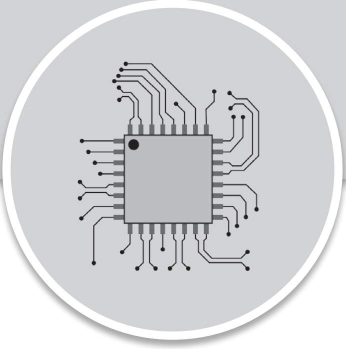
# ELECTRONICS ENGINEERING

# BASIC ELECTRICAL ENGINEERING



Comprehensive Theory
*with* Solved Examples *and* Practice Questions

MADE EASY PUBLICATIONS

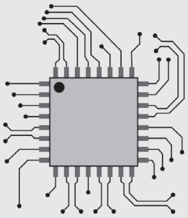
www.madeeasypublications.org

**MADE EASY Publications Pvt. Ltd.**
**Corporate Office:** 44-A/4, Kalu Sarai (Near Hauz Khas Metro
Station), New Delhi-110016 | **Ph. :** 9021300500
**Email :** infomep@madeeasy.in | **Web :** www.madeeasypublications.org

# Basic Electrical Engineering

EDITIONS

First Edition : 2017
Second Edition : 2018
Third Edition : 2019
Fourth Edition : 2020
Fifth Edition : 2021
Sixth Edition : 2022
Seventh Edition : 2023
Eighth Edition : 2024
Ninth Edition : 2025
**Tenth Edition : 2026**



# CONTENTS

# Basic Electrical Engineering

## CHAPTER 1

## CHAPTER 2

## CHAPTER 3

## CHAPTER 4

## CHAPTER 5

## CHAPTER 6

■■■■

CHAPTER

1

# Electromagnetism

## 1.1 ELECTRIC CURRENT

Electric current is defined as a stream of charged particles-such as electrons or ions-moving through an electrical conductor or space. It is the flow rate of electric charge through a conducting medium with respect to time.

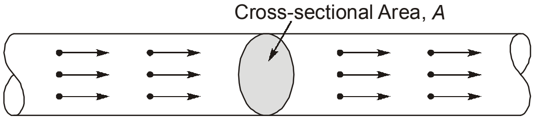
"Electric current may be defined as the time rate of net motion of electric charge across a cross-sectional area.".

The flow of current depends on the conductive medium. For example:

- In **conductor**, the flow of current is due to electrons.
- In **semiconductors**, the flow of current is due to electrons or holes.
- In an **electrolyte**, the flow of current is due to ions.
- In **plasma** – an ionized gas, the flow of current is due to ions and electrons.

i.e., electric current, $i$ = Rate of transfer of electric charge

$$= \frac{\text{Quantity of electric charge transferred during a given time duration}}{\text{Time duration}} = \frac{dQ}{dt}$$



Coulomb is the practical as well as SI unit for measurement of electric charge. One coulomb is approximately equal to sum of $624 \times 10^{16}$ electrons charge.

Since current is the rate of flow of electric charge through a conductor and coulomb is the unit of electric charge, the current may be specified in coulombs per second or Ampere.

Also, $$1e^{-} = 1.602 \times 10^{-19}\ \text{C}$$

## 1.2 ELECTROMOTIVE FORCE AND POTENTIAL DIFFERENCE

### 1.2.1 Electromotive Force (EMF)

The characteristic of any energy source capable of pushing electric charge around a circuit is called electromotive force or EMF, which is the force inside a voltage source that drives current around a circuit. The electromotive force or EMF is the amount of energy provided by a cell to the unit charge. It is denoted by E.

### 1.2.2 Potential Difference (P.D)

When a Coulomb charge flows from one point to another, the potential difference, or voltage, is simply an indication of how much potential energy is gained or lost per coulomb. It's also known as the amount of work required to move potential energy per coulomb from one point to another. The energy released in the movement of a unit quantity of electricity from one place to the other is represented by the potential difference between two points in an electrical or electronic circuit. It is denoted by V.

