2365 Level 3

Electrotechnical Qualification

Unit 302: Principles of Electrical Science

Pre-attendance Workbook

v2.0

Unit 302: Principles of electrical science

Unit introduction

Unit aim

The aim of this unit is to enable the candidate to understand the principles of electrical science related to AC theory, machines, devices and systems. This understanding is applied when designing wiring systems for clients and fault diagnosis.

Learning outcomes

There are six learning outcomes for this unit.

The learner will:

1. Understand electrical supply systems
2. Understand how different electrical properties can affect electrical circuits, systems and equipment
3. Understand the operating principles and applications of DC machines and AC motors
4. Understand the operating principles of electrical components
5. Understand the principles and applications of electrical lighting systems
6. Understand the principles and applications of electrical heating

Assessment

This unit is assessed via a practical assignment.

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Handout 1: Resistance in an AC circuit

Learning outcome

The learner will:

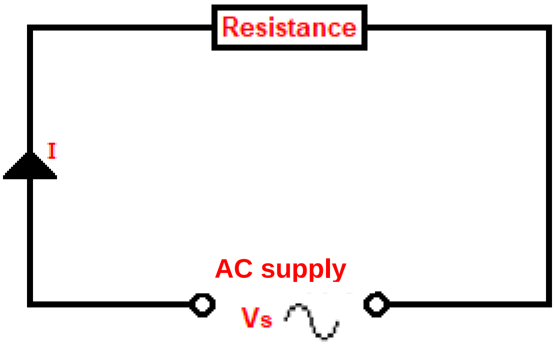
2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

The learner can:

2.1 explain the relationship between resistance, inductance, capacitance and impedance currents.

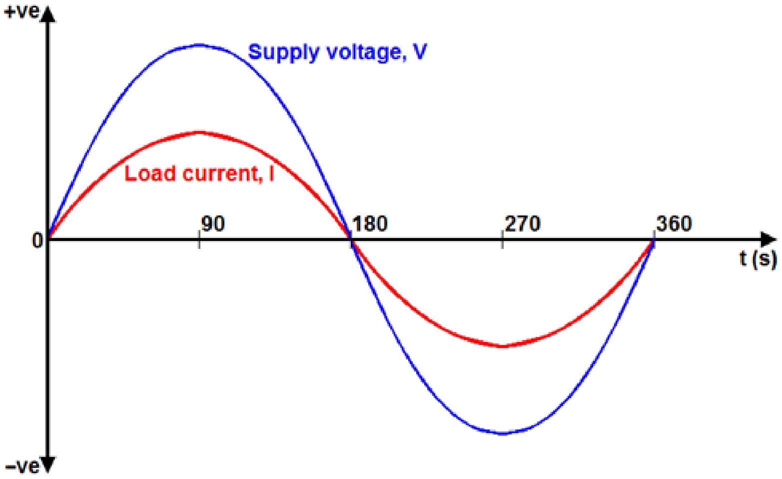
Resistance in an AC circuit



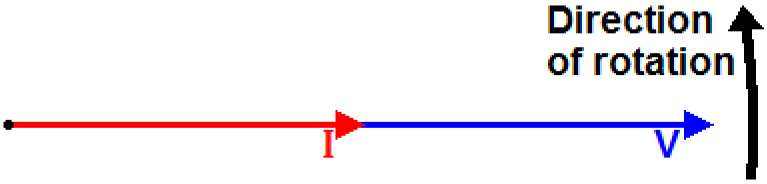
When a pure resistance is connected across an alternating current supply (AC), the current that will flow through it, at any instant in time, is governed by Ohm's Law.

I = V/R at any moment in time during the cycle.

What this means is that the current waveform for a purely resistive circuit is exactly the same shape as the wave form for the emf applied to that circuit and is in phase with it, as is shown by the diagram below.



The phasor diagram that represents this waveform is as shown below:



The current in the circuit can be found by using the expression **I = V/R**, where I and V are the RMS. values of current and emf respectively.

In a purely resistive circuit, the current through the resistor is unaffected by the frequency of the supply and is therefore in phase with the voltage.

The power consumed by a resistor connected across an ac supply can be found by using the formula:

$$\mathbf{P = V.I.\cos\phi}$$

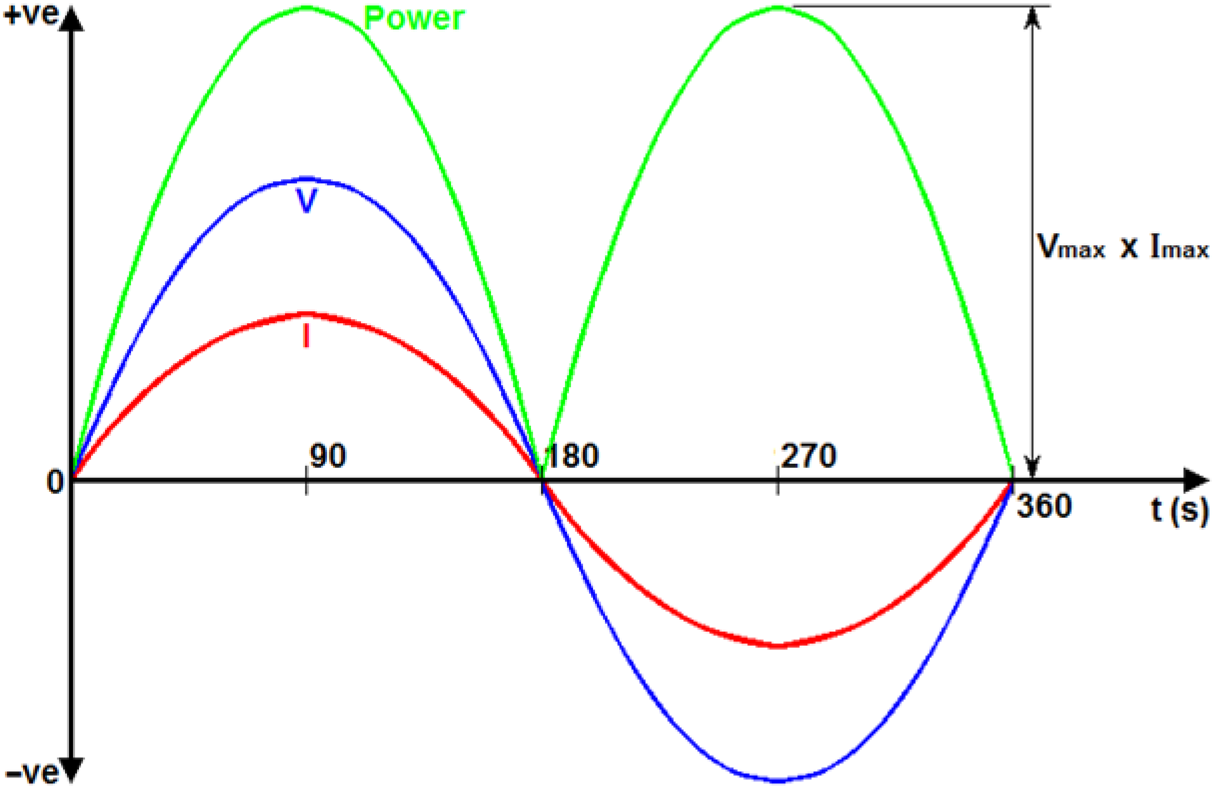
The cosine of the angle will be the cosine of zero (0)degrees, since there is no phase angle (difference between V & I).

$$\mathbf{\cos\phi = 1}$$

$$\therefore \quad \mathbf{P = V.I.\cos\phi}$$

$$\therefore \quad \mathbf{P = V.I.1}$$

$$\therefore \quad \mathbf{P = V.I\ (for\ a\ purely\ resistive\ circuit)}$$



It can be seen from the wave shape that a resistor consumes power on both halves of the wave. This is because in applying the formula $P = V_{max} \times I_{max}$ in the first half cycle, both V & I are positive values, which give a positive answer. In the next half cycle both V & I are negative values, which also gives a positive answer.

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Worksheet 1: Resistance in an AC circuit

Using your notes answer the following questions.

1. Describe with the aid of graph the relationship between the current and voltage of an AC supply connected to a pure resistance.

2. When an AC supply is connected to a pure resistor, state why the power produced is always ‘positive’ despite the current and the voltage going negative as well as positive.

3. Draw the phasor diagram for voltage and current when connected to a pure resistance.

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Handout 2: Inductance in an AC circuit

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

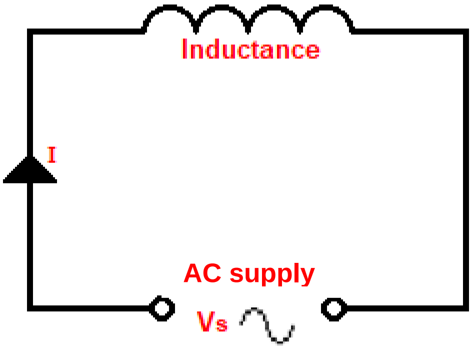
The learner can:

2.1 explain the relationship between resistance, inductance, capacitance and impedance currents.
2.2 determine **electrical quantities** in alternating current circuits

Range

Electrical quantities: resistance, inductance, inductive reactance, capacitance, capacitive reactance, impedance.

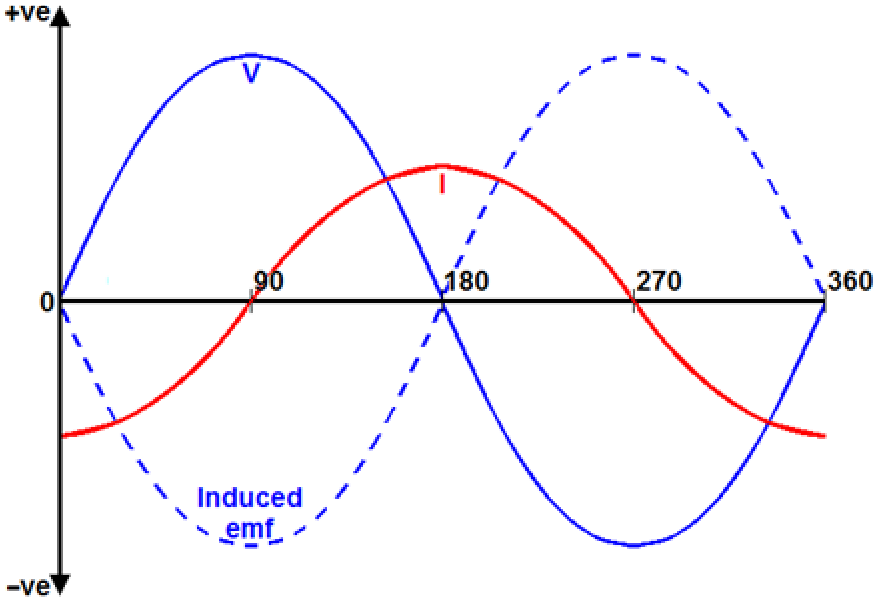
Inductance in an AC circuit



When an alternating current flows through a pure inductor, the value of the current is perpetually changing, so producing a self-induced emf at every instant.

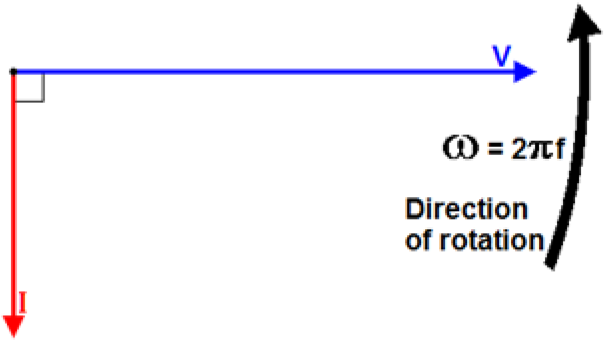
If current changes in such a coil, an emf will be induced in the coil, to oppose the change. This self-induced emf provides the only opposition to current flow. If the current is increasing, the emf will oppose the supply voltage to limit the rate of increase, and if decreasing, will try to keep the current flowing.

The unit of self-inductance is the **henry** (symbol **H**). The induced emf depends upon the rate of change of current.



Induced emf must be at a maximum when the rate of change of current is a maximum. Since this maximum occurs when the current passes through zero, maximum emf must coincide with zero current.

When the current is going positive the induced emf must therefore be negative (as it opposes change).



The current can therefore be seen to lag the voltage by 90° as shown in the phasor diagram.

We have assumed that the inductive circuit has no resistance, but since the resulting current flow is not infinite, it must therefore be limited by some property other than resistance.

This property is called the **INDUCTIVE REACTANCE** of the coil whose symbol is $\mathbf{X_L}$, and it can be shown that:

$$X_L = V/I$$

$$X_L = 2\pi f L$$

$$X_L = \omega L$$

Where: X_L = reactance of the inductor in ohms
V = voltage across the coil
I = resulting current flow
f = supply frequency in Hz
L = coil inductance in Henrys
ω = 2πf

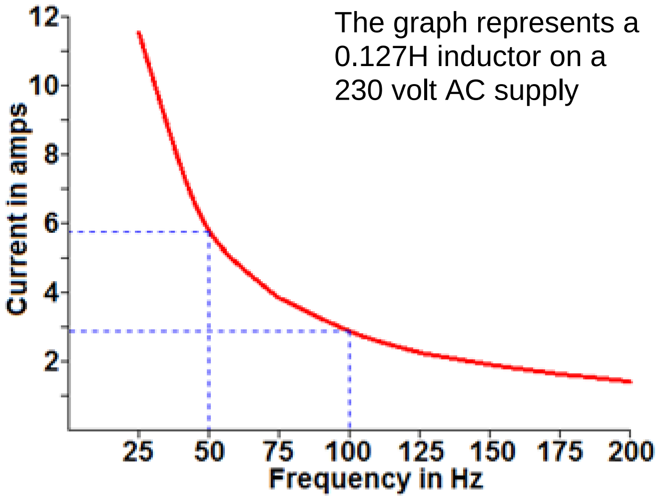
The formula shows that the inductive reactance X_L depends not only on the value of inductance, but also on the frequency of the supply.

That is, if the frequency is increased, then X_L will increase in direct proportion to it, and if it is decreased it will decrease in direct proportion.

If we took an inductor of 0.127H and connected it across a 230 volt AC supply, and then took readings of current against frequency, we should get the following readings:

Freq Hertz	Current Amps
25	11.54
50	5.77
75	3.85
100	2.88
125	2.31
150	1.92
175	1.65
200	1.44

If we plotted a graph of these readings it would look like this:



The graph represents a 0.127H inductor on a 230 volt AC supply

Using the readings obtained, it is possible to calculate the value of X_L at several different points and plot a graph of these points.

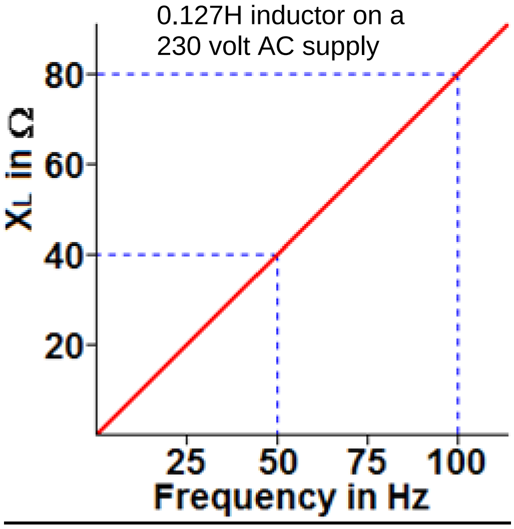
For example:

$$\begin{aligned} X_L &= V/I \\ &= 230/5.77 \\ &= \underline{40\Omega \text{ (at 50Hz)}} \\ X_L &= V/I \\ &= 230/2.88 \\ &= \underline{80\Omega \text{ (at 100Hz)}} \end{aligned}$$

The shape of the graph will be like the one shown right:

It will also be noted that, when f = 0, the inductive reactance will be zero. Thus, the inductance of a coil has no effect on the steady flow of a **direct current (DC)** through it; therefore, the current is only limited by the coil resistance.

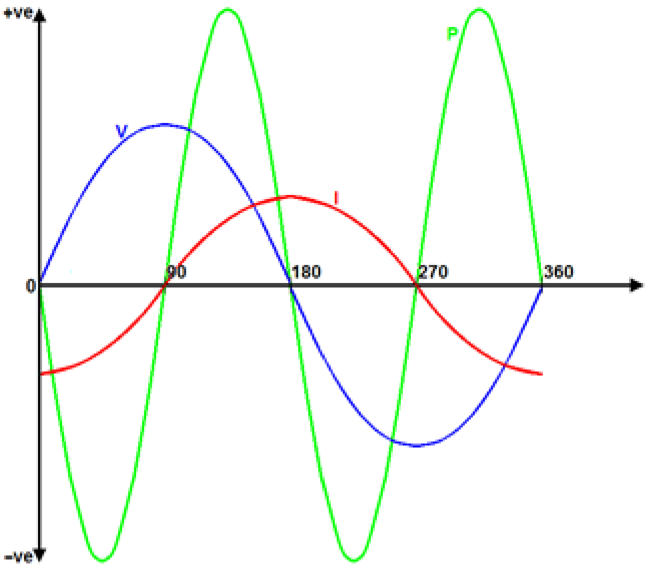
If we do the same for any inductor we will always get the same shape graphs.



The graph represents a 0.127H inductor on a 230 volt AC supply

A pure inductance consumes no power at all during operation, which can be clearly seen from the diagram below. Using the formula **$P = I^2.R$**, since R = 0 then P must equal zero.

If we use the simple expression for power as we did for the resistance, (+ × - etc.) it explains why there is a positive and a negative power wave.



Example

A coil has a self-inductance of 0.318H and a negligible resistance. Calculate its inductive reactance and the resulting current that will flow, if connected to:

a) 230v, 50Hz supply

b) 230v, 400Hz supply

a)

$$\begin{aligned} X_L &= 2\pi fL \\ &= 2 \times 3.14 \times 50 \times 0.318 \\ &= 100\Omega \\ I &= \frac{V}{X_L} \\ &= \frac{230}{100} \\ &= \underline{2.3A} \end{aligned}$$

b)

$$\begin{aligned} X_L &= 2\pi fL \\ &= 2 \times 3.14 \times 400 \times 0.318 \\ &= 800\Omega \\ I &= \frac{V}{X_L} \\ &= \frac{230}{800} \\ &= \underline{0.29A} \end{aligned}$$

It can be seen from the above example that as the frequency of a circuit is increased, then the inductive reactance increases in direct proportion to the frequency and the current falls inversely proportionally to the frequency.

It can also be seen that the ratio between 50Hz & 400Hz is 8, which is also the ratio between 100Ω and 800Ω inductances.

The current has also decreased by the same ratio, ie from 2.3A to 0.29A.

The energy stored in an inductor is calculated by using the formula:

$$\boxed{\text{Energy stored, } Q = \frac{1}{2}.L.I^2 \text{(joules)}}$$

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Worksheet 2: Inductance in an AC circuit

Using your notes, answer the following questions. Use π = 3.14.

1. An inductance with a value of 1H is connected across a 230v 50Hz supply. Calculate:

a) The Inductive reactance of the circuit.

b) The current that will flow.

2. An inductance with a value of 20mH is connected across a 400v 60Hz supply. Calculate:

a) The Inductive reactance of the circuit.

b) The current that will flow.

3. An inductance with a value of 0.15H is connected across a 100v 400Hz supply. Calculate the current that will flow in the circuit.

4. When an Inductor is connected across a 230v 50Hz supply, a current of 2.5A is recorded as flowing in the circuit. Calculate the Inductance of the coil in Henrys.

5. When an Inductor is connected across a 100v 25Hz supply, a current of 4.0A is recorded as flowing in the circuit. Calculate the Inductance of the coil in Henrys.

6. When an Inductor is connected across a 110v 325Hz supply, a current of 5.0A is recorded as flowing in the circuit. Calculate the Inductance of the coil.

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Handout 3: Capacitance in an AC circuit

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

The learner can:

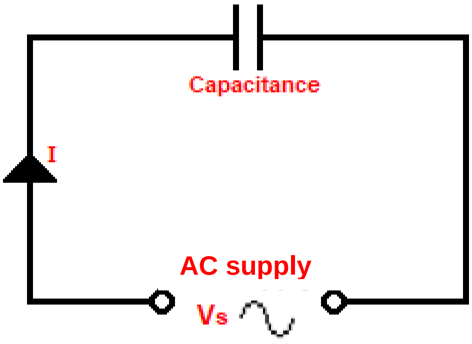
2.1 explain the relationship between resistance, inductance, capacitance and impedance currents.

2.2 determine **electrical quantities** in alternating current circuits

Range

Electrical quantities: resistance, inductance, inductive reactance, capacitance, capacitive reactance, impedance.

Capacitance in an AC circuit



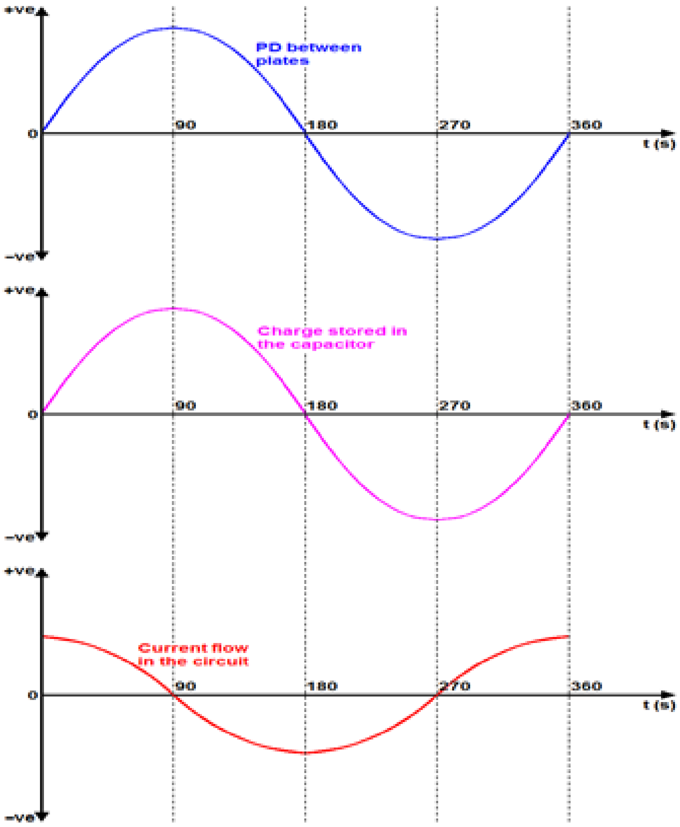
A capacitor is a device for storing an electric charge, the amount of change stored on the plates is directly proportional to the voltage applied, i.e. **Q = V.C**

Where:

Q = Charge in coulombs

V = Voltage in volts

C = Capacitance in farads

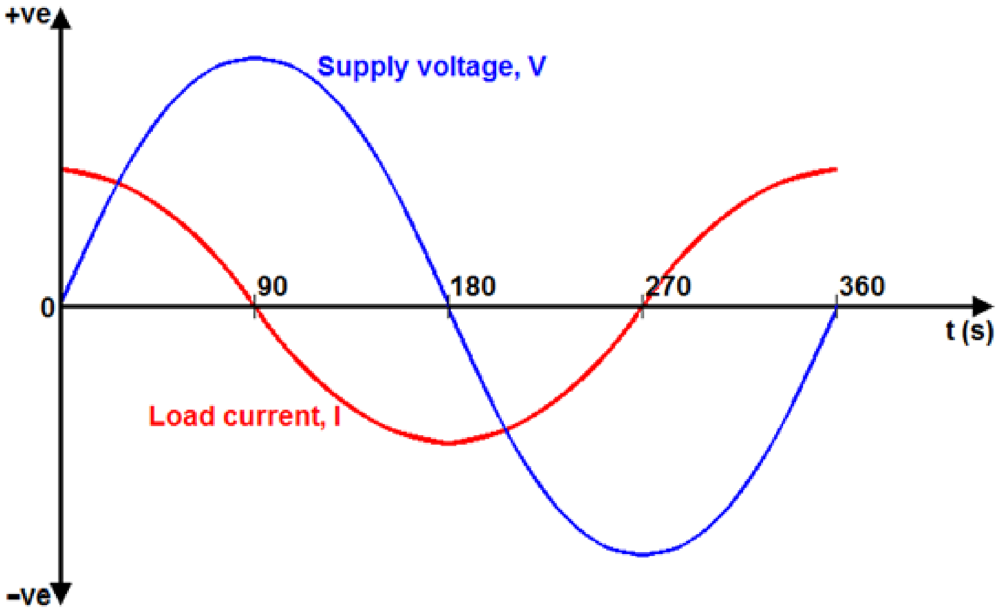


When a capacitor is connected across an AC supply, the capacitor will alternatively charge and discharge with opposite polarity. Thus, although no current actually passes through the capacitor, an alternating current exists in the circuit, because there is a movement of electrons, which can be measured with a suitable ammeter.

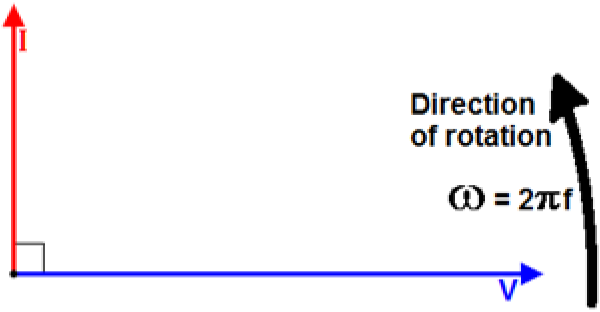
An electric current must flow either into or out of the capacitor to maintain the charge at its correct value.

When an alternating PD is applied to the capacitor the charge increases with the increasing PD. The current is at a maximum when the voltage and charge are at a minimum.

This is because a large current is required to cause a charge and when the capacitor is fully charged, no current is required.



It can be seen from the diagram above that the current is at its maximum value when the voltage and charge are at their greatest rate of change. Hence the current wave leads the voltage wave by 90°.



Since the capacitor is assumed to have an infinite resistance (as we understand it in DC), then there can be no current flow, but this is not so as the diagrams show. There is therefore, some property which allows current to flow and yet limits its value.

This property is called the **CAPACITIVE REACTANCE** (symbol **X_C**) and it can be shown that:

$$X_C = V/I$$

$$X_C = \frac{1}{2\pi f C}$$

$$X_C = \frac{1}{\omega C}$$

Where: X_C = reactance of the capacitor in ohms

V = voltage across the capacitor

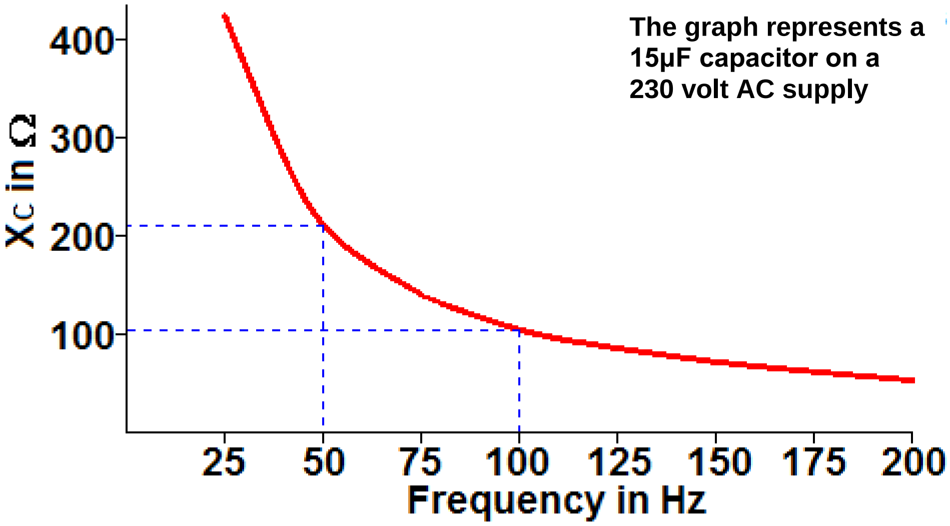
I = resulting current flow

f = supply frequency in Hz

C = capacitance in Farads

ω = $2\pi f$

The formula shows that the capacitive reactance X_C depends not only on the value of capacitance but on the frequency as well. If the frequency is increased, then X_C will decrease, and if the frequency decreases then X_C will increase. It can therefore be seen that the frequency has an inverse effect on the capacitive reactance.

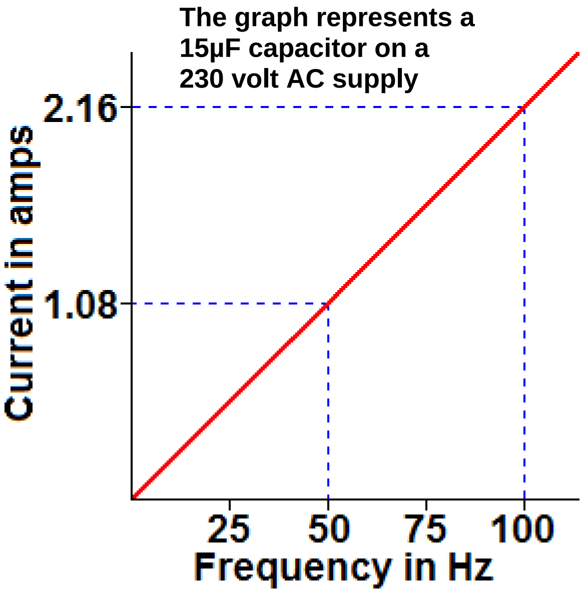


It will also be noted that when f = 0 the capacitive reactance will be at its maximum (infinity) and thus there will be no current flowing. I = V / R, then R = infinity.

If the frequency is increased the charge will have less time in which to flow into the capacitor (because there are more changes per second) and therefore the rate of flow of current must increase to keep the charge constant in the capacitor.

$$Q = V \times C \text{ (joules)}$$

$$Q = I \times t \text{ (joules)}$$



It follows that the current flowing through a capacitor is proportional to:

a) Size of the capacitor in microfarads (µF)
b) The voltage applied to the capacitor (V_C)
c) The frequency (f).

The energy stored in a capacitor is calculated by the formula:

$$\mathbf{Energy\ stored, Q = \frac{1}{2}. C. V^2 (joules)}$$

EXAMPLE
Calculate the capacitive reactance and current that will flow, to each of the following capacitors, when connected to a 230 volt supply at:

a) 50Hz

b) 200Hz

for the following capacitors:

(i) 2μF

(ii) 8μF

(iii) 16μF

a) **At 50Hz**

i)

$$X_C = \frac{1}{2\pi fC}$$

$$= \frac{1}{2 \times 3.14 \times 50 \times 2 \times 10^{-6}}$$

$$= 1592\Omega$$

$$I = \frac{V}{X_C}$$

$$= \frac{230}{1592}$$

$$= \underline{0.14A}$$

ii)

$$X_C = \frac{1}{2\pi fC}$$

$$= \frac{1}{2 \times 3.14 \times 50 \times 8 \times 10^{-6}}$$

$$= 398\Omega$$

$$I = \frac{V}{X_C}$$

$$= \frac{230}{398}$$

$$= \underline{0.58A}$$

iii)

$$\begin{aligned} X_C &= \frac{1}{2\pi fC} \\ &= \frac{1}{2 \times 3.14 \times 50 \times 16 \times 10^{-6}} \\ &= 199\Omega \\ \mathbf{I} &= \frac{\mathbf{V}}{\mathbf{X_C}} \\ &= \frac{230}{199} \\ &= \underline{1.16\mathrm{A}} \end{aligned}$$

b) **<u>At 200Hz</u>**

i)

$$\begin{aligned} X_C &= \frac{1}{2\pi fC} \\ &= \frac{1}{2 \times 3.14 \times 200 \times 2 \times 10^{-6}} \\ &= 398\Omega \\ \mathbf{I} &= \frac{\mathbf{V}}{\mathbf{X_C}} \\ &= \frac{230}{398} \\ &= \underline{0.58\mathrm{A}} \end{aligned}$$

ii)

$$\begin{aligned} X_C &= \frac{1}{2\pi fC} \\ &= \frac{1}{2 \times 3.14 \times 200 \times 8 \times 10^{-6}} \\ &= 100\Omega \\ \mathbf{I} &= \frac{\mathbf{V}}{\mathbf{X_C}} \\ &= \frac{230}{100} \\ &= \underline{2.3\mathrm{A}} \end{aligned}$$

iii)

$$X_C = \frac{1}{2\pi fC}$$

$$= \frac{1}{2 \times 3.14 \times 200 \times 16 \times 10^{-6}}$$

$$= 50\Omega$$

$$I = \frac{V}{X_C}$$

$$= \frac{230}{50}$$

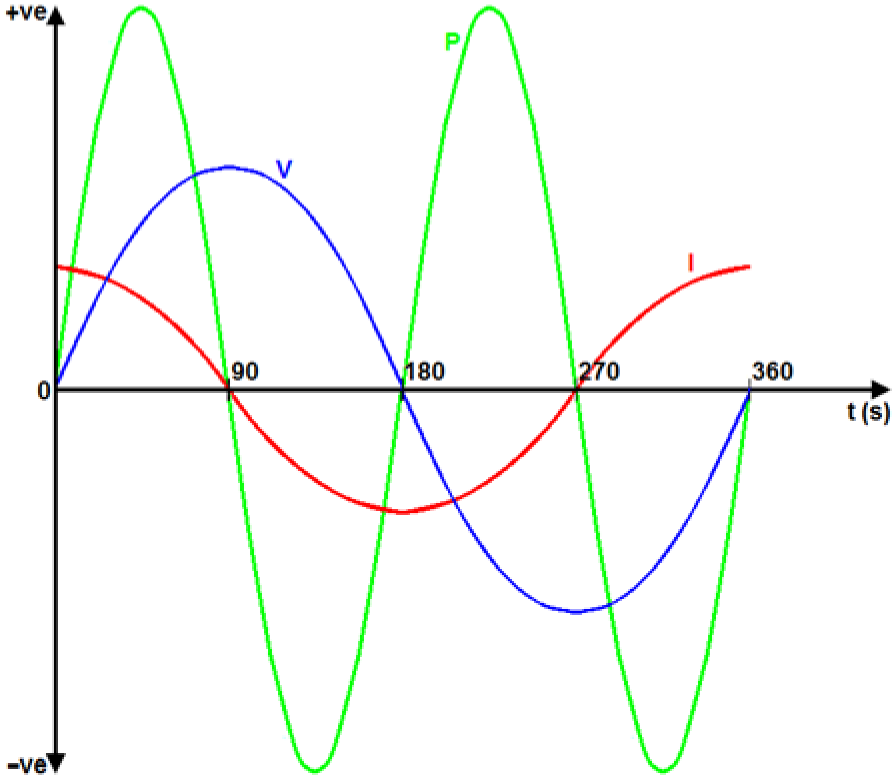
$$= \underline{4.6A}$$

It can be seen from the above examples that the capacitive reactance decreases proportionally with an increase in frequency and capacitance, but the current increases proportionally with both.

A capacitor consumes no power at all; it is a wattless component. Since it is basically an open circuit, ie infinite resistance, then no current will flow, and therefore:

$$\boxed{P = I^2R \text{ therefore } P = \text{zero watts}}$$

If we use the simple expression for power as we have previously done (V × I), then we can see that any power drawn from the supply during part of the cycle, is given back during the next part of the cycle.



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Worksheet 3: Capacitance in an AC circuit

Using your notes answer the following questions. Use π = 3.14.

1. Calculate the current that will flow in the circuit, when a capacitor of 25μf is connected across a 400v 60Hz supply.

2. Calculate the current that will flow in the circuit, when a capacitor of 40μf is connected across a 100v 40Hz supply.

3. Calculate the current that will flow in the circuit, when a capacitor of 60μf is connected across a 230v 50Hz supply.

4. Calculate the size of capacitor that causes a current of 2A to flow when it is connected across a 480v 50Hz supply.

5. Calculate the size of capacitor that causes a current of 4A to flow when it is connected across a 300v 60Hz supply.

6. Calculate the size of capacitor that causes a current of 5A to flow when it is connected across a 400v 50Hz supply.

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Handout 4: Impedance in an AC circuit

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

The learner can:

2.1 explain the relationship between resistance, inductance, capacitance and impedance currents.
2.2 determine **electrical quantities** in alternating current circuits
2.4 calculate power factor

Range

Electrical quantities: resistance, inductance, inductive reactance, capacitance, capacitive reactance, impedance.

Impedance in an AC circuit

In circuits where there is more than one component, we must find the total opposition (Ω) of the circuit before the amount of current flowing can be found.

In an AC circuit the total opposition to current flow is called the **Impedance** and the symbol for it is '**Z**. The total opposition is measured in **Ohms** (Ω).

Impedance is the name given to the combined effect of resistance (R) and inductive reactance (X_L) or capacitive reactance (X_C) and is measured in ohms (Ω).

Because the current and voltage are in phase in a resistor, but with the current lagging the voltage in an inductor and the current leading the voltage in a capacitor, we cannot simply add these values together.

The Impedance is calculated by adding the phasors of the resistance and reactance(s) together, ie the phasor sum of the reactances and resistances.

For series circuits, impedance (Z) is calculated by one of the formulae given below:

$$\mathbf{Inductive\ circuits, Z = \sqrt{R^2 + {X_L}^2}}$$

$$\mathbf{Capacitive\ circuits, Z = \sqrt{R^2 + {X_C}^2}}$$

$$\mathbf{Combined\ circuits, Z = \sqrt{R^2 + (X_L - X_C)^2}}$$

With the last formula, whichever is the larger (X_L or X_C) is put first, ie ($X_L – X_C$) or ($X_C – X_L$) respectively. This formula is based on **Pythagoras' Theorem**.

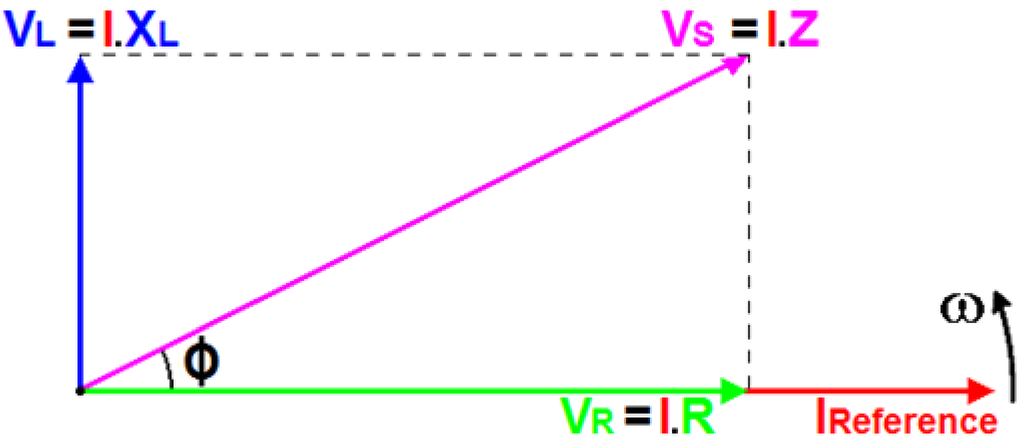
The current in any ac circuit may be found by first finding the impedance of the circuit (Z) and then by dividing V by Z.

$$\mathbf{I = \frac{V}{Z}}$$

A coil will always have both resistance and inductance and although they cannot be physically separated, it is convenient for the purpose of calculating impedance etc to show them as separate in circuit diagrams.

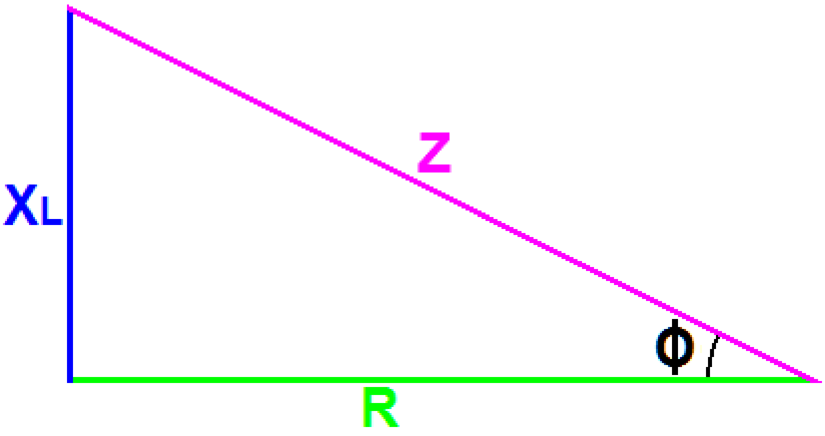
Impedance triangles

If we draw the phasor diagram for a circuit containing resistance and inductance, it will look like the phasor diagram shown immediately below:

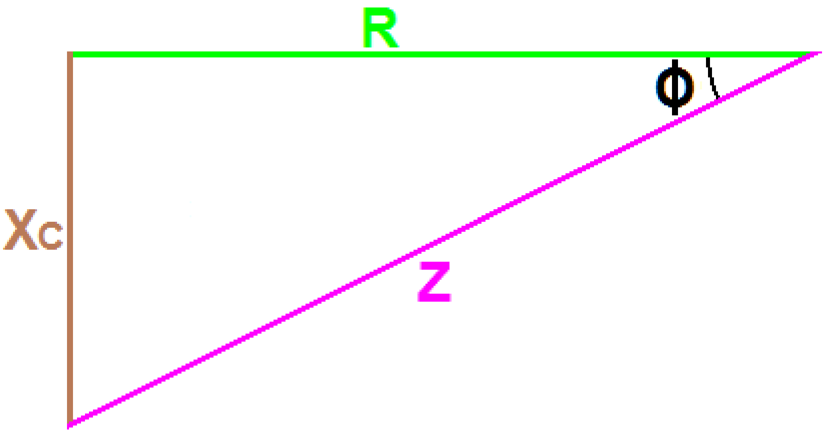


Since I is present in each term, if we divide each term by I, we get what is known as the **IMPEDANCE TRIANGLE**:

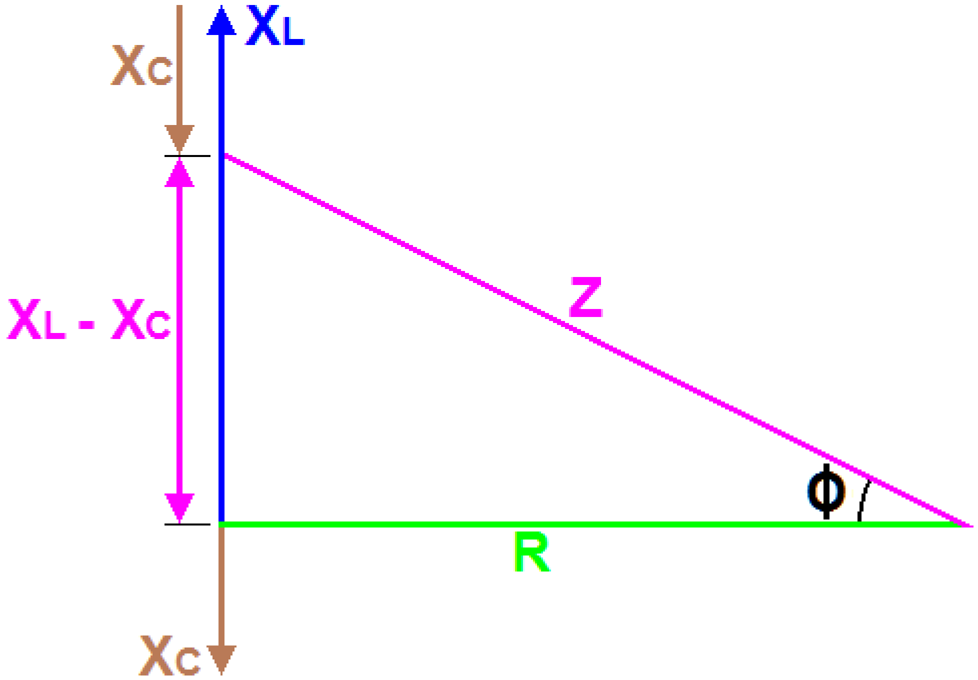
For a circuit containing R and X_L



For a circuit containing R and X_C



For a circuit containing R, X_L and X_C



The phase angle of the circuit is the difference between the applied voltage and the supply current.

The power factor of the circuit is the cosine of the phase angle, ie cos Φ = pf

The power factor of any circuit can always be found from the formula:

$$\mathrm{pf} = \frac{R}{Z}$$

$$\cos\Phi = \frac{R}{Z}$$

$$\cos\Phi = \mathrm{pf}$$

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Worksheet 4: Impedance in an AC circuit

Using your notes, answer the following questions.

1. Calculate the impedance (Z) when an inductor with an inductive reactance (X_L) of 30Ω is connected in a circuit with a resistance (R) of 40Ω.

2. Calculate the power factor and the phase angle difference for the arrangement in question 1.

3. Calculate the impedance (Z) when a conductor with a capacitive reactance (X_C) of 65Ω is connected in a circuit with a resistance (R) of 100Ω.

4. Calculate the power factor and the phase angle difference for the arrangement in question 3.

5. Calculate the impedance (Z) when an inductor with an inductive reactance (X_L) of 100Ω is connected in a circuit with a capacitive reactance (X_C) of 30Ω and a resistance (R) of 50Ω.

