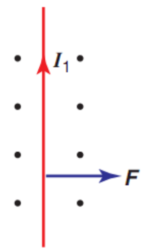
Motors and Generators

2.1 Current-carrying conductors and the Motor Effect

2.1.1 Discuss the effect on the magnitude of the force on a current-carrying conductor of variations in the strength of the magnetic field in which it is located, the magnitude of the current in the conductor, the length of the conductor in the external magnetic field and the angle between the direction of the external magnetic field and the direction of the length of the conductor



- Right hand grip rule:
  - Straight current and circular B-field (magnetic field).
- ***A current carrying conductor placed in a magnetic field experiences a force.***
- The direction of this force can be determined using right hand push/palm rule.
- The magnitude of the force can be determined using:

$$F = BIl\sin\theta$$

  - Note: θ is angle *between* the plane of the conductor and the magnetic field lines.
  - B, I and l are all directly proportional to F.
  - θ has a sinusoidal relationship with F, and its magnitude will vary between max & min.
- For a point charge moving through a magnetic field:

$$F = qvB\sin\theta$$

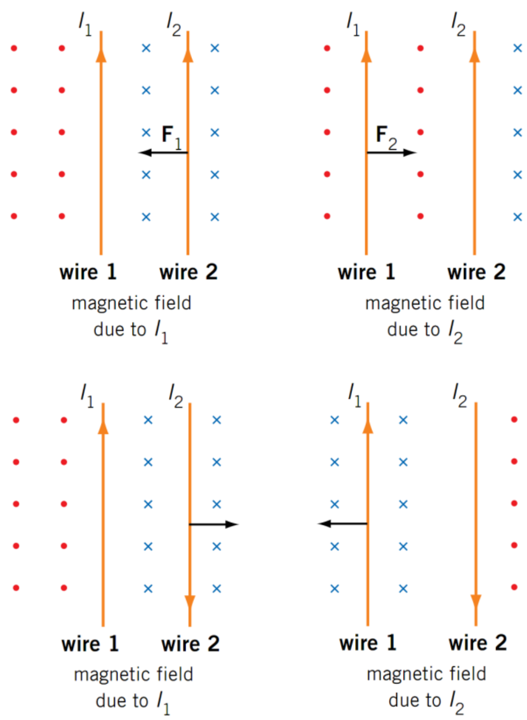
2.1.2 Describe qualitatively and quantitatively the force between long parallel current-carrying conductors

- ***The force between long parallel current carrying conductors exists because the magnetic field set up by one conductor interacts with the current in the other conductor.***

  Quantitatively:

$$\frac{F}{l} = k\frac{I_1 I_2}{d}$$

  - l is the length of conductors which *overlaps*.
- Qualitatively: I_1 sets up a B-field around I_2 into the page as shown. This B-field will interact with the current in I_2 to produce a force towards I_1 (R-hand push rule). Similarly, I_1 experiences a force towards I_2.
  - If currents are anti-parallel, the forces are reversed on each conductor.
- *Parallel* currents produce **attractive** forces.
- *Anti-parallel* currents produce **repulsive** forces.
- Force experienced by either conductor is the same, regardless of current.
- *Force* between parallel conductors is the actual force between them. *Force per unit length* is when length of conductors is 1.0m.

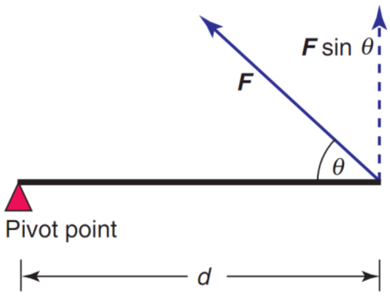


2.1.3 Define torque as the turning moment of a force

- **Torque** is the **turning effect** of a force acting on an object:

$$\tau = F_{\perp}d$$

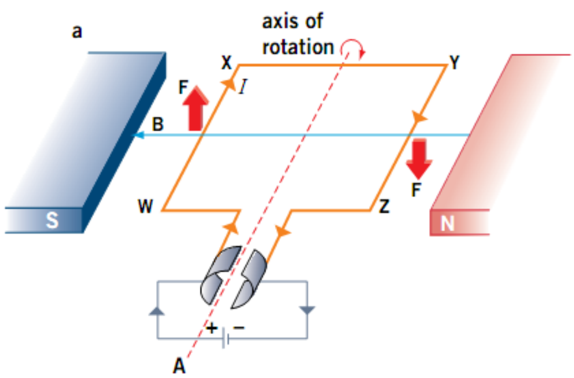
  - $F_{\perp}$ is the tangential component of F.
- It is the product of the tangential component of the force and the distance the force is applied from the axis of rotation. Only the component of force tangential to the lever arm, applied at a distance away from the axis, has a turning effect.
- If F is *tangential* to the axis: $\tau = Fd$
- If F is applied at an *angle* to the axis: $\tau = Fd\sin\theta$



2.1.4 Identify that the motor effect is due to the force acting on a current-carrying conductor in a magnetic field

2.1.5 Describe the forces experienced by a current-carrying loop in a magnetic field and describe the net result of the forces

- ***The motor effect is due to the force acting on a current carrying conductor in a magnetic field.***
- The forces experienced by a current carrying loop in a B-field will depend on the orientation of the loop relative to the B-field.
- Assume that the plane of the rectangular coil is parallel to the B-field, and current goes $W \rightarrow X \rightarrow Y \rightarrow Z$.
- Each side of the coil will experience a force; $F = BIl\sin\theta$
- *The long sides of the coil (WX & YZ) will always be perpendicular to the B-field, so F is constant on these sides, but will be in opposite directions.*
- The direction of the forces on each side will always be perpendicular to the axis of rotation.
- As the forces are in opposite directions and act on opposite sides of the axis, they produce a **net rotational torque**.



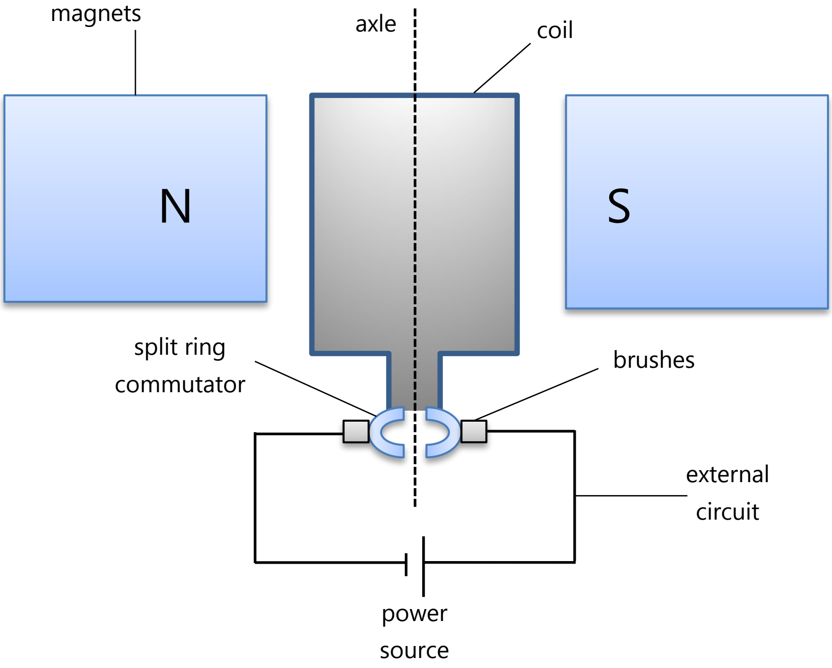
  - The torque varies according to the relationship $\tau = BIA\cos\theta$
  - For n coils, $\tau = nBIA\cos\theta$ and $F = nBIl\sin\theta$
- The magnitude of *forces* acting in WX and YZ remains constant throughout rotation, but the *torque* acting on the coil varies.
- The ends of the coil (XY & WZ) will experience a force which varies sinusoidally depending on the angle between the sides and the B-field ($F = BIl\sin\theta$). It will be 0 when the plane of the coil is parallel to the B-field, and maximum when they are perpendicular.
- Net Effect:
  - WX & YZ: Torque (rotation of coil): $\tau = BIA\cos\theta$
  - XY & WZ: Forces act along the axis in opposite directions and are equal in magnitude, so they *cancel out*. The coil is not free to move in these directions: $\Sigma F_{XY+WZ} = 0$

2.1.6 Describe the main features of a DC electric motor and the role of each feature

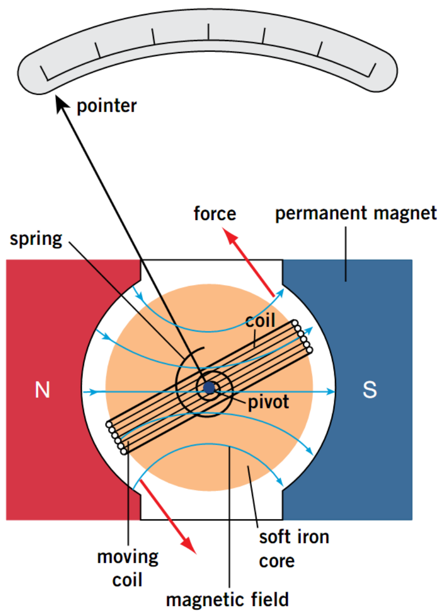
2.1.7 Identify that the required magnetic fields in DC motors can be produced either by current-carrying coils or permanent magnets

- A motor is a device which transforms **electrical** energy into **rotational (kinetic)** energy. Motors produce rotational motion by passing a current through a coil in a B-field, using the motor effect.