**NOTE** The important thing to understand is that EMF is the driving force, whereas the potential difference is the outcome of EMF.

In SI system of units, volt is the unit of electromotive force (EMF) and potential difference (P.D).

### 1.2.3 Difference Between EMF and Potential Difference

Both EMF and potential difference are measured in volts but there is a huge difference in their meaning. The main difference between EMF and potential difference is that the energy per unit charge exerted by an energy source is known as the EMF whereas the energy released when a unit quantity of electricity travels from one point to another is known as the potential difference. EMF or electromotive force is referred to as the terminal potential difference when no current flows.

**Key Difference Between EMF and Potential Difference**

| EMF | Potential Difference |
|---|---|
| The quantity of energy delivered to each coulomb of charge is known as the electromotive force. | One coulomb of charge expends a certain amount of energy, which is called the potential difference. |
| The unit of EMF is Volt. | The unit of potential difference is Volt. |
| It is independent of resistance. | It depends upon resistance between two points. |
| It is measured using an emf meter. | It is measured using a voltmeter. |
| The electric, gravitational and magnetic fields are responsible for this. | The electric field is the sole source of potential difference. |

## 1.3 RESISTANCE

Resistance may be defined as that property of a substance which opposes (or restricts) the flow of an electric current (or electrons) through it.

The SI unit of resistance is ohm (Ω), which is defined as resistance between two points of a conductor when a potential difference of one volt, applied between these points, produces in this conductor a current of one ampere, the conductor not being a source of any emf.

When an electric current flows through a bulb or any conductor, the conductor offers some obstruction to the current and this obstruction is known as electrical resistance and is denoted by *R*. Every material has an electrical resistance and this is the reason why conductors give out heat when current passes through it.

According to Ohm's law, there is a relation between the current flowing through a conductor and the potential difference across it. It is given by,

$$V \propto I \quad \Rightarrow V = IR$$

where, $V$ is the potential difference measured across the conductor (in volts)
$I$ is the current through the conductor (in amperes)
$R$ is the constant of proportionality called resistance (in ohms)

Electric charge flows easily through some materials than others. The electrical resistance measures how much the flow of this electric charge is restricted within the circuit.

Resistance of a material: $R = \dfrac{\rho L}{A}$

Where, $\rho$ = Resistivity of material

### 1.3.1 Factors Affecting Electrical Resistance

The electrical resistance of a conductor is dependent on the following factors:

- The cross-sectional area of the conductor. ($A$)
- Length of the conductor. ($L$)
- The material of the conductor. ($\rho$)
- The temperature of the conducting material.

Electrical resistance is directly proportional to length ($L$) of the conductor and inversely proportional to the cross-sectional area ($A$). It is given by the following relation.

## 1.4 OHM'S LAW

Ohm's law states that the voltage across a conductor is directly proportional to the current flowing through it, provided all physical conditions and temperature remain constant.

Mathematically, this current-voltage relationship is written as,

$$V = IR$$

In the equation, the constant of proportionality, $R$, is called Resistance and has units of ohms, with the symbol W.

The same formula can be rewritten in order to calculate the current and resistance respectively as follows:

$$I = \frac{V}{R} \quad \Rightarrow R = \frac{V}{I}$$

Ohm's law only holds true if the provided temperature and the other physical factors remain constant.

Ohm's law cannot be applied to circuits consisting of electronic tubes or transistors because such elements are not bilateral i.e., they behave in different way when the direction of flow of current is reversed as in case of a diode. Ohm's law also cannot be applied to circuits consisting of nonlinear elements such as powdered carbon, thyrite, electric arc etc. For example, for silicon carbide, the relationship between applied voltage (for potential difference) $V$ and current flowing $I$ is given as $V = KI^m$ where $K$ and $m$ are constants and $m$ is less than unity.