6. Calculate the power factor and the phase angle difference for the arrangement in question 5.

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Handout 5: Resistance and inductance in series

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

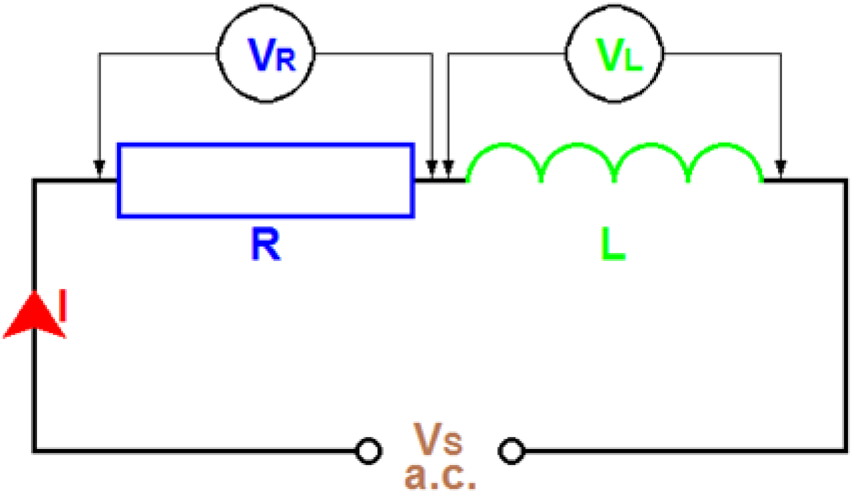
The learner can:

2.1 explain the relationship between resistance, inductance, capacitance and impedance currents.
2.2 determine **electrical quantities** in alternating current circuits
2.4 calculate power factor

Range

Electrical quantities: Resistance, Inductance, Inductive reactance, Capacitance, Capacitive reactance, Impedance.

Resistance and inductance in series



In the circuit shown above, the supply voltage will cause a current to flow in the circuit as shown. The current flowing through the components in the circuit will cause a volt drop across each component.

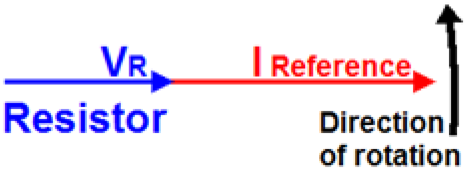
The voltage across the resistor will be in phase with the current, whilst the voltage across the inductor will be out of phase with the current for the reason previously explained.

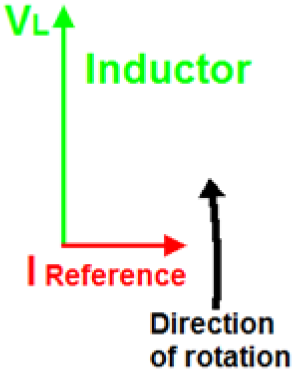
The voltage will be 90° leading the current in the inductor, or it can be said that the current lags the voltage by 90°.

Since these voltages are out of phase with each other, the supply voltage **cannot** be calculated by simple arithmetic means. This can only be done using Pythagoras' theorem.

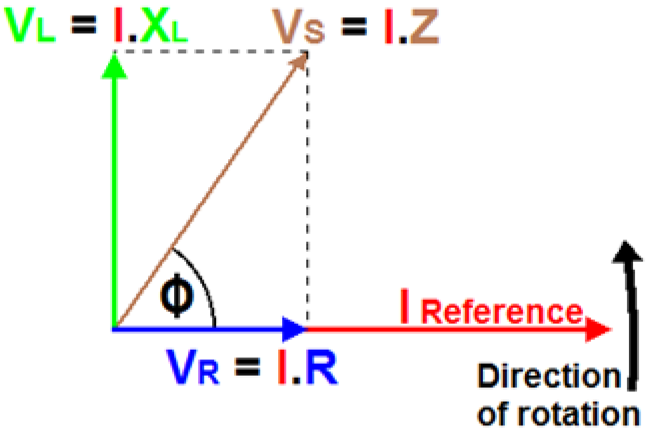
Phasor diagrams

Since I is the same in all components it must be used as the reference phasor.





Superimposing the phasors on each other, we will get the phasor diagram shown below, from which the supply voltage and phase angle of the circuit can be calculated.



$$\mathrm{V_S} = \sqrt{\mathrm{V_R^2} + \mathrm{V_L^2}}$$

$$\cos\Phi = \frac{\text{Adjacent}}{\text{Hypotenuse}}$$

$$= \frac{\mathrm{V_R}}{\mathrm{V_S}}$$

$$= \text{Power factor (pf)}$$

$$\cos^{-1}\frac{\mathrm{A}}{\mathrm{H}} = \text{Angle in degrees}$$

It can be seen that the current lags the supply voltage by some angle Φ. This angle is called the **PHASE ANGLE**. The larger the resistance the smaller is the angle.

$$\text{Power factor} = \frac{R}{Z}$$

$$\cos\Phi = \text{pf} = \frac{\mathrm{V_R}}{\mathrm{V_S}}$$

$$\cos^{-1}\text{pf} = \text{Angle in degrees}$$

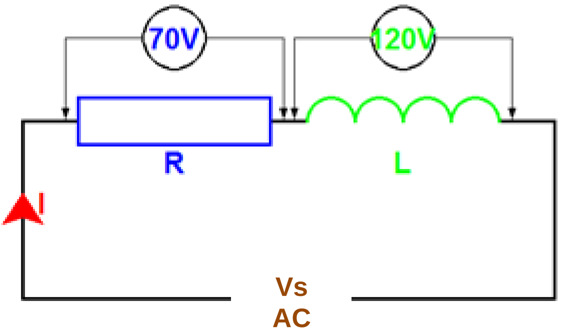
Example 1

If the voltages across V_R and V_L are 70V and 120V respectively:

a) Calculate the supply voltage.

b) Calculate the phase angle of the circuit.

c) Sketch the phasor diagram.



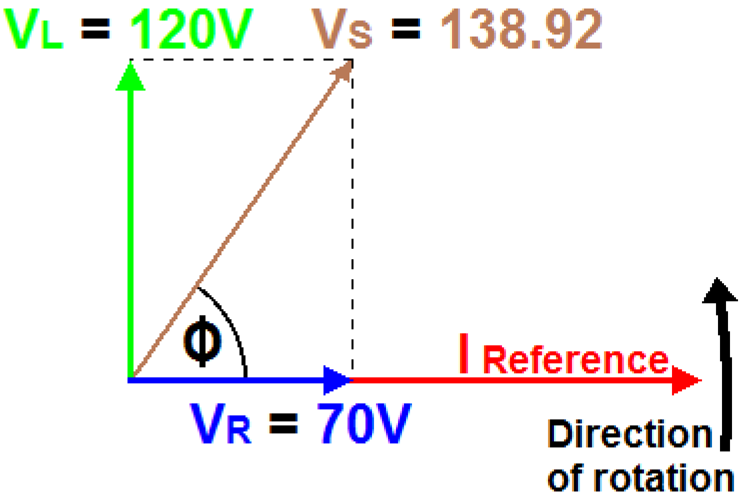
a)

$$\begin{aligned} V_s &= \sqrt{V_R^2 + V_L^2} \\ &= \sqrt{70^2 + 120^2} \\ &= \sqrt{19300} \\ &= \underline{138.92\ \text{volts}} \end{aligned}$$

b)

$$\begin{aligned} \cos\Phi &= \frac{V_R}{V_S} \\ &= \frac{70}{138.92} \\ &= 0.5039\ \text{lagging} \quad \text{(because it is an inductive circuit)} \\ \cos^{-1} 0.5039 &= \underline{59.74°\ \text{lagging}} \end{aligned}$$

c)



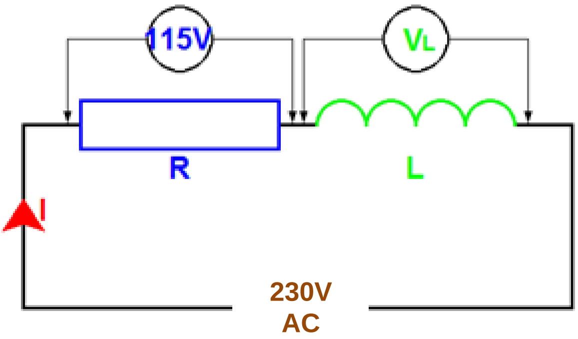
Example 2

An inductor and a resistor are connected in series across a 230V 50Hz supply. If the voltage across the resistance is 115V:

a) Calculate the voltage across the inductor (V_L).

b) Calculate the phase angle of the circuit.

c) Draw the phasor diagram with all the relevant information on it.



a)

$$\text{Transposing } V_s = \sqrt{V_R^2 + V_L^2}$$

$$V_L = \sqrt{V_S^2 - V_R^2}$$

$$= \sqrt{230^2 - 115^2}$$

$$= \sqrt{39675}$$

$$= \underline{199 \text{ volts}}$$

b)

$$\cos \Phi = \frac{V_R}{V_S}$$

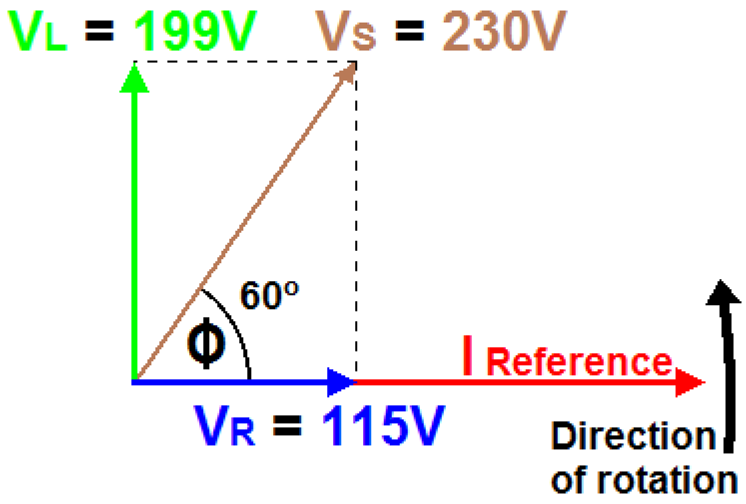
$$= \frac{115}{230}$$

$$= 0.5 \text{ lagging}$$

(because it is an inductive circuit)

$$\cos^{-1} 0.5 = \underline{60° \text{ lagging}}$$

c)



Example 3

A circuit supplied at 230V 50Hz consists of a resistor of 25Ω and an inductor of 0.05H connected in series. Calculate:

a) The impedance of the circuit.
b) The phase angle of the current.
c) The current flowing in the circuit.
d) The voltage across each component.
e) The power consumed by the circuit.

a)

$$\begin{aligned} X_L &= 2\pi f L \\ &= 2 \times 3.14 \times 50 \times 0.05 \\ &= 15.7\Omega \\ Z &= \sqrt{R^2 + X_L^2} \\ &= \sqrt{25^2 + 15.7^2} \\ &= \sqrt{871.5} \\ &= \underline{29.5\Omega} \end{aligned}$$

b)

$$\begin{aligned} \cos\Phi &= \frac{R}{Z} \\ &= \frac{25}{29.5} \\ &= 0.85 \text{ lagging} \\ \cos^{-1} 0.85 &= \underline{31.1^\circ \text{ lagging}} \end{aligned}$$

c)

$$\begin{aligned} I &= \frac{V}{Z} \\ &= \frac{230}{29.5} \\ &= \underline{7.8A} \end{aligned}$$

d)

$$\begin{aligned} \text{V across inductor}, V_L &= I \times X_L \\ &= 7.8 \times 15.7 \\ &= \underline{122.5V} \\ \text{V across resistor}, V_R &= I \times R \\ &= 7.8 \times 25 \\ &= \underline{195V} \end{aligned}$$

e)

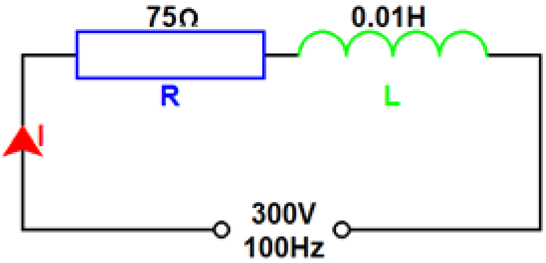
$$\begin{aligned} \text{Power} &= I^2 R \\ &= 7.8^2 \times 25 \\ &= \underline{1521 \text{ watts (or } 1.521\text{kW)}} \end{aligned}$$

Unit 302: Principles of electrical science

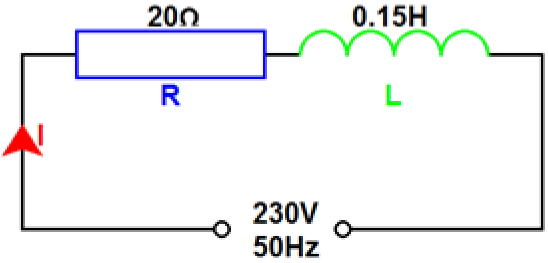
Worksheet 5: Resistance and inductance in series

Using your notes answer the following questions. Take π as 3.14

1. For the arrangement in the diagram right calculate:
   a) the impedance of the circuit
   b) the phase angle of the current
   c) the current flowing in the circuit
   d) the voltage across each component
   e) the power consumed by the circuit



2. For the arrangement in the diagram right calculate:
   - a) the impedance of the circuit
   - b) the phase angle of the current
   - c) the current flowing in the circuit
   - d) the voltage across each component
   - e) the power consumed by the circuit



302: Principles of electrical science

Handout 6: Resistance and capacitance in series

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

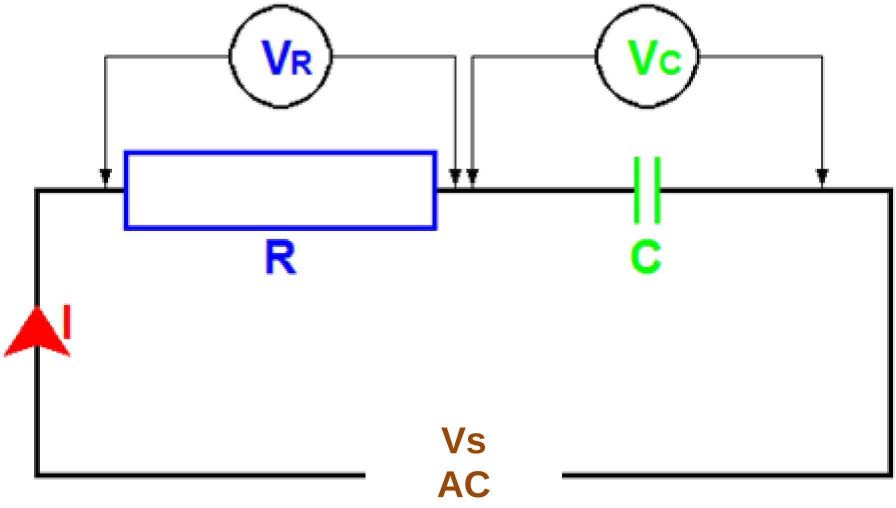
The learner can:

2.1 explain the relationship between resistance, inductance, capacitance and impedance currents.
2.2 determine **electrical quantities** in alternating current circuits
2.4 calculate power factor

Range

Electrical quantities: resistance, inductance, inductive reactance, capacitance, capacitive reactance, impedance.

Resistance and capacitance in series



In the circuit above the supply voltage will cause a current to flow in the circuit as shown. This current will cause a volt drop across each component in the circuit.

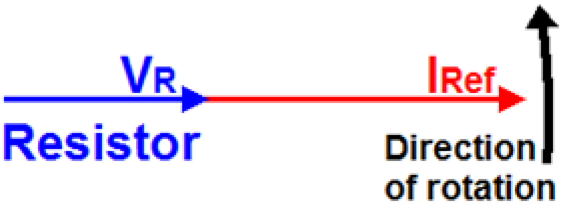
The voltage across the resistor will be in phase with the current whilst the voltage across the capacitor will be out of phase with the current.

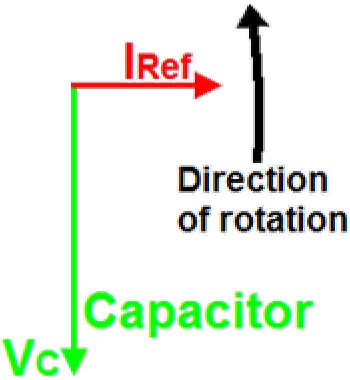
The capacitor voltage will be 90° lagging the current in the capacitor, or it can be said that the current leads by 90°.

Since these voltages are out of phase with each other, the supply voltage **cannot** be calculated by simple arithmetic means. This can only be done by Pythagoras' theorem (Phasor addition).

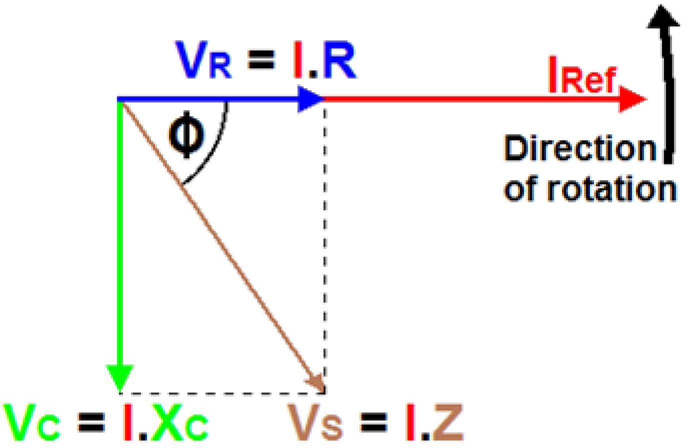
Phasor diagrams

Since I is the same in all components it must be used as the reference phasor.





Superimposing the phasors on each other, we will get the phasor diagram shown below, from which the supply voltage and phase angle of the circuit can be calculated.



$$V_S = \sqrt{V_R^2 + V_C^2}$$

$$\cos\Phi = \frac{\text{Adjacent}}{\text{Hypotenuse}}$$

$$= \frac{V_R}{V_S}$$

$$= \text{Power factor (pf)}$$

$$\cos^{-1} A/H = \text{Angle in degrees}$$

It can be seen that the current lags the supply voltage by some angle Φ. This angle is called the **PHASE ANGLE**. The larger the resistance the smaller is the angle.

$$\text{Power factor} = \frac{R}{Z}$$

$$\cos\Phi = \text{pf} = \frac{V_R}{V_S}$$

$$\cos^{-1}\text{pf} = \text{Angle in degrees}$$

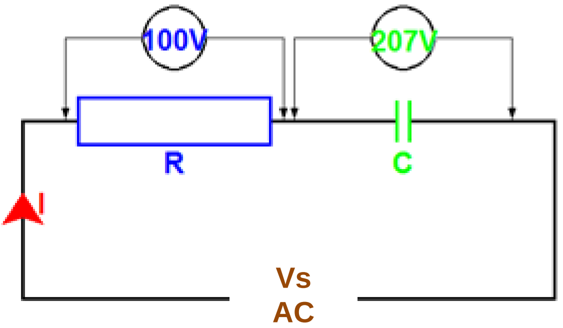
Example 1

A capacitor and a resistor are connected in series across an ac supply. If the voltages across the capacitor and resistor are 207V and 100V respectively,

a) Calculate:

- (i) The supply voltage.
- (ii) The phase angle.

b) Sketch the phasor diagram.



a)

$$V_s = \sqrt{V_R^2 + V_C^2}$$

$$= \sqrt{100^2 + 207^2}$$

$$= \sqrt{52849}$$

$$= \underline{230 \text{ volts}}$$

b)

$$\cos \Phi = \frac{V_C}{V_S}$$

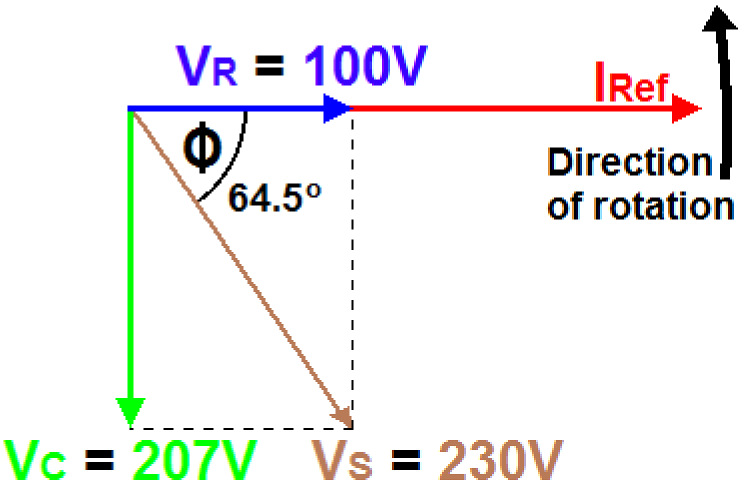
$$= \frac{100}{230}$$

$$= 0.43 \text{ leading}$$

(because it is a capacitive circuit)

$$\cos^{-1} 0.43 = \underline{64.5° \text{ leading}}$$

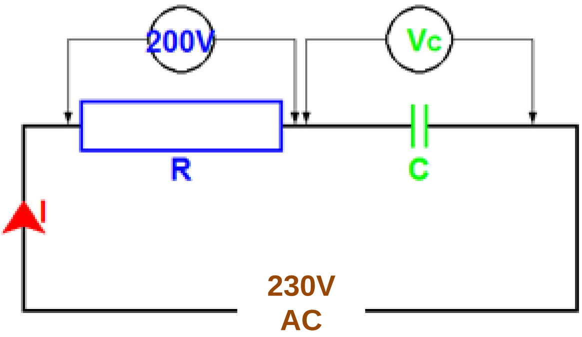
c)



Example 2

A resistor and capacitor are connected in series across a 230V 50Hz supply. If the voltage across the resistor is 200V, calculate:

a) The voltage across the capacitor (V_C).
b) Phase angle of the circuit.
c) Draw the phasor diagram with all the relevant information on it.



a)

$$\text{Transposing } V_s = \sqrt{V_R^2 + V_C^2}$$

$$V_C = \sqrt{V_S^2 - V_R^2}$$

$$= \sqrt{230^2 - 200^2}$$

$$= \sqrt{12900}$$

$$= \underline{114 \text{ volts}}$$

b)

$$\cos \Phi = \frac{V_R}{V_S}$$

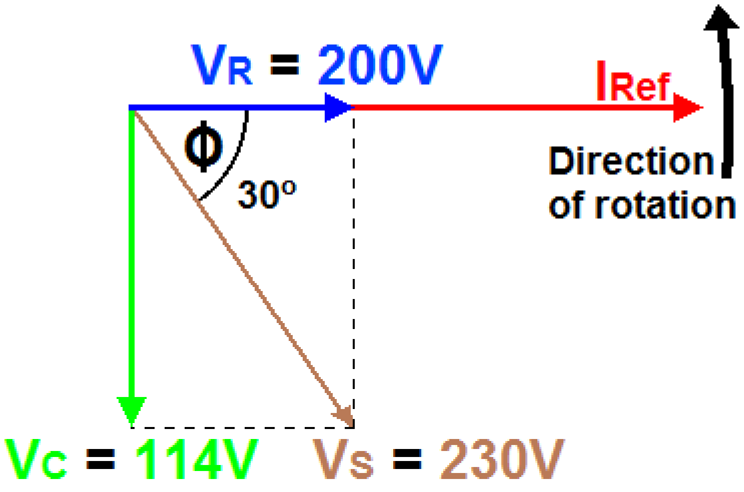
$$= \frac{200}{230}$$

$$= 0.87 \text{ leading}$$

(because it is a capacitive circuit)

$$\cos^{-1} 0.87 = \underline{30° \text{ leading}}$$

c)



Example 3

A 31.9μF capacitor is connected in series with a 60Ω resistor across a 230V 50H supply.
Calculate:

a) The impedance of the circuit
b) The phase angle of the current
c) The current flowing in the circuit
d) The voltage across each component
e) The power consumed by the circuit.

a)

$$\begin{aligned} X_C &= \frac{1}{2\pi f C} \\ &= \frac{1}{2 \times \pi \times 50 \times 31.9 \times 10^{-6}} \\ &= 100\Omega \\ Z &= \sqrt{R^2 + X_C^2} \\ &= \sqrt{60^2 + 100^2} \\ &= \sqrt{13600} \\ &= \underline{116.6\Omega} \end{aligned}$$

b)

$$\begin{aligned} \cos\Phi &= \frac{R}{Z} \\ &= \frac{60}{116.6} \\ &= 0.52 \text{ leading} \\ \cos^{-1} 0.52 &= \underline{59^\circ \text{ leading}} \end{aligned}$$

c)

$$\begin{aligned} I &= \frac{V}{Z} \\ &= \frac{230}{116.6} \\ &= \underline{1.97A} \end{aligned}$$

d)

$$\begin{aligned} \text{V across capacitor, } V_C &= I \times X_C \\ &= 1.97 \times 100 \\ &= \underline{197V} \\ \text{V across resistor, } V_R &= I \times R \\ &= 1.97 \times 60 \\ &= \underline{118V} \end{aligned}$$

e)

$$\begin{aligned} \text{Power} &= I^2 R \\ &= 1.97^2 \times 60 \\ &= \underline{233 \text{ watts}} \end{aligned}$$

Unit 302: Principles of electrical science

Worksheet 6: Resistance and capacitance in series

Using your notes answer the following questions. Take π as 3.14

1. A resistance of 80Ω is connected in series with a capacitor of 20μF across a 230V 50Hz supply. Calculate:
   - **a)** the impedance of the circuit
   - **b)** the phase angle of the current
   - **c)** the current flowing in the circuit
   - **d)** the voltage across each component
   - **e)** the power consumed by the circuit

2. A resistor of 30Ω and a capacitor of 79.58μF are connected in series across a 250V 50Hz supply. Calculate:
   a) the impedance of the circuit
   b) the phase angle of the current
   c) the current flowing in the circuit
   d) the voltage across each component
   e) the power consumed by the circuit

3. A resistor and a capacitor are connected in series across a 50Hz AC supply and a current of 0.4139A is flowing. If the voltages across the resistor and capacitor respectively are 66.22V & 87.83V, calculate:
   a) the supply voltage
   b) the value of the resistor
   c) the value of the capacitor
   d) the power factor of the circuit

302: Principles of electrical science

Handout 7: AC Power

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

The learner can:

2.3 explain the relationship between kW, kVAr, kVA and power factor
2.4 calculate power factor

AC Power

Power is the rate of doing work, measured in watts and represented by the letter P.

The electric power in watts produced by an electric current I, consisting of a charge of Q coulombs every t seconds passing through an electric potential (voltage) difference of V is:

$$P = \text{Work done per unit time}$$

$$P = \frac{QV}{t}$$

$$I = \frac{Q}{t}$$

$$\therefore \quad P = IV$$

This applies to DC circuits but what happens with AC circuits?

If we have a purely resistive load connected to an AC supply, the power produced is known as the **true power**. It is the power that performs work in the circuit and it is measured in Watts (W) or, for larger values, **kilowatts (kW)**. This is the power that will drive a piece of equipment, eg a motor. It is the desired outcome of an electrical system.

We know that reactive loads such as inductors and capacitors dissipate zero power, yet the fact that they drop voltage and draw current gives the deceptive impression that they actually do dissipate power. This 'phantom power' is called **reactive power** and it is measured in a unit called volt-amps-reactive (VAr) or, for larger values, **kilovolt-amps-reactive (kVAr)** rather than watts or kilowatts.

A capacitor will cause the current to lead the voltage and an inductor will cause the current to lag the voltage, by 90° in both cases. The resulting power will have a value of zero every time the voltage or current has a zero value, since the two quantities are multiplied to get power.

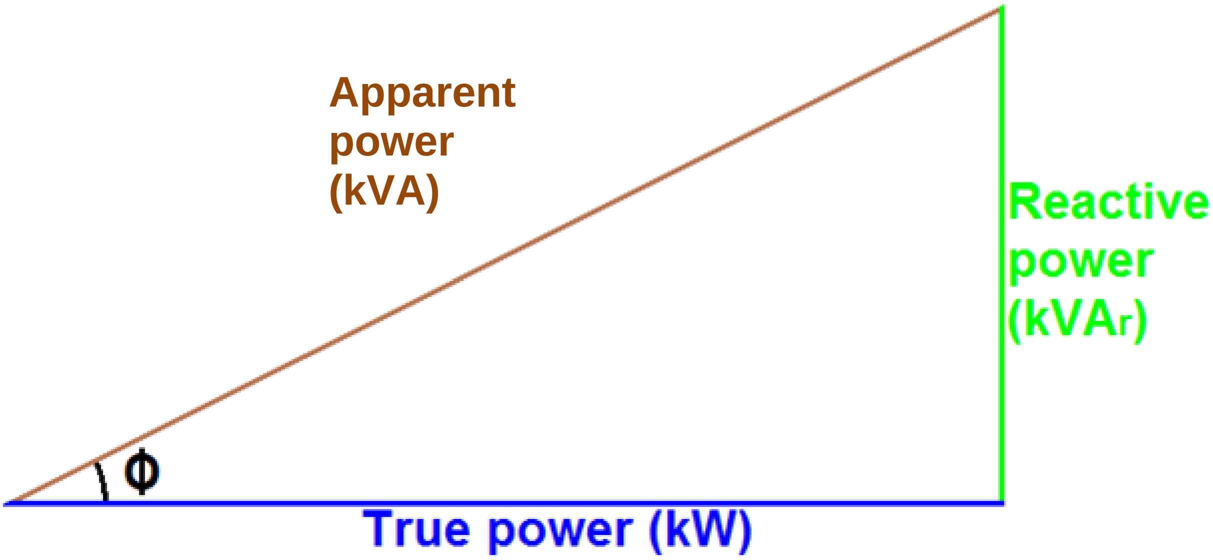
This is not a desirable model because although the source is generating power, no work is being done at the load. This type of power is known as 'reactive' power because it counteracts the effects of true power.

Reactive power is the lazy brother of true power. True power is doing all the work, while reactive power is actually taking away from the power in the system making the true power work harder to get the job done. A capacitive load will introduce negative reactive power and the voltage 'lags' the current waveform by 90°. An inductive load will introduce positive reactive power and the voltage leads the current waveform by 90°. This is because capacitors 'generate' reactive power and inductors 'consume' reactive power.

Why are these values important?

The reason is because all practical electrical applications will contain a combination of resistive, capacitive and inductive elements. Therefore, any practical AC circuit or system will have a combination of both true and reactive power which will vary the phase angle between voltage and current.

The desired outcome is to maximize true power while limiting reactive power. Taking both into account, the end result of the tug of war battle between true and reactive power is called **apparent power**. It is measured in volt-amps (VA) or, for larger values, **kilovolt-amps (kVA)**.



- True Power: power that performs work, measured in Watts (W) or kW
- Reactive Power: power that does not perform work (sometimes called ‘wattless power’) measured in VA reactive (VAr) or kVAr.
- Apparent Power: the vector sum of the true and reactive power measured in volt amps (VA) or kVA
- Φ = phase angle. This is the angle used to describe the phase shift between the voltage and current. The larger the phase angle, the greater the reactive power generated by the system.

The relationship of these three values can be expressed as follows:

$$\textbf{Apparent power} = \sqrt{\textbf{True power}^2 + \textbf{Reactive power}^2}$$

or

$$\textbf{kVA} = \sqrt{\textbf{kW}^2 + \textbf{kVAr}^2}$$

The cosine of the angle of lag (or lead) is the power factor (pf) and can be found using the following formula:

$$\textbf{pf} = \frac{\textbf{True power}}{\textbf{Apparent power}}$$

or

$$\textbf{pf} = \frac{\textbf{kW}}{\textbf{kVA}}$$

Example 1
A particular inductive circuit produces 4kW of true power whilst producing 3kVAr of reactive power. Calculate:
a) The apparent power.
b) The power factor.

a)

$$\begin{aligned}\mathbf{kVA} &= \sqrt{\mathbf{kW}^2 + \mathbf{kVAr}^2}\\ &= \sqrt{4^2 + 3^2}\\ &= \sqrt{25}\\ &= \underline{\mathbf{5kVA}}\end{aligned}$$

b)

$$\begin{aligned}\mathbf{pf} &= \frac{\mathbf{kW}}{\mathbf{kVA}}\\ &= \frac{4}{5}\\ &= \underline{\mathbf{0.8\ lagging}}\end{aligned}$$

Example 2
A single phase AC machine draws a current of 10.87A from a 230V supply. The power factor is 0.6 lagging. Calculate:

a) The apparent power
b) The true power
c) The reactive power.

a)

$$\begin{aligned}\mathbf{kVA} &= \frac{\mathbf{I.V}}{1000}\\ &= \frac{10.87 \times 230}{1000}\\ &= \underline{\mathbf{2.5kVA}}\end{aligned}$$

b)

$$\begin{aligned}\mathbf{pf}\ (\cos\phi) &= \frac{\mathbf{kW}}{\mathbf{kVA}}\\ \mathbf{kW} &= \cos\phi \times \mathbf{kVA}\\ &= 0.6 \times 2.5\\ &= \underline{\mathbf{1.5kW}}\end{aligned}$$

c)

$$\begin{aligned}\mathbf{kVA} &= \sqrt{\mathbf{kW}^2 + \mathbf{kVAr}^2}\\ \mathbf{kVAr} &= \sqrt{\mathbf{kVA}^2 - \mathbf{kW}^2}\\ &= \sqrt{2.5^2 - 1.5^2}\\ &= \sqrt{4}\\ &= \underline{\mathbf{2kVAr}}\end{aligned}$$

Unit 302: Principles of electrical science

Worksheet 7: AC power

Using your notes answer the following questions.

A particular inductive circuit produces 6kW of true power while producing 4kVAr of reactive power. Calculate:

a) the apparent power
b) the power factor

2. A single-phase AC machine draws a current of 15A from a 400V supply. The power factor is 0.8 lagging. Calculate:

a) the apparent power
b) the true power
c) the reactive power

302: Principles of electrical science

Handout 8: Power factor correction

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

The learner can:

2.5 explain what is meant by power factor correction
2.6 specify methods of power factor correction

Power factor correction

The **power factor** of an AC electrical power system is defined as the ratio of the true power flowing to the load, to the apparent power in the circuit, and is represented by a dimensionless number between 0 and 1.

Power factor is a measure of how efficiently electrical power is consumed. In the ideal world, power factor would be unity (or 1). Unfortunately, in the real-world, power factor is reduced by highly inductive loads to 0.7 or less. This induction is caused by equipment such as lightly loaded electric motors, luminaire transformers and fluorescent lighting ballasts and welding sets, etc.

Drawback of low power factor

In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, regional electricity companies will usually charge a higher rate to industrial or commercial customers where there is a low power factor.

What causes low power factor?

Inductive loads (which are sources of reactive power) include:

- Transformers
- Induction motors
- Fluorescent luminaires.

These inductive loads constitute a major portion of the power consumed in industrial installations and cause a lagging power factor, that is, the current lags the voltage.

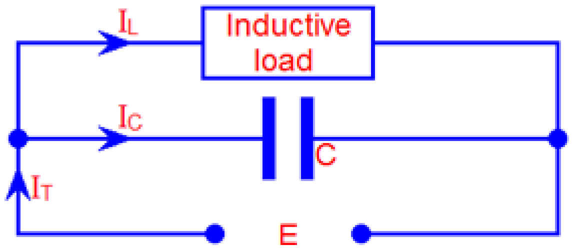
Power factor correction

To correct a lagging power factor, we connect a device that creates a leading power factor. This usually takes the form of:

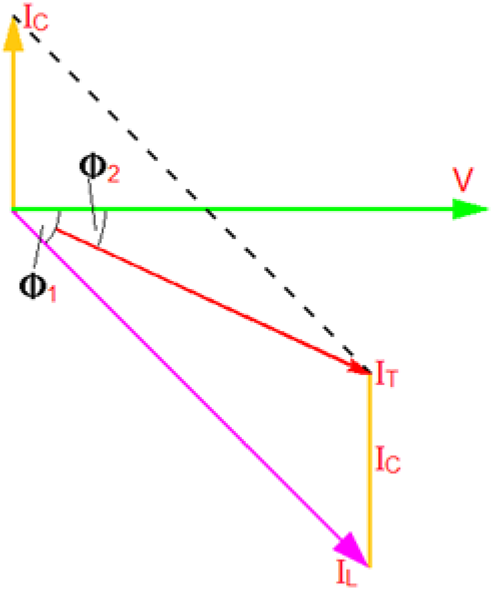
- Capacitors (load correction)
- Capacitors (bulk correction)
- Synchronous motor.

Capacitors can be connected across the whole installation at the supply (**bulk correction**) or across individual pieces of equipment (**load correction**). For example, an individual fluorescent light fitting has a capacitor connected across its incoming line and neutral terminals.

Consider an inductive load taking a current I_L lagging by a phase angle Φ from a supply of E volts. To improve the overall power factor (pf), a capacitor of C μF taking a current I_C can be connected in parallel with the load as shown below.



The phasor sum of the capacitor current I_C and the load current I_L, produces a resultant current I_T which is at a smaller phase angle and hence a better power factor (pf) than the original load current I_L.



It can be seen from the above explanation that if the power factor of a circuit is low, the amount of current required to supply a given load can be large, but by adding a capacitor in parallel, the supply current is decreased and the power factor is increased.

A LOW power factor has a LARGE angle in degrees.
A HIGH power factor has a SMALL angle in degrees.

Synchronous motors are naturally constant-speed motors. They operate in synchronism with line frequency and are commonly used where precise constant speed is required. The synchronous motor is an electric motor that is driven by an AC supply, consisting of two basic components: a stator and rotor.

Most factories and industries use very large numbers of inductive loads. These may range from fluorescent lights to high power induction motors. Thus, these inductive loads have a drastic lagging power factor. An over-excited synchronous motor (a synchronous capacitor), having a leading power factor, is used to improve the power factor of these supply systems

Unit 302: Principles of electrical science

Worksheet 8: Power factor correction

Using your notes answer the following questions.

1. Explain what is meant by the term 'power factor'.

2. Compare methods of power factor correction.

302: Principles of electrical science

Handout 9: Star-delta configurations

Learning outcome

The learner will:

2. Understand how different electrical properties can affect electrical circuits, systems and equipment.

Assessment criteria

The learner can:

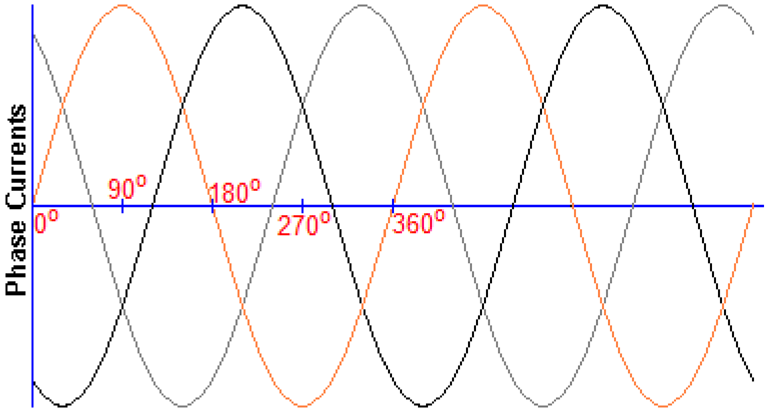
2.7 determine the neutral current in a three-phase and neutral supply and why systems should be balanced

2.8 calculate values of voltage and current in star and delta connected systems

Star-delta configurations

Three phase supplies

We have seen previously that rotating a coil in a magnetic field produces an emf and that if this emf is fed out via slip-rings then an alternating current is produced. If three separate windings are equally positioned around the rotor then three separate alternating currents will be produced, each 120° out of phase with each other as shown in the diagram below:



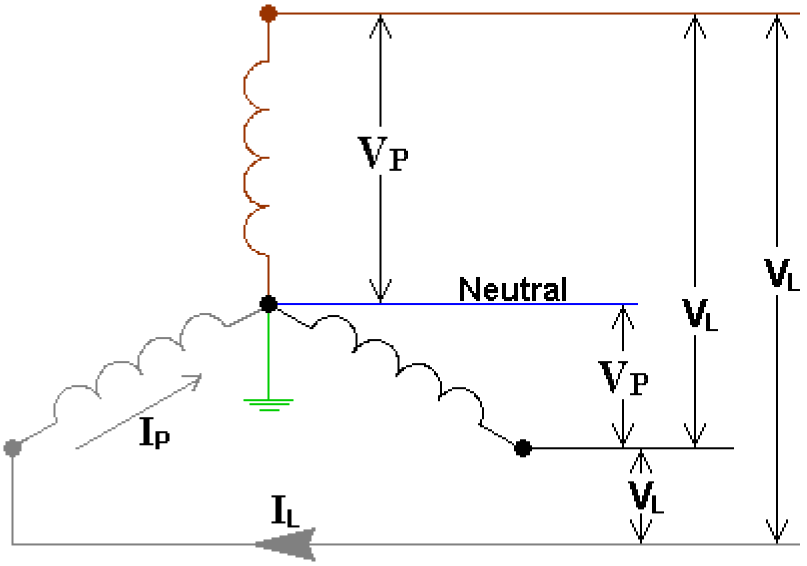
Depending on how these windings are connected together, a range of voltages are available and these can be used to power a variety of different loads.

Connection of three phase supplies

There are two main methods of connecting the phases to produce a three phase system. These are called **STAR** connection and **DELTA** connection (also known as **MESH**).

Star connection

It can be seen that this connection produces a voltage that is $\sqrt{3}$ times larger between any two connecting lines than between any line and neutral (or earth). The current in each phase coil is the same as the current in the line connected to it.



$$V_L = \sqrt{3} \times V_P \qquad \& \qquad I_L = I_P$$

Example 1

A 3 phase 4 wire star connected transformer has a line voltage of 520 volts and supplies a line current of 25 amps. Calculate:

a) The phase voltage of the transformer.

b) The phase current in each winding.

a) In star $V_L = \sqrt{3} \times V_P$

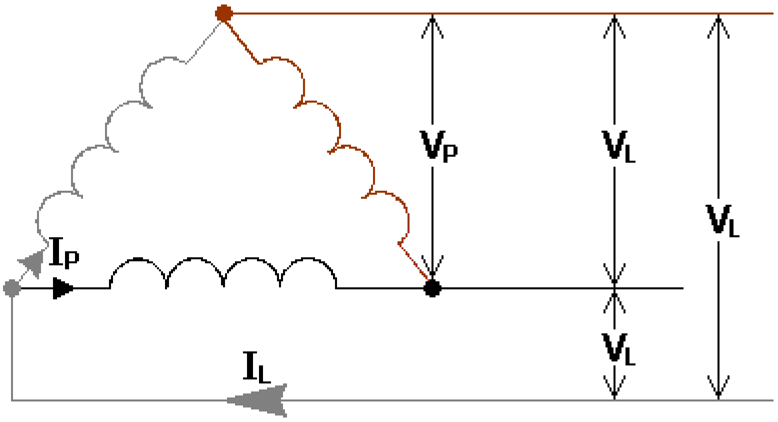
$$V_P = \frac{V_L}{\sqrt{3}} = \frac{520}{\sqrt{3}} = \underline{300 \text{ volts}}$$

b) In star $I_L = I_P$

$\therefore$ $I_P = \underline{25 \text{ amperes}}$

Delta connection

When this connection is used it can be shown that the line voltage is the same as the phase voltage and that the line current is $\sqrt{3}$ times larger than the phase current.



$$\boxed{V_L = V_P \qquad \& \qquad I_L = \sqrt{3} \times I_P}$$

Example 2
A 3 phase balanced delta connected resistive load is supplied from a transformer at a line voltage of 400 volts and draws a line current of 13.86 amps. Calculate:

a) The phase voltage.

b) The phase current.

c) The resistance of the load.

a) **In delta** $V_P = V_L$

∴ $V_P = \underline{400 \text{ volts}}$

b) **In delta** $I_L = \sqrt{3} \times I_P$

$$I_P = \frac{I_L}{\sqrt{3}}$$

$$= \frac{13.86}{\sqrt{3}}$$

$$= \underline{8 \text{ amps}}$$

c)

$$R = \frac{V_P}{I_P}$$

$$= \frac{400}{8}$$

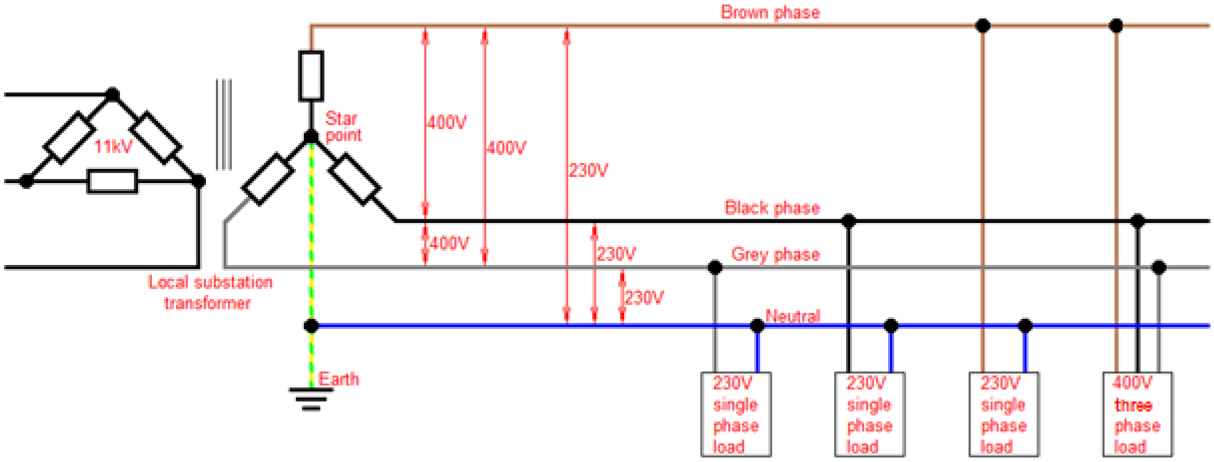
$$= \underline{50\Omega}$$

Balancing loads

All local distribution in England and Wales is by underground cables from sub-stations placed close to the load centre and supplied at 11kV. Transformers in these local sub-stations reduce the voltage to 400 volts. Three phase and neutral distributor cables connect this supply to the consumers. Connecting to one phase and neutral of a three phase 400 volt supply gives a 230 volt single phase supply suitable for domestic consumers.

