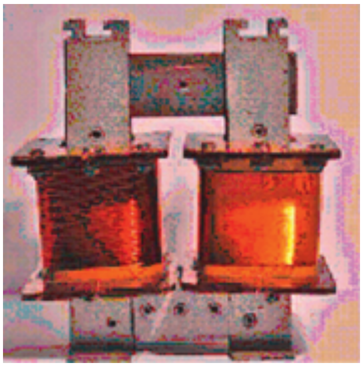


6

ELECTROMAGNETIC INDUCTION

ELECTROMAGNETIC INDUCTION

A current-carrying conductor produces magnetism around it. This important discovery by Ã–ersted in 1820 suggests that there is a link between **magnetism** and **current.** Michael Faraday and Joseph Henry, working independently, discovered that if a conductor cuts through a magnetic field, current is produced in it. The production of electric current from magnetism is called **electromagnetic induction.**

OBJECTIVES

At the end of the topic, students should be able to:

- →state and explain Faradayâ€™s law of electromagnetic induction ;
- →state and explain the implication of Lenzâ€™s law;
- →explain how the conservation principle is involved in both laws with regards to (i) charge (ii) energy;
- →explain the principles underlying the production of direct or alternating current;
- →explain the difference in the construction of d.c. and a.c. generators;
- →explain the principle of a transformer; state the use of induction coils and transformers;
- →explain why the cores of the induction coil and the transformer are laminated;

Production of electric current

Electromagnetic induction is the production of current or voltage in a wire or coil when it is placed in a changing magnetic field.

I. Coil and magnet experiment

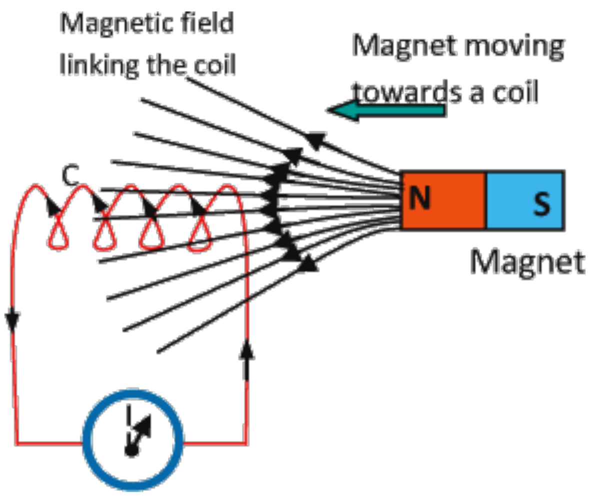


Figure 6.1 Coil and magnet experiment

Figure 6.1 shows a coil with the terminals connected to a galvanometer (G). This simple apparatus is used to demonstrate the induction of current or voltage in a coil.

(i) The N-pole of a strong magnet is moved towards the coil. The galvanometer deflects for a short time to the right as shown in Figure 6.2a. The deflection of the galvanometer implies that current or voltage is induced in the coil. If the S-pole of a magnet is moved towards the coil, the galvanometer deflects in the opposite direction. See Figures 6.2a and b.

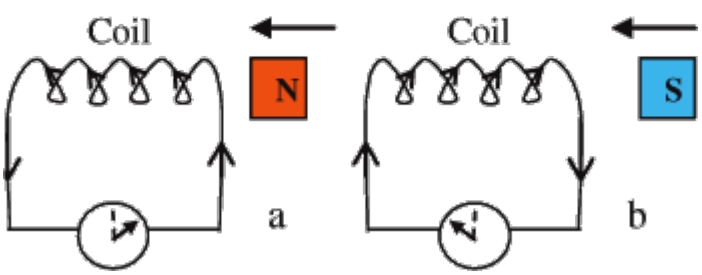


Figure 6.2 magnets moving towards the coil

(ii) When the magnet is stationary inside the coil, the galvanometer does not deflect. This indicates that no current or voltage is induced in the coil.

(iii) If the N-Pole of the magnet is moved away from the coil, the galvanometer deflects to the left as shown in Figure 6.2c. The direction of the induced current or voltage is opposite to that induced when the magnet is moved towards the coil.

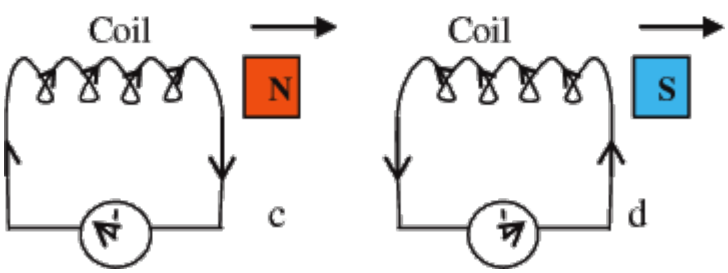


Figure 6.2 magnets moving away from the coil

(iv) Moving the magnet and the coil at the same speed towards or away from each other does not deflect the galvanometer. No current or voltage is induced in the coil when there is no relative motion between the coil and the magnet.

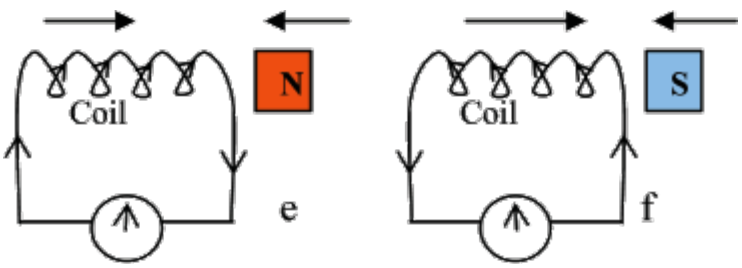


Figure 6.2 Magnet and coil moving towards each other at the same speed

We conclude as follows:

- Current or voltage is induced in a coil if there is relative motion between it and the magnet.
- The size of the induced current or voltage is proportional to the relative speed between the coil and the magnet. Moving the magnet fast towards the coil, increases the rate of change of magnetic field or flux linking the coil, therefore, current induced in it is high.
- The direction of the induced current or voltage depends on (i) the direction in which the pole of the magnet used is moving; (ii) the pole of the magnet used.

II. Current /voltage (e.m.f.) induced in a straight conductor

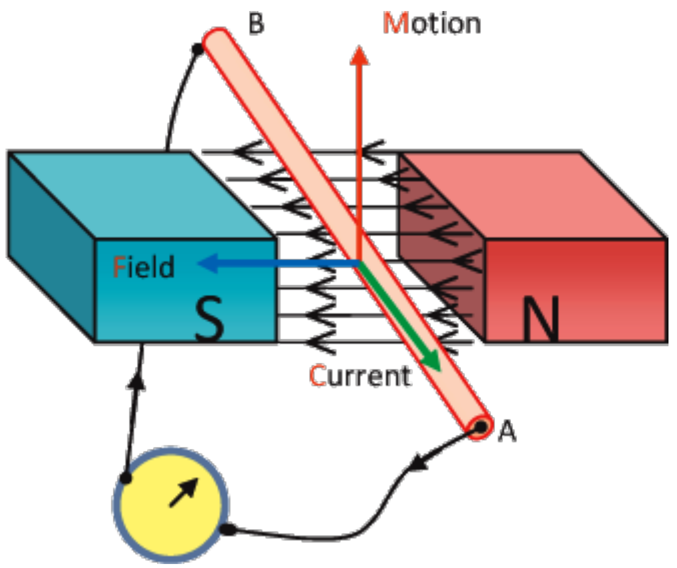


Figure 6.3 Straight conductor in a magnetic field

When a straight conductor AB is moved up and down in a magnetic field, it cuts through the field and current/voltage (e.m.f.) is induced in it. If the conductor is moved out of the paper, the induced current/voltage (e.m.f.) moves in the direction shown. If the conductor is moved towards the paper, the induced current/voltage (e.m.f.) moves in the opposite direction. Current is induced in the conductor only if it is cutting through the magnetic field. No current or e.m.f. is induced in the conductor if it is not cutting through the magnetic field or when it is lying parallel to the magnetic field.