### 1.4.1 Calculating Electrical Power Using Ohm's Law

The rate at which energy is converted from the electrical energy of the moving charges to some other form of energy like mechanical energy, heat energy, energy stored in magnetic fields or electric fields, is known as electric power. The unit of power is the watt. The electrical power can be calculated using Ohm's law and by substituting the values of voltage, current and resistance

**Formula to find power**

When the values for voltage and current are given,

$$P = VI$$

When the values for voltage and resistance are given,

$$P = \frac{V^2}{R}$$

When the values for current and resistance are given,

$$P = I^2R$$

### 1.4.2 Ohm's Law Applications

The main applications of Ohm's law are:

- To determine the voltage, resistance or current of an electric circuit.
- Ohm's law maintains the desired voltage drop across the electronic components.
- Ohm's law is also used in DC ammeter and other DC shunts to divert the current.

### 1.4.3 Limitations of Ohm's Law

Following are the limitations of Ohm's law.

- Ohm's law is not applicable for unilateral electrical elements like diodes and transistors as they allow the current to flow through in one direction only.
- For non-linear electrical elements with parameters like capacitance, resistance etc. the ratio of voltage and current won't be constant with respect to time making it difficult to use Ohm's law.

## 1.5 WORK, POWER AND ENERGY

**Work :** For a work to be done, a force must be exerted and there must be motion or displacement in the direction of the force. The work done by a force acting on an object is equal to the magnitude of the force multiplied by the distance moved in the direction of the force.

Work has only magnitude and no direction.

i.e., $$\text{Work done, } W = \text{Force } [\vec{F}] \cdot \text{distance } [\vec{d}] = Fd\cos\theta$$

From work equation, we can say that no work is done if:

- the displacement is zero.
- the force is zero.
- the force and displacement are mutually perpendicular to each other.

The SI or MKS unit of work is the joule, which is defined as the work done when a force of one newton acts through a distance of one metre in the direction of the force. Hence, if a force $F$ acts through distance $d$ in its own direction,

$$W = F\,[\text{newtons}] \times d\,[\text{metres}] = Fd \text{ joules}$$

**Power :** Power is defined as the rate of doing work or the amount of work done in unit time.

The MKS or SI unit of power is the joule/second or watt. In practice, the watt is often found to be inconveniently small and so a bigger unit, the kilowatt is frequently used.

$$1 \text{ kilowatt} = 1{,}000 \text{ watts}$$

**Energy :** Energy is the ability to perform work. Energy can neither be created nor be destroyed, and it can only be transformed from one form to another.

All forms of energy are either kinetic or potential energy. The energy in motion is known as kinetic energy, whereas potential energy is the energy stored in an object and is measured by the amount of work done.

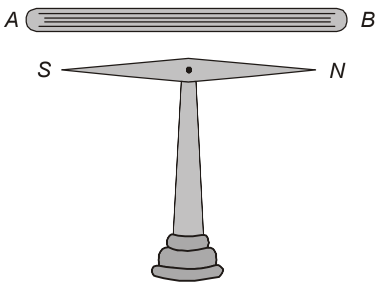
As already stated, in SI system the unit of energy of all forms is joule. Bigger unit of energy is mega joules (MJ) where 1 MJ = $10^6$ J.

**Calorie :** It is the amount of heat required to raise the temperature of one gram of water through 1°C.

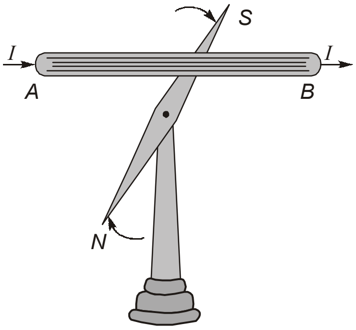
$$1 \text{ calorie} = 4.18 \text{ J} = 4.2 \text{ J}$$

## 1.6 MAGNETIC FIELD DUE TO A CURRENT CARRYING CONDUCTOR

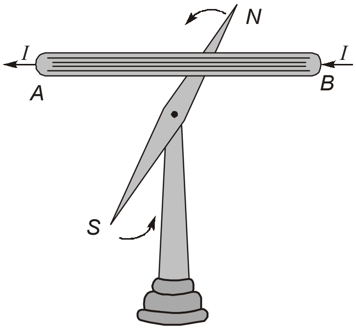
In 1819, it was discovered by a Danish Physicist, Hans Christian Oersted that an electric current is always accomplished by certain magnetic effects.



