Edexcel Physics A-level

Topic 7: Electric and Magnetic Fields

Key Points

Electric Fields

All charged particles and surfaces produce an electric field around themselves. An electric field is a region where **charged particles** experience a **non-contact force**. Unlike gravitational fields, this force can be **attractive or repulsive**.

- Same charges **repel** each other
- Opposite charges **attract** each other

Electric **field lines** point in the **direction** that a **positive** charge would experience a force and so point from positive to negative.

Coulomb’s Law

The force that acts between two charges is determined by Coulomb’s Law. This states that:

- The force is **directly** proportional to product of the **charges** involved
- The force is **inversely** proportional to the square of the **separation** between the two charges

As an equation, this is:

$$F = \frac{KQq}{r^2} \quad \textit{where....} \quad K = \frac{1}{4\pi\varepsilon_0}$$

If the force has a **positive** value, it is a **repulsive** force.
If the force has a **negative** value, it is an **attractive** force.

Electric Field Strength

Electric field strength (E) is defined as the **electrostatic force** that a **unit positive charge** would experience, at a **given point** in the field. As an equation this is:

$$E = \frac{F}{Q}$$

There are two further equations for finding the electric field strength, this first is for a radial field, while the second is for a field formed by parallel plates:

$$E = \frac{KQ}{r^2} \quad \textit{where....} \quad K = \frac{1}{4\pi\varepsilon_0}$$

$$E = \frac{V}{d}$$

The electric field strength around a point charge **decreases** as you move further away from it.

The **weaker** the electric field strength, the **less dense** the electric field lines are.

Electric Potential

Electric potential at a point is the amount of **work done** in moving a unit **positive point charge** from **infinity** to that point. As an equation this is:

$$V = \frac{KQ}{r} \quad \text{where....} \quad K = \frac{1}{4\pi\varepsilon_0}$$

Electric potential difference is the work done moving a positive charge from one point to another. This means that when you move a charge through a **potential difference**, work is done, equal to:

$$\Delta W = Q\Delta V$$

As with gravitational fields, **equipotentials** are planes of points where the electric potential is the same, consequently **no work is done** when moving along these lines.

Capacitance

The **capacitance (C)** of a capacitor is the amount of **charge** it can store per unit of **potential difference**, measured in **Farads**.

$$C = \frac{Q}{V}$$

Capacitors consist of two metal plates separated by a **dielectric**. The capacitance of a given capacitor depends on the **surface area** of the plates, their **separation** and the **dielectric** being used.

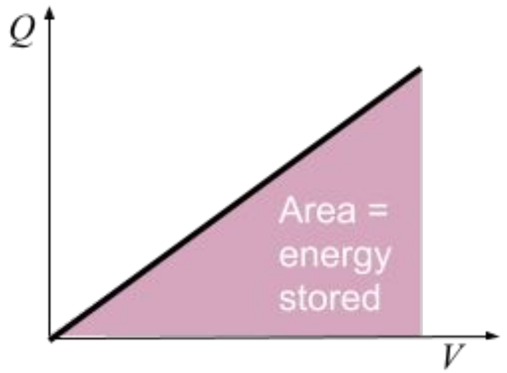
$$C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

Energy Stored by a Capacitor

A number of equations can be used to calculate the **energy stored** in a capacitor.
The second and third equations are derived by substituting the capacitance equation into the first.

$$E = \frac{1}{2} QV \qquad E = \frac{1}{2} CV^2 \qquad E = \frac{Q^2}{C}$$

The energy stored can also be calculated by determining the **area** under a charge-voltage graph. The first energy stored equation above is derived from this fact.

