EM ELECTRICAL MACHINES

Advanced electrical machines

Contents

Health and safety

ELECTRICAL
MACHINES

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.

Transformers can increase the AC voltage to levels that present a risk of shock. When using transformers make sure that you only use the shrouded 4mm to 4mm connectors supplied with the kit.

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.

Please:

Should an accident happen while the equipment is being used, please report it to us,

at the address below, so that we can consider how to make the equipment even safer.

Design team

> **Caution:**
> **When using transformers make sure that you only use the safety shrouded 4mm to 4mm leads supplied with the kit.**
>
> **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.**

Induction motor construction

The three phase induction motor is the most common electrical machine in industry, where it used to drive pumps, fans, compressors and machine tools. Around 50% of the total industrial energy consumed in Europe is expended in motor drives of which an estimated 70-80% are induction motors.

An induction motor has the same physical stator as a synchronous machine, with a different rotor construction. There are two different types of rotor, the *squirrel cage rotor* (also called cage rotor) and the *wound rotor.* A squirrel cage rotor consists of a series of conducting bars laid into slots and shorted at each end by conducting rings called end rings. In small machines the bars tend to be constructed using extruded aluminium along the rotor slots and solid end rings are formed which are often shaped to act as internal fans as shown in Figure 8. In larger machines (typically lOOkW) the cage is manufactured using copper bars brazed at each end to copper end rings.

The wound rotor is made from distributed windings which are connected externally to shaft mounted slip rings. The rotor windings are then short circuited either directly across the slip rings or through an external impedance.

Key relationships

Calculating torque

Torque is the turning effect of a **force**.

The balance always measures force. This can be related to mass. Force and mass are linked by:

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

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:

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

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:

torque (in Nm) = **balance reading** (in kg) x **9.81** (m/s^2) x **0.03812** (m).

Calculating power

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

For a rotating body:

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

For a DC motor:

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

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

For a single phase AC motor:

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

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

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

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

Calculating synchronous speed and slip

Synchronous speed in r.p.m = (**f** x 60) / (number of pairs of poles)

(Number of pairs of poles relates to how the motor windings are configured:

a 2-pole motor has one pair of poles, a 4-pole motor has two pairs of poles etc.)

Slip = ((synchronous speed - slip speed) / synchronous speed) x 100%

Key relationships

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

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

Where **fs** = supply frequency and **p** is the number of pole pairs - in our case 1.

## 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:

$$Vphase = SQRT(3) \times Vline$$

Equivalent circuit of a transformer

The transformer can be conveniently represented by the equivalent circuit shown below.
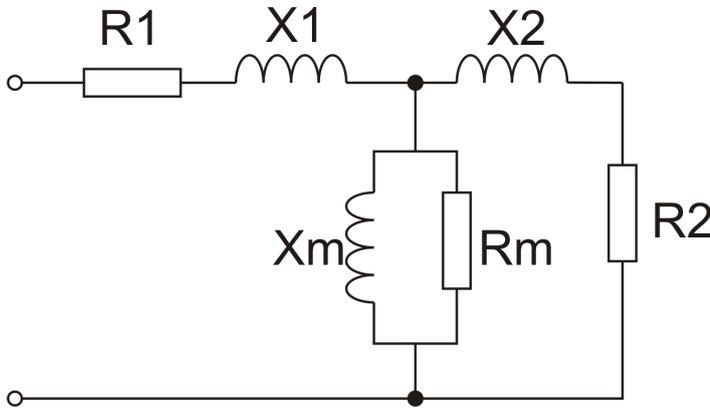
Where:

R1 is the primary winding resistance

X1 is the primary leakage reactance (not all of the flux produced by the primary will link to the secondary)

Rm is called the iron loss resistance and represents the losses in the core due to eddy currents

Xm is the magnetizing reactance

R2 is the secondary winding resistance (not the true resistance but the effective resistance as seen from the primary taking into account the turns ratio)

X2 is the referred secondary reactance

With a few assumptions and some practical tests it is possible to measure the values of these parameters and build an electrical model of an transformer.- provided we know the phase angle shift between the voltage and the current.

Step 1: perform the open circuit test

The open circuit test is performed by running the transformer at full voltage with no secondary load. At the same time it can be assumed that Rm and Xm are significantly bigger than R1 and X1 so that the equivalent circuit can be approximated by the diagram shown below.
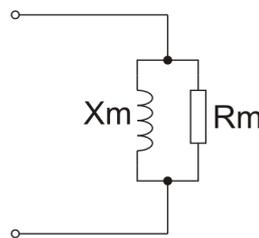
Equivalent circuit of a transformer with no secondary load

As we can measure the phase angle between the voltage and current using the on board oscilloscope then we can deduce the relative values of Rm and Xm.

At this point Rm and Xm can be calculated as follows:

Equivalent circuit of a transformer

$$Zm = Vp / Ip$$

$$Ixm = Ip \sin(\emptyset)$$

$$Xm = Vp / Ixm$$

$$Irm = Ip \cos(\emptyset)$$

$$Rm = Vp / Irm$$

As we can measure the phase angle between the voltage and current using the on board oscilloscope then we can deduce the relative values of Rm and Xm. As Rm can be measured with a multimeter then we can deduce both Rm and Xm. So this first step helps us determine Rm and Xm.

Step 2: perform the short circuit test

The short circuit test is performed by shorting out the secondary winding. In this case Xm and Rm is much larger than the secondary branch, so that the equivalent circuit can be given by the diagram below:
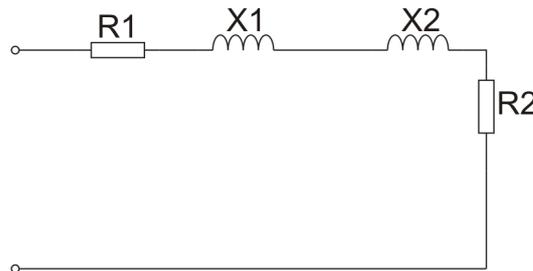
Equivalent circuit of a transformer with sort circuit secondary

We can calculate the values as follows:

$$ZT = Vp / Ip$$

$$XT = ZT \sin(\emptyset)$$

$$X1 = X2 = XT / 2$$

(assuming windings are identical)

$$RT = ZT \cos(\emptyset)$$

$$R1 = RT - a^2 R2$$

$$R1 = Rt - a^2 * R2s$$

In the last two lines a refers to the ratio of the number of turns in the primary and secondary windings:

$$a = Np/Ns$$

This allows us to build circuit equivalents for transformers with other than a 1:1 ratio.

Equivalent circuit of an induction machine

The induction motor can be conveniently represented by the equivalent circuit shown below. This equivalent circuit represents a single phase of the machine.
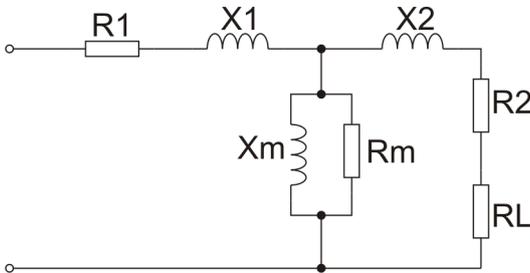
Equivalent circuit of an induction machine

Where:

R1 is the stator winding resistance

X1 is the stator leakage reactance (not all of the flux produced by the stator will link the rotor windings. This leakage is represented by X1)

Rm is called the iron loss resistance and represents the losses in the stator and rotor cores due to eddy currents

Xm is the magnetizing reactance

R2 is the referred rotor winding resistance (not the true resistance but the effective resistance as seen from the stator taking into account the turns ratio between rotor and stator)

X2 is the referred rotor reactance

RL is the term used to model the shaft output power (dependent on slip). It can be defined as : R2(1-s)/s (s defined as a fraction)

With a few assumptions and some practical tests it is possible to measure the values of these parameters and build an electrical model of an induction motor. This set of worksheets shows you how to do this. There are a number of steps to this:

Step 1: perform the open circuit or free running test

The open circuit test is performed by running the motor at full voltage with no mechanical load. Assuming motor windage and friction losses are negligible the machine will run very close to synchronous speed. At that point the value of RL given by RL = R2(1-s)/s approaches infinity. At the same time it can be assumed that Rm and Xm are significantly bigger than R1 and X1 so that the equivalent circuit at synchronous speed can be approximated by the diagram shown below.
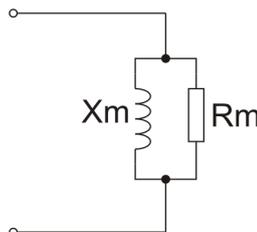
Equivalent circuit of an induction machine at synchronous speed

Equivalent circuit of induction machine

As we can measure the phase angle between the voltage and current using the on board oscilloscope then we can deduce the relative values of Rm and Xm.

At this point Rm and Xm can be calculated as follows:

$$Zm = Vp / Ip$$
$$Ixm = Ip \sin (\emptyset)$$
$$Xm = Vp / Ixm$$
$$Irm = Ip \cos (\emptyset)$$
$$Rm = Vp / Irm$$

As Rm can be measured with a multimeter then we can deduce both Rm and Xm.

Step 2: perform the locked rotor test

The locked rotor test is performed by locking the rotor and applying a voltage to the stator. In this case the value of RL given by RL = R2(1-s)/s is equal to zero and the magnetising branch given by Xm and Rm is much larger than the rotor branch, so that the equivalent circuit can be given by the diagram below:
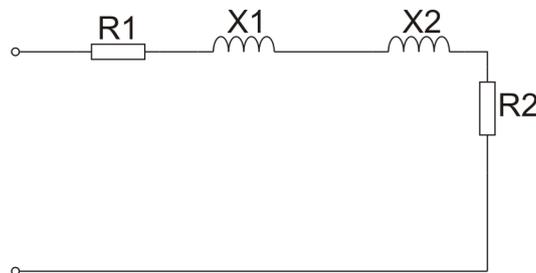
Equivalent circuit of an induction machine with locked rotor

We now know Rm. With the motor at standstill and not powered RL goes to infinity.
From experience we know that X1 and X2 are similar.

$$ZT = Vp / Ip$$
$$XT = ZT \cos (\emptyset)$$
$$X1 = X2 = XT / 2$$
$$RT = ZT \sin (\emptyset)$$
$$R2 = RT - R1$$

Equivalent circuit of induction machine

Lastly we can simply use a multimeter to measure the resistance of R1 by measuring the resistance across a single winding as L1 provides an effective short circuit for a DC ohmmeter.

Conclusion

By carrying out the open circuit test and the locked rotor test we can gather the terms in the equivalent circuit of the induction machine.

In the following worksheets you will work through this process step by step to build a model for the machine. Then you will use a mathematics package like Matlab or GNU Octave to verify your model.

Induction motor drive systems

The Control unit makes use of five powerful FET based driver devices. Three of these are used to drive the induction motor using a Pulse Width Modulated signal. You will probably have come across simple PWM based driving systems for driving DC motors. The mark space ratio of the driving voltage is varied between 0% and 100% to achieve power control similar to simply varying the amplitude of the DC driving voltage. This system needs refining somewhat for the three phase motor power supply.

