Lecture (6)

Electricity and Magnetism II

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Faraday Henry Law

One of the many electromagnetic phenomena familiar to student is electromagnetic induction, which was discovered almost simultaneously but independently, around 1830 by Michael Faraday and Joseph Henry. Electromagnetic induction is the working Principle of the electric generator, the transformer and many other device in daily use.

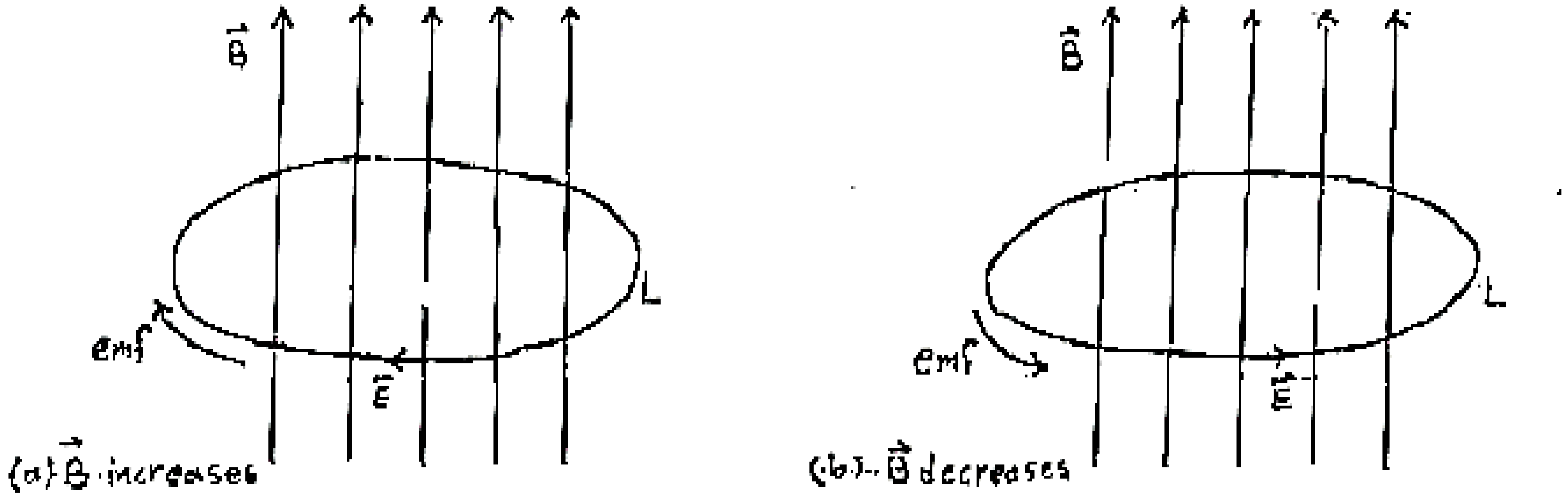

Figure electric field produced by a time dependent magnetic field (a) $d\phi_B/dt$ positive, V_E negative (b) $d\phi_B/dt$ negative, V_E positive

The magnitude of the induced emf depends on weather the magnet (or the circuit) is moved rapidly or slowly. The greater the rate of change of the flux, the larger the induced emf. The direction in which the induced emf acts depends on weather the negative flux is increasing or decreasing. One can use the right hand rule to determine the direction in which the emf acts, as indicated in above figure.

To be more precise, let us refer to above figure where the path **L** has been oriented accordingly to the right hand rule. When the magnetic flux increases ($\boldsymbol{d\phi_B/dt}$ positive) the induced emf. $\boldsymbol{V_E}$ acts in the negative sence, while when the magnetic flux decreases ($\boldsymbol{d\phi_B/dt}$ negative) the induced emf. $\boldsymbol{V_E}$ acts in the positive sence.

Therefore, we may write:

$$\boldsymbol{V_E = -\frac{d\phi_B}{dt}}$$

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Which expresses the Faraday Henry Law of electromagnetic induction we may state this in words as a varying magnetic field, an emf is induced in any closed circuit which is equal to the negative of the time rate of change of the magnetic flux through the circuit.

