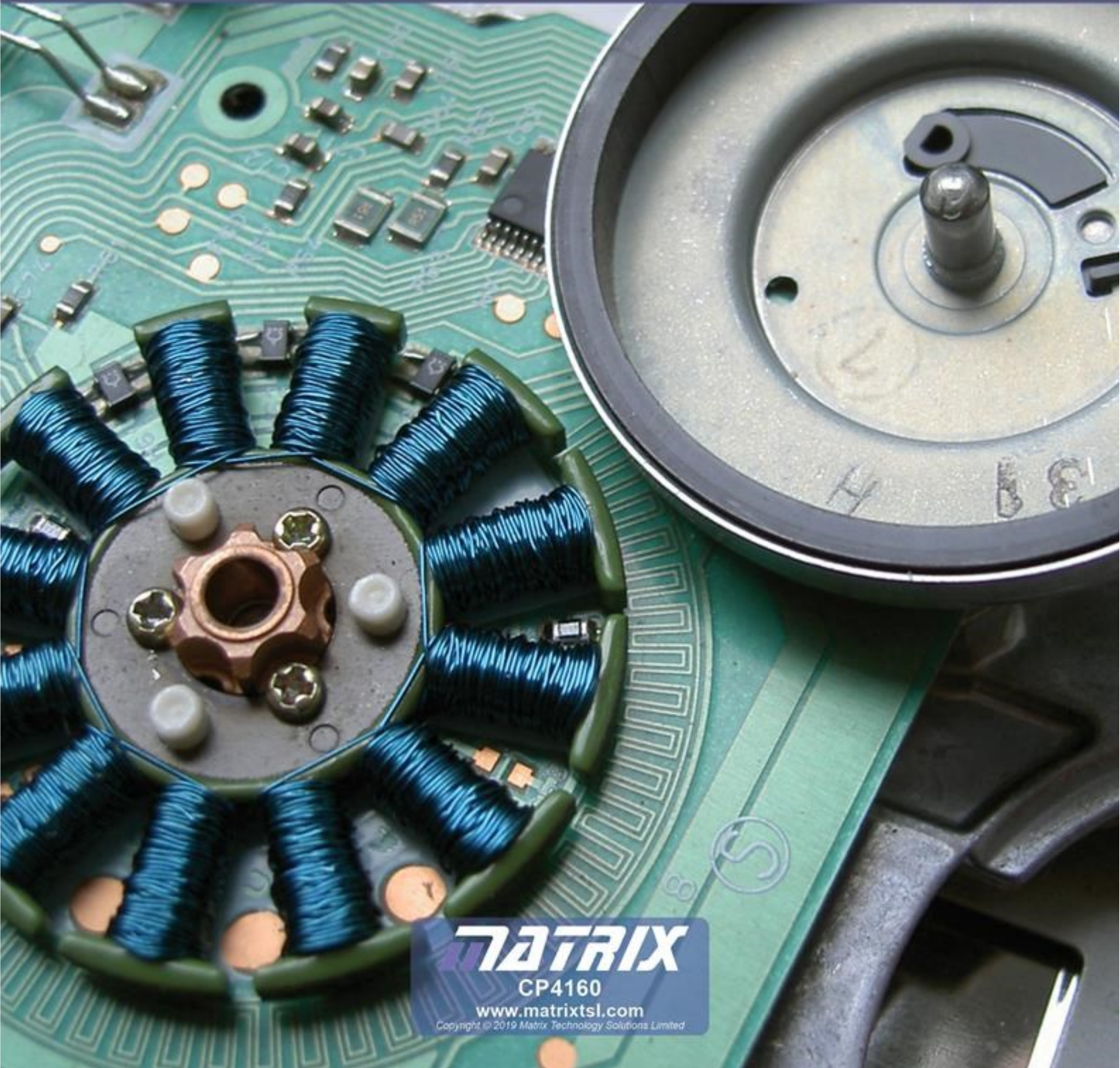
ELECTRICAL
MACHINES

Electrical machines for installation/Manual control



CP4160
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Safety

The design of this product reflects the care taken to address potential risks present when studying electric motors.

Read the sections below carefully!

Electric shock

The risk is minimal. The output from the control unit is limited to 24V AC or DC.

The dynamometer generates DC voltages.
At maximum speed, around 3,000 rpm., the generated voltage is less than 30VDC.
The control unit operates only if a motor is plugged into the dynamometer.
This prevents the use of third party motors with the system.

Physical shock

The equipment is heavy!

Should anyone drop a device, it could cause substantial injury. You need to decide on the level of responsibility that students take here.

The risk is reduced by:
- positioning the equipment on the benches ready for use;
- remaining seated whilst using the equipment.

Exposed rotating parts create potential hazards as hair and clothing can get caught in them. The use of relatively low-power motors reduces the risk. The plastic guard present between the dynamometer and the motor under test means that no rotating parts are exposed.

Please:

Should an accident happen while the equipment is being used, report it to us, at the address below, so that we can consider how to make the equipment even safer.

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Introduction

The course aims to prepare you for the following units within City and Guilds diplomas 2357 and 2365-03:

- Unit 302 - “Principles of Electrical Science” Learning Outcome 3;
- Unit 609 - “Understanding the electrical principles associated with the design, building, installation and maintenance of electrical equipment and systems”
  Learning Outcome 8.

As you work through the course, the layouts show you how to build the systems and each task details how to test them. There are a variety of different tasks, identified by a series of icons:

Icon	Significance
i	Content gives information about electricity, or explains some terminology
⚙	Practical activity
🏭	Relates the current activity to jobs in the industrial / domestic realm
🏅	Open-ended activity designed by the students
!	Health and Safety related issue
x^2	Activity involves a formula or calculation
So what 🎯	The outcome(s) of the investigation

For your records:

- it is important that you keep accurate records of what you do;
- a Student Handbook will be issued to assist with these records;
- in addition, take whatever notes you feel are necessary to help with this.

Power

Power supply:

- drives current around the circuit by applying a voltage.
- has two terminals (connection points) one ‘positive’ the other ‘negative’;
- current flows from the positive terminal to the negative terminal.

DC power supply - (DC = direct current):

- one terminal is always positive, the other always negative;
- ‘one-way traffic’ - current always flows the same way around the circuit.

AC power supply - (AC = alternating current):

- terminals change polarity repeatedly, one positive, the other negative and then they swap;
- ‘two-way traffic’ - current flows clockwise, then anticlockwise around the circuit.

AC or DC - which is used?

Each has its uses!

Electricity is usually generated and transmitted as AC. because:

- alternators (AC) are generally more efficient than dynamos (DC);
- ‘step-up’ and ‘step-down’ transformers can modify voltage and current to allow more efficient distribution.

Electronic devices - mobile phones, computers, televisions etc. usually require DC.

AC power can be converted into DC using the processes of rectification and regulation.

DC power can be converted into AC using a device called an inverter.

DC power supplies:

- **battery** - chemical reactions generate DC voltages, e.g. ‘lead-acid’ batteries;
- **solar cell** - photo-voltaic cells convert light energy into DC electrical energy;
- **dynamo** - a rotating coil of wire near a magnet generates DC provided a ‘commutator’ connects the coil to the rest of the circuit.

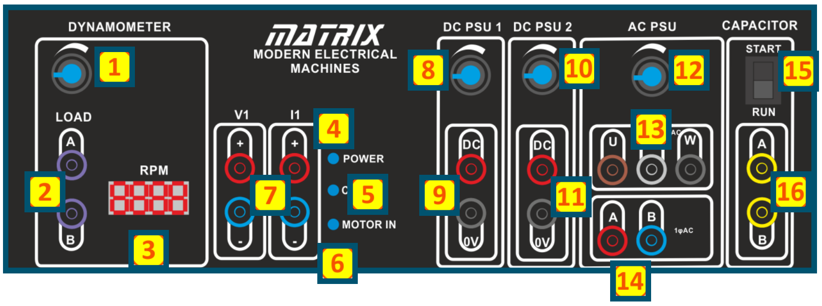
AC power supplies:

- **alternator** - another example of a rotating coil of wire near a magnet;
  - a ‘slip-ring’ connects to the rest of the circuit;
  - the coil can be rotated by high-pressure steam in a power station, by wind (wind-generator) or by falling water (hydro-electricity).

A tour of the kit

The control unit:

offers a choice of variable DC and AC power supplies, including single phase and three-phase AC supplies and other motor control features.

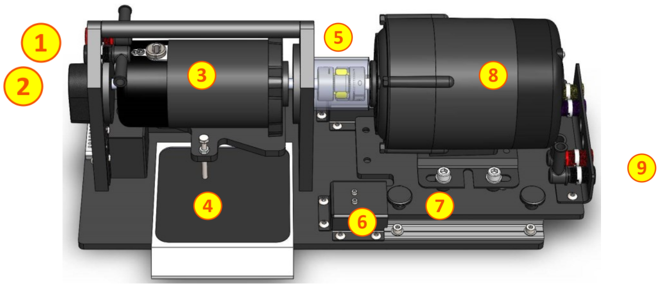


① Dynamometer resistance (load) adjustment:
Controls the load driven by the dynamometer and so controls how hard it works.
(A low electrical resistance means a large load and vice-versa)
② Dynamometer load sockets.
③ Display shows the speed of the motor in revolutions per minute (rpm).
④ 'Power' LED lights when the control unit is powered up.
⑤ 'COMMS' LED lights when the control unit is connected to a PC.
⑥ 'Motor In' LED lights when a machine is plugged into the dynamometer.
⑦ Connections to the internal software 'ammeter' and 'voltmeter'.
⑧ 'DC 1' power supply output control.
⑨ 'DC 1' power supply output sockets.
⑩ 'DC 2' power supply output control.
⑪ 'DC 1' power supply output sockets.
⑫ AC frequency control.
⑬ Three-phase supply sockets.
⑭ Single phase supply sockets.
⑮ 'Capacitor mode' selector switch. This selects which capacitor is connected to the motor There are two values: 'START' and 'RUN'.
⑯ Sockets used to connect the chosen capacitor to the motor.

A tour of the kit

The dynamometer:

measures the force produced and speed of a rotating machine (here, an electric motor). These are used to calculate torque and output power.



① Sockets to connect the load, set in the control unit, to the dynamometer.

② Encoder - generates signals used by the control unit to measure the speed of rotation of the dynamometer.

③ The dynamometer.

④ The digital balance used to measure the force produced by the dynamometer.

⑤ The shielded coupling between the dynamometer and the motor under test.

⑥ The safety switch used to check whether a motor is attached to the dynamometer.

⑦ One of the screw clamps used to hold the motor in place.

⑧ The motor under test.

⑨ The sockets used to connect the motor to the power supply.

In this dynamometer, the force created can be measured in one of two ways:

- the digital balance shown in the diagram;
- a load cell (behind the dynamometer and hidden by it in the diagram above,) connected to the control unit and using software it contains.

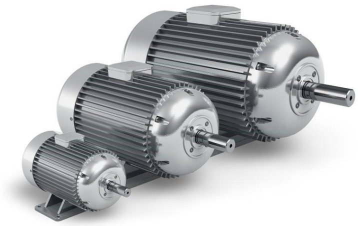
The direction of rotation of the dynamometer determines whether the balance or the load cell is used.

Safety features:

- Motors under test are attached using the coupling shielded by a plastic tube to prevent clothing and hair from getting caught in the mechanism.
- Two microswitches are provided on the dynamometer. Unless a test motor is in place, the control unit will not activate.

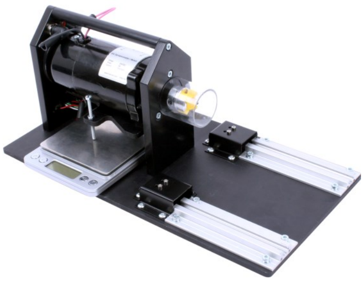
Getting started

Motors vary tremendously in size, shape and structure. However, within a family of motors, DC motors, for example, the performance is similar - regardless of physical size and operating voltage.



This section shows how to set up the equipment. Then the testing can begin.

Connect the control unit to mains power using the IEC power connector.



The 7-segment display and Power LED on the control unit should light up.

Connect the dynamometer to the control unit with the 25-way D-type lead.

Make sure that the software and control unit driver are correctly installed.

When the control unit is **not** connected to a PC with the USB lead, it is in manual mode - the potentiometers on the front panel determine the control unit outputs.

Make sure that the rubber ‘spider’, the buffer between the dynamometer and the motor, is in place. The system will work without this - it will just be noisy.

Line up the DC motor in the grooves of the dynamometer test bed. If necessary, loosen the screw clamps on the motor base plate. (You might have to push hard!)

As you push home the motor, you should hear the safety microswitches in the dynamometer cradle ‘click’.

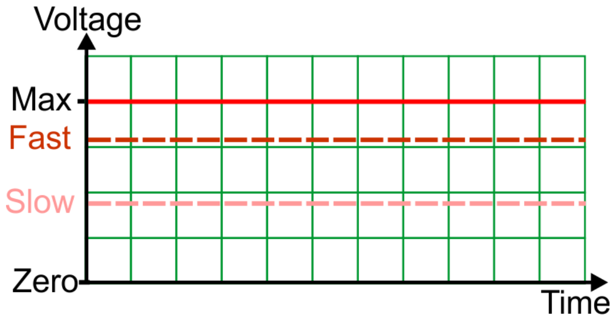
Tighten the screw clamps to make sure that the DC motor is secured in place.

Position the digital balance and remove **both** protective plastic covers.

Exploring the DC power supply

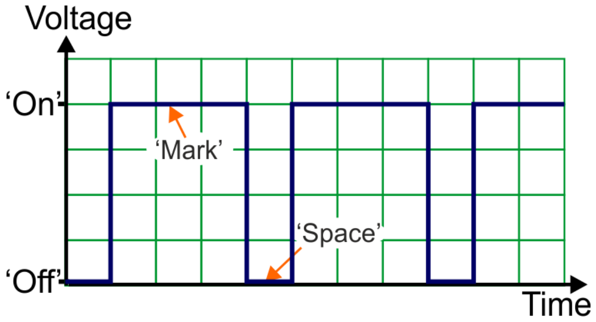
The DC motor is controlled by varying the power supply output.

However, it is not simply a matter of increasing or decreasing a steady DC voltage - a form of control, called 'analogue' - illustrated in the diagram.

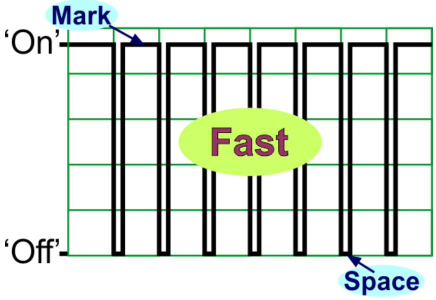


Instead, the power supply outputs a series of 'on/off' pulses.

