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

**LEARNING OUTCOMES**

There are seven learning outcomes to this unit. The learner will:

1. Understand the principles of a.c. theory
2. Understand the principles of lighting systems
3. Understand electrical quantities in star delta configurations
4. Understand the principles of electrical machines
5. Understand the principles of electrical devices
6. Understand the principles of electrical heating systems
7. Understand the principles of electronic components in electrical systems.

The unit will be assessed by:
- practical assignment
- written short-answer examination.
OUTCOME 1
Understand the principles of a.c. theory

INTRODUCTION

Alternating currents (a.c.) are universally used in the supply industry and also in most industrial, commercial and domestic applications. In the past, supplies in the UK were direct current (d.c.) but as d.c. cannot be transformed, that is stepped up or stepped down, a.c. was soon adopted.

The pure a.c. waveform follows a sine wave, rising and falling twice per cycle in both the voltage and current components. Understanding the effects that different types of load have on an a.c. waveform is important when considering power factor and any necessary correction required.

THE EFFECTS OF COMPONENTS IN A.C. CIRCUITS

Different components have different effects on a.c. circuits; these effects vary with frequency, depending on the components in the circuit. Other factors, such as resistance, have no effect on the waveform except to resist current flow.

Resistance

When a resistor is used in an a.c. circuit, the voltage drop and the current through the resistor are in phase, as the resistor has no effect on the circuit voltage or current, other than to restrict current flow proportionally to the voltage. The sinusoidal voltages and currents have no phase shift and are described as being ‘in phase’. This in-phase or unity relationship can be understood using Ohm’s law for the voltage and current:

\[ V = I \times R \]

As there is no phase shift effect, there is no requirement in a resistive circuit to include the power factor. Resistive loads in a.c. circuits include items such as incandescent lamps, water heater (immersion) elements and electric kettles. Any load that relies on current passing through a material and producing heat is resistive.

Assessment criteria

1.1 Explain the effects of components in a.c. circuits

ASSESSMENT GUIDANCE

Ohm’s law states that the current flowing in a circuit is proportional to the applied voltage and inversely proportional to the resistance.

ASSESSMENT GUIDANCE

Power factor is the ratio of true power (watts) to volt-amperes:

\[ PF = \frac{W}{VA} \]
The relationship between the voltage, current and resistance in an a.c. circuit can be shown as a circuit diagram, phasor diagram and sine wave, together with the appropriate formula.

**Relationship between voltage, current and resistance as shown by a circuit diagram**

The circuit diagram shows the resistor connected to an a.c. supply.

**Relationship between the voltage and current as shown by a phasor diagram**

The phasor diagram shows the relationship between the voltage and current. As the voltage and current are together, they are in phase or unity.

**ASSESSMENT GUIDANCE**

A phasor always rotates anti-clockwise.
The sine wave shows the voltage and current rising and falling at the same time. In a.c. circuits involving resistance only, Ohm’s law applies as:

\[ V = I \times R \]

**Inductance**

An inductor is a length of wire; sometimes this is a longer wire wound into a coil with a core of iron or air. An inductor is a component, such as a solenoid or field winding in a motor or a ballast unit in a fluorescent luminaire, that induces (produces) magnetism. Inductance is proportional to the inductor’s opposition to a.c. current flow.

- The symbol for inductance is \( L \).
- The unit of inductance is the henry (H).

As inductance increases and all other factors, such as frequency, remain the same, a.c. current flow reduces. This opposition to a.c. current flow is indicated as an increase in inductive reactance \( X_L \).

We will assume that an inductor in a circuit produces pure inductance but this is actually impossible; as an inductor is a coiled wire, it also has resistance.

An inductor in a circuit

A pure inductance, as shown in the circuit, will create a phase shift that causes the current to lag behind the voltage by 90°.

Phasor diagram showing phase shift
The phasor diagram shows the phase shift. When the phasor is rotated in the direction shown, the voltage leads the current or, as we normally say, the current lags behind the voltage. If the inductance was pure, this lag would be 90°. We will explore how to create a phasor diagram later in this outcome.

If you look at the lagging current sine wave, you will see that the current does not begin its cycle until the voltage is 90° into its cycle. Where the voltage begins its negative half-cycle, the current is still in a positive cycle – meaning the two values are opposing or reacting to one another. This opposition is known as reactance, \( X \), measured in ohms (\( \Omega \)). As the reactance is linked to an inductor, we call this inductive reactance (\( X_L \)).

The reactance in the circuit can be determined using the value of inductance (\( L \)) in henrys (\( H \)) and the frequency of the supply (\( f \)) measured in hertz (Hz). So

\[
X_L = 2\pi fL
\]

**Example calculation**

Determine the reactance when an inductance of 40 mH is connected to a 230 V 50 Hz supply.

As:

\[
X_L = 2\pi fL
\]

then:

\[
X_L = 2\pi \times 50 \times 40 \times 10^{-3} = 12.56 \Omega
\]
If the inductance is pure, the reactance replaces resistance in Ohm’s law so:

\[ I = \frac{V}{X_L} \]

So using the example above, the value of circuit current would be:

\[ I = \frac{230}{12.56} = 18.3 \text{ A} \]

Assuming the resistance to be pure, this current would lag the voltage by 90°. Remember, however that the inductance cannot be pure as the coil or winding is made up of a conductor which has resistance. We will study the effect of resistance on an inductor later in this outcome.

**Capacitance**

A capacitor is a device that is used to store and discharge energy. It does not contain a resistance so it does not dissipate energy. A capacitor can be pure. Capacitors are used in circuits for many reasons; most commonly, capacitors are found in fluorescent luminaires for power factor correction purposes. Capacitance (C) is measured in farads (F) – usually expressed in micro-farads. One micro-farad (μF) is one-millionth (10⁻⁶) of a farad.

A capacitor has the opposite effect to an inductor when connected to an a.c. circuit; it causes the current to lead the voltage by 90°.

The capacitor produces a reactance. This reactance, known as capacitive reactance (X_C), affects current flow.

**ASSESSMENT GUIDANCE**

The amount of energy stored in a capacitor is very small. In a typical fluorescent capacitor it is about 0.1 J.
The phasor shows that the current leads the voltage by 90° in the direction of rotation.

Sine wave diagram showing phase shift due to a capacitor

The sine wave diagram shows the current leading the voltage and, once again, the current and voltage are in opposition. At various points in the cycle there will be reactance.

The capacitive reactance of a capacitive circuit can be determined using

\[ X_C = \frac{1}{2\pi fC} \]

**Example calculations**

Determine the reactance when a 120 μF capacitor is connected to a 230 V 50 Hz supply.

As:

\[ X_C = \frac{1}{2\pi fC} \]

then:

\[ X_C = \frac{1}{2\pi \times 50 \times 120 \times 10^{-6}} = 26.52 \, \Omega \]

Where the capacitance is pure (that is no other components are connected in that part of the circuit), then \( X_C \) replaces resistance in Ohm’s law.
Determine, using the example above, the current drawn by the capacitor.

So as:

\[ I = \frac{V}{X_C} \]

then:

\[ I = \frac{230}{26.52} = 8.6 \text{ A} \]

**Impedance**

Impedance is the product of resistance and one or more of the other two components in a circuit. Where resistance and another component are connected in a circuit, the effect reduces the angle by which the current leads or lags. As resistance is in unity and the other components cause the current to lead or lag the voltage, and since more than one current cannot exist, the resulting current will fall in between, depending on the values of all the components.

**ASSESSMENT GUIDANCE**

Most loads are either resistive (heaters and tungsten lamps) or a mixture of resistive and inductive.

**ASSESSMENT GUIDANCE**

A two-core cable has capacitance as it consists of two plates (conductors) and a dielectric (insulation).
The value of reactance \((X)\) depends on the component used so, if an inductance is connected with an impedance, \(X_L\) is used and for capacitance \(X_C\) is used.

Where a circuit contains both, the resulting reactance is used; this is the smallest value taken from the largest.

**Example calculation**

As an example, determine the impedance if a circuit contained a 30 \(\Omega\) resistance, an inductor having a 12.56 \(\Omega\) reactance and a capacitor having a 26.52 \(\Omega\) reactance.

The total reactance is:

\[X = X_C - X_L\]

as the capacitive reactance is the larger value.

So as:

\[Z = \sqrt{R^2 + X^2}\]

then:

\[Z = \sqrt{30^2 + (26.52 - 12.56)^2} = 33.08 \Omega\]

**Impedance triangle**

The relationship between the different components in a circuit can be explored using an impedance triangle, as shown in the diagram.

Using the triangle and Pythagoras' theorem, we can see that the impedance value alters depending on the values of resistance or reactance. Impedance triangles are drawn to scale. If the value of reactance increases or decreases, this affects the angle between the resistance \((R)\) and impedance \((Z)\). We will explore this relationship later in this outcome when we look at power factor.
LO1 Principles of a.c. theory

**CALCULATE QUANTITIES IN A.C. CIRCUITS**

Components in a.c. circuits can be arranged in series, parallel or in combination. Each configuration has different effects on circuit properties.

**Series connected circuits (RL series)**

When an inductor is connected into a circuit, we consider that the inductor has pure inductance (pages 150–152). This, in reality, is not possible as the conductor that is used to form the inductor’s coil has a resistance. These two properties are in series with one another. As with d.c. circuits, if components are connected in series, the current is constant (that is, it is the same through each component), but the voltage changes as it is ‘lost’ across each component, creating voltage drop or a potential difference.

![Diagram of series connected circuits](image)

Components connected in series

The circuit shown in the diagram has the following values:

- \( R = 40 \, \Omega \)
- \( L = 38 \, \text{mH} \)
- Supply = 230 V 50 Hz

**Example calculation**

Determine:

- **a)** the inductive reactance \((X_L)\)
- **b)** the impedance \((Z)\)
- **c)** the total circuit current \((I)\)
- **d)** the value of voltage across each component \((R, V)\).

**Assessment criteria**

1.2 Calculate quantities in a.c. circuits

**ACTIVITY**

Calculate the current drawn by a 10 μF capacitor when connected to a 230 V 50 Hz a.c. supply.
Determine the voltage across each component part from Ohm's law:

\[ V_R = I \times R \quad \text{so} \quad V_R = 5.51 \times 40 = 220.4 \text{ V} \]

\[ V_L = I \times X_L \quad \text{so} \quad V_L = 5.51 \times 11.93 = 65.73 \text{ V} \]

As you can see, the two voltages do not add up to the supply voltage of 230 V. This is because the supply voltage would be the phasor sum of the two values as each component reacts differently to a.c. current.

We can determine the phasor sum in two ways, by calculation (using Pythagoras' theorem) or by constructing a phasor to represent the two components.

**Determining the phasor sum by calculation**

\[ V_{\text{supply}} = \sqrt{V_R^2 + V_L^2} \]

so

\[ V_{\text{supply}} = \sqrt{220.4^2 + 65.73^2} = 229.99 \text{ V or 230 V} \]

**Constructing a phasor**

As we have seen, a phasor diagram is a representation of the component values in an a.c. circuit and how the components lead or lag. Also, it shows the resulting supply characteristics.

To construct a phasor, we must first decide on a reference line. In a series circuit the common component is current as it is the same throughout the circuit; in a parallel circuit, this would be voltage.
A phasor must be drawn to scale. We draw the resistor voltage line which is in unity to the supply (reference line).

Then we add the value of the inductor voltage to the same scale. As the current lags in an inductive circuit, the voltage $V_L$ is drawn upwards. This is to show that the current (reference line) lags the voltage (given the direction of rotation). As we must assume this component to be pure, the line is drawn 90° from the reference line.

Then we construct a parallelogram from the two voltage values.

Finally, the resulting supply voltage is drawn in, connecting the origin to the point where the two sides of the parallelogram intersect. The length of this line, to the scale used, represents the supply voltage $V_S$. We can see from the phasor that the current lags behind the supply voltage by a particular angle less than 90° – the resistance acts against the pure inductance, meaning the current lag is not fully 90°.
If a circuit contains all three components, as in the diagram shown in the

**RLC series circuits**

The components behave differently as the circuit current changes.

The circuit shown in the diagram has the following values:

- \( R = 40 \, \Omega \)
- \( L = 38 \, \text{mH} \)
- \( C = 120 \, \mu\text{F} \)
- Supply = 230 V 50 Hz

**Example calculation**

Determine:

a) the inductive reactance \((X_L)\)

b) the capacitive reactance \((X_C)\)

c) the impedance \((Z)\)

d) the total circuit current \((I)\)

e) the value of voltage across each component \((V_R), (V_L)\) and \((V_C)\).

**ASSESSMENT GUIDANCE**

In an RLC series circuit where the inductive and capacitive reactance cancel each other out, \( R = Z \) and the power factor is 1 (unity). The current is \( V/R \). High voltage may appear across the reactive components.