The magnitude of induced current or voltage (e.m.f.)

The magnitude of the induced current or voltage (e.m.f.) depends on the following factors:

(i) The strength of the magnetic field

The induced current is proportional to the strength of the magnetic field or magnetic flux density.

(ii) The size (length) **of the conductor**

The induced current is proportional to the size or length of the conductor.

(iii) The speed or rate at which the conductor cuts through the magnetic field

The induced current is high if the rate at which the conductor is cutting through the magnetic field is high.

The magnitude of the induced e.m.f. or current is given by:

$$E = Blv\sin\alpha$$

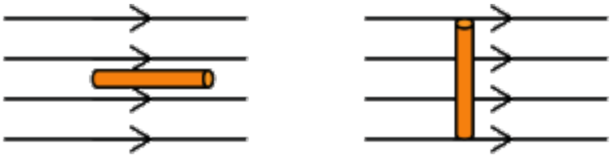
E = induced e.m.f., B = magnetic field density

l = length of conductor, v = speed of the conductor through the magnetic field and Î± = angle between the conductor and the magnetic field.

Maximum e.m.f. or current is induced in the conductor if it is cutting through the field at a right angle (Î± =90Â°).

$$E_{max} = Blv$$

The size of the induced e.m.f. or current decreases until it is zero (0) when the conductor is lying parallel to the magnetic field (Î± = 0).



$\alpha = 0^{o}$, E = 0 $\alpha = 90^{o}$, E = Blv

Worked examples

1.Calculate the voltage induced in a straight conductor of length 0.6 m as it cuts through a magnetic flux density 0.8 T perpendicularly at a speed of 20 m s^{-1}.

Solution

E = Blv

E = 0.8 Ã— 0.6 Ã— 20 = 9.6 V

2.A straight conductor of length 0.5m cuts through a magnetic flux density 0.8 T. If the voltage induced in the conductor is 1.2 V when the speed is 10ms^{-1}, calculate the angle between the conductor and the magnetic field at that instant.

Solution

$E = Blv\sin\alpha$

$$\sin\alpha = \frac{E}{Blv} = \frac{1.2}{0.8 \times 0.5 \times 10} = 0.3$$

$$\therefore \alpha = \sin^{-1}_{(0.3)} = 17.5^0$$

The direction of the induced current or e.m.f.

The direction of the induced current or e.m.f. is found by applying Flemingâ€™s right hand rule. The rule states that:

If the right hand is held so that the first three fingers are mutually at right angles to each other, the Forefinger points in the direction of the magnetic Field, the thuMb points in the direction of Motion (force) of the conductor, then the seCond finger points in the direction of Current or e.m.f.

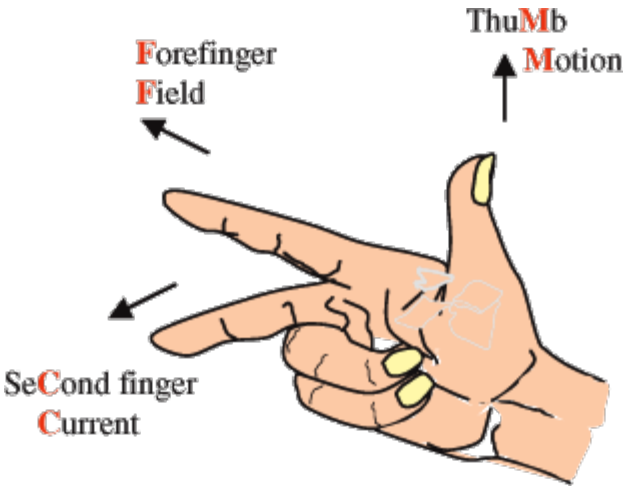


Figure 6.4: Flemingâ€™s right hand rule

The laws of electromagnetic induction

1. Faradayâ€™s law:

Current / voltage are induced in a coil anytime the magnetic flux linking it is changed. The magnitude of the induced current/voltage is proportional to the rate of change of magnetic flux linking the coil.

The induced voltage (e.m.f.) or current is given by:

$$E = N\frac{d\phi}{dt}$$

E = induced voltage or e.m.f., N = the number of turns in the coil or the length of the wire

$\frac{d\phi}{dt}$ = rate of change of magnetic flux and the (–) sign means that the direction of induced voltage/current oppose the change producing it. This is known as Lenzâ€™s law.

2. Lenzâ€™s law:

The direction of induced current/voltage is such that it opposes the change or motion producing it.

Lenzâ€™s law and conservation of energy

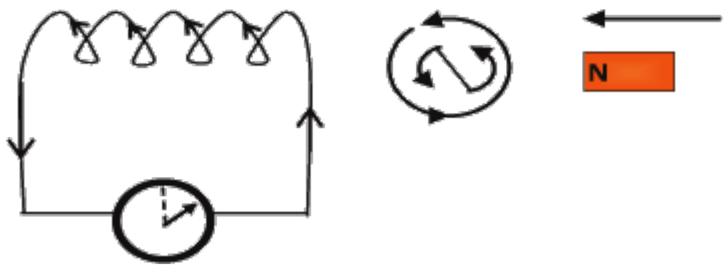


Figure 6.5a: North pole of magnet moving towards the coil

When the N-pole of a magnet is moved towards a coil, current is induced in it. The induced current flows in an anticlockwise direction; the coil becomes a N-pole. The two N-poles repel (i.e. the induced current oppose the motion of the approaching magnet). To move the magnet towards the coil, work is done against the repulsive force of the two N-poles.

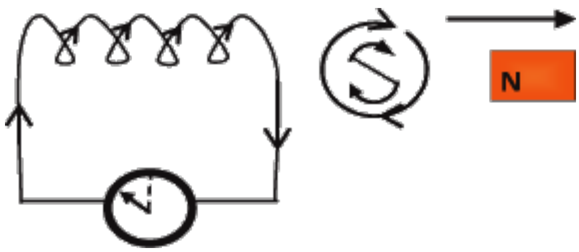


Figure 6.5b: North pole of the magnet moving away from the coil

If the N-Pole of the magnet is moved away from the coil, the induced current flows in a clockwise direction. The end of the coil nearest to the receding N-pole becomes a S-pole attracting the receding N-pole. Work is done against the attractive force between the coil and the magnet in order to move the N-pole away from the coil.

The mechanical work done in moving the magnet towards or away from the coil is transformed into electrical energy (induced current in the coil). Lenzâ€™s law is therefore an example of energy conservation.

Eddy current

Eddy current is a circulating current induced in a metal disc or plate moving in a magnetic field.

Current is induced in a metal plate placed in a changing magnetic field or rotating in a gap between the poles of a strong magnet. The induced current circulates in the plate or disc in a way that it tends to resist the motion of the plate or disc producing it.

Damping effect of eddy current

Eddy current acts as a breaking force because it always slows the motion of a metal plate or disc in a magnetic field. The slowing down of the motion of a disc in a magnetic field is called the damping effect of eddy current. We can demonstrate the damping effect of eddy current using Figure 6.6.

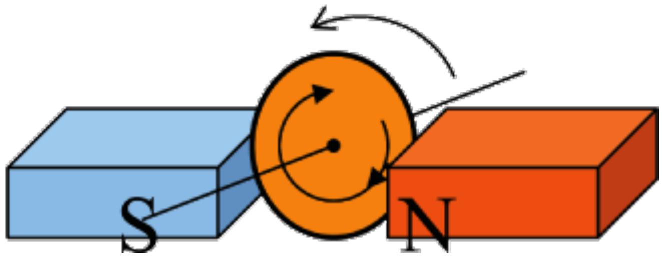


Figure 6.6a : Solid disc slows down fast in a magnetic field

Eddy current is induced in a solid disc rotating in a strong magnetic field. The disc has a low resistance; therefore, the eddy current circulating in it is large. This slows the motion of disc bringing it rest quickly. When another disc with slits replaces the solid disc, the eddy current induced in the disc with slits is small, see Figure 6.6b. This is because the slits increase the resistance of the disc. The low eddy current in the disc makes it turn in the magnetic field for a longer time.