We know that V_E is expressed in V or $m^2\,kg\,s^{-2}\,C^{-1}$ and $\frac{d\phi_B}{dt}$ must be expressed in $Wb\,s^{-1}\;or\;m^2\;kg\;s^{-1}\;C^{-1}$. Thus both sides of above equation are expressed in the same units.

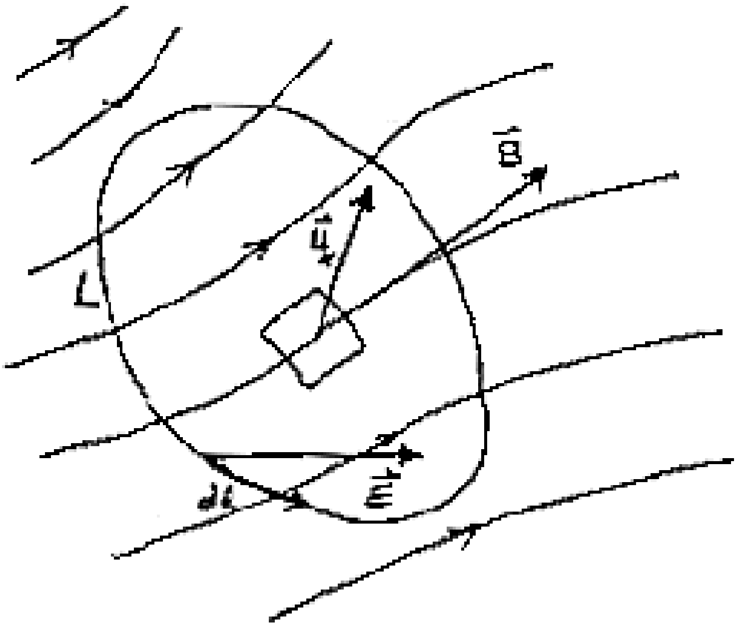


Figure relation between a time varying magnetic flux and the electric circulation

Referring to above figure, if we divide the area limited by **L** into infinite small area elements, each oriented according to the rule established of the vector representation of surfaces, the magnetic flux through **L** is:

$$\boldsymbol{\phi_B = \int_S \vec{B}\,\vec{u}_N\, dS}$$

Also the emf implies the existence of an electric field $\vec{\boldsymbol{E}}$ such that

$$\boldsymbol{V_E = \oint_L \vec{E}\,.\,\vec{dl}}$$

Thus, we may write:

$$\boldsymbol{\oint_L \vec{E}\,.\,\vec{dl} = \frac{d}{dt}\int_S \vec{B}\,.\,\vec{u}_N\, dS}$$

Let us forget now that the path L coincides with an electric conductor such as a closed wire and instead consider a region of space where a magnetic field, varying with time, exist. Then above equation is equivalent to saying ‘A time dependent magnetic field implies the existence of an electric field such that the circulation of the electric field along an arbitrary closed path is equal to the negative of the time rate of the change of the magnetic flux through a surface bounded by the path’.

This is another way of stating the Faraday Henry Law of electromagnetic induction.