**ACTIVITY**

A capacitor and inductor each of 200 Ω reactance are connected in series to a 115 Ω resistor. What is the voltage across the capacitor if the supply voltage is 230 V?
LO1 Principles of a.c. theory

a) As \( X_L = 2\pi fL \) then \( X_L = 2 \times \pi \times 50 \times 38 \times 10^{-3} = 11.93 \Omega \)

b) As \( X_C = \frac{1}{2\pi fC} \) then \( X_C = \frac{1}{2 \times \pi \times 50 \times 120 \times 10^{-6}} = 26.52 \Omega \)

c) As \( Z = \sqrt{R^2 + X^2} \) and \( X = X_C - X_L \) then

\[
X = X_C - X_L = 26.52 - 11.93 = 14.59 \Omega
\]

So \( Z = \sqrt{40^2 + 14.59^2} = 42.57 \Omega \)

d) As \( I = \frac{V}{Z} \) then \( I = \frac{230}{42.57} = 5.4 \text{ A} \)

e) The value of voltage across each component part is determined from Ohm’s law:

\[
V_R = I \times R \quad \text{so} \quad V_R = 5.4 \times 40 = 216 \text{ V}
\]

\[
V_L = I \times X_L \quad \text{so} \quad V_L = 5.4 \times 11.93 = 64.42 \text{ V}
\]

\[
V_C = I \times R_C \quad \text{so} \quad V_C = 5.4 \times 26.52 = 143.2 \text{ V}
\]

Once again, we could prove the circuit supply voltage by calculation or phasor.

**Determining the phasor sum by calculation**

\[
V_{\text{supply}} = \sqrt{V_R^2 + V_X^2} \quad \text{where} \quad V_X = V_C - V_L
\]

Once again, subtract the smallest value from the largest:

\[
V_X = 143.2 - 64.42 = 78.78 \text{ V}
\]

So

\[
V_{\text{supply}} = \sqrt{216^2 + 78.78^2} = 229.5 \text{ or } 230 \text{ V}
\]

**Constructing a phasor**

We construct the phasor as before, but this time we insert the voltage across the capacitor before we construct the parallelogram. Remember, as the current leads the voltage in a capacitor, the voltage lags the reference line (in the downwards direction) by 90°.

Following this, we take the smallest value of voltage in the capacitor or inductor from the largest, just as in the calculation, so we end up with a resulting voltage \( V_X \) from which the parallelogram may be formed.

We can see that the current now leads the voltage by a particular angle as the capacitor is the stronger component.
Components in parallel

When components are connected in parallel, the voltage becomes the common component and current is split through each component.

The circuit shown in the diagram has the following values:

\[ R = 40 \, \Omega \]
\[ C = 120 \, \mu F \]
\[ \text{Supply} = 230 \, V \, 50 \, Hz \]

Example calculation

Determine:

a) the capacitive reactance \( X_C \)
b) the value of current through each component
c) the total circuit current.

\[ a) \quad X_C = \frac{1}{2\pi fC} \quad \text{then} \quad X_C = \frac{1}{2 \times \pi \times 50 \times 120 \times 10^{-6}} = 26.52 \, \Omega \]
\[ b) \quad I_R = \frac{V}{R} \quad \text{so} \quad I_R = \frac{230}{40} = 5.75 \, A \]
\[ c) \quad I_C = \frac{V}{X_L} \quad \text{so} \quad I_C = \frac{230}{26.52} = 8.67 \, A \]

In the same way as we did for voltage, we can prove the circuit supply current by calculation or phasor.

Proving the circuit supply current by calculation

\[ I_{\text{supply}} = \sqrt{I_R^2 + I_C^2} \]

So

\[ I_{\text{supply}} = \sqrt{5.75^2 + 8.67^2} = 10.4 \, A \]

Constructing a phasor

Once again, drawn to a suitable scale, the phasor is used to determine the supply current. Notice that, this time, the voltage is the reference line as it is common to all components. The capacitor is the stronger component so, as a result, the supply current ends up leading.
Circuits with both series and parallel components

In practice, in electrical installations, electricians are more likely to come across circuits where the inductor and resistor are in series, such as in motor winding or in the choke/ballast in a fluorescent luminaire, and the capacitor is in parallel for power factor correction purposes.

In this situation, the current in the series section of the circuit is determined using impedance and the capacitor is determined using capacitive reactance.

The circuit shown in the diagram has the following values:

$R = 12 \, \Omega$
$L = 88 \, mH$
$C = 150 \, \mu F$

Supply = 230 V 50 Hz

Example calculation

First, we determine the inductive reactance:

$$X_L = 2\pi fL$$

so:

$$X_L = 2\pi \times 50 \times 88 \times 10^{-3} = 27.64 \, \Omega$$

and:

$$Z = \sqrt{R^2 + X_L^2}$$

so:

$$Z = \sqrt{12^2 + 27.64^2} = 30.13 \, \Omega$$

The current in the inductive/resistive section of the circuit is:

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

so:

$$I = \frac{230}{30.13} = 7.63 \, A$$

ACTIVITY

R and L in series with C in parallel is a typical power factor correction arrangement. It is not usually required to correct to unity power factor. Explain why this is.
The current drawn by the capacitor is based on the capacitive reactance:
\[ X_c = \frac{1}{2\pi fC} \]
so:
\[ X_c = \frac{1}{2\pi \times 50 \times 150 \times 10^{-6}} = 21.22 \, \Omega \]
therefore as:
\[ I = \frac{V}{X_c} \]
then:
\[ I = \frac{230}{21.22} = 10.83 \, \text{A} \]

Showing this as a phasor to determine the total current requires a slightly different approach to before; we need first to construct a phasor using the series circuit values, then draw in the capacitance values. Before we do this, we need to understand how power factor affects the circuit and, therefore, the resulting phase angle.

**POWER FACTOR**

The power factor is defined as the cosine of the angle by which the current leads or lags the voltage (\( \cos \theta \)). The power factor does not have a unit of measurement as it is a factor. The value can range from 0.01 to 0.99. A power factor of 1 is unity, the same as having a resistive circuit where the current rises and falls in phase with the voltage.

Power factors are used to express the effect of leading and lagging currents and many machines have a power-factor rating stated on the rating plate. The value is used to determine the current demand of the machine. As circuits with leading or lagging currents introduce reactance, this creates the effect of additional loading and, therefore, additional current demand in a circuit. We need to understand and allow for this additional load when selecting equipment and cables for a circuit or installation.

**Assessment criteria**

1.4 Calculate power factor

**Activity**

Use your calculator to find the cosine of 1°, 10°, 30°, 45°, 70° and 90°. Can you see that the greater the angle, the smaller the factor; the smaller the angle, the closer the factor is to 1, or unity?

If you reverse the process and choose a factor, you can determine the angle by using the \( \cos^{-1} \) feature on your calculator. Try \( \cos^{-1} 0.75 \).

**Key Point**

A power factor cannot go beyond 0.00 (which represents 90°) as any current that lags by more than 90° becomes a leading current.
Calculating power factor

To determine the values of the power factor at circuit level, we can apply the following equation:

\[
\text{power factor} = \cos \theta = \frac{R}{Z}
\]

The circuit shown in the diagram has the following values:

- \( R = 40 \, \Omega \)
- \( L = 38 \, \text{mH} \)
- Supply = 230 V 50 Hz

Example calculation

Determine:

a) the inductive reactance (\( X_L \))

\[
X_L = 2\pi fL = 2 \times \pi \times 50 \times 38 \times 10^{-3} = 11.93 \, \Omega
\]

b) the impedance (\( Z \))

\[
Z = \sqrt{R^2 + X_L^2} = \sqrt{40^2 + 11.93^2} = 41.74 \, \Omega
\]

c) the total circuit current (\( I \))

\[
I = \frac{V}{Z} = \frac{230}{41.74} = 5.51 \, \text{A}
\]

d) the power factor and angle by which the current lags the voltage.

\[
\text{power factor} = \cos \theta = \frac{R}{Z}
\]

\[
\cos \theta = \frac{40}{41.74} = 0.958 \, \text{A}
\]

So if the power factor is 0.95, the angle by which the current lags the voltage (inductive circuit) is:

\[
\cos^{-1} 0.958 = 16.7^\circ
\]

Power factors and impedance triangles

Power factors can also be determined from impedance triangles as the angle formed by the \( R \) and \( Z \) lines represents the angle by which the current leads or lags the voltage. The cosine of this angle is the power factor.

We will look again at power factors once we have looked at values of power quantities in the next section.
In an earlier example (page 162), we examined a circuit with components in series and in parallel. Here is the circuit again.

Recall the information given for this circuit:

- \( R = 12 \, \Omega \)
- \( L = 88 \, \text{mH} \)
- \( C = 150 \, \mu\text{F} \)
- Supply = 230 V 50 Hz

As we have previously determined:

\[ X_L = 2\pi fL \]

so:

\[ X_L = 2\pi \times 50 \times 88 \times 10^{-3} = 27.64 \, \Omega \]

and:

\[ Z = \sqrt{R^2 + X_L^2} \]

so:

\[ Z = \sqrt{12^2 + 27.64^2} = 30.13 \, \Omega \]

The current in the inductive/resistive section of the circuit is:

\[ I = \frac{V}{Z} \]

so:

\[ I = \frac{230}{30.13} = 7.63 \, \text{A} \]

The current drawn by the capacitor is based on the capacitive reactance:

\[ X_C = \frac{1}{2\pi fC} \]

so:

\[ X_C = \frac{1}{2\pi \times 50 \times 150 \times 10^{-6}} = 21.22 \, \Omega \]

As:

\[ I = \frac{V}{X_C} \]

then:

\[ I = \frac{230}{21.22} = 10.83 \, \text{A} \]
We can now go on to determine the power factor and angle of the lagging current in the series branch of the circuit in order to construct our phasor.

As the power factor \( \cos \theta = \frac{R}{Z} \)

then \( \cos \theta = \frac{12}{30.13} = 0.398 \)

So the angle is \( \cos^{-1} 0.398 = 66.55^\circ \) lagging (inductive circuit)

We can construct the phasor, firstly, by showing that the current drawn by the impedance (series branch) part of the circuit lags the voltage reference line by 66.55° to a scale value of 7.63 A.

We can then add the capacitor in parallel, drawing 10.83 A and leading the voltage by 90°. Forming a parallelogram from these two points gives us the point from which to draw the supply circuit current. This should work out to be 4.8 A to scale. From this, we can also see the angle at which it leads the voltage. The cosine of this angle is the power factor of the circuit.

We will return to power factor once we have explored power quantities.

**THE RELATIONSHIP OF POWER QUANTITIES IN A.C. CIRCUITS**

When we explored power at Level 2, we described the relationship between voltage and current as:

\[ P = V \times I \]

If a load was purely resistive, this would be true. However, as many a.c. circuits have impedances and capacitors, the power behaves differently as an element of the power dissipated, due to the reactance of the circuit.

**Power triangle**

In power terms, this reactive part of the circuit (together with the true power relationship) can be explained using a power triangle.

As we can see, a resistive load gives the true power. The reactive (capacitive or inductive) load creates the reactive power element that affects the overall impedance. This is the apparent power.
Therefore, having a reactive component in the load creates an apparent power. This draws more current from the load than if this was a purely resistive load. The apparent load is measured in volt-amperes (VA) or kilovolt-amperes (kVA). We can also see that an angle forms between the true power and apparent power. The cosine of this angle gives the power factor for the circuit or load.

So in order to determine the true power of a circuit we must apply this equation:

\[
\text{true power (watts, W)} = V \times I \times \cos \theta
\]

And from this, we could also state:

\[
\text{power factor } \cos \theta = \frac{\text{true power}}{\text{apparent power}} \text{ or } \frac{\text{kW}}{\text{kVA}}
\]

Like a phasor, a power triangle could help us to determine appropriate values of capacitance to improve the power factor.

**Example calculation**

A 230 V 4 kW motor has a power factor rating of 0.4. Determine a suitably sized capacitor to improve the power factor to 0.85. Supply frequency is 50 Hz.

Let us first work out some values to see the extent of the problem.

If we ignore reactance and, therefore, power factor, this motor should draw a current of:

\[
\frac{4000 \text{ W}}{230 \text{ V}} = 17.4 \text{ A}
\]

But in reality it draws a current of:

\[
\frac{4000 \text{ W}}{230 \text{ V} \times 0.4} = 43.5 \text{ A}
\]

So, you can see that the reactance in the circuit causes the motor to draw 43.5 A instead of 17.4 A. This is a huge difference. By installing a correctly sized capacitor into the circuit, we could improve this, reducing the overall current demand. As the motor is an inductive load causing the current to lag, a capacitor will draw the current back towards unity and, therefore, closer to the value of true power.

To work out the size of capacitor needed, we need to determine the amount of reactive power the capacitor consumes. Remember, this reactive power drawn by the capacitor doesn’t increase overall power demand, it simply off-sets the reactance caused by the impedance as it draws the current towards leading and, therefore, reducing reactance.
To determine the amount of reactive power, we need to draw a power triangle to show the relationship before correction.

Using a suitable scale, we draw true power to represent 4 kW. Then we measure an angle from this of \( \cos^{-1} 0.4 = 66.4^\circ \).

