Three Phase Systems 2.0

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Contents

Worksheet 1
Single-phase AC

‘Mains’ electricity is traditionally distributed as AC.
The reasons for this include:

- alternators that generate electricity at the power stations are lighter, and cheaper than equivalent DC generators;
- transformers can be used to step the voltage up or down, allowing efficient transmission of electrical power at high voltage (and low current) over large

Over to you:

This worksheet looks at aspects of single-phase AC, using the signal obtained from one output of the three-phase generator.

Equipment Setup

- Software: Run Matrix Three-Phase Application (indicated by light green "Application" and "Comms").
- Circuit Requirement: No physical or virtual circuit configuration is needed for this exercise.
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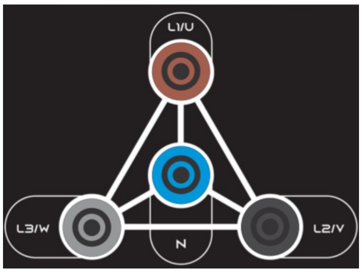


Procedure : Part A: 50 Hz, 8 V RMS Configuration

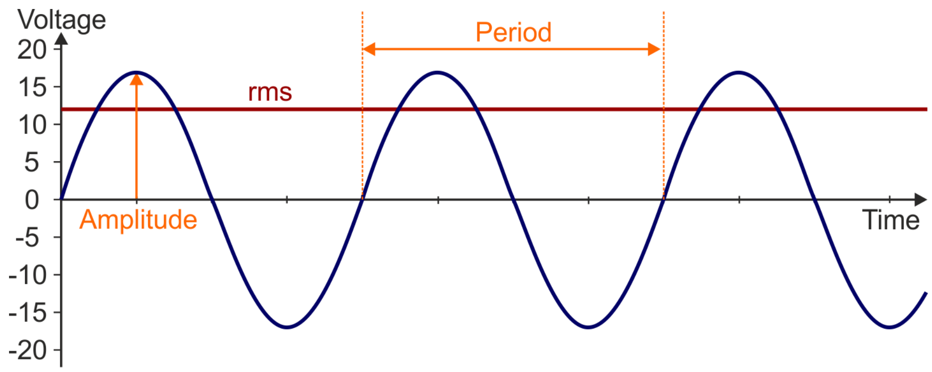
- Frequency Setting:
    - Adjust the generator frequency to 50 Hz using one of the following methods:
        - Drag the frequency slider to 50 Hz.
        - Click the “Set Frequency” button, enter 50, and confirm.
- Voltage Setting:
    - Set the amplitude to 8 V RMS using one of the following methods:
        - Drag the voltage slider to 8 V. or
        - Click the “Set Voltage” button, enter 8, and confirm.
- Activate the Generator:
    - Press the Run button (status turns green).
- Component Properties Configuration:
    - Enable “U Voltage” (set to Yes).
    - Disable all other voltage and current displays (set to No).
- Data Capture:
    - Click the Capture button to record the AC output trace.
    - Save Data:
        - The app automatically saves data to a CSV file.
        - Alternatively, take a screenshot for your records.
- Stop and Reset:
    - Click Stop to halt the generator output.
    - Click Clear to reset the app display.

Worksheet 1
Single-phase AC

Procedure : Part B: 200 Hz, 12 V RMS Configuration

- Frequency Setting:
  - Adjust the generator frequency to 200 Hz using one of the following methods:
    - Drag the frequency slider to 200 Hz.
    - Click the “Set Frequency” button, enter 200, and confirm.
- Voltage Setting:
  - Set the amplitude to 12 V RMS using one of the following methods:
    - Drag the voltage slider to 12 V.
    - Click the “Set Voltage” button, enter 12, and confirm.
- Activate the Generator:
  - Press the Run button (status turns green).
- Component Properties Configuration:
  - In the Component Properties menu:
    - Enable “U Voltage” (set to Yes).
    - Disable all other voltage and current displays (set to No).
- Data Capture:
  - Click the Capture button to record the AC output trace.
  - Save Data:
    - The app automatically saves data to a CSV file.
    - Alternatively, take a screenshot for your records.
- Stop and Reset:
  - Click Stop to halt the generator output.
  - Click Clear to reset the app display.

So What?



Amplitude - the maximum voltage in the signal.

Period - the time taken to produce one cycle of the wave, (i.e. 1 peak plus 1 trough)
- measured in seconds.

Frequency - the number of cycles of the wave produced per second;
- measured in hertz. (1 Hz means one cycle produced every second.)

The relationship between them is:

Frequency = 1 / period

Worksheet 1
Single-phase AC

Delivering power:
At times, an AC supply delivers zero volts. At other times, it delivers higher or lower values.
A useless fact - the average voltage for an AC supply (any AC supply) is zero!
This certainly does NOT mean that AC supplies do nothing - far from it! - the average power delivered is NOT zero. (For a resistor, R, power delivered = V2 / R, i.e. depends on voltage squared! Hence, the voltage may be negative but the power delivered is still positive. A negative voltage simply means that the current flows the other way, as you saw in the third circuit.)

For an AC supply, a measure more significant than average voltage is rms voltage. Although it stands for 'root-mean-square' voltage, it is better to think of it as the DC voltage which would deliver the same power to a load.
For a sine-wave signal, peak and rms voltage are linked by:

Vrms = 0.7 x Vpeak

For your records:

- Copy the diagram of the AC signal, and explain the meaning of the terms *amplitude, period* and *frequency.*
- Copy the table and use the measurements you took in the first part of the investigation to complete it.

Amplitude in V	Period in s	Frequency in Hz

- Copy and complete the statement by calculating the rms voltage:
  In the first circuit, the rms voltage was …….

Worksheet 2
Three-phase AC

Electrical power is transmitted around the country using a three-phase, rather than a single-phase system due to several advantages:

- Requires less copper for transmission cables.
- Delivers smoother power, reducing motor vibration.
- Three-phase alternators are smaller and lighter than single-phase equivalents.
- Supports both single-phase and three-phase devices, unlike single-phase supplies.

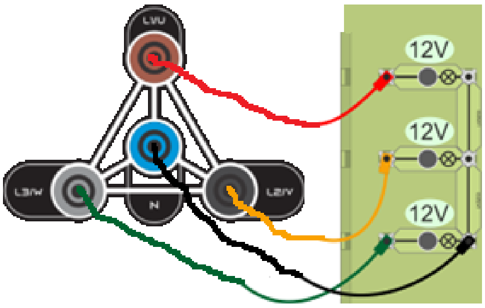
This worksheet covers the fundamentals of three-phase power distribution.

Over to you:

This investigation explores why a 'three-phase' system is so named. It consists of two experiments: one at a low frequency using lamps and another at a higher frequency.