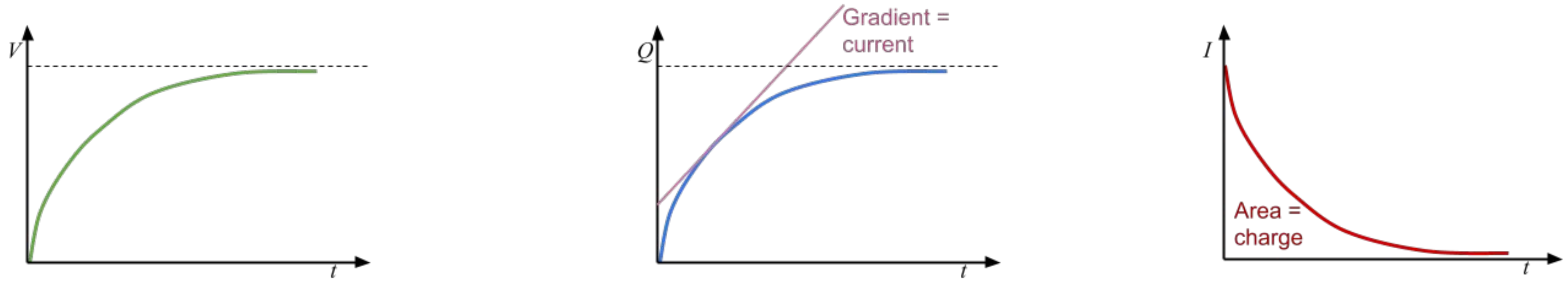


The **gradient** of the graph is equal to the capacitance.

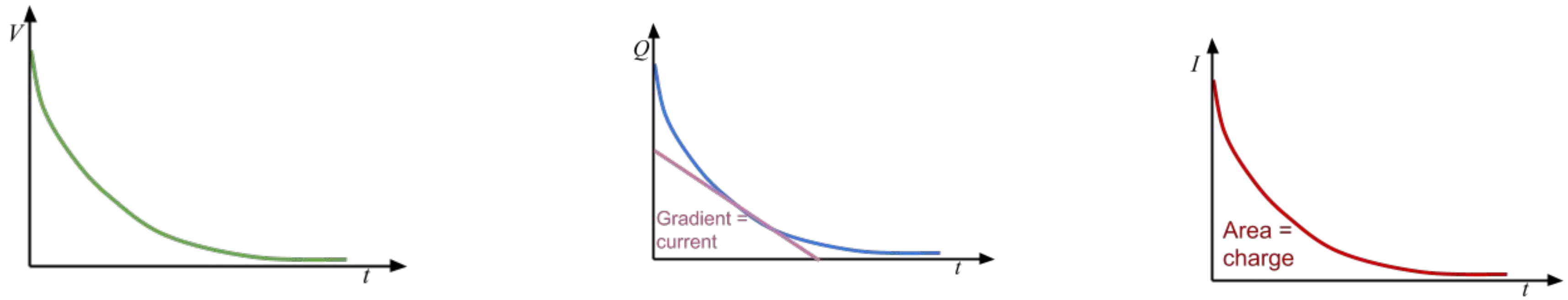
Charging and Discharging

You should know the shapes of the charging and discharging graphs for a capacitor, for potential difference, charge and current:

Charging



Discharging



Capacitor discharging calculations

You should know the following formulas for the current, potential difference and charge of a discharging capacitor:

$$I = I_0 e^{-t/RC} \qquad V = V_0 e^{-t/RC} \qquad Q = Q_0 e^{-t/RC}$$

You should also be able to **derive** the following log equations by taking natural logarithms of both sides of the above equations, and simplifying them using the log rules:

$$\ln I = \ln I_0 - \frac{t}{RC}$$

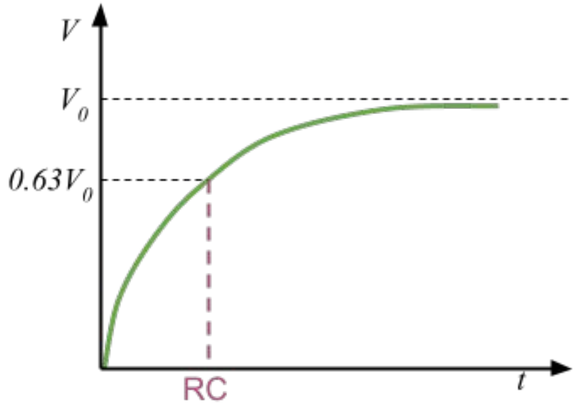
$$\ln V = \ln V_0 - \frac{t}{RC}$$

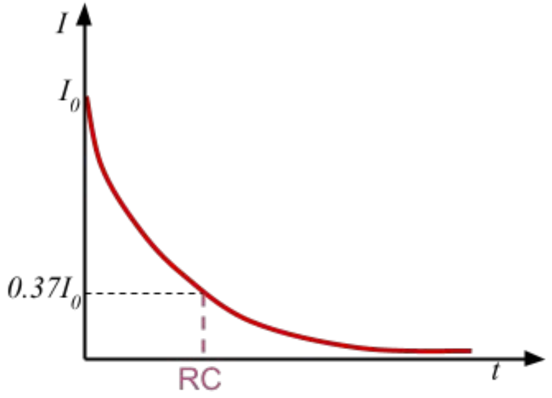
$$\ln Q = \ln Q_0 - \frac{t}{RC}$$

Time Constant

An important value when working with capacitors is the **time constant**. It is equal to:

- The product of the resistance in the circuit and the capacitance of the capacitor
- The time taken to **charge** the capacitor to (1 - 1/e) of its final value
- The time taken to **discharge** the capacitor to 1/e of its initial value





Magnetic Flux Density

When a **current** passes through a wire, a magnetic field is **induced** around it. This field consists of **concentric circles** around the wire.

If a current carrying wire is placed in a magnetic field, the **two fields interact** and a force acts on the wire. The magnitude of this force depends on:

- The **length** of the wire
- The **current** passing through the wire
- The **magnetic flux density** of the field

Magnetic flux density is a measure of the strength of a field and its unit is the **Tesla**.

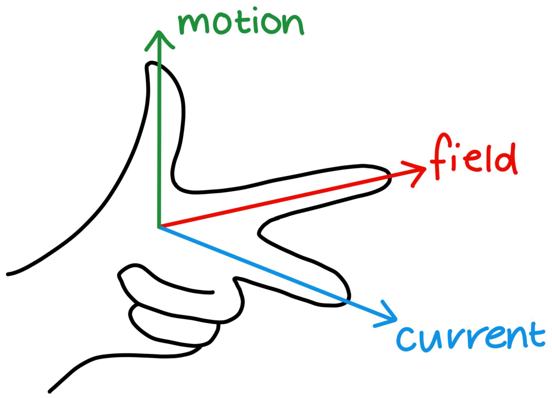
Motor Effect

When a current-carrying wire experiences a **force** in a field, it is referred to as the motor effect. The **magnitude** of the force can be calculated using:

Force (N) = Magnetic Flux Density (T) x Current (A) x Length of Wire (m)

$$F = B\,I\,L \sin\theta$$

The **direction** of the force (motion) can be determined using **Fleming's Left**



Moving Charges in a Field

When a charge moves in a magnetic field, it will experience a force. The magnitude of this force depends on:

- The **magnitude** of the charge
- The **magnetic flux density** of the field
- The **velocity** of the charge

The equation used to calculate the force is:

$$Force\ (N) = Magnetic\ Flux\ Density\ (T) \times Charge\ (C) \times Velocity\ (ms^{-1})$$

$$F = BQv \sin\theta$$

Use **Fleming's Left Hand Rule** to determine the **direction**, with the second finger being the direction of a **positive** charge (so if its a negative charge, point it in the opposite direction)!

Magnetic Flux and Flux Linkage

Magnetic flux is a measure of the **magnetic field** that passes through a given **area**. It can be thought of as a measure of the number of field lines passing through the surface, or the density of the field lines that are passing through it. It is calculated using:

Magnetic Flux (Wb) = Magnetic Flux Density (T) x Area (m²)

$$\Phi = B\,A$$

This only applies when the magnetic field lines are **perpendicular** to the area.

If using a coil, a more useful quantity is **magnetic flux linkage**. This is the magnetic flux multiplied by the number of turns of the coil the field passes through.

$$N\Phi = B\,A\,N$$

Electromagnetic Induction

If a current-carrying conductor moves relative to a magnetic field, an **EMF** is **induced**. This is as a result of the charge carriers in the conductor experiencing a force. If the conductor forms a **complete loop**, a **current** flows as a result of the induced EMF.

The law that governs the magnitude of the induced EMF is **Faraday's Law** which states that:

The magnitude of the induced EMF is directly proportional to the rate of change of magnetic flux linkage.

