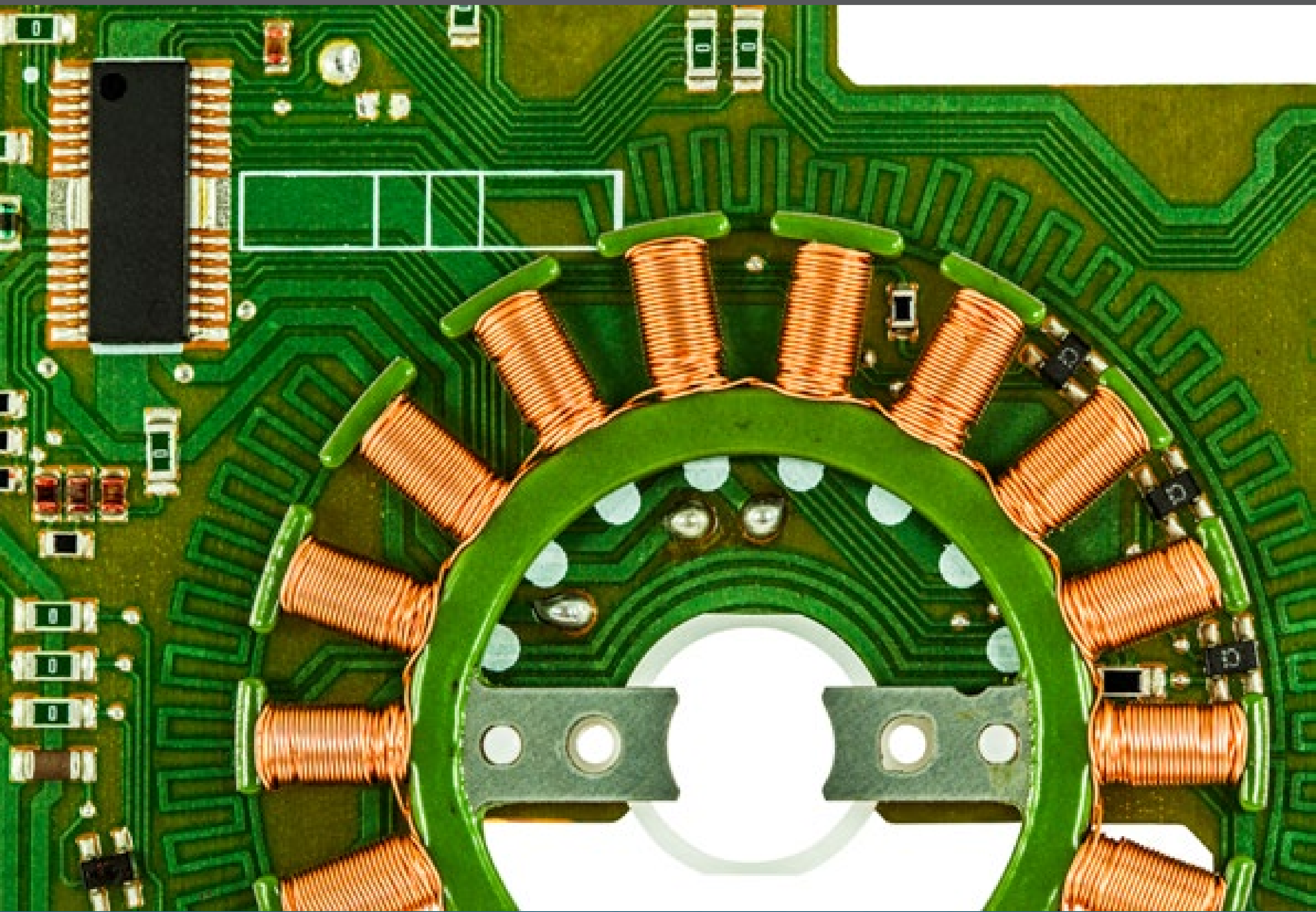

ELECTRICAL MACHINES FOR INSTALLATION/MANUAL CONTROL

CP3897

Inspiring The Next Generation Of Engineers

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Contents

Safety	3
Getting started	5
Exploring the DC power supply	6
Pulse-width modulation	7
Activity 1 - exerting torque	9
Activity 2 - Exploring the DC motor	11
Activity 3 - exploring the Dynamo	16
Activity 4 - investigating the shunt motor	20
Activity 5 - investigating the series motor	22
Activity 6 - exploring the universal motor	25
Activity 7 - exploring the induction motor	28
Activity 8 - exploring the three-phase motor	33
Activity 9 - investigating the brushless DC motor	36
Activity 10 – Investigating the stepper motor	38
Student Handout	39

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Health and 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 36V 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.

Physical Shock

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.

Design team
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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).