**(a) No current flow**



**(b) Current flowing from *A* to *B***

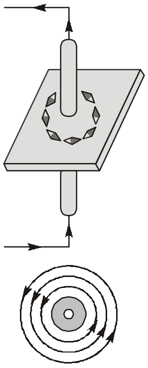


**(c) Current flowing from *B* to *A***

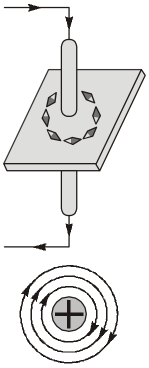
Oersted found that when current is passed through a conductor placed above the magnetic needle, the needle turns in a certain direction, as shown in figures above. He also found that when the direction of flow of current is reversed the magnetic needle also deflects in opposite direction.

Further investigation showed that the field around the current carrying conductor consists of lines of force, which encircles the conductor. It can be proved experimentally by passing a current carrying conductor AB in the card board and plotting the field with the help of magnetic needle on it, as shown in figures below.

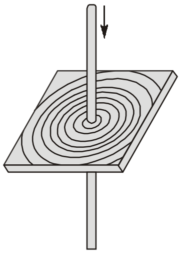
It is observed that when the current is passed through conductor in upward direction, the direction of lines of force is counterclockwise direction (observed from the top of the conductor) and when the current is passed through the conductor in downward direction, the direction of lines of force is clockwise (observed from the top of the conductor).



**(d)**



**(e)**



Magnetic field around
A current carrying counductor

The properties of the lines of magnetic induction around a current carrying conductor are summarized as below:

(i) Lines of magnetic induction are circles, symmetrical about, and concentric with, the axis of the conductor.

(ii) The spacing between the lines of induction decreases as we move closer to the conductor.

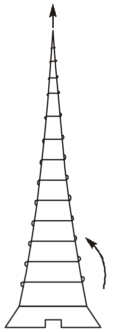
(iii) The direction of lines of magnetic induction depends on the direction of flow of current through the conductor.

(iv) Magnetic induction or flux density depends upon the strength (or magnitude) of the current flowing through the conductor.

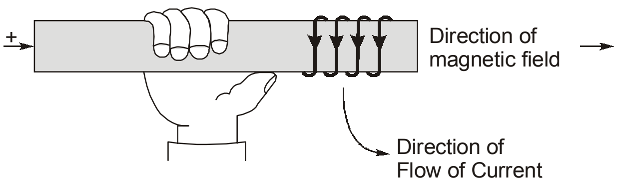
## 1.7 DETERMINATION OF DIRECTION OF MAGNETIC FIELD AROUND A CURRENT CARRYING CONDUCTOR

The direction of lines of force (magnetic field) around a straight current carrying conductor may be determined by any of the following rules :

1. **Corkscrew Rule :** If the right handed corkscrew is held with its axis parallel to the conductor pointing the direction of flow of current and the head of the screw is rotated in such a direction that the screw moves in the direction of flow of current then the direction in which the head of screw is rotated, will be the direction of magnetic lines of force.
2. **Right Hand Rule :** If the current carrying conductor is held in right hand by the observer so that it is encircled by fingers stretching the thumb at right angle to the fingers in the direction of flow of current then finger tips will point the direction of magnetic lines of force, as shown in figure (b).



**(a) Corkscrew Rule**



**(b) Right hand rule**

## 1.8 MAGNETIC FIELD DUE TO A CIRCULAR LOOP

If a single turn wire carrying current is bent in the form of a loop (or ring) as shown in figure. The lines of magnetic induction around it will be concentric circles, leaving the plane of the loop (or ring) on one side and entering on the other. The loop acts as the true magnet having north and south poles.

