



ELECTRICAL
MACHINES

Modern Electrical Machines



MATRIX

CP6490

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ELECTRICAL
MACHINES

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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 24V AC or DC

The dynamometer is capable of generating DC voltages. At maximum speed, around 3,000 r.p.m., 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 his 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 and motor under test means that no rotating parts are exposed..

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.

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:

$$\text{Force} = \text{mass} \times \text{acceleration} \text{ or } \mathbf{F = m \times a},$$

where **a** is usually the acceleration due to gravity, 9.81 m/s^2 .

This allows us to calculate the force pressing down on the balance, generated by the dynamometer.

Torque = force x distance from the axis of rotation. It is measured in newton-metres (Nm).

Combining these equations:

$$\text{Torque, } \mathbf{T = m \times a \times r}$$

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:

$$\text{torque (in Nm)} = \text{balance reading (in kg)} \times \mathbf{9.81 \text{ (m/s}^2\text{)}} \times \mathbf{0.03812 \text{ (m)}}.$$

Calculating power

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

For a rotating body:

$$\text{Mechanical power} = (2 \times \mathbf{n} \times \pi \times \mathbf{T}) / 60 \text{ where } \mathbf{n} \text{ is the speed of the motor in r.p.m.}$$

For a DC motor:

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

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

For a single phase AC motor:

$$\text{Electrical power supplied to the motor} = \mathbf{V_{IN} \times I_{IN} \times \cos(\Theta)}$$

where $\mathbf{V_{IN}}$ is the AC rms input voltage, $\mathbf{I_{IN}}$ is the rms input current

and $\cos(\Theta)$ is the power factor where Θ is the phase angle between $\mathbf{V_{IN}}$ and $\mathbf{I_{IN}}$.

For a three phase AC induction motor:

$$\text{Electrical power supplied to the motor} = 3 \times \text{electrical power supplied to one phase}$$

Calculating efficiency

$$\text{Efficiency } (\eta) = (\text{Mechanical power delivered} / \text{Electrical power supplied}) \times 100\%$$

Calculating synchronous speed and slip

Synchronous speed in r.p.m = $(f \times 60) / (\text{number of pairs of poles})$

(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.)

$$\text{Slip} = ((\text{synchronous speed} - \text{slip speed}) / \text{synchronous speed}) \times 100\%$$

A three phase supply connected to the stator of an induction machine produces a magnetic field given by the formula:

$$N_s = (f_s/p) \times 60$$

Where f_s = 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:

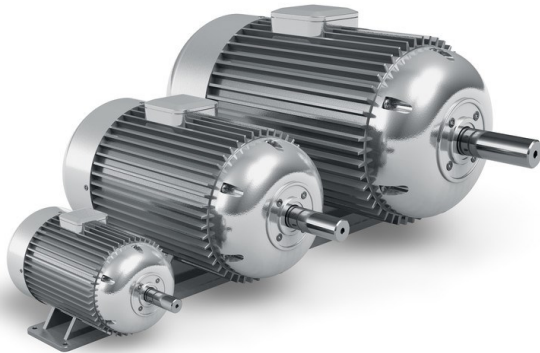
$$V_{\text{line}} = \text{SQRT}(3) \times V_{\text{phase}}$$



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 control unit to the mains power using the IEC connector. The quad 7-segment display and Power LED 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 driver are correctly installed.
- 2) Make sure the packaging strap and sensor block are removed - see Unpacking in the reference section
- 3) Make sure that the rubber 'spider' which buffers the dynamometer and motor under test is in place. The system will work without this - it will just be noisy. (On first use you might have to push hard!)

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

Now you are ready to test the set up .

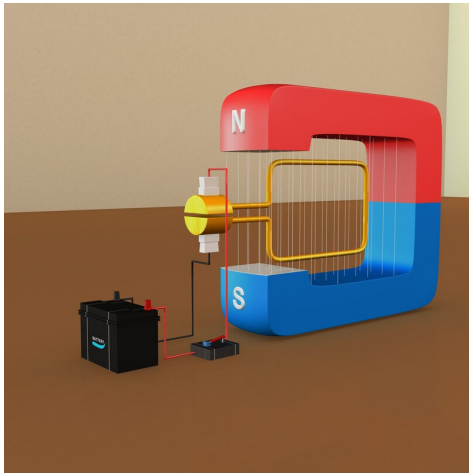
Set up a machine test

- 1) Line up the DC motor in the grooves of the dynamometer test bed.
It should slide in easily. You may have to undo the knurled nuts on the motor bed.
- 3) Make sure the motor and dynamometer couplings are aligned before pushing the motor home.
- 4) As you push home the DC motor into the dynamometer test bed you should hear the safety microswitches in the dynamometer cradle click.
- 5) Tighten the knurled lock nuts to make sure that the DC motor is secured in place.
- 6) Insert the balance and remove **both** protective plastic covers.

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

Worksheet 2

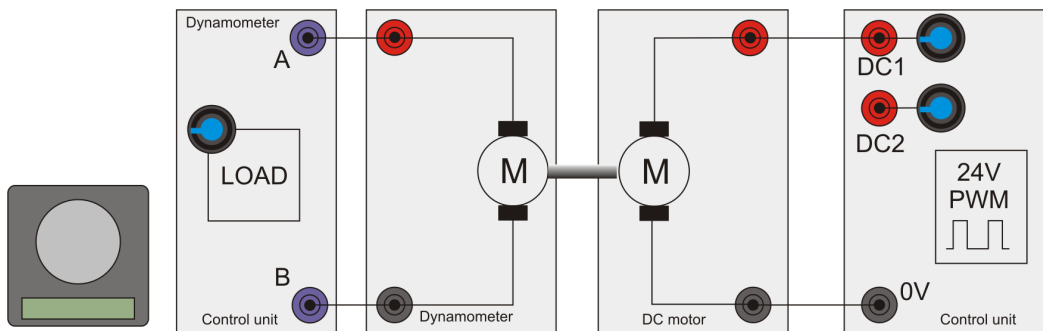
Understanding torque and mass



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:

With the control box in manual mode:

- 1) Put the balance under the swing arm and turn it on.
- 2) Turn the control unit potentiometers to minimum (fully anti-clockwise.)
- 3) Slowly increase the value of DC1 until the DC motor starts to turn.
- 4) Is there a reading on the balance?
If not, swap over the positive and negative connections on the motor to change the direction of rotation.
- 5) With DC1 potentiometer in the middle of its range, note of the balance reading and motor speed in the table below. (The motor speed will vary a little - estimate an average.)
- 6) Turn the DC1 PSU pot to increase the voltage slightly. Measure and record the new balance

reading and speed.

- 7) Referring to the 'Key Relationships' (page 4,) use the readings to calculate the torque for the two settings and record your answers .

Speed	Balance torque

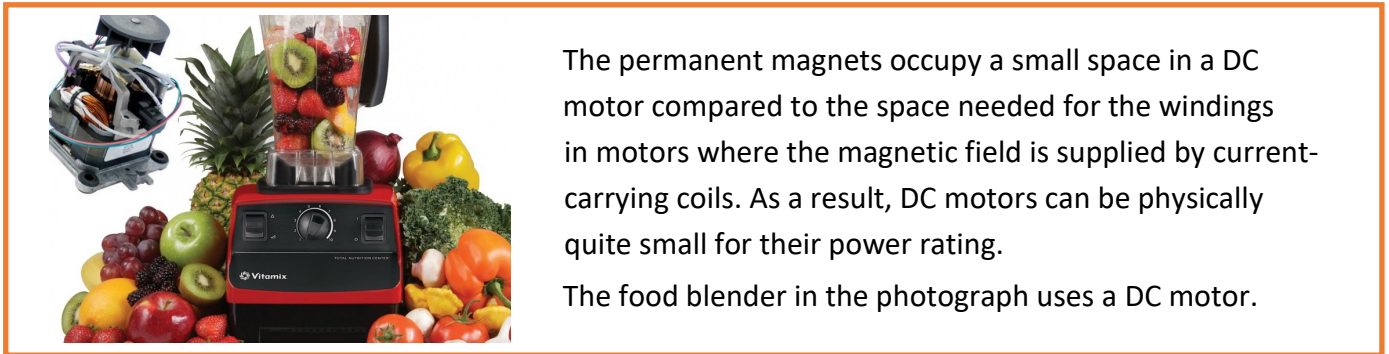
So what?

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

The swinging-arm dynamometer can rotate in either direction. The torque produced is the same for both. When rotating counter-clockwise, pressure is applied to the balance. When rotating clockwise, the pressure is on the load cell at the back of the dynamometer.

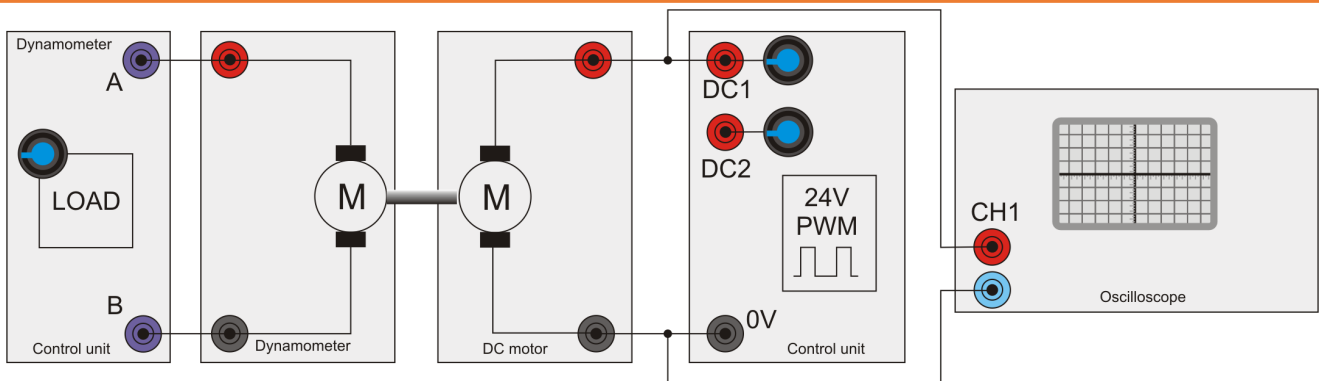
Worksheet 3

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

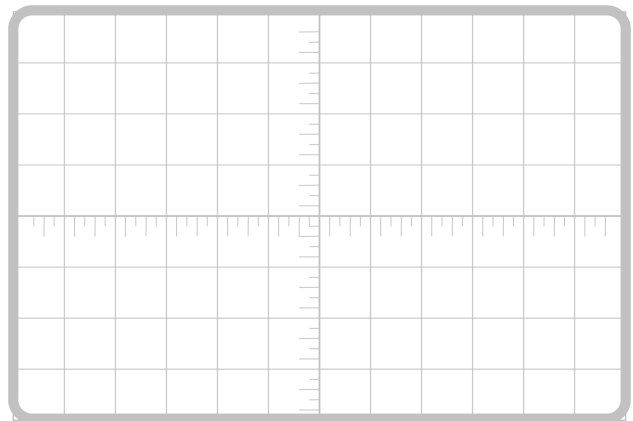
- 1) Adjust the DC1 potentiometer so that it is in about a quarter way of the way round.
- 2) Use an external oscilloscope, not a PC-based one, to look at the signal from DC1.
- 3) Use the upper graph opposite to sketch the waveform of this signal.
- 4) Turn the DC1 potentiometer about three-quarters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

So what?

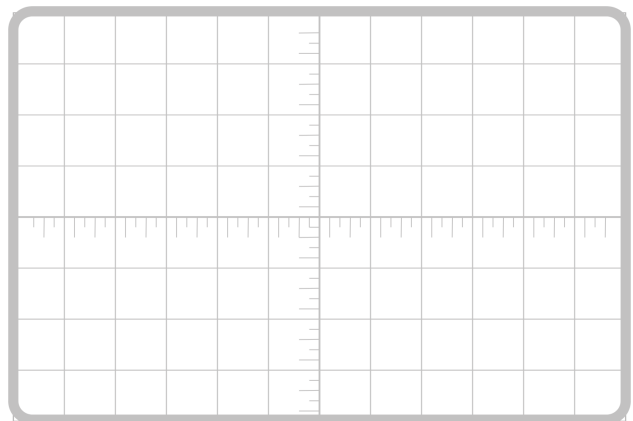
Modern DC motor power supplies do not vary the output in an analogue fashion, but use pulse-width modulation or PWM. In this, the mark : space ratio of the output is varied.

In the control unit, a bank of FET's deliver a PWM signal generated by a computer. This can be used with DC, with single-phase and with three-phase motors.

Do not use a PC-based oscilloscope.



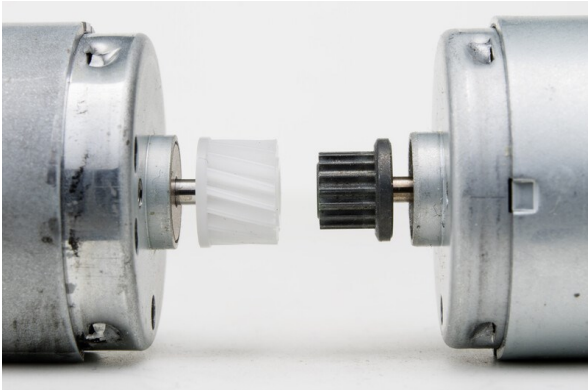
DC1 - one-quarter max.



DC1 - three-quarters max.

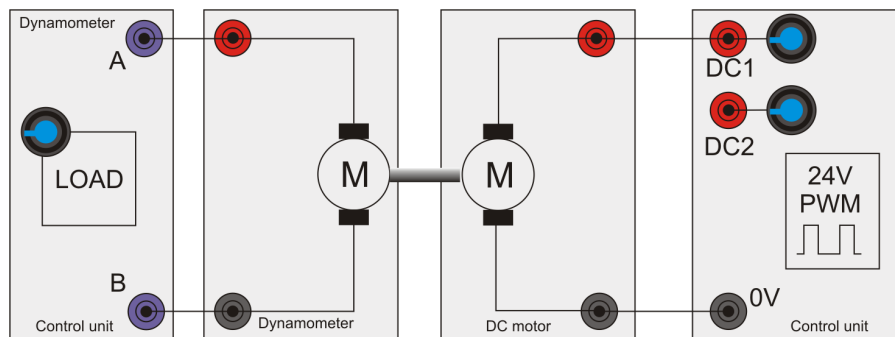
Worksheet 4

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) Energise the DC motor to put pressure on the dynamometer load cell rather than the balance. (If necessary, reverse the power supply connections.)
- 3) Connect the dynamometer to the load terminals on the control unit to set a load across the dynamometer.
- 4) Connect the control box to your computer using the USB lead.
- 5) On the computer, load the 'Open Control DC' program. Press the 'PLAY' style button on the top left and then click on the 'RUN' button.
- 6) Set the PWM DC output to around 30%.
- 7) Give the DC motor a small load of around 50% on the dynamometer.
- 8) Investigate the effect of varying the PWM voltage 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.
- 9) Use the information in the 'Key Relationships' section on page 4 to calculate the mechanical power delivered to the dynamometer.
- 10) In addition, calculate the efficiency of the motor at each of the six settings.
- 11) On the graph paper provided, use these readings to plot a graph to show how the torque (y-axis) varies with speed (x-axis).

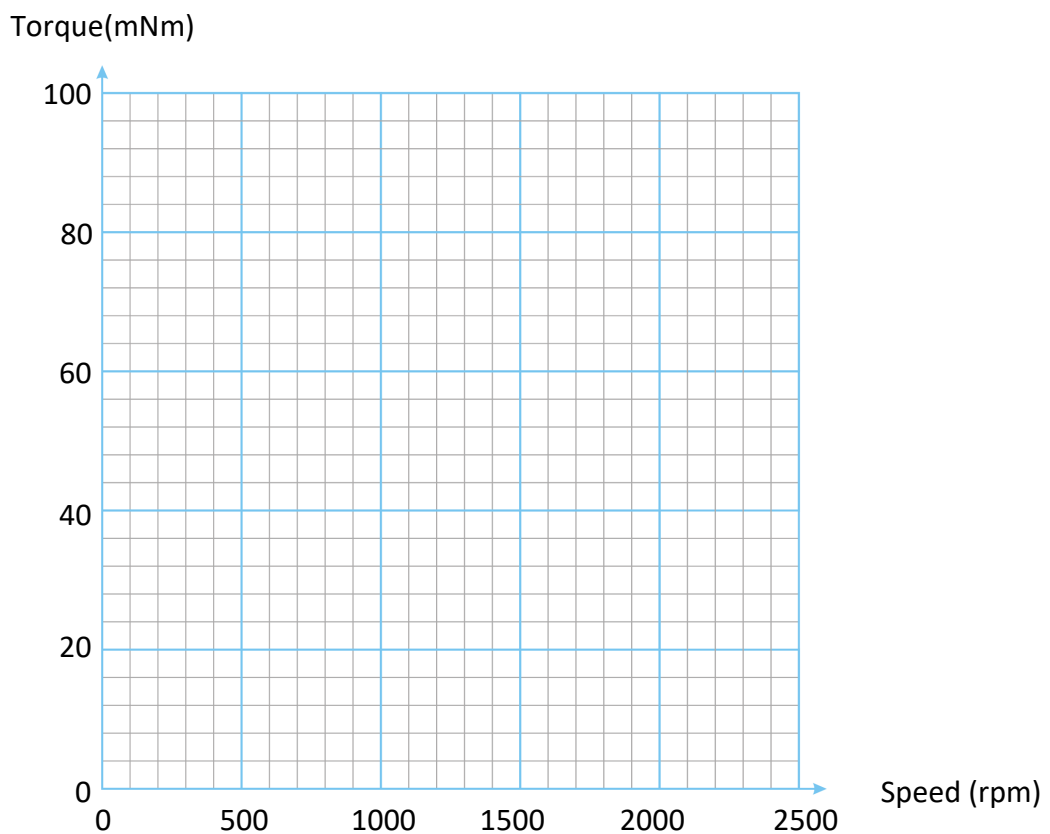
Note that for repeated calculations you will find it easier to use a spreadsheet.

Worksheet 4

DC motor characteristics 1



Voltage	Speed	Torque	Electrical power	Mechanical power	Efficiency



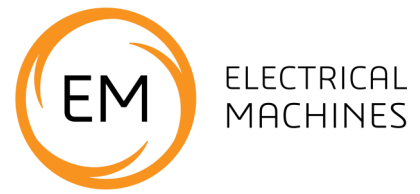
Variation of torque with speed

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.

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?

Worksheet 5

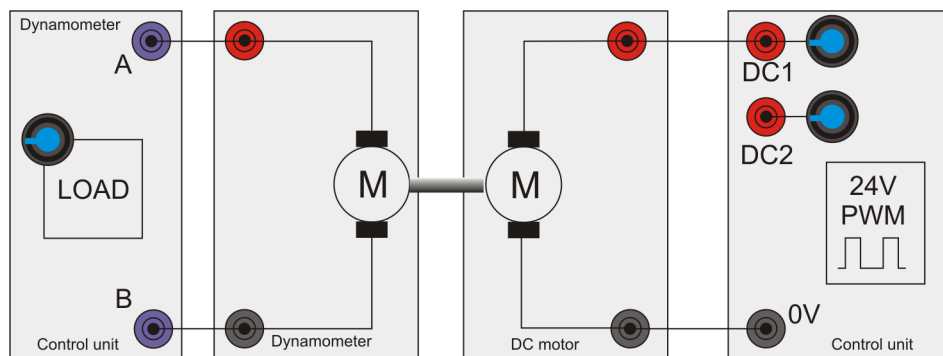
DC motor characteristics 2



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 'Open LogDC.bat'.
- 5) Set the PWM DC output to around 50%.
- 6) Press the 'Sweep' button to run an automatic speed / torque log.
- 7) Repeat step 6 for DC outputs of 40%, 60%, 70%, 80% and 90%

- 8) The program logs the results into an Excel file. Its name is given in the 'Properties' section on the right of the screen. The program is stored 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.

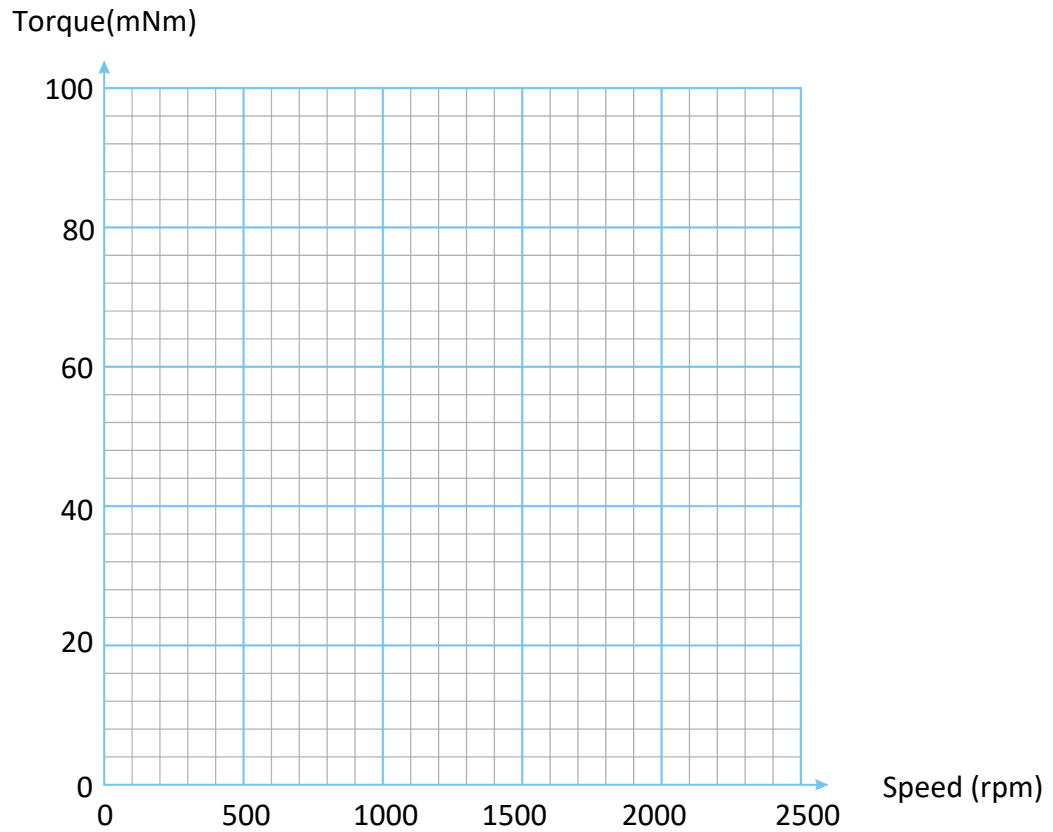
- 9) On the next page, sketch the results.

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.

Worksheet 5

DC motor characteristics 2



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

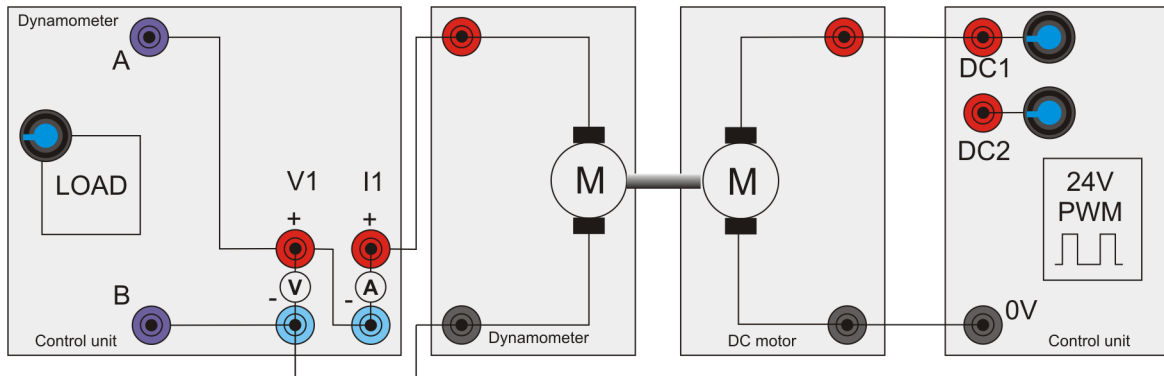
Worksheet 6

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 'Open Control_DC.bat'.
- 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?

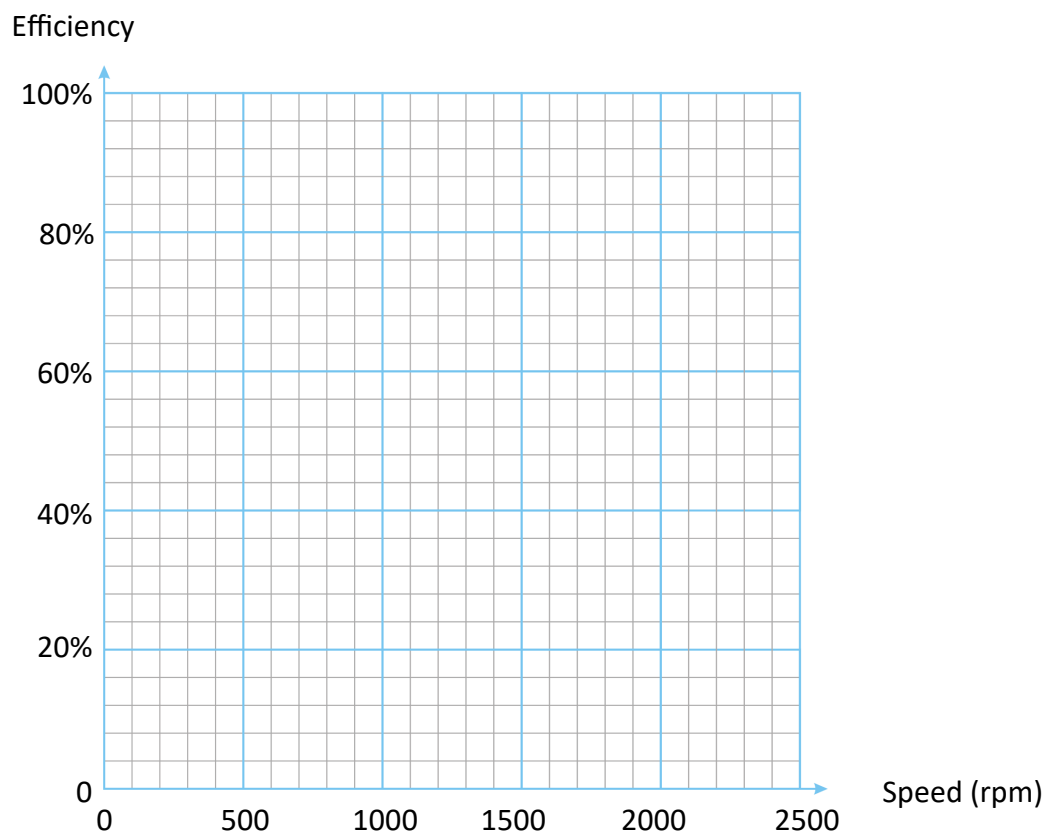
The efficiency of an electrical machine changes with its speed. Choosing the right combination of machine and gearbox for an application will help to get optimal efficiency.

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%.

Worksheet 7

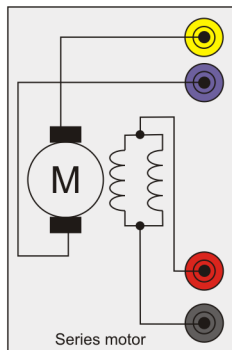
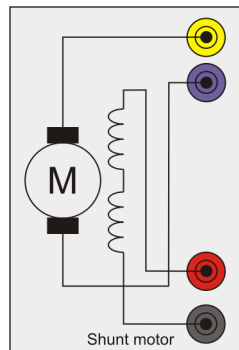
Shunt and series motor basics



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.
- 2) Use the Ohm's law formula, $I = V/R$, to calculate the theoretical field currents when the field windings are connected to a 24V DC supply.
- 3) Repeat the resistance measurement for the rotor windings
- 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		

Worksheet 7

Shunt and series motor basics

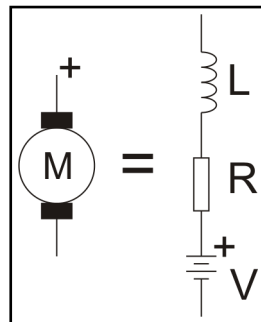
So what?