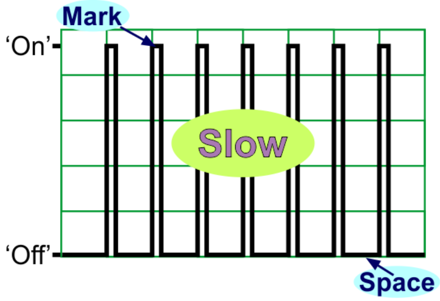
The 'on' part of the pulse is known as the 'mark' and the 'off' part as the 'space'.
The pulses arrive so quickly that the motor cannot follow them exactly
- it just runs.



Increasing the output means that the mark increases and the space decreases - the motor is 'on' for longer and 'off' for less time.
As a result, it runs faster.



Decreasing the output means that the motor is off for longer and on for a shorter time
- more space and less mark!
As a result, it runs more slowly.

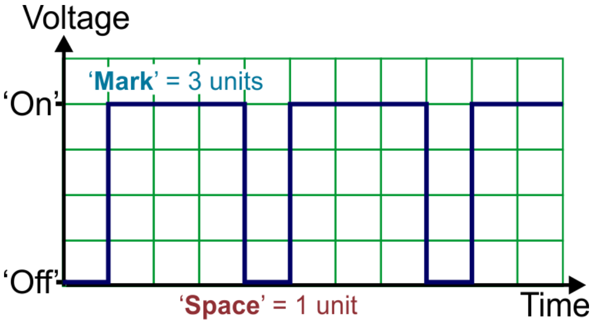


Find out why this form of control is preferred to simple analogue control.

Pulse-width modulation

This form of control is called pulse-width modulation (PWM).

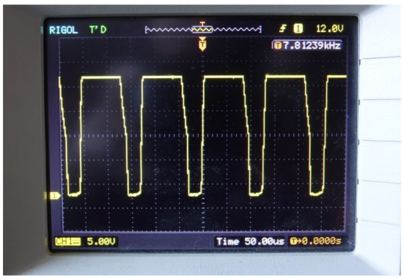
The motor is controlled by modulating (modifying) the width of the pulse, i.e. changing the 'mark:space ratio' (m:s) of the pulse, i.e. the on:off ratio.



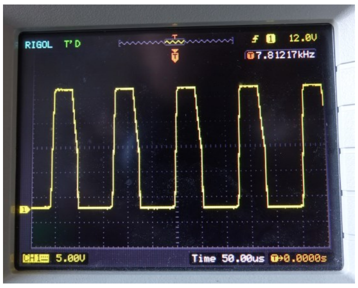
In the diagram, the 'mark' lasts for three units of time, whereas the 'space' lasts only one. This gives a m:s of 3:1.

This can also be described using the term 'duty cycle' - the fraction of the signal for which the motor is 'on'. A m:s of 3:1 is the same as duty cycle of 75%.

The top photograph shows an oscilloscope displaying a PWM signal with a m:s of 3:1.



The second photograph shows a PWM signal with a m:s of 2:3, i.e. a duty cycle of 40%.



Pulse-width modulation

i

Without the use an oscilloscope to measure duty cycle, we rely on a multimeter.

For a low pulse frequency, the meter would follow the voltage changes and show the actual reading. Outputs DC1 and DC2 pulse at a frequency of nearly 8kHz - too fast for the meter, which shows the average voltage instead.

The DC1 and DC2 outputs give a peak voltage of 24V.

The average voltage when the m:s is 3:1 is:

$$\frac{(3 \times 24) + (1 \times 0)}{4} = 18\text{V}.$$

In general, this average DC output is calculated from the formula:

average voltage = duty cycle x peak voltage.

This is not the same thing as the 'rms' value - we haven't got there yet!

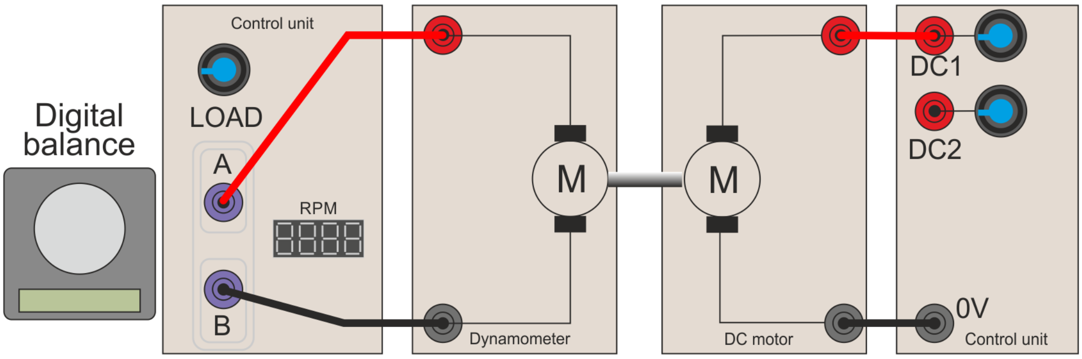
The table shows the results for other values of duty cycle:

Duty cycle	Average output voltage
30%	7.5
50%	11.9
70%	16.2

Activity 1 - exerting torque

Place the digital balance under the dynamometer swing arm and turn it on.

The equipment is now set up as shown in the following diagram:



Switch on the control unit.

Check that the 'Motor In' LED is lit. If not, withdraw the motor and refit it.

Turn the power supply potentiometers on DC1 and DC2 to minimum (fully anti-clockwise.)

Slowly rotate the DC1 potentiometer until the DC motor starts to turn.
Is there a reading on the balance? If not, swap over the positive and negative connections on the motor to change the direction of rotation.

When rotating counter-clockwise, pressure is applied to the balance.
When rotating clockwise, pressure is on the load cell, located at the back of the dynamometer.

So what

To change the direction of a DC motor, reverse the electrical connections.

The swinging-arm dynamometer can rotate in either direction.
The torque produced is the same for both.

Torque is an important measure of a motor's performance.
The next page explains what is meant by 'torque'.

What is torque?

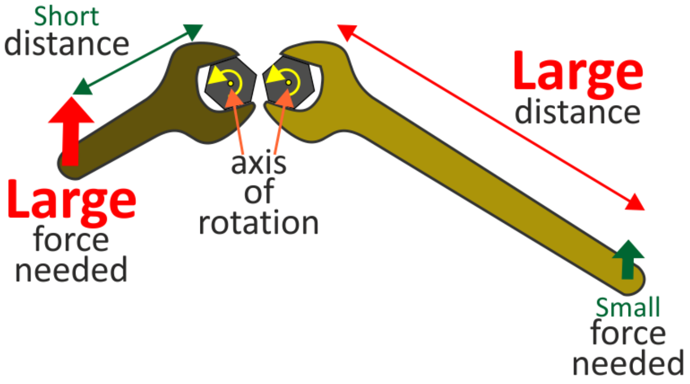
What is torque?

Torque is the *turning effect* of a force.

It depends on:

- the size of the force;
- how far it is applied
  from the axis of rotation .

This is why it is easier to use a long spanner than a short one (or no spanner,) to turn a nut.



Torque **T** is calculated from the equation:

T = **force** x **distance from the axis**

For the dynamometer, this distance = 0.04m.

Torque is measured in units called Newton.metres (N.m).

What does the digital balance measure?

It measures **mass**, the quantity of matter in a body, not force. Force and mass are linked by ‘g’, the gravitational field strength - how hard the Earth’s gravity pulls down on matter - around 10N force on every kilogram. This means that the force pressing down on the balance, generated by the dynamometer, = 10 x balance reading.

An example:

Calculate the torque which produces a digital balance reading of 250g.

1000g = 1kg

so 250g = 0.25kg

This corresponds to a force (due to gravity) of 0.25 x 10 = 2.5N.

This force is applied at a distance of 0.04m from the axis of rotation of the dynamometer and produces

a torque of 2.5 x 0.04 = **0.1N.m**

Activity 2 - exploring the DC motor

Turn the Load output potentiometer about half way round. This adds a load to the output of the motor, making it convert its rotational, (kinetic) energy into heat.

Investigate the effect of changing the DC1 voltage by turning the potentiometer:

- one third of the way round;
- two thirds of the way round;
- to the maximum.

In the Student Handbook, record the speed, shown on the 7-segment display and the digital balance reading, in g, for each power supply setting (i.e. complete the second and third columns of the table,).

Next, convert the balance reading (currently in grammes) to kilogrammes by dividing by 1000 and record your answers in the fourth column of the table.

Now, use the balance readings (in kg) to calculate the torque produced by the motor for each power supply setting. using:

Force = balance reading (kg) x 10.

Torque = force x 0.04 = balance reading (kg) x 10 x 0.04.

Record your answers in the fifth column of the table.

As the average power supply voltage increases:

- the motor rotates more rapidly;
- the torque it generates increases.

Activity 2 - exploring the DC motor

We can use these readings to work out the efficiency of the motor at these speeds.

Efficiency is a measure of how much of the energy supplied by the control unit is used effectively and how much is wasted (as heat usually.) High efficiency means that less energy needs to be supplied to achieve the same output.

It is calculated using the formula:

$$\text{Efficiency} = \frac{\text{energy delivered by the motor to the load}}{\text{energy inputted by the control unit}} \times 100\%$$

In this case, it is easier to work with power rather than energy. Power is the rate at which energy is delivered, i.e. energy delivered per second.

The formula becomes:

$$\text{Efficiency} = \frac{\text{mechanical power developed by the motor}}{\text{electrical power delivered by the control unit}} \times 100\%$$

Mechanical power is calculated using the formula:

$$\text{Mechanical power} = (2 \times \mathbf{n} \times \pi \times \mathbf{T}) / 60$$

where **n** is the speed of the motor in rpm and **T** is the torque developed.

The electrical power is calculated using the formula:

$$\text{Electrical power supplied} = \mathbf{V_{IN}} \times \mathbf{I_{IN}}$$

where $\mathbf{V_{IN}}$ = input voltage and $\mathbf{I_{IN}}$ = input current.

Use your results to complete the following table:

Power supply setting	Electrical power delivered to the motor	Mechanical power delivered to the load	Efficiency
One third			
Two thirds			
Maximum			

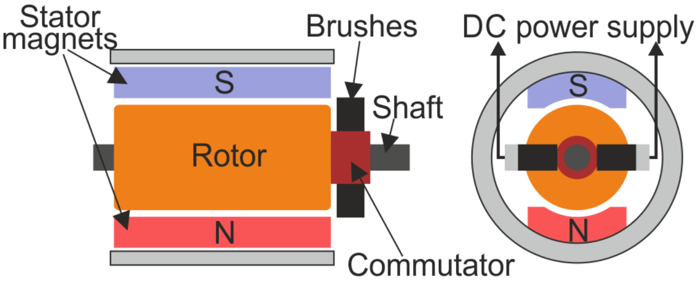
Investigate what happens to the speed, torque, current and power supply voltage when you change the load settings.

Try to explain your results.

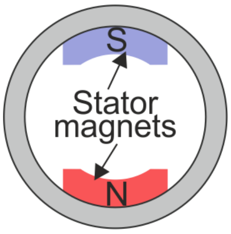
Activity 2 - exploring the DC motor

The (brushed) DC motor
is made up of:

- stator,
- rotor (or armature),
- commutator and brushes.

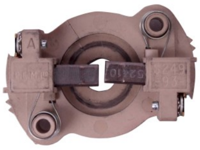


The **stator** generates a stationary magnetic field using either permanent magnets or electro-magnets. This field surrounds the rotor .



The **rotor**, (also known as the armature) is made up of a number of insulated coils. When these pass a current, they generate a magnetic field, which interacts with that generated by the stator, causing the rotor to turn.

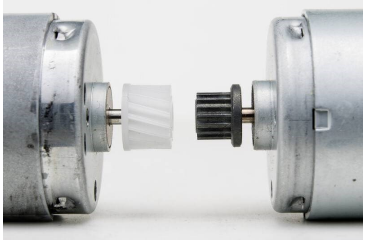
The **commutator** has the job of reversing the flow of current around the rotor windings to keep the rotor spinning. It consists of a drum attached to the rotor, split into several sections.



The **brushes** slide over the commutator, as the motor turns. In doing so, they make contact with different segments of the commutator, which are attached to different rotor windings.

The magnetic fields produced in this way interact with the field of the stator to keep the motor rotating.

Activity 2 - exploring the DC motor



Different types of motor have different characteristics, such as top speed, torque at different speeds, voltage/ current rating, power output, efficiency.

Permanent magnet DC (PMDC) motor characteristics:

- Motor speed depends on power supply voltage.
- Motor torque depends on power supply current.

- ***A bigger power supply voltage makes the motor spin faster.***

Not a surprise! Greater voltage ⇒ bigger current ⇒ stronger magnetic field in the rotor windings ⇒ bigger magnetic force on the rotor because of its interaction with the magnetic field of the stator ⇒ **faster the motor spins!**

- ***Increasing the load slows the motor down but increases the current it requires.***

  OR

  put another way, the faster the motor spins, the lower the current taken from the power supply!

The explanation relies on 'back-emf'. When the rotor spins around in the stator's magnetic field, a voltage, called 'back-emf', is generated in its windings that opposes the power supply voltage. As a result, the overall voltage applied to the rotor windings is reduced.

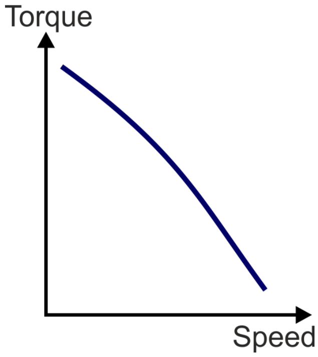
The faster the rotation, the bigger this back-emf, the smaller the overall voltage and so the smaller the current that results.

Adding a load to the motor slows it down. This reduces the back-emf, increases the overall voltage and so increases the current.

It does seem logical that the harder the motor is made to work, the greater the current needed!

Activity 2 - exploring the DC motor

The permanent magnet DC (PMDC) motor:



Two advantages of the permanent magnet DC motor are illustrated in the speed/torque characteristic graph opposite:

- It has a high starting torque.
- Its behaviour is (almost) linear - double the speed, half the torque etc.

One disadvantage is that the brushes wear over time and are the components most likely to fail.

Do some research to discover other advantages and disadvantages of the permanent magnet DC motor!

Uses of the PMDC motor include:

- at home -
  computer drives, electric toothbrushes, portable vacuum cleaners, food mixers, portable drills, hedge trimmers.
  The food blender in the photograph uses a DC motor.
- in vehicles -
  windscreen wipers/washers, electric windows, heater fan.

Fairground ‘dodgem’ cars use simple DC electric motors operating at between 12 and 48V. The vehicles have two brushes - one touching the metal floor, for 0V, and the other touching the metal ceiling, at a positive voltage. Speed control is usually simple on-off.

