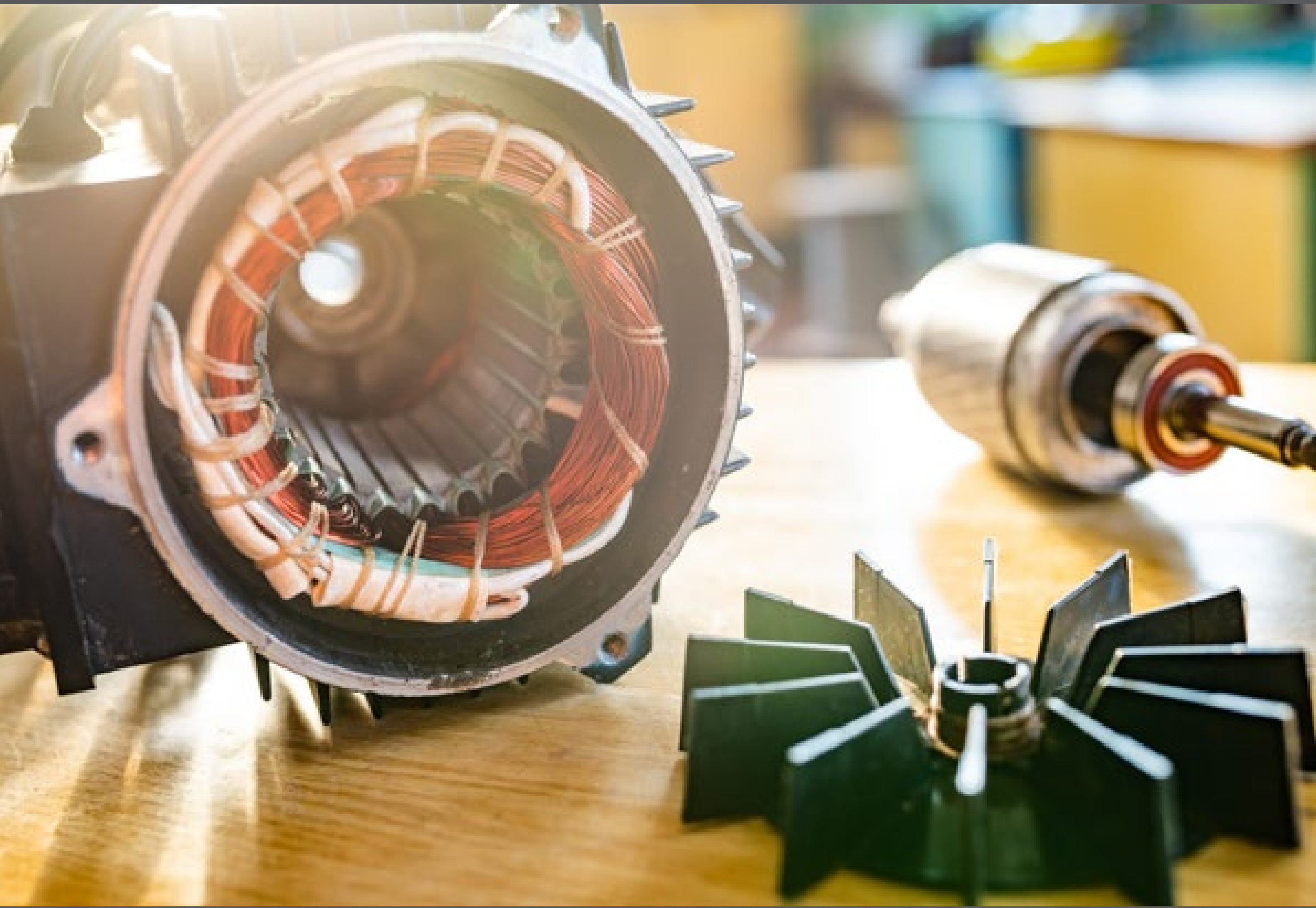
MATRIX | ELECTRICAL MACHINES



MODERN ELECTRICAL MACHINES

CP7479

Inspiring The Next Generation Of Engineers

www.matrixtsl.com

Contents

Health and Safety

Safety

During the design of this product we have paid considerable attention to the potential risks of studying electric motors. We believe that we have come up with the safest possible design. However there are still some risks that you need to be aware of. This page shows how we have considered each danger. You need to read this and make sure that your students are protected whilst using the equipment.

Electric Shock

This is minimal: the output from the control box is limited to 36V AC or DC

The dynamometer is capable of generating DC voltages. At maximum speed, around 3,000 RPM, the generated voltage is less than 30VDC.

The control unit will not generate power until a motor is plugged into the dynamometer. This prevents the use of third party motors with the system.

Physical Shock

The equipment is heavy. As with other heavy lab. equipment, if a student drops a device on their foot, it could cause considerable damage. You need to decide on the level of responsibility that students take here.

You can reduce risk by having a technician lay the equipment out on benches and ensuring that students are seated at desks whilst using the equipment.

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

Test Standards

UL 61010-1, 3rd Edition, 2012-05-11
CSA C22.2 No. 61010-1:2018

Caution:
Do not use a PC-based oscilloscope with the equipment.
Earth loop currents may flow between its earth connection and the control box's earth connection.

Key Relationships

Calculating Torque

Torque is the turning effect of a **force**.
The balance always measures force. This can be related to mass. Force and mass are linked by:
Force = mass x acceleration or **F = m x a,**
where **a** is usually the acceleration due to gravity, 9.81 m /s2.
This allows us to calculate the force pressing on a load cell, generated by the dynamometer.
Torque = force x distance from the axis of rotation. It is measured in newton-metres (Nm).
Combining these equations:
Torque, T = m x a x r
where, here, **r** is the distance of the pressure point from the centre of the machine.
Putting in the value of **r** for the dynamometer used in this kit:
Torque, T (in Nm) = load cell force (in kg) x 9.81 (m/s2) x 0.045 (m).

Calculating Power

Power is the rate at which energy is delivered and is measured in watts (W).

For a rotating body:

Mechanical power = (**2 x n x π x T**) / 60 where **n** is the speed of the motor in RPM (revolutions per minute).

For a DC motor:

Electrical power supplied to the motor = $\mathbf{V_{IN} \times I_{IN}}$
where $\mathbf{V_{IN}}$ = input voltage and $\mathbf{I_{IN}}$ = input current.

For a single phase AC motor:

Electrical power supplied to the motor = $\mathbf{V_{IN} \times I_{IN} \times \cos(\theta)}$
where $\mathbf{V_{IN}}$ is the AC rms input voltage, **IIN** is the rms input current
and cos(**θ**) is the power factor where **θ** is the phase angle between $\mathbf{V_{IN}}$ and $\mathbf{I_{IN}}$.

Key Relationships

For a three phase AC induction motor:

Electrical power supplied to the motor = 3 x electrical power supplied to one phase

line to line power = $\sqrt{3} \times V_{LL} \times I \times PF$

line to neutral power = $3 \times V_{LN} \times I \times PF$

Calculating efficiency

Efficiency (ηη) = (Mechanical power delivered / Electrical power supplied) x 100%

Calculating synchronous speed and slip

Synchronous speed in RPM = (f x 60) / (number of pairs of poles)
(Number of pairs of poles relates to how the motor windings are configured:
a 2-pole motor has one pair of poles, a 4-pole motor has two pairs of poles etc.)

Slip = ((synchronous speed - slip speed) / synchronous speed) x 100%
A three phase supply connected to the stator of an induction machine produces a magnetic field given by the formula:

$$Ns = (fs/p) \times 60$$

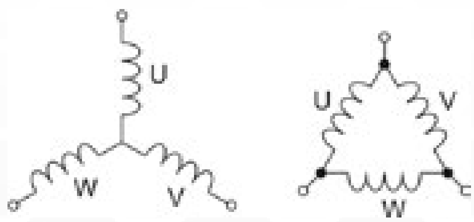
Where fs = supply frequency and p is the number of pole pairs - in our case 2.

Relationships between three phase star and delta systems

Three phase systems consist of machines connected in star and delta configuration. With U, V and W connections the line voltage is the voltage between any of U, V, W and ground. The phase voltage is the voltage between any two of U, V, W. The line and phase voltage are linked by the equation:

$$V_{line} = \mathrm{SQRT}(3) \times V_{phase}$$

Star Delta



WORKSHEETS

WORKSHEETS

Worksheet 1 – Getting Started

Motors vary hugely in size, shape and technology. Within a family of motors, for example DC motors, the characteristics of the machines are very similar - independent of their physical size and operating voltage. This section looks at setting up the equipment. Then the testing can begin.

Over to you:

1. Connect the digital drive box to the mains power using the IEC connector. The graphical display should light up.
2. Connect the dynamometer to the control unit with the 25 way D-type lead.
3. Make sure that the software applications and control unit USB driver are correctly installed.

When the control box is **not** connected to the PC using the USB lead, the box is in manual mode - the graphical display on the front panel determine the control box parameters.

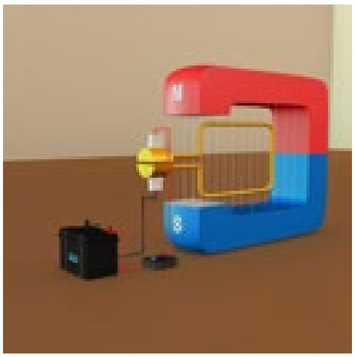
Now you are ready to test the set up.

Set up a Machine Test

1. Line up the Dynomometer in the shorter grooves of the main base. It should slide in easily. You may have to undo the knurled nuts on the motor bed.
2. Repeat for the DC motor on the other side of the main base.
3. Make sure that the yellow rubber 'spider' which buffers the dynamometer and motor under test is in place.
4. Make sure the motor and dynamometer couplings are aligned in the 'spider' before pushing the motor home.
5. As you push home the DC motor into the dynamometer coupling the specific motor should appear on the main screen of the graphical display.
6. Tighten the knurled lock nuts to make sure that the dynamometer and motor are both secured in place.
7. Wire up the 4mm terminals on the dyno and motor modules to the digital drive box as shown in the diagram on the next page.

You are now ready to start experimenting with the equipment, in manual mode.

Worksheet 2 - Understanding Torque and Mass



DC motors use a permanent magnet in the stator and direct current powered windings in the rotor. A commutator is used to reverse the direction of the current in the rotor to maintain the force on it as the motor turns. The graphic shows a very simple commutator. In practice, the ring has several splits in it, allowing several rotor circuits to provide more continuous torque.

Over to you:

1. Using the graphical display press the Stats button and then press the Grams button to put the load cell into grams mode. Press the back button to return to the main screen.
2. Press the Control button to get to the motor control sliders.
3. Set the Dyno Load to 50%.
4. Move the Voltage 1 slider to roughly half way and press the Run button to start the motor spinning. Press the Back button to return to the main screen.
5. Take note of the Dyno speed and measured weight in grams.
6. Return to the Control screen and increase the voltage slightly. Back on the home screen measure and record the new speed and applied weight.
7. Referring to the 'Key Relationships' (page 4,) use the readings to calculate the torque for the two settings and record your answers. Note that the calculation requires weight in kg so divide your recorded weight by 1000.

Speed	Weight	Torque

So What?

To change the direction of a DC motor you reverse the electrical connections. The dynamometer can rotate in either direction. The weight produced is negative when rotating counter-clockwise and positive when rotating clockwise. When calculating Torque in NM we automatically do the calculation from a weight to a positive Torque.

Worksheet 3 - Understanding the DC Power Supply

The permanent magnets occupy a small space in a DC motor compared to the space needed for the windings in motors where the magnetic field is supplied by current-carrying coils. As a result, DC motors can be physically quite small for their power rating. The food blender in the photograph uses a DC motor.

A motor can be controlled by varying the DC voltage, and hence the power, supplied to it.

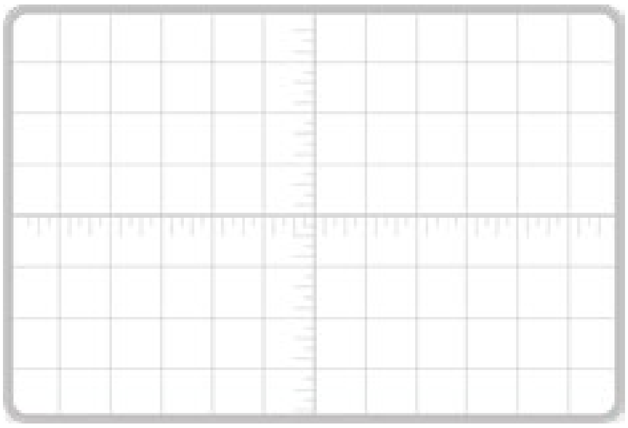
Over to you:

1. Adjust the voltage control so that it is in about a quarter way along the slider.
2. Use an external oscilloscope, not a PC-based one, to look at the signal from DC1.
3. Use the upper graph opposite to sketch the waveform of this signal.
4. Adjust the voltage control to about three-quarters of the way along the slider and draw the resulting waveform on the lower graph.

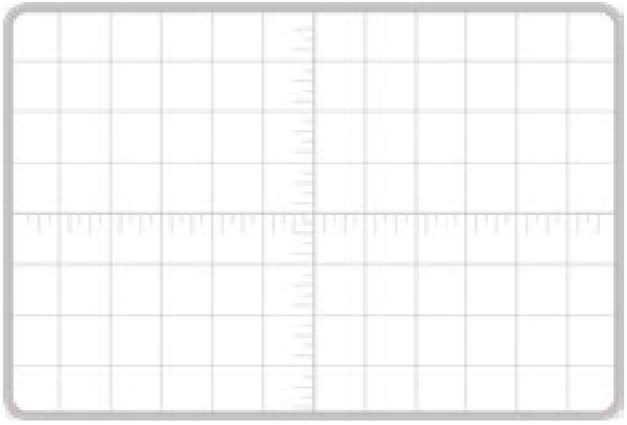
So what?

Modern DC motor power supplies do not vary the output in an analogue fashion, but use pulse width modulation or PWM. In this, the mark : space ratio of the output is varied. In the control unit, a bank of FET's deliver a PWM signal generated by a controller. This can be used with loads such as motors to enable analogue control over the motor.

Do not use a PCbased oscilloscope.



DC1 - onequarter max.

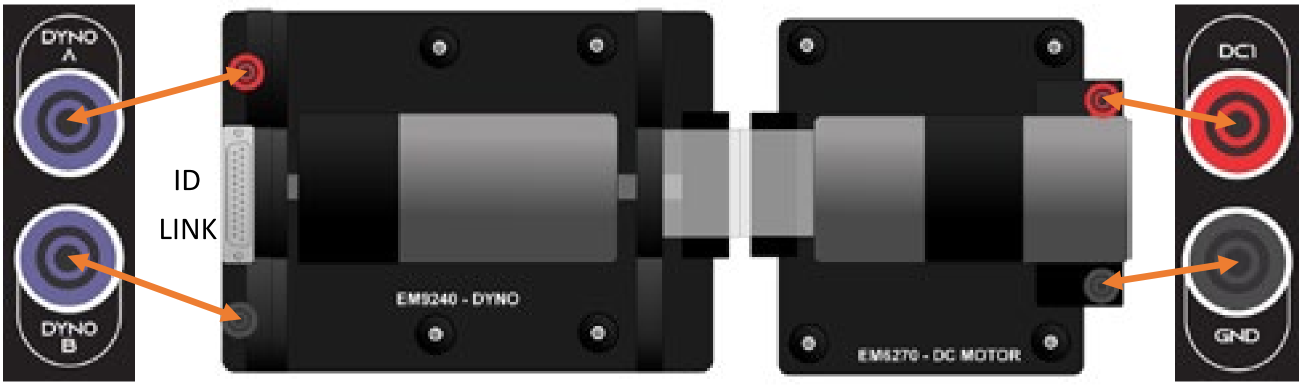


DC1 - threequarters max.

WORKSHEETS

Worksheet 4 - DC Motor Characteristics 1

Different types of motor have different characteristics, such as top speed, torque at different speeds , voltage and current ratings, power output and efficiency.
Photo: these tiny DC motors are used in small handheld devices like toys.

