HL IB Physics

Induction

Contents

Induced Emf (HL)

Induced e.m.f.

- Electromagnetic induction is a phenomenon which occurs when an e.m.f. is induced due to **relative movement** between a conductor and a magnetic field
- This could occur when:
  - a **conductor** moves relative to a magnetic field
  - a **magnetic field** varies relative to a conductor
- When a conductor cuts through magnetic field lines:
  - the free electrons in the conductor experience a **magnetic force**
  - this causes **work to be done** as charges in the conductor become **separated**
  - mechanical work is **transferred** to the charges as electric potential energy
  - a potential difference is created between the ends of the conductor, or in other words, an **e.m.f. is induced**
- This induced e.m.f. is defined as:

  The amount of work done per unit charge in separating the charges to the ends of a conductor

- If the ends of the conductor are connected to a closed circuit, an **induced current** will be able to flow
- Therefore, we can define **electromagnetic induction** as:

  The process in which an e.m.f or current is induced in a closed circuit due to changes in magnetic flux

- To induce a current in a straight **current-carrying conductor** in a magnetic field
  - it must be placed in a **perpendicular** field, so when it moves it **cuts** the magnetic field lines
  - the closed circuit must be positioned **outside** of the field, so the e.m.f. is induced across the conductor in the field **only**, and **not** the entire circuit (which would mean no current flow)
- The induced e.m.f in the conductor, as it moves through the magnetic field, is:

$$\varepsilon = BLv$$

- Where:
  - ε = induced e.m.f. (V)
  - B = magnetic flux density (T)
  - L = length of the conductor in the field (m)
  - v = velocity of the conductor travelling through the field (m s^{-1})
- This equation shows that the size of the induced e.m.f increases if:
  - the **length** of the conductor in the field is increased
  - the magnetic field **strength** is increased
  - the conductor cuts through the field lines **faster**
- Coiling a wire to form many loops or turns, will also increase the size of the induced e.m.f.
- For a coil moving through a magnetic field, the induced e.m.f. is:

$$\varepsilon = BLvN$$

- Where N = number of turns on the coil

- The phenomenon of EM induction can be demonstrated using a magnet and a coil, or a wire and two magnets

Experiment 1: Moving a magnet through a coil

- When a coil is connected to a sensitive voltmeter, a bar magnet can be moved in and out of the coil to induce an e.m.f

The expected results are...

1. **When the bar magnet is not moving, the voltmeter shows a zero reading**

    - When the bar magnet is held still inside, or outside, the coil, the rate of change of flux is zero, so, there is **no e.m.f induced**

2. **When the bar magnet begins to move inside the coil, there is a reading on the voltmeter**

    - As the bar magnet moves, its magnetic field lines 'cut through' the coil, generating a **change in magnetic flux** ($\Delta\Phi$)
    - This induces an **e.m.f** within the coil, shown momentarily by the reading on the voltmeter

3. **When the bar magnet is taken back out of the coil, an e.m.f is induced in the opposite direction**

    - As the magnet changes direction, the direction of the current changes
    - The voltmeter will momentarily show a reading with the opposite sign

4. **Increasing the speed of the magnet induces an e.m.f with a higher magnitude**

    - As the speed of the magnet increases, the rate of change of flux increases

- Factors that will **increase** the magnitude of the induced e.m.f are:
    - Moving the magnet **faster** through the coil
    - Adding more **turns** to the coil
    - Increasing the **strength** of the bar magnet

Experiment 2: Moving a wire through a magnetic field

- When a long wire is connected to a voltmeter and moved between two magnets, an e.m.f is induced
  - **Note:** there is no current flowing through the wire to start with

The expected results are...