Activity 3 - exploring the Dynamo

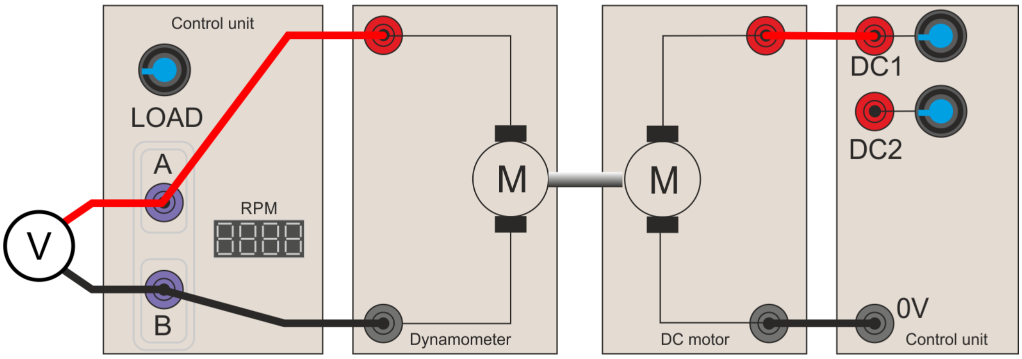
The permanent magnet DC motor rotates when supplied with electrical power.
The dynamo (e.g. the one inside the dynamometer) has the same basic structure but works the other way round - when rotated, it generates electricity.

The photograph shows a bicycle dynamo, used to power the lights on a cycle.

This section uses the dynamo in the dynamometer to look into the behaviour of a permanent magnet generator (i.e. a dynamo).

The first investigation looks at how the dynamo output voltage depends on its speed.

Set up the system shown in the diagram.



Turn the DC1 and DC2 potentiometers to minimum and switch on the control unit.

Switch on the multimeter and set it to measure DC voltages.

Turn the 'Load' potentiometer about half-way round.

Slowly rotate the DC1 potentiometer until the dynamo spins at 200rpm.

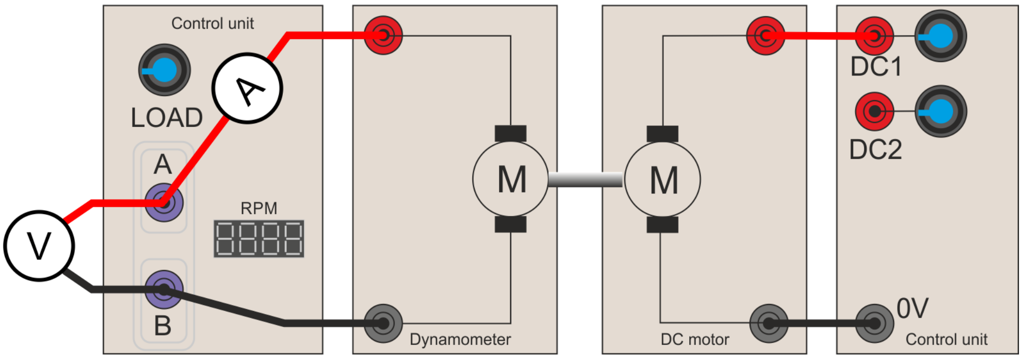
Measure the voltage generated by the dynamo. Note it in the Student Handbook.

Repeat this for the other speeds listed in the table.

Increase the load and notice the effect this has on the dynamo.
In the Student Handbook, comment on the effect.

Activity 3 - exploring the Dynamo

The next part investigates how the power output of the dynamo changes with different loads. Set up the system shown in the diagram. It is identical to the previous one except that an ammeter has been added to measure the output current.



Turn the DC1 and DC2 potentiometers to minimum and switch on the control unit.

Switch on one multimeter, set to measure DC voltage and the other to measure DC current.

Turn the 'Load' potentiometer one-quarter of the way round.

Slowly rotate the DC1 potentiometer until the dynamo spins at 1000rpm.

Measure the voltage and current generated by the dynamo and note them in the Student Handbook.

Repeat this for the other loads listed in the table.

Estimate the efficiency of the dynamo driving a filament lamp:

- Disconnect the 'Load' from the control unit and replace it with a 12V filament bulb.
- Turn the DC1 potentiometer until the dynamo spins at 400rpm.
- Use the formula given on page 15 to calculate the power delivered **to** the dynamo.
- Measure the output voltage and current delivered **by** the dynamo to the bulb.
- Calculate the output power and hence the efficiency of the dynamo.
- Repeat this for a speed of 800rpm.
- Record all your observations in the Student Handbook.

Take care !

Don't exceed the voltage rating of the bulb, 12V, or you may 'blow' it!

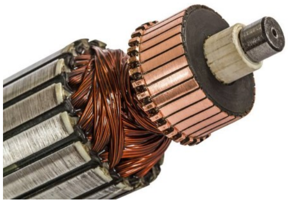
Shunt and series motor basics

In a DC motor, the **stator** creates a stationary magnetic field around the rotor. In the PMDC motor, this magnetic field is produced by permanent magnets.

In wound-stator DC motors, it is generated by passing electric current through a coil, or coils, of wire, called the field windings, turning them into electromagnets.

In both types, coils of wire in the **rotor** (or armature) create magnetic fields that react with those of the stator.

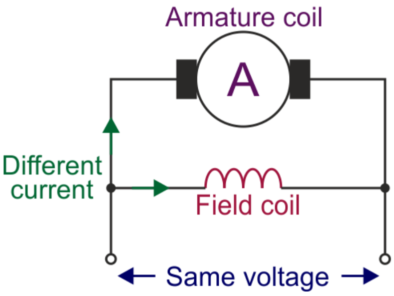
The photograph shows a wound rotor with a split-ring commutator. Pairs of copper segments around the commutator connect to the ends of coils of wire in the rotor.



There are two types of wound-stator DC motor:

The **shunt-wound** motor:

- the field and armature coils are connected in parallel;
- the current in the field coil can be different from that in the armature coil;
- both coils experience the same voltage.



In practice, the field coil must have a higher resistance than the armature coil as otherwise most of the current would by-pass the armature coil, reducing the torque created. As a result, the field coil uses a large number of turns of thin wire and, in the Matrix version, consists of two coils connected in series.

With the motor disconnected from the test rig,
use a multimeter to measure the resistance of the:

- field windings - (between **red** and **black** terminals.)
- armature windings - (**purple** and **yellow** terminals.)

Record your results in the table in the Student Handbook and explain how they relate to the structure of the two types of motor.

Shunt motor

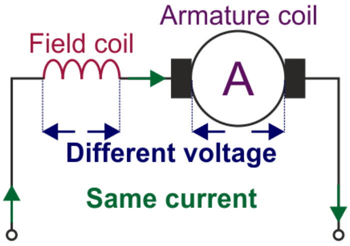
Shunt and series motor basics

When direct current flows through the coils of a motor, the electrical behaviour can be predicted using Ohm’s law.

However, once the motor is running, the rotating magnetic fields in the motor alter the behaviour drastically.
The effect is caused by the ‘back-emf’, described earlier, on page 17.
This increases as speed increases. Equally, when a motor stalls, the back e.m.f. is zero. The current in the coils then increases significantly and can result in the motor burning out.

The **series-wound** motor:

- the field and armature coils are connected in line, one after the other;
- the same current flows through them;
- there is usually a different voltage across them.



In practice, the stator field coil uses a few turns of thick wire, in order to lower its electrical resistance. In the Matrix version, there are two field coils, connected in parallel for the same reason.

High resistance in the stator coil would reduce the current flowing through the armature and reduce the torque created.

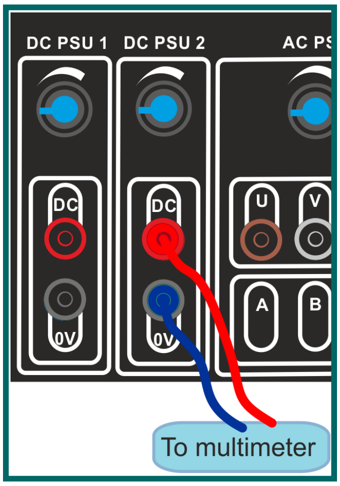
With the motor disconnected from the test rig,
use a multimeter to measure the resistance of the:

- field windings - (between **red** and **black** terminals.)
- armature windings - (**purple** and **yellow** terminals.)

Record your results in the table in the Student Handbook and explain how they relate to the structure of the two types of motor.

Universal / series motor

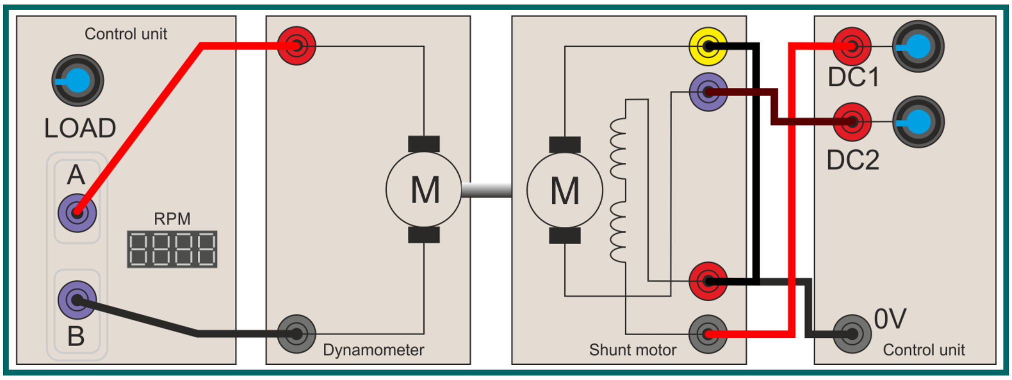
Activity 4 - investigating the shunt motor



Connect a multimeter to the DC2 power output sockets to measure the voltage supplied to the stator windings of the motor.

Turn the DC2 potentiometer until the multimeter shows an output of 12V. Remember this position of the potentiometer.

Set up the system shown in the diagram.



Follow the wiring between the motor and power supply to convince yourself that the rotor and stator windings are connected in parallel.
Notice that the stator windings are shown as two coils connected in series, as explained earlier.

Turn the DC1 and DC2 potentiometers to minimum and switch on the control unit.

Turn the ‘Load’ potentiometer about half-way round.

Turn the DC2 potentiometer slowly to the 12V position found earlier.

Slowly rotate the DC1 potentiometer to increase the power supply to the motor armature windings.

It should spin.

Activity 4 - investigating the shunt motor

How do you reverse the direction of rotation?

(There is a risk that ‘blanket’ experimentation might short-circuit the power supply. The following gives you a list of ‘safe’ things to try.)

1. Reverse the DC1 power supply connections to the stator.
2. Reverse the DC2 power supply connections to the rotor.
3. Reverse both sets of power supply connections.

In the Student Handbook, comment on what effect, if any, each of these changes had on the direction of rotation of the motor and offer an explanation.

Set up the shunt motor so that it exerts a force on the digital balance.

Although the balance gives a reading in grammes, it is a measure of how hard the dynamometer is pressing down on it. In other words, it is a measure of the torque exerted by the motor.

Switch on the digital balance.

Turn the ‘Load’ potentiometer about half-way round.

Connect a multimeter to the DC2 power output sockets to measure the voltage supplied to the rotor.

Switch on the control unit and slowly rotate the DC2 potentiometer until the meter shows a reading of 5V.

Now slowly rotate the DC1 potentiometer to increase the voltage applied to the stator windings until the motor is spinning at maximum speed.

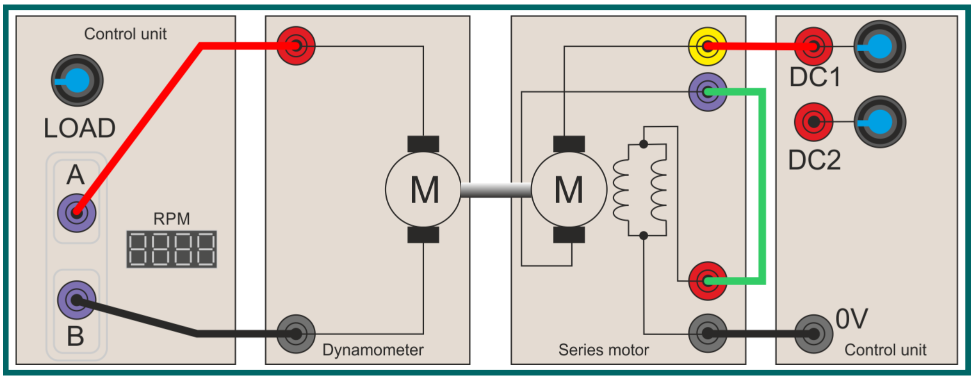
In the table in the Student Handbook, note down the maximum balance reading (measure of maximum torque) and maximum speed.

Repeat this procedure for the other rotor voltages, shown in the table.

Note down the results and comment on what happened.

Activity 5 - investigating the series motor

Set up the system shown in the diagram.



Follow the wiring between the motor and power supply to convince yourself that the rotor and stator windings are connected in series.
Notice that the stator windings are shown as two coils in parallel, as explained on the previous page.

Turn the DC1 and DC2 potentiometers to minimum and switch on the control unit.

Turn the ‘Load’ potentiometer about half-way round.

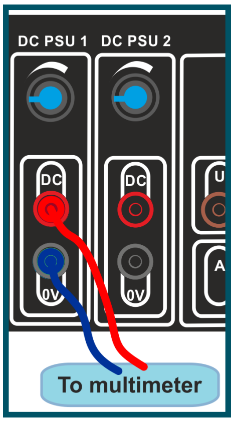
Slowly rotate the DC1 potentiometer to increase the voltage applied to the motor. It should spin.

How do you reverse the direction of rotation?
(There is a risk that ‘blanket’ experimentation might short-circuit the AC power supply. The following gives you a list of ‘safe’ things to try.)

1. Reverse the connections to the power supply sockets A and B.
2. Reverse the connections to the rotor, by swapping over the wires in the yellow and purple sockets.
3. Reverse the connections to the stator, by swapping over the wires in the red and black sockets.

In the Student Handbook, comment on what effect, if any, each of these changes had on the direction of rotation of the motor.

Activity 5 - investigating the series motor



Set up the series motor so that it exerts a force on the digital balance.

Switch on the digital balance.

Turn the ‘Load’ potentiometer about half-way round.

Connect a multimeter to the DC1 power output sockets to measure the voltage supplied to the motor.

Switch on the control unit and slowly rotate the DC1 potentiometer until the meter shows a reading of 5V.

The motor should now be spinning and there should be a reading on the digital balance.

In the table in the Student Handbook, note down the balance reading and speed.

Repeat this procedure for the other supply voltages, shown in the table.

Note down the results and comment on what happened.

The control unit delivers an output power up to 100W. It cuts out when this is exceeded and shows a message ‘*Err*’ on the display.

Experiment to find the maximum permitted voltage and motor speed before the power supply cuts out.

In addition, investigate the effect of changing the load on these values.

Record your results in the Student Handbook.

Series vs shunt:

Speed control is an important aspect of motor design.

A more detailed investigation would show that:

- the shunt motor offers really good speed self-regulation and so is often used in devices which need to run at a constant speed, like lathes.
- the series-wound motor has the highest start-up torque of any motor and so is ideally suited to applications such as winches and cranes. (However, its speed depends on the load and so can vary.)

