Semester- 2
PHYGE202
Unit- 3

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Electromagnetic Induction

Electromagnetic induction is the induction of an electromotive force in a circuit by varying the magnetic flux linked with the circuit. *See* Faraday's law of induction.

The phenomenon called electromagnetic induction was first noticed and investigated by Faraday; the law of induction is its quantitative expression. Faraday discovered that, whenever the magnetic field about an electromagnet was made to grow and collapse by closing and opening the electric circuit of which it was a part, an electric current could be detected in a separate conductor nearby. Moving a permanent magnet into and out of a coil of wire also induced a current in the wire while the magnet was in motion. Moving a conductor near a stationary permanent magnet caused a current to flow in the wire, too, as long as it was moving.

Faraday visualized a magnetic field as composed of many lines of induction, along which a small magnetic compass would point. The aggregate of the lines intersecting a given area is called the magnetic flux. The electrical effects were thus attributed by Faraday to a changing magnetic flux. Some years later the Scottish physicist James Clerk Maxwell proposed that the fundamental effect of changing magnetic flux was the production of an electric field, not only in a conductor (where it could drive an electric charge) but also in space even in the absence of electric charges. Maxwell formulated the mathematical expression relating the change in magnetic flux to the induced electromotive force (*E,* or *emf*). This relationship, known as **Faraday's law of induction (to distinguish it from his laws of electrolysis).**

Faraday's Law of Induction

It is the quantitative relationship between a changing magnetic field and the electric field created by the change, developed on the basis of experimental observations made in 1831 by the English scientist Michael Faraday.

It states that **the magnitude of the *emf* induced in a circuit is proportional to the rate of change of the magnetic flux that cuts across the circuit.** If the rate of change of magnetic flux is expressed in units of webers per second, the induced *emf* has units of volts. Faraday's law is one of the four Maxwell equations that define electromagnetic theory.

Faraday's discovery of Electric Induction

Faraday, the greatest experimentalist in electricity and magnetism of the 19th century and one of the greatest experimental physicists of all time, worked on and off for 10 years trying to prove that a magnet could induce electricity. In 1831 he finally succeeded by using two coils of wire wound around opposite sides of a ring of soft iron. The first coil was attached to a battery; when a current passed through the coil, the iron ring became magnetized. A wire from the second coil was extended to a compass needle a metre away, far enough so that it was not affected directly by any current in the first circuit. When the first circuit was turned on, Faraday observed a momentary deflection of the compass needle and its immediate return to its original position. When the primary current was switched off, a similar deflection of the compass needle occurred but in the opposite direction. Building on this observation in other experiments, Faraday showed that changes in the magnetic field around the first coil are responsible for inducing the current in the second coil. He also demonstrated that an electric current can be induced by moving a magnet, by turning an electromagnet on and off, and even by moving an electric wire in Earth's magnetic field. Within a few months, Faraday built the first, albeit primitive, electric generator.