Part	Function & Description
Stator (magnets)	• The stator provides the **external B-field** which interacts with the current in the coils to produce the **motor effect**. • Permanent magnets are **curved** to create a **radial B-field**, which keeps the plane of the coil parallel to the magnetic field at a greater range of positions, thus maintaining **maximum torque**. • Magnetic field can be provided by: – Stationary **permanent magnets**: on opposite sides of motor with opposite poles facing each other. – Pairs of **electromagnets**: each consists of coils of wire wound around a soft iron core. • Electromagnets are more useful in motors than permanent magnets because: – They produce stronger B-fields, resulting in greater torque. – The direction of the B-field can be reversed by switching the current direction, which can run the motor backwards. – Their B-fields can be adjusted in strength and switched on/off as desired.
Armature (axle + iron core)	• The armature is a cylinder of laminated soft iron mounted on an axle. – The iron core intensifies the external B-field to **maximise τ**. – **Laminations** limit the size of eddy currents which may overheat the armature. • The *axle* provides the axis of rotation for the coils. • For DC motors the armature is the rotor, but for AC motors it is usually the stator.
Rotor (armature + coil)	• Coils of insulated wire wound around a laminated iron frame (the armature). • Rotor coils transmit **current** which **interacts with the B-field** to provide torque. – Offsetting the coils (e.g. three coils aligned at 120° to each other), maximises the torque that can act on the coils. When one loop is at a position of no torque, another will be at a position of maximum torque. • Enamelled copper wire ensures electrical insulation and prevents short circuits. • Each end of the rotor coils is attached to one half of the split ring commutator.
Split ring commutator	• 2 conducting metal half-rings that **reverse the direction of current** every half-rotation of the rotor coils, so that the coil continues rotating in the same direction. This ensures **unidirectional torque**. • This changing of direction of the forces and the **momentum** of the coil enable the coil to keep rotating in the same direction.
Brushes	• Spring loaded graphite blocks that maintain **electrical contact** between rotor coils and external circuit, allowing current to be transferred to the coils. Graphite is used because it conducts electricity and is a lubricant. • Brushes allow **free rotation of the coils** without tangling of wires in the circuit.

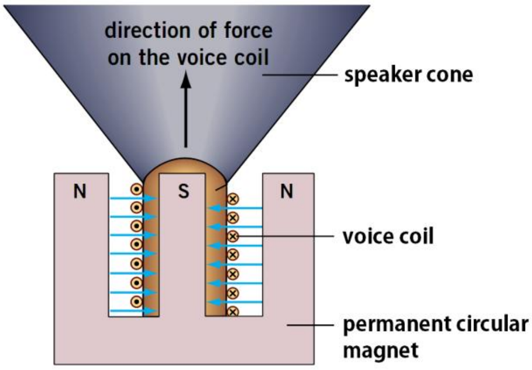


2.1.8 Identify data sources, gather and process information to qualitatively describe the application of the motor effect in the galvanometer and the loudspeaker



- <u>**Galvanometer**</u>:
  - A **galvanometer** is a device which measures very small currents. It is the basic form of an ammeter or voltmeter.
  - <u>Description</u>:
    - A galvanometer has a rotor (consisting of the iron core, about which coils are wound) surrounded by curved permanent magnets on the stator.
    - A spring and pointer needle is attached to the pivot point.
    - The current which is to be measured is supplied to the coils via the external circuit.
  - <u>How it works</u>:
    - The current interacts with the external B-field to produce a force by the **motor effect**.
    - The forces on either side of the coil act in opposite directions, producing a **torque** which rotates the coils. This causes the needle to move along the scale and the spring to tighten.
    - When the restoring force of the spring equals the torque, the needle comes to rest along the scale, giving a reading.
  - The **curved magnets** provide a uniform **radial B-field** regardless of the angle of rotation of the coil. This allows a **linear scale** to be used, with the amount of deflection being proportional to the current flowing through the coil.

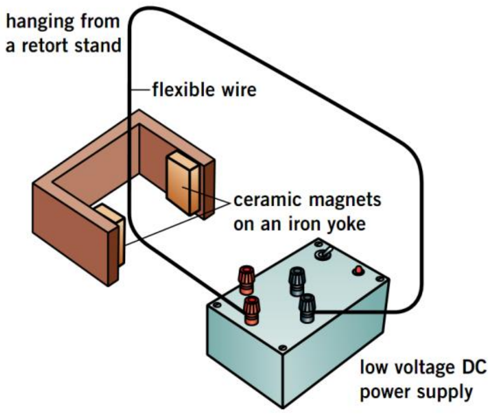
- **Loudspeaker**:
  - A **loudspeaker** is a device which transforms *electrical* energy into *sound* energy (vibration).
  - Description:
    - A loudspeaker consists of a circular magnet that has one pole on the outside and the other on the inner, central pole.
    - A conducting voice coil is wrapped about the central pole and is connected to the output of an amplifier.



  - How it works:
    - The current in the voice coil interacts with the surrounding B-field to produce a force by the **motor effect**.
    - The changing direction of the AC electric signal causes the voice coil to move in and out along the central pole.
    - The movement of the coil vibrates an attached speaker cone, which in turn vibrates air particles to produce sound.
  - The **frequency** of the electrical signal (AC input) determines the *pitch* of the sound.
  - The **current** in the voice coil determines the *amplitude* of vibrations and hence the *volume*.

2.1.9 Perform a first-hand investigation to demonstrate the motor effect

- Aim: To observe the motor effect on a current-carrying conductor placed in a magnetic field, and investigate factors affecting the magnitude of this force.
- Equipment: insulated copper wire, variable resistor, power pack, bar magnets mounted on a yoke.

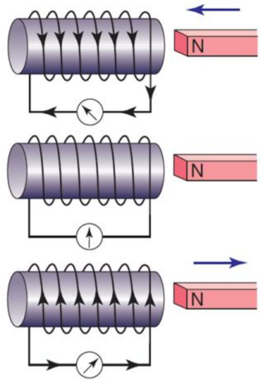


- Method:
  1. The wire was suspended vertically between the magnets by hanging it from the retort stand.
  2. The magnets were held on either side of the wire, with the plane of the B-field at 90° to the wire.
  3. The power supply was switched on.
  4. This was repeated with stronger bar magnets, more magnets on either side in a row and lower resistance to increase current ($V = IR$).
- Results:
  - The direction of the force acting on the wire was confirmed by using the R-hand push rule.
  - Increasing the strength of the bar magnet, increasing the I (by decreasing R) of the wire and increasing the length l of the wire within the B-field (by using more bar magnets) all increased the degree of movement of the wire.
  - Suspending the wire vertically, $\perp$ to the B-field, gave maximum deflection of the wire. Moving it away from this angle, towards the horizontal, reduced deflection.
- Discussion:
  - All variables (B, I, l) were kept constant except for the one being tested, to ensure validity.
  - A variable resistor was used to prevent short circuiting and overheating of the circuit due to resistive heating. The power pack was turned on only very briefly before being turned off.

2.2 Induction and Electricity Generation

2.2.1 Outline Michael Faraday's discovery of the generation of an electric current by a moving magnet

- ***Electromagnetic induction is the generation of an emf (electromotive force) or current due to the relative motion between a conductor and a*** B***-field.***
- Faraday discovered EM induction by connecting a conducting coil in series with a galvanometer, and moving a bar magnet in and out of the coil.
- The direction of current depended on the direction of movement of the magnet. The magnitude of induced current depended on how fast the magnet was moved and the strength of the magnet.