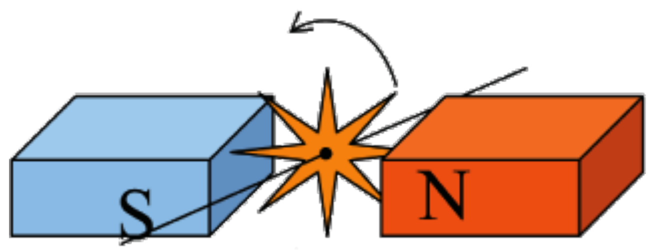


Figure 6.6b : Disc with slits move in a magnetic field for longer time

Uses of eddy current

(i) The damping effect of eddy current is used to control the movement of pointers in moving coil meters.

(ii) Eddy current flowing through a metal plate can be very high. This can be used in induction cooker for cooking and in induction furnace for melting large quantity of precious metals.

Disadvantages of eddy current

(i) Eddy current resists the motion of a plate moving in a magnetic field.

(ii) Eddy current produces heat in the cores of transformers, armatures of electric motor and generators leading to loss of energy and power.

(iii) Eddy current reduces the efficiency of electric motors, generators and transformers.

Reduction of eddy current

Power/energy loss in the core of transformers, armatures electric motor and generators can be reduced by **lamination.** Lamination is the cutting of the metal disc into small sheets and separating the sheets from each other by an insulator. The bundle of these metal sheets each separated by an insulator is called the **laminated core.** Lamination increases the resistance of the metal core to make the eddy current small.

The generator

A generator is a machine that changes the mechanical work done in rotating a coil in magnetic field to electrical energy.

Generators work on the principle that current/voltage is induced in a coil of wire or conductor moving and cutting a magnetic field. Practical generators are divided into **alternating current (a.c.) generator or alternator** and **direct current (d.c.) generator or dynamo.**

The alternating current (a.c.) generator

The alternating current (a.c.) generator generates current or voltage (e.m.f.) which changes continuously in both **magnitude** and **direction.** It has the following important parts:

- a **strong magnet** (permanent or electromagnet) to produce strong magnetic field;
- **coil of wire** wound on a laminated soft-iron core (armature);
- **two slip-rings** (R_1 and R_2) fixed to the ends of the wire of loop or coil;
- **two carbon brushes** (B_1 and B_2) which make contact with the slip-rings; current leaves the coil through the brushes.

The coil ABCD or the armature is mounted on an axle and allowed to rotate in the magnetic flux produced by the poles of strong magnet. As the coil rotates in the magnetic field, current/ voltage (e.m.f.) is induced in it. The induced current/voltage varies as shown in Figure 6.7b. Maximum current/voltage is induced in the coil when it is cutting through the magnetic field at maximum rate. The sides of the coil are cutting the magnetic field at right angles (Î± = 90Â°) or horizontally as represented by the positions S, U and W in Figure 6.7b.

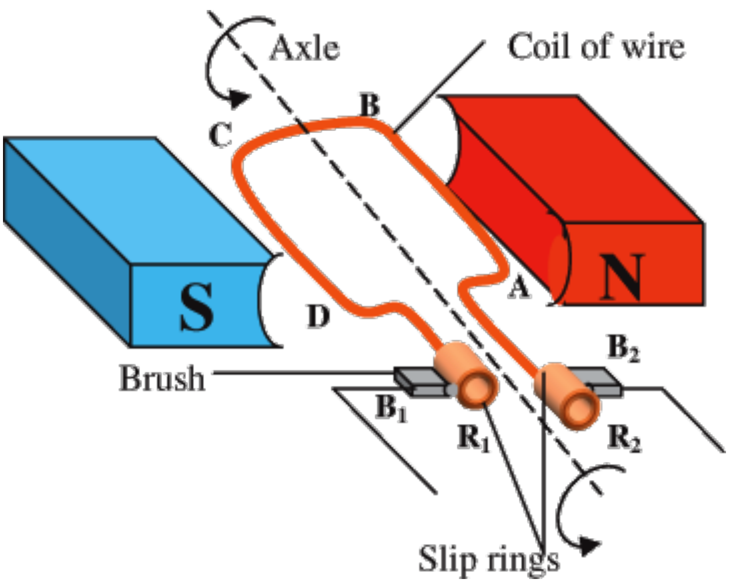


Figure 6.7a: Alternating current generator

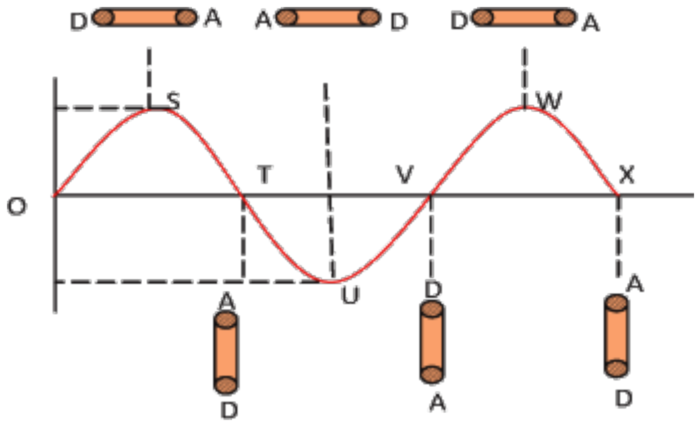


Figure 6.7a: Waveform of e.m.f. /current

The current/voltage induced in the coil is zero (0) in the positions O, T, V and X when the conductor is vertical or moving parallel to the magnetic field.

Why the induced current/voltage is an alternating one

When the coil is at the position O, the induced current is zero (0). As the coil turns about its axle steadily, the induced current/voltage increases from zero to maximum when the coil is the position S. Between S and T, the induced current/voltage decreases to zero. During the first half-turn of the coil, the induced current/voltage is positive. It flows through the coil in the direction ABCD and leaves the coil through the brush B_1 In the next half-turn of the coil the induced current/ voltage is negative as it flows in the coil in the opposite direction (DCBA) and leaves the coil through the brush B_2. The induced current/voltage alternate or changes its direction in the coil every half-turn. This is the reason it is called an alterna-ting current/voltage.

The waveform of the current/voltage produced in the coil as it rotates continuously through the magnetic field is **sinusoidal.** It can be represented by a **sine** or **cosine curves** as shown below. The mathematical representation of the curve is given by;

E = E_0 sin Ï‰t or I = I_0 sinÏ‰t

E/I = induced e.m.f.(voltage)/current at a given time.

E_0/I = Peak (maximum) value of induced E.m.f. (voltage)/ current.

Ï‰ = angular speed of the coil as it cuts the magnetic field.

The faster the coil turns the higher the peak value of the induced e.m.f. (voltage)/current.

Direct current generator

Direct current generator produces electric current, which flows in one direction only although the size or magnitude varies. An a.c. generator is converted to a d.c. generator by replacing the **slip-rings** with a **split-ring commutators.** The function of the split-ring commutator is to *reverse the direction of the current flowing in the external circuit every half-turn of the coil.*