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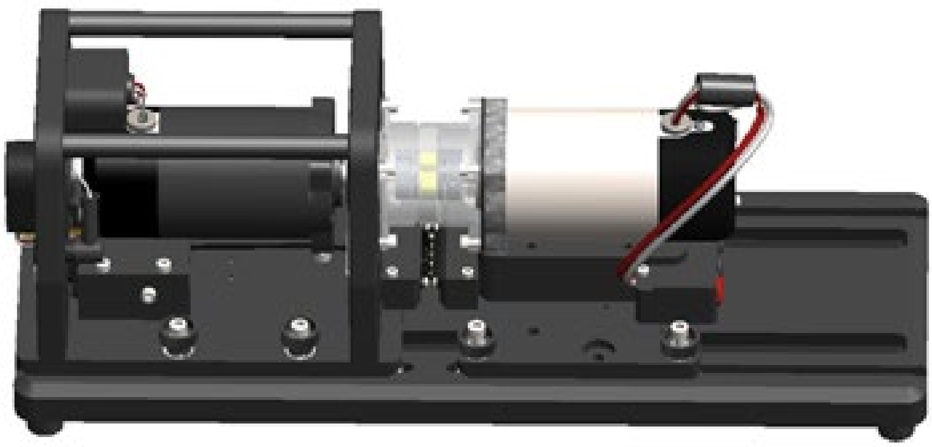
Getting Started

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 graphical display on the digital drive box should light up.



Slide the dynamometer module onto the shorter side of the base plate and connect to the digital drive box with the 25-way D-type lead. Make sure that the software and control unit driver are correctly installed.

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.

Slide the DC motor onto the longer side of the base plate. If necessary, loosen the screw clamps on the motor base plate. As you push home the motor, you should see the
corresponding module icon appear on the graphical display.

Tighten the screw clamps to make sure that the dyno and motor modules are secured in place.

You are now ready to start experimenting with the equipment.

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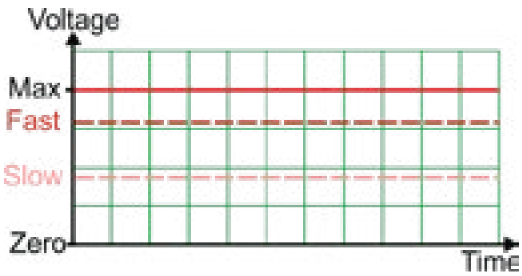
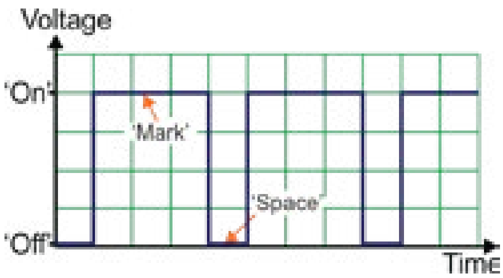
Exploring the DC Power Supply

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

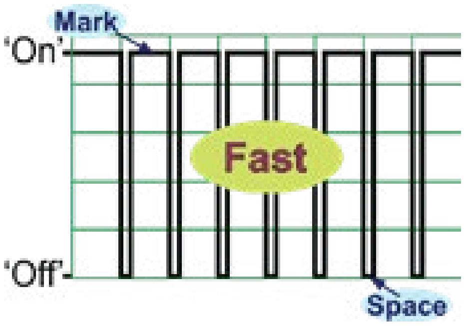


However, it is not simply a matter of increasing or decreasing a steady DC voltage - a form of control, called ‘analogue’ - illustrated in the diagram.

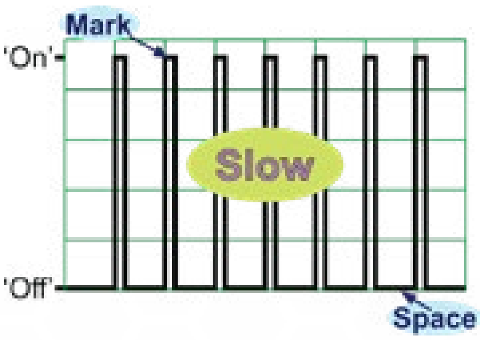
Instead, the power supply outputs a series of ‘on/off’ pulses.



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.

PWM (Pulse Width Modulation) is often preferred over varying voltage because it’s more energy-efficient, reduces heat generation, and provides more precise control, especially in applications like motor speed control and dimming LEDs

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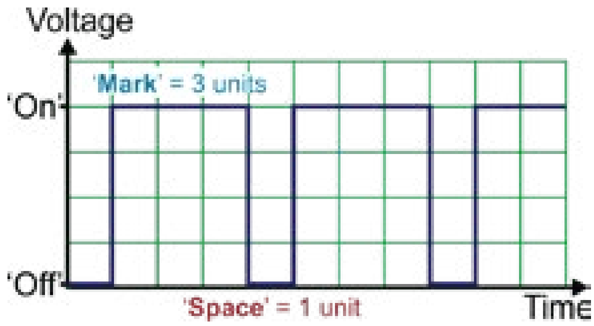
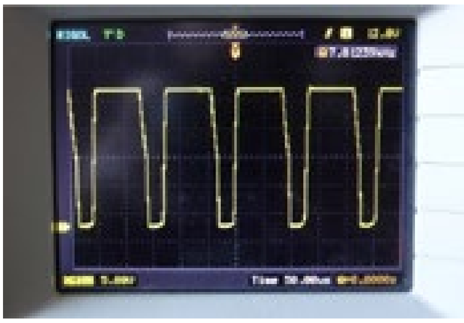
Pulse-Width Modulation

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.

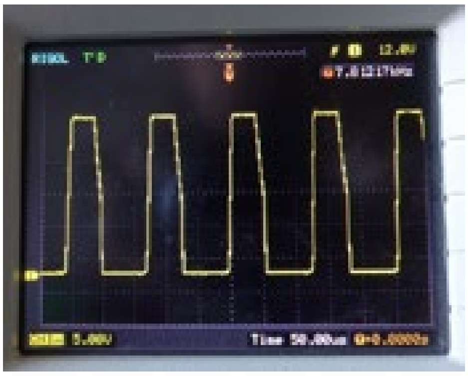


In the diagram, the 'mark' lasts for three units of time, whereas the 'space' lasts only one. This gives a m:s of 3:1.