- Observations:
  - When one pole of the magnet was moved in, the needle of the galvanometer deflected one way. When the same pole moved out, the needle deflected the other way.
  - *Magnet at rest* – no deflection of needle; *slower movement* – less deflection; *faster movement* – more deflection.
- Importance of a changing B-field to EM induction: For an iron ring with a primary and secondary coil, there is a momentary flow of current in the secondary coil only when the DC power is switched on or off in the primary coil, but no current registered while the power source is left on. This is because when the DC power source is switched on, the current builds up to its maximum value in the primary circuit over a short time, so there is a brief period of increasing current and hence increasing B-field strength. This increasing, and thus *changing*, B-field induces an emf or current in the secondary coil. However, the current quickly reaches its maximum value in the primary circuit and remains at this value as long as there is a supply of DC power. This is a period of constant current and hence constant B-field strength, so no electricity is induced. Thus, after a brief moment, the reading on the meter drops to 0. When the DC power is switched off, there is no longer a supply of voltage to the primary coil. The current takes a brief moment to drop back to 0, and this produces a decrease in the B-field strength. This *changing* B-field causes another momentary flow of electricity in the secondary coil, but in the opposite direction.

2.2.2 Define magnetic field strength *B* as magnetic flux density

- ***Magnetic field strength (***B***) is magnetic flux density.***
- It is the number of flux lines (ϕ) per unit area (A) (i.e. amount of magnetic field per unit area).

$$B = \frac{\phi_B}{A}$$

  - B is measured in Tesla (T) or Weber per m^2 (Wb/m^2).

2.2.3 Describe the concept of magnetic flux in terms of magnetic flux density and surface area

- ***Magnetic flux (***ϕ_{B}***) is the number of magnetic field lines passing through a given area.***
- Magnetic flux is the product of magnetic flux density (B) and the perpendicular surface area (A):

$$\phi_B = BA$$

  - ϕ_B is measured in Weber (Wb)

- If the flux lines are not perpendicular to the area, only the perpendicular component of the magnetic field is taken into consideration:

$$\phi_B = BAcos\theta$$

2.2.4 Describe generated potential difference as the rate of change of magnetic flux through a circuit

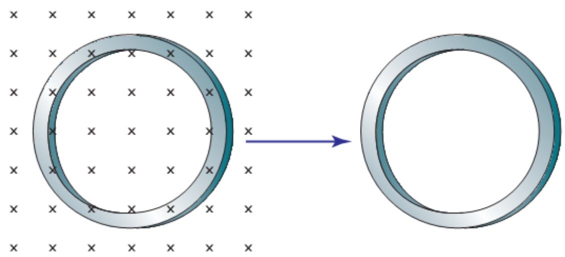
- Electromagnetic induction is due to the net change in magnetic flux threading the conductor.
- In a closed circuit, EM induction produces emf (generated voltage), which gives rise to "induced current".
- **Induced emf** is equal to the rate of change of magnetic flux through the circuit:

$$\varepsilon = -n\frac{\Delta\phi_B}{\Delta t}$$

- <u>Faraday's Law</u>: ***The relative motion between a conductor and a magnetic field sets up a net change in magnetic flux threading the conductor. This gives rise to an induced emf which is equal to the rate of change of magnetic flux through the circuit.***
  - Essentially, Faraday's Law states that a changing magnetic flux induces an emf in the circuit.
- The maximum rate of change of flux occurs from the horizontal position (flux increasing from 0).
- The **rate** of relative movement between conductor and B-field affects **magnitude** of induced emf.
- The **relative direction** of movement affects the **direction** of induced emf.

2.2.5 Account for Lenz's Law in terms of conservation of energy and relate it to the production of back emf in motors

- <u>Lenz's Law</u>: ***An induced emf always gives rise to an induced current that produces a* B*-field that opposes the original change in flux through the circuit.***
- Alternatively, the relative motion between a conductor and a B-field sets up a net change in flux threading the conductor. This induces an emf and a current in a direction such that the B-field and current interact by the motor effect to produce a force that opposes the original motion.
- <u>Example</u>: *What would happen if the loop was moved outside the B-field in the direction shown?*
  - *The coil's movement causes a net decrease in flux threading the coil into the page. By Faraday's Law, this results in an induced emf, which sets up an induced current, which by Lenz's Law will give a B-field that opposes the original change in flux. Thus, induced current is clockwise.*

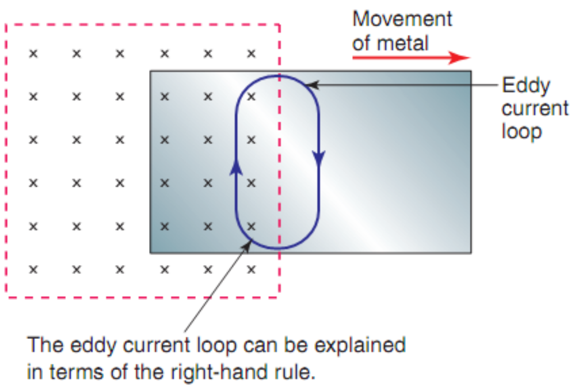


  - *Alternatively, to oppose the motion, force pushes coil to the left, and current is induced clockwise (using R-hand push rule).*
- Lenz's Law is an application of the <u>Law of Conservation of Energy</u>:
  - Suppose that Lenz's Law was reversed so that the current is set up to produce a B-field that magnifies the original change in flux.
  - This would increase the net change in flux threading the conductor (i.e. $\frac{\Delta\phi_B}{\Delta t}$ increases).
  - Since $= -n\frac{\Delta\phi_B}{\Delta t}$, the magnitude of induced emf, and thus induced current, would increase.
  - This will continuously result in the creation of electrical energy, which violates the Law of Conservation of Energy. Thus, Lenz's Law must hold true.

2.2.6 Explain that, in electric motors, back emf opposes the supply emf

- In motors, the rotation of the rotor coils within the external B-field produces relative motion between the two, resulting in a net change in flux threading the coils.
- By Faraday's Law, emf is induced in the conducting rotor coils: $\varepsilon = -n\frac{\Delta\phi_B}{\Delta t}$
- By Lenz's Law, this emf, known as **back emf**, is produced so as to oppose the supply emf.
- If this was not the case, the current would increase and the coil would rotate increasingly faster forever.
- Net voltage (net emf) across the coil equals input voltage (supply emf) minus back emf:
$$\boldsymbol{\varepsilon_{net} = \varepsilon_{supply} - \varepsilon_{back}}$$
  - When there is no load on the motor, the back emf increases as the coil speed increases, until most of the supply emf has been cancelled out by the back emf, and the motor reaches its maximum speed. Only a small current flows, which is required to overcome friction within the motor. There is no net force acting on the coil so it rotates at a constant inertial speed.
  - When there is a load on the motor, the coil rotates at a slower rate, so ε_{back} is reduced. The applied potential difference (ε_{net}) will increase and since $\varepsilon_{net} = IR$, a larger current flows through the coil, resulting in an increased torque to do work and match the extra load.
- When a motor first starts, back emf is small so the net current through the coil will be large. To protect the motor from high currents which may burn out the motor, a **series resistor** is used to limit the current ($V = IR$). As the coil speeds up and back emf increases, this resistor is switched out as the back emf results in a lower current in the coil.
- Back emf is a maximum when the rate of change of flux is a maximum.
- Increasing the rate of change of flux ($\frac{\Delta\phi_B}{\Delta t}$) causes both the magnitude and frequency of back emf to increase.

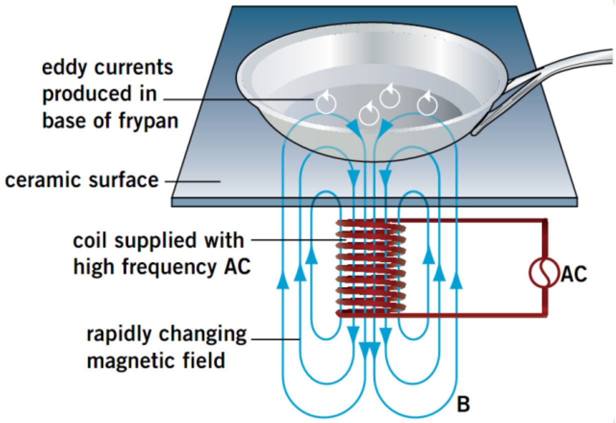
2.2.7 Explain the production of eddy currents in terms of Lenz's Law



- ***Eddy currents are small circular or whirling currents induced in the surface of a flat conductor when it is moving relative to a* B*-field.***
- A flat sheet of conductor moving relative to a B-field experiences a net change in flux, which by Faraday's Law results in an induced current. These currents are circular and induced in the surface of the conductor.
- By Lenz's Law, they are produced in a direction so as to set up a B-field that opposes the original change in magnetic flux.
- These are eddy currents. They are the same as induced currents in wires subjected to changing flux, except that the currents are not confined to a loop of wire. This is because many conductors that experience a changing B-field and produce an induced current are much larger than a wire.
- If slits are cut through the piece of metal, the slits will limit the size of the eddy currents that can be produced and thus the size of the induced B-field.