1. **When the wire is not moving, the voltmeter shows a zero reading**

- When the wire is held still inside, or outside, the magnets the rate of change of flux is zero so there is **no e.m.f induced**

2. **As the wire moves between the magnets, an e.m.f is induced within the wire**

- This is shown momentarily by the reading on the voltmeter
- As the wire moves through the magnetic field, it 'cuts through' the magnetic field lines, generating a **change in magnetic flux**

3. **When the wire is moved back out of the field, an e.m.f is induced in the opposite direction**

- As the wire changes direction, the direction of the current changes
- The voltmeter will momentarily show a reading with the opposite sign
- Factors that will increase the magnitude of the induced e.m.f are:
  - Increasing the **length** of the wire
  - Moving the wire between the magnets **faster**
  - Increasing the **strength** of the magnets

Magnetic Flux (HL)

Emf, Magnetic Flux & Magnetic Flux Linkage

- Magnetic flux is a quantity which signifies how much of a magnetic field passes **perpendicularly** through an area
- It is defined as:

  The product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density

- Magnetic flux when the field and motion are at 90° can be calculated using the simple equation:

$$\Phi = BA$$

- Where:
  - Φ = magnetic flux (Wb)
  - B = magnetic flux density (T)
  - A = cross-sectional area (m^2)

- it is defined by the symbol Φ (greek letter 'phi') and measured in units of **Webers** (Wb)

How does magnetic flux change with angle?

- Since the flux is the total magnetic field that passes through a given **area**
  - It is a maximum when the magnetic field lines are **perpendicular** to the plane of the area
  - It is zero when the magnetic field lines are **parallel** to the plane of the area

- For a coil, the amount of magnetic flux varies as the coil rotates within the field

- In other words, magnetic flux is the **number of magnetic field lines through a given area**

- When the magnetic field lines are **not** completely perpendicular to the area *A*, then the **component** of magnetic flux density *B* is **perpendicular** to the area is taken
- The equation then becomes:

$$\Phi = BA\cos(\theta)$$

- Where:
  - Φ = magnetic flux (Wb)
  - B = magnetic flux density (T)
  - A = cross-sectional area (m^2)
  - θ = angle between magnetic field lines and the line perpendicular to the plane of the area (often called the normal line) (degrees)

- This means the magnetic flux is:
  - **Maximum** = BA when cos(θ) =1 therefore **θ = 0°**. The magnetic field lines are perpendicular to the plane of the area
  - **Minimum** = 0 when cos(θ) = 0 therefore **θ = 90°**. The magnetic field lines are parallel to the plane of the area

Magnetic Flux Linkage

- More coils in a wire mean a **larger** e.m.f is induced
- The **magnetic flux linkage** is a quantity commonly used for solenoids which are made of *N* turns of wire
- The flux linkage is defined as:
- It is calculated using the equation:

$$\textbf{Magnetic flux linkage} = \Phi N = BAN$$

- Where:
  - Φ = magnetic flux (Wb)
  - N = number of turns of the coil
  - B = magnetic flux density (T)
  - A = cross-sectional area (m^2)

- The flux linkage ΦN has the units of **Weber turns (Wb turns)**
- An e.m.f is induced in a circuit when the magnetic flux linkage changes with respect to time
- This means an e.m.f is induced when there is:
  - A changing magnetic flux density B
  - A changing cross-sectional area A
  - A change in angle θ

- Magnetic flux linkage also **changes** with the rotation of the coil
  - It is at a **maximum** when the field lines are **perpendicular** to the plane of the area they are passing through
  - This is the same pattern as the magnetic flux
- Therefore, the component of the flux density which is perpendicular is equal to:

$$\Phi N = BAN\cos(\theta)$$

- Where:
  - N = number of turns of the coil

Faraday's Law of Induction (HL)

Faraday's Law of Induction

- Faraday's Law connects the **rate** of change of magnetic flux linkage with induced e.m.f
- It is defined in words as:

  The magnitude of an induced e.m.f is directly proportional to the rate of change of magnetic flux linkage

- Faraday's Law of induction is defined by the equation:

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

- Where:
  - ε = induced e.m.f (V)
  - $N\Delta(\Phi)$ = change in magnetic flux linkage (Wb turns)
  - Δt = time interval (s)
- When a coil is completely vertical relative to the magnetic field lines:
  - The change in magnetic flux linkage is at a **maximum** - the field lines are travelling through the area of the coil
  - There is **no e.m.f** induced - there is no cutting of field lines i.e. there is no change in magnetic flux linkage
- When a coil is completely horizontal relative to the magnetic field lines:
  - The change in magnetic flux linkage is **zero** - there are no field lines travelling through the area of the coil
  - **Maximum e.m.f** is induced - there is the maximum cutting of field lines

Lenz's Law (HL)

Lenz's Law

- Lenz's Law is used to predict the **direction** of an induced e.m.f in a coil or wire
  - It is a consequence of the principle of conservation of energy
- Lenz's Law is summarised below:

  The induced e.m.f is such that it will oppose the change causing it

- Lenz's law combined with Faraday's law is given by the equation:

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

- This equation shows:
  - When a bar magnet goes through a coil, an e.m.f is induced within the coil due to a change in magnetic flux
  - A current is also induced which means the coil now has its own magnetic field
  - The coil's magnetic field acts in the **opposite direction** to the magnetic field of the bar magnet (shown by the minus sign)
- If a direct current (d.c) power supply is replaced with an alternating current (a.c) supply, the e.m.f induced will also be alternating with the same frequency as the supply

Experimental Evidence for Lenz's Law

- To verify Lenz's Law, the only apparatus needed is:
  - A bar magnet
  - A coil of wire
  - A sensitive ammeter
- Note: a cell is **not** required

- A known pole (either north or south) of a bar magnet is pushed into the coil
  - This induces an e.m.f in the coil
  - The induced e.m.f drives a current (because it is a complete circuit)
- Lenz's Law dictates:
  - The direction of the e.m.f, and hence the current, must be set up to **oppose** the incoming magnet
  - Since a **north pole** approaches the coil face, the e.m.f must be set up to create an induced **north pole**
  - This is because the two north poles will **repel** each other

- The direction of the current is therefore as shown in the image above
  - The direction of the current can be verified using the right-hand grip rule
  - Fingers curl around the coil in the direction of current and the thumb points along the direction of the flux lines, from **north** to **south**
  - Therefore, the **current** flows in an **anti-clockwise** direction in the image shown, in order to induce a north pole opposing the incoming magnet

- **Reversing** the magnet direction would give an **opposite** deflection on the voltmeter
  - Lenz's Law would then predict a **south** pole induced at the coil entrance (next to the bar magnet)
  - This would create a north pole at the exist, **attracting** the bar's south pole attempting to leave
  - Therefore, the induced e.m.f **always** produces effects to **oppose** the changes causing it
- This means:
  - The coil will try and **push** the bar magnet to stop it from entering
  - The coil will try and **pull** the bar magnet to stop it from leaving
  - This means the poles of the coil **swaps around** as the bar magnet travels through
- Lenz's Law is a direct consequence of the **principle of conservation of energy**
  - Electromagnetic effects will not create electrical energy out of nothing
  - In order to induce and sustain an e.m.f, for instance, **work** must be done in order to overcome the repulsive effect due to Lenz's Law

Self Induction & Mutual Induction

- When changes in current within a circuit occur, particularly when the current is alternating at high frequencies, changes in magnetic flux will also occur
- Two types of induction can be observed
  - **Self-induction** - induction within the **same** circuit
  - **Mutual induction** - induction **between** circuits
- These both occur as a consequence of **Lenz's law**

Self Induction

- When induction occurs within the same circuit, this is known as self-induction
- Self-induction is defined as

  The effect in which a change in the current tends to produce an induced emf which opposes the change of current in the same circuit