Pseudo sine drive waveform

Microcontroller drive circuit
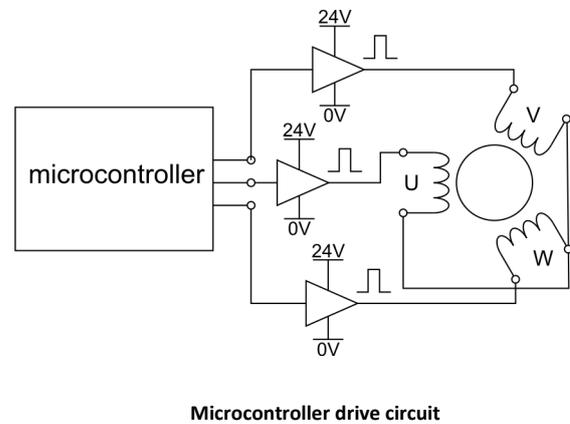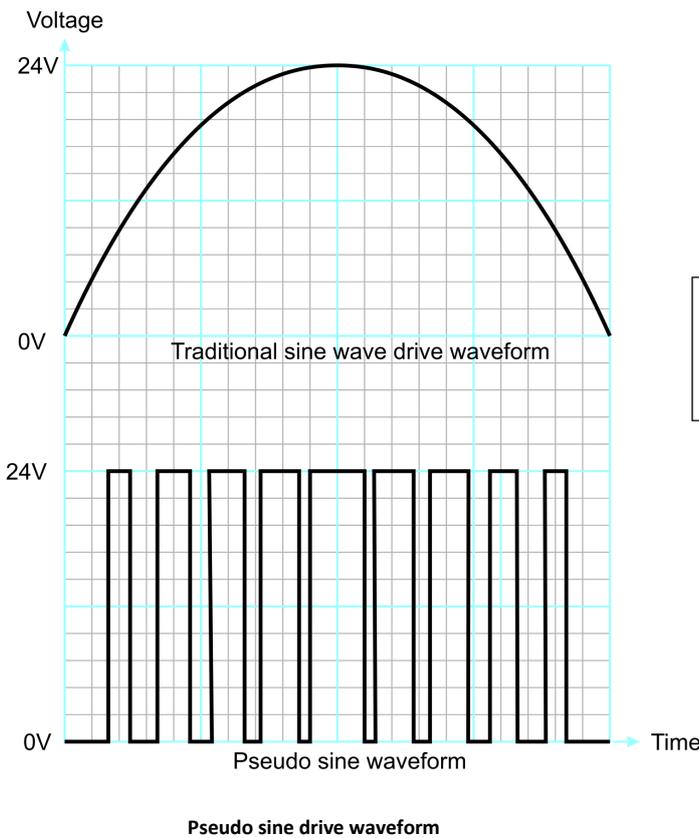
The PWM voltage driving algorithm can be varied to produce a power waveform much like a sinusoid as can be seen in the diagram above. This diagram is very coarse: in practice a resolution of 5 degrees is used with a PWM frequency close to 8kHz. This allows us to produce sinusoidal currents in the windings as the inductance of the windings acts as a very efficient low pass filter.

The windings in the tests here are connected in 'Star' format: one end of the U, V, W windings is connected to the drive circuit and the other ends of the three windings are simply connected together to form a virtual earth.

From the waveform above you can see that one half of the driving waveform can easily be produced by an amplifier using PWM with a sinusoidally varying mark space ratio. In a DC PWM motor drive circuit an H bridge circuit is used with four FETs to allow a motor to be driven at varying speeds in ei-

Induction motor drive systems

ther direction. From a 24V DC power supply the H bridge circuit allows 24V to be switched to the motor in either direction. This effectively gives +24V or -24V across the motor terminals.

The driving circuit for the three phase motor in the Control unit is similar: the output drivers can be set to sink current as well as to source it. This allows an efficient sinusoidal current to be produced in the windings using a fast microcontroller, variable mark space PWM and three amplifiers.

The connection of the three phase motor is in Star format. Because the drivers need to be set to sink current for part of the waveform the driving signal needs some careful thought. We can not simply generate sinusoidal voltages on the U, V, W outputs and connect the motor. This would not generate sinusoidal currents. So the question is: What waveform do we need to put out at U, V, W to introduce sinusoidal currents in the motor?

Ideal voltage waveform

Practical drive voltage waveform
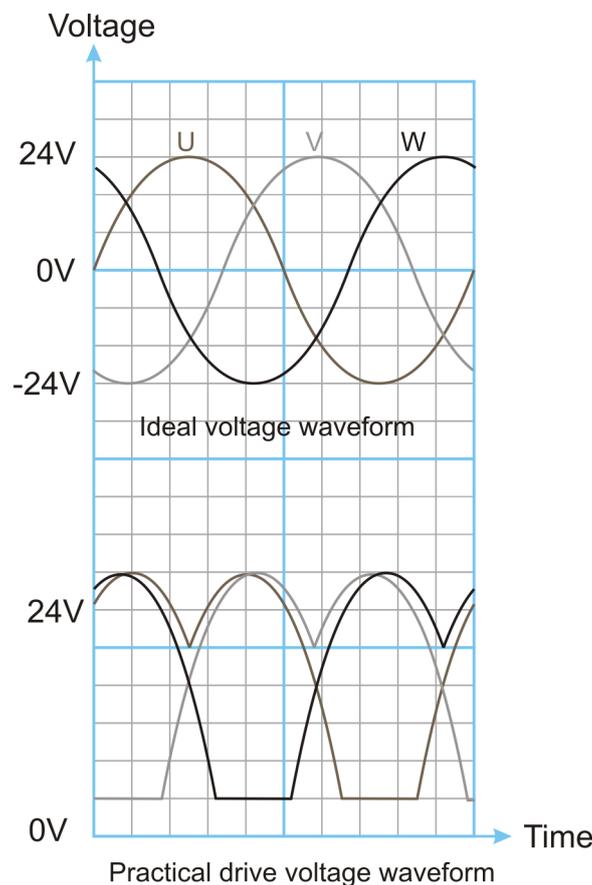
The answer can be seen in this diagram. We use a third harmonic phase profile to the driving waveform to drive the motor. When the currents in U, V and W are resolved for a star connected drive system then sinusoidal currents flow in the motor.

You might want to satisfy yourself of this by independently monitoring the current through 3 resistors when they are connected in a star configuration as shown in the next diagram:

Induction motor drive systems
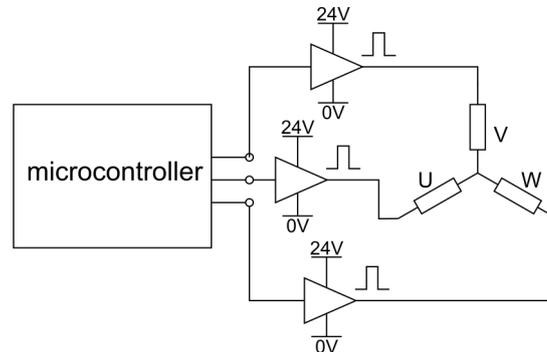
In the equipment you will find that there is a Locktronics board with three resistors and you can easily use this and an external oscilloscope (make sure it has an isolated power supply - not a PC based scope) to verify the currents are sinusoidal: place the earth terminal on the centre connection and measure the voltage across one phase resistor. Whilst this is a little confusing in terms of understanding how toe actual voltage produces an effective voltage you need to bear in mind that there is only one thing that matters: the currents need to be sinusoidal. You can easily verify that with the control unit oscilloscope.

The next issue we have is that in making calculations we need to understand the effective voltage that we are driving the motor with. We are using a 24V DC power supply, an H bridge circuit, and a variable mark space sinusoidal drive waveform. So this is not straightforward. This is done for you as the SCADA software makes the appropriate calculations and gives you an effective voltage reading for the U,V, W outputs.

You can confirm the voltage reading using an RMS multimeter (preferably a Fluke Multimeter which is true RMS). If you place an RMS multimeter across two of the U, V, W terminals you can get an effective reading of the Delta equivalent voltage. You can convert this into a phase equivalent voltage using a little Delta to star mathematics:
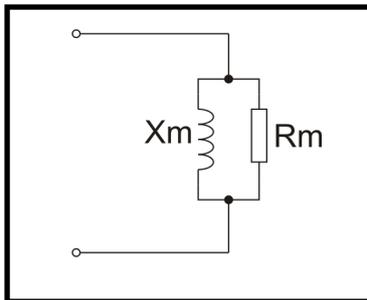
$$V\ phase = V\ line\ /\ SQRT(3)$$

The on board oscilloscope has a selector switch that allows you to see the actual driving line voltage with respect to ground for each of U, V, W, or it allows you to see the equivalent adjusted phase voltage.
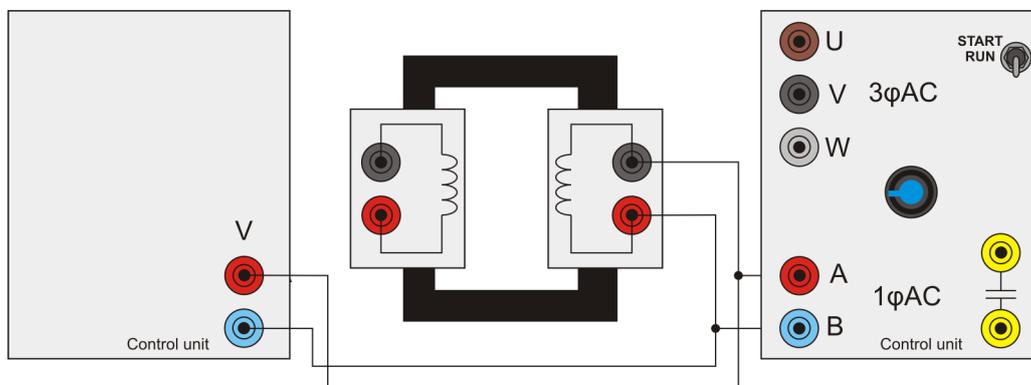
Worksheets

In this experiment you will determine the value of Xm and by looking at the phase angle between the two. And calculating the power and then applying a mathematical sequence of calculations to find Xm and Rm.

1) Set up a transformer with 400 turns in the primary and 600 turns in the secondary.
2) Using a multimeter measure the resistance across the secondary winding. This is R2.
3) Wire up the system above. Note that you should use the internal Voltmeter to get an accurate reading of the voltage: the dials on the software give a calculated output rather thana real output.
4) Connect the AC power supply to the transformer.
5) Load the app 'Open Control_1Phase.bat' app onto your computer.
6) Press the PLAY button to start the program. RUN the app.
7) You may wish to run the test at a slightly lower voltage to reduce distortion.
8) Use the internal oscilloscope software to measure the phase angle between voltage and current.
9) Complete the sequence of calculations to deduce Rm and Xm.

Worksheet 1
Transformer open circuit test

Speed (rpm)	Current Ip (A)	Voltage (Vp)

Voltage peak VØpk (degrees)	Current peak IØpk (degrees)

Ø = ((VØpk - IØpk) / 360) x 2 x Pi

Phase shift Ø rads

Zm = Vp / Ip

Zm Ohms

Ixm = Ip sin (Ø)

Ixm A

Xm = Vp / Ixm

Xm Ohms

Irm = Ip COS (Ø)

Irm A

Rm = Vp / Irm

Rm Ohms

This gives you the first two parameters in your model: The iron loss resistance Rm and the magnetizing reactance Xm.