2.2.8 Gather, analyse and present information to explain how induction is used in cooktops in electric ranges

- ***An induction cooktop uses a rapidly changing*** B***-field to produce eddy currents in the base of a pan, causing it to heat up and cook food.***
- An induction coil is supplied with a **high frequency AC source** to set up a rapidly changing B-field, which causes a net change in flux across the base of the pan.

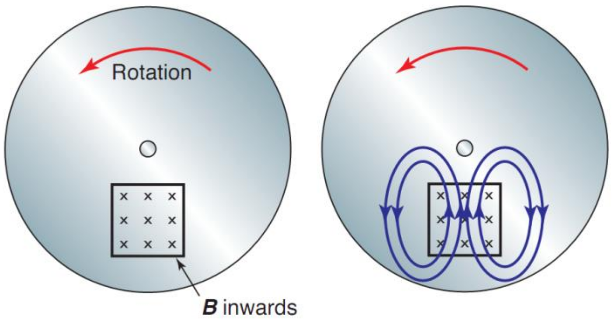


- This induces **eddy currents** within the flat metal conducting base, so as to oppose the original change in flux by Lenz's Law.
- These eddy currents cause the pan to heat up by **resistive heating**, allowing food to be cooked. Thus, *electrical energy* is converted to *heat energy*.
  - Note: Resistive heating occurs due to the collision of moving electrons (in eddy currents) with nuclei in the metallic lattice structure, causing them to vibrate, increasing kinetic energy and hence producing heat.
- A glass container/saucepan will not be heated as glass is an insulator.
- Iron saucepans are better than copper saucepans because iron has a higher resistance, so the resistive heating effect is greater.

Advantages	Disadvantages
• Fast heating • Energy efficient (minimal heat loss to external environment) • Safety (stovetop itself does not heat up, only the pan does)	• More expensive than conventional cooktops • Only ferromagnetic pans may be used, e.g. iron and steel • Aluminium saucepans cannot be used • Steel/iron jewellery may heat up

2.2.9 Gather secondary information to identify how eddy currents have been utilised in electromagnetic braking

- Consider the rotation of a conductive disc/wheel within a localised external B-field.



- The **relative motion** between the B-field and wheel sets up a change in flux threading the section of the wheel adjacent to the B-field's area of influence.
- This induces **eddy currents** in the surface of the wheel, which by Lenz's Law, set up B-fields that oppose the original change in flux.
- The induced currents interact with the B-field to produce a **force** by the **motor effect**, which opposes the rotation of the wheel, causing it to brake.

Advantages	Disadvantages
• The strength of the induced eddy currents is proportional to the rate of change of magnetic flux (Faraday's Law) and hence the speed of the vehicle, so the braking force is reduced as the vehicle slows, resulting in a smooth stop • Does not rely on physical contact between moving parts, so there is less wear and tear and hence low maintenance effort and cost	• Only works for metal wheels and at higher speeds • Cannot provide as strong a braking force as conventional brake-pad contact systems, so unsuitable for use in vehicles that may need to suddenly come to a quick stop

2.2.10 Perform an investigation to model the generation of an electric current by moving a magnet in a coil or a coil near a magnet

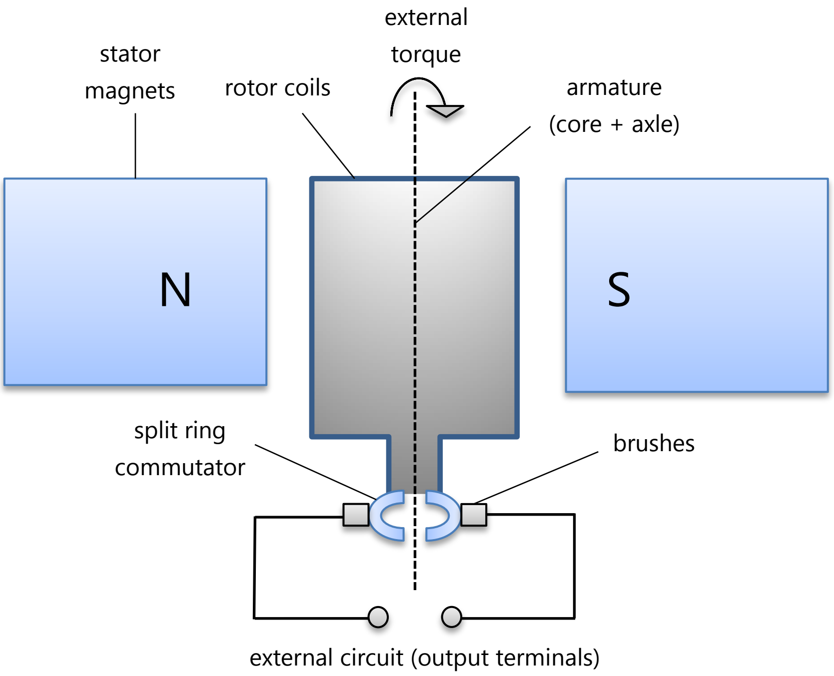
2.2.11 Plan, choose equipment or resources for, and perform a first-hand investigation to predict and verify the effect on a generated electric current of varying the distance between the coil and magnet, the strength of the magnet and the relative motion between the coil and the magnet

- Aim: To demonstrate electromagnetic induction by generating an electric current in a coiled conductor, and investigate the factors affecting the magnitude and nature of this current.
- Equipment: bar magnets of varying strengths, copper wire coil, galvanometer, iron core.
- Method:
  1. A wire coil was connected in series with the galvanometer.
  2. A magnet was moved in and out of the coil, and its effect on the galvanometer was observed.
  3. The distance between the coil and magnet and the speed and direction of their relative motion were varied, and changes to the galvanometer reading were observed.
  4. A magnet of different strength was used. An iron core was placed within the coil.
  5. Wire coils with varying numbers of turns were used.
- Results & Discussion:
  - The galvanometer initially indicated that a current had been induced due to relative motion between the coil and B-field. This confirmed Faraday's principle of electromagnetic induction.
  - The following observations were made:
    - The induced current was weaker when the magnet was positioned further away from the coil.
    - Increasing the speed of relative motion induced a current of greater magnitude.
    - The direction of relative motion determined the direction of induced current flow.
    - A stronger magnet (and hence stronger B-field) induced a current of greater magnitude.
    - Placing an iron core inside the coil resulted in a stronger B-field and hence increased magnitude of induced current.
    - A coil with more turns induced current of greater magnitude, as the B-field acts upon each loop.
  - Note:
    - As the resistance of the wire was constant, the current shown by the galvanometer was proportional to the emf generated in the wire ($V = IR$).

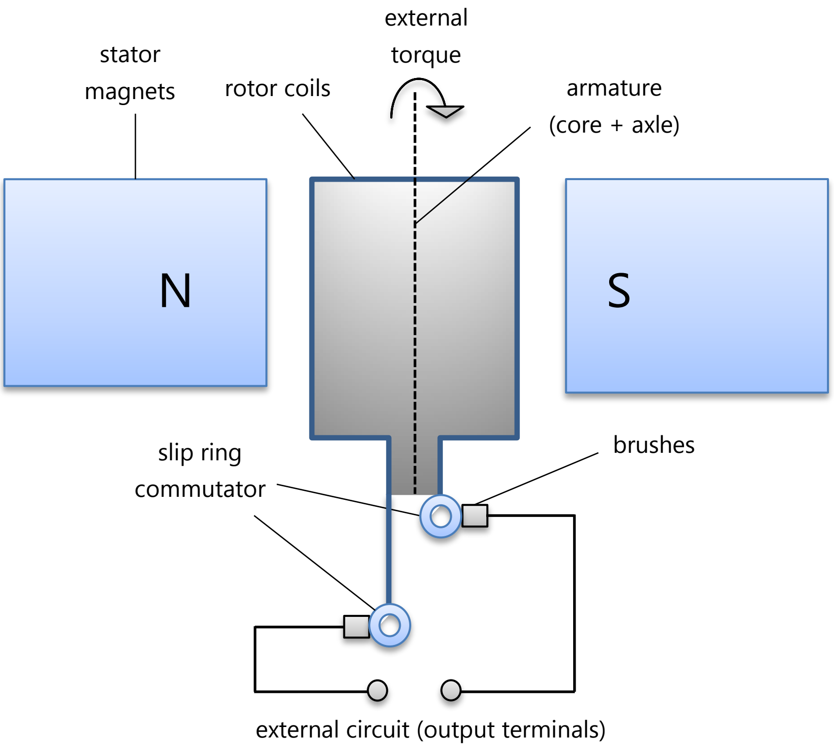
2.3 Generators and Transmission

2.3.1 Describe the main components of a generator

- ***A generator is a device which transforms mechanical energy into electrical energy.***
- When a generator is physically turned, the coil experiences a changing B-field, which results in an induced emf, causing a current to flow.
- Simple DC Generator:



