BEEE-UNIT 2

D.C Machines & A.C Machines	
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Sinusoids, Generation of AC, Average, RMS values, Form and peak factors	Sinusoids, Generation of AC, Average, RMS values, Form and peak factors
Analysis of single phase AC circuit, Real, Reactive, Apparent power, Power factor	Analysis of single phase AC circuit, Real, Reactive, Apparent power, Power factor
Magnetic materials, B-H Characteristics Simple magnetic circuits	Magnetic materials, B-H Characteristics Simple magnetic circuits
Faraday's laws, induced emfs and inductances.	Faraday's laws, induced emfs and inductances.
1 - phase transformers: Construction, types, ideal, practical transformer	1 - phase transformers: Construction, types, ideal, practical transformer
EMF equation, Regulation, Efficiency	EMF equation, Regulation, Efficiency
Problem Solving Session	Problem Solving Session
Lab 4: Transformer Operation, Efficiency	Lab 4: Transformer Operation, Efficiency
Construction, working of DC Generators	Construction, working of DC Generators
Types of DC generators	Types of DC generators
Characteristics of Generators	Characteristics of Generators
Armature reaction, Losses	Armature reaction, Losses
Power stages of DC generators	Power stages of DC generators

GENERATION OF ALTERNATIVE EMF

Sinusoidal emf or Sinusoidal voltage

Consider a coil of n turns placed in a magnetic field of maximum value ϕ_m Webers [see Fig. 4.1 (a)]. The coil is initially along the reference axis. In this position, the field is perpendicular to the plane of the coil.

Let the coil be rotated in the anticlockwise direction with an angular velocity of ω rad/sec.

When the coil is along the reference axis at $\omega t = 0$, it is called as zero e.m.f. position. This is because the movement of the coil at this instant $\omega t = 0$ is along the field.

Let at any instant t sec. the coil takes a position as shown in Fig. 4.1(b).

At this instant, the coil makes an angle $\theta = \omega t$ with the reference axis.

At this position, the normal component of the mangnetic flux with respect to the plane of the coil is equal to

$$\phi_m \cos \theta \qquad (\therefore \quad \theta = \omega t)$$

The normal component = $\phi_m \cos \omega t$

Flux linkages (ψ) at this instant (y) is equal to $N\phi_m \cos \omega t$. According to Faraday's law.

The emf induced in the coil at the instant under consideration.

$$e = -\frac{d\psi}{dt} = \frac{-d}{dt}(N\phi_m \cos \omega t)$$

$$= -N\phi_m \omega(-\sin \omega t)$$

$$e = (N\phi_m \omega) \sin \omega t \tag{4.1}$$

With the above expression, we can calculate the emf induced at various instants.

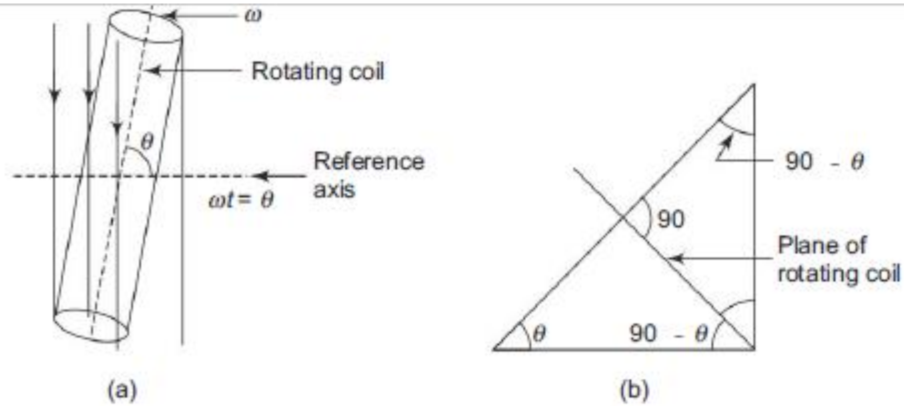


Fig. 4.1

When $\omega t = 0$ or $180°$

$$= (N\phi_m \omega) \sin 0 = (N\phi_m\, \omega) \sin 180°$$

$$e = 0$$

when $\omega t = 90°$ $e = (N\phi_m\omega) \sin 90°$

when $\omega t = 270°$ $e = N\phi_m\omega \sin (270°)$

$$e = -N\phi_m\omega$$

Let $N\phi_m\omega = E_m$ denote the maximum value of induced emf then from Eq. (4.1) we can write,

Instantaneous emf $\quad e = E_m \sin \omega t$ (Refer Fig. 4.2) $\quad$ (4.2)

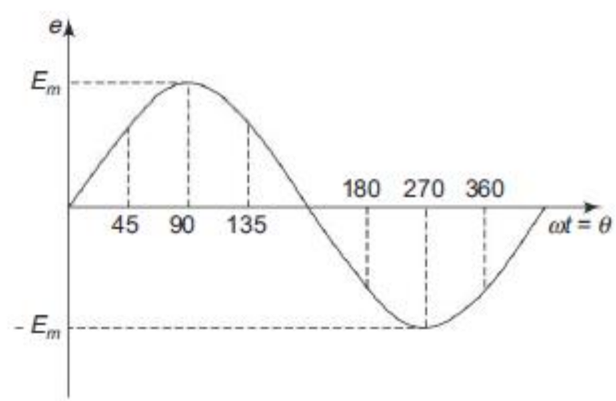


Fig. 4.2 Alternating emf wave for one complete cycle

4.2 TERMINOLOGY

1. Waveform A waveform is a graph in which the instantaneous value of any quantity is plotted against time. Examples of waveforms are shown in Fig. 4.3.