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 (e.m.f.) which acts to oppose the flow of current in the windings. You can see the equivalent circuit below.

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

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



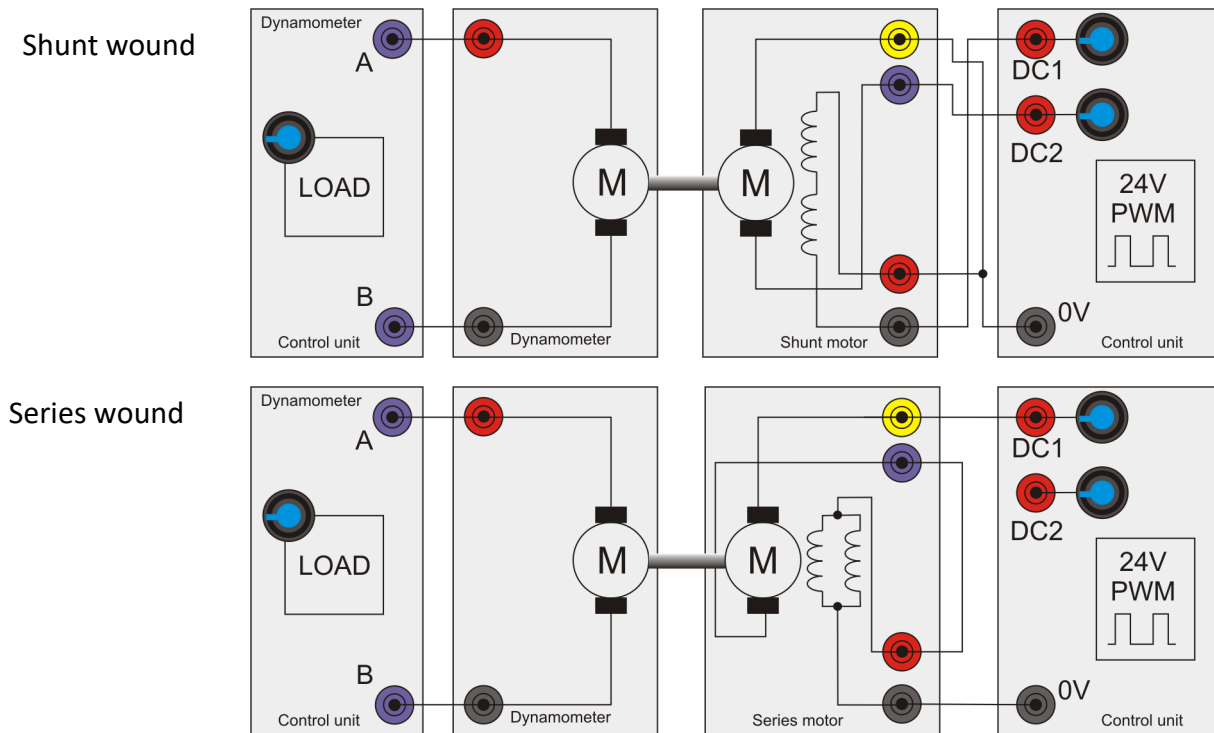
Equivalent circuit of a simple DC machine.

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.

Worksheet 7

Shunt and series motor basics



Note: the circuits are similar but not quite the same.

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 'Open Control_DC.bat' program. Set the output on DC1 (the field coils) to 100% or 24V. Set the output on DC2 (the rotor) to around 70% and press 'RUN'.
- 3) Increase DC2 in steps of 10% up to 100%. 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 output on DC1 to 40% and press RUN.
- 6) Increase DC1 in steps of 5%. Again, record the output voltages and currents each time. The currents eventually get so high that the control unit cuts out.

So what?

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

The control unit cuts out at a certain speed (current) for the series motor. The current is limited to protect the motor and the control unit.

The control unit delivers an output power up to 100W. It cuts out when this is exceeded and shows an 'Err' message on the front of the unit. The software application stops.

Worksheet 7

Shunt and series motor basics



Shunt motor

DC1 %	DC2 %	I1 in A	I2 in A	Speed in RPM
100	70			
100	80			
100	90			
100	100			

Series motor

DC1 %	I1 in A	I2 in A	Speed in RPM
40			
45			
50			
55			

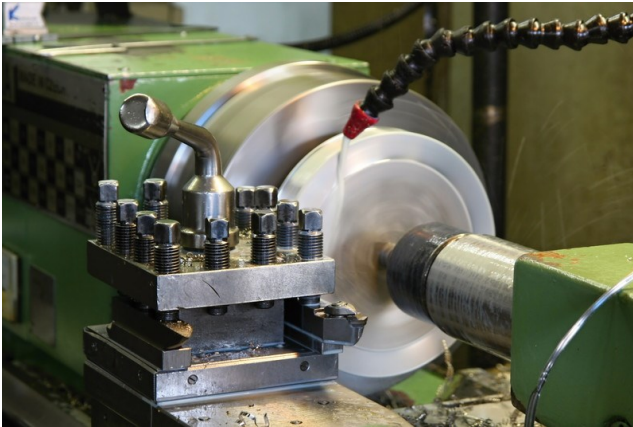
Indicate clearly the point at which the control unit cuts out.

So what?

The speed of the Series motor is very high. The Control unit is designed to cut out at speeds above 3100 RPM. Above this the Dynamometer produces voltages that can be dangerous.

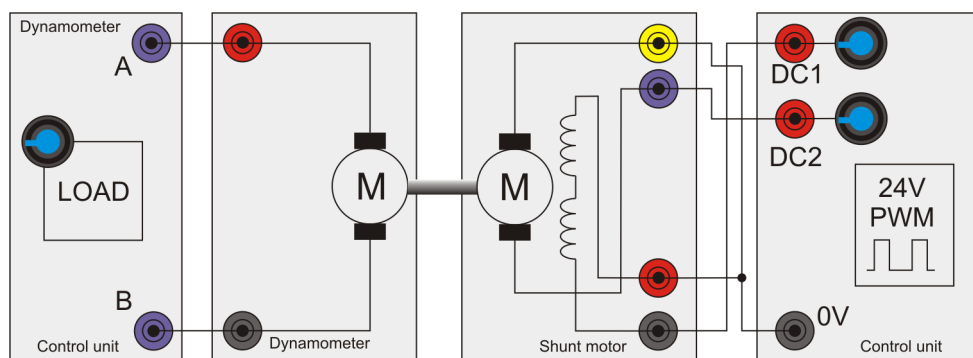
Worksheet 8

Shunt-wound motor characteristics



Speed control is an important element of electromechanical 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.

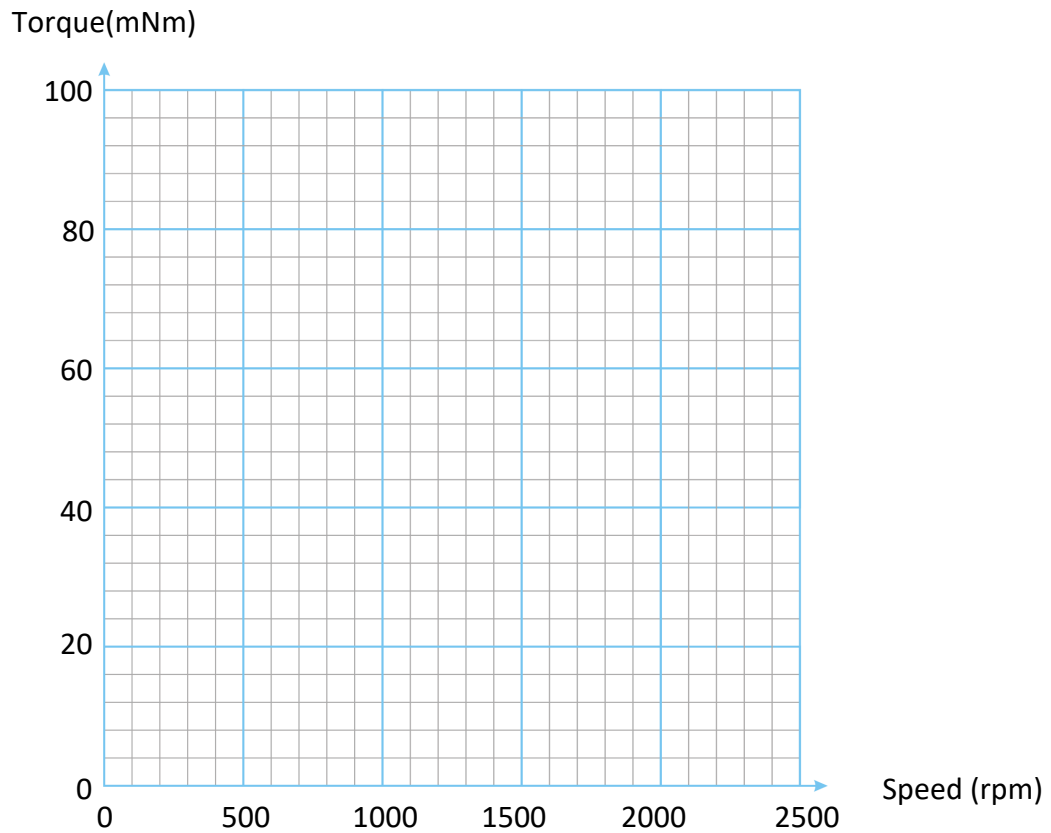


Over to you:

- 1) Set up the shunt motor as shown above.
- 2) On your PC, run the program 'Open Log_DC.bat'.
- 3) Open the program. Set the DC1 output to 100% to power the **stator winding** and the DC2 output to around 50% for the **rotor**.
- 4) Run the program and press 'Sweep' to take an automatic set of readings for a range of dynamometer loads.
- 5) Repeat steps 4 for **rotor** DC outputs of 60%, 70%, and 80%.
- 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.

Worksheet 8

Shunt wound motor characteristics



The effect of speed on torque for different values of stator coil volt-

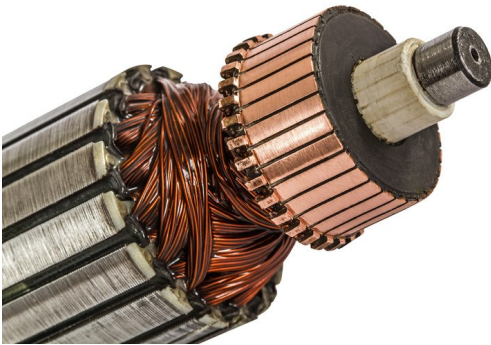
Over to you:

- 1) With the same equipment set up, load the program 'Open Control_DC.bat'
- 2) Route the Dynamometer output to the control unit Voltmeter. The software gives Dynamometer current. Now you can get Dynamometer voltage and current and calculate power in.
- 3) Run the program and set the DC output for the rotor to 50% and the output for the stator winding to around 50%.
- 4) Complete the table to show speed, output power, dynamometer power and efficiency.

Stator Voltage DC1 (V)	Rotor Voltage DC2 (V)	Input power (W)	Speed (rpm)	Angular speed (rads/s)	Torque (Nm)	Output power (W)	Efficiency (%)
50%	50%						
70%	70%						

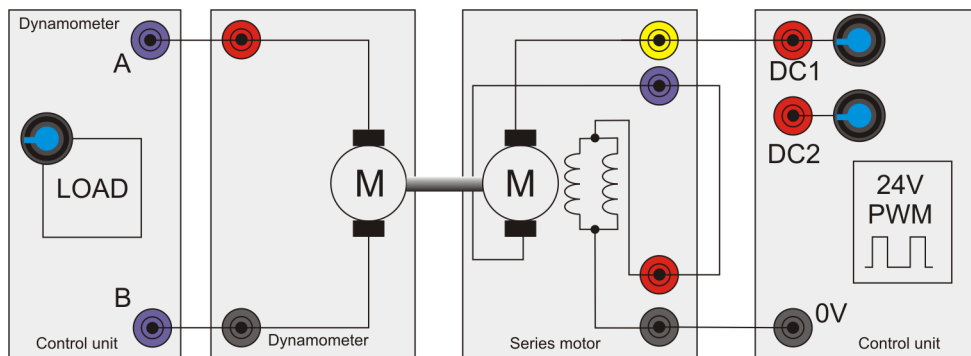
Worksheet 9

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.

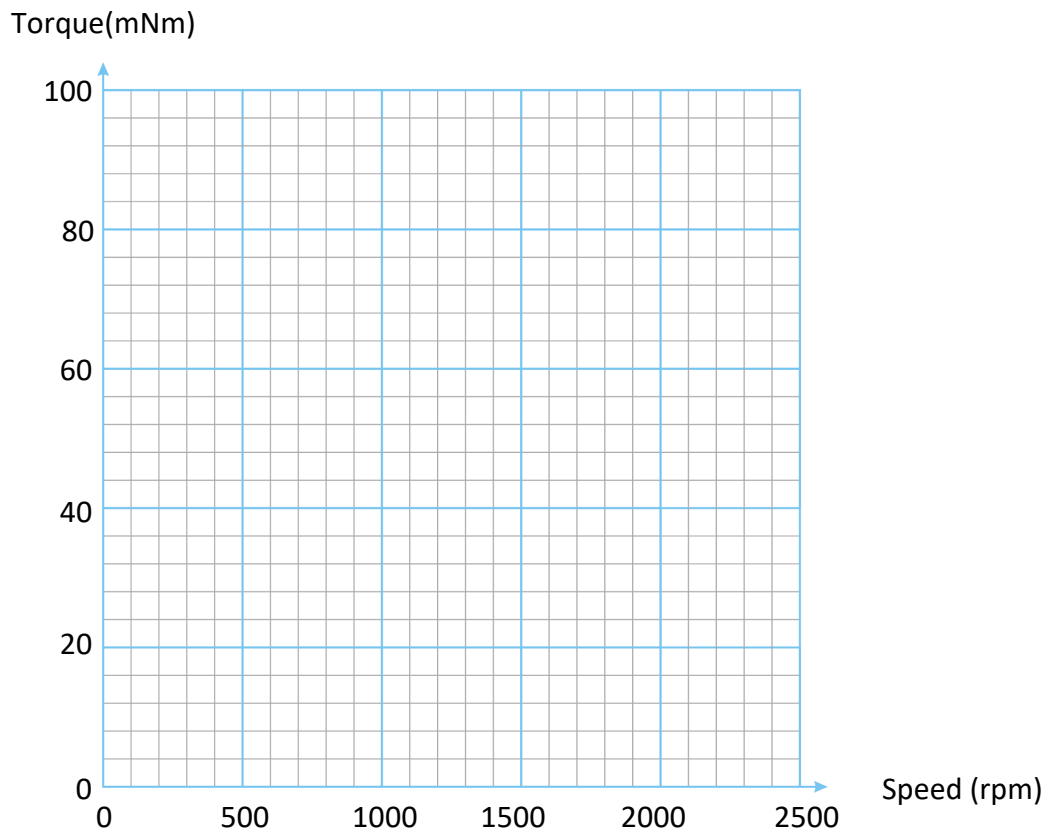


Over to you:

- 1) Set up the series motor as shown above.
- 2) On your PC, run the program 'Open Log_DC.bat'.
- 3) Run the program with the DC output set to around 35%.
- 4) Make sure the motor is putting pressure on the load cell rather than the balance - just reverse the direction of rotation if it is not.
- 5) Press 'Sweep' to take an automatic set of readings for a range of dynamometer loads.
- 6) Repeat steps 3, 4 and 5 for DC outputs of 40%, 45%, and 50%.
- 7) When the sequence has finished load the results into Excel and use Excel to plot a graph of speed vs torque.
- 8) On the next page sketch graphs to show traces for all output voltages.

Worksheet 9

Series wound motor characteristics



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

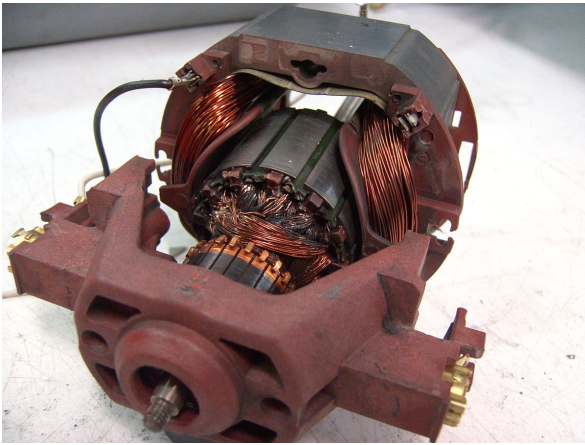
Over to you:

- 1) With the same equipment set up, load the program 'Open Control_DC.bat'.
- 2) Route the Dynamometer output to the control unit Voltmeter. The software gives Dynamometer current. Now you can get Dynamometer voltage and current and calculate power in.
- 3) Run the program and set the DC1 output to around 30%
- 4) Complete the table to show speed, output power, dynamometer power and efficiency.

Supply Voltage DC1 (V)	Input power (W)	Speed (rpm)	Angular speed (rads/s)	Torque (Nm)	Output power (W)	Efficiency (%)
30%						
60%						

Worksheet 10

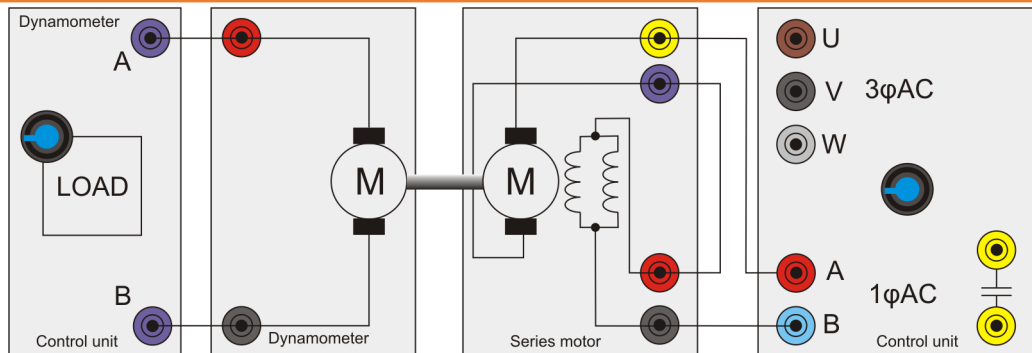
Universal motor



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 'Open Log_1Phase.bat' and press 'Play'.
- 3) Set the Driver voltage to around 20V.
- 4) With the output frequency set at 50Hz, run the program and use the 'Sweep' function to take an automatic set of readings over a range of dynamometer loads.
- 5) When the sequence has finished, use Excel to plot a graph of speed vs torque.
- 6) Repeat this procedure for frequencies of 60, 70, and 80Hz.
- 7) On the next page sketch graphs to show traces for all frequencies. Compare AC and DC

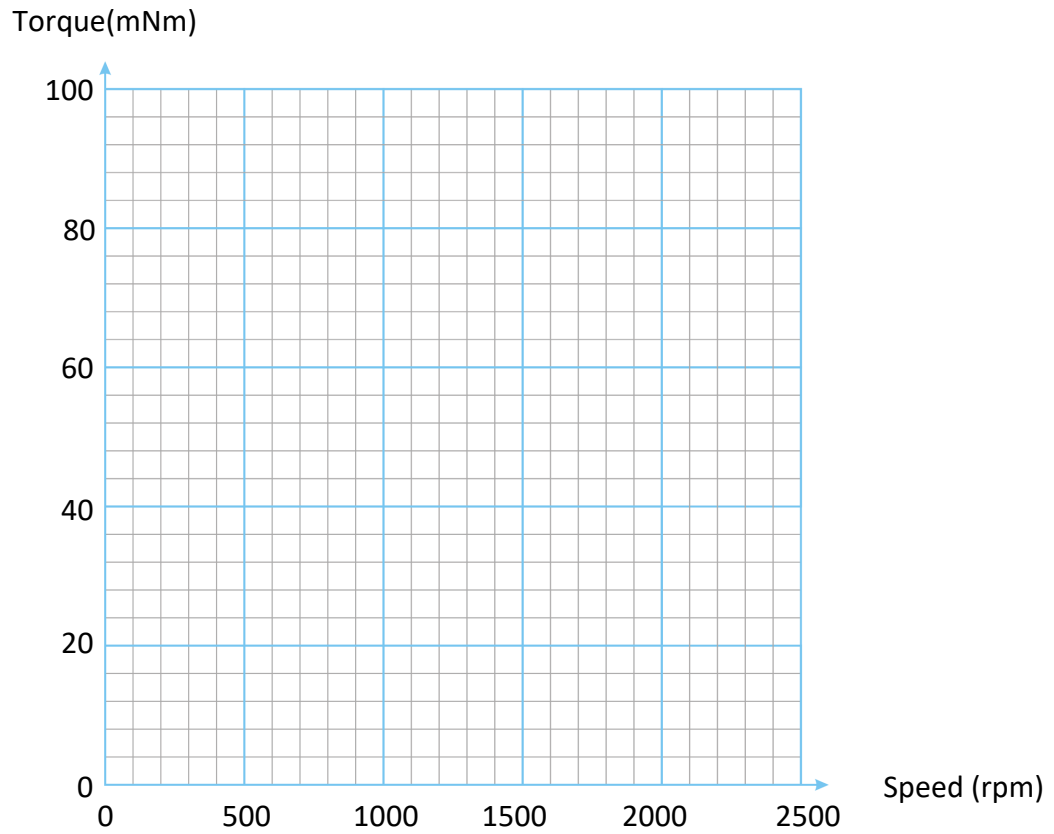
properties of the universal motor.

How do you change direction of motion?

Set the frequency to 40Hz - what happens?

Worksheet 10

Universal motor



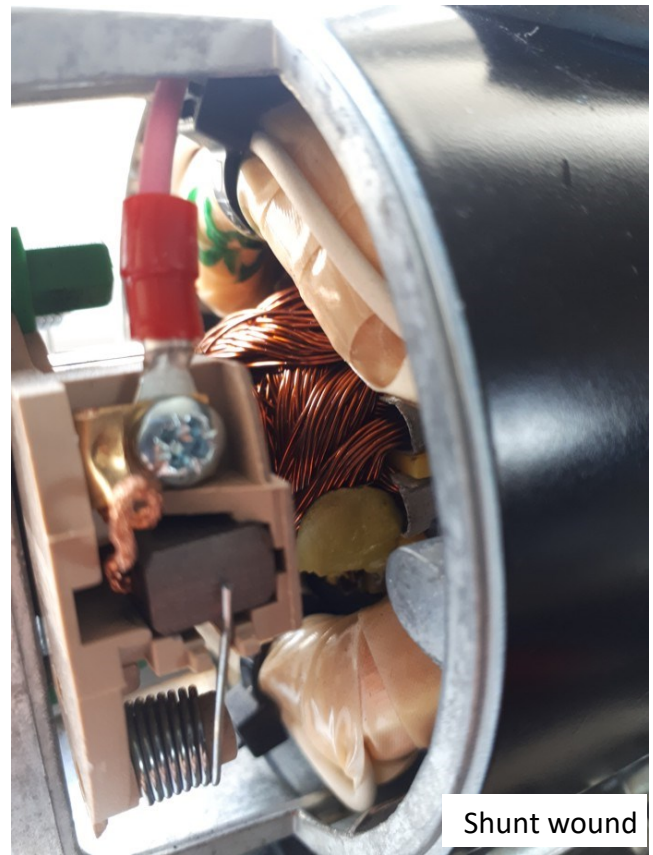
The effect of speed on torque for different values of output frequency.

Worksheet 11

Comparing shunt and series motors



Series wound



Shunt wound

Over to you

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

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

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

Worksheet 12

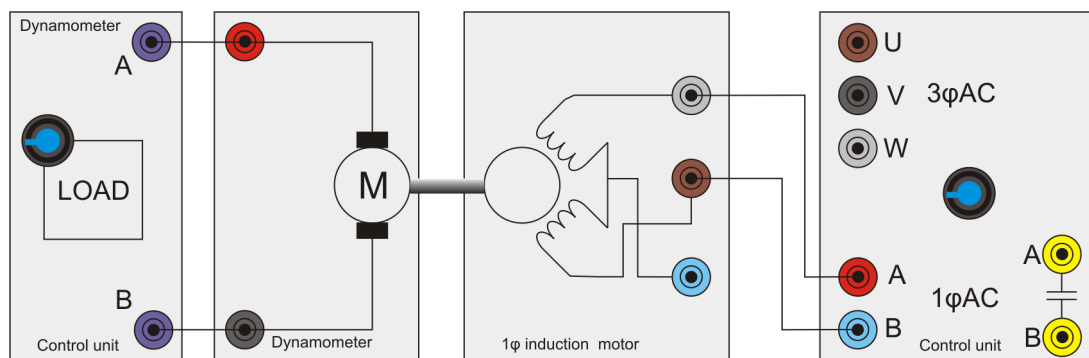
Single-phase induction motor



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 maintenance.

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 'Open Control_1Phase.bat'
- 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.

Worksheet 13

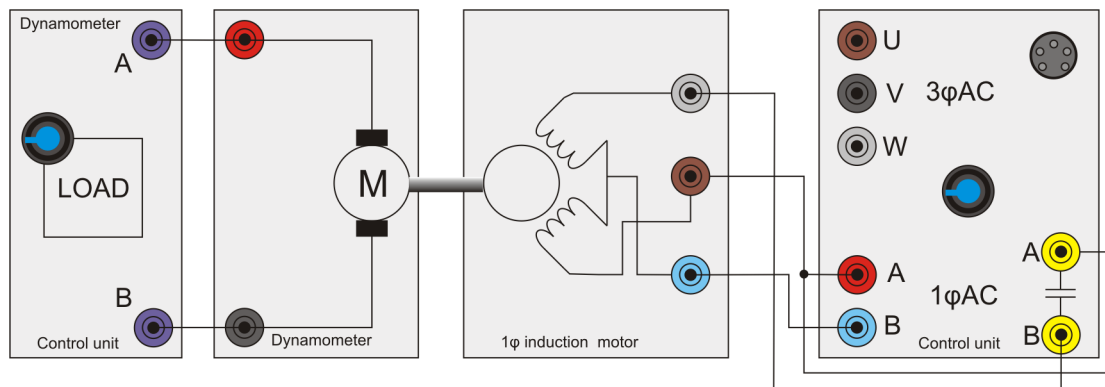
Single phase induction motor - cap start



In many situations, engineers have a choice over which type of motors to use.

For simple AC applications, 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 long-term reliability required.



Over to you:

- 1) Set up the single phase induction motor as shown in the diagram above.
- 2) On your PC load 'Open Log_1phase.bat' and press 'Play'.
- 3) Use settings Voltage: 20V, CAP start, SINE.
- 4) Once the motor is running select CAP Run.
- 5) With the output frequency set at 50Hz, 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.
Repeat this procedure for frequencies of 60, 70, 80, 90 and 100Hz.
- 8) On the next page, sketch graphs to show trac-

es for all frequencies.

So what?

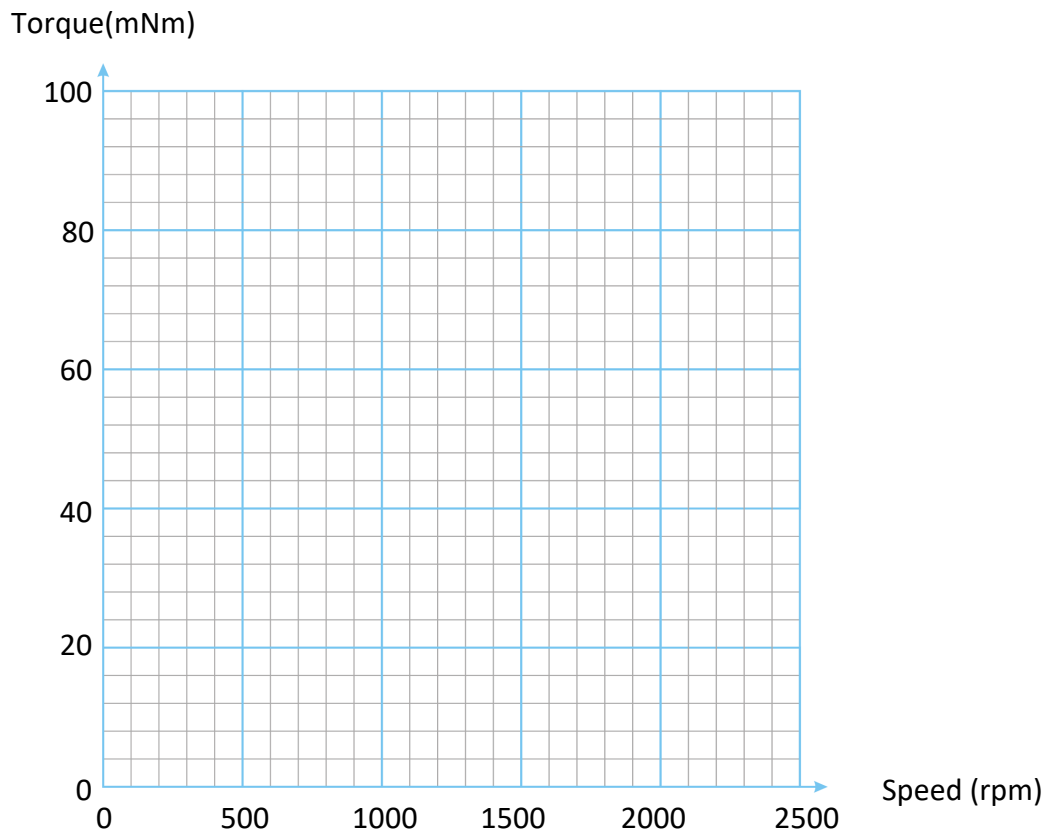
How do you change direction of rotation?