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%.

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Pulse-Width Modulation

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 36V.

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

$$\frac{(3 \text{ x } 36) + (1 \text{ x } 0)}{4} = 27\text{V}.$$

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%	10.8V
50%	18V
70%	25.2V

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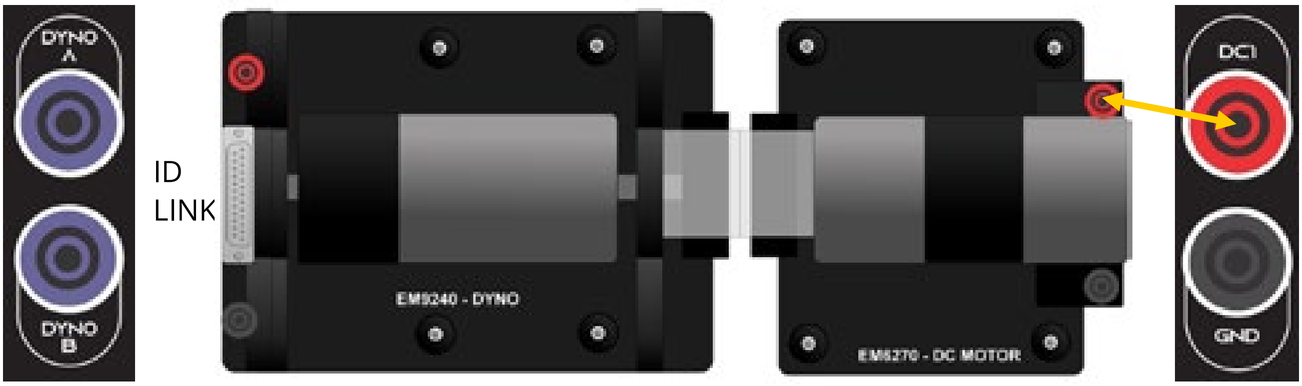
ACTIVITIES

Activity 1 - Exerting Torque

Refer to the getting started guide for an introduction to the hardware.

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



Switch on the digital drive box.

Check that the Dyno and DC Motor icons are shown on the graphical display. If not the return to page 5 and repeat the initial setup process.

Connect 4mm wires from the dyno and motor modules to the digital drive box as shown above.

Press the Stats Button and then press the Grams button to set the box to output the load cell reading as a weight. Press Back to return to the main screen.

Press the Control button and then adjust the voltage slider to 0.0V, Then press the Run button to enable the motor output.

Adjust the DC1 voltage slider until the DC motor starts to turn. The torque produced by the motor is shown to the right hand side of the Load slider.

Torque is an important measure of a motor’s performance.

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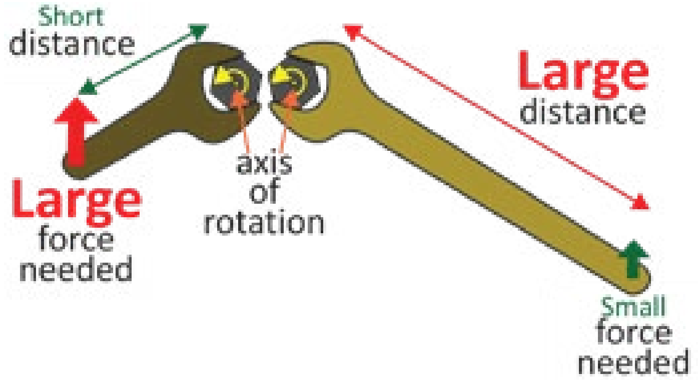
What is Torque?

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 = 0.045m.
Torque is measured in units called Newton.metres (N.m).

What does the digital load cell 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 - 9.81N force on every kilogram. This means that the force pressing down on the load cell, generated by the dynamometer, = 9.81 x load cell 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 9.81 = 2.45N.
This force is applied at a distance of 0.045m from the axis of rotation of the dynamometer and produces a torque of 2.45 x 0.045 = **0.11 N.m**

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ACTIVITIES

Activity 2 - Exploring the DC Motor

Adjust the Load slider to about 50%. 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 changing the DC1 slider:

- 12V— 33% Voltage;
- 24V— 66% Voltage;
- 36V— 100% Voltage.

In the Student Handbook, record the speed, shown on the display and the weight in grams measured by the load cell. for each power supply setting (i.e. complete the second and third columns of the table,).

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

Now, use the load cell 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.

The Digital Drive box features an internal computer that can do the Torque calculations for you. Return to the Stats screen and put the box back into Torque mode by pressing the NM button. This will then automatically take the weight on the load cell and convert to a Torque in Nm. Compare your readings with the values calculated by the box.

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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:

Mechanical power = $(2 \times n \times \pi \times T) / 60$
where **n** is the speed of the motor in RPM and T is the torque developed.