2. Alternating Waveform This is a wave which reverses its direction at regularly recurring intervals, e.g. Fig. 4.3(a).

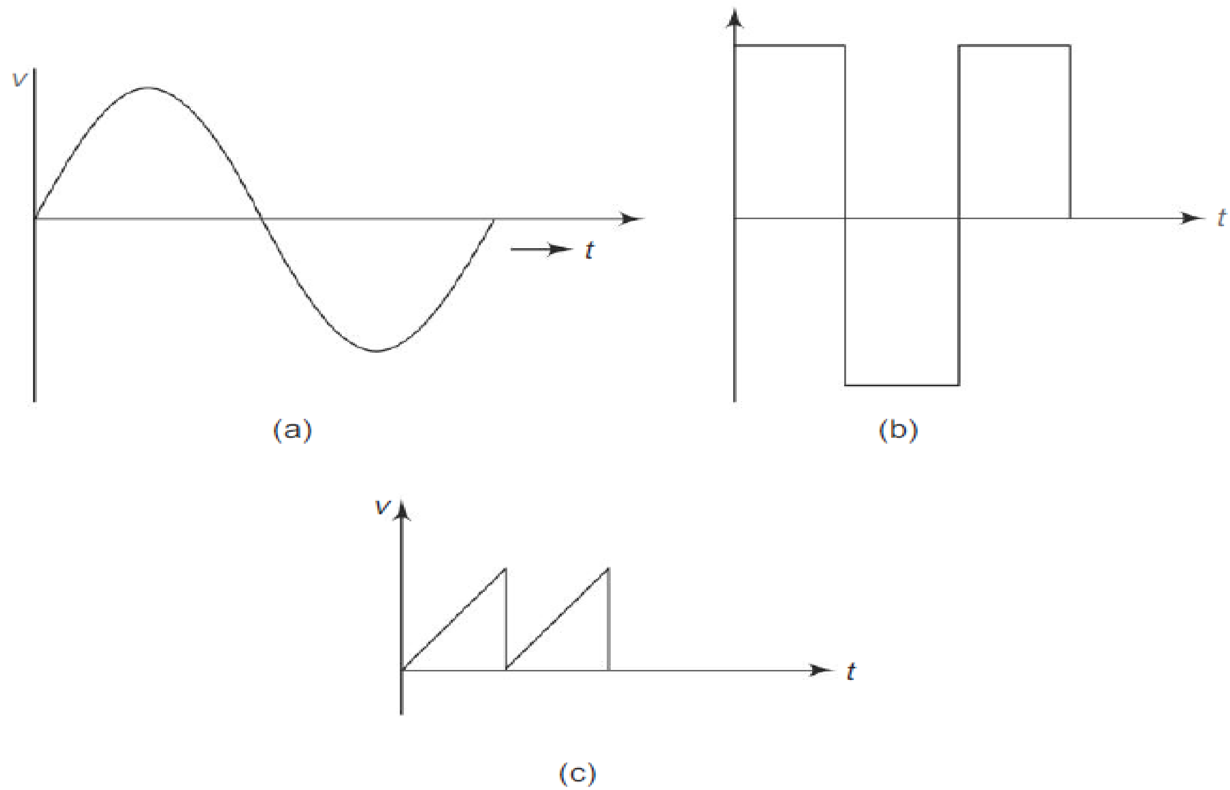


Fig. 4.3 (a) Sinusoidal waveform (b) Rectangular waveform (c) Sawtooth waveform

3. *Periodic Waveform* Periodic waveform is one which repeats itself after definite time intervals.

4. *Sinusoidal and Non-Sinusoidal Waveform*

Sinusoidal waveform It is an alternating waveform in which sine law is followed.

Non-sinusoidal waveform It is an alternating waveform in which sine law is not followed.

5. *Cycle* One complete set of positive and negative halves constitute a cycle.

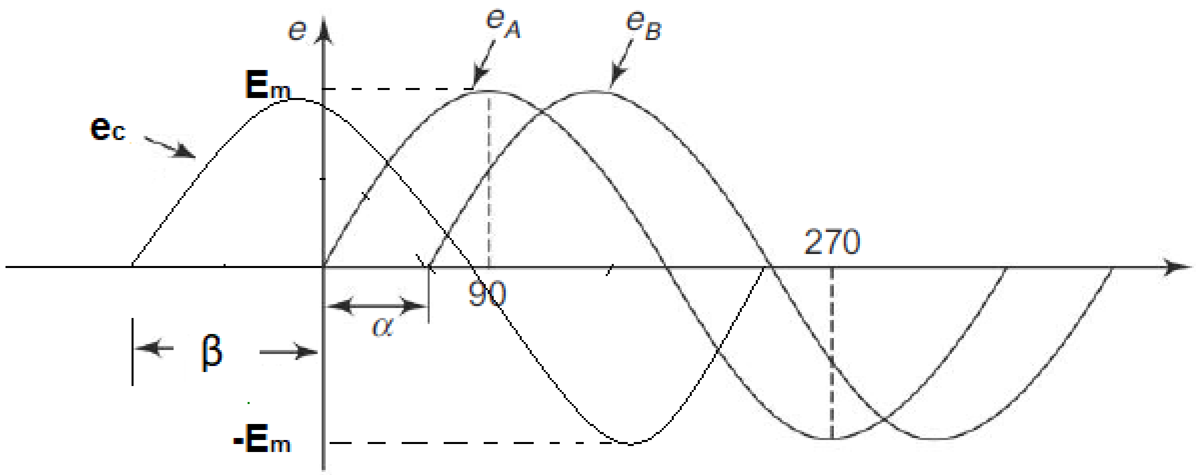
6. *Amplitude* The maximum positive or negative value of an alternating quantity is called the amplitude.

7. *Frequency* The number of cycles per second of an alternating quantity is known as frequency. Unit for frequency is expressed as c/s or Hertz (Hz).

8. *Period (T)* Time period of an alternating quantity is the time taken to complete one cycle. Time period is equal to the reciprocal of frequency. Time period is expressed in secs.

9. *Phase* The phase at any point on a given wave is the time that has elapsed since the quantity has last passed through zero point of reference and passed positively.

10. *Phase Difference* The term is used to compare the phase of two waveforms or alternating quantities.



$$e_A = E_m \sin \omega t$$ Voltage A is reference

$$e_B = E_m \sin(\omega t - \alpha)$$ Voltage B lags voltage A by an angle α

$$e_c = E_m \sin(\omega t + \beta)$$ Voltage C leads voltage A by an angle β

ROOT MEAN SQUARE (RMS) OR EFFECTIVE VALUE

Definition Effective or RMS value of an alternating current is deifned by that steady value of current (dc) which when flowing in a given circuit for a given time produces the same heat as would be produced by the alternating current flowing in the same circuit for the same time.

Method to Obtain the RMS Value for Sinusoidal Currents

Let the alternating current be represented by

$$i = I_m \sin \omega t$$

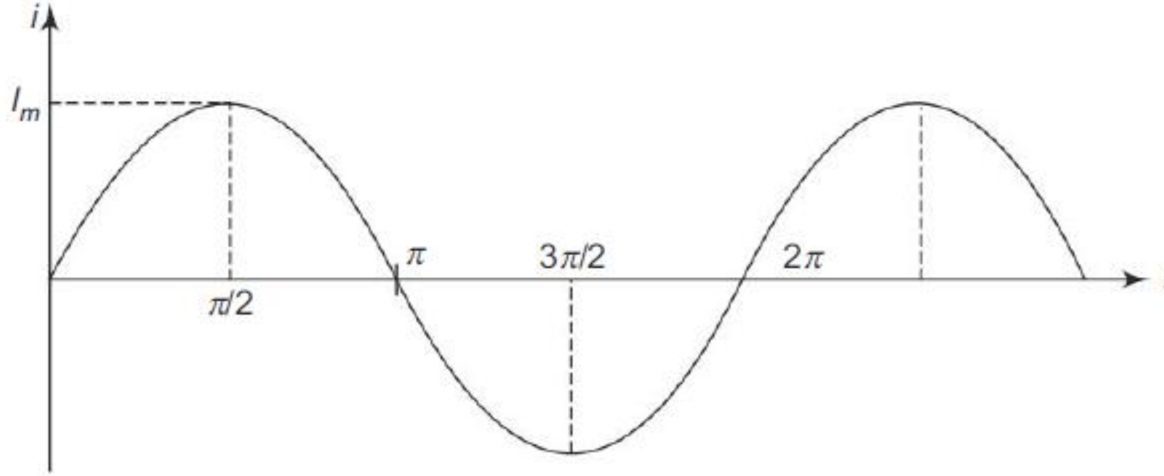
$$= I_m \sin \theta \, (\theta = \omega t)$$

$$i^2 = I_m^2 \sin^2 \theta$$

Mean square of $\quad \text{AC} = \int_0^{2x} \frac{I_m^2 \sin^2 \theta}{2\pi} d\theta$