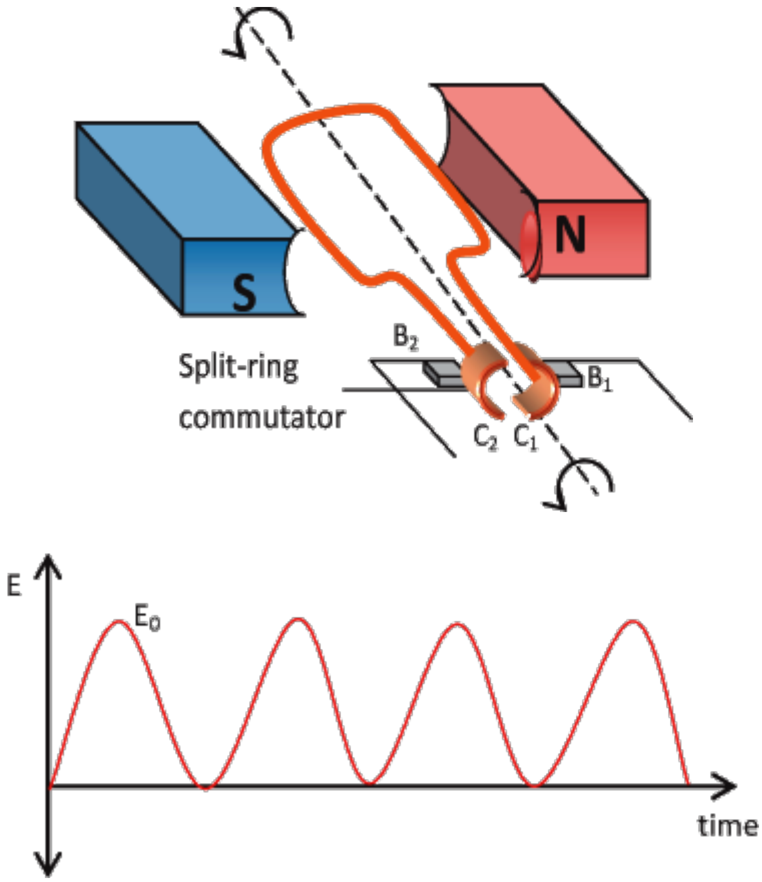


Figure 6.8b : waveform of e.m.f / current

This ensures that the current keeps flowing in the same direction as the coil completes its cycle. During the first half-turn of the coil, the brush B_1 is in contact with the commutator C_1. After half-turn of the coil, the brush B_1 changes position from C_1 to C_2 so that the brush B_1 is always connected to the positive terminal of the external circuit. The alternating current in the coil is converted to direct current flowing in the same direction. The output of a d.c. generator varies as shown in Figure 6.8b.

Factors affecting e.m.f. produced by generators

The magnitude of induced current/voltage produced by a generator can be increased if the:

(i) the **speed** of rotation of the coil is increased. The faster the coil cuts the magnetic flux the greater the current/ voltage induced in it.

(ii) the **number of turns** in the coil is increased.

(iii) a **stronger magnet** is used in place of a weak one.

(iv) the **coil** is wound on a laminated **soft-iron core.**

Measurement of a.c. current

Alternating current changes in both magnitude and direction. To measure its magnitude, a meter whose working principle does not depend on the direction of current is required. These meters include:

(i) **The hot wire meter:** the hot wire meter uses the heating effect of current to measure current. Electric current flowing through a wire heats up the wire making it sag. The movement of the wire moves the pointer attached to it. It is suitable for measuring a.c. current since heating of the wire does not depend on the direction of current.

(ii) **The moving-iron meter:** the moving-iron meter uses the force of repulsion or attraction between two iron rods to measure a.c. current. When current flows through the meter the iron rods are magnetized with the same poles repelling or attracting each other. The meter therefore measures current irrespective of the direction of the current.

(iii) **Moving-coil meter with a rectifying circuit:** the rectifier changes the direction of current so that it flows in the same direction. This helps the meter measure both a.c. and d.c. current.

Summary

- **Electromagnetic induction** is the production of current or voltage in a wire or coil when it is placed in a changing magnetic field.
  The magnitude of the induced current or voltage (e.m.f.) depends on:
- relative speed between the conductor and the magnet;
  â€¢the strength of the magnet;
  â€¢the size or length of the conductor.
- **The laws of electromagnetic induction**
- **Faradayâ€™s law:** Current/voltage are induced in a coil anytime the magnetic flux linking it is changed; the magnitude of the induced current/voltage is proportional to the rate of change of magnetic flux linking the coil.
- **Lenzâ€™s law:** The direction of induced current/voltage is such that it opposes the change or motion producing it.
- **Eddy current** is a circulating current induced in a metal disc or plate moving in a magnetic field. Eddy current is reduced by laminating metal disc to increase the resistance of the disc to flow of eddy current.
- **A generator** is a machine that changes the mechanical work done in rotating a coil in magnetic field to electrical energy. The two types of generators are: alternating current generator and direct current generator.
- The **alternating current (a.c.) generator** generates current or voltage (e.m.f.) which changes continuously in both magnitude and direction. The change in the direction of current is achieved by slip-rings.
- **Direct current generator** produces electric current which flows in one direction only although the size or magnitude varies. Current is kept flowing in one direction by using split-ring commutators.
- An a.c. generator is converted to a d.c. generator by replacing the slip-rings with a **split-ring commutator.**

Practice Questions 6a

1.E.m.f. is induced in a conductor moving in a magnetic field.

(a)State the factors that determine the magnitude of induced e.m.f.

(b)State the direction the conductor will move relative to the magnetic field to induce a maximum e.m.f. in the conductor.

(c)State the effect of increasing the speed of the conductor on the induced e.m.f.

2.(a) State Faradayâ€™s law of electromagnetic induction.

(b)Describe an experiment to show that current is induced in a conductor when it is moved in a magnetic field.

(c)A straight conductor of length 0.4 m is moved in a magnetic field of flux density 0.9 T. Calculate the magnitude of maximum induced e.m.f. in the conductor when it is cutting through the magnetic field with a speed of 30 m s^{-1}.

3.(a) State Lenzâ€™s law of electromagnetic induction.

(b)Explain how Lenz law of electromagnetic induction illustrates the law of energy conservation.

(c)An e.m.f. of 12V is induced in a wire of total length l when it cuts through a magnetic field with a speed of 100 ms^{-1}. Find the length of the wire if the magnetic flux density is 0.8T.

4.(a) What is eddy current?

(b)Explain how eddy current can be reduced.

(c)State two: (i) uses of eddy current;

(ii) disadvantages of eddy current.

5.(a) State the laws of electromagnetic induction.

(b)Make a well labelled diagram of a simple a.c. generator and explain how it works.

(c)State how the efficiency of a generator can be improved.

(d)State two ways energy may be lost in practical generators.

6. (a) Describe a simple a.c. generator and explain how it can be changed to a d.c. generator.

(b) Explain why the output of an a.c. generator is an alternating one.

(c) Sketch the waveform of the output e.m.f. show on your sketch, the peak value of e.m.f. and explain why the maximum e.m.f. occurs at that point.

7. (a) Draw a labelled diagram of simple direct current generator.

(b) Explain how the alternating current produced in the coil (armature) is changed to direct current in the external circuit.

(c) Explain why the armatures of practical generators are laminated.

9. Name two meters which can be used to measure alternating current.

STEPPING UP AND STEPPING DOWN VOLTAGES

OBJECTIVES

At the end of the topic, students should be able to:

- →explain self-inductance and mutual inductance;
- →explain the principle of a transformer;
- →state the use of induction coils and transformers;
- →explain why the cores of the induction coil and transformer are laminated;
- →explain why it is preferred to have a high voltage instead of high current transmission over a long distance;
- →solve simple problems on power losses.

Self-inductance (L)

A changing magnetic field will induce current or voltage (e.m.f.) in a coil or conductor. This is called **inductance.**

When an electric current flows through a coil or solenoid, magnetic field is produced around it. If the current flowing in the coil is changed, the magnetic field linking it also changes. The changing magnetic field of the coil induces a current/voltage (e.m.f.) in the same coil.

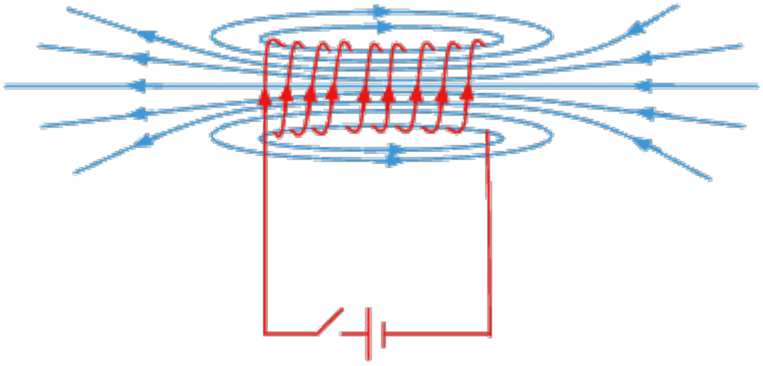


Figure 6.9 : Self-inductance

The direction of induced voltage (e.m.f.) is such that it opposes the change in current producing it (Lenzâ€™s law). It is therefore, called **back e.m.f.** or **self-induced e.m.f.** The back e.m.f. is proportional to the rate at which the current flowing through the coil is changing.