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

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

Worksheet 13

Single phase induction motor - cap start



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

Worksheet 14

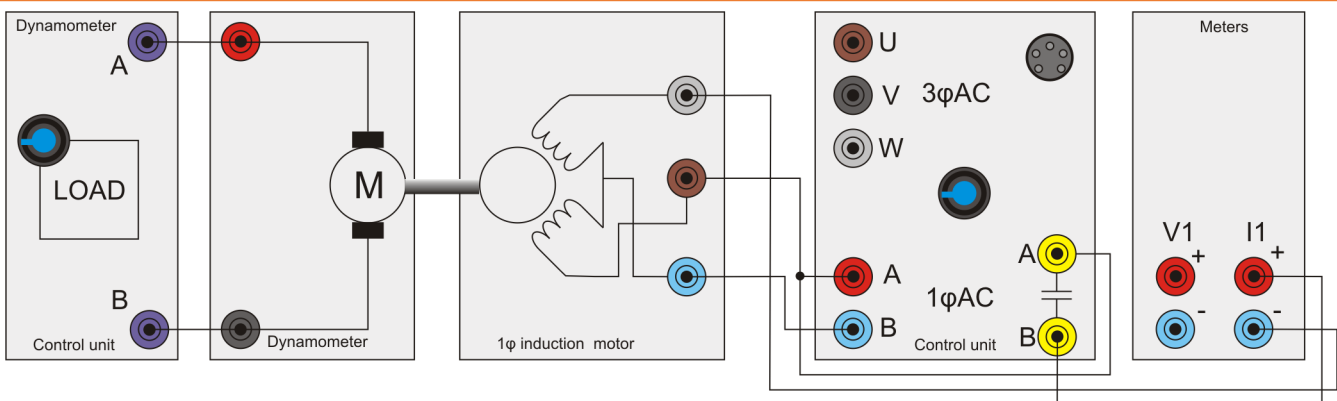
Phase shift in induction motors



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 Start/Run capacitors.
- 2) On your PC run 'Open Control_1Phase.bat'.
- 3) Use settings Voltage: 20V, CAP start, SINE.
- 4) Set the frequency to 50Hz.
- 5) Set the 'scope to show I and IA, using the 'Properties' on the right hand side of the screen. Capture the waveform.
- 6) Sketch what you see on oscilloscope grid on the next page .
- 7) Repeat the procedure for frequencies of 60Hz, and 70Hz. For each frequency, record the currents and phase shift.
- 8) Investigate the effect of changing from the 'Start' to the 'Run' capacitor, using the 'Capacitor Start / Run' selector switch.

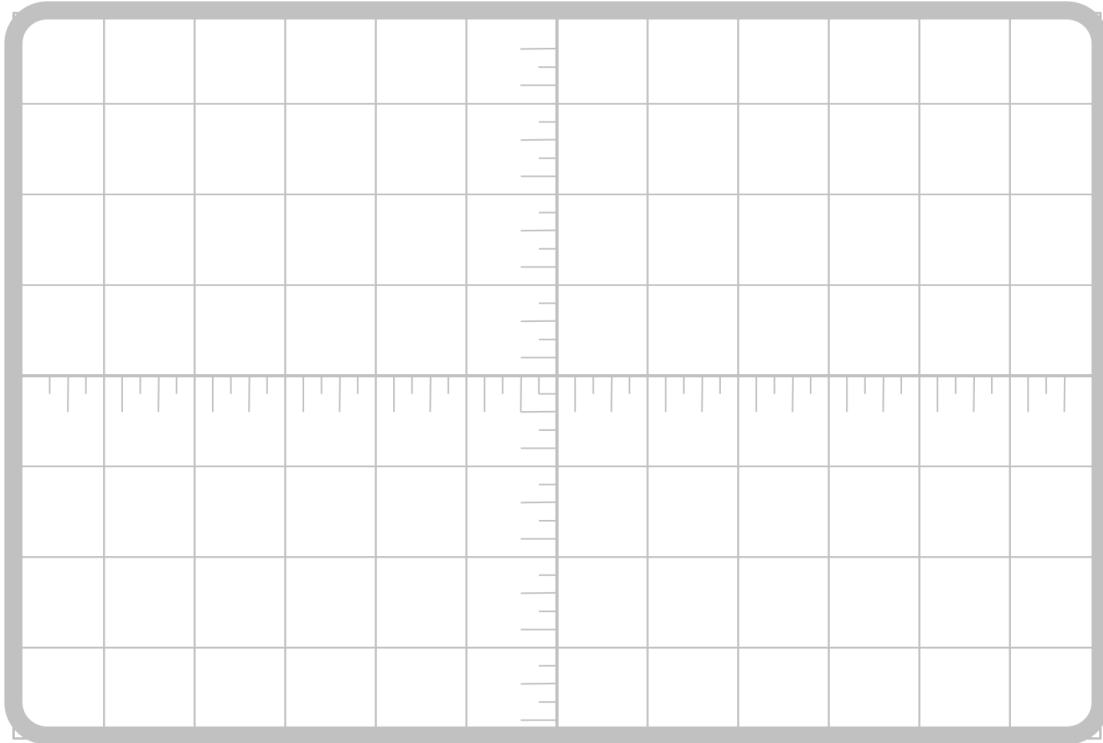
So what?

Without a capacitor, the motor would not start. In some systems - like this one - 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' capacitor than the 'Start' capacitor for each frequency?

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

Worksheet 14

Phase shift in induction motors



AC drive frequency (Hz)	Output power (W)	Output voltage (V)	Output current A (A)	Phase (deg)	Resolved power (W)	Efficiency (%)
50Hz						
60Hz						
70Hz						

Note that you can change the current settings in the software properties box on the right of the screen.

The Resolved power can be determined through trigonometry using $V \times I \times \cos(\text{Phase})$.

Worksheet 15

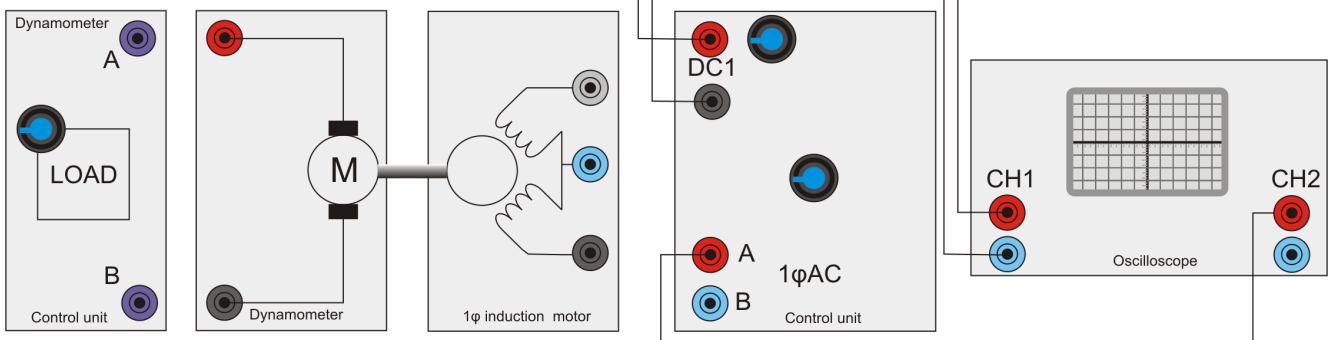
Variable frequency drive strategies



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.



**Do not use a PC-based oscilloscope.
Use a traditional 'scope with no USB connection to the PC.**

Over to you:

- 1) Set up the single-phase induction motor as shown in the diagram above.
In this exercise, we are just looking at signals and so the motor and dynamometer do not need to be connected. However, the motor must be in the dynamometer cradle in order to activate the power supply.
- 2) On your PC run 'Open Control_1Phase.bat'.
- 4) Select an output voltage of 24V and a frequency of 50Hz.
- 3) Connect the oscilloscope as shown. In this application, the DC1 output gives a pulse at the start of each cycle. This can be used to trigger the scope on channel 1 whilst looking at the waveform from output A on channel 2.

- 4) On the next page, sketch the waveform of the single-phase AC output A.

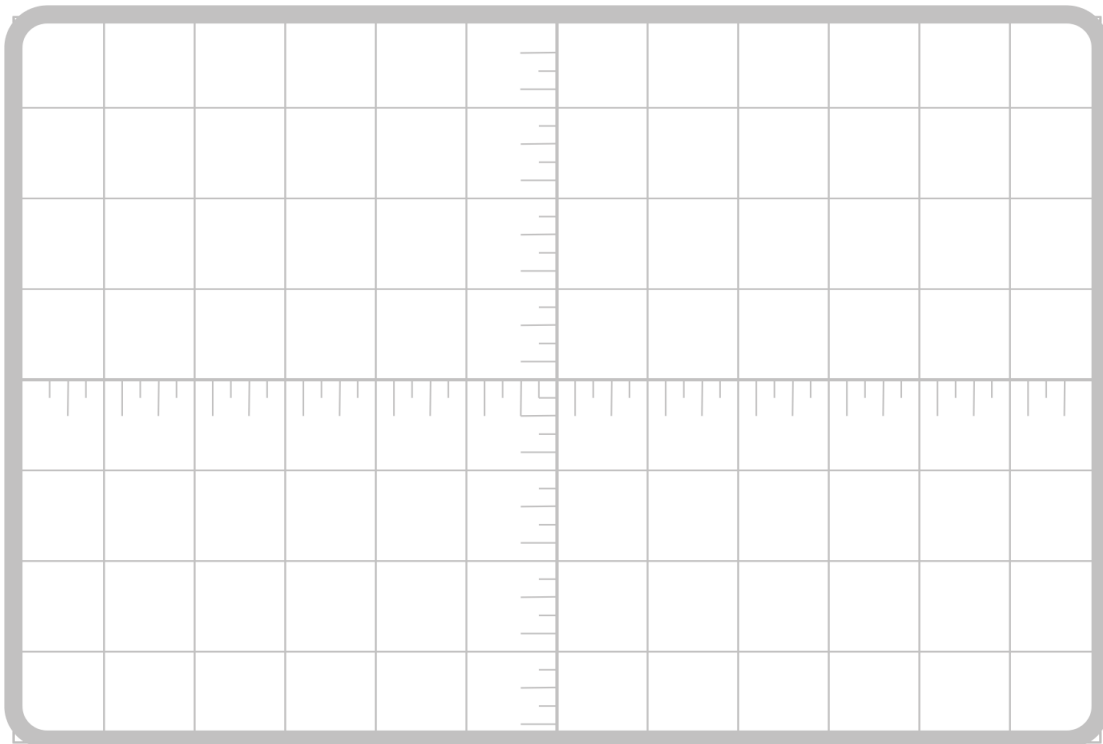
So what?

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.

Worksheet 15

Variable frequency drive strategies



Over to you:

- 1) Alter the output from SINE to DIGITAL. Sketch the output waveform on the same graph above.
- 2) With the oscilloscope connections unchanged add the single phase AC induction motor and start/run capacitor . Refer to the connection diagram in the Worksheet on Single phase induction motor if you need to.
- 3) With the dynamometer load at around 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 characteristics

AC drive frequency	Speed in rpm	Torque	Output power	Input power
50Hz				
60Hz				
70Hz				

Worksheet 15

Variable frequency drive strategies



Over to you:

- 1) In the software application, click on the button marked 'Sine'. This reverts the output of the drive back to a pseudo-sine wave.
- 2) Sketch the output at **A** when using the trigger pulse on DC1. (You could compare the signal from **B**.)
- 3) Then, with the dynamometer load at around 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 characteristics

AC drive frequency	Speed in rpm	Torque	Output power	Input power
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.

Worksheet 15

Variable frequency drive strategies



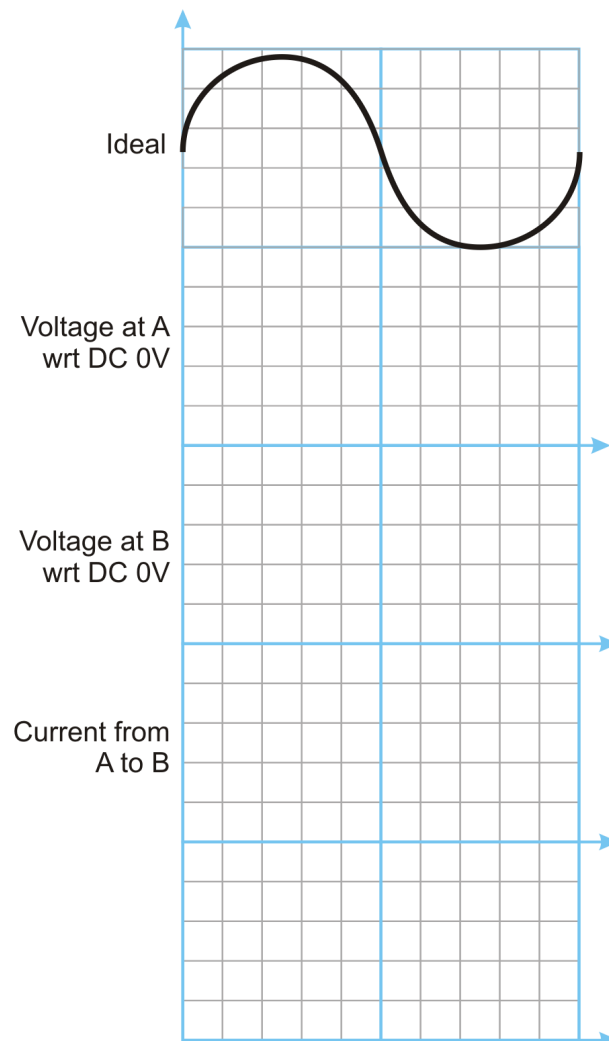
Over to you:

1) In the block diagram of the control unit in the 'Reference' section, 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.

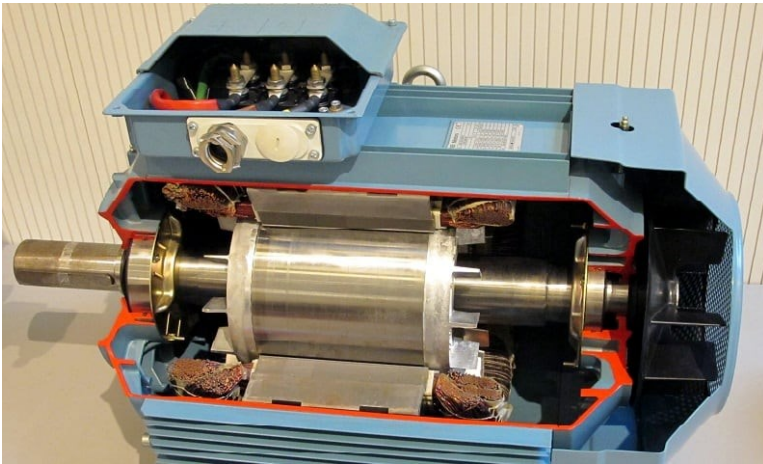
2) Obtain the waveforms and sketch them on the axes below.

You can use the on board oscilloscope here to look at the current waveform.
However the on-board scope is not fast enough to show PWM accurately.



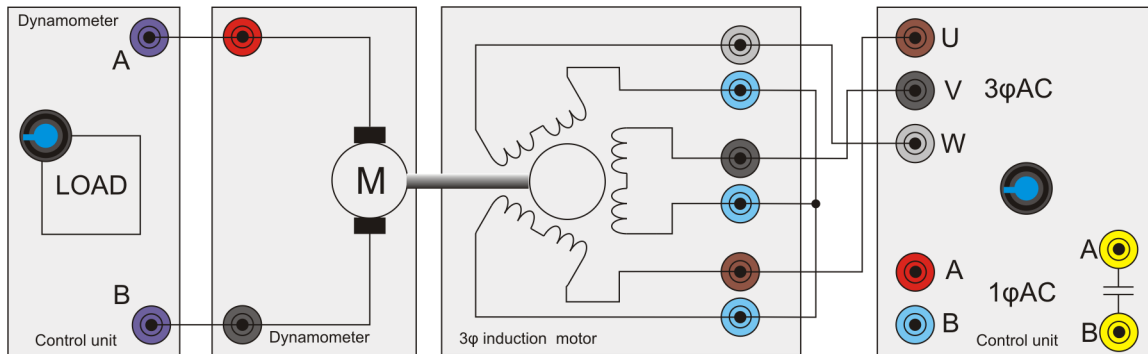
Worksheet 16

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.



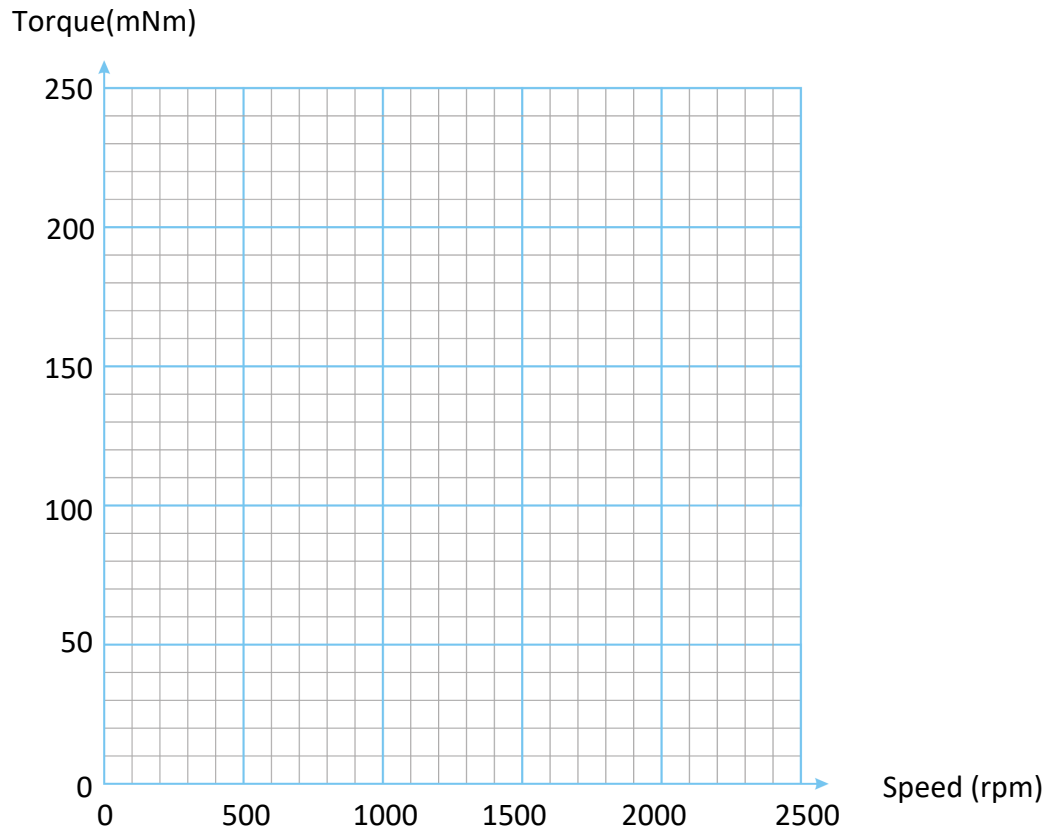
Over to you:

- 1) Set up the three phase induction motor as shown in the diagram above.
- 2) On your PC, load 'Open Log_3phase.bat'.
- 3) Use settings SINE, 20V, IMPROVED.
- 4) With an output frequency of 50Hz, run the program and take an automatic set of readings over a range of dynamometer loads.
- 5) Repeat this for output frequencies of 60, 70, 80, 90, 100 Hz.
- 6) If you can plot all output lines on the same graph.
- 7) On the next page, sketch the results .

How do you change direction of rotation?

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.

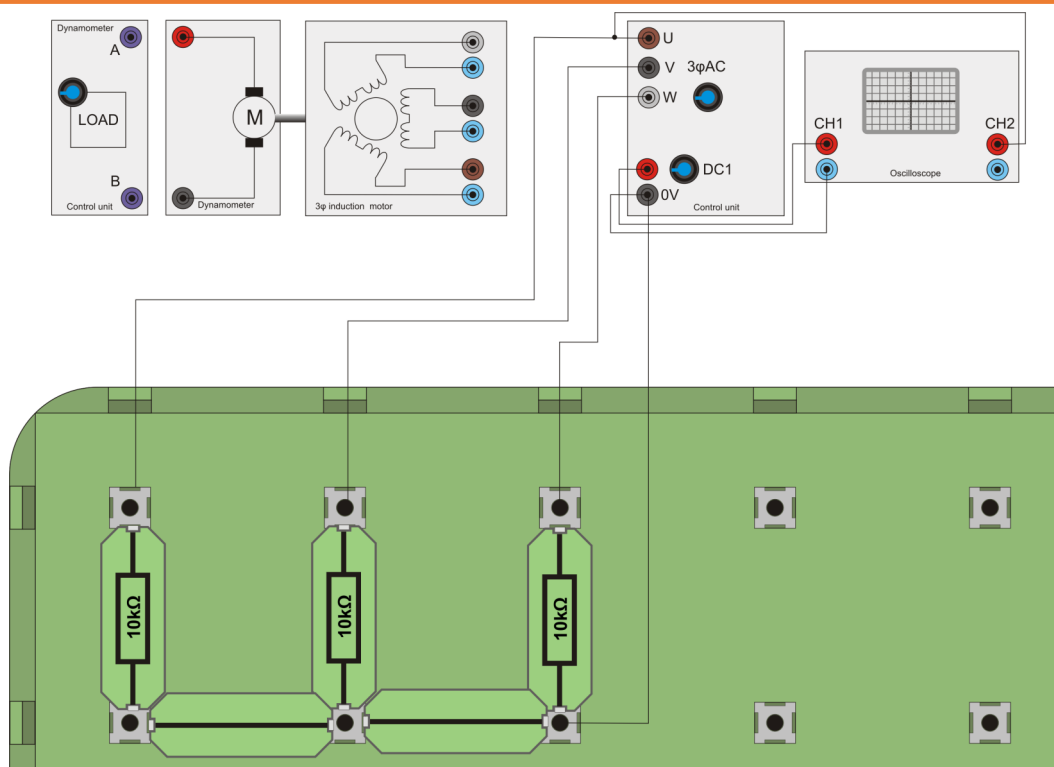
How does it compare for efficiency? Research the reason for this and give your findings below.

Worksheet 17

Three-phase motor drive strategies



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. The photograph shows a three-phase induction motor factory in China.

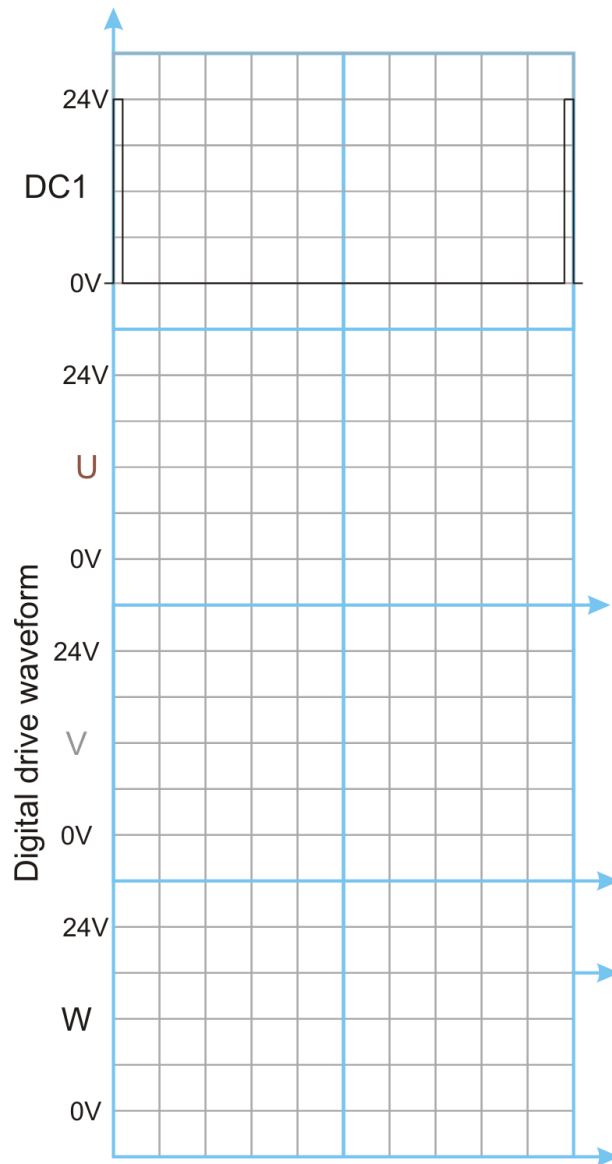


Over to you:

- 1) Set up the three-phase induction motor as shown in the diagram above. As this exercise looks only at the signals the generator unit creates, there is no need to connect the three-phase motor to the supply.
- 2) Connect three $10\text{k}\Omega$ resistors as loads between U, V, W and 0V.
- 3) On your PC run 'Open Control_3Phase.bat'.
- 4) Press 'Play' and put the software into digital mode by pressing the 'Sine' button. This changes the waveform from pseudo-sine, constructed with PWM to a simple digital waveform where U, V, and W are 120 degree shifted square waves. Set the output frequency to 50Hz and press 'Run'.
- 5) Trigger an oscilloscope on the DC1 output. On the second channel display the output U.
- 6) Sketch the waveforms of signals U, V, and W, relative to the timing waveform on DC1.

Worksheet 17

Three phase motor drive strategies



So what?

Notice that these pulses are 120° apart. Together, they make up the basic three-phase waveform.

You should notice that each waveform spends some time at 0V, some time at 24V and some time when it is in between, at around a volt or so. What you are seeing is the three stages of drive of each output - forced to 0V, forced to +24V and left open circuit. In this last stage, the voltage is not dictated by the power supply but by the rest of the circuit.

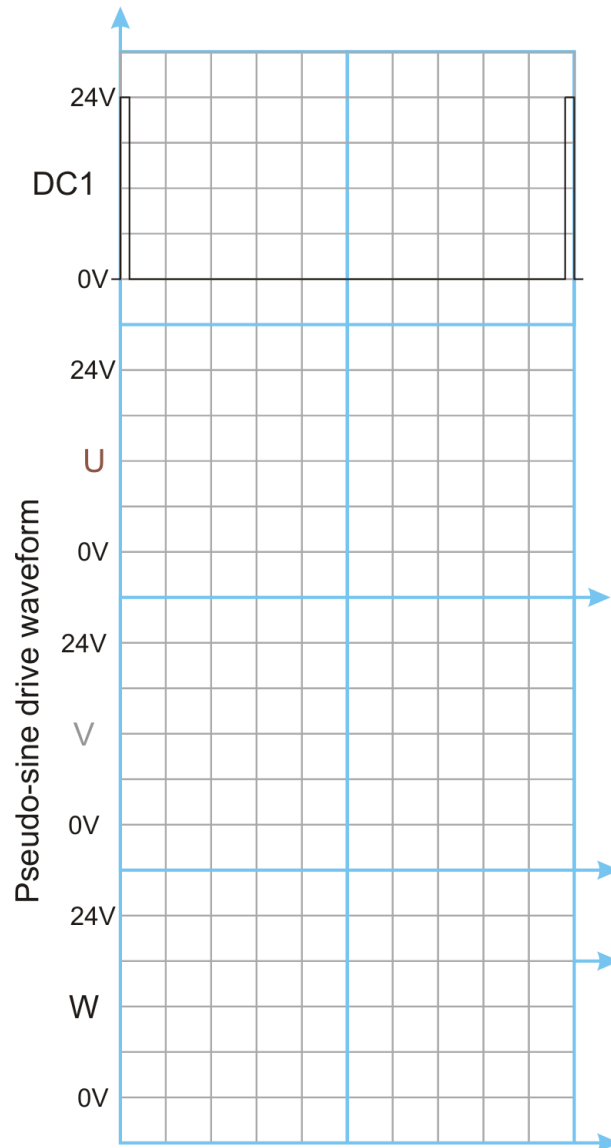
Worksheet 17

Three phase motor drive strategies



Over to you:

- 1) Still with the $10k\Omega$ resistive loads in place, change the drive waveform to pseudo sine at 50Hz.
- 4) Once again, sketch the waveforms of signals U, V, and W , relative to the timing waveform on DC1.