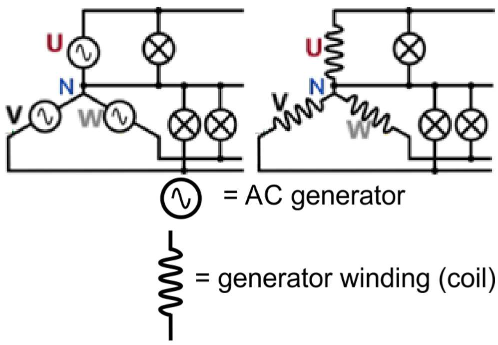
Experiment 1: Low-Frequency Observation (0.1Hz)

- Equipment Required:
    - Three 12V MES bulbs with holders
    - Three-phase generator
    - Matrix Three Phase software



1 **Procedure:**

- Assemble the circuit using the three 12V MES bulbs and holders.
- Set the three-phase generator parameters, using App, as follows:
    - Frequency: **0.1Hz** (fixed)
    - Amplitude: **10V**
- Switch on the generator and observe the bulbs.
    - Notice that the bulbs are neither fully in sync nor completely out of sync.
    - Each bulb reaches its maximum brightness at different times.
- In the Matrix Three Phase software:
    - Click **Capture** to record the data.
    - Observe the **x-axis** to determine the time taken for one complete cycle.
    - In the **Component Configuration Properties**, set:
        - **U Voltage, V Voltage, W Voltage**: Yes
        - **U Current, V Current, W Current**: No
- Click **Clear** to reset the graph.



1 **Experiment 2: High-Frequency Observation (50Hz)**

2 **Procedure:**

- Repeat the setup as in Experiment 1.
- Adjust the three-phase generator settings:
    - Frequency: **50Hz**
    - Amplitude: **10V**
- Switch on the generator and observe the bulbs again.

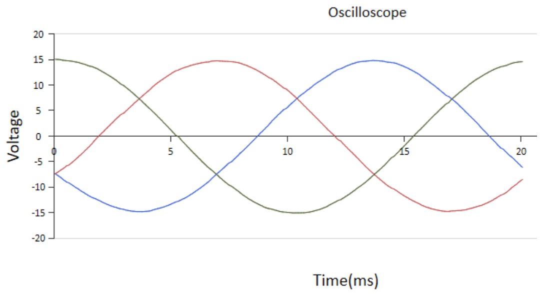
Worksheet 2
Three-phase AC

Analysis & Observations:

- Compare the behaviour of the bulbs at **0.1Hz** and **50Hz**.
- Observe how the phase relationship affects the illumination pattern.
- Analyse the recorded waveforms in the Matrix Three Phase software.

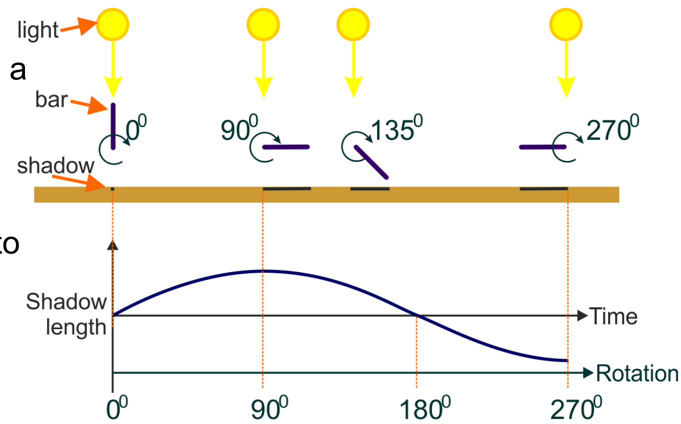
So What?

The diagram on the opposite side illustrates a typical output from the app. Each phase, represented in different colours, has an identical time period of 20ms (corresponding to 50Hz). The peaks of these phases occur at intervals of 20/3 ≈ 6.67ms, corresponding to a phase.



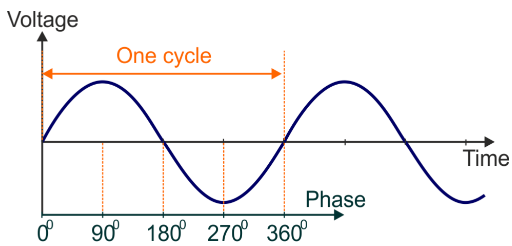
Phase angle:

Imagine a bar rotating around one end. Above it, a light shines down, creating a shadow of the bar. As the bar rotates, the shadow gets longer, then shorter, then zero, then longer in the other direction, and so on. As the bar continues to rotate, the shadow sequence repeats. One complete rotation of the bar creates one cycle of the sequence.



We can use the same idea to describe phase in alternating voltage signals. Here, the starting point and end point of one cycle of the signal are separated by a phase difference of 3600.

Using the information given above, one cycle of each phase lasts 20ms, so points which are 20ms apart have a phase angle of 3600 between them. The peaks of the three phases are separated by 6.66ms. In other words, the phases are separated by phase angles of (360/20) x 62/3 = 1200.



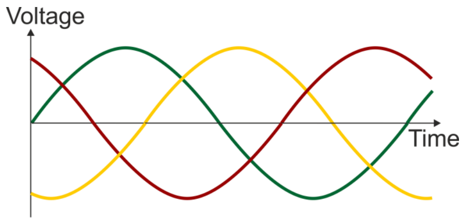
For your records:

- Describe five advantages of three-phase over single-phase power transmission. (You may need to carry out a little research on this, using the internet, for example.)
- Draw two cycles of a sine wave signal. Add a second signal where the phase angle between them is 1800.
- Do the same again, with a phase angle of 2700 between the two signals.

Worksheet 3

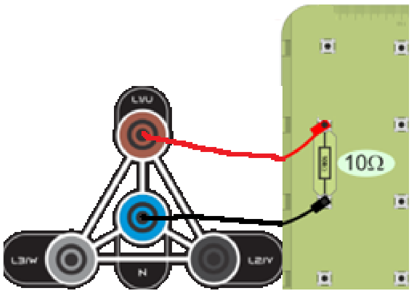
More phase basics

It's complicated!
The voltages and currents change in size, and direction over time. There appear to be three separate sources, all peaking at different times.
We need a word to describe all of this - phase.



Over to you:

These investigations focus on the relationship between current and voltage in three different types of load - resistive, capacitive and inductive. The inductive load is created by joining the coils of the three-phase motor in series.



- Build the circuit shown opposite.
  This time we are monitoring the AC voltage across the 10Ω resistor and the current flowing through it.
- ***Check that the three-phase generator is set to the '6V' @ 50 Hz output or the 10Ω resistor may overheat!***
- Click "Run"
- Click Capture to obtain a trace comparing the AC voltage across the resistor with the current flowing through it
- Get screenshot
- Notice that the two AC signals (the voltage across the resistor and the current through it), are in step (in phase,) with each other.
- Switch off the three-phase generator.