Self induced e.m.f. or back e.m.f. = Self inductance × Rate of change of current

$$E = -L\frac{dI}{dt}$$

The induced e.m.f. in the coil is due to the changing magnetic field produced by current changing in the same coil. This property of the coil inducing e.m.f. in itself is called **self-inductance.**

Self-inductance is the ability of a coil to induce a back e.m.f. in itself when the current flowing through it is changing.

The unit of self-inductance (L) is Henry (H).

A coil has a self-inductance (L) of 1H if an e.m.f. of 1V is induced in it when a current of 1A flows through the coil for 1 second.

Inductors or chokes

An inductor or choke is a coil of wire wound on a laminated soft-iron core. The function of a choke or inductor in a circuit is to oppose or choke a changing current. A choke has an inductance (L) measured in Henry (H).

When current flows through an inductor, it produces magnetic field around itself. Energy is given by the current and stored in a magnetic field of the inductor. The energy stored in an inductor is given by:

$$W = \frac{1}{2} L I^2$$

W = energy stored in the inductor in joules (J)
L = inductance of the inductor in Henry (L)
I = current passing through the inductor.

Worked examples

1. Calculate the e.m.f. induced in a coil of inductance 0.05 H when the current flowing through it is changing at the rate of 10,000 A s^{-1}.

Solution

$$E = -L \frac{dI}{dt}$$

E = induced e.m.f.
L = inductance of the coil = 0.05 H

$\frac{dI}{dt}$ = rate of change of current = 10,000 A s^{-1}.

$\therefore$ E = 0.05 × 10,000 = 500 V.

2. A coil of inductance 0.5 H takes a current of 10 A from a source. Calculate the energy dissipated by the coil.

Solution

$$W = \frac{1}{2} L I^2 = \frac{1}{2} \times 0.5 \times 10^2 = 25\ J$$

3. A current of 10 A flowing through an inductor dissipates an energy of 100 J, what is the inductance of the inductor?

Solution

$$L = \frac{2W}{I^2} = \frac{2 \times 100}{10^2} = 2.0\ H$$

Mutual induction

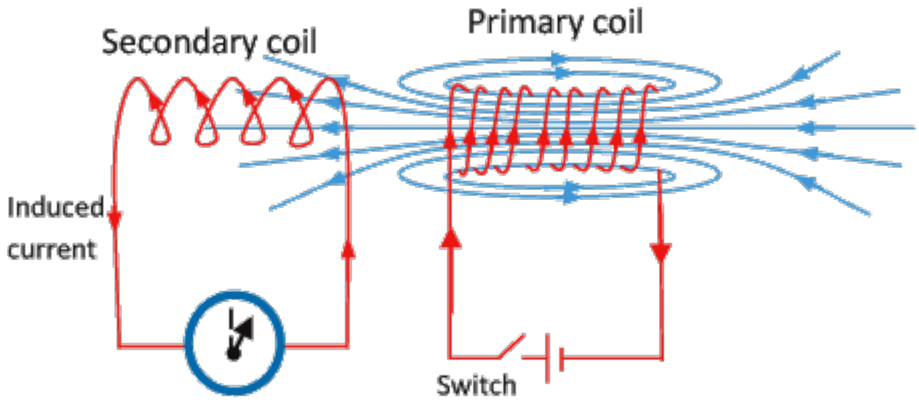


Figure 6.10 : Mutual inductance

If two coils are close to each other, when the current flowing in one coil changes; the coil produces a changing magnetic field. The changing magnetic field produced by first coil links the second coil to induce current in it. This is known as **mutual induction.**

Mutual inductance is the ability of a coil to induce current / voltage in another coil by changing the current flowing in it.

The coil, which produces the magnetic field, is called the **primary coil.** The coil in which current is induced as result of changing magnetic field is called the **secondary coil.**

Current is induced in the secondary coil by switching on or off the current in the primary coil. If the current is switched on in the primary circuit, the magnetic field grows fast, links the secondary coil, and induces current in it. The galvanometer deflects for a short time, indicating that current is induced in it. When the current is switched off in the primary coil, the magnetic field decays fast. The fading magnetic field links the secondary coil to induce current in it in the opposite direction. **Current is induced in the secondary coil anytime the current flowing in the primary coil is changed.**

Higher current is induced in the secondary coil if the rate of the growth or decay of the magnetic field is increased and the number of turns in the secondary coil increased.

Continuous changing of the magnetic field is produced by the primary coil if the current flowing through it is changed continuously. This is achieved by using alternating current to produce a continuous changing magnetic field in the primary coil.

Uses of mutual induction

The **induction coil** and the **transformer** use mutual inductance between two coils to generate high voltage. The induction coil uses direct current to produce higher voltage while transformer uses alternating current to produce higher/lower voltage.

The induction coil

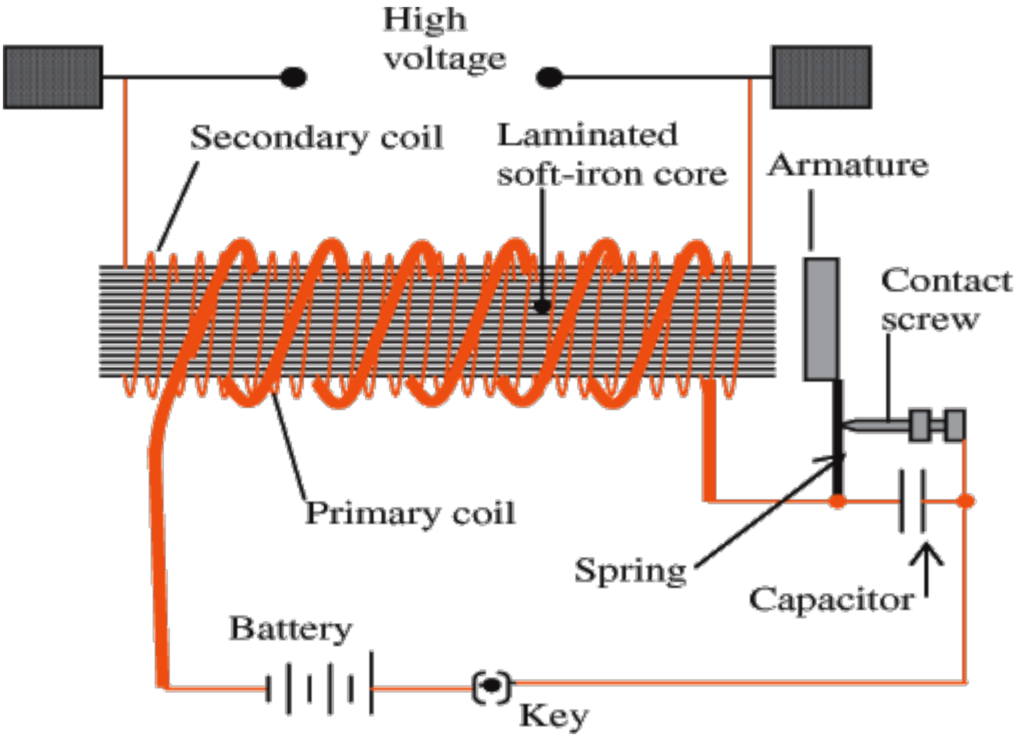


Figure 6.11 : Induction coil

An induction coil has two coils wound on a laminated soft-iron core. A primary coil of few turns of thick copper wire is wound on the soft-iron core. The secondary winding is thin copper wire of many turns wound on the primary coil. When the switch in the primary coil is closed, current flows in it to magnetize the soft-iron core. The electromagnet formed by the soft-iron core because of current flowing in the primary coil attracts the armature and breaks the circuit. The laminated soft-iron core demagnetizes and the spring pulls the armature back to complete the circuit. Current again flows through the primary coil and the process is repeated. The continuous make and break contact of the armature makes it to vibrate continuously.