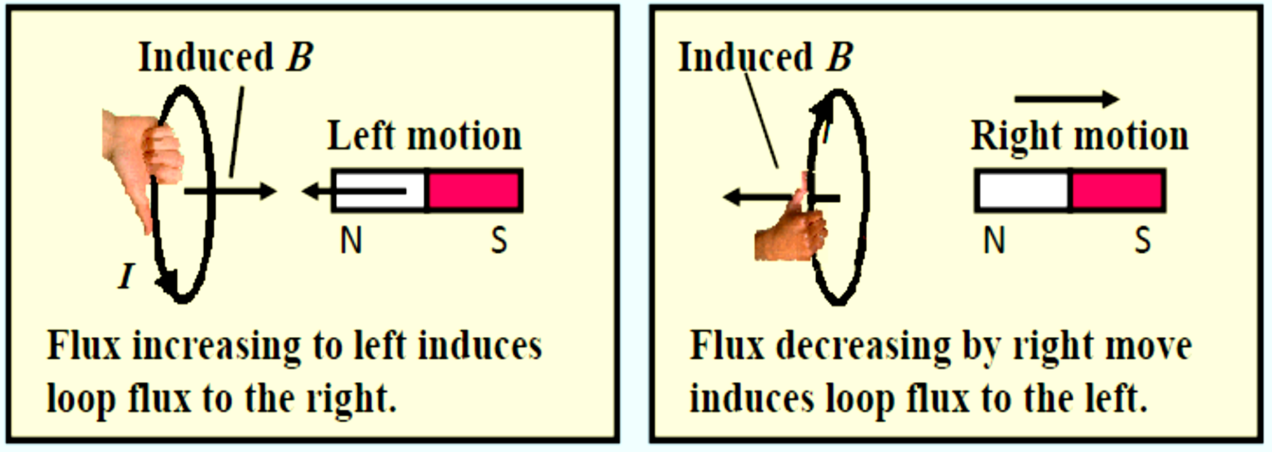
Lenz’s Law

Lenz's law states: The direction of any magnetic induction effect is such as to oppose the cause of the effect.

The “cause” may be changing flux

- through a stationary circuit due to a changing **B-field**
- due to motion of the conductors that make up the circuit

Lenz’s law: An induced current will be in such a direction as to produce a magnetic field that will oppose the motion of the magnetic field that is producing it.

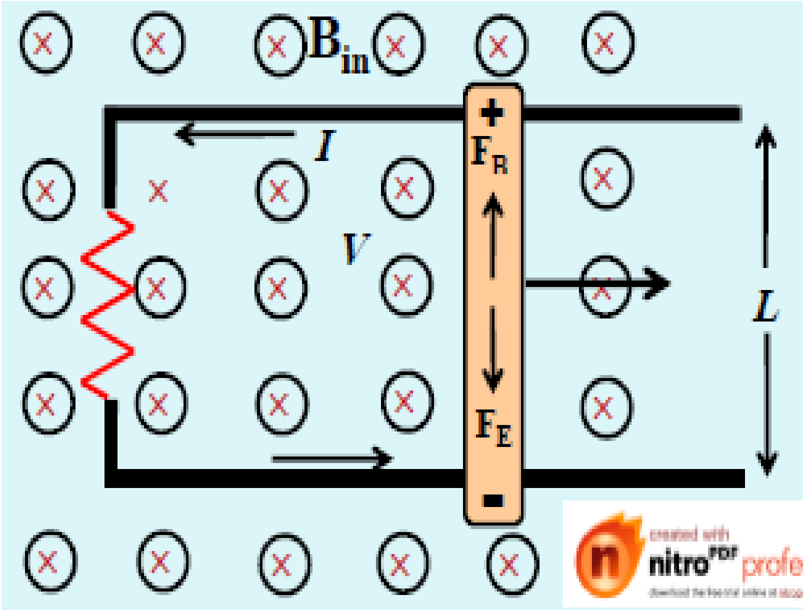


Motional Electromotive Force

In faraday's Law, we can induce emf in the loop when the magnetic flux, $\emptyset_B$, changes as a function of time. There are two cases when $\emptyset_B$ is changing,

1) change the magnetic field (non-constant over time)

2) change or move the loop in a constant magnetic field



In this example, with only the side bar moving, the area of the loop is increasing, so the flux through the loop is increasing.

and we get a net emf around the loop and a current flow.

Charge carriers in the wire experience an upward force of magnitude $\boldsymbol{F_B = qvB}$.