- The induced current is produced by a **back e.m.f.** i.e. an induced e.m.f. that opposes a change of current (in the same circuit)
  - Note: this is the same induced e.m.f. as described by Lenz's law
- The back e.m.f. is proportional to minus the rate of current change

$$\text{back e.m.f.} \propto -\frac{\Delta I}{\Delta t}$$

Mutual Induction

- When induction occurs in a separate circuit from the one producing the change, this is known as mutual induction
- Mutual induction is defined as

  The effect in which a change in the current in one circuit tends to produce an induced emf which opposes the change of current in a neighbouring circuit

- An important application of mutual induction is **transformers**

Transformers

- A transformer is

  A device that changes high alternating voltage at low current to low alternating voltage at high current, and vice versa

- A transformer is designed to reduce heat energy loss whilst transmitting electricity through power lines from power stations to the national grid
- A transformer is made up of:
  - A primary coil
  - A secondary coil
  - An iron core
- The primary and secondary coils are wound around the **soft iron core**
  - The soft iron core is necessary because it enhances the strength of the magnetic field from the primary to the secondary coil
  - Soft iron is used because it can easily be magnetised and demagnetised
- In the primary coil, an alternating current producing an alternating voltage is applied
  - This creates an **alternating magnetic field** inside the iron core and therefore a changing magnetic flux linkage
- A changing magnetic field passes through to the secondary coil through the iron core
  - This results in a changing magnetic flux linkage in the secondary coil and from Faraday's Law, an **e.m.f is induced**
- An e.m.f produces an alternating output voltage from the secondary coil
  - The output alternating voltage is at the **same** frequency as the input voltage
- In a **step-up** transformer
  - The secondary coil has **more turns** than the primary coil
  - Hence, the secondary voltage is **larger** than the primary voltage
- In a **step-down** transformer
  - The primary coil has **more turns** than the secondary coil
  - Hence, the primary voltage is **larger** than the secondary voltage

AC Generators (HL)

The AC generator

- If a coil of wire is rotated inside a magnetic field by an external force, an e.m.f. will be generated in the wire which causes current to flow within the coil
- A simple A.C. generator converts mechanical energy into electrical energy in the form of alternating current
- A rectangular coil is forced to spin in a **uniform magnetic field**
- The coil is connected to a centre-reading meter by **metal brushes** that press on two metal **slip rings** (or commutator rings)
  - The slip rings and brushes provide a continuous connection between the coil and the meter
- When the coil turns in one direction:
  - The pointer defects first one way, then the opposite way, and then back again
  - This is because the coil **cuts through** the magnetic field lines and a **potential difference,** and therefore current, is **induced** in the coil
- The pointer deflects in both directions because the current in the circuit repeatedly **changes direction** as the coil spins
  - This is because the induced potential difference in the coil repeatedly changes its direction
  - This continues as long as the coil keeps turning in the **same** direction
- The induced potential difference and the current **alternate** because they repeatedly **change direction**

Emf Induction in a Rotating Coil

- When a coil rotates in a uniform magnetic field, the flux through the coil will vary as it rotates
- Since e.m.f is the rate of change of flux linkage, this means the e.m.f will also change as it rotates
  - The maximum e.m.f is when the coil **cuts through** the most field lines
  - The e.m.f induced is an **alternating** voltage
- Flux linkage is given by

$$N\Phi = BAN \cos \theta$$

- Angular speed ω is defined as the rate of change of angular displacement, so

$$\omega = \frac{\theta}{t}$$

- Therefore, for a rotating coil, the angle θ depends on the angular speed of the coil ω:

$$\theta = \omega t$$

- Hence, flux linkage can also be written as:

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

- Where:
  - $N\Phi$ = flux linkage (Wb turns)
  - B = magnetic flux density (T)
  - A = cross-sectional area of the coil (m^2)
  - N = number of turns of coil
  - ω = angular speed of the coil (rad s^{-1})
  - t = time (s)