How are fields used to move electrical energy?

Reference: Heinemann Physics 12 4th Edition Chapter 4 Pages 107 – 131

Physics with Synno – Electrical Energy – Lesson 1

EP.1 **Magnetic Flux**

Video: Magnetic flux and magnetic flux density for beginners

Magnetic flux is the concentration of the magnetic field. The flux through an area A, at an angle to a field of flux density **B** , is given by

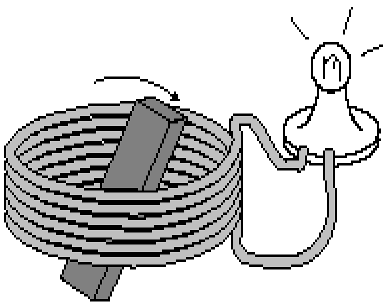
$$\Phi = B\ A\cos\phi$$

Where ϕ is the angle between the magnetic field and the normal to the surface of the area

The unit of magnetic flux is the Weber (Wb)
Note 1.0 Tesla equals 1.0 Weber per square meter,
i.e. 1.0 T = 1.0 Wb/m^2

To change the magnetic flux we can

move a wire through a constant field	or	rotate a loop of wire in a constant field	or	change the strength of the magnetic field



The creation of an electric current in a conductor by changing the magnetic flux is called Electromagnetic Induction. The effect was discovered by the British physicist Michael Faraday and led directly to the development of the rotary electric generator, which converts mechanical motion into electric energy.

Devices that utilise Electromagnetic Induction are called Generators, for the simple reason that they "generate electricity".

In fact, generators are opposite to D.C. motors in that they convert mechanical energy (moving a magnet, or a coil of wire) into electrical energy (the induced current.)

When a car is being driven, the engine recharges the battery continuously using a device called an alternator, which is really just a generator like the one shown to the left, except that the coil rotates while the permanent magnet is fixed in place.

EP.2 Electromagnetic Induction

Video: Electromagnetic Induction

EP.2.1 Induced Current

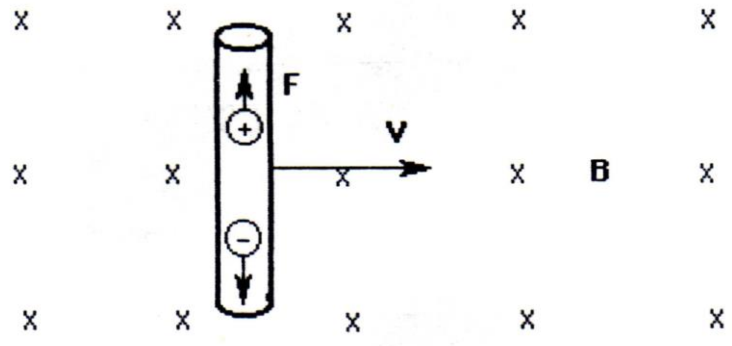
In the previous area of study, we saw that a charge moving through a magnetic field experiences a force whose magnitude is given by

$$F = vBq \sin\phi$$

If the charge is moving at right angles to the field then the magnitude of the force is

$$F = vBq$$

Consider a conductor moving at right angles to a magnetic field. A conductor is filled with positive and negative charges each of these will experience a force (direction given by the right-hand rule). This is shown in the diagram below.



Thus an electric current will be produced and $I \;\alpha\; \dfrac{\Delta\Phi}{\Delta t}$

The direction of the induced current is given by the **right-hand push rule**. Thumb in direction of **v,** Fingers in the direction of **B**, Palm gives direction of current (force on positive charges and they move in that direction).

No current is produced when the wire moves parallel to the field.

Example.

A student places a horizontal 5 cm square coil of wire into a uniform vertical magnetic field of 0.1 T.

a How much flux cuts through the coil?

b She then pulls the coil out of the field at such a rate that it takes 1 s for the coil to lose all the flux. While the coil is coming out of the field, she finds that a current of +2 mA is registered on the ammeter connected to it. If she puts the coil back into the flux at the same rate, what current will she observe?

c If she pulls it out again, but twice as fast as before, what current will be induced?

d Now she steadily rotates the loop while it is fully in the field in such a way that it takes 2 s to rotate through 180°. Describe the current that will be induced.

Solution

a $\Phi_B = BA_\perp$

$= 0.1 \times 0.05^2$

$= 2.5 \times 10^{-4}$ Wb (1 T m^2 = 1 Wb)

b The same current but in the opposite direction: –2 mA.

c $I_{in} \propto \Delta\Phi_B/\Delta t$. This time Δt was halved so the current will be doubled. The current will be +4 mA.

d The total change of flux that occurs in the 2 s is –5 · 10–4 Wb (as the flux changes from +2.5 · 10–4 to –2.5 · 10–4 Wb). The average rate of this flux change is the same as in part a (–2.5 · 10–4 Wb s–1), so the average current will again be >2 mA. However, this will not be uniform. It will be a maximum (>2 mA) as the loop passes through the vertical. (Although the flux is momentarily zero when the coil is vertical, this is the point of maximum flux *change*.)