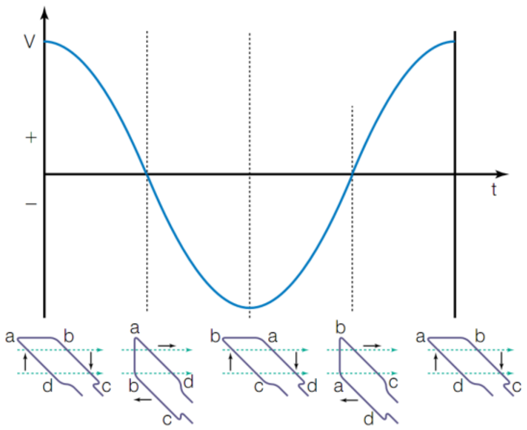
- Simple AC Generator:



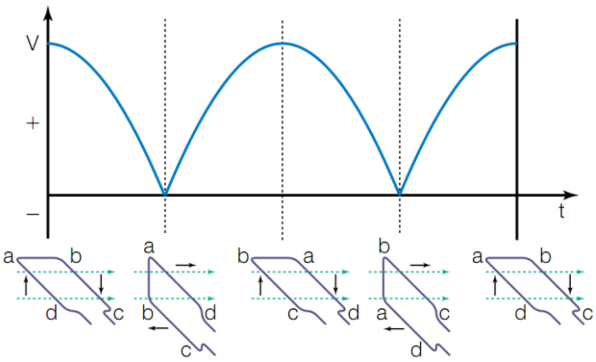
Part	Function & Description
Stator (magnets)	• The stator supplies the **$\boldsymbol{B}$-field** which interacts with rotating coils to induce current. • Magnetic field can be provided by: – Stationary **permanent magnets**: on opposite sides of generator with opposite poles facing each other. – Pairs of **electromagnets**: each consists of coils wound around iron core.
Armature	• The armature is a cylinder of laminated soft iron mounted on an axle. – The **iron core** intensifies the B-field, and **laminations** limit size of eddy currents which may overheat the armature. • The *axle* provides the axis of rotation. • Torque is applied to the axle to make the rotor spin. • Multiple coil armatures are common for large scale electric generators.
Rotor	• Coils of wire wound around a laminated iron frame (the armature). • Current is induced in rotor coils, which rotate within the B-field.
Split ring commutator (DC generator)	• 2 conducting metal half-rings that **reverse the direction of output current** every half-rotation to provide **unidirectional (DC) output**. • As induced emf changes polarity every half-rotation, voltage fluctuates between 0 and max while current flows in a constant direction.
Slip ring commutator (AC generator)	• 2 conducting circular rings that maintain **constant connection** between coil and external circuit. These do not reverse direction of output current, so **AC output** is produced. • As induced emf changes polarity every half-rotation, voltage varies like a sine wave and the current alternates in direction.
Brushes	• Spring loaded graphite blocks that maintain **electrical contact** between coils and external circuit via slip rings (AC) or split ring commutator (DC). • Brushes also allow the **free rotation of the coils** without tangling of wires.

- Output:
  - When using flat, permanent magnets, the flux threading the coils varies sinusoidally.

AC



DC



- Note:
  - When the coil of a generator is parallel to the B-field, the magnetic flux is 0. However, the forces on *ad* and *bc* are 'cutting' the B-field lines perpendicularly (i.e. a maximum cut), so the changing flux at this position is greatest. Thus, the emf induced at this position is the greatest.

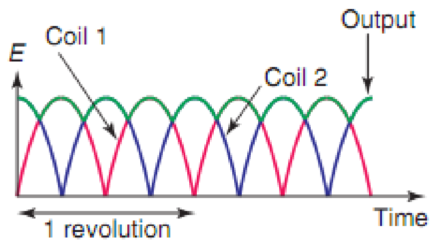
- As the coil rotates, the magnetic flux threading the coil gradually increases, so the changing of magnetic flux (the cutting) and hence the size of induced emf, gradually decreases.
- When the coil reaches a vertical position, the magnetic flux is a maximum. At this position, the forces on *ad* and *bc* are parallel to the B-field so there is no cutting of the field lines. Thus, the changing of flux is 0, and the size of induced emf is 0.

2.3.2 Compare the structure and function of a generator to an electric motor

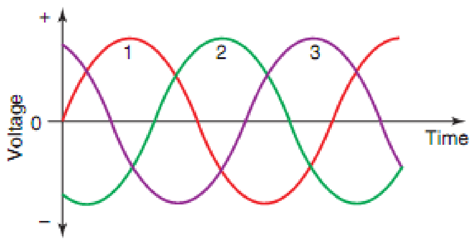
- Similarities:
  - Generators and electric motors are similar in **structure**, consisting of a stator (provides a B-field), rotor (coils, axle, laminated iron core.
  - Back emf in motors is equivalent to the induced emf in generators. However, there is no opposing supply emf in a generator, so this induced back emf produces an output current.
  - Lenz's Law applies to both motors and generators.
    - In motors, back emf opposes supply emf as a result of Lenz's Law.
    - In generators, the production of an induced B-field reduces the E_k of the rotor.
- Differences:
  - Motors and generators have reverse **functions**:
    - Motors use an input of current via a voltage source, and convert this electrical energy to rotational mechanical energy to provide output torque.
    - Generators use an input of torque via a handle, and convert this rotational mechanical energy into electrical energy to provide an output of current to the external circuit.
  - AC motors and generators use slip rings. DC motors and generators use split-ring commutators.

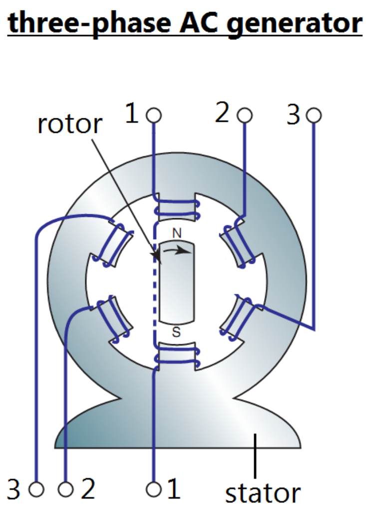
2.3.3 Describe the differences between AC and DC generators

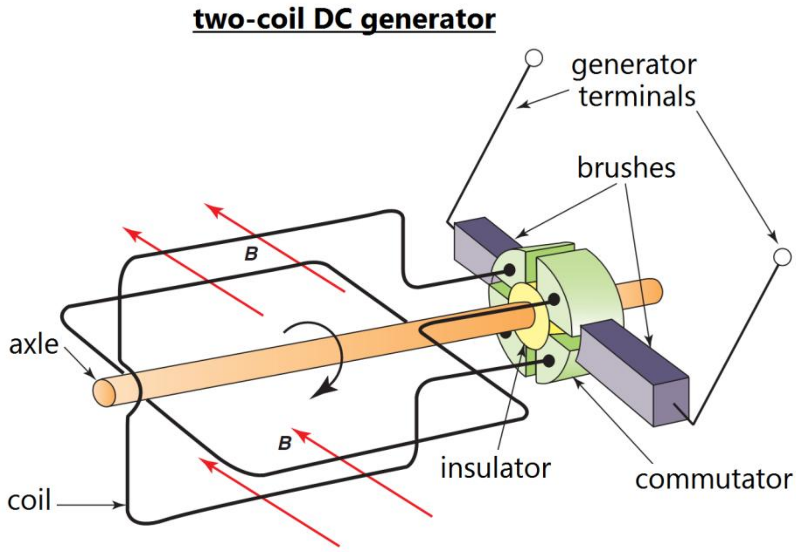
- DC Generators:
  - Simple generator uses a split-ring commutator.
  - Can use a multi-part commutator with coils placed at a range of angles to one another. Brushes are in contact with the coils producing the largest output.
  - Produces a rippling current with a relatively constant output for applications requiring a steady voltage (e.g. battery charging).
  - Industrially, the rotor consists of the coils and armature.



- AC Generators:
  - Simple generator uses a slip-ring commutator.
  - Can use many coils placed at regular angles to one another about the axis, each with separate commutators and brushes.
  - Produces multi-phase output current, such as 3-phase AC output, which is useful industrially.
  - Industrially, an AC generator has magnets as the rotor and coils on the stator.







