English Michael Faraday (1791 – 1867) who experimented with electric and magnetic phenomena discovered that a changing magnetic field produces an induced emf (voltage – source of electrical energy). Faraday’s law of electromagnetic induction is one of the great laws of physics. This phenomenon is the basis for many practical devices such as transformers, reading computer memory, electronic devices, alternators and generators. Without generators we could not produce large quantities of electrical energy required for our modern society to function.

Why do you often observe sparks when a plug is pulled out of a power point?

**MAGNETIC FLUX \( \Phi_B \) \( [T.m^{-2} = W\text{ webber}] \)**

A useful quantity is to consider the number of magnetic field lines crossing an area. This concept is called the magnetic flux and is illustrated and defined in figure (12).

Magnetic flux for constant B-field

\[
\Phi_B = B A \cos \theta
\]

Each point on a surface is associated with a direction, called the surface normal; the magnetic flux through a point is then the component of the magnetic field along this direction.

\[
\begin{align*}
\theta = 90^\circ & \quad \cos \theta = 1 \\
\Phi_B &= B A \\
\end{align*}
\]

\[
\begin{align*}
\theta = 0^\circ & \quad \cos \theta = 0 \\
\Phi_B &= 0 \\
\end{align*}
\]

Fig. 1. Magnetic flux when the magnetic field B is uniform over an area A.
**FARADAY’S LAW – ELECTROMAGNETIC INDUCTION**

- A changing magnetic field induces a changing electric field.
- A changing magnetic flux induces a changing electric field
- The changing electric field induces an emf in a conductor.
- In a conductor loop, the changing emf induces a current.

The above processes are known as **electromagnetic induction**.

**Lenz’s law** – the induced emf and induced current are in such a direction as to oppose the change that produces them.

**Faraday’s law** is expressed mathematically by equation (1).

\[
\varepsilon = -\frac{\Delta \Phi_B}{\Delta t}
\]

- **induced emf** \(\varepsilon\) [V]
- **magnetic flux** \(\Phi_B\) [Wb or T.m\(^2\)]
- **change in magnetic flux** \(\Delta \Phi_B\) [Wb or T.m\(^2\)]
- **small time interval** \(\Delta t\) [s]

The negative sign gives the direction of the induced emf.

More formally, Faraday’s law is

\[
\varepsilon = -\frac{d\Phi_B}{dt}
\]

The induced emf is equal to the negative of the time rate of change of the magnetic flux.

**Predict Observe Explain**

Write and sketch **your predictions** for a permanent magnet passing through a solenoid (coil):

- How do the forces on the permanent magnet change as the magnet enters and exits the solenoid?
- How does the current in the solenoid change as the magnet passes through it?
- Sketch a graph of the current vs time as the magnet passes through the solenoid.
- How do Faraday’s law and Lenz’s law apply to this situation.
**Observe** the animation of the permanent magnet as it passes through the coil windings of the solenoid. Use the right hand screw rule to verify the directions of the induced magnetic fields shown in the animation.

**Explain** – compare your predictions with your observations, and explain any discrepancies.

View the animation

The magnetic flux through a circuit can be changed in many ways – increasing the current through a coil will increase the magnetic field surrounding it; a permanent magnetic maybe moved toward or away from a circuit; the circuit itself maybe moved toward or away from a magnet; the orientation of a coil in a magnetic field can be changed. In every case, the induced emf is given by the rate of change of the magnetic flux and the direction of the emf can be determined by applying Lenz’s Law. A

When the magnetic field through a conductive loop is increasing, an electric field is induced which produced an induced emf and a resulting induced current. The emf is distributed throughout the loop (there is no positive or negative terminals to drive the current as in the emf of a battery). The direction of the electric field, induced emf and induced current are determined by using Lenz’s law and the right hand screw rule (curl of fingers – current; thumb – direction of induced magnetic field) as shown in figure (2).

Fig. 2. Changing magnetic flux through a coil.
Faraday experimented with a Faraday ring as shown in figure (3). A changing magnetic flux in the iron ring induced a current in the galvanometer coil. The changing magnetic flux is produced only when the switch is opened or closed. There is no deflection of the galvanometer pointer when a steady current is flowing in the coil on the left.

Fig. 3. Faraday’s ring.

Two coils are placed on top of each other as shown in figure (4). The lower coil (P) has a changing current through it. The upper coil (S) has a current induced in it because of the changing magnetic flux produced by the changing current in coil P. The direction of the induced magnetic field and induced current for coil S is determined by Lenz’s law and the right hand screw rule.

The induced B-field opposes the increase in the B-field produced by coil P.

The induced B-field opposes the decrease in the B-field produced by coil P.

Fig. 4. The coils placed on top of each other.
Why do you often observe sparks when a plug is pulled out of a power point? When the plug is pulled quickly away from a powerpoint socket when turned on, the current abruptly drops to zero and the magnetic field due to the current collapses. This changing magnetic flux produces an emf that tries to maintain the original current, resulting in a spark at the terminals of the plug and socket.