As an equation, this is:

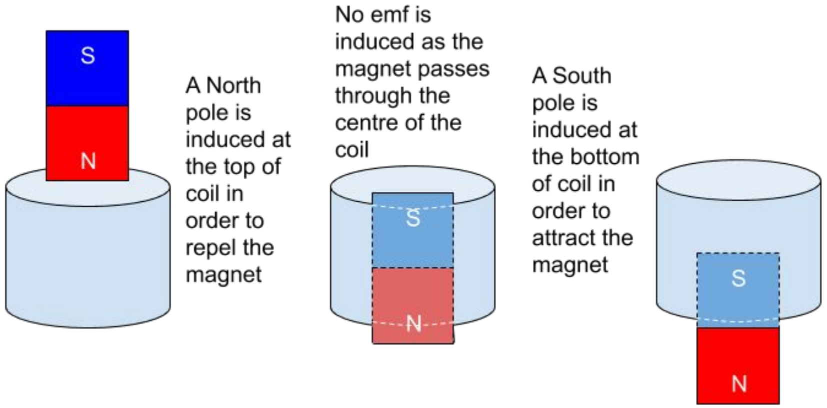
$$\varepsilon = N \frac{\Delta \Phi}{\Delta t}$$

Lenz's Law

The **direction** of the induced EMF is governed by a second law known as Lenz's Law. This states that:

The direction of an induced current is such that is opposes the change that created it.

An example of this is a magnetic falling through a non-magnetic metal tube.



Combining Faraday’s and Lenz’s Laws

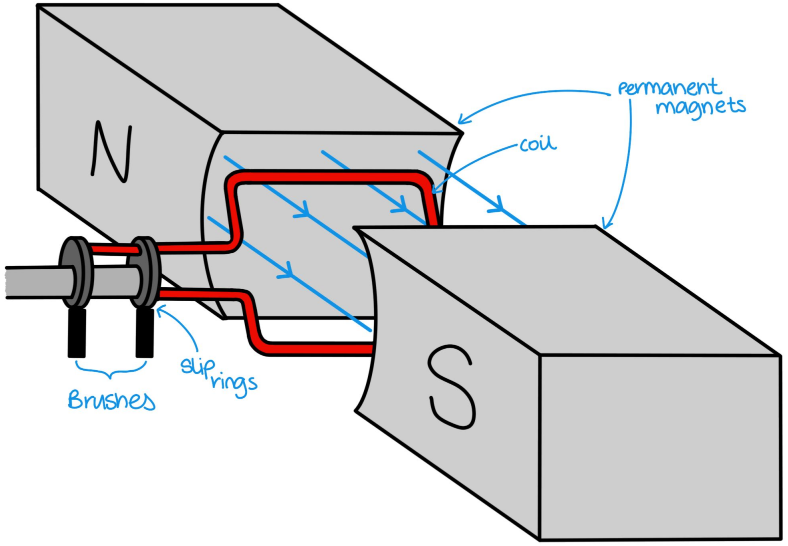
Faraday’s and **Lenz’s laws** can be combined in order to form the following equation for the value of emf generated:

$$\varepsilon = -\frac{d(N\Phi)}{dt}$$

The above equation shows the the magnitude of induced emf is equal to the **rate of change of flux linkage**, and that the emf is induced in the **opposite direction** to the change causing it.

Generators

An **A.C generator** consists of a metal coil in a magnetic field. As the coil turns, the changing magnetic flux linkage passing through it induces an EMF.

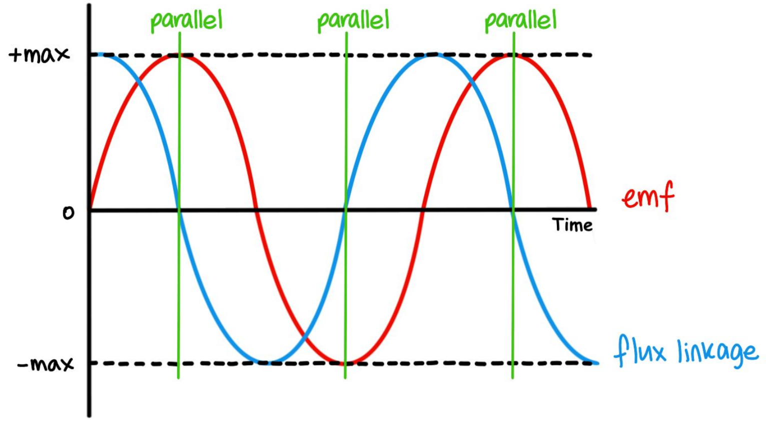


The **flux linkage** varies sinusoidally between +BAN and -BAN.