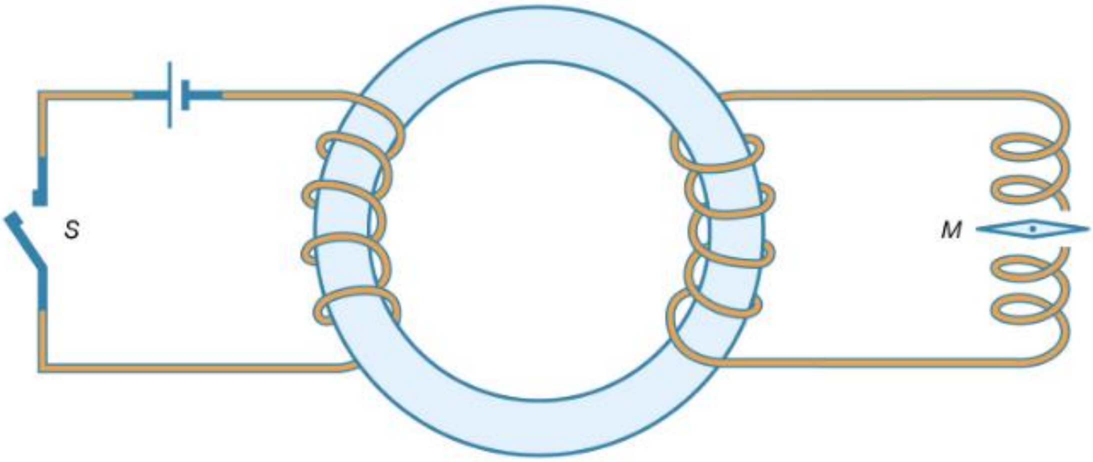

Figure: Faraday's magnetic induction experiment. When the switch S is closed in the primary circuit, a momentary current flows in the secondary circuit, giving a transient deflection of the compass needle M.

Henry had discovered electric induction quite independently in 1830, but his results were not published until after he had received news of Faraday’s 1831 work, nor did he develop the discovery as fully as Faraday. In his paper of July 1832, Henry reported and correctly interpreted self-induction. He had produced large electric arcs from a long helical conductor when it was disconnected from a battery. When he had opened the circuit, the rapid decrease in the current had caused a large voltage between the battery terminal and the wire. As the wire lead was pulled away from the battery, the current continued to flow for a short time in the form of a bright arc between the battery terminal and the wire.

Faraday’s thinking was permeated by the concept of electric and magnetic lines of force. He visualized that magnets, electric charges, and electric currents produce lines of force. When he placed a thin card covered with iron filings on a magnet, he could see the filings form chains from one end of the magnet to the other. He believed that these lines showed the directions of the forces and that electric current would have the same lines of force. The tension they build explains the attraction and repulsion of magnets and electric charges. Faraday had visualized magnetic curves as early as 1831 while working on his induction experiments; he wrote in his notes, “By magnetic curves I mean lines of magnetic forces which would be depicted by iron filings.” Faraday opposed the prevailing idea that induction occurred “at a distance”; instead, he held that induction occurs along curved lines of force because of the action of contiguous particles. Later he explained that electricity and magnetism are

transmitted through a medium that is the site of electric or magnetic “fields,” which make all substances magnetic to some extent.
Faraday was not the only researcher laying the groundwork for a synthesis between electricity, magnetism, and other areas of physics. On the continent of Europe, primarily in Germany, scientists were making mathematical connections between electricity, magnetism, and optics. The work of the physicists Franz Ernst Neumann, Wilhelm Eduard Weber, and H.F.E. Lenz belongs to this period. At the same time, Helmholtz and the English physicists William Thomson (later Lord Kelvin) and James Prescott Joule were clarifying the relationship between electricity and other forms of energy. Joule investigated the quantitative relationship between electric currents and heat during the 1840s and formulated the theory of the heating effects that accompany the flow of electricity in conductors. Helmholtz, Thomson, Henry, Gustav Kirchhoff, and Sir George Gabriel Stokes also extended the theory of the conduction and propagation of electric effects in conductors. In 1856 Weber and his German colleague, Rudolf Kohlrausch, determined the ratio of electric and magnetic units and found that it has the same dimensions as light and that it is almost exactly equal to its velocity. In 1857 Kirchhoff used this finding to demonstrate that electric disturbances propagate on a highly conductive wire with the speed of light.

Faraday’s discovery in 1831 of the phenomenon of magnetic induction is one of the great milestones in the quest toward understanding and exploiting nature. Stated simply, Faraday found that

- a changing magnetic field in a circuit induces an electromotive force in the circuit
- the magnitude of the electromotive force equals the rate at which the flux of the magnetic field through the circuit changes. The flux is a measure of how much field penetrates through the circuit. The electromotive force is measured in volts and is represented by the equation

$$\text{emf} = -\frac{d\Phi}{dt}. \qquad (1)$$

Here, Φ, the flux of the vector field $\boldsymbol{B}$ through the circuit, measures how much of the field passes through the circuit. To illustrate the meaning of flux, imagine how much water from a steady rain will pass through a circular ring of area *A*. When the ring is placed parallel to the path of the water drops, no water passes through the ring. The maximum rate at which drops of rain pass through the ring occurs when the surface is perpendicular to the motion of the drops. The rate of water drops crossing the surface is the flux of the vector field ρv through that surface, where ρ is the density of water drops and v represents the velocity of the water. Clearly, the angle between v and the surface is essential in determining the flux. To specify the orientation of the surface, a vector $\boldsymbol{A}$ is defined so that its magnitude is the surface area A in units of square metres and its direction is perpendicular to the surface. The rate at which raindrops pass through the surface is

$$\rho v \cos \theta A,$$

where θ is the angle between v and $\boldsymbol{A}$.

