CHAPTER 6

Electromagnetic Induction

Electromagnetic Induction Laws

- Electromagnetic Induction is the one in which by which electric current is generated with the help of a magnetic field.
- ***The Experiments of Faraday and Henry***

  The observations from the experiments of Faraday and Henry concluded that it is the relative motion between the magnet and the coil that is responsible for generation or induction of the electric current in the coil.
- ***Magnetic Flux***

  It is the amount of field lines cutting through a surface area A defined by unit area vector. The magnetic flux that passes through a plane of area A and has a uniform magnetic field B, is given by, $\phi_B = B.A = BA\cos\theta$ where θ is the angle between magnetic field B and Area A. Magnetic flux is a scalar quantity and its SI unit is weber.

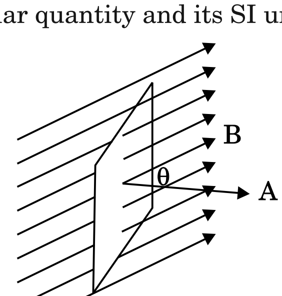

Fig. Field lines in a magnetic field

Faraday's Law of Induction

- **Faraday's First Law:** Whenever a conductor is placed in a varying magnetic field, there is an induced emf and if the conductor circuit is closed, there is an induced current.
- Faraday's Second Law: This law of electromagnetic induction states that the magnitude of the induced emf in a circuit is equal to the time rate of change of magnetic flux through the circuit. Mathematically, the induced emf is given by $\varepsilon = \frac{-d\,\phi_B}{dt}$, the negative sign indicates direction of the induced emf and hence the direction in a closed loop.

Lenz's law and Conservation of Energy

The Lenz's law states that the polarity of induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produced it.

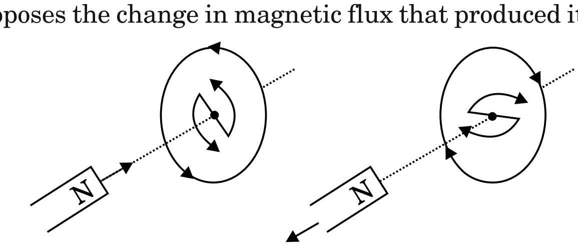

Fig. Lenz's law

Motional Electromotive Force

The relationship between induced emf and a wire moving at a constant speed v is given by $\varepsilon = Blv$

Energy Consideration: A Quantitative Study

- 'r' is the resistance of the movable arm PQ of the rectangular conductor. Assume that remaining arms QR, RS, SP have negligible resistance compared to r. In the presence of magnetic field there will be a force on the arm AB. This force I(l × B) is outwards directed in a direction opposite to the velocity of rod.
- Magnitude of force is $F = IlB = \frac{B^2l^2v}{r}$.
- Magnitude to push arm PQ $= Fv = \frac{B^2l^2v^2}{r}$

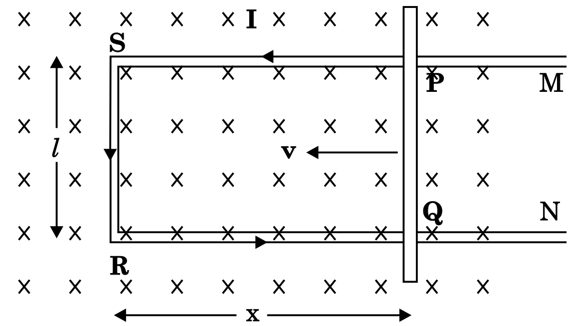

Fig. Energy Consideration in a Magnetic field

Eddy currents, self and mutual inductance

Eddy Currents

- When bulk pieces of conductors are subjected to changing magnetic flux then induced currents are produced in them which are called as eddy currents.
- Eddy currents create a significant drag known as magnetic damping.
- The applications of eddy currents are in magnetic braking in trains, electromagnetic damping, electric power meters and induction furnace.

Inductance

- Flux change produced by another coil in the close proximity of a coil or flux exchange produced by the same coil induces electric current.
- The inductance in series is given by $L_s = L_1 + L_2 + L_3 + ...$
- The inductance in parallel is given by $\frac{1}{L_p} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + ...$

Mutual- Inductance

- When the emf is induced into the adjacent coil situated within the same magnetic field, the emf is said to be induced magnetically or by mutual induction.
- Mutual inductance of a pair of coils, solenoids etc. depends on their relative orientation as well as their separation.

  $\varepsilon_1 = -M \frac{dI_2}{dt}$

- Mutual Inductance of two coils is given by $M = \frac{\mu_0 \mu_r N_p N_s A_s}{l_p}$ where A_p, A_s are the cross sectional areas of primary and secondary coil in m^2, I is the coil current and N_s, N_p are the number of turns of secondary and primary coils respectively.

Self – Inductance

- The production of induced emf in a circuit when the current changes in the same circuit is called self-induction.
- The induced emf is given by $\varepsilon = -L \frac{dI}{dt}$, where is the coefficient of self-induction.
- The direction of induced emf is given by Lenz's Law.