**emf INDUCED IN A MOVING CONDUCTOR**

Consider a straight conductor of length $L$ moving through a uniform magnetic field $B$ as shown in figure (5). The conductor is moving with a speed $v$ and travels a distance $\Delta x = v \Delta t$ in the time interval $\Delta t$. The area swept out by the conductor in transgressing the B-field is $\Delta A = L(v \Delta t)$. Therefore, there will be a changing magnetic flux and an emf induced in the conductor. This is often referred to as a motional emf. By Faraday’s law, the magnitude of the induced emf $\varepsilon$ across the end of the conductor is given by

$$\varepsilon = \frac{\Delta \Phi_B}{\Delta t} = \frac{B \Delta A}{\Delta t} = (B L v) \left( \frac{\Delta t}{\Delta t} \right) = B L v$$

This equation is valid provided $B$ is constant and $B$, $L$ and $v$ are mutually perpendicular.

The direction of the induced emf is determined by Lenz’s rule and the right hand palm rule. The force on the electrons in the moving conductor is up which causes a charge separation – the top of the conductor becomes negative while the bottom of the conductor becomes positive.
When there is a complete circuit, the induced emf will give a current. For the arrangement shown in figure (6), the direction of the induced current is clockwise. The induced emf drives the current through the complete circuit. The conductor carrying the current in the magnetic field will experience a force to oppose its motion (right hand palm rule). As the conductor moves to the right, the area swept out increase, so the magnetic flux increases. By Lenz’s law, the induced current must produce a magnetic field to oppose the change, so the induced magnetic field must be into the page, therefore, the current must be in a clockwise direction.

Fig. 6. A conductor sliding on conductive rails through a uniform magnetic field.

Thus, when a conductor moves in a magnetic field it acts as a source of electrical energy. This is the basis of a generator.

**Example**

Consider the conductor moving through a region of uniform magnetic field as shown in figure (6). The parameters are:

\[ B = 0.555 \, \text{T} \quad v = 6.23 \, \text{m.s}^{-1} \quad L = 125 \, \text{mm} \quad R = 10.2 \, \Omega \]

Calculate the following (assume negligible resistance for conductor & rails):

- Induced emf \( \varepsilon \)
- The inducted electric field in the conductor \( E \)
- The current in the circuit \( I \)
- The external applied to the conductor to move it as a constant speed \( F \)
- The power dissipated in the resistor \( P \)
Solution
How to approach the problem
• Re-draw the diagram and annotate it with the unknown and unknown data.
• Type of problem: conductor moving through a magnetic field / circuits.
• Knowledge – equations
  • Faraday’s law (conductor moving in uniform magnetic field) \( \varepsilon = BLv \)
  • Electric field and potential difference \( |E| = \frac{\Delta V}{\Delta x} \)
  • Ohm’s law \( I = \frac{V}{R} \)
  • Force on a conductor in a uniform magnetic field \( F_B = BIL \)
  • Power dissipated in a resistor \( P = I^2R \) or \( P = I^2RP = Fv \)

Knowns
\( B = 0.555 \text{T} \) \quad \( v = 6.23 \text{ m.s}^{-1} \) \quad \( L = 125 \times 10^{-3} \text{ m} \) \quad \( R = 10.2 \ \Omega \)

Unknowns
\( \varepsilon = ? \text{ V} \) \quad \( E = ? \text{ V.m}^{-1} \) \quad \( I = ? \text{ A} \) \quad \( F = ? \text{ N} \) \quad \( P = ? \text{ W} \)

\( \varepsilon = BLv = (0.555)(125 \times 10^{-3})(6.23) \text{ V} = 0.432 \text{ V} \)

\( |E| = \frac{\Delta V}{\Delta x} = \frac{\varepsilon}{L} = \frac{0.432}{125 \times 10^{-3}} \text{ V.m}^{-1} = 3.46 \text{ V.m}^{-1} \)

\( I = \frac{V}{R} = \frac{\varepsilon}{10.2} \text{ A} = 0.0424 \text{ A} \)

\( F_B = BIL = (0.555)(0.0424)(125 \times 10^{-3}) \text{ N} = 2.90 \times 10^{-3} \text{ N} \)

\( P = I^2R = (0.432)^2(10.2) \text{ W} = 0.0183 \text{ W} \)

\( P = Fv = (2.90 \times 10^{-3})(6.23) \text{ W} = 0.0183 \text{ W} \)
Lenz’s Law

Lenz’s law is a consequence of the law of conservation of energy.

Consider what would happen when a permanent magnet is pushed towards a conductive coil. According to Lenz’s law a current is induced in the coil which induces a magnetic field that interacts with the B-field of the magnet to oppose the motion towards it.

What happens if Lenz’s law was not true? Then, the induced current would create a magnetic field to attract the magnet. The permanent magnet under the action of this attractive force would accelerate and increase its speed and kinetic energy. But, the greater the speed the greater the change in magnetic flux and hence the induced current would increase and the greater the attractive force. The current would continually grow indefinitely and the kinetic energy of the magnet would also increase indefinitely – this would be a violation of the law of conservation of energy.

Questions and problems

P6133 P6148 P6173 P6457 P6480 P6575 P6633 P6674
P6754 P6755 P6933