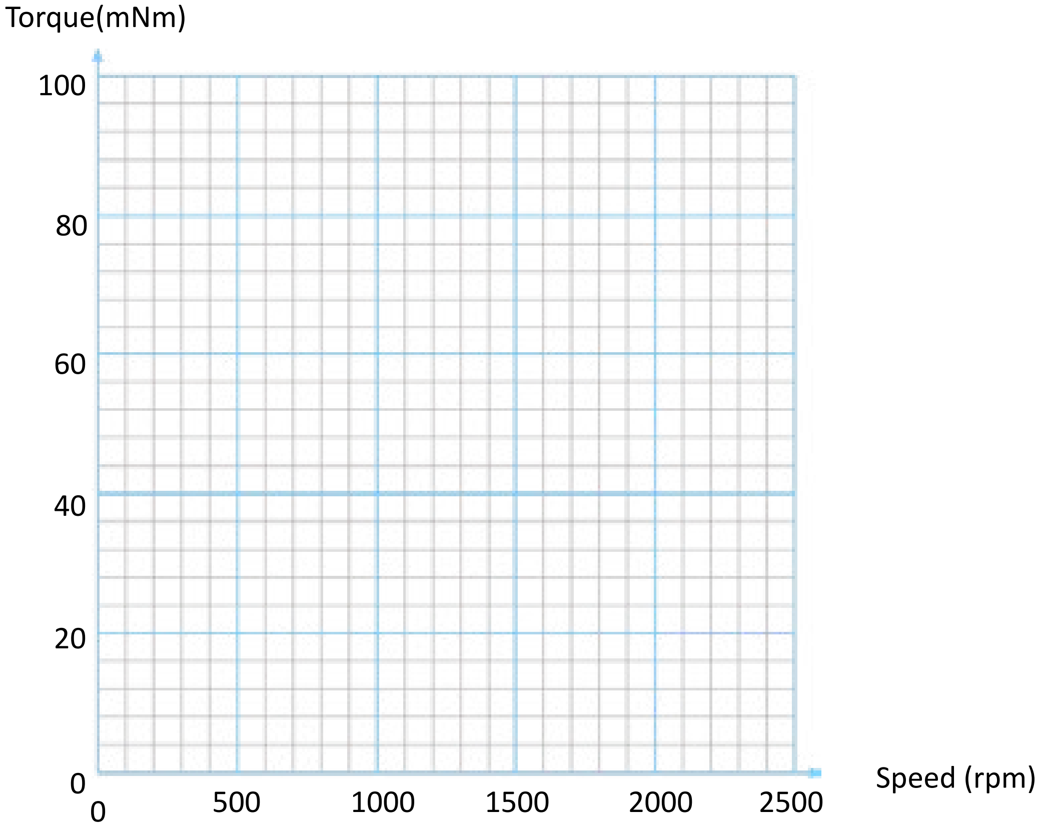


Over to you:

1. Set up the circuit shown above. Connect the DC motor to the control unit's DC1 power supply V+ and 0V terminals.
2. Connect the dynamometer to the load terminals on the control unit to set a load across the dynamometer.
3. Connect the control box to your computer using the USB lead.
4. On the computer, load the ElectricalMachines program. Press the 'PLAY' style button on the top left and then click on the 'RUN' button.
5. Set the DC output to around 30%.
6. Give the DC motor a small load of around 50% on the dynamometer.
7. Investigate the effect of varying the PWM duty between 30% and 100%, taking six readings across that range. In the table on the next page record the speed, torque, and Driver Power coming from the power supply.
8. Use the information in the 'Key Relationships' section on page 4 to calculate the mechanical power delivered to the dynamometer.
9. In addition, calculate the efficiency of the motor at each of the six settings .
10. On the graph paper provided, use these readings to plot a graph to show how the torque (y-axis) varies with speed (x-axis).

Note that for repeated calculations you will find it easier to use a spreadsheet.

Voltage (V)	Speed (RPM)	Torque (Nm)	Electrical Power (W)	Torque (Nm)	Torque (Nm)
30%					
40%					
50%					
60%					
70%					
80%					
90%					
100%					



Variation of torque with speed

So What?

Each motor has characteristics that make it suitable for particular applications in industry. In this learning package, you meet a variety of motor types and learn to appreciate their characteristics.

WORKSHEETS

Worksheet 4 - DC Motor Characteristics 1

Over to you

Describe some of the characteristics of the DC motor.

What speeds give maximum and minimum torque?

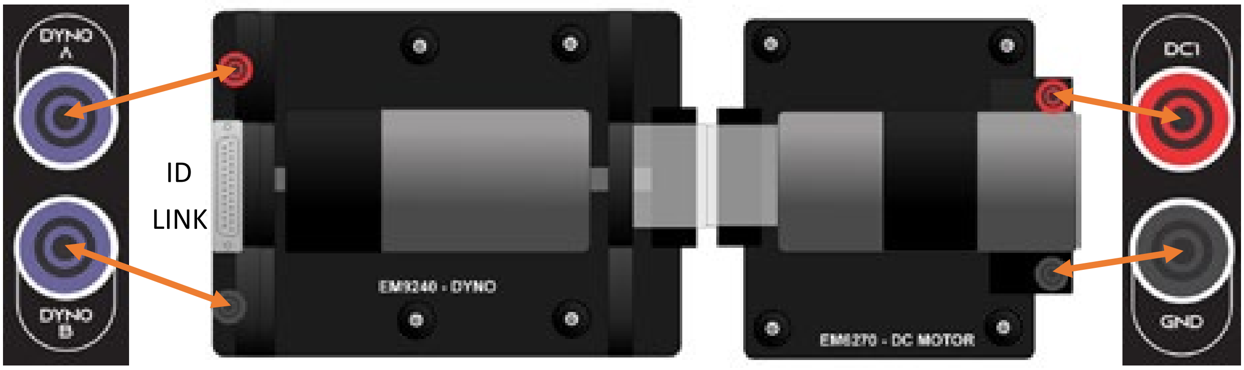
At what speed is it most efficient?

When would you use a DC motor as opposed to a different type?

WORKSHEETS

Worksheet 5 - DC Motor Characteristics 2

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.



Over to you

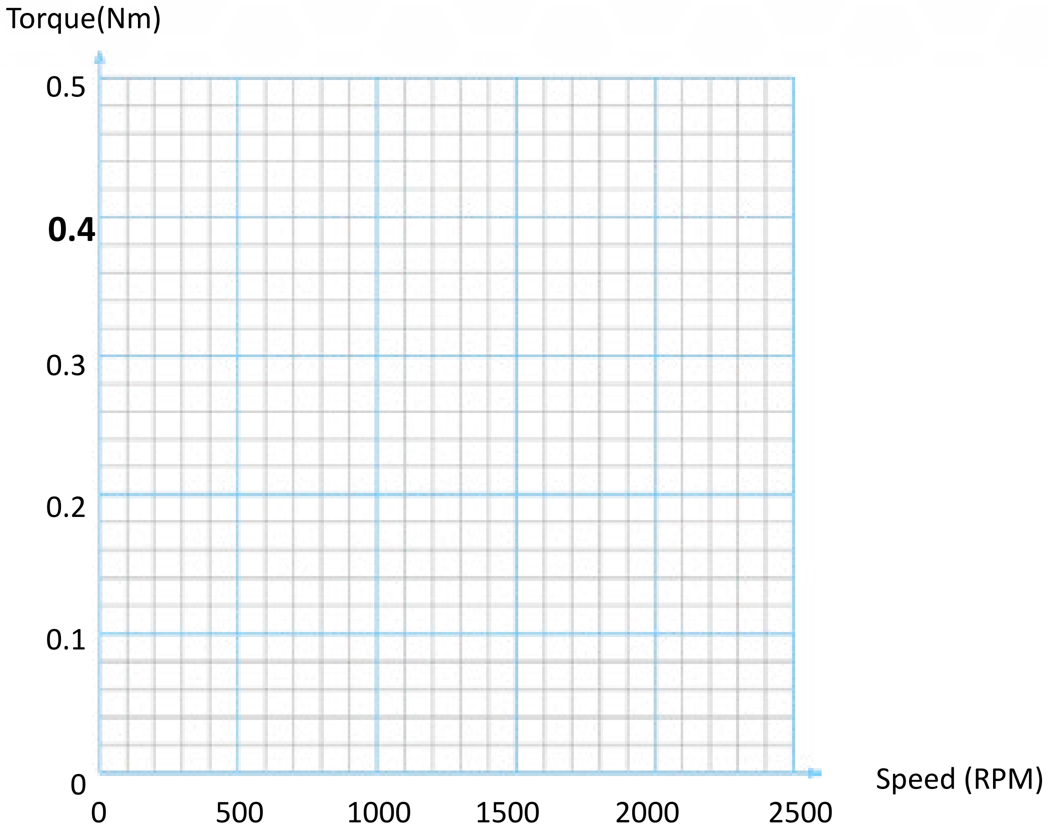
1. Set up the circuit , connecting the DC motor to the control unit's DC1 power supply
2. Connect the dynamometer to the load terminals on the control unit to set a load across the dynamometer.
3. Connect the control box to the computer using the USB lead.
4. On the computer, run the program Electrical Machines.
5. Set the PWM DC output to around 40%.
6. Press the 'Sweep' button to run an automatic speed / torque log.
7. Repeat step 6 for DC outputs of 50%, 60%, 70%, 80% and 90%
8. The program logs the results into an Excel file. The file is stored with todays date in the 'Logs' subdirectory.When the sequence is finished, load the results into Excel and use it to plot accurate speed torque graphs of the motor.
9. On the next page, sketch the results.

So What ?

When looking at a motor's specification to check its suitability for a particular application, you often see a family of graphs showing its performance for different driving conditions. Understanding this information helps you to make the right choice. The settings for the sweep are available in the software properties on the right hand side of the screen under Sweep Parameters.

WORKSHEETS

Worksheet 5 – DC Motor Charcteristics 2

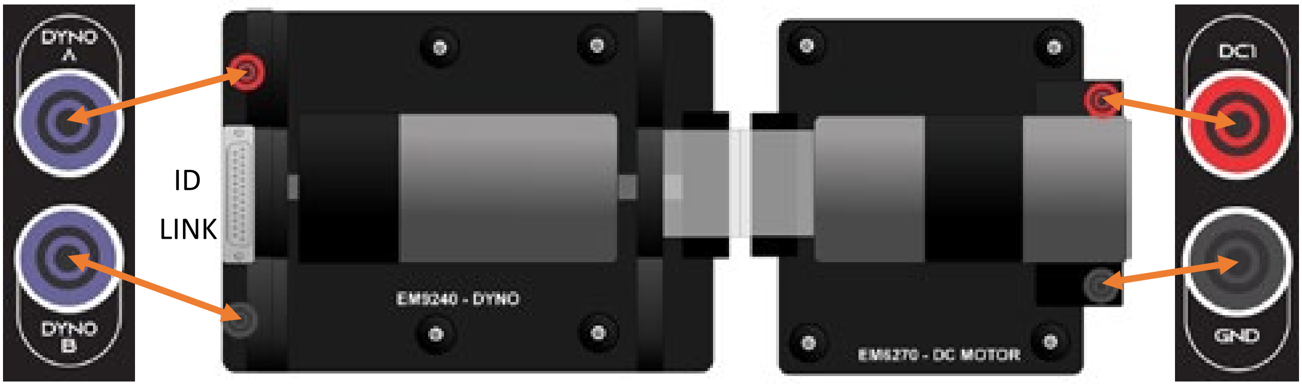


Effect of motor speed on torque for different values of DC power supply voltages

WORKSHEETS

Worksheet 6 - Permanent Magnet Generator (Dynamo)

The electrical machine in the dynamometer has exactly the same characteristics as the DC motor. The only difference is physical - the drive shaft is longer. The photograph shows a bicycle dynamo, used to power electric lights on the front and rear of the bike.



This worksheet examines the properties of a permanent magnet generator or 'dynamo', using the dynamo found in the dynamometer.

Over to you

1. Set up the system shown in the diagram.
2. On your PC, run the program Electrical Machines.
3. Set the dynamometer load to 80%.
4. Use the program to take measurements of power out, speed, and torque generated by the dynamo for DC motor driving voltages of 40%, 50%, 60%, 70%, 80% and 90%
5. Use the formulae in the 'Key Relationships' section on page 4 to work out the mechanical power delivered into the dynamometer.
6. Calculate the efficiency of the conversion from mechanical to electrical power in the dynamometer.
7. Use the results to plot a graph, using the axes on the next page.

You may find it easier to use a spreadsheet to do the calculations.

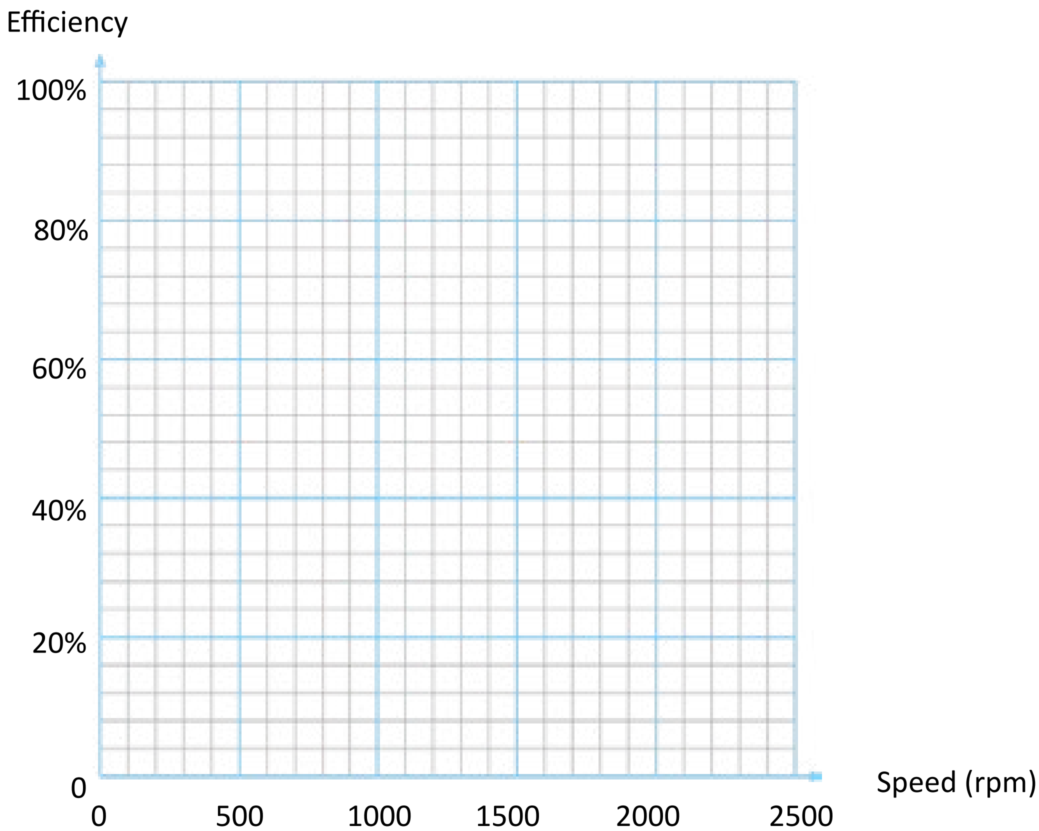
So What ?

The efficiency of an electrical machine changes with its speed. Choosing the right combination of machine and gearbox for an application will help to get optimal efficiency.

WORKSHEETS

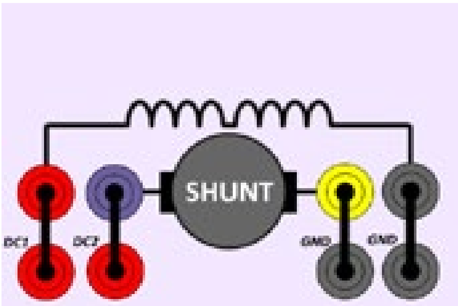
Worksheet 6 - Permanent Magnet Generator (Dynamo)

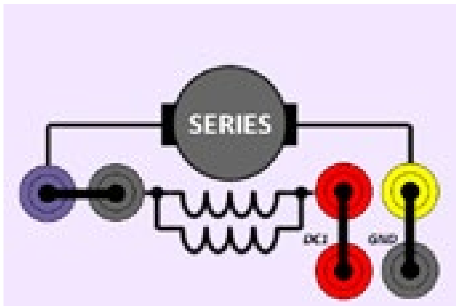
DC Motor Drive	Speed	Torque	Mechanical Power	Dyno Power	Dyno Efficiency
40%					
50%					
60%					
70%					
80%					
90%					



Variation of efficiency with speed for a dynamo with a load of 80%.

Wound stator DC motors are often configured as either **shunt** wound or **series** wound. The separate connections for the field windings of the stator and rotor / armature allow us to control the current in both parts of the motor separately, in order to examine the motor's behaviour. The photograph shows an old shunt wound motor.





Red and black terminals are for the stator windings, yellow and purple terminals for the rotor windings.

Over to you:

1. With both the series and shunt motors disconnected from the test rig, use a digital multimeter to measure the resistance of the stator windings on both the shunt and series motors. (Black and Red terminals).
2. Use the Ohm's law formula, I= V/R, to calculate the theoretical field currents when the field windings (Red & Black) are connected to a 12V DC supply.
3. Repeat the resistance measurement for the rotor windings (Purple & Yellow terminals)
4. Record your results in the table opposite.
5. In practice, you get different values of current which we discuss below.

Stator Windings

Motor	Resistance in Ω	Current in A
Shunt		
Series		

Rotor Windings

Motor	Resistance in Ω	Current in A
Shunt		
Series		

WORKSHEETS

Worksheet 7 - Shunt and Series Motor Basics

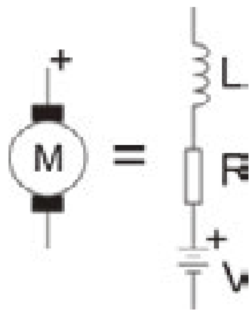
So What?

Electrical machines are made up of multiple windings. When DC flows through them, their electrical characteristics can be predicted using the Ohm's law formula. However, once the electrical machine is running the rotating magnetic fields in the machine alter their behaviour drastically.

The equivalent circuit of the machine then becomes more complicated. In particular, the rotating magnetic components in the machine induce an electromagnetic force (EMF) which acts to oppose the flow of current in the windings. You can see the equivalent circuit below.

Understanding how to calculate this opposing EMF is outside the scope of this learning package - but you need to be aware that it exists.

The reverse EMF increases as speed increases. When a machine stalls, therefore, the reverse EMF is reduced. The current flowing then increases significantly, increasing the risk of burning out the motor.