EP.2.2 Induced EMF

When a current is induced an EMF is also induced. One of the scientists to work in this area was Michael Faraday, from his experiments he concluded that the strength of the induced EMF depended on three things:

1. the speed of the coil or magnet
2. the strength of the magnetic field
3. the number of turns in the coil.

These facts lead him to state a law, which is summarised in the following formula (Faraday's Law of induction)

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

Where N = number of turns of wire

$\Delta\Phi$ = change in magnetic flux (i.e. $B_2A_2 - B_1A_1$)

Δt = time taken

Consider a conductor moving with constant velocity **v** then

$\mathbf{F}_{applied} = -\mathbf{F}_{magnetic}$

$= -I\,L\,\mathbf{B}$

If we then assume that there is no energy loss, we have

mechanical energy supplied = electrical energy generated

$$F \times d = EMF \times q$$

$$-\boldsymbol{I\,L\,B} \times \boldsymbol{v\,t} = \boldsymbol{EMF\,I\,t}$$

Hence

$$EMF = -B\,L\,v$$

Example

What is the maximum EMF which would be induced across the wings of a Boeing 747 with a wing span of 64 m, flying at 990 km h^{-1} through the Earth's magnetic field? Take the maximum magnitude of the Earth's magnetic field as 60 ∝T.

Solution

The maximum magnitude of the induced EMF near the poles is found from **E** = vBl.

v = 990 km h^{-1}
= 990 ÷ 3.6
= 275 m s^{-1}
B = 60 μT
= 60 × 10^{-6} T
= 6 × 10^{-5} T
So:
E = vBl
= 275 × 6 × 10^{-5} × 64
= 1.06 V

Example

A student winds a coil of area 40 cm^2 with 20 turns. He places it horizontally in a vertical uniform magnetic field of 0.1 T, and connects it to a galvanometer with resistance 200 Ω.

a How much flux passes through the coil?

b If it is then withdrawn from the field in a time of 0.5 s, what would be the average current reading on the galvanometer?

Solution

a $\Phi_B = BA_\perp$. Here B = 0.1 T and $A_\perp$ = 40 cm^2 = 0.0040 m^2. Thus the flux through the coil is Φ_B = 0.1 × 0.0040 = 4 × 10^{-4} Wb.

b The average EMF induced in each turn is given by the average rate of change of flux, i.e.

$$EMF = \frac{\Delta\Phi_B}{\Delta t}$$

$$= \frac{4 \times 10^{-4}}{0.5}$$

= 8 × 10^{-4} V

Hence the total EMF generated in the coil of 20 turns will be:

$\mathbf{E}_{coil}$ = 20 × 8 × 10^{-4}
= 0.016 V

Assuming that the only significant resistance in the circuit is the galvanometer, the average induced current is given by Ohm's law:

I = VRt

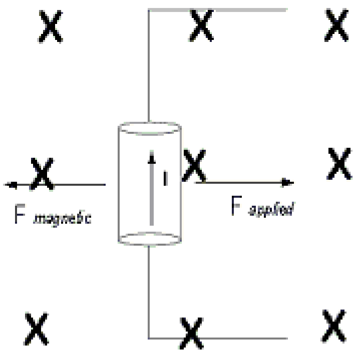
= 0.016 200

= 8 · 10^{-5} A or 80 ∝A

Note:

The flux can be changed in a number of ways.

Changing the flux by <u>moving a wire through area</u>



In the diagram, the wire is being moved to the right due to an applied force $\mathbf{F_{applied}}$.

The <u>direction</u> of the induced current is up. Why?