Using oscilloscopes

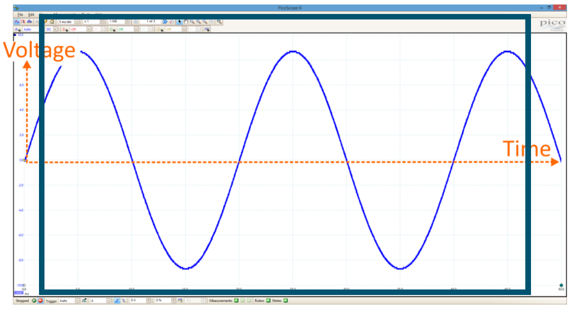
AC vs DC:

In a DC circuit, the current always flows in the same direction. The voltage may vary, but it never reverses.

In an AC circuit however, the current does flow in one direction and then the other. The voltage pushing it is at times ‘positive’ and then at other times ‘negative’.

Displaying AC signals often calls for the use of an *oscilloscope*, which produces a voltage / time graph of the signal.

The diagram shows the output of an AC power supply, captured on an oscilloscope. Voltage and time axes are shown in orange. An important measure with an AC signal is its frequency - the number of peaks (or troughs) that occur each second.



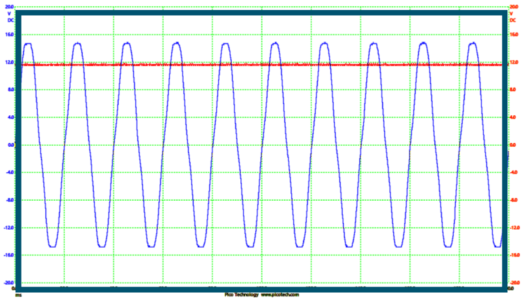
Notice:

- the average voltage is zero - the voltage is positive for half of the time and negative for half of the time;
- the signal may be described as having a peak voltage of 9V, but for most of the time the voltage is much smaller.

So what is the “average” ***effect*** of an AC supply? How can we compare AC and DC? The answer - look for the two having the ***same effect*** on a device like a bulb.

The next oscilloscope trace shows AC and DC power supply signals that give a bulb the ***same brightness***.

Notice that the DC supply sits well below the AC peak value. This DC equivalent is called the r.m.s. value of the AC supply.

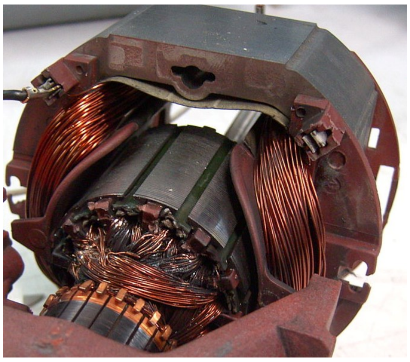


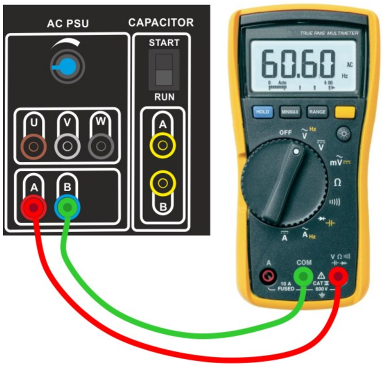
The symbols shown in the diagram on the right are often used to distinguish between these forms of electrical power. They are used on multimeters, for example.

Activity 6 - exploring the universal motor

The series-wound motor is also known as the ‘universal motor’, because it can be operated from an AC power supply as well as from DC.

This flexibility means that these motors are amongst the most widely used. Typical applications include planes, routers, sanders, grinders, saws etc.





Connect a multimeter to outputs **A** and **B** of the AC power supply to read its frequency.

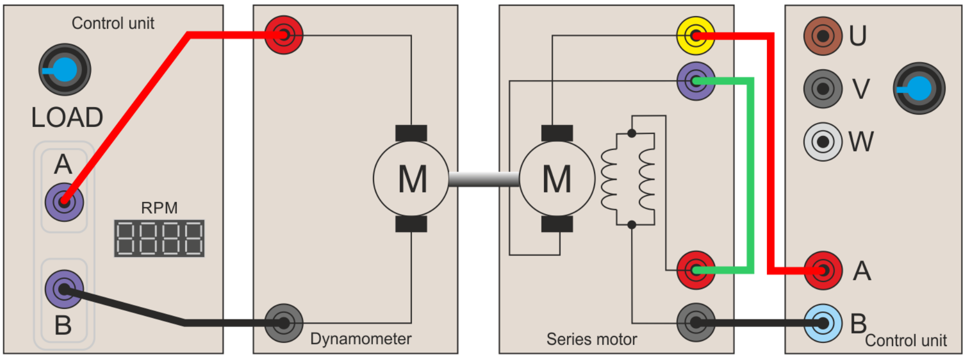
Turn all potentiometers to minimum and switch on the control unit.

Now rotate the ’AC PSU’ potentiometer ***slowly***.

Notice that the AC supply frequency increases, (though the voltage does not.)

Turn the potentiometer back to minimum and switch off the control unit.

Now set up the system shown in the diagram.



Compare the wiring with that shown for the DC controlled series motor on page 24. The only difference is in the type of power used.

Switch on the control unit and turn the ‘Load’ potentiometer about half-way round.

Slowly rotate the frequency control potentiometer to increase the frequency applied to the motor.

It should soon start to spin.

Activity 6 - exploring the universal motor

How do you reverse the direction of rotation?

Try the following:

1. Reverse the connections to the power supply sockets A and B.
2. Reverse the connections to the rotor, by swapping over the wires in the yellow and purple sockets.
3. Reverse the connections to the stator, by swapping over the wires in the red and black sockets.

In the Student Handbook, comment on what effect, if any, each of these Changes had on the direction of rotation of the motor.

As you increase the frequency of the AC supply, the speed of the motor and the reading on the digital balance (measure of the torque exerted,) increase.

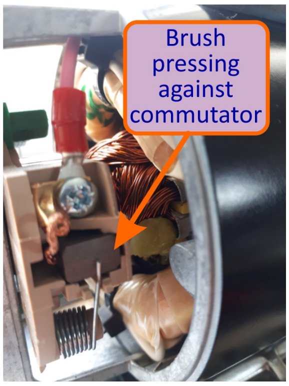
- Experiment to find the maximum speed and balance reading.
- What is the effect on these of increasing the load?
- Suggest a cause for the drop in speed at high frequencies.

Record your findings in the Student Handbook.

The induction motor

A problem -

All the motors studied so far need external electric current supplied to the rotor windings to generate a magnetic field.



This requires the use of brushes, that press against the commutator to make an electrical connection.

Single phase induction mo-

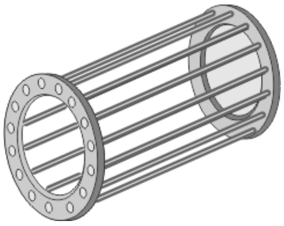
These brushes wear out eventually and need replacing. Induction motors have no brushes and so require less maintenance.

What is electromagnetic induction?

When an electrical conductor, like a piece of wire, moves through a magnetic field, a voltage is ‘induced’ in it. Equally, when a magnetic field moves across a conductor, the same thing happens. Similarly, if a conductor is sitting in a magnetic field and that field changes, a voltage is induced in the conductor. When the conductor is part of an electric circuit, a current can flow around the circuit, as a result.

How does an induction motor work?

The **rotor** is usually either a coil of wire or a **squirrel cage**, an set of copper or aluminum bars, short-circuited by the end rings. These bars are usually not parallel to the axis of the motor but skewed at a shallow angle to it.



Squirrel cage rotor

The **stator** windings are connected to an external power supply and are supplied with AC. This creates a **rotating** magnetic field, which induces an electric current in the rotor. This current, in turn, produces its own magnetic field, which reacts with the rotating magnetic field of the stator and causes the rotor to spin.

That is why it is called an induction motor.

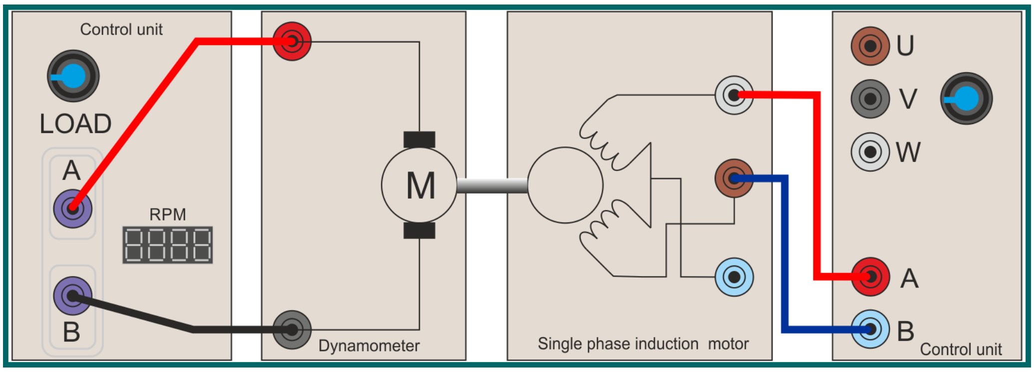
Investigate:

- the relative advantages and disadvantages of squirrel cage and wound-rotor motors;
- why bars in a squirrel cage rotor are not parallel to the axis of the motor.

Write your findings in the Student Handbook.

Activity 7 - exploring the induction motor

Set up the system shown in the diagram.



Turn the ‘Load’ potentiometer about half-way round.

Slowly rotate the ’AC PSU’ (frequency control) potentiometer to increase the AC supply frequency.

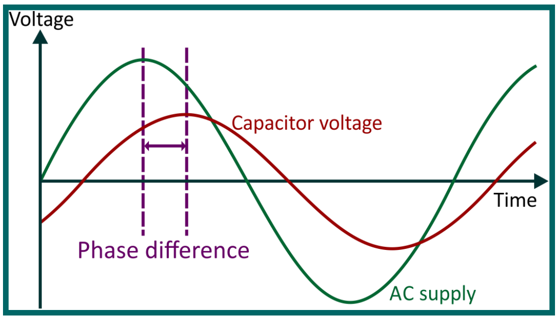
The motor does **not** start! In this configuration, the motor does not self-start.

The reason is that we are treating the whole of the stator as a single coil. The AC supply is connected across that single coil and creates an alternating magnetic field, but not a rotating field. To do this we need two distinct magnetic fields, oscillating out of step with each other.

(If we could give the motor shaft a flick, it would rotate, but the shield around the link between motor and dynamometer does not allow this. The direction of rotation would be unpredictable. It would depend on which way we flicked it!)

The answer is to involve a capacitor to introduce a phase shift between the signals applied to the coils in the stator.

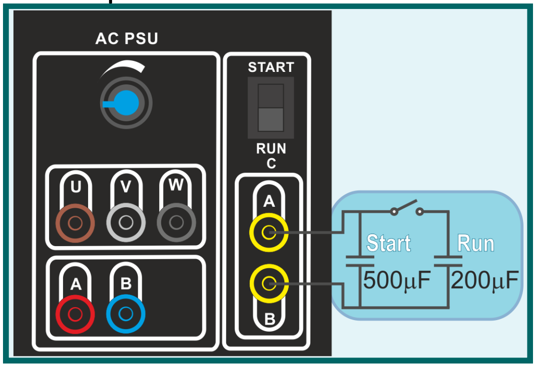
i



When an AC voltage is applied, the capacitor, charges and discharges in such a way that the voltage across it is ‘out of phase’ (out of step) with the supply voltage.

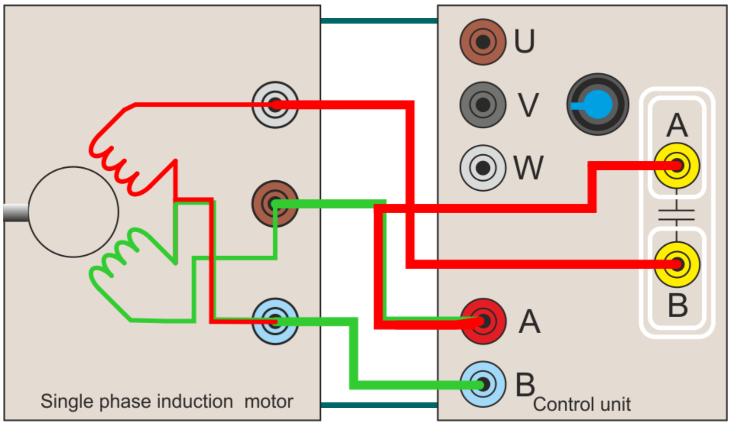
The peak in capacitor voltage occurs at a different time to the peak in supply voltage. There is a ‘phase difference’ between them.

The control unit contains two capacitors, called ’Start’ and ’Run’, available via the yellow **A** and **B** sockets. The switch above them selects which value of capacitor is used.



The next arrangement will make use of this phase difference.

The diagram shows the connections needed in detail.



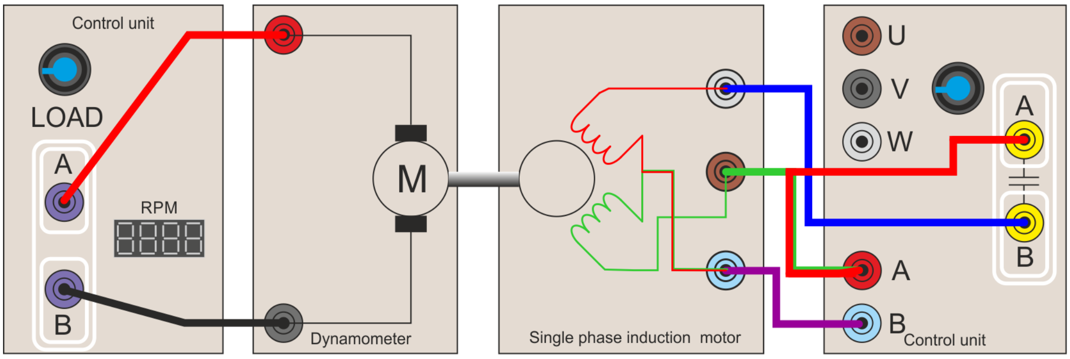
The stator now has effectively two separate coils. Each is supplied with AC power but, because of the effect of the capacitor, these supplies have a phase difference between them.

Each one produces an alternating magnetic field but these reach maximum intensity at different times. The combination gives the appearance of being a rotating magnetic field.

Activity 7 - exploring the induction motor

Set up the arrangement shown below.

It includes the connections shown on the previous page but now using different colours to distinguish between the leads.



Turn the ‘Load’ potentiometer about half-way round.

Slowly rotate the ’AC PSU’ potentiometer to increase the AC supply frequency.

The motor runs!