Worksheet 2
Transformer short circuit test
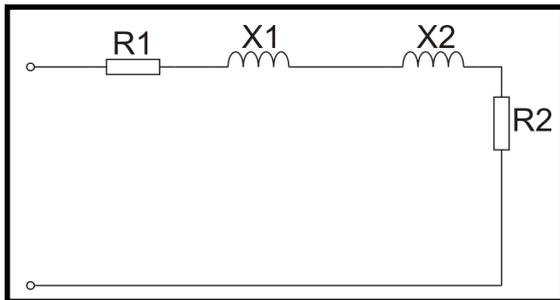
In this experiment you will determine the value of Xm and by looking at the phase angle between the two. And calculating the power and then applying a mathematical sequence of calculations to find Xm and Rm.
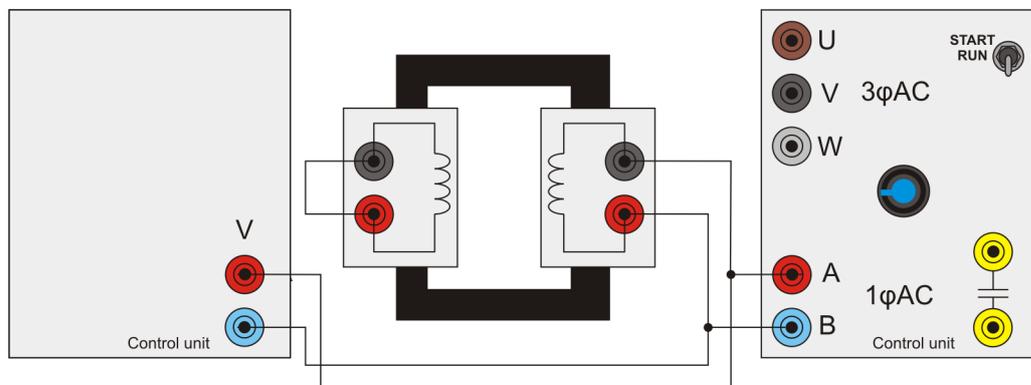
1) Connect the AC power supply to the transformer.
2) Load the app 'Open Control_1Phase.bat' app onto your computer.
3) For a frequency of 50Hz make a note of the input current and voltage.
4) Use the internal oscilloscope software to measure the phase angle between voltage and current.
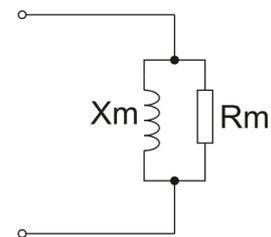5) Complete the sequence of calculations to deduce X1, X2, R2.

Worksheet 2
Transformer short circuit test

EM ELECTRICAL MACHINES

Calculating values using power, voltage and current

R2s (ohms)	Current Ip (A)	Voltage Vp (V)

Voltage peak VØpk (degrees)	Current peak IØpk (degrees)

$Ø = ((VØpk - IØpk) / 360) \times 2 \times Pi$

Phase shift Ø rads

Turns ratio a

$a = Np / Ns$

$Zt = Vp / Ip$

Impedance Zt (Ohms)

$Xt = Zt \sin (Ø)$

Reactance Xt (ohms)

$X1 = X2 = Xt/2$

Rectane X1, X2 (Ohms)

$Rt = Zt \cos (Ø)$

Rt (ohms)

$R1 = Rt - a^2 R2s$

Resistance R1

EM ELECTRICAL MACHINES

In this experiment you will determine the value of Xm and by measuring at the phase angle between voltage and current and then calculating the power and then applying a mathematical sequence of calculations to find Xm and Rm.
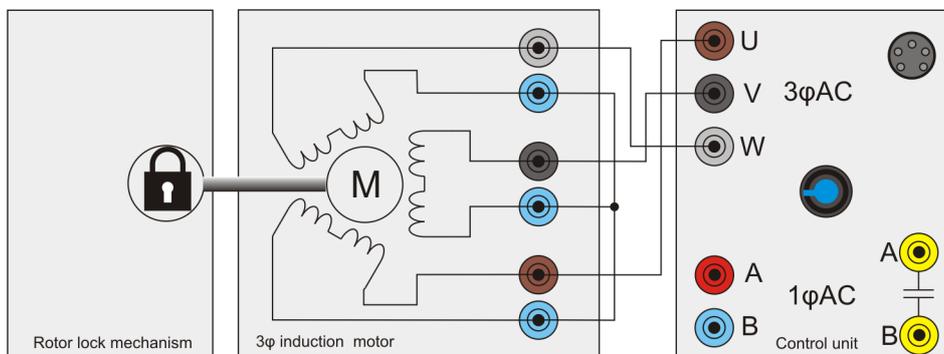
1) Set up the Rotor lock mechanism and the three phase induction machine as shown in the diagram above.

2) Connect the power supply to the three phase induction machine and connect the 25way D-type on the locked rotor mechanism to the back of the power supply.

3) Set the rotor lock to off: so that there is no load on the induction machine and it is free running.

4) Load the app 'Open Control_3Phase.bat' app onto your computer.

5) For a frequency of 50Hz measure the input power, current and voltage.

6) Use the oscilloscope software to measure the phase angle between voltage and current.

7) Complete the sequence of calculations to deduce Xm and Rm.

8) Remember that you are measuring line current and line voltage. You need to convert line voltage to phase voltage for your calculations.

9) You may want to use the V input to get a more accurate measurement of the phase voltage. The dials on the control unit give calculated voltage. This will be fine for measuring the phase angle.

Worksheet 3
Induction motor free running test

Information from software:

Speed (rpm)	Frequency f (Hz)	Phase current Ip (A)	Line voltage V_L (V)	Voltage peak VØpk (degrees)	Current peak IØpk (degrees)

$Vp = V_L \times SQRT(3)$

Phase voltage (Vp)

$Ø = ((VØpk - IØpk) / 360) \times 2 \times Pi$

Phase shift Ø (rads)

$Zm = Vp / Ip$

Zm (Ohms)

$Ixm = Ip \sin (Ø)$

Irm (A)

$Xm = Vp / Ixm$

Rm (Ohms)

$Irm = Ip \cos (Ø)$

Irm (A)

$Rm = Vp / Irm$

Rm (Ohms)

Vector diagram showing Rm, Xm, Zm

This gives you the first two parameters in your model: The iron loss resistance Rm and the magnetizing reactance Xm.

Worksheet 4
Induction motor locked rotor test

As with the previous experiment you will measure the phase angle between voltage and current and then deduce the values of the equivalent reactances and resistances with a sequence of calculations.
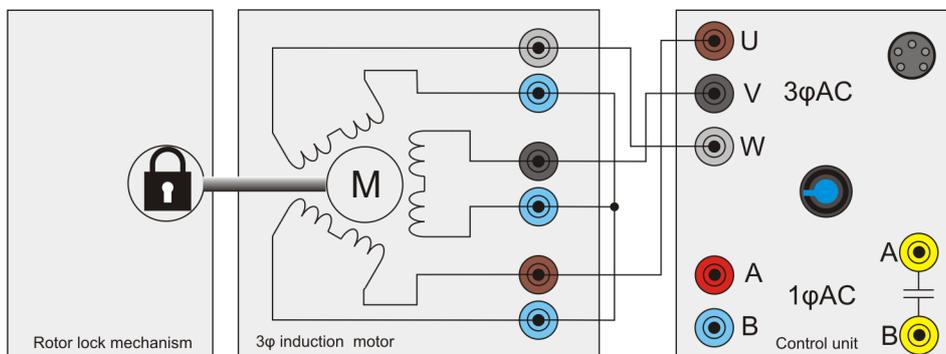
1) With the motor wired up but not connected to the control unit measure the resistance between U and V. This is the effective resistance of two windings. Halve it to get a value for R1.
2) Set up the Rotor lock mechanism and the three phase induction machine as shown in the diagram above.
3) Connect the power supply to the three phase induction machine and connect the 25 way D-type to the back of the power supply.
4) Set the rotor lock to on: so that there is no movement in the induction machine and the rotor is locked.
5) Load the app 'Open Control_3Phase.bat' app onto your computer.
6) For a frequency of 50Hz measure the input power, current and voltage.
7) Use the ocsilloscope software to measure the phase angle between voltage and current.
8) Complete the sequence of calculations to deduce X1, R2, X2.
9) Remember that you are measuring line current and line voltage. You need to convert line voltage to phase voltage for your calculations.

Worksheet 4
Induction motor locked rotor test

EM ELECTRICAL MACHINES
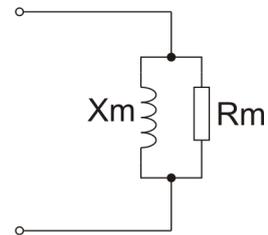
Calculating values using power, voltage and current

Speed (rpm)	Frequency f (Hz)	Phase current Ip (A)	Line voltage V_L (V)	Voltage peak VØpk (degrees)	Current peak IØpk (degrees)	Resistance of stator R1 (Ohms)

Phase voltage Vp

$Vp = V_L / SQRT(3)$

Phase shift Ø (rads)

$Ø = ((VØpk - IØpk) / 360) \times 2 \times Pi$

Impedance ZT (ohms)

$ZT = Vp / Ip$

Reactance XT (ohms)

$XT = ZT\ SIN\ (Ø)$

Reactance XT (ohms)

$X1 = X2 = XT / 2$

Resistance RT (ohms)

$RT = ZT\ COS\ (Ø)$

Resistance Rm (ohms)

$R2 = RT - R1$

R1   X1   X2

R2
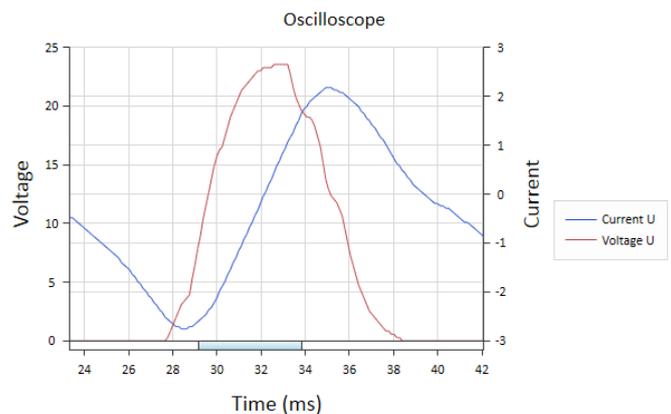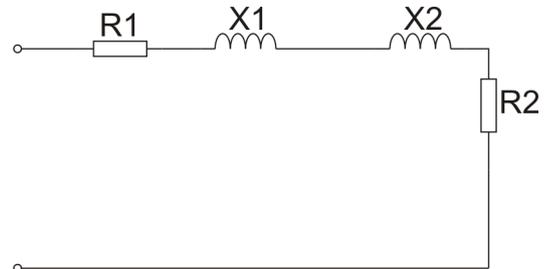
Oscilloscope

You can use the oscilloscope in the Open Control_3Phase.bat' application to measure phase angle between Vp and Ip

Conclusions

You now have values for R1, X1, X2, R2, Xm and Rm.