A challenge:

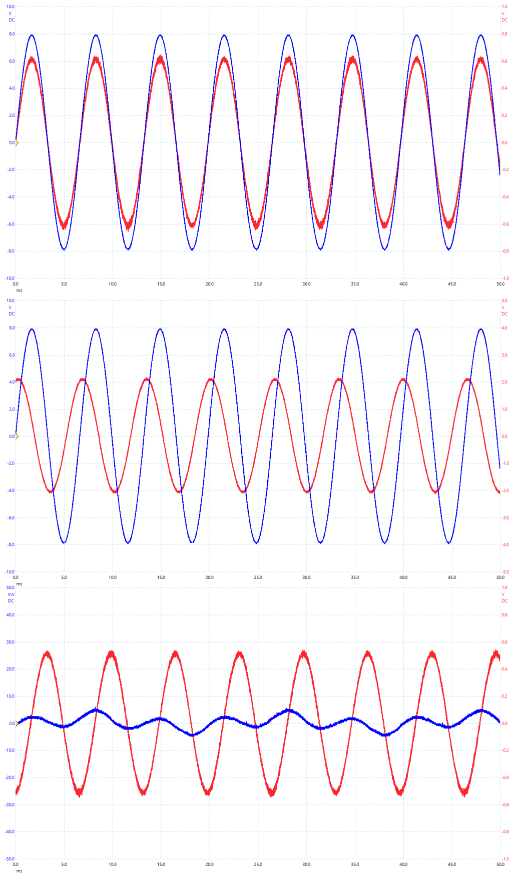
Using the same approach, modify the circuit to obtain voltage and current traces for:

- a 33μF capacitor;
- an inductor, made by using one of the motor coils.

Worksheet 3

More phase basics

So what?



A typical Oscilloscope trace for the resistor is shown opposite.

The red trace indicates the current flowing through The resistor and the blue trace the voltage across it. They rise and fall in step. They are in phase.

When you modified the circuit to investigate the other components, you should have obtained traces like the ones shown opposite.

- In the capacitor, current reaches peak value when the voltage is zero!
- In the inductor, the voltage peaks when the current is zero.

Phase angle:

Using phase angles, we can refine our earlier statements:

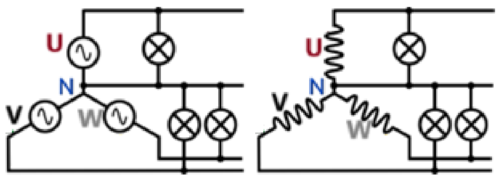
- In a capacitor, the current signal leads the voltage signal by a phase angle of 90^0.
- In the inductor, voltage leads current by a phase angle of 90^0.

Phase voltage vs line voltage:

In discussing three-phase systems, two different measures of voltage are used - phase voltage and line voltage.

- Phase voltage - measured between a phase terminal and the common (‘N’) terminal.
- Line voltage - measured between one phase and another.

  The circuit you set up earlier measured phase voltages.



For your records:

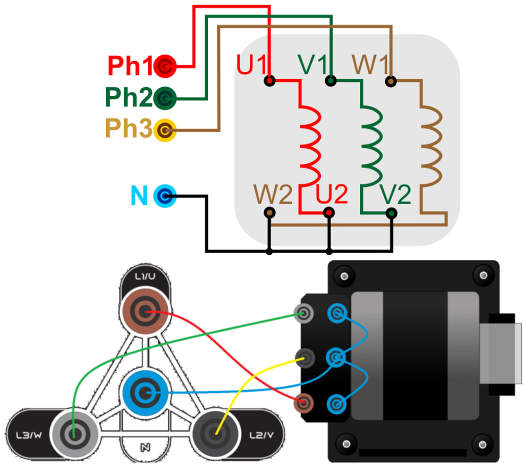
- Copy the diagram showing the difference between phase and line voltage.
- Copy and complete the statement:

  For a resistive load, AC voltage and current are …….
- What is the phase angle between current and voltage in a resistor?
- Copy the two bullet points describing phase angles in capacitors and inductors.

Worksheet 4
And now the phasor

It is even more complicated than we made out! We saw that the current flowing through the component may not be in phase with the voltage across it. What's worse, the size and direction of both change over time! The language of AC is now extended, bringing in the phasor, (not the 'phaser' - that belongs in 'Star Trek'!) The worksheet begins by using the three-phase motor, on a three-phase supply and then on a single phase and then turns to phasors and their interpretation.

Over to you:



Three-phase supply:

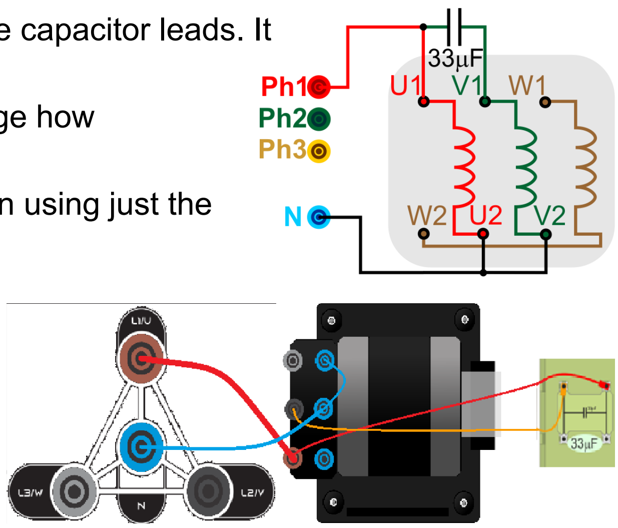
- Build the first circuit, shown opposite.
- Set the frequency to 50 Hz and the amplitude to 6V.
- Switch on the three-phase supply.
- What is the effect of turning the amplitude to 9V?
- What is the effect of increasing the frequency to 60Hz?
- What happens when you increase the frequency to 120Hz?

Challenges:

Investigate what happens when you change to phase connections to the motor, or leave one disconnected? Can you reverse the direction of rotation?

Single-phase supply:

- Build the second circuit, shown opposite. It uses only one phase of the power supply to drive two sets of coils, the 'U' and 'V' coils, (if set up as in the diagram). The capacitor adds a phase shift between the supplies to the two coils.
- Using the same frequency and amplitude of 8V, switch on.
- When the motor is running, disconnect one of the capacitor leads. It should continue running.
- Again, rest a finger on the motor flywheel, to judge how smoothly the torque is applied.
- Does the motor need the second coil, or will it run using just the supply to one coil?
  (Test by disconnecting one of the capacitor leads.)
- Investigate the effects of changing the frequency and amplitude of the supply, with and without the capacitor connected.