$$N\Phi = -BAN\cos\omega t$$

According to **Faraday's law**, the EMF is the rate of change of flux linkage.

$$\varepsilon = \omega BAN\sin\omega t$$



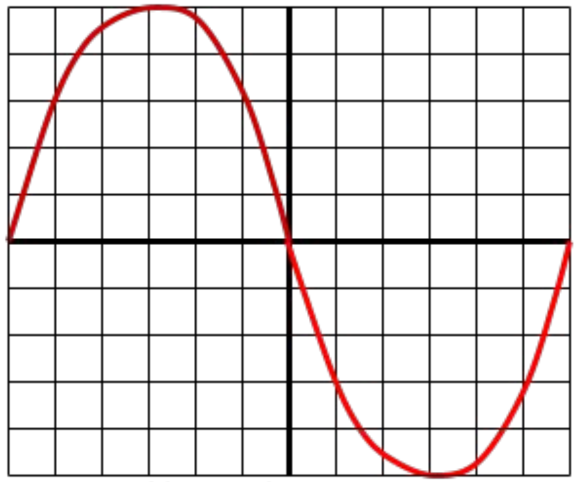
Increasing the **speed/frequency** of rotation or increasing the magnetic flux density will increase the maximum EMF.

Alternating Current

An oscilloscope is used to show voltage against time.

The time base controls how fast the wave moves across the screen (e.g 2ms per division)

The Y-gain is the voltage per division (e.g. 2V per division.)



Alternating current
Time base turned on

$$V_{rms} = \frac{V_0}{\sqrt{2}}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}}$$

V_0 is the **peak voltage**. However the 'average voltage' is not the peak voltage, and therefore we find the **root mean square (rms)**. The rms value is usually quoted when referring to a AC power supply.

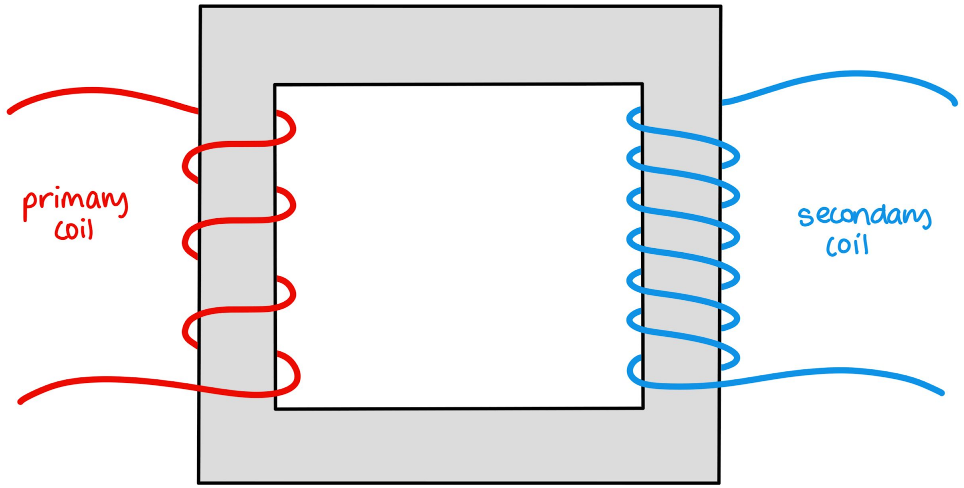
$$Power_{rms} = I_{rms} \times V_{rms}$$

Transformers

Transformers are used to **increase** or **decrease** the voltage of a power source. They come in two main types:

1. **Step-Up**: Number of coils on secondary coil > Number of coils on primary coil
2. **Step-Down**: Number of coils on primary coil > Number of coils on secondary coil

- A current pases through the **primary** coil which induces a magnetic field in the core
- The current is an **alternating-current** so that the magnetic field in the core is constantly changing
- This constantly changing field causes a change of **flux linkage** in the **secondary** coil, which induces an **EMF** and therefore a current



Inefficiencies

If a transformer was **100% efficient** the power input would equal the power output - however power is lost due to:

- Eddy currents (looping currents which generate heat in the core)
- Heat loss in the wires
- Work done when magnetising and demagnetising the core

To **reduce** these factors:

- The core can be **laminated** to prevent eddy currents flowing
- The wires can be **low resistance** wires to reduce heating
- The core can be made from **soft** iron, which is easily magnetised