$$= \frac{I_m^2}{2\pi} \int_0^{2\pi} \sin^2 \theta \, d\theta$$

$$= \frac{I_m^2}{2\pi} \int_0^{2\pi} \frac{I - \cos 2\theta}{2} \, d\theta$$



$$= \frac{I_m^2}{2\pi}\left[\frac{\theta}{2} - \frac{\sin 2\theta}{4}\right]_0^{2\pi}$$

$$= \frac{I_m^2}{2\pi}\frac{2\pi}{2} = \frac{I_m^2}{2}$$

RMS value of the alternating sinusoidal current is

$$I = \sqrt{\frac{I_m^2}{2}} = \frac{I_m}{\sqrt{2}} = 0.707\, I_m$$

$$I_{\text{RMS}} = 0.707\, I_m$$

Similarly, For a sinusoidal voltage

$$V_{\text{RMS}} = \frac{V_m}{\sqrt{2}} = 0.707\, V_m$$

AVERAGE VALUE OF AC

Definition The average value of an ac is given by that steady current which transfers across a circuit the same charge as would be transferred by the ac across the same circuit in the same time.

Method to Obtain the Average Value for Sinusoidal Current

Let $$i = I_m \sin \theta$$

Since this is a symmetrical wave it has two equal half cycles namely positive and negative halves.

Considering one half cycle for this symmetrical wave the average value is obtained by

$$I_{av} = \frac{1}{\pi}\int_0^{\pi} i d\theta = \frac{1}{\pi} I_m \sin \theta \, d\theta$$

$$= \frac{I_m}{\pi} (-\cos \theta)_0^x$$

$$= \frac{I_m}{\pi}(1 + 1) = \frac{I_m}{\pi} \times 2$$

$$I_{av} = \frac{2 I_m}{\pi}$$

$$I_{av} = 0.637 I_m$$

where I_m is the maximum value of current.

For a sinusoidal voltage wave,

$$V_{av} = 0.637 V_m.$$

Form Factor and Peak Factor The relation between average, RMS and maximum values can be expressed by two factors namely form factor and peak factor. Form factor (K_f): Form factor is defined as the ratio of RMS value to the average value.

i.e. $$\text{Form factor} = \frac{\text{RMS value}}{\text{Average value}}$$

Peak factor or Cost factor) (K_p): Peak factor is defined as the ratio of peak value to the R.M.S. value.

i.e. $$\text{Peak factor} = \frac{\text{Peak value}}{\text{RMS value}}$$

For a sinusoidal wave,

$$\text{Form factor } (K_f) = \frac{0.707\, I_m}{0.637\, I_m} = 1.11$$

$$\text{Peak factor } (K_f) = \frac{I_m}{I_m/\sqrt{2}} = \sqrt{2} = 1.414.$$

ANALYSIS OF AC CIRCUIT

1. Real power / True power / Average power/ Power

$P = V\,I\,COS\,\Phi$ **or**

$P = V_{RMS}\,I_{RMS}\,COS\,\Phi$

$P = |V|\,|I|\,COS\,\Phi$

$P = I^2 R$

Unit: Watts

Where Φ Angle between voltage and current

2. **Reactive Power** $Q = V\,I\,SIN\,\Phi$

$Q = V_{RMS}\,I_{RMS}\,SIN\,\Phi$

Unit: VAR

3. Apparent power $S = VI$

$S = \sqrt{P^2 + Q^2}$

Unit : VA

4. Power Factor = $COS\,\Phi$

$= \dfrac{R}{|Z|}$

No Unit

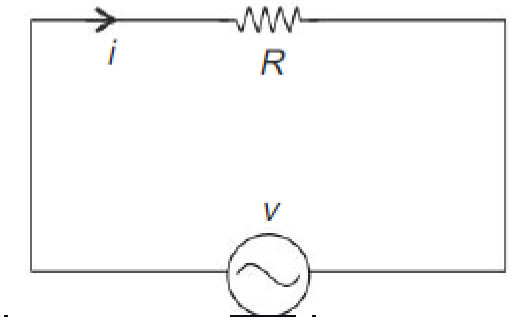
Where Φ Angle between voltage and current

Where $|Z| = R^2 + (X_L - X_C)^2$

ANALYSIS OF AC CIRCUIT

The response of electric circuits to alternating current can be studied by passing an alternating current through the basic circuit elements resistor (R), inductor (L) and capacitor (C).

1 . Pure Resistive Circuit



Let the sinusoidal voltage applied across the resistance be

$$v = V_m \sin \omega t$$

The resulting current has an instantaneous value, i By Ohm's law,

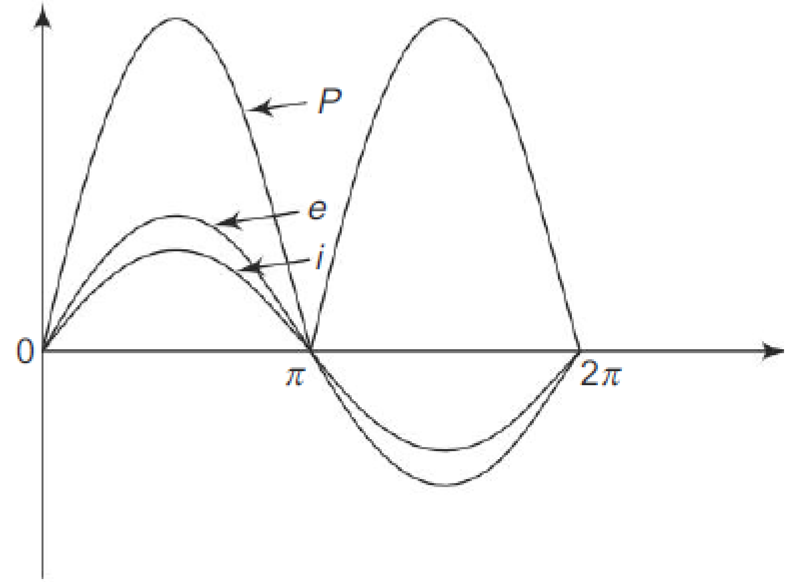
$$i = I_m \sin \omega t$$

where $I_m = \frac{V_m}{R}$

Phasor Representation

In a pure resistive circuit,there is no phase difference between the voltage applied and the resulting current, i.e the phase angle $\phi = 0$. .If the voltage is taken as the reference phasor, thephasor representation for voltage and current in a pure resistive circuit is given in Fig.

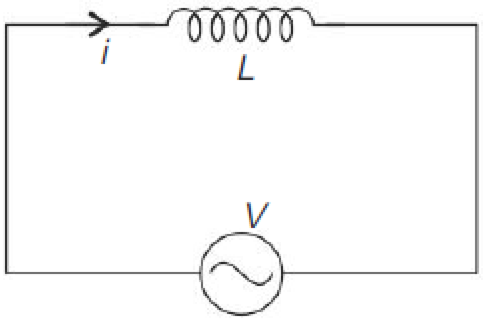
Waveform Representation



Power Factor It is the cosine of the phase angle between voltage and current
$\cos \phi = \cos 0 = 1$ (unity)

2. Pure Inductive Circuit

Consider the circuit of Fig. (4.16). In this circuit, an alternating voltage is applied across a pure inductor of self inductance L Henry.