Worksheet 4
And now the phasor

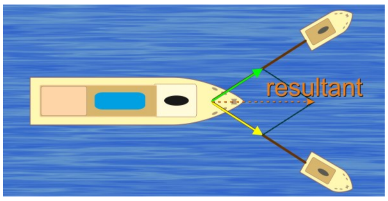
So what?

To understand AC circuits containing capacitors and inductors, you will need to understand phasors. The first step is to look at vectors:

Vectors - vector quantities, like forces and velocities, are described fully only when both size and direction are given. Combining them together is not straightforward!

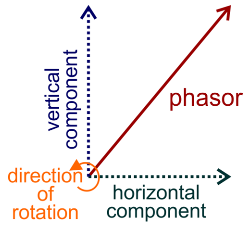
For example, the diagram shows two tugs pulling a ship. The force exerted by each tug is shown as an arrow.

- its length represents the size of the force;
- its direction is the direction of the force.



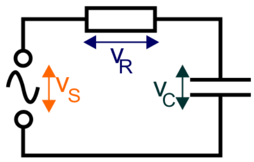
To find the total (resultant) force, complete the parallelogram and construct the diagonal, as shown. Its length gives the size of the resultant force, its direction, the direction of the resulting force.

Phasors - Current and voltage have size and direction, like vectors, but these change with time! They can also be represented by arrows, but these rotate!



The length of the horizontal component gives the size of the voltage or current at that instant. As the phasor rotates, this increases to a maximum, decreases to zero, increases and so on, (like the rotating bar in worksheet 2.) Direction - when the horizontal component is on the right-hand side of the diagram, current flows to the right, say, and when the component is on the left-hand side, it flows to the left.

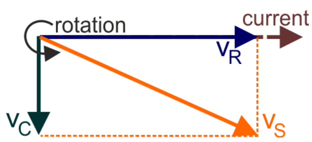
Combining phasors - also uses the parallelogram rule, but the current is being 'pulled' by a number of voltages!



For example, in the circuit described by the diagram opposite:

- the supply voltage, v_S, is split between the resistor and capacitor;
- the current through both is the same as they are in series;
- current is in phase with resistor voltage, v_R, but leads capacitor voltage, v_C, by 90^0.

This leads to the phasor diagram opposite. (The lengths for v_R and v_C are arbitrary.) Although all phasors are rotating, (at the supply frequency,) the diagram shows the situation when current is maximum.



- Check the diagram to make sure that you can see the information about v_R, v_C and current. The vector parallelogram rule gives v_S as the resultant of v_R and v_C.
- For your records:

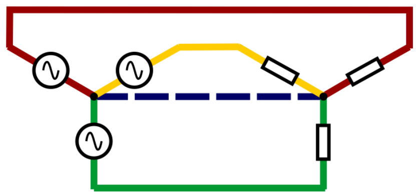
Describe how a current phasor contains information about its size and direction.
Copy the circuit diagram and phasor diagram given above. Explain the link between them.
A pure inductor (no resistance) is added in series with the resistor and capacitor. Draw the circuit diagram and phasor diagram for the new circuit. Choose equal sizes for vC and vL. (When added together, they cancel each other out!)

Worksheet 5
It's a star!

There are two ways to connect up three-phase supplies and loads - the star, (or 'Wye', because of its resemblance to the letter 'Y') and the delta configurations.

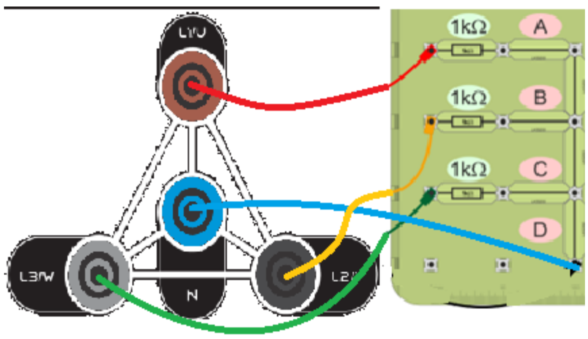
The diagram shows a star-connected three-phase supply driving a star-configured load.

In the star configuration, there is a 'neutral' point, where all phases, or loads are connected together.



Over to you:

- Build the circuit shown opposite.
- On the three-phase generator, set the frequency to 60Hz and the amplitude to 10V and switch on.



Voltages in a star configuration:

Phase voltages:

- Use a multimeter on the measure the 'brown' phase voltage, $\mathbf{V_U}$,
  across the top resistor.
- Similarly, measure 'Black' phase voltage, $\mathbf{V_V}$, across the middle resistor and 'Gray' phase voltage ,$\mathbf{V_W}$, across the bottom one.
- Enter all values into the table.

Line voltages:

- With the same settings, measure the line voltage, $\mathbf{V_{UV}}$, between the 'Brown' phase and the 'Black" phase.
- Similarly, measure the line voltages $\mathbf{V_{VW}}$ and $\mathbf{V_{UW}}$.
- Enter all values into the table.

Voltage	Value in V
'Brown' phase voltage, V_U	
'Black' phase voltage, V_V	
'Gray' phase voltage, V_W	
line voltage V_{UV}	
line voltage V_{VW}	
line voltage V_{UW}	

Currents in a star configuration:

- Remove connecting link A. With a multimeter on measure the phase current $\mathbf{I_U}$, and enter the result in the table.
- Replace connecting link A.
- In the same way, measure phase currents $\mathbf{I_V}$ and $\mathbf{I_W}$. Enter their values in the table.
- Remove connecting link D. Measure the current in the neutral wire, $\mathbf{I_N}$ and enter its value in the table.

Current	Value in mA
'Brown' phase current, I_U	
'Black' phase current, I_V	
'Gray' phase current, I_W	
Neutral current, I_N	

Worksheet 5
It's a star!

So what?

Phase voltages - The magnitudes of the three phase voltages are virtually identical. This is because of the way the three-phase generator is constructed.

Line voltages - Theory predicts the relationship:

Line voltage = √3 x Phase voltage

- Complete the table, using your measurements from the previous page.

Voltage	Value in V	√3 x phase voltage
'Red' phase voltage, V_R		
'Yellow' phase voltage, V_Y		
'Blue' phase voltage, V_B		
line voltage V_{RY}		
line voltage V_{YB}		
line voltage V_{BR}		

- Do the results support this relationship?

Current in a star configuration -

This circuit has the three-phase power source connected in a star, and the loads connected in a star. The neutral points in each star are connected together. In this case, the load is known a **balanced load**, as the impedance (in this case resistance) in each phase is identical (1kΩ).

- As can be seen from the circuit, phase current and line current are identical.
- Notice that the currents in the three phases are identical - not surprising, as the phase voltages are identical and the loads are identical.
- What may be a surprise is the value of current in the neutral wire - virtually zero!
  This is the result of the phase differences between the currents.
    - They are not in phase.
    - They do not all reach maxima together.
    - They do not add together arithmetically.