RL can be calculated from the formula:

RL = R2(1-s)/s

where s is the slip.
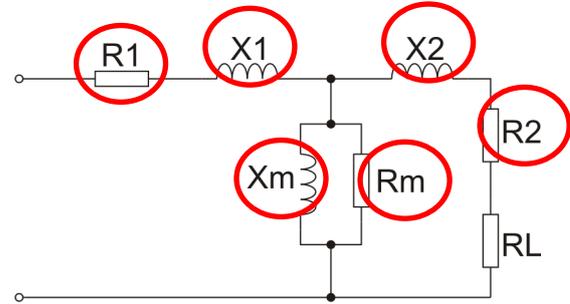
Equivalent circuit of an induction machine

Worksheet 5
Induction motor characteristics
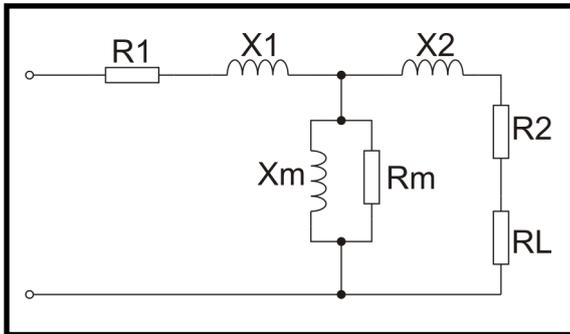
In this experiment you will gather some information about the performance of the three phase induction machine. In the next worksheet you will Simulate your model of the induction machine and you will then be able to compare the two results.

1) Set up the three phase induction motor and the dynamometer as shown in the diagram above.

2) Load the application Open_log_3phase.bat.

3) 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.

Torque(mNm)

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

Worksheet 6
Effects of friction and losses
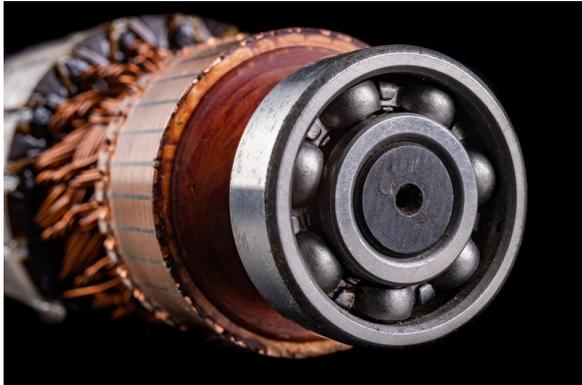
Every mechanical system has friction and other factors that change the real results from an ideal model. Our model for a three phase motor is purely electrical: there are no considerations for bearings, seals, couplings and other sources of friction – including air resistance. We need to account for these in our model before making predictions of motor performance.
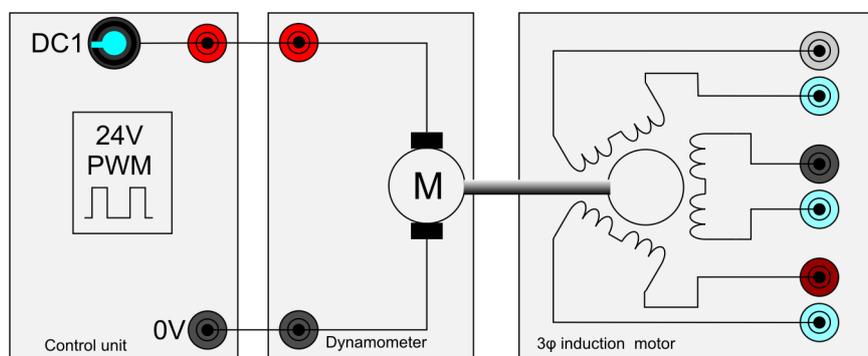
We can make a reasonable attempt to asses the friction and mechanical losses in the three phase induction motor and the dynamometer by measuring the losses whilst driving the motor with the dynamometer which is itself a DC motor. We won't use the three phase motor to generate any current, we will drive it disconnected electrically. This means any resistance we measure will be purely down to the bearing friction and other mechanical losses in the system.

Over to you:

1) Set up the Dynamometer and three phase motor as shown above.

2) On your PC, run the program 'Open Control_DC.bat'.

3) Open the program. Set the DC1 output to 10% .

4) Take several readings from the speed torque curve that is produced by increasing the drive in 10% increments up to 100%.

5) Generate a simple straight line graph using these points on the next page.

6) Find the equation of the line in the form of y=mx + c. The intercept on the torque axis represents the torque that is "lost" independent of speed, whilst the gradient represents the increase of "lost" torque dependant on speed.

7) You now have an equation that shows the approximate losses in the dynamometer and three phase motor due to friction and other mechanical losses. You can add this to the electrical equivalent circuit to calculate the performance of the three phase induction motor to get a more accurate simulation of the performance of the induction motor.

Worksheet 6
Effects of friction and losses

Torque(mNm)
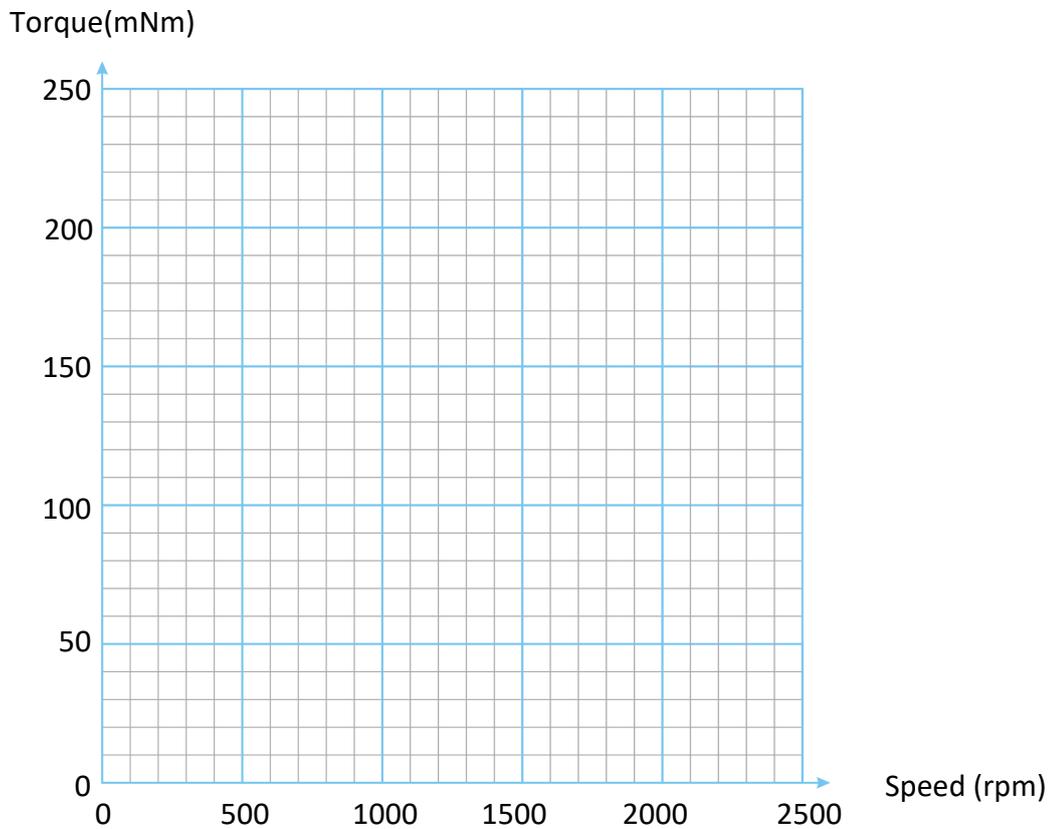
The effect of speed on torque for different values of output frequency.

Slope	
Slope, m	

Intercept	
Intercept on y axis, c	

Formula for Torque loss	
Mechanical loss equivalent y = mx +c	

Worksheet 7
Simulating the motor model
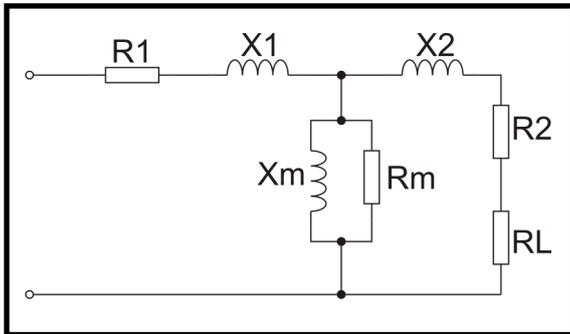
IN this experiment you will use a mathematical package to simulate the model you build and then you will compare it to the practical results you obtained in the previous worksheet.

1) Build a mathematical model in a package like GNU Octave or Matlab. The program for GNU Octave is given on the next page but you should use the values that you have found experimentally. In this program our values were:

f = 50Hz

Open rotor measurements:

Rcoils = 1.6 (across U,V - 2 coils)

Vol = 14.6

Io = 1.3

Phase difference = 77 degrees

Locked rotor measurements

Vll = 14.4

Il = 3.1

Phase difference = 47 degrees

2) Build a mathematical model in a package like GNU Octave or Matlab and plot the simulated speed torque curves over a range of drive frequencies.

3) Using the results of your work on the torque losses due to the effects of friction add a compensating factor to your program to account for these losses.

4) Make a plot in you program of:

- Measured performance
- Simulated performance
- Simulated performance adjusted for friction and losses

On the next page you will find a script for GNU Octave which allows you to plot the Predicted results, the predicted results with losses and the actual results captured by the SCADA software and saved into a CSV file.