When single phase loads are supplied from a three-phase supply, as shown in the diagram below, the load should be 'balanced' across the phases. That is, the load should be equally distributed across the three phases so that each phase carries approximately the same current. This prevents any one phase being overloaded.

On the standard supply system in Great Britain, the secondary of the supply transformer is connected in star as shown in the diagram below:

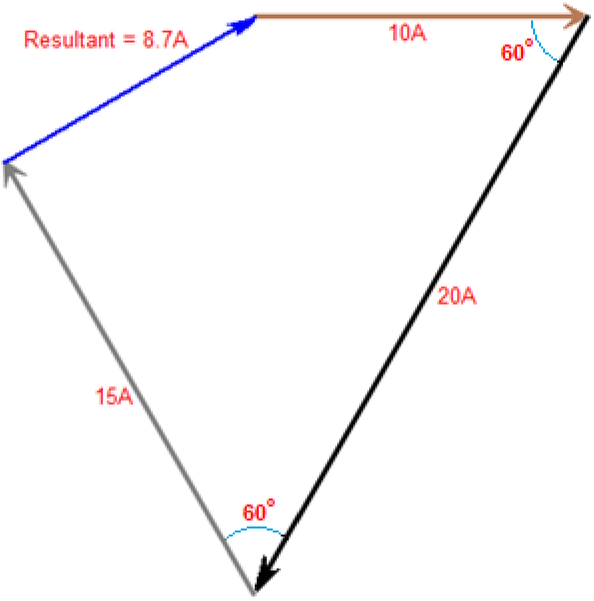


If the loads on each phase are balanced, that is, the same, then the neutral current at the supply transformer will zero; this is the ideal condition. However, if the individual phase currents are not the same, because the systems s not balanced, there will be some current flow in the neutral at the supply transformer. This neutral current can be found using a number of ways, but the simplest is to draw the three individual currents to scale in a phasor diagram.

Example 3
A 3 phase unbalanced star connected system has the following loads connected to each phase:

- Brown phase – 10 amperes
- Black phase – 20 amperes
- Grey phase – 15 amperes

Using the graphical method (phasors) determine the neutral current.



Neutral current = 8.7A

An alternative, and more accurate, method of calculating neutral current is by using the following formula:

$$\mathbf{I_n = \sqrt{((Ia^2 + Ib^2 + Ic^2) - (Ia \times Ib) - (Ib \times Ic) - (Ia \times Ic))}}$$

Where: In = neutral current

Ia = current in brown phase

Ib = current in black phase

Ic = current in grey phase

Example 4

Using the figures in example 3, calculate the neutral current.

$$\begin{aligned} \mathbf{I_n} &= \mathbf{\sqrt{((Ia^2 + Ib^2 + Ic^2) - (Ia \times Ib) - (Ib \times Ic) - (Ia \times Ic))}} \\ &= \mathbf{\sqrt{((10^2 + 20^2 + 15^2) - (10 \times 20) - (20 \times 15) - (10 \times 15))}} \\ &= \mathbf{\sqrt{(725 - 200 - 300 - 150)}} \\ &= \mathbf{\sqrt{75}} \\ &= \underline{\mathbf{8.66\ amperes}} \end{aligned}$$

Unit 302: Principles of electrical science

Worksheet 9: Star–delta configurations

Using your notes, answer the following questions.

1. A three-phase, four-wire Star connected transformer has a phase voltage of 190 volts and supplies a phase current of 10 amps. Calculate:
   a) the line voltage of the transformer
   b) the line current.

2. A three-phase balanced Delta connected resistive load is supplied from a transformer at a line voltage of 230 volts and draws a phase current of 11.5 amps. Calculate:
   a) the phase voltage
   b) the line current
   c) the resistance of the load.

3. A three-phase circuit delivers 55A on the brown phase, 2A on the black phase and 97A on the grey phase. Calculate the neutral current.

4. A three-phase circuit delivers 62A on the brown phase, 29A on the black phase and 18A on the grey phase. Calculate the neutral current.

302: Principles of electrical science

Handout 10: DC machines

Learning outcome

The learner will:

3. Understand the operating principles and applications of DC machines and AC motors.

Assessment criteria

The learner can:

3.1 state the basic types, applications and describe the operating principles of **DC machines**.

Range

DC machines: series, shunt, compound

DC machines

DC motors

It has been shown in previous studies that if a conductor carrying current is placed in a magnetic field, then a force will be exerted on to that conductor. The magnitude of that force can be calculated from the formula:

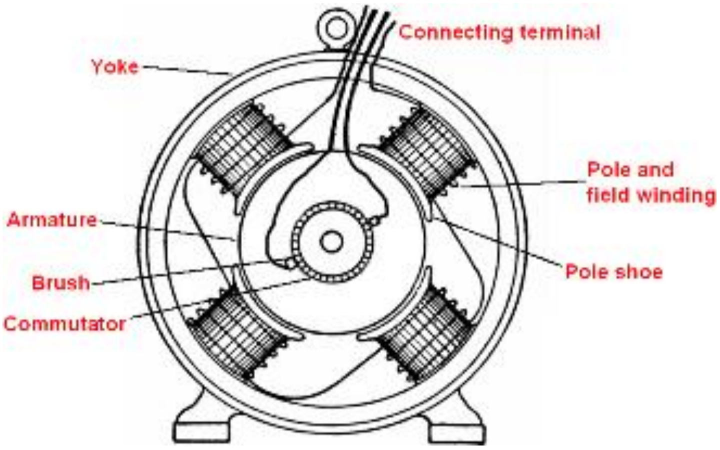
$$\mathbf{F = B \times I \times L}$$

The direction that force acts can be found by using Fleming's Left-Hand Law for motors. This is the principle of operation of all electric motors.

Generally,DC motors contain two windings as follows:

- field winding
- armature winding.

The rotating part of the machine is referred to as the **ARMATURE**. Mounted on this is the armature winding and this connected to the outside world by **BRUSHES** bearing on a commutator. The field winding is mounted in the machine body, referred to as the **FRAME** or **YOKE**, and surrounds the armature. Both of these windings will produce a magnetic field and the reaction between the two windings will produce the torque causing the armature to rotate.

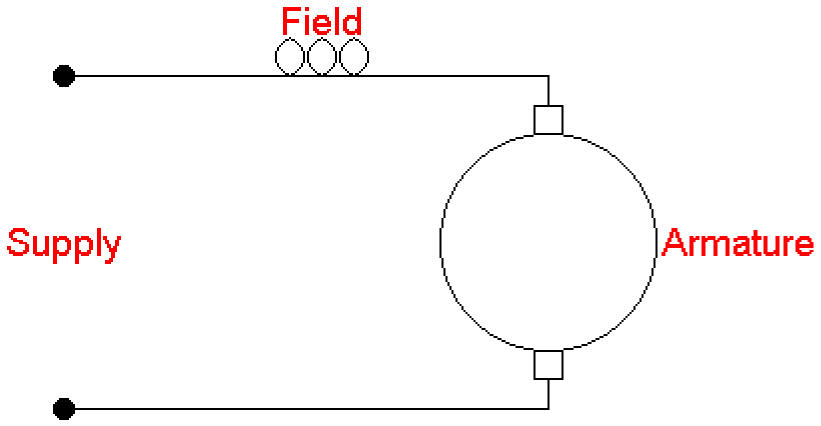


The type of DC motor is classified by how the two windings are connected together, with each type having advantages and disadvantages over the others. Three main types are:

- series wound motor
- shunt (or parallel) wound motor
- compound wound motor

Series wound motor

Because the series and armature windings are connected in series, when the machine is loaded, eg during starting, the armature draws more current. This will increase the strength of the magnetic field generated by the field winding and generate more torque.

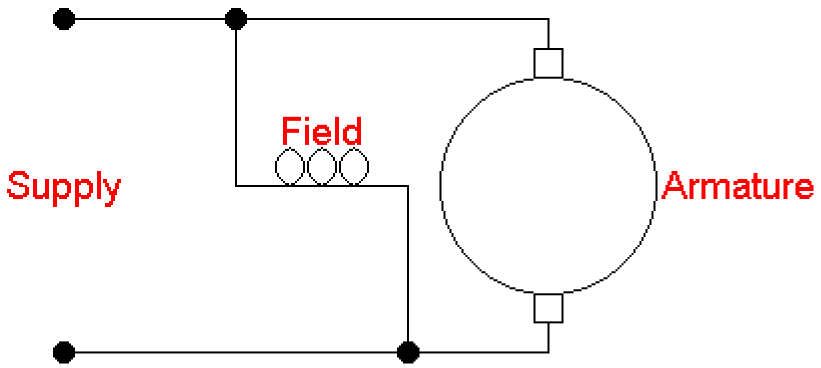


Main Characteristics

- High starting torque.
- Speed falls off as load increases (and vice versa).
- Must be started and run with load permanently connected as motor will speed up to dangerous levels off load.
- Reversal of motor can be achieved by reversing either the field or armature – NOT both.

Parallel (or shunt) wound motor

The parallel wound motor is also known as a shunt wound motor. Because the field winding is connected in parallel across the supply, it will always draw the same current irrespective of the current drawn by the armature.



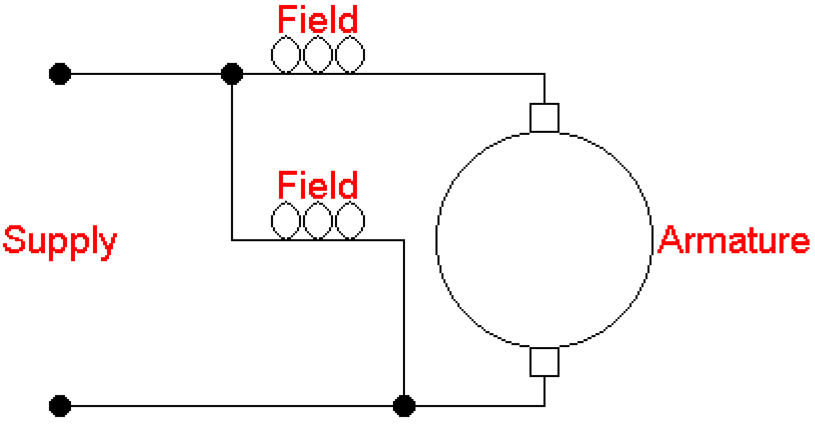
This means that regardless of the load on the shaft and hence the armature current, the speed of the armature will be relatively constant, even when the machine is not mechanically loaded. The parallel wound motor has low starting torque so is only suitable for small loads.

Main Characteristics

- Low starting torque.
- Speed falls off by only about 5% as load is increased therefore has constant speed once started.
- Start with load disconnected.
- Reversal of motor can be achieved by reversing either the field or armature – **NOT** both.

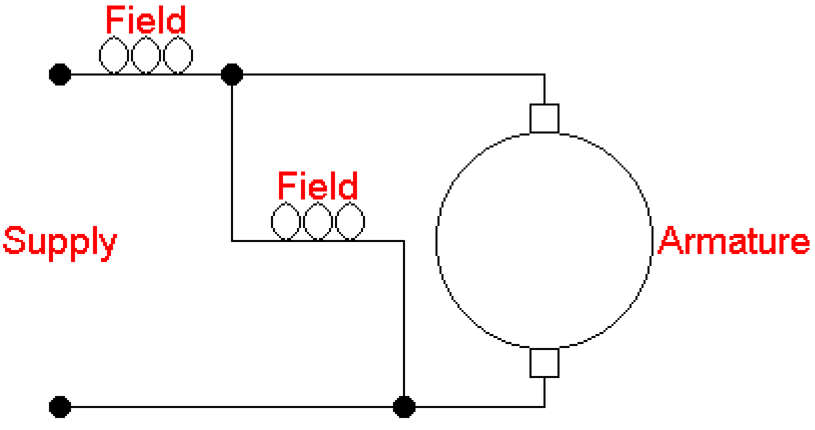
Compound wound motor

It has two field windings; one connected in series and one in parallel (shunt). A compound DC motor connects the armature and fields windings in a shunt and a series combination to give it characteristics of both a shunt and a series DC motor. This motor is used when both a high starting torque and good speed regulation is needed.



Long shunt

The motor can be connected in two arrangements depending on how the polarities of the armature and shunt field are wound: cumulatively or differentially. Cumulative compound motors connect the series field to aid the shunt field, which provides higher starting torque but less speed regulation. Differential compound DC motors have good speed regulation and are typically operated at constant speed.



Short shunt

Main Characteristics

- Good starting torque.
- Speed is almost constant under varying load conditions.
- Reversal – same as for series and shunt.

DC generators

It has been shown in previous studies that if a moving conductor cuts a magnetic field, then an emf will be produced across the ends of that conductor. The magnitude of that emf can be calculated from the formula:

$$\mathbf{E = B \times L \times V}$$

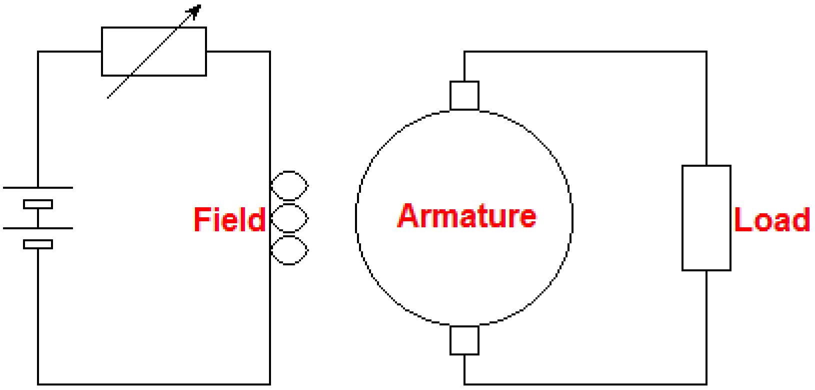
and the direction of that emf can be found by using Fleming's Right Hand Law for generators. This is the principle of operation of all electric generators.

The construction of a DC generator is much the same as a DC motor with an armature winding connected to the outside by a commutator and one or more field windings installed in the frame or yoke.

DC generators fall into two distinct categories:

- separately excited DC
- self-excited DC

A **separately excited** DC generator has its field winding supplied from an independent external DC source (eg, a battery). The voltage output depends upon the speed of rotation of the armature and the field current; the greater the speed and field current, the greater the generated emf Separately excited DC generators are rarely used in practice.



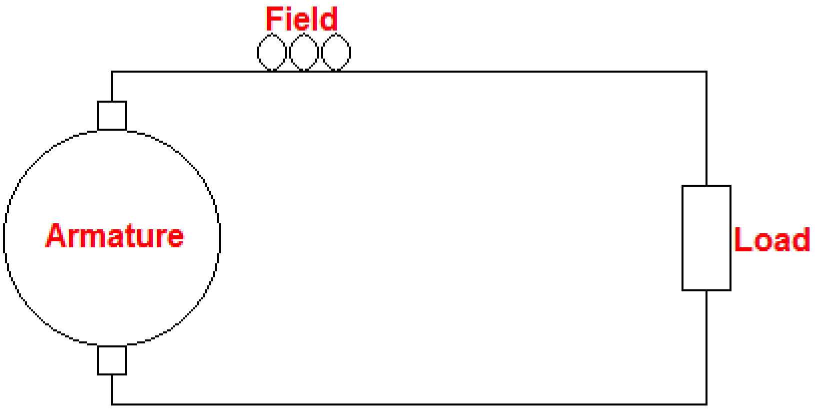
A DC generator whose field magnet winding is supplied current from the output of the generator itself is called a **self-excited** generator. There are three types of self-excited generators, depending on how the field winding is connected to the armature, namely:

- series wound generator
- shunt (or parallel) wound generator
- compound wound generator.

Series wound generator

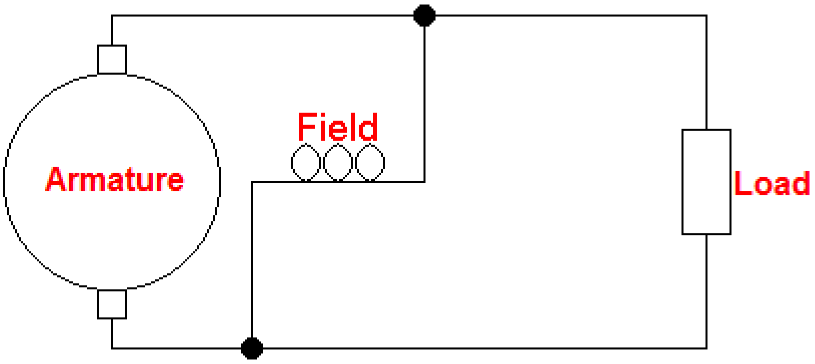
In a series wound generator, the field winding is connected in series with the armature winding so that whole armature current flows through the field winding as well as the load.

Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.



Shunt (or Parallel) wound generator

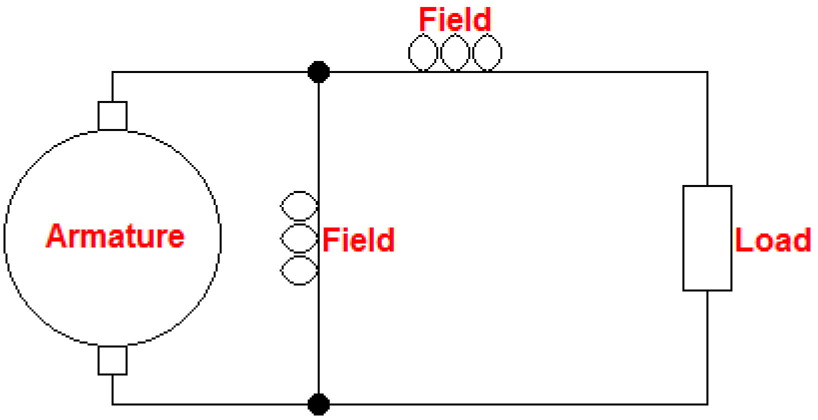
In a shunt generator, the field winding is connected in parallel with the armature winding so that the terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of the armature current flows through the shunt field winding and the rest flows through the load.

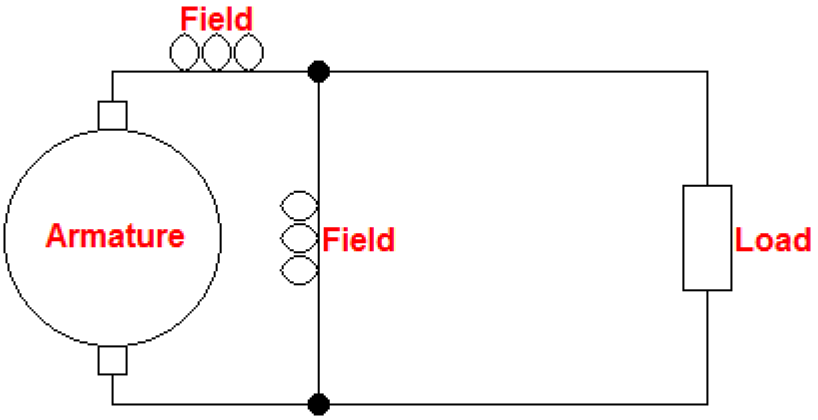


Compound wound generator

In a compound-wound generator, there are two sets of field windings on each pole — one is in series and the other in parallel with the armature. A compound wound generator may be:

- Short Shunt in which only the shunt field winding is in parallel with the armature winding.
- Long Shunt in which the shunt field winding is in parallel with both series field and armature winding.



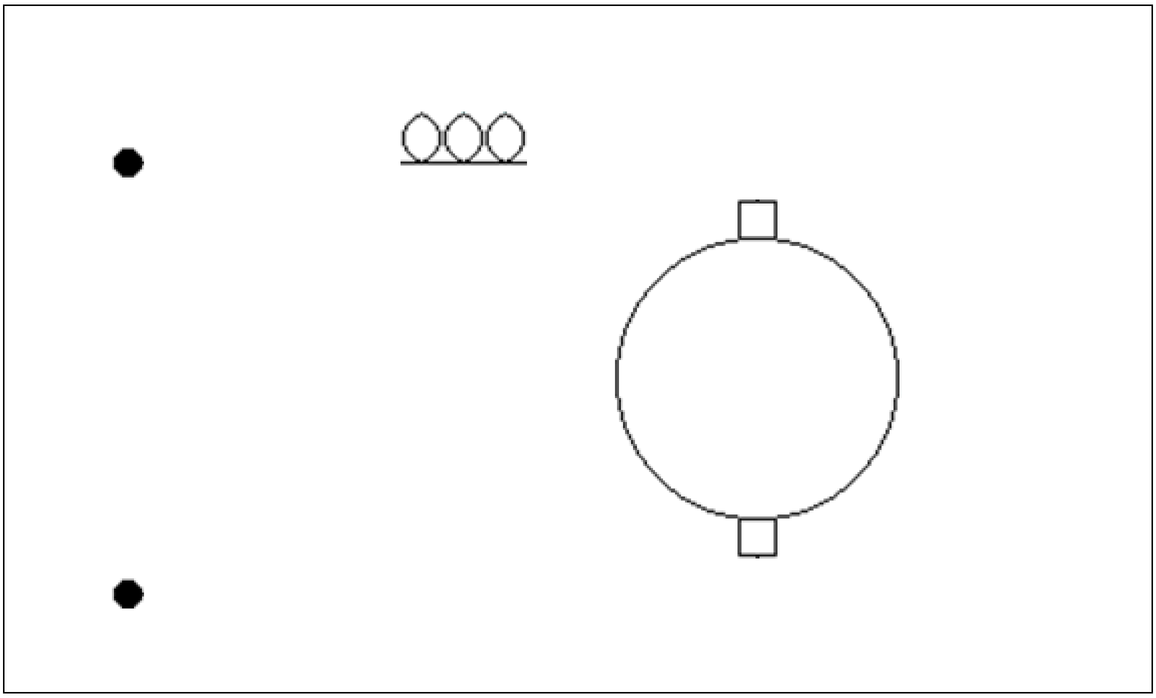


Unit 302: Principles of electrical science

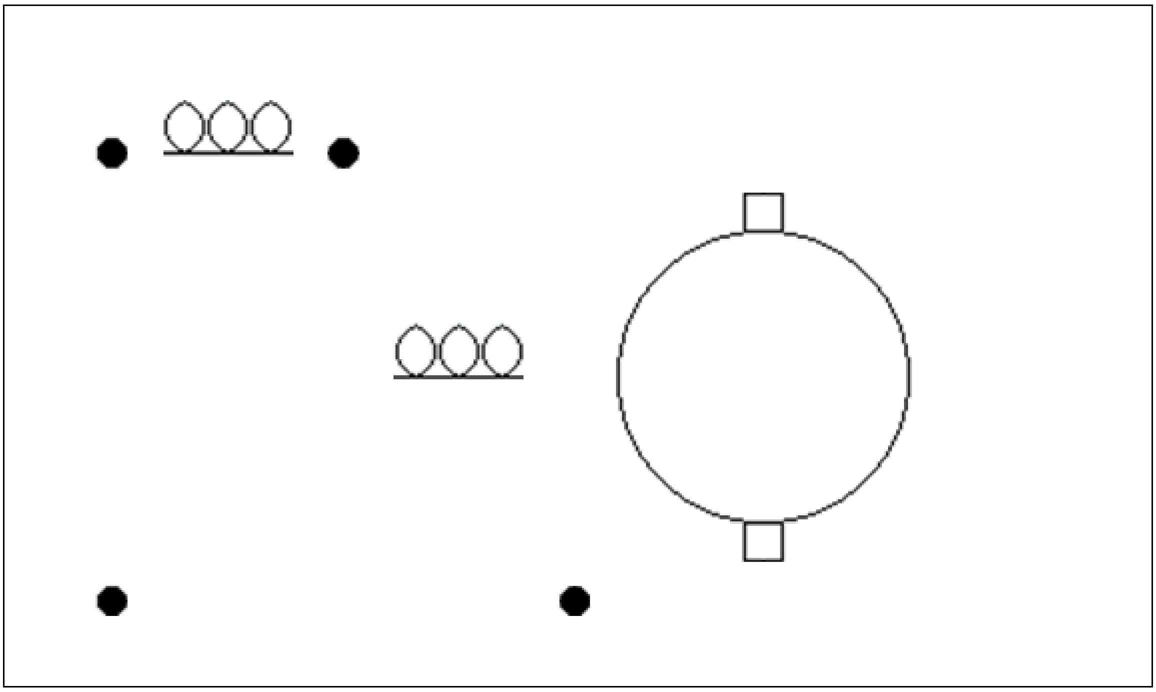
Worksheet 10: DC machines

Using your notes answer the following questions.

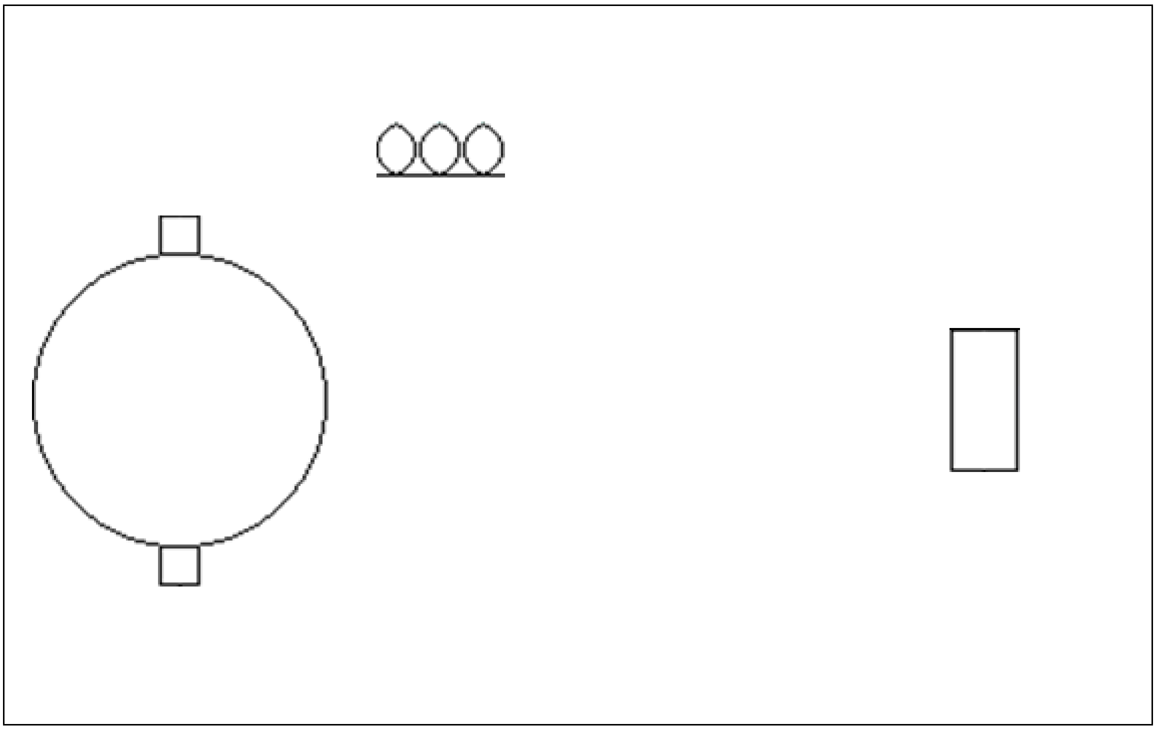
1. Complete and label the following diagram for a series wound DC motor.



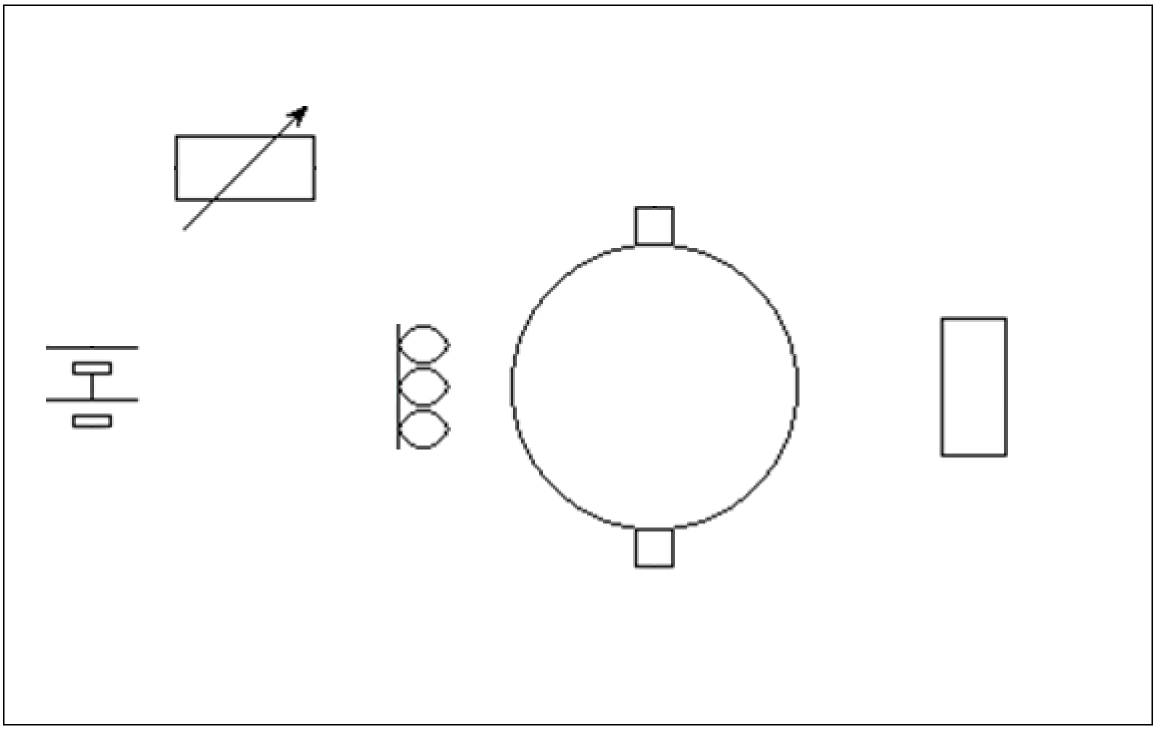
2. Complete and label the following diagram for a compound wound DC motor.



3. Complete and label the following diagram for a series wound DC generator.



4. Complete and label the following diagram for a separately excited DC generator.



302: Principles of electrical science

Handout 11: Three-phase AC machines

Learning outcome

The learner will:

3. Understand the operating principles and applications of DC machines and AC motors.

Assessment criteria

The learner can:

3.2 describe the operating principles of **AC motors**.
3.3 state the basic types, applications and limitations of AC motors

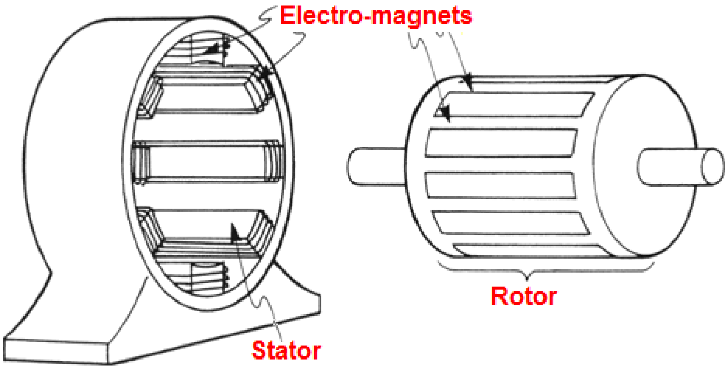
Range

AC motors: single phase AC motors (induction, capacitor start, split phase, universal, synchronous), three phase AC motors (induction; wound-rotor).

Three-phase AC machines

Basic AC motor operation

An AC motor has two basic electrical parts: a **STATOR** and a **ROTOR** as shown in the diagram below. The stator is in the stationary electrical component. It consists of a group of individual electro-magnets arranged in such a way that they form a hollow cylinder, with one pole of each magnet facing toward the centre of the group. The rotor is the rotating electrical component. The rotor, obviously, is located inside the stator and is mounted on the motor's shaft.



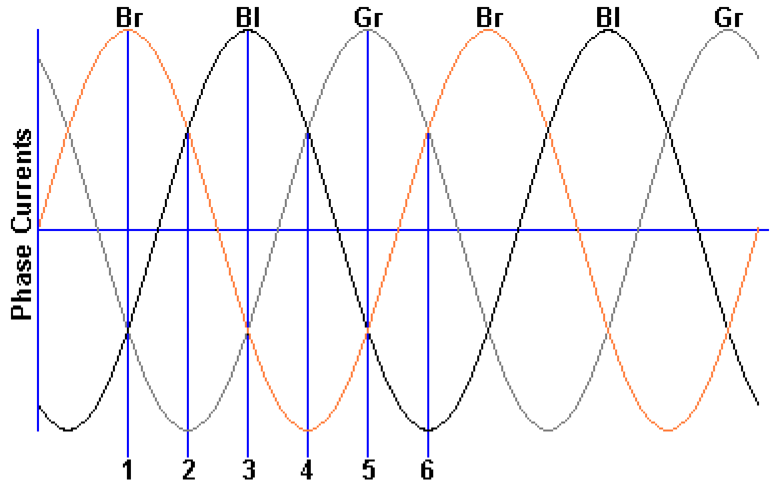
The most common form of AC machine available is the **INDUCTION** motor. This type of machine produces a rotating magnetic field in the stator that induces an emf into the rotor. The interaction between the rotating magnetic field in the stator and the magnetic field produced in the rotor by the induced emf will cause torque (tendency of a force to rotate an object about an axis, fulcrum, or pivot) to be produced in the rotor.

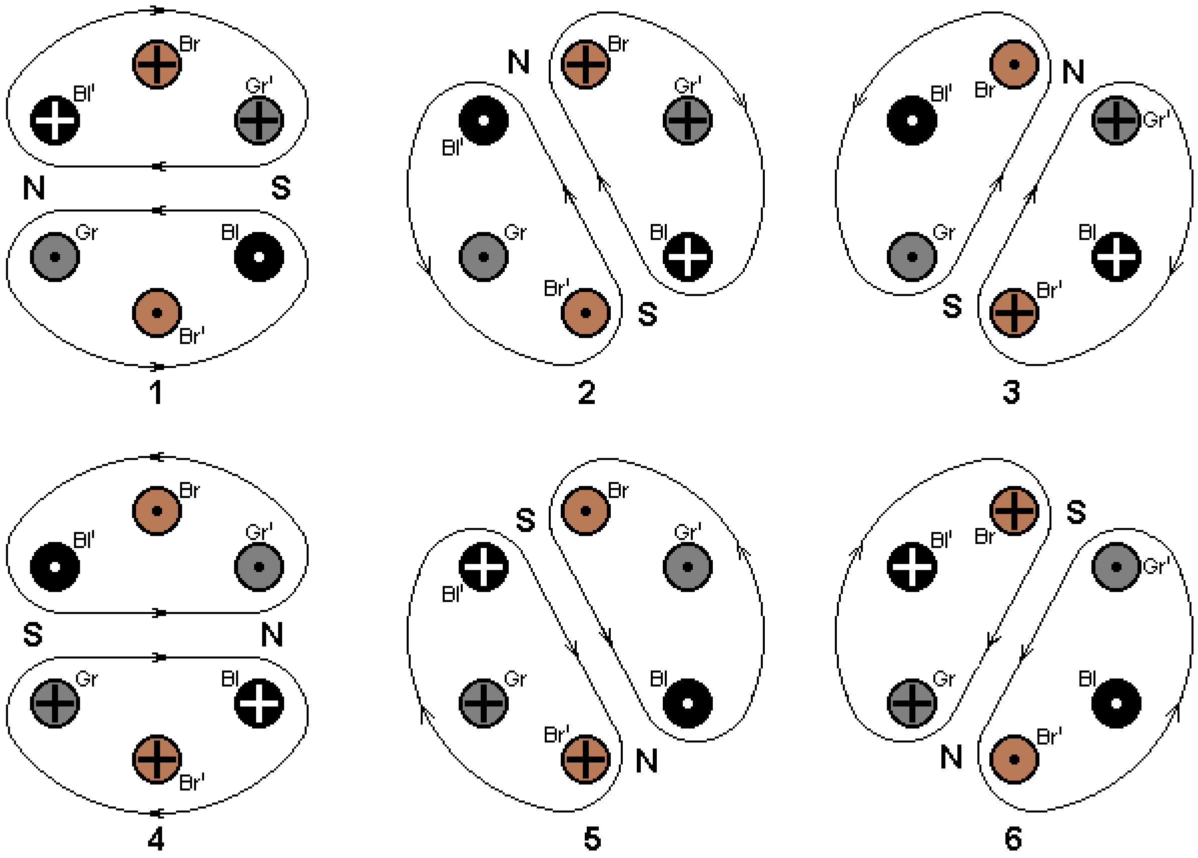
It is easier to discuss torque production with three-phase machines.

Production of a rotating magnetic field

For an AC machine to work it must produce a rotating magnetic field in the stator. This is achieved in a three-phase machine by distributing three windings, one for each phase, around the stator. Because the three phases are 120° out of phase from each other, the magnetic fields produced by each phase will interact to produce a rotating magnetic field.

The diagrams below show how this rotating magnetic field is produced in three sets of windings distributed around the stator and fed with a three-phase supply:





The diagram shows the magnetic field produced by currents flowing in the three phase stator windings, when supplied with an alternating current. The positive half of the cycle produces currents shown ⊕ in the start of the coils (Br, Bl & Gr) and ⊙ in the end of the coils (Br', Bl' & Gr'). The negative ½ cycles produce opposite polarity, i.e. ⊙ in the start of the coils (Br, Bl & Gr) and ⊕ in the end of the coils (Br', Bl' & Gr').

Synchronous speed

The speed of the rotating magnetic field is reliant on two factors: the supply frequency and the number of pairs of poles in the stator. This can be summarised by the following formula:

$$\mathbf{N\ (rps)} = \frac{\mathbf{F}}{\mathbf{P}} \qquad\qquad \mathbf{N\ (rpm)} = \frac{\mathbf{F \times 60}}{\mathbf{P}}$$

Where: **N** = **Revolutions**
rps is revolutions per second
rpm is revolutions per minute

F = **Frequency in Hertz (Hz)**

P = **the number of pairs of poles**

Example 1
A 4 pole AC three-phase machine is fed with a supply at a frequency of 50Hz. Calculate synchronous speed in:

a) rps
b) rpm

<u>NB</u>: the machine has 4 poles so that is 2 pairs of poles.

a)

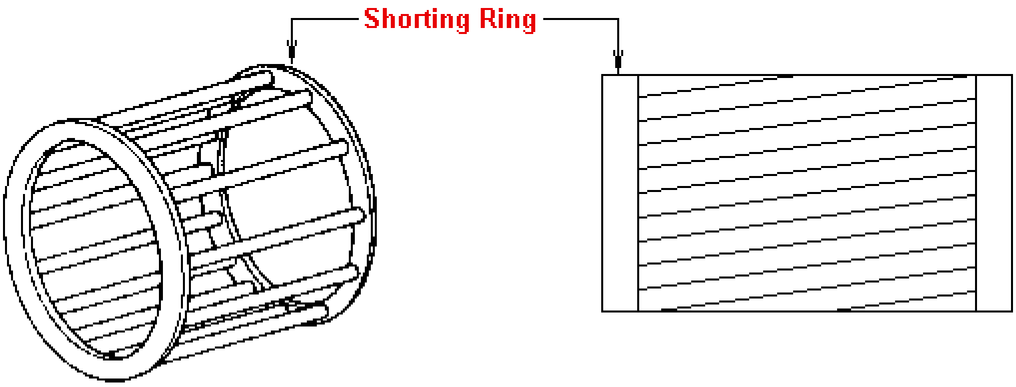
$$\begin{aligned} \mathbf{rps} &= \frac{\mathbf{F}}{\mathbf{P}} \\ &= \frac{\mathbf{50}}{\mathbf{2}} \\ &= \underline{\mathbf{25\ revs\ per\ second}} \end{aligned}$$

b)

$$\begin{aligned} \mathbf{rpm} &= \frac{\mathbf{F \times 60}}{\mathbf{P}} \\ &= \frac{\mathbf{50 \times 60}}{\mathbf{2}} \\ &= \underline{\mathbf{1500\ revs\ per\ minute}} \end{aligned}$$

Production of torque in an induction motor

The most common type of induction motor uses a cage rotor sometimes referred to as a 'squirrel cage' rotor. The basic arrangement is shown below:



When the supply is connected to the stator a rotating magnetic field is produced as described previously. The lines of flux will cut the bars of the cage rotor, which will induce an emf into these bars. Because of the shorting rings at either end of the cage rotor, the induced emf will produce a current flowing through the bars and the shorting rings. This current will produce its own magnetic field that will interact with the stator magnetic field and produce torque.

Slip

As the rotor speed increases, so the rate at which the rotating magnetic field flux cuts the cage rotor will reduce, thus reducing the induced emf, the resulting cage current and rotor magnetic field and torque will reduce as the rotor speed approaches synchronous speed. The rotor speed can never reach synchronous speed because in this situation no emf will be induced in the rotor and no torque produced. Therefore, rotor speed will always be less than synchronous speed and the difference between these two values is referred to as **SLIP**.

Slip is defined in two ways:

- Per unit slip
- % slip

and can be calculated as follows:

$$\mathbf{Per\ unit\ slip} = \frac{(n_s - n_r)}{n_s} \qquad \mathbf{\%\ slip} = \frac{(n_s - n_r)}{n_s} \times 100$$

Where:
n_s = **Synchronous speed**
n_r = **Rotor speed**

The calculation can be carried out using either revs per second or revs per minute as long as the same units are used for both synchronous and rotor speeds.

Example 2

A two-pole induction motor runs at 2880 rpm when connected to the 50 Hz mains supply. Calculate the:

a) per unit slip
b) percentage slip

$$\mathbf{Sync\ speed,}\ n_s = \frac{F \times 60}{P} = \frac{50 \times 60}{1} = 3000\ \mathrm{rpm}$$

a)

$$\mathbf{Per\ unit\ slip,}\ S = \frac{(n_s - n_r)}{n_s} = \frac{(3000 - 2880)}{3000} = \underline{0.04}$$

b)

$$\begin{aligned}
\%\ \text{slip} &= \frac{(n_s - n_r)}{n_s} \times 100 \\
&= \frac{(3000 - 2880)}{3000} \times 100 \\
&= \underline{4\%}
\end{aligned}$$

Example 3

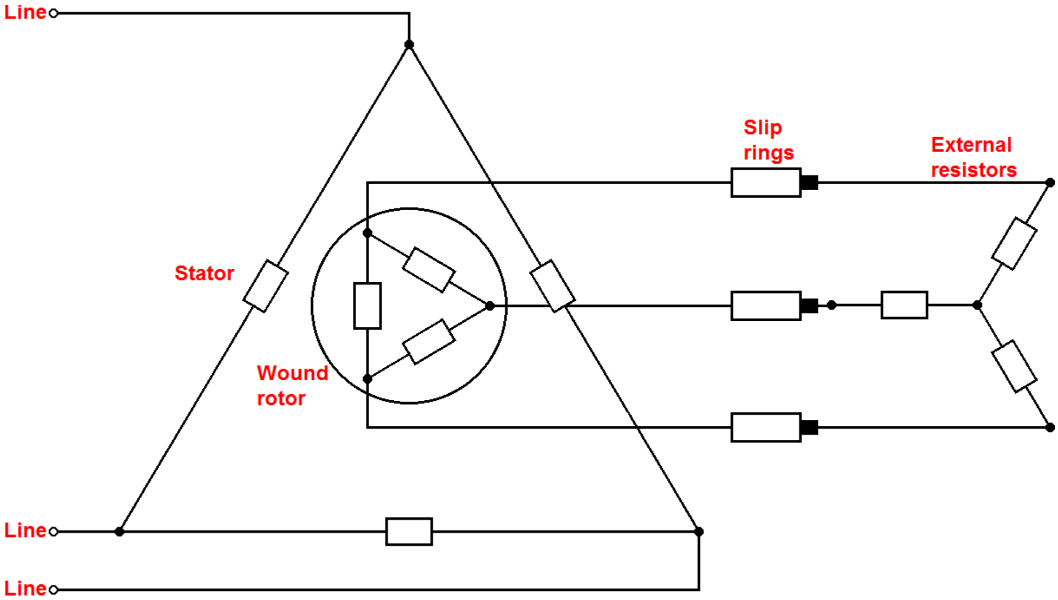
A 4-pole 50 Hz induction motor has a per-unit slip of 0.03 on full load. Calculate the full load speed.

$$\begin{aligned}
\text{Sync speed}, n_s &= \frac{F \times 60}{P} \\
&= \frac{50 \times 60}{2} \\
&= 1500\ \text{rpm} \\
\text{Per unit slip}, S &= \frac{(n_s - n_r)}{n_s} \\
S \times n_s &= n_s - n_r \\
S \times n_s + n_r &= n_s \\
n_r &= n_s - S \times n_s \\
&= 1500 - (0.03 \times 1500) \\
&= 1500 - 45 \\
&= \underline{1455\ \text{rpm}}
\end{aligned}$$

A disadvantage of the squirrel cage machine is its fixed rotor characteristic. The starting torque is directly related to the rotor circuit impedance, as is the percentage slip when running at load and speed. Ideally, a relatively high rotor impedance is required for good starting performance (torque against current) and a low rotor impedance provides low full-load speed slip and high efficiency.

To overcome the issue of inherently low starting torque, **wound rotor motors** are used. A wound-rotor motor is a type of induction motor where, instead of having a cage rotor, the rotor has three windings that are connected through slip rings to external resistances. Adjusting the resistance allows control of the speed/torque characteristic of the motor. Wound-rotor motors can be started with low inrush current, by inserting a high resistance into the rotor circuit; as the motor accelerates, the resistance can be decreased.