Let the applied alternating voltage be

$$v = V_m \sin \omega t$$

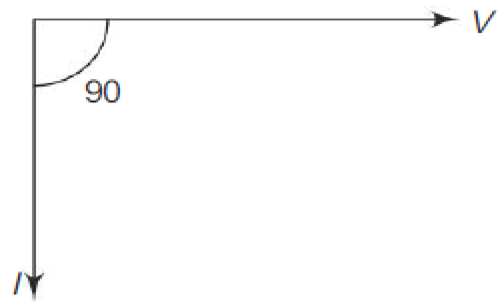
We know that the self induced emf always opposes the applied voltage.

$$v = L \frac{di}{dt}$$

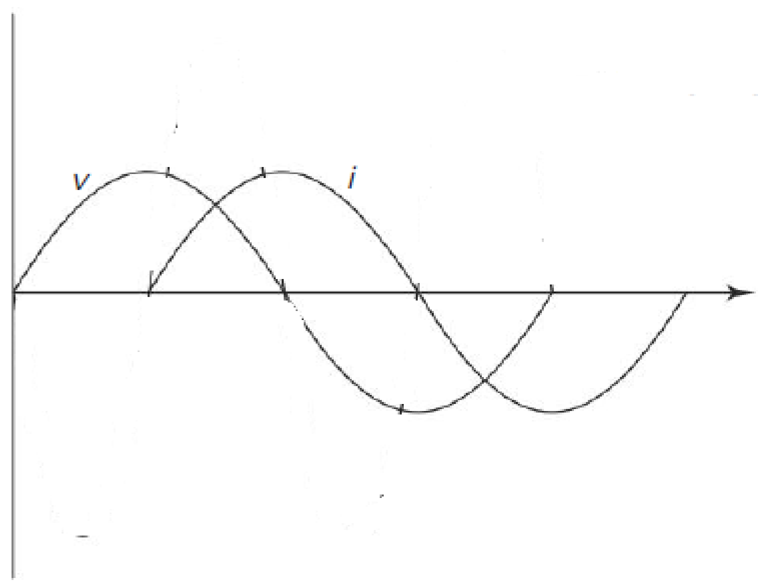
$$\therefore \quad i = \frac{1}{L}\int \cdot v \, dt = I_m \sin(\omega t - \pi/2)$$

we can say that the current through an inductor lags the applied voltage by 90°.

Phasor Representation Taking the voltage phasor as reference, the current phasor is shown to lag the voltage by 90° (Fig. 4.18).



Waveform Representation The current waveform is lagging behind the voltage waveforms by 90°.



Since $\phi = 90^\circ$ Real power P=0

The pure inductor does not consume any real power

Power Factor In a pure inductor the phase angle between the current and the voltage phasors is 90°.

i.e. $\phi = 90^\circ$; $\cos\theta = \cos 90^\circ = 0$

Thus the power factor of a pure inductive circuit is zero lagging.

3 Pure Capacitive Circuit

Consider the circuit of Fig. 4.19 in which a capacitor of value C Farad is connected across an alternating voltage source.

Let the sinusoidal voltage applied across the capacitance be

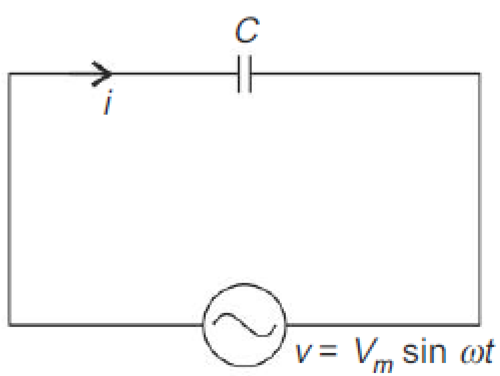
$$v = V_m \sin \omega t$$

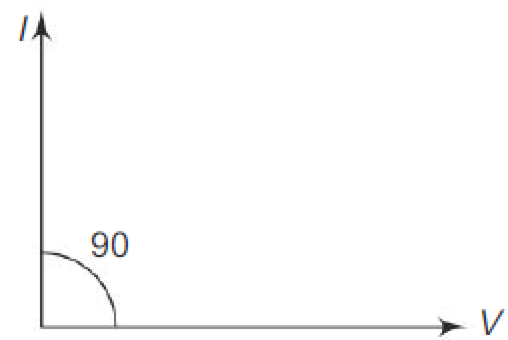
The characteristic equation of a capacitor is

$$V = \frac{1}{C}\int i\,dt$$

$$i = I_m \sin(\omega t + 90)$$

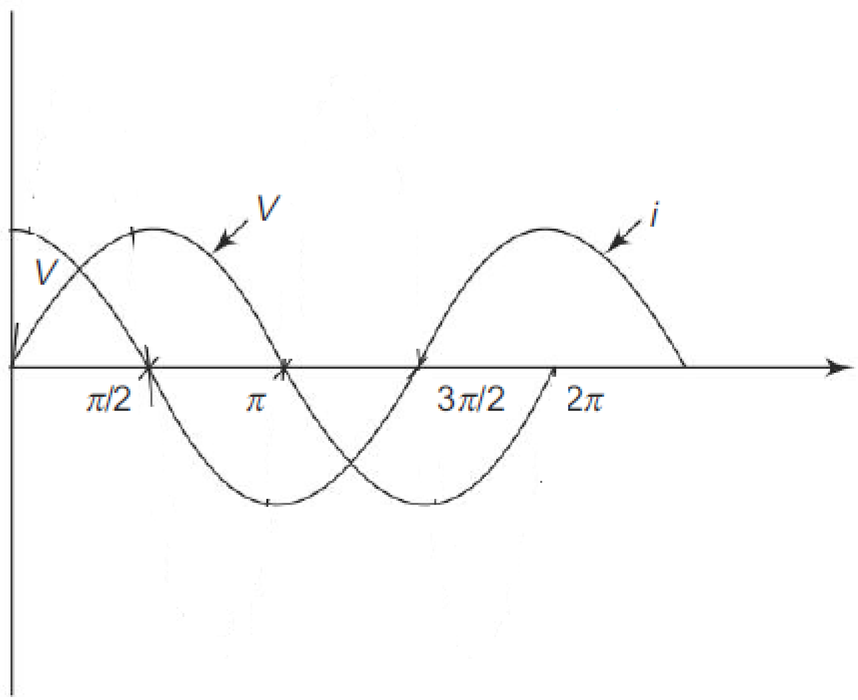
The current in a pure capacitor leads the applied voltage by an angle of 90°.



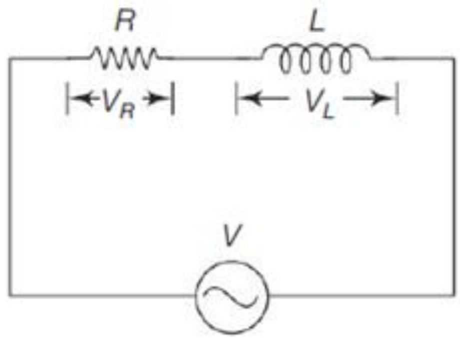


Phasor Representation In the phasor representation, voltage phasor is taken as the reference. The current phasor leads an angle of 90°

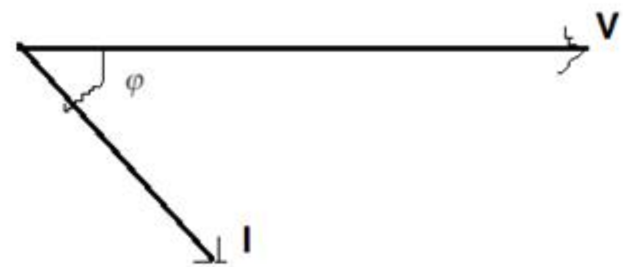
Waveform Representation The current waveform is ahead of the voltage waveform by an angle of 90°.