The line from this angle represents the apparent power. We then draw a line up at 90° from the other end of the true power line. This line represents the apparent power. The two lines meet to form the power triangle, as seen in the diagram.

As we need to improve power factor to 0.85, we need to measure another angle from the true power line at \( \cos^{-1} 0.85 = 31.79 \) (32°). This line represents the new apparent power following correction, and gives a value by which reactance must be reduced.

By measurement, this line represents 6.6 kVA, so:

\[
\frac{kVA \times 100}{V} = I_c
\]

so:

\[
\frac{6.6 \times 1000}{230} = 28.70 \text{ A}
\]

So, we need a capacitor that will draw a current of 28.70 A.

Then we need to carry out some of the previous calculations in reverse.

So:

\[
\text{as } I_c = \frac{V}{X_c} \text{ then } X_c = \frac{V}{I_c} \frac{230}{28.70} = 8 \Omega
\]

And then:

\[
X_c = \frac{1}{2\pi fC} \text{ so } C = \frac{1}{2\pi fX_c} = \frac{1}{2\pi \times 50 \times 8} = 398 \times 10^{-6}
\]

A 398 \( \mu \)F capacitor is needed.
**POWER FACTOR CORRECTION**

There are different types of power factor (PF) correction that the designer can use; however, not all methods are practicable in all circumstances.

In order to correct the power factor on the supply, it is necessary to measure it. In order to do this, metering can be applied, as indicated in the diagram.

![Connection of instruments to calculate PF](image)

The wattmeter is used to indicate true power (P in watts, W), whereas the volt and ammeter are used to calculate the apparent power (volt-amperes in VA).

Since:

\[ PF = \frac{\text{true power}}{\text{apparent power}} \]

then the above connected meters will enable the PF to be calculated.

**Correction by capacitors**

The application of power factor correction capacitor banks is employed in electrical installations to correct the power factor.

This is due to the fact that most circuits are inductive in nature, which creates a lagging power factor. By adding power factor correction capacitors to the circuit, the kVA, is reduced as the capacitive kVA, cancels out the inductive kVA.

In the past, power factor correction was also carried out using synchronous motors to supplement capacitor banks but this practice is now very rare.
Larger automatic switchable unit

Power factor correction in many installations is achieved by a bank or banks of fixed capacitors. Alternatively, where the load changes or more accurate correction is required, power factor correction is achieved through automatically switched capacitors. Automatic switching units use monitoring technology to switch capacitors in and out of the load automatically as the load profile changes. These units are in banks, normally in multiples of 50kVA, so that the first bank of fixed capacitors deals with the base load. Remember that going too far with capacitors causes a leading power factor, which is again chargeable.

Therefore, it is ideal to balance the load and switch in capacitors throughout the changing load profile to ensure the PF stays around 0.95. These units are normally installed at or near the intake position in a building in order to deal with the overall power factor correction.

As well as using capacitor banks to correct power factor at source, the power factor may be corrected through the equipment. Installing suitably rated capacitors in parallel with a load improves the power factor. As an example, fluorescent luminaires contain capacitors for this reason. The capacitor is connected between line and neutral in the luminaire. If the capacitor is removed, the luminaire will still operate but it will draw slightly more current due to the power factor.
Lighting is a specialist area in electrical installations work. Many designers and installers rely on specialists to manage the design of lighting, but there are some basic areas of knowledge that an electrician needs to know in order to install and maintain luminaires effectively.

**LAWS OF ILLUMINATION AND ILLUMINATION QUANTITIES**

Two laws explain how light behaves when it is emitted from a luminaire onto a surface: the inverse square law and the cosine law. First, look at the terms and units used to explain and quantify lighting.

**Lighting terms and units**

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous intensity</td>
<td>$I$</td>
<td>candela (cd)</td>
<td>The amount of light emitted per solid angle or in a given direction</td>
</tr>
<tr>
<td>Luminous flux</td>
<td>$F$</td>
<td>lumen (lm)</td>
<td>The total amount of light emitted from a source</td>
</tr>
<tr>
<td>Illuminance</td>
<td>$E$</td>
<td>lumens per metre$^2$ (lux)</td>
<td>The amount of light falling on a surface</td>
</tr>
<tr>
<td><strong>Efficacy</strong></td>
<td>$K$</td>
<td>lumens per watt (lm/W)</td>
<td>This is a term used to measure the <strong>efficiency</strong> of a lamp or luminaire. It compares the amount of light emitted to the electrical power consumed.</td>
</tr>
<tr>
<td>Maintenance factor</td>
<td>$M_f$</td>
<td>none</td>
<td>These factors are used to de-rate the light output of a lamp, allowing for dust. The factor used depends on the environment. An average office environment would have a factor of 0.8 whereas a factory where lots of dust accumulates may be 0.4.</td>
</tr>
<tr>
<td>Or Light loss factor</td>
<td>$L_l$</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Coefficient of utilisation or utilisation factor</td>
<td>$U_f$</td>
<td>none</td>
<td>This factor takes the surfaces in a room, such as walls and ceilings, into account. Emitted light bounces off walls that reflect light well, giving more light. An average factor for a room is 0.6. The lighter the colour of the room, the higher the factor.</td>
</tr>
<tr>
<td>Space–height ratio</td>
<td></td>
<td></td>
<td>This ratio is used to determine how close together luminaires need to be, taking into account their height from a given surface, in order to illuminate a room with an even spread of light from multiple luminaires.</td>
</tr>
</tbody>
</table>
Some lamps, such as light-emitting diode (LED) lamps, are rated in lumens whereas others are rated in candela. Take care with this as the choice of lamp depends on its application. To illuminate a particular point, such as a kitchen work surface, the candela rating is important as it rates the intensity of light in a particular direction. For illuminating a general area, such as a driveway, the luminous flux (lumens) is a better indicator as it measures the total light output in all directions.

**Inverse square law**

The amount of light falling onto a surface changes depending on the distance from the light source. If you hold a torch just above a surface, the light falling on the surface is intense. As you move the torch further away, the light directly below the torch becomes less intense because the light spreads. The amount of light on the surface is the illuminance. To determine the amount of light on the surface directly below the source, use the inverse square law.

\[ E = \frac{I}{d^2} \text{ (lux)} \]

where:
- \( I \) = luminous intensity in candela (cd)
- \( E \) = illuminance on the surface in lux
- \( d \) = distance between the lamp and surface in metres (m).

**ACTIVITY**

A luminaire emits 1250 candela in all directions. Calculate the illuminance at a) 2.5 m and b) 5 m directly below the luminaire.
Example

A 1000 cd light source is suspended above a level plane. Calculate the illuminance of the surface at 2 m and 4 m from the source.

At 2 m:

\[ E = \frac{I}{d^2} \]

Therefore:

\[ E = \frac{1000}{2^2} = 250 \text{ lux} \]

At 4 m:

\[ E = \frac{I}{d^2} \]

Therefore:

\[ E = \frac{1000}{4^2} = 62.5 \text{ lux} \]

Cosine law of illumination

When light falls obliquely on a surface, not at right angles to it, the light spreads over an increasing area as the angle (θ) between the perpendicular to the surface and the direction of the light increases.
To calculate illumination in such cases, use the cosine law, which takes the additional area illuminated into account. It is expressed as:

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

where:
- $I$ = luminous intensity in candela (cd)
- $E$ = illuminance on the surface in lux
- $d$ = distance between the lamp and surface in metres (m)
- $\cos \theta$ = cosine of the angle at which the light is emitted from the lamp.

Calculating illumination at different angles

If the angle is unknown, the cosine of the angle can be determined by using Pythagoras’ theorem and trigonometry.

As:

$$h = \sqrt{d^2 + L^2}$$

and:

$$\cos \theta = \frac{d}{h}$$
Example
A 1200 cd light source is suspended above a level plane. Calculate the illuminance of the surface at 2 m directly below the source \( (E_1) \) and then calculate the illuminance on a surface 4 m away \( (E_2) \).

\[
E_1 = \frac{I}{d^2}
\]

Therefore:
\[
E_1 = \frac{1200}{2^2} = 300 \text{ lux}
\]

To determine \( E_2 \), find \( \cos \theta \).

So:
\[
h = \sqrt{d^2 + L^2}
\]
Therefore:
\[ h = \sqrt{2^2 + 4^2} = 4.47 \text{ m} \]
and
\[ \cos \theta = \frac{d}{h} \]
Therefore:
\[ \frac{2}{4.47} = 0.44 \]
Therefore:
\[ E_2 = \frac{1200}{2^2} \times 0.44 = 132 \text{ lux} \]

**Lumen method**

As can be seen from the cosine law, the level of light varies across an area due to the distance and angle of the light source. When a desired level of illuminance is specified, an average figure is used across the area or working surface.

Lighting guides give values of illuminance that are suitable for use in various areas. The average value is usually quoted in lux.

The lumen method is used to determine the number of lamps that should be installed for a given area or room to achieve a specific average illuminance level.

**Guided average illuminance levels for different activities or areas**

<table>
<thead>
<tr>
<th>Activity or area</th>
<th>Illumination (lux, lumen/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public areas with dark surroundings</td>
<td>20–50</td>
</tr>
<tr>
<td>Working areas where visual tasks are only occasionally performed</td>
<td>100–150</td>
</tr>
<tr>
<td>Warehouses, homes, theatres, archives</td>
<td>150</td>
</tr>
<tr>
<td>Classrooms</td>
<td>250–350</td>
</tr>
<tr>
<td>Normal office work, computer work, study library</td>
<td>350–450</td>
</tr>
<tr>
<td>Supermarkets, mechanical workshops</td>
<td>750</td>
</tr>
<tr>
<td>Normal drawing work, detailed mechanical workshops</td>
<td>1000</td>
</tr>
<tr>
<td>Detailed drawing work, very detailed mechanical works</td>
<td>1500–2000</td>
</tr>
<tr>
<td>Performance of very prolonged and exacting visual tasks</td>
<td>5000–10 000</td>
</tr>
</tbody>
</table>
Calculating for the lumen method

The lumen method is appropriate for use in lighting design 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 room surfaces.

Usually, the illuminance will already have been specified by the designer, eg office 350–450 lux.

The formula is:

\[
N = \frac{E_{\text{average}} \times \text{area}}{Mf \times Uf \times F}
\]

where:

- \(E_{\text{average}}\) = average illuminance over the horizontal working plane in lux
- \(N\) = number of luminaires required
- \(F\) = luminous flux of each luminaire selected in lumens (as declared by the manufacturer)
- \(Uf\) = utilisation factor based on the reflectance of the room walls, ceiling and work surface
- \(Mf\) = maintenance or light loss factor (llf)
- \(A\) = area to be illuminated.

Example

Determine the number of luminaires required in an office measuring 18 m by 20 m. The room is to be illuminated using recessed modular luminaires with a luminous flux given as 4800 lumens per fitting. The room has a white ceiling and walls painted a light colour; as a result, the utilisation factor is 0.9. As dust in an office is minimal, the maintenance factor is 0.8. The average illuminance desired is 400 lux.

Using:

\[
N = \frac{E_{\text{average}} \times \text{area}}{Mf \times Uf \times F}
\]

\[
N = \frac{400 \times (18 \times 20)}{0.9 \times 0.8 \times 800} = 41.66 \text{ or } 42 \text{ luminaires}
\]

ASSESSMENT GUIDANCE

The maintenance or light loss factor is composed of three items: dirt on the walls and in the air, dirt on the fittings and aging of the lamps.

ACTIVITY

Determine the number of luminaires needed to illuminate your classroom to an average illuminance of 350 lux. Determine the utilisation factor and maintenance factor, based on the brightness and dust accumulation of the room. Use manufacturer’s data to obtain the luminous flux of a luminaire.
OPERATION OF LUMINAIRES

Space–height ratio

The space–height ratio determines how far apart luminaires should be in relation to their intended mounting height, or visa versa. The ratio depends on the particular luminaire and is determined by the manufacturer.

Example

If the space–height ratio of a luminaire is 3:2 and the mounting height is 2.4 m above the working plane (the area where the maximum illuminance is needed), determine the distance needed between luminaires.

\[
\frac{S}{H} = \frac{s}{h}
\]

where:
- \( S \) is the space ratio
- \( H \) is the height ratio
- \( S \) is the actual spacing between luminaires (centre to centre)
- \( H \) is the height the luminaires are mounted.

\[
\frac{3}{2} = \frac{s}{2.4}
\]

So:

\[
\frac{3 \times 2.4}{2} = S = 3.6 \text{ m}
\]

Assessment criteria 2.3 continues on page 180.

APPLICATION OF LUMINAIRES

Efficacy

Lamps are given an efficacy rating based on the amount of luminous flux (in lumens) emitted by the lamp for every watt of power consumed by the lamp, including losses (in watts). An efficacy rating is a good indication of a particular lamp’s energy efficiency. The higher the efficacy rating, the better the energy efficiency.

\[
\text{efficacy} = \frac{\text{light output (lm)}}{\text{electrical input (W)}} = \frac{\text{Im}}{\text{W}}
\]
The purpose of a lamp is to produce light. Many lamps also produce heat during operation. As energy is required to produce the heat, this counts as a loss of energy because heat is not the intended product of the lamp.