Compared to a squirrel-cage rotor, the rotor of the slip ring motor has more winding turns; the induced voltage is then higher, and the current lower, than for a squirrel-cage rotor. During the start-up a typical rotor has 3 poles connected to the slip rings. Each pole is wired in series with a variable power resistor. When the motor reaches full speed the rotor poles are switched to short circuit. During start-up the resistors reduce the field strength in the stator. As a result the inrush current is reduced. Another important advantage over squirrel-cage motors is higher start-up torque.



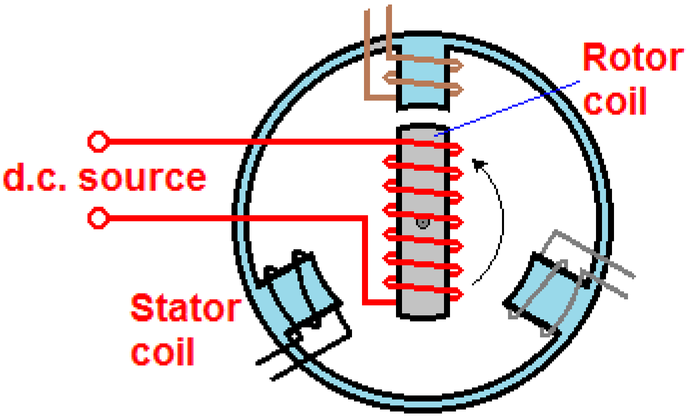
AC three phase generator

Electricity is most often generated at a power station by electromechanical generators, primarily driven by heat engines fuelled by chemical combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind. Other energy sources include solar photovoltaic and geothermal power.

Whilst in power stations the generators are generally powered by steam turbines, many smaller generators (eg, emergency back-up generators in hospitals) are powered by diesel engines. Whatever the prime-mover source, the principles of operation are the same.

The rotor has a winding supplied via slip-rings from a DC source. The rotor turns within the stator which has three separate windings spaced at 120° degrees from each other. The magnetic field produced in the rotor winding cuts the stator windings inducing a sinusoidal (AC) wave form into each of the stator windings.

It can be seen that the three-phase generator produces three separate single phase outputs each 120° out of phase with the next.



In power stations the output of each generator is connected in **delta** and then fed via transformers on to the National Grid. For systems providing back-up supplies in hospitals or factories the generator output will be connected in **star** to enable the provision of a neutral conductor to run single-phase loads as well as three-phase loads.

Whilst the rotor could contain a permanent magnet, this is only used in small generators as an appropriate sized magnet would too large for big generators. Also there is less control of the output with a permanent magnet rotor.

The DC source for many generators is derived from a small DC exciter generator connected to the shaft of the main generator, which is itself powered by the prime-mover.

Unit 302: Principles of electrical science

Worksheet 11: Three-phase AC machines

Using your notes, answer the following questions.

1. Calculate the synchronous speed of a six-pole motor when connected to a 60Hz supply.

2. A four-pole motor rotates at a synchronous speed of 50rps. Calculate the supply frequency.

3. A motor rotates at a synchronous speed of 30rps when connected to a 60Hz supply. Calculate the number of poles in the motor.

4. A motor has a synchronous speed of 50rps and runs at 2850rpm when connected to a 230 volt 50Hz supply. Calculate:
   a) per unit slip
   b) percentage slip.

5. A motor has a synchronous speed of 60rps and runs with 2% slip. Calculate its actual speed of rotation.

302: Principles of electrical science

Handout 12: Single-phase AC machines

Learning outcome

The learner will:

3. Understand the operating principles and applications of DC machines and AC motors.

Assessment criteria

The learner can:

3.2 describe the operating principles of **AC motors**.
3.3 state the basic types, applications and limitations of AC motors

Range

AC motors: single phase AC motors (induction, capacitor start, split phase, universal, synchronous), three phase AC motors (induction; wound-rotor).

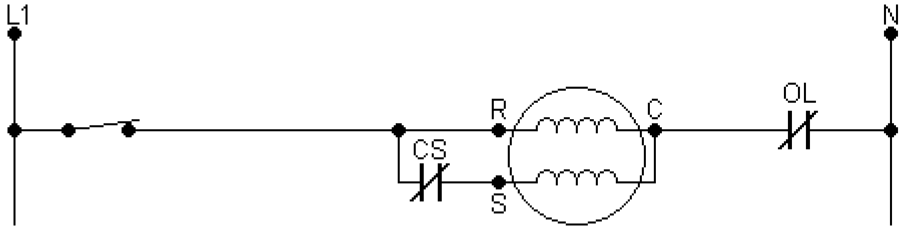
Single-phase AC machines

With 3-phase machines the interaction of three out of phase windings gives us the rotating magnetic field necessary to produce induction in the rotor and hence torque. This rotating magnetic field cannot be produced in the same way with single phase.

To start a single-phase induction motor we must artificially create a rotating magnetic field. To achieve this artificial rotating field two windings are provided, one a start or auxiliary winding and the other a run winding. By various means the start or auxiliary winding is slightly out of phase with the run winding. Once the machine has started rotating we no longer need this artificial rotating magnetic field and in most cases the start or auxiliary winding is disconnected. The name of the various types of single phase machine describes the means of achieving the phase difference.

Split-phase (resistance start) motors

Below is a basic one-line diagram of the split-phase motor. It shows the run and start winding of the starter as well as the centrifugal switch (CS).



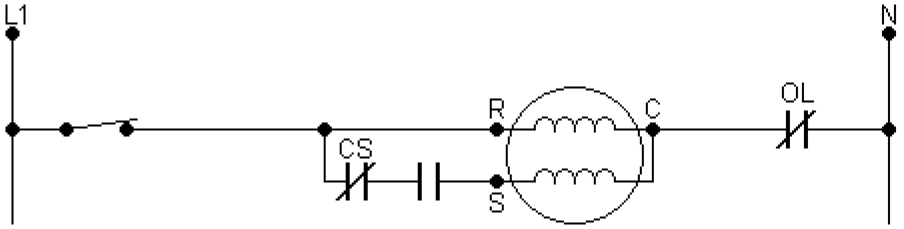
The resistance of the start or auxiliary winding will be different to the run winding and this will cause it to have a different impedance to the run winding and hence a different phase angle between the two windings. This provides sufficient phase difference to provide a starting torque, albeit very small.

Reversal of direction of rotation: The rotor will always turn from the start winding to the adjacent run winding of the same polarity. Therefore, the relationship between the start and run windings must be changed. To change the relationship and the direction of rotation, the polarity of only one of the fields must be reversed.

Split-phase motor applications: Split-phase motors are generally limited to the ⅓ horsepower size. They are simple to manufacture and inexpensive. The starting torque is very low and can be used for starting small loads only.

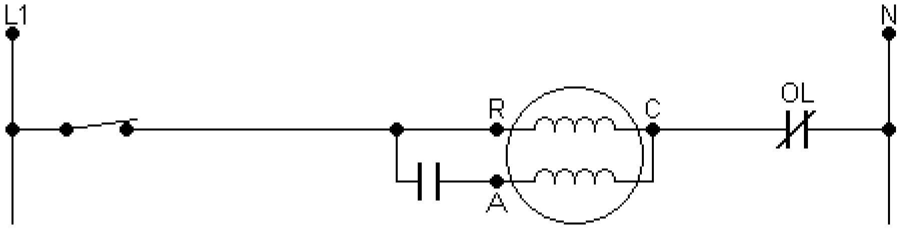
Capacitor start motors

To increase the phase angle difference and hence increase the torque a capacitor is placed in series with the start (or auxiliary) winding as shown in the diagram below.



Once the motor has attained 75% of its rated speed, the start capacitor and the start winding, can be eliminated by the centrifugal switch. It is not necessary for this motor to operate on both windings continuously.

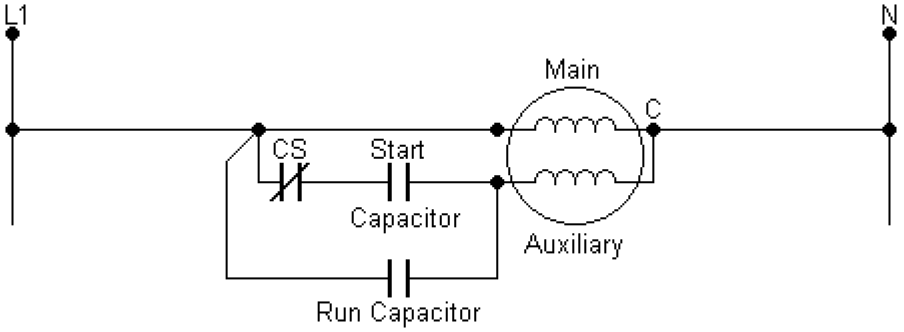
The capacitor of the capacitor-start motor improves the power factor of the electrical system only on starting. Letting a capacitor remain in the circuit will improve the electrical power factor that was modified initially by the use of a motor. The permanent capacitor is placed in series with one of the windings. The two windings are now called the main and auxiliary windings. They are constructed exactly alike. Both are left in the circuit during the operation of the motor. A centrifugal switch is no longer needed.



Capacitor-start/capacitor-run motor

When additional torque is required to start and keep a motor operating, additional capacitors can be added.

The diagram below shows the two-capacitor motor. It is commonly referred to as the capacitor-start/capacitor-run motor. Notice that the start capacitor is in series with the auxiliary winding. The centrifugal switch is used to control the start capacitor in the same manner as it did in the capacitor-start motor. This capacitor is used only to develop enough torque to start the motor turning.

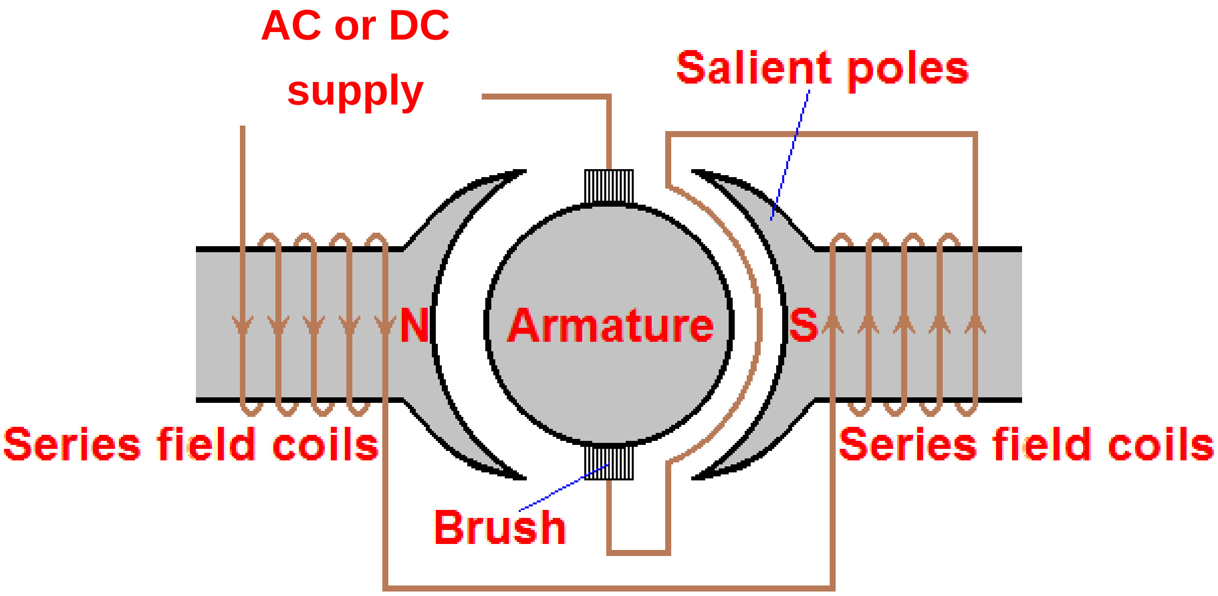


The run capacitor is connected in parallel with the start capacitor. In this manner, both capacitor capacitances add together to increase the total phase angle displacement when the motor is started. The run capacitor is also connected in series with the auxiliary winding. With the run capacitor connected in series with the auxiliary winding, the motor always has the auxiliary winding operating, and increased torque is available.

Universal motor

The universal motor is a type of electric motor that can operate on both AC and DC power supplies. It is a commutated series-wound motor where the stator's field coils are connected in series with the rotor windings through a commutator. This type of electric motor can operate well on AC because the current in both the field coils and the armature (and the resultant magnetic fields) will alternate (reverse polarity) in synchronism with the supply. Hence the resulting mechanical force will occur in a consistent direction of rotation, independent of the direction of the applied voltage, but determined by the commutator and polarity of the field coils.

Universal motors have high starting torque, run at high speed, are lightweight and are commonly used in portable and domestic equipment. They're also relatively easy to control electronically. The commutator, however, has brushes that wear, so they are much less often used for equipment that is in continuous use. In addition, partly because of the commutator, universal motors are typically very noisy.



AC single phase generator

A single-phase AC generator works in the same manner as a three-phase generator. That is, a rotating magnetic field on the rotor within the stator but this time only containing one coil instead of three.

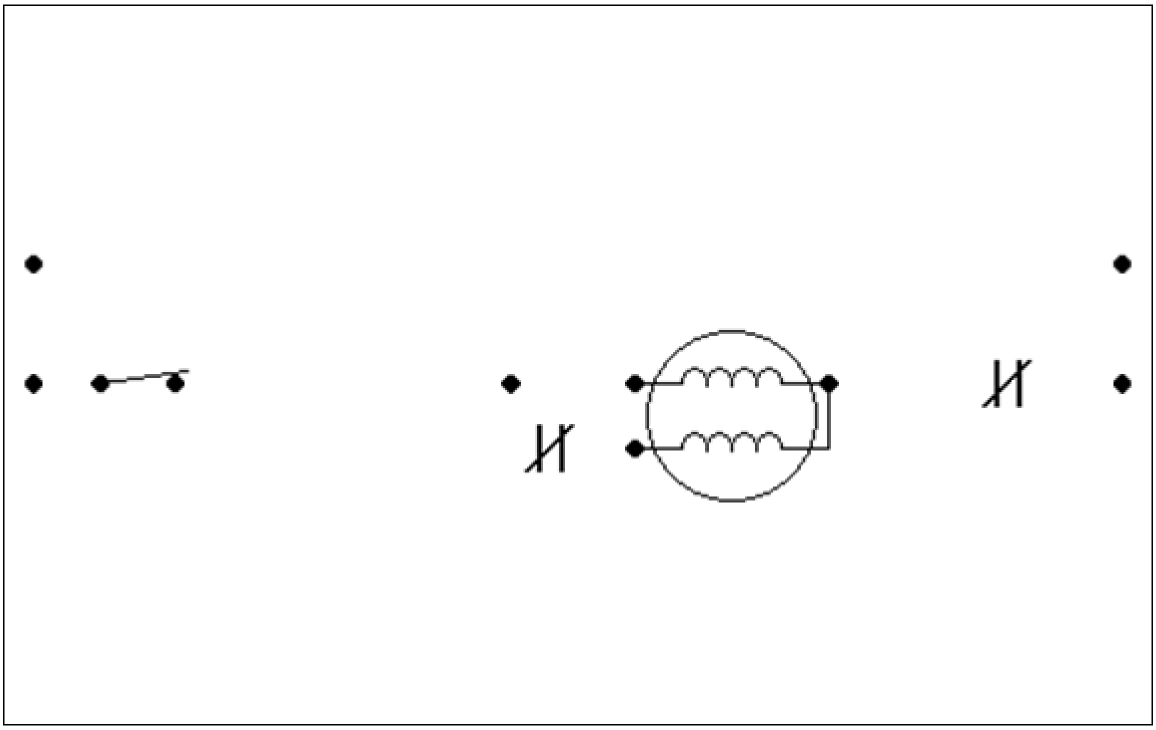
These are used for smaller power requirements, usually portable, for powering such things as portable power tools, touring caravans, etc.

Unit 302: Principles of electrical science

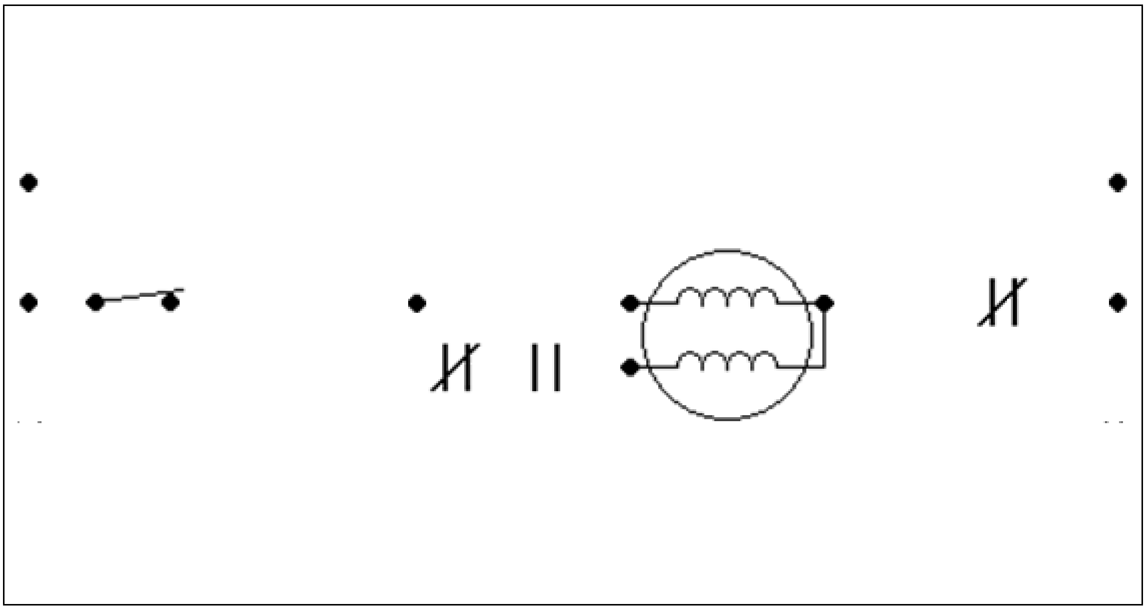
Worksheet 12: Single-phase AC machines

Using your notes, answer the following questions.

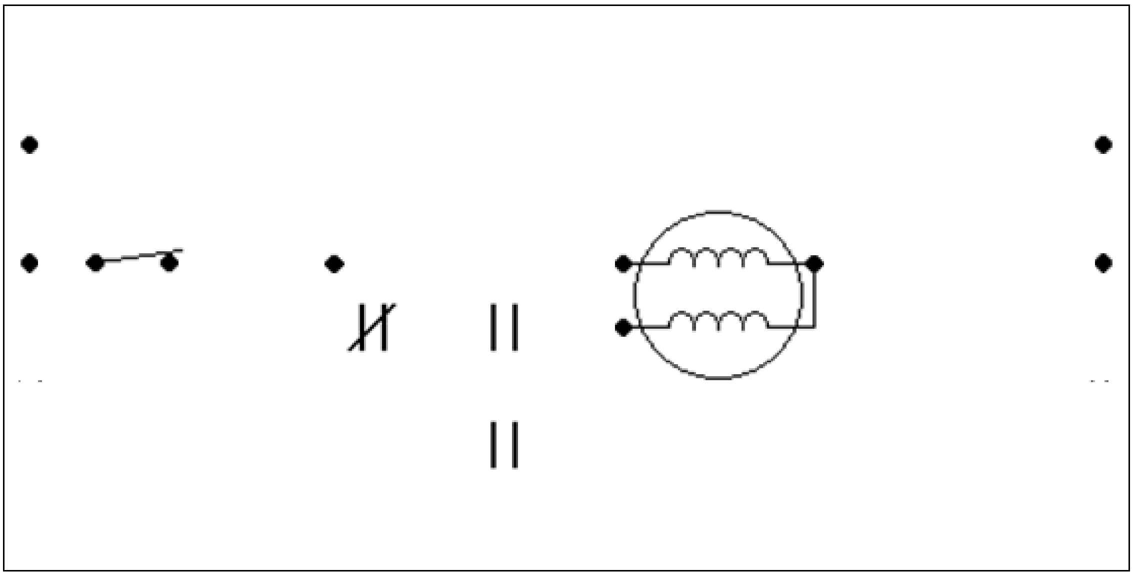
1. Complete and label the following diagram for a split-phase AC motor.



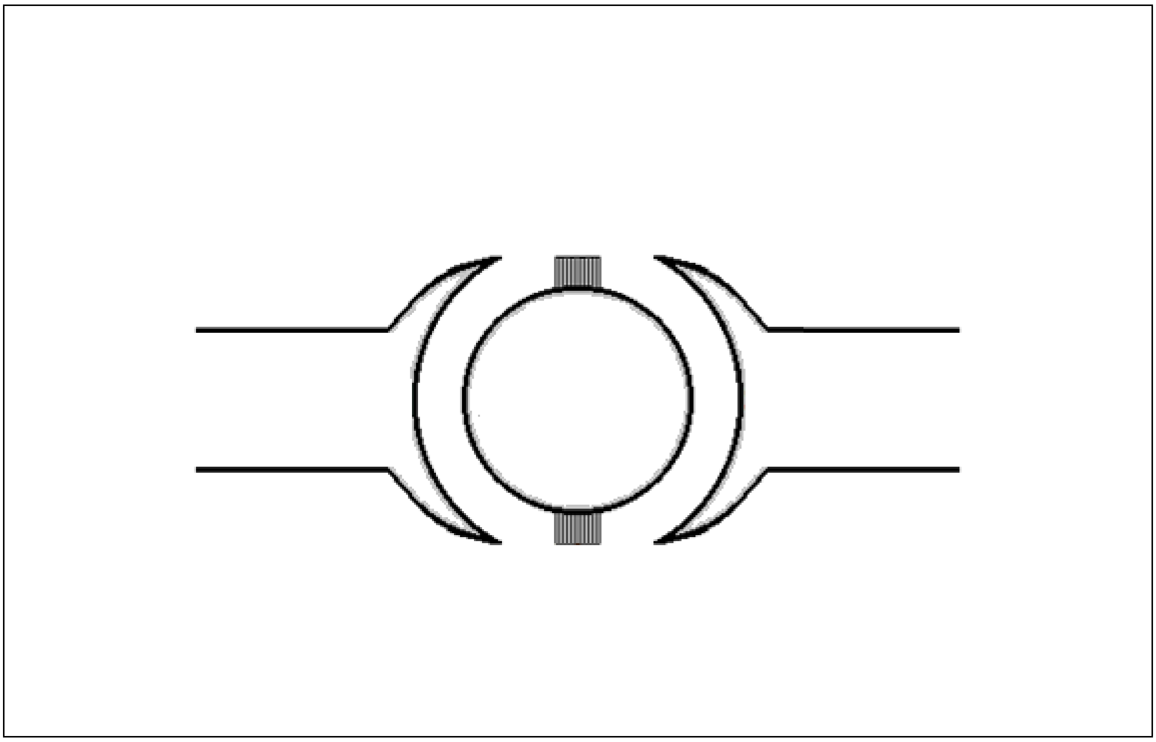
2. Complete and label the following diagram for a capacitor start AC motor.



3. Complete and label the following diagram for a capacitor start, capacitor run AC motor.



4. Complete and label the following diagram for a universal motor.



302: Principles of electrical science

Handout 13: Motor starting

Learning outcome

The learner will:

3. Understand the operating principles and applications of DC machines and AC motors.

Assessment criteria

The learner can:

3.4 describe the basic operating principles, limitations and applications of **motor control**.

Range

Motor control: direct-on-line, star-delta, rotor-resistance, soft-start, variable frequency.

Motor starting

When an electric motor is connected to the supply, the only opposition to current flow is the ohmic resistance of the motor windings and this is relatively low, particularly with larger motors. Consequently, the initial current is quite high (I = V/R).

As the machine starts to speed up, the magnetic fields generated not only produce torque, but also an induced back-emf, that opposes the current producing these magnetic fields. This is known as '**Lenz's Law**'. This states:

> *"An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux."*

This back-emf reduces the current drawn by the machine until the machine reaches its normal running speed and the current stabilises. It must be remembered that the starting current can reach five to eight times the normal run current.

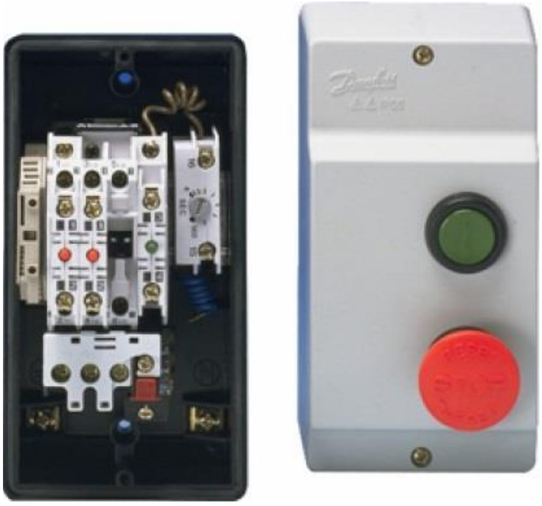
The torque produced on the shaft of a machine can cause a mechanical shock to the drive-train which can bring about its failure, sometimes quite catastrophically.

These electrical and mechanical stresses occurring during motor starting must be correctly managed if damage is not to be caused to the equipment or to the electrical supply system.

Very small machines such as those in vacuum cleaners can be controlled simply by the on/off switch fitted to the appliance. For larger machines, however, and for those with exposed rotating parts, specific motor starting must be employed.

It is not only necessary to manage the starting current and mechanical stresses during starting, but also the dangers of a machine starting unexpectedly after a power outage or reduction, as well as protecting against the motor becoming overloaded due to stalling, eg too much mechanical load on the shaft.

This process is covered by the term 'motor starting' and many different forms are available depending on the situation.



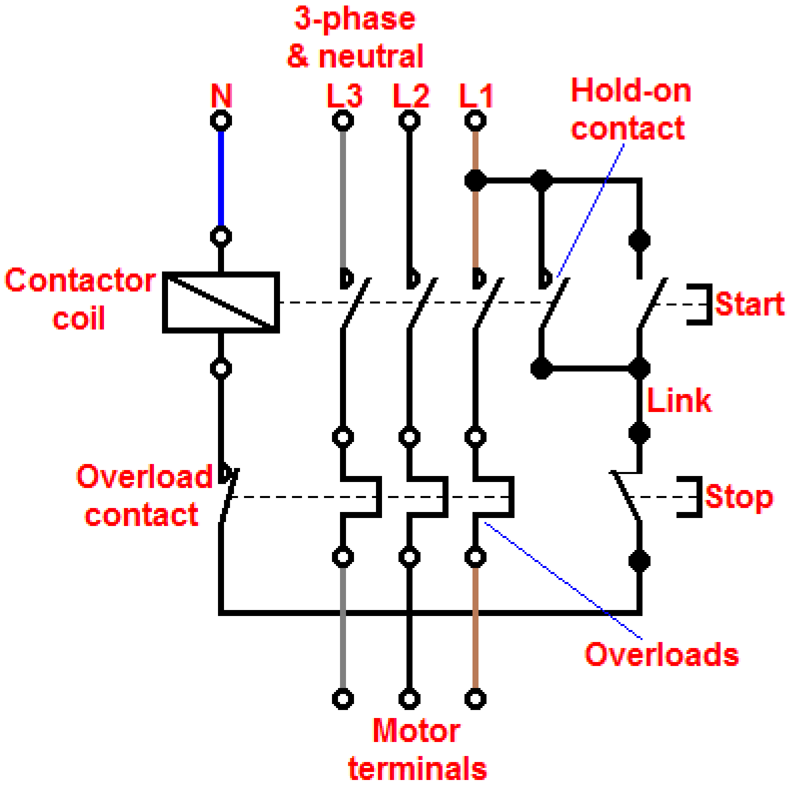
Direct-on-line (DOL) starting

Direct-on-line starting (DOL) is the simplest and most cost effective method of starting a motor. As the name suggests, in DOL starting the motor is simply connected to the electrical supply and accelerates according to its inherent electrical and mechanical characteristics. It can be used for both single and three-phase machines.

If the power supply can provide the necessary starting currents, voltage drops are not unfavourable and the mechanical load is not adversely affected by the high starting torque and acceleration, then DOL would usually be the first choice – there is less to go wrong.

It usually contains a contactor (although semiconductor starters are available) and a means to detect when an overload has occurred so the supply can be automatically disconnected. It will also contain low (or no) volt protection. This prevents the machine from starting unexpectedly after a voltage reduction or a power cut.

A typical DOL contactor circuit is shown right:



The circuit shown represents a three-phase DOL starter but a single-phase starter would have the same control arrangements.

When the **START** button is pressed, current flows from **L1**, through the **START** button, then the **LINK**, followed by the **STOP** button and then the **OVERLOAD CONTACT** and finally the **CONTACTOR COIL** before returning to the **NEUTRAL**; the **CONTACTOR COIL** magnetises and closes its four contacts.

Three of the **CONTACTS** extend the three-phase supply to the **MOTOR TERMINALS** via the **OVERLOADS** and the motor will start to run. The fourth contact, the **HOLD-ON CONTACT**, shorts out the **START** button allowing it to be released, maintaining the **CONTACTOR COIL** circuit energised and the motor continues to run.

To stop the motor the control circuit feeding the **CONTACTOR COIL** needs to be broken and this is achieved in one of three ways.

- Pressing the **STOP** button opening the circuit
- If the OVERLOADS detect an overcurrent of the appropriate magnitude and time the **OVERLOAD CONTACT** will open
- If the supply voltage drop drops below a certain level the **CONTACTOR COIL** will de-energise thus providing low (or no) volt protection.

Whichever occurs, the **CONTACTOR COIL** will de-energise and the motor will stop running. To restart the motor the **START** button must again be pressed.

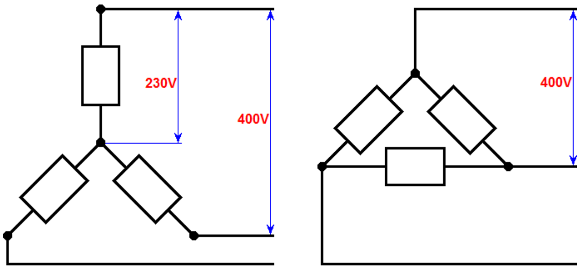
Star – delta starting

As mentioned earlier, if the power supply can provide the necessary starting currents, voltage drops are not unfavourable and the mechanical load is not adversely affected by the high starting torque and acceleration then DOL would usually be the first choice.

However, with larger machines it is often necessary to limit the starting current until the machine reaches its normal running speed. Apart from limiting the starting current drawn from the supply, this it will also reduce cable voltage drop during starting as well as limiting torque, thus causing less mechanical shock to the drive-train of the equipment. One way of achieving this is by starting the motor in **star** until a predetermined time has elapsed and then switching it to **delta** for normal running when maximum torque and power can be achieved.

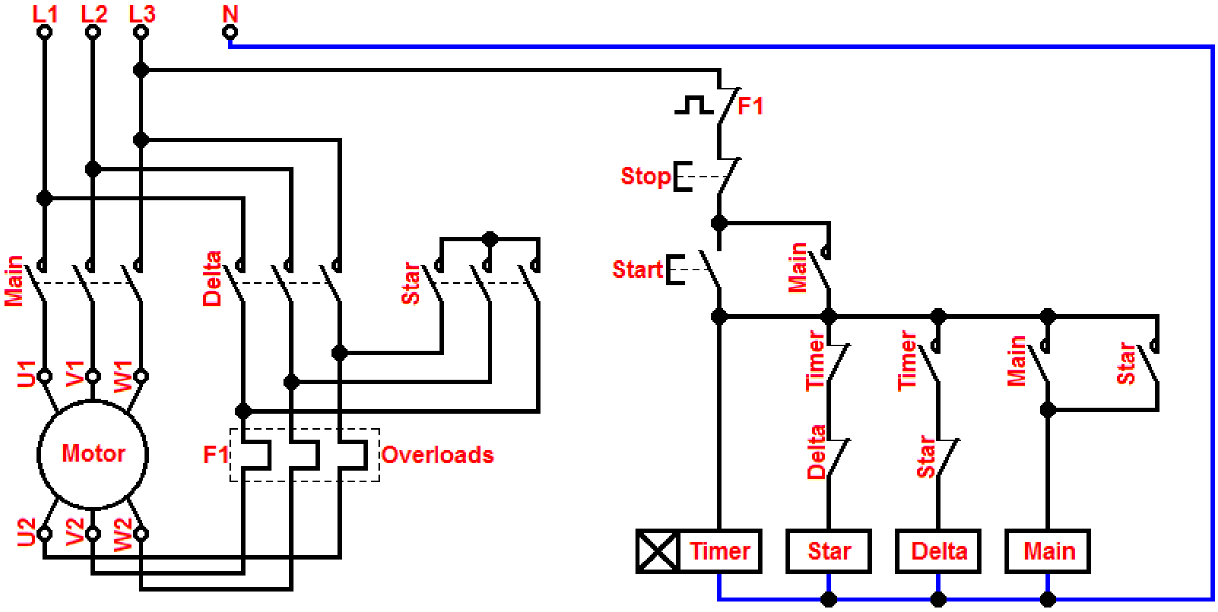
The current is limited by limiting the applied voltage. This is simply achieved by connecting the motor in star so each coil only receives 230 volts. When the motor is connected in delta each coil receives the full 400 volts.

Whilst manual star-delta starters are available it is more usual to use automatic star-delta starters.



Star connection

Delta connection



When the **start** button is pressed a feed is applied to the **timer** relay that starts its timing process whilst a feed is simultaneously applied to the **star** contactor coil. With the **star** contactor energised, a feed is applied to the **main** contactor coil. With both the **main** and **star** contactors operated, the motor is connected to the three-phase supply in star configuration and the motor will start to run; this will be at reduced current and torque due to only 230 volts being applied to each winding.

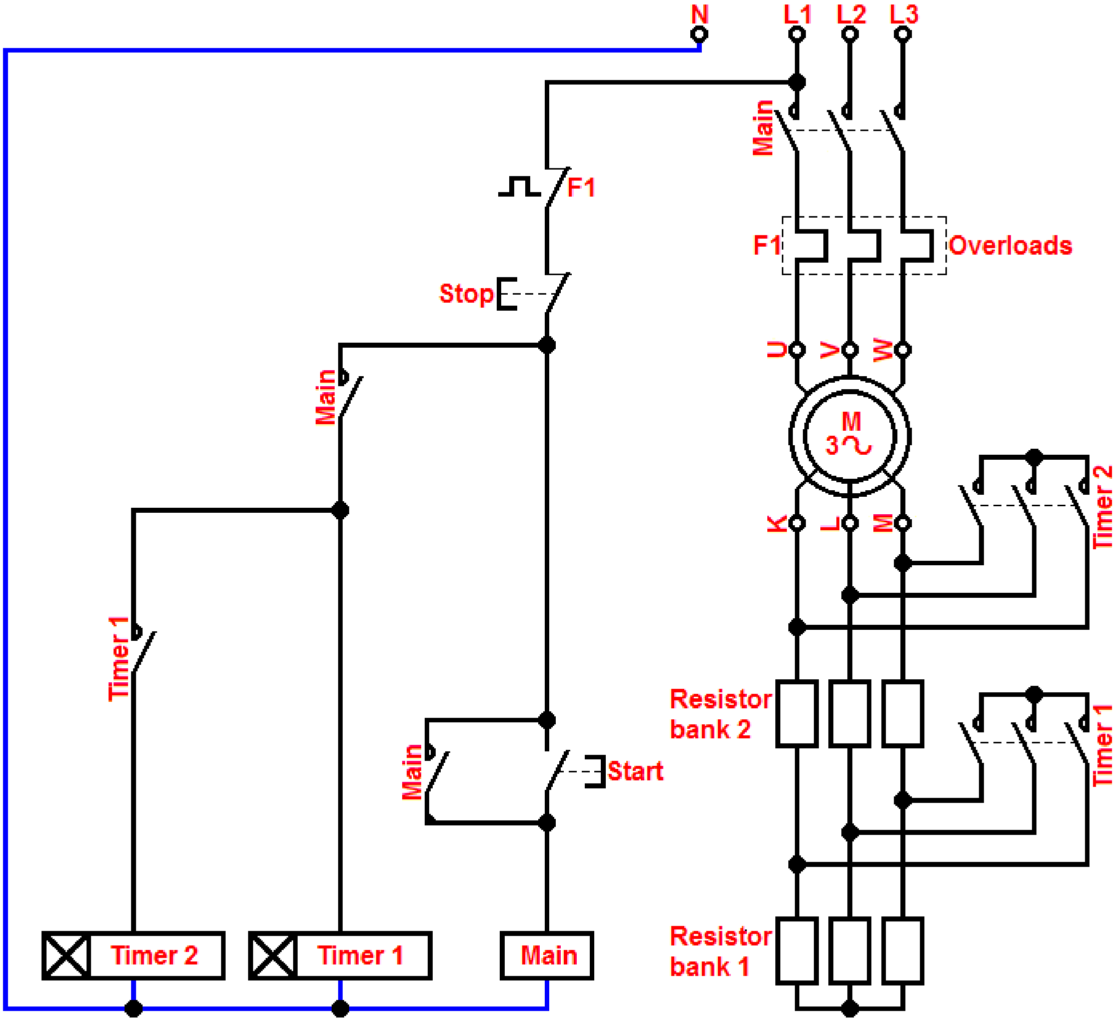
When the **timer** relay completes its timing process, its contact in the **star** contactor circuit will open, causing the **star** contactor to open. At the same time, the **timer** contact in the **delta** contactor coil circuit closes and once it is proved that the **star** contactor has de-energised, the **delta** contactor energises and switches the motor to delta configuration; the motor will then produce full power as it now has 400 volts applied to each winding.

To turn off is the same as with DOL starters, namely stop button, overload or low voltage.

Rotor resistance starting

Another method of limiting starting current is to use a wound rotor motor with resistors connected to the rotor windings via slip rings. These can be a single set of variable resistors or banks of fixed resistors switched in and out as required.

The current in the rotor windings is induced by the rotating magnetic field in the stator, much like a transformer. The current drawn from the supply to feed the stator winding will be dependent on the rotor winding current, which can be controlled by the value of resistances connected across the rotor windings. A typical circuit arrangement for rotor resistance starting is shown below:



When the **start** button is pressed, the **main** contactor will energise. This contactor will apply the three-phase supply to the **stator** windings of the motor as well as starting the timing process of **timer 1**. Each of the three rotor windings will have two resistors in series with it connected in **star** to the other rotor windings/resistors. This will limit the current drawn from the supply and also the torque.

When **timer 1** completes its timing process it will close its contactor contacts causing **timer 2** to start its timing process as well shorting out **resistor bank 1** thus allowing the motor to develop more power.

When **timer 2** completes its timing process, it will close its contactor contacts resulting in **resistor bank 2** being shorted out, allowing the motor to develop maximum power.

Soft start

A motor soft starter is a device used with AC electric motors to temporarily reduce the current surge of the motor during start-up. This reduces the electro-dynamic stresses on the attached power cables and electrical distribution network, extending the lifespan of the system.

Electrical soft starters can be any control system that reduces the torque by temporarily reducing the voltage or current input, or a device that temporarily alters how the motor is connected in the electric circuit.

Electrical soft starters can use solid state devices to control the current flow and therefore the voltage applied to the motor. They can be connected in series with the line voltage applied to the motor, or can be connected inside the delta loop of a delta-connected motor, controlling the voltage applied to each winding.

Solid state soft starters can control one or more phases of the voltage applied to an induction motor, with the best results achieved by three-phase control. Typically, the voltage is controlled by reverse-parallel-connected silicon-controlled rectifiers (thyristors).

Operating principles

Soft starters use a combination of power electronics and electronic control circuitry to slowly increase the voltage on the motor during starting; ensuing a smooth acceleration.

As mentioned earlier, soft starters use thyristors to control the energy delivered to the motor. A thyristor is a device which turns on when a pulse is applied to its gate and will continue to conduct until the current drops to zero (at which time it turns off). In an ac sine wave, current goes to zero each half cycle, allowing the current to be turned off and making it possible to use thyristors to implement soft starting. Reverse-parallel connected thyristors enable voltage to be delivered on both half-cycles of the AC sine wave.

If the thyristors are turned on at the start of each half cycle, the full voltage is applied to the motor. If the thyristors are never turned on, then no voltage is applied. If the thyristors are turned on part way through the half cycle only a proportion of the voltage will be applied to the motor. By controlling the turning on (firing angle) of the thyristors, the amount of voltage on the motor can be controlled. Starting with a large firing delay, this is gradually reduced and the voltage on the motor will ramp-up during starting.

In addition to use in starting, soft start units can also be used for stopping the motor, by ramping the voltage down. This is particularly useful where sudden loss of driving torque would create mechanical shock on the load.

Electronic soft starters contain the thyristors (power side) and necessary electronics to control the firing (via user settings). Modern soft starters have a host of features; the most common being options to set varying start and stop ramps, setting of the initial starting voltage, current limiting control and thermal overload protection.

Some of the benefits:

- 3 conductors to the motor
- Variable starting torque
- No current peak
- No torque peaks
- One simple switching device
- Optional: Guided soft stop, protective functions, etc.
- Zero maintenance.

Variable-frequency drive and invertors

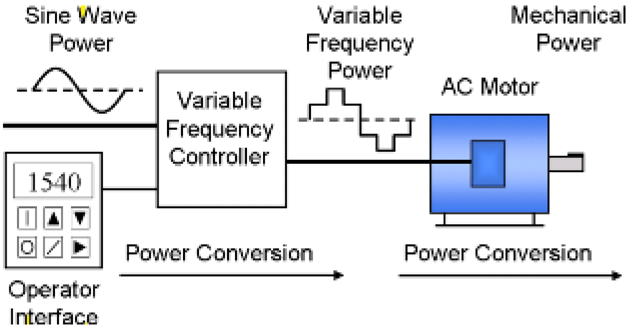
Variable-frequency drives (VFD) are effectively an extension of the soft start equipment discussed earlier.

A VFD is a type of adjustable-speed drive used in electro-mechanical drive systems to control ac motor speed and torque by varying motor input frequency and voltage.

VFDs are used in applications ranging from small appliances, to the largest industrial machines. About a third of the world's electrical energy is consumed by electric motors in fixed-speed mode. VFDs' global market penetration for all applications is still, however, relatively small. This highlights the significant energy efficiency improvement opportunities for retrofitted and new VFD installations.

Over the last four decades, power electronics technology has reduced VFD cost and size and improved performance through advances in semiconductor switching devices, drive topologies, simulation and control techniques, and control hardware and software.

The AC motor used in a VFD system is usually a three-phase induction motor. Some types of single-phase motors can be used, but three-phase motors are usually preferred. Motors that are designed for fixed-speed operation are often used. Elevated voltage stresses imposed on induction motors that are supplied by VFDs require that such motors be purposely designed for VFD-fed duty.

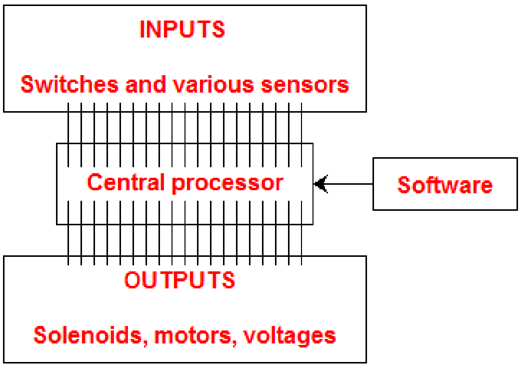


Programmable Logic Controllers (PLC)

A Programmable Logic Controller, PLC or Programmable Controller is a digital computer used for automation of electromechanical processes, such as control of machinery on factory assembly lines, amusement rides, or light fixtures.

The abbreviation "PLC" and the term "Programmable Logic Controller" are registered trademarks of the Allen-Bradley Company (Rockwell Automation).

PLCs are used in many industries and machines. Unlike general-purpose computers, the PLC is designed for multiple input and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact.