AC Generator

- The electromagnetic induction has its applications in an AC generator, where mechanical energy is converted to electrical energy.

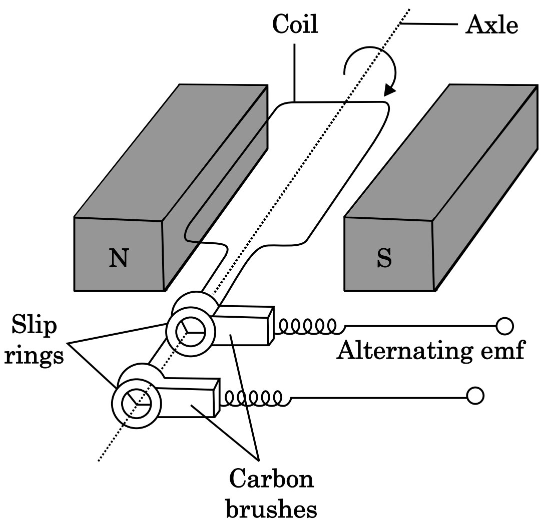

Fig. A.C. Generator

- The motional emf is of a coil with N turns and area A, rotated at v revolutions per second in a uniform magnetic field B is given as, $\varepsilon = -NBA \dfrac{d}{dt}(\cos \omega t)$

Exercise

1. In electromagnetic induction, the induced e.m.f. in a coil is independent of

(*a*) Change in the flux
(*b*) Time
(*c*) Resistance of the circuit
(*d*) None of these

2. Lenz's law is consequence of the law of conservation of

(*a*) Charge (*b*) Momentum
(*c*) Mass (*d*) Energy

3. In electromagnetic induction, the induced charge in a coil is

(*a*) Change in the flux
(*b*) Time
(*c*) Resistance in the circuit
(*d*) None of these

4. The magnetic flux linked with a coil is given by an equation $\phi = 8t^2 + 3t + 5$. The induced e.m.f. in the coil at the fourth second will be

(*a*) 16 units (*b*) 39 units
(*c*) 67 units (*d*) 145 units

5. The direction of induced e.m.f. during electromagnetic induction is given by.

(*a*) Faraday's law (*b*) Lenz's law
(*c*) Maxwell's law (*d*) Ampere's law

6. According to Faraday's law of electromagnetic induction

(*a*) The direction of induced current is such that it opposes the cause producing it
(*b*) The magnitude of induced e.m.f. produced in a coil is directly proportional to the rate of change of magnetic flux.
(*c*) The direction of induced e.m.f. is such that it opposes the cause producing it
(*d*) None of these

7. Lenz's law gives

(*a*) The magnitude of the induced e.m.f.
(*b*) The direction of the induced current
(*c*) Both the magnitude and direction of the induced current
(*d*) The magnitude of the induced current

8. Faraday's laws are consequences of conservation of

(*a*) Energy
(*b*) Energy and Magnetic field
(*c*) Charge
(*d*) Magnetic field

9. Lenz's law is expressed by the following formula (here e = induced e.m.f., ϕ = magnetic flux in one turn and N = number of turns)

(*a*) $e = -\phi \frac{dN}{dt}$ (*b*) $e = -N \frac{d\phi}{dt}$

(*c*) $e = -\frac{d}{dt}\left(\frac{\phi}{N}\right)$ (*d*) $e = N \frac{d\phi}{dt}$

10. A two metre wire is morning with a velocity of 1 m/sec perpendicular to a magnetic field of 0.5 weber/m^2. The e.m.f. induced in it will be

(*a*) 0.5 volt

(*b*) 0.1 volt

(*c*) 1 volt

(*d*) 2 volt

11. A conducting wire is dropped along east-west direction, then

(*a*) No emf is induced

(*b*) No induced current flows

(*c*) Induced current flows from west to east

(*d*) Induced current flows from east to west

12. A 50 mH coil carries a current of 2 ampere. The energy stored in joules is

(*a*) 1 (*b*) 0.1

(*c*) 0.05 (*d*) 0.5

13. Average energy stored in a pure inductance L when a current i flows through it, is

(*a*) Li^2 (*b*) $2Li^2$

(*c*) $\frac{Li^2}{4}$ (*d*) $\frac{Li^2}{2}$

14. In what form is the energy stored in an inductor

(*a*) Magnetic

(*b*) Electrical

(*c*) Both magnetic and electrical

(*d*) Heat

15. When the number of turns in a coil is doubled without any change in the length of the coil, its self inductance becomes.