The electrical power is calculated using the formula:

Electrical power supplied = $\mathbf{V_{IN} \times I_{IN}}$
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
12V			
24V			
36V			

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

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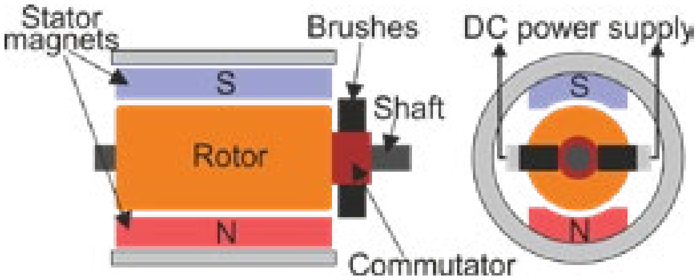
ACTIVITIES

Activity 2 - Exploring the DC Motor

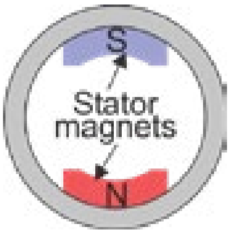
The (brushed) DC motor
is made up of:

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

The stator generates a stationary magnetic field using eitherpermanent magnets or electromagnets. 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.

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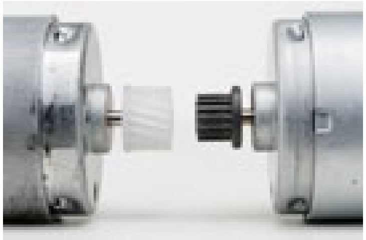
ACTIVITIES

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!

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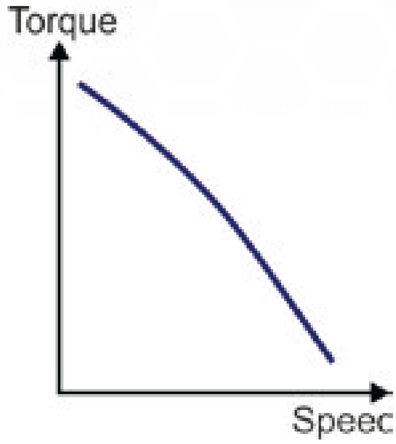
ACTIVITIES

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.

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ACTIVITIES

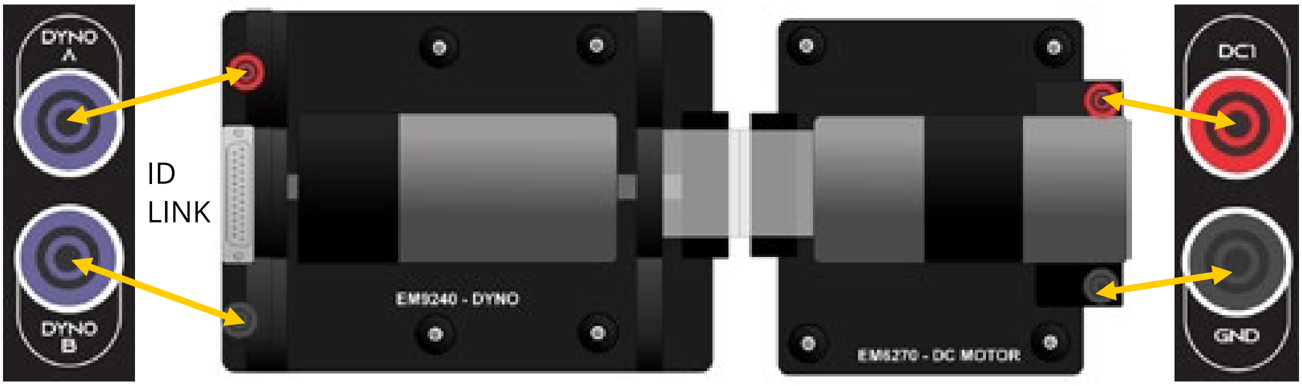
Activity 3 - Exploring the Dynamo

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.



Using the Control screen adjust the DC1 voltage to minimum and press the Run button. Switch on the multimeter and set it to measure DC voltages.

Connect the multimeter between the Red and Black terminals on the Dyno module. Adjust the Load slider to 50%.

Slowly adjust the DC1 slider until the dynamo spins at approx 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 speed.

In the Student Handbook, comment on the effect.

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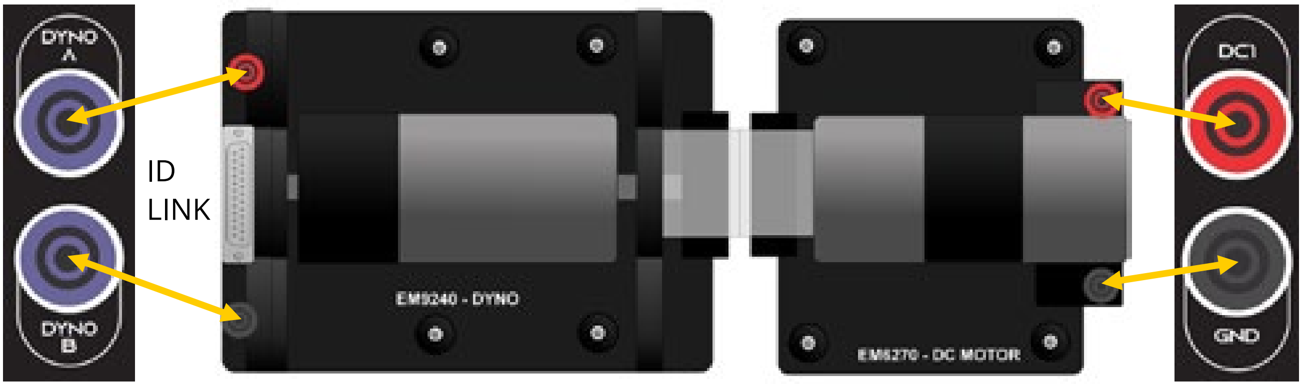
ACTIVITIES

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.