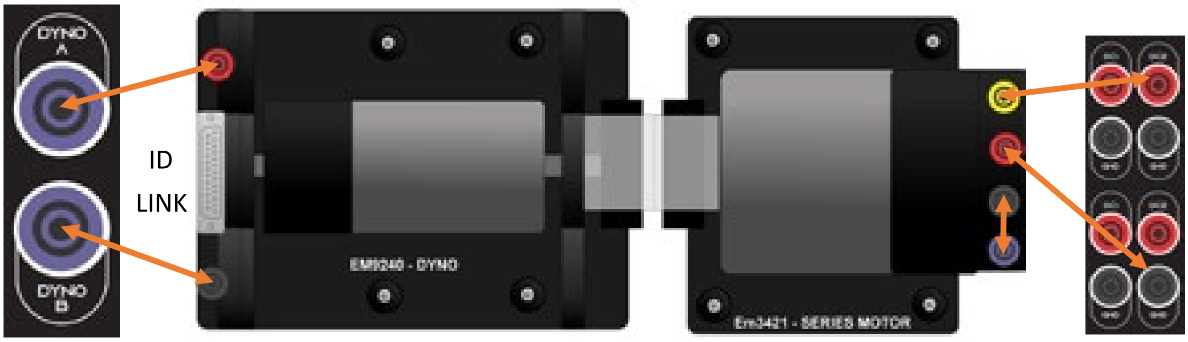
Equivalent circuit of a simple DC machine.

Over to you:

1. Connect the multimeter to the rotor winding of the Shunt motor on the ohmmeter setting.
2. Slowly turn the motor shaft. Explain what you see on the meter.

Shunt wound

Series wound



With all wound-stator DC motors, you swap over the connections to either the stator or rotor windings to make the motor rotate in the opposite direction. Reversing the voltage to both sets of windings keeps the motor rotating in the same direction, as both fields are reversed.

Over to you:

1. Set up the shunt motor as in the top diagram.
2. On your PC, load the ElectricalMachines program. Set the output on DC1 (the field coils) to 24V. Set the output on DC2 (the rotor) to around 16V and press 'RUN'.
3. Increase DC2 in steps of 2V up to 24V. In the table on the next page, record the voltages and currents at each stage.
4. Now, change to the series motor and wire it up as in the lower diagram.
5. Set the drive mode to DC.
6. Set the output on DC1 to 2V and press RUN.
7. Increase DC1 in steps of 2V up to 8V. Again, record the output voltages and currents each time.

So What?

This experiment shows that the speeds of the series and shunt motors are very different for similar voltage inputs .

Worksheet 7 - Shunt and Series Motor Basics

Shunt Motor

DC1 V	DC2 V	I1 in A	I2 in A	Speed in RPM
24	16			
24	18			
24	20			
24	22			
24	24			

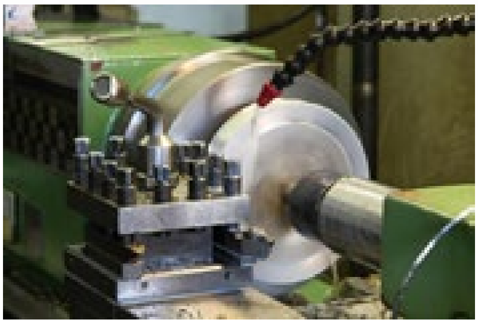
Series Motor

DC1 V	I1 in A	Speed in RPM
2		
4		
6		
8		

So What?

The speed of the Series motor is very high. The Control unit is designed to limit the speed of the motor by reducing the voltage available to it. Above this limit voltage the Dynamometer produces voltages that can be dangerous.

Worksheet 8 - Shunt-Wound Motor Charcateristics



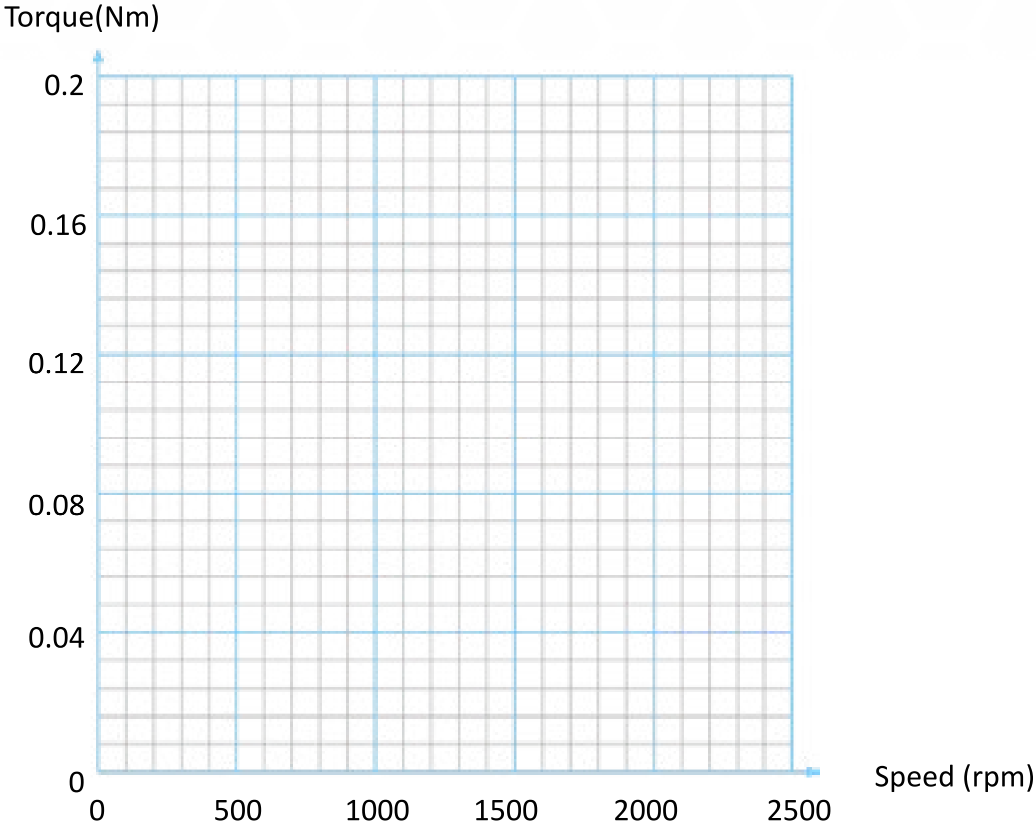
Speed control is an important element of electro - mechanical system design. Some motors are better than others at self regulating speed. The shunt motor is really good at speed regulation and for this reason they are often used in devices like lathes, which need to run at a constant speed.

Over to you:

1. Set up the shunt motor as shown above.
2. On your PC, run the ElectricalMachines pro-gram.
3. Set the DC1 output to 24V to power the stator winding and the DC2 output to around 12V for the rotor.
4. Run the program and press 'Sweep' to take an automatic set of readings for a range of dyna-mometer loads.
5. Repeat steps 4 for rotor DC outputs of 14V, 16V, 18V and 20V.
6. When the sequence has finished load the results into Excel and use Excel to plot a graph of speed and torque.
7. On the next page, use the axes provided to sketch the results.

WORKSHEETS

Worksheet 8 - Shunt-Wound Motor Charcateristics



The effect of speed on torque for different values of stator coil voltage

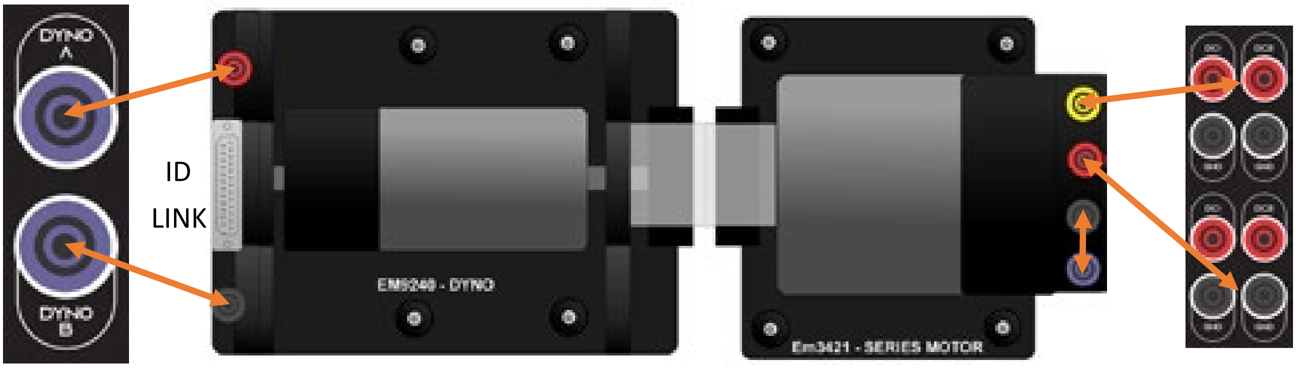
Over to you:

1. With the same equipment set up, load the ElectricalMachines program.
2. Run the motor and set the DC output for the rotor to 12V and the output for the stator winding to around 12V, set the load to 50%.
3. Click the capture button to display the current and voltages of the motor.
4. Complete the table to show speed, output power, dynamometer power and efficiency. Efficiency being electrical power out to the motor vs electrical power in from the dyno.

Sator Voltage DC1 (V)	Rotor Voltage DC2 (V)	Power Out-To Motor (W)	Speed (rpm)	Efficiency (%)
12V	12V			
18V	18V			

Worksheet 9 - Series Wound Motor Characteristics

A series-wound motor has the highest torque on start-up of any motor. However, its speed varies as the load varies. It is ideally suited to applications such as winches and cranes where the initially high torque is important. The photograph shows a typical wound rotor with split ring commutator.

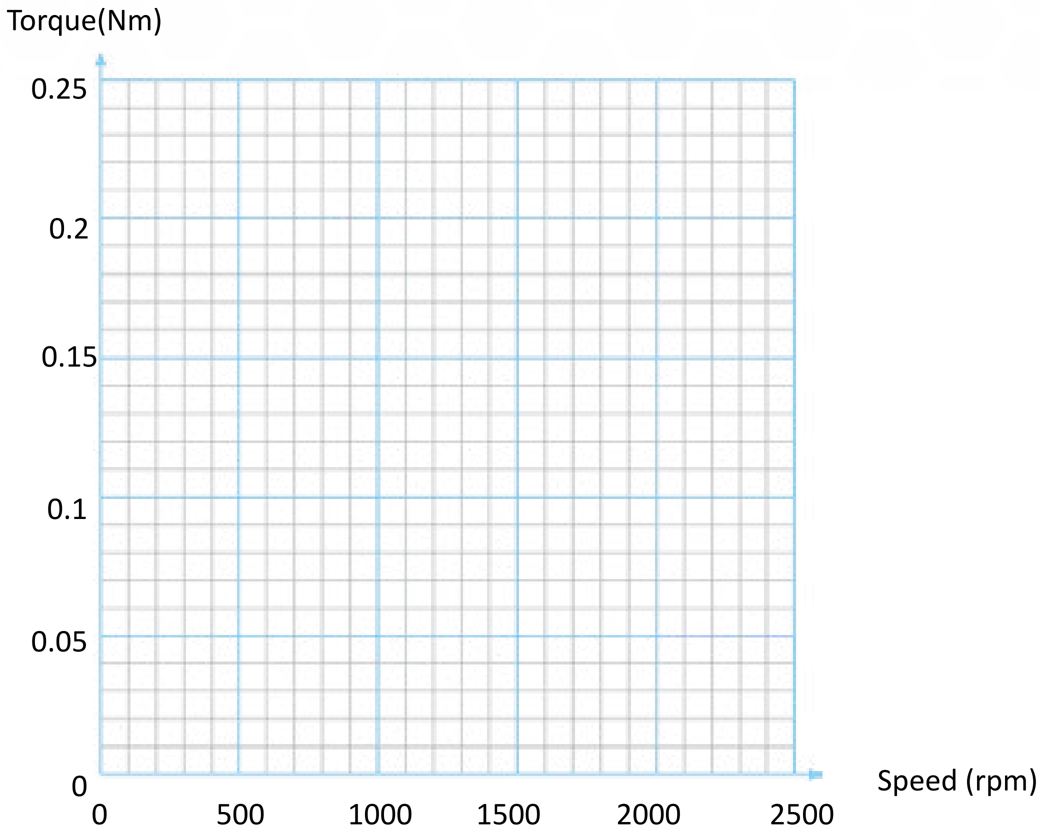


Over to you:

1. Set up the series motor as shown above.
2. On your PC, run the ElectricalMachines program.
3. Set the DC output to around 3V.
4. Press 'Sweep' to take an automatic set of readings for a range of dynamometer loads.
5. Repeat steps for DC outputs of 4V, 5V, 6V and 7V
6. When the sequence has finished load the results into Excel and use Excel to plot a graph of speed vs torque.
7. On the next page sketch graphs to show traces for all output voltages.

WORKSHEETS

Worksheet 9 - Series Wound Motor Characteristics



The effect of speed on torque for different values of DC output voltage.

Over to you:

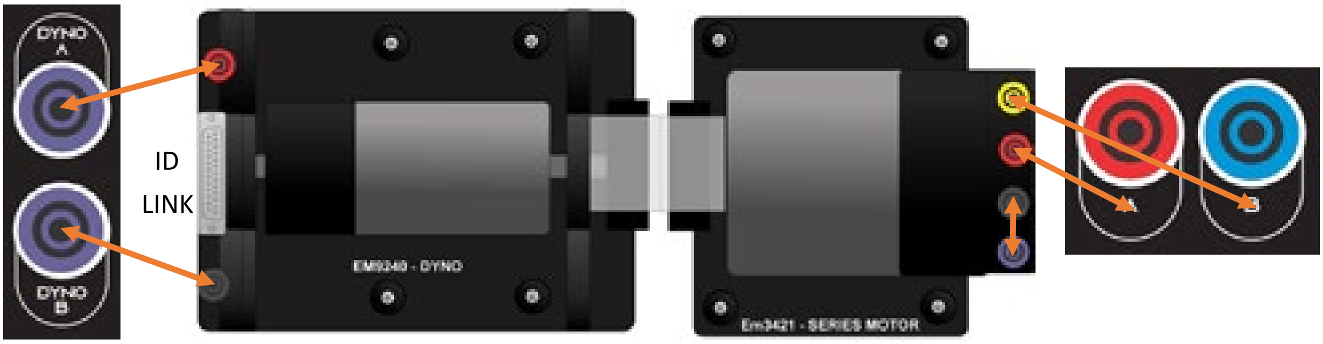
1. With the same equipment set up, load the ElectricalMachines program.
2. Run the program and set the DC1 output to around 4V and the load to 50%.
3. Click the capture button to display the current and voltages of the motor.
4. Complete the table to show speed, output power, dynamometer power and efficiency. Efficiency being electrical power out to the motor vs electrical power in from the dyno.

Sator Voltage DC1 (V)	Power Out-To Motor (W)	Speed (rpm)	Efficiency (%)
4V			
6V			

WORKSHEETS

Worksheet 10 - Universal Motor

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. Typical applications include planes, routers, sanders, grinders, saws etc.



This worksheet examines the AC behaviour of the series-wound motor.

Over to you:

1. Set up the series motor as shown above.
2. On your PC, load the ElectricalMachines program.
3. Press the mode button to put the motor into AC mode
4. Set the Driver voltage to around 14V.
5. With the output frequency set at 30Hz, run the program and use the 'Sweep' function to take an automatic set of readings over a range of dynamometer loads.
6. When the sequence has finished, use Excel to plot a graph of speed vs torque.
7. Repeat this procedure for frequencies of 40 and 50Hz.

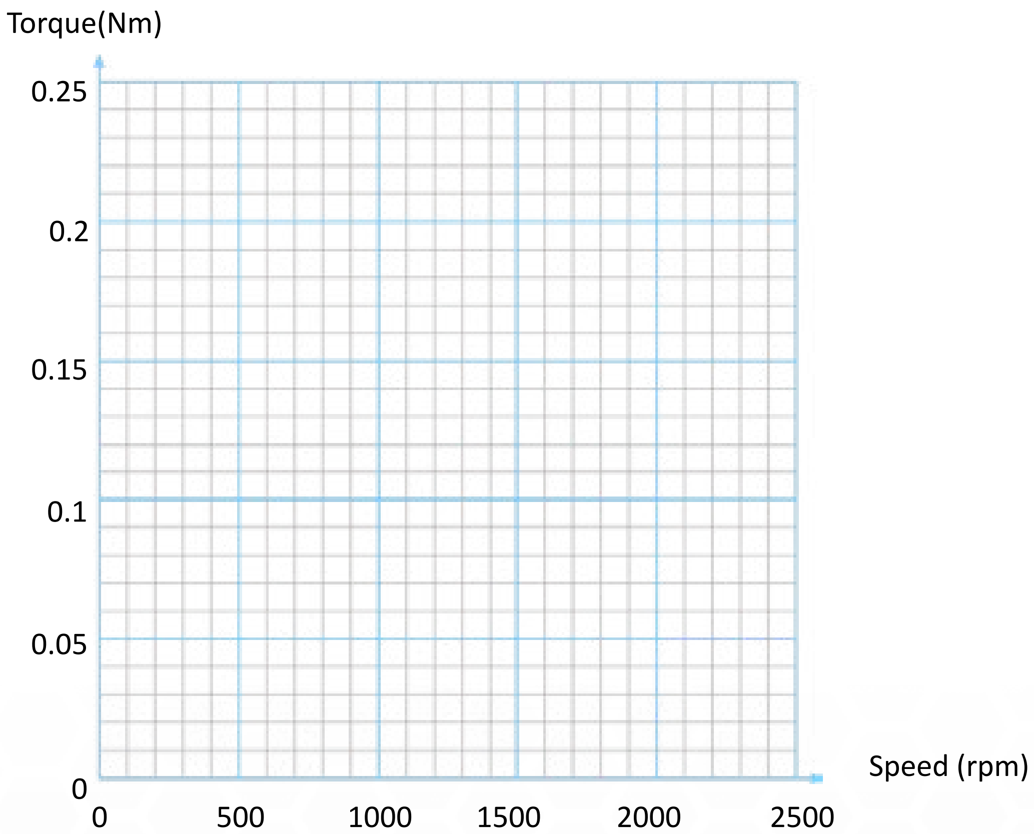
WORKSHEETS

Worksheet 10 - Universal Motor

Sketch graphs to show traces for all frequencies. Compare AC and DC properties of the universal motor.