A challenge - Remove the neutral wire. Does it make any difference to your readings? Investigate what happens when the load is unbalanced. (Swap one of the 1kΩ resistors for a different value, such as 2.2kΩ.)

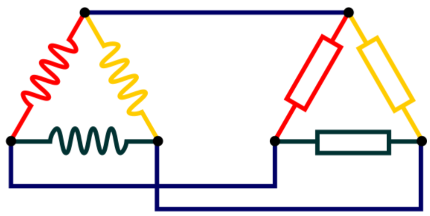
For your records:

- Draw the circuit diagram for the system you built for this investigation.
- Summarise the findings given in the previous section.
- Explain the mystery of the 'missing current' when a balanced load was used. Where has it gone?
- Explain why electricity is usually transmitted using a four-wire system, rather than a three-wire system.

Worksheet 6
On the delta

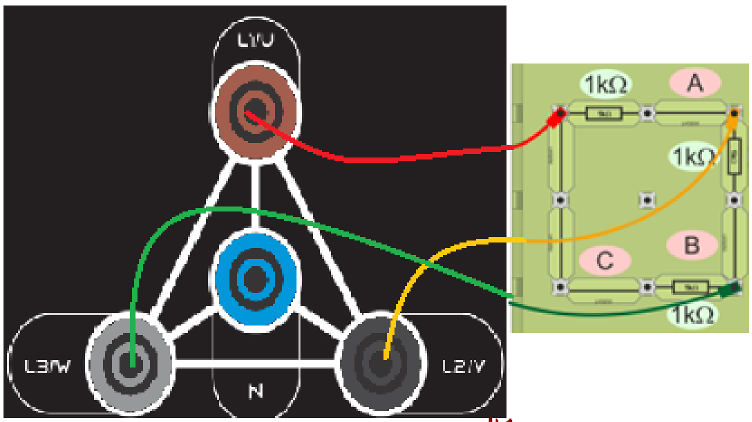
The other way to configure three-phase circuits is to use the ‘delta’ connection, (so-called because of the similarity of the shape to the Greek letter ‘delta’ (Δ).

The diagram shows a three-phase power source, connected in delta configuration to a load, also in delta configuration.
This time, there is no neutral point, and only three wires link the power source and load.

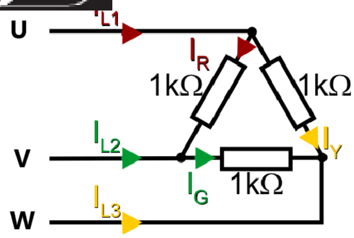


Over to you:

- Build the circuit shown opposite. The delta connection may not be immediately obvious. Compare it with the circuit diagram that follows:
  - phases are connected together through 1kΩ loads;
  - the three load resistors are connected in a loop.
- On the generator, set the frequency to 50Hz and the amplitude to 6V and switch on.



Voltages in a delta configuration:



As can be seen from the diagram, phase voltage and line voltage are now identical.

- Use a multimeter to measure the line voltages across the three 1kΩ loads and Record them in the table.

Line voltage	Value in V
V_{12}	
V_{13}	
V_{23}	

Currents in a star configuration:

- Remove connecting link A. With the multimeter on the 20mA AC range, measure the phase current, **I_1**, through the 1kΩ resistor connected between phases **U** and **V**.
- Enter the result in the table.
- Replace connecting link A. Next, measure phase currents **I_2** and **I_3.** Enter their values in the table.
- Remove the red wire connecting **U** to the load.
- Replace it with the multimeter and read line current **I_{L1}**. Enter its value in the table.
- Do the same for the other two line currents, **I_{L2}** and **I_{L3}**.

Current	Value in mA
phase current, I_1	
phase current, I_2	
phase current, I_3	
line current I_{L1}	
line current I_{L2}	
line current I_{L3}	

So what?

Theory predicts the relationship:

Line current = √3 x Phase current

- Complete the table, using your measurements from the previous page.

Current	Value in mA	√3 x phase current
phase current, I_1		
phase current, I_2		
phase current, I_3		
line current I_{L1}		
line current I_{L2}		
line current I_{L3}		

- Does it support this relationship?

Summary:

In a delta configuration:

Line voltage = Phase voltage
Line current = √3 x Phase current

A challenge -

- Connect the three-phase motor using a delta configuration:
    - connect the three coils in delta formation - U2 to V1, V2 to W1 and W2 to U1.
    - connect the three phases to U1, V1 and W1.
- What happens when you reverse two of the phases?
- Compare the performance of the motor in delta configuration with that seen earlier using the star configuration.

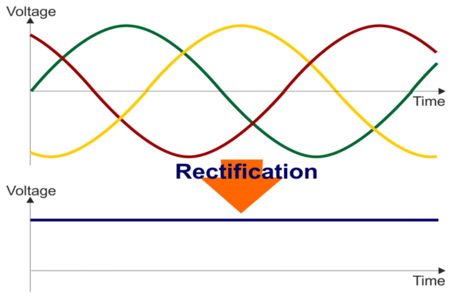
For your records:

- Copy the circuit diagram showing a delta-configured three-phase supply, driving a delta-configured three-phase load.
- Summarise the findings of this investigation.
- Using an internet search engine, or text books, draw up a table of relative advantages and disadvantages for star and delta configurations.
- Draw the circuit diagram for the delta-configured motor on the three-phase supply.
- Compare the performance of the motor when in star and in delta configuration.

Worksheet 7

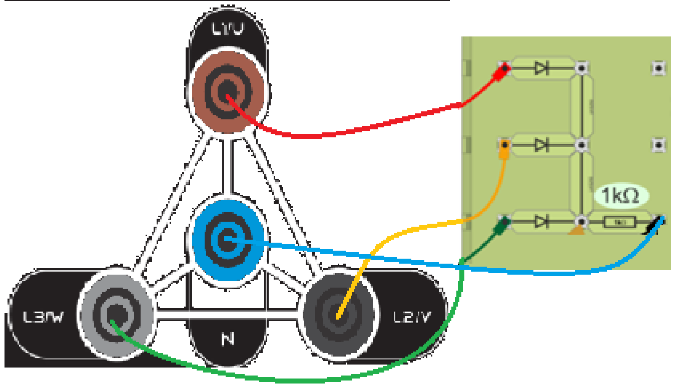
Half-wave rectification

Some electrical devices require a DC supply and will not run on AC.
Rectification is the process of turning an AC supply into DC.
It relies on the fact that diodes allow appreciable current to flow in one direction only. Comparing rectified three-phase to single-phase:
The advantage is, result is much smoother.
The disadvantage is, requires more diodes to accomplish it.