Each time the contact is broken, the soft-iron core loses its magnetism and the magnetic field fades. The fading magnetic field induces a high voltage in the secondary coil. The high voltage between the terminals of the secondary coil produces a spark across the gap. The induction coil therefore produces high voltage from a low voltage at the primary coil

A capacitor is connected across the contact point for two reasons to:

- reduce the spark produced during the make and break contact.
- allow for rapid decay of the magnetic field when the circuit is broken. The rapid decay of magnetic field increases the size of induced voltage in the secondary coil.

The induction coil is used anytime a high voltage is needed to produce a spark between two terminals. This is used in car ignition system, radio transmitters and electric discharge tube like X-ray tubes where very high voltage is required.

The transformer

A transformer is a device, which changes the size of alternating current/voltage applied to the primary coil to a higher or smaller alternating current/voltage in the

secondary coil.

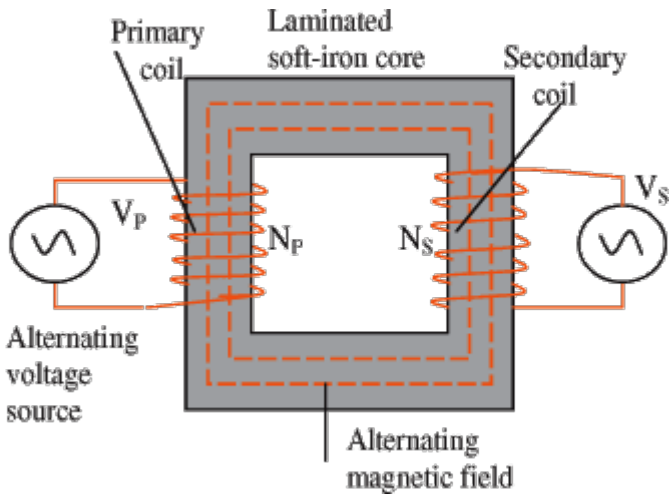


Figure 6.12 : Transformer

A transformer has two coils; the **primary coil** and the **secondary coil** each wound on a laminated soft-iron core. The laminated soft-iron core magnetically links the two coils. The primary coil is connected to the alternating current source to be stepped up or down while the secondary coil is connected to the load.

When an alternating current flows in the primary coil, it produces an alternating magnetic field in the iron core. The alternating magnetic field links the secondary coil and induces in it an alternating voltage or current.

The size of induced voltage/current in the secondary coil is proportional to the number of turns of wire N_S in the secondary coil and the rate at which the magnetic field is changing. The size of the induced voltage in the secondary coil according Faradayâ€™s law of electromagnetic induction is:

$$V_S = -N_S \frac{d\phi}{dt} \text{..........} i$$

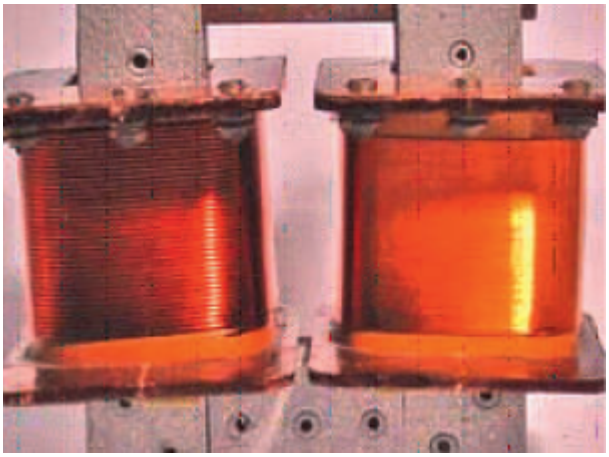
The induced voltage in the primary coil is proportional to the number of turns of wire N_P in the primary coil.

$$V_P = -N_P \frac{d\phi}{dt} \text{..........} ii$$

Dividing equations *(i) and (ii)* leads to:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

V_S = induced voltage in the secondary coil
V_P = induced voltage in the primary coil
N_S = number of turns in the secondary coil
N_P = number of turns in the primary coil



Efficiency of transformers

Transformers are highly efficient machines. Efficiency of practical transformers is close to 100%.

$$Efficiency = \frac{Power\ output}{Power\ input} \times 100\%$$

$$Efficiency = \frac{I_S V_S}{I_P V_P} \times 100\%$$

For ideal transformers, there is no loss of power or energy; therefore the transformer is 100% efficient. The power input is equal to the power output for ideal transformer.

$$I_P V_P = I_S V_S$$

$$\frac{V_S}{V_P} = \frac{I_P}{I_S}$$

Step up and step down transformers

(a) Step up transformers:

$\frac{V_S}{V_P}$ = voltage ratio, $\frac{N_S}{N_P}$ = turns ratio

and $\frac{I_P}{I_S}$ = current ratio.

A step up transformer has more turns in the secondary coil than the primary coil. The turn ratio is greater than one; therefore, the secondary voltage is more than the primary voltage.

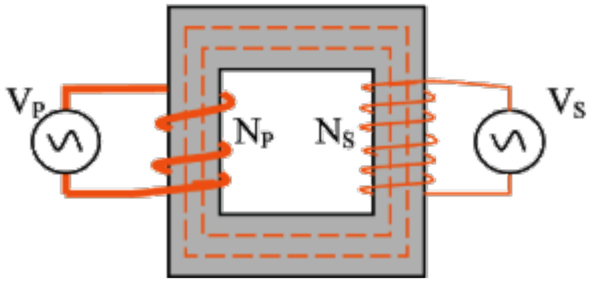


Figure 6.13 : Step up transformer

Stepping up the voltage by a certain ratio means that the current is stepped down by the same ratio.

$$\frac{N_S}{N_p} > 1 \text{ or } N_S > N_P \text{ but } \frac{I_P}{I_S} > 1 \Rightarrow I_p > I_s$$

(b) Step down transformers:

Step down transformers have less number of turns in the secondary coil than the primary coil. The ratio $\frac{N_S}{N_P} < 1$, therefore the secondary voltage V_S is less than the primary voltage V_P. The current in primary coil is less than the current in the secondary coil.

$$\frac{I_P}{I_S} < 1 \Rightarrow I_p < I_s$$

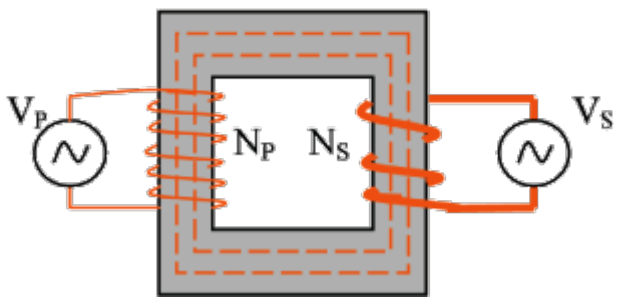


Figure 6.14 : step down transformer

Stepping down the voltage means that the current is stepped up by the same ratio.

Energy losses in transformers

Practical transformers are never 100% efficient. They can be designed to be nearly 100% efficient by laminating the soft-iron core and using low resistant wires in winding the coils. However, energy is lost in a transformer in one of the following ways:

- **I^2Rt loss or heating in the resistance of the coils of the primary and secondary.**
  Current flowing in the primary and secondary coils produces heat, which lowers the efficiency of the transformer. I^2Rt loss is reduced by using low resistant wires like thick copper wires in winding the coils of the transformers.
- **Eddy current loss in the core of the transformers.**
  Energy is wasted as heat in the core of the transformers because of the eddy current

induced in it by the changing magnetic field. Energy loss due to the circulating eddy current is reduced by laminating the core.

- **Hysteresis loss**

  Energy is wasted as heat in the core of a transformer due to the reversal of magnetic field in the core. Hysteresis loss is reduced by using soft magnetic materials with high magnetic permeability.

- **Leakage of magnetic flux from the core of the transformer:**

  Not all the magnetic flux produced by the primary coil links the secondary the coil. Some leak out of the core before reaching the secondary coil.

Worked examples

1. A step down transformer is used to operate a CD player rated 12V, 60 watts. If voltage input to the transformer is 240V calculate the:
   (a)current flowing in the secondary coil;
   (b)turn ratio of the transformer;
   (c)number of turns in the secondary coil if the number of turns in the primary coil is 40,000.