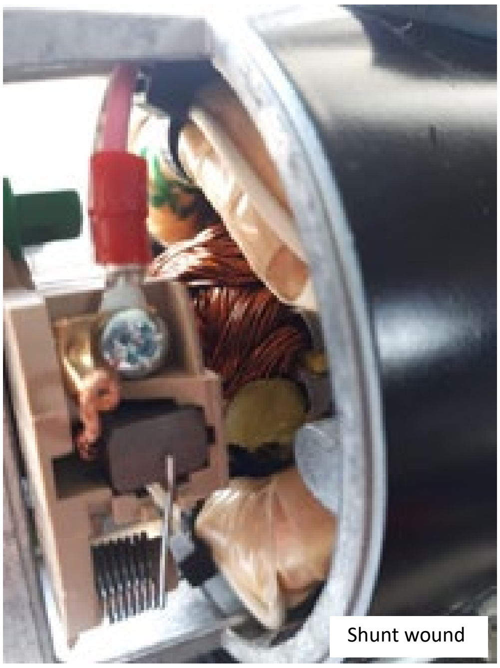
How do you change direction of motion?

Set the frequency to 20Hz - what happens?



The effect of speed on torque for different values of output frequency.

Worksheet 11 - Comparing Shunt and Series Motors



Over to you:

1. Comparing the photographs, what is the difference between the rotor windings?

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2. Earlier you measured the resistance of the shunt and series motor windings Do these photographs corroborate your findings?

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3. Research the term 'separately excited'. What does this mean?

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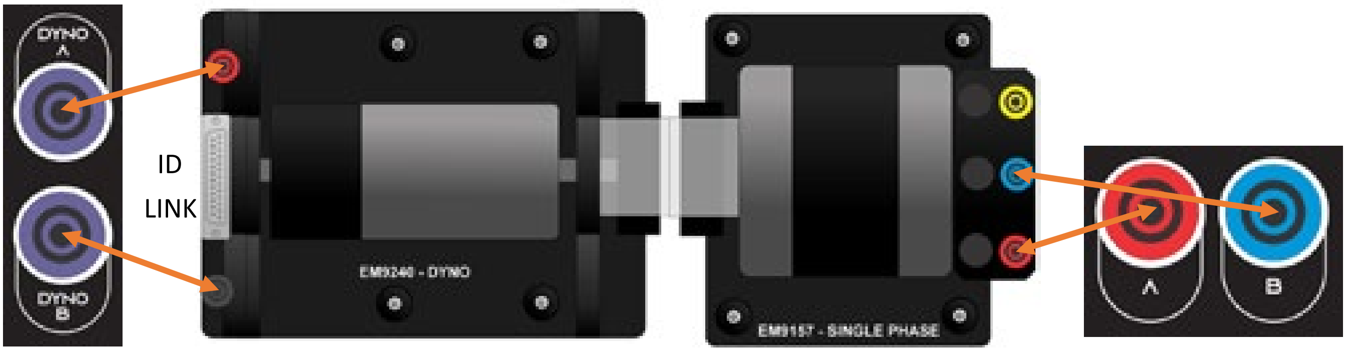
WORKSHEETS

Worksheet 12 - Single Phase Induction Motor

One problem with series and shunt motors is that they use 'brushes' in the rotor circuit. These wear out and need replacing from time to time. Induction motors have no brushes and so require less main -tenance. The photograph shows an induction motor and its fitted gearbox.



Over to you:

1. Set up the single phase induction motor as shown in the diagram above.
2. On your PC run the ElectricalMachines program.
3. Connect the windings to terminals A and B. When the software application is running, these give a single phase output signal.
4. However, you will find that the motor does not start. Oh dear!

So What?

You have just discovered a problem with the induction motor - it needs something to get it started.

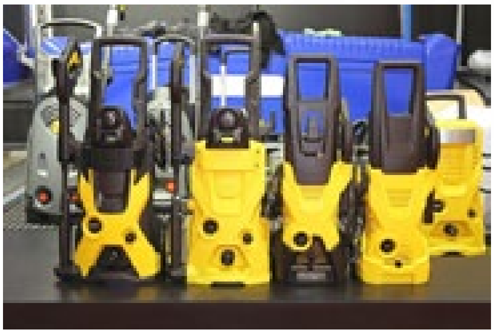
When the induction motor is powered, a little physical nudge in one direction often starts it. Unfortunately, in this rig, you cannot touch the shaft, for safety reasons.

Another problem is that it does not matter which direction you nudge the motor in - it can rotate either way.

Next we will look at how to make the system more predictable.

WORKSHEETS

Worksheet 13 - Single Phase Induction Motor - Cap Start



In many situations, engineers have a choice over which type of motors to use. For simple AC appli - cations, like pressure washers, they can use either an induction motor or a series motor. The choice is governed by the electromechanical properties of the motor - the cost, size and longterm reliability required.

Over to you:

1. Set up the single phase induction motor as shown in the diagram above.
2. On your PC load ElectricalMachines program.
3. Use settings: 20V, 50Hz, 500uF, AC Mode.
4. Once the motor is running select 200uF.
5. Use the ‘Sweep’ function to take an automatic set of readings over a range of dynamometer loads.
6. When the sequence has finished, use Excel to plot a graph of speed vs torque. Repeat this procedure for frequencies of 60, 70, 80Hz.
7. On the next page, sketch graphs to show traces for all frequencies.

So What?

How do you change direction of rotation?

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How do the speed / torque curves compare to the other motors you have looked at?

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What are the advantages and disadvantages of DC and AC machines?

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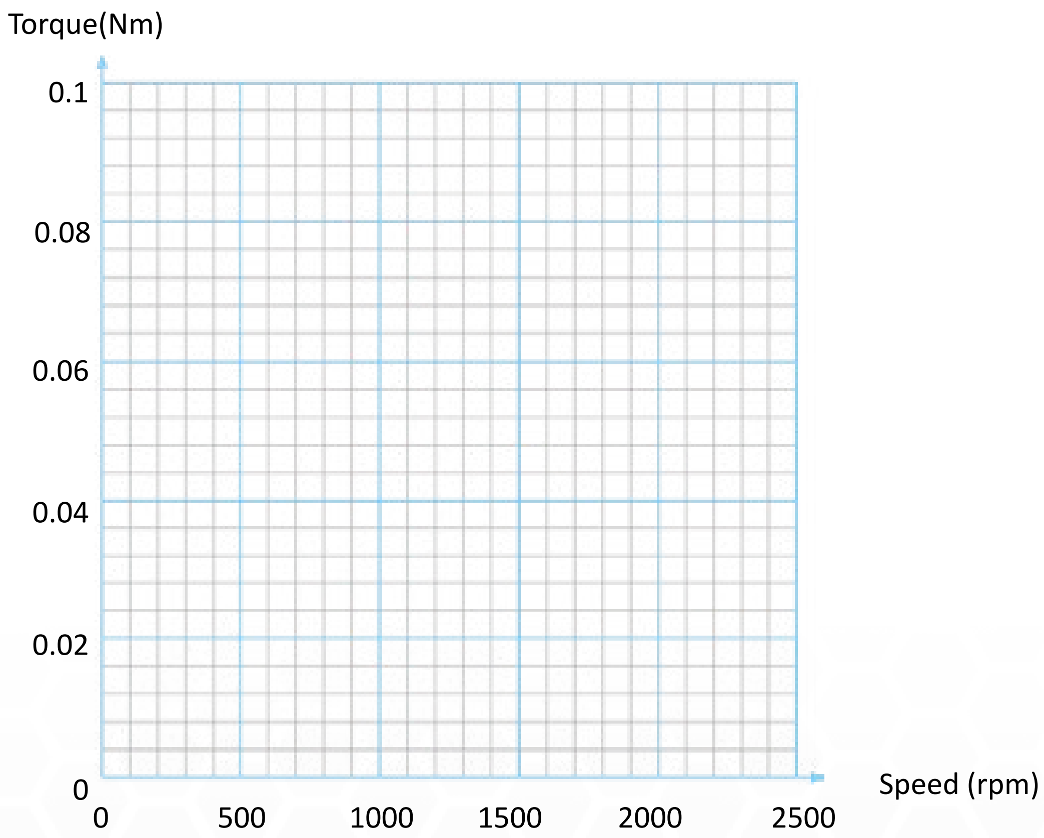


The effect of speed on torque for different values of output frequency.

Worksheet 14 - Phase Shift in Inductionn Motors

One of the drawbacks of the single-phase induction motor is that it needs an external capacitor to make it operate. The induction motor is very reliable because it has no brushes. However the capacitor used to start the motor must be switched out of the circuit once the motor is running.This needs either additional electronic switching circuitry or a centrifugal mechanical switch.

Over to you:

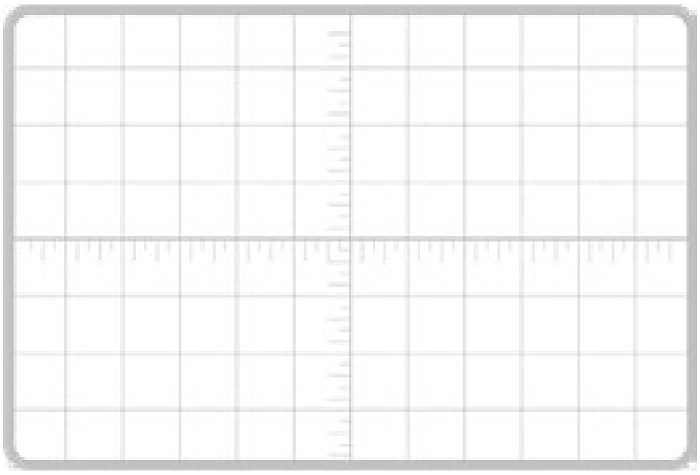
1. Set up the single-phase induction motor as shown in the diagram. This experiment uses the oscilloscope built into the control unit to look at the phase shifts in the windings caused by the capacitor value.
2. On your PC run Electrical Machines program.
3. Use settings: 20V, 50Hz, 500uF, AC Mode, 50% load and set the motor running.
4. Use the Capture button to collect the voltage and current waveforms. Ensure the Show Capacitor property is set to Yes.
5. Sketch what you see on oscilloscope grid on the next page .
6. Change the capacitor value and record the values in the table.

So What?

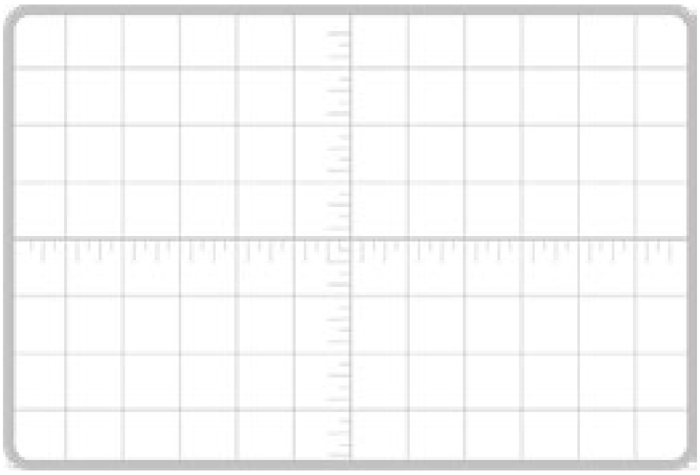
Without a capacitor, the motor would not start.In some systems - the motor has two capacitors, one value for starting and one for running. The phase shift for each is different. For the same voltage, how much more efficient is the Run 200uF capacitor than the Start 500uF capacitor for each frequency?

Investigate why a different value is needed for 'Start' and 'Run'.

Voltage



Current



Capacitance Value	Power Out-To Motor (W)	Speed (RPM)	Torque NM)	Phase Difference (deg)
500uF				
400uF				
300uF				
200uF				
100uF				

WORKSHEETS

Worksheet 15 - Variable Frequency Drive Stratergies

In factories, induction motors are often used at fixed speeds, dictated by the 50 or 60Hz mains supply. Where speed control is needed it requires a change in strategy. This photograph shows variable frequency drives used in a mineral water plant.

Over to you:

1. Set up the single-phase induction motor as shown in the diagram above.
2. On your PC run ElectricalMachines program.
3. Use settings: 20V, 50Hz, 500uF, DC Mode and set the motor running.
4. Click the capture button to collect the voltage and current waveforms
5. Change the DC mode to AC mode and click the capture button again.
6. On the next page, sketch the voltage wave-forms of the single-phase AC output A and B for the AC and DC modes.

So What?

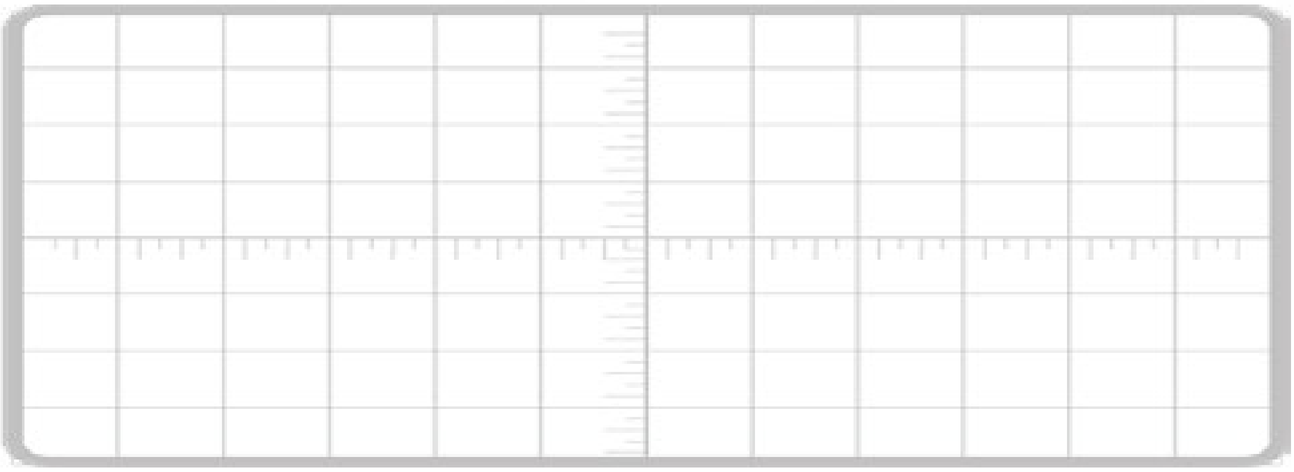
This exercise illustrates how PWM (Pulse Width Modulation) is used to create a waveform with variable pulse width but constant period, the period of the fundamental waveform.

When connected the motor drive coils act as a low-pass filter for AC signals, smoothing out the waveform. If you plotted the current through the windings it would be much more like a traditional sine wave.

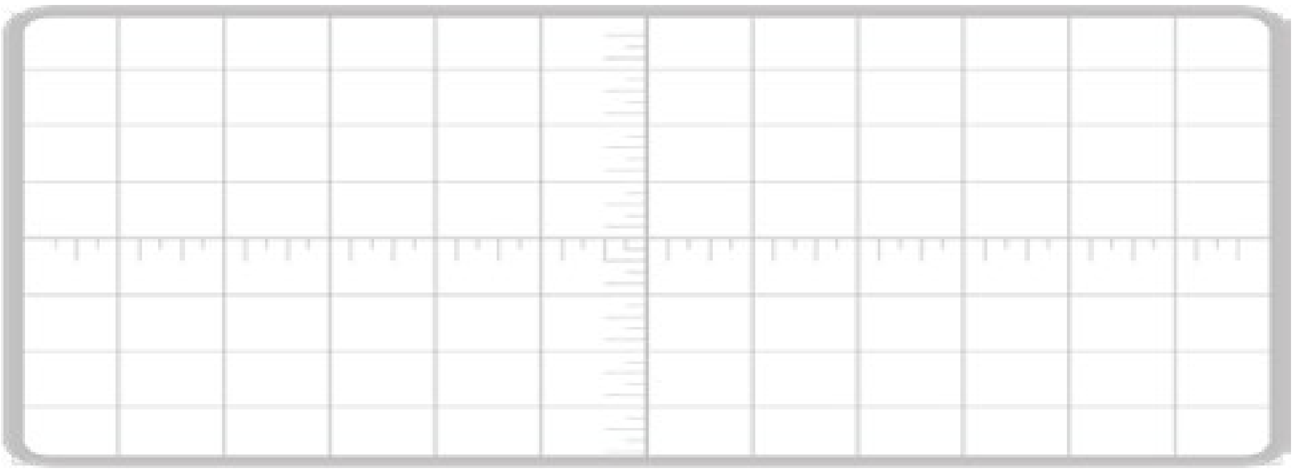
WORKSHEETS

Worksheet 15 - Variable Frequency Drive Stratergies

Digital drive DC Waveforms



Pseudo sine drive AC Waveforms



Over to you:

With the output mode set to DC and Dynamometer load set to 50%, measure and record in the table below the speed, torque, output power and input power, for frequencies of 50, 60 and 70Hz.

Digital drive DC Waveforms

AC Drive Frequency	Speed in rpm	Torque Nm	Electrical power w	Mechannical power w	Efficiency %
50Hz					
60Hz					
70Hz					

Over to you:

With the output mode set to AC and Dynamometer load set to 50%, measure and record in the table below the speed, torque, output power and input power, for frequencies of 50, 60 and 70Hz.