Using vector notation, the flux is $\rho v \cdot \boldsymbol{A}$. For the magnetic field, the amount of flux through a small area represented by the vector $d\boldsymbol{A}$ is given by $\boldsymbol{B} \cdot d\boldsymbol{A}$. For a circuit consisting of a single turn of wire, adding the contributions from the entire surface that is surrounded by the wire gives the magnetic flux Φ of equation (1).

- The rate of change of this flux is the induced electromotive force. The units of magnetic flux are webers, with one weber equaling one tesla per square metre.
- Finally, the minus sign in equation (1) indicates the direction of the induced electromotive force and hence of any induced current.
- The magnetic flux through the circuit generated by the induced current is in whatever direction will keep the total flux in the circuit from changing.
- The minus sign in equation (1) is an example of Lenz's law for magnetic systems. This law, deduced by the Russian-born physicist Heinrich Friedrich Emil Lenz, states that "what happens is that which opposes any change in the system."

$$\text{emf} = -\frac{d\Phi}{dt}. \qquad (1)$$

Faraday's law is valid regardless of the process that causes the magnetic flux to change. It may be that a magnet is moved closer to a circuit or that a circuit is moved closer to a magnet. Figure below shows a magnet brought near a conducting ring and gives the direction of the induced current and field, thus illustrating both Faraday's and Lenz's laws. Another alternative is that the circuit may change in size in a fixed external magnetic field or, as in the case of alternating-current (AC) generation, that the circuit may be a coil of conducting wire rotating in a magnetic field so that the flux Φ varies sinusoidally in time.

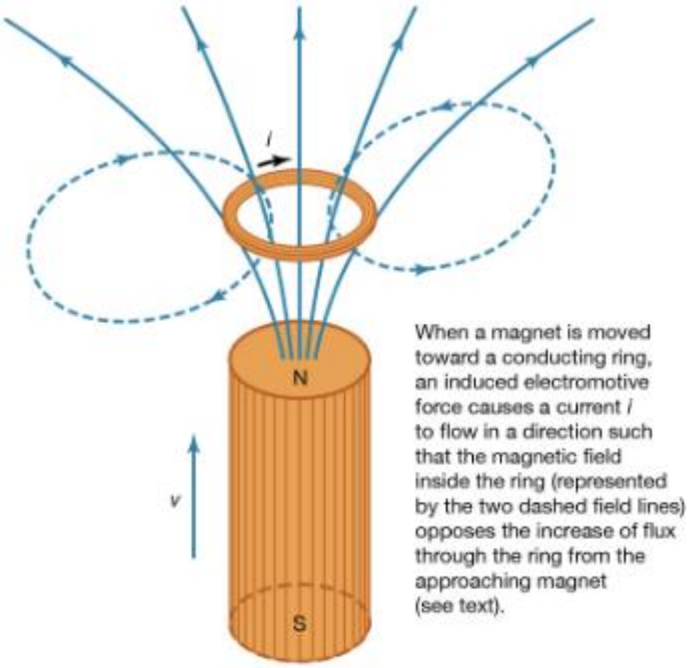

Figure: Demonstration of Faraday's and Lenz's laws.

The magnetic flux Φ through a circuit has to be considered carefully in the application of Faraday's law given in equation (1). For example, if a circuit consists of a coil with five closely spaced turns and if ϕ is the magnetic flux through a single turn, then the value of Φ for the five-turn circuit that must be used in Faraday's law is $\Phi = 5\phi$. If the five turns are not the same size and closely spaced, the problem of determining Φ can be quite complex.