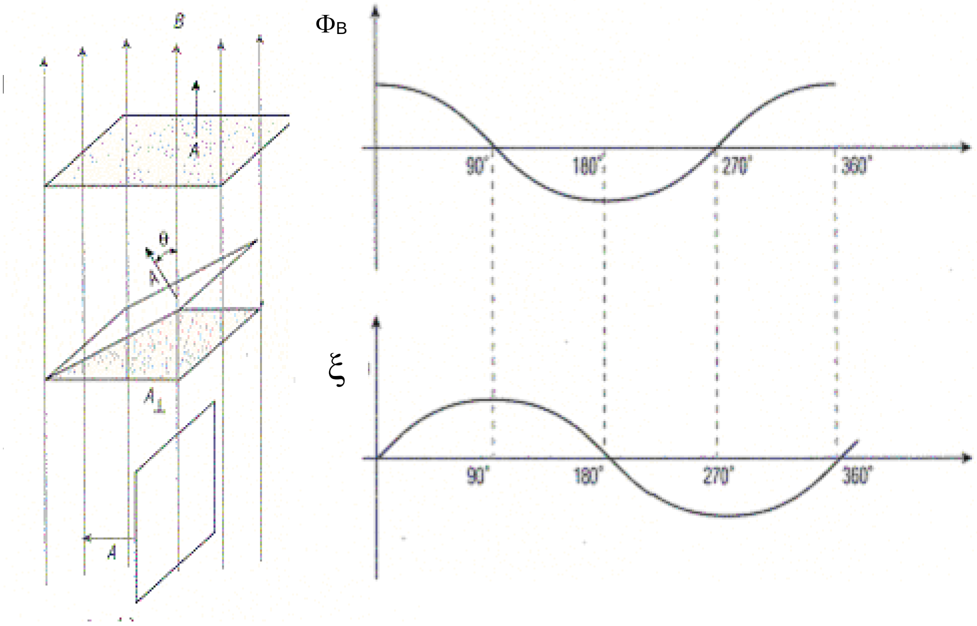
The induced current acts to create a magnetic field and associated force that will oppose the applied force.
Using the right hand rule, when

- the current flows **up**, and
- the field acts **into** the page

then the force due to the magnetic field around the wire is to the **left**.
This $\mathbf{F_{magnetic}}$ force acts to oppose the applied force, (and to attempt to stop motion.)

A current is induced in the wire only when it moves, cutting through the magnetic field i.e. perpendicular to the field. The current depends on the speed of the wire. **No current is produced when the wire moves parallel to the field.**

Changing the flux by <u>rotating a loop of wire</u>



From the graphs it is easy to see that the induced EMF

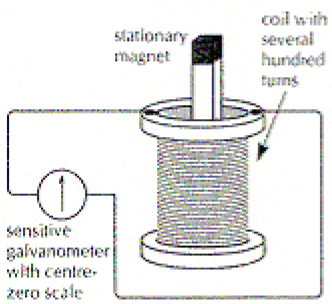
- is maximum/minimum when the flux is 0
- is 0 when the flux is a maximum/minimum

Notice that the instantaneous gradient of the flux/time graph allows the instantaneous EMF to be calculated. We can also, however, calculate the average EMF generated in any given amount of time as the average rate of change in flux in the given time.

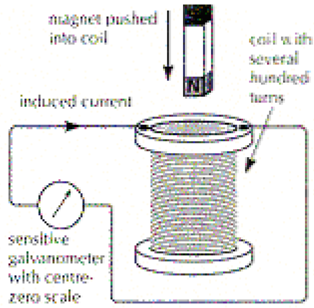
$$\xi = -\frac{\Delta\Phi_B}{\Delta t} \quad \text{hence} \quad \xi = -\frac{(\Phi_2 - \Phi_1)}{t}$$

Changing the flux by <u>changing the field strength</u>

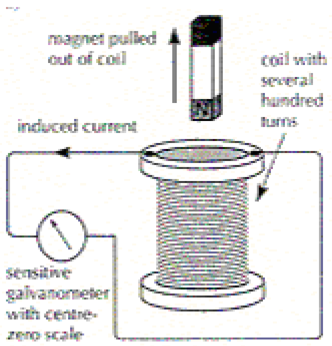
When the magnet is stationary, there is no current in the circuit



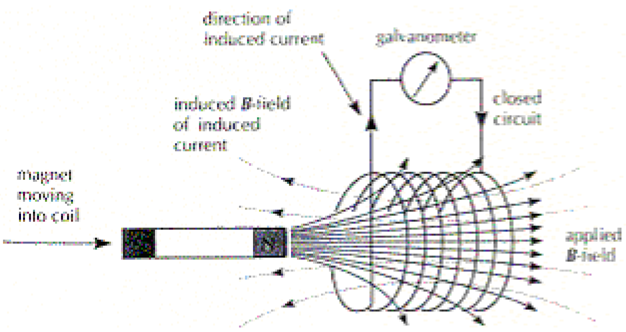
When the magnet is pushed down, the current is clockwise



When the magnet is pulled up, the current is anti-clockwise



Note: An emf (ξ) and hence a current, are induced in the solenoid when the magnet is moving into, or out of, the solenoid. The size of the emf (ξ) depends on the speed of movement and the number of turns on the solenoid, as well as the strength of the magnet.



As the north of the magnet is pushed toward the solenoid, an EMF is induced that will oppose this movement. The left end of the solenoid will act as a North Pole to repel the magnet.

After establishing this fact, we can use the right hand solenoid rule to determine the current direction that will create a north at the left end of the solenoid.

This means a conventional current direction flowing from the bottom to the top on the front side of the coil.

Text Questions: Text Page 113 Ex 4.1 All Questions
Text Page 117 Ex 4.2 All Questions