Pseudo sine drive AC Waveforms

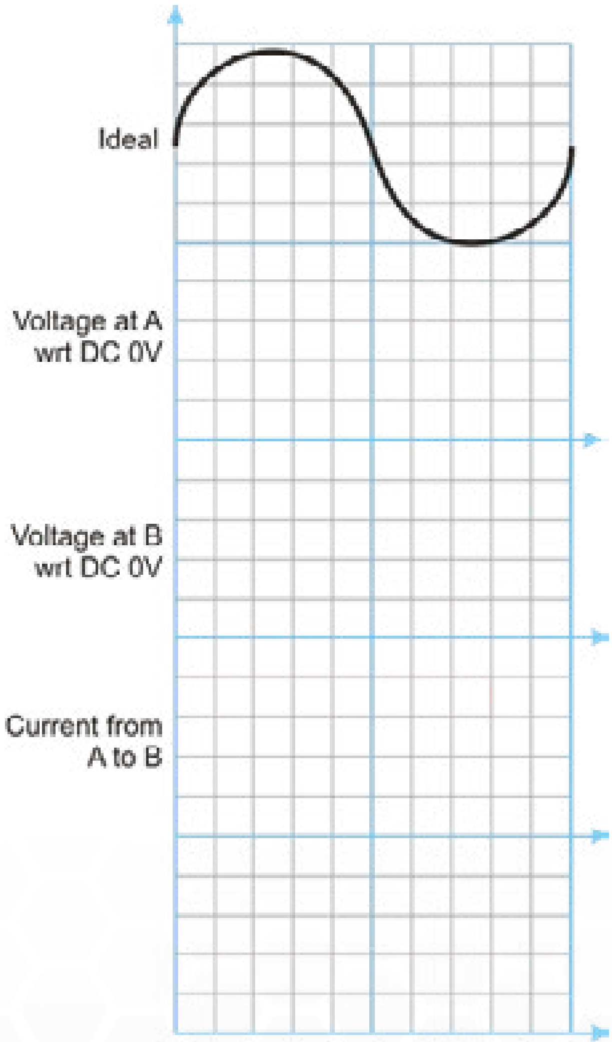
AC Drive Frequency	Speed in rpm	Torque Nm	Electrical power	Mechannical power	Efficiency
50Hz					
60Hz					
70Hz					

So What?

It is surprising how well a simple digital drive signal works for the induction motor. However, when energy conservation is paramount, the cost of a few bits of silicon needed to create the drive circuit is of secondary importance.

Over to you:

1. In the block diagram of the control unit in the Quick Start Guide, the motor drive outputs are shown as ‘tri state’. This means that each output voltage can be high, low or open circuit. The single phase 24V maximum outputs A and B are alternately positive and negative, effectively creating a maximum peak-to-peak voltage of 48V across the motor.
2. Obtain the AC waveforms using the Capture button and sketch them on the axes below.
3. The Voltage Mode property in the Waveform Capture sub category will show you the real output voltages when you use the DC mode setting. The AC mode setting shows the voltage seen by the motor.



Worksheet 16 - Three Phase Motor Characteristics

This photograph shows a section of a three phase motor with the outer shell cut away. Note the lack of brushes and the lack of a winding in the rotor. Induction motors work by inducing a current, and magnetic field, into the rotor which has a slightly different phase to the driving current/field.

Over to you:

1. Set up the three phase induction motor as shown in the diagram above.
2. On your PC run ElectricalMachines program.
3. Use settings: 20V, 50Hz, AC Mode
4. Run the motor and use the sweep button to characterise the motor at different loads.
5. Repeat this for output frequencies of 60, 70, 80 Hz.
6. On the next page, sketch the results .

How do you change direction of rotation?

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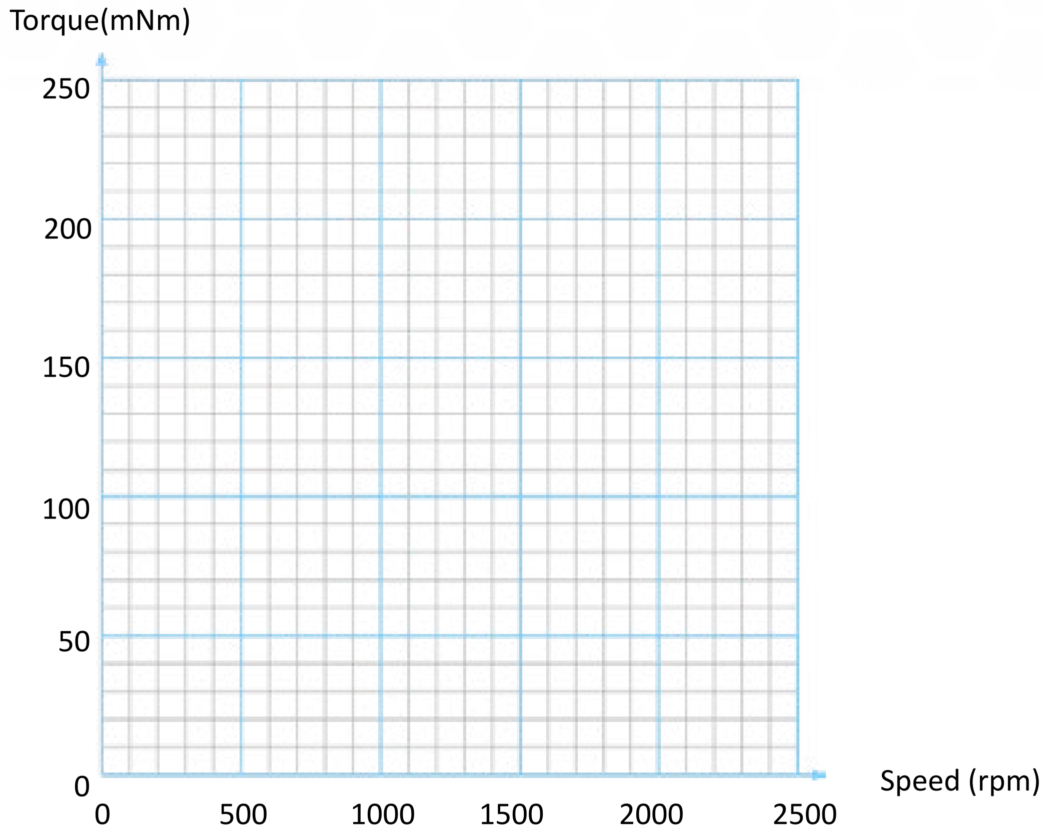
WORKSHEETS

Worksheet 16 - Three-Phase Motor Characteristics



The effect of speed on torque for different values of output frequency.

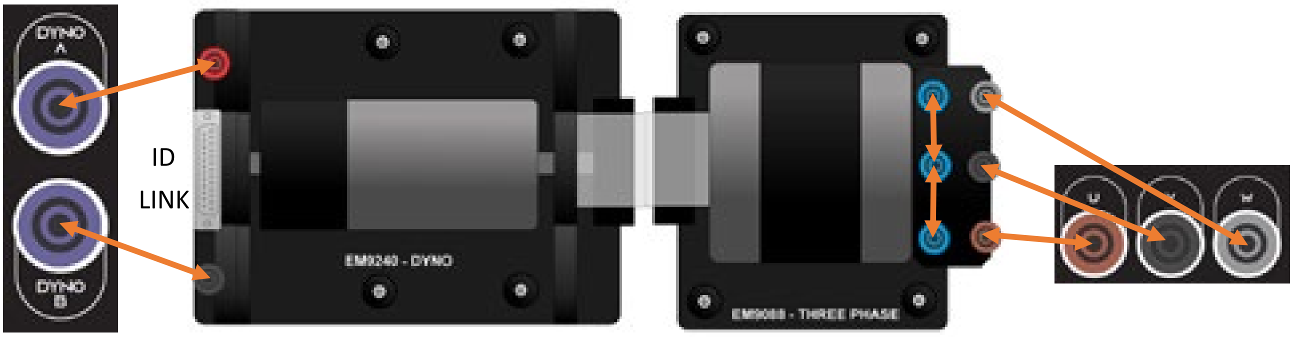
So What?

Compare the speed/torque curves to those of the single-phase motor. How does it compare for efficiency? Research the reason for this and give your findings below.

WORKSHEETS

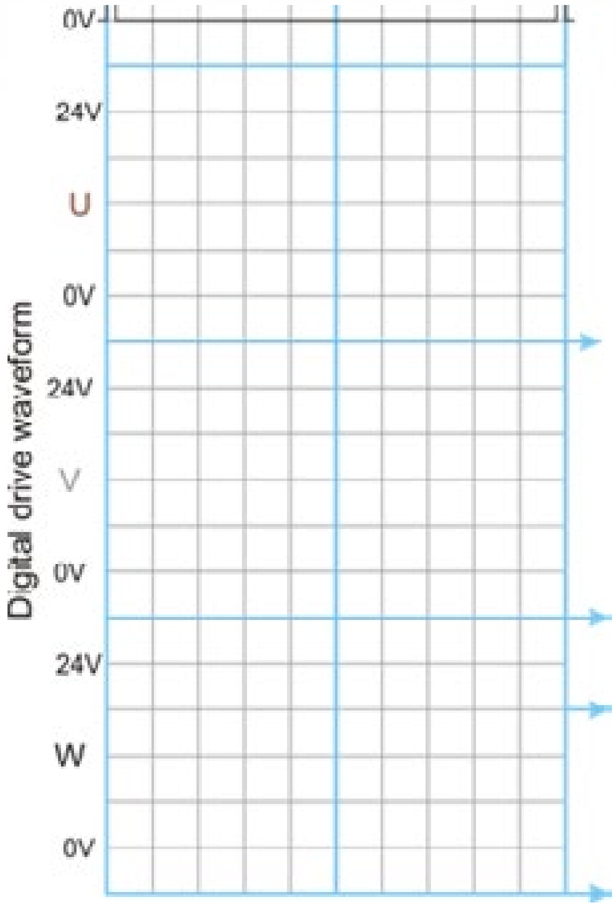
Worksheet 17 - Three-Phase Motor Drive Stratergies

The National Grid distributes electricity in three separate phases rather than the single-phase found in homes. Three-phase generation is more energy efficient. Factories use three-phase motors as they too are more efficient than single-phase systems. wThe photograph shows a three-phase induction motor factory in China.



Over to you:

1. Set up the three-phase induction motor as shown in the diagram above.
2. On your PC run ElectricalMachines program.
3. Use settings: 24V, 50Hz, DC Mode.
4. Change the Voltage mode property in the Waveform Capture section to DC.
5. Set the motor running and press the Capture button to collect the output waveforms.
6. Sketch the waveforms of signals U, V, and W using the highlight trace property to make the individual traces easier to see.

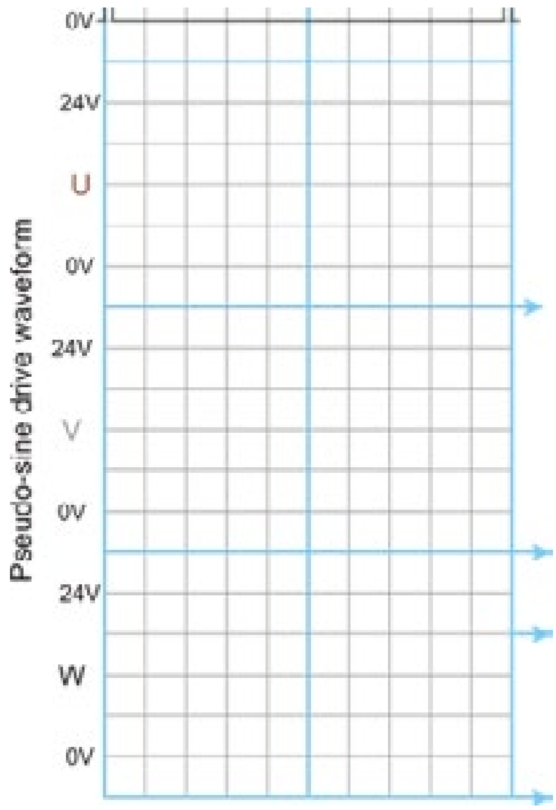


So What?

Notice that these pulses are 120º apart. Together, they make up the basic three-phase waveform. You should notice that each waveform spends approx. 1/3rd of the time at 0V, and 2/3rd of the time at 24V.

Over to you:

1. Change the drive mode to AC and the Voltage Mode Property to DC
2. Once again, sketch the waveforms of signals U, V, and W.

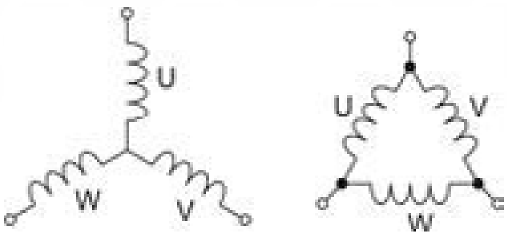


3. The waveforms feature a double hump as part of each phase output. Switch the Voltage Mode Property from DC to AC and Capture the waveforms again. How have the voltages changed and what's the difference between the AC and DC modes?

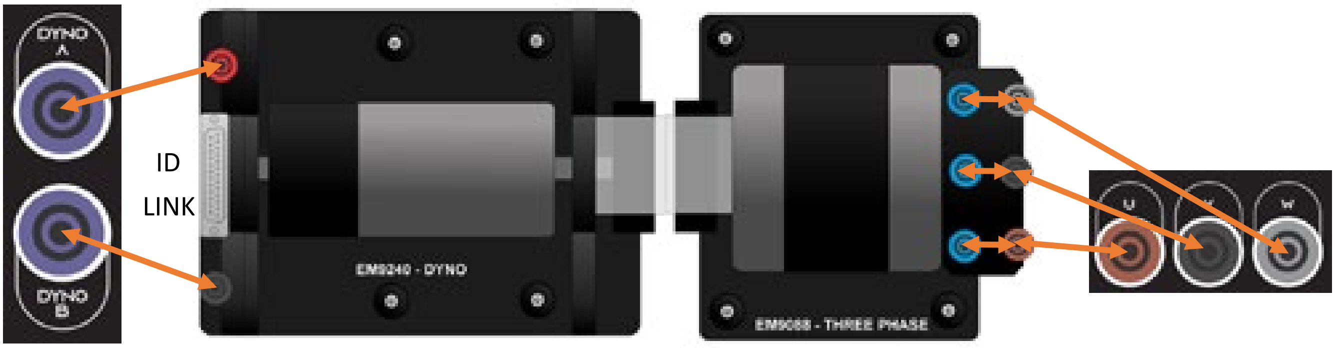
So What?

You now see the waveforms that make up the three-phase drive. Some three-phase speed control systems use simple square waves for driving motors. However the pseudo-sine wave you have examines is much more efficient.

Worksheet 18 - Delta Configuration



Induction motors can be used in 'star' or 'delta' configuration. This terminology just refers to the way the windings are connected to the supply. Delta connection tends to be used when higher current or higher power is needed. Image shows the wiring connections of star and delta.



Over to you:

1. Set up the three phase induction motor as shown in the diagram above.
2. On your PC run ElectricalMachines program.
3. In Delta configuration the resistance of the windings to the power supply is much lower and the control box will trip if you draw too much current.
4. Use settings: 12V, 50Hz, AC Mode
5. Use the Sweep button to capture an automated speed torque profile.
6. Repeat this for output frequencies of 60, 70 and 80 Hz.
7. Plot all output lines on the same graph.
8. On the next page, sketch the results .

How do you change direction of rotation?

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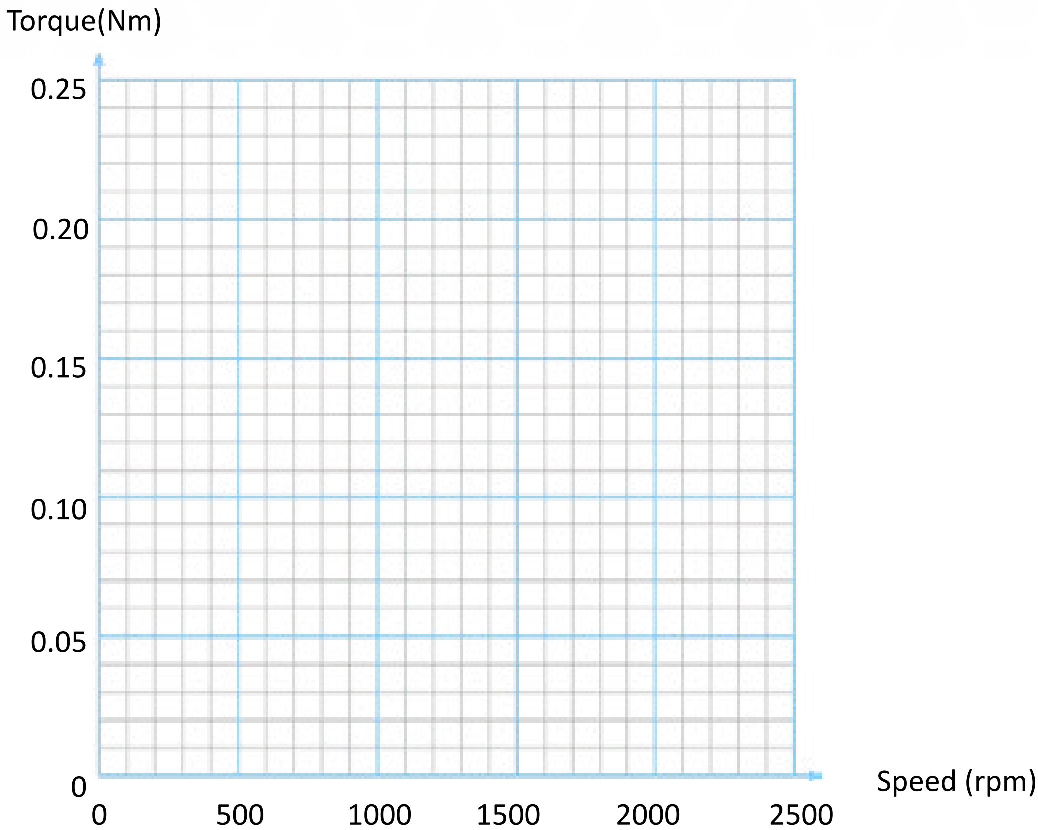


The effect of speed on torque for different values of output frequency.