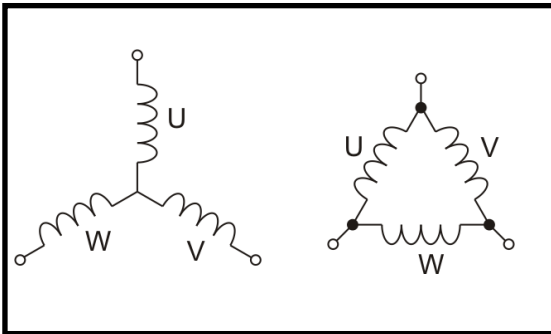
So what?

You now see the waveforms that make up the three-phase drive. There are in fact six separate steps to this. Hence it is often called the 'six step three-phase motor drive system'.

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.

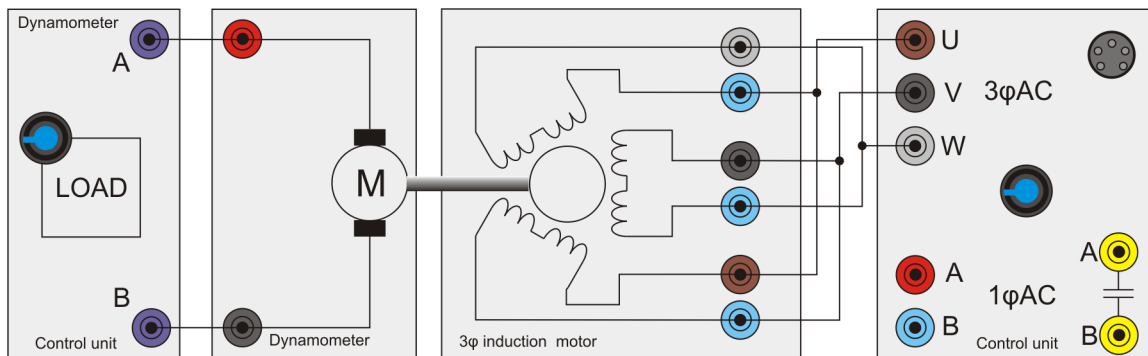
Worksheet 18

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.



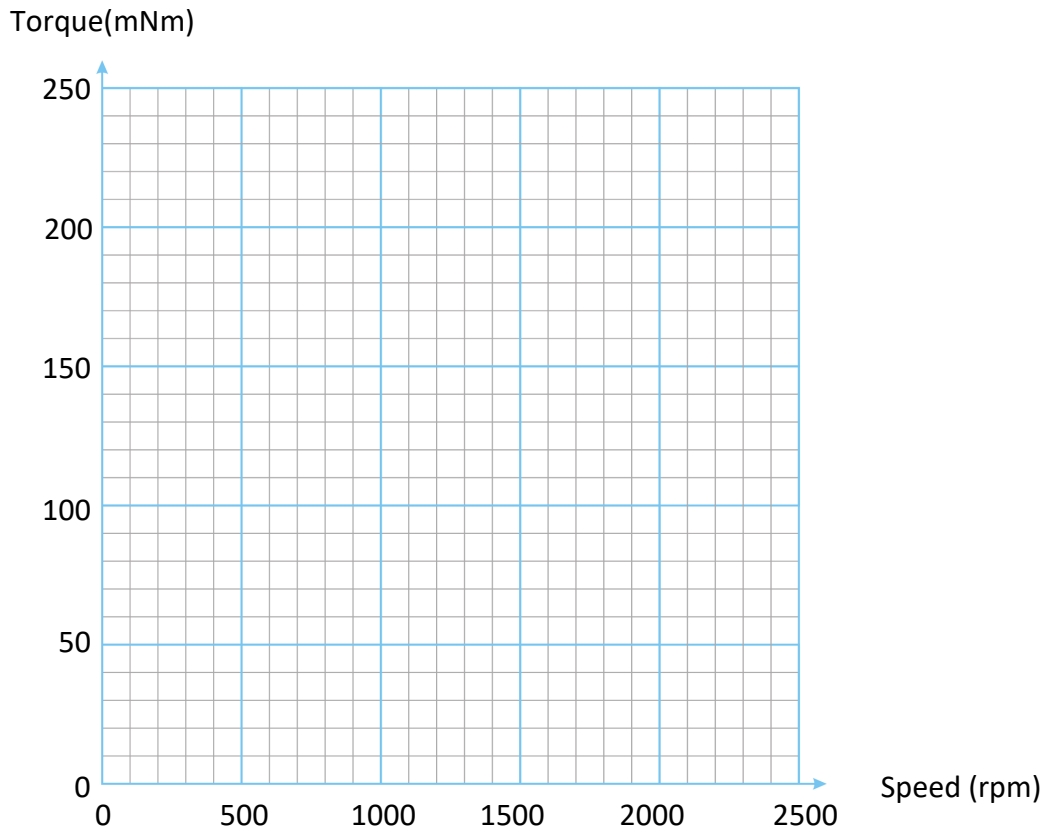
Over to you:

- 1) Set up the three phase induction motor as shown in the diagram above.
- 2) On your PC, load 'Open Log_3phase.bat'.
- 3) Reduce the output voltage to 12V using the slider. 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) With an output frequency of 50Hz, run the program and take an automatic set of readings over a range of dynamometer loads.
- 4) Repeat this for output frequencies of 60, 70, 80, 90, 100 Hz.
- 5) If you can plot all output lines on the same graph.
- 6) On the next page, sketch the results .

How do you change direction of rotation?

Worksheet 18

Delta configuration



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.

Worksheet 19

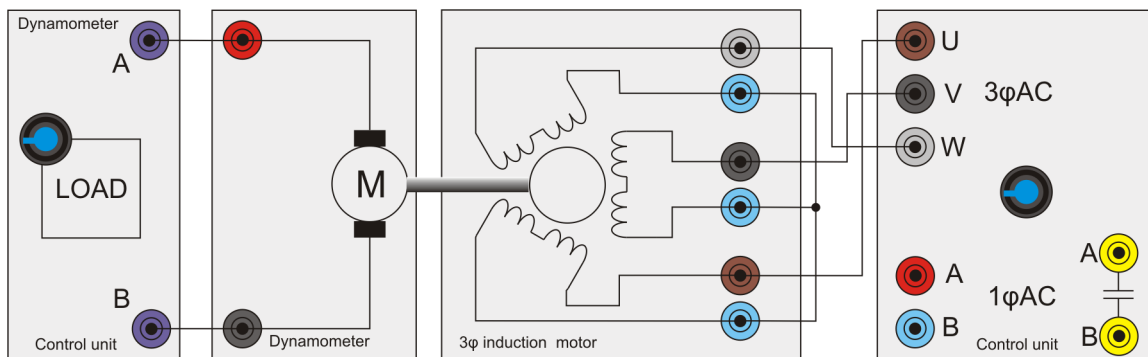
Understanding slip



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 'Open Control_3Phase.bat'.
- 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, 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	Speed	Slip
40Hz		
50Hz		
60Hz		
70Hz		
80Hz		

Slip vs drive frequency - no load

Dyno load	Speed	Slip
0%		
50%		
75%		
90%		
full		

Slip vs load - drive frequency = 50%

Worksheet 18

Understanding slip



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Over to you:

Explain these readings.

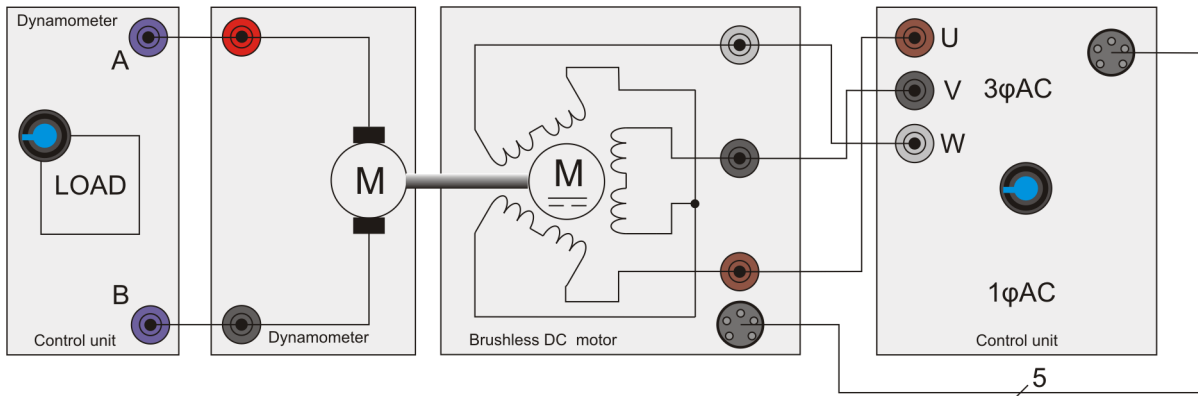
Worksheet 20

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.



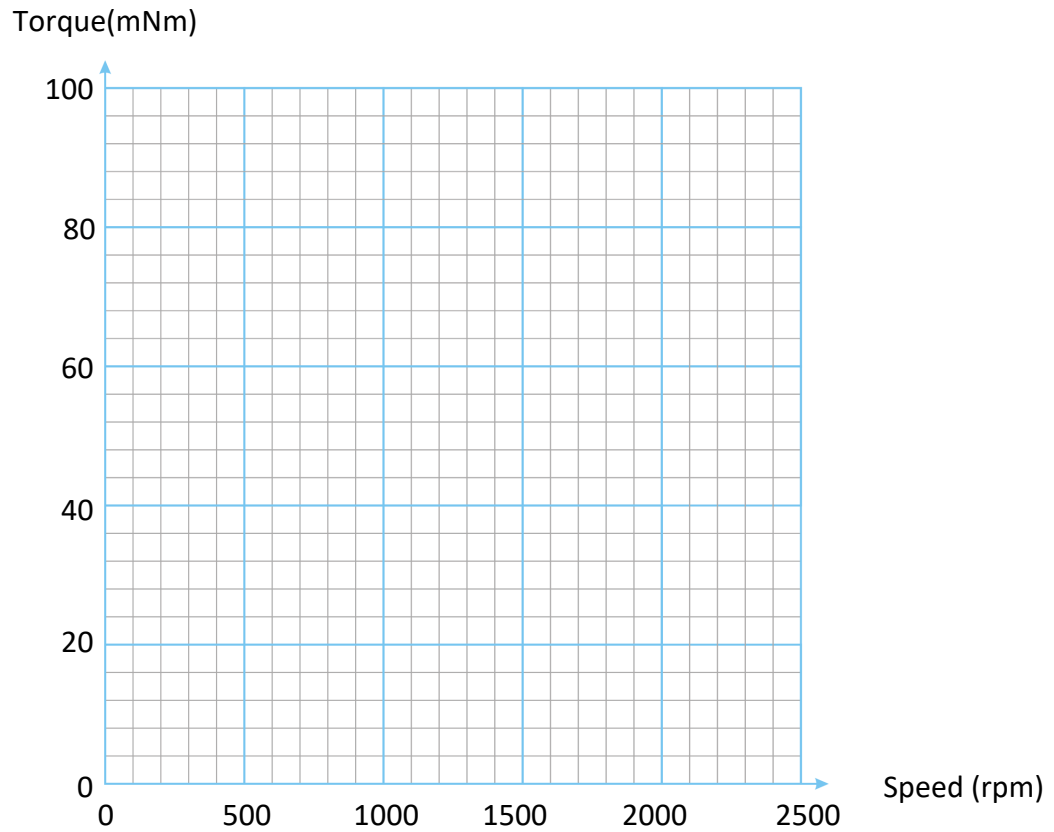
Over to you:

- 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 load 'Open Log_3phase.bat.'
- 3) With the initial frequency set to 40Hz, run the program to get a set of readings.
- 4) Repeat this step for drive frequencies of 50, 60, 70, and 80Hz.
- 5) On the next page, sketch the results.

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

Worksheet 20

Brushless DC motor



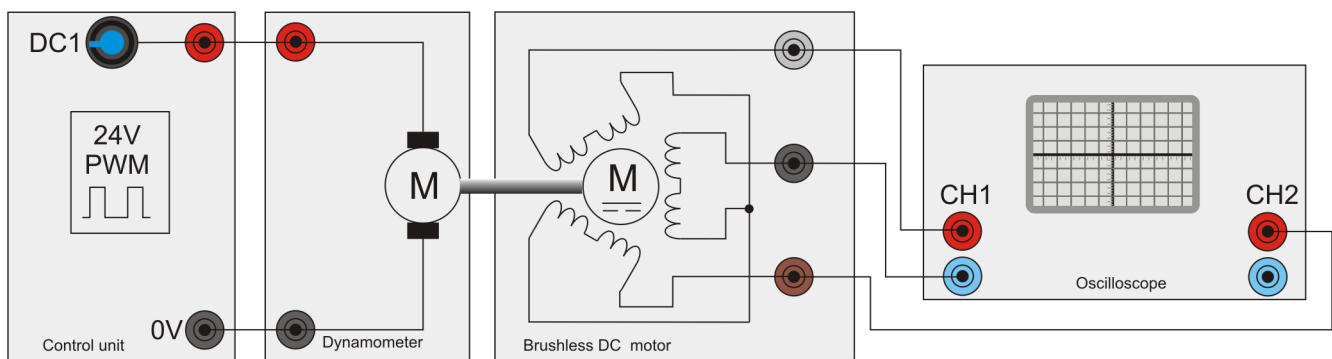
The effect of speed on torque for different values of output frequency.

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.



Do not use a PC-based oscilloscope.

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.
- 2) On your PC load 'Open Control_DC.bat'.
- 3) Set a duty cycle of 40% on the DC1 output.
- 4) Press the 'RUN' button on the software.
- 5) Vary the DC output from 40% to 100% in 10% steps.
- 6) Make a note of the peak to peak output voltage from the brushless motor and fill in the table on the next page.
- 7) Sketch the three phase waveform on the next page.
- 8) How does the waveform relate to the motor RPM?

3p motor drive	Speed rpm	Vout pk-to-pk
40%		
50%		
60%		
70%		
80%		
90%		
100%		

So what?

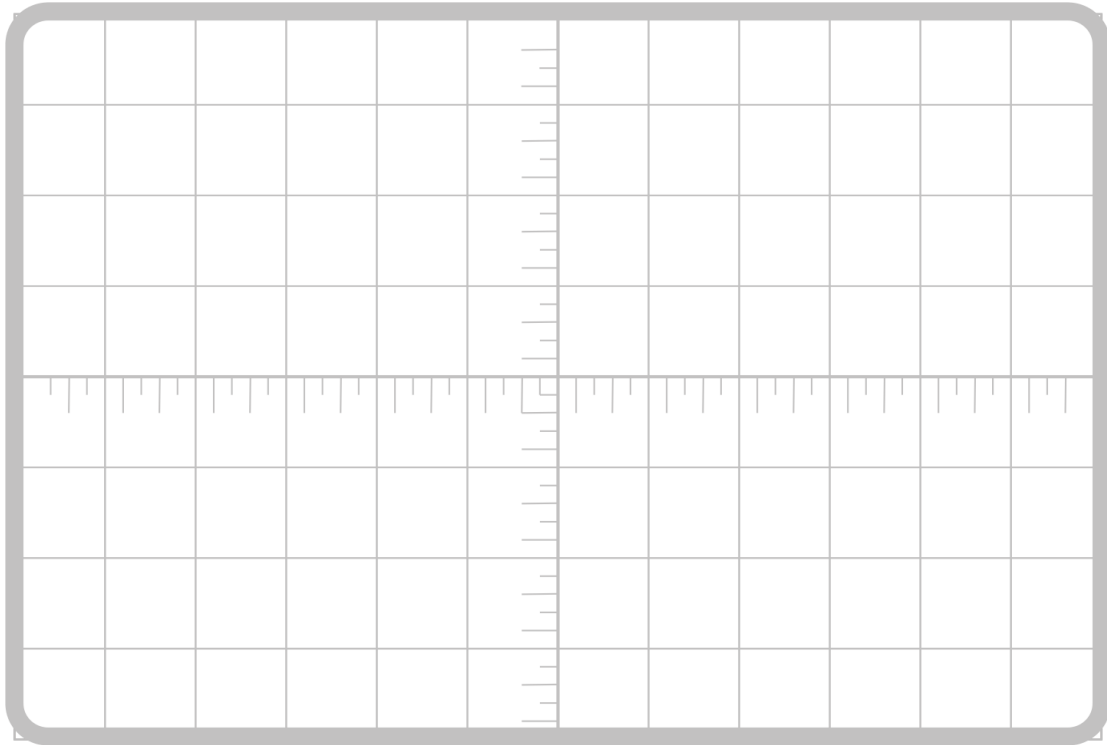
The great thing about the brushless motor is the small size of the package and the fact that there are no brushes for ease of maintenance.

Worksheet 21

Three phase generator



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Over to you:

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



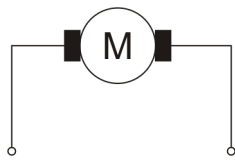
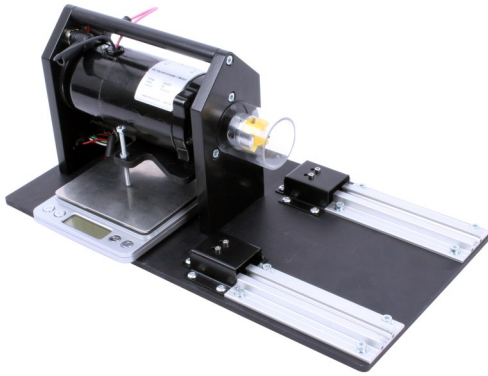
Machine information

Reference

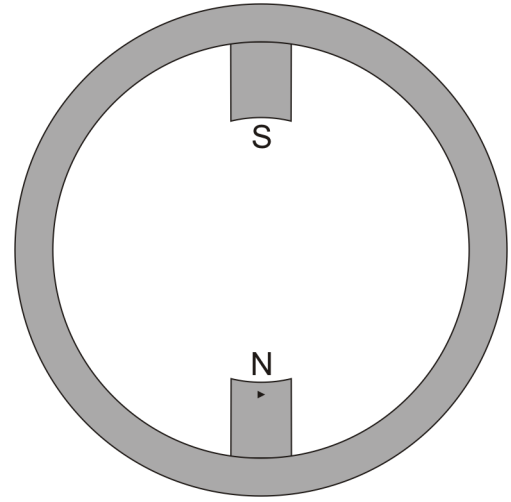
The dynamometer



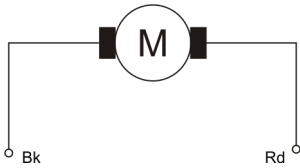
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Conventional symbol



Stator winding circuit



Actual circuit

Connection

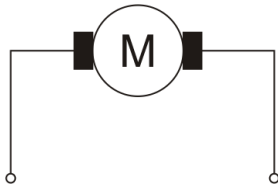
Colour

V+

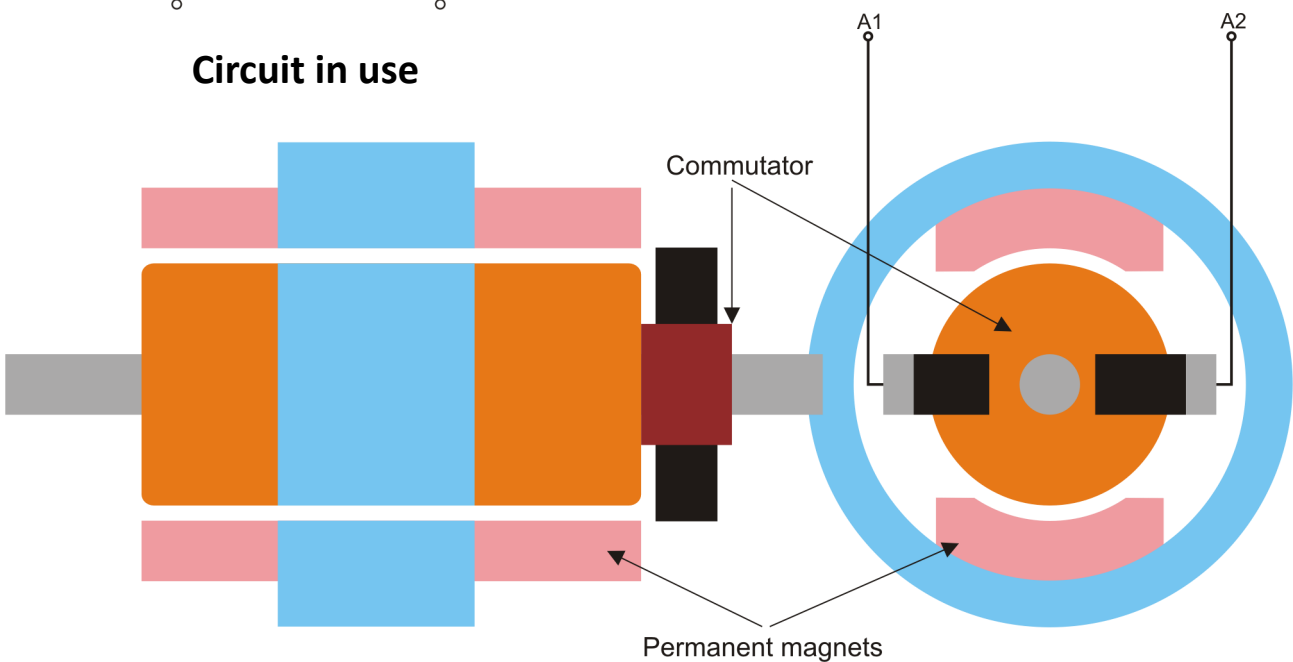
Red

V-

Black



Circuit in use



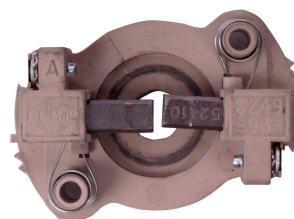
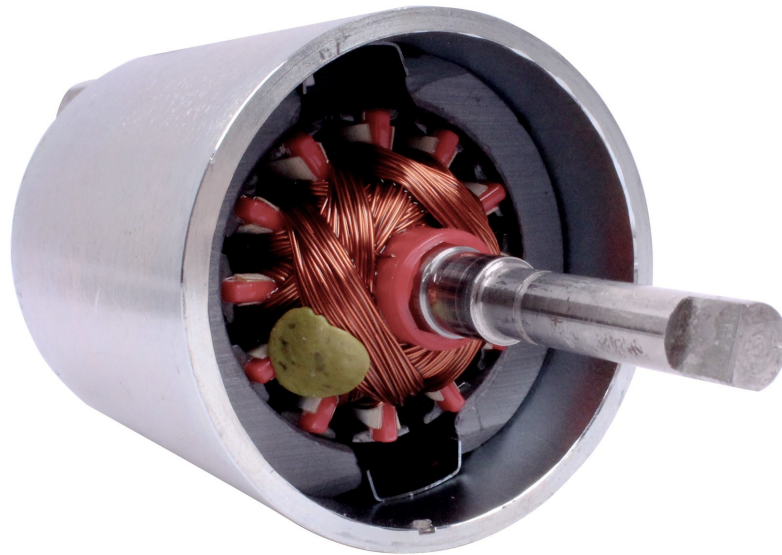
Construction

Reference

The dynamometer

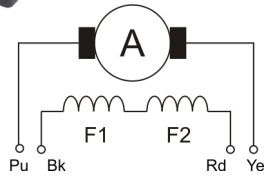
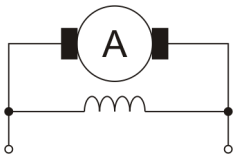
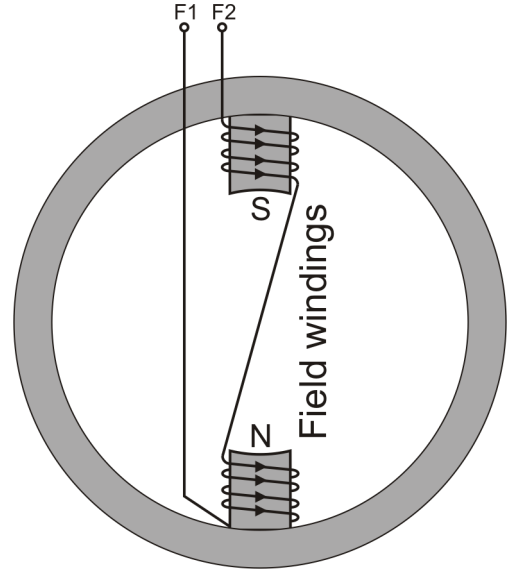


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Reference

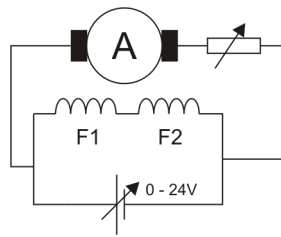
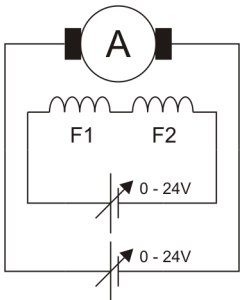
The shunt motor



Conventional symbol

Actual circuit

Stator winding circuit



Connection

Colour

Armature

Purple

Armature

Yellow

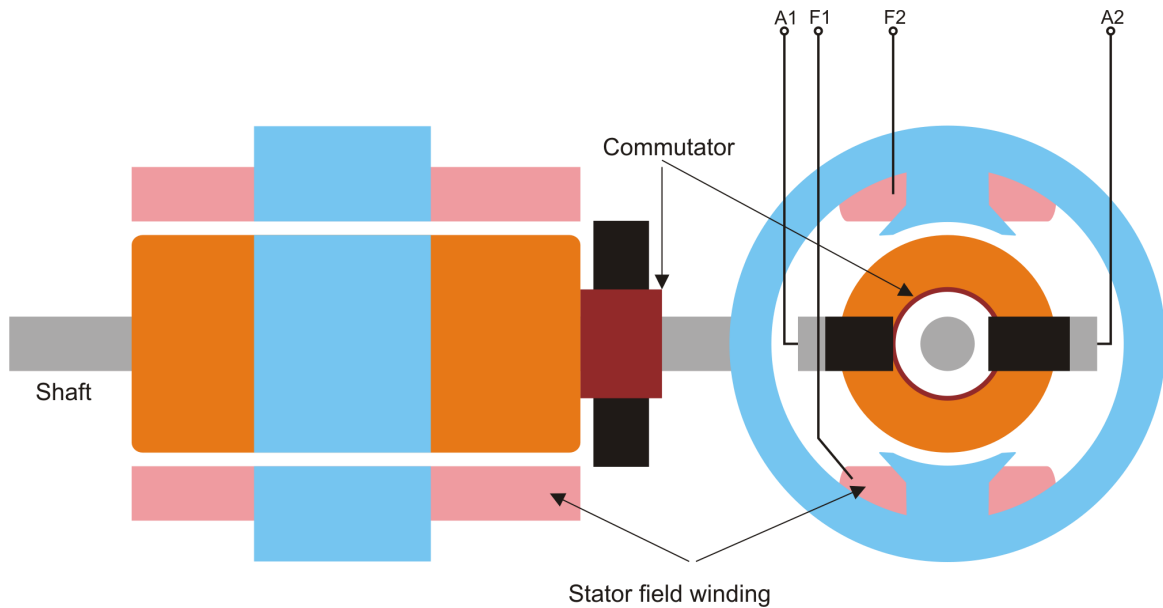
Field coil

Black

Field coil

Red

Circuit in use



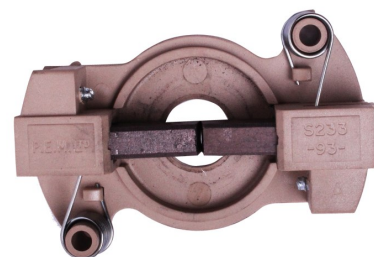
Construction

Reference

The shunt motor



ELECTRICAL
MACHINES

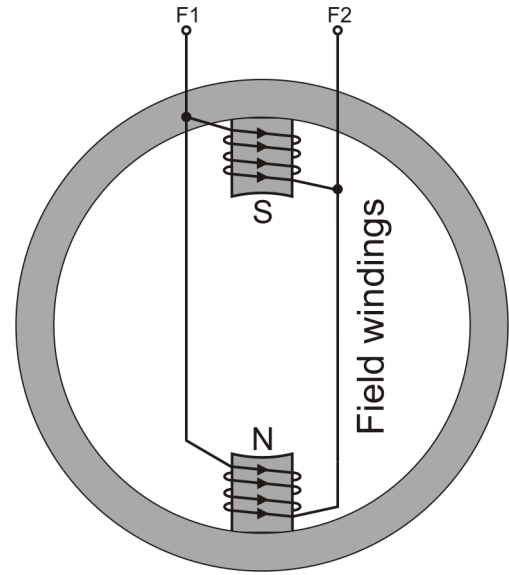


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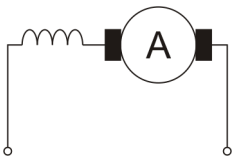
The series motor