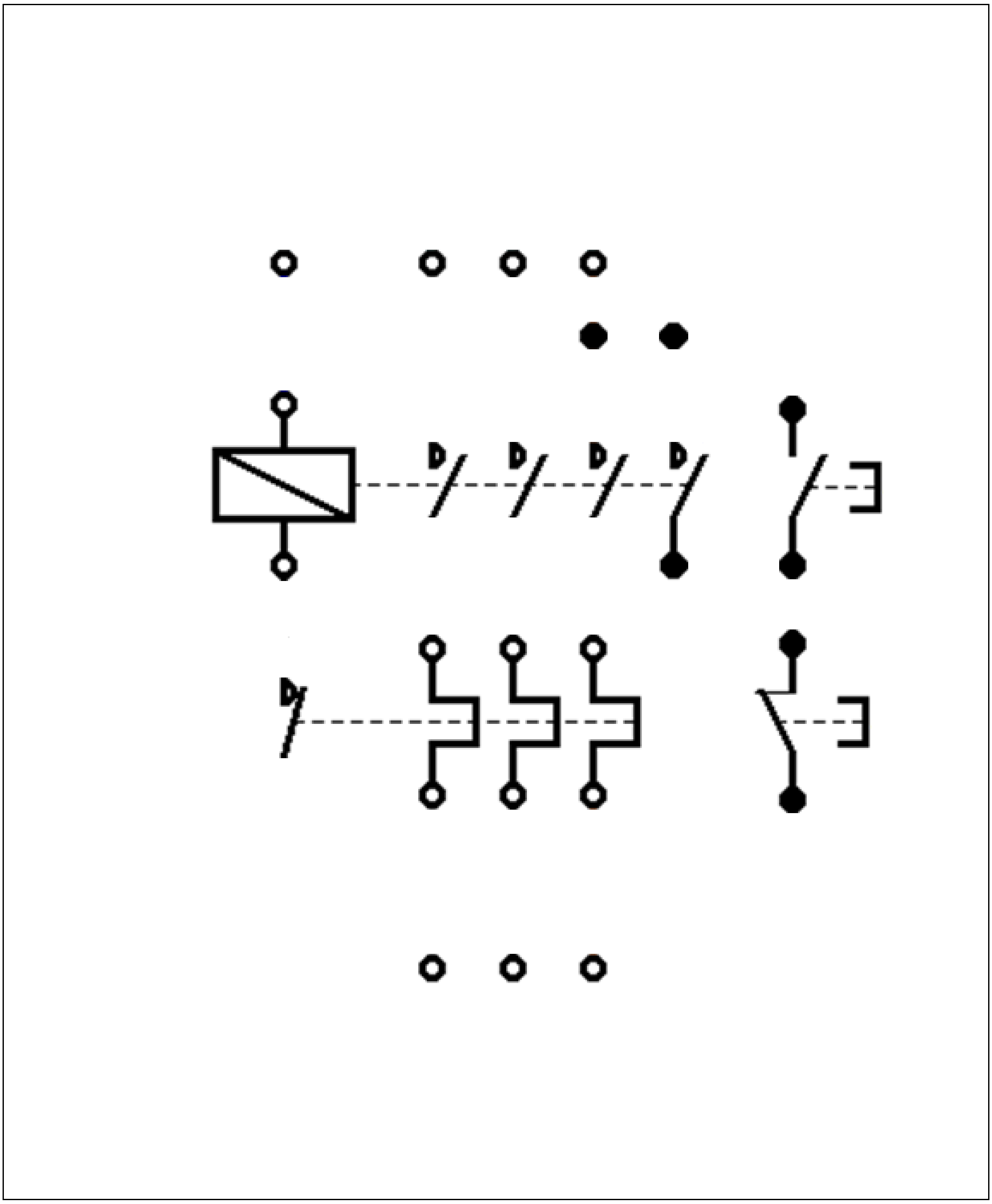
Programs to control machine operation are typically stored in battery-backed-up or non-volatile memory. A PLC is an example of a hard, real time system since output results must be produced in response to input conditions within a limited time, otherwise unintended operation will result.

Unit 302: Principles of electrical science

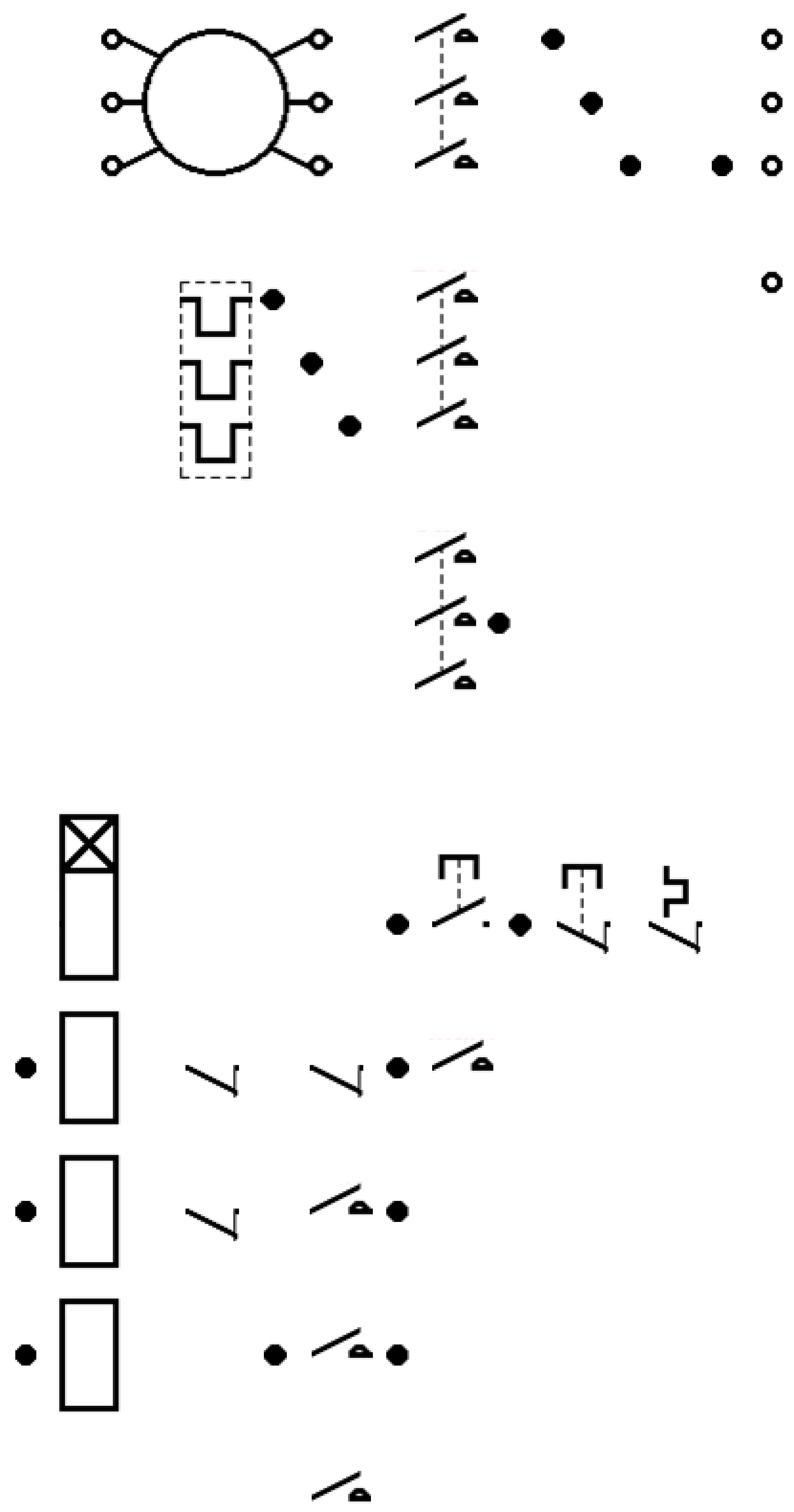
Worksheet 13: Motor starting

Using your notes, answer the following questions.

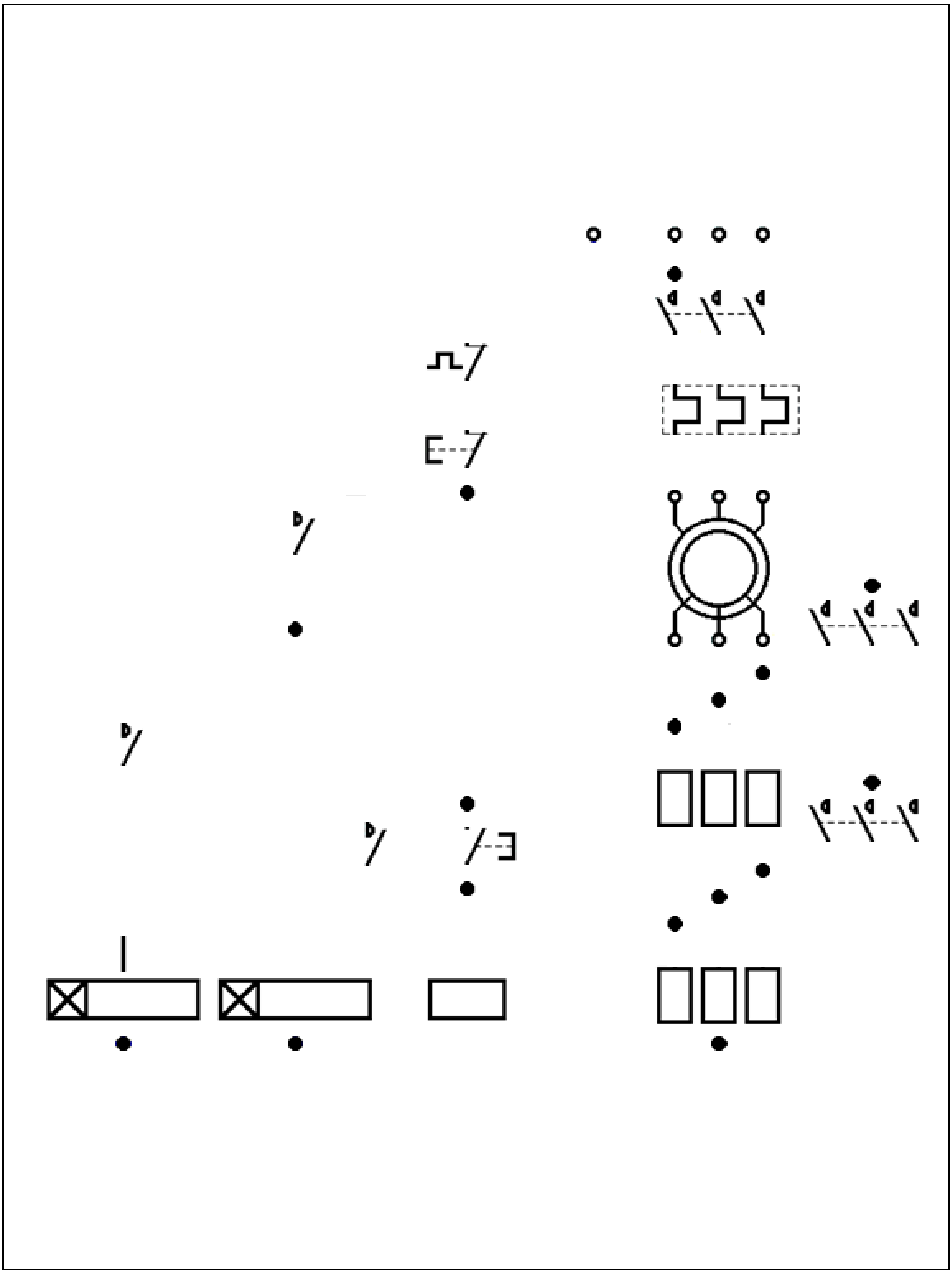
1. Complete and label the following diagram for a DOL starter.



2. Complete and label the following diagram for a star–delta starter.



3. Complete and label the following diagram for a rotor resistance starter.



302: Principles of electrical science

Handout 14: Illumination

Learning outcome

The learner will:

5. Understand the principles and applications of electrical lighting systems.

Assessment criteria

The learner can:

5.1 explain the basic principles of illumination and state the applications of: a) inverse square law, b) cosine law, c) lumen method.

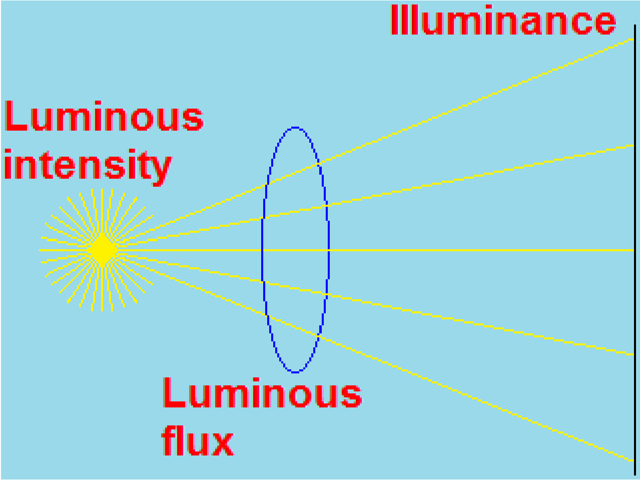
Illumination

Well planned lighting is important to help work to be done efficiently and safely and also plays an important part in creating pleasant and comfortable surroundings both indoors and out.

Many types of light fitting (or luminaire) are used in lighting designs, each with their own specific characteristics. BS 7671:2018 (page 32) defines the term ‘luminaire’ as, ***“Equipment which distributes filters or transforms the light transmitted from one or more lamps and which includes all the parts necessary for supporting, fixing and protecting the lamps, but not the lamps themselves, and where necessary, circuit auxiliaries together with the means for connecting them to the supply”***. There are a number of common illumination quantities that we must remember:

Luminous Intensity - symbol I

The luminous intensity of a light source is the power of light. It is defined in a given direction and is measured in **candela**, cd. The candela specifies the luminous intensity at one specific angle from a light source. It doesn’t indicate anything about the total amount of light being radiated from the light source.



Luminous Flux - symbol F

The luminous flux is the total amount of light energy radiated from a light source in all directions. The luminous flux is measured in **lumens** and is the parameter used to describe the “brightness” of a light source.

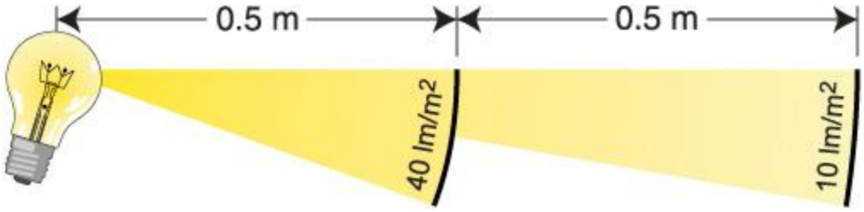
Illuminance - symbol E

The illuminance or light level is the amount of light energy reaching a given point on a defined surface area, namely the luminous flux (ie lumens) per square meter. Illuminance is measured in **lux** and is the illumination produced by one lumen over an area of one square metre.

Laws of illumination

Inverse square law

The inverse square law defines the relationship between the irradiance from a point source and distance. It states that the intensity per unit area varies in inverse proportion to the square of the distance. Distance is measured to the illuminated surface from the lighting point.



$$E = \frac{I}{d^2}\,(\text{lux})$$

Where:
E = Illuminance in lux
I = Luminous intensity in candela
d = distance between light source and the illuminated surface in metres

Example 1
A lamp of luminous intensity 450 candela is suspended 3 metres above a bench. Calculate the illuminance directly below the lamp.

$$\begin{aligned} E &= \frac{I}{d^2} \\ &= \frac{450}{3^2} \\ &= \frac{450}{9} \\ &= \underline{50\ \text{lux}} \end{aligned}$$

Example 2
A lamp of luminous intensity 600 candela is suspended 5 metres above a work area. Calculate the illuminance directly below the lamp.

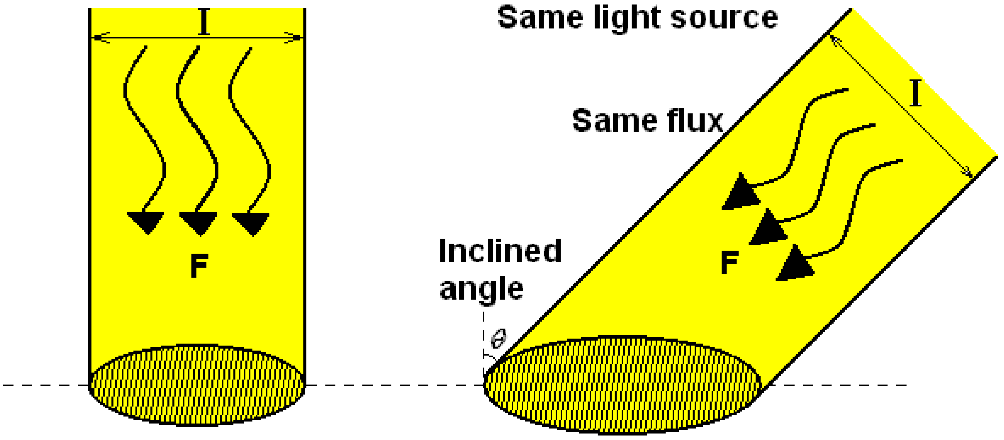
$$\begin{aligned} E &= \frac{I}{d^2} \\ &= \frac{600}{5^2} \\ &= \frac{600}{25} \\ &= \underline{24\ \text{lux}} \end{aligned}$$

Recommended lighting levels (Chartered Institute of Building Services Engineers)

Educational			
Classrooms	300 lux	Computer practice rooms	300 lux
Technical drawing room	750 lux		
Healthcare - wards			
General lighting	100 lux	Simple examinations	300 lux
Reading lighting	300 lux	Examination and treatment	1000 lux
Hotels and restaurants			
Kitchen	500 lux	Self service restaurant	200 lux
Restaurant, dining room, function room	-	Conference rooms	500 lux
Offices			
Filing, copying etc.	300 lux	Conference and meeting rooms	500 lux
Writing, typing, reading, data processing	500 lux	Reception desk	300 lux
Technical drawing	750 lux	Archives	200 lux
CAD work stations	500 lux		
Residential - Flats /Bedsits			
Lounge	100 – 300 lux	Bathrooms	150 lux
Kitchens	150 – 300 lux	Toilets	100 lux
Retail Premises			
Sales area	300 lux	Wrapper table	500 lux
Till area	500 lux		
Theatres, Concert Halls and Cinemas			
Practice rooms, dressing rooms	300 lux	Auditoria	100 lux

Cosine law

If the luminous flux strikes the surface at 90° then the calculation for illuminance given above applies. However, if the luminous flux strikes the surface at any other angle the light will be spread over a larger area and the illuminance will be reduced.



The cosine law defines the relationship between the irradiance from a point source, distance and the angle that the light strikes the surface. It states that the intensity per unit area at the surface varies according to the cosine of the angle at which the light strikes the surface.

$$E = \frac{I\cos\theta}{d^2}\,(\text{lux})$$

Where: $E = \text{Illuminance in lux}$

$I = \text{Luminous intensity in candela}$

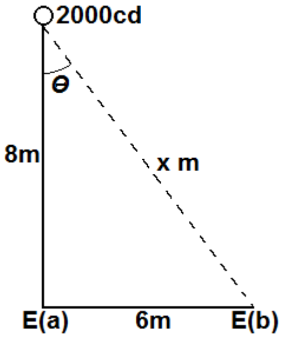
$\cos\theta = \text{Cosine of the angle from perpendicular}$

$d = \text{distance between light source and the illuminated surface in metres}$

Example 3

A street lighting column suspends a 2000 cd light source 8m above the ground. Determine the illuminance directly below the lamp and 6m to one side of the lamp base.

See diagram right for layout of this arrangement.



Illuminance below the lamp E_a:

$$E_a = \frac{I}{d^2} = \frac{2000}{8^2} = \frac{2000}{64} = \underline{31.25\ \text{lux}}$$

Illuminance at 3m to one side of the lighting column E_B:

The distance between the light source and the position on the ground at E_B can be found by Pythagoras' theorem.

$$x = \sqrt{8^2 + 6^2} = \sqrt{100} = 10\text{m}$$

$$\text{Cos}\theta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{8}{10} = 0.8$$

$$E_b = \frac{I\cos\theta}{d^2}$$

$$= \frac{2000 \times 0.8}{10^2}$$

$$= \frac{1600}{100}$$

$$= \underline{16\ \text{lux}}$$

Lumen method

This method is used to determine the number of lighting sources that are required to be installed to provide a given light level for a given area or room.

This method of calculating the number of luminaires required is only valid if the luminaires are to be mounted overhead in a regular pattern.

The luminous flux output (**lumens**) of each lamp needs to be known as well as details of the luminaires and the reflectivity of the room surfaces.

Usually the illuminance is already specified, for example, office 500 lux, classroom 300 lux, the designer chooses suitable luminaires and then wishes to know how many are required.

The number of lamps required is given by the formula:

$$\boxed{\mathbf{N = \frac{E \times A}{F \times UF \times MF}}}$$

Where: $\text{N} = \text{number of lamps required}$

$\text{E} = \text{illuminance level required (lux)}$

$\text{A} = \text{area at working plane height } (\text{M}^2)$

$\text{F} = \text{average luminous flux from each lamp (lumens)}$

$\text{UF} = \text{utilisation factor, allowance for light distribution and room surfaces}$

$\text{MF} = \text{maintenance factor}$

Example 4

An office measures 50 metres x 20 metres.

Find the number of lamps required if each lamp has a lighting design lumen (LDL) output of 16,000 lumens. The illumination required for the office area is 500 lux. Utilisation factor = 0.4 and lamp maintenance factor = 0.75

$$\mathbf{N} = \frac{\mathbf{E \times A}}{\mathbf{F \times UF \times MF}}$$

$$= \frac{500 \times (50 \times 20)}{16000 \times 0.4 \times 0.75}$$

$$= 104.167$$

$$= \underline{105\ \text{lamps}}$$

Unit 302: Principles of electrical science

Worksheet 14: Illumination

Using your notes, answer the following questions.

1. The unit and symbol for luminous intensity is the:

2. The unit and symbol for luminous flux is the:

3. The unit and symbol for illuminance is the:

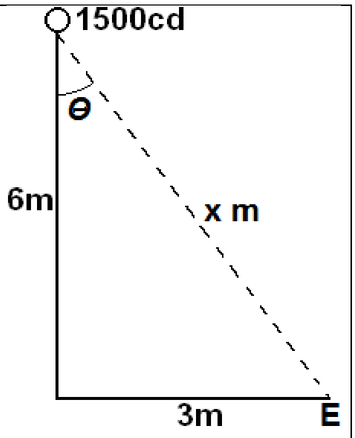
4. With regard to illumination, briefly explain the inverse square law.

5. A lamp of luminous intensity 500 candela is suspended 2 metres above a work area. Calculate the illuminance directly below the lamp.

6. The lamp in question 5 is moved to 3 metres above the work surface. Calculate the illuminance at the work area.

7. With regard to illumination, briefly explain the cosine law.

8. A street lighting column suspends a 1500 cd light source 6m above the ground. Determine the illuminance 3m to one side of the lamp base.



9. A warehouse measures 80 metres x 30 metres.

Find the number of lamps required if each lamp has a Lighting Design Lumen (LDL) output of 18,000 lumens. The illumination required for the warehouse area is 400 lux. Utilisation factor = 0.45 and Lamp Maintenance Factor = 0.7

302: Principles of electrical science

Handout 15: Lighting sources – incandescent

Learning outcome

The learner will:

5. Understand the principles and applications of electrical lighting systems.

Assessment criteria

The learner can:

5.2 explain the operating principles, types, limitations and applications of **luminaires**.

Range

Luminaires: General Lighting Service (GLS): Tungsten, Halogen), Discharge lighting: (Low and high pressure mercury vapour, Low and high pressure sodium vapour, Metal halide), Energy saving (such as compact fluorescent lamps), LED.

Lighting sources – incandescent

In this section we are going to look at the various lighting sources in use along with their applications. Currently, three types of lighting sources are generally available and examples of these are shown below:

Incandescent lamp

Discharge lamp

Light emitting diode (LED) lamp

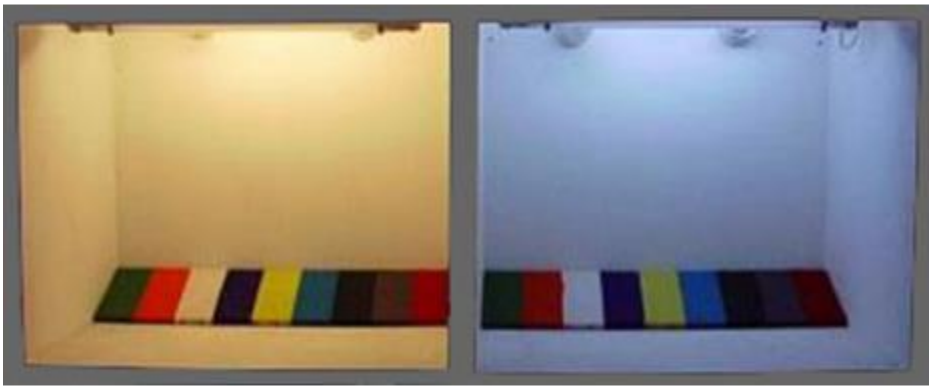
Because lighting plays such an important part of our daily life, it is essential to select the right lighting source for a given application. Not only must we ensure that lighting levels are adequate we must also ensure that colour rendering is satisfactory. Also, in this day and age where energy conservation and the reduction of our carbon footprint is paramount; we must ensure our lighting systems are as efficient as possible.

The efficiency, or as it is referred to in lighting ***'luminous efficacy'*** or just efficacy, allows various light sources to be compared. The luminous efficacy is given as the ratio of lamp lumens/lamp watts and is measured in ***'lumens per watt'*** – the higher the figure the greater the efficacy.

The colour rendering of a light source is an indicator of its ability to show object colours ‘realistically’ or ‘naturally’ compared to a familiar reference source, either incandescent light or daylight. The accepted method is to use the **Colour Rendering Index** (CRI).

The Colour Temperature of a light source defines its ‘whiteness’, its yellowness or blueness.

The Colour Rendering Index (CRI) was created to help indicate how colours appear under different light sources.



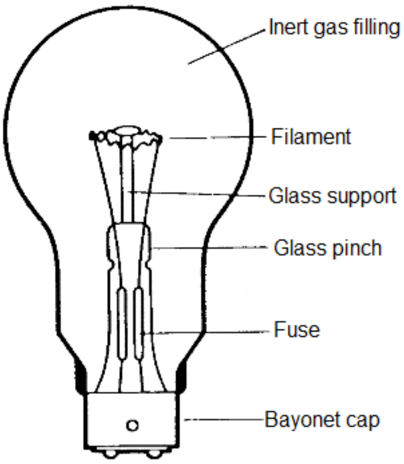
The system was devised some years ago and mathematically compares how a light source shifts the location of eight specified pastel colours as compared to the same colours lighted by a reference source of the same colour temperature. If there is no change in appearance, the source in question is given a CRI of 100 by definition. From 2000K to 5000K, the reference source is the black body radiator (normally an incandescent lamp) and above 5000K, it is an agreed upon form of daylight.

An incandescent lamp, virtually by definition, has a CRI close to 100. This does not mean that an incandescent lamp is a perfect colour rendering light source; it is not. It is very weak in blue, as anyone knows, who has tried to sort out navy blues, royal blues and black under low levels of incandescent lighting. On the other hand, outdoor north sky daylight at 7500K is weak in red, so it isn't a "perfect" colour rendering source either. However, it also has a CRI of 100 by definition.

Technically, CRI's can only be compared for sources that have the same colour temperatures. However, as a general rule *‘the higher the better.* Light sources with high (80-100) CRI's tend to make people and things look better than light sources with lower CRI's.

Why use CRI if it has so many drawbacks? It is the only internationally agreed upon colour rendering system that provides some guidance. It will be used until the scientific community can develop a better system to describe what we really see. It is an indicator of the relative colour rendering ability of a source and should only be used as such.

Incandescent lamp – general lighting service (GLS)



An incandescent lamp produces light with a filament wire, usually tungsten, heated to a high temperature by an electric current passing through it, until it glows. The hot filament is protected from oxidation with a glass bulb that is filled with inert gas (or evacuated).

Incandescent bulbs are manufactured in a wide range of sizes, light output and voltage ratings, from 1.5 volts to about 300 volts. They require no external regulating equipment, have low manufacturing costs and work equally well on either alternating current or direct current. As a result, the incandescent lamp has been used in household and commercial lighting, for portable lighting such as table lamps, car headlamps and flashlights, and for decorative and advertising lighting.

If a straight conductor filament were to be used, the inert gas would have a cooling effect on the conductor. This would result in a loss of light output. By winding the tungsten filament into a fine helical coil, the overall temperature can be raised, improving the light output of the lamp. This efficiency increases further when a coiled coil filament is used.

Due to the high internal temperatures (2000-2500°C) the GLS incandescent lamp suffers with the evaporation of tungsten from the filament. This weakens the filament and over a period of time results ultimately in the filament breaking and the lamp failing. In addition, the evaporated tungsten accumulates on the inside of the bulb and causes a progressive reduction in the light output. Incandescent bulbs are much less efficient than most other types of lighting. Most incandescent bulbs convert less than 5% of the energy they use into visible light, with the remaining energy being converted into heat. The luminous efficacy of a typical incandescent bulb is **16 lumens/watt**, compared to 60 lumens/watt for a compact fluorescent bulb.

Incandescent bulbs also have short lifetimes compared with other types of lighting; average around **1000 hours** for home light bulbs against 10,000 hours for compact fluorescents.

Because of their inefficiency, incandescent light bulbs are gradually being replaced in many applications by other types of electric lights, such as fluorescent lamps, compact fluorescent lamps (CFL), cold cathode fluorescent lamps (CCFL), high-intensity discharge lamps and light-emitting diode lamps (LED). Some jurisdictions, such as the European Union, are in the process of phasing out the use of incandescent light bulbs.

GLS lamp key points

- efficacy ranges between 12 and 18 lumens per watt
- colour rendering index (CRI) 100
- pearl or clear bulb
- can be operated in any position
- average life 1 000 hours for standard GLS lamps
- suitable for dimmer circuits
- no control gear required – connected direct to the source of voltage
- low initial cost
- applications – domestic commercial and industrial uses
- lamp designation – GLS

Incandescent lamp – Tungsten halogen

A halogen lamp, also known as a tungsten halogen lamp or quartz iodine lamp, is an incandescent lamp that has a small amount of a halogen such as iodine or bromine added. The combination of the halogen gas and the tungsten filament produces a **halogen cycle** chemical reaction which redeposits evaporated tungsten back onto the filament, increasing its life and maintaining the clarity of the envelope. Because of this, a halogen lamp can be operated at a higher temperature than a standard gas-filled lamp of similar power and operating life, producing light of a higher luminous efficacy and colour temperature. The small size of halogen lamps permits their use in compact optical systems for projectors and illumination.

Safety

Halogen lamps get hotter than ordinary incandescent lamps because the heat is concentrated on a smaller envelope surface, and because the surface is closer to the filament. This high temperature is essential to their operation. Because the halogen lamp operates at very high temperatures, it can pose fire and burn hazards.

To reduce unintentional ultraviolet (UV) exposure, and to contain hot bulb fragments in the event of explosive bulb failure, halogen lamps usually have a UV-absorbing glass filter over or around the bulb.

Handling precautions

Any surface contamination, notably the oil from human fingertips, can damage the quartz envelope when it is heated. Contaminants will create a hot spot on the bulb surface when the lamp is turned on.

This extreme, localized heat causes the quartz to change from its vitreous form into a weaker, crystalline form that leaks gas. This weakening may also cause the bulb to form a bubble, weakening it and leading to its explosion. Consequently, manufacturers recommend that quartz lamps should be handled without touching the clear quartz, either by using a clean paper towel or carefully holding the porcelain base. If the quartz is contaminated in any way, it must be thoroughly cleaned with alcohol and dried before use.

Tungsten halogen lamp key points

- efficacy ranges between 10 and 30 lumens per watt
- colour rendering index (CRI) 100
- operating position – certain low wattage lamps may be operated in any position while linear lamps may have horizontal operation only (reference should be made to the manufacturer's literature)
- no control gear required – connected directly to the source of voltage
- suitable for dimmer circuits
- more expensive than GLS lamps
- average life 2 000 or 4 000 hours depending on wattage and type
- many applications including – floodlighting, display, security, exhibitions, photographic, general domestic, commercial and industrial uses
- lamp designation – TH.

Unit 302: Principles of electrical science

Worksheet 15: Lighting sources – incandescent

Using your notes, answer the following questions.

1. Describe what is meant by the term ‘colour rendering’ with regard to lighting and how it is generally expressed:

2. Describe how the efficiency of lighting sources can be compared and the units used:

3. What do the initials GLS stand for?

4. What is the operating position for a GLS lamp?

5. What is the operating position for a tungsten halogen lamp?

6. Describe the main safety precautions to be observed with tungsten halogen lamp.

302: Principles of electrical science

Handout 16: Lighting sources – low pressure mercury

Learning outcome

The learner will:

5. Understand the principles and applications of electrical lighting systems.

Assessment criteria

The learner can:

5.2 explain the operating principles, types, limitations and applications of **luminaires**.

Range

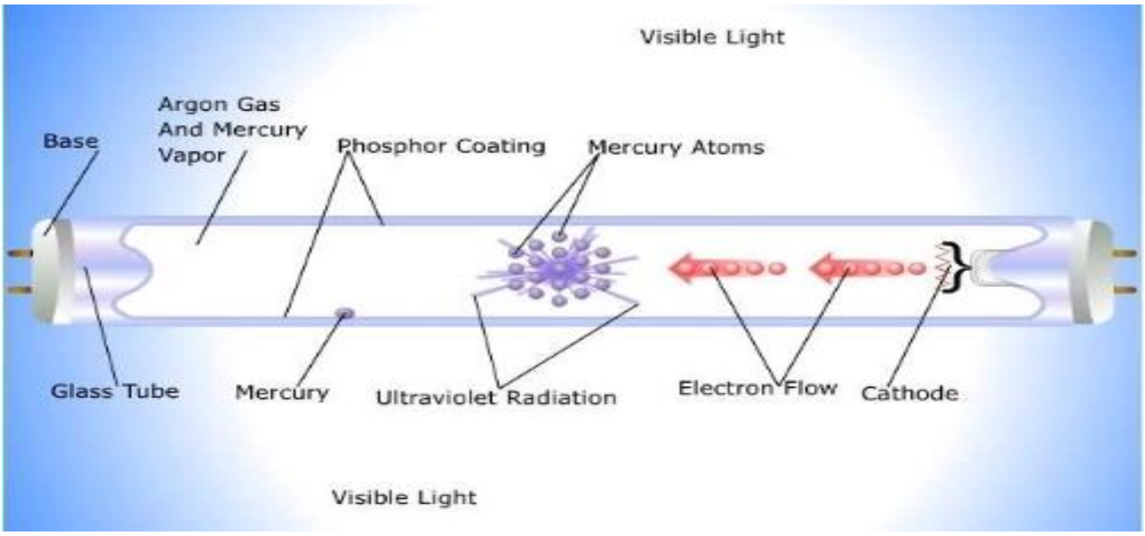
Luminaires: General Lighting Service (GLS): Tungsten, Halogen), Discharge lighting: (Low and high pressure mercury vapour, Low and high pressure sodium vapour, Metal halide), Energy saving (such as compact fluorescent lamps), LED.

Lighting sources – low pressure mercury

Discharge lighting – low pressure mercury

Gas-discharge lamps are a family of artificial light sources that generate light by sending an electrical discharge through an ionized gas.

Typically, such lamps use a noble gas (argon, neon, krypton and xenon) or a mixture of these gases. Most lamps are filled with additional materials, such as mercury, sodium, and metal halides.

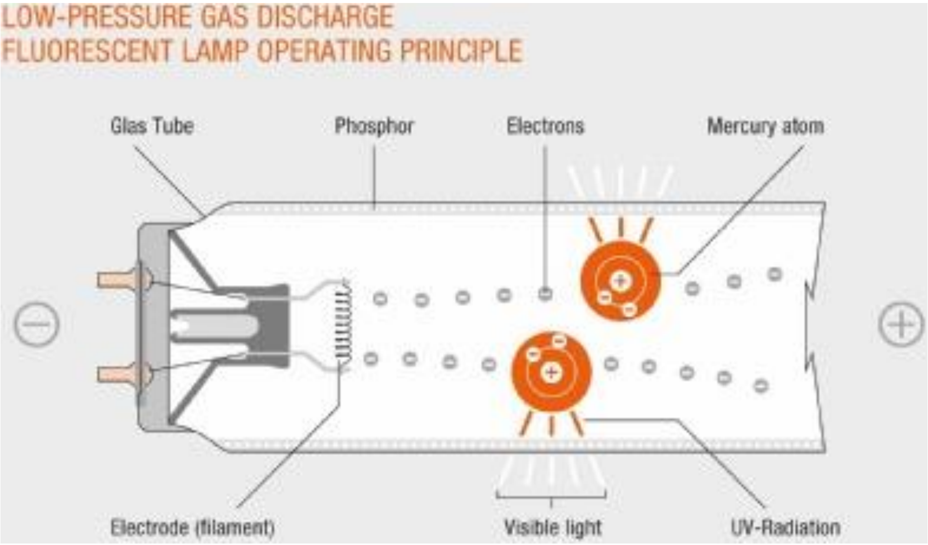


In operation the gas is ionized, and free electrons, accelerated by the electrical field in the tube, collide with gas and metal atoms. Some electrons in the atomic orbitals of these atoms are excited by these collisions to a higher energy state. When the excited atom falls back to a lower energy state, it emits a photon of a characteristic energy, resulting in infrared, visible light or ultraviolet radiation. Some lamps convert the ultraviolet radiation to visible light with a fluorescent coating on the inside of the lamp's glass surface. The fluorescent lamp is perhaps the best known gas-discharge lamp.

Gas-discharge lamps offer long life and high efficiency, but are complicated to manufacture, and they require auxiliary electronic equipment such as ballasts to control current flow through the gas. Due to their greater efficiency, gas-discharge lamps are replacing incandescent lights in many applications.

Low pressure mercury vapour (Fluorescent)

A low pressure mercury vapour lamp, or more commonly, a fluorescent lamp or fluorescent tube, is a gas-discharge lamp that uses electricity to excite mercury vapour. The excited mercury atoms produce short-wave ultraviolet light that then causes a phosphor coating on the glass tube to fluoresce, producing visible light.

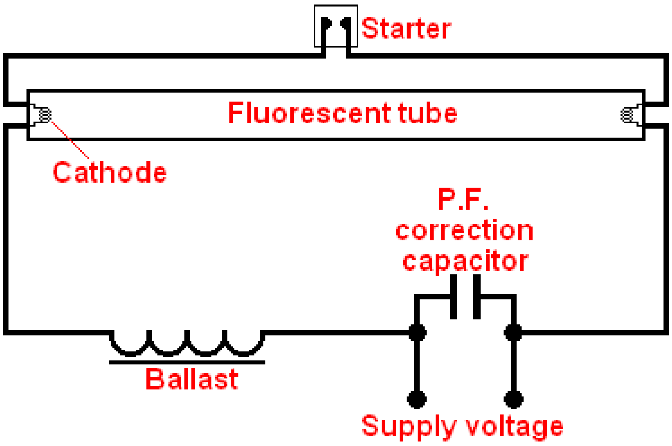


A fluorescent lamp converts electrical power into useful light much more efficiently than incandescent lamps. The luminous efficacy of a compact fluorescent light bulb is about **60 lumens per watt**, four times the efficacy of a typical incandescent bulb. For conventional tube fluorescent lamps, the fitting is more costly because it requires a ballast to regulate the current through the lamp, but the lower energy cost typically offsets the higher initial cost.

There are many types of fluorescent light fitting available including:

- Switch (glow) start
- Quick start
- Semi-resonant
- High frequency.

Switch (glow) start: The circuit for this is shown below along with the contents of a glow starter:



The ionisation of the mercury vapour does not occur spontaneously and must be given a 'kick' from the ballast. This 'kick' is initiated from the starter.

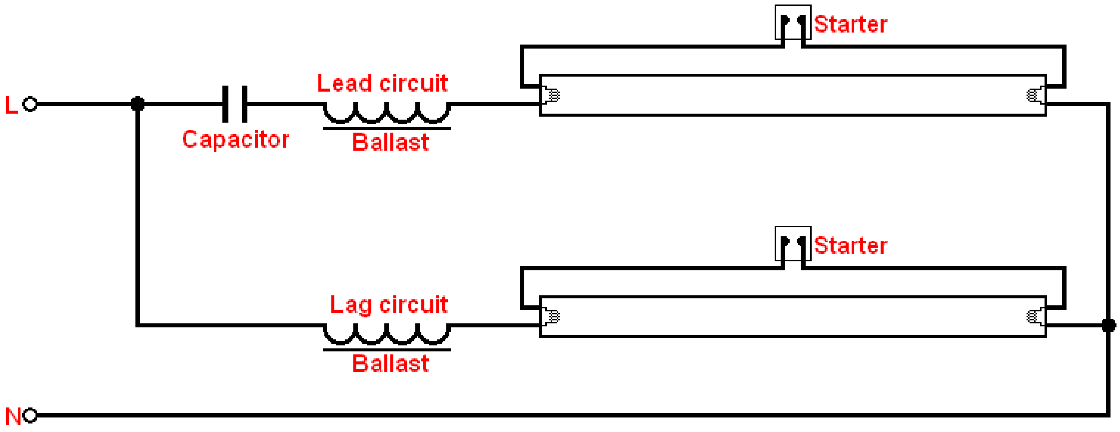
The glow tube (see picture right) incorporates a switch which is normally open. When power is applied, a glow discharge takes place which heats a bimetal contact. A second or so later, the contacts close and provide current to the fluorescent filaments. Since the glow is extinguished, there is no longer any heating of the bimetal and the contacts open. The inductive kick generated at the instant of opening triggers the main discharge in the fluorescent tube. If the contacts open at the wrong time, there isn't enough inductive kick and the process repeats.

Once the tube has 'struck' the resistance across the tube greatly reduces and the starter is no longer required. However, if left unchecked, the current would rise to an unacceptably high value so, after providing the starting kick, the ballast then regulates the current flowing in the circuit.

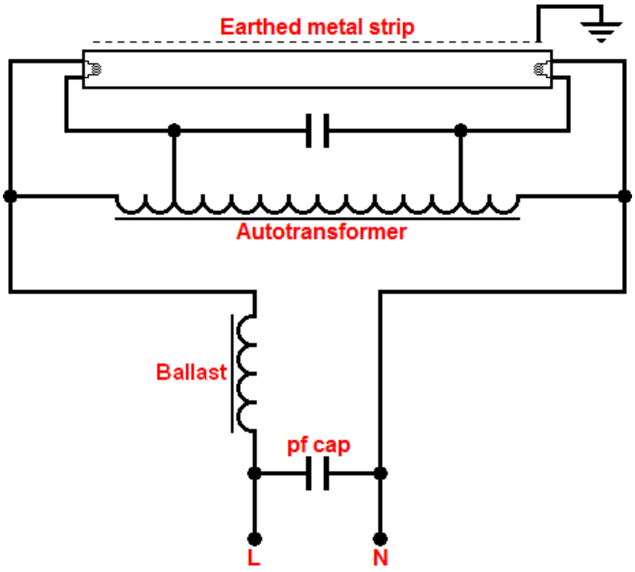
Stroboscopic effect

A fluorescent fitting produces a flicker twice for every cycle of the supply frequency. This is not generally noticeable to the naked eye but may give the impression that rotating machinery is slowing down or even stationary. This is referred to as ***'stroboscopic effect'***.

One way of overcoming the stroboscopic effect is to use a twin ***'lead-lag'*** fitting. This will have one tube wired in the usual way and the other tube wired with a capacitor in series giving it a leading power factor. Whilst the lamps will still flicker these will occur at different times with one filling in the 'darkness' whilst the other is dim. A typical lead-lag circuit is shown below:

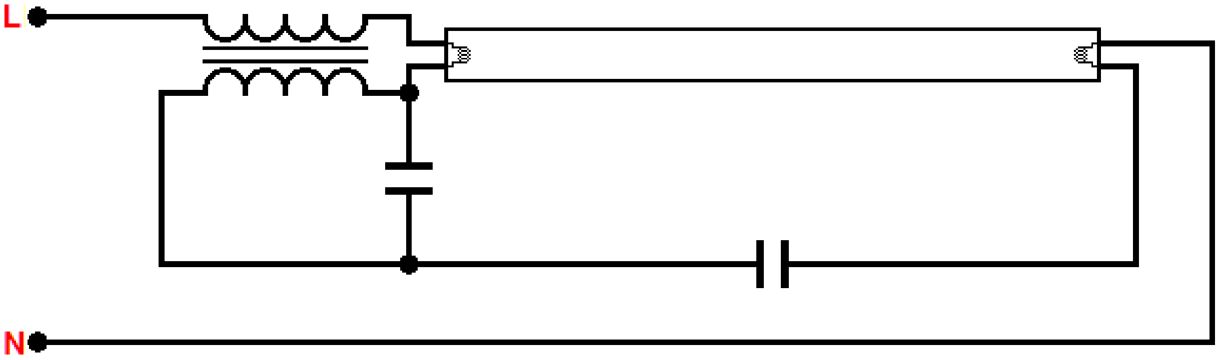


Quick start: The circuit for this is shown below:



Quick-start ballasts use a small auto-transformer to heat the filaments when power is first applied. When an arc strikes, the filament heating power is reduced and the tube will start within half a second. The auto-transformer is either combined with the ballast or may be a separate unit. Tubes need to be mounted near an earthed metal reflector or strip in order for them to strike.

Semi-resonant: The circuit for this is shown below:



This method uses a double wound transformer and a capacitor. With no arc current, the transformer and capacitor resonate at line frequency and generate about twice the supply voltage across the tube and a small electrode heating current. This tube voltage is too low to strike the arc with cold electrodes, but as the electrodes heat up to thermionic emission temperature, the tube striking voltage reduces below that of the ringing voltage and the arc strikes. As the electrodes heat, the lamp slowly, over three to five seconds, reaches full brightness. As the arc current increases and tube voltage drops, the double wound transformer acts as a ballast providing current limiting.

Semi-resonant start circuits are mainly restricted to use in commercial installations because of the higher initial cost of circuit components. However, there are no starter switches to be replaced and cathode damage is reduced during starting making lamps last longer, reducing maintenance costs. Due to the high open circuit tube voltage, this starting method is particularly good for starting tubes in cold locations. Additionally, the circuit power factor is almost 1.0, and no additional power factor correction is needed in the lighting installation.

High frequency electronic ballasts: These devices are basically switching power supplies that eliminate the copper and iron of conventional ballasts with an integrated high frequency inverter or switch.

Simply described, the ballasts contain three sections. A filter that protects the device from the irregularities in the mains supply and prevents RF and other interference to and from the ballast. A second stage that converts the 50Hz AC supply to DC and a third that consists of an inverter that supplies the lamp at high frequency with the correct voltage. This last section also includes a circuit that enables the preheating of the lamp where required and which is important for maximising lamp life.