Over to you:

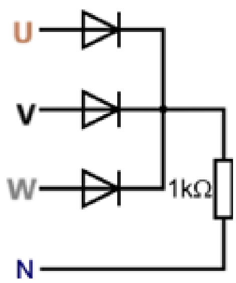
- Build the circuit shown opposite. (The circuit diagram is given underneath it.)
  It uses the three-phase generator, in star configuration, to drive current through a 1kΩ load.
  Each phase has a diode in series to ensure that current flows only one way through the load.
  Notice the Oscilloscope ground clip!



- On the three-phase generator, set :
  - the frequency to 50Hz;
  - the amplitude to 9V.
- Use the following Oscilloscope settings:

Timebase	5ms/div
Channel A, B, C and D	Auto
Trigger	Auto
Threshold	0V
Pre-trigger	0%

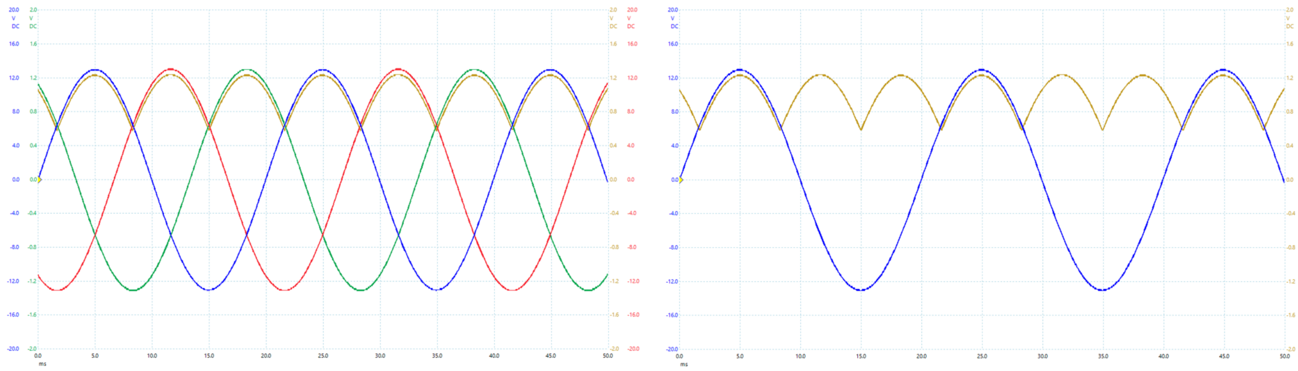
- Switch on the three-phase generator.
- Obtain a trace showing the three phases delivering power to the load and the half-wave rectified output applied to it.
- Save it for your records.
- To make it clearer what is happening, turn off channels B and C on Oscilloscope and obtain another trace, showing the outputs on channels A and D, i.e. one input phase and the output.
- Save it for your records with an explanation of what it shows.



Worksheet 7
Half-wave rectification

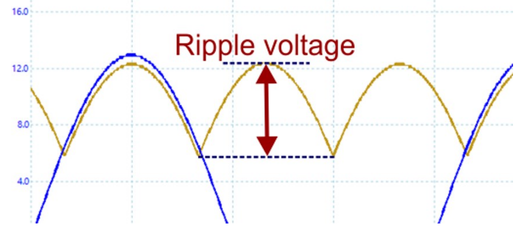
So what?

The diagrams show typical signals. The rectified output is on channel D, shown in gold.



Notice that it sits below the corresponding AC phase signal. This is because of the 0.7V (approx.) drop across a conducting silicon diode. The trace is always positive, and so it is a DC signal, though not smooth DC.

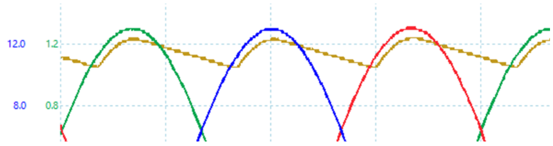
In one AC cycle, there are three peaks in the rectified signal, one for each of the three phases. This indicates that it is half-wave rectification only - the negative half-cycle of each phase is ignored. (Compare this with the next worksheet!)



The variation in the output voltage, (across the load,) is known as the ripple voltage.

Challenges -

- Connect a 33μF non-electrolytic capacitor in parallel with the 1kΩ load.
- Obtain new Oscilloscope traces to see the effect on the ripple voltage.
  A typical output is shown opposite.
  Notice the reduced ripple!



- What is the effect on ripple voltage of using different values of load resistor?
  You could increase the load resistance by connecting several 1kΩ resistors in series, or reduce it by connecting them in parallel. (Two 1kΩ resistors in parallel have a combined resistance of 0.5kΩ, four in parallel have a combined resistance of 0.25kΩ.)

For your records:

- Draw the circuit diagram for a three-phase half-wave rectifier, and include capacitor smoothing.
- Explain why the output of this circuit is considered to be DC.
- Explain the term 'ripple voltage' and explain why adding a smoothing (or 'reservoir',) capacitor reduces the ripple.

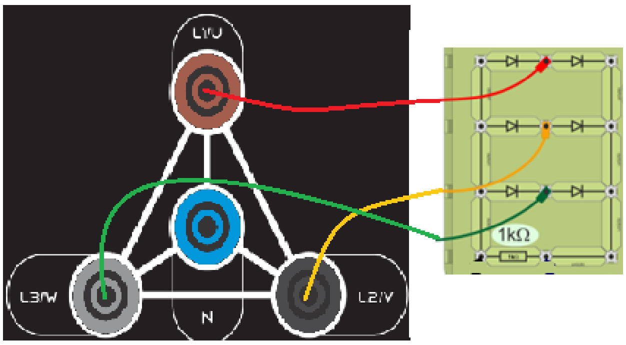
Worksheet 8
Full-wave rectification

A common use of rectification is in motor vehicles. These generate three-phase electricity using alternators, which are smaller and lighter than equivalent DC generators.The majority of the vehicle's electrical system requires a DC supply, and so, built into the alternator is a full-wave rectifier. The previous worksheet looked at half-wave rectification, leading to a DC output voltage, but with a ripple voltage. This is often undesirable, as it can cause audible 'hum' in audio equipment and spurious effects in digital systems.

Over to you:

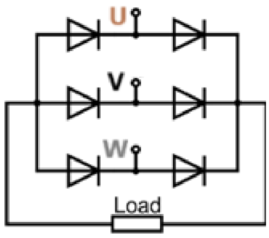
- Build the circuit shown opposite. Notice the Oscilloscope ground clip! Make sure that all diodes are connected the right way round!

  Without specialised probes, you can not obtain traces of all phases AND the full-wave output simultaneously - that would short-circuit part of the circuit. Instead, use only one probe to monitor the output across the load, as shown.