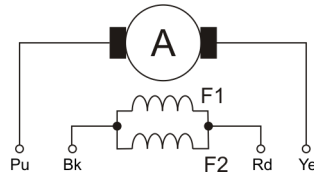
ELECTRICAL
MACHINES



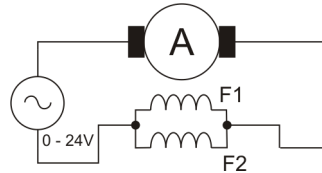
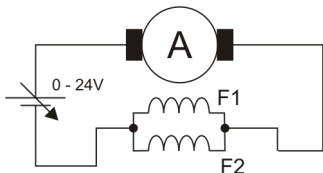
Stator winding circuit



**Conventional
symbol**



Actual circuit



Circuit in use

Connection

Armature

Armature

Field coil

Field coil

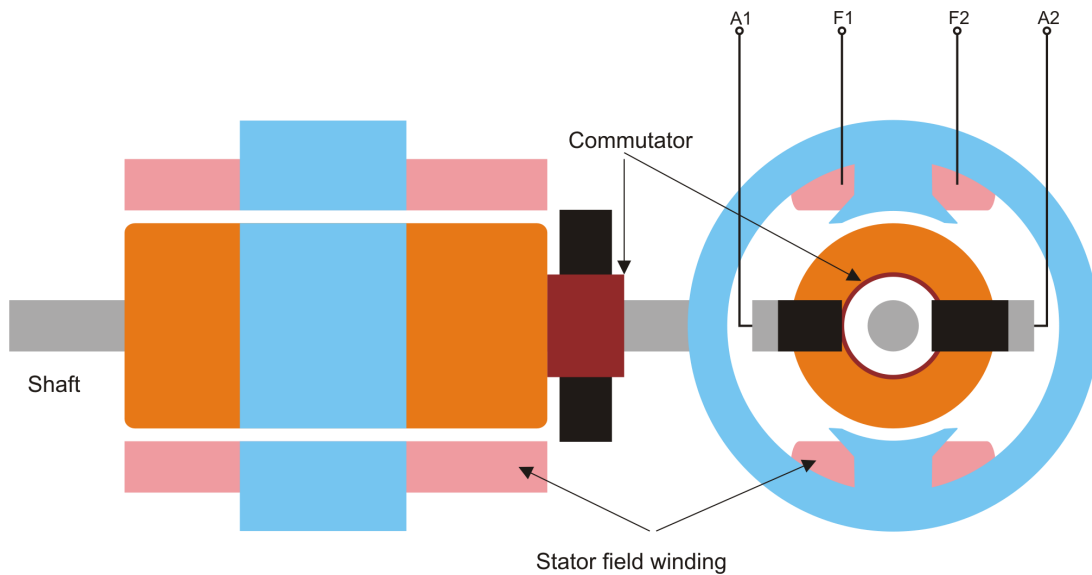
Colour

Purple

Yellow

Black

Red



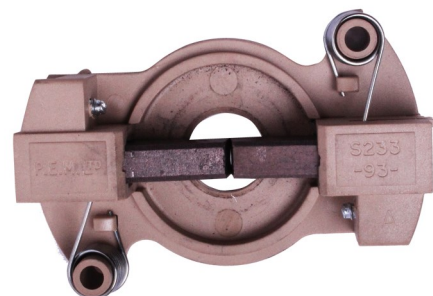
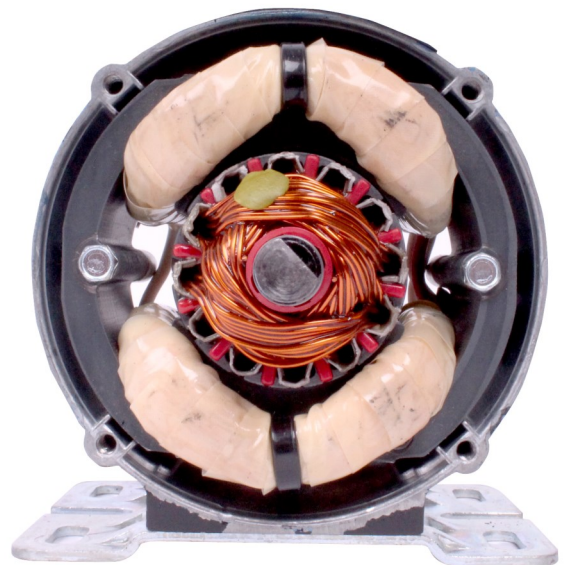
Construction

Reference

The series motor

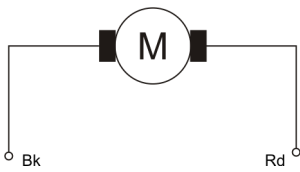


ELECTRICAL
MACHINES

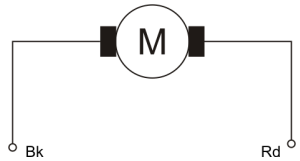


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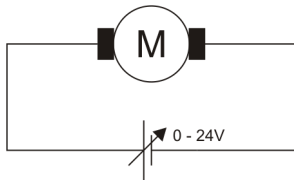
The DC motor



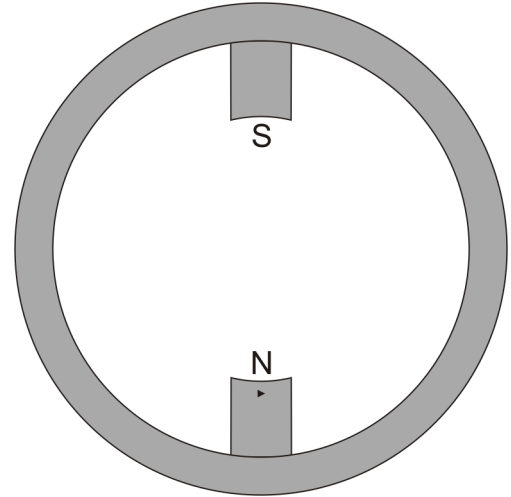
Conventional symbol



Actual circuit



Circuit in use



Stator winding circuit

Connection

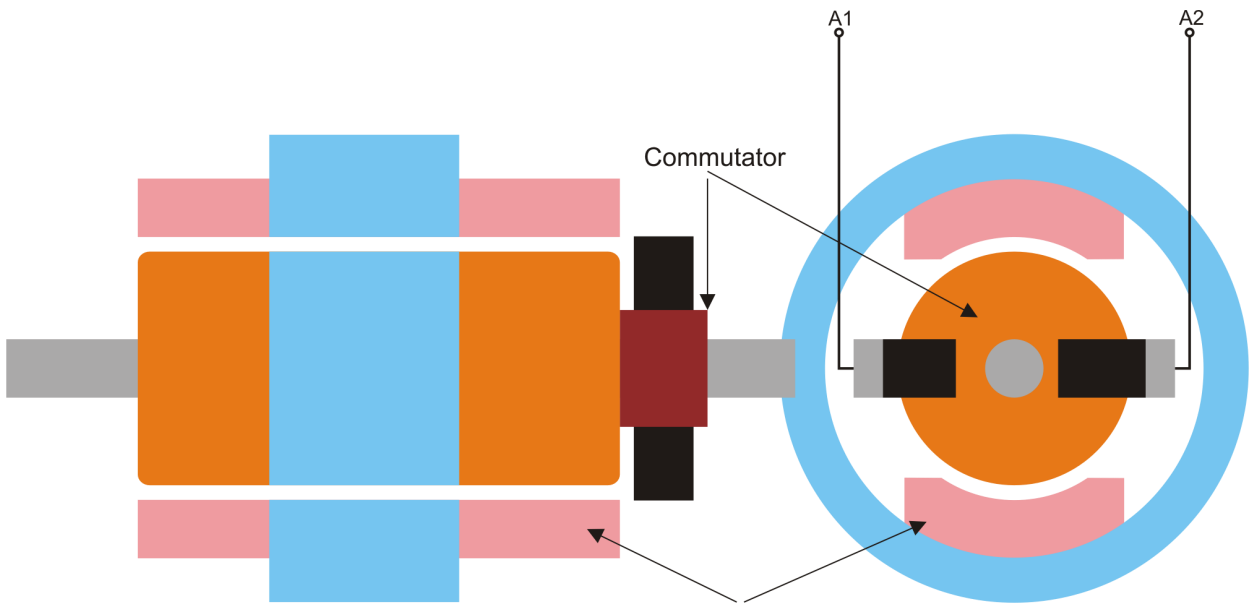
V+

V-

Colour

Red

Black



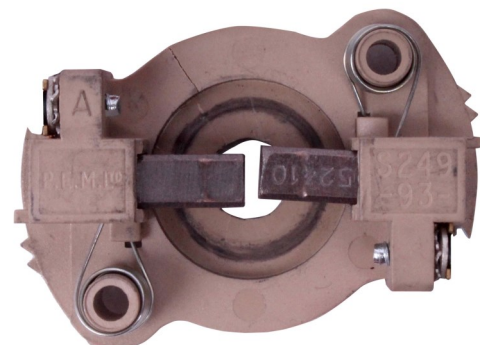
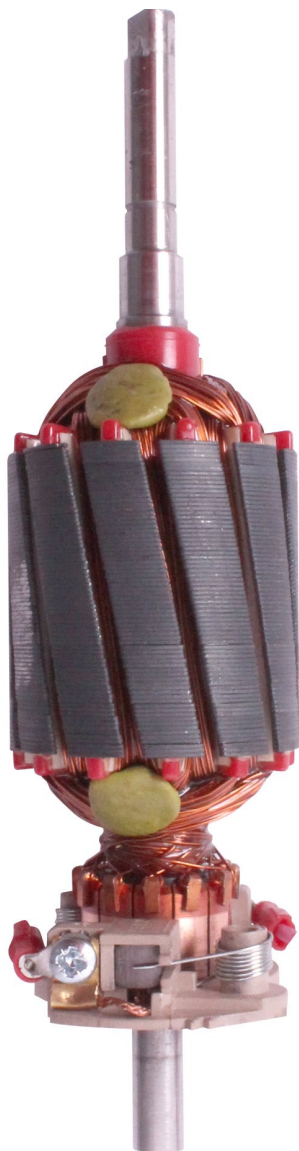
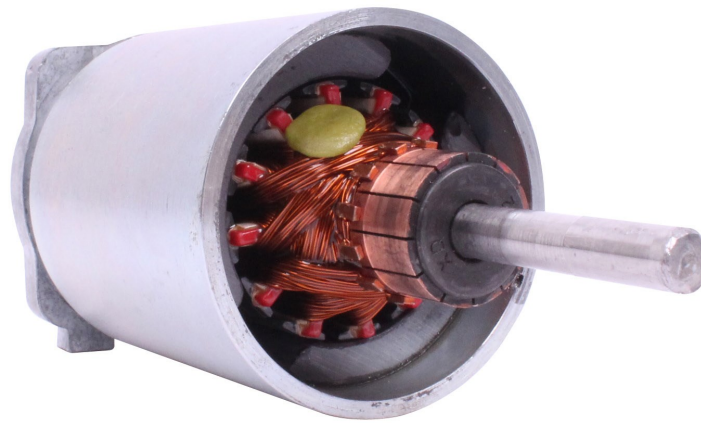
Construction
Permanent magnets

Reference

The DC motor



ELECTRICAL
MACHINES

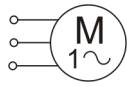


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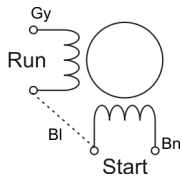
The single phase AC induction motor



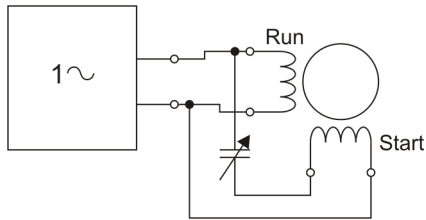
ELECTRICAL
MACHINES



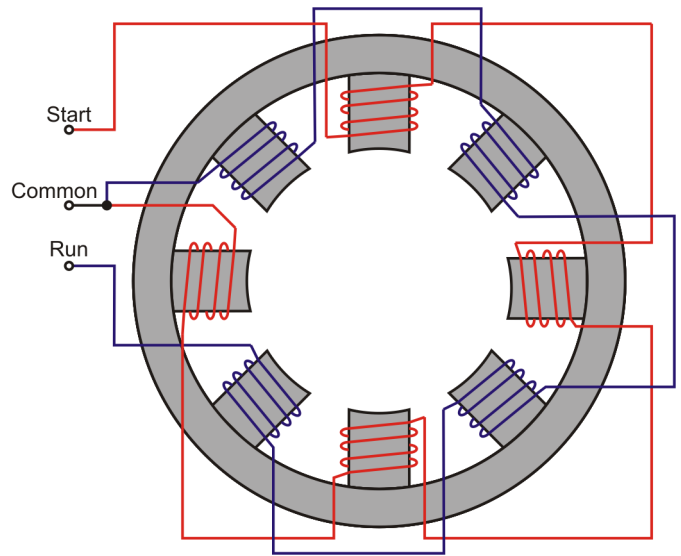
Conventional symbol



Actual circuit

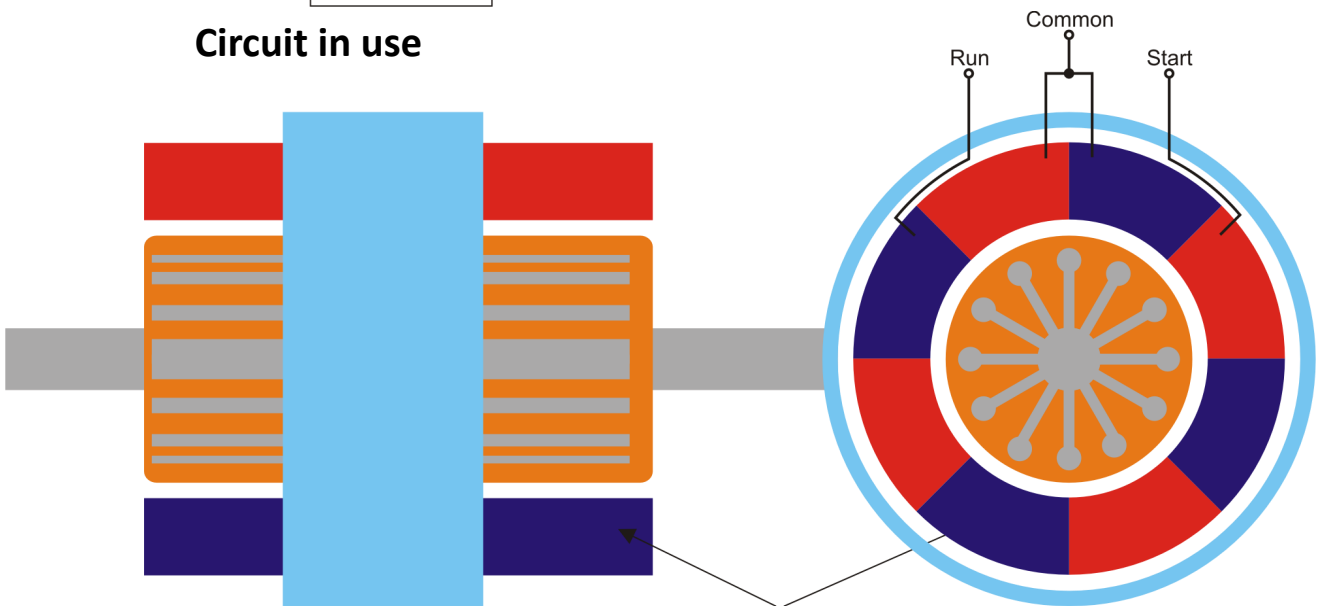


Circuit in use



Stator winding circuit

Connection	Colour
Run	Grey
Start	Brown
Common	Blue



Stator field winding

Construction

Reference

The single phase AC induction motor

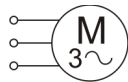
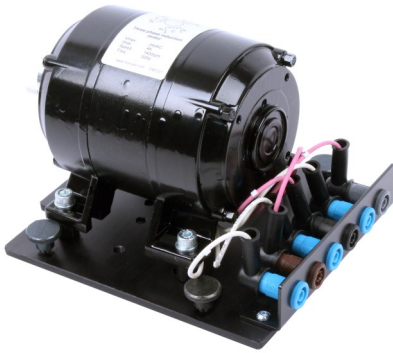


ELECTRICAL
MACHINES

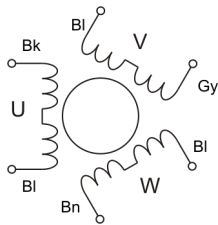


Reference

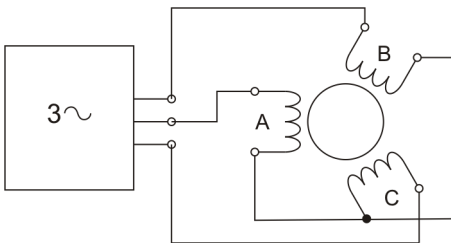
The three phase AC induction motor



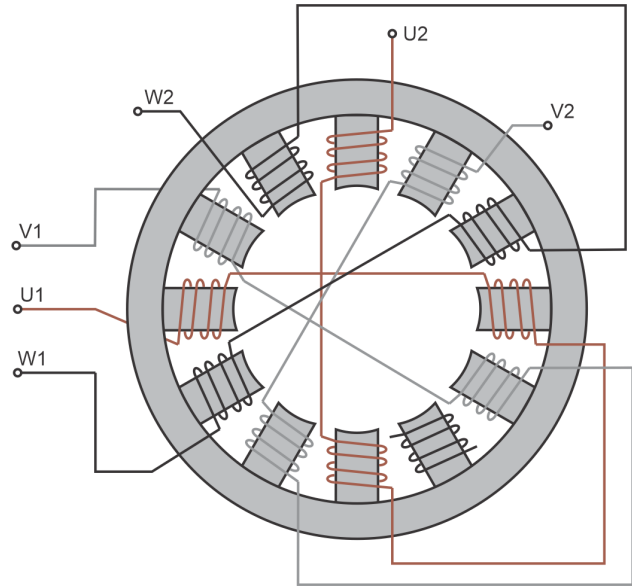
Conventional symbol



Actual circuit



Circuit



Stator winding circuit - 2 pole pairs

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



Stator field winding

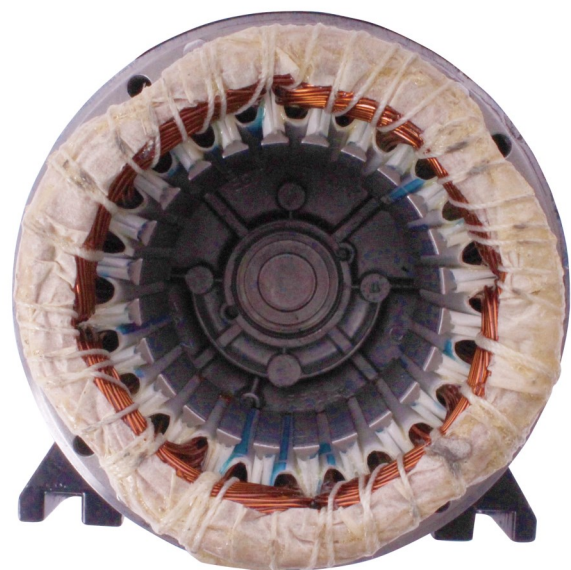
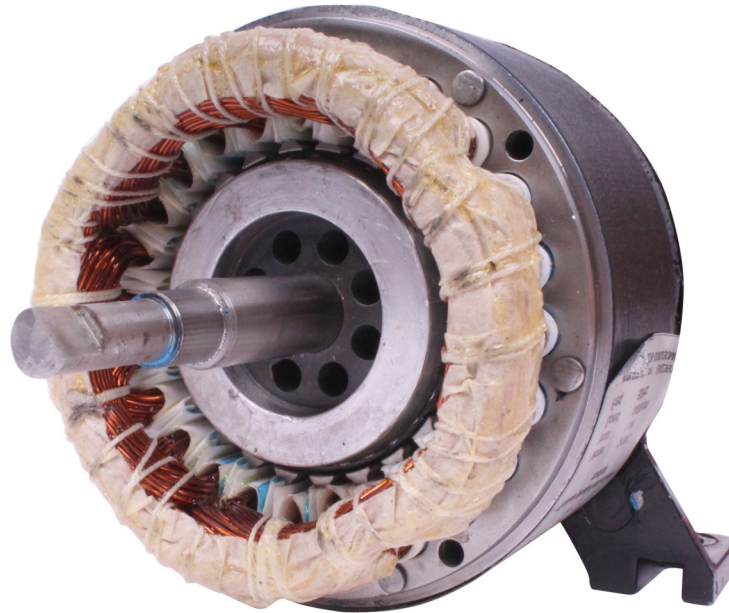
Construction

Reference

The three phase AC induction motor



ELECTRICAL
MACHINES

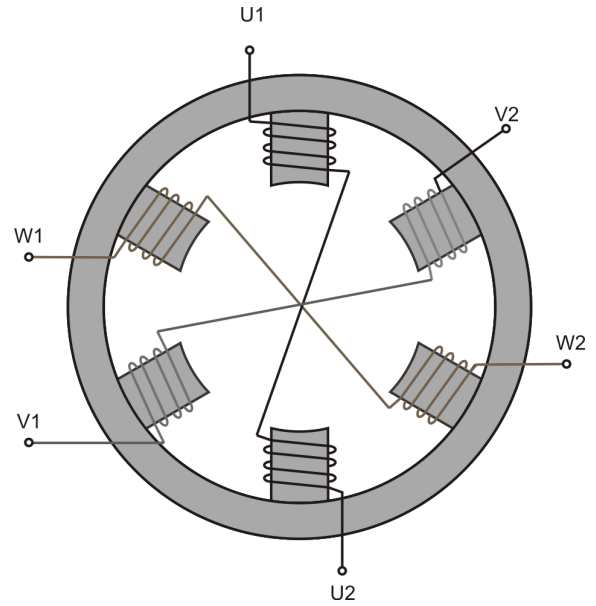
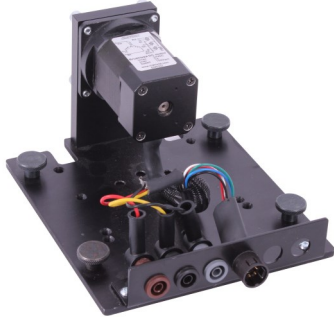


Reference

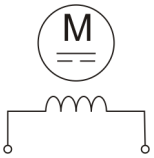
The Brushless DC motor



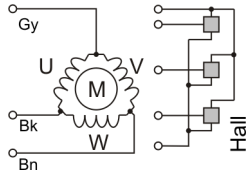
ELECTRICAL
MACHINES



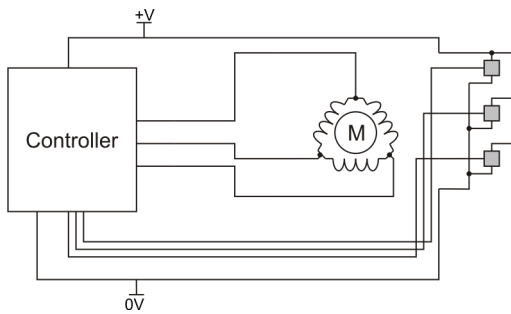
Stator winding circuit



**Conventional
symbol**



Actual circuit



Circuit in use

Connection

Phase U

Phase V

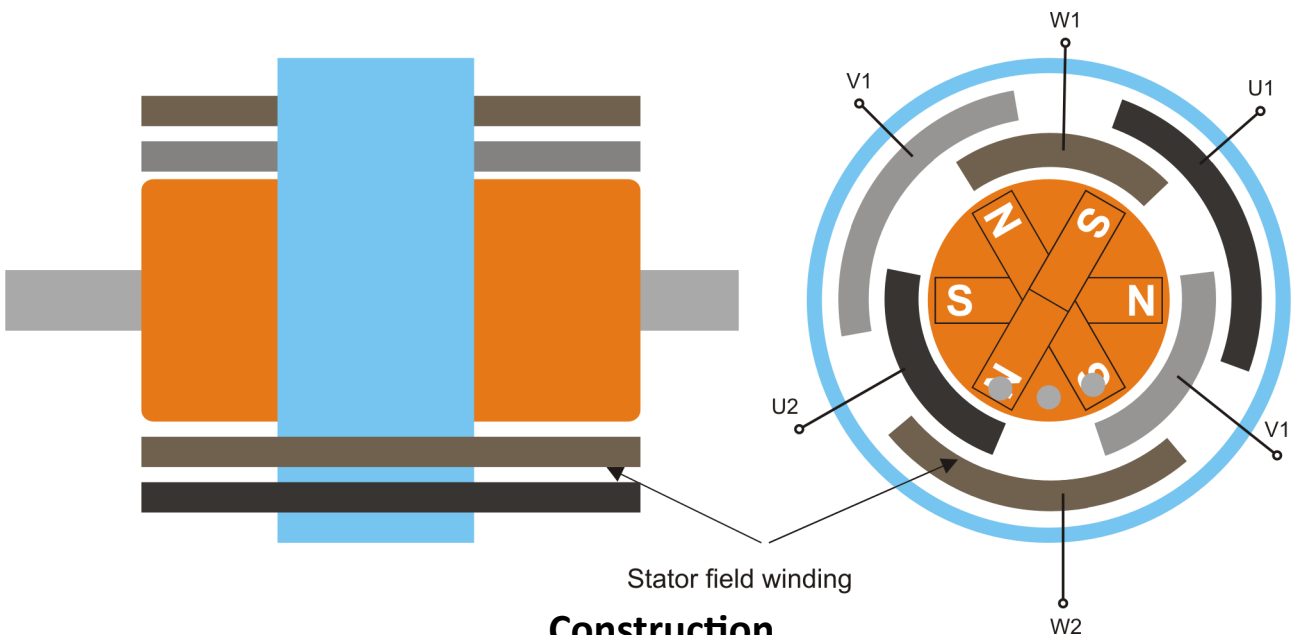
Phase W

Colour

Black

Grey

Brown



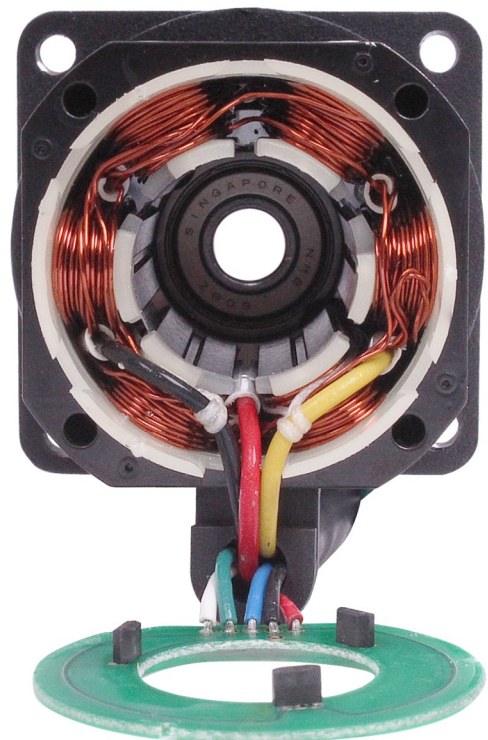
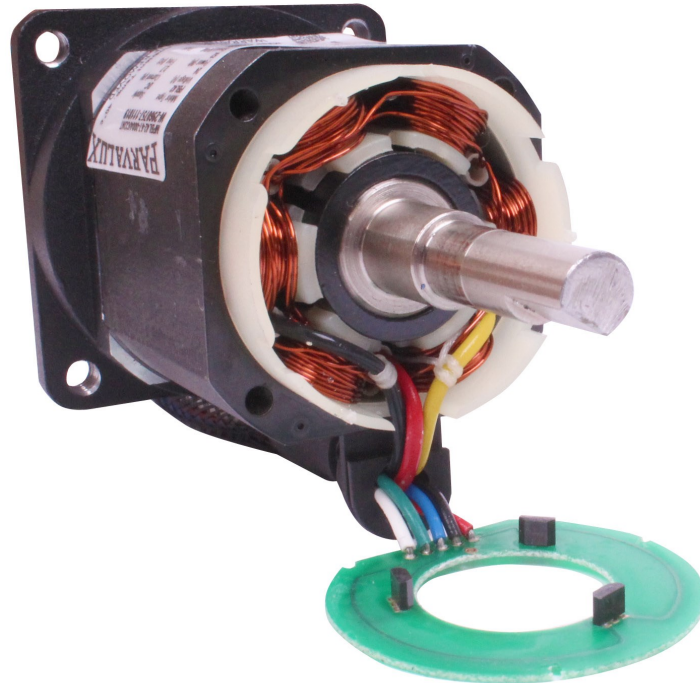
Construction