Properly designed electronic ballasts are very reliable. In practice, reliability generally depends on their location in respect to the heat produced by the lamp, but other factors, such as wild, over voltage fluctuations, spikes etc can also affect them. Since these ballasts include rectification, filtering, and operate the tubes at a high frequency, they usually eliminate the flicker associated with conventional ballasts.

Operating at anywhere between 20 000 and 40 000Hz they consume up to 30% less power whilst producing the same amount of light. They are also quieter, lighter and have the potential for dimming. There is no need for any additional components such as a starter or capacitor and this makes them quick and easy to install.

Amongst the other advantages are the ability to work on 50 or 60Hz and DC voltages, the ability to supply one or more lamps and lamps of different wattages, high power factor and the possibility of developing devices to take into account manufacturers' space and other design limitations.

Compact fluorescent lamps

A compact fluorescent lamp (CFL), also called compact fluorescent light, energy-saving light, and compact fluorescent tube, is a fluorescent lamp designed to replace an incandescent lamp; some types fit into light fixtures formerly used for incandescent lamps. The lamps use a tube which is curved or folded to fit into the space of an incandescent bulb and a compact electronic ballast in the base of the lamp.

Compared to general-service incandescent lamps giving the same amount of visible light, CFLs use one-fifth to one-third the electric power and last eight to fifteen times longer. A CFL has a higher purchase price than an incandescent lamp, but can save over five times its purchase price in electricity costs over the lamp's lifetime. Like all fluorescent lamps, CFLs contain mercury, which complicates their disposal. In many countries, governments have established recycling schemes for CFLs and glass generally.

CFLs radiate a spectral power distribution that is different from that of incandescent lamps. Improved phosphor formulations have improved the perceived colour of the light emitted by CFLs, such that some sources rate the best "soft white" CFLs as subjectively similar in colour to standard incandescent lamps.

Low pressure mercury key points

- efficacy ranges between 38 and 67 lumens per watt
- colour rendering index (CRI) between 51 and 76
- operating position – any position
- can only be dimmed using special ballasts
- control gear required
- average life 9,000 or 10,000 hours depending on wattage and type
- many applications including domestic, commercial and industrial premises.

Unit 302: Principles of electrical science

Worksheet 16: Lighting sources – low pressure mercury

Using your notes, answer the following questions.

1. The colour rendering of a low pressure mercury lamp is:

2. The efficacy of a low pressure mercury lamp is:

3. The average life of in hours of a low pressure mercury lamp is:

4. The purpose of the ballast in a low pressure mercury lamp is to:

5. In the switch start fluorescent fitting, state why a capacitor is placed across the in-coming supply terminals:

6. The light produced by the discharge in a low pressure mercury lamp is ultra-violet, state how this is converted to visible light:

7. Draw a fully labelled circuit diagram of a switch (glow) start low pressure mercury fitting (fluorescent).

302: Principles of electrical science

Handout 17: Lighting sources – high pressure mercury and metal halide

Learning outcome

The learner will:
5. Understand the principles and applications of electrical lighting systems.

Assessment criteria

The learner can:
5.2 explain the operating principles, types, limitations and applications of **luminaires**.

Range

Luminaires: General Lighting Service (GLS): Tungsten, Halogen), Discharge lighting: (Low and high pressure mercury vapour, Low and high pressure sodium vapour, Metal halide), Energy saving (such as compact fluorescent lamps), LED.

Lighting sources – high pressure mercury and metal halide

Discharge lighting – high pressure mercury

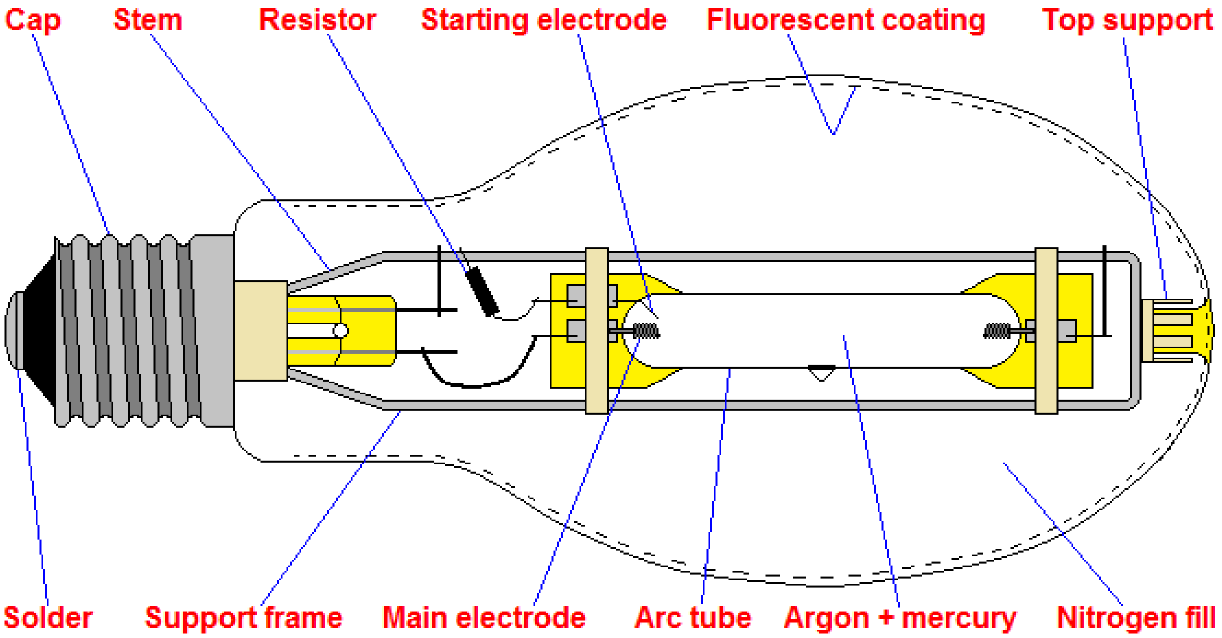
A mercury-vapour lamp is a gas discharge lamp that uses an electric arc through vaporized mercury to produce light. The arc discharge is generally confined to a small fused quartz arc tube mounted within a larger borosilicate glass bulb. The outer bulb may be clear or coated with a phosphor; in either case, the outer bulb provides thermal insulation, protection from the ultraviolet radiation the light produces and a convenient mounting for the fused quartz arc tube.

Mercury vapour lamps are more energy efficient than incandescent and most fluorescent lights, with luminous efficacies of 35 to 65 lumens/watt. Their other advantages are a long bulb life in the range of 24 000 hours and a high intensity, clear white light output. For these reasons, they are used for large area overhead lighting, such as in factories, warehouses, and sports arenas as well as for streetlights.

Clear mercury lamps produce white light with a bluish-green tint due to mercury's combination of spectral lines. This is not flattering to human skin colour, so such lamps are typically not used in retail stores. "Colour corrected" mercury bulbs overcome this problem with a phosphor on the inside of the outer bulb that emits white light. They offer better colour rendition than the more efficient high or low-pressure sodium vapour lamps.

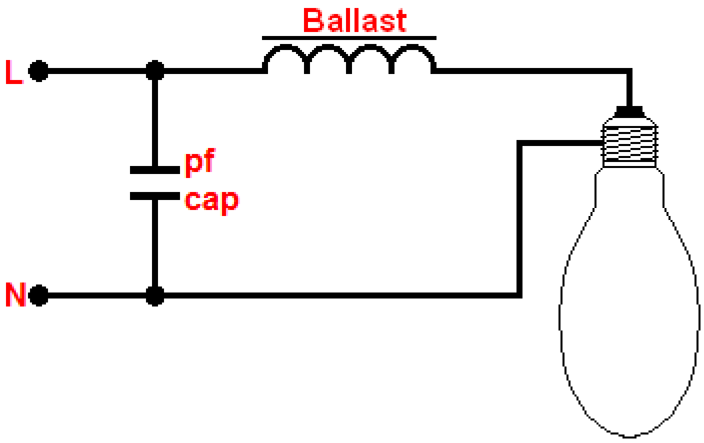
They operate at an internal pressure of around one atmosphere and require special fixtures, as well as an electrical ballast. They also require a warm-up period of 4 – 7 minutes to reach full light output. Mercury vapour lamps are becoming obsolete due to the higher efficiency and better colour balance of metal halide lamps.

How they work



The mercury in the tube is a liquid at normal temperatures. It needs to be vaporized and ionized before the tube will conduct electricity and the arc can start. So, like fluorescent tubes, mercury vapour lamps require a starter, which is usually contained within the mercury vapour lamp itself. A third electrode is mounted near one of the main electrodes and connected through a resistor to the other main electrode. In addition to the mercury, the tube is filled with argon gas at low pressure.

When power is applied, there is sufficient voltage to ionize the argon and strike a small arc between the starting electrode and the adjacent main electrode. This starting arc discharge heats the mercury and eventually provides enough ionized mercury to strike an arc between the main electrodes. This process takes from 4 to 7 minutes, so mercury lamps are slow starting. Some bulbs include a thermal switch which shorts the starting electrode to the adjacent main electrode, extinguishing the starting arc once the main arc strikes.



The mercury vapour lamp is a negative resistance device. This means its resistance decreases as the current through the tube increases. So if the lamp is connected directly to a constant-voltage source like the electricity supply, the current through it will increase until it destroys itself. The lamp, therefore, requires a ballast to limit the current through it. Mercury vapour lamp ballasts are similar to the ballasts used with fluorescent lamps. In fact, the first British fluorescent lamps were designed to operate from 80-watt mercury vapour ballasts.

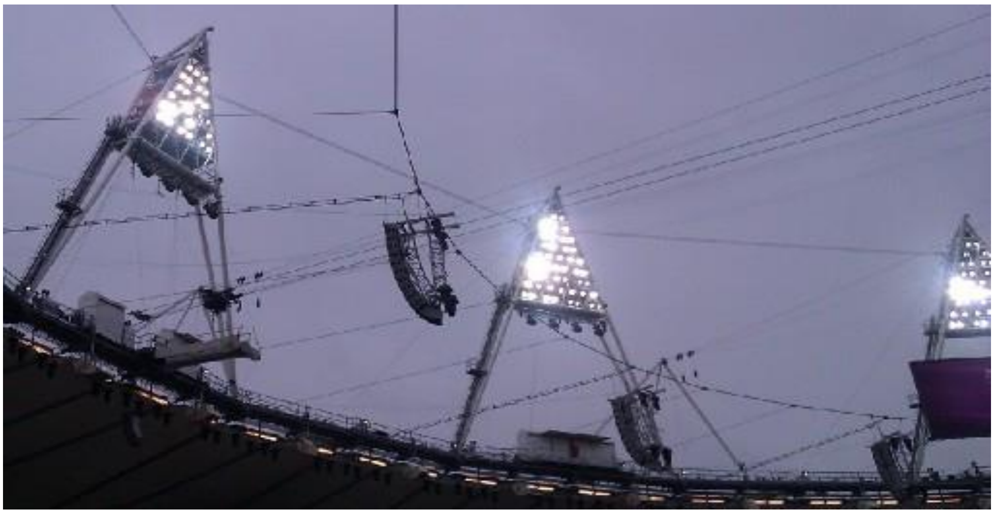
High pressure mercury key points

- efficacy ranges between 35 and 65 lumens per watt
- colour rendering index (CRI) between 17 and 49
- operating position – any position
- will take 4 to 7 minutes to reach full brightness
- after switching off, it will not restart until the pressure inside the lamp has fallen
- control gear required
- average life 24,000 hours
- applications: used where colour rendering is not of major importance, for example street lighting, car parks, floodlighting of buildings, general outdoor commercial and industrial uses.

Discharge lighting – metal halide

A metal-halide lamp is an electric light that produces light by an electric arc through a gaseous mixture of vaporized mercury and metal halides (compounds of metals with bromine or iodine). It is a type of high-intensity discharge (HID) gas discharge lamp. Developed in the 1960s, they are similar to mercury vapour lamps, but contain additional metal halide compounds in the arc tube, which improve the efficiency and colour rendition of the light.

Metal-halide lamps have high luminous efficacy of around 75 - 100 lumens per watt, about twice the efficiency of high pressure mercury vapour lights and 3 to 5 times that of incandescent lights, moderately long bulb life (6,000 to 15,000 hours) and produce an intense white light. As one of the most efficient sources of high CRI white light, metal halides are the fastest growing segment of the lighting industry. They are used for wide area overhead lighting of commercial, industrial, and public spaces, such as car parking, sports arenas, factories, and retail stores, as well as residential security lighting and automotive headlamps (xenon headlights).



The lamps consist of a small fused quartz or ceramic arc tube which contains the gases and the arc, enclosed inside a larger glass bulb which has a coating to filter out the ultraviolet light produced. Like other HID lamps, they operate under high pressure (4 to 20 atmospheres) and require special fixtures to operate safely, as well as an electrical ballast to limit the current once struck. They also require a warm-up period of several minutes to reach full light output, so they are not typically used for residential room lighting, which is turned off and on frequently.

Metal halide key points

- efficacy ranges between 75 and 100 lumens per watt
- colour rendering index (CRI) between 85 and 96
- operating position – any position
- will take about 5 minutes to reach full brightness
- after switching off, it will not restart until the pressure inside the lamp has fallen – about 6 to10 minutes
- control gear required
- average life 6,000 to 15,000 hours
- wide area overhead lighting of commercial, industrial, and public spaces, such as car parking, sports arenas, factories, and retail stores, as well as residential security lighting and automotive headlamps.

Unit 302: Principles of electrical science

Worksheet 17: Lighting sources – high pressure mercury and metal halide

Using your notes, answer the following questions.

1. The colour rendering of a high pressure mercury lamp is:

2. The colour rendering of a metal halide lamp is:

3. The efficacy of a high pressure mercury lamp is:

4. The efficacy of a metal halide lamp is:

5. The purpose of the ballast in a high pressure mercury lamp is to:

6. In both the high pressure mercury and metal halide lamps, state why argon is in the discharge tube:

7. High pressure mercury vapour and metal halide lamps are described collectively as HIDs. What does ‘HID’ stand for?

8. Draw a fully labelled circuit diagram of a high pressure mercury vapour fitting.

302: Principles of electrical science

Handout 18: Lighting sources – low and high pressure sodium

Learning outcome

The learner will:

5. Understand the principles and applications of electrical lighting systems.

Assessment criteria

The learner can:

5.2 explain the operating principles, types, limitations and applications of **luminaires**.

Range

Luminaires: General Lighting Service (GLS): Tungsten, Halogen), Discharge lighting: (Low and high pressure mercury vapour, Low and high pressure sodium vapour, Metal halide), Energy saving (such as compact fluorescent lamps), LED.

Lighting sources – low and high pressure sodium

A sodium vapour lamp is a gas-discharge lamp that uses sodium in an excited state to produce light. There are two varieties of such lamps:

- low pressure
- high pressure.

Low-pressure sodium lamps are the most efficient electrical light sources, but their yellow light restricts applications to outdoor lighting such as street lamps. High-pressure sodium lamps have a broader spectrum of light than the low pressure versions, but poorer colour rendering than other types of lamp. Because sodium vapour lamps cause less light pollution than mercury vapour and metal halide lamps, many areas that have large astronomical observatories use them.

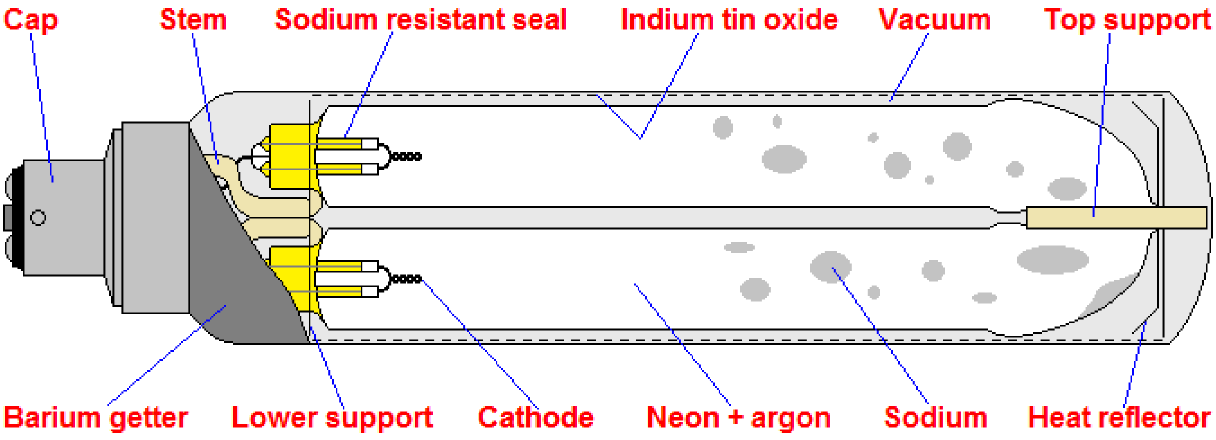
Low pressure sodium

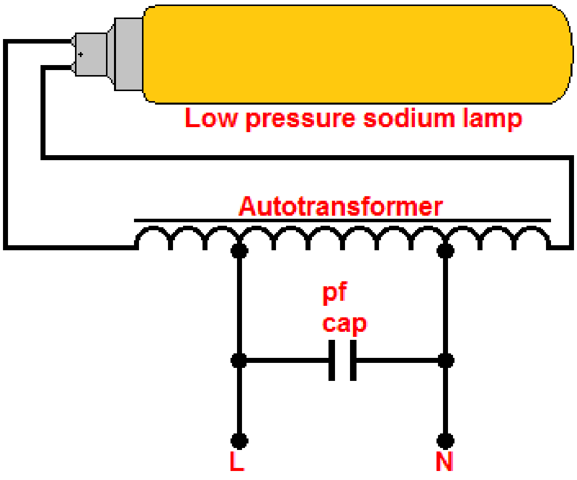
Low-pressure sodium (LPS) lamps have glass gas discharge tube (arc tube) containing solid sodium and a small amount of neon and argon gas to start the gas discharge. The discharge tube may be linear (SLI lamp) or U-shaped. When the lamp is turned on, it emits a dim red/pink light to warm the sodium metal and within a few minutes it turns into the common bright yellow as the sodium metal vaporizes. These lamps produce a virtually monochromatic yellow light. As a result, the colours of illuminated objects are not easily distinguished because they are seen almost entirely by their reflection of this narrow bandwidth yellow light.

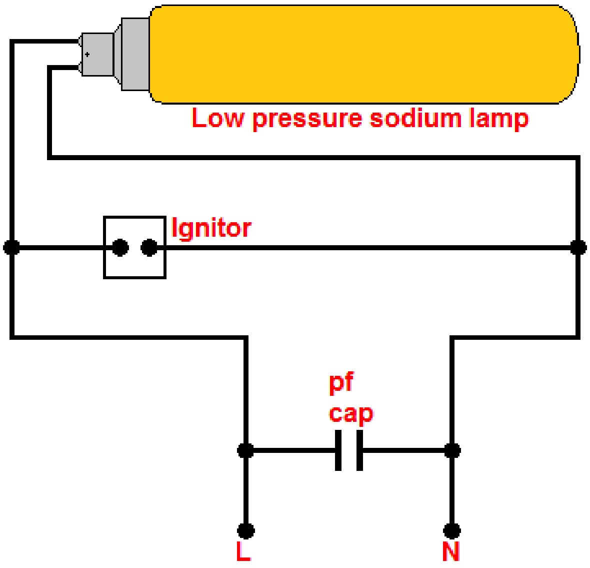
LPS lamps have an outer glass vacuum envelope around the inner discharge tube for thermal insulation, which improves their efficiency. Further improvement was attained by coating the glass envelope with an infrared reflecting layer of indium tin oxide, resulting in SOX lamps.

LPS lamps are the most efficient electrically powered light source - up to 180 lm/W, mainly because the output is light at a wavelength near the peak sensitivity of the human eye. As a result they are widely used for outdoor lighting such as street lights and security lighting where faithful colour rendition was once considered unimportant. Recently, however, it has been found that under conditions typical of night-time driving, whiter light can provide better results at lower power.

Unlike HID lamps, which can go out during a voltage dip, low pressure sodium lamps restrike rapidly to full brightness. LPS lamps are available with power ratings from 10W up to 180W. The, longer bulb lengths, however, create design and engineering problems.







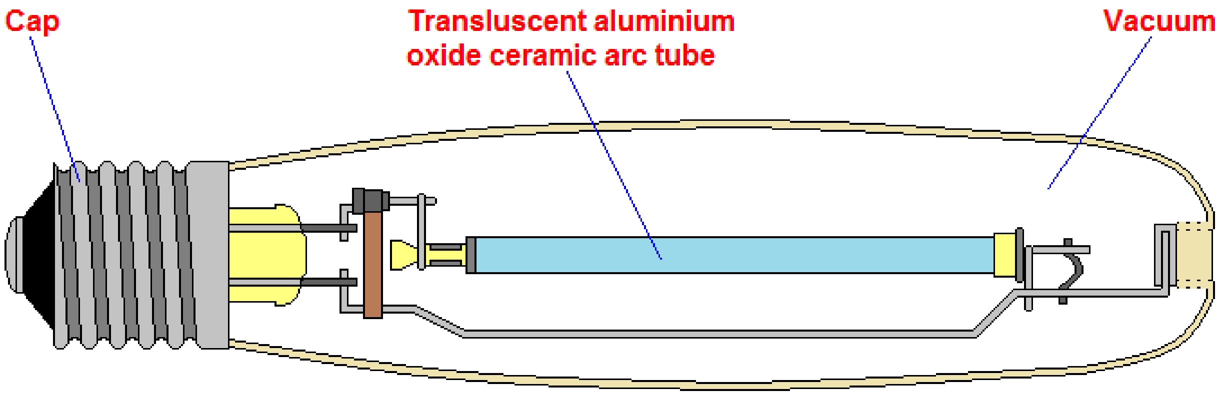
Low pressure sodium key points

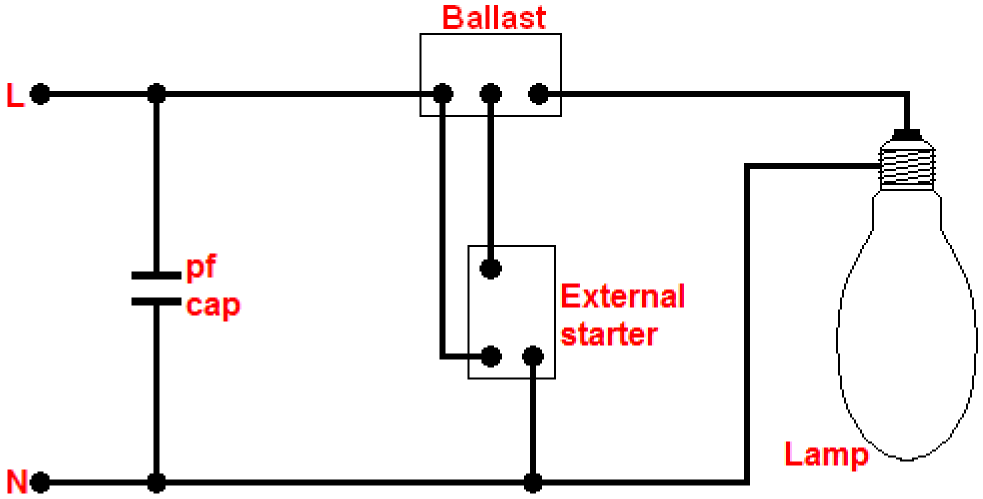
- efficacy up to 180 lumens per watt
- colour rendering index (CRI) –5
- will take time to reach full brightness
- control gear required
- average life 16,000 hours
- applications: used where colour rendering is not of major importance, for example, roadways, motorways (good performance in foggy conditions), car parks, floodlighting of buildings, general outdoor commercial and industrial uses.

High pressure sodium

High-pressure sodium (HPS) lamps are smaller and contain additional elements such as mercury, and produce a dark pink glow when first struck and an intense pinkish orange light when warmed. On account of the emissions from mercury as well as sodium, more colours can be distinguished compared to a low-pressure sodium lamp. This leads them to be used in areas where improved colour rendering is important or desired. Thus, its model name SON is the variant for "sun" (a name used primarily in Europe and the UK).

HPS Lamps are favoured by indoor gardeners for general growing because of the wide colour spectrum produced and the relative efficiency and low running costs.





High pressure sodium lamps are quite efficient—about 100 lm/W. The higher powered versions, of 600W, have an efficacy of 150 lm/W. They have been widely used for outdoor area lighting such as streetlights and security.

Because of the extremely high chemical activity of the high pressure sodium arc, the arc tube is typically made of translucent aluminium oxide.

Xenon at a low pressure is used as a "starter gas" in the HPS lamp. It has the lowest thermal conductivity and lowest ionization potential of all the non-radioactive noble gases. As a noble gas, it does not interfere with the chemical reactions occurring in the operating lamp. The low thermal conductivity minimizes thermal losses in the lamp while in the operating state, and the low ionisation potential causes the breakdown voltage of the gas to be relatively low in the cold state, which allows the lamp to be easily started.

High pressure sodium key points

- efficacy up to 100 lumens per watt
- colour rendering index (CRI) 24
- will take time to reach full brightness
- control gear required
- average life 16 000 hours
- applications: used where colour rendering is not of major importance, for example, industrial installations, street lights, tunnels, underpasses, car parks, courtyards, parks and gardens, buildings, monuments, bridges, horticulture.

Unit 302: Principles of electrical science

Worksheet 18: Lighting sources – low and high pressure sodium

Using your notes, answer the following questions.

1. The colour rendering of a low pressure sodium lamp is:

2. The colour rendering of a high pressure sodium lamp is:

3. The efficacy of a low pressure sodium lamp is:

4. The efficacy of a high pressure sodium lamp is:

5. The purpose of the ballast in a high pressure sodium lamp is to:

6. In the high pressure sodium lamp, state why xenon is in the discharge tube:

7. High pressure mercury vapour and metal halide lamps are described collectively as HIDs. What does ‘HID’ stand for?

8. Draw a fully labelled circuit diagram of a high pressure sodium vapour fitting.

302: Principles of electrical science

Handout 19: Lighting sources – Light emitting diode (LED)

Learning outcome
The learner will:
5. Understand the principles and applications of electrical lighting systems.

Assessment criteria
The learner can:
5.2 explain the operating principles, types, limitations and applications of **luminaires**.

Range
Luminaires: General Lighting Service (GLS): Tungsten, Halogen), Discharge lighting: (Low and high pressure mercury vapour, Low and high pressure sodium vapour, Metal halide), Energy saving (such as compact fluorescent lamps), LED.

Lighting sources – Light emitting diode (LED)

LED lamps differ from traditional incandescent bulbs in the way they produce the light. LEDs produce light through the use of semi-conductors and are some of the most efficient lamps on the market, using around 90% less energy than incandescent bulbs.

LED lamps have been around for many years, typically used in gadgets such as digital clocks, TV remotes and as Christmas lights.

But because they have not been widely used for home lighting, they tend to be the most expensive type of energy-saving lamp. However, the technology behind LED lights is developing quickly so they are now cheaper than they used to be.

Benefits of LEDs

- use 90% less energy than incandescent lamps (CFLs use 60%-80% less than incandescent lamps, and halogens use 20-30% less)
- can last for 25-30 years, dependent on use
- give out their light quickly at start-up, so it's not necessary to put up with a few moments of dim light when turned on
- lights don't contain mercury (CFLs do, although it's only a small amount)
- LED lights, like halogens, work fine in low temperatures, whereas CFLs do not.

Until recently, LED light bulbs have generally only been available in lower wattages and lumen levels than other types of lamps. Although they are quick to reach their full brightness and suffer no decrease in performance over time, they are often only available in dimmer varieties than CFL and halogen bulbs. The range of LED lamps is, however, improving all the time, with brighter LEDs becoming increasingly available.

Some people don't like the quality of light given out by LED light bulbs, as they tend to produce a cooler bluish light, so take this into consideration when choosing the best one for the customer.

LED lamps can be made interchangeable with other types of lamps. Assemblies of high power light-emitting diodes can be used to replace incandescent or fluorescent lamps. Some LED lamps are made with bases directly interchangeable with those of incandescent bulbs. For example, the Edison screw base, an MR16 shape with a bi-pin base, or a GU5.3 (bi-pin cap) or GU10 (bayonet socket).

Since the luminous efficacy (amount of visible light produced per unit of electrical power input) varies widely between LED and incandescent lamps, lamps are usefully marked with their lumen output to allow comparison with other types of lamps. LED lamps are sometimes marked to show the watt rating of an incandescent lamp with approximately the same lumen output, to help consumers when choosing a lamp that will provide a similar level of illumination.

Efficacy of LED devices continues to improve, with some chips able to emit more than 100 lm/W. LEDs do not emit light in all directions and their directional characteristics affect the design of lamps. The efficacy of conversion from electric power to light is higher than for incandescent lamps, but since the light output of many types of light-emitting diodes is small compared to incandescent and compact fluorescent lamps, in most applications, multiple diodes are assembled.

Light-emitting diodes use direct current (DC) electrical power. To use them on AC power they are operated with internal or external rectifier circuits that provide a regulated current output at low voltage. LEDs are degraded or damaged by operating at high temperatures, so LED lamps typically include heat dissipation elements such as heat sinks and cooling fins.

General purpose lighting needs white light. LEDs emit light in a very small band of wavelengths, emitting light of a colour characteristic of the energy bandwidth of the semiconductor material used to make the LED. To emit white light from LEDs requires mixing light from red, green, and blue LEDs, or using a phosphor to convert some of the light to other colours.

LED tubes are made that are pin-compatible with, and designed to replace, standard fluorescent tubes. Most LED tubes available can be used in place of T8, T10, or T12 tube designations, in lengths of 2, 4, and 8 feet. Some LED tubes are designed to drop directly into an existing fixture, while others require rewiring of the fixture to remove the ballast. An LED tube generally uses many individual LEDs to point light downward toward the subject. This differs from most fluorescent tubes that create light 360 degrees around the centre axis of the tube, which the fixture then reflects downward.

In 2013, Philips announced they had developed the world's most energy-efficient LED tube, producing 200 lm/W compared with a standard 100 lm/W achieved with traditional strip lighting.

LED key points

- efficacy up to 200 lumens per watt
- colour rendering index (CRI) 70-90
- full brightness achieved immediately
- no control gear required
- average life 30 000 hours
- applications: can replace lighting in many domestic and commercial situations.

Unit 302: Principles of electrical science

Worksheet 19: Lighting sources – light emitting diode (LED)

Using your notes, answer the following questions.

1. The colour rendering of LED lamps is:

2. The efficacy of LED lamps is:

3. State the main disadvantage currently of LEDs lamps:

4. State the **five** benefits of LEDs lamps:

302: Principles of electrical science

Handout 20: Electrical components

Learning outcome

The learner will:

4. Understand the operating principles of electrical components.

Assessment criteria

The learner can:

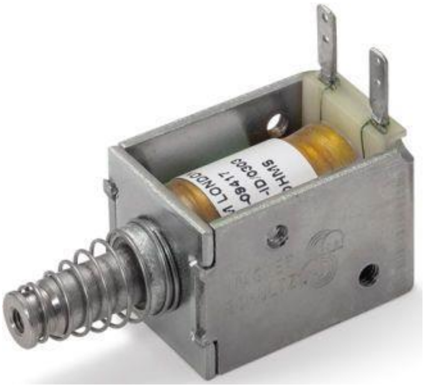
4.1 specify the main types and operating principles of **electrical components**.

Range

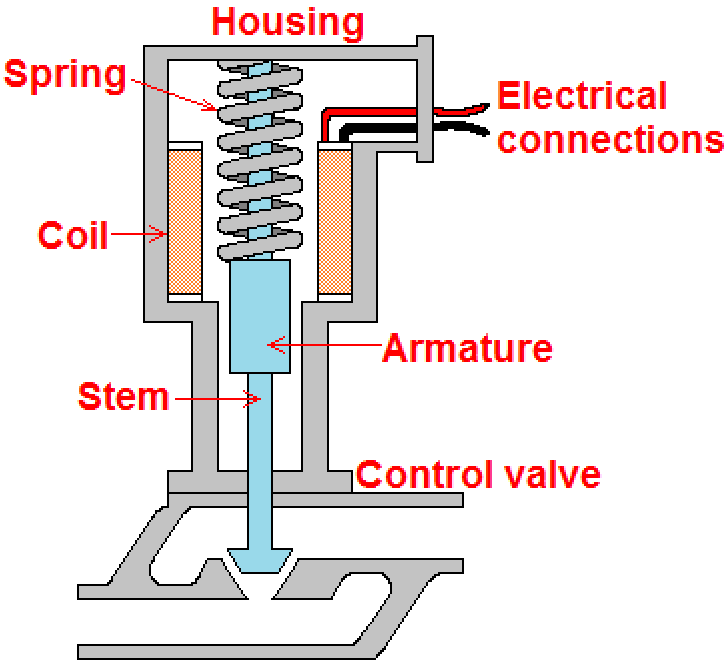
Electrical components: Contactors, Relays, Solenoids, Over-current protection devices: (Fuses [HRC, cartridge and re-wireable], Circuit-breakers, RCBOs), RCDs.

Electrical components

Solenoids



The term refers to a variety of transducer devices that convert electrical energy into linear motion. The term is also often used to refer to a solenoid valve, which is an integrated device containing an electromechanical solenoid which actuates either a pneumatic or hydraulic valve, or a solenoid switch, which is a specific type of relay that internally uses an electromechanical solenoid to operate an electrical switch; for example, an automobile starter solenoid.



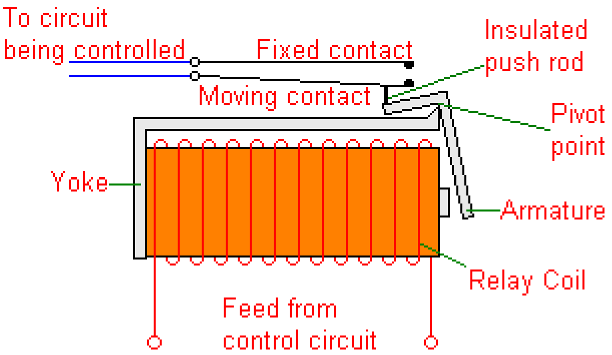
Electromechanical solenoids consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature). The coil is shaped such that the armature can be moved in and out of the centre, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve).

Although typically weak over anything but very short distances, solenoids may be controlled directly by a controller circuit, and thus have very low reaction times.

Relays

A relay is an electro-magnetic device that has many uses but mainly in control circuits where small control currents are used to switch large load currents. A typical relay is shown in the diagram right.

The basic relay consists of a coil wound around a soft iron core which is connected to a soft iron yoke. Pivoted on the end of the yoke is an armature, also made of soft iron.

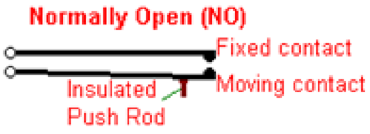


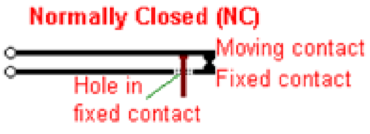
When the relay coil is energised, it magnetises and the armature is then attracted to the pole face; the insulated push rod at the top of the armature will then operate contacts on the contact set.

When the supply to coil is removed, the coil will demagnetise, the armature will return to its original position and the contacts will also return to their original position.

The magnetic circuit is made of soft iron, as this magnetises easily when the magnetic field is established but loses its magnetism when the coil is de-energised.

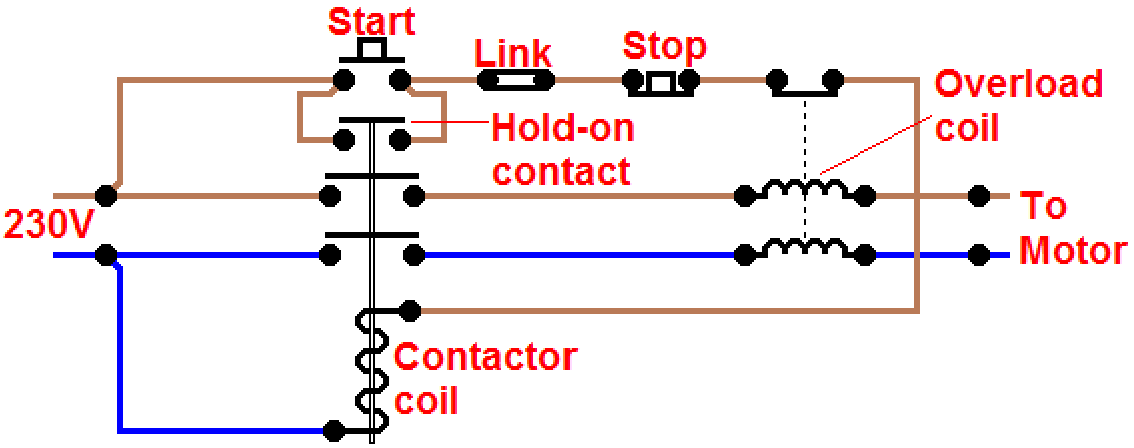
More than one set of contacts can be operated simultaneously from the armature, controlling a number of different circuits at the same time. A ‘**normally open**’ contact is shown in the diagram above but many combinations can be incorporated on the same relay, including normally open, normally closed, changeover and make before break, just to mention the more common arrangements. Some of these are shown below:





A contactor is basically a heavy-duty relay and works to the same general principle, ie an electromagnet energising and causing an armature to be attracted, thus operating contacts, and, when de-energised, moving the contacts back to their ‘normal’ position.

In most applications, relay contacts shown on diagrams are normally shown in the de-energised position. The diagram below shows a circuit diagram for a typical direct-on-line motor starter employing a contactor.



Unit 302: Principles of electrical science

Worksheet 20: Electrical components

Using your notes, answer the following questions.

1. Briefly describe the operation of a solenoid.

2. Briefly describe the operation of a relay.

302: Principles of electrical science

Handout 21: Protective devices

Learning outcome

The learner will:

4. Understand the operating principles of electrical components.

Assessment criteria

The learner can:

4.1 specify the main types and operating principles of **electrical components**.

Range

Electrical components: Contactors, Relays, Solenoids, Over-current protection devices: (Fuses [HRC, cartridge and re-wireable], Circuit-breakers, RCBOs), RCDs.

Protective devices

Overcurrent protective devices

It is necessary to install protective devices in circuits for when faults occur, to provide protection against electric shock and also protection to ensure the premises and wiring systems are not damaged as a result of, for example, fire.

Faults will generally cause one or both of the following to occur:

- overcurrent
- earth leakage.

Overcurrent

An overcurrent is defined in BS 7671:2018 as ***'a current exceeding the rated value. For conductors the rated value is the current-carrying capacity'*** (page 34).

Protection against overcurrent can be provided by a fuse, circuit breaker or a residual current operated circuit breaker with integral overcurrent protection (RCBO).

Overcurrent can be further subdivided into two categories:

- overload current
- fault current.

BS 7671:2018 defines an overload current as ***'an overcurrent occurring in a circuit which is electrically sound'*** (page 34). This generally occurs when a circuit is abused, eg too many appliances plugged in to socket outlets, or it was badly designed or modified or a machine is trying to drive a mechanical load that is too much for that machine. An overload normally results in an overcurrent up to two to three times the rated value of the circuit.

BS 7671:2018 defines a fault current as ***'a current resulting from a fault'*** (page 30). A fault is further defined as ***'a circuit condition in which current flows through an abnormal or unintended path. This may result from an insulation failure or a bridging of insulation. Conventionally the impedance between live conductors or between live conductors and exposed- or extraneous-conductive-parts at the fault position is considered negligible'*** (page 30). A fault current can be many hundreds of times the rated current of the circuit.

In either case, the purpose of circuit protection is to interrupt the circuit quickly before damage is caused to the installation, as well ensuring that the risk of electric shock is removed. To achieve this, protective devices are placed in the line conductor(s).

Earth leakage

In BS 7671:2018, earth leakage is referred to as 'protective conductor current' and is defined as an ***'electric current appearing in a protective conductor, such as leakage current or electric current resulting from an insulation fault'*** (page 34).

Protection against earth leakage can be provided by a fuse, circuit breaker, a residual current operated circuit breaker with integral overcurrent protection (RCBO) or a residual current device (RCD).

Whilst the most common cause of earth leakage is as a result of an insulation fault, it must be borne in mind that some equipment, eg computer power supplies, are naturally 'leaky'. If a number of similar pieces of equipment are connected to the same circuit, the earth leakage current could reach dangerously high levels as their effect will be cumulative.

Some typical current levels (ac) and their effect on the average human body are given below:

- 1mA – perception level (you would start to feel a slight 'tingle').
- 10–15mA - can cause powerful muscle contractions; the victim is unable to voluntarily control muscles and cannot release an electrified object.
- >30mA – can cause ventricular fibrillation, which can lead to cardiac arrest.

Fuses

BS 3036 semi-enclosed fuse

Also referred to as a re-wireable fuse.

These were commonly used but due to their inferior protection characteristics resulting in cables having to be de-rated, they are now very rarely installed. However, there will still be numerous installations that are protected by these devices.

A fuse wire is connected between the two blades and provides a 'weak link' in the circuit. When a certain current flows through this wire it will become hot and melt and will break the circuit.

Available sizes:

- 5A (white)
- 15A (blue)
- 20A (yellow)
- 30A (red)
- 45A (green)

Advantages of BS 3036 fuses

- Simple to check if blown
- Low cost to replace fuse element
- No moving parts

Disadvantages of BS 3036 fuses

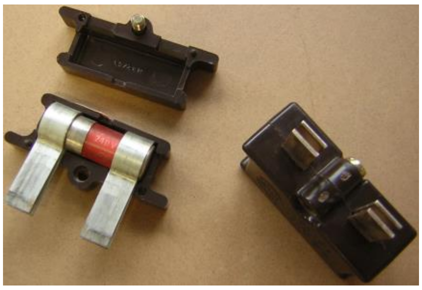
- Danger of being repaired with wrong size wire
- Deteriorate with age
- Circuit cannot be quickly restored
- Cannot break large fault currents
- Danger if replaced on faulty circuit (melting wire)
- Fusing factor of around 1.8–2.0 means that operation cannot be guaranteed if less than twice the rated current is flowing. As a result cables protected by them must have a larger current-carrying capacity.

BS 88-3:2010 cartridge fuses (replacing BS 1361)

These cartridge fuses are for use by unskilled persons mainly for household and similar applications.

The cartridge fuse breaks a faulty circuit in the same way as a semi-enclosed fuse, but its construction eliminates some of the disadvantages experienced with an open fuse element.

The cartridges are manufactured such that higher rated fuses are physically larger in size; this is done to minimise the risk of replacing a blown fuse with an overrated cartridge.



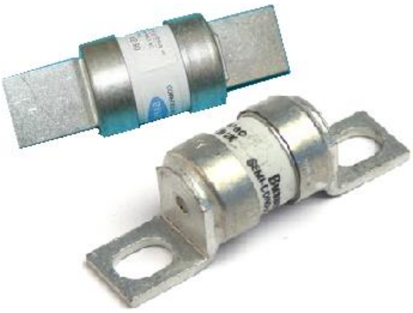
Advantages of BS 88-3:2010 fuses

- Small physical size
- No mechanical moving parts
- Accurate current rating
- Not liable to deterioration with age
- Fusing factor 1.6 – 1.9

Disadvantages of BS 88-3:2010 fuses

- More expensive than re-wireable
- Can be shorted by silver foil
- Cannot safely break fault currents over 31.5kA

BS 88-2:2010 fuses (replacing BS 88-2 and BS 88-2.1)



These cartridge fuses are for use by authorised persons, mainly for industrial applications and include bolted and clip type.

These generally have a high current breaking capacity and are often referred to as HBC fuses (high breaking capacity) formerly HRC (high rupturing capacity).

These fuses can be classified as either gG or gM depending on their intended usage.

The difference between the two is that gG fuses are general purpose and gM are motor rated.

A gG fuse will have a single rating, eg 20A which means it can carry 20 amperes indefinitely.

A gM fuse will have a double rating, eg 20M32. The first figure will be the continuous current rating whilst the second figure is a short-term characteristic that will allow the motor starting current to subside before the device operates.

Motor rated fuses are handy because you can use smaller rated cables and switchgear.

Advantages of BS 88-2 fuses

- No mechanical moving parts
- Declared rating is very accurate
- Operation is very quick
- gM fuses, can distinguish between a persistent fault and a transient fault such as the large starting current taken by motors
- Reliable–can break large current safely
- Fusing factor 1.25–1.70

Disadvantages of BS 88-2 fuses

- Expensive

BS 1362 cartridge fuses

These cartridge fuses are especially for use in the standard UK BS 1363 13 ampere plug top.

This cartridge fuse breaks a faulty circuit in the same way as other fuses, ie by the internal fuse wire melting when current becomes excessive.

When the BS 1363 plug was first introduced, there were 5 fuses in the official BS1362 range which were (with their specified colour): 2 (blue), 5 (grey), 7 (black) 10 (yellow), and 13 (brown) amps.

The current version, BS 1362:1973, allows any fuse rating up to 13A, with 3 amp (coloured red) and 13 amp (coloured brown) as the preferred (but not mandated) values when used in a plug. All other ratings to be coloured black (this is why 5 amp fuses are now black instead of grey).

The purpose of the plug-mounted fuse is to protect the flexible cord, NOT the appliance itself.

Circuit breaker to BS EN 60898

With their continual reduction in cost, circuit breakers (CB) are for most electricians the most common type of protective device installed.

BS EN 60898 includes ratings up to 100A and maximum fault capacities of 9kA.

CBs provide much closer overcurrent protection compared to traditional fuses and it is much easier to reset the circuit when the fault is cleared.

Formerly referred to as ‘miniature circuit breakers’ (MCB) they are now simply referred to as ‘circuit breakers’ (CB).