Adjust the DC1 slider to minimum and press the Run button.
Switch the first multimeter to measure DC voltage and connect between the Red and Black terminals of the dyno module.
Switch the second multimeter to measure DC current and connect between the Red terminal of the dyno module and the DYNOA terminal of the digital drive box.
Adjust the 'Load' slider to 25%.
Slowly adjust the DC1 slider until the dynamo spins at approx. 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 DYNOA and DYNOB cables from the digital drive box and replace it with a 12V filament bulb.
- Adjust the DC1 slider until the dynamo spins at approx. 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!

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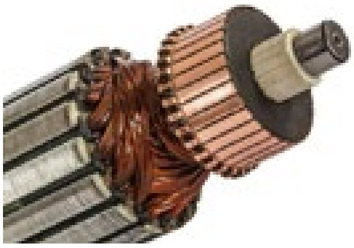
Shunt and Series Motor Basics

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.

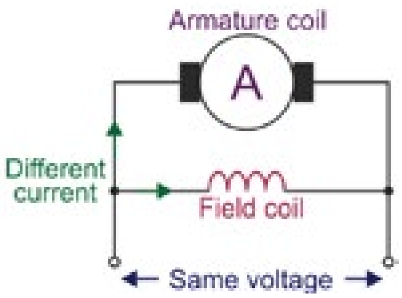
In both types, coils of wire in the **rotor** (or armature) create magnetic fields that react with those of the stator.

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:

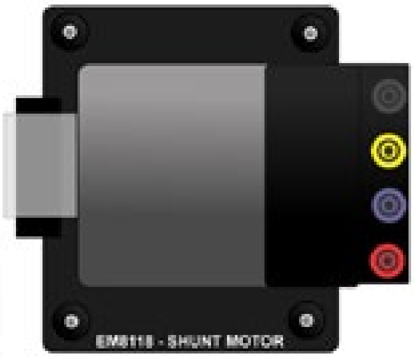
- The field and armature coils are connected in parallel;
- The current in the field coil can be different from that in the armature coil;
- Both coils experience the same voltage.



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.

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Shunt and Series Motor Basics

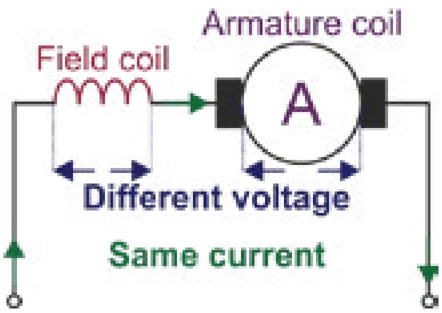
When direct current flows through the coils of a motor, the electrical behaviour can be predicted using Ohm's law.

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.

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ACTIVITIES

Activity 4 - Investigating the Shunt 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 parallel.

Notice that the stator windings are shown as two coils connected in series, as explained earlier.

Adjust the DC1 and DC2 sliders to minimum and press the Run button.
Adjust the Load slider to 50%.
Adjust the DC2 slider to approx. 12V

Slowly increase the DC1 slider to increase the power supply to the motor armature windings.

It should spin.

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ACTIVITIES

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.

Although the load cell gives a reading in grams, 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.

Adjust the Load slider to approx. 50%.
Adjust the DC1 and DC2 sliders to the 0V position.
Press the run button and adjust the DC2 slider to output approx 6V.

Now slowly increase the DC1 slider 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 torque reading and maximum speed.

Repeat this procedure for the other rotor voltages, shown in the table.
Note down the results and comment on what happened.

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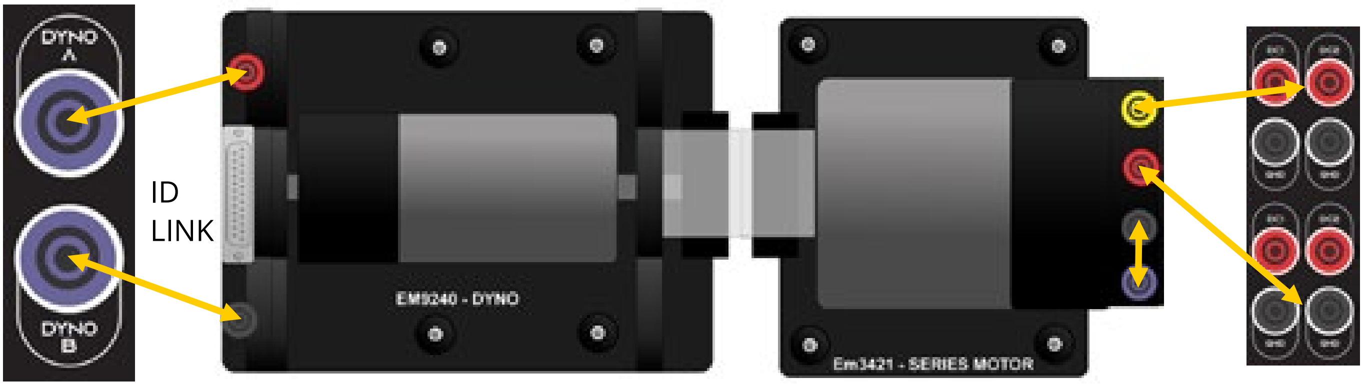
ACTIVITIES

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.