Reference

The Brushless DC motor



ELECTRICAL
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Package information

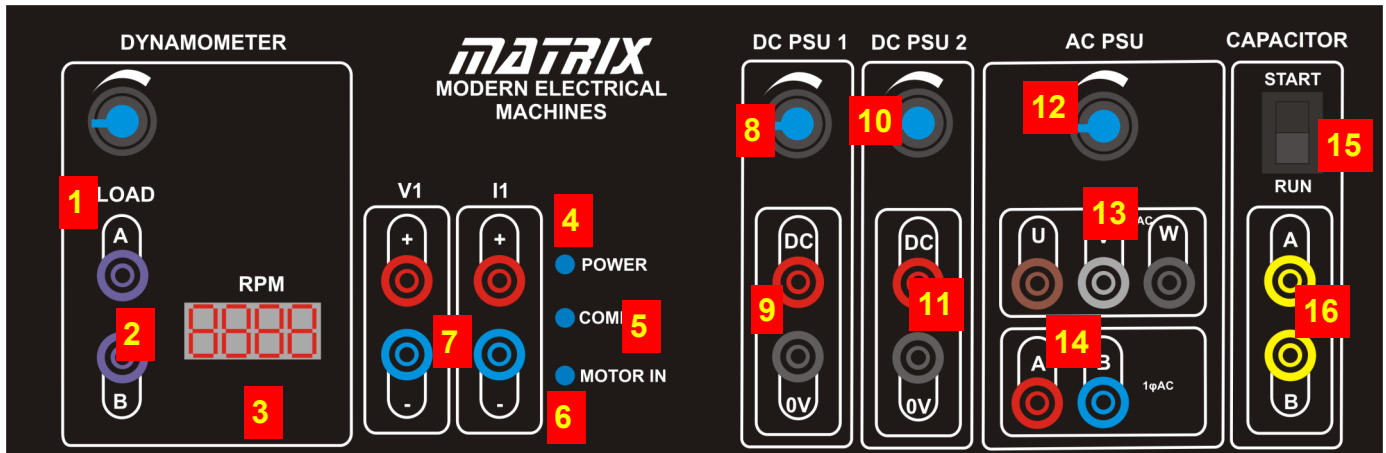


The system consists of a number of 24V electrical machines, a control unit, software applications for driving the control unit and a set of worksheets. The photograph above shows these parts. They are:

- 1) The dynamometer and cradle which connects to the control unit using a 25way D-type lead
- 2) Balance
- 3) Motor under test - in this case a shunt wound motor
- 4) The control unit which connects to a PC using a USB lead.
- 5) A series wound motor
- 6) Single-phase AC induction motor
- 7) Brushless DC motor
- 8) DC motor
- 9) Three-phase AC induction motor
- 10) The software application running on a PC

Understanding the control unit

Note - manual controls are overridden as soon as the unit is plugged into a computer.



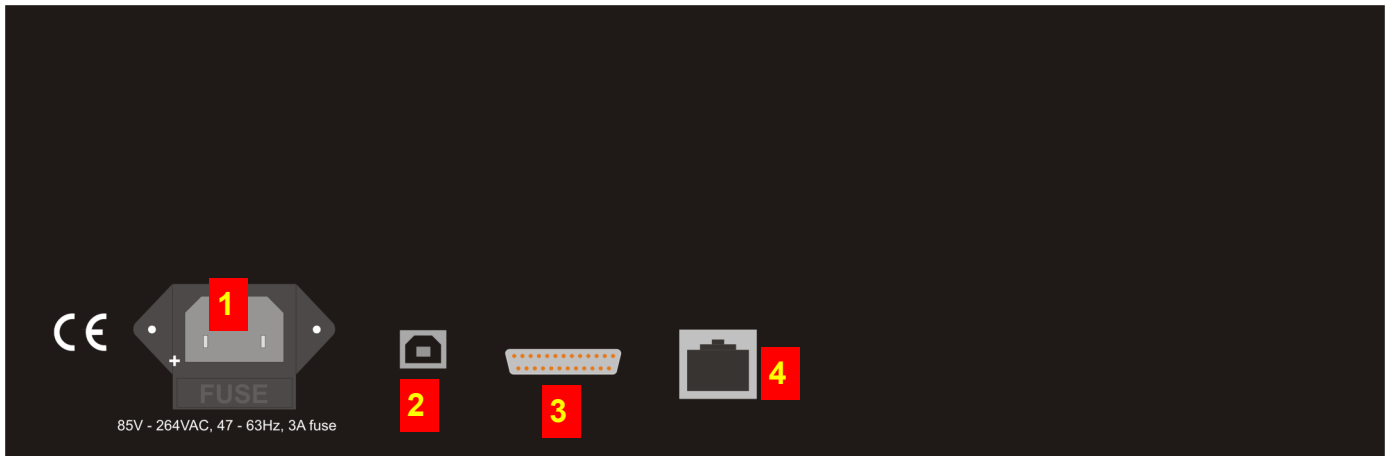
- 1) The dynamometer resistance: use this to control the effective resistance placed across the dynamometer: low electrical resistance means a large mechanical resistance, and high electrical resistance means low mechanical resistance
- 2) The dynamometer connections
- 3) The speed of the motor in Revolutions Per Minute - RPM.
- 4) The power LED which shows the control unit is powered up.
- 5) The COMMS LED which is lit when the PC software has communication with the control unit.
- 6) The 'Motor In' LED which indicates that a machine is physically connected to the dynamometer.
- 7) The internal ammeter and voltmeter connections
- 8) The DC 1 Supply output control.
- 9) The DC 1 connections.
- 10) The DC 2 Supply output control.
- 11) The DC2 connections.
- 12) The AC frequency control
- 13) The three-phase supply connections
- 14) The single phase supply connections
- 15) The capacitor mode selector switch: this controls the internal value of capacitor connected to the A and B terminals. There are two values: START, RUN.
- 16) Variable capacitance terminals.

Reference

Understanding the control unit



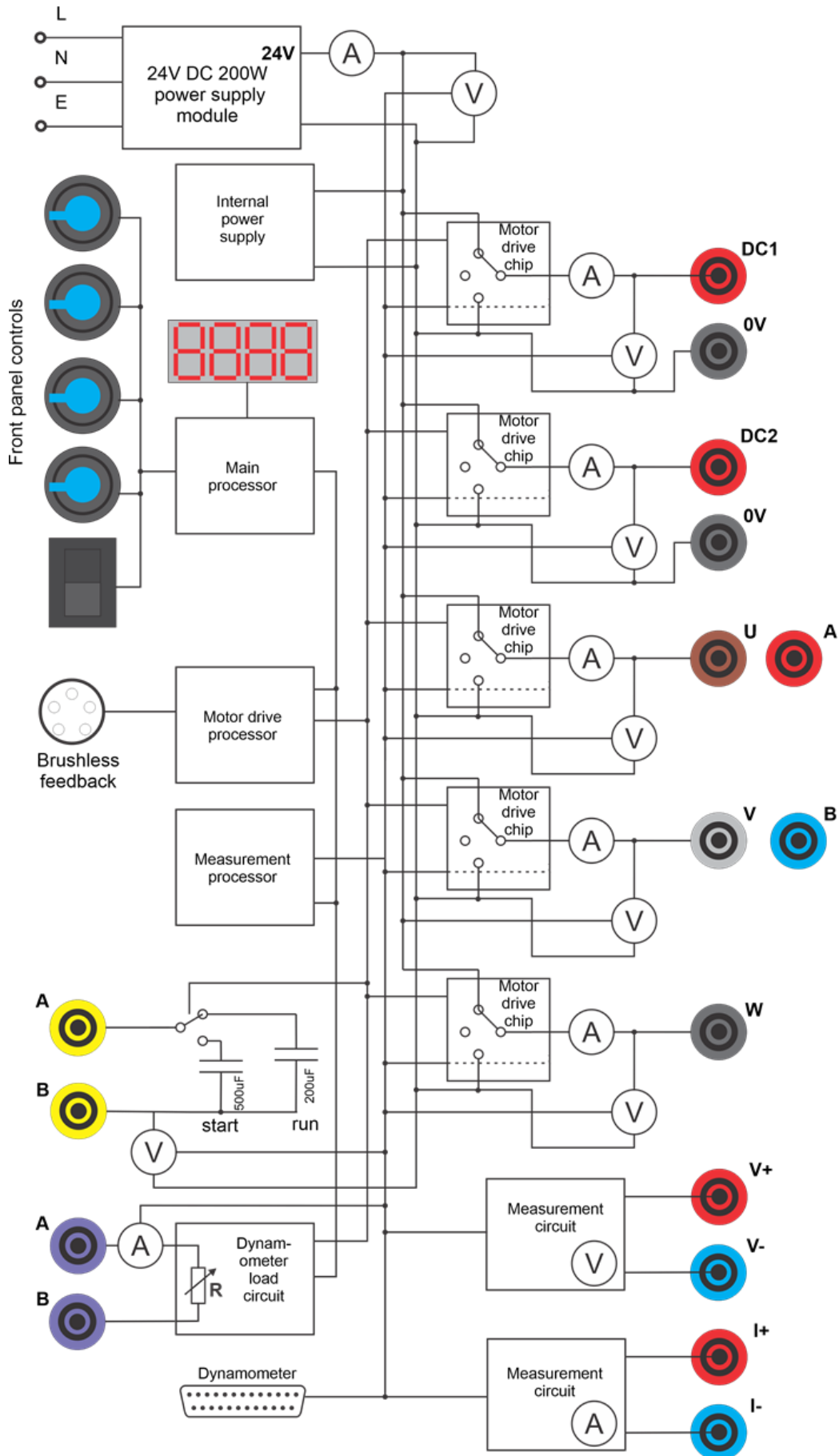
ELECTRICAL
MACHINES



- 1) The Mains input plug - the unit takes 240V or 110V
- 2) The USB connector
- 3) A 25 way D-type connector which is used to connect the Control unit to the Dynamometer
- 4) RJ45 LAN/internet connection socket.

Reference

Control unit schematic



Reference

Control unit description



Please refer to the block diagram on the previous page.

The control unit shipped with the Matrix Modern Electrical Machines system is one of the most up to date in the World. Inside the unit there are three separate processors: a main processor handling all user interface and communication tasks, a motor drive processor handling all the high current outputs and dealing with all waveform and timing systems, and a measurement processor. These three processors use buses to communicate between themselves and between the different electronic circuits in the unit.

A key feature of the control unit is that almost every quantity in the unit can be measured. On the schematic you can see that there are 16 separate ammeters and voltmeters in the system. This gives the instrumentation software and the user lots of options when displaying what is happening in an electrical machine system. The measurement of each quantity takes place thousands of times per second and can be processed by PC software applications to display a quantity or a waveform.

The motor drive chips are all low voltage drop FET based units. As you can see from the schematic all the outputs are digital 24V outputs. Simple pulse width modulation algorithms are used to vary the effective output power on the DC outputs. On the AC outputs Pulse width modulation is again used but with a more advanced pseudo-sine with third harmonic wave algorithm which varies the output power sinusoidally over the period of the output waveform. This technique is used by the more advanced motor controllers in industry. Older, and perhaps cheaper, motor driver systems sometimes use a simple digital output waveform for driving

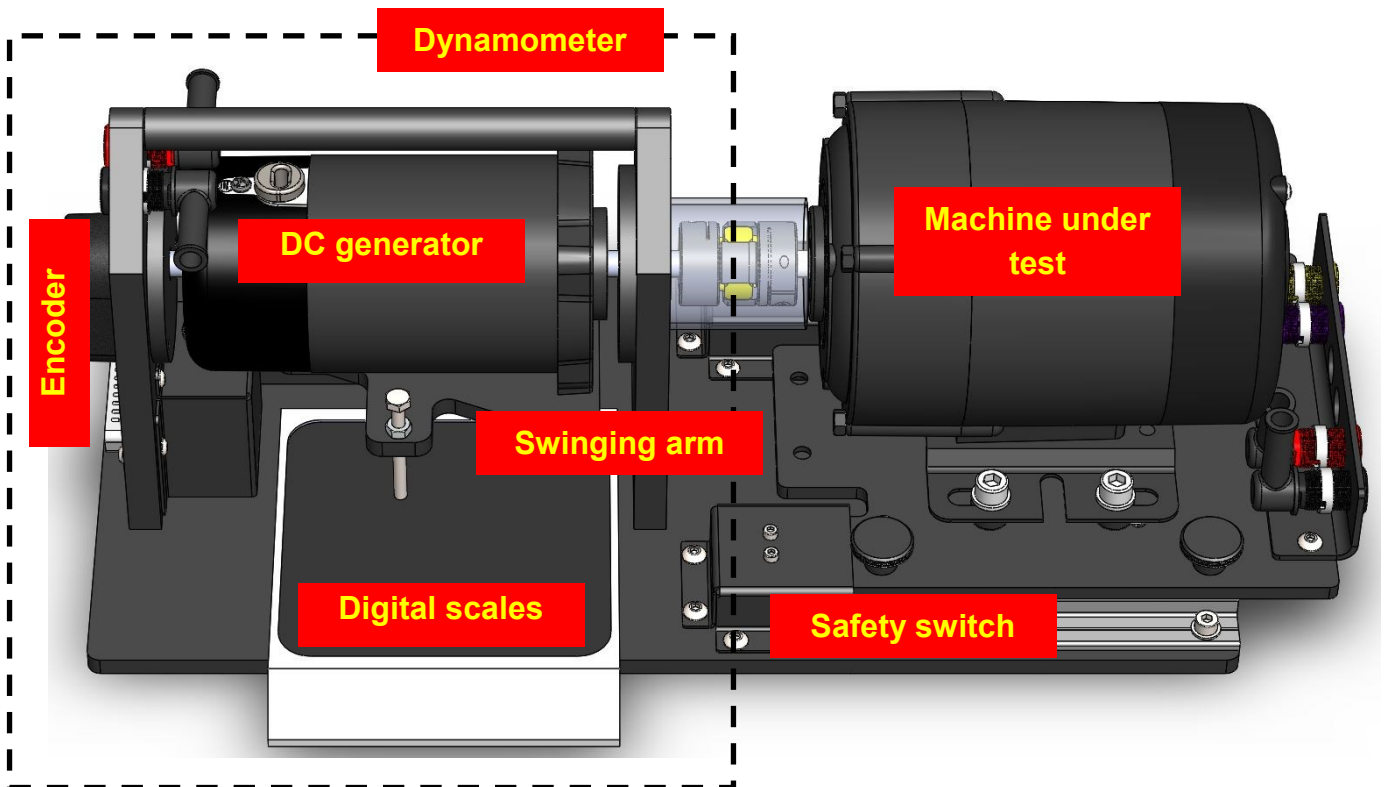
three phase induction motors where the three outputs are simply digital outputs phase shifted by 120 degrees. This digital output is also available in some software applications shipped with the system so that students can investigate the efficiency of each method.

The motor driver chip outputs can be placed in one of three states: 24V, 0V and open circuit. This allows for different drive strategies when generating waveforms for driving motors. As part of the learning package students investigate PWM for driving DC motors, and Pseudo-sine waves for driving single phase AC motors. The unit also performs more complex six step pseudo-sine wave generation for driving the three phase motor and this can be examined with the internal multi channel oscilloscope as well as an external oscilloscope. To facilitate this when in AC mode a small pulse is given on the DC1 output which allows an external oscilloscope to be triggered to capture the various waveforms.

Note that most of the internal ammeters and voltmeters are on the Driver board in the unit. The topmost ammeter and voltmeter in the block diagram monitor power to the Driver board and this is displayed in the applications.

The unit includes two values of capacitor with a simple relay for start / run investigation for single phase induction motors.

The unit also includes a FET based load for the dynamometer whose effective resistance is controlled by software.



A dynamometer is an instrument that directly measures the force produced and speed of a rotating machine (the motive force). Torque and power can be calculated from the measured force and speed. In our case the mechanical rotation is produced by one of the DC or AC electrical motors. This Dynamometer is an absorption type swing arm / balanced beam dynamometer, where the motive force is used to drive a DC generator with a variable resistance load attached. The resulting force can be measured in one of two ways:

- A digital scale (shown in the image above) can be used to measure the effective vertical force on the scale and it gives a reading in Kilograms. This can be converted into newtons and newton metres - see below.
- A load cell (behind the dynamometer and not shown in the image above) connected to the control box gives the same infor-

mation - give or take a few percent.

Note that the rotation of the dynamometer dictates whether the balance or the load cell is used. Controlling the direction of motion of each machine is discussed below.

The encoder on the shaft of the dynamometer allows the control unit to detect the rotational speed. This is displayed on the control unit in revolutions per minute (rpm) and on the software application.

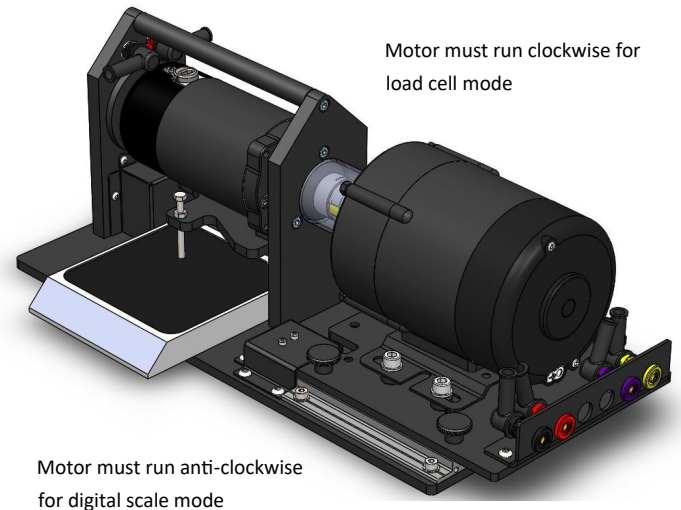
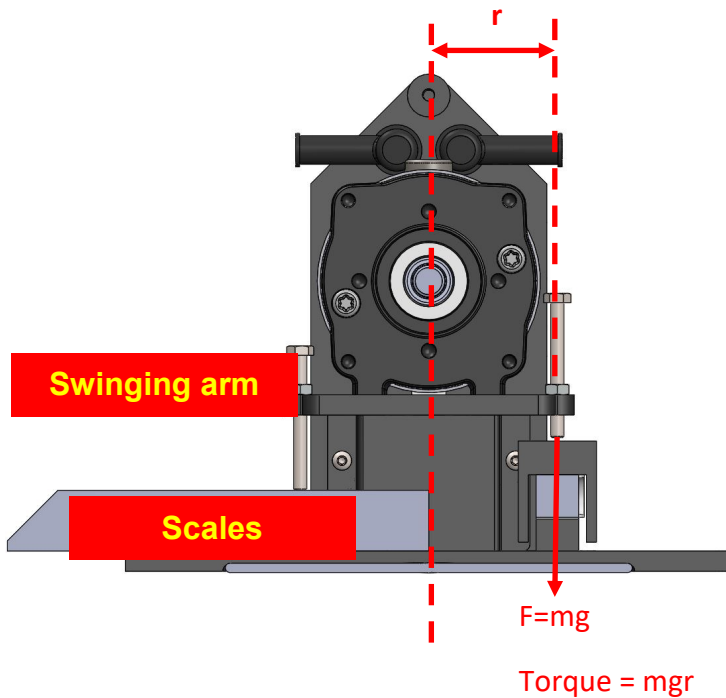
Machines under test are coupled to the dynamometer using a coupling which is housed in a plastic tube to prevent clothes and hair getting caught in the mechanism. Two microswitches are provided on the dynamometer - unless a machine under test is in place the control unit will not activate.

Reference

Measuring torque



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The dynamometer rotates in the same direction as the machine under test. It provides a mechanical resistance for the machine under test. It also generates a voltage and - if a resistance is placed across the Dynamometer terminals - it produces a current.

If voltage and current flow then power is being generated - work is being done. The more power generated by the Dynamometer, the more mechanical power has to be generated by the machine under test.

We test electrical machines to understand their properties so we know when to use the various types of machine. The way we test them is to vary their speed and the mechanical power they need to generate. The dynamometer and the Control unit allow us to do this.

The Dynamometer is made up of a DC motor and a cradle. The DC motor also acts as a DC

generator. The cradle suspends the DC machine in two bearings that allow the body of the machine to rotate. The force on the load cell (or digital scale when the motor is running anti-clockwise) creates a weight on the load cell or scale (which represents mass). If the swing arm is perfectly balanced and horizontal when it is at rest, the force produced on the load cell or digital scale is Force = mass \times 9.81m/s^2 . The torque can be calculated from the formula Torque = Force \times Distance. In this case, the distance is from the centre of rotation of the generator to the centre line of action of the swing arm. **For the Matrix dynamometer, $r = 38.12\text{mm}$**

More discussion on calculations is given below.



Software Information



The Modern Electrical Machines equipment can be used in two ways:

Manual mode - no software

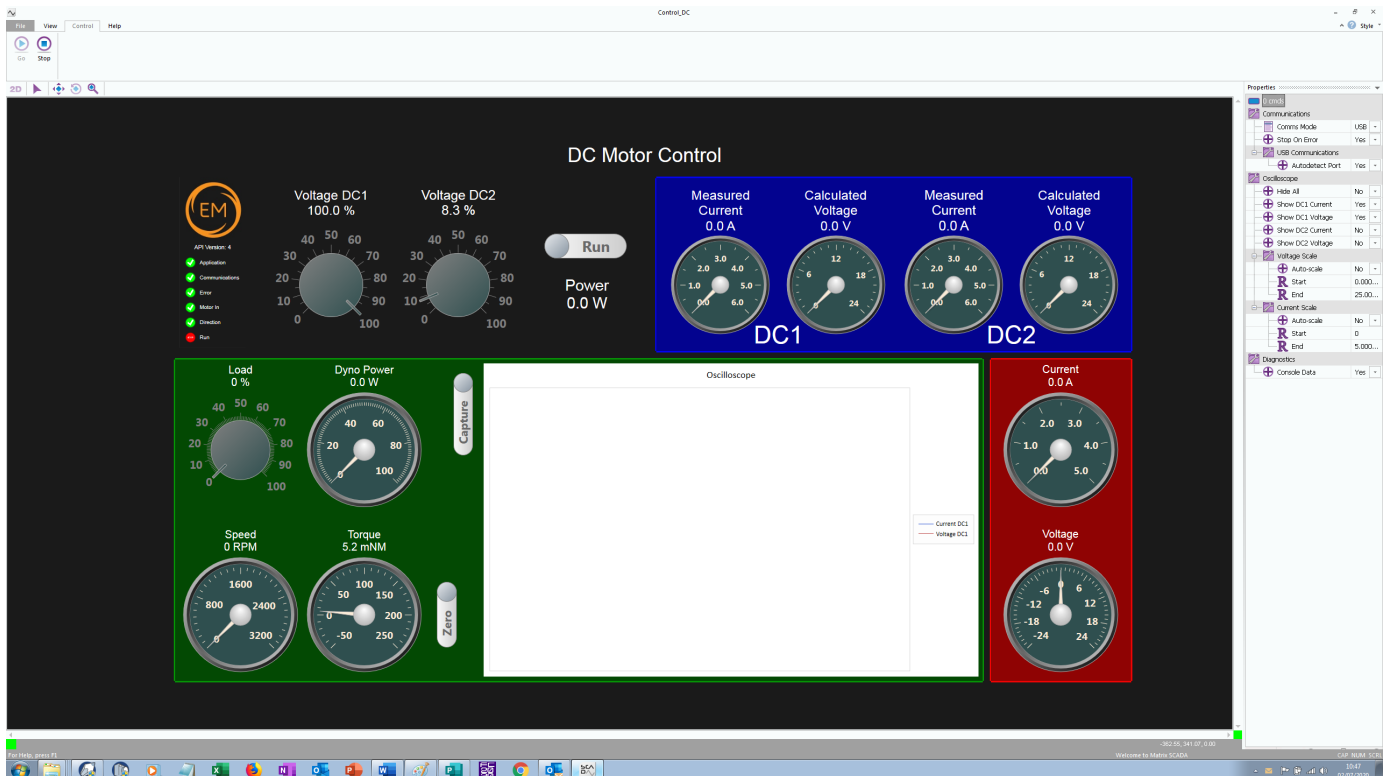
When no USB lead is plugged into the unit then the control unit is in manual mode. This allows users control of the DC and AC power supply outputs using the potentiometers on the front of the unit. The capacitor start / run is controlled by the front panel switch and the speed of the dynamometer is displayed by the 7 segment display. Manual mode is useful when teaching students the basics of electrical machine control and will be useful when used with true RMS multimeters to measure voltages and currents.

In Manual mode we make use of a small balance to measure torque. The swinging arm of the Dynamometer has two modes of use: when rotating counter-clockwise it presses down on

the balance. When rotating clockwise it presses down on the load cell for computer based measurement. Users simply reverse the direction of motion of the machine under test to change rotational direction.

Software mode

When the USB lead is plugged in to the Control unit the front panel controls are disabled. Six separate software applications are available to the user for carrying out experiments with the different machines.



Applications

Six different PC based applications are shipped with the unit. Each of them is a self contained executable '*.BAT' file. Drivers for the Control unit will need installing - the applications will not. These applications are:

Open Control_DC.bat: for direct DC measurement for DC motors.

Open Log_DC.bat: for gathering speed torque data and logging the results for DC motors.

Open Control_1Phase.bat: for direct measurement for single phase AC induction machines.

Open Log_1Phase.bat: for gathering speed torque data and logging the results for single phase AC induction machines.

Open Control_3Phase.bat: for direct measurement for three phase induction and brushless DC motors.

Open Log_3Phase.bat: for gathering speed torque data and logging the results for three phase induction and brushless DC motors.

These are explained below.

An API for use with LabView or MATLAB is also available.

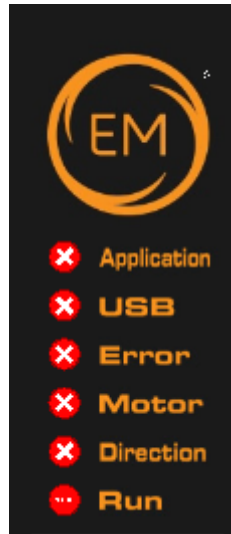
Naming of these applications may vary slightly as updates are released.

Reference

Software flags



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Each application has a set of software flags which are displayed on the top left hand side. These are:

Application: green when the application is in Play mode.