The direction of magnetic field may be determined by applying either of the two rules namely (i) right hand rule or (ii) corkscrew rule.

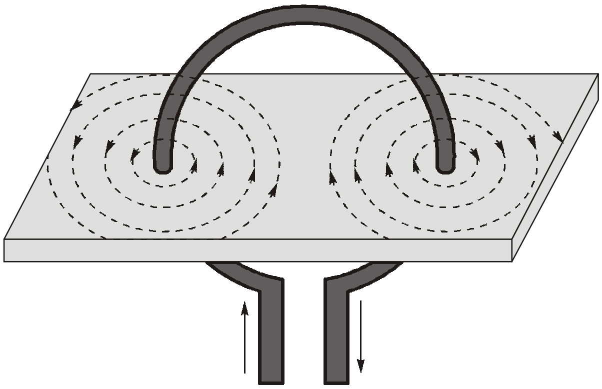


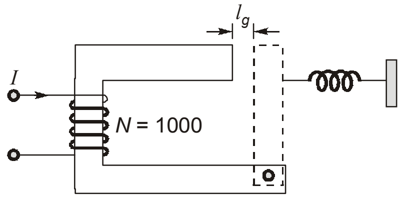
*Fig.: Magnetic Field due to A Circular Loop*

**EXAMPLE : 1.3**

A relay (Given below) has a coil of 1000 turns and an air-gap of area 10 $\text{cm}^2$ and length 1.0 mm. Calculate the rate of change of stored energy in the air-gap of the relay when

(a) Armature is stationary at 1.0 mm from the core and current is 10 mA but is increasing at the rate of 25 A/s.

(b) Current is constant at 20 mA but inductance is changing at the rate of 100 H/s.



***Solution:***

$$L = \frac{\mu_0 N^2 A}{l_g} = \frac{4\pi\times10^{-7}\times(10^3)^2\times10\times10^{-4}}{1\times10^{-3}} = 1.26\ \text{H}$$

(i) Here, $dI/dt = 25$ A/s, $dL/dt = 0$ because armature is stationary.

$$\therefore \qquad \frac{dE}{dt} = LI\frac{dI}{dt} = 1.26\times10\times10^{-3}\times15 = 0.315\ \text{W}$$

(ii) Here, $dL/dt = 100$ H/s, $dI/dt = 0$ because current is constant

$$\therefore \qquad \frac{dE}{dt} = \frac{1}{2}I^2\frac{dL}{dt} = \frac{1}{2}(20\times10^{-3})^2\times100 = 0.02\ \text{W}$$

## OBJECTIVE BRAIN TEASERS

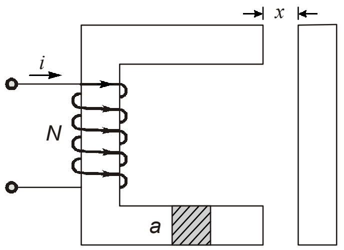
**Q.1** **Assertion (A) :** In an electric circuit, the current is due to the presence of electromotive force.
**Reason (R) :** In a magnetic circuit, the magnetic flux is due to the presence of a magnetomotive force.
(a) Both A and R are true and R is a correct explanation of A.
(b) Both A and R are true but R is not a correct explanation of A.
(c) A is true but R is false.
(d) A is false but R is true.

**Q.2** **Assertion (A):** Leakage flux has a path dominated through the surrounding air.
**Reason (R):** Leakage flux may be defined as that flux which does not follow the intended path in a magnetic circuit.
(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

**Q.3** A conductor 20 cm long moves at right angle to its length at a constant speed of 30 m/s in a uniform magnetic field of flux density 1.2 T. The emf induced in case the conductor motion is normal to the field flux is
(a) 0 volt (b) 28.8 volt
(c) 7.2 volt (d) 14.4 volt