Being the force to move, positive charges flow upward and negative charges downward. The charge separation creates an electric field in the conductor. **E** increases as more charges flows. The charge flow continuous until the downward electric force $\boldsymbol{F_E = qE}$ is larger enough to balance the upward magnetic force $\boldsymbol{F_B}$. Then the net force on a charge is zero the current ceases.

$$\boldsymbol{F_B = F_E} \quad \Longrightarrow \quad \boldsymbol{qvB = qE}$$

$$\boldsymbol{E = vB} \quad \boldsymbol{or} \quad \boldsymbol{\varepsilon = vB}$$

For uniform E-field: $$\boldsymbol{|\Delta V| = \int \vec{E}.d\vec{s} = El = vBl}$$

Current is in a magnetic field

$$\boldsymbol{F = I(L \times B)}$$

If $\boldsymbol{v = 0}$, then $\boldsymbol{F_B = qvB \sin\theta = 0}$ and $\boldsymbol{F_E}$ will reunite the + and – charges, thus eliminating the emf.

$$\boldsymbol{I = \frac{\varepsilon}{R}}$$

Example 1: emf induced in a plane circuit composed of **N** turns, each of area S placed perpendicular to an alternating uniform magnetic field that varies sinusoidal with time. The field is expressed by:

$$\boldsymbol{B = B_o \sin \omega t}$$

Example 2: A loop of wire enclosing an area A is placed in a region where the magnetic field is perpendicular to the plane of the loop. The magnetiude of B varies in time according to the expression