In the Stats Screen check that the AC button is shown, press the DC button if shown. Back in the control screen, adjust the DC1 and DC2 sliders to minimum and press the run button. Adjust the Load slider approx. 50%.

Slowly increase the DC1 slider 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 digital drive box power supply. The following gives you a list of 'safe' things to try.)

1. Reverse the connections to the power supply sockets DC1 and GND.
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.

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ACTIVITIES

Activity 5 - Investigating the series Motor

Adjust the Load slider approx. 50%.

Reduce the DC1 slider to the 0V setting

Press the Run button to activate the motor output

Slowly increase the DC1 slider to the 2V position.

The motor should now be spinning and there should be a Torque reading on the right hand side of the load slider.

In the table in the Student Handbook, note down the Speed and Torque.

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

Note down the results and comment on what happened.

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.)

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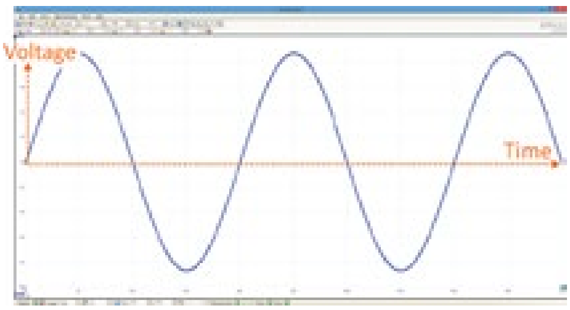
Using Oscilloscopes

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.

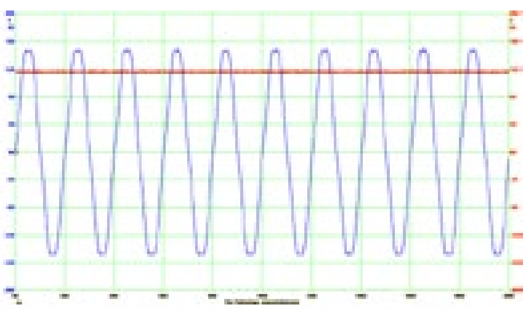


Notice:

- 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.

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ACTIVITIES

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.

Now set up the system shown in the diagram.

In the Stats Screen check that the DC button is shown, press the AC button if shown Back in the control screen, adjust the DC1 sliders to minimum, set the frequency to 50Hz and press the run button. Adjust the Load slider approx. 50%.

Slowly increase the voltage slider to increase the voltage applied to the motor.
It should spin.

Compare the wiring with that shown for the DC controlled series motor on page 23. The only difference is in the type of power used.

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 decrease the frequency of the AC supply, the speed of the motor and the torque increase.

- Experiment to find the maximum speed and torque 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.

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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.

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.

ACTIVITIES
Activity 7 - Exploring the Induction Motor

Now set up the system shown in the diagram.

Set the load to 50%, the voltage to 18V, the frequency to 50Hz and press the run button.

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 may 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.

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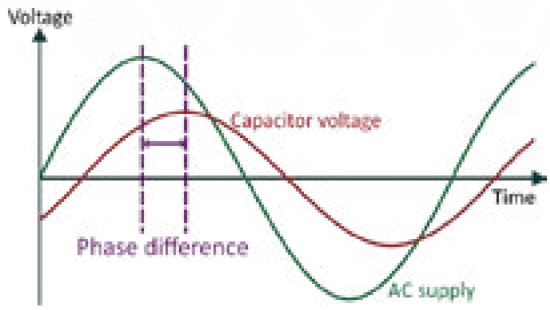
ACTIVITIES

Activity 7 - Exploring the Induction Motor

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 five capacitors, each with a capacitance of 100uF that can be connected across the yellow CAPIN and CAPOUT sockets. The value of capacitor can be selected in the Setup -> Capacitor screen.

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.

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Set up the arrangement shown below.

On the Setup -> Capacitor screen set the capacitance to 500uF.
Back on the Control screen set the load to 50%, the voltage to 18V, the frequency to 50Hz and press the run button.

The motor runs!
Increase the frequency slider up to 80Hz.
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. Unplug the leads from the red motor input socket and the lead from the blue motor input socket and swap them over.
3. Unplug the leads from the red motor input socket and the lead from the yellow motor input socket and swap them over.

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

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ACTIVITIES

Activity 7 - Exploring the Induction Motor

On the Setup -> Capacitor screen set the capacitance to 500uF.
Back on the Control screen set the load to 50%, the voltage to 18V, the frequency to 50Hz and press the run button.

In the table in the Student Handbook, note down the torque reading and speed.
Repeat this procedure for the other frequencies, shown in the table.
Note down the results and comment on what happened.

Revert to 50Hz and then use the Setup -> Capacitor screen to switch between the capacitor values. Use the Stats screen to show Motor Power.
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.