Rotate the ’AC PSU’ potentiometer to increase the AC supply frequency still further. Notice the effect on the motor and write a comment about this in the Student Handbook.

How do you reverse the direction of rotation?

(There is a risk that ‘blanket’ experimentation might short-circuit the AC power supply. The following gives you a list of ‘safe’ things to try.)

1. Reverse the connections to the power supply sockets A and B.
2. Reverse the connections to the yellow capacitor sockets **A** and **B**.
3. Unplug the ‘red’ and ‘green’ leads from the brown motor input socket and the ‘blue’ lead from the grey motor input socket and swap them over so that the ‘red’ and ‘green’ leads are now in the grey socket and the ‘blue’ lead is in the brown socket.

In the Student Handbook, comment on what effect, if any, each of these changes had on the direction of rotation of the motor.

Activity 7 - exploring the induction motor

Set up the induction motor so that it exerts a force on the digital balance.

Switch on the digital balance.

Turn the ‘Load’ potentiometer about half-way round.

Make sure that the ‘Start’ capacitor is selected.

Switch on the control unit and slowly rotate the frequency control ‘pot’ on the AC PSU to about one-quarter of the way round.

The motor should now be spinning and there should be a reading on the digital balance.

In the table in the Student Handbook, note down the balance reading and speed.

Repeat this procedure for the other positions of the frequency control, shown in the table.

Note down the results and comment on what happened.

Use the switch to switch between the ‘Start’ capacitor and the ‘Run’ capacitor.
Which gives the greater maximum speed?
Note your findings in the Student Handbook.

How does increasing the load affect the maximum speed? Comment on this in the Student Handbook.

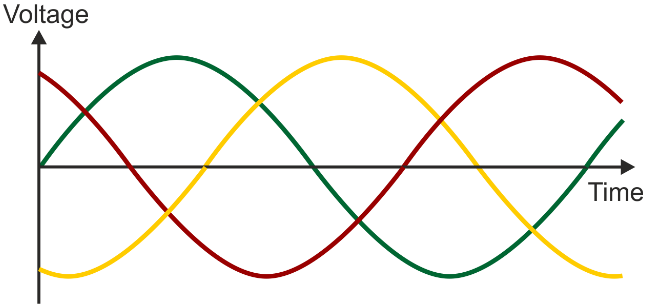
Research the factors that affect ‘stall-speed’ and maximum torque in single-phase induction motors. Record your findings in the Student Handbook.

Three-phase AC

The type of AC described on page 26 is known as single-phase AC. It is the variety used in relatively low-power situations, such as homes and small offices, and is delivered down two wires.

Where more power is required, in large motors, for example, it is more economical to use a three-phase electricity supply.

This delivers three separate AC voltages, down three wires.
They are not in phase (in step), as the diagram shows.



Looking at the voltage shown as a green trace, when it is positive, current flows down the corresponding wire to the motor and flows back to the source down the other wires, since one or both of the other voltages, shown as yellow and red, are negative at this time.
Hence, a three-phase supply can transmit three times as much power using only one and a half times as much wire - single phase needs two wires, three phase needs three!

With a single-phase supply, at times the supply voltage is very small, even zero. With a three-phase supply, at no time are all three phases zero and the peaks of successive waves are closer together. This means that a three-phase motor runs more smoothly and efficiently.

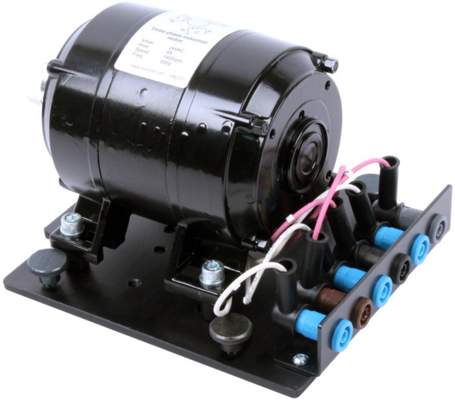
Activity 8 - exploring the three-phase motor

Lighter and more compact than alternative types, three-phase motors now provide the driving force in many electric vehicles.

Three-phase motors are self-starting. The separate, staggered, alternating magnetic fields from the three sets of stator coils create, in effect, a rotating magnetic field. The structure of the motor is therefore simpler - no need for capacitor starting!

The photograph shows a three-phase motor with part of the outer shell cut away. Notice the lack of brushes and windings in the rotor.

Induction motors work by inducing a current and hence a magnetic field, in the rotor .



The three-phase motor uses six coloured sockets to connect the power supply to the stator coils.

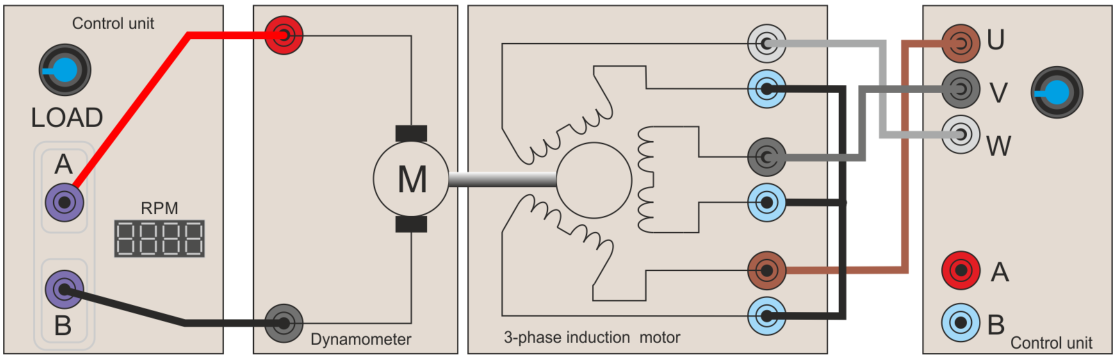
In the diagram below, these are labelled ‘A’ to ‘F’.

Use a multimeter set to measure resistance to work out which pairs of sockets are connected to each coil.

Record your results in the table in the Student Handbook.

Activity 8 - exploring the three-phase motor

Set up the arrangement shown below.



(The colours of the leads in the diagram are chosen to clarify the connections. Connect all the blue motor sockets together and then connect the other motor sockets to the corresponding coloured socket on the power supply.)

Turn the ‘Load’ potentiometer about half-way round.

Rotate the ’AC PSU’ potentiometer about one-third of the way round. (As we have seen, this increases the AC supply frequency.)

The motor probably twitches but then the display shows ‘Err’!

Wait for a few seconds and the motor begins to spin.

The power supply is designed to sense the initial rush of current and cut out.

It then waits a few seconds, clears the fault condition and restores the current.

Use the ’AC PSU’ potentiometer to adjust the AC supply frequency.

Notice the effect on the motor and describe what you find in the Student Handbook.

Estimate the maximum speed and torque (as indicated by the balance reading.)

How do you reverse the direction of rotation?

(Again, resist ‘blanket’ experimentation that might short-circuit the power supply! The following gives you a list of ‘safe’ things to try.)

1. Swap over the wires plugged into the ‘U’ and ‘V’ outlets of the power supply.
2. Swap over the wires plugged into the ‘U’ and ‘W’ outlets of the power supply.
3. Swap over the wires plugged into the ‘V’ and ‘W’ outlets of the power supply.

In the Student Handbook, comment on what effect, if any, each of these changes had on the direction of rotation of the motor.

The brushless DC motor

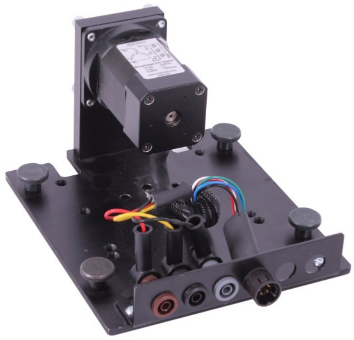
In a **brushed** DC motor, the stator generates a magnetic field, from either a permanent magnet or from an electromagnet. The rotor is an electromagnet that spins because the direction of current in the electromagnet is reversed periodically, using a commutator and brushes.

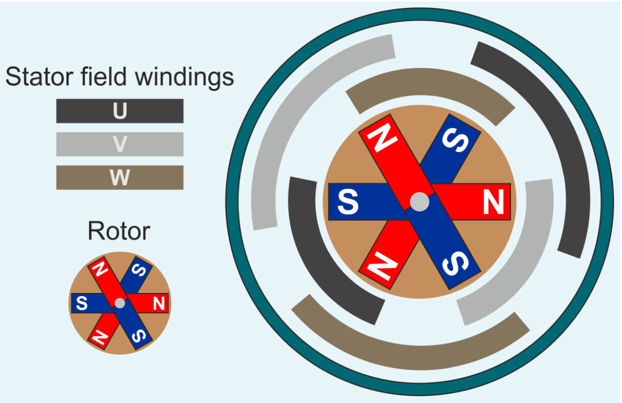
There are problems with this design:

- The brushes limit the maximum speed of the motor and eventually wear out.
- Making and breaking contact, the brushes cause sparking and electrical noise.

In the **brushless** DC motor, the structure is reversed.

The stator contains a number of electromagnets. The rotor is a spinning permanent magnet. The electromagnets in the stator are electronically controlled to generate magnetic fields that cause the rotor to spin.



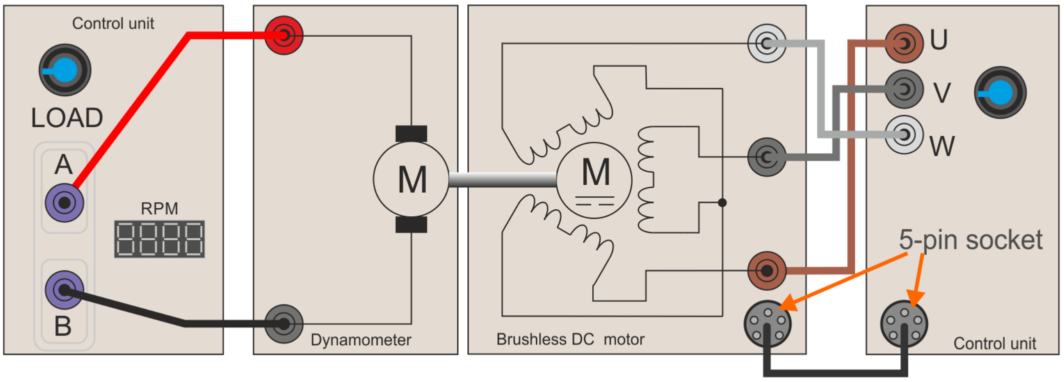


The advantages of this arrangement are:

- Brushless DC motors have a greater power-output-to-weight ratio, which makes them useful in weight sensitive applications like drones.
- Electronic control is more precise and can modify the control signals to optimise efficiency at the required speed.
- There are no brushes to wear out and much less electrical noise.

Activity 9 - investigating the brushless DC motor

Set up the arrangement shown below.



(Once again, the colours of the leads in the diagram are chosen to clarify the connections. An additional multi-strand cable is used to feedback information about the rotor position.)

Turn the 'Load' potentiometer about half-way round.

Slowly rotate the 'AC PSU' potentiometer to increase the AC supply frequency. The motor now spins.

Adjust the AC supply frequency and notice the effect on motor speed. Estimate the maximum speed possible.

In the Student Handbook, describe your findings.

The rotor position is sensed by a set of Hall-effect sensors. Signals from them, travelling through the five-pin plugs and cable, inform the control unit of the position of the rotor allowing it to adjust its driving signals accordingly.

What happens if you unplug one of the five-pin plugs while the motor is spinning? Try it!

The complex control system does not allow us to reverse the direction of rotation easily.

Research the topic of Hall-effect and write a summary of your findings in the Student Handbook.

Electrical machines

Student Handbook

Safety

Electric shock

The risk is minimal:

- The output from the control unit is limited to 24V AC or DC.
- The dynamometer generates DC voltages.
- At maximum speed, the generated voltage is less than 30VDC.
- The control unit operates only if a motor is plugged into the dynamometer.

Physical shock

The equipment is heavy!

Should anyone drop a device, it could cause substantial injury.

The risk is reduced by remaining seated whilst using the equipment.

Exposed rotating parts create potential hazards as hair and clothing can get caught in them. The plastic guard present between the dynamometer and the motor under test means that no rotating parts are exposed.

Page 5 - Power supplies:

DC power supply - (DC = direct current):

- one terminal is always positive, the other always negative;
- 'one-way traffic' - current always flows the same way around the circuit.

AC power supply - (AC = alternating current):

- terminals change polarity repeatedly, one positive, the other negative and then they swap;
- 'two-way traffic' - current flows clockwise, then anticlockwise around the circuit.

AC power can be converted into DC using the processes of rectification and regulation.

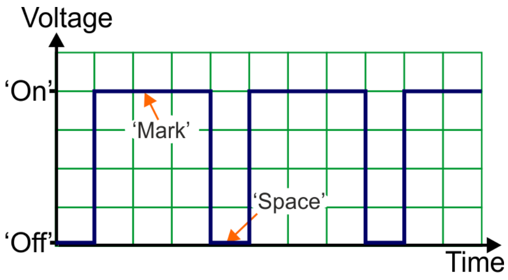
DC power can be converted into AC using a device called an inverter.

Page 7 - Exploring the DC power supply:

The DC motor is controlled using pulse-width modulation (PWM). The power supply outputs a series of 'on/off' pulses.The 'on' part of the pulse is known as the 'mark' and the 'off' part as the 'space'.

Increasing the output - increase the duration of the mark and decrease the space - the motor is 'on' for longer. As a result, it runs faster.

Decreasing the output means that the motor is off for longer and on for a shorter time - more space and less mark! As a result, it runs more slowly.



Using the jargon, motor speed is controlled by changing the 'mark: space ratio' of the pulse, i.e. the on:off ratio.

This form of control can be described using the term 'duty cycle'. This is the fraction of the signal for which the motor is 'on'. A mark:space ratio of 3:1 is the same as a duty cycle of 75%.

Challenge - The advantage of PWM over simple analogue control is:

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Page 12 - Exerting torque:

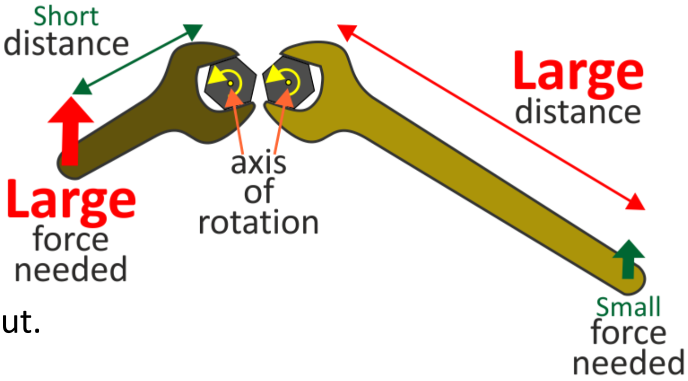
To change the direction of a DC motor, reverse the electrical connections.

