25 Electromagnetic Induction

25.1 Generating Electricity

When a magnet is moved near a wire, an **emf is induced** in the wire. This effect is known as **electromagnetic induction**.

- Occurs whenever a wire **cuts across magnetic field lines**.
- If the wire is part of a complete circuit, the induced emf **forces electrons around the circuit**.
- The induced emf can be increased by
  - Moving the wire **faster**.
  - Using a **stronger magnet**.
  - Making the wire into a **coil**, and pushing the magnet in or out of the coil.

No emf is induced in the wire if the wire is **parallel to the magnetic field lines** as it moves through the field - the wire must cut across field lines for an emf to be induced.

Other methods of generating an induced emf

- Using an **electric motor** in reverse.
- Using a **cycle dynamo**.

In both cases an emf is induced because there is **relative motion** between the coil and the magnet.

Energy Changes

An electric current **transfers energy** from the source of the emf in a circuit to the other components in the circuit. The induced emf becomes zero when the relative motion between the magnet and the wire ceases.

- **Work must be done** to keep it spinning.
- The energy transferred by the coil is equal to the work done on the coil to keep it spinning.

Electromagnetic Induction in a Metal Rod

1. A metal rod is a tube containing lots of **free electrons**.
2. If the rod is moved across a magnetic field, the field **forces the free electrons** in the rod to one end away from the other end.
3. One end of the rod becomes negative and the other end positive, an emf is induced in the rod.

If the relative motion ceases, the induced emf becomes zero because the magnetic field no longer exerts a force on the electrons in the rod.

The **dynamo rule**, or Fleming's right-hand rule can be used to find the direction of the induced current.

25.2 The Laws of Electromagnetic Induction

A magnetic field is produced in and around a coil when a current is passed through it. The pattern of the magnetic field lines is **like the pattern for a bar magnet**. The field lines pass through the solenoid and loop round outside the solenoid from one end to the other end.

- Current passes anticlockwise round the north pole end.
- Current passes clockwise round the south pole end.

Lenz's Law

Lenz's law states that the direction of the induced current is always such as to oppose the change that causes the current.

The explanation to Lenz's law is that energy is never created or destroyed - the induced current would never be in a direction to help the change that causes it, as it would produce electrical energy out of nowhere.

Faraday's Law of Electromagnetic Induction

Consider a conductor a length l which is part of a complete circuit cutting through lines of a magnetic field B.

If the conductor moves a distance Δs in time Δt

- The conductor experiences a force $F = BIl$ due to carrying a current in a magnetic field.
- Word done by the applied force $W = F\Delta s = BIl\Delta s$
- The charge transfer in this time is $Q = I\Delta t$.
- The induced emf is $\varepsilon = \dfrac{W}{Q} = \dfrac{BIl\Delta s}{I\Delta t} = \dfrac{Bl\Delta s}{t} = \dfrac{BA}{\Delta t}$

where A is the area swept out by the conductor in time Δt.

- **Magnetic flux** is the product of magnetic flux density and the area swept out.

$$\phi = BA$$

- **Magnetic flux linkage** through a coil of N turns $\Phi = N\phi = NBA$.

The unit of magnetic flux is the **weber**, equal to $1\,\mathrm{Tm}^2$.

When the magnetic field is at angle θ to the normal at the coil face, the flux linkage through the coil is $N\phi = BAN\cos\theta$.

Faraday's law of electromagnetic induction states that the induced emf in a circuit is equal to the rate of change of flux linkage through the circuit.

$$\varepsilon = -N\frac{d\phi}{dt}$$

- For a moving conductor

$$\begin{aligned}\varepsilon &= \frac{Bl\Delta s}{\Delta t} \\ &= Blv\end{aligned}$$

- For a fixed coil in a changing magnetic field

$$\begin{aligned}\varepsilon &= \frac{N\Delta\phi}{\Delta t} \\ &= \frac{NA\Delta B}{\Delta t}\end{aligned}$$

25.3 The Alternating Current Generator

The simple AC generator consists of a **rectangular coil** that spins inside a uniform magnetic field.

1. When the coil spins at a steady rate, the **flux linkage changes continuously**.
2. At an instant when the normal to the plane of the coil is at angle θ to the field lines.

$$N\phi = BAN\cos\theta$$

3. For a coil spinning at a steady frequency, $\theta = \omega t$

$$N\phi = BAN\cos\omega t$$
$$\varepsilon = -N\frac{d\phi}{dt} = BAN\omega\sin\omega t$$

Or $\varepsilon = \varepsilon_0 \sin\omega t$ where ε_0 is the peak voltage.

- The **induced emf is zero** when the sides of the coil move parallel to the field lines.

  The rate of change of flux is zero and the sides of the coil do not cut the field lines.
- The **induced emf is a maximum** when the sides of the coil cut the field lines at right angles.

  The emf induced in each wire of each side is Blv, where v is the speed of each wire.

$$\varepsilon_0 = 2NBlv$$

The peak emf can be increased by

- Increasing the speed (frequency of rotation).
- Using a stronger magnet.
- Bigger coil.
- Coil with more turns.