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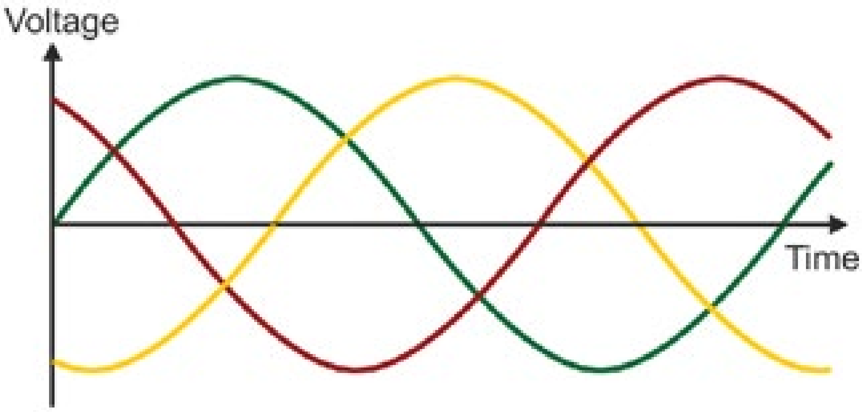
Three-Phase AC

The type of AC described on page 25 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.

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ACTIVITIES

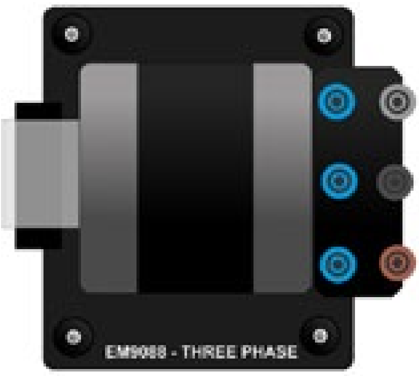
Activity 8 - Exploring the Three-Phase Motor

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.



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.

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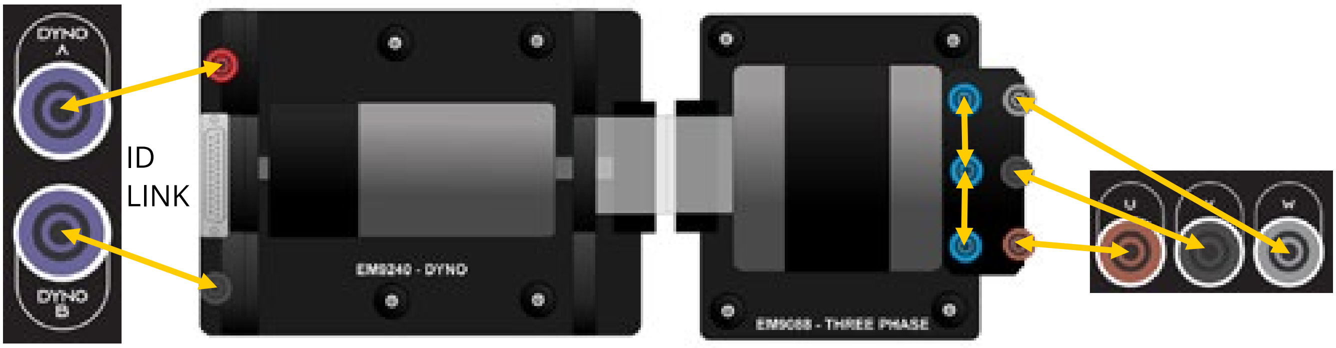
ACTIVITIES

Activity 8 - Exploring the Three-Phase Motor

Set up the arrangement shown below.



Connect all the blue motor sockets together and then connect the other motor sockets to the corresponding coloured socket on the power supply.

Set the load to 50%, the voltage to 18V, the frequency to 50Hz and press the run button.

Increase the drive frequency and notice the effect on the motor and describe what you find in the Student Handbook.
Record the maximum speed and torque.

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.

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The Brushless DC Motor

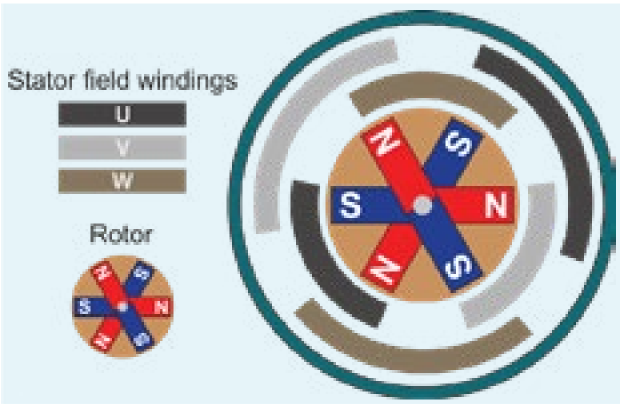
In a brushed DC motor, the stator generates a magnetic field, from either a permanent magnet or from an electromagnet. The rotor is an electromagnet that spins because the direction of current in the electromagnet is reversed periodically, using a commutator and brushes.

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.

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ACTIVITIES

Activity 9 - Investigating the Brushless DC Motor

Set up the arrangement shown below.

Set the load to 50%, the voltage to 8V, the frequency to 50Hz and press the Run button.

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 feedback cable, inform the digital drive box of the position of the rotor allowing it to adjust its driving signals accordingly.
What happens if you unplug the feedback cable while the motor is spinning? Try it!

With the feedback cable unplugged try reducing the load to 0% and the frequency to 20Hz and then ramping back up the frequency. How does the amount of load effect how high you can ramp up the frequency before the motor stalls. Does the motor stall with the feedback cable connected?

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.

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The Stepper Motor

A stepper motor is a brushless DC electric motor that rotates in a series of small and discrete angular steps. Stepper motors can therefore be set to any given step position without needing a position sensor for feedback. The step position can be changed at regular intervals to provide continuous rotation or the motor can be ordered to actively hold its position at one given step.

The disadvantages of this arrangement are:

- Due to the much higher number of positions per revolution the motor will rotate significantly slower then a corresponding brushless DC motor.