(*a*) Four times (*b*) Doubled

(*c*) Halved (*d*) Unchanged

16. Mutual inductance of two coils can be increased by

(*a*) Decreasing the number of turns in the coils

(*b*) Increasing the number of turns in the coils

(*c*) Winding the coils on wooden core

(*d*) None of the above

17. The current flowing in a coil of self inductance 0.4 mH is increased by 250 mA in 0.1 sec. The e.m.f, induced will be

(*a*) +1 V

(*b*) –1 V

(*c*) +1 mV

(*d*) –1 mV

18. The self inductance of a solenoid of length L, area of cross-section A and having N turns is

(*a*) $\frac{\mu_o N^2 A}{L}$ (*d*) $\frac{\mu_o NA}{L}$

(*c*) $\mu_o N^2 LA$ (*d*) $\mu_o NLA$

19. The SI unit of inductance, henery, can be written as

(*a*) weber/ampere

(*b*) Volt-second/ampere

(*c*) Joule/(ampere)^2

(*d*) All of these

20. The self inductance of a straight conductor is

(*a*) zero

(*b*) very large

(*c*) Infinity

(*d*) very small

21. The current in a coil of inductance 5H decreases at the rate of 2A/S. The induced e.m.f. is

(*a*) 2V (*b*) 5V

(*c*) 10V (*d*) –10V

22. In a choke coil, the resistance X_L and resistance R are such that

(*a*) $X_L = R$ (*b*) $X_L >> R$

(c) $X_L << R$ (d) $X_L = \infty$

23. Use of eddy currents is done in the following except

(*a*) Moving coil galvanometer

(*b*) Electric brakes

(*c*) Induction motar

(*d*) Dynamo

24. The device that does't work on the principle of mutual induction is

(*a*) Induction coil

(*b*) Motor

(*c*) Tesla coil

(*d*) Transformer

Answer Keys

1. (*c*)	**2.** (*d*)	**3.** (*b*)	**4.** (*c*)	**5.** (*b*)	**6.** (*b*)	**7.** (*b*)	**8.** (*a*)	**9.** (*b*)	**10.** (*c*)
11. (*c*)	**12.** (*b*)	**13.** (*d*)	**14.** (*a*)	**15.** (*a*)	**16.** (*b*)	**17.** (*d*)	**18.** (*a*)	**19.** (*d*)	**20.** (*a*)
21. (*c*)	**22.** (*b*)	**23.** (*d*)	**24.** (*c*)						

Solutions

1. The induced e.m.f. in a coil is independent of resistance of the circuit.

2. The energy of the field increases with the magnitude of the field. Lenz's law infers that there is an opposite field created due to increase or decrease of magnetic flux around a conductor so as to hold the law of conservation of energy.

3. We know that $|e| = \frac{d\phi}{dt}$

But $e = iR$ and $i = \frac{dq}{dt} \Rightarrow \frac{dq}{dt}R = \frac{d\phi}{dt}$

$\Rightarrow dq = \frac{d\phi}{R}$

4. $e = -\frac{d\phi}{dt} = -(16t + 3) = -67$ units

5. The direction of induced e.m.f. during electromagnetic induction is given by Lenz's law.

6. According to Faraday's law of electromagnetic induction, the magnitude of induced e.m.f. produced in a coil is directly proportional to the rate of change of magnetic flux.

7. Lenz's law gives the direction of the induced current.

8. Faraday's laws involve conversion of mechanical energy into electrical energy. This is in accordance with the law of conservation of energy.

9. Lenz's formula. $e = -N\frac{d\phi}{dt}$

10. We know that

$e = Bvl = 0.5 \times 1 \times 2$

$= 1$ volt

11. A conducting wire is dropped along east-west direction, then induced current flows from west to east.

12. Energy stored

$E = \frac{1}{2}Li^2 = \frac{1}{2} \times 50 \times 10^{-3} \times 4$

$= 0.1$ Joule

13. As we know, $e = -\frac{d\phi}{dt} = -L\frac{di}{dt}$

Work done against back e.m.f. (e) in time dt and current (i) is

$dw = -eidt = L\frac{di}{dt}idt$

$= Lidi$

$\Rightarrow W = L\int_o^i i\,di = \frac{1}{2}Li^2$

14. The energy stored in an inductor is in the form of magnetic.

Energy stored $= \frac{1}{2}Li^2$, where Li is magnetic flux.

15. $\because L \propto N^2$

i.e. $\frac{L_1}{L_2} = \left(\frac{N_1}{N_2}\right)^2$

$\Rightarrow L_2 = L_1\left(\frac{N_2}{N_1}\right)^2 = 4L_1$

16. Mutual inductance of two coils can be increased by increasing the number of turns in the coils.

17. $e = -L\frac{di}{dt} = -0.4 \times 10^{-3} \times \frac{250 \times 10^{-3}}{0.1} = -1mV$

18. The self inductance of a solenoid $= \frac{\mu_o N^2 A}{L}$

19. All of these

20. $\because L \propto N$ (number of turns)

For straight conductor N = 0

Hence, L = 0

21. $e = -L\frac{di}{dt}$, since current decreases

so, $\frac{di}{dt}$ is negative.

Hence, $e = -5 \times (-2) = +10V$

22. A choke coil is an electrical appliance used for controlling current in an a.c. circuit. In a choke coil $R << X_L$ to avoid power dissipation.

23. Eddy current is not used in dynamo.

24. The device that does't work on the principle of mutual induction is Tesla coil.