In order for buildings to comply with current Building Regulations or the Code for Sustainable Homes, guidelines are given for the minimum lumens of light per circuit watt consumed.

Example
The light output from a lamp is 8000 lumens and the input power is 150 watts. Calculate the efficacy of the lamp.

\[
\text{efficacy} = \frac{\text{lm}}{\text{W}} = \frac{8000}{150} = 53.33 \text{ lm/W}
\]

Indication of the efficacy of different lamp types. Consult manufacturer’s data for accurate ratings for particular lamps.

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>Efficacy (lm/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 W GLS incandescent lamp</td>
<td>14</td>
</tr>
<tr>
<td>100 W tungsten halogen</td>
<td>16</td>
</tr>
<tr>
<td>50 W high-pressure sodium (SON)</td>
<td>120</td>
</tr>
<tr>
<td>18 W compact fluorescent (CF)</td>
<td>61</td>
</tr>
<tr>
<td>70 W metal halide</td>
<td>64</td>
</tr>
<tr>
<td>20 W T5 fluorescent tube</td>
<td>99</td>
</tr>
<tr>
<td>2 W LED</td>
<td>100</td>
</tr>
<tr>
<td>90 W low-pressure sodium (SOX)</td>
<td>180</td>
</tr>
</tbody>
</table>

Colour rendering
The term ‘colour rendering’ describes the ability of a lamp or luminaire to keep objects looking their true colour. Some lamps emit orange light and so objects lit by the lamp appear orange.

Colour rendering is very important when selecting luminaires, depending on their application. For example, general amenity lighting or street lighting does not require good colour rendering unless closed circuit TV (CCTV) is present, in which case this factor is important. Studies have shown that better colour rendering of street lighting in some areas can reduce crime, as criminals are aware that they can be identified more easily.
Colour rendering is also important in shops. Installing the correct type of fluorescent tube can make clothes look vibrant, food look appetising and also reduce eye strain. There are many types of fluorescent tube colours available from warm white to daylight and colouright tubes.

More information relating to the application of different types of luminaires and lamps is given in Assessment criteria 2.3 below.

**OPERATION OF LUMINAIRES**

There are several types of lamp, which work in different ways:

- incandescent lamps
- discharge lamps
- compact fluorescent lamps
- LED lamps.

**Incandescent lamps**

This is the simplest form of lamp, with a current passed through a filament. The filament gets white hot and therefore emits light.

**Tungsten filament lamps**

Tungsten has a high melting temperature (3380 °C) and the ability to be drawn out into fine wire.

In order to prevent premature failing through oxidisation, oxygen must be removed from the enclosing glass bulb. Small lamps are evacuated, creating a vacuum in the bulb, but larger lamps are filled with argon, which reduces filament evaporation at high temperatures. The efficacy of filament lamps is relatively low but increases with the larger sizes. Colour rendering is generally very good but does depend on the glass finish of the lamp.

**Tungsten-halogen lamps**

Adding a halogen, such as iodine, to the enclosure prevents evaporation and allows the lamp to be run at a higher temperature. Colour rendering is very good with these lamps.

**Halogen cycle**

If a halogen gas is present in a lamp with a tungsten filament, the atoms of tungsten that are driven off the filament attach to halogen molecules instead of collecting on the lamp wall. They are eventually returned to the filament and separated. The tungsten is deposited on the filament. The halogen gas molecules are free to circulate again and available to intercept other tungsten atoms.
Halogen regenerative cycle

Halogens, condense at about 300 °C, so the lamp must be kept above this temperature. The lamp is made of quartz glass, which can be weakened if touched by a person. Oil from the skin can lead to gas leaking from the glass. Handling these lamps without protection can therefore shorten their lifespan.

Tungsten-halogen lamps are widely used for floodlighting and vehicle-lighting applications as well as low-voltage recessed lighting.

**Discharge lamps**

The way a heated filament produces light is relatively simple to understand. How light is emitted when an electric current flows in a gas or vapour can be more difficult to understand. Think about how in nature lightning produces large quantities of light when electric current passes through a gas (air).

Several types of lamp produce light by establishing a permanent electric arc in a gas. This process is known as electric discharge or gaseous discharge. It is used to produce light in fluorescent and high-intensity discharge lamps.

**How discharge lamps work**

Electrons are driven through the gas or vapour by the tube voltage, colliding with atoms as they go. The collisions are severe enough to break a loosely held electron from an atom, leaving behind a positively charged ion. This type of collision needs a fairly high tube voltage and results in ionisation to produce light.

Different gases and pressures of gas produce light of different wavelengths or colours, which can be further enhanced by using a coating such as phosphor around the inside of the gas tube.

**ACTIVITY**

Consult manufacturers’ data sheets for circuit diagrams of high- and low-pressure sodium discharge lamps.

**ASSESSMENT GUIDANCE**

Some discharge lamps will not restart immediately after being switched off; the pressure has to drop before they will restrike.
When gas is cold, it has a high resistance and therefore requires a high-voltage ‘strike’ to ionise the gas. Once gas is ionising, its resistance falls, meaning lower voltages can maintain ionisation. However, as proved by Ohm’s law, a lower resistance will result in larger currents flowing. In order to create a high-voltage strike and limit running currents, discharge luminaires require control gear.

For a.c. supplies, an electronic control or an iron-cored inductor (also known as a choke or ballast) is used, rather than the resistor used for d.c. supplies.

To understand how the control gear works, look at the process, using the fluorescent luminaire (low-pressure mercury discharge lamp) as an example.

The sequence of events in this discharge luminaire is as follows:

1. When the luminaire is switched on, the starter switch closes and current flowing through the inductor induces a magnetic field within the inductor. As the gas in the tube is cold, the voltage is not enough to break down the resistance.

2. The starter switch opens, which open circuits the inductor. This causes the magnetic field in the inductor suddenly to collapse, creating a high voltage. This voltage strikes across the tube, ionising the gas, which reduces in resistance, and completing the circuit.

3. With the circuit once again complete, current flows through the inductor, which re-induces a magnetic field, causing self-induction, which limits the current flow. The starter switch is no longer required as the gas remains ionised with a constant current passing through it.
The switch starter
The switch starter is enclosed in a small glass tube containing neon gas, which glows and produces heat. The switch contacts are bimetals and the heat causes them to bend so that they touch.

When the fluorescent tube is lit, the current in the tube causes a voltage drop in the choke, so that the lamp voltage across the switch contacts is too low to cause a glow in the neon. As it is open circuit when unheated, the switch starter has no more effect on the luminaire circuit. If the tube fails to strike first time, the process repeats until striking is achieved.

Fluorescent tubes come in many lengths, shapes, colours and ratings.

Other types of discharge lamp
Other discharge lamps that work on a similar principle as the fluorescent tube (low-pressure mercury discharge lamp) above, include:

- high-pressure mercury
- low-pressure sodium
- high-pressure sodium
- metal halide.

High-pressure mercury (MBFU)
This type of lamp produces a near-white light with a blue tinge. It is commonly used for:

- amenity lighting
- street lighting in residential areas
- bollard lighting.

Because of its good colour correction, it is good for CCTV applications or areas where coloured objects need identifying.

ACTIVITY
Look on the internet at a wholesaler’s website to see the various types of fluorescent tube.

ASSESSMENT GUIDANCE
M = mercury
B = high pressure
SO = sodium
X = low pressure
N = high pressure
F = fluorescent coating
E = external ignitor
U = universal operation
Low-pressure sodium (SOX)

As well as containing a low-pressure sodium gas, this type of lamp will also contain a neon-based gas that ionises at lower temperatures. The neon-based gas, which gives a pink appearance when starting, heats up the sodium gas, which then produces orange light.

These lamps have poor colour rendering but very good efficacy. They were widely used for most roadway applications but, due to increasing use of CCTV in towns and on roads, they are slowly being phased out and replaced with high-pressure sodium lamps.

High-pressure sodium (SON)

These lamps are commonly used for street and amenity lighting as well as car parks, high-bay lighting and security perimeter lighting. They have reasonably good colour rendering although the light output is light orange. They have a good efficacy despite the colour rendering, which is why they are a common choice of lamp. They come in two varieties: SON-E elliptical and SON-T tubular.

Some lamps contain internal ignition (starter) switches, but others rely on separate starter units within the control gear. If you are replacing one of these lamps, make sure you check the type needed, which should be indicated by the appropriate triangular symbol.

Metal halide (HID)

Older types of SOX lamp used a step-up auto transformer for starting. Modern types use an ignitor for starting.
These lamps have excellent colour rendering and good efficacy. They are extensively used for sports arena floodlighting as well as general amenity or security lighting.

The Waste Electrical and Electronic Equipment Regulations 2006 (WEEE) and other environmental legislation place strict controls on the disposal of discharge tubes. Care is required when handling these tubes and lamps as the mercury in the tubes is toxic and the sodium in the lamps burns when in contact with moisture. Therefore it is important that the tubes and lamps remain intact for specialist disposal.

**Compact fluorescent lamps**

These are miniature fluorescent tubes compacted into a small space. The control gear is contained in the base of the lamp. They are intended as energy-saving replacements for incandescent lamps although the colour rendering and flickering mean that many people find them difficult to use for reading or close work.

**LED lights**

The LED is a light-emitting diode. These lights are usually made from inorganic substances such as gallium indium nitride and gallium phosphide. The colour of the light output depends on the material used for the diode. The main colours are red, orange and green, and a variety of shades of blue.

The light output is usually monochromatic, ie the light emitted is at a single wavelength. The most common way to create a white light is to apply a phosphor-based coating to a blue diode. The phosphor converts the blue light to white light in a range of colour temperatures. The quality of the white light is affected both by the choice of LED and by the properties of the phosphor.

LEDs are very small; the active light-emitting surface is no bigger than 1–2 mm². A single diode can rarely produce enough light for a given lighting situation. For the unit to work, it must be mounted on a circuit board, with multiple LEDs in a cluster to form a LED module.

LEDs can be powered in two ways: with constant current or constant voltage. The ballast, which is referred to as the driver, is the unit that drives an LED array.
Retrofit LED lamp with cut-away showing internal parts

Although some LEDs run on conventional transformers, these can lack certain kinds of safety feature, such as short-circuit protection. When driven correctly, LEDs are claimed to be able to run for 50 000 hours, which is considerably longer than other technologies.
Star (Y) and delta (Δ) configurations are used throughout the building services industry. Each configuration has different characteristics in terms of voltage and current values. Calculation of these values is essential in modern electrical engineering.

**VOLTAGE AND CURRENT IN STAR-CONFIGURED SYSTEMS**

In a star (Y) connected load:
- the line current \( I_L \) flows through the cable supplying each load
- the phase current \( I_P \) is the current flowing through each load.

So:

\[ I_L = I_P \]

and:
- the voltage between any line conductors is the line voltage \( V_L \)
- the voltage across any one load is the phase voltage \( V_P \)

so:

\[ V_P = \frac{V_L}{\sqrt{3}} \text{ or } V_L = V_P \times \sqrt{3} \]

In a balanced three-phase system there is no need to have a star-point connection to neutral as the current drawn by any one phase is taken out equally by the other two. Therefore the star point is naturally at zero.

**Assessment criteria**

3.1 Calculate values of voltage and current in star-configured systems

**ACTIVITY**

For a star-connected system calculate the phase voltage when the line voltage is a) 400 V, b) 415 V, c) 11 kV, d) 110 V.
So if a line current is 10 A, the phase current will also be 10 A. If the line voltage was 400 V, the phase voltage would be:

\[
\frac{400}{\sqrt{3}} = 230 \text{ V}
\]
**VOLTAGE AND CURRENT IN DELTA-CONFIGURED SYSTEMS**

Delta-connected load similar to delta-connected supply

In a delta (Δ) connected load:
- the line current ($I_L$) flows through the cable supplying each load
- the phase current ($I_P$) is the current flowing through each load.

So:

$$I_P = \frac{I_L}{\sqrt{3}} \quad \text{or} \quad I_L = I_P \times \sqrt{3}$$

and:
- the voltage between any line conductors is the line voltage ($V_L$)
- the voltage across any one load is the phase voltage ($V_P$)

So:

$$V_L = V_P$$

As there is no provision for a neutral connection, items such as delta motors would automatically be balanced – but complex loads on transmission systems could be unbalanced.
**NEUTRAL CURRENT IN THREE-PHASE AND NEUTRAL SUPPLIES**

In a balanced three-phase system there is no requirement to have a star-point connection as the three phases have a cancellation effect on each other. Therefore the star point is naturally at zero current. While the load is balanced and the waveforms are symmetrical (not containing harmonics or other waveform distorting influences), this statement is relatively accurate. However, in practice, this is sometimes not the case.

Where the load is not in balance, different currents circulate in the load through the source winding and back. This gives rise to a change in star-point voltage, which can result in the system 'floating' away from its earthed reference point. In essence, a current will flow in the neutral. The three ways in which this current value could be determined are:

- by phasor, an accurate method that indicates the angle at which the maximum current occurs
- by calculation, which gives an accurate value
- by equilateral triangle, which gives a good indication of the value.