Advantages of BS EN 60898 CBs

- Tripping characteristics and therefore circuit protection are set by the installer
- Circuit protection difficult to interfere with
- The circuit provides discrimination
- A faulty circuit may be easily and quickly restored by an unskilled operator.

Disadvantages of BS EN 60898 CBs

- They contain mechanical moving parts.

Circuit breakers' (CBs) two means of tripping:

- Thermal trip that operates relatively slowly and is ideal for detecting overload currents
- Magnetic tripping device that operates very quickly and is ideal for detecting fault currents.

A typical circuit breaker is shown to the right:

1. Box terminal
2. Thermal element
3. Magnetic hammer action solenoid
4. Arc chamber
5. Trip bar
6. Moving contact
7. Fixed contact
8. DIN clip

Circuit breakers are graded according their tolerance to overload and this is summarised in the table below which is Table 7.2.7(ii) from the IET On-Site Guide (BS 7671:2018 – page 80):

Table 7.2.7(ii) Application of circuit breakers

Circuit-breaker type	Trip current (0.1 s to 5 s)	Application
1	**2.7 to 4 I_n**	**Domestic and commercial installations having little or no switching surge**
B	**3 to 5 I_n**	
2	**4 to 7 I_n**	**General use in commercial/industrial installations where the use of fluorescent lighting, small motors, etc., can produce switching surges that would operate a Type 1 or B circuit breaker. Type C or 3 may be necessary in highly inductive circuits such as banks of fluorescent lighting.**
C	**5 to 10 I_n**	
3	**7 to 10 I_n**	
4	**10 to 50 I_n**	**Not suitable for general use.**
D	**10 to 20 I_n**	**Suitable for transformers, X-ray machines, industrial welding equipment, etc., where high inrush currents may occur.**

Note: I_n is the nominal rating of the circuit-breaker.

Whilst you will encounter types 1, 2, 3 and 4 already installed, these types are now not available. The recognised types readily available are types B, C and D.

Residual current device (RCD) BS EN 61008

All the devices mentioned so far will provide protection against both overcurrent and earth leakage. However, to provide earth leakage protection with these devices requires a large current to flow to earth.

To detect much smaller leakage currents that could still be lethal to life, an RCD must be used.

An RCD compares the current flowing out through the line conductor with the current returning through the neutral; if the current exceeds a predetermined value, the device will trip and disconnect the circuit.

The rated value is referred to as the $I_{\Delta n}$ and is usually rated in mA.

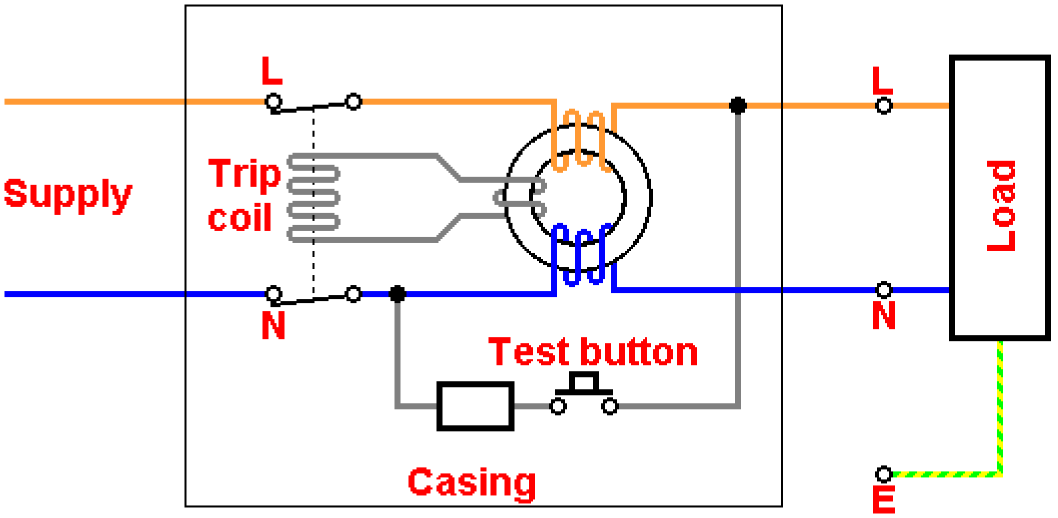
Until the introduction of the 17th Edition of BS 7671 the use of RCDs was generally limited to protecting socket outlets feeding appliances used outside the premises.

However, it is now likely that most circuits will require RCD protection including the following:

- Locations containing a bath or shower (Regulation 701.411.3.3 – page 241)
- Socket circuits with a rated current less than 32A (Regulation 411.3.3 – page 59)
- Mobile equipment with a current rating not exceeding 32A for use outdoors (Regulation 411.3.3 – page 59)
- Where cables are concealed in walls at a depth less than 50mm without mechanical protection (Regulation 522.6.202 – page 139).

This list shows examples of use and is not exhaustive.

The diagram below shows the internal circuit arrangement which has been drawn to best show the operation of the RCD:



IMPORTANT NOTE: An RCD does **NOT** provide overcurrent protection – it will only provide earth leakage protection.

Residual current operated circuit breaker with integral overcurrent protection (RCBO) BS EN 61009

An RCBO is a combination of a thermal-magnetic circuit breaker and an RCD that enables both overcurrent protection and earth fault protection to be provided in a single unit for individual circuits, usually, but not exclusively in domestic installations.

The major advantage is that this allows earth fault protection to be restricted to a single circuit and therefore only the circuit with the fault is interrupted thus providing better discrimination.

With most devices, two additional wires must be connected for this device to function. One wire connects to the neutral block whilst the other connects to the earth block. However, there are RCBOs on the market that do not need an earth connection.

RCBOs are available in types B and C but not in type D.

Unit 302: Principles of electrical science

Worksheet 21: Overcurrent protective devices

Using your notes, answer the following questions.

1. What is meant by the term 'overcurrent'?

2. Overcurrent can be subdivided in to **two** categories. These categories are:

3. What is meant by the term 'overload current'?

4. What is meant by the term 'fault current'?

5. What is meant by the term 'protective conductor current'?

6. List the **five** sizes of BS 3036 fuses including their colours.

7. State **three** advantages of BS 3036 fuses.

8. State **three** disadvantages of BS 3036 fuses.

9. State **three** advantages of BS 88-3:2010 fuses.

10. State **three** disadvantages of BS 88-3:2010 fuses.

11. State **three** advantages of BS 88-2:2010 fuses.

12. State a disadvantage of BS 88-2:2010 fuses.

13. State **three** advantages of BS EN 60898 circuit breakers.

14. State a disadvantage of BS EN 60898 circuit breakers.

15. State the **three** type classifications of circuit breakers currently available.

16. State the general principle of operation of an RCD.

302: Principles of electrical science

Handout 22: Electricity generation

Learning outcome

The learner will:

1. Understand electrical supply systems.

Assessment criteria

The learner can:

1.1 describe how electricity is generated and transmitted for domestic and industrial/commercial consumption.

Electricity generation

Electricity is a vital part of our everyday lives in the United Kingdom and, compared with the rest of the world, we are large consumers. For example, although the UK accounts for less than 1% of the global population, in 2008 it used 2% of the total electrical energy generated in the world.

There are many means available to generate electricity, including the following:

- coal
- oil
- biomass
- wind
- wave
- hydro
- nuclear
- photo-voltaic
- gas
- micro-generation.

Each has its advantages and disadvantages. We generally cannot choose where the electricity that comes from the supply company is generated; this will be a combination of the methods listed above.

However, we need to be able to give advice to customers who may want to install their own small-scale generation systems in their premises, such as biomass, wind or photo-voltaic, which can all fall under the category of micro-generation.

Coal

During the 1940s some 90% of the UK generating capacity was fired by coal, with oil providing most of the remainder. By 2004 the use of coal-fired power stations had dropped to about 40% of the total generating capacity.

Coal-fired power stations burn coal that heats water and produces steam, which powers turbines connected to generators.

The biggest problems with the use of coal are:

- it uses non-renewable fossil fuels
- it produces a lot of air pollution
- it requires large quantities of cooling water.

Oil

The use of oil to generate electricity has dropped considerably and by 2004 had dropped to just over 1% of the total generating capacity.

Larger oil-fired power stations produce electricity in a similar manner to coal, but instead they burn oil to heat water that produces steam, which powers turbines connected to generators.

On a smaller scale, generators can be powered by internal combustion engines (petrol or diesel) and these are used frequently on-site. Alternatively, some power stations that can be run-up quickly to meet transient demand, are powered by aero gas turbines driving generators.

The biggest problems with the use of oil are:

- it uses non-renewable fossil fuels
- it produces air pollution
- larger stations require large quantities of cooling water.

Biomass

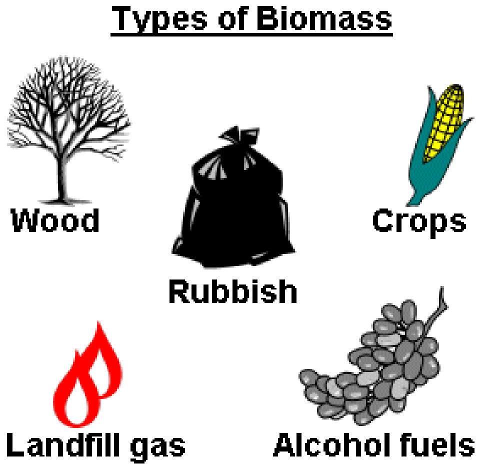
Biomass is biological material derived from living or recently living organisms. In the context of biomass for energy, this is often used to mean plant-based material, but biomass can equally apply to both animal- and vegetable-derived material.

It usually involves the burning of organic material to heat water for local hot water supplies (hot water and central heating) or to produce steam to power generators.

These generators can be either small scale ‘micro-generation’ or much larger plants feeding into the National Grid.

It is also possible to produce ‘bio-fuel’ for use in internal combustion engines to power generators.

Biomass is currently the largest source of renewable energy in the UK.



Wind

Wind power currently constitutes the second largest source of renewable energy in the UK with over 5 gigawatts capacity in 2010 and still increasing.

Whilst generating, the turbines produce no pollution. However, provision must be made for ‘windless’ days when the turbines will not be generating.

The installation and maintenance costs are quite high and the turbines will require replacing after 20–25 years.

There are aesthetic implications of land-based wind turbines, with a large number of the population objecting to them being built near their homes.

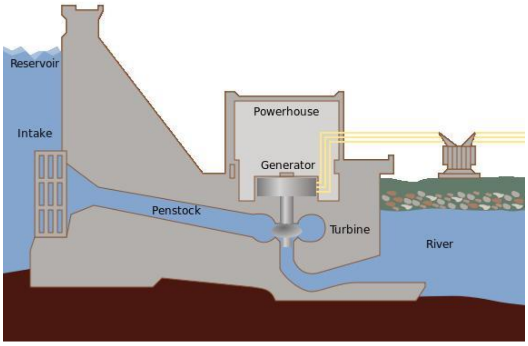
Individual consumers can supplement their electrical supply by installing small scale wind generators (C.1-2kW).

Wave

Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work, such as electricity generation, water desalination, or the pumping of water (into reservoirs). Machinery able to exploit wave power is generally known as a wave energy converter (WEC).

Wave-power generation is not currently a widely employed commercial technology, although there have been attempts to use it since at least 1890. In 2008, the first experimental wave farm was opened in Portugal, at the Aguçadoura Wave Park. The major competitor of wave power is off-shore wind power.

Hydro



Hydroelectricity is the term referring to electricity generated by hydropower. This is the production of electrical power through the use of the gravitational force of falling or flowing water.

It is the most widely used form of renewable energy, accounting for 16% of global electricity generation – 3,427 terawatt-hours of electricity production in 2010 – and is expected to increase about 3.1% each year for the next 25 years.

Despite being one of the cheapest forms of renewable energy, it has limited applications in England and Wales due to the limited locations that are suitable for this type of project.

However, pumped-storage systems have been used, eg Dinorwig, to store energy generated during off-peak periods, which can be utilised during periods of high electricity demand.

Nuclear

A nuclear power station is a thermal power station in which the heat source is a nuclear reactor.

As in a conventional thermal power station, the heat is used to generate steam that drives a steam turbine connected to a generator, which produces electricity.

Nuclear power plants are usually considered to be base-load stations, since large quantities of energy generation can be sustained to meet the regular demand of the nation.

In the UK, approximately one sixth of electricity generation is from 16 operational nuclear reactors.

The biggest problems with the use of nuclear energy are:

- it uses non-renewable fuels
- radioactive material can be very dangerous
- safe disposal of spent radioactive fuel is very difficult.

Photo-voltaic

Solar panel electricity systems, also known as solar photo-voltaics (PV), capture the sun's energy using photo-voltaic cells. These cells don't need direct sunlight to work – they can still generate some electricity on a cloudy day.

The cells convert the sunlight into electricity, which can be used to run household appliances and lighting.

These are gaining widespread popularity in the UK thanks to incentive schemes for consumers to have them installed.

Apart from reducing the consumers' electricity bill by supplementing the electricity supply, the customer can 'sell back' surplus electricity to the electricity supplier via a 'smart meter', using a feed-in tariff.

Whilst the equipment is relatively expensive to install initially, the payback over a number of years will benefit the consumer. Additionally, as photo-voltaic is another example of a renewable energy source, the consumer's carbon footprint is greatly reduced.

Gas

A gas-powered station is a thermal power station in which the heat source is obtained by burning natural gas.

As in a conventional thermal power station, the heat is used to generate steam that drives a steam turbine connected to a generator, which produces electricity.

In 1990 only 0.05% of electricity in the UK was produced using gas but this had risen to 39.93% by 2004.

The biggest problems with the use of gas are:

- it uses non-renewable fossil fuels
- it produces air pollution
- larger stations require large quantities of cooling water.

Micro-generation

Micro-generation is the small-scale generation of heat and electric power by individuals, small businesses and communities, to meet their own needs, as alternatives or supplements to traditional centralised grid-connected power.

Although this may be motivated by practical considerations, such as unreliable grid power or long distance from the electrical grid, the term is mainly used currently for environmentally conscious approaches that aspire to zero or low-carbon footprints.

Examples include:

- solar thermal (hot water)
- ground source heat pump
- air source heat pump
- biomass
- solar photo-voltaic
- micro-wind
- micro-hydro
- micro-combined heat and power (heat led)

Unit 302: Principles of electrical science

Worksheet 22: Electricity generation

Using your notes, answer the following questions.

1. List **ten** methods of generating electricity:

• • • • • • • • • •

302: Principles of electrical science

Handout 23: Generation and transmission

Learning outcome

The learner will:

1. Understand electrical supply systems.

Assessment criteria

The learner can:

1.2 specify the **features and characteristics** of a generation and transmission system.

Range

Feature and characteristics: Power Stations, Fossil fuels, Hydro, Nuclear, Super-grid and standard grid system, Transformers, Transmission voltages, Distribution voltages, Sub-stations, Above and below ground distribution.

Generation and transmission

The electricity supply industry comprises:

- generation
- transmission
- distribution.

Generation

In the UK, power stations are often sited close to the fuel source and other important resources required for generation, eg a large source of cooling water. Most base-load power stations produce electricity at around 25,000 volts (25kV).

Transmission

This electricity needs to be transmitted around the country to the load centres. These transmission lines form the basis of the National Grid. The National Grid is the high-voltage electric power transmission network in Great Britain, connecting power stations and major sub-stations, and ensuring that electricity generated anywhere in England, Scotland and Wales can be used to satisfy demand elsewhere.

By connecting the power stations and load centres in the form of a grid, greater security of supplies can be ensured. Additionally, during periods of light loading, eg in the summer, individual power stations can be shut down to enable maintenance operations to be carried out, whilst maintaining supply to consumers.

Using a step-up transformer, the output from power stations is stepped up to the transmission voltage. The reason why transmission is carried out at high voltages is to reduce the I^2R losses across the system.

Three transmission voltages are used:

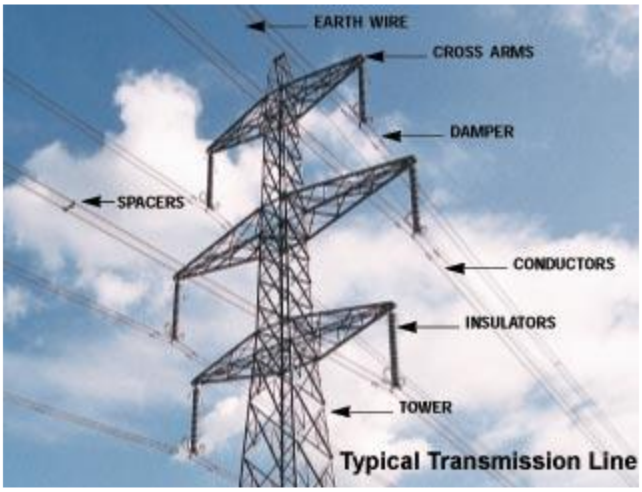
- 400kV
- 275kV
- 132kV.

The original Grid that came into operation in 1933 operated at 132kV. In 1949, the British Electricity Authority decided to upgrade the grid by adding 275kV links. From 1965, the Grid was partly upgraded to 400kV to become the supergrid, defined as referring to those parts of the British electricity transmission system that are connected at voltages in excess of 200kV.

Most of the grid is formed by overhead power lines, with cables suspended from insulators mounted on metal pylons or, to give them their proper name – transmission towers.

The cables are run in three phase sets (three conductors to a set). Normally, there are two sets on each pylon. One or two earth wires, also called ‘guard’ wires, are placed on top to intercept lightning and harmlessly divert it to ground.

The conductors are generally made of a steel inner core for strength, surrounded by aluminium conductors around the outside; the cable has no insulation applied.



Typical Transmission Line

Distribution

When these transmission lines are in the vicinity of the load centres, using a step-down transformer, the voltage is reduced for secondary transmission (132kV; 66kV). When the load centre is reached, it is stepped down again for local distribution at 33kV and 11kV. Supplies to individual users will see a further step-down to 400V for commercial and industrial users (heavy industry will be supplied at 33kV or 11kV, depending on demand) and 230V for domestic users.

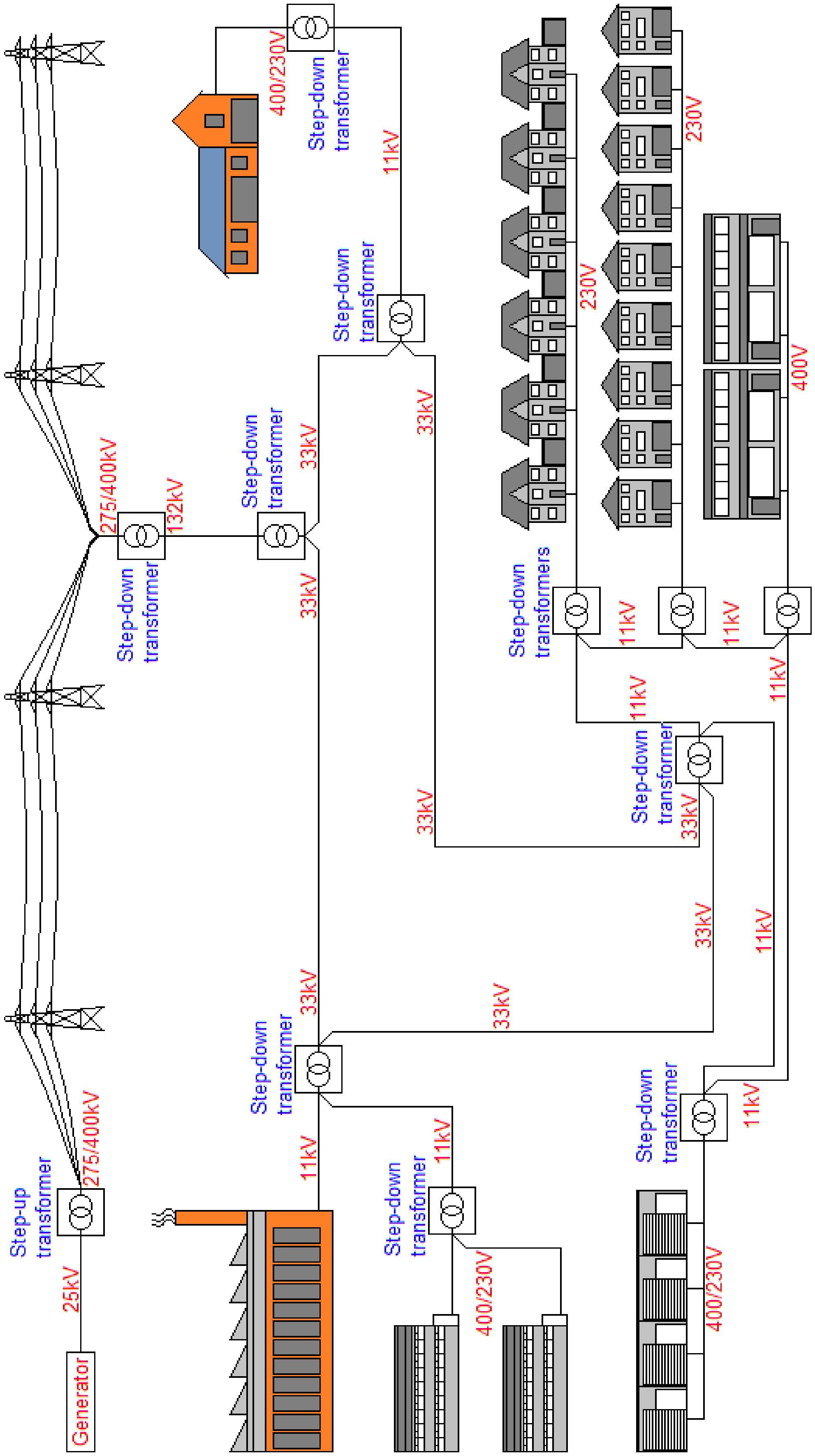
Three distribution voltages are used:

- 33kV
- 11kV
- 400/230V

Component parts of the electrical distribution network include:

- sub-stations
- pylons
- power stations
- cables
- insulators
- transformers.

See the diagram on the following page for the transmission and distribution supply system.


Generator
25kV
Step-up transformer
275/400kV
275/400kV
Step-down transformer
132kV
Step-down transformer
33kV
33kV
Step-down transformer
33kV
11kV
Step-down transformer
11kV
400/230V
33kV
Step-down transformer
11kV
Step-down transformer
400/230V
33kV
33kV
33kV
Step-down transformer
11kV
Step-down transformers
11kV
11kV
11kV
230V
230V
400V
33kV
11kV
Step-down transformer
11kV
400/230V

Unit 302: Principles of electrical science

Worksheet 23: Generation and transmission

Using your notes, answer the following questions.

1. Identify the various voltages used for generation, transmission and distribution.

302: Principles of electrical science

Handout 24: Distribution

Learning outcome

The learner will:

1. Understand electrical supply systems.

Assessment criteria

The learner can:

1.4 describe the main characteristics of: a) single phase electrical supplies, b) three phase electrical supplies, c) three phase and neutral supplies, d) sub-station transformers.

Range

Feature and characteristics: Power Stations, Fossil fuels, Hydro, Nuclear, Super-grid and standard grid system, Transformers, Transmission voltages, Distribution voltages, Sub-stations, Above and below ground distribution

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Distribution

Why use alternating current (AC) instead of direct current (DC)

With direct current, the electromotive force (EMF) is always in one direction only. The resultant flow of electrons (electric current) will also be in one direction only and therefore current flow is always in one direction.

However, with alternating current the EMF periodically reverses its direction. The resultant flow of electrons will also periodically reverse their direction and therefore current flow periodically reverses its direction. Alternating current is used for the electricity supply network in Britain and most countries of the world. The main reasons for this are as follows:

AC can be easily transformed from one voltage to another

AC produces less arcing and sparking on contacts, etc

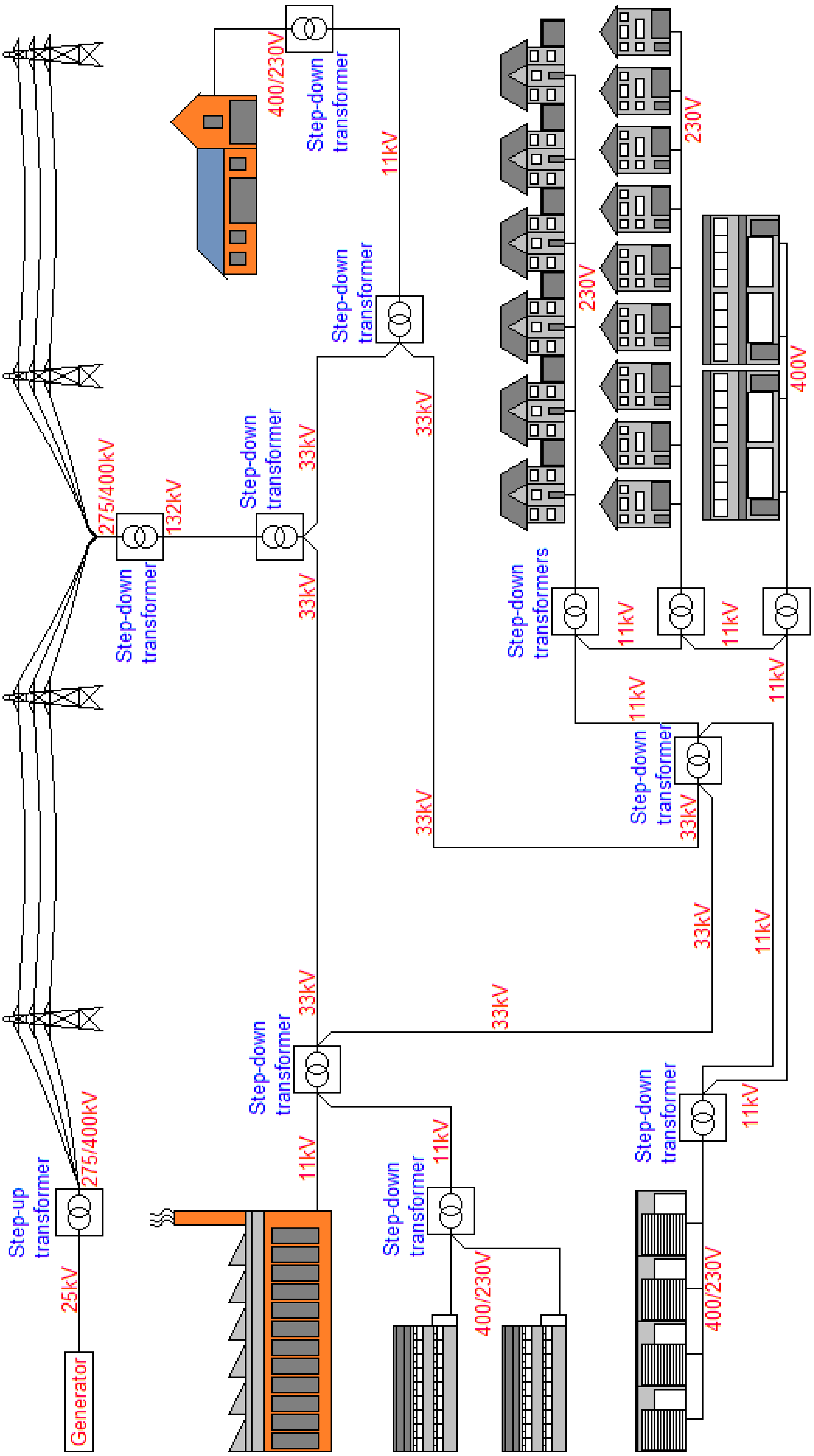
If electricity is transmitted and distributed nationally at very high voltages, the current will be low and, hence, transmission losses will be low. As voltage drop in a cable can be found by multiplying the cable resistance by the current, with low current the voltage drop will also be low. With low current, power losses in the cable will be reduced. This means we can use cables with a smaller cross-sectional area, thus reducing costs.

These high voltages are far too high and dangerous for consumer use, so must be reduced to the levels that we are familiar with (230 volt single phase; 400 volt three phase).

In the UK, for example, generators in power stations produce electricity at around 25,000 volts (25kV). Using a **step-up** transformer, this is then increased to 400,000 volts (400kV) for transmission around the country, from the power stations to the load centres. By using a **step-down** transformer when these transmission lines are in the vicinity of the load centres, the voltage is stepped down for secondary transmission (132kV; 66kV). When the load centre is reached, it is stepped down again for local distribution at 33kV and 11kV. Supplies to individual users will see a further step-down to 400V for commercial and industrial users (heavy industry will be supplied at 33kV or 11kV depending on demand) and 230V for domestic users.

The device used to '**transform**' the voltages is a **transformer**, which will only work on alternating current – **not** direct current – and this is why we do not transmit and distribute electricity using dc.

See the diagram on the following page for the transmission and distribution supply system.

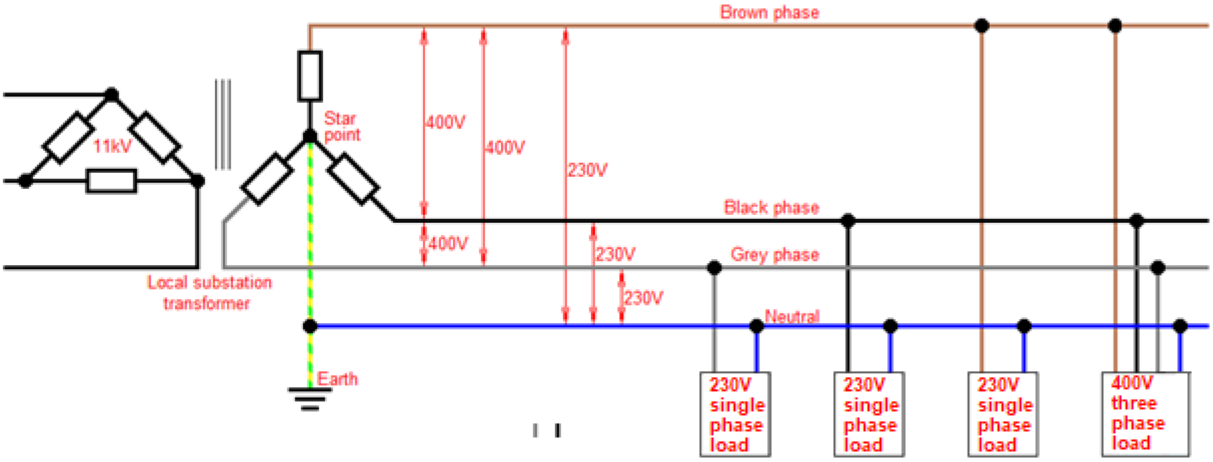

Generator
25kV
Step-up transformer
275/400kV
275/400kV
Step-down transformer
132kV
Step-down transformer
33kV
33kV
Step-down transformer
33kV
11kV
Step-down transformer
11kV
400/230V
Step-down transformer
11kV
400/230V
33kV
33kV
33kV
33kV
Step-down transformer
33kV
11kV
11kV
Step-down transformer
11kV
400/230V
Step-down transformer
11kV
Step-down transformers
11kV
11kV
230V
230V
400V

Distribution

Local distribution in England and Wales is by underground cables from sub-stations placed close to the load centre and supplied at 11kV. Transformers in these local sub-stations reduce the voltage to 400 volts. Three phase and neutral distributor cables connect this supply to the consumers. Connecting to one phase and neutral of a three phase 400 volt supply gives a 230 volt single phase supply suitable for domestic consumers.

When single phase loads are supplied from a three-phase supply, as shown in the diagram below, the load should be 'balanced' across the phases. That is, the load should be equally distributed across the three phases so that each phase carries approximately the same current. This prevents any one phase being overloaded.

On the standard supply system in Great Britain, the secondary of the supply transformer is connected in star as shown in the diagram below:



As can be seen from the diagram above a domestic premise is fed with **two live conductors**, line and neutral. The maximum fuse rating (I_n) fitted in the Distribution Network Operator (DNO) service cut-out is usually **100 amperes**. The point at which the consumer's installation starts is at the outgoing terminals of the energy meter.

A three-phase and neutral supply is normally used to supply an industrial installation for the following reasons:

- it provides a choice of two voltages, (400V for power and motors, 230V for lighting and sockets)
- it reduces switchgear and fuse gear ratings
- it balances the load on the supply system
- reduction in cable sizes
- neutral to accommodate unbalanced loads

Sub-station transformers

The basis of the transmission and distribution system is the ability to step-up and step-down voltages at different points in the system. This is carried out in sub-stations by using transformers. The theory of transformers will be covered in a different lesson. Although transformers are very efficient devices, they still produce heat and, in the larger transformers, the amount of heat can be very great, so some form of cooling is necessary.

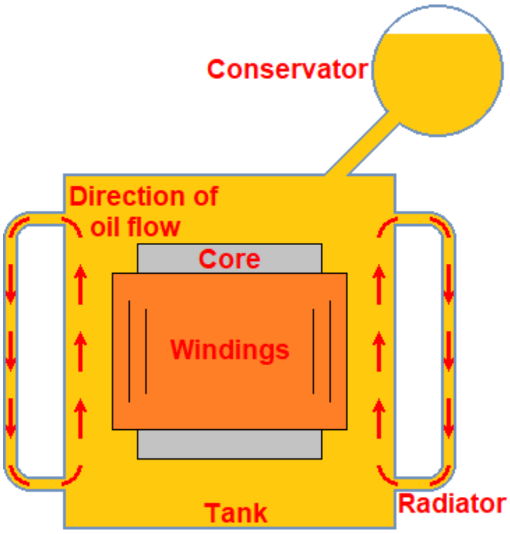
There are generally three different cooling methods used to cool transformers used in electricity supply and distribution networks, identified as follows:

- Air cooled
- Oil cooled
- Gas cooled (Sf6).

Air Cooled Transformer: Generally used for small transformers up to 3MVA and uses natural airflow to cool the transformer. For larger transformers up to 15MVA blowers or fans can be used to cool the transformer. These are referred to as '**air blast**' transformers.

Oil Cooled Transformer: For transformers up to about 30MVA oil cooling is generally used. The transformer is immersed in oil and heat from the transformer is transferred to the oil. The heated oil, due to convection, flows upward to the radiator and the heat is dissipated into the atmosphere due to the natural air flow around the transformer. Cooled oil is drawn from the radiator in to the bottom of the transformer, again by convection. This convection flow of the oil through the transformer and the radiator keeps the cooling oil circulating.

Various means can be used for cooling the oil. In the picture shown the heat dissipates naturally into the air. This process can be accelerated by fans blowing air over the radiator. Instead of just having the radiator tubes, a heat exchanger can be used to extract even more heat from the oil.



Gas Cooled (Sf6) Transformer: For transformers with very high MVAs and those operating at high voltages, gas cooling is often used. Sulphur hexafluoride (**SF6**) is an inorganic, colourless, odourless, non-flammable, extremely potent greenhouse gas, which is an excellent electrical insulator used in gas cooled transformers. Apart from its cooling properties, transferring heat from the transformers, its excellent properties as an insulator are vital when used in transformers operating at very high voltages, for example, on the supergrid. As already mentioned, however, it is a very potent greenhouse gas with a global warming potential of 23,900 times that of CO_2 when compared over a 100-year period, so its use and disposal must be closely monitored.

Electrical items in a substation

A range of separate electrical items can be found in a sub-station, relevant to the distribution of electricity. These include:

- Transformers
- Isolators
- fuses/circuit breakers
- switchgear

Unit 302: Principles of electrical science

Worksheet 24: Distribution

Using your notes, answer the following questions.

1. Why is AC preferred over DC for transmission and distribution of electricity?

302: Principles of electrical science

Handout 25: Transformers

Learning outcome

The learner will:

1. Understand electrical supply systems.

Assessment criteria

The learner can:

1.5 identify types of transformers.
1.6 describe the **operating principles, applications and limitations** of transformers.
1.7 determine by calculation and measurement: a) primary and secondary voltages, b) primary and secondary current, c) kVA rating of a transformer.

Range

Operating principles, applications and limitations: Iron loss, Copper loss, Relationship between current and voltage, Primary and secondary windings, Step-up and step-down transformers.

Transformers

Electromagnetic Induction

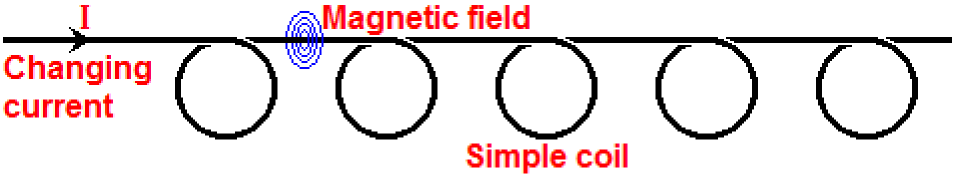
When a conductor cuts, or is cut by, magnetic lines of force (magnetic flux) a voltage is induced in the conductor. This is known as **electromagnetic induction**.

If a conductor is held steady in a magnetic field, or is moved parallel to a magnetic field, then no lines of force will be cut and therefore no voltage is induced in the conductor.

In general, electromagnetic induction is the production of an emf in a circuit due to a change of flux linkage within the circuit and this can be shown in two ways.

Self-Inductance

This is the changing flux linkage within the same circuit.



Any circuit in which a change of current produces a change of flux and therefore produces an induced EMF is said to possess **self inductancE**.

The unit of self-inductance, called the **henry** (**H**) is the inductance of a closed circuit in which an EMF of 1 volt is produced when an electric current in the circuit is varied uniformly at the rate of 1 ampere in 1 second.

$$\boxed{\textbf{Induced emf} = -\frac{\mathbf{L.(I_2 - I_1)}}{\mathbf{t}}\ \textbf{volts}}$$

Where: L = The value of inductance in Henrys (H)

t = Time in seconds (s)

I_1 and I_2 = are values of current

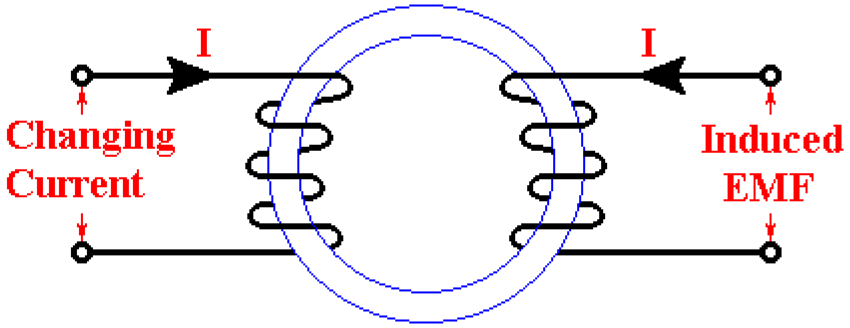
NB: The negative sign indicates that the voltage opposes the current change.

Example 1
If the current flowing through a coil of inductance of 0.7H increases from 2A to 10A in 40 milli seconds, calculate the average value of an induced emf.

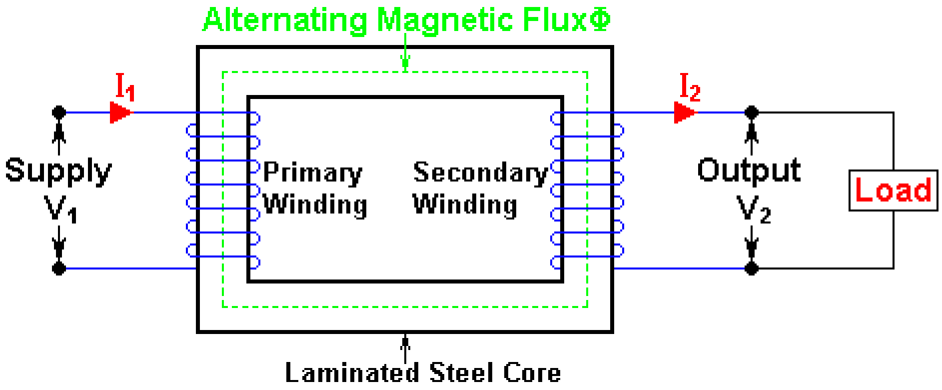
$$
\begin{aligned}
E &= -\frac{L.(I_2 - I_1)}{t} \\
&= -\frac{0.7 \times (10 - 2)}{(40 \times 10^{-3})} \\
&= -\frac{0.7 \times 8}{(40 \times 10^{-3})} \\
&= -\frac{5.6}{(40 \times 10^{-3})} \\
&= \underline{-140 \text{ volts}}
\end{aligned}
$$

Mutual-Inductance

This is when the induced emf in a circuit is due to a changing current in another circuit, i.e. a transformer.



Practical transformer



When AC voltage is applied to the **PRIMARY** winding, it produces an AC current flowing through the primary winding and this produces a flux in the iron core that is also alternating. This alternating flux cuts the conductors in **SECONDARY** winding and induces an emf into this secondary winding.

The emf induced in each turn of the secondary will be the same as the voltage across each turn in the primary. If N_1 and N_2 are the number of turns on primary and secondary respectively, then since both coils of the transformer are linked by the same flux, their induced emf's will be proportional to the number of turns in each coil, and so:

$$\frac{V_P(\text{primary emf})}{V_S(\text{secondary emf})} = \frac{N_P(\text{primary turns})}{N_S(\text{secondary turns})}$$

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \text{ or } \frac{V_1}{V_2} = \frac{N_1}{N_2}$$

Since the full load efficiency of a transformer is nearly 100%, then:

$$V_1 . I_1 = V_2 . I_2$$

then

$$\frac{V_1}{V_2} = \frac{I_2}{I_1}$$

Hence $$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

The above is known as the transformer equation.

Example 2

A transformer connected to a 230 volt 50Hz supply has a primary winding of 1200 turns. Calculate:

a) The emf induced in a secondary winding of 300 turns.

b) The number of turns that would be required in the secondary winding, if it is to produce an emf of 100 volts.

c) The volts per turn there are on the primary and secondary windings in part (a) above.

a)

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$V_2 = \frac{N_2}{N_1} \times V_1$$

$$= \frac{300}{1200} \times 230$$

$$= \underline{57.5V}$$

b)

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$N_2 = \frac{V_2}{V_1} \times N_1$$

$$= \frac{100}{230} \times 1200$$

$$= \underline{521.7\ \text{turns}}$$

c)

$$\text{Primary volts/turn} = \frac{V_1}{N_1}$$

$$= \frac{230}{1200}$$

$$= \underline{0.19\ \text{volts}}$$

$$\text{Secondary volts/turn} = \frac{V_2}{N_2}$$

$$= \frac{57.5}{300}$$

$$= \underline{0.19\ \text{volts}}$$

It can be seen from the above calculations, that the volts per turn on a transformer, are the same on the secondary winding as on the primary winding.

Turns ratio

It is not necessary to know the exact number of turns on the primary and secondary of the transformer. We can carry out calculations as long as we know the ratio between the primary and secondary turns.

Example 3

A transformer connected to a 240 volt 50Hz supply has a primary/secondary turns ratio of 20:1. Calculate the emf induced in a secondary winding.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$V_2 = \frac{N_2}{N_1} \times V_1$$

$$= \frac{1}{20} \times 240$$

$$= \underline{12\text{V}}$$

Transformers are rated by their output capabilities

The output of a transformer is measured in kVA or MVA. Therefore, if a transformer is rated at 20.7kVA at 230 volts, it is capable of delivering a load current of 90 amps.

This is arrived at by dividing the kVA rating by the rated voltage.

Since $$\mathbf{kVA} = \mathbf{Volts} \times \mathbf{amps}$$

then $$\mathbf{amps} = \frac{\mathbf{kVA}}{\mathbf{Volts}}$$

eg $$\mathbf{I} = \frac{\mathbf{20.7kVA}}{\mathbf{230V}}$$

$$= \underline{\mathbf{90\ amperes}}$$

Example 4

A 50KVA single phase transformer has a turns ratio of 440/20. The primary winding is connected to a 220 Volt 50Hz supply. Calculate:

a) The secondary voltage on no load.
b) The approximate values of primary and secondary currents on Full load.

a) $$\frac{\mathbf{V_1}}{\mathbf{V_2}} = \frac{\mathbf{N_1}}{\mathbf{N_2}}$$

$$\mathbf{V_2} = \frac{\mathbf{N_2}}{\mathbf{N_1}} \times \mathbf{V_1}$$

$$= \frac{\mathbf{20}}{\mathbf{440}} \times \mathbf{220}$$

$$= \underline{\mathbf{10V}}$$

b) $$\mathbf{I_1} = \frac{\mathbf{kVA}}{\mathbf{V_1}}$$

$$= \frac{\mathbf{50kVA}}{\mathbf{220V}}$$

$$= \underline{\mathbf{227A}}$$

$$\mathbf{I_2} = \frac{\mathbf{kVA}}{\mathbf{V_2}}$$

$$= \frac{\mathbf{50kVA}}{\mathbf{10V}}$$

$$= \underline{\mathbf{5\ 000A}}$$

Transformer losses

Transformers are very efficient pieces of electrical equipment with efficiencies in the +90% range. Because they are not 100% efficient, where do losses take place? When dealing with transformer losses two types are recognised:

- Iron loss
- Copper loss

Iron loss: This can be broken into two further categories: **Hysteresis** loss and **eddy** current loss.

Hysteresis losses result because every time the AC goes alternatively positive and negative it needs to magnetise the iron core of the transformers. Despite being made of soft iron that is designed so that it does not retain magnetism, there will be some residual magnetism that must be overcome when the current, and hence, the magnetic field, reverses; this will result in some loss in energy.

As already discussed, the alternating magnetic field induces an emf into the secondary winding by mutual inductance. However, because the transformer core is also a conductor, the alternating magnetic field will induce an emf into the transformer core and currents will circulate; these currents are called **eddy currents** and will produce heat in the core. These eddy currents are reduced by laminating the core, that is, constructing it with thin layers of iron electrically insulated from each other as opposed to using a solid piece of iron.