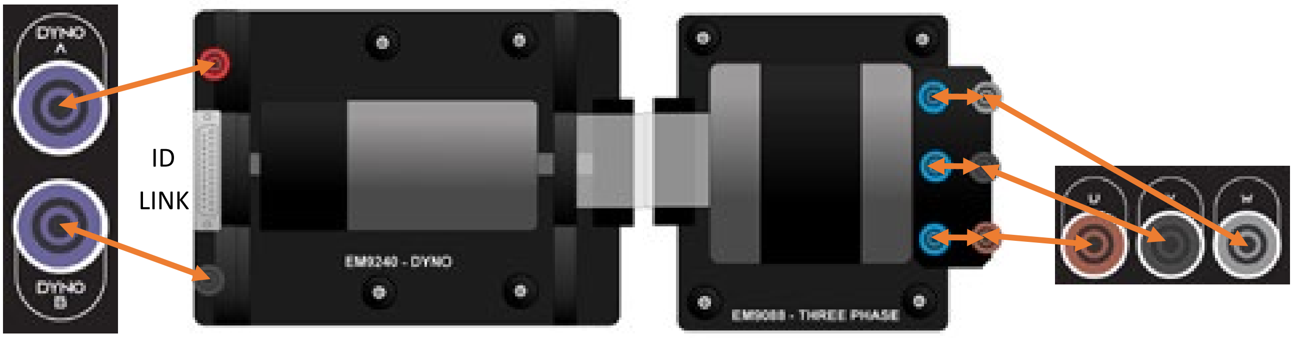
So What?

What can you say about the power consumed and the torque of both star and delta configurations.

WORKSHEETS

Worksheet 19 - Understanding Slip

Whilst induction motors may vary in size, their characteristics are all similar. Larger motors can be very expensive. When they fail, they are refurbished by hand - a specialist task. In the photograph, an engineer is re-winding an induction motor.



Over to you:

1. Set up the three-phase induction motor as shown in the diagram above.
2. On your PC run ElectricalMachines program.
3. Calculate the synchronous speed for the three-phase motor using the formula in the ‘Key relationships’ section. (Refer to the cross-section drawings in the ‘Reference’ section to see how many poles this motor has.)
4. With no dynamometer load, 24V, for drive frequencies of 40Hz, 50Hz, 60Hz, 70Hz and 80Hz, calculate the slip at each frequency. Record the results in the table opposite.
5. Set the drive frequency to 50Hz. Increase the dynamometer load to 50%, then 75%, then 90% and finally full load. Calculate the slip at each step. Record the results in the table.

3p Motor Drive	Synchronos Speed	Speed	Slip
40Hz			
50Hz			
60Hz			
70Hz			
80Hz			

Dyno Load	Speed	Slip
0%		
50%		
75%		
90%		
Full		

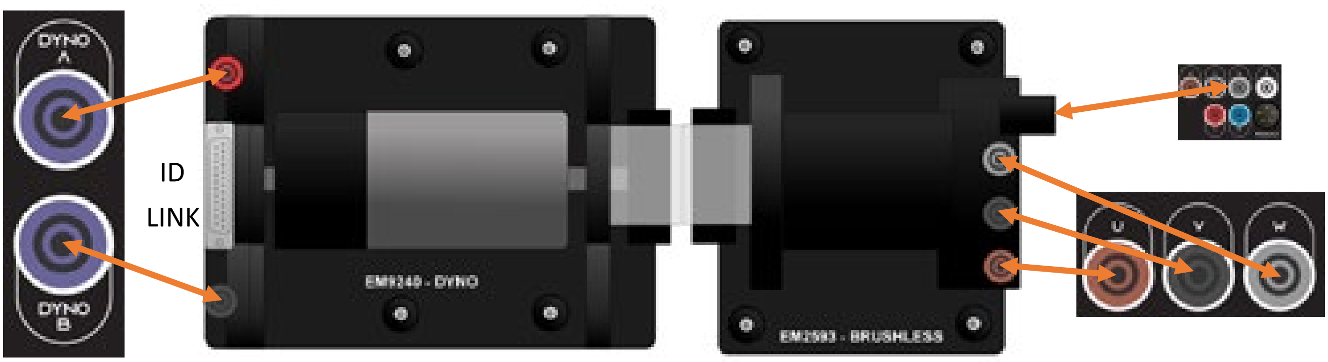
Over to you

Explain these readings.

WORKSHEETS

Worksheet 20 - Brushless DC Motor

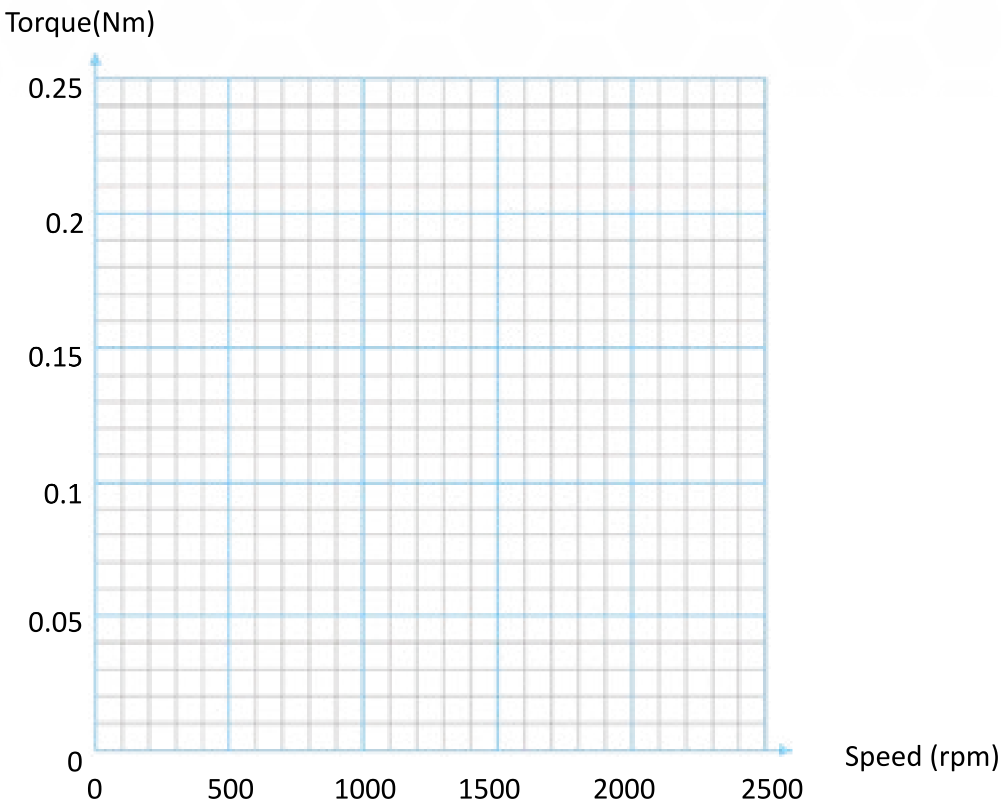
Brushless DC motors have a great power output to weight ratio which makes them useful in weight sensitive applications like drones. Their construction means that they need to be started at a slow speed and then ramped up to full speed.



Over to you

1. Set up the brushless motor, as shown in the diagram above. Don't forget to connect the brushless DC motor to the control unit with the 5-pin lead.
2. On your PC run ElectricalMachines program.
3. Use settings: 10V, 40Hz
4. Click the sweep button to put the motor through an automated load
5. Repeat this step for drive frequencies of 60 and 80Hz.
6. On the next page, sketch the results.

Find out why a brushless DC motor is powered by a three-phase AC supply.



The effect of speed on torque for different values of output frequency.

So What?

When the feedback cable in inserted the box will check for the current state of the motor at the frequency specified. At higher frequencies the motor can be serviced as needed even at higher speeds. At lower frequencies the motor will go un-serviced at higher frequencies meaning the is a slight drop in the RPM at the lower loads. As the load increases and the speed decreases to match the motor will resume its usual characteristic of acting like a DC motor.

Try removing the feedback cable, the motor can be ran by setting the load to 0% and lowering the control frequency to 20Hz. Then slowly increase the control frequency back up to 50Hz. What happens if you try to do a sweep without the feedback cable? Add this to your graph above.

WORKSHEETS

Worksheet 21 - Three-Phase Generator

We see small wind turbines everywhere. The efficiency of three-phase over single-phase means that even small wind generators use three-phase machines to generate electricity.

In this experiment, the brushless DC motor acts as a three-phase generator. It is mechanically linked to, and driven by, the dynamometer, which is supplied with a DC voltage.

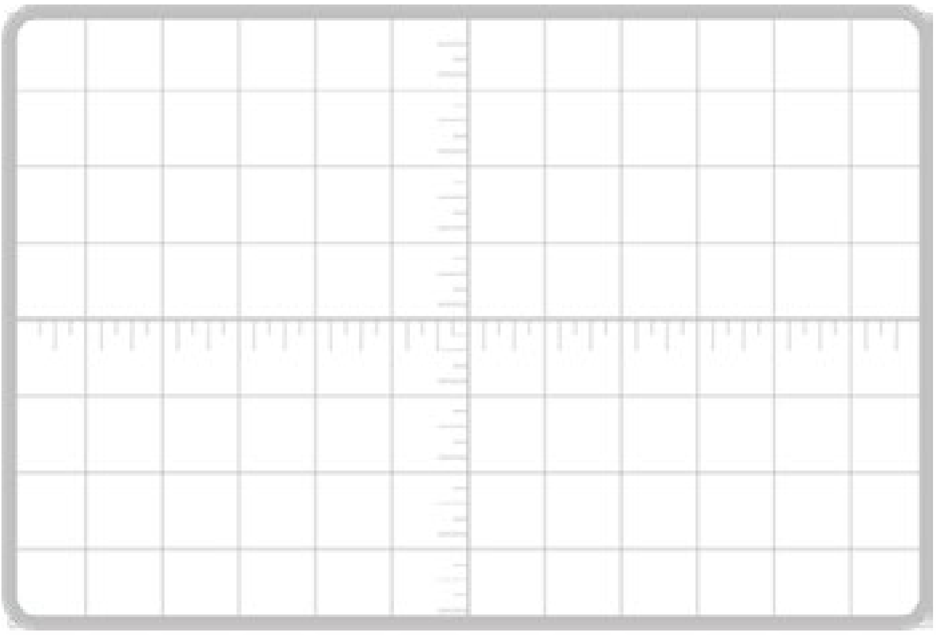
Over to you

1. Set up the brushless motor as shown in the diagram above using a multimeter in voltage AC mode.
2. On your PC run ElectricalMachines program.
3. Set an output of 10V on the Submodule Drive.
4. Press the ‘RUN’ button on the software.
5. Vary the DC output from 10V to 24V in 2V steps.
6. Make a note of the voltage from the brushless motor and fill in the table on the next page.
7. Use an oscilloscope and sketch the three phase waveform on the next page.
8. How does the waveform relate to the motor RPM?

Dyno Voltage	Speed rpm	Vout pk-to-pk
10v		
12v		
14v		
16v		
18v		
20v		
22v		
24v		

So What?

The great thing about the brushless motor is the small size of the package and the fact that there are no brushes for ease of maintenance.



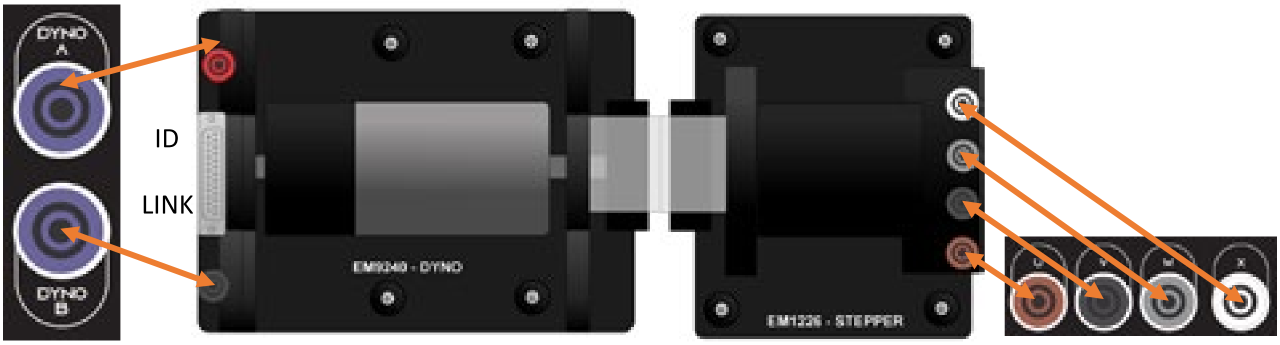
Over to you

Use the tools available to investigate the efficiency of the brushless motor and compare it to that of the DC motor.

WORKSHEETS

Worksheet 22 - Stepper Motor

Stepper motors are often used in robotics where precise controlled movements are required. Rather then spin the motor will have a fixed number of discreet steps or positions that the output shaft can move between.



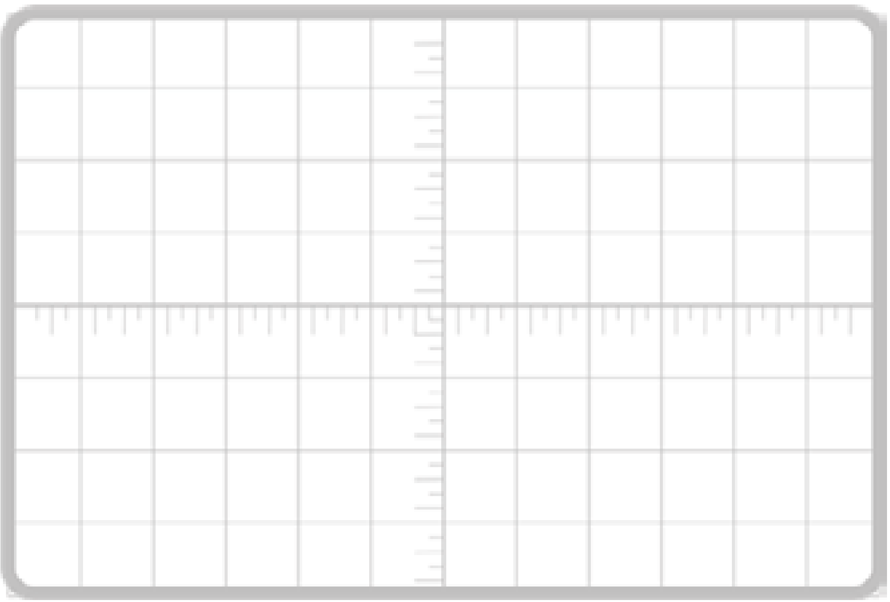
Over to you

1. Set up the stepper motor as shown in the diagram above.
2. On your PC run ElectricalMachines program.
3. Use settings: 3V, 40Hz
4. Press the ‘RUN’ button on the software.
5. With the Voltage Mode property set to AC click the Capture button to collect the motor control waveforms.
6. Sketch the stepper motor waveform on the next page.
7. Make a note of the speed in RPM and fill in the table on the next page.
8. Vary the frequency output from 50Hz to 80Hz in 10Hz steps to complete the table.
9. How does the output frequency relate to the motor RPM?

Speed Motor Frequency	Speed rpm
40Hz	
50Hz	
60Hz	
70Hz	
80Hz	
90Hz	
100Hz	

So What?

The stepper motor has a step angle of precisely 1.8 degrees. Therefore for a single rotation we need to provide 200 steps. For each Hz on our output we are outputting 4 steps on the motor and so at 50Hz we get 1 rev / second or 60 RPM.



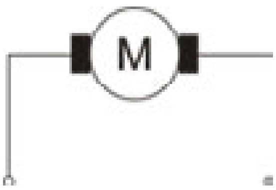
Over to You

The stepper motor starts to stall around 70Hz at 3V. What happens if you increase the voltage to the motor? Compare both the max available output frequency as well as the output wattage. What happens to the stall voltage and frequency if you change the drive mode from AC to DC.