**Q.4** A magnetic circuit with relative permeability of 100 has a core cross-sectional area of 5 $\text{cm}^2$ and mean core length of 25 cm. The coil has 120 turns with an mmf of 1000 AT. The magnetic core flux is
(a) 0.75 mWb (b) 1 mWb
(c) 0.05 mWb (d) 0.25 mWb

**Q.15** In the electromagnetic relay of given figure below the reluctance of the iron path is negligible. The coil self-inductance is given by the expression



(a) $\mu_0 N^2 a/x$ (b) $\mu_0 N/2\,ax$

(c) $\mu_0 N^2 a/2x$ (d) $\mu_0 N^2/2\,ax$

**Q.16** An iron-cored choke with 1 mm air-gap length, draws 1 A when fed from a constant voltage AC source of 220 V. If the length of air-gap is increased to 2 mm, the current drawn by the choke would

(a) become nearly one half

(b) remain nearly the same

(c) become nearly double

(d) become nearly zero

## ANSWERS KEY

**1.** (b) **2.** (a) **3.** (c) **4.** (d) **5.** (b)

**6.** (b) **7.** (b) **8.** (d) **9.** (1498.24)

**10.** (Sol) **11.** (Sol) **12.** (c) **13.** (c) **14.** (b)

**15.** (c) **16.** (c)

## HINTS & EXPLANATIONS

**1. (b)**

$$I = \frac{\text{EMF}}{R} \text{ ( for an electric circuit)}$$

$$\phi = \frac{\text{MMF}}{\text{Reluctance}}$$

(for a magnetic circuit)

**3. (c)**

Given, $\theta = 90°$

$\therefore$ emf induced $= B\,l\,v\sin\theta$

$= 1.2 \times 0.2 \times 30 \times \sin 90°$

$= 7.2$ volt

**4. (d)**

Given, $\mu_r = 100$, $a = 5\text{ cm}^2$, $l = 25$ cm,
$N = 120$ turns, $NI$ = MMF = 1000 AT
We know that,

$$\text{Flux} = \frac{\text{MMF}}{\text{Reluctance}}$$

$$= \frac{NI}{\left(\dfrac{l}{\mu_0 \mu_r A}\right)} = \frac{NI \cdot \mu_0 \mu_r A}{l}$$

$$\text{or, Flux} = \frac{1000 \times 4\pi \times 10^{-7} \times 100 \times 5 \times 10^{-4}}{25 \times 10^{-2}}$$

$$= \frac{4\pi}{5} \times 10^{-4} = 0.25 \text{ mWb}$$

**5. (b)**

Building steel core out of stampings increases the path of eddy currents, which leads to the increase in effective resistance, thereby reducing eddy current losses.

**6. (b)**

It should be noted that each time the conductor passes under a pole, it cuts a flux of 15 mWb. Hence, the flux cut in one revolution is 15 × 4 = 60 mWb. Since conductor is rotating at $\frac{600}{60} = 10$ rps.

Time taken for one revolution is

$$\frac{1}{10} = 0.1 \text{ sec}$$

$$\therefore \quad \text{emf} = \frac{N d\phi}{dt}$$

$$d\phi = 6 \times 10^{-2} \text{ Wb}$$

$$dt = 0.1 \text{ sec}$$

$$e = \frac{1 \times 6 \times 10^{-2}}{0.1} = 0.6 \text{ V}$$

**8. (d)**

Emf induced,

$$e = N\phi\omega$$

Here, $\phi = B \times A$

$= 60 \times 10^{-3} \times 5 \times 10^{-2}$

$= 3 \times 10^{-3}$ Wb

And, $\omega = \dfrac{2\pi}{60}N = \dfrac{2\pi \times 1500}{60} = 50\,\pi$ rad/s

Given, $N$ = Number of turns = 800

So, emf induced,

$$e = 800 \times 3 \times 10^{-3} \times 50\,\pi = 377 \text{ volt}$$

**9. (1498.24)**

Length of iron path,

$$l_i = 30 \text{ cm} = 30 \times 10^{-2} \text{ m}$$

Length of air gap,

$$= 2 \text{ mm} = 2 \times 10^{-3} \text{ m}$$

$$B = NI \times \frac{\mu_o\mu_r}{l}$$

$$NI = \frac{Bl}{\mu_o\mu_r}$$

$$NI_{\text{air}} = \frac{0.8 \times 2 \times 10^{-3}}{4\pi \times 10^{-7}} = 1273.24 \text{ AT}$$