2.3.4 Gather secondary information to discuss advantages/ disadvantages of AC and DC generators and relate these to their use

- The advantages and disadvantages for using AC and DC generators relate to their structure, function, output and ability to be used with transformers.
- Structure: (split vs. slip rings)
  - *AC generators* use **slip-rings** with smooth, continuous surfaces which the brushes are constantly in contact with. This means they do not wear down quickly, require little maintenance and are quite reliable.
  - *DC generators* use **split-rings**, so the brushes are constantly striking the edges of the commutator, causing them to wear quickly and requiring regular and costly maintenance.
    - As they wear, they do not maintain proper contact with the commutator and thus reduce the efficiency of the generator.
    - Conductive objects may also become lodged in the gaps between half-rings, causing sparking and reducing the quality of the output signal.
- Function of parts: (role of rotor and stator)
  - In an *AC generator* designed for **high current applications**, the **current is produced in the stator windings** rather than the rotor (the rotor creates the B-field).
    - It is easier to draw the current through a fixed connection on the stator, and the output current can be increased by adding coils to the stator. This does not increase the load on moving parts, and so maintains the efficiency of the generator.
  - A *DC generator* **produces current in the rotor**, so an increased output can only be achieved by adding more coils to the rotor, placing higher demands on bearings and other moving parts.
    - This causes more friction, mechanical wearing and heat loss, decreasing the efficiency of the generator.
    - Drawing large currents through the brush-commutator connection increases the likelihood of electrical arcs forming, which decrease efficiency and introduces electrical "noise" into the output signal.
    - This limits DC to fairly **low current applications**.

- Output signal:
  - *AC generators* can be designed using 6 stator poles in pairs and a single electromagnetic rotor to produce 3-phase output. This makes AC generators ideal for **large scale, industrial applications** (such as power stations).
    - However, the rapidly oscillating direction of current creates a change in flux that induces eddy currents and hence back emf, lowering the generator's power output.
  - *DC generators* can be designed with multiple rotor coils placed at regular angles to one another around the armature.
    - A multipart commutator has brushes which are only ever in contact with the commutator part with the largest output.
    - The result is an output voltage that "ripples" about a mean value, rather than fluctuating between 0 and max.
    - This current is suitable for applications requiring a **steady voltage**, which cannot be achieved with an AC generator without using rectifying circuits.
  - The output of AC generators is 10 times more dangerous than the equivalent DC generator output. AC, with its conventional 50 Hz frequency, can readily cause heart fibrillation.
- Transformers:
  - *AC generators* can be used with **transformers**, allowing:
    - More efficient, affordable and longer distance power transmission.
    - The use of fewer wires (more aesthetically appealing).
    - The ability to use electricity to meet many different voltage requirements in different applications.
  - *DC generators* cannot be used with transformers, so electricity transmission is over shorter distances, with expensive power losses, and requires different transmission lines for different voltage requirements.

2.3.5 Discuss the energy losses that occur as energy is fed through transmission lines from the generator to the consumer

- **Power loss** in transmission lines is due to resistance. Energy is lost mainly in the form of heat.
- The resistance of a metallic conductor is proportional to length (l) and resistivity (p) and inversely proportional to the cross-sectional area (A). Electricity generated over large distances will have greater resistance in the wires, causing power loss as heat is dissipated.
- Since $P = VI$, $V = IR$ and power loss is due to resistance,

$$P_{loss} = I^2R$$

  - Maximising voltage will minimise current, reducing power loss.
- *Locations* at which power loss occurs:
  - Generator:
    - Resistance in coils
    - Resistive heating due to eddy currents induced in the generator's iron core
    - Friction between moving parts produces heat
  - During transmission:
    - Resistive heating in transmission lines
    - Induced eddy currents in nearby wires/objects
  - Within transformers:
    - Resistive heating due to eddy currents in iron core or coils

2.3.6 Gather and analyse information to identify how transmission lines are insulated from supporting structures and protected from lightning strikes

- Insulation from supporting structures:
  - **Suspension/chain insulators** prevent discharge or sparking occurring between the transmission lines and metal supporting towers.
    - They consist of ceramic disc segments linked together. This shape is designed to increase the distance the current has to pass over, which decreases the risk of current leaks.
    - There is also less chance that dirt and grime (which becomes conductive when wet) will collect on the underside of the sections.
    - They are usually quite long – the higher the voltage, the longer the suspension insulator.
- Protection from lightning strikes:
  - When lightning strikes, it will usually pass between the bottom of a thundercloud and the highest point on the earth below, such as metal transmission towers.
  - **Continuous earth wires** usually carry no current, but can if there is a power surge. They are positioned higher than other transmission lines and run from the top of the tower to the bottom and into the ground. If the tower or transmission lines are struck by lightning, the current can be conducted directly into the ground.
  - **Chain insulators** place distance between transmission lines and tower. This prevents conduction of lightning-current from metal towers to power lines, avoiding dangerous and damaging power surges.
  - **Towers** (or pylons) are conducting structures which are taller than cables and are well-earthed (go below the ground). Lightning is more likely to strike the top of these towers, and the charge can be dissipated into the ground.
    - The transmission towers are also placed large distances apart to ensure that lightning cannot jump to adjacent towers.

2.3.7 Analyse secondary information on the competition between Westinghouse and Edison to supply electricity to cities

- In the late 19th century, **Edison** favoured generating and supplying *DC*, while **Westinghouse** promoted the use of *AC* electricity.
- Initially, Edison's DC was favoured because DC technology was well established, and it worked well over short distances. However, DC could only be generated and distributed at one voltage, leading to expensive power losses over a relatively short distance. Many generators and transmission lines were also required to supply a small population.
- AC electricity avoided these issues because it could be used with transformers. Transmission could therefore occur over longer distances with minimal loss of power, fewer generators and power lines, and the electricity could be stepped-down to supply a range of voltage requirements.
- AC electricity became more popular following Tesla's invention of the induction motor which operated on AC only. Westinghouse purchased the patent for Tesla's AC generator.
- When Westinghouse secured the Niagara Falls commission and was able to supply all of New York City with only 10 generators, AC electricity was eventually adopted as the global standard.

2.3.8 Assess the effects of the development of AC generators on society and the environment

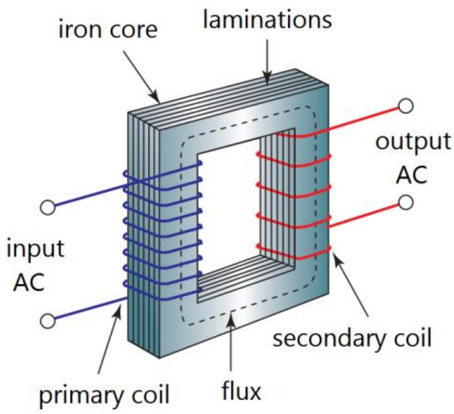
- The development of AC generators has led to the widespread application of some of the useful features of AC electricity. AC can be used with transformers, allowing extensive, reliable and efficient electricity networks to be set up. This has many effects on society and the environment.
- **Society**:
  - Advantages
    - **Accessibility**
      - The ability to use transformers with AC electricity means that voltage can be stepped-up and current can be stepped-down to minimise power loss ($P_{loss} = I^2R$).
      - This means AC electricity can be transmitted over long distances, allowing access to electricity even in rural/remote areas, and hence improving quality of life.
    - **Affordability**
      - More efficient electricity transmission minimises costly power losses, making AC more affordable for the consumer.
      - AC generators are cheaper to build, more reliable in use and efficient than DC alternatives.
    - **Applications**
      - AC has allowed more applications for electricity to be developed, improving the ease, convenience and comfort of everyday life. These include lighting, refrigeration, heating, air-conditioning, appliances, computers and communications.
      - In industry, there has been increased automation and increased reliability and affordability of products, as industrial process is more efficient, accurate and reliable.
    - **Aesthetics**
      - Power stations can be located further away from population centres and fewer transmission lines are required at the end-point, as AC electricity can be transformed depending on the application. This is aesthetically more appealing for society.
  - Disadvantages
    - The widespread use and increased demand for AC electricity has led to:
      - Increased risks to personal safety in the form of electrocution.
      - Automation of industry, which decreases demand for unskilled labour, leading to a loss of jobs.
      - Increased dependence on the constant availability of electricity in our daily lives.
- **Environment**:
  - The generation of electricity by burning fossil fuels has increased air pollution and levels of greenhouse gases.
  - Natural habitats and wildlife have been destroyed by mining (to supply fossil fuels) and deforestation (to allow construction of transmission lines and other infrastructure).
  - Radioactive waste has been generated from nuclear power plants.
- **Assessment**: Despite the disadvantages of AC electricity (e.g. dependence, electrocution and environmental detriment), the benefits of AC on society far outweigh the negative effects.