USB: Green when there is a USB connection between the control unit and the PC.

Error: red when there is an Error in the control unit. Most often this happens due to an over current error. The unit is capable of providing 100 watts of power. When this is exceeded the unit shuts down. In this case you should lower the output voltage and try again.

Motor: green when the microswitches in the Dynamometer are activated by the presence of a machine under test. The unit will not run unless a machine under test is present.

Direction: green when the direction of rotation is clockwise which will press down on the

torque sensor.

Run: green when the run switch is triggered.



There are two types of software application supplied with the Electrical Machines course:

- Manual control
- Automatic

Manual control applications allow you to manually set all of the parameters inside the control box. Automatic applications allow you to automatically take multiple sets of readings for producing speed torque graphs. This page and the following 5 pages show you the screen layouts and controls.

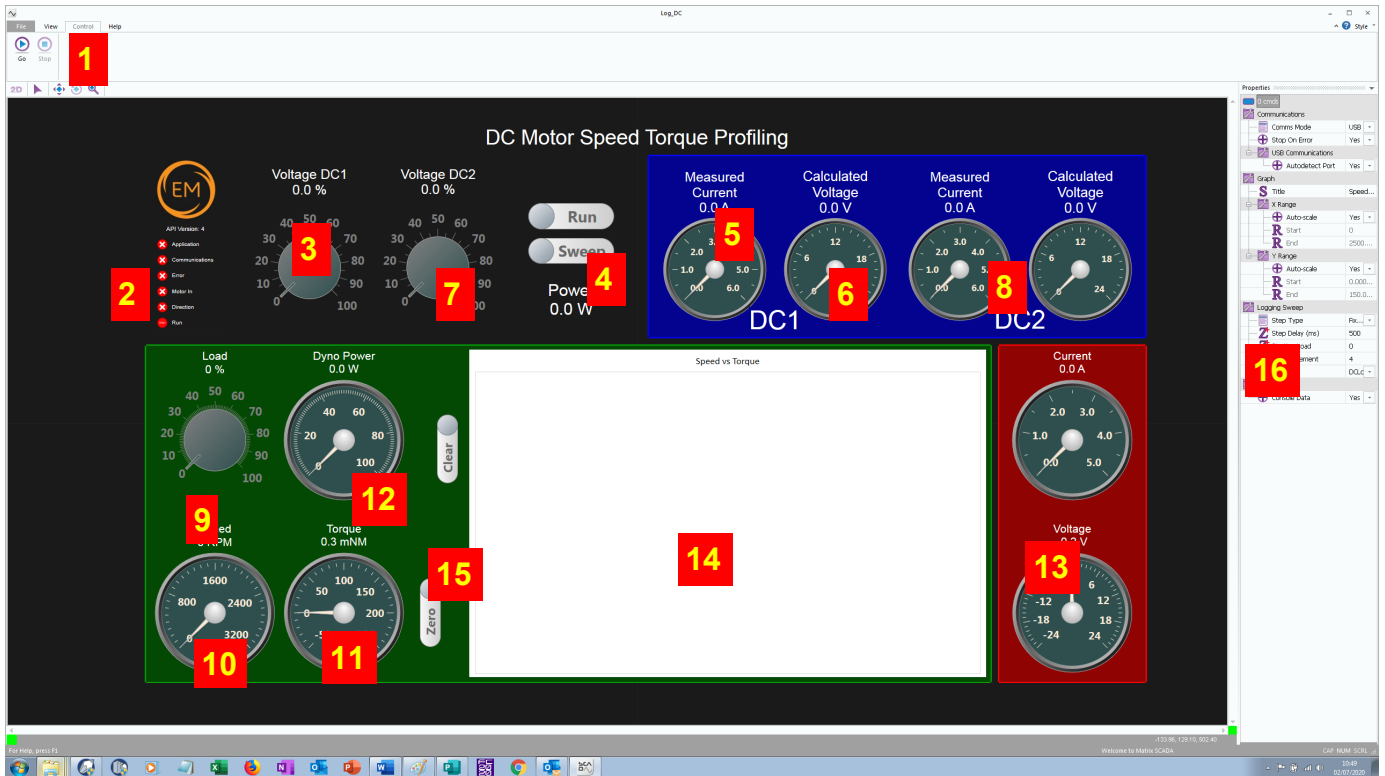
The file name for this program is 'Open Control_DC.bat' and it is intended for manual DC measurements.

- 1) Program control - hit 'PLAY' to start
- 2) Flags for App running, USB comms and Motor in place etc. The box will not start until all show green ticks.

- 3) DC1 output - shows PWM duty cycle for DC output 1 with voltage and current.
- 4) Run / Stop switch - needs pressing to turn outputs on
- 5) DC2 output - shows PWM duty cycle for DC output 2
- 6) Meter for Current terminals
- 7) Meter for Voltage terminals
- 8) Dynamometer load as a %
- 9) Dynamometer speed in RPM
- 10) Torque in mNm
- 11) Dynamometer power in watts
- 12) Oscilloscope
- 13) Properties for the program and scope.

Reference

Automatic DC software



The file name for this program is 'Open Log_DC.bat'

- 1) Program control - hit 'PLAY' to start
- 2) Flags for App running, USB comms and Motor in place. The box will not start until all three show green ticks
- 3) DC1 output - shows PWM duty cycle for DC output 1
- 4) Sweep - takes a set of readings sweeping the Dynamometer from 0-% to 100%
- 5) RUN and SWEEP switches.
- 6) DC2 output - shows PWM duty cycle for DC output 2
- 7) Meters for DC 1 - RMS values
- 8) Meters for DC 2 - RMS values
- 9) Dynamometer load as a %
- 10) Dynamometer speed in RPM

- 11) Torque in mNm
- 12) Dynamometer power in watts
- 13) Internal ammeter and voltmeter V1 and I1
- 14) On screen graph of plot data
- 15) Graph / log clear button
- 16) Program properties

When the Run button is pressed the control box will - at the specified voltage on DC1 and DC2 take readings from 0 load to 100% load in 2% increments. The results will be stored in the file LOG_DC1.CSV for plotting in Excel.

Whilst the readings are being taken the on screen graph will show an approximate plot so that you can be sure you are getting valid data. Up to 8 data sets can be captured and displayed at one time.



The file name for this program is 'Open Control_1Phase.bat'

- 1) Program control - hit 'PLAY' to start
- 2) Flags for App running, USB comms and Motor in place. The box will not start until all three show green ticks
- 3) Frequency of output
- 4) AC voltage output
- 5) SINE/DIGITAL: Sine wave or square wave output.
- 6) CAP START/CAP RUN: selects the internal capacitor value.
- 7) RUN switch - needs pressing to turn outputs on.
- 8) Meters for the outputs - RMS values
- 9) Dynamometer load as a %

- 10) Dynamometer speed in RPM
- 11) Torque in mNm
- 12) Dynamometer power in watts
- 13) REAL V / EFFECTIVE V: shows the voltage on the graph in real terms or effective terms.
- 14) PHASE / TIME: shows X axis in degrees or in mS
- 15) CAPTURE: captures a waveform
- 16) Oscilloscope / graph plot area
- 17) Internal ammeter and voltmeter V1 and I1
- 18) Properties control



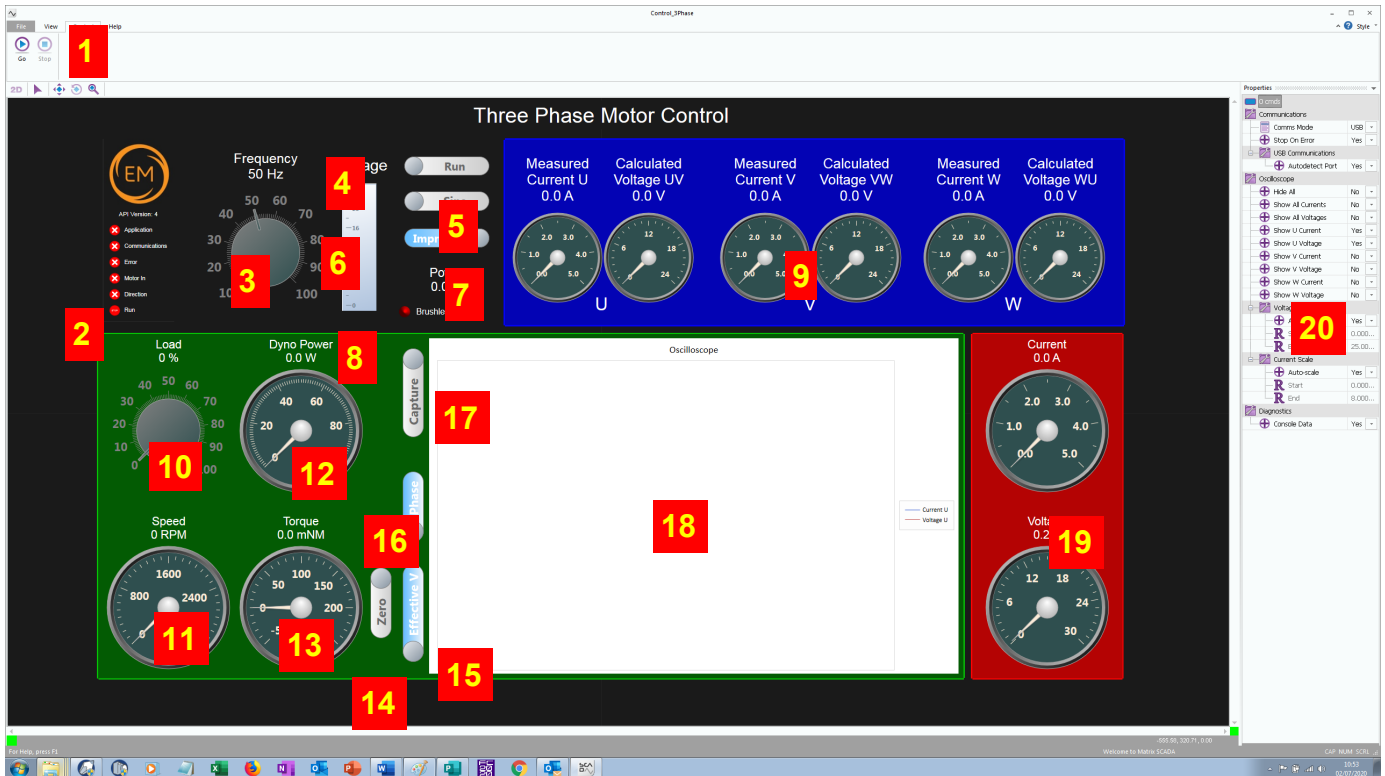
The file name for this program is 'Open Log_1Phase.bat'

- 1) Program control - hit 'PLAY' to start
- 2) Flags for App running, USB comms and Motor in place. The box will not start until all three show green ticks
- 3) Frequency of output
- 4) Voltage of output
- 5) Run switch - starts automatic logging of data
- 6) Drivemode - default is pseudo-sine, on is trapezoid
- 7) CAP START / RUN switch controls the value of internal capacitor on the variable capacitor terminals
- 8) SWEEP: starts sweep function
- 9) Meters for the output - RMS values
- 10) Dynamometer load as a %

- 11) Dynamometer speed in RPM
- 12) Torque in mNm (Zero switch is used on start up)
- 13) Dynamometer power in watts
- 14) Internal ammeter and voltmeter V1 and I1
- 15) On screen graph of plot data
- 16) Graph / log clear button
- 17) Torque zero button
- 18) Properties

When the SWEEP button is pressed the control box will - at the specified frequency output take readings from 0 load to 100% load in 2% increments. The results will be stored in the file LOG_1phase.CSV for plotting in Excel.

Whilst the readings are being taken the on screen graph will show an approximate plot so that you can be sure you are getting valid data.



The file name for this program is 'Open Control_3Phase.bat'

- 1) Program control - hit 'PLAY' to start
- 2) Flags for App running, USB comms and Motor in place.
- 3) Frequency of output
- 4) RUN: needs pressing to turn outputs on
- 5) SINE / DIGITAL: Sine or Square wave output
- 6) 20V / 12V output: alters the output voltage
- 7) IMPROVED / STANDARD: alters output waveform quality
- 8) BRUSHLESS MODE: indicates Brushless motor is plugged in
- 9) Meters for the output - RMS values
- 10) Dynamometer load as a %
- 11) Dynamometer speed in RPM

- 12) Dynamometer power in watts
- 13) Torque in mNm
- 14) ZERO: Zeros the torque sensor
- 15) REAL/EFFECTIVE: adjusts the way the graph plots the output waveform.
- 16) PHASE / TIME: shows X axis in degrees or in mS
- 17) CAPTURE: captures a waveform.
- 18) Oscilloscope plot area
- 19) Internal ammeter and voltmeter V1 and I1
- 20) Properties

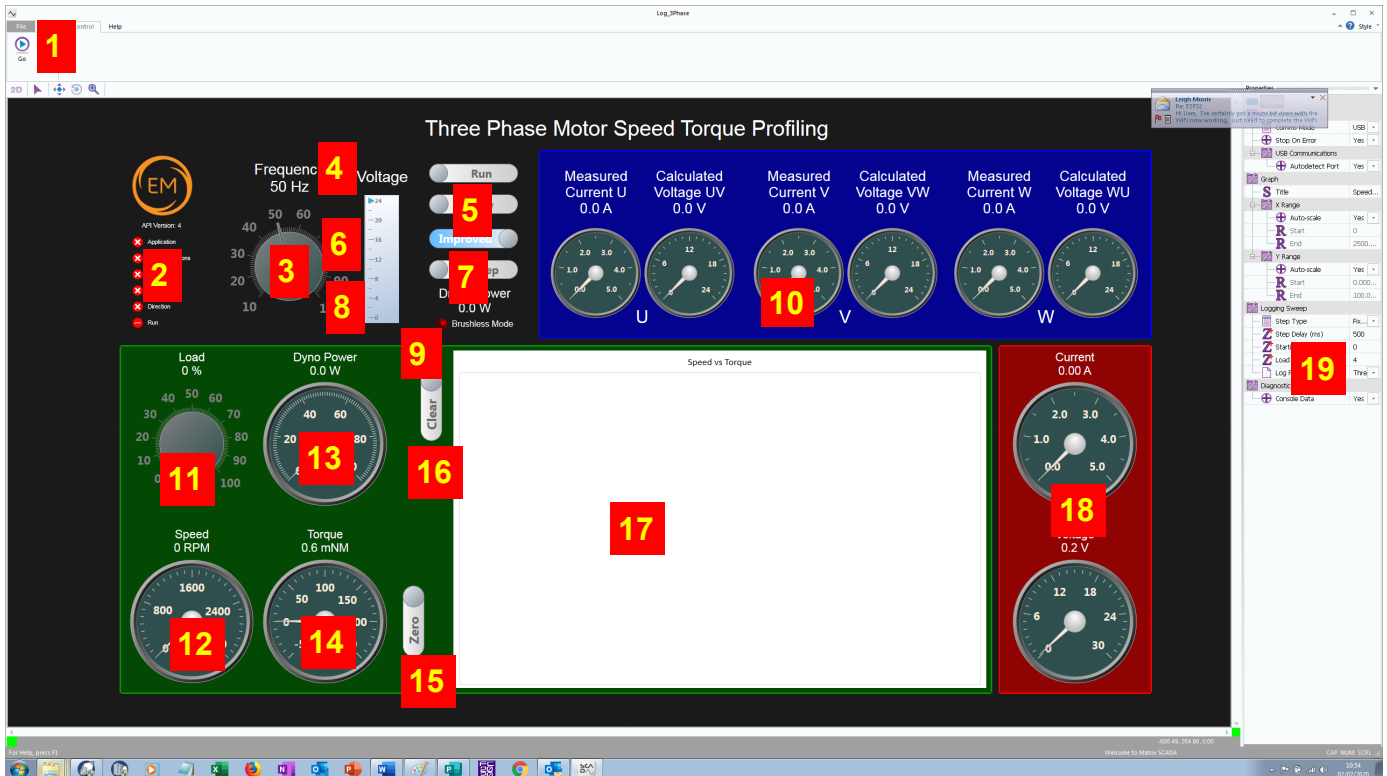
This application runs the three phase motor and the Brushless DC motor.

Reference

Three phase AC automatic



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The file name for this program is 'Open Log_3Phase.bat'

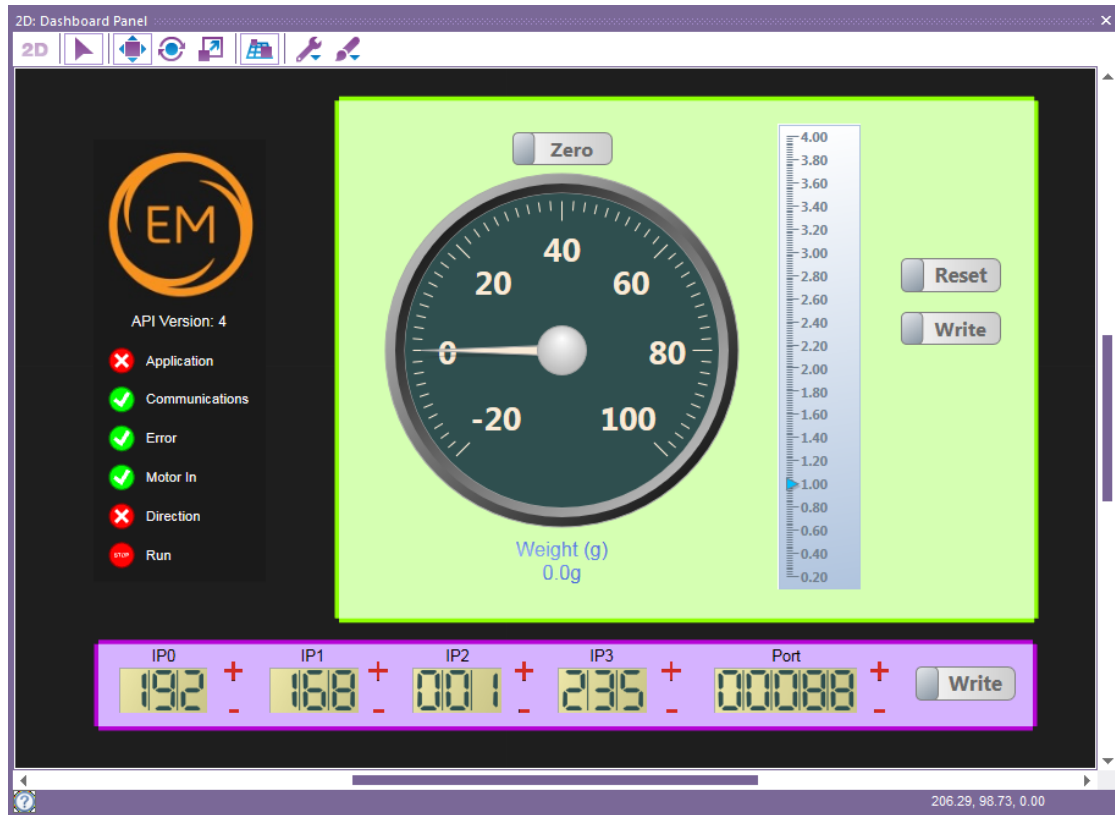
- 1) Program control - hit 'PLAY' to start
- 2) Flags for App running, USB comms and Motor in place.
- 3) Frequency of output
- 4) RUN: needs pressing to start the program
- 5) SINE / DIGITAL: Sine or Square wave output
- 6) 20V / 12V output: alters the output voltage
- 7) IMPROVED / STANDARD: alters output waveform quality
- 8) SWEEP: starts sweep function
- 9) BRUSHLESS MODE: indicates Brushless motor is plugged in
- 10) Meters for the output - RMS values
- 11) Dynamometer load as a %

- 12) Dynamometer speed in RPM
- 13) Dynamometer power in watts
- 14) Torque in mNm
- 15) ZERO: Zeros the torque sensor
- 16) Graph / log clear button
- 17) On screen graph of plot data
- 18) Internal ammeter and voltmeter V1 and I1
- 19) Properties

This application runs the three phase motor and the Brushless DC motor.

When the SWEEP button is pressed the control box will - at the specified frequency output take readings from 0 load to 100% load in 2% increments. The results will be stored in the file LOG_3phase.CSV for plotting in Excel.

Up to 8 data sets can be captured and displayed at one time.



The file name for this program is 'Open Calibration.bat'. This software application has two functions: it allows you to calibrate the load cell and it allows you to set the IP address of the control unit.

Calibration

- 1) Connect the Dynamometer to the control unit with the 25 way D type.
- 2) Twist the dynamometer anti clockwise so that it is not pressing on the load cell at the back of the Dynamometer.
- 3) Press PLAY on the software App. Press RESET. Press Zero.
- 4) Place a 20 gram weight on the end of the load cell. Use the slider multiplier on the App to adjust the dial so that it reads 20g.
- 5) Click on the Write button to save the calibra-

tion into the control box.

- 6) Remove the weight. Press Zero. Your Control unit and Dynamometer are now calibrated together.
- 7) Check the calibration by putting the weight on and making sure the display reads 20g.

If you have multiple sets of Electrical Machines then make sure that they are paired for the next time you use them. This will have been performed for you in the factory so this should not need doing on starting.

IP set up

- 1) Press PLAY on the App
- 2) Use the '+' and '-' buttons on the IP number fields to set the IP address you want
- 3) Click on the WRITE button to save this IP address to the Control box.

Remote Lab Connection

This document outlines the process users should follow to remotely connect an electrical machines control box to a network or internet to allow remote control. This can only be actioned on units purchased since June 2020.

Accessing using local network

The default IP address of the Electrical Machines box is 192.168.1.235 and the default port is 88. The IP address and Port can be changed by connecting to the box using a USB connection and running the calibration application. The Ethernet connection must be connected to the network and then the IP address and Port can be used in the software applications to connect to the Electrical Machines box.

Accessing using the Internet

Before accessing the Electrical Machines box from the internet make sure the box is functioning correctly on the local network. This helps to pin point any connection problems down to the IP and Port of the box or the configuration of the router.

To access the Electrical Machines box from the Internet the user must ensure they have enabled port forwarding on their own router, (the connection from your local network to the internet). This takes incoming connections from the internet and routes them to the correct internal IP address. Use the routers IP address in the software applications.

Information on enabling Port Forwarding on your router: <https://portforward.com/>

Information on finding your routers IP address. <https://whatismyipaddress.com/>

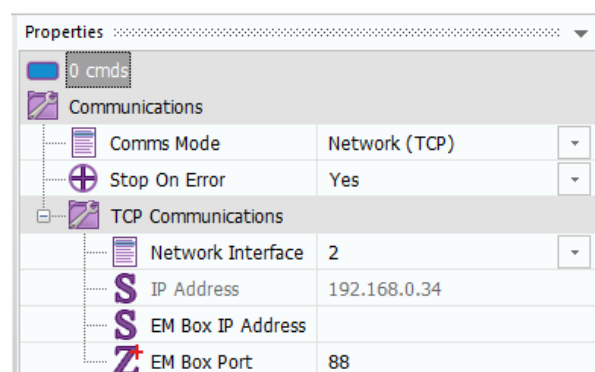
On a home routers (for example in the students' or lecturers home) you may also need to enable a demilitarised zone (DMZ) to the Electrical Machine box IP address to allow incoming Internet traffic to reach it. A commercial router may not have to do this.

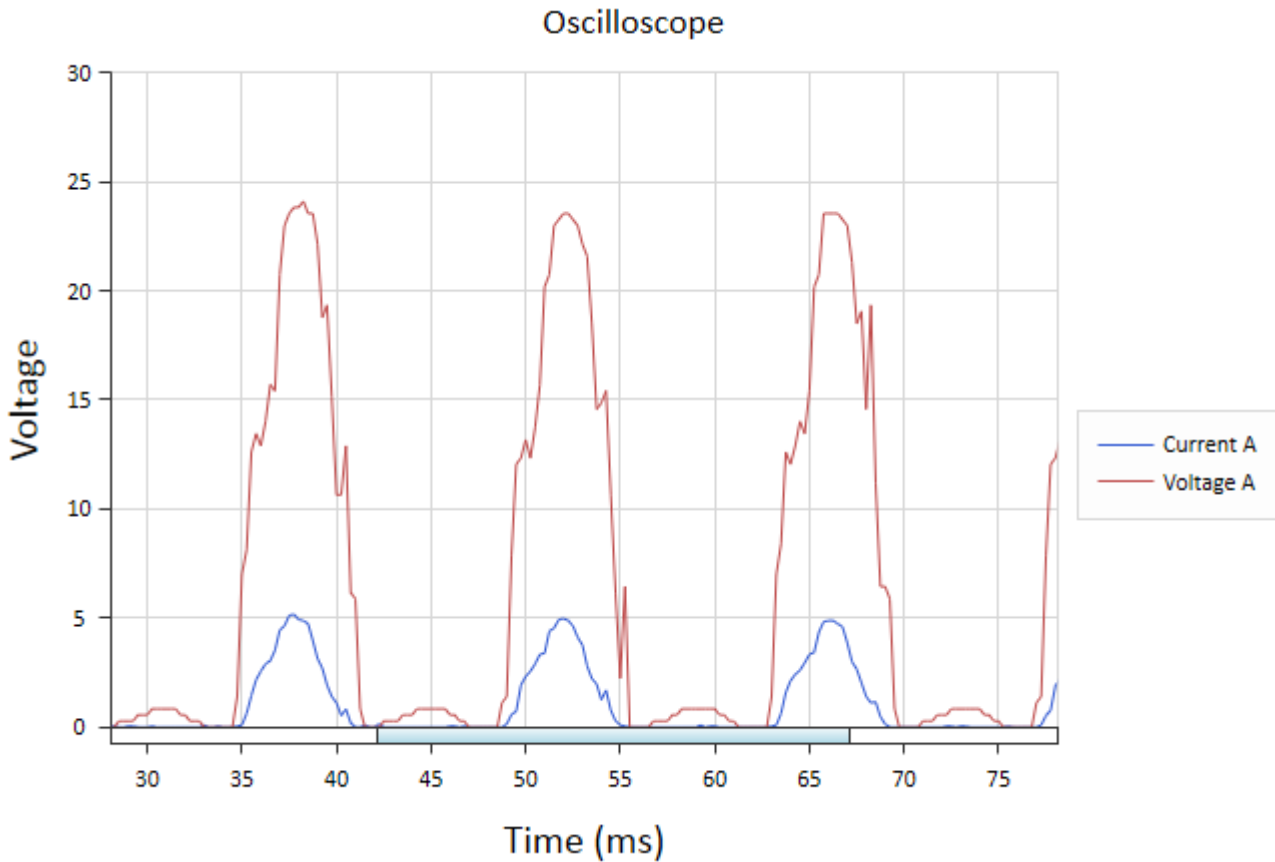
Configuring the software application

Using the software application downloadable from the Matrix website: www.matrixtsl.com/electrical-machines/resources/, the user starts the Electrical Machines software application for the specific machine they have in test.

Ensure Network (TCP) communications is selected (not USB). Under the TCP communications menu, select the network interface that provides a sensible IP value. In the EM box IP address, enter the IP for your control box. In the EM box Port, enter the Port number for your control box.

NB: Matrix TSL are unable to provide help in configuring the IP systems of third parties because of the complexities inherent in this. Local area network managers should be able to provide this support.





The oscilloscope in the Control unit takes measurements of every ammeter and voltmeter in the unit at a rate of 64kHz. There are 16 channels in total - that gives us an effective measurement rate of 4kHz for each channel.

Y axis, Timebase and traces can be set by clicking on the appropriate words in the Properties section at the right hand side of each application.

To alter the time base: click on the oscilloscope area and use the mouse wheel to zoom in and out.

The oscilloscope is useful for seeing voltages and currents at close to the driving frequencies. In fact we use a small capacitor on the input to deliberately slow the effective rate of sampling to make the instrument work better for this

purpose.

Because the PWM frequency used is 7kHz and the effective sampling rate is 4kHz then Nyquist effects can be seen when zooming in to examine the PWM drive frequency. Because of this an external oscilloscope needs to be used when examining waveform structure in detail.

The oscilloscope is particularly good at showing currents the pattern of voltage and current and the phases between voltage and current.

The oscilloscope in the three phase programs has the ability to show Real voltage or Effective voltage as standard. Users at this level should always use Effective voltage.