If you are using Matlab you should be able make a similar script using the GNU Octave code as a basis.

```
# Input section
# ------------------------------------------------------------

# Maximum RPM for test
RPMmax = 1500;

# Winding resistance measurement (U-V)
Rcoils = 1.85;

# Open rotor measurements (Line voltage, Phase Current, Total Power)
Vol = 14.1;
Io = 1.3;
Po = 11.893;

# Locked rotor measurements (Line voltage, Phase Current, Total Power)
Vll = 13.9;
Il = 3.0;
Pl = 56.915;

# Measured torque/speed CSV log file
# The first two rows will be ignored
# Column 2 = RPM:         Starts at B3
# Column 3 = Torque (mNm):   Starts at C3

# Absolute path example:
# logData = csvread("C:\\Users\\User\\Desktop\\TorqueData.csv");

# .csv file in the same folder as the script:
logData = csvread("TorqueData.csv");

# ------------------------------------------------------------

Rreg = 0.24; #compensation for losses in control unit

R1 = Rcoils / 2 + Rreg;

Vop = Vol / sqrt(3);
Vlp = Vll / sqrt(3);


# Calculate motor equivalent circuit component values from
# open and locked rotor test results
function EqComps = CalcComps (TestVals)
  # Calculate component values
  EqComps.R1 = TestVals.R1;
  EqComps.RM = TestVals.Vo ^ 2 / (TestVals.Po / 3);
  EqComps.XM = 1 / sqrt((TestVals.Io / TestVals.Vo) ^ 2 - (1 / EqComps.RM) ^ 2);

  RT = TestVals.Pl / 3 / TestVals.Il ^ 2;
  EqComps.R2 = RT - TestVals.R1;
  XT = sqrt((TestVals.Vl / TestVals.Il) ^ 2 - RT ^ 2);

  # X1 and X2 assumed to be equal
  EqComps.X1 = XT * 0.5;
  EqComps.X2 = XT * 0.5;
endfunction


# Calculate predicted torque using the motor equivalent circuit.
function t = torqueCalc(Results, rpm_vals, EqComps)
  # Complex representations of equivalent circuit components
  r1c = complex(EqComps.R1, 0);
  x1c = complex(0, EqComps.X1);
  rmc = complex(EqComps.RM, 0);
  xmc = complex(0, EqComps.XM);
  x2c = complex(0, EqComps.X2);

  # Input and magnetic impedance values
  z1c = r1c + x1c;
  zmc = rmc * xmc / (rmc + xmc);

  # Slip at calculated RPM values
  s = (Results.RPMmax - rpm_vals) / Results.RPMmax;

  # Load resistance as a function of slip
  rl = EqComps.R2 * (1 - s) ./ s;

  # Equivalent rotor impedance
  z2c = complex(EqComps.R2 + rl, 0) + x2c;

  # ZE = Z2 || ZM
  zec = z2c * zmc ./ (z2c + zmc);

  # V2 potential divider
  v2c = Results.Vo * zec ./ (z1c + zec);

  # Rotor equivalent current
  i2c = v2c ./ z2c;

  # Power in RL (per phase)
  p2 = abs(i2c .* i2c) .* rl;

  # Torque developed by RL (P / W)
  t = 3 * p2 ./ (rpm_vals / 30 * pi);
endfunction


# Calculate system losses over the test speed range
function l = lossCalc(rpm_vals)
  dyno_bearings = 0.3 * ((0.0203 * rpm_vals) + 5.0523);
  motor_losses = 45.9 + (0.0116 * rpm_vals);
  l = (dyno_bearings .+ motor_losses) / 1000;
endfunction

TestResults.Vo = Vop;
TestResults.Io = Io;
TestResults.Po = Po;
TestResults.Vl = Vlp;
TestResults.Il = Il;
TestResults.Pl = Pl;
TestResults.R1 = R1;
TestResults.RPMmax = RPMmax;

# Motor equivalent circuit
EqComps = CalcComps(TestResults);

# Speed range (starting at 100rpm, 25rpm increments)
RPMrng = 100: 25: RPMmax;

# Predicted torque
T_Calc = torqueCalc(TestResults, RPMrng, EqComps);

# Log data from .csv file
RPMlog_01 = logData(3 : end, 2);
Torque_log_01 = logData(3 : end, 3) / 1000;

# System losses
Losses = lossCalc(RPMrng);

# Subtract calculated system losses from the calculated torque
Torque_res = T_Calc .- Losses;
Torque_res_sz = size(Torque_res);
idx_max = Torque_res_sz(2);

# Zero any negative torque results - the motor will have stalled.
for idx = 1:idx_max
  if( Torque_res(1,idx) < 0)
    Torque_res(1,idx) = 0;
  endif
endfor

# Plot the curves
plot(RPMrng, T_Calc, RPMrng, Torque_res, RPMlog_01, Torque_log_01);
xlabel ("RPM");
ylabel ("Torque (Nm)");
title ("Torque - Losses/Speed @ 50Hz, 20V");
```

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

Reference

Understanding the control unit
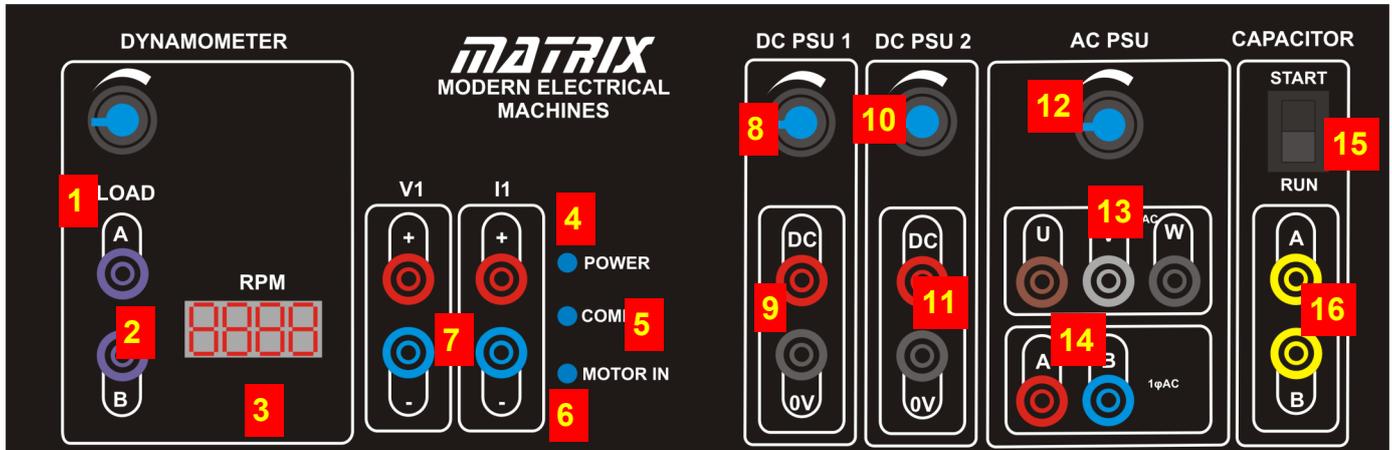
1) The dynamometer resistance: use this to control the effective resistance placed across the dynamometer: low electrical resistance means a large mechanical resistance, and high electrical resistance means low mechanical resistance

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

FUSE

85V - 264VAC, 47 - 63Hz, 3A fuse

USB
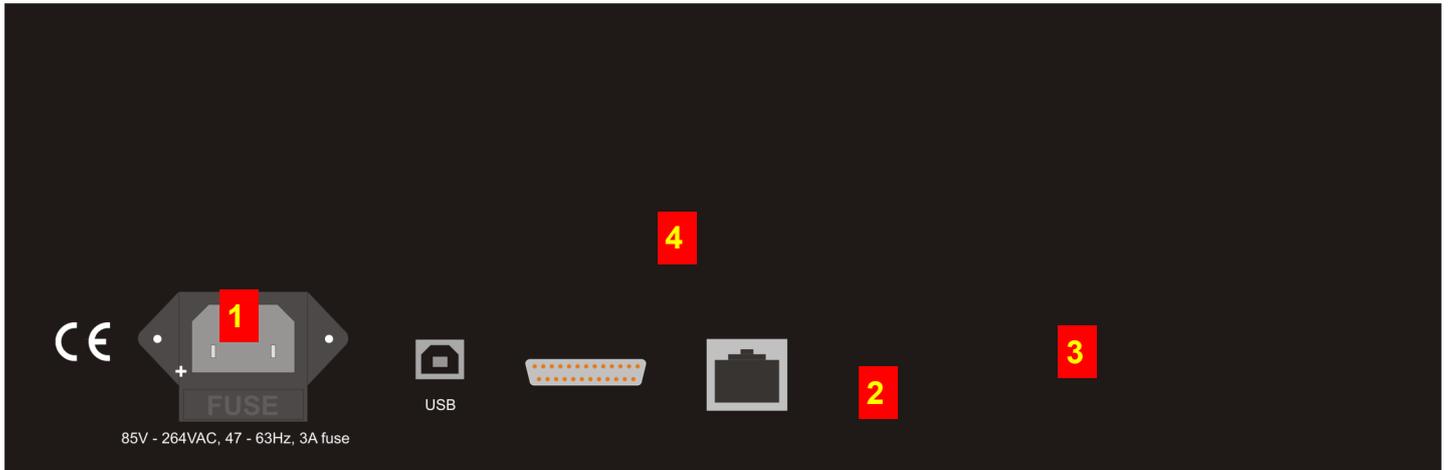
1)   The Mains input plug - the unit takes 240V or 110V

2)   The USB connector

3)   A 25 way D-type connector which is used to connect the Control unit to the Dynamometer

4)   Vent holes for internal fan - do not cover.

Control unit schematic
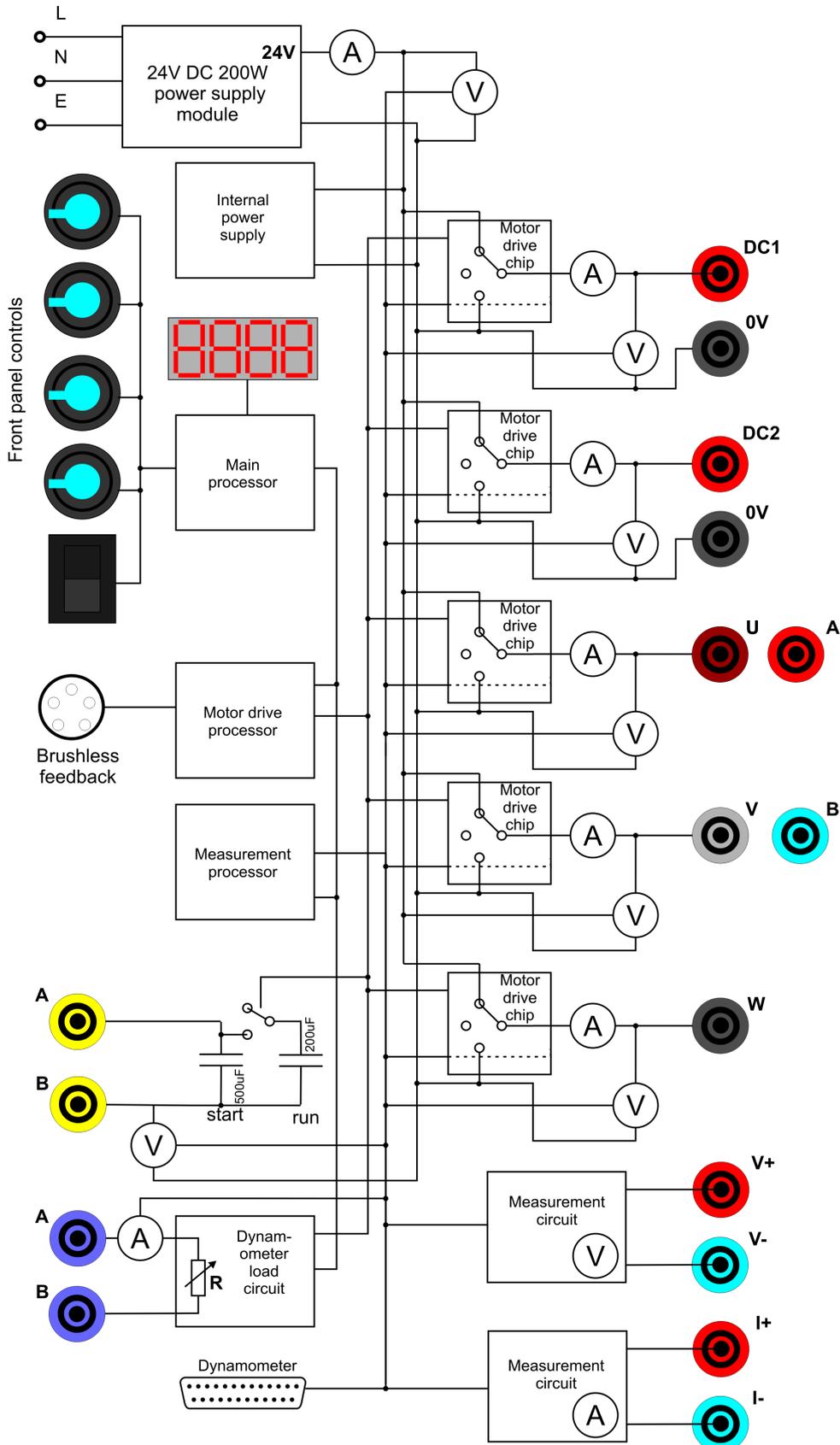
ELECTRICAL MACHINES

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 around 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 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.