Page 13 - What is torque:

Torque is the *turning effect* of a force. **It** is calculated from the equation:

torque T = **force** x **distance from the axis**

The bigger the force and the bigger the distance from the axis of rotation, the bigger the torque. This is why it is easier to use a long spanner than a short one to loosen a nut.



The digital balance measures **mass,** the quantity of matter in a body, not force. Force and mass are linked by 'g', the gravitational field strength - how hard the Earth's gravity pulls down on matter - around 10N force on every kilogram.

This means that:

dynamometer force on the balance = 10 x balance reading

For example:

Calculate the torque which produces a digital balance reading of 250g.

1000g = 1kg

so 250g = 0.25kg

This corresponds to a force (due to gravity) of 0.25 x 10 = 2.5N.

For the dynamometer, this is applied at a distance of 0.04m from the axis of rotation. The resulting torque is 2.5 x 0.04 = **0.1N.m**

Page 14 - Exploring the DC motor:

Power supply setting	**Speed (rpm)**	**Balance reading (g)**	**Balance reading (kg)**	**Torque (N.m)**
One third				
Two thirds				
Maximum				

As the increases, the motor rotates more rapidly and it generates more torque.

Page 15 - Exploring the DC motor:

Efficiency is a measure of how much of the energy supplied by the control unit is used effectively and how much is wasted (as heat usually.) High efficiency means that less energy needs to be supplied to achieve the same output.

It is calculated using the formula:

$$\text{Efficiency} = \frac{\text{energy delivered by the motor to the load}}{\text{energy inputted by the control unit}} \times 100\%$$

In this case, it is easier to work with power rather than energy.
Power is the rate at which energy is delivered, i.e. energy delivered per second.
The formula becomes:

$$\text{Efficiency} = \frac{\text{mechanical power developed by the motor}}{\text{electrical power delivered by the control unit}} \times 100\%$$

Mechanical power is calculated using the formula:

$$\text{Mechanical power} = (2 \times \mathbf{n} \times \pi \times \mathbf{T}) / 60$$

where **n** is the speed of the motor in rpm and **T** is the torque developed.

The electrical power is calculated using the formula:

$$\text{Electrical power supplied} = \mathbf{V_{IN}} \times \mathbf{I_{IN}}$$

where $\mathbf{V_{IN}}$ = input voltage and $\mathbf{I_{IN}}$ = input current.

Power supply setting	Electrical power delivered to the motor	Mechanical power delivered to the load	Efficiency
One third			
Two thirds			
Maximum			

These results show that the efficiency of the motor depends on its speed.

Effects of changing the load:

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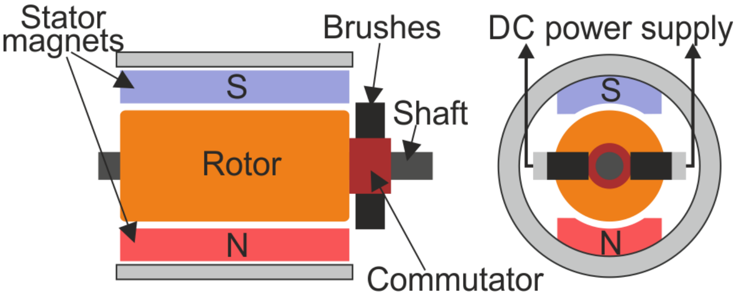
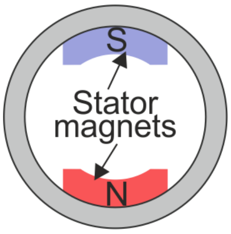
Page 16 - Exploring the DC motor:

The (brushed) DC motor is made up of the stator, the rotor (or armature), the commutator and brushes.

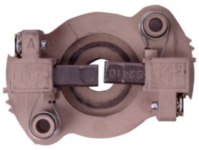




The **stator** generates a stationary magnetic field using either permanent magnets or electromagnets. This field surrounds the rotor.

The **rotor** is made up of a number of insulated coils. When these pass a current, they generate magnetic fields, which interact with the stator field, causing the rotor to turn.

The **commutator** reverses the flow of current around the rotor windings to keep the rotor spinning. It consists of a drum attached to the rotor, split into several sections.



The **brushes** slide over the commutator, as the motor turns. In doing so, they make contact with different segments of the commutator, which are attached to different rotor windings.

Page 17 - Exploring the DC motor:

Permanent magnet DC (PMDC) motor characteristics:

- Motor speed depends on power supply voltage.
- Motor torque depends on power supply current.

- ***A bigger power supply voltage makes the motor spin faster.***

Not a surprise!

Greater voltage ⇒ bigger current ⇒ stronger magnetic field in rotor windings ⇒ bigger magnetic force on rotor because of interaction with stator magnetic field ⇒ **faster the motor spins!**

- ***Increasing the load slows the motor down but increases the current it requires.***
  OR the faster the motor spins, the lower the current taken from the power supply!

The explanation - '**back-emf**':

- Rotor windings spinning around in the stator's magnetic field generate a voltage, called 'back-emf'.
- This opposes the power supply voltage.
- As a result, the overall voltage applied to the rotor windings is reduced.
- The faster the rotation ⇒ the bigger the back-emf ⇒ the smaller the overall voltage ⇒ the smaller the current that results.

Adding a load to the motor:

- slows it down;
- reduces the back-emf;
- increases the overall voltage;
- and so increases the current.

Page 18 - Exploring the DC motor:

Two advantages of the PMDC motor are its high starting torque and the (almost) linear behaviour of the speed / torque graph.

One disadvantage is that the brushes wear over time and are the components most likely to fail.

Other advantages and disadvantages are:

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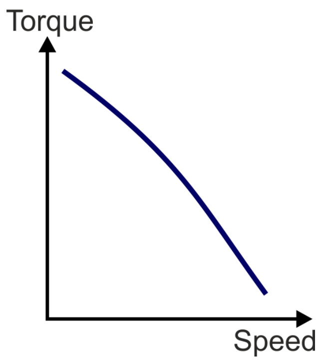
Uses of the PMDC motor include:

- at home - computer drives, electric toothbrushes, portable vacuum cleaners, food mixers, portable drills, hedge trimmers.
- in vehicles - windscreen wipers/washers, electric windows, heater fan.



Page 19 - And now the dynamo:

The permanent magnet DC motor rotates when supplied with electrical power. The dynamo has the same basic structure but works in reverse - when rotated, it generates electricity.

1. Output voltage vs speed:

Speed rpm.	Voltage generated
200	
400	
600	
800	

Effects of changing the load:

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2. Output power vs load:

Load	Input power	Voltage generated	Output current	Output power	Efficiency
One-quarter					
Half					
Three-quarters					
Full					

Challenge - Lighting the bulb:

Speed rpm	Input power	Voltage generated	Output current	Output power	Efficiency
400					
800					

The verdict:

The efficiency of the dynamo changes with its speed. Choose the right combination of machine and gearbox to get maximum efficiency.

Page 20 - Series and shunt motor basics:

In a DC motor, the **stator** creates a stationary magnetic field around the rotor. In the PMDC motor, this is produced by permanent magnets.

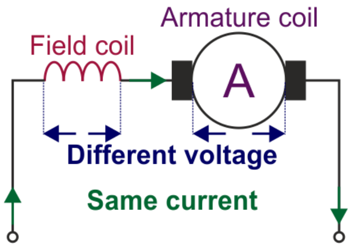
In wound-stator DC motors, it is generated by passing an electric current through coils of wire, called the field windings, turning them into electromagnets.

In both types, coil(s) of wire in the rotor (or armature) create magnetic fields that react with those of the stator.

There are two types of wound-stator DC motor:

The **series-wound** motor:

- the field and armature coils are connected in line, one after the other;
- the same current flows through them;
- there is usually a different voltage across them.

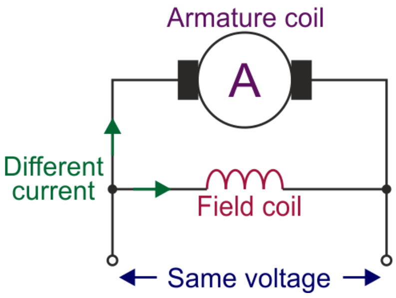


In practice, the field coil uses a few turns of thick wire, in order to lower its electrical resistance.

Otherwise it would reduce the current flowing through the armature and reduce the torque created.

The **shunt-wound** motor:

- the field and armature coils are connected in parallel;
- the current in the field coil can be different from that in the armature coil;
- both coils experience the same voltage.



In practice, the field coil must have a higher resistance than the armature coil as otherwise most of the current would by-pass the armature coil, reducing the torque created. To achieve this, the field coil uses a large number of turns of thin wire.

When direct current flows through the coils of a motor, the electrical behaviour can be predicted using Ohm’s law. However, once the motor is running, the rotating magnetic fields in the motor alter the behaviour drastically.

The effect is caused by the ‘back-emf’, described earlier. This increases as speed increases. Equally, when a motor stalls, the back-emf is zero. The current in the coils then increases significantly and can result in the motor burning out.

The series-wound motor is often called the ‘universal motor’ because it can be operated from AC as well as DC. This flexibility means that universal motors are amongst the most widely used, in applications such as planes, routers, sanders, grinders, saws etc.

Coil resistance measurements:

Wound-stator motor	**Armature resistance (Ω)**	**Field coil resistance (Ω)**
Series		
Shunt		

Explain how these measurements support the description of the structure of the two types of motor made on the previous page.

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Page 22 - Investigating the shunt motor:

Challenge - How do you reverse the direction of rotation?

Attempt 1 - reverse the DC1 power supply connections to the stator.

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Attempt 2 - reverse the DC2 power supply connections to the rotor.

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Attempt 3 - reverse both sets of power supply connections.

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Shunt motor performance:

DC2 (rotor) supply voltage (V)	Maximum speed (rpm)	Maximum balance reading (g)
6		
9		
12		
15		

Comments:

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Series vs shunt:

Speed control is an important aspect of motor design. The shunt motor offers really good speed self-regulation. As a result, it is often used in devices which need to run at a constant speed, like lathes.

The series-wound motor has the highest start-up torque of any motor. It is ideally

Page 24 - Investigating the series motor:

Challenge - How do you reverse the direction of rotation?

Attempt 1 - reverse the connections to the power supply sockets A and B.

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Attempt 2 - reverse the connections to the rotor, by swapping over the wires in the yellow and purple sockets.

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Attempt 3 - reverse the connections to the stator, by swapping over the wires in the red and black sockets.

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Series motor performance:

DC1 power supply voltage (V)	Speed (rpm)	Balance reading (g)
5		
8		
11		
14		

Comments:

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Page 24 - Investigating the series motor:

Challenge - The control unit delivers an output power up to 100W. It cuts out when this is exceeded and shows a message '*Err*' on the display.

Maximum permitted voltage and motor speed before cut-out:

Maximum power supply voltage = ………………………..

Maximum speed = ……………………….

Effect on these values of changing the load:

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Series vs shunt:

Speed control is an important aspect of motor design. The shunt motor offers really good speed self-regulation. As a result, it is often used in devices which need to run at a constant speed, like lathes.

The series-wound motor has the highest start-up torque of any motor. It is ideally suited to applications where that initially high torque is important, such as winches and cranes. However, its speed depends on the load and so can vary.

Page 26 - Exploring the universal motor:

Challenge - How do you reverse the direction of rotation?

Attempt 1 - reverse the connections to the power supply sockets A and B.

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Attempt 2 - reverse the connections to the rotor, by swapping over the wires in the yellow and purple sockets.

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Attempt 3 - reverse the connections to the stator, by swapping over the wires in the red and black sockets.

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Challenge - Effect of frequency on motor performance:

Maximum power supply voltage = ………………………..

Maximum speed = ………………………..

Effect on these values of changing the load:

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Possible cause of drop in speed at high frequency:

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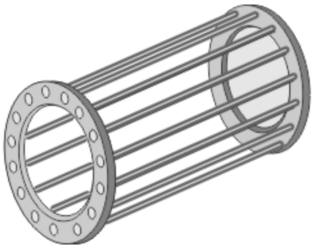
Page 29 - Introducing the induction motor:

Single phase induction motor

Induction motors have no brushes to wear out and so require less maintenance.

How does this work?

The **rotor** is not connected to an external power supply. It is usually either a coil of wire or a **squirrel cage**, an arrangement of metal bars, rather like that shown in the diagram.



Squirrel cage rotor

The **stator** windings are connected to an external power supply and are supplied with AC. This creates a **rotating** magnetic field.

This field induces an electric current in the rotor. The induced current produces its own magnetic field, which reacts with the rotating magnetic field of the stator and causes the rotor to spin.

That is why it is called an induction motor.

Challenge - What are the relative advantages and disadvantages of squirrel cage and wound-rotor motors?

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Why are the conductors in a squirrel cage rotor not parallel to the axis of the motor?

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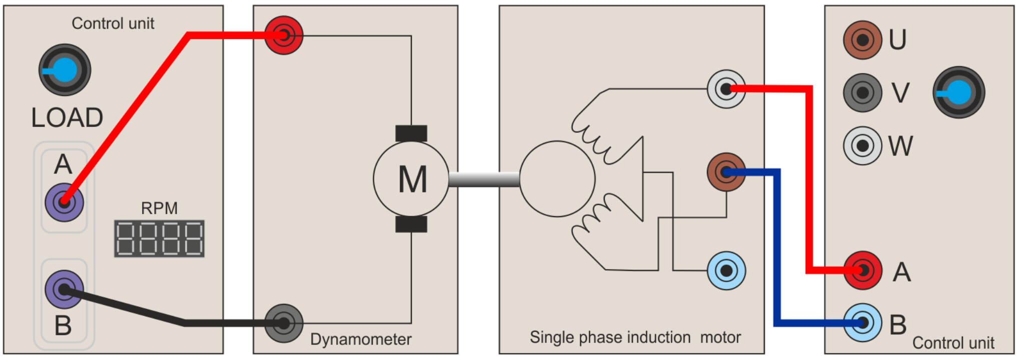
Page 31 - Exploring the induction motor:

In its raw form, connected as in the diagram, this motor is not self-starting!

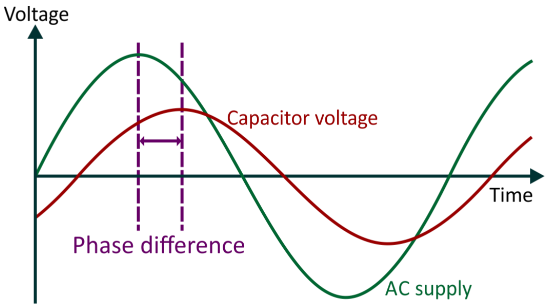


The reason is that we are treating the whole of the stator as a single coil. The AC supply is connected across that single coil and creates an *alternating* magnetic field, but not a *rotating* field. To do this we need two distinct magnetic fields, oscillating out of step with each other.

One answer is to involve a capacitor to introduce a phase shift between the signals applied to the coils in the stator.