4 R–L SERIES CIRCUIT



Phasor

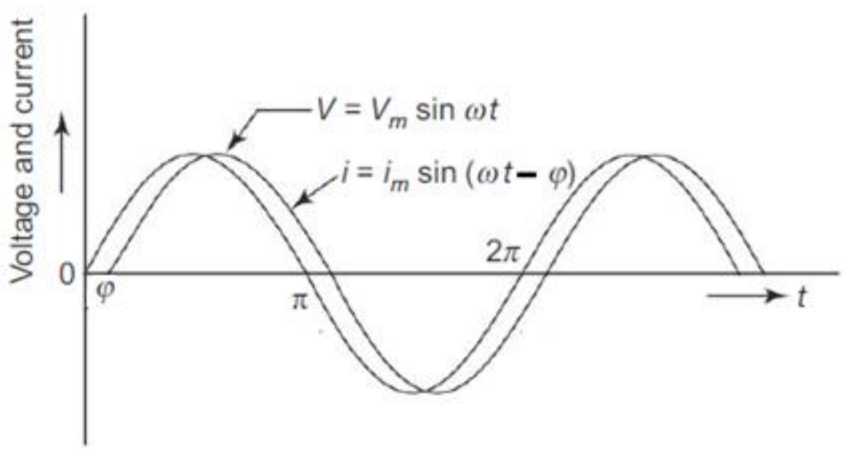


Let $v = V_m \sin \omega t$ be the applied voltage

then the current equation is

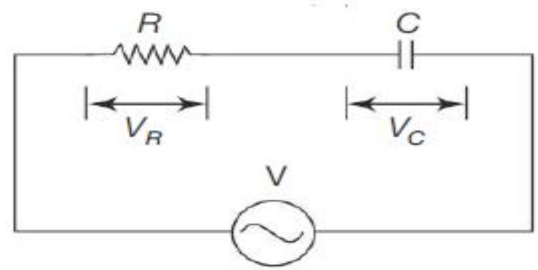
$$i = I_m \sin(\omega t - \phi)$$

Waveform



The current I lag Voltage V by an angle φ

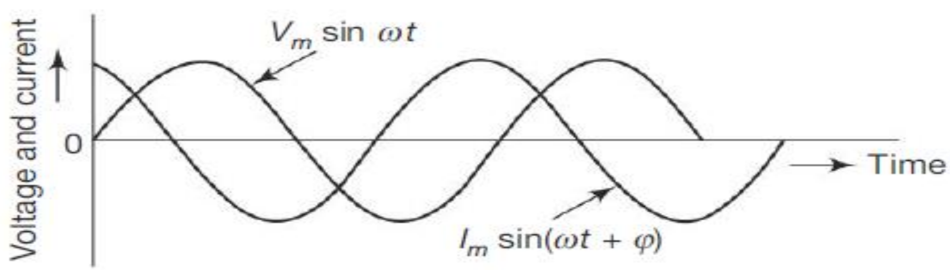
5 R-C SERIES CIRCUIT



Let $v = V_m \sin \omega t$ be the applied voltage

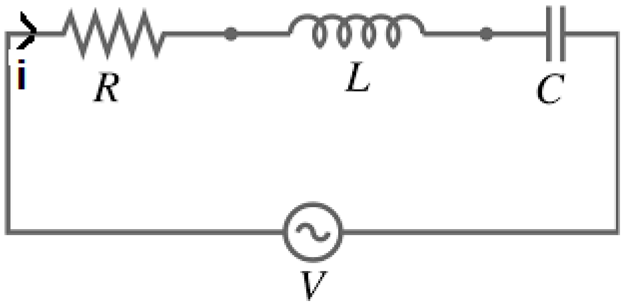
Then the current equation is $i = I_m \sin (\omega t + \phi)$

Waveform



Phasor

6. R-L-C SERIES CIRCUIT



Depends upon the value of X_L and X_C, the circuit behaves

If $X_L > X_C$, then the circuit behaves as RL circuit

If $X_L < X_C$, then the circuit behaves as RC circuit

Impedance $Z = R + j X_L - j X_C$ Unit: Ω

or

$Z = R + j(X_L - X_C)$

Where i or j = $\sqrt{-1}$

$X_L = 2\pi fL$ Unit: Ω

$X_C = \dfrac{1}{2\pi fC}$ Unit: Ω

f-Supply Frequency in Hz

PROBLEMS

1 A voltage 100 sin ωt is applied to a 10-ohm resistor. Find the instantaneous current, the current (rms) and the average power.

Solution: V or $e = 100 \sin \omega t$

$R = 10$ ohms

$i = e/R = 100/10 \sin \omega t = 10 \sin \omega t$ A

$I_{rms} = I_m / \sqrt{2}$

$= 10 / \sqrt{2}$

$= 7.07$ A

P= V I COS ϕ

$= \frac{100}{\sqrt{2}} \times \frac{10}{\sqrt{2}}$ X COS 0

= 500 Watts

2. A voltage v = 340 sin 314t is applied to a circuit and the resulting current, i = 42.5 sin 314t. Identify and hence find the values of the component. Find the value of power consumed.

Solution: $v = 340 \sin 314t = \frac{340}{\sqrt{2}} \angle 0$ Volts $= 240 \angle 0$ Volts

$i = 42.5 \sin 314\,t = \frac{42.5}{\sqrt{2}} \angle 0$ Amps $= 30 \angle 0$ Amps

From the above voltage and current equations, we find that they are in phase with each other. Thatis angle between V and I is 0. Hence, the basic component connected in the circuit must be resistor.

$$R = V / I$$

$$= 240.4 / 30$$

$$= 8\ \Omega$$

Note

$$V_{rms} = |V| = V$$

$$P = VI \cos \Phi$$

$$= 240. \times 30 \times \cos 0$$

$$= 7200 \text{ Watts}$$

$$P = I^2 R$$

$$= 30 \times 30 \times 8$$

$$= 7200 \text{ Watts}$$

3 In a series circuit containing pure resistance and pure inductance. the current and voltage expressed as $i\,(t) = 5 \sin\,(314\,t + 2\,\pi/3)$ and $V\,(t) = 20\,(314\,t + 5\,\pi/6)$.

(i) What is the impedance of the circuit?

(ii) What are the values of resistance, inductance and power factor?

(iii) What is the average power drawn by the circuit?