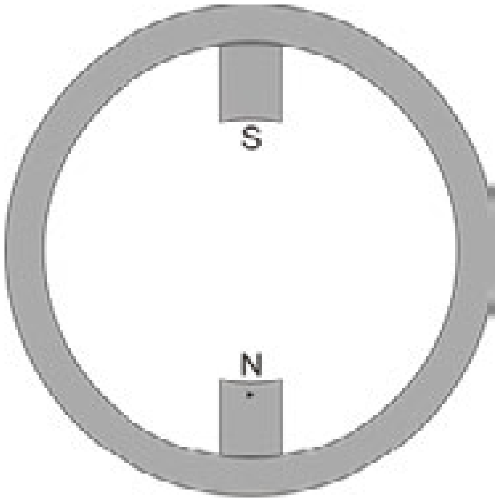
MACHINE INFORMATION

Conventional Symbol

Actual Circuit

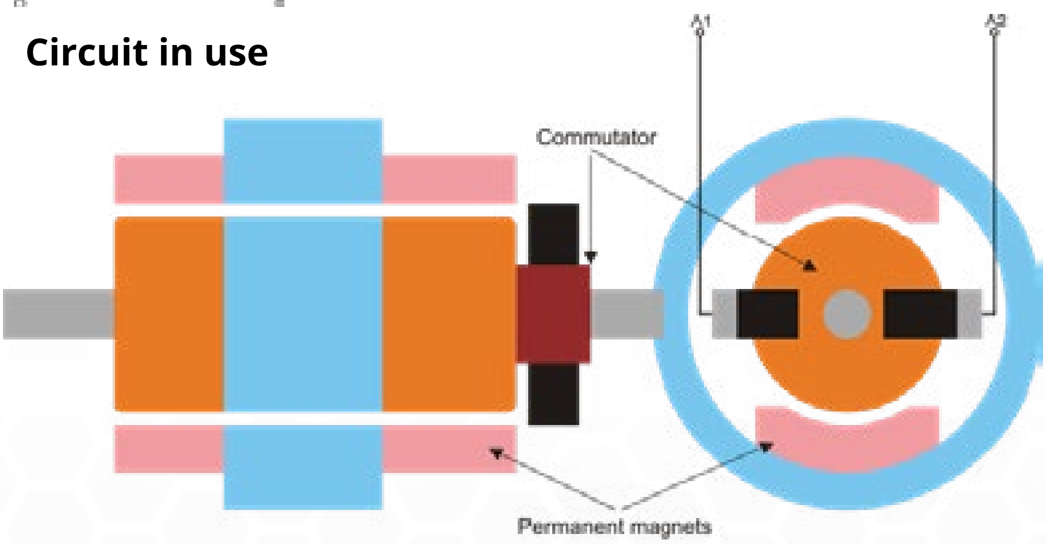


Circuit in use



Stator Winding Circuit

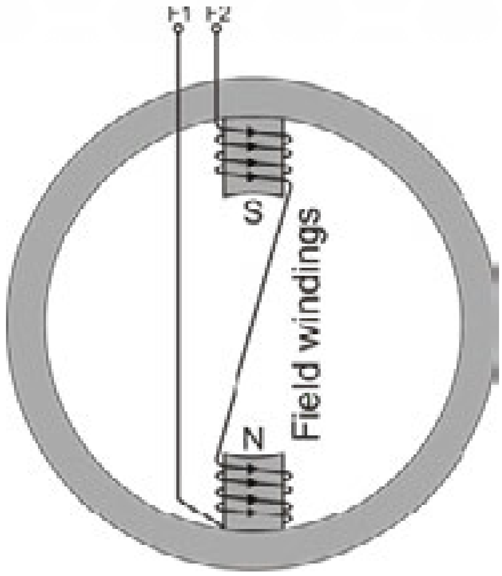
Connection	Colour
V+	Red
V-	Black

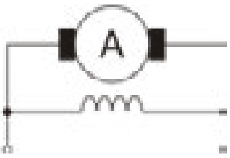


Construction

Reference
The Dynamometer

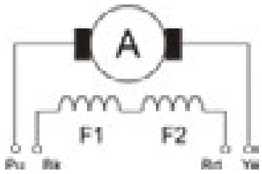
Reference
The Shunt Motor





DYNO A

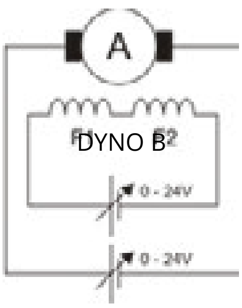
Conventional

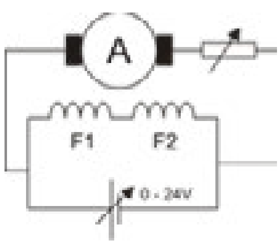


Actual CIrcuit

Stator Winding Circuit

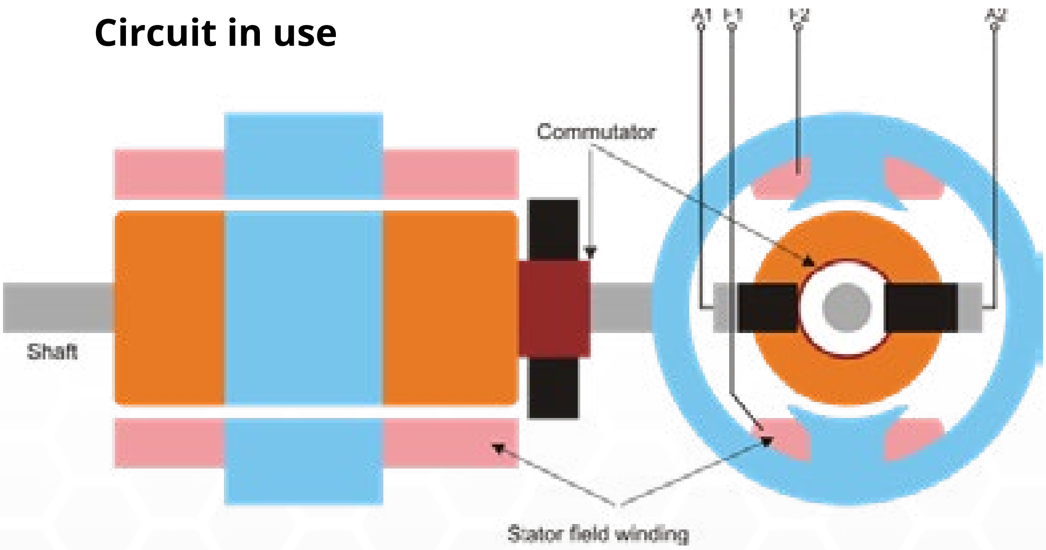
COMMS ID





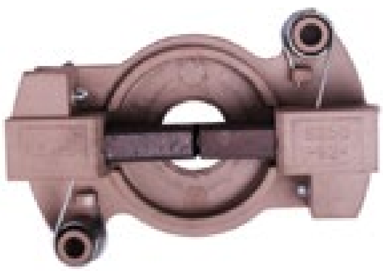
Connection	Colour
Armature	Purple
Armature	Yellow
Field Coil	Black
Field Coil	Red

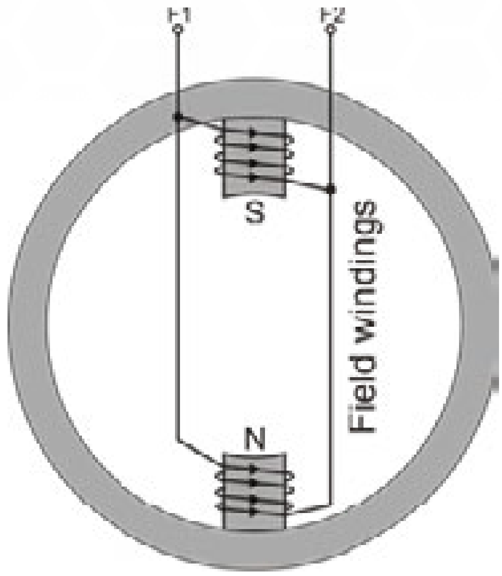
Circuit in use



Constuction

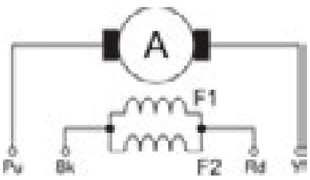
Reference
The Shunt Motor





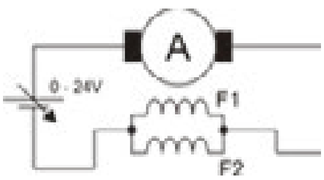
Stator Winding Circuit

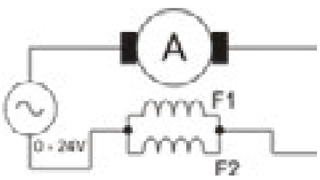
Conventional Symbol



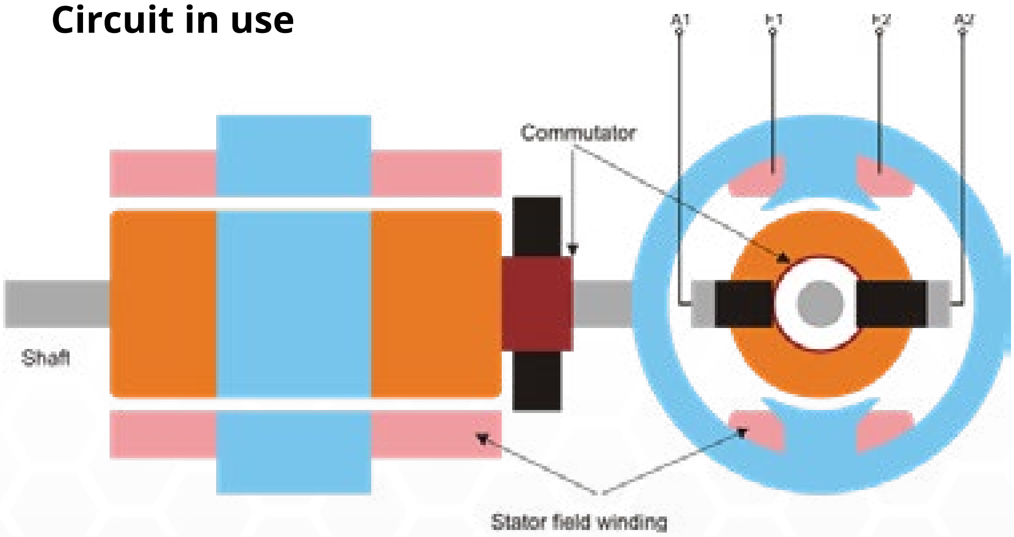
Actual CIrcuit

Connection	Colour
Armature	Purple
Armature	Yellow
Field Coil	Black
Field Coil	Red