When an AC voltage is applied to a capacitor, it charges and discharges in such a way that the voltage across it is ‘out of phase’ (not in step) with the supply voltage.

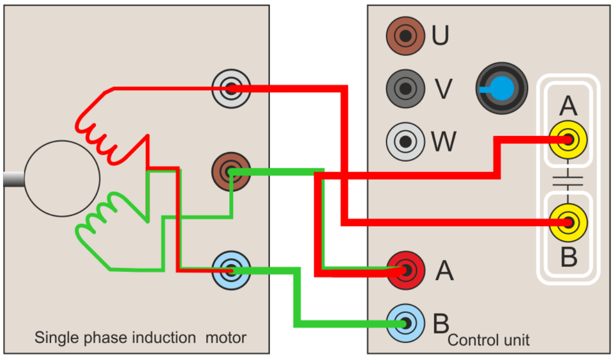
The peak in the capacitor voltage occurs at a different time to the peak in the supply voltage.



The arrangement opposite shows how to make use of this effect:

The motor now rotates when supplied with AC.

The speed of the motor depends on the frequency of the supply - the higher the frequency, the faster it rotates.



Challenge - How do you reverse the direction of rotation?

Attempt 1 - reversing the connections to the power supply sockets A and B:

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Attempt 2 - reversing the connections to the yellow capacitor sockets **A** and **B**:

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Attempt 3 - swapping over the connections to the brown input socket and the grey input socket:

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To be successful in reversing the rotation, one of the fields created by the stator coils had to be reversed.

Page 33 - Using the induction motor:

When the supply frequency is changed, the behaviour of the motor running on the ‘Start’ capacitor is shown in the table:

Frequency control ‘pot’	**Speed (rpm)**	**Balance reading (g)**
one-quarter turn		
one-half-turn		
three-quarters turn		
maximum		

Comment on these result:

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Comparing motor performance of the ‘Start’ and ‘Run capacitors:

Capacitor	**Maximum Speed (rpm)**	**Balance reading (g)**
Start		
Run		

Effect of load on maximum speed:

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Factors affecting stall speed and maximum torque:

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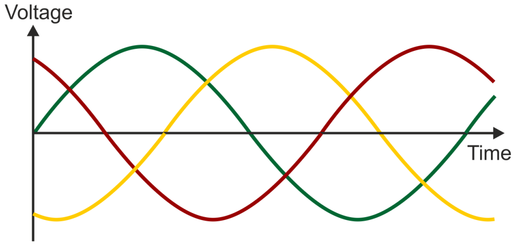
Page 34 - Three-phase AC:

Where more power is required, in large motors for example, a three-phase electricity supply is often used.



This delivers three separate AC voltages, down three wires. They are not in phase (in step), as the diagram shows.

As the phases are never zero at the same time and the peaks of successive waves are closer together, a three-phase motor runs more smoothly and efficiently.

Three-phase motors are self-starting - the separate, staggered, alternating magnetic fields from the three sets of stator coils create the effect of a rotating field. Hence, the structure of the motor is simpler - no need for capacitor starting!

Page 35 - Exploring the three-phase motor:

The photograph shows a cut-away view of a three-phase motor. Notice the lack of brushes and windings in the rotor.

Induction motors work by inducing a current and hence a magnetic field, in the rotor.

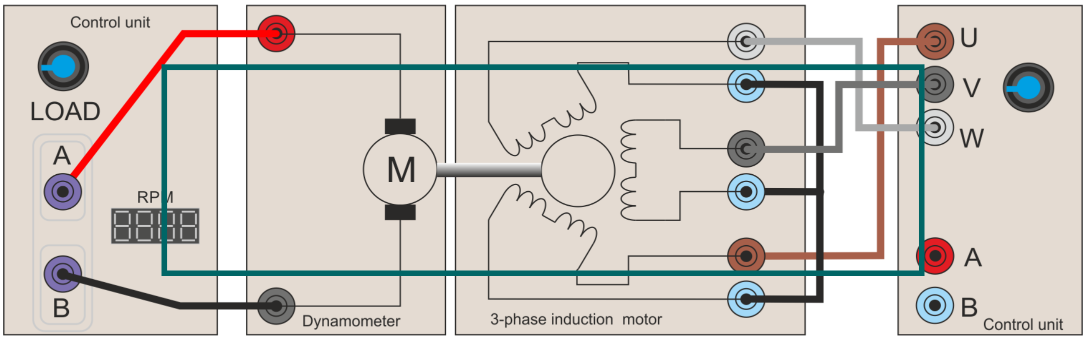
The Matrix three-phase motor uses six coloured sockets to connect the power supply to the stator coils. In the diagram, these are labelled 'A' to 'F'.

Record of measurements made:

Coil	**Connected to sockets**	**Coil resistance (Ω)**
Coil 1		
Coil 2		
Coil 2		

Page 36 - Investigating the three-phase motor:

The diagram shows how the motor is connected to the three-phase power supply.



- The blue sockets on the motor are all connected together.
- Each of the other motor sockets is connected to the corresponding coloured socket on the power supply.

With the ’AC PSU’ potentiometer about one-third of the way round, to increase the AC supply frequency, the motor twitches but then the display shows ‘Err’.

The power supply is designed to sense the initial rush of current and cut out. It then waits a few seconds, clears the fault condition and restores the current.

Effect of frequency on motor performance:

Effect of increasing the frequency:

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Maximum speed = ………………………… Maximum balance reading = …………………………

Possible cause of drop in speed at high frequency:

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Challenge - How do you reverse the direction of rotation?

Attempt 1 - Swap over the wires plugged into the ‘U’ and ‘V’ supply outlets .

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Attempt 2 - Swap over the wires plugged into the ‘U’ and ‘W’ supply outlets.

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Attempt 3 - Swap over the wires plugged into the ‘V’ and ‘W’ supply.

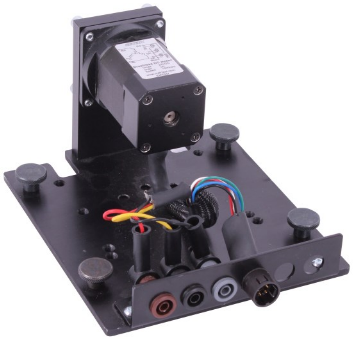
Page 37 - The brushless DC motor:

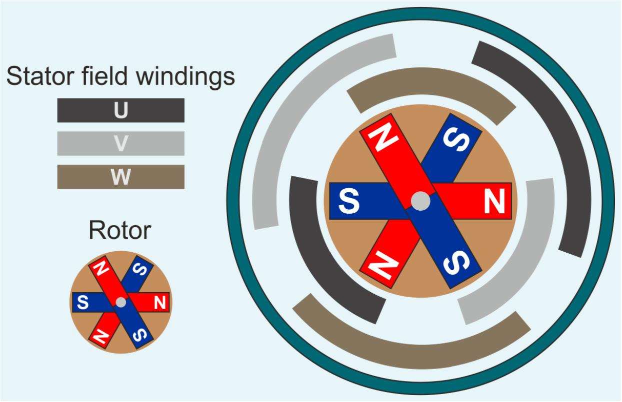
In a **brushed** DC motor, the stator generates a magnetic field, from either a permanent magnet or from an electromagnet. The rotor is an electromagnet that spins because the direction of current in the electromagnet is reversed periodically, using a commutator and brushes.

Problems:

- The brushes limit the maximum speed of the motor and eventually wear out.
- Making and breaking contact, the brushes cause sparking and electrical noise.

In the **brushless** DC motor, the structure is reversed. The stator contains a number of electromagnets. The rotor is a spinning permanent magnet. The electromagnets in the stator are electronically controlled to generate magnetic fields that cause the rotor to spin.



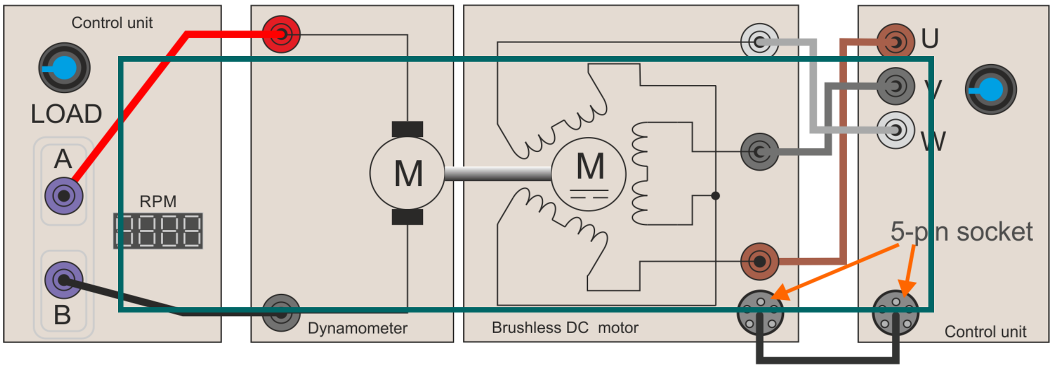


The advantages of this arrangement are:

- Brushless DC motors have a greater power output to weight ratio which makes them useful in weight sensitive applications like drones.
- Electronic control is more precise and can modify the control signals to optimise efficiency at the required speed.
- There are no brushes to wear out and much less electrical noise due to sparking.

Page 38 - Investigating the brushless DC motor:

The diagram shows how the motor is connected to the three-phase power supply.



A multi-strand cable is used to feedback information about the rotor position, which is sensed by a set of Hall-effect sensors.The complex control system does not allow us to reverse the direction of rotation easily.

Effect of frequency on motor performance:

As the frequency is increased:

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Maximum speed = ……………………….

Effect of removing the feedback signal:

When the feedback cable is unplugged:

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Challenge - What is the Hall-effect?

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Instructor
Guide

Instructor Guide

Introduction

The course explores a range of electrical motors through practical exercises. Practical implications and applications of the theory are highlighted to make the course more relevant to the students. The equipment can be used for additional experimentation should the instructor wish it.

Aim

It is important that students understand that electrical machines have distinct characteristics. Different applications have different demands and the engineer will be tasked with choosing a motor with characteristics appropriate to meeting those demands. The course introduces students to concepts and devices used in a range of electrical machines. It prepares students for the following units within City and Guilds diplomas 2357 and 2365-03:

- Unit 302 - “Principles of Electrical Science” Learning Outcome 3;
- Unit 609 - “Understanding the electrical principles associated with the design, building, installation and maintenance of electrical equipment and systems” Learning Outcome 8.

Prior Knowledge

It is recommended that students have followed the ‘Electricity Matters 1’, ‘Electricity Matters 2’ courses, or have equivalent knowledge, covering basic electrical concepts - current, voltage, resistance, energy and power and the use of a multimeter.

About these worksheets

This course provides a practical environment for the study of modern electric motors. The experimental work outlined in this course should be integrated with the theory behind motors and reinforced with written examples, assignments and calculations. Students will need additional information provided through lectures, tutorials, text books and other resources. The internet is a rich source of information and students should be encouraged by the instructor to carry out focussed research on relevant topics.

This format aims to encourage self-study, with students working at a rate that suits their ability. The instructor should monitor that students’ understanding keeps pace with their progress through the course. One way to do so is to ‘sign off’ each activity, as a student completes it, and in doing so have a brief chat with the student to assess grasp of the ideas involved in it.

We recommend that each student gets a print out of the Student handbook and writes their answers in there as they work through the material in this course.

Time:

It should take students between 12 and 17 hours to complete the worksheets. (A similar length of time will be needed to support the learning that takes place as a result.)

Learning Objectives

On successful completion of this course the student will be able to:

- recognise the need for safety when handling electrical equipment;
- distinguish between AC and DC electricity and name at least one source of each;
- describe the properties of a PWM power source;
- explain the meaning and significance of ‘mark’, ‘space’, ‘mark-to-space ratio’ and ‘duty cycle’;
- state the advantage of using a PWM power source for motor control, rather than a simple variable voltage (analogue) power source;
- calculate the average supply voltage for a PWM power source, given the duty cycle and peak voltage;
- reverse the direction of rotation of a DC motor by reversing the power supply connections;
- describe the role of the digital balance in the test rig;
- explain the meaning of the term ‘torque’ and calculate the torque given the size of the force and its distance from the axis of rotation;
- calculate the torque generated by a motor given the digital balance reading in grammes and the distance from the axis of rotation;
- recognise that the speed and torque generated by the motor depend on average power supply voltage;
- calculate the mechanical power delivered by a motor, given its speed and the torque developed;
- calculate the electrical power delivered to the motor, given the input current and voltage;
- calculate the efficiency of the motor, given the electrical power delivered to it and the mechanical power it develops as a result;
- name the four main components of a brushed DC motor (the stator, rotor, commutator and brushes);
- describe the function of the commutator in a brushed DC motor;
- state that in a brushed DC motor, speed depends on the input voltage and torque on the input current;
- explain what is meant by ‘back-emf’;
- explain why increasing the load slows the motor down but increases the current it requires;
- state two advantages and one disadvantage of the permanent magnet DC motor;
- identify three devices likely to use a permanent magnet DC motor;
- describe the effect on the output of a dynamo of increasing the electrical load;
- describe an experiment to measure the efficiency of a dynamo;
- distinguish between the PMDC motor and the wound-stator DC motor;
- distinguish between the structure of a shunt-wound DC motor and that of a series-wound DC motor;
- explain why the field coil in a shunt-wound motor usually consists of a large number of turns of fine wire;
- explain why the field coil in a series-wound motor usually consists of a few turns of thick wire;
- measure the resistance of the field and armature windings of a DC motor;
- describe how to reverse the direction of rotation of a shunt-wound motor and a series-wound motor;
- compare the performance characteristics of shunt-wound and series-wound motors in terms of speed regulation and torque;
- explain what is meant by the rms value of an AC voltage;
- explain why the series-wound motor is often called the ‘universal’ motor;
- describe how to reverse the direction of rotation of a series-wound motor running on an AC supply;
- describe what happens to the speed of a series-wound motor, running on an AC supply, when the AC frequency is increased;
- explain why an induction motor works, even though there is no external electricity supply for the rotor;
- describe the role of the capacitor in a ‘capacitor-start’ single-phase induction motor;
- describe how to reverse the direction of rotation of an induction motor;
- describe the effect of changing the AC frequency and the load on a single-phase induction motor;
- explain what is meant by a ‘three-phase AC supply’ and state one advantage over a single-phase supply;
- describe two advantages of using a three-phase motor over a single-phase motor;
- describe how to reverse the direction of rotation of a three-phase motor;
- describe the structure of a brushless DC motor and state two advantages it has over other motors;
- describe the Hall effect.