Solution

$$v(t) = 20 \sin\,(314t + 5\,\pi/6)$$

$$i(t) = 5 \sin\,(314t + 2\,\pi/3)$$

$$\text{Phase angle of voltage} = \frac{5\pi}{6}\ \text{radians} = 5 \times \frac{180^\circ}{6} = 150^\circ$$

$$\text{Phase angle of current} = \frac{2\pi}{3}\ \text{radians} = 2 \times \frac{180^\circ}{3} = 120^\circ$$

$$V = \frac{20}{\sqrt{2}} \angle 150^\circ \text{ Volts} = 14.14 \angle 150^\circ \text{ Volts}$$

$$I = \frac{5}{\sqrt{2}} \angle 120^\circ \text{ Amps} = \qquad \text{Amps}$$

Current lags the voltage by 150 –120° = 30°.

Lagging p.f. means that it is an R–L circuit.

$$Z = V / I$$

$$= \frac{14.14 \angle 150^\circ}{3.53 \angle 120^\circ} = 3.46 + j\,2 \text{ Ohms}$$

$$= R + j X_L$$

Therefore R= 3.46 Ohms

X_L = 2 Ohms

X_L = 2 Ohms

$\omega L =$ 2 Ohms

314L = 2 Ohms

ω = 314 rad/s [given]

L= 2/314
=6.36 mH

Power Factor = COS Φ

= COS 30

= 0.866 [LAGGING]

Average Power P = VI COS Φ

= 14.14 x 3.53 x cos 30
= 43.22 Watts

$P = I^2 R$

$= 3.53^2$ X 3.46

= 43.22 Watts

4. Find the circuit constants of a two element series circuit which consumes 700 W with 0.707 leading p.f. The applied voltage is $V = 141.4 \sin 314\, t$.

Solution

$$v = 141.4 \sin 314t$$

$$P = 700 \text{ W}, \quad \text{p.f.} = 0.707 \text{ leading}$$

Leading p.f. means $R\text{–}C$ circuit

Max. value of supply voltage = 141.4 V

R.M.S. value of supply voltage $= \dfrac{141.4}{\sqrt{2}} = 99.98$ V

$$\cos\phi = 0.\,707 \text{ leading; Power} = VI\cos\phi$$

$$700 = 99.98 \times I \times 0.707; \quad I = 9.9 \text{ A}$$

Impedance $\quad |Z| = \dfrac{V}{I} = \dfrac{99.98}{9.9} = 10.09$ ohms

$$\cos\phi = \frac{R}{|Z|} \Rightarrow R = |Z|\cos\phi$$

$$R = 10.09 \times 0.707 = 7.13\ \Omega$$

$$X_C = \sqrt{Z^2 - R^2} = \sqrt{10.09^2 - 7.13^2} = 7.13 \text{ ohms}$$

$$\frac{1}{\omega C} = 7.13; \quad \frac{1}{314 \times C} = 7.13 \Rightarrow C = \frac{1}{314 \times 7.13}$$

$$C = 4.466 \times 10^{-4} \text{ F}$$

$$= 446.6 \times 10^{-6} \text{ F}$$

$$C = 446.6 \, \mu\text{F}$$

ANOTHER METHOD IN NEXT PAGE

ANOTHER METHOD

$$v = 141.4 \sin 314t$$

$$P = 700 \text{ W}, \quad \text{p.f.} = 0.707 \text{ leading}$$

Leading p.f. means $R-C$ circuit

Max. value of supply voltage = 141.4 V

R.M.S. value of supply voltage $= \dfrac{141.4}{\sqrt{2}} = 99.98$ V ; $V = 99.98 \angle 0^\circ$ V

$$\cos\phi = 0.707 \text{ leading; Power} = VI\cos\phi$$

$$700 = 99.98 \times I \times 0.707; \quad I = 9.9 \text{ A} ; \quad I = 9.9 \angle 45^\circ \text{ A}$$

Impedance $Z = V / I$ — Since Current is leading, it is $+45^\circ$

$$= \frac{99.98 \angle 0^\circ}{9.9 \angle 45^\circ}$$

$$= 7.13 - j\,7.13 \text{ Ohms}$$

$$= R - j\,X_C$$

$$R = 7.13\ \Omega \qquad X_C = 7.13 \text{ ohms}$$

$$\frac{1}{\omega C} = 7.13; \quad \frac{1}{314 \times C} = 7.13 \Rightarrow C = \frac{1}{314 \times 7.13}$$

$$C = 4.466 \times 10^{-4} \text{ F}$$

$$= 446.6 \times 10^{-6} \text{ F}$$

$$C = 446.6\ \mu\text{F}$$

3.12 MAGNETIC MATERIALS

Magnetic field is present around a current carrying conductor. It is also exist around magnet. An electron revolving around the nucleus of its atom in its orbit forms a tiny electric current loop. This current loop produces a magnetic field. Most of the substances would exhibit magnetic effects and some of them are magnetically weak. Depending on their magnetic behaviour, substances can be classified into three groups. They are

1. diamagnetic
2. paramagnetic
3. ferromagnetic

The metals and other elements having slight magnetic properties are called ***diamagnetic*** materials in which the magnetization is opposite to the applied field. If the magnetization is in the same direction as the applied field, such materials are called as ***paramagnetic*** materials. Infact these two materials which have feeble magnetic effects are called non-magnetic materials. Ferro magnetic materials show very strong magnetic effects. THe magnetization is in the same direction as the field. Iron, Steel, Nickel and Cobalt are known as ferromagnetic materials.

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Relative permeability decides the material which belongs to whether diamagnetic, paramagnetic or ferromagnetic. For vacuum, $\mu_r = 1$, vacuum is taken as reference medium.

If $\mu_r \leq 1$, the materials are diamagnetic

If $\mu_r \geq 1$, the materials are paramagnetic

If $\mu_r >> 1$, the materials are ferromagnetic.

Substances classified according to their relative permeability are tabulated in Table 1.

Table-1

Classification of substances according to their relative permeability

Substance	Magnetic type	Relative permeability (μ_r)
Silver	Diamagnetic	0.99998
Copper	Diamagnetic	0.999991
Vacuum	Non-magnetic	1
Aluminium	Paramagnetic	1.00002
Palladium	Paramagnetic	1.0008
Cobalt	Ferromagnetic	250
Nickel	Ferromagnetic	600

3.13 MAGNETIZATION CURVE

The ratio between B and H may be constant for all values of H, especially in the case of ferromagnetic materials. The characteristic curve showing the variation of flux density (B) with field intensity (H) is called ***Magnetization Curve.***

Consider a toroid with ferromagnetic core which has primary and secondary coils. The primary coil is excited by a variable DC power supply which produces the change in field intensity H and its corresponding effect can be measured by a flux meter at the secondary coil as shown in Fig.3.11(a). The value of H can be increased or decreased by increasing or decreasing the current through the toroid. Now H is increased from zero to a certain maximum value and the corresponding value of B is noted. This is represented as **oc** in B-H curve as shown in Fig.3.11 (b). The point **c** is called magnetic saturation.