Back Emf

An emf is induced in the spinning coil of an electric motor because the flux linkage through the coil changes. The induced emf **acts against the pd applied** to the motor in accordance of Lenz's law.

$$\begin{aligned} V - \varepsilon &= IR \\ IV - I\varepsilon &= I^2 R \\ IV &= I\varepsilon + I^2 R \end{aligned}$$

power supplied = power transferred to mechanical power + power wasted due to circuit resistance

$$\text{efficiency of an electric motor} = \frac{\text{mechanical power output}}{\text{electrical power supplied}}$$

25.4 Alternating Current and Power

An alternating current is a current that repeatedly reverses its direction.

- The **frequency** of an alternating current is the number of cycles it passes through each second.
- Mains electricity has a frequency of 50Hz.
- The **peak value** of an alternating current is the maximum current in either direction. The peak current in a circuit depends on the **peak pd** of the alternating current source, and the components in the circuit.
- The **peak pd** in a mains current is 325V.
- The **peak-to-peak value** is twice the peak value.

The heating effect of an electric current varies according to the **square of the current**.

$$\text{Power supplied to the heater } P = I^2 R$$

- At **peak current** I_0, the maximum power supplied is equal to ${I_0}^2 R$.
- At zero current, zero power is supplied.

The Root Mean Square

For a **sinusoidal current**, the **mean power** over a full cycle is **half the peak power**.

$$P_{\text{mean}} = \frac{1}{2}{I_0}^2 R$$

The root mean square value of an alternating current is the value of direct current that would give the same heating effect as the alternating current in the same resistor.

$$(I_{\text{rms}})^2 R = \frac{1}{2} {I_0}^2 R$$
$$I_{\text{rms}} = \frac{1}{\sqrt{2}} I_0$$

The root mean square value of an alternating pd is

$$V_{\text{rms}} = \frac{1}{\sqrt{2}} V_0$$

25.5 Transformers

A transformer changes an alternating pd to a different peak value.

- A transformer consists of **two coils -** the primary coil and the secondary coil.
- The two coils have the **same iron core**.

When the primary coil is connected to a source of **alternating pd**.

1. An **alternating magnetic field** is produced in the core.
2. The field passes through the secondary coil, so an **induced emf** is induced in the secondary coil by the changing magnetic field.

A transformer is designed so that all the magnetic flux produced by the primary coil passes through the secondary coil.

The Transformer Rule

Let ϕ be the flux in the core passing through each turn when an alternating pd V_p is applied to the primary coil.

- The flux linkage in the secondary coil is $N_s\phi$, by Faraday's law

$$V_s = N_s \frac{d\phi}{dt}$$

- The flux linkage in the primary coil is $N_p\phi$, by Faraday's law

$$V_p = N_p \frac{d\phi}{dt}$$

The induced emf in the primary coil **opposes the pd applied** to the primary coil. Assuming the resistance of the primary coil is negligible, all the applied pd acts against the induced emf in the primary coil.

$$\text{Applied pd} = V_p$$

$$\frac{V_s}{V_p} = \frac{N_s \frac{d\phi}{dt}}{N_p \frac{d\phi}{dt}} = \frac{N_s}{N_p}$$

which is the **transformer rule**.

- A **step-up transformer** has more turns on the secondary coil than the primary coil, so the secondary voltage is stepped up compared to the primary voltage.
- A **step-down transformer** has fewer turns on the secondary coil than the primary coil, so the secondary voltage is stepped down compared with the primary voltage.

Transformer Efficiency

Transformers are almost 100% efficient because they are designed with

- **Low-resistance windings** to reduce power wasted due to the heating effect of the current.
- A **laminated core** which consists of layers of iron separated by layers of insulator. **Eddy currents** are reduced so the magnetic flux is as high as possible, and the heating effect of induced currents in the core is reduced.
- A core of **soft iron** core which is easily magnetised and demagnetised. This reduced power wasted through repeated magnetisation and demagnetisation of the core.

$$\text{Transformer efficiency} = \frac{I_s V_s}{I_p V_p}$$

The Grid System

Electricity from power stations in the UK is fed into the National Grid System, which **supplies electricity** to most parts of the country.

The national grid is a **network of transformers and cables**, which covers all regions o the UK.

1. **Step-up transformers** at the power station increases the alternating voltage to 400kV for long-distance transmission via the grid system.
2. **Step-down transformers** operate in stages to reduce the transmitted voltage to 230V.

Transmission of electrical power over long distances is much more efficient at high voltage than at low voltage.

- If the voltage is increased, power wasted due to the heating effect of the current is reduced.
- To deliver power P at voltage V, the current required is $I = \dfrac{P}{V}$.

  If the resistance of the cables is R, the power in heating the cables is $I^2R = \dfrac{P^2R}{V^2}$

- Therefore the higher the voltage is, the smaller the ratio of wasted power to the power transmitted is.