**Phase and line currents in the load**

Therefore if the phase current is 100 A and the phase voltage is 400 V, the line current can be calculated as follows:

\[
I_{\text{line}} = 1.732 \times 100 = 173.2 \text{ A}
\]
Determining current value by phasor

Assuming that a load has the current values $L_1 = 85$ A, $L_2 = 50$ A and $L_3 = 60$ A per phase, the current value can be determined by the following steps.

1. Construct a basic three-phase phasor to a suitable scale, ensuring the phases are 120° apart.

2. Now construct another parallelogram between the new line and the remaining phase. Where the two new parallelogram lines intersect represents the neutral current value to the scale selected.
**LO3**

Electrical quantities in star delta configurations

---

**ASSESSMENT GUIDANCE**

You may find the neutral current by any method you choose.

**ACTIVITY**

Three equal 40 A loads are connected in star to a 400 V supply. The neutral current is zero. What will be the neutral current if:

- a) one phase is disconnected
- b) two phases are disconnected?

---

**KEY POINT**

Remember, an equilateral triangle is formed by three equal sides and has three equal angles of 60°.

---

**Determining current value by equilateral triangle**

The value of the neutral current can be determined using a scale drawing based on an equilateral triangle. If all phases are balanced, and therefore equal, all sides of the triangle are equal in length and meet to give equal angles of 60°.

If the phases are not balanced, there will be a gap at the top of the two sloping sides which represents the neutral current. The triangle here represents a balanced system.

---

A balanced system represented by an equilateral triangle
Now consider an unbalanced system with these values:

- L1 = 70 A
- L2 = 100 A
- L3 = 60 A

In an unbalanced system, the gap (shown in light blue) represents the neutral current. The neutral current is represented by the gap left where the two sides do not meet (shown in light blue). In this example, that gap represents a current of approximately 37 A.

**KEY POINT**

When constructing scaled diagrams, it is crucial that you use a good scale and measure accurately.
It is important to understand the differences in a.c. and d.c. machines and to appreciate where there are similarities in certain machine configurations.

**HOW D.C. MACHINES OPERATE**

Direct current (d.c.) machines were once the most popular type of machine because of the ability to control speed and direction. With advances in cheaper a.c. alternatives, d.c. machines were used less. Now that the parts and control devices for d.c. machines are cheaper, the use of d.c. is on the increase again. The competent electrician must therefore have a knowledge of d.c. machine operating principles.

There is no difference in the construction of d.c. motors and generators. They are rotating machines with three basic features: a magnetic-field system, a system of conductors and provision for relative movement between the field and the conductors.

The magnetic field in most d.c. machines is set up by the stationary part of the machine, called the field windings. The rotating part, known as the armature, is made up of multiple loops of cable linked to a commutator. Power is either delivered to (motor) or taken from (generator) the armature by brushes in contact with the moving commutator.
**d.c. generators**

The d.c. generator is supplied with mechanical energy and gives out most of the energy, less losses, as electrical energy.

The d.c. generator has many loops and a multi-segmented commutator. With electricity flowing in the armature through brushes, the commutator reverses current flow as it passes from one pole to another so that the current in both conductors will always be the same.

When the loops within the armature are rotated within the magnetic field, an emf is induced into the loop. The commutator ensures that the brushes are always in contact with the loop, which is in the strongest part of the magnetic field, at all times. This ensures a steady flow of direct current.
d.c. motors

The d.c. motor takes in electrical energy and provides mechanical power, less losses.

There are three types of d.c. motor: series, shunt and compound.

Series motors

Series motors are also known as universal motors as they can also be used on alternating current. The field and armature in a series motor carry the same current and are capable of providing high starting torques. As the current is common to both parts, the windings are heavy gauge. Series motors can be reversed in direction if a switch device is inserted between the field and armature, allowing simple reverse polarity of either the field or armature, but not both at the same time.

ASSESSMENT GUIDANCE

In the past, d.c. shunt generators were used in automobiles to keep the battery charged. In modern cars a three-phase alternator and bridge rectifier are used as this arrangement has a much higher output.

ASSESSMENT GUIDANCE

Series machines should always be connected to a load, otherwise they will run dangerously fast.

Simplified series motor arrangement
Shunt motors
A shunt-connected d.c. motor consists of a field winding in parallel with the armature. This type of motor does not have the same common current characteristics as the series motor and therefore does not have a high starting torque. However, speed control of the shunt motor is considerably easier than the series motor as the field current can be controlled independently from the armature. Shunt motors can be reversed in direction if the polarity of either the field or armature is reversed, but not both at the same time.

**ACTIVITY**
What is the difference between a self-excited and separately excited machine?

**ASSESSMENT GUIDANCE**
The shunt motor uses a shunt field regulator to control the speed. Increasing resistance decreases the current and flux, causing the motor speed to increase.
Compound motors

The compound motor is a mixture of the series and shunt motor circuits, offering the benefits of each type of machine, i.e., high starting torque and good speed control. To reverse a compound motor, the armature field must be reversed.

**Applications of D.C. Machines**

Series-wound motors have excellent torque (load) characteristics and are used for applications such as dragline excavators, where the digging tool moves rapidly when unloaded but slowly when carrying a heavy load.

Shunt motors are best used where constant speed and torque are to be maintained, for example, on a production line, so that items placed on it do not affect the speed.

Compound motors offer the benefits of both series and shunt motors and have been used in older underground trains.

Direct current generators do not have many practical uses in their own right. However, they can provide a reliable energy supply directly into batteries or where a d.c. supply is required.
Three-phase a.c. machines are motors and generators that use or produce three-phase power.

### Three-phase a.c. generators

A three-phase a.c. generator has a stator with three sets of windings arranged so that there is a phase displacement of 120°. The three-phase output is produced by either star- or delta-connected windings on the stator.

In the UK, three-phase generators are used in power stations.

### How a.c. generators work

For simplicity, the description below relates to one phase. However, it is important to remember that there are three phases, displaced at 120° from each other.

As each pair of poles passes through the strongest part of the magnetic field at right angles, the maximum electromotive force (emf) is induced into that particular phase. At that point, the other two pairs are in a weaker part of the field and a lower voltage is induced. The moving rotor is connected to the stationary stator by slip rings, which keep each phase in constant contact.

The output of an a.c. system, when measured and tracked, is usually referred to as a waveform. This is because, as the rotating machine induces an emf, the value rises to a peak, falls to zero, then to a negative peak value and then rises back to zero.

### Assessment criteria

4.3 Explain the operating principle of three-phase a.c. machines

### ACTIVITY

A three-phase a.c. alternator has four poles per phase. Calculate the speed in revs/sec needed to produce an output of:

- a) 40 Hz
- b) 50 Hz
- c) 60 Hz

### Assessment guidance

\[
N = \frac{f}{p}
\]

where \(N\) = speed in revs/s,

\(f\) = frequency and \(p\) = pairs of poles per phase
The emf-generated per phase per rotation

The time taken for the cycle to return to its starting position (from position 1 back to 1 in the example above) is the periodic time \( t \). This process can be described in terms of Faraday’s law because the rotation of the coil continually changes the magnetic flux through the coil and therefore generates an emf.

**Three-phase a.c. motors**

Three-phase a.c. motors have a number of advantages over their single-phase equivalents, including:

- smaller physical size for a given output
- steady torque output
- the ability to self-start without additional equipment.

The induction motor is the simplest and most common form of motor. The stator consists of a laminated body with slots for the field windings to pass through. The rotor is a laminated cylinder with conducting bars just below the surface.

In its simplest form, the rotor consists of a number of conductors passing through holes in a rotor drum. The ends are brazed together, causing the formation of a cage, which is why it is called a cage rotor.

Cage induction motors are cheaper and smaller, but produce less torque, than wound rotor induction motors. Wound rotor motors provide speed control via resistors and slip rings, but this is an inefficient method of controlling speed.
How cage induction motors work

Component parts of a six-pole cage induction motor

If a rotor is placed in the field set up by the field windings in the stator, it will be cut by alternate north and south fields as the field rotates through one cycle. This creates an emf in the rotor, which causes current to flow in the conductor bars of the rotor. This current flow sets up a magnetic field, which causes the rotor to move and follow the rotating magnetic field in the stator.

The rotor rotates faster, heading towards synchronous speed. However, as the rotor speed increases, the difference between rotor speed and stator field speed reduces, causing the emf induced to reduce. The reduction in torque reduces the acceleration/velocity, meaning that synchronous speed cannot be met because no field cuts the rotor and, in turn, no emf or current in the rotor is induced.

This means that induction motors reach an ideal balancing velocity where there is sufficient slip to ensure that an emf is generated, resulting in a torque to turn the rotor. The fundamental operating principle of induction motors is that there has to be slip for the motor to work.

Slip may be represented as a percentage or a factor. If a motor with a synchronous speed of 16.67 revolutions/second had a slip of 8%, the rotor speed would be:

\[
\text{rotor speed (}\text{n}_r\text{)} = \text{synchronous speed} - \frac{\text{synchronous} \times \text{slip percentage}}{100}
\]

\[
= 16.67 - \left(\frac{16.67 \times 8}{100}\right)
\]

\[
= 15.34 \text{ r/s}
\]

ASSESSMENT GUIDANCE

The three-phase coils set up a rotating magnetic field in the stator. This can be reversed by changing over any two supply phases.

Synchronous speed

The speed that the rotating field rotates around the field poles

Rotor speed

The actual speed at which the rotor rotates in revolutions/second (r/s)

Slip

The difference between the synchronous speed and the rotor speed expressed as a percentage or per unit value

KEY POINT

Consider that a particular pole is north and that north then moves to the next pole (and the next) until there has been one complete rotation. The synchronous speed is the number of rotations completed in one second. The synchronous speed is affected by the supply frequency and the number of pairs of poles. For example, if a motor had six poles (three pairs) and the supply frequency was 50 Hz, the synchronous speed would be:

\[
\text{synchronous speed (}\text{n}_s\text{)} = \frac{f}{\frac{p}{3}} = \frac{50}{\frac{6}{3}} = 16.67 \text{ r/s}
\]
Induction motor principles

The speed of an induction motor can be varied by switching field pole pairs in and out.

Example

Calculate the synchronous speed of a two-, a four- and a six-pole motor fed from a 50Hz supply.

For a two-pole motor = one-pole pair:

\[ n_s = \frac{f}{p} = \frac{50}{1} = 50 \text{ r/s} \]

For a four-pole motor = two-pole pair:

\[ n_s = \frac{f}{p} = \frac{50}{2} = 25 \text{ r/s} \]

For a six-pole motor = three-pole pair:

\[ n_s = \frac{f}{p} = \frac{50}{3} = 16.66 \text{ r/s} \]

It can be seen that the speed of a motor is varied by the number of poles. However, electronic controls such as inverter drives are more effective and allow the speed to be varied over a wide range, matching it to the load requirements.

Wound rotor induction motors

In wound rotor induction motors, the rotor windings are connected through slip rings to external resistances. Adjusting the resistance allows control of the speed/torque characteristic of the motor. These motors can be started with low inrush current by inserting high resistance into the rotor circuit; as the motor accelerates, the resistance can be decreased.
### Principles of electrical science

**UNIT 302**

**Wound rotor arrangement**

The wound rotor has more winding turns than a cage and has a series variable power resistor in the circuit. In start-up, the inrush current is reduced by the resistors with, resulting in a higher torque than the cage motor. However, the ease of speed control has been overtaken by the use of simple induction motors with readily available variable frequency drives, as changing frequency will also affect the synchronous speed and therefore the rotor speed.

### APPLICATIONS OF THREE-PHASE A.C. MACHINES

**a.c. generators**

The a.c. generator or alternator is very widely used, eg in hybrid electrical vehicle drives, small and large-scale power generators, wind turbines or micro-hydro systems (small hydro-electric plant using stream water).

**Induction motors**

The cage induction motor is a simple, cost-effective induction motor. Advances in technologies for drive systems (eg Thyristor (silicon-controlled rectifier)) and speed-control drives have enabled simple induction motors to replace more expensive wound rotor induction...
and some d.c. motors. Such technologies offer simple speed-controlled drives and reduced current starting for ‘soft start’ systems.

As a result, induction motors are used in a wide range of applications such as pumps, hoists, lifts and many other machines. The cage rotor is particularly useful because it has fewer parts that are subject to wear, having no brushes or slip rings.

**Assessment criteria**

4.5 Explain the operating principle of single-phase a.c. machines

**HOW SINGLE-PHASE A.C. MACHINES OPERATE**

A single-phase generator is composed of a single stator winding with one pair of terminals. With a single pair of rotating poles, the output waveform is as shown below.

Two-pole machine and output

When a four-pole machine is used, the output waveform is changed as follows.

Four-pole machine and output
**Single-phase induction motors**

Three-phase motors use one phase to induce current into the rotor bars with another phase, at a different polarity, creating the repulsion/attraction. However, the single-phase motor will not start by itself. This is due to the magnetic flux components being equal and opposite, cancelling out and leaving no torque to turn the rotor. Single-phase motors need to be modified to give the phase shift needed for the motor to start by itself.