2.3.9 Plan, choose equipment or resources for, and perform a first-hand investigation to demonstrate the production of an alternating current

- Aim: To demonstrate the production of an alternating current.
- Equipment: galvanometer, copper coil, leads and alligator clips, permanent bar magnet.
- Method:
  1. The ends of the copper coil were connected to the terminals of the galvanometer.
  2. The bar magnet was moved directly in and out of the coil, and the direction of the galvanometer needle deflection was observed.
  3. The speed at which the magnet was moved was increased, and changes to the deflection of the galvanometer needle were observed.
- Results:
  – The movement of the magnet into the coil produced deflection of the needle in one direction, while movement of the magnet out of the coil produced deflection in the other direction.
    - This movement of the galvanometer needle back and forth indicated the production of an alternating current.
  – Faster magnet movement gave greater needle deflection.
- Discussion:
  – The production of AC can be explained by Faraday's Law. When the direction of movement of the magnet was changed, the relative change in flux threading the coil was reversed. Thus, the induced emf and hence the induced current was reversed.
  – Increasing the speed of movement of the magnet increased the rate of change of flux, which increased the induced emf and hence the induced current.
  – A coil was used instead of a wire so that the generation of AC was more distinct, as the effect was enhanced by having the magnetic flux cutting the many turns of wire in the coil.
  – The current produced was small so it was measured with a microammeter or a galvanometer scaled in microamps (mA). A centre-reading galvanometer was used to indicate the direction of the current.

2.4 Transformers

2.4.1 Describe the purpose of transformers in electrical circuits



- ***A transformer is a device which can increase or decrease the size of AC voltages.***
- An AC source is supplied to the primary coil, setting up an oscillating B-field. This is conducted by the iron core through to the secondary coil, setting up a net change in flux threading the secondary coil.
- By Faraday's Law: $\varepsilon \propto \Delta\phi$, so an emf and output current are induced in the secondary coil. The *output current* has the same frequency as the *input current*.
- The soft iron core *intensifies* the magnetic flux so that the mutual induction process is more efficient, and acts as a *medium* through which magnetic flux can flow (ϕ_B travels best in soft iron).
- Transformers do not work with DC input as there is no changing magnetic flux.

2.4.2 Discuss why some electrical appliances in the home that are connected to the mains domestic power supply use a transformer

- In Australia, *domestic supply* voltage is 240 V single phase AC, while *industrial supply* is 415 V three-phase AC.
- However, many appliances are designed to operate on different voltages (e.g. imported devices which are made to run on voltages common to the country of manufacture). In this case, a transformer is placed in between the mains supply and the device to reduce the supply voltage.
- Many devices contain components which require different voltages, both above and below the supply (e.g. a laptop CPU requires a very low voltage, while the screen requires a very high voltage).
- In these cases, step up/down transformers are built into the appliances in order to change voltages for individual components.

2.4.3 Compare step-up and step-down transformers

Step-up transformer	Step-down transformer
• Secondary coil has more turns than primary coil. Voltage output is larger than voltage input. • Used at power stations to increase voltage and reduce current for long-distance transmission.	• Secondary coil has fewer turns than primary coil. Voltage output is smaller than voltage input. • Used at substations and in towns to reduce transmission line voltage for domestic and industrial use.

2.4.4 Identify the relationship between the ratio of the number of turns in the primary and secondary coils and the ratio of primary to secondary voltage

- By Faraday's Law, an emf and current induced in a coil:

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

  - Note: This assumes the transformer is *100% efficient* (i.e. ideal).
    - $\Delta\phi$ is the same through primary and secondary coils.
- *Step-down* transformers: $n_p > n_s \rightarrow V_p > V_s \rightarrow I_s > I_p$
- *Step-up* transformers: $n_s > n_p \rightarrow V_s > V_p \rightarrow I_p > I_s$

2.4.5 Explain why voltage transformations are related to conservation of energy

- By the Conservation of Energy (C.O.E.), power in a transformer in the primary and secondary coils must be conserved (assuming it is ideal):

$$P = VI$$
$$P_p = V_p I_p$$
$$P_s = V_s I_s$$
$$P_p = P_s \ (by\ C.O.E.)$$
$$V_p I_p = V_s I_s$$
$$\boldsymbol{\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{n_p}{n_s}}$$

- Step-up voltage = step-down current
- Step-down voltage = step-up current

2.4.5 Explain the role of transformers in electricity sub-stations

- In NSW, electricity generated at the **power station** is 23 kV (50 Hz), which is stepped up to 330 kV for AC transmissions on **major transmission lines**.
- At **regional sub-stations**, step-down transformers reduce this to 110 kV for regional distribution.
- **Local sub-station transformers** step this down to 11 kV for distribution along suburban streets.
- **Pole-mounted transformers** step this down further for domestic supply (single-phase 240 V) and industrial use (3-phase 415 V).

2.4.6 Gather and analyse secondary information to discuss the need for transformers in the transfer of electrical energy from a power station to its point of use

- If electricity was supplied without the use of transformers, transmission would occur at high currents, leading to large, expensive power losses. Cities would need to have power generators close-by, thereby limiting the accessibility of electricity. Electricity would need to be transmitted through different lines in order to supply different applications, requiring a large, expensive network of cables.
- Transformers allow power to be generated (stepped-up) to high voltages for long distance transmission. Since $R \propto l$, a long transmission wire will have high resistance, and there will be a large amount of heat dissipated when electricity passes through it. Since $P = VI$, stepping up V steps down I and since $V = IR$, $P_{loss} = I^2R$. Thus, a lower I minimises P_{loss} to increase the transmission distance and lower the cost..
- Transformers also allow voltages to be progressively stepped-down as electricity enters more populated regions for safety.
- Transformers can also be used to step up/down voltages to meet the demands of different applications. Thus, one main supply can be transformed to power many devices.

2.4.7 Discuss the impact of the development of transformers on society

- The development of transformers has led to the increased use of AC electricity.
- Advantages:
  - The ability of transformers to step-up voltage and step-down current significantly **reduces power loss** in transmission ($P_{loss} = I^2R$).
  - This allows electricity to be **transmitted over longer distances**, so remote areas can be supplied. Large, unsightly power stations can be located near reserves of coal or hydroelectric dams, which are far away from city centre populations.
  - Longer distance transmission has also become much more **efficient** and **affordable** for the consumer.
  - Ability to step up/down voltages and currents at the point of use means electricity can **meet the demands of many appliances and components**.
- Disadvantages: (relate to disadvantages of AC electricity)
  - Increased **dependence** on electricity.
  - **Automation of industry**, reducing demand for unskilled labour and causing a loss of jobs.
  - Increased **risk** of electrocution.
  - Increased demand for AC electricity has led to the increased burning of fossil fuels, causing **air pollution** and increases in greenhouse gases.

2.4.8 Gather, analyse and use available evidence to discuss how difficulties of heating caused by eddy currents in transformers may be overcome

- Transformers are not 100% efficient as eddy currents convert electrical energy to heat in the core, preventing all the input electrical energy being transferred to the secondary coil.
- As the changing flux intersects the core, eddy currents are induced, leading to resistive heat loss.
- This heat causes increased resistance, leading to increased power loss, and can damage wiring in the transformer if heat becomes excessive.
- Minimising eddy currents:
  - A **laminated core**, made from layers of iron separated by thin layers of insulation perpendicular to the changing flux, limits the size of eddy currents to reduce the heat lost through resistive heating.
  - **Ferrite soft iron cores**, which are good conductors of magnetic fields but poor conductors of electricity, have high resistivity which reduces the size of eddy currents and minimises heating.
- Cooling techniques:
  - Transformers have cases with **heat sinks/cooling fins** which increase surface area for heat dissipation.
  - The use of **fans** and **ventilated cases** improves air circulation and heat dissipation.
  - Transformer cases are made out of **dark material** to encourage the radiation of internal heat to external environment.
  - The use of **cooling oil** to absorb heat assists with dissipation of heat away from the transformer.
  - The transformer is kept above the ground and out of direct sunlight.