Page	Notes for the Instructor	Time
3 Safety	Safety is paramount! The issue of electrical safety has been addressed throughout the design of the equipment. Nevertheless, the instructor should emphasise the points made in this section. Physical safety is equally important. The motors and control unit are heavy items and should be in place ready for students' use. Again, the instructor should enforce strict observance of the issues highlighted here.	5 - 10 mins
5 Power supplies	Since some of the motors in this course run on DC supplies and some on AC supplies, it is important, from the outset, that students appreciate the difference between these supplies. Common misunderstandings include: • DC means that the voltage is constant. • In AC, the current reverses when the voltage decreases after the peak of the AC curve. If possible, the instructor should use an oscilloscope to demonstrate the differences between the two types of electrical power.	15 - 25 mins
6 Tour of the kit	The instructor should judge how to approach this. Good students will absorb the information easily and by themselves. Slower students may need a demonstration and explanation of the various parts of the control unit, for example.	5 - 10 mins
8 Getting started	All students should be shown how to assemble a motor on the test rig. It is important that the motor is lined up with the slots in the rubber 'spider' in the coupling. At first, this may be stiff and require a good push. Similarly, the motor base plate must slide into the microswitch housings as otherwise the control unit will not function. The torque generated by a motor can be measured in two ways. When the dynamometer rotates in one direction, it presses on a built-in load cell. When it rotates in the other direction, its arm can press down on a digital balance. The mass reading it produces is a measure of torque. The first of these is used when the control unit is in automatic mode - using the software applications developed for the CP6490 module. The second is used in this course. Students may need to be shown where to sit the digital balance and how to set it up. The control unit is in automatic mode when it is connected to the PC using the USB lead. In this course, the control unit is used in manual mode - the switches and knobs on the front panel fix the control box parameters. No USB lead is used.	15 - 25 mins

Page	Notes for the Instructor	Time
9 Exploring the DC power supply	This section distinguishes between simple analogue control, where the power supply voltage rises and falls, depending on the position of a 'pot' usually, and PWM, a common form of digital control, where the supply voltage is switched 'on' and 'off' rapidly. The advantage of PWM is that it is more energy efficient. With analogue control, some of the supply voltage is dropped across the 'pot', and a current flows through it. As a result, power is dissipated in it. With PWM, either all of the supply voltage is across the motor and all of the power is dissipated in it, or there is no voltage across the motor and no power dissipation. Either way, little or no power is wasted. It is important that students appreciate what is happening and that they understand the meaning of 'mark', 'space', 'mark-to-space ratio' and 'duty cycle', relating to PWM. The instructor may wish to demonstrate these aspects of PWM using an oscilloscope to show what happens when the DC power supply 'pots' are turned. The formula for average voltage allows students to calculate the duty cycle, using a multimeter to measure peak and average voltage.	25-40 minutes
12 Exerting torque	This is the first time that the students set up and run a motor. The issues are those raised on page 8 - ensuring that the motor is fully engaged in the coupling and that it operates the microswitches on either side of the rig (and lights the 'motor in' LED on the control unit. When first switched on, the digital balance display shows the unit of mass in use. This should be grammes (g). If not, prss the 'M' button repeatedly to cycle through the units. If, in use, the reading does not return to zero, press and hold the tare 'T' button until the display shows zero, (or switch off and restart.) The 'PCS' button is used when counting the number of samples being weighed and is not used in this course. With the motor running, there should be a positive reading on the display. If not, the instructor should check that the motor is spinning in the right direction, to press down on the balance.	20-30 minutes
13 What is torque	There are some crucial concepts in this section and the instructor needs to spend as long as it takes to drive them home. The balance measures mass, not weight. Mass is how much matter a body contains and is measured in g and kg. Weight is the force that gravity pulls down on that matter and, like all forces, is measured in newtons, N. Everyday English is often sloppy. We speak of "...weighing..." things on the balance because we do not have a word "...massing...". Torque means 'twisting effect'. It depends on the size of the force and where it is applied. It measures how much 'leverage' a force creates. The instructor might focus on tools like claw hammers, scissors and wrecking bars to illustrate the idea. It is worth giving the students a few questions involving torque calculations to drive home the concept.	20-30 minutes

Page	Notes for the Instructor	Time
14 Exploring the DC motor	The permanent magnet DC motor is probably the most widely used low-power motor. Using modern rare-earth magnets, it is a viable alternative to traditional wound-stator motors. Absence of stator windings means that it can be smaller than its counterparts. This section gives students a chance to calculate the torque created by a motor, the DC motor, under three power supply settings. The results are then used to calculate the efficiency of the motor at each power supply setting. The instructor may wish to expand on the meaning of efficiency and give some everyday examples - traditional motor vehicles around 15% efficient, electric vehicles around 60%, tungsten filament lamps around 3%, LED lighting around 70%... (This could be a research task for the students.) The outcome is not surprising - speed and torque increase as (average)supply voltage increases. An important aspect of electric motor selection is the way in which torque varies with rotational speed. Different types of motors offer different performance. The section goes on to look at the structure of the motor. Of particular significance is the role of the commutator and brushes. Without them, the motor would not rotate but would just twitch backwards and forwards. However, friction between the brushes and commutator leads to wear and eventual need for replacement. This system of supplying electric current to the rotor also limits the maximum motor speed. At high speed, the contact between brushes and commutator is insufficient to deliver enough current. The concept of back-emf is raised to resolve the possibly weird statement that the faster the motor spins, the smaller the current it draws. Depending on the ability of the students, the instructor may choose to elaborate on the outline given in the notes.	30-50 minutes
19 And now - the dynamo!	The dynamo is a familiar item to many students. The dynamometer in the test rig has an internal dynamo that generates a current through the load. This section investigates its performance. First of all, students look at how the output voltage of the dynamo changes with speed of rotation. (The precise position of the load 'pot' is not crucial as long as it does not change during the investigation). The students then investigate the effect on output voltage of changing the load. Different groups could be allocated different loads allowing all the results to be pooled later in a class discussion. The students should focus on the energy flows involved here. The motor delivers mechanical power to the dynamo in the dynamometer. In turn, it delivers electrical power to the load. The next investigation adds an ammeter to measure output current as well. Combining output voltage and current gives the output electrical power (using P = I x V). The students use this and the input mechanical power to calculate the efficiency of the dynamo for a number of load settings. The challenge is to do the same when the load is a filament lamp - giving a much more visual sense of what is happening at the output! The efficiency is measured at two rotational speeds.	30-50 minutes

Page	Notes for the Instructor	Time
21 Series and shunt motor basics	In a wound-rotor motor, there are two sets of coils - those in the stator and those in the rotor. These sets can be connected together in two ways - in series or in parallel. That gives rise to two types of wound-rotor motors, known as series wound and shunt wound. This section describes these differences and their consequences for the structure of the windings. Students measure the resistance of the windings in both types to confirm these. The point is made that electrical resistance is not the only factor in determining the resulting current. As before, once the motor is spinning, back emf must be taken into account.	20-30 minutes
23 Investigating the shunt motor	The shunt-wound motor is studied first because the series-wound can be used with an AC supply as well, and so involves more experimentation. As the stator and rotor windings are connected in parallel, they can be run from different DC supplies, allowing more control over the behaviour. Here, 'DC1' supplies current to the stator windings and 'DC2' to the rotor. Following the instructions given on page 23, the students should make the motor spin. Then comes the task of reversing the direction of spin. Rather than invite wholesale reorganisation of every connecting wire, with the real possibility of causing a short-circuit, the instructions suggest a number of changes to try. The result is logical - when the current through one of the windings, stator or rotor, is reversed, the resulting magnetic field is also reversed and the motor spins in the other direction. When both sets of windings are reversed, the motor continues to spin in the same direction. The next part of the investigation looks at the effect of the stator voltage on the maximum speed. It assumes that the students have arranged the direction of rotation of the motor so that the dynamometer arm presses on the digital balance. This allows the student to record the maximum speed and (a measure of) maximum torque for each DC1 voltage setting.	20-40 minutes
25 Investigating the series motor	The series-wound motor is now subjected to a very similar investigation. As the stator windings and rotor windings are connected in series, they are run from the same DC supply, the 'DC1' supply in this case. The investigation mirrors that for the shunt-wound motor, including the task of reversing the direction of spin. As before, the instructions suggest a number of changes to try. The result, again, is logical - when the current through one of the windings, stator or rotor, is reversed, the magnetic field and hence direction of rotation, is also reversed. Swapping the connections to the power supply sockets A and B, reverses both fields and the motor continues to spin in the same direction. The next part looks at the effect of supply voltage on maximum speed and torque. As before, students need to arrange the direction of rotation to make the dynamometer arm presses on the digital balance. Students then record maximum speed and balance reading for a range of voltage settings. continued on next page...	20-40 minutes

Page	Notes for the Instructor	Time
26 Investigating the series motor	continued from previous page... The series motor has an extremely small resistance, meaning that huge currents can flow. The control unit will cut out eventually, when the series motor is used. This is a safety precaution to prevent the control unit from overheating, and is a feature of all well-designed power supplies. The series-wound motor is now subjected to a very similar investigation. As the stator windings and rotor windings are connected in series, they are run from the same DC supply, the 'DC1' supply in this case. The section ends with a comparison of the two wound-stator motors. The instructor may need to explain further the concepts of 'self-regulation' and 'start-up torque'.	20-40 minutes
27 And now AC again	This revisits earlier work where AC and DC power were compared. The focus here is AC and two measures applied to it - frequency and rms voltage. The latter may need additional explanation from the instructor, who may wish to expand on why it is called 'root-mean-square' (rms). Power depends on the square of the voltage. That 'voltage-squared' curve can be averaged (to find the mean.) However, that is still a voltage squared. To get back to a voltage, we take the square root of that quantity. If possible, the instructor should use an oscilloscope to demonstrate these aspects of AC power.	10-20 minutes
28 Exploring the universal motor	We are now moving from DC to AC motors. As pointed out on page 5, AC is in many ways a more flexible and readily available form of electrical power. The series-wound motor is also known as the universal motor because it can use either AC or DC power. Whereas, in DC motors, speed depended on (average) voltage, using PWM, AC motors are controlled by varying the frequency of the AC. This motor performs better (i.e. produces higher torque) when running as a DC motor. When running on AC, there is an increase in impedance (AC 'resistance',) due to the AC, which causes a reduction in the motor current. As with all motors, lower current means lower torque. With more able groups, the instructor could discuss the effect of frequency on impedance as part of the introduction to this investigation. The first activity shows that the 'pot' on the AC power supply controls the frequency of the AC supply. There can be an issue with this activity. The AC output is synthesised and is not a pure sine wave. The frequency meter may measure the frequency of harmonics present in the synthesised wave. As for other motors, the student is then tasked with reversing the direction of rotation, following a list of suggested changes. As before, the solution is to reverse the magnetic field produced by either the rotor windings or the stator windings, (suggestions 2 and 3,) but not both (suggestion 1,)!	20-40 minutes

Page	Notes for the Instructor	Time
30 Introducing the induction motor	Up to this point, all the motors studied have required a supply of electric current to windings in the rotor. This is achieved by having ‘brushes’, pads of graphite usually, rubbing against a commutator or slip-ring. A problem - those brushes wear out. The next set of motors operate without this external rotor current. They rely on electromagnetic induction, which is described on page 30. The instructor may decide to expand on this description, depending on the previous experience of the students. The instructor could develop the description of a squirrel-cage rotor. The students could be tasked with researching the device, combining this with the tasks given in the challenge. The section goes on to set up an induction motor, connected to the single-phase AC supply. All the ingredients see to be there - an alternating electric current generating an alternating magnetic field, a rotor in which to induce a current and an induced alternating magnetic field. However, the motor does not spin. The fields in the rotor and stator need to be offset from each other to cause a rotational force between them. This offset can be created by means of a capacitor. These act as reservoirs (i.e. buckets) of electric charge. They take time to fill with electric charge, especially if the electric current filling it is impaired by electrical resistance. As a result, there is a time lag (phase difference) between the voltage across the capacitor and the supply voltage. The induction motor usually has two separate coils in the field windings, a ‘main’, or ‘run’ coil and an ‘auxiliary’ or ‘start’ coil. One of these is supplied directly from the AC supply. The other is supplied from the AC supply, but via a capacitor. The latter has a current and magnetic field that is out of phase with that in the other coil. This provides the offset needed to cause rotation. (The ‘start’ and ‘run’ windings of the Matrix motor are identical, so they windings can be swapped in order to change the direction of rotation of the motor. One end of the ’run’ winding is connected internally to one end of the ’start’ winding to form the ‘common’ connection.) The students then test the motor in the same way as the earlier ones. They try to reverse the direction of rotation and test the effect of changing the AC supply frequency and load. They measure the maximum speed of rotation and torque. An added task is to compare the effects of the two capacitors, labelled ‘Start’ and ‘Run’ contained in the control unit. These differ in the size of the capacitance but are otherwise identical. The instructor may wish to help the task outlined in the challenge by introducing the significance of the term ‘stall speed’.	30-50 minutes

Page	Notes for the Instructor	Time
35 Three phase AC	Single-phase AC is the type of electricity we are all used to, in our homes and offices. It has its limitations: • At times, the supply voltage falls to zero. • It requires two wires to deliver it, to complete the circuit. Three-phase AC is equivalent to having three separate AC supplies, rising to peak values at different times and delivered down only three wires. It offers advantages e.g. where large amounts of power are needed. Used to drive an electric motor, it offers smoother running, which reduces wear and tear on bearings and so reduces maintenance costs. Where a three-phase generator or a simulator is available, the instructor could demonstrate the waveform on an oscilloscope.	10-20 minutes
36 Exploring the three-phase motor	A big advantage of three-phase motors is that they are self-starting - no need for electronic wizardry to create phase shifts! They are induction motors, so no need for heavy rotor windings, brushes and commutators. All this means a simpler and lighter structure. Their stators contains a number of separate windings. The first task for the students is to identify which motor terminals are connected to which coils. In use, three of the coil terminals are connected together. This allows current to flow to the motor through one phase and back to the supply down another, reducing the number of wires needed in the supply. When activated, a safety mechanism in the control unit trips on the initial surge of current, but then restores it a few seconds later. Initially, this may worry some students, fearing that they may have mis-wired the motor. The instructor should pre-empt this by warning them about this effect. Once the motor is running, the students tackle the usual task of finding out how to reverse the direction of rotation. The answer is to swap over any two of the three phases. The students could be set the task of producing a presentation contrasting the properties of three-phase and single-phase motors.	30-50 minutes
38 The brushless DC motor	Induction motors overcome the difficulty of supplying external electric current to the rotor windings by using induced current instead. The brushless DC motor tackles the problem in a different way, using permanent magnets to generate the rotor's magnetic field. Electromagnets in the stator, providing its field - electrically a much simpler solution. As a result, the brushless DC motor is smaller, lighter and more reliable. However, there is still the need for a rotating magnetic field to drag the rotor around. The solution is to use electronics. The separate coils in the stator are provided with AC synthesised from a digital electronic system such as a microcontroller. The position of the rotor is sensed by Hall-effect sensors, which generate a voltage when they are in a magnetic field. This feedback allows the electronic control system to time the AC to each coil, to maintain the rotation. The students connect up and run the brushless DC motor from the three-phase AC supply. When they unplug the feedback cable, the motor stops.	25-45 minutes