Single-phase motors have some form of additional start winding. The current in this winding can be made to lead or lag the main field winding by various methods. We saw in Assessment criteria X.X that a motor winding is an inductor and resistance. The phase angle can be changed by changing resistance values or by adding a capacitor.

As a result, single-phase motors can create a phase-shift in a start winding with:

- split-phase induction motors
- capacitor-start motors
- shaded-pole motors.

**Split-phase induction motors**

The split-phase induction motor has a separate start winding connected to the main supply through a centrifugal switch.

![Split-phase induction motor diagram]

The separate winding causes a slight phase shift by having a different resistance. This causes the rotation. The direction of rotation is determined by the polarity of the start winding, which is switched out by the centrifugal switch once a particular speed is achieved.
**Capacitor-start motors**

The capacitor-start motor is a variation of the split-phase induction motor. A starting capacitor is in series with the start winding, which creates a phase shift in the circuit due to the inductive and capacitive circuit formed by the winding and the capacitor.

![Capacitor-start motor diagram](image)

In most capacitor-start motors, the capacitor is switched out of circuit by a centrifugal switch. The capacitor-start-and-run motor is a variant that does not switch out the capacitor.

**Shaded-pole motors**

The shaded-pole motor is a quite commonly used in devices, such as domestic appliances, that require low starting torque.

The motor is constructed with small single-turn copper shading coils, which create the moving magnetic field required to start a single-phase motor. A small section of each pole is encircled by a copper coil or strap; the induced current in the strap opposes the change of flux through the coil. This causes a time lag in the flux passing through the shading coil, creating an opposing pole to the main part of the pole.

![Shaded-pole motor diagram](image)
Universal motors

An a.c. universal motor is very similar in construction to a d.c. series-wound motor. These devices combine the advantages of a.c. machines with some of the characteristics of d.c. machines, including high starting torques.

Applications of single-phase a.c. machines

The commonly used shaded-pole motor is used where a high starting torque is not required, for example, in electric fans or drain pumps for washing machines and dishwashers, and in other small household appliances.

Universal motors are commonly used in small household appliances, such as food blenders, or power tools, such as drills, where smaller motors are beneficial.

Assessment criteria

4.6 State the applications of single-phase a.c. machines
Capacitor-start motors are commonly found in applications such as central-heating circulation pumps.

Split-phase motors are better suited to belt-drive applications due to poorer starting torque.

**HOW MOTOR STARTERS OPERATE**

Motors are started in various ways. The choice of motor starting/control device depends on:

- available supply (single- or three-phase)
- motor start-up current
- starting speed.

**Direct online starters (DOL)**

These motor control devices literally switch a motor on or off with no varying speed or reduction in starting current. They are suitable for small, low-powered motors and can be used for single- or three-phase applications. The unit contains an electromagnetic coil that operates a contactor. The unit also incorporates overload contacts, finely tuned to the motor’s start and running current to trip the device should an overcurrent occur. The coil that operates the contactor also provides undervoltage protection, as the contactor will open should a voltage lower than the coil voltage rating occur, eg during loss of supply. This means that the machine will not automatically restart unexpectedly should power resume.

**Assessment criteria**

4.7 Explain methods of starting motors

**Assessment guidance**

When adding remote controls, remember stop buttons are connected in series with the original stop, and start buttons are connected in parallel with the original start.
Star-delta starters

Star-delta starters must be connected to three-phase motors, which have six connection points at the motor. The motor is started by being put into a star connection, which reduces the starting current. Once the motor reaches a given speed, an electronic time switch switches over the contactors automatically, putting the motor into delta connection and allowing full load current. The purpose of this is to reduce high current on start-up.

To avoid short circuits, the star and delta contactors are normally physically interlocked by an electrical interlock and a mechanical connecting rod to prevent both contactors being in circuit at the same time.

**Activity**

What fraction of power is available in a star connection compared with a delta connection?

**Assessment Guidance**

Star-delta starting requires access to all six ends of the motor windings.
**Rotor resistance starters**

This type of starting device works by introducing variable resistance to the rotor windings. It requires the motor to be a wound rotor induction motor, not a cage induction motor. The rotor windings are connected to an external variable resistance unit by slip rings and bushes. Variations in resistance can reduce start-up currents in the rotor.

![Rotor resistance control circuit](image)

**Electronic motor starters**

These motor soft-starters are used with a.c. motors to reduce the load and torque in the motor circuit during start-up. This is normally achieved by reducing the voltage; then, as the motor starts to achieve running speed, the voltage is ramped up. The term ‘soft-start’ also applies to the mechanical stresses placed on the components as they are also not subjected to intense starting forces.

Variable frequency drives (VFD) control the motor speed and torque of a.c. induction motors, by adjusting the frequency and voltage. They save energy and money by adjusting constant-speed devices such as pumps and fans to match the appropriate outputs.
HOW ELECTRICAL COMPONENTS OPERATE

To understand how and why particular components are used in electrical installations, and to be able to make judgements on their suitability, requires some knowledge of how they operate.

Many of the common components used in electrical installations for protection and control rely on electromagnetism. So first, refresh your memory on magnetism and electromagnetism.

Electromagnets are often thought of as large magnets in vehicle salvage yards, lifting scrap metal from one place to another. Although this is one example, electromagnets are also used in lots of electrical installation equipment such as circuit breakers, RCDs, contactors and relays.

Before exploring electromagnets, first consider what a magnet is.

The pattern of magnetic flux lines that pass through a magnet from south to north

The bar magnet above shows a magnet and its north and south poles. It also shows the pattern of the lines of magnetic flux that pass through the magnet from south to north, and also outside the magnet from north to south. These flux patterns can be seen when a piece of paper is put over a bar magnet and iron filings are sprinkled over the paper. When the paper is tapped, the iron filings form a pattern because they are drawn into the flux lines.

Two magnets, showing that opposite charges attract
When two magnets are put together, with a north pole facing a south pole, the lines of flux move together in the same direction. This causes the magnets to attract, pulling together and forming one larger magnet. Opposites attract.

When two magnets are placed with the same poles together, the flux paths move against each other. The force of the magnetic flux causes the magnets to repel and move away from each other.

The planet we live on is a giant magnet with a magnetic field. People navigate around the world, using this magnetic field by placing a small piece of iron on a pivot. Like the iron filings, this small piece of iron follows the flux direction. It is called a compass.

**Magnetic flux patterns of electromagnets**

Experimentation with a compass needle or iron filings on a sheet of paper with a conductor passing vertically through it shows that a magnetic field is created around a conductor when current flows through it. If the current is removed, the effect on the compass or iron filings disappears.

This effect occurs throughout the length of a conductor. However, the effect on iron filings on a sheet of paper shows a ‘slice’ of the field in the plane where the paper is at right angles to the conductor.

**Current and field convention**

It is usual to indicate current flow in a conductor because there is a three-dimensional relationship between current flow and magnetic field. Current flowing away from the viewer is shown with a cross, rather like an arrow or dart passing through a tube. Current flowing towards the viewer is shown as a large dot, like an arrow or dart point emerging from a hollow tube.
The direction of the magnetic field (field rotation) of the concentric rings can be checked with a compass needle. When current flows away from the viewer, the magnetic field rotates clockwise. When current flows towards the viewer, the magnetic field rotates anticlockwise. The magnetic field rotates in the same way as a screw: clockwise to tighten the screw (forcing it away), anti-clockwise to undo it (drawing it closer).

The strength of the magnetic flux is proportional to the current flowing through the conductor. The more current flowing, the stronger the magnetic field will be.

Placing two conductors together changes the effects. If two conductors are placed together in a conduit, for example, with the current flowing in opposite directions, there is a cancelling effect between the opposing magnetic fields, as long as the magnetic fields are of equal strength. This arrangement is therefore adopted in electrical installations. Magnetic fields can cause problems in electrical installations and therefore need to be cancelled and minimised as far as is reasonably practicable.

KEY POINT
Remember that parallel conductors with currents flowing in opposite directions will push away from each other. Currents flowing in the same direction will cause the conductors to pull towards each other.

Cancellation effect of opposing conductors

Where conductors are placed together, with the current flowing in the same direction, there is an additional effect. This is undesirable in electrical installations as the increase in the magnetic field will cause additional losses in the circuit and possibly electromagnetic compatibility issues.

Total effect of magnetic fields
**Solenoids**

The strength of a magnetic field is proportional to the current flowing through it. Even with high currents passing through the conductors the field produced is relatively weak, in terms of useful magnetism. To obtain a stronger magnetic field a number of conductors can be added by turning the cable.

The most common form of this is the solenoid, which consists of one long insulated conductor wound to form a coil. The winding of the coil causes the magnetic fields to merge into a stronger field similar to that of a permanent bar magnet. The strength of the field depends on the current and the number of turns.

![Diagram of a solenoid](image)

A cable wound around a tube: the current at the top moves away from the viewer and the current at the bottom moves towards the viewer

![Diagram of magnetic field](image)

Coiling produces a bar magnet effect

As a solenoid is the electrically powered equivalent of a bar magnet, its field strength is dependent on the current passing through it. The magnetic field can be switched on or off.

The polarity of a solenoid is determined by the current direction. Using the NS rule, the letter N and/or S can be drawn, following the current direction.
The arrow heads on the letters, as shown in this diagram, indicate the direction of the magnetic field rotation.

![Diagram showing magnetic field rotation](image)

The direction of magnetic field rotation can also be determined using the right-hand grip method. If the fingers of the right hand follow the current flow direction, the thumb points to the north pole.

![Right-hand grip method](image)

Holding a solenoid in a right-hand grip indicates the direction of magnetic field

### Units of magnetic flux

The unit of magnetic flux is the weber (which is pronounced ‘veyber’), abbreviated to Wb. It is represented by the Greek letter phi (\(\Phi\)). Magnetic flux is a measure of the quantity of magnetic flux not a density.

Flux density (the amount of flux in a given area) is represented by the symbol \(B\) which is measured in webers per square metre (Wb/m\(^2\)), called teslas (T). One weber of flux spread evenly across a square metre of area will give a flux density of 1 tesla. Therefore:

\[
B = \frac{\Phi}{A}
\]

where:

- \(B\) = magnetic flux density (T) in webers per square metre (Wb/m\(^2\))
- \(\Phi\) = magnetic flux in webers (Wb)
- \(A\) = the cross-sectional area of flux path in square metres (m\(^2\)).
Relays
A relay is an electrically operated switch, which uses an electromagnet to operate a set of contacts mechanically. This mechanical movement allows complete isolation from the initial signalling.

Relay showing contact positions
Relays are used often to control a circuit by a low-power signal in complete isolation from the larger circuit, or multiple circuits, being controlled. The first relays were used in long-distance telegraph circuits, repeating the signal coming in from one circuit and re-transmitting it to another. Relays were then used extensively in telephone exchanges to perform logic functions and operations.

With modern technological advances, not all relays consist of a coil operating a set of magnets. Solid-state relays either replace or are available in conjunction with electromechanical relays. Solid-state relays control electrical circuits despite having no moving parts. Instead, they use a semiconductor device to perform the switching.

Contactors
A relay that can handle the high power used to control directly an electric motor or other loads is called a contactor. There is little difference between a relay and a contactor, but generally contactors are devices that switch heavier loads on and off, whereas relays either switch or divert (like a two-way switch) lower current loads.

APPLICATION OF ELECTRICAL COMPONENTS IN ELECTRICAL SYSTEMS

A typical application of a contactor is to control a large heating load by the use of a thermostat. The thermostat can operate at extra low voltage but still control a large heating load.

Assessment criteria
5.2 State the application of electrical components in electrical systems
Solenoids

Solenoids have a number of functions. They are often used as electrical–mechanical transducers (converters), i.e., they convert an electrical signal into mechanical action. This can be as some form of limit switch that trips a non-automatically resettable device or, more commonly, to operate a control valve on heating and other similar systems.

Solenoid valve

Solenoids are also often used in electromagnetic locking devices, either to engage or to retract the locking mechanism. Where safety is essential, such solenoids are usually positioned so that the system drops to a safe position if the electrical circuit fails. For example, a door release magnet will release the door in the event of a fire.

Relays

A relay is used so that one circuit, normally a low-current circuit, controls another by use of remote contacts. Some relays operate a large number of contacts, switching multiple circuits, with complete electrical isolation of the switching circuit from the operating circuit. Others switch high-current circuits using either low-power circuits or even extra low-voltage circuits, which are in turn controlled by logic devices such as programmable logic controllers (PLCs).

Contactors

The term ‘contactor’ is often used instead of ‘relay’; however, ‘contactor’ is more accurately used for a large relay operating large loads, such as a motor.