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.

Reference

Understanding the dynamometer
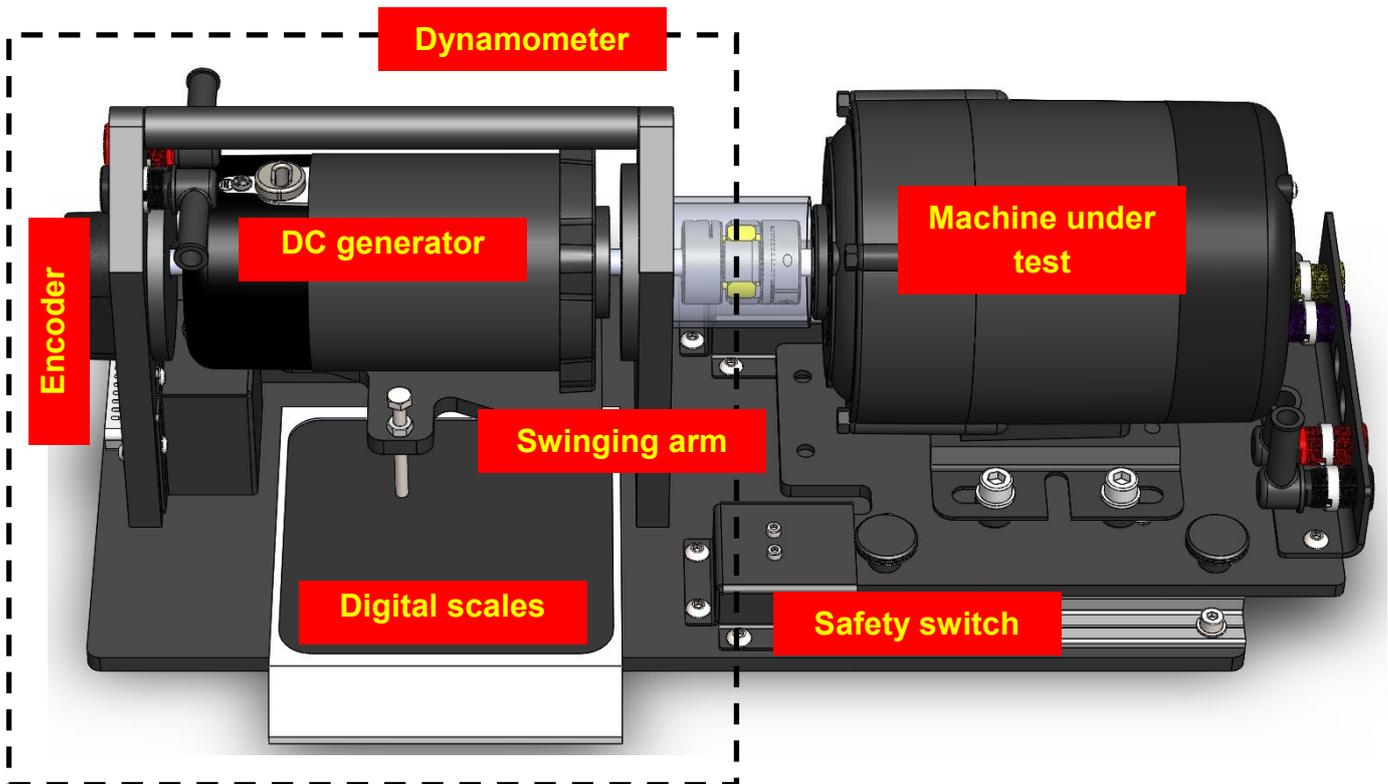
A dynamometer is an instrument that directly measures the force produced and speed of a rotating machine (the motive force). Torque and power can be calculated from the measured force and speed. In our case the mechanical rotation is produced by one of the DC or AC electrical motors. This Dynamometer 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 information - 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

r

Swinging arm

Scales

F=mg

Torque = mgr

Motor must run clockwise for load cell mode

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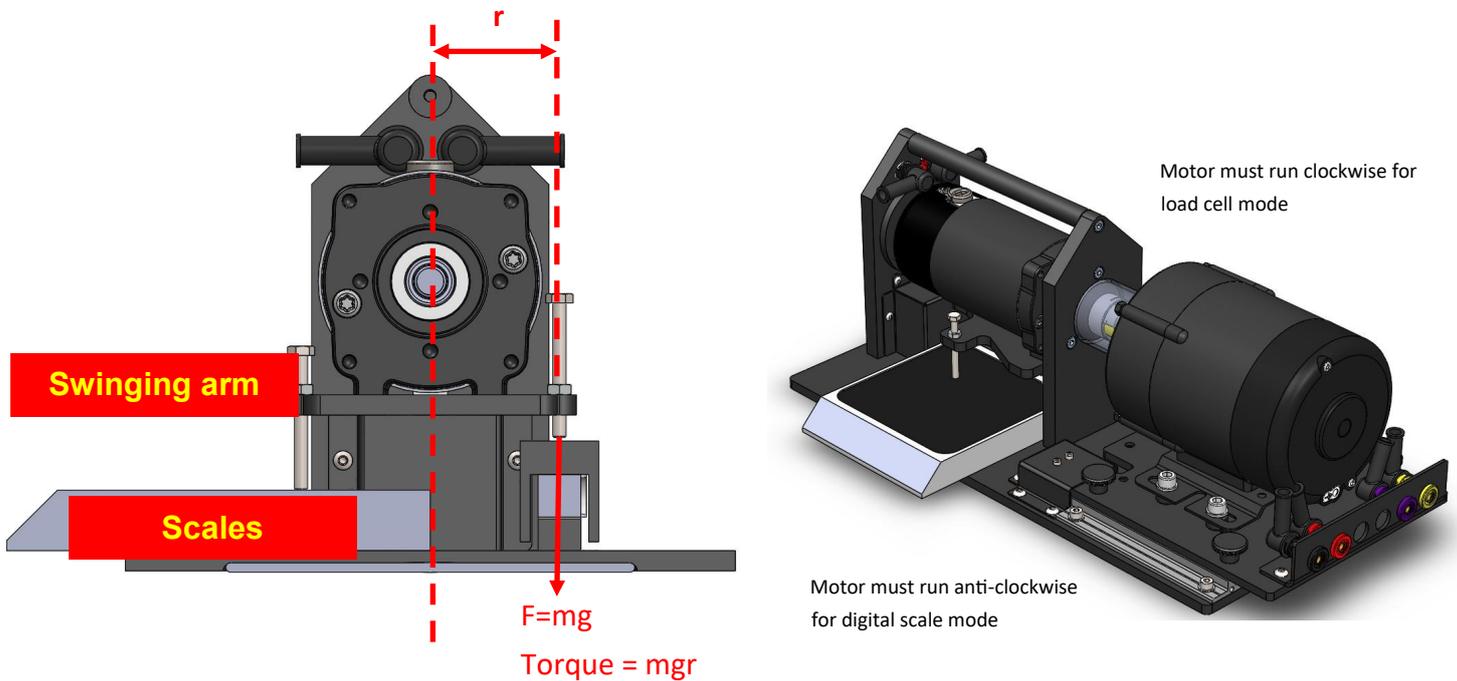
The dynamometer rotates in the same direction as the machine under test. It provides a mechanical resistance for the machine under test. It also generates a voltage and - if a resistance is placed across the Dynamometer terminals - it produces a current.

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 anticlockwise) 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 x 9.81m/s^2. The torque can be calculated from the formula Torque = Force x 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 = 38.12mm**

More discussion on calculations is given below.

Induction machine locked rotor rig
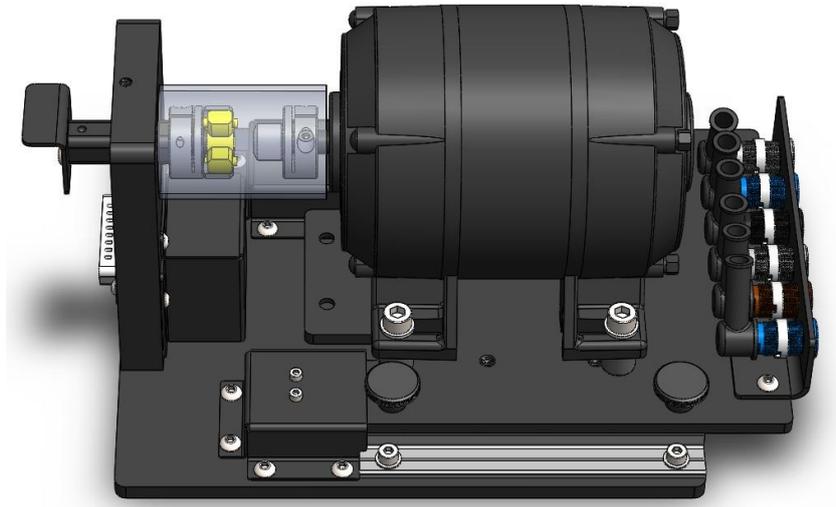
The locked rotor rig is used to physically clamp the three phase induction motor to a standstill whilst allowing safe measurements of the motor characteristics to be obtained.

The Control unit and mechanics of the Modern Electrical Machines equipment are designed in such a way to allow safe operation by students of all ages. Key to this are the safety switches hidden in the Dynamometer rig. The Control unit will not operate until both switches have been closed by a machine under test which indicates to the unit that a machine is in position. The switches are effectively connected to the Control unit via the 25 way D-type cable.

The locked rotor rig allows the three phase induction motor to be powered by the Control unit whilst clamping its motion using the square limiting pin. The pin can be removed to allow the three phase induction motor to run free from any friction and other losses that the Dynamometer might introduce into the system.