If H is reduced to zero gradually, B will not decrease to zero but has a value **od**. This is called ***residual*** or ***remanent*** value. In order to bring down the value of to zero (i.e. to demagnetize the toroid), H has to be applied in reverse (negative) direction. When H is reversed, then B is reduced to zero at point **e**. The field at **e** ($H = -H_e$) is called *Coercive force.* The value of H is further increased in the negative direction, the value of B is reached in saturation level in negative direction at f . By taking H back from its value for negative saturation to its value for positive saturation, a similar curve **fabc** is obtained.It is concluded that B always lags behind H. This is called ***hysteresis.*** The closed loop **cdefabc** is termed as ***BH loop*** or ***hysteresis loop.***

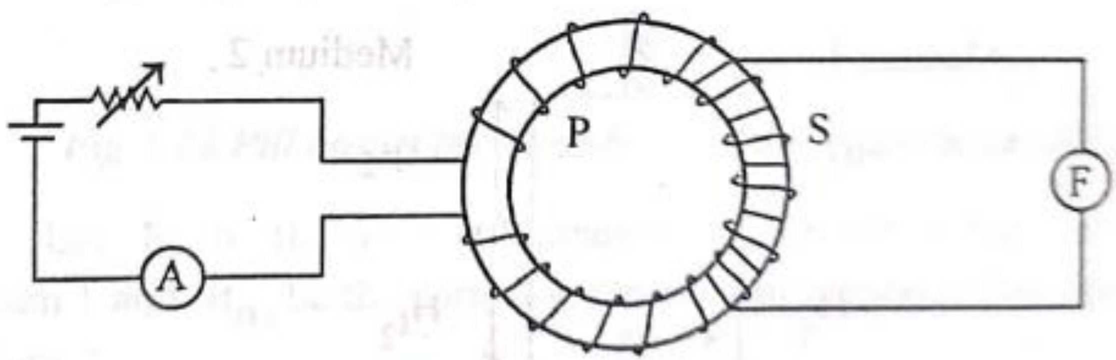
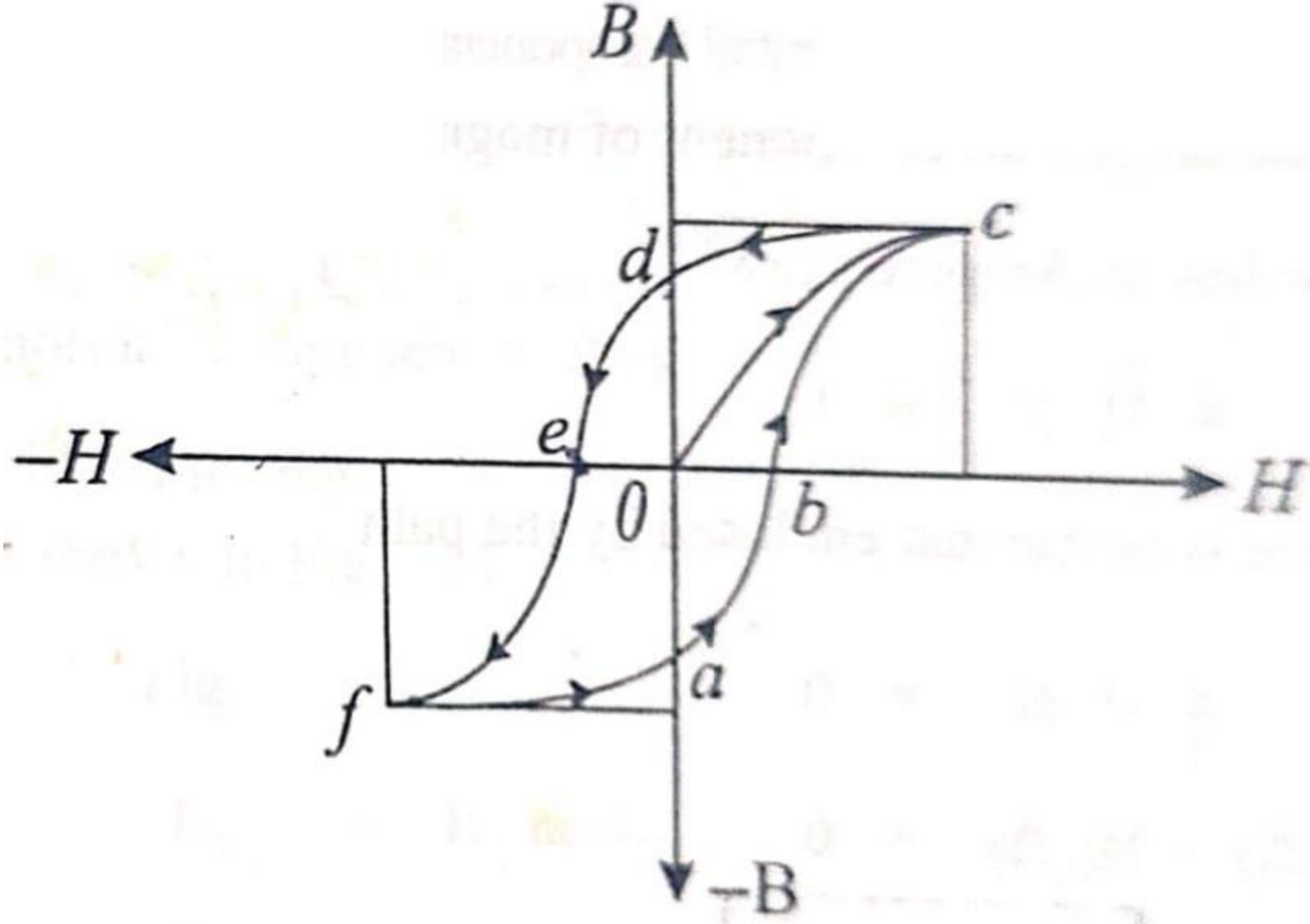


Fig 3.11 (a) Toroidal



B
c
d
e
−H
H
0
b
a
f
−B

MAGNETIC CIRCUITS

The various terms involved with magnetism are grouped as follows:

1. Magnetic Flux [Φ]

The magnetic lines of force produced by a magnet is called magnetic flux.
Its unit is Weber.   1 wb = 1 x 10^8 magnetic lines

.2 Magnetic Flux Density (B)

Magnetic flux density is the flux per unit area at right angles to the flux.

$$B = \frac{\phi}{a} \text{ wb/m}^2$$

where ϕ(wb) is the magnetic flux and a (m^2) is the area of cross section. Its unit is wb/m^2 or Tesla.

.3 Magneto Motive Force (F)

MMF is the cause for producing flux in a magnetic circuit. It is obtained as the product of the current (I amps) flowing through a coil of N turns. Its unit is Ampere.

Thus, $$F = N\,I \text{ Amps.}$$

The term, M.M.F. is normally referred to as Ampere Turns (AT).

4 Magnetic Field Intensity (or) Magnetising Force (H)

It is defined as M.M.F. per unit length of the magnetic flux path. It is a measure of the ability of a magnetised body to produce magnetic induction in other magnetic substances. Its unit is Ampere/metre.

With reference to Fig. 2.2 $$H = \frac{N\,I}{l}$$

.5 Permeability (μ)

This is the property of the magnetic medium. The flux density (B) is proportional to the magnetising force which produces it.

i.e.
$$B \propto H$$
$$B = \mu H$$
$$\mu = B/H$$

where μ is the constant of proportionality and is called permeability.

6 Relative Permeability (μ_r)

The relative permeability of a medium or material is defined as the ratio of the flux density produced in that medium or material to the flux density produced in vaccum by the same magnetising force.

$$\mu_r = \frac{\text{Flux density in the medium}}{\text{Flux density in vaccum}}$$

The absolute permeability of vaccum or free space has the value of $4\pi \times 10^{-7}$ Henry/m.

