Physics 1214 — Chapter 21: Electromagnetic Induction

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1 Induction Experiments

emf or electromotive force: (from Chapter 19) the influence that moves charge from lower to higher potential.
induced current: changing magnetic field causing a current in a circuit.
induced emf: the emf that is present to cause a current.

2 Magnetic Flux

Magnetic flux through a plane surface in a constant magnetic field

For a plane surface with area A in a uniform magnetic field $\vec{B}$, both $B_\perp$ and ϕ are the same at all points on the surface. The magnetic flux Φ_B through the surface is

$$\Phi_B = B_\perp A = BA\cos\phi.$$

If $\vec{B}$ happens to be perpendicular to the surface, then $\cos\phi = 1$ and the previous equation reduces to $\Phi_B = BA$.
Unit: The SI unit magnetic flux is the unit magnetic field (1 T) times the unit of area (1 m^2):
(1 T)(1 m^2) =[1 N/(A · m)](1 m^2)= 1 N · m/A.
This unit is call 1 weber (1 Wb).
1 weber = 1 Wb = 1 T · m^2 = 1 N · m/A.

magnetic flux density

$$B = \frac{\Delta\Phi_B}{\Delta A}$$

$$1\ \text{T} = 1\ \text{Wb/m}^2$$

3 Faraday's Law

The common element in ALL induction effects is changing magnetic flux through a circuit.

Faraday's law of induction

The magnitude of the induced emf in a circuit equals the absolute value of the time rate of change of the magnetic flux through the circuit.
In symbols, Faraday's law is

$$\mathcal{E} = \left|\frac{\Delta\Phi_B}{\Delta t}\right|.$$

In this definition, $\mathcal{E}$ is the magnitude of the emf and is always positive.

For a coil with N identical turns:

$$\mathcal{E} = N\left|\frac{\Delta\Phi_B}{\Delta t}\right|.$$

generator: a device that converts mechanical energy to electrical energy.

4 Lenz's Law

Lenz's Law

The direction of any magnetically induced current or emf is such as to oppose the direction of the phenomenon causing it.

Induced current tends to preserve the *status quo* by opposing the motion or the change of flux that originally induced it.

5 Motional Electromotive Force

motional emf: emf created by motion of a conductor; denoted by $\mathcal{E}$. When velocity (v), magnetic field (B), and length (L) are mutually perpendicular ($\perp$)

$$\mathcal{E} = vBL.$$

6 Eddy Currents

eddy currents: induced currents circulating throughout the volume of a conducting material; resulting flow patterns resembles swirling eddies in a fluid.

7 Mutual Inductance

Mutual inductance

The mutual inductance M of two coils is given by

$$M = M_{21} = M_{12} = \left|\frac{N_2\Phi_{B2}}{i_1}\right| = \left|\frac{N_1\Phi_{B1}}{i_2}\right|.$$

From the preceding analysis, we can also write

$$\mathcal{E}_2 = M\left|\frac{\Delta i_1}{\Delta t}\right| \text{ and } \mathcal{E}_1 = M\left|\frac{\Delta i_2}{\Delta t}\right|.$$

Unit: The SI unit of mutual inductance is called the **henry** (1 H).
1 H = 1 Wb/A = 1 V · s/A = 1 Ω · s.

8 Self Inductance

self-induced emf: an induced emf in a circuit resulting from the variation of its own magnetic field.

Inductance or self-inductance

The self-inductance L of a circuit is the magnitude of the self-induced emf $\mathcal{E}$ per unit rate of change of current, so that:

$$\mathcal{E} = L\left|\frac{\Delta i}{\Delta t}\right|$$

where the inductance L is given by

$$L = \left|\frac{N\Phi_B}{i}\right|$$

and where there are N turns of the wire carrying a current i, and Φ_B is the magnetic flux The SI unit of self-inductance is the same as for mutual inductance, one **henry**.

inductor or choke: a circuit or part of a circuit that is designed to have a particular inductance.

The inductance of a circuit depends on its *size*, *shape*, and *number of turns* and the *magnetic properties* of the material enclosed by the circuit.

9 Transformers

transformer: device that transforms one voltage into another; consists of two coils–the **primary** (voltage supplied) and **secondary** (voltage delivered).

Relation of voltage to winding turns for a transformer

For an ideal transformer (with zero resistance),

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}.$$

By choosing the appropriate turns ration N_2/N_1, we may obtain any desired secondary voltage from a given primary voltage.

If $V_2 > V_1$, we have a *step-up* transformer; if $V_2 < V_1$, we have a *step-down* transformer. The V's can be either both amplitudes or both rms values.

10 Magnetic Field Energy

Average power supplied by the current source during the small time interval Δt is:

$$\boxed{P = V_{ab} i = L i \frac{\Delta i}{\Delta t}}$$

Energy stored in an inductor

The energy stored by an inductor with inductance L carrying a current I is

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

energy density: the energy per unit volume, denoted by u, is

$$u = \frac{U}{V} = \frac{B^2}{2\mu_0}.$$

11 The R-L Circuit

R-L circuit: a circuit containing a resistor and an inductor. Due to inductance/resistance, there is no sudden change in current in an R-L circuit and thus we have current growth and current decay. Current growth is given by

$$i = \frac{\mathcal{E}}{R}\left(1 - e^{-(R/L)t}\right);$$

current decay, by

$$i = I_0 e^{-(R/L)t}.$$

time constant: $\tau = L/R$.

12 The L-C Circuit

L-C circuit: a circuit containing an inductor and a capacitor leading to an oscillating current and charge called **electrical oscillation**. The angular frequency of the oscillatory behavior is given by

$$\boxed{\omega = \sqrt{\frac{1}{LC}}}$$

13 Links

MIT Video Demonstration of Lenz's Law