Reference

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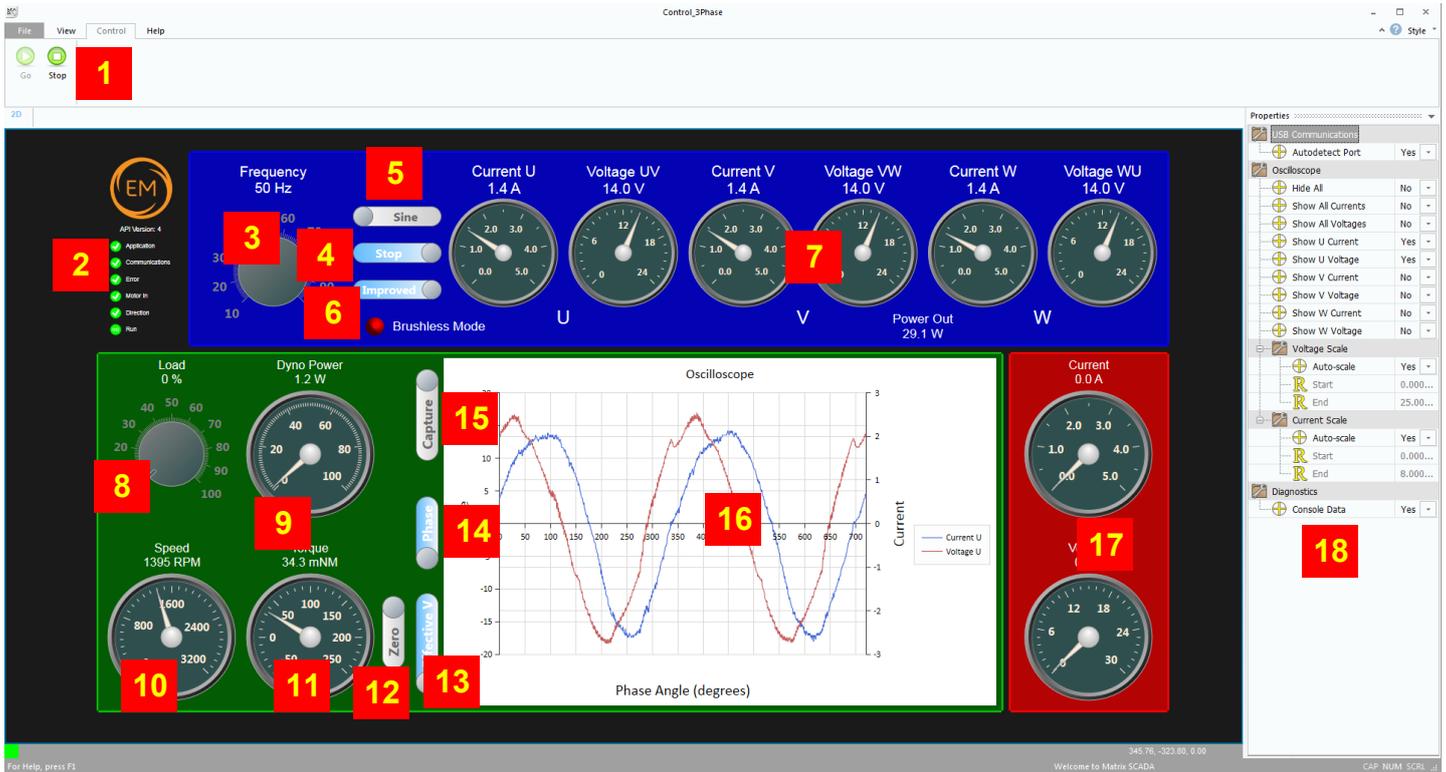
The file name for this program is 'Open Control_3Phase.bat'

1) Program control - hit play to start

2) Flags for App running, USB comms and Motor in place.

3) Frequency of output

4) Run/Stop switch - needs pressing to start the sweep

5) Drivemode - default is pseudo-sine, on is trapezoid

6) Sinusoid drive mode, simple sinusoid or advanced third harmonic sinusoid.

7) Meters for the output - RMS values

8) Dynamometer load as a %

9) Dynamometer speed in RPM

10) Torque in mNm

11) Dynamometer power in watts

12) Torque zero button, used to reset the torque reading to zero.

13) Display the real voltage or effective AC three phase voltage on the graph.

14) Controls the X axis of the graph showing the scale in time (ms) or in phase angle.

15) Capture button - starts waveform capture

16) On screen graph of plot data

17) Internal ammeter and voltmeter V1 and I1

18) Properties bar - controls properties of the program and the graphing

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

When the Run 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.

Reference
Software installation

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 Electri-

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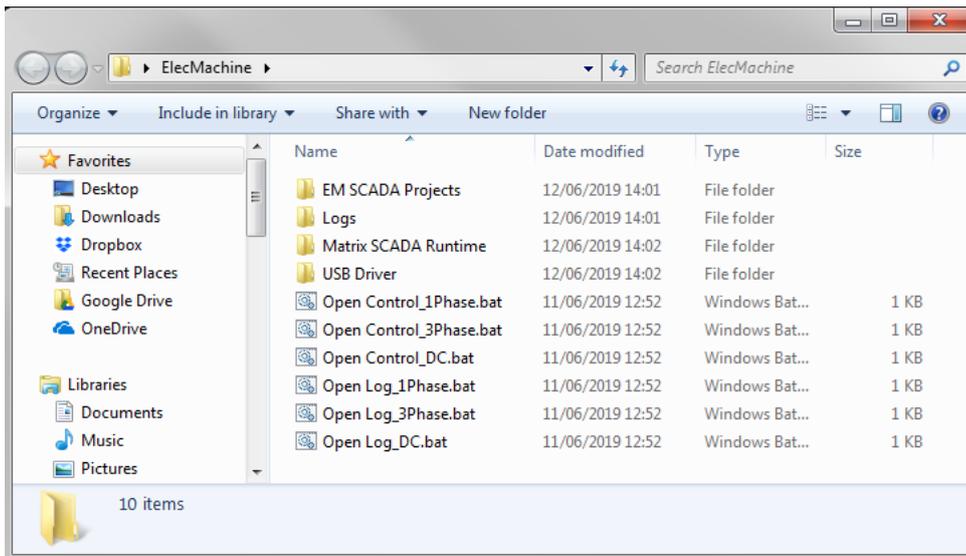
Please copy these programs and directories into a suitable location on your hard drive. You can make short cuts to the *.BAT files if you wish.

Rin 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 y our 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.

Reference

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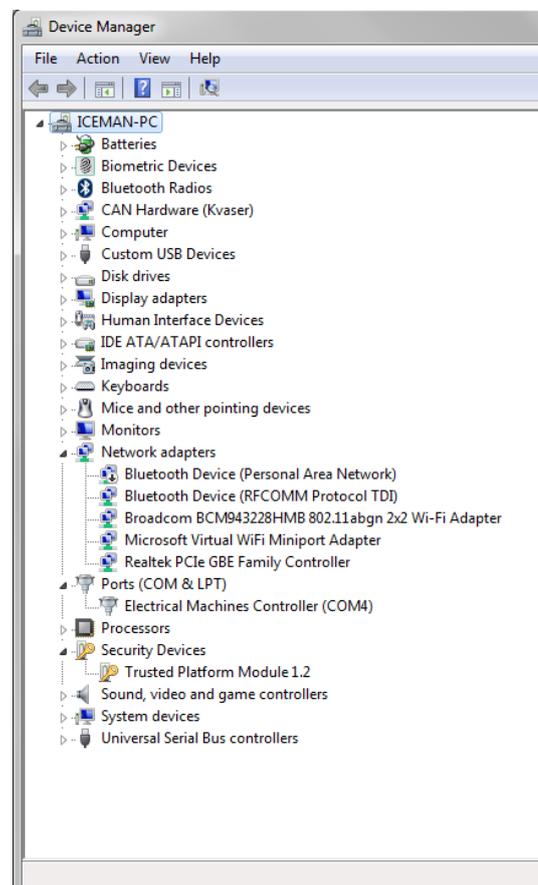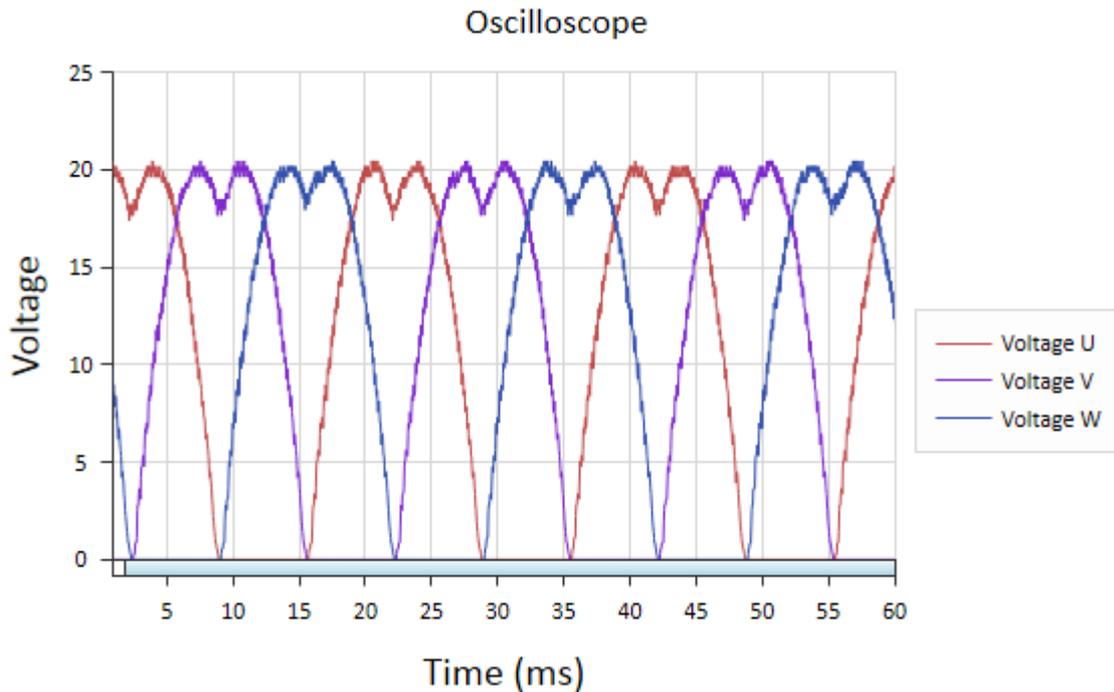
The oscilloscope in the Control unit takes measurements of every ammeter and voltmeter in the unit at a rate of 64kHz. There are 16 channels in total - that gives us an effective measurement rate of 4kHz for each channel.

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 third harmonic adjusted voltage out waveform is confusing for students and will need to be explained.