Oscilloscope settings:

Timebase	5ms/div
Channel A	Auto
Channels B, C and D	Off
Trigger	Auto
Threshold	0V
Pre-trigger	0%



- Set the three-phase generator frequency to 50Hz and amplitude to 9V.
- Switch it on.
- Obtain a trace showing the output across the 1kΩ load.
- Save it for your records with an explanation of what it shows.
- Connect a 33μF capacitor in parallel with the 1kΩ load and repeat the process.

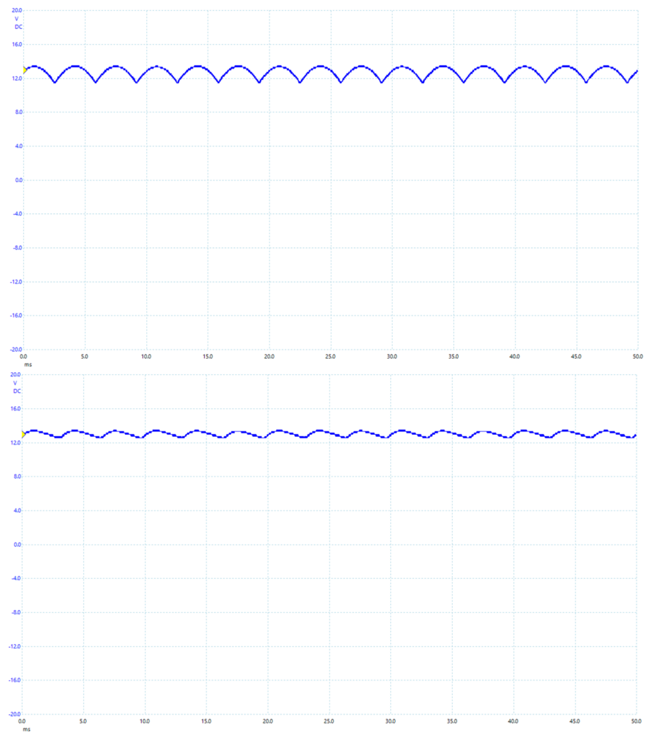
  (To see the relationship between the output and phases, move the Oscilloscope channel A probe to examine each phase in turn.)

So what?

The two traces opposite show typical Oscilloscope results, without (top trace) and with smoothing (bottom trace).

Compare them with those obtained for half-wave rectification.

The amplitude of the ripple voltage is much smaller and the frequency is higher than with half-wave rectification.



A challenge -

As in the previous worksheet, investigate the effect of load resistor size on ripple voltage.

For your records:

- Draw the circuit diagram for a three-phase full-wave rectifier, including capacitor smoothing.
- In investigating this circuit:
    - what indicated that the output was DC?
    - what indicated that it was a full-wave rectified output, as opposed to half-wave?
- Describe *and explain* the effect on ripple voltage of increasing the size of:
    - the load resistor
    - the smoothing capacitor.

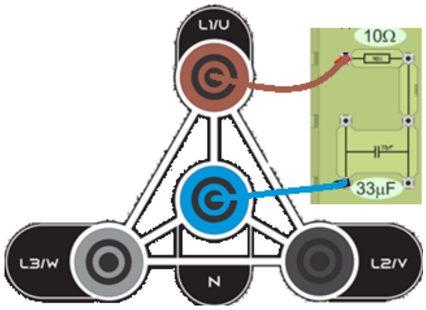
Worksheet 9
Delivering power

In the end it is a matter of delivering power from transmitter to load. Not surprisingly, there is a complication! Real power is the product of voltage and current *in phase with the voltage*. As we have seen, for many loads, current and voltage are not in phase.

This worksheet examines how this situation is handled, in three circuits. Two use a single phase supply in circuits which contain reactance. The third uses a three-phase supply to drive the three-phase motor.

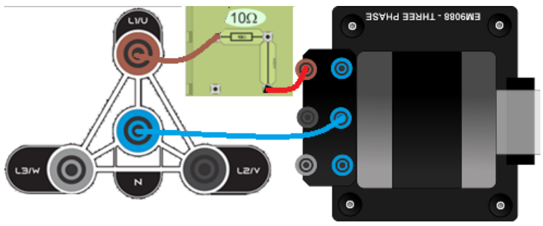
Over to you:

An R-C circuit:



- Build the top circuit shown opposite .
- Set the three-phase generator frequency to 150Hz and amplitude to 6V. Switch it on.
- Use the same Oscilloscope settings as in the previous worksheet.
- Obtain and save a trace showing the supply voltage and current through the circuit.
- Switch off the generator.

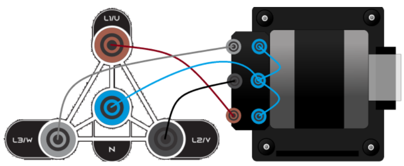
An R-L circuit:



- Build the middle circuit.
- Use the same settings as before for the three-phase generator and for the Oscilloscope.
- Switch on the generator.
- Obtain and save a trace showing supply voltage and current through this circuit.
- Switch off the generator.

The three-phase motor:

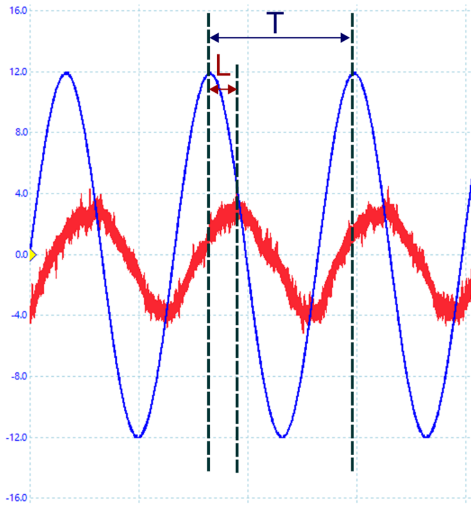
- Build the bottom circuit.
- Once more, use the same settings for the three-phase generator and for the Oscilloscope.
- Switch on the generator.
- Obtain and save a trace showing supply voltage and current through one phase of this circuit.
- Switch off the generator.



Worksheet 9
Delivering power

So what?

The traces produced in the three circuits can be analysed to extract the real power delivered to the load devices. The procedure is outlined below, using a section of a current/voltage trace obtained for a R-L circuit to extract phase angle ϕ.



The applied voltage is shown by the blue trace, current by the red. The amplitude of the current trace is small and affected by electrical noise. Voltage leads current, as we expect in a circuit containing inductance.