The advantages of this arrangement are:

- High repeatability and positional accuracy allowing for high precision movement in areas like robotics.
- Capable of holding in place
- There are no brushes to wear out and much less electrical noise.

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Activity 10 - Investigating the Stepper Motor

Set up the arrangement shown below.

Set the load to 50%, the voltage to 3V, the frequency to 40Hz and press the Run button.

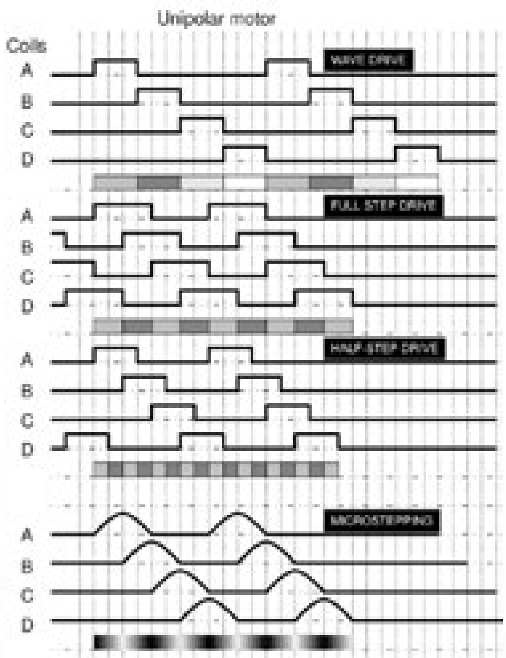
The motor now spins.

Adjust the AC supply frequency and notice the effect on motor speed.
Estimate the maximum speed possible, does this vary with voltage?

In the Student Handbook, describe your findings.

As shown there are multiple ways to control a stepper motor. Wave or Full stepping will move the motor by the full step angle specified. For example a stepper with 30 step positions will rotate by 12 degrees for each step. By controlling the motor slightly differently a half step can be achieved which essentially doubles the resolution or halves the angle.

Explain how a microstep could be achieved to further enhance the angle resolution.



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STUDENT HANDOUT

Electrical 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.

Exploring the DC Supply

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.

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

Pulse Width Modulation

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

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

Power Supply Setting	Speed (rpm)	Balance reading (g)	Balance Reading (kg)	Torque (N.m)
33%				
66%				
100%				

Power Supply Setting	Electrical power delivered to the motor	Mechanical power delivered to the load	Efficiency
33%			
66%			
100%			

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

Effects of changing the load:

____

____

____

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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.

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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.

Output Voltage vs Speed

Speed rpm	Voltage generated
200	
400	
600	
800	

Effects of changing the load:

____

____

____

Output Power vs Load

Load	Input Power	Voltage Generated	Output Current	Output Power	Efficiency
25%					
50%					
75%					
100%					

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Challenge - Lighting the Bulb

Load	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.

Shunt and series motor basics:

Coil resistance measurements:

Speed	Weight	Torque

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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Challenge - How do you Reverse the Direction of Rotation?

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

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

Attempt 3 - Reverse both sets of power supply connections.

Shunt motor performance:

DC (rotor) Supply Voltage (V)	Speed (rpm)	Maximum Load Cell reading (Nm)
25%		
50%		
75%		
100%		

Comments:

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Challenge - How do you Reverse the Direction of Rotation?

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

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

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

Shunt motor performance:

DC1 Power Supply Voltage (V)	Speed (rpm)	Torque (Nm)
25%		
50%		
75%		
100%		

Comments:

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Challenge - How do you Reverse the Direction of Rotation?

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

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

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

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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Challenge - What are the Relative Advantages and Disadvantages of Squirrel Cage and Wound-Rotor Motors?

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

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Challenge - How do you Reverse the Direction of Rotation?

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

Attempt 2 - unplug the leads from the red motor input socket and the lead from the blue motor input socket and swap them over.

Attempt 3 - unplug the leads from the red motor input socket and the lead from the yellow motor input socket and swap them over.

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

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

Frequency control	Speed (rpm)	Torque (Nm)
30Hz		
50Hz		
70Hz		
90Hz		

Comment on these result:

Comparing motor performance based on the value of capacitor:

Capacitor	Speed (rpm)	Torque (Nm)	Power Usage (W)
500uF			
200uF			

Effect of load on maximum speed:

Factors affecting stall speed and maximum torque:

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Record of Measurements Made:

Coil	Connected to Sockets	Coil Resistance (Ω)
Coil 1		
Coil 2		
Coil 2		

Effect of Frequency on Motor Performance

Effect of increasing the frequency:

____

____

Maximum speed = ... Maximum torque = ...

Possible cause of drop in speed at high frequency:

____

____

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.

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

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Effect of Frequency on Motor Performance

As the frequency is Increased

Maximum speed = ...

Effect of Removing the Feedback Signal

When the feedback cable is unplugged

Effect of Frequency on Motor Performance With Feedback Cable Disconnected

As the frequency is increased:

Effect of load - Feedback Cable Disconnected

Effect of load - Feedback Cable Connected

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Challenge - What is the Hall-efect?

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Effect of Frequency on Motor performance

As the frequency is Increased

Maximum speed = ...

Challenge - What is the Micro Stepping and How Can it be Applied

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Notes

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Notes

ELECTRICAL MACHINES FOR INSTALLATION/ MANUAL CONTROL

CP3897

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