API calls

Comp Code	Cmd Code	Function	Param1	Param2	Param3	Param4	Return	Return Size	Description
0	0	GetAPIVersion					VersionNumber	Byte	Gets firmware API version - Should be set to 1 on release
0	1	SetMotorType	Type (0-3)						Sets the motor drive type - 0=DC, 1=1 Phase, 2=3 Phase, 3=PIDControl
0	2	SetVoltage	VoltageLSB	VoltageMSB	Channel (0-1)				Sets the voltage of one of the DC outputs (0-3000)
0	3	SetFrequency	FreqLSB	FreqMSB					Sets the AC drive frequency (10 - 100)
0	4	SetActive	Run (0-1)						Controls if the outputs are live or not
0	5	SetPhase	Channel (0-2)	PhaseLSB	PhaseMSB				Allows one of the AC phases to be shifted from the default 180 or 120
0	6	ZeroWeight							Zeros the output of the load cell
0	7	SetACDriveMode	Mode (0-1)						Sets the AC output waveform mode 0=Sine Wave PWM 1=Trapezoidal
0	8	SetFanSpeed	SpeedLSB	SpeedMSB					Controls the fan speed, largely redundant now and fan should be automatic (0-3000)
0	10	SetCapBank	Value (0-3)						Controls the capacitors connected to the C terminals - 0=0F, 1=200uF, 2=300uF, 3=500uF
0	11	SetDynoLoad	Value (0-255)						Controls the dynomometer load resistance (0=approx 145R, 255=approx 5R)
0	12	SetACGenMode	Value (0-1)						Controls the Three phase sine wave generation (0=Simple, 1=Accurate (double hump))
0	13	GetLogData						Byte[64]	Collects a 64-byte packet containing log data
0	14	LogDataReady					Ready (0-1)	Byte	Checks to see if the log data is ready to send
0	15	IsBrushlessActive					Bactive (0-1)	Byte	Checks to see if the brushless feedback is connected
0	16	GetLogStartAngle					Angle(0-35)	Byte	Gets the Current U phase angle at the start of the log, 0-35 = 0 to 350 degrees
0	17	Load Cell Calibration	FloatLSB	Float1	Float2	FloatMSB			Sets the load cell scaling factor - usually 0.004608294908756
0	20	GetRPM					RPM	Unsigned Int	Returns RPM reading with resolution of 0.1 RPM
0	21	GetAbsolutePosition					AbsPosition	Unsigned Long	Returns the absolute encoder position with resolution of 0.25 Degrees
0	22	GetVoltage	Channel (0-5)				Voltage	Unsigned Int	Returns Voltage reading with resolution of xxx V
0	23	GetCurrent	Channel (0-7)				Current	Unsigned Int	Returns Current reading with resolution of xxx V
0	24	GetErrorStatus					ErrorStatus	Byte	Gets the current error status
0	25	GetSwitches					Switch	Byte	Returns the state of the saftey switches (0=Stop, 1=OK)
0	26	GetLoadCell	Mode (0-1)				Load	Unsigned Int	Returns the weight on the load cell 0=Weight in G 1=Torque in mNM
0	27	GetPhaseAngle	Channel						Returns the phase angle difference measured using peaks in the waveform
0	28	GetMotorDir					Direction	Byte	Returns the direction the motor is turning
0	29	ResetAbsPosition							Resets the absolute angular position to 0
0	50	SetSetpoint	FloatLSB	Float1	Float2	FloatMSB			Sets the angle setpoint
0	51	SetKP	FloatLSB	Float1	Float2	FloatMSB			Sets the proportional gain
0	52	SetKI	FloatLSB	Float1	Float2	FloatMSB			Sets the integral gain
0	53	SetKD	FloatLSB	Float1	Float2	FloatMSB			Sets the derivative gain
0	54	GetFeedback					Angle	Float	Gets ths absolute position as a floating point angle
0	55	GetControlOutputs					OP,OI,OD,Sum	Float[4]	Gets the PID control outputs as floating point values
0	56	SetMaxDriveDuty	FloatLSB	Float1	Float2	FloatMSB			Sets the max drive duty as a floating point value between 0 and 1.
0	57	GetDataArraySize					Number of sampl	Byte	Collect number of control samples in the buffer
0	58	GetDataArray						Float[5]	Collect SP, FB, PO, IO, DO
0	59	Get3xDataArray						Float[15]	Collect Data Array x 3
0	80	SetIPAddress	IP0	IP1	IP2	IP3			Sets the IP Address of the box, default 192.168.1.235
0	81	SetIPPort	PortLSB	PortMSB					Sets the Port for the box, default 88

Instructor Guide

Instructor Guide

About this course

Introduction

This course is designed for undergraduate students of electrical or power engineering who are taking a module in electrical machines. At this level students need to be able to understand how electrical machines are modelled by an equivalent circuit so that their performance can be predicted. This helps students who want to go on to design the machines themselves, design machine controllers, or design electrical and power systems that include machines. Intrinsic to this is the use mathematics to model a machine's performance and the use of some kind of mathematical modelling software that can be used for this purpose. For the sake of these worksheets we have used the open source software GNU Octave (although many university students will want to use Matlab) and the use of such software is a key learning objective of this course.

Aim

On successful completion of this course the pupil will have learned.

- Equivalent circuits for electrical machines
- Approximations in modelling of electrical machines
- Testing parameters of electrical machines
- Mathematical modelling of electrical machine characteristics using GNU Octave or Matlab
- Loss compensation modelling in electrical machines
- Frequency controlled drives for three phase induction motors
- Modern electrical machine drive algorithms and techniques

Prior knowledge

This manual and the equipment that accompanies it is a practical resource for the study of Electrical Machines modelling Itis not a full learning resource for Electrical Machines. It includes some reference to the formulae needed and contains some information on how the equipment works, but it is anticipated that this forms part of a typical 60 hour module in Electrical Machines and that the student has access to a good text book. Prior knowledge will include:

- Electrical Circuit theory
- Electrical Machines basics - such as Matrix Electrical machines level 3 - BTEC unit 15
- Some knowledge of programming and modelling software such as Matlab or GNU Octave
- Advanced level mathematics

Time:

It is anticipated that the work in this manual will take approximately 15 to 20 hours to complete; the actual experiments take relatively little time. You can extend this by removing information on the worksheets and asking students to create the calculation algorithms and create the entire simulation modelling software themselves.

Learning Objectives

On successful completion of this course the pupil will have learned.

- Equivalent circuits for electrical machines
- Approximations in modelling of electrical machines
- Testing parameters of electrical machines
- Mathematical modelling of electrical machine characteristics using GNU Octave or Matlab
- Loss compensation modelling in electrical machines
- Frequency controlled drives for three phase induction motors
- Modern electrical machine drive algorithms and techniques

Instructor Guide

Before starting

We assume that this forms part of a second year of Electrical Engineering study. Students should be familiar with the types and construction of electrical machines. They should be familiar with the use of Speed Torque curves as a method of assessing and describing machine performance and we anticipate that students have been through a course on this subject in the first year of their study.

We have included a summary of the steps that need to be taken to calculate and measure the terms in the equivalent circuit. We anticipate that this process will needs some introduction to students in the form of a lecture or tutorial. Students will find the steps in approximating the parameters in the model, and the accompanying assumptions that need to be made, confusing.

Students will be using the SCADA software supplied with the Control Unit to make measurements. They will need to be familiar with this and the Electrical Machines level 3 course is ideal for this. If they have not completed this course then instructors could select a few worksheets from this course and ask students to work through them to familiarise the students with the equipment.

The use and modelling of modern electrical machines is complicated by the fact that industry now uses FET based driving circuits which do not create sinusoidal driving voltages. Students need to be introduced to the use of pseudo-sinusoidal waveforms combined with traditional DC power supplies to create power systems for electrical machines. Students need an understanding of this to make sense of the effective voltages in the system so that the equations used make sense. A key part of this will be understanding the star delta transformation mathematics. Some pages of information summarising this are given in the manual but again students will need accompanying explanation.

Throughout the worksheets we have given a very step by step explanation of the mathematical steps needed to calculate the terms in the model. In that sense the students are perhaps 'watching' the process rather than 'creating' the process. We think that is appropriate for their first outing in this subject. You can of course make it harder for them by not giving them the entire process in the printed worksheets.

Instructor Guide

ELECTRICAL MACHINES

Similarly we have also given the source code for the GNU Octave simulation. This can easily be transferred to Matlab. You can make this a bigger task for students by not giving them access to this source code.

Worksheet 1 - Transformer open circuit test - 1 hour
The real purpose of this package is to model the characteristics of an electrical rotating machine. These two first worksheets on transformers are included to show that really the model of a transformer is very similar to the model of an induction machine. This worksheet simply asks students to make a basic model but does not then ask students to model a second transformer, predict the results and measure the prediction's accuracy. Although the equipment is provided for you to do that with your students should you decide to do so.

Note that to carry out this, and the next, experiment students will need to have the locked rotor system connected to the Control unit using the 25way D type. This bypasses the safety system in the Control unit.

Worksheet 2 - Transformer short circuit test - 1 hour
See above.

Worksheet 3 - Induction motor open circuit test - 1 hour
In this worksheet students connect the three phase induction machine to the locked rotor kit, remove the locking pin and power up the machine. Slip here is assumed to be 0 so RL becomes infinite and this branch of the circuit model can be ignored. Rm and Xm can be determined using a little bit of vector mathematics.
The phase angle between voltage and current needs to be measured. The values of Xm and Rm can be corroborated by using a little trigonometry and the core values. Students should probably use a spreadsheet to set up all the calculations as they will repeat them more than once.

Worksheet 4 - Induction motor locked rotor test - 1 hour
The students now lock the rotor of the induction machine with the locking pin and take

measurements. Xm and Rm can now be assumed to be very large and ignored. X1 is assumed to be equal to X2 which is a little difficult to explain without experience. (You can prove this later by asking students to look at the difference in their simulation results where X1 and X2 are assumed to different in, say, a ratio of 70:30: it does nto make much difference to the curves produced.) As with worksheet 1 some mathematics allows students to calculate the resistance and reactance in the circuit.

In worksheet 1 and 2 the strange shape of the Voltage waveform on the Control Unit oscilloscope will puzzle students. You have a choice here: you can either go through the mathematics of how a DC power supply and FET based system is used to create three phase system waveforms using phase shifted third harmonics from a mathematical point of view, or you can simply ask them to prove to themselves that the resulting current in each phase is a good representation of a sinusoid. Or you can just ask them to take your work for it that it all works out.

Don't be tempted to use a PC based oscilloscope for any external measurements as the earth loops may cause damage. Use a traditional scope with its own power supply.

Worksheet 5 - Induction motor practical results
In this experiment students use the SCADA software, the Control unit, the Dynamometer and the induction motor to obtain a practical set of speed torque results. These can be exported as a CSV file for later processing.

Worksheet 6 - Effects of friction and losses
One of the potential problems with using low power electrical machines is that the mechanical losses are quite large with respect to the overall powers. However the adjustments to the model to make the practical results and the theoretical results are quite simple to make and this is a great learning exercise. Students drive the induction machine with the Dynamometer - effectively just a permanent magnet DC motor - which allows them to derive a surprisingly accurate straight line formula for the mechanical losses in the system. Students later use this formula in their model. The losses are surprisingly low so don't make that much difference to the final simulation.

Worksheet 7 - Simulating the motor model

Once the equivalent circuit parameters are known then it is possible to build a model in a modelling package. We have used GNU Octave because it is quite functional and it is free. As this is likely students' first time at modelling an electromechanical system we have given a full script for the model. The student is then assigned a task of entering the code and making sure it all works out. You can of course make the task more difficult by not giving the students the code to start with. We have not shown the compensation for the friction losses and students should be able to add this.

We have not made it so easy for students - the script uses a slightly different technique so they will have to think about the formulae used. But it's a great head start.

Further work

For the induction motor we have run through the whole modelling process. The Modern Electrical Machines range has a number of other machines in it - DC motor, Series motor, Shunt motor, Brushless DC motor. The unit has access to all voltages and currents in its 16 on board sensors and it should be possible to task students to model other machines if additional exercises in modelling are needed.

Equipment checklist

To deliver this set of worksheets you will need the Modern Electrical Machines Dynamometer, the Three phase induction motor, the Locked rotor add-on and associated cables.

Modern Electrical Machines - full set   EM6637, EM6637EU, EM6637USA

Or:

Modern Electrical Machines - Core set   EM7632, EM7632EU, EM7632USA

And:

Electrical Machines locked rotor add-on: EM2551

Those who want to carry out the first two worksheets on transformers can do so with product code EM4425: transformers kit.

Troubleshooting

Dynamometer arm sticking - V1 only.

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.

Version control

01 05 2020 first release

01 07 2020 added transformer worksheet. Updated API reference for V1.1 control unit.

09 12 22   small calculation errors fixed

08 02 23   information on transformer number of turns added

28 07 23 Reformatted to new style