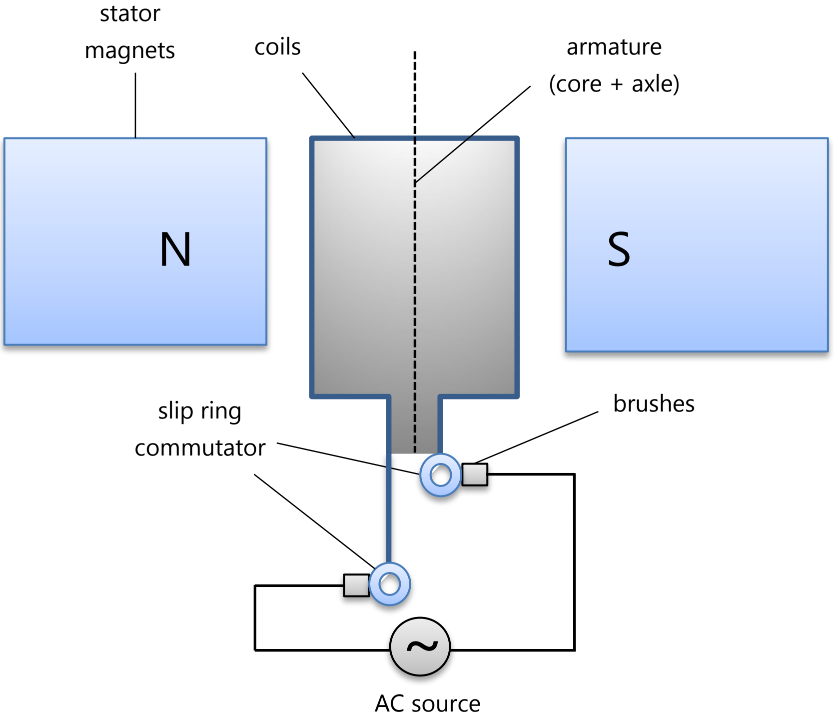
2.4.9 Perform an investigation to model the structure of a transformer to demonstrate how secondary voltage is produced

- Aim: To model the structure of a transformer and demonstrate how it acts to convert input (primary) voltage into output (secondary) voltage.
- Equipment: 2 copper wire coils with different number of turns, 2 voltmeters, power pack, soft iron core, leads and alligator clips.
- Method:
  1. One coil was placed inside the other coil. A voltmeter was connected in parallel to each coil.
  2. The power pack was connected to the external coil and AC voltage was switched on.
  3. The voltage was recorded in both coils. This was repeated for the reverse configuration.
- Results & Discussion:
  - Initially, the larger external wire coil had more turns than the smaller internal coil. When voltage was supplied to the outer coil, the voltage in the inner coil was observed to be smaller, as it had been stepped down. For the reverse configuration, voltage was stepped up.

2.5 AC Motors and Energy Transformations

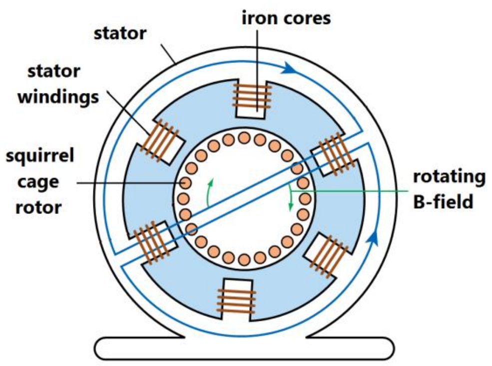
2.5.1 Describe the main features of an AC electric motor

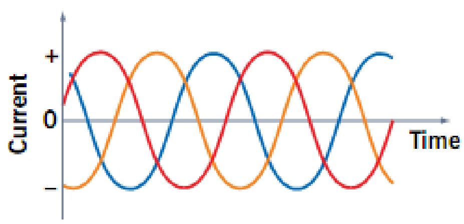
- **<u>Simple AC electric motor</u>**:

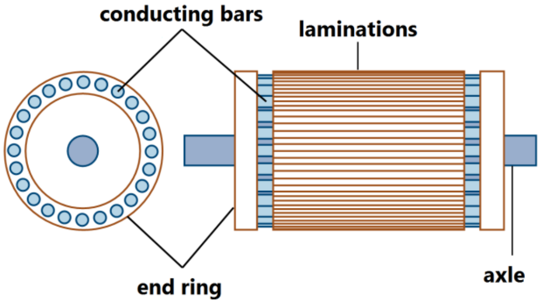


  – The main structural difference between AC and DC motors is that AC motors have *slip ring commutators*. As the coil rotates past a vertical position, the changing polarity of the voltage, and hence the current, of AC power allows the coil to rotate in a constant direction. Thus, the speed of an AC motor is limited by the frequency of the AC power.

- **<u>AC Induction motor</u>**: (*3-phase induction motor*)
  – In an induction motor, a rotating B-field (produced by the stator) interacts with current *induced* in the rotor to produce torque.
  – The **stator** consists of three pairs of coils with iron cores, mounted on a cylindrical frame. Each pair of coils is attached to one phase of 3-phase AC. This sets up a B-field which rotates around the cylindrical frame. As each coil goes through one phase of AC, the B-field "rotates" such that the coil with max B-field strength changes.







- The **rotor** consists of copper or aluminium conducting bars. These are attached to two end-rings to form the squirrel-cage rotor. The cage is encased in a laminated armature, with a **soft iron core** for intensifying the B-field, **laminations** to limit eddy currents and an **axle** with bearings to provide an axis of rotation while minimising friction.
- How it works: As the B-field rotates around the rotor, the bars of the cage experience a net change in flux. This causes an emf to be induced in the cage that sets up a current through the bars of the rotor to produce a B-field that opposes the original change in flux (Lenz's Law). This induced current in the bars of the squirrel-cage rotor interacts with the external B-field to produce a force by the **motor effect**. The forces acting on the bars of the rotor produce a **net torque** which causes the rotor to rotate in the same direction as the B-field.
- When operating the induction motor, there is always a load on the rotor, leading to friction which slows it down. Therefore, the rotor can never reach the exact speed as the B-field.
- The difference in rotational speed between the cage and the B-field is the **slip speed**. This constant speed difference means there is always **relative motion** between the conductor and the B-field, so torque is constantly produced. If the rotor rotated at the same rate as the magnetic field, there would be no relative motion between the bars and the B-field so there would be no induced current and hence no force.
- Induction motors produce **low power** as the mechanical work they achieve is low compared with the electrical energy consumed. The power loss is due to energy transformations in magnetising and inducing currents in the rotor.

- Comparison of AC induction motor and DC electric motor:
  - Both motors convert electricity to rotational mechanical energy, but in different ways.
  - DC motors reverse the direction of current in the coil every half-rotation using a split ring commutator. AC induction motors do not need commutator brushes as the current in the squirrel cage is *induced* due to a changing B-field.
  - Induction motors have fewer moving parts, so they are **more reliable compared to DC motors** and can be made very light, but they need a source of AC to operate.

2.5.2 Gather, process and analyse information to identify some of the energy transfers and transformations involving the conversion of electrical energy into more useful forms in the home and industry

- ***An energy transfer occurs when energy moves from one object or location to another, in the same form.***

Home	Industry
• Energy from the heating element in a kettle boils water	• Heat from burning of fossil fuels used to heat water or melt metals

- ***An energy transformation occurs when energy is changed from one form to another within an appliance.***

Home	Industry
• Electrical energy → light energy in light bulbs • Electrical energy → heat (vibrational) energy in heaters • Electrical energy → kinetic/ rotational energy in fans • Electrical energy → EM radiation in microwaves	• Electrical energy → heat energy in induction furnaces used for the production of metals • Electrical energy → kinetic/rotational energy in motors • Electrical energy → chemical change in electrolysis • Electrical energy → EM radiation (X-rays in imaging the interior of motors; foundations, etc.)

2.5.3 Perform an investigation to demonstrate the principle of an AC induction motor

- Aim: To demonstrate the principle of an AC induction motor.
- Equipment: aluminium foil, compass needle, bar magnet, string, retort stand, clamp, beaker.
- Method:
  1. An aluminium disc was made by wrapping a single sheet of foil over the end of a beaker and cutting it into a circular shape. A small, raise impression was made in the centre, which allowed the disc to balance on the compass needle.
  2. The bar magnet was attached to the string and suspended from a retort stand over the disc.
  3. The string was twisted in one direction and then released, allowing the magnet to spin freely in one direction over the top of the disc.
  4. The movement of the disc was observed. The string was allowed to completely untwist. The magnet came to rest and then rotated in the opposite direction.
- Results & Discussion:
  – The motion of the disc was in the same direction as the magnet. The change in flux across the foil induced eddy currents in it, which acted to resist the rotating B-field (Lenz's Law). These currents interacted with the B-field to produce a force (motor effect). Thus, the disc was 'chasing' the circular motion of the magnet, and was 'dragging along' to try and resist the movement of the B-field.
  – The speed of the disc increased to try and reach, but never surpass, the speed of rotation of the bar magnet. As the magnet's rotation slowed, came to a momentary halt and then reversed, so too did the disc.
- Assessment of the effectiveness of this model:

Advantages	Disadvantages
• Shows the rotation of the rotor • Able to visualise how the induction of eddy currents gives rise to a force • Simple and easy to understand	• Does not model the application of a load • Influenced by air currents • Cannot model certain parts of the AC motor (e.g. iron core, laminations)