- Draw vertical lines through two adjacent voltage peaks and a current peak, as shown.
- Use the time scale to measure times **T** and **L**.
  T is the period of the signal.
  L is the time lag experienced by the current.
  Sample results are: **T** = 6.7ms **L** = 1.3ms
- **T** is the time between points with a phase angle of 360^0 between them.
  Hence, 1.3ms represents a phase difference of (1.3 / 6.7) x 360^0 or 70^0 approximately
  In this R-L circuit, voltage leads current by a phase angle of around 70^0.
  This implies a phase factor of 0.34 (i.e. cos 70^0).
- From the traces,
  peak voltage = 12.0V giving V_{rms} = 8.4V.
  peak current reading = 7mV.
  With the current clamp on the 20A (i.e. 1mV/10mA) range,
  peak current is 7 x 10 = 70mA, giving I_{rms} = 49mA.

Putting all this together:

Real power delivered to the system, $P = V_{rms} I_{rms} \cos \varphi$
$= 8.4 \times 49 \times 10^{-3} \times 0.34$
= **0.14W**

Apparent power, $S = V_{rms} I_{rms}$
= **0.41VA**

For your records:

- In the same way, determine the real and apparent power for the R-C and R-L circuits you set up in this investigation.
- The three-phase motor is a balanced load.
  The total power delivered = 3 x power delivered to one phase.
  Use your results from the third circuit to determine the real power delivered to the motor.

Worksheet 10
Power factor correction

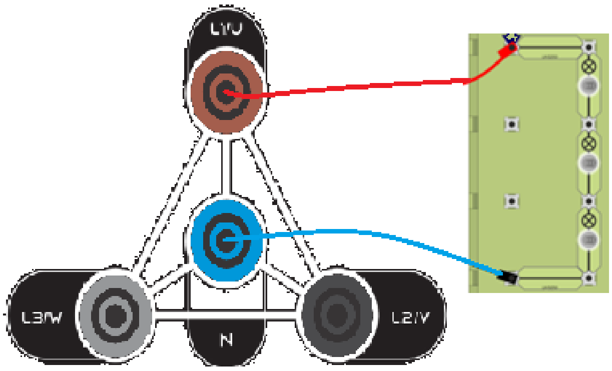
A low power factor means that more current is needed to transfer a given quantity of useful energy.
The extra current stores energy, temporarily, in the magnetic field of a motor for example. It then returns to the power supply a short time later. It delivers the same useful power but thicker cables, heavier transformers etc. may be needed to cope with the extra current and the consumer may incur extra charges as a result.

Over to you:

A resistive load:

The three lamps represent a purely resistive load.

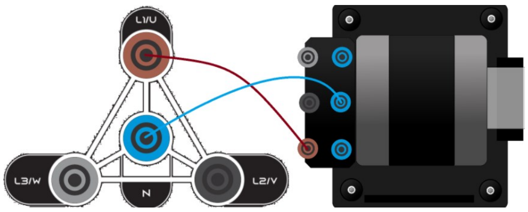
- Build the circuit shown opposite .
- Set the three-phase generator frequency to 150Hz and amplitude to 6V. Switch it on.
- Use the same Oscilloscope settings as in worksheet 8.
- Obtain and save a trace showing the supply voltage and current through the circuit.
- Switch off the generator.



An inductive load:

One coil of the motor is used as an inductive load.

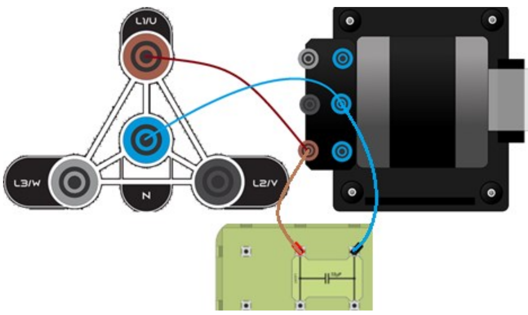
- Build the second circuit.
- Use the same generator and Oscilloscope settings.
- Switch on the generator.
- Obtain and save a trace showing the supply voltage and current through this circuit.
- Switch off the generator.



An inductive load with power factor correction:

A capacitor balances the inductive reactance of the load.

- Build the third circuit.
- Use the same generator and Oscilloscope settings.
- Switch on the generator.
- Obtain and save a trace showing the supply voltage and current through the circuit.
- Switch off the generator.



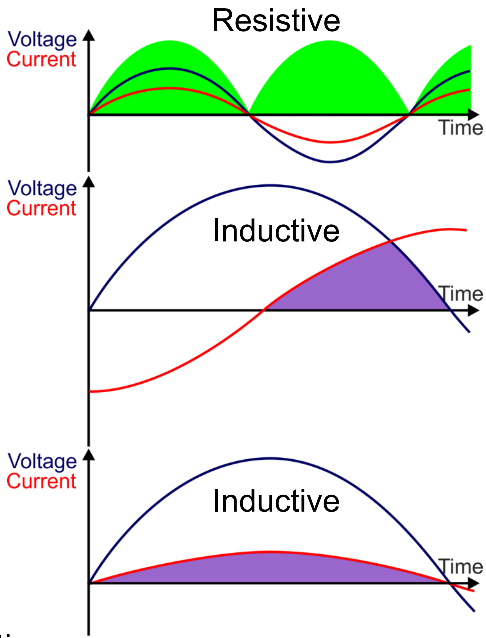
Worksheet 10
Power factor correction

So what?

With a resistive load, current is in phase with voltage, the optimum arrangement for efficient power delivery.

For the uncorrected inductive load, however, that is not the case. In inductors, current lags behind voltage.
The coloured area shows the time over which power is delivered to the load. As this is a relatively short period, the current must be large to deliver enough energy.

The aim of power factor correction is to bring current and voltage back into phase - extending the time over which power is delivered. The current needed to deliver the required energy can then be smaller.



In reality, most loads are resistive or inductive overall.
Here are some examples:

- resistive - incandescent lamp, heater;
- inductive - motors, relays, transformers.

Inductive loads use added capacitors for power factor correction.
For a motor, the value of capacitor needed to do this depends on aspects like the speed of the motor, its load and the frequency of the supply. This causes complications when there are a number of motors on the same power supply and when their speed and loads vary.

Some industrial sites use banks of capacitors to move the overall power factor back towards a value of unity in order to reduce electricity costs.

The benefits of power factor correction:

- reduced electricity charges and no financial penalty from the electricity supplier;
- reduced heat losses in cables, switchgear, transformers and distribution equipment;
- prolonged life of transmission and generation equipment;
- reduced voltage drop in cables, allowing the use of smaller gauge cables.

A challenge:

Investigate the effect of changing the frequency of the three-phase supply. What frequency gives the best power factor correction for the inductive load?

For your records:

- Explain, using voltage / time graphs, the meaning of the term ‘power factor correction’.
- Describe two advantages of power factor correction to an industrial consumer.
- Draw the circuit diagram for circuit that uses a single-phase AC supply to drive an electric motor and incorporates power factor correction.