Reference

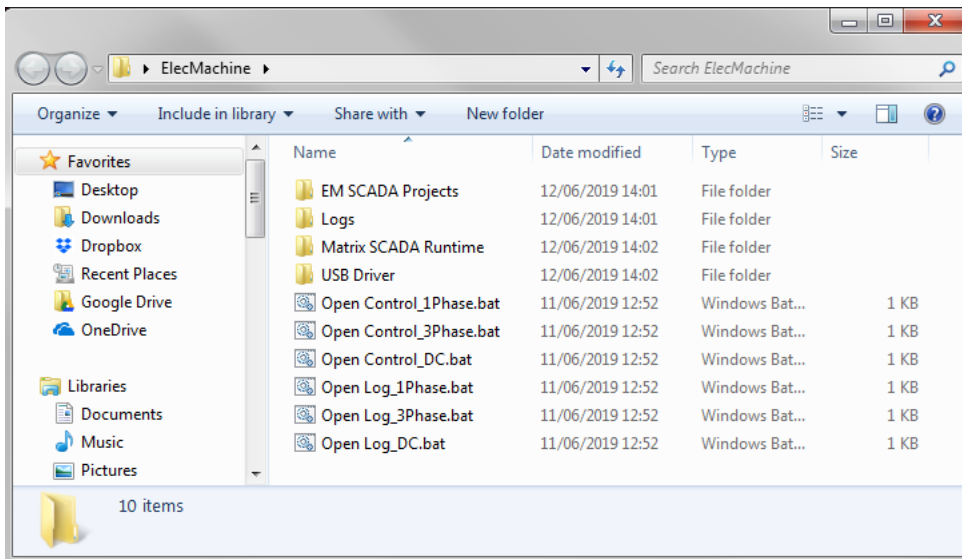
Software installation



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Copying over the software

The software for Electrical Machines is available as a download from the Matrix web site. When you unpack the zip file you will see the following files:



There are 6 applications that are used for the Electrical Machines range. These are documented below.

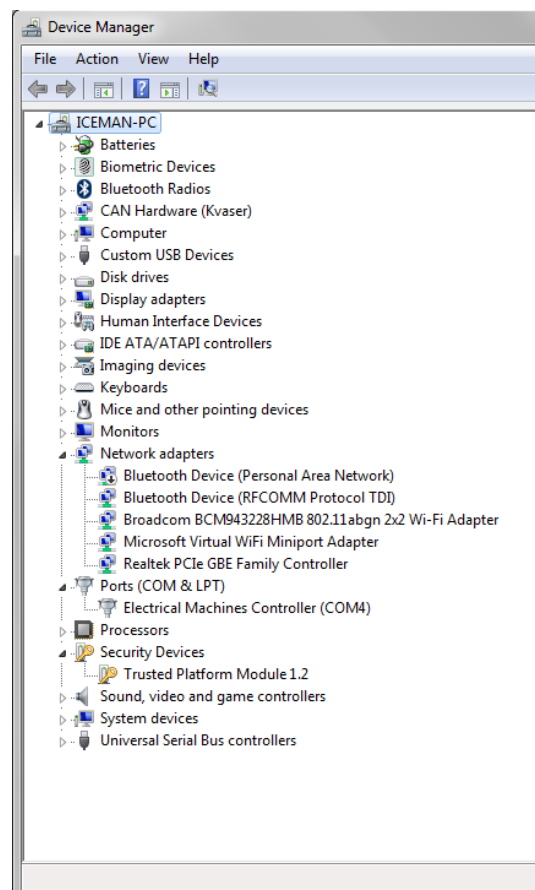
Please copy these programs and directories into a suitable location on your hard drive. You can make short cuts to the *.BAT files if you wish.

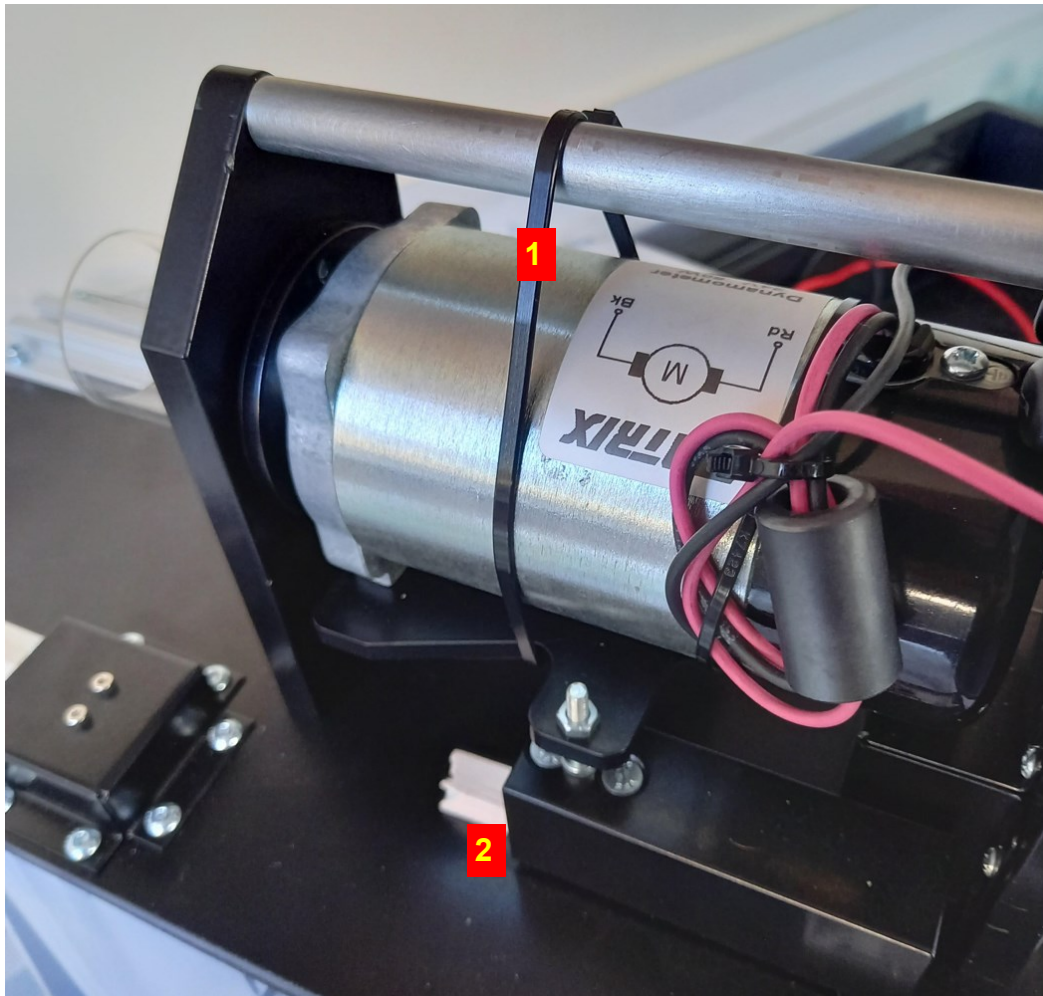
Run each program by clicking on the '*.BAT' file.

Installing drivers

Go into the USB drivers folder and run the 32 bit or 64 bit as appropriate for your computer. This should install the driver for the control box.

You can check the driver is installed properly by looking at Device Manager and checking that the Electrical Machines controller appears under Ports - see opposite.





Packaging may vary from one batch to another. To prevent the mechanism of the Dynamometer from damaging itself or losing calibration during shipping the Dynamometer body and load cell are protected from each other. Please refer to the photograph above.

- 1) To protect the product in shipping a cable tie is strapped round the Dynamometer body to prevent it moving and damaging the mechanism. This should be cut with a pair of wire cutters to allow the Dynamometer to rotate.
- 2) To protect the sensor a block of wood is fitted under the load cell sensor. This can be removed manually.



Instructor Guide

About this course

Introduction

The course is essentially a practical one. Where possible, practical implications and applications of the theory are highlighted to make the course more relevant to the students.

The equipment offers tremendous scope for additional research on the topic and instructors may wish to encourage and support this research.

Aim

The course introduces students to concepts and devices used in a range of electrical machines. It covers much of the content of Unit 15 - Electrical Machines in the BTEC Level 3 Diploma in Electrical and Electronic Engineering, and similar qualifications.

Other modules relevant to the Diploma course are:

LK9392 - 'Introduction to digital electronics';

LK8473 - 'Advanced electrical principles - DC';

LK8749 - 'Advanced electrical principles - AC';

LK2686 - 'Three-phase systems';

LK3568 - 'Power and Energy Electronics'.

Prior Knowledge

It is recommended that students have followed the 'Electricity Matters 1', 'Electricity Matters 2' courses, or have equivalent knowledge, covering the basic electrical concepts of current, voltage and resistance, energy and power and are able to construct and test circuits, using a multimeters and oscilloscopes.

About these worksheets

These worksheets provide a practical environment for the study of Modern Electrical Machines. This is not the only resource a student will need. Students will also benefit from lectures, tutorials, text books and other provided by the instructor. The experiments in this course should be integrated with teaching to introduce the theory behind it, and reinforced with written examples, assignments and calculations. The internet is a rich source of information on this topic and the instructor should give students research assignments accordingly.

We have set out the learning resource as a series worksheets, followed by a Reference section. It is expected that the students will be given their own copy of the worksheets, either one by one, or as a pack.

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

'Answers' are not included. They are easy to calculate and are often subjective.

Time:

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

Learning Objectives

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

- describe the precautions required when operating electric motors;
- calculate the force exerted by an object due to gravity, given its mass and the acceleration due to gravity;
- explain what is meant by the term 'torque';
- calculate the torque about an axis, given the force and distance from the axis
- explain the meaning of the term 'power' and calculate the power delivered by:
 - a rotating shaft;
 - a DC electric motor;
 - a single-phase AC electric motor;
 - a three-phase electric motor;
- explain the meaning of the term 'energy efficiency' and calculate it for an electric motor;
- explain the meaning of the term 'synchronous speed' and calculate it for an AC motor;
- explain the meaning of the term 'slip' and calculate it for an AC motor;
- describe the structure of a simple DC motor;
- describe the function of a commutator in a DC motor;
- take measurements that allow the torque applied by a rotating motor to be measured;
- describe how to reverse the direction of rotation of a DC motor;
- describe what is meant by 'pulse-width modulation, (PWM)' and explain its use in controlling the speed of a DC motor.
- explain what is meant by the term 'mark:space' used in connection with a PWM signal;
- describe the energy flow when a powered DC motor is connected to a dynamometer which has a resistive load attached to it;
- describe three domestic or industrial applications of the DC motor;
- describe the effect of rotational speed on torque for a DC motor;
- take measurements to investigate the variation of efficiency with speed for a dynamo under load;
- describe the differences between a shunt-wound and series-wound DC motor;
- explain the meaning and significance of the term 'back e.m.f.';
- measure the resistance of the windings in series-wound and shunt-wound DC motors and explain the significance of the results;
- describe how to reverse the direction of rotation of a wound-stator DC motor;
- explain the meaning of the term 'separately excited' when applied to wound-stator DC motors;
- compare the performance characteristics of shunt-wound and series-wound DC motors;
- explain why series-wound motors are widely used and list six common applications;
- describe the main difference in structure between a universal AC motor and a single-phase AC induction motor;
- explain the need for a starting circuit in a single-phase AC induction motor;

continued on next page ...



continued ...

- describe how to reverse the direction of rotation of an AC induction motor;
- explain the need for 'start' and 'run' capacitors in a single-phase AC induction motor;
- draw a graph to illustrate the phase shift between currents flowing in the windings of an AC induction motor;
- describe the use of a variable frequency drive for speed control in an AC induction motor;
- explain what is meant by a 'tri-state' driver;
- distinguish between a single-phase and a three-phase AC supply;
- describe how to reverse the direction of rotation of a three-phase AC motor;
- compare the performance of a single-phase and a three-phase AC induction motor;
- investigate the variation of slip with speed and load for a three-phase AC induction motor;
- describe the significant features of a 'brushless' DC motor;
- describe the power supply requirements of a brushless DC motor;
- describe the speed/torque characteristics of a brushless DC motor;
- investigate the use of a brushless DC motor as a three-phase generator;
- investigate how the efficiency of the brushless motor compares to that of the DC motor.

Worksheet	Notes for the Instructor	Time
<p>1 Getting started</p>	<p>The first worksheet looks at setting up the system. It is important that students take care to line up the components as directed in the worksheet. The instructor should check that the balance has been positioned correctly. The balance is used when in manual mode to obtain a mass (and hence force) reading. The software receives torque data from the load cell. Instruction (3), about software applications and drivers may not be relevant to students in some establishments but it is given as a reminder to those responsible for such matters. This is a good time to go over the health and safety aspects of using the kit. The students should be encouraged to read the 'Key Relationships' section on page 4 and to familiarise themselves with the content of the extensive 'Reference' section, particularly page 63, which allows them to identify the various components in the kit. Note that the equipment may have a packing strap around the dynamometer that will need removing to allow the dynamometer to move freely, and may also have a small block of wood under the sensor. These need removing before use.</p>	<p>20 - 30 mins</p>
<p>2 Understanding torque and mass</p>	<p>Here the students learn how to use the dynamometer to measure torque. The kit is used in manual mode and students should read carefully the description of the dynamometer given on page 68 before attempting to use the kit. Torque can be derived using the balance reading and applying the appropriate formula in the 'Key Relationships' section. The Instructor may need to reinforce ideas about the concepts involved - mass, force and torque in particular. Students may need help with some of the calculations depending on previous experience and mathematical ability.</p>	<p>40 - 60 mins</p>
<p>3 Understanding the DC power supply</p>	<p>The focus here is on pulse-width modulation and its use to control motor speed. An introduction to the topic by the instructor will ease the students' progress through the exercise. They need to understand the concept of mark:space ratio. The worksheet also allows them to practice triggering a 'scope. Once again, an introduction by the instructor will help where students have not met the technique before. A key technique in the learning resource is the sketching of waveforms. Students need to get used to doing this, not in a highly accurate way, but in a way that conveys key timing information.</p>	<p>40 - 60 mins</p>
<p>4 DC motor characteristics - 1</p>	<p>This worksheet introduces the operation of probably the most widely used low-power motor, the DC permanent magnet motor. With the benefit of modern rare earth magnets, this type of motor is a viable alternative to traditional wound stator motors. The lack of stator windings means that this type of motor can be smaller than its counterparts. This motor produces more torque than any of the other motors in the Matrix set. In this exercise, students use a software application to examine the motor's performance. Students should appreciate that they are not seeing an on-screen simulation, but are using SCADA (supervisory control and data acquisition,) to collect data in real time from the motor. The students sketch a graph based on readings from the computer. This recognises that there is a danger, when using IT, that students press buttons rather than understand. The idea of sketching some of the graphs is to improve understanding and retention. The instructor may wish to focus on the meaning of power and efficiency.</p>	<p>50 - 70 mins</p>

Worksheet	Notes for the Instructor	Time
<p>5 DC motor characteristics - 2</p>	<p>In this worksheet students use a logging application to capture the characteristics of a DC motor for a range of output voltages. It is suggested that students then view that data in 'Excel' using that application's graph-plotting function.</p> <p>Using Excel in this way is a useful key skill. What we want to avoid is students just copying and pasting graphs into a Word document without understanding their significance. Using 'Excel' for all the worksheets is probably too time consuming and so the instructor needs to use judgement here.</p> <p>A key issue here is the equivalent data for the load that the motor will be driving and how it is plotted on the same graph. Understanding the load / speed / torque requirements for an installation is not examined in the worksheet but is a valid extension at this point should the instructor wish it.</p>	<p>50 - 70 mins</p>
<p>6 Permanent magnet generator (dynamo)</p>	<p>It is important that by this stage, students have a firm grasp of the meaning and significance of the concepts power and efficiency. Here, the motor delivers mechanical power to the dynamo contained in the dynamometer. In turn, it delivers electrical power to the load. Taking appropriate readings, the students calculate the energy efficiency of this conversion for a range of supply voltages (and hence speeds.) The results are plotted as a graph.</p> <p>Should the instructor think it appropriate, students could use 'Excel' to produce the graph.</p>	<p>30 - 50 mins</p>
<p>7 Shunt and series motor basics</p>	<p>This exercise focuses on the construction of motors and the significance of the terms 'shunt' and 'series'. The photographs in the 'Reference' section are a valuable aid. Students should study them carefully and could be asked to identify the salient features of each.</p> <p>First of all, they test the windings of motors, using an ohmmeter. Depending on previous experience, the students may require input from the instructor to help them with this.</p> <p>Students also need to understand the concept of 'back emf'. They measure the absolute resistance of the windings and might expect to use this to predict the current flowing in them. However, when the winding is in the motor, rotating inside a magnetic field, a voltage (back emf) is induced which opposes the driving voltage, reducing the overall voltage experienced by the motor. As a result, a smaller current flows. It is a concept that will take time to develop. At this stage, students are not expected to perform calculations on it.</p> <p>The second part of the worksheet investigates the behaviour of the two types of motor, when running. The circuits are different - two separate power supplies are used for the shunt motor, but only one for the series motor. For some students, it is advisable to check the wiring. Students measure the current through the coils and rotational speed over a range of supply voltages.</p> <p>The series motor has an extremely small resistance, meaning that huge currents can flow. The control unit will cut out eventually, when the series motor is used. This is a safety precaution to prevent the control unit from overheating, and is a feature of all well-designed power supplies.</p>	<p>30 - 50 mins</p>

Worksheet	Notes for the Instructor	Time
<p>8 Shunt-wound motor characteristics</p>	<p>This worksheet investigates the operation of the separately-excited DC shunt motor to obtain the speed/torque curve for the machine.</p> <p>A key aim of the module is to get student to understand that electrical machines have different characteristics. Different applications have different demands and the engineer will be tasked with choosing a motor with characteristics appropriate to meeting those demands. Understanding speed, torque and efficiency and their roles in motor operation are a big part of this.</p> <p>As pointed out in the last worksheet, the shunt motor uses separate supplies for the armature (or rotor) and the field windings (stator.) For some students, it is advisable to check the wiring.</p> <p>The software produces lovely speed/torque curves. The reason for asking students to redraw them by hand is to encourage them to think a little more about the numbers!</p> <p>The activity ends with an investigation into the effect of the field windings voltage on the energy efficiency of the motor. There is scope with this arrangement to expand the investigation into factors affecting efficiency</p>	<p>40 - 60 mins</p>
<p>9 Series-wound motor characteristics</p>	<p>Next, students investigate the series-wound motor in the same way.</p> <p>The DC power supply is designed to ramp up to the required value when you 'Run' the application, rather than deliver the final value straight away. Part of the reason for this is to limit the current on start up. With more able students, the instructor could lead a discussion on back emf and its implications for series and shunt motors.</p> <p>Typical of all wound-rotor motors, to reverse the direction of rotation requires reversing the polarity of one (only) of the windings. Reversing all power supply connections keeps the motor rotating in the original direction since both fields have changed polarity.</p> <p>Again, for the reason given in the last worksheet, students sketch graphs by hand, as well as obtaining them from 'Excel'.</p> <p>Mirroring the investigation into the shunt motor, the activity ends with the effect of the power supply voltage on the energy efficiency of the motor.</p>	<p>40 - 60 mins</p>
<p>10 Universal motor</p>	<p>This worksheet builds on the knowledge gained in worksheet 9, using the same series-wound motor to investigate the operation of the universal motor, now powered by AC.</p> <p>This motor performs better (i.e. produces higher torque) when running as a DC motor. When running as an AC motor, the increase in impedance due to the AC causes a reduction in the motor current. As with all motors, lower current means lower torque. The instructor could discuss the effect of frequency on impedance as part of the introduction to this investigation.</p> <p>Afterwards, students are asked to compare the characteristics of this motor in its DC and AC modes of operation.</p>	<p>40 - 60 mins</p>

Worksheet	Notes for the Instructor	Time
<p>11 Comparing shunt and series motors</p>	<p>Students compare the construction of the two types of motor, using the photographs provided. They should study closely the photographs on pages 50 to 53 of the 'Reference' section, as well. (Please discourage them from taking the actual machines apart!)</p> <p>The instructor should remind them of their earlier findings on the resistance of the windings and current demand of the two types of motor.</p>	<p>15 - 25 mins</p>
<p>12 Single-phase induction motor</p>	<p>This worksheet introduces the AC single-phase induction motor. The name 'induction' refers to the way in which the current is induced in the rotor by the moving magnetic field created by the AC current in the field windings.</p> <p>Students find out that this type of motor does not self-start. They could be given the task of researching various starting / running circuits used with the induction motor. The instructor could discuss the meaning and cause of phase shift at this point, in anticipation of the coming investigations.</p> <p>The induction motor usually has two separate coils in the field windings, a 'main', or 'run' coil and an 'auxiliary' or 'start' coil. The 'start' and 'run' windings of this motor are identical, so they windings can be swapped in order to change the direction of rotation of the motor. One end of the 'run' winding is connected to one end of the 'start' winding to form the 'common' connection.</p> <p>To run the motor in the opposite direction, stop the motor and reverse the connections to the dynamometer and the 'nudge' will cause the motor to reverse.</p>	<p>15 - 25 mins</p>
<p>13 Single-phase induction motor - cap start</p>	<p>In this exercise, a capacitor is incorporated to create a phase shift between the magnetic field of the 'run' coil and that of the 'start' coil. We now have a self-starting induction motor.</p> <p>The phase shift is frequency dependent. This is be one outcome of interpreting the graphs resulting from the measurements. Ask the students to remove one of the windings and observe that the motor still rotates – once started.</p>	<p>40 - 50 mins</p>
<p>14 Phase shift in induction motors</p>	<p>This worksheet reinforces the notion of a phase shift caused by the start / run capacitors and the resulting shift in the magnetic fields inside the motor. It explores the link between AC driving frequency, speed and energy efficiency.</p> <p>The internal oscilloscope has been added to the control unit for this purpose and you will find that will a little practice it is a superb tool for understanding phases involved in driving the motor. The instructor may be in demand to help with using the software, controlling the oscilloscope and interpreting the results.</p>	<p>40 - 50 mins</p>
<p>15 Variable frequency drive strategies</p>	<p>Just with PWM in DC motors, students may need help to understand how induction motors are controlled using pseudo-sine waveforms and FET based circuits. and how FETs can provide a 48V peak-to-peak waveform from a 24V supply.</p> <p>The DC1 output is used to trigger the oscilloscope to view the waveform of the single-phase output A signal . Use an external 'scope for this, but not a PC-based device. The internal oscilloscope is not good for this as the sampling frequency is too low. However, it is a really useful tool for looking at the current flowing in the motor. The final task, examining the waveforms of signals A and B is left as an investigation for more able students.</p>	<p>40 - 50 mins</p>

Worksheet	Notes for the Instructor	Time
<p>16 Three-phase motor characteristics</p>	<p>This worksheet builds on student's knowledge of single-phase motors to three-phase induction motors.</p> <p>The investigation should show that three-phase motors are more efficient in equivalent situations. They have a number of other advantages over single-phase induction motors, such as uniformity of torque, smaller size/weight and self-starting. The students could be set the task of producing a presentation contrasting the properties of three-phase and single-phase motors.</p>	<p>40 - 50 mins</p>
<p>17 Three-phase motor drive strategies</p>	<p>This is quite a lengthy worksheet, which aims to help students to understand how three FET-based circuits provide a three-phase driving signal.</p> <p>As a simplification, resistors are used as a load for the three-phase power supply. This makes it much easier to study the driving waveforms. When the inductive load of the three-phase motor is connected, the waveforms are much more complicated and difficult to interpret.</p> <p>Students might find the concepts of open circuit and floating outputs difficult to understand. The instructor may need to spend some time with the system diagram, describing to the students the waveforms they are likely to see on the oscilloscope. Understanding these waveforms will help students to understand what to look for when testing three-phase speed control circuits.</p>	<p>40 - 50 mins</p>
<p>18 Delta connection</p>	<p>This worksheet covers Delta connection. Its value is to show students the difference between star and delta and that delta connection is more current hungry because of the fact that the windings are across the power supply - a lower effective resistance than star connection.</p>	
<p>19 Understanding slip</p>	<p>The instructor may need to introduce this exercise with an explanation of the meaning of synchronous speed and slip.</p> <p>They need to be confident in their ability to relate a driving frequency in Hz into a speed of rotation in RPM and vice-versa. The issue of the number of poles (and pairs of poles) in a motor is potentially confusing and will probably require input from the instructor. The diagrams in the Reference section, pages 56 to 59, will help to resolve this.</p>	<p>40 - 50 mins</p>

Worksheet	Notes for the Instructor	Time
<p>20 Brushless DC motor</p>	<p>This worksheet introduces the student to the permanent magnet three-phase synchronous motors (PMSM). This type of motor and the similar brushless DC motor (BLDC) are gaining popularity in various industries e.g. electrical vehicle motor/generators.</p> <p>This motor cannot achieve synchronous speed instantaneously. It is started at low speed, where the permanent magnets can move and keep up with the rotating magnetic field. The frequency is then increased slowly until the motor is running at full synchronous speed.</p> <p>This worksheet focuses more on understanding how the Brushless motor works and on the connections to it than on the significance of the speed/torque graphs. Its hard to show this well as the driving waveform is dictated by the position of the Hall sensors and showing all this at one time is difficult.</p> <p>However, as more and more applications use Brushless motors, students need to be familiar with it.</p>	<p>40 - 50 mins</p>
<p>21 Three-phase generator</p>	<p>This worksheet introduces the permanent magnet three-phase synchronous generator (PMG). This is in fact the Brushless DC motor studied in the previous worksheet.</p> <p>Typically, this dual motor/generator functionality is this motor's strength. In electric vehicles, it can be used to provide the rotational energy to drive the wheels and act as a generator to charge the battery, under regenerative braking.</p> <p>Note - three diodes are included in the kit so that you can build a full three-phase rectification system from the output of the Brushless DC motor.</p>	<p>40 - 50 mins</p>

Equipment checklist



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To deliver this set of worksheets you will need:

Code	Description	Qty
COM7414	RS232 lead	1
EM1100	Red 100cm lead	3
EM1125	Black 100cm lead	3
EM1150	Green 100cm Lead	2
EM1175	Yellow 100cm lead	2
EM1190	Blue 100cm lead	2
EM2159	Dyno	1
EM2391	3 phase motor	1
EM5337	Brushless motor	1
EM6066	Control box	1
EM6574	DC motor assembly	1
EM7432	Series motor	1
EM8614	Single phase motor	1
EM9856	Shunt motor	1
HP2045	Shallow tray	2
HP3701	Mains lead	1
HP3844	Foam	5
HP4039	Lids	6
HP5540	Deep tray	3
HP6002	Cable for brushless motor	1
HP6529	Binding post	2
HP6640	Extra deep tray	1
HPUSB	USB lead	1
LK2346	Bulb	3
LK5203	10Kohm resistor	3
LK5243	Diode 1A	3
LK5250	link	5
LK5291	Lampholder	3
LK5297	Lead - black 4mm to 4mm unshrouded	1
LK5298	Lead - red 4mm to 4mm unshrouded	3
LK8900	baseboard	1
XXXXX	Locktronics foam insert	1

If you intend to use an external meter, please note that it needs to be a true RMS meter.

Problem: On newer models the Dynamometer arm can stick in the powder coating of the load cell. This affects readings at low torque.

Remedy: put a little WD40 on the load cell so that the arm does not stick.

Problem: comms errors.

Solution: some lap tops seem to reduce the USB response speed as a battery saving measure .In Task manager set the SCADA app as a higher priority.

Problem: results don't make sense

Solution: make sure the unit is calibrated.

Problem: when in manual mode using the three phase power supply the control unit simply gives an error and there is no output:

Solution: At low frequencies the unit has to deliver a lot of power when the motor is at standstill and the overcurrent protection kicks in.

Disconnect, set the frequency to mid range, power up and the motor will start.

Version control



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04 07 19 first release

05 12 19 errors on page 23 fixed - too high %

01 07 20 changes for V1.1 software and control box. Addition of delta worksheet. Addition of IP and calibration information. Changes to all software apps pages. Other small changes.

07 07 20 Remote connection information added.

04 11 20 changes in power efficiency instructions for ws8 and ws9.

22 02 22 Addition to Troubleshooting

30 06 22 wording changes worksheet 8

29 07 22 Various changes suggested by a customer.

20 06 23 % limits on some worksheets altered.

28 07 23 reformatted to new style