$$NI_{\text{cast steel}} = 750 \text{ AT/m} \times l_i$$

$$= 750 \times 30 \times 10^{-2} = 225 \text{ AT}$$

$$NI_{\text{Total}} = NI_{\text{cast steel}} + NI_{\text{air}}$$

$$= 1498.24 \text{ AT}$$

**10. (Sol)**

(a) The cross-sectional area

$$= \frac{\pi d^2}{4} \times 10^{-4} = \frac{\pi \times 9}{4} \times 10^{-4}$$

$$= 7.068 \approx 7.1 \times 10^{-4} \text{ m}^2$$

The flux density,

$$B = \frac{\phi}{A} = \frac{0.5 \times 10^{-3}}{7.1 \times 10^{-5}} = \frac{5}{7.1}$$

$$= 0.705 \text{ Wb/m}^2$$

∴ AT required = 670 × 0.8 = 536

∴ The current required

$$= \frac{\text{AT}}{N} = \frac{536}{600} = 0.89 \text{ A}$$

(b) Flux without air gap = 0.5 mWb

$$\phi = \frac{NI}{S_i}$$

$$0.5 \times 10^{-3} = \frac{600 \times 0.8933}{S_i}$$

$S_i$ = Reluctance of iron (steel)

$= 1072000$

$S_a$ = Reluctance of air

$$= \frac{2 \times 10^{-3}}{4\pi \times 10^{-7} \times \left(\pi \times \dfrac{d^2}{4}\right)}$$

$= 2251581.9$

$S_T$ = Total reluctance

$= S_i + S_a = 3323581.9$

$\phi_{\text{new}}$ = new flux with air gap

$$\phi_{\text{new}} = \frac{536}{3323581.9}$$

$$\phi_{\text{new}} = 0.16127 \text{ mWb}$$

(c) Ampere turn required = $NI$

$= \phi \times S_T$ (Flux × Total Reluctance)

$= (0.5 \times 10^{-3}) \times (3323581.9)$

$NI = 1661.8$ AT

$$I = \frac{1661.8}{600}$$

$$I = 2.769 \text{ A}$$

**11. (Sol)**

The reluctance,

$$S = \frac{l}{A\mu}$$

∴ The total reluctance

$$= S_1 + S_2$$

$$= \frac{1 \times 10^{-3}}{A\mu_0} + \frac{0.5}{300\,A\mu_0}$$

$$= \frac{8 \times 10^{-3}}{3\,A\mu_0} \text{ AT/Wb}$$

$$\therefore \text{ The total flux} = \frac{\text{Total AT}}{\text{Relutance}} = \frac{200\times 1\times 3\,A\mu_0}{8\times 10^{-3}}$$

∴ The flux density

$$= \frac{600\times\mu_0}{8\times 10^{-3}}\ \text{Wb/m}^2$$

$$= \frac{600\times 4\pi\times 10^{-7}}{8\times 10^{-3}}$$

$$= 94.2\ \text{mWb/m}^2$$

**12. (c)**

In order to reduce the eddy current losses, laminations made in the core are insulated from one-another by thin layers of varnish.