In the case of motor starters such as the direct online (DOL) starter above, the contactor is also coupled to an overload device. The contactor itself provides control (on and off) as well as undervoltage protection, which is required where the loss of supply and subsequent restoration may cause danger. In the case of a motor or machine, the machine cannot restart after a loss of supply until someone physically pushes the start button on the starter.
A typical example of a contactor: direct online (DOL) starter arrangement

In the case of motor starters such as the direct online (DOL) starter above, the contactor is also coupled to an overload device. The contactor itself provides control (on and off) as well as undervoltage protection, which is required where the loss of supply and subsequent restoration may cause danger. In the case of a motor or machine, the machine cannot restart following loss of supply until someone physically pushes the start button on the starter.

**PROTECTIVE DEVICES**

Protective devices may be one or a combination of:

- fuses
- circuit breakers (CBs)
- residual current devices (RCDs).

**Fuses**

Fuses have been a tried and tested method of circuit protection for many years. A fuse is a very basic protection device that melts and breaks the circuit should the current exceed the rating of the fuse. Once the fuse has ‘blown’ (ie the element in the fuse has melted or ruptured), it needs to be replaced.

Fuses have several ratings.

- \( I_n \) is the nominal current rating. This is the current that the fuse can carry, without disconnection, without reducing the expected life of the fuse.
- \( I_a \) is the disconnection current rating. This is the value of current that will cause the disconnection of the fuse in a given time.
- Breaking capacity (kA) rating. This is the current up to which the fuse can safely disconnect fault currents. Any fault current above this rating may cause the fuse and carrier to explode.

**ACTIVITY**

A direct online motor starter is a type of contactor with built-in start and stop controls. It also has overload protection. Name two types of overload protection that are used.
BS 3036 rewirable fuses

In older equipment, the fuse may be just a length of appropriate fuse wire fixed between two terminals. There are increasingly fewer of these devices around as electrical installations are rewired or updated.

One of the main problems associated with rewirable fuses is the overall lack of protection, including insufficient breaking capacity ratings. Another major problem is that the incorrect rating of wire can easily be inserted when changing the fuse, leaving the circuit underprotected.

BS 88 fuses

These modern fuses are generally incorporated into sealed cylindrical ceramic bodies (or cartridges). If the element inside blows, the whole cartridge needs to be replaced. Although these devices have fixed time current curves, they can be configured to assist discrimination. The benefit of BS 88 and similar fuses is their simplicity and reliability, coupled with high short-circuit breaking capacity.

Within some types of BS 88 fuse, usually the bolted type, there may be more than one element. The purpose of this is to minimise the energy from a single explosion, should the fuse be subjected to high fault currents. Instead there will be several smaller explosions, allowing these devices to handle much higher fault currents of up to 80 kA.

Other BS 88 devices may be the clipped type, which do not have the two bolt tags. They are simply barrel shaped and slot into place in the carrier. They are often called cartridge fuses.

Another type of cartridge fuse is the BS 1362 plug fuse. These are fitted into 13 A plugs and are available in a range of ratings. Typical ratings are 3 A, 5 A and 13 A.
Circuit breakers

Circuit breakers (CB) have several ratings.

- $I_n$ is the nominal current rating. This is the current that the device can carry, without disconnection and without reducing the expected life of the device.
- $I_a$ is the disconnection current. This is the value of current that will cause the disconnection of the device in a given time.
- $I_{cn}$ is the value of fault current above which there is a danger of the device exploding or, worse, welding the contacts together.
- $I_{cs}$ is the value of fault current that the device can handle and remain serviceable.

Section through a circuit breaker

Circuit breakers are thermomagnetic devices capable of making, carrying and interrupting currents under normal and abnormal conditions. They fall into two categories: miniature circuit breakers (MCBs), which are common in most installations for the protection of final circuits, and moulded-case circuit breakers (MCCBs), which are normally used for larger distribution circuits.
Both types work on the same principle. They have a magnetic trip and an overload trip, which is usually a bimetallic strip. If a CB is subjected to overload current, the bimetallic strip bends due to the heating effect of the overcurrent. The bent strip eventually trips the switch, although this can take considerable time, depending on the level of overload.

**Miniature circuit breakers (MCBs)**

These thermomagnetic devices have different characteristics, depending on their manufacture. They generally have a lower prospective short-circuit current rating than a high-rupturing capacity (HRC) fuse, ranging from approximately 6 kA to 10 kA. Specialist units are available for higher values.

The operating characteristics of MCBs can be shown in graphical form by a time–current curve. MCBs are generally faster acting than the standard curve in BS 88 fuses. A CB has a curve, then a straight line, whereas the BS 88 fuse is fully curved. This demonstrates the two tripping mechanisms in a CB. The magnetic trip is represented by the straight line on the graph, indicating that a predetermined value of fault current will disconnect the device rapidly. The curve represents the device's thermal mechanism. Like a fuse, the thermal mechanism reacts within a time specific to the overload current. The bigger the overload, the faster the reaction.

### Table 7.2.7(i) Rated short-circuit capacities

<table>
<thead>
<tr>
<th>Device type</th>
<th>Device designation</th>
<th>Rated short-circuit capacity (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-enclosed fuse to BS 3036 with category of duty</td>
<td>S1A, S2A, S4A</td>
<td>1, 2, 4</td>
</tr>
<tr>
<td>Cartridge fuse to BS 1361 type I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>type II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General purpose fuse to BS 88-2</td>
<td></td>
<td>16.5, 33.0</td>
</tr>
<tr>
<td>BS 88-3 type I</td>
<td></td>
<td>50 at 415 V</td>
</tr>
<tr>
<td>type II</td>
<td></td>
<td>16, 31.5</td>
</tr>
<tr>
<td>General purpose fuse to BS 88-6</td>
<td></td>
<td>16.5 at 240 V</td>
</tr>
<tr>
<td>Circuit-breakers to BS 3871 (replaced by BS EN 60898)</td>
<td>M1, M1.5, M3, M4.5, M6, M9</td>
<td>1, 1.5, 3, 4.5, 6, 9</td>
</tr>
<tr>
<td>Circuit-breakers to BS EN 60898* and RCBOs to BS EN 61009</td>
<td>In, Io</td>
<td>1.5, 6, 10, 20, 25</td>
</tr>
</tbody>
</table>

*Two short-circuit capacities are defined in BS EN 60898 and BS EN 61009:

- \(I_{\text{In}}\): the rated short-circuit capacity (marked on the device).
- \(I_{\text{Io}}\): the in-service short-circuit capacity.

**Rated short circuit capacities of protective devices (from the On-Site Guide, IET)**

**KEY POINT**

BS 7671 refers to both miniature circuit breakers (MCB) and moulded case circuit breakers (MCCB) as circuit breakers (CB).

**ASSESSMENT GUIDANCE**

The cost of circuit breakers has come down as their use has become more widespread.
Moulded-case circuit breakers (MCCBs)
Although moulded case circuit breakers (MCCBs) work on the same principle as MCBs, the moulded case construction and physical size of MCCBs gives them much higher breaking capacity ratings than those of MCBs. Many MCCBs have adjustable current settings.

Residual current devices (RCDs) and residual current circuit breakers with overload (RCBOs)
Residual current devices (RCDs) operate by monitoring the current in both the line and neutral conductors of a circuit. If the circuit is healthy with no earth faults, the toroidal core inside the device remains balanced with no magnetic flux flow. If a residual earth fault occurs in the circuit, slightly more current flows in the line conductor compared to the neutral. If this imbalance exceeds the residual current setting of the device, the flux flowing in the core is sensed by the sensing coil, which induces a current to a solenoid, tripping the device.

Internal circuit diagram for an RCD
Residual current breakers with overload (RCBOs) combine an overcurrent protective device with a RCD in the body of the CB.

Unlike CBs, RCDs and RCBOs have a test button, which should be pressed at very regular intervals to keep the mechanical parts working effectively. If the mechanical components in a CB stick, there is not much concern as the energy needed to trip a CB is large enough to unstick any seized parts. As RCDs and RCBOs operate under earth fault conditions, with relatively small residual currents, there may not be enough energy to free any seized parts.
APPLICATION OF PROTECTIVE DEVICES

BS 3036 rewireable fuses
Unlike most other protective devices, the BS 3036 fuse arrangement does not have a very accurate operating time or current as it is dependent upon factors such as age, level of oxidation on the element and how it has been installed (eg whether it was badly tightened, open to air movement).

The lack of reliability of these fuses is a concern to designers and duty holders. Due to the lack of sensitivity, special factors have been applied to Appendix 4 of BS 7671 Requirements for Electrical Installations (the IET Wiring Regulations) to account for these fuses. This rating factor to be applied \(C\) is 0.725. This rating factor is explained in greater detail in Unit 305, pages 195–301.

A range of BS 3036 rewireable fuses: 5 A (white), 15 A (blue) and 20 A (yellow)

BS 88 fuses
High-rupturing capacity (HRC) or high-breaking capacity (HBC) fuses are common in many industrial installations. They are also very common in switch fuses or fused switches controlling specific items of equipment. They are particularly suited to installations with a high prospective fault current \(I_{pf}\) as they have breaking capacities of up to 80 kA. BS 88 fuses come in two categories:

- gG for general circuit applications, where high inrush currents are not expected
- gM for motor-rated circuits or similar, where high inrush currents are expected.

MCBs
There are three common types of MCB: Type B, Type C and Type D. The difference between the devices is the value of current \(I_M\) at which the magnetic part of the device trips. The different types are selected to suit loads where particular inrush currents are expected.

Assessment criteria
5.4 State the application of overcurrent protective devices in electrical systems

ACTIVITY
Identify two other rewireable fuse carrier ratings and colours?

ASSESSMENT GUIDANCE
In a fused switch the fuses are mounted on the moving contacts. In a switch fuse, the fuse and switch are in series and the fuse does not move.
Type B trips between three and five times the rated current (3 to 5 × Iₜₐₚ). These MCBs are normally used for domestic circuits and commercial applications where there is no inrush current to cause it to trip. For example, the magnetic tripping current in a 32 A Type B CB could be 160 A. So Iₚ = 5 × Iₚ. These MCBs are used where maximum protection is required and therefore should be the choice for general socket-outlet applications.

Type C trips between five and ten times the rated current (5 to 10 × Iₜₐₚ). These MCBs are normally used for commercial applications where there are small to medium motors or fluorescent luminaires and where there is some inrush current that would cause the CB to trip. For example, the magnetic tripping current in a 32 A Type C CB could be 320 A. So Iₚ = 10 × Iₚ.

Type D trips between ten and twenty times the rated current (10 to 20 × Iₜₐₚ). These MCBs are for specific industrial applications where there are large inrushes of current for industrial motors, x-ray units, welding equipment, etc. For example, the magnetic trip in a 32 A Type D CB could be 640 A. So Iₚ = 20 × Iₚ.

Sample time–current characteristic graph which is found in Appendix 3 of BS 7671
**MCCBs**

MCCBs are available in various ranges. Lower-cost simpler versions are thermodynamic with no adjustment. Other devices have electronic trip units and sensitivity settings or the ability to be de-rated.

Most MCCBs are used on larger circuits or distribution circuits where larger prospective short circuits are likely but the flexibility of an electronic trip is also required.
Electric heating includes any process in which electrical energy is converted to heat, such as cooking and heating space and water.

**HOW ELECTRICAL SPACE-HEATING SYSTEMS WORK**

The three ways to transfer heat from one medium to another are:

- convection
- conduction
- radiation.

Many heat sources use a combination of these methods.

**Convection**

Hot air rises and colder air falls through the process of convection. A simple convection panel heater mounted on a wall uses this principle to move warm air around a room.
A convection heater usually has a low-temperature ‘black-heat’ element. Air in contact with the element is warmed and becomes less dense, so that it rises and is replaced by colder air, which is then warmed in turn.

Some convection heaters heat up another medium by conduction. For example, the element can be submersed in oil. The oil transfers heat around the unit, giving a larger body of heat to start the convection cycle.

Traditionally, convection heaters such as central heating emitters (radiators) are positioned where colder air is present, such as under windows, as this produces a larger cycle effect. This is less relevant today as modern windows provide better insulation.

**Conduction**

Conduction is the effect of heating something by direct contact. For example, the underfloor heating elements directly below a tiled floor warm the tiles and heat is transferred up through them. Similarly, in an immersion heater, a heating element is placed in water and the heat is transferred from the element directly to the water.

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**ASSESSMENT GUIDANCE**

Immersion heaters are usually considered for back-up heating, perhaps in conjunction with solar thermal systems.
Radiation

In this process heat is radiated (or thrown out) from a source and warms objects nearby. A standard coal fire does this; the heat can be felt on surfaces facing the fire, but not on surfaces facing away from the heat source.

Radiant heaters include:
- traditional electric fires
- infrared heaters
- oil-filled radiators
- tubular heaters
- underfloor heaters.

Heat sources

Underfloor heating

Underfloor heating systems have been around for centuries, although electrically powered versions have been available for a much shorter period. Since the 1960s the popularity of electric underfloor heating has fluctuated. In more recent times, it has become particularly associated with bathrooms and tiled areas. In many cases, underfloor heating is only installed in new houses or extensions as it is very costly to install into existing floors.