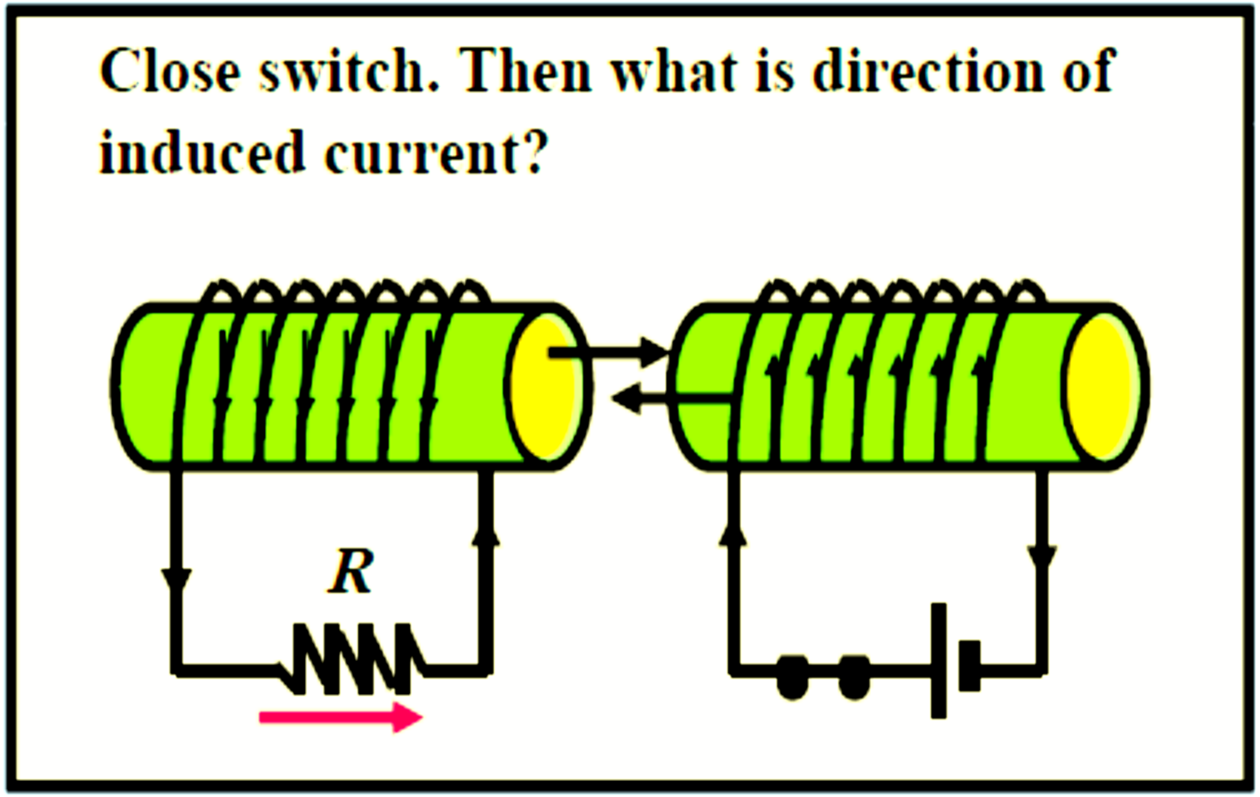
$$\boldsymbol{B = B_{max}\, e^{-at}}$$

Where **a** is some constant. That is at **t=0** the field is $\boldsymbol{B_{max}}$ and for **t>0** the field decreases exponentially. Find the induced emf in the loop as a function of time.

Example 3: Acoil has 200 turns of area $30\ cm^3$. It flips from vertical to horizontal position in a time of 0.03 s. what is the induced emf if the constant B-field is 4 mT?

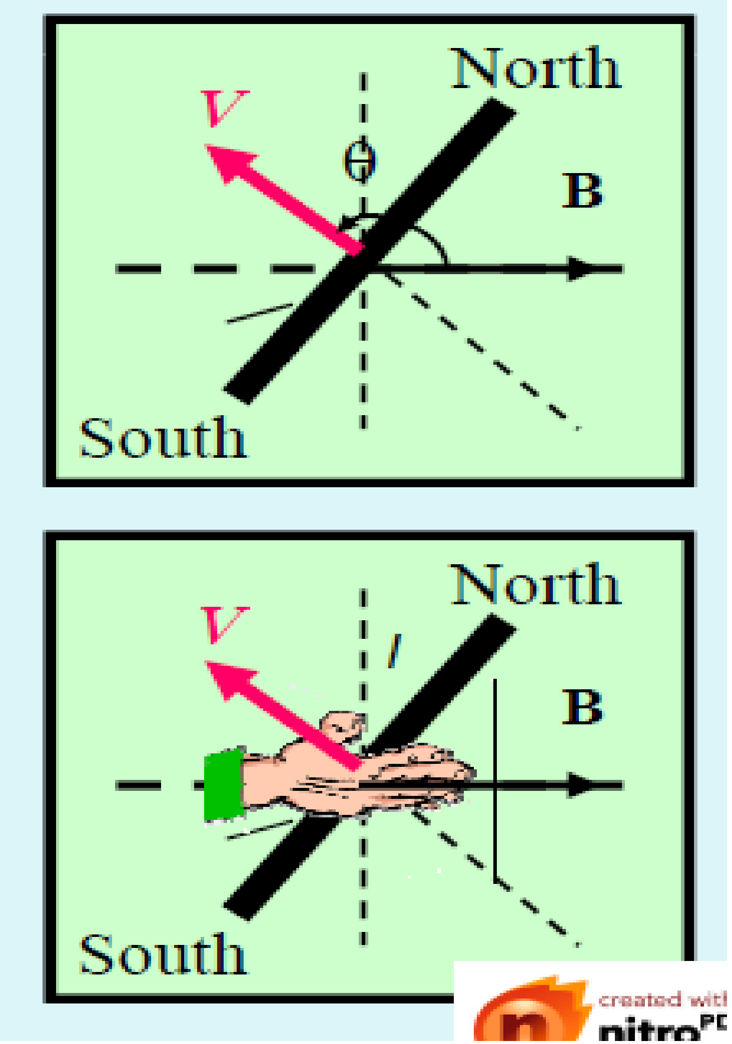
Sol.

Example 4: Use Lenz's law to determine direction of induced current through R if switch is closed for circuit below (B increasing).



Example 5: A 0.20 m length of wire moves at a constant speed of 5 m/s in at 140^{o} with a 0.4 T B-Field. What is the magnitude and direction of the induced emf in the wire?

Sol.



Example 6: a motor contain a coil with a total resistance of 10 Ω and is supplied by a voltage of 120 V. when the motor is running at its maximum speed, the back emf is 70 V.

(A) Find the current in the coil at the instant the motor is turned on.

(B) Find the current in the coil when the motor has reached maximum speed.

Sol.