**13. (c)**

$$\phi \propto \frac{V}{f}, \text{ i.e., flux} \propto \frac{\text{Voltage}}{\text{Frequency}}$$

**14. (b)**

$$\because \quad W = \frac{1}{2}\phi^2 S$$

$$\therefore \quad W \propto S\,(\text{Reluctance})$$

**15. (c)**

$$\phi = \frac{NI}{S} = \frac{Ni}{\dfrac{2x}{\mu_o a}}$$

$$= \frac{Ni\mu_o a}{2x}$$

$$\because \quad N\phi = Li$$

$$\therefore \quad L = \frac{N\phi}{i} = \frac{N^2\mu_o a}{2x}$$

**16. (c)**

$$\phi = \frac{NI\mu_o A}{l}$$

(ignoring reluctance of iron)

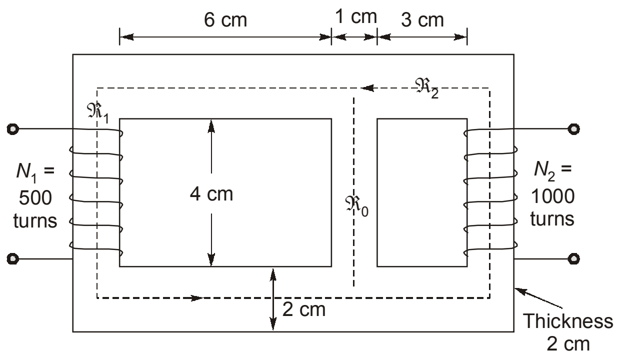
$$I = \frac{l\phi}{N\mu_o A}$$

$$I \propto l$$

$$I' = 2I \text{ for } l' = 2l$$

## CONVENTIONAL BRAIN TEASERS

**Q.1** For the magnetic circuit of figure find the self and mutual inductances between the two coils. Core permeability = 1600.



**1. (Sol)**

$$l_1 = (6 + 0.5 + 1)\times 2 + (4 + 2) = 21 \text{ cm}$$

$$l_2 = (3 + 0.5 + 1)\times 2 + (4 + 2) = 15 \text{ cm}$$

$$l_0 = 4 + 2 = 6 \text{ cm}$$

$$R_1 = \frac{21\times10^{-2}}{4\pi\times10^{-7}\times1600\times2\times2\times10^{-4}} = 0.261\times10^6$$

$$R_2 = \frac{15\times10^{-2}}{4\pi\times10^{-7}\times1600\times2\times2\times10^{-4}} = 0.187\times10^6$$

$$R_0 = \frac{6\times10^{-2}}{4\pi\times10^{-7}\times1600\times1\times2\times10^{-4}} = 0.149\times10^6$$

(i) Coil 1 excited with 1 A

$$R = R_1 + R_0 \parallel R_2$$

$$= 0.261 + 0.1871 \parallel 0.149 = 0.344\times10^6$$

$$\phi_1 = \frac{(500\times1)}{(0.344\times10^6)} = 1.453 \text{ mWb}$$

By flux division (similar to current division) :

$$\phi_{21} = \phi_2 = \frac{1.453\times0.149}{(0.149+0.187)} = 0.64 \text{ mWb}$$

$$L_{11} = N_1\phi_1 = 500\times1.453\times10^{-3} = 0.7265 \text{ H}$$

$$M_{21} = N_2\phi_{21} = 1000\times0.649\times10^{-3} = 0.64 \text{ H}$$

(ii) Coil 2 excited with 1 A

$$R = R_2 + \frac{(R_0R_1)}{(R_0R_1)}$$

$$= \frac{0.187+(0.149\times0.281)}{(0.149+0.281)}\times10^6 = 0.284\times10^6$$

$$\phi_2 = \frac{(1000\times1)}{(0.284\times10^6)} = 3.52 \text{ mWb}$$

$$L_{22} = N_2\phi_2 = 1000\times3.52\times10^{-3} = 3.52 \text{ H}$$

$$M_{12} = M_{21} \text{ (bilateral)} = 0.65 \text{ H}$$

**Q.2** An electromagnet of square cross-section similar to the one shown in figure below has a tightly wound coil with 1500 turns. The inner and the outer radii of the magnetic core are 10 cm and 12 cm, respectively. The length of the air gap is 1 cm. If the current in the coil is 4 A and the relative permeability of the magnetic material is 1200, determine the flux density in the magnetic circuit.