Storage heaters

Storage heaters charge up at night when energy is available at low cost on off-peak tariffs. The energy is then stored in the unit in fireclay blocks, which release it slowly during the day. Radiator- and fan-type storage heaters are available.
The radiator type is heated by elements in fireclay blocks. The release of heat is controlled by insulation. The storage heater is sized to store enough heat to last all day, under controlled release conditions.

Electric storage heater

Fan-type storage heaters have thicker insulation so that very little heat is lost. A small unit, on a 24-hour supply for the fan, will provide warm air controlled by a thermostat. Because of the fan, it is possible to use up the heating charge, so there is often a short boost option. However, daytime boosting is not an economical way to use storage heaters.

Name the tariff that should be used with storage heaters.

Block storage heating tends to be retrofitted where the installation of a wet system could cause considerable disruption.
The fan-assisted storage heater is usually larger and always noisier than the radiator-type equivalent.

Panel heaters
Panel heaters heat spaces by convection and radiation. They can be slim in design and can even be fitted to the front of storage heaters to provide daytime heating if the stored charge has been lost.

Most panel heaters are provided with thermostatic and time controls. Although they can be fairly expensive to run, they are often chosen as a means of heating reasonably small locations or locations where other services, such as hot-water central-heating systems, are difficult to install.

Radiant or infrared heaters
These types of heater are particularly useful in large, cold areas where heating the air is difficult. Examples are garage workshops and warehouses. The heat radiated warms bodies but not the air around them. They would work just as effectively in a vacuum.

HOW ELECTRICAL WATER-HEATING SYSTEMS WORK
There are many different types of electrically powered water heaters, including rod-type immersion heaters and instantaneous water heaters.

Immersion heater systems
Immersion heater systems usually contain large amounts of water, that are heated over a period of time. The size of the vessel and limited amount of circulation and mixing allows relatively hot water to be used on demand. Then the heat is replenished over a period of time.

A large copper or stainless steel vessel is filled with water from a separate cold-water tank or sealed pressurisation unit. The vessel has an electric heater element fitted through a screw-threaded fitting, known as a boss.

The heater element can be the length of the cylinder, but in some instances two shorter elements are used, one positioned high and the other positioned low in the vessel. In domestic premises, the two heater elements used to be known as the ‘bath and sink’ function. By switching on the top element, just a small proportion of the water is heated, saving energy. This relies on the stratification process (ie hot liquids stay at the top) and works if the water is used before significant circulation takes place.
Cylinder element arrangements

To ensure that there is a full tank of hot water, a longer element is fitted to heat the whole tank. Temperature is controlled by a rod thermostat fitted in a pocket tube in the head of the heater. However, there are also strap-on thermostats that fix to the exterior of the hot water cylinder. Many immersion heaters also have a thermal cut-out to open the element circuit, should the thermostat fail and the water reach dangerously high temperatures, which could lead to enormous pressures in the tank and the venting of scalding water through the overflow or expansion pipe.

In order to save energy, thermal insulation is added to the vessel during manufacture or a thermally insulated jacket is fitted after installation.

**Instantaneous water heaters**

There are many examples of instantaneous water heaters; most common are electric showers and point-of-use hand washers, fitted above or below sinks.

With all of these heaters there is a limit to how much water can be raised to a specific temperature in a given time. This depends on the flow rate. The slower the flow rate, the hotter the water will get.

There are two types of instantaneous hot-water system. The tank type is like a miniature hot water cylinder. In the other type, the elements wrap around the water pipe inside the unit.
ASSESSMENT GUIDANCE

Water heaters should be supplied via a double-pole switch.
HOW TO CONTROL HEATING SYSTEMS

Heating and hot-water systems are not controlled just for economic reasons. Control is also a legal requirement for safety reasons. Building Regulations demand control.

Room thermostats and control circuits

Room thermostats are used to provide temperature control when heating spaces. Traditionally, this is done by means of a simple adjustable bimetallic sensor incorporating a set of contacts. When the desired temperature is reached, the contacts open due to the bimetal bending. This stops water-based heating systems pumping heat around or, on more advanced systems, operates a valve that shuts off the water, but still heats water until it reaches the desired temperature, when the pump or boiler/heater will switch off.

The valve control arrangement is always used in commercial premises as it gives more accurate and zoned control, as required by Approved document L to the Building Regulations.
LO6 Principles of electrical heating systems

Simplified central heating system

- Boiler
- Circulating pump
- Zone valves
- Hot water tank
- Radiators
As the bimetal thermostatic control is accurate to only plus or minus 3 Celsius degrees, many commercial and some domestic systems use digital thermostats containing temperature-sensitive electronic thermistors. These units give a signal that can be converted directly into a temperature, usually with an accuracy of up to 0.1 of a Celsius degree.

**Time switches and programmers**

Time switches and similar devices are used to provide energy at the correct time and minimise wastage (eg not heating an office at weekends or a house when everyone is out.

In its simplest form, a 24-hour time switch cannot differentiate between days of the week. This is wasteful and a nuisance on days when the heating is required at different times from the norm. A programmable time controller is therefore normally installed as a minimum requirement for Building Regulations and convenience.

Simple domestic programmers allow the user to select the temperature required at set points on individual days of the week.
In commercial environments, controllers can be more sophisticated with optimum start functions. The user inputs the time at which they wish a specific temperature to be reached. The programmer uses thermostats to estimate the start-up time in order to reach the specified temperature and the time to switch off again in order to reduce the temperature at the end of the day.

Taking into account the thermal mass of the building, and the actual temperatures inside the building, the system adjusts itself for the next day. As with all systems that use computers to estimate comfort conditions, this type of system is often criticised because British weather is very unpredictable and conditions can change rapidly.
OUTCOME 7
Understand the principles of electronic components in electrical systems

In today’s world of micro-components, it is becoming increasingly common to replace a whole circuit board rather than replacing single components. Nevertheless, it is far easier to diagnose faults in electrical systems if you understand how particular electronic components function.

HOW ELECTRONIC COMPONENTS WORK

Diodes
A diode is a silicon P-N junction, which allows current flow in one direction, but not the other. When current flows through a diode, it is called ‘forward bias’. When current is restricted, it is called ‘reverse bias’. There are several types of diode, from the simple one described above, used for rectification or signalling, to:

■ a zener diode, which only allows current flow when a set voltage is reached
■ a light-emitting diode (LED), which emits a light when current flows through it
■ a photo diode, which allows forward bias current flow when it detects light.

Diacs
A diac is a junction of two zener diodes, with two terminals. It works on a.c. circuits, hence the name diode for a.c. A diac will not allow current flow unless a pre-set voltage is reached. Once this voltage is reached, current can flow in both directions. Current will continue to flow until the voltage falls below the level set, at which point the diac restricts current flow.

KEY POINT
Always take care when handling or replacing electronic components or circuit boards as many can be damaged by static electricity. It is always important to ensure that static risks are minimised by earthing yourself to the equipment before handling components.

Assessment criteria
7.1 Describe the operating principle of electronic components

ACTIVITY
How could a capacitor, zener diode and resistor be used to smooth the output of a full-wave bridge rectifier?
Thyristors

A thyristor is a solid-state switch that allows current flow between two of its terminals if a small current is sensed on the third. There are two types: silicon-controlled rectifiers (SCR) and triacs.

SCRs

The SCR is similar to the diode, in that current can only flow between the anode and cathode in one direction. However, it also has a gate terminal, which controls the switch when a small current is sensed on that terminal. Essentially, it allows a large current to be controlled by a small current. The SCR will continue to allow current flow between anode and cathode until this current is stopped. It does not require a constant gate terminal current, except when allowing the main current to pass.

Triacs

A triac has three terminals, one called the gate. If the gate senses a very small control current, a.c. is allowed to flow between the other two main terminals (MT1 and MT2). If the gate current is removed, the device will stop current flow when the alternating cycle reaches 0 V.

Transistors

The transistor is the fundamental building block of modern electronics and the reason why electronic systems are now so affordable.

The three terminals on a bipolar transistor are known as base (B), collector (C) and emitter (E).

A transistor may be used either as a switch or an amplifier. When the base of an NPN transistor is grounded (0 V), no current flows between emitter and collector, so the transistor is off. If the base voltage is increased above 0.6 V, a current will flow from emitter to collector and the transistor is on. If the base current varies in value, the emitter to collector current will follow this pattern of variation with a larger current flow; in this situation, the transistor acts as an amplifier.

A PNP transistor operates in the same way as an NPN transistor but with current flow allowed in the reverse direction.
An NPN and a PNP transistor, showing the polarity of each device

Another type of transistor is the field effect transistor (FET), which has terminals marked gate, source and drain. The FET is much cheaper to produce as it requires less silicon. It also has the major advantage of operating at virtually no current on the gate terminal as long as a voltage above 0.6 V is present.

### Resistors

Symbols for different types of resistor

Resistors are used to control or reduce current flow in electronic circuits. With a sufficiently high resistance, they can also be used as voltage dividers on certain circuits to allow a fixed voltage, less than the input voltage, to be obtained. Fixed-value resistors are either made from carbon film with an insulated coating, as shown below, or are wire wound for larger power applications.

Section through a carbon-film resistor

Carbon-film resistors are colour-coded to indicate their value and tolerance as shown below:

Resistor colour-coding system
Resistor colour values

<table>
<thead>
<tr>
<th>Colour</th>
<th>Digit</th>
<th>Multiplier</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
<td>10</td>
<td>1.0%</td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
<td>100</td>
<td>2.0%</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td>100000</td>
<td>0.5%</td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
<td>1000000</td>
<td>0.25%</td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
<td>10000000</td>
<td>0.1%</td>
</tr>
<tr>
<td>Grey</td>
<td>8</td>
<td>100000000</td>
<td>0.05%</td>
</tr>
<tr>
<td>White</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td></td>
<td>0.10</td>
<td>5.0%</td>
</tr>
<tr>
<td>Silver</td>
<td></td>
<td>0.01</td>
<td>10.0%</td>
</tr>
</tbody>
</table>

Wire-wound resistors are normally coded in order to establish the value, e.g. a 2R resistor is 2 Ω, whereas 2R2 is 2.2 Ω.

Thermistors

A thermistor is a type of resistor in which the resistance varies significantly with temperature. This variation is so defined that there is a definite temperature-related use for them. Thermistors typically achieve high precision within a limited temperature range, typically −90°C to 130°C.

Thermistors are widely used as temperature sensors, self-resetting overcurrent protectors for self-regulating heating elements and current inrush limiters.

Effect of temperature on resistance in a thermistor
Photoresistors

These are resistors that vary in resistance depending on the amount of light falling on them. They are often referred to as photocells and used to control lighting as day/night switches.

Variable resistors or potentiometers

These resistors are used to vary resistance in a circuit manually. Their applications are wide, including use as sound volume controllers and speed controllers.

Capacitors

Capacitors are widely used in electrical circuits in many common electrical devices. A capacitor is a passive two-terminal electrical component used to store energy electrostatically in an electric field, rather than by chemical reaction as in a battery. (Originally capacitors were known as condensers, but the original term has now been widely superceded.)

Capacitors vary widely, but all contain at least two electrical conductors separated by a dielectric (insulating layer), which acts as an insulator between the conducting plates. The plates are usually made from foils. The capacitance is varied by the area of the plates and the size of gap between the plates. The narrow gaps that are used require a very high dielectric strength.

ACTIVITY

Name five different types of capacitor.
Rectifiers

A rectifier is an electrical device that uses diodes to convert alternating current (a.c.), which periodically reverses direction as it cycles, to direct current (d.c.), which flows in only one direction.

Half-wave and full-wave rectifiers are available.

Half-wave rectification

In half-wave rectification of a single-phase supply, either the positive or negative half of the a.c. wave is passed, while the other half is blocked. Half-wave rectification requires a single diode in a single-phase supply, or three in a three-phase supply.

As only one half of the input waveform reaches the output, the mean voltage is lower than full-wave rectification.

Full-wave rectification

A full-wave rectifier converts the whole of the input, both positive and negative components, of the waveform to one of constant polarity at its output. Full-wave rectification output gives a pulsating d.c waveform with a higher average output voltage than its half-wave counterpart.

The unit works with two diodes and a centre-tapped transformer, or four diodes in a bridge configuration, as shown opposite.
The function of electronic components in electrical systems

Most electronic systems use many different electrical components in their power supply and in their operational systems.

Security alarm systems use full-wave rectification and smoothing through capacitors to supply a 12 V operating system. In addition, the closed-loop system uses transistor and similar technology to convert low-level signals from components such as passive infrared (PIR) detectors into an alarm output signal to components that operate the alarm.

Thyristors or SCRs are used extensively in motor speed-control circuits for heating and other applications, where motors and pumps require variable output. The ability to trigger a high-power switch is essential for controlling the output waveform, which in turn controls the motor speed.

Heating control systems use a number of components. The most important element of any form of heating control is probably the ability to sense temperature in the airspace or water systems that are being heated. A thermistor is used to determine accurately the temperature of the space or heating medium. The heating control system then uses feedback from the sensor to determine how much heat needs to be passed. The temperature is controlled via valves and/or variable speed pumps.

Assessment criteria

7.2 Describe the function of electronic components in electrical systems