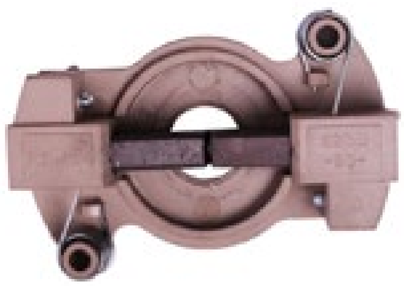


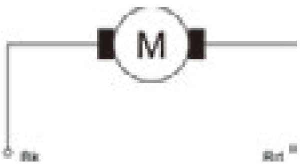
Circuit in use



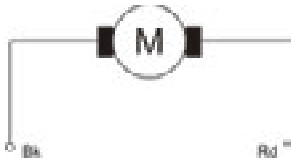
Constuction

Reference
The Series Motor



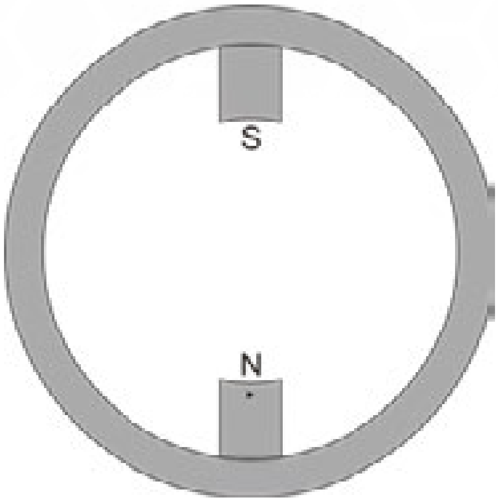


Conventional Symbol



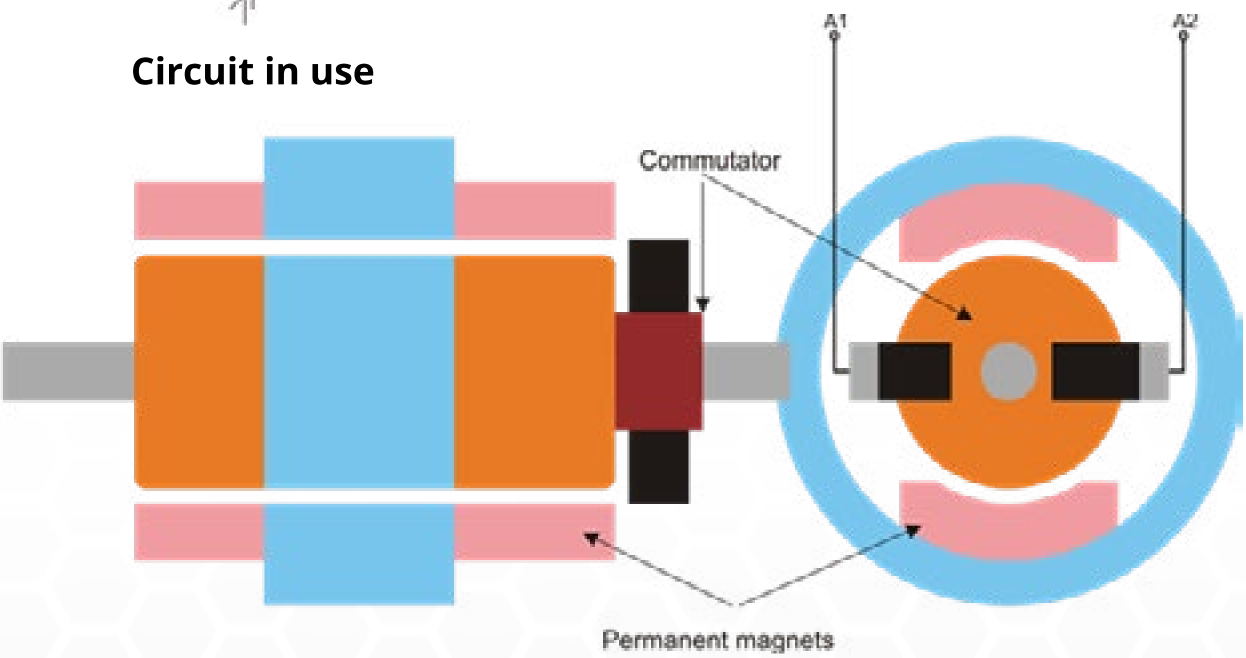
Actual CIrcuit

Circuit in use



Stator Winding Circuit

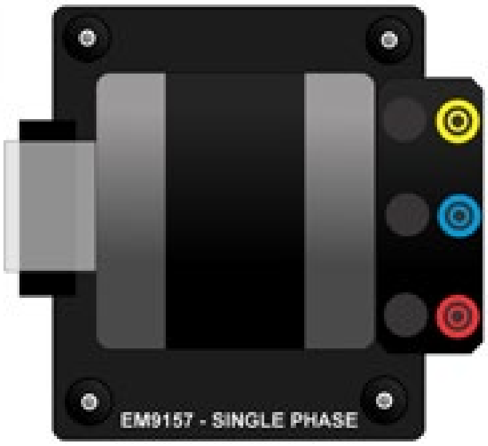
Connection	Colour
V+	Red
V-	Black

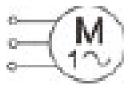


Constuction

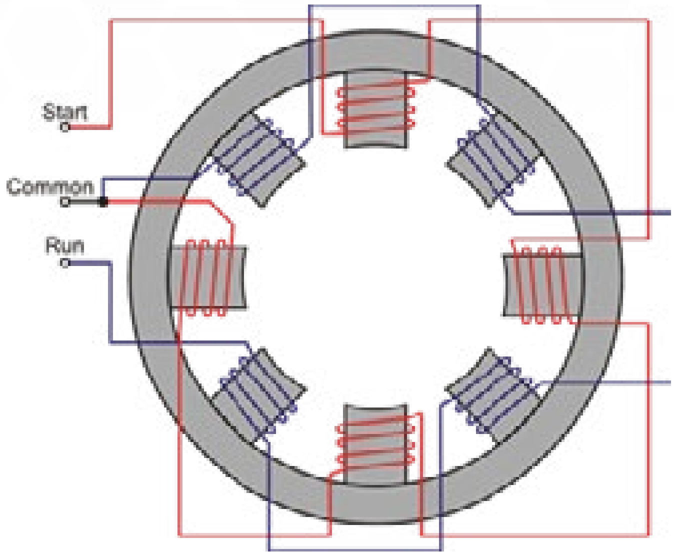
Reference
The DC Motor

Reference
The Simple Phase AC Induction Motor

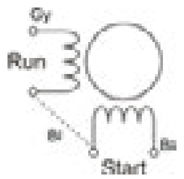




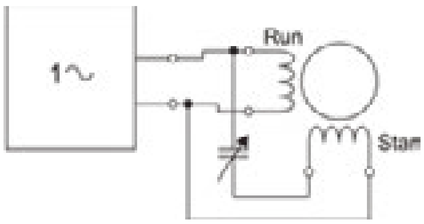
Conventional Symbol



Stator Winding Circuit

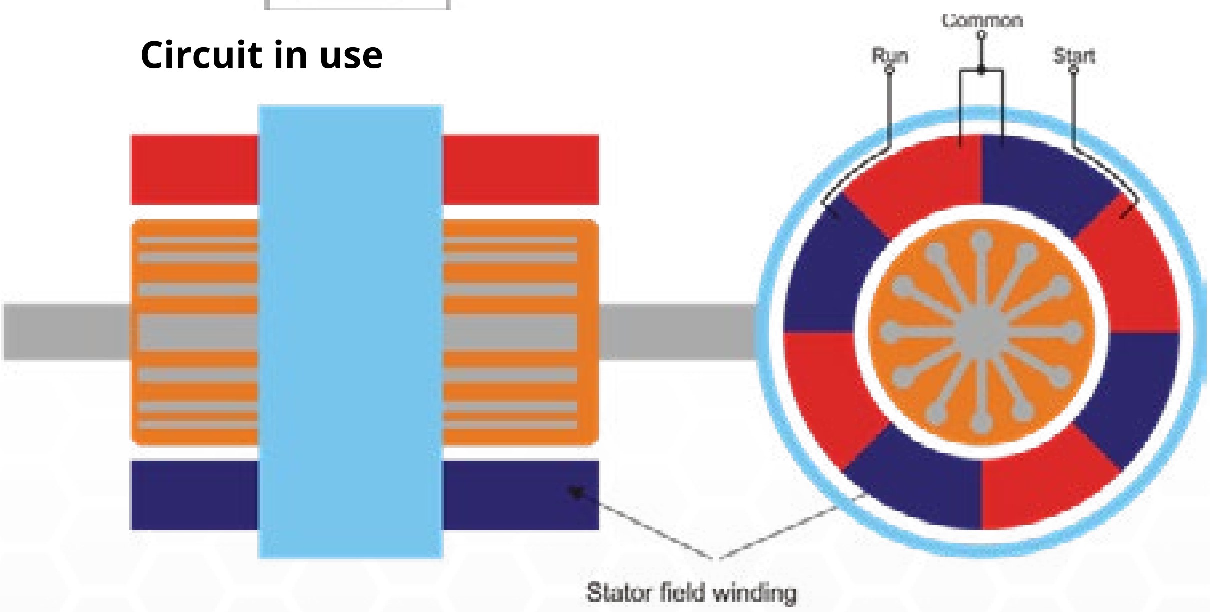


Actual CIrcuit



Circuit in use

Connection	Colour
Run	Red
Start	Yellow
Common	Blue

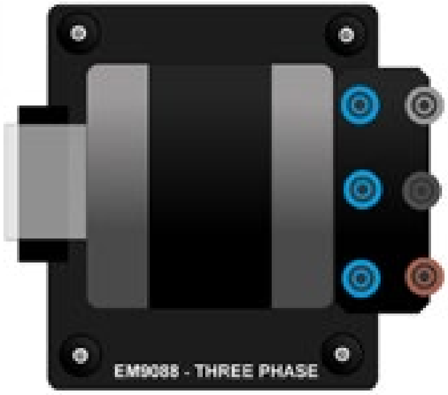


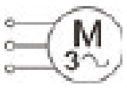
Constuction

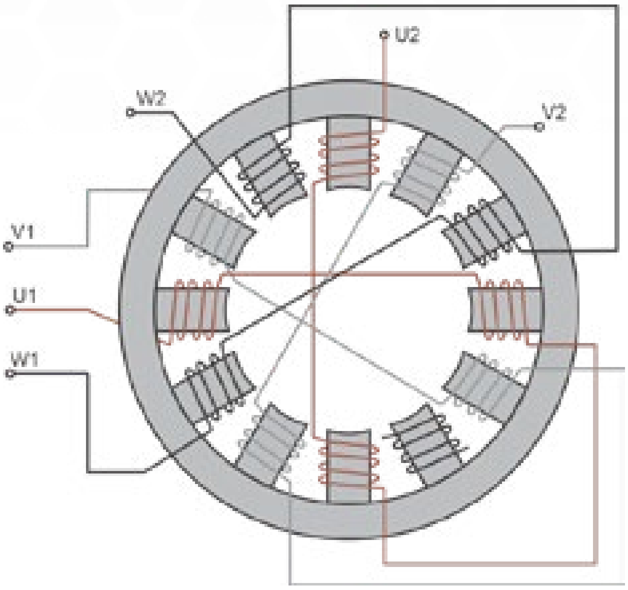
Reference

The Simple Phase AC Induction Motor

The Three Phase AC Induction Motor

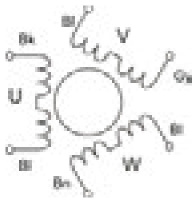






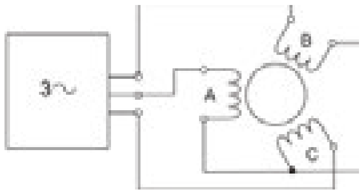
Conventional Symbol

Stator Winding Circuit- 2 Pole Pairs

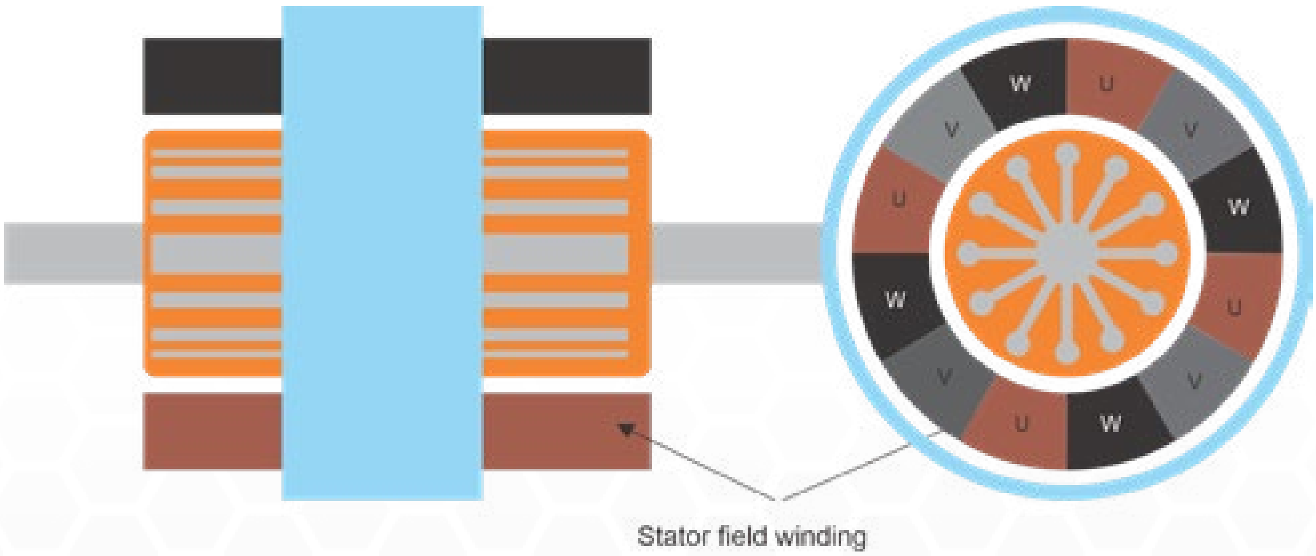


Actual CIrcuit

Connection	Colour
Phase U1	Brown
Phase U2	Blue
Phase V1	Black
Phase V2	Blue
Phase W1	Grey
Phase W2	Blue



Circuit in use

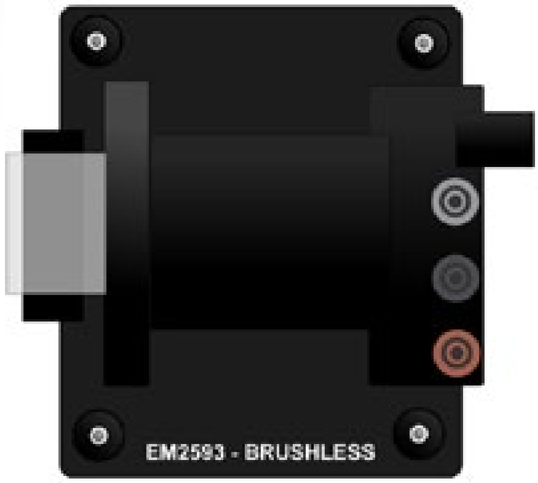


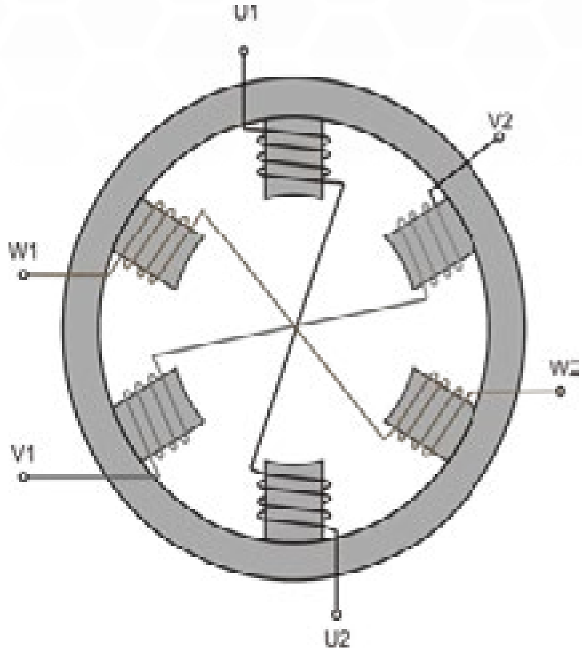
Constuction

Reference

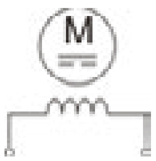
The Three Phase AC Induction Motor

Reference
The Brushless DC Motor

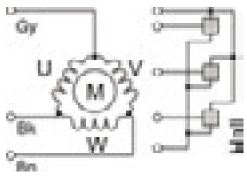




Stator Winding Circuit

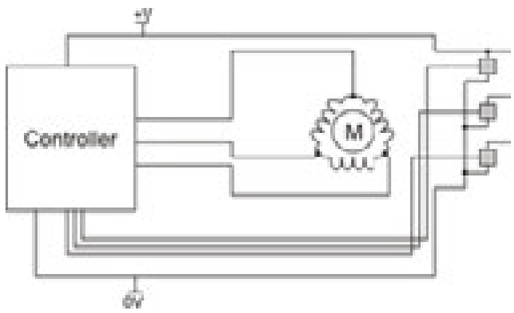


Conventional Symbol

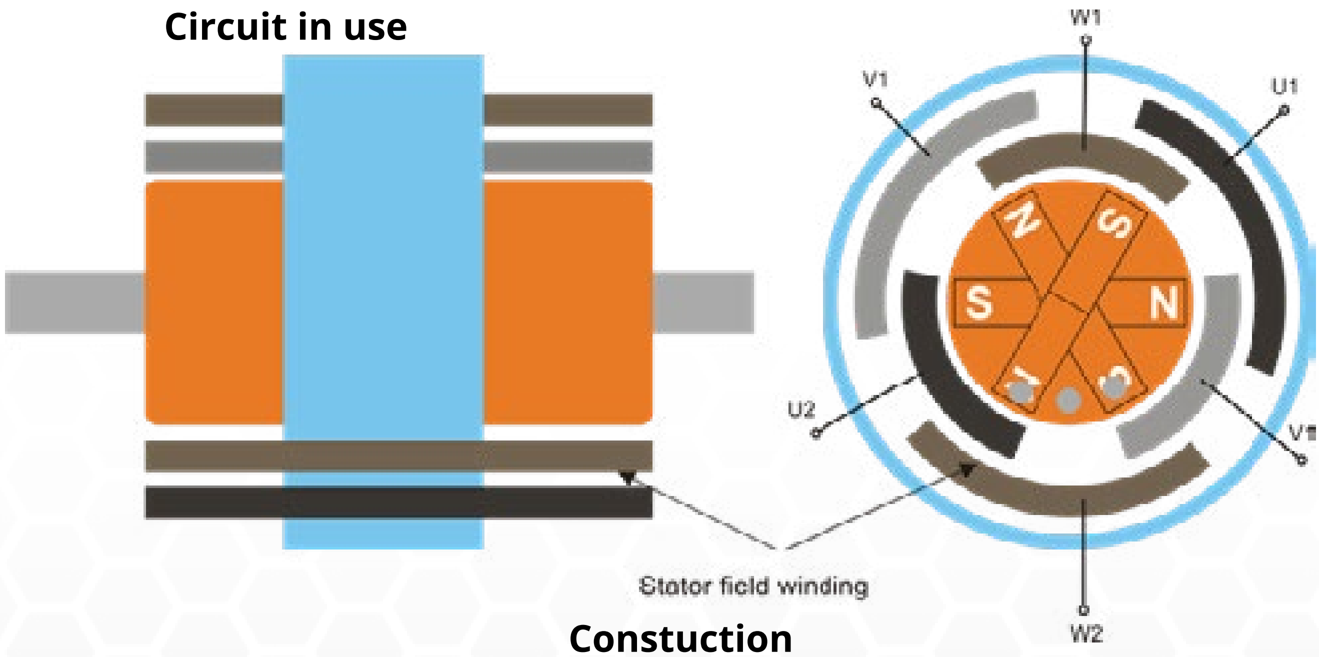


Actual CIrcuit

Connection	Colour
Phase U	Brown
Phase V	Black
Phase W	Grey



Circuit in use

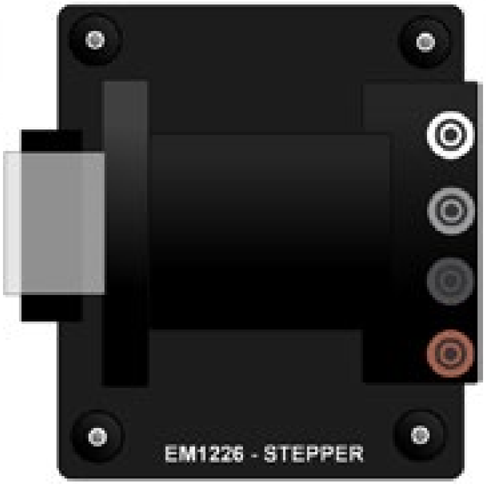


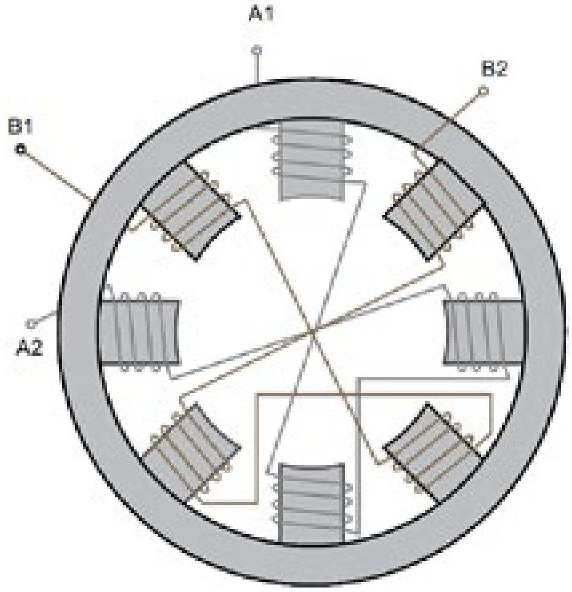
Constuction

Reference

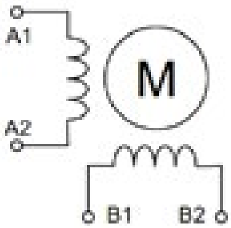
The Brushless DC Motor

Reference
The Stepper Motor

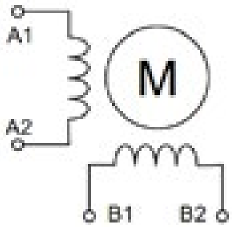




Stator Winding Circuit

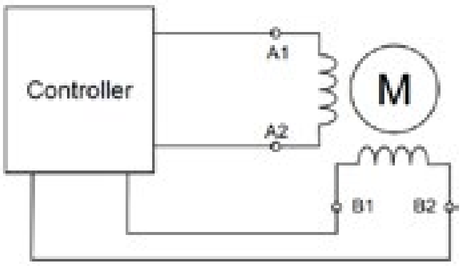


Conventional Symbol

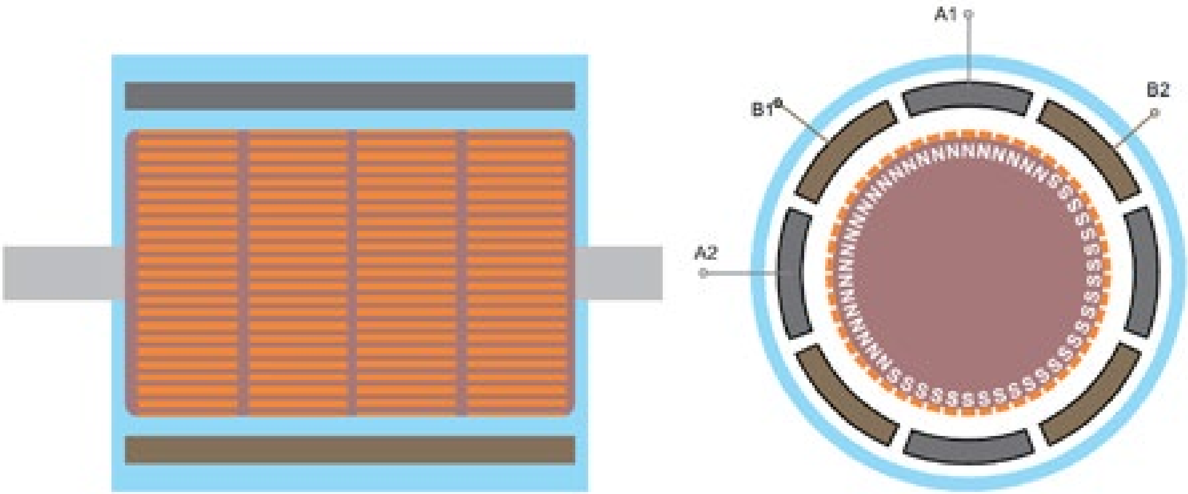


Actual CIrcuit

Connection	Colour
Phase A1	Brown
Phase B1	Black
Phase A2	Grey
Phase B2	White

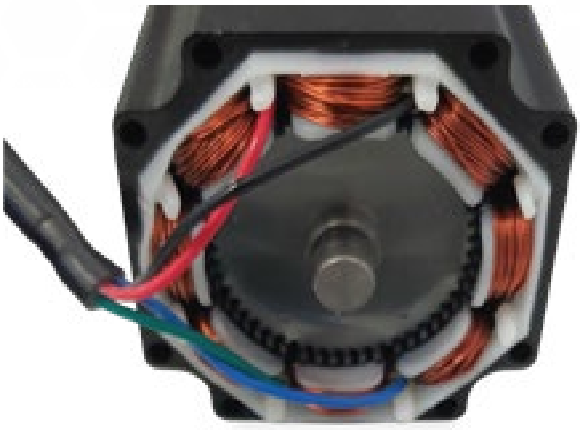


Circuit in use



Constuction

Reference
The Stepper Motor



Version Control

26 02 25 first release

Notes

MODERN ELECTRICAL MACHINES

CP7479

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