Solution

$$(a)\ Current = \frac{Power}{Voltage} = \frac{60}{12} = 5A$$

$$(b)\ \frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{12}{240} = \frac{1}{20}$$

$$N_S : N_P = 1:20$$

$$(c)\ \frac{N_s}{N_p} = \frac{1}{20}$$

$$N_S = \frac{N_P}{20} = \frac{40,000}{20} = 2000\ turns$$

2.A step down transformer has 500 turns in the secondary coil and 10,000 turns in the primary coil. When it is connected to a video player it draws a current of 5 A, calculate the current flowing in the primary coil if the transformer is 100% efficient.

Solution

$$\frac{I_p}{P_S} = \frac{N_S}{N_P} \qquad \frac{I_p}{5} \quad \frac{500}{10,000}$$

$$I_P = \frac{500}{10,000} \times 5 = 0.25\,A$$

3.A transformer is used to step up a 240 V supply to 6000 V. If the current in the primary coil is 15 A, calculate the current in the secondary coil if the transformer is 90% efficient.

Solution

$$Efficiency = \frac{I_S V_S}{I_P V_P} \times 100\%$$

$$90 = \frac{I_S \times \ 6000}{15 \times 240} \times 100\%$$

$$I_S = \frac{90 \times 15 \times 240}{6000 \times 100} = 0.54A$$

Transmission of electrical power over long distances

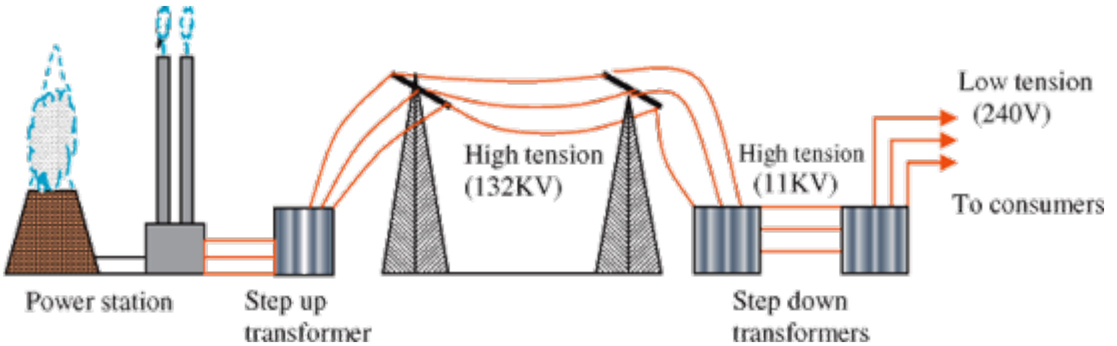


Figure 6.15 : Transmission of power at high voltage and low current

When electrical power is transmitted from city to city, power/energy is lost along the transmission line because of the heating of the wires. The energy lost or dissipated in the wires is given by:

Energy lost (W) = I^2Rt.

Two possible ways electrical power or energy can be transferred from power generating station to other parts of the country are:

- Power transmission at low voltage and high current;
- Power transmission at high voltage and low current.

When power is transmitted at high current and low voltage, energy lost along the transmission line is very high due to the heating of the wires. To conserve energy, electrical power is transmitted at high voltage and low current. **Transmission of electrical power at high voltage and low current is referred to as high-tension transmission.**

The voltage produced by the alternator at the power generating station is about 25,000 V or 25 KV. This is too low; therefore, a step up transformer is used to step up the voltage to 132,000 V (132K V) or more before transmitting it to far cities on grid. The high voltage is stepped down at the other end of the transmission line using a step down transformer. The stepped down voltage is then distributed to consumers.

1. Advantages of high-tension transmission

1. Electrical power can be transmitted over long distances without much loss of power at high voltage, low current.
2. Transformers can be used to step up or step down voltages easily without power or energy loss. This is the reason power is transmitted from one to another using alternating current.
3. Cables with small thickness can be used to transmit power over long distances since the current flowing in it is small; therefore, the cost of laying the power lines is reduced.

Summary

- **Self-inductance** is the ability of a coil to induce a back e.m.f. in itself when the current flowing through it is changed The unit of self-inductance (L) is Henry (H). The energy of an inductor is given by:

$$W = \frac{1}{2}LI^2$$

W= energy stored in the inductor in joules (J).
L = inductance of the inductor in Henry (L).
I = current passing through the inductor.

- **Mutual inductance** is the ability of a coil to induce current /voltage in another coil by changing the current flowing in it.
- **An induction coil** has two coils wound on a laminated soft-iron core. A primary coil of few turns of thick copper wire is wound on the soft-iron core. The secondary winding is thin copper wire of many turns wound on the primary coil.
- **A transformer** is a device, which changes the size of alternating current/voltage applied to the primary coil to a higher or smaller alternating current/voltage in the secondary coil.
- Transmission of electrical power at high voltage and low current is referred to as **high tension transmission.**

Practice Questions 6b

1. (a) What is self-inductance?

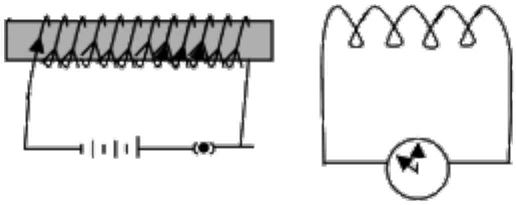
   (b) Explain why e.m.f. is induced in coil when the current flowing through it is changed.

   (c) An inductor of inductance 2.0 H is connected to an electric circuit. Calculate the energy stored in the inductor when the current is 5 A.

2. (a) What is a back e.m.f.?

   (b) A coil of inductance 0.5 H is used in radio tuning circuit. Calculate the e.m.f. induced in the coil at a time the current is changing at the rate 100 A s^{-1}.

3. (a) Explain what is meant by mutual induction?

(b) 

The diagram above shows an electromagnet placed close to a coil with a galvanometer connected to its terminal. Use the diagram to answer the questions:

(i) Explain why current is induced in the coil when the key is switched on or off.

(ii) State **two** ways to increase size of the induced current in the coil.

4. (a) What is a transformer?

(b) Draw a labelled diagram of transformer and explain how it works.

(c) State **three** ways energy may be lost in a transformer. Explain how the loss of energy may be reduced.

5. (a) Explain what is meant by a *step down transformer* and *turn ratio.*

(b) Draw a labelled diagram of a step down transformer and explain why the voltage is stepped down.

(c) The transformer in a disc video decoder is used to step down 240 V supply to 12 V. If there are 2400 turns in the secondary coil find:

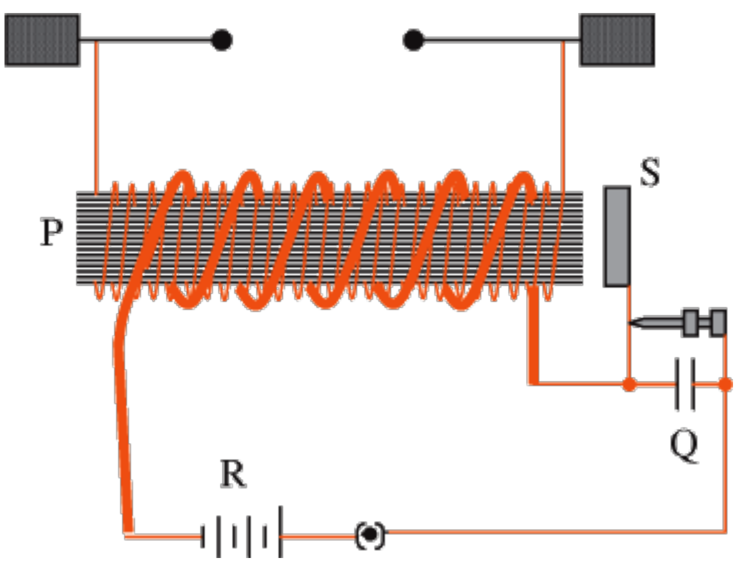
 (i) the turn ratio of the transformer;

 (ii) the number of turns in the primary coil.