Copper loss: Also referred to as **I^2R losses**, this results from the resistance (in ohms) of the windings themselves and the current flowing through them. We have seen elsewhere that when a conductor carries current, power is dissipated and this can be calculated by multiplying the square of the current by the resistance. For a standard double-wound transformer there will be **two** copper losses that need to be calculated

$$\mathbf{Primary\ copper\ loss} = \mathrm{I_P^2} \times \mathrm{R_P}$$

$$\mathbf{Secondary\ copper\ loss} = \mathrm{I_S^2} \times \mathrm{R_S}$$

Where:
$\mathrm{I_P}$ = Current in the primary winding
$\mathrm{R_P}$ = Resistance of the primary winding
$\mathrm{I_S}$ = Current in the secondary winding
$\mathrm{R_S}$ = Resistance of the secondary winding

The copper losses will be dependent on the current being drawn from the transformer so will vary with load.

Transformer regulation

When the windings are conducting current, like any other conductor, there will be a voltage drop across the windings. In its simplest form the voltage drop on the secondary winding can be calculated by:

$$\textbf{Secondary voltage drop} = \mathbf{I_S \times R_S}$$

Whilst the resistance of the secondary remains constant, the secondary current will vary according to the load connected to the transformer and so will the voltage drop on the winding. This voltage drop will be subtracted from the secondary voltage calculated using the transformer formulae.

With no-load, there will be no voltage drop in the winding and the terminal voltage will be that calculated using the transformer formulae. However, as the load current increases, so will the voltage drop across the secondary winding, resulting in the terminal voltage feeding the load, to reduce.

Voltage regulation is the percentage difference between no-load terminal voltage and full load terminal voltage and can be calculated by the following formula:

$$\textbf{Voltage regulation \%} = \frac{\mathbf{V_{no-load} - V_{full-load}}}{\mathbf{V_{full-load}}} \times \mathbf{100}$$

Ideally, the voltage regulation percentage should be as low as possible and for power transformers should be less than 3%. This simple calculation is based on resistive loads but reactive loads with a power factor of less than 1 will result in a worsening of the voltage regulation, so care needs to be taken when carrying out calculations for these loads.

Example 5

A transformer has a terminal voltage of 9.99 volts at no-load and a terminal voltage of 9.35 volts when fully loaded. Calculate the voltage regulation of the transformer.

$$\begin{aligned}
\textbf{Voltage regulation \%} &= \frac{\mathbf{V_{no-load} - V_{full-load}}}{\mathbf{V_{full-load}}} \times \mathbf{100} \\
&= \frac{\mathbf{9.99 - 9.35}}{\mathbf{9.99}} \times \mathbf{100} \\
&= \frac{\mathbf{0.64}}{\mathbf{9.99}} \times \mathbf{100} \\
&= \mathbf{0.064 \times 100} \\
&= \mathbf{6.4\%}
\end{aligned}$$

Unit 302: Principles of electrical science

Worksheet 25: Transformers

Using your notes, answer the following questions.

1. A transformer is to be wound to change an input potential of 250 volts, to an output potential of 110 volts, which is to be used for portable tools supplies. If there are 750 turns on the primary winding, how many turns will there have to be on the secondary winding.

2. A transformer has a primary winding with 300 turns and a secondary winding of 600 turns. Calculate the secondary voltage if 250 volts is applied to the primary winding.

3. Calculate the full load current of a transformer rated at 3300/400volts, 60kVA.

4. A transformer is rated at 150kVA & delivers 375 amps at full load. Calculate the output voltage of the transformer.

5. A 200KVA 3300/240v 50Hz single phase transformer has 80 turns on the secondary winding. Assuming an ideal transformer, i.e. 100% efficient, calculate.
   a) Primary and secondary currents on full load.
   b) The number of primary turns.

302: Principles of electrical science

Handout 26: Space heating

Learning outcome

The learner will:

6. Understand the principles and applications of electrical heating.

Assessment criteria

The learner can:

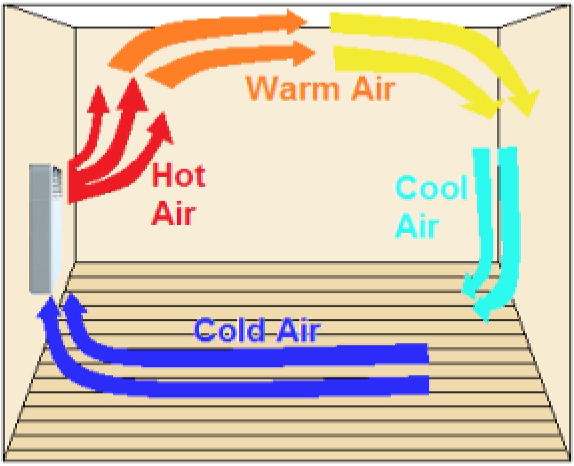
6.1 explain the basic principles of electrical space heating and electrical water heating.
6.2 explain the operating principles, types, limitations and applications of electrical space and water heating appliances and components.

Space heating

Space heating is generally employed to warm an enclosed space in premises and is usually contrasted with central heating, which warms many connected spaces at once from one heating source.

Space heaters can be divided into those that transfer their heat primarily by convection and those that transfer their heat primarily by radiation.

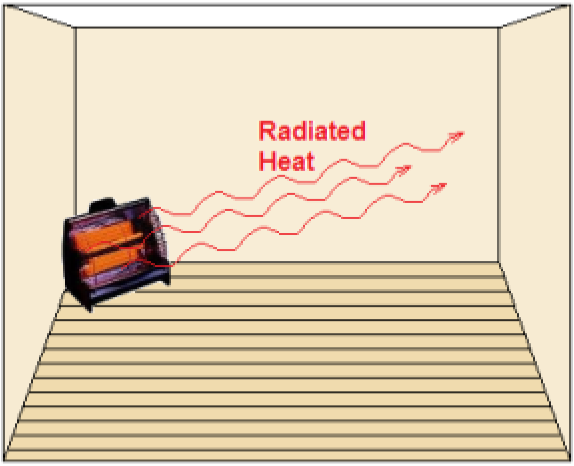
Convection heaters



With convection heaters, heating elements either warm the air directly or heat oil or another filler, which in turn transfers heat to the air. The warm air rises into the room drawing cold air into the bottom of the heater. This starts convection currents circulating throughout the room the temperature of which will increase over a period of time.

Convective heaters are suitable for providing constant, diffuse heat in well-insulated rooms. Oil heaters warm up slowly but do not reach dangerous surface temperatures; wire-element heaters, which may be fan-assisted, reach operating temperature much more quickly but may pose a fire hazard.

Radiant heaters



Radiant heaters usually comprise tungsten filaments in heat-resistant quartz envelopes, mounted in front of a metal reflector in a plastic or metal case. They operate much like light bulbs, but radiate their energy primarily in the infrared spectrum. They convert up to 86% of their input power to radiant energy, losing the remainder to conductive and convective heat.

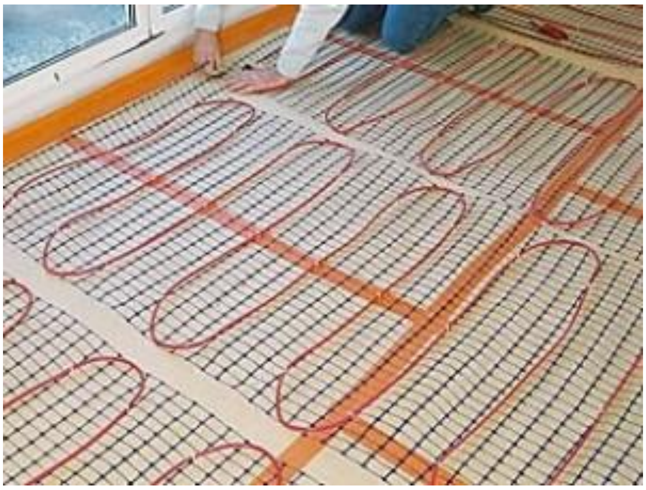
The advantage of radiant heaters is that the radiation they produce is absorbed directly by clothing and skin, without first heating the air in the space. This makes them suitable for warming people in poorly insulated rooms, or even outdoors.

Most small electrical convector and radiant heaters can be connected via a flexible cord to a plug-top inserted into a convenient socket outlet. If the (small) heater is fixed to the wall it can be permanently connected into a socket outlet using a switched fused connection unit with a flex outlet (see right).

For larger heating appliances, for example, electric storage heaters, a separate circuit for each heater wired back to its own protective device will be required. A flex outlet will be installed adjacent to the heater to make the final connections.

The type of flex required to make the final connection to the heater, whatever type it is, needs to be carefully considered, usually requiring to be heat resistant flexible cable.

Underfloor heating



Under floor heating systems, which can sit beneath stone, tile, wooden or even carpeted surfaces, will help to keep cold floors and rooms warm and can offer an alternative to using radiators to deliver central heating.

A series of electric wires are installed beneath or within the flooring as a means of heating an area or room; a cold, tiled bathroom floor, for example.

The electric system installed will depend on the size of the room and the type of flooring it has. Options include loose-fit wiring flexible enough to fit into small or awkward spaces and electric cable systems, or heating mats you roll out to cover larger areas.

Under floor heating is generally associated with stone or tiled floors, but can be installed in a carpeted room. It is necessary of course to ensure that the carpet and underlay isn't so dense that it stops the heat moving upwards.

The electric heating sheets or cables are fitted beneath the flooring and usually on top of a layer of screed (to ensure the surface is completely flat) and a layer of floor insulation (to keep the heat travelling upwards rather than down).

To allow control of the temperature, a sensor is installed in the floor and connected to a thermostat. This often incorporates a time clock to allow the user to pre-set when the heating turns on and off.

Storage heaters

Heat retaining clay bricks inside the storage heater are charged over night by a heating element. They store the heat and release it during the day. Convection and radiation provide a comfortable balance of heat in the room.

Storage heaters offer comfortable economical warmth throughout the day, by taking advantage of low tariff Economy 7 electricity at night. The Economy 7 electric tariff is designed to save money on heating bills.

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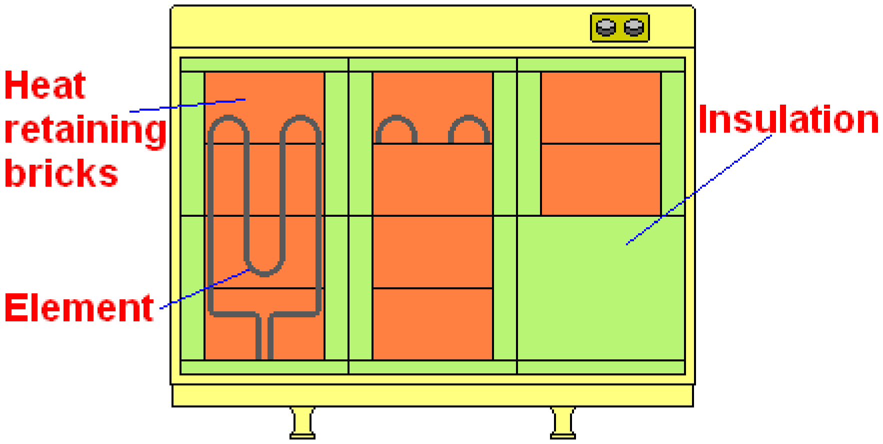


Unit 302: Principles of electrical science

Worksheet 26: Space heating

Using your notes, answer the following questions.

1. In an underfloor heating system, what is a cold tail?

2. State the **two** main types of heat transference used in space heating.

3. Research what is meant by the term 'Economy 7' and the benefits for the consumer.

302: Principles of electrical science

Handout 27: Water heating

Learning outcome

The learner will:

6. Understand the principles and applications of electrical heating.

Assessment criteria

The learner can:

6.1 explain the basic principles of electrical space heating and electrical water heating.
6.2 explain the operating principles, types, limitations and applications of electrical space and water heating appliances and components.

Water heating

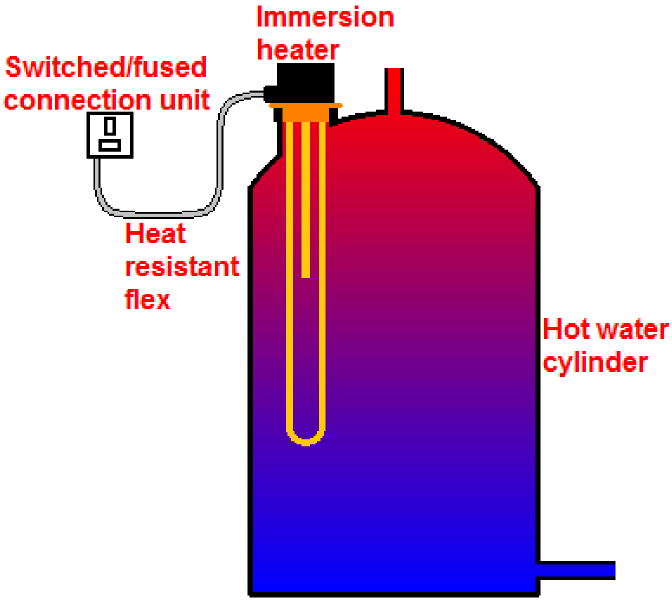
Water heating

There are various types of water heater, but they can be classified into two groups:

- stored hot water
- instantaneous.

Stored hot water

The most common form of this group is the immersion heater that is installed into a hot water cylinder (see right).

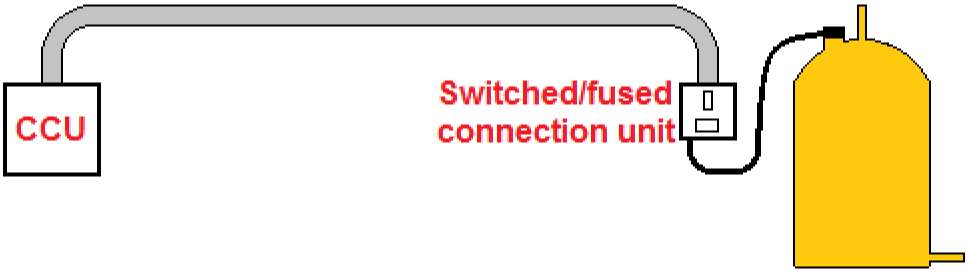


The heating element is constructed with resistance wire that will get hot when current flows through it and this heats the water.

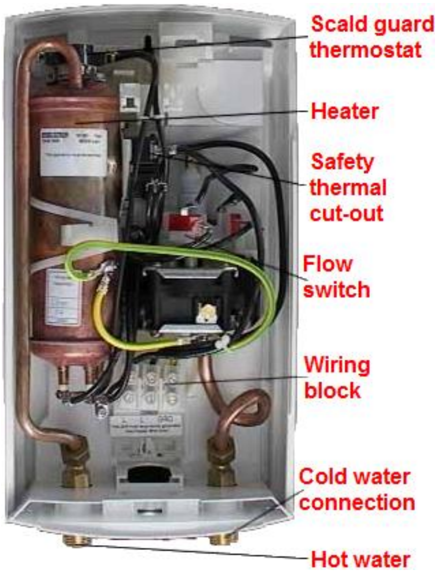
A thermostat is fitted to disconnect the supply when the water reaches the required temperature; usually set at 55-60° which is a compromise between low enough to reduce the risk of scalding and high enough to prevent the risk from Legionella bacteria.

In addition to a thermostat, Regulation 554.2.1 of BS 7671 (page 212) requires a means to automatically prevent a dangerous rise in temperature (thermal cut-out).

The immersion heater must be fed from its own circuit and connected into a switched/fused connection unit installed adjacent to the cylinder and connected by heat resistant flex as shown below:



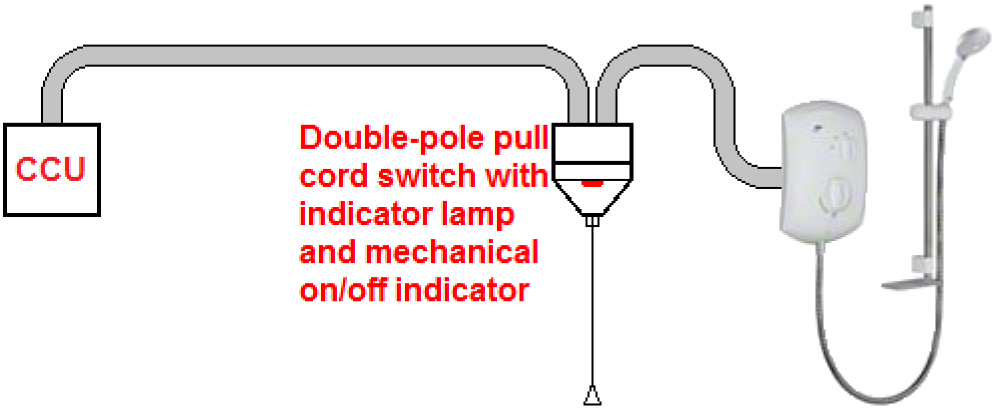
Instantaneous water heater



These high-powered appliances heat water instantly as it flows through the device, and do not retain any water internally except for what is in the heat exchanger coil. Common examples include instantaneous showers and point of use (POU) water heaters for supplying the hot tap of a sink or basin. The inside of an electric shower is shown right.

When the shower unit is turned on, water flows through the heater chamber and is heated quickly by the high-powered heating element. This then passes to the hot water outlet. The temperature of the water is regulated by the flow rate; a slow flow rate gives hot water and a fast flow rate gives cooler water.

The shower unit is fed from its own circuit in the consumer control unit and a double-pole switch is installed in the vicinity of the shower unit. See the circuit arrangement below:



302: Principles of electrical science

Handout 28: Heating controls

Learning outcome
The learner will:
6. Understand the principles and applications of electrical heating.

Assessment criteria
The learner can:
6.1 explain the basic principles of electrical space heating and electrical water heating.
6.2 explain the operating principles, types, limitations and applications of electrical space and water heating appliances and components.

Heating controls

To be efficient and cost effective, it is essential that heating systems, whether space or water, be properly controlled. This includes ensuring that the heating is available at the right times, using timers and programmers and ensuring heating is controlled to the right temperature using thermostats.

Thermostats

A thermostat is a component of a heating system which senses the temperature of a system so that the system's temperature is maintained near a desired set point. The thermostat does this by switching heating or cooling devices on or off, or regulating the flow of a heat transfer fluid as needed, to maintain the correct temperature.

A thermostat may be a control unit for a heating or cooling system or a component part of a heater or air conditioner. Thermostats can be constructed in many ways and may use a variety of sensors to measure the temperature.

The output of the sensor controls the heating or cooling apparatus. A thermostat may switch on and off at temperatures either side of the set point. The extent of the difference is known as hysteresis and prevents too frequent switching of the controlled equipment. Common sensor technologies in use today include:

- bimetallic sensors
- electronic thermistors and semiconductor devices
- electrical thermocouples.

Space heating systems generally make use of a room thermostat to measure the air temperature. The thermostat is best located in a living room, rather than the hallway, as is commonly done, as the hall temperature can be affected by the front door being used.

The thermostat detects the home's temperature and if it is at or above the set level (20°C/68°F is usually adequate) the heating is turned off automatically. When the temperature drops below the desired temperature, the heating is turned back on.

Water heating systems that store the heated water in a cylinder will have a thermostat, referred to as a *'cylinder stat'* strapped to the side of the cylinder. The cylinder stat detects the temperature of the water within the cylinder and if it is at or above the set level, the water heating is turned off automatically. When the temperature drops below the desired level, the water heating is turned back on.

The optimum temperature for stored water is a compromise, where the water must not be too hot, to reduce the risk of scalding, but also not too low, to reduce the risk of Legionella bacteria. For example, NHS Estates Health Guidance Notes recommended that water temperature should not be higher than 44°C/111°F. However, to prevent Legionella, hot water should be stored at or above 60ºC/140°F. Therefore, the cylinder stat should be set at 60°C; the water temperature will be reduced during distribution to the point of use, reducing the risk of scalding.

If the water in a cylinder is heated by an electric immersion heater, the heater itself will contain a built-in *'invar* rod' thermostat. This thermostat will have a means of setting the temperature. Additionally, later thermostats should have a means of preventing over-heating if the contacts fail to open.

Programmers and timers

The electronic timer or programmer decides when the heating is able to run. It is not true that heating works best when it is running continuously or that energy is saved by leaving the heating on all day, even if the home is unoccupied. Whenever the heating is on, it is using energy and whenever the home is being heated to a temperature above that outside, it will be losing heat to the outside world. In spring and autumn there is no need to keep the heating on all day; a reasonably well insulated home can be left to cool down slowly with the heating timed to come on perhaps an hour or so before people return home from work.

A seven-day timer is also strongly recommended, so that it is possible to set a different heating pattern for weekdays and weekends. Some timers allow different patterns for each day of the week; this can be useful for those working part-time or on shifts that vary from the conventional Monday–Friday work pattern.

Electrically operated pumps and valves

With central heating systems that use a boiler to heat water that is then circulated around the premises through heat emitters (eg radiators, under-floor heating), pumps and valves are used to produce and control the flow of hot water.

An example of a circulating pump is shown in the picture to the right.

The pump (or circulator) usually has three speed settings and at the highest speed it will draw less than ½ ampere.

Two types of motorised valves are generally used for central heating systems:

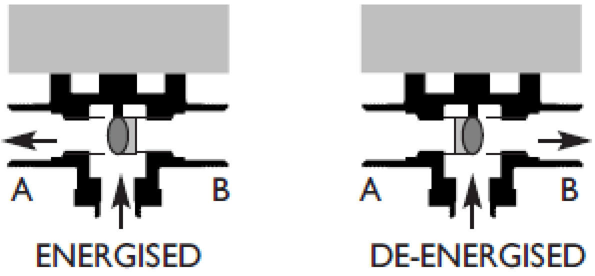
- zone valve
- three port valve.

The zone valve has two water connections and is used control the flow of water through a pipe, turning it on and off much like a light switch turns lights on and off.

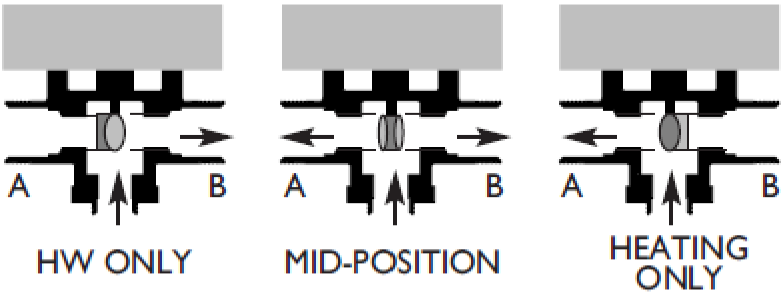
The three-port valve has one inlet connection and two outlet connections.

Two main types of three-port valve are available.

The ***diverter valve*** has spring return valves that allow water to be directed out of either one of two outlets. When the motor is energised, flow is out of port A. When the drive motor is de-energised the flow is from the inlet port and out of port B.



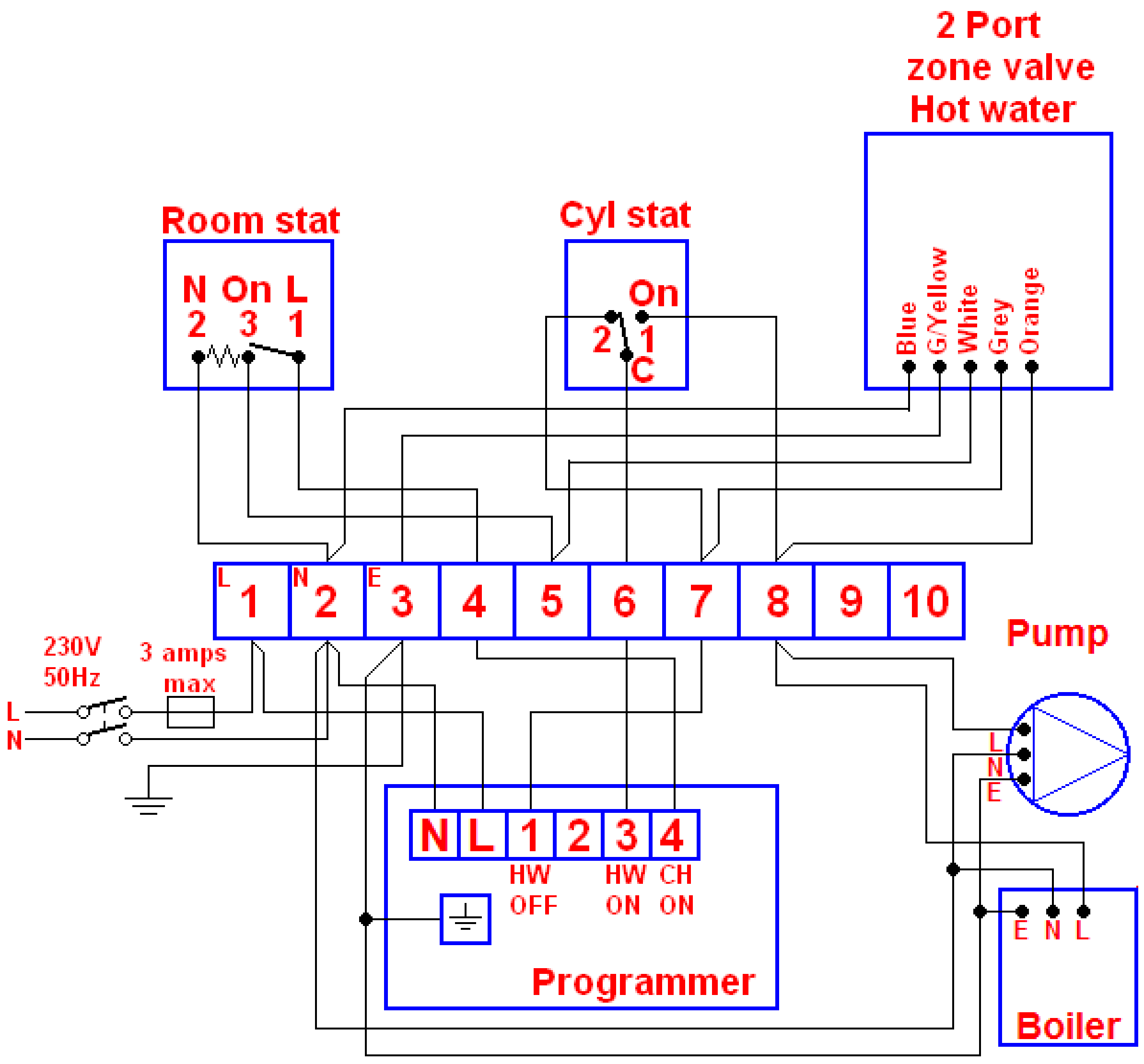
In the **mid-position valve,** the flow of water from the valve inlet can be directed to either of two outlets, or through both at the same time (mid-position). Power-from-room-and-cylinder thermostats enables the valves electronic circuitry to close either one of the outlet ports or to hold the swivel seal in the mid-position with both outlets open.



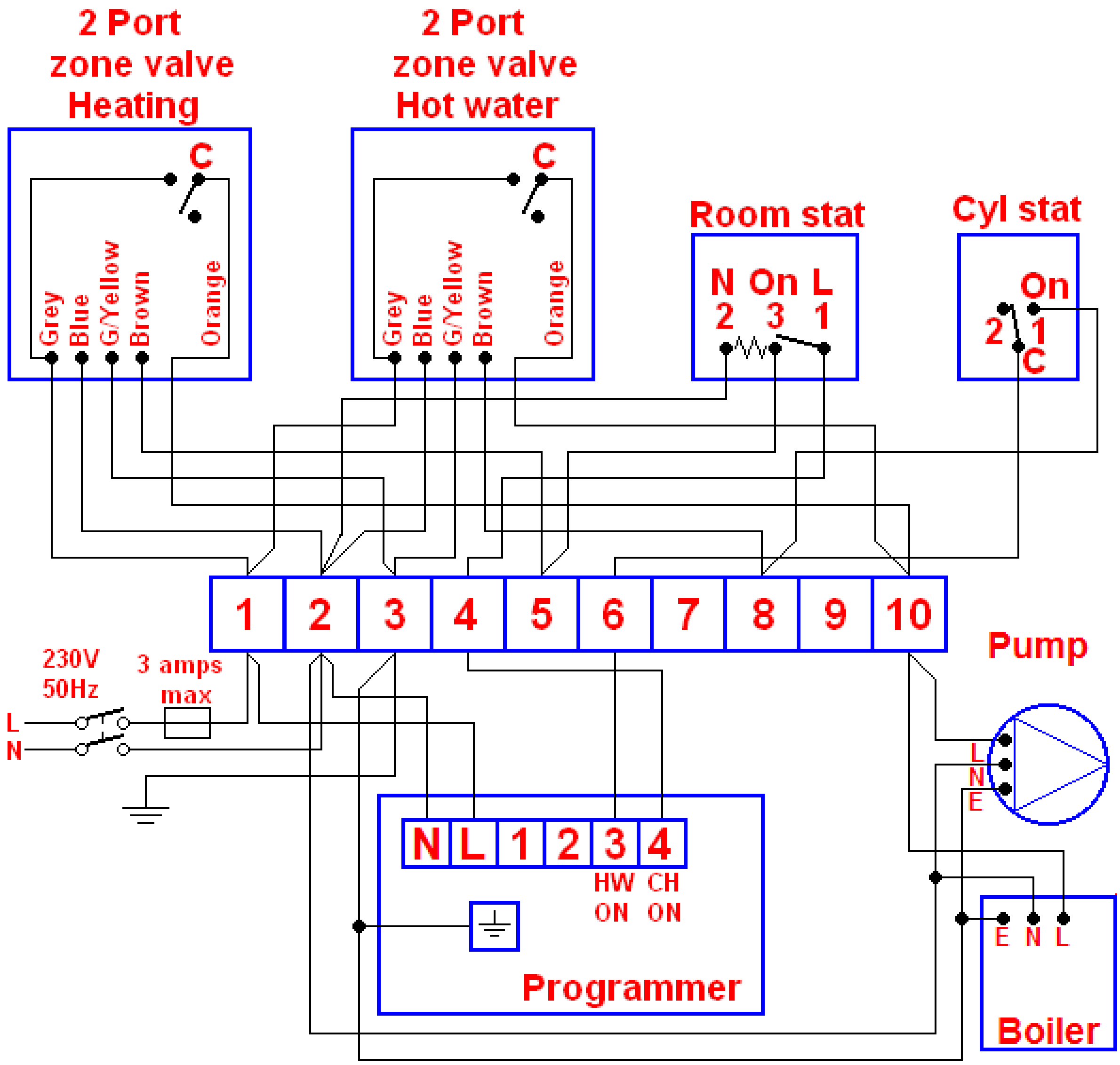
Both types of valve have an electric servo to power the valve to the 'energised' position. Additionally, the valves will contain contacts to show the position the valves are actually in. The contacts can be used to control other equipment associated with the heating system.

For example, if a pipe has a zone valve in it, it would be undesirable for the pump to be running whilst the valve is closed. The contacts on the zone valve enable the pump to be turned on when the valve is open and turned off when the valve closes.

Y-Plan


2 Port
zone valve
Hot water
Room stat
N On L
2 3 1
Cyl stat
On
2 1
C
Blue
G/Yellow
White
Grey
Orange
L
N
E
1
2
3
4
5
6
7
8
9
10
Pump
230V
50Hz
3 amps
max
L
N
L
N
E
N
L
1
2
3
4
HW
OFF
HW
ON
CH
ON
Programmer
E
N
L
Boiler

S-Plan


2 Port zone valve Heating
C
Grey
Blue
G/Yellow
Brown
Orange
2 Port zone valve Hot water
C
Grey
Blue
G/Yellow
Brown
Orange
Room stat
N On L
2 3 1
Cyl stat
On
2 1
C
1 2 3 4 5 6 7 8 9 10
Pump
L
N
E
230V
50Hz
3 amps
max
L
N
N L 1 2 3 4
HW CH
ON ON
Programmer
E N L
Boiler

Unit 302: Principles of electrical science

Worksheet 28: Heating controls

Using your notes, answer the following questions.

1. When setting the temperature of thermostat for water heating the temperature must not be too high or too low. State **two** factors that directly affect this.

2. What temperature would it be usual for room thermostat to be set to?

3. State briefly the purpose of the programmer.

4. State the **two** main types of electrically operated valves used in central heating systems.

302: Principles of electrical science

Handout 29: Alternative energy sources

Learning outcome
The learner will:
1. Understand electrical supply systems.

Assessment criteria
The learner can:
1.3 state the basic operating principles of **other sources** of electricity.

Range
Other sources: Batteries, cells or UPS systems, Solar power (thermal and photovoltaic), Wind energy, Wave energy, Micro hydro, Combined Heat and Power (CHP) including micro CHP.

Alternative energy sources

So far, we have discussed large-scale electricity generation. However, there are many means of generating electricity and energy conservation for individual consumers as well as storing energy for later or emergency use.

Battery systems

These are used as back up supplies to keep systems running during power outages. Examples include emergency lighting, alarm systems and equipment that must keep going at all times (for example, railway signalling). The batteries for such systems are trickle-charged whilst the mains supply is available, but when it fails, the equipment is switched over to run off the battery supply instead.

With IT equipment particularly, a power outage of even a second or so could cause valuable data to be lost. **Uninterruptable Power Supplies** or **Uninterruptable Power Source** (**UPS**) are available to ensure data integrity in the event of a power outage. UPS differs from an auxiliary or emergency power system or standby generator in that it will provide near-instantaneous protection from input power interruptions by supplying energy stored in batteries. The on-battery runtime of most uninterruptible power sources is relatively short (only a few minutes) but sufficient to start a standby power source or properly shut down the protected equipment.

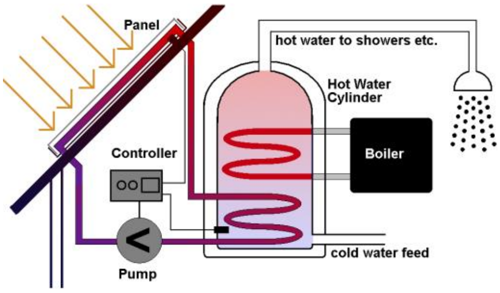
UPS is typically used to protect hardware such as computers, data centres, telecommunication equipment or other electrical equipment where an unexpected power disruption could cause injuries, fatalities, serious business disruption or data loss. UPS units range in size from units designed to protect a single computer without a video monitor (around 200-volt-ampere rating) to large units powering entire data centres or buildings.

Micro-generation or micro-renewable energies

Most of these are relatively new technologies and it is important to determine the specific requirements for each one. These requirements include:

- legal
- regulatory
- building location
- building fabric.

Solar thermal (hot water)



Solar thermal (hot water) is a renewable energy system for generating domestic hot water by using solar panels (known as 'collectors') fitted at an optimal angle on a south-facing roof or other suitable surface.

Solar heat warms fluid, usually anti-freeze, in the collectors and this is then pumped to heat water stored in a hot water cylinder.

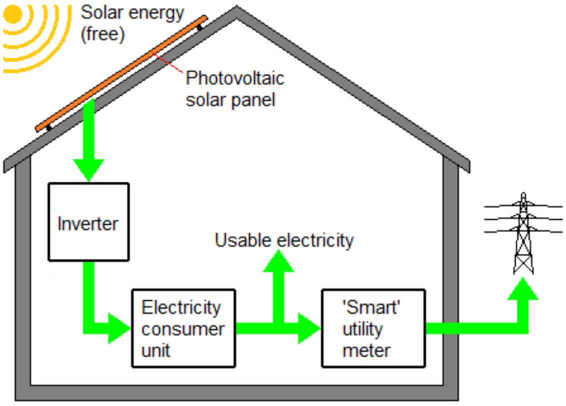
A boiler or immersion heater tops up the water to the temperature set by the cylinder's thermostat (>60°C).

In England, Wales and Scotland, planning permission is not needed for most home solar water heating systems, as long as they are below a certain size, but you should check with your local planning officer, especially if the premise is a listed building, or in a conservation area or World Heritage Site.

Here are the benefits of solar thermal.

- It should work all year round during the day, but consumers will probably need to heat the water further in winter months, using a boiler or immersion heater.
- It can save on fuel bills.
- It should be eligible for renewable heat incentives.
- It can cost a lot less to install than other micro-generation technologies.
- It does not cost more than £5,000.

Photo-voltaic (PV)



These are gaining widespread popularity in the UK with incentive schemes for consumers to have them installed.

Solar panel electricity systems – also known as solar photo-voltaics (PV) – capture the sun's energy using photo-voltaic cells. These cells don't need direct sunlight to work – they can still generate some electricity on a cloudy day.

The cells convert the sunlight into electricity, which can be used to run household appliances and lighting.

Apart from reducing the consumer's electricity bill by supplementing the electricity supply, the customer can 'sell back' surplus electricity to the electricity supplier via a 'smart meter' using a feed-in tariff.

Whilst the equipment is relatively expensive to install initially, the payback over a number of years will benefit the consumer. Additionally, as photo-voltaic is another example of a renewable energy source, the consumer's carbon footprint is greatly reduced.

In England, Wales and Scotland, planning permission is not required for most home photo-voltaic systems – as long as they are below a certain size – but you should check with your local planning officer, especially if the premises are a listed building, or in a conservation area or World Heritage Site.

Here are the benefits of photo-voltaic.

- Sunlight is free so, after the initial installation, electricity costs will be reduced.
- The government's feed-in tariffs pay the consumer for electricity generated, even if they use it.
- If the system is producing more electricity than needed by the consumer, or when they can't use it, the surplus can be sold back to the Grid.

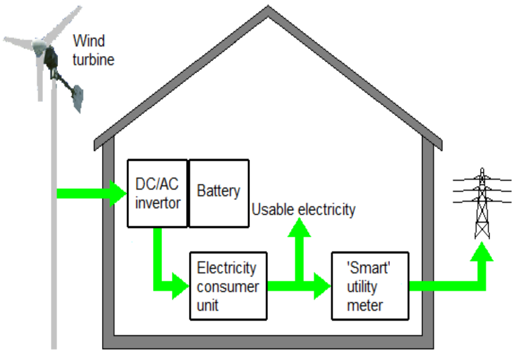
You will cut your carbon footprint. Solar electricity is 'green', renewable energy and doesn't release any harmful carbon dioxide or other pollutants. A typical home solar PV system could save over a tonne of carbon dioxide per year – that's more than 30 tonnes over its lifetime.

Micro-wind

Wind turbines harness the power of the wind and use it to generate electricity.

The UK is an ideal country for domestic turbines (known as 'micro-wind' or 'small-wind' turbines), as 40% of all the wind energy in Europe blows over it.

A typical system in an exposed site could easily generate more power than your lights and electrical appliances use.



Wind turbines use large blades to catch the wind. When the wind blows, the blades are forced round, driving a turbine which generates electricity. The stronger the wind, the more electricity produced.
There are two types of domestic-sized wind turbine.

- Pole mounted: these are free-standing and are erected in a suitably exposed position, Often these are around 5kW to 6kW in size.
- Building mounted: these are smaller than mast mounted systems and can be installed on the roof of a home where there is a suitable wind resource. Often these are around 1kW to 2kW in size.

Wind turbines are eligible for the UK government's feed-in-tariffs, which means that the consumer can earn money from the electricity generated by the turbine. Payments can also be received for the electricity not used by the consumer and exported to the local grid.

In order to be eligible, the installer and wind turbine product must be certified under the Microgeneration Certification Scheme (MCS).

If the turbine is not connected to the local electricity grid (known as off grid), unused electricity can be stored in a battery for use when there is no wind. **NB:** the feed-in tariffs scheme is not available in Northern Ireland.

Planning permission is required to install a wind turbine in Wales or Northern Ireland; contact your local authority for details.

In England and Scotland, a domestic wind turbine may be classified as Permitted Development, in which case planning permission will not be needed. However, the criteria are complex – and very different in England and Scotland – so we recommend that you contact your local planning office at an early stage to check whether planning permission is required.

For **building-mounted turbines**, the criteria include:

- the house is detached
- the top of the turbine blades is no more than three metres above the top of the house, or 15 metres above the ground
- all of the turbine is at least five metres from the edge of the householder's property.

For **pole-mounted turbines**, the criteria include:

- the top of the turbine is no more than 11.1 metres above ground
- all of the turbine is at least 1.1 times the height of the turbine away from the edge of the householder's property.

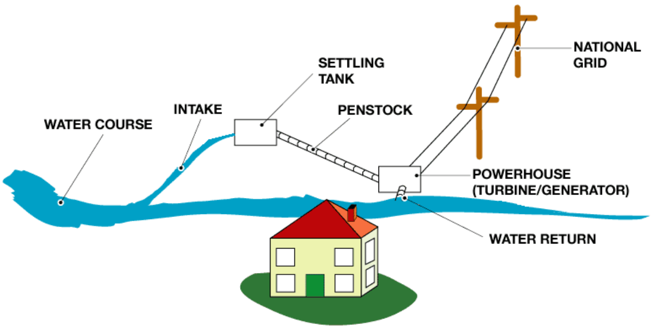
And for **both types of turbine**:

- there is no other wind turbine and no air source heat pump on the site
- the bottom of the blades is at least five metres above ground
- the turbine's swept area is no more than 3.8m^2
- the site is not on land safeguarded for aviation or defence purpose.

Micro-hydro

Running water can be used to generate electricity, whether it's a small stream or a larger river.

Small or micro-hydroelectricity systems – also called hydropower systems or just hydro systems – can produce enough electricity for lighting and electrical appliances in an average home.



All streams and rivers flow downhill. Before the water flows down the hill, it has potential energy because of its height. Hydropower systems convert this potential energy into kinetic energy in a turbine, which drives a generator to produce electricity. The greater the height and the more water there is flowing through the turbine, the more electricity can be generated.

The amount of electricity that a system actually generates also depends on how efficiently it converts the power of the moving water into electrical power.

Here are the benefits of micro-hydro.

- A hydro system can generate 24 hours a day, often generating all the electricity the consumer needs and more.
- If eligible, the consumer will get payments from the feed-in tariff for all the electricity generated, as well as for any surplus electricity sold back to the Grid.
- A hydro system may generate more electricity than needed for lighting the home and powering the electrical appliances – so the excess electricity can be used to heat the home and hot water too.
- Installing a hydro system can be expensive, but in many cases it's less than the cost of getting a connection to the National Grid if the premises do not already have one.
- Hydroelectricity is 'green', renewable energy and doesn't release any harmful carbon dioxide or other pollutants.

Hydropower is very site specific. Most homes will not have access to a suitable resource even if they have a water course running nearby. Assessing a hydro site properly is a job for a professional.

In order to be suitable for electricity generation, a river needs to have a combination of:

- **flow** – how much water is flowing down the river per second, and
- **head** – a difference in height over a reasonably short distance.

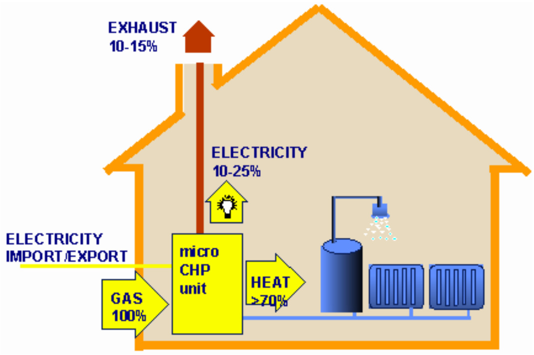
Developing a hydroelectric system can take a long time, mainly because of the need to obtain planning permission and an abstraction licence, and because of the number of organisations that may need to be involved in giving consent.

All new hydroelectric systems require planning permission and an abstraction licence.

Micro-combined heat and power (micro-CHP)

This technology generates heat and electricity simultaneously, from the same energy source, in individual homes or buildings. The main output of a micro-CHP system is heat, with some electricity generation, at a typical ratio of about 6:1 for domestic appliances.

A typical domestic system will generate up to 1kW of electricity once warmed up; the amount of electricity generated over a year depends on how long the system is able to run. Any electricity you generate and don't use can be sold back to the Grid.



Domestic micro-CHP systems are currently powered by mains gas or LPG; in the future there may be models powered by oil or bio-liquids. Although gas and LPG are fossil fuels rather than renewable energy sources, the technology is still considered to be a 'low carbon technology' because it can be more efficient than just burning a fossil fuel for heat and getting electricity from the National Grid.

Micro-CHP systems are similar in size and shape to ordinary, domestic boilers and like them can be wall-hung or floor standing. The only difference to a standard boiler is that they are able to generate electricity while they are heating water.

Here are the benefits of micro-CHP.

- When the micro-CHP is generating heat, the unit will also generate electricity to be used in the home (or exported).
- By generating electricity on-site, the consumer could be reducing carbon dioxide output compared with using Grid electricity and a standard heating boiler.
- Micro-CHP is eligible for feed-in tariffs. **NB:** the feed-in tariff is not available in Northern Ireland.
- For the householder, there is very little difference between a micro-CHP installation and a standard boiler. If the consumer already has a conventional boiler then a micro-CHP unit should be able to replace it, as it's roughly the same size. However, the installer must be approved under the Microgeneration Certification Scheme (MCS).
- Servicing costs and maintenance are estimated to be similar to those of a standard boiler, although a specialist will be required.

Wave

Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work – for example, electricity generation, water desalination, or the pumping of water (into reservoirs). Machinery able to exploit wave power is generally known as a wave energy converter (WEC).

Wave-power generation is not currently a widely employed commercial technology, although there have been attempts to use it since at least 1890. In 2008, the first experimental wave farm was opened in Portugal, at the Aguçadoura Wave Park. The major competitor of wave power is offshore wind power.

Unit 302: Principles of electrical science

Worksheet 29: Alternative energy sources

Using your notes, answer the following questions.

1. What does **UPS** stand for in terms of electricity supply?

2. List **four** factors that must be considered when thinking of the installation of renewable energy sources.

3. State briefly some issues that may arise when considering the installation of a micro-wind powered generation systems in a domestic installation.