6. (a) The diagram below shows an induction coil. Identify the labelled parts.

(b) Explain why P is laminated.

(c) state two functions of Q.



7. (a). With the help of good labelled diagram describe and explain how a step up transformer works.
   (b) Explain why the transformer core is laminated.
   (c) An ideal step-up transformer has a voltage ratio 20:1. If there are 500 turns of wire on the primary coil and the current flowing in the secondary coil is 2.5 A, calculate:
      (i) the current flowing in the primary coil;
      (ii) the number of turns of wire in the secondary coil.
8. (a) What is high tension transmission?
   (b) Explain why power is transmitted over long distances at low current and high voltage.
   (c) state two advantages of transmitting power at low current and high voltage.

Past Questions

1. Which of the following reduce(s) the effect of the back e.m.f generated in the primary coil of an induction coil?
   I. The capacitor in the circuit.
   II. The make and break contact in the circuit.
   III. The ratio of turns in the secondary to that in the primary.
   A. I only.
   B. II only.
   C. I and II only.
   D. II and III only.
   E. I, II and III.

WAEC

2. A house is supplied with 240 V a.c. mains. To operate a door bell rated at 8 V, a transformer is used. If the number of turns in the primary coil is of the transformer is 900. Calculate the number of turns in the secondary coil of the transformer.
   A. 30
   B. 240
   C. 248
   D. 450
   E. 1248

WAEC

3. An induction coil is generally used to
   A. rectify an alternating current.
   B. produce a large input voltage.

C. smoothen a pulsating direct current.

D. modulate an incoming radio signal.

E. produce a large output voltage.

WAEC

4. Which of the following is **not** a part of an a.c. generator?

A. Carbon brushes

B. Slip rings

C. Commutator

D. Field magnet

E. Armature

WAEC

5. A magnet is inserted into a coil of wire. On which of the following does the induced e.m.f. in the coil depend?

I. Number of the turns in the coil.

II. Strength of the magnet.

III. Speed with which the magnet is inserted into the coil.

A. I only.

B. II only.

C. III only.

D. I and II only.

E. I II and III

WAEC

6. The current in the primary coil of a transformer is 2.5 A. If the primary coil has 50 turns and the secondary 250 turns. Calculate the current in the secondary coil. [Neglect energy losses in the transformer.]

A. 0.2 A

B. 0.5 A

C. 2.5 A

D. 5.0 A

E. 12.5 A

WAEC

7 Lenzâ€™s law of electromagnetic induction is essentially a statement of the

A. inverse-square law of gravitation.

B. inverse-square law of magnetism.

C. inverse-square law of electrostatics.

D. law of conservation of momentum.

E. law of conservation of energy.

WAEC

8. The voltage and the current in the primary of a transformer are 200 V and 2A respectively. If the transformer is used to light ten 12 V, 30 W bulbs, calculate its efficiency.

A. 100%

B. 90%

C. 75%

D. 50%

WASSCE

9. A device used to prevent wearing away of the make-and-break contacts of an induction coil is called a/an

A. fuse.

B. electroscope.

C. resistor.

D. capacitor.

WASSCE

10. A transformer has 400 turns and 200 turns in the primary and secondary windings respectively. If the current in the primary and secondary windings are 3A and 5A respectively, calculate the efficiency of the transformer.

A. 85.0%

B. 83.3%

C. 37.5%

D. 30.0%

WASSCE

11. The direction of current induced in a straight wire placed in a magnetic field is determined by using

A. Flemingâ€™s right hand rule.

B. Maxwellâ€™s screw rule.

C. Faradayâ€™s law.

D. Lenzâ€™s law.

WASSCE

12. When electric power is transmitted over long distances, the voltage is stepped up so that

A. the resistance of the wire may be increased proportionately to the potential difference.

B. the time of transmission between generating and receiving stations may be reduced.

C. there is increased current to produce brighter light.

D. the rate of electrical consumption is increased.

E. the energy waste may be minimized as the current is lowered.

NECO

13. The electric supply from Kanji dam is transmitted at high voltages of the order of hundreds of kilovolts but is converted to domestic use of about 220 V by

A. commutators

B. transistors

C. valves and diodes

D. rectifiers

E. transformers.

JAMB

14. High tension (H.T.) transmission means

A. to transmit a given amount of power, the tension in the conducting wire must be high.

B. heat is not lost when current is passed through a conductor.

C. heat is gained when a given amount of power is transmitted.

D. a big transformer is required to transmit power.

E. transmission of power at low current and high voltage.

JAMB

15. Which of the following ammeters may be used to measure alternating currents?

I. Moving-coil ammeter

II. Moving-iron ammeter

III. Hot-wire ammeter

A. I and II only.

B. II and III only.

C. I and III only.

D. I, II and III.

JAMB

16. The iron core of an induction coil is made from bundles of wire so as to

A. minimize eddy-currents.

B. generate eddy-currents.

C. prevent sparking at the contact breaker.

D. get the greatest possible secondary voltage

JAMB1998

17. In Flemingâ€™s right hand rule, the thumb, the forefinger and middle finger if held mutually at right angles represent respectively

    A. motion, the field and the induced current.
    B. induced current, the motion and the field.
    C. field, the induced current and the motion.
    D. induced current, the field and the motion.

JAMB

18. Energy losses due to eddy currents are reduced by using

    A. low resistance wires.
    B. insulated soft iron wires.
    C. few turns of wire.
    D. high resistance wires

JAMB

19. Which of the following devices may be used to step up the voltage in a d.c. circuit?

    A. A step up transformer.
    B. A d.c. generator.
    C. A wattmeter.
    D. An induction coil.

JAMB

20. From the generating station to each substation, power is transmitted at a very high voltage so as to reduce

    A. eddy current.
    B. hysteresis loss.
    C. heating in the coils.
    D. magnetic flux leakage

JAMB

21. (a) State the laws of electromagnetic induction.

    (b) (i) Describe a simple experiment to show how an induced e.m.f. can be produced.

    (ii) State **two** factors on which the magnitude of the induced e.m.f. depends.

WAEC

22. (a) State Faradayâ€™s law of electromagnetic induction.

    (b) State **one** advantage of a.c. over d.c. power transmission.

    (c) (i) Draw and label a simple diagram of a step up transformer and explain how it works.

(ii) State **three** ways by which energy is lost in a transformer and how they can be minimized.

(d) A transformer is used to light a lamp rated at 250 V, 100 W from a 25-V a.c. mains supply. Calculate the

(i) efficiency of the transformer if the current in the primary circuit is 5A.

(ii) peak value of the output voltage.

WAEC

23. (a) Draw a simple labelled diagram illustrating the principle of a step down transformer and explain how it works.

(b) State **three** ways by which energy is lost in a transformer and how they can be minimized.

(c) If a transformer is used to light a lamp rated at 60 W, 220 V from a 4400 V a.c. supply, calculate the

(i) ratio of the number of turns of the primary coil to the secondary coil in the transformer;

(ii) current taken from the mains circuit if the efficiency of the transformer is 95%.

WAEC

24. (a) Draw a simple labelled diagram illustrating the principle of a step down transformer and explain how it works.

(b) (i) State **three** ways by which energy is lost in a transformer.

(ii) Describe how the losses can be minimised.

(c) (i) Explain the term â€˜ eddy currentsâ€™.

(ii) State two devices in which eddy currents are applied.

NECO

25. (a) State the laws of electromagnetic induction.

(b) Draw a labelled diagram of a simple d. c. generator and explain how it works.

(c) State **three** methods by which higher e. m.f. could be obtained from the generator.

WAEC

26. (a) State the laws of electromagnetic induction.

(b) Explain how one of the laws illustrates the principle of conservation of energy.

WAEC

27. (a) State Faradayâ€™s law of electromagnetic induction.

(b) Draw a labelled diagram of an induction coil and explain how it works.

(c) How is the effect of eddy currents minimized in the coil?

(d) State two reasons why a capacitor should be included in the primary circuit of the coil.

(e) State **three** uses of induction coil.

WAEC