The permeability for any other medium is

$$\mu = \mu_r \times \mu_0$$

The relative permeability of vaccum or free space is unity and that of air and other non-magnetic materials is very nearly equal to unity.

7 Reluctance (S)

Reluctance is the property of an magnetic circuit by which the setting up of flux is opposed. It is defined as the ratio of the magnetomotive force to the flux.

The unit of reluctance is Amp./Weber and is denoted by *S*.

8 Permeance (P)

It is the reciprocal of reluctance and is the readiness with which magnetic flux is developed. It is analogous to conductance in an electric circuit. Its unit is weber per Amp.

MAGNETIC CIRCUIT

Magnetic circuit is the path followed by magnetic flux. Magnetic flux follows a complete loop or circuit coming back to its starting point. In any magnet, magnetic flux leaves its north pole, passing through air, enters the magnet at its south pole and finally reaches point where they start.

LEAKAGE FLUX

The flux which does not follow the desired path in magnetic circuit is known as *leakage flux*.

Usually, we assume that all the flux lines take the path of the magnetic medium. But, practically, it is impossible to confine all the flux to the iron path only. It is because, to prevent the leakage of flux, there is no perfect magnetic insulator. Even in air, flux is conducted fairly well. Hence, some of the flux leaks through air as shown in Fig. 2.8 and is known as leakage flux. All the magnetic flux which completes the desired magnetic circuit is the *useful flux*.

To account for the leakage flux, the term, "leakage coefficient" is introduced.

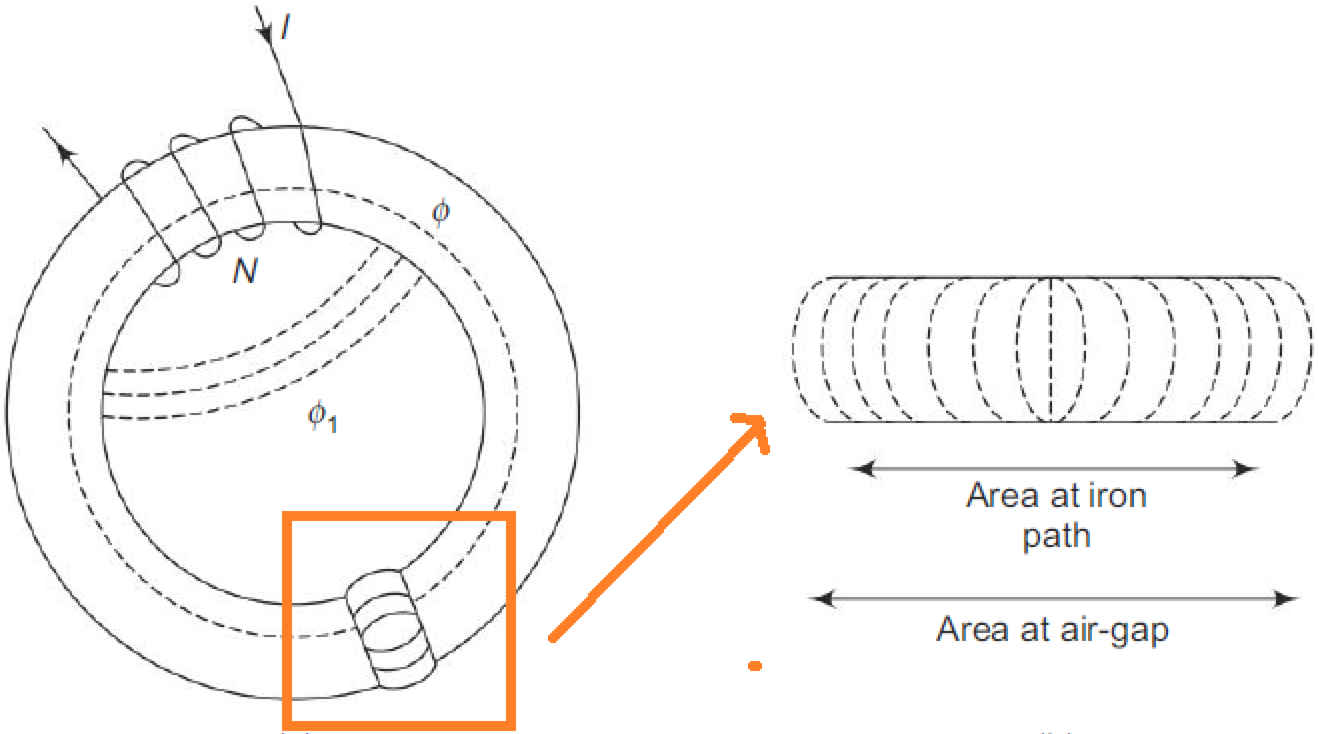
Leakage coefficient is defined as follows and it is defined by λ.

$$\text{Leakage coefficient, } \lambda = \frac{\text{total flux}}{\text{useful flux}} = \frac{\phi + \phi'}{\phi}$$

Usually, leakage factor is greater than unity.

FRINGING EFFECT

An air gap is often inserted in magnetic circuits out of necessity. When crossing an air gap, the magnetic lines of force have a tendency to bulge out. This is because the magnetic lines of force repel each other when they are passing through a non-magnetic material. This phenomenon is known as *fringing*.



(a) (b)

Analysis of Simple Magnetic Circuit

Consider a circular solenoid or a toroidal iron ring having a magnetic path of l meters, area of cross-section, a m^2 and a coil of turns carrying I amperes wound anywhere on it as in Fig. 2.3.

M.M.F. Produced = NI Amps.

According to the definition of H, the field-strength inside the solenoid is

$$H = \frac{N\,I}{l} \text{ Amp./metre}$$

$$= \frac{NI}{2\pi R_m}$$

Now $$B = \mu_0\mu_r H \qquad (\because \quad \mu = B/H)$$

$$B = \frac{\mu_0\mu_r\,N\,I}{l} \text{ wb/m}^2\ldots$$

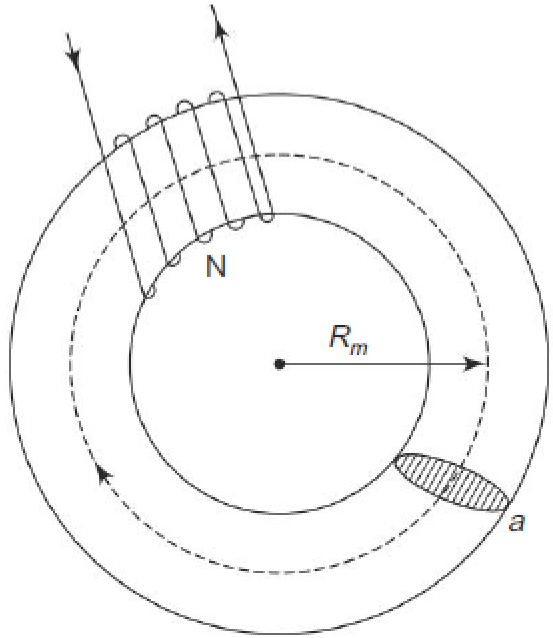
Total flux produced

$$\phi = Ba = \frac{\mu_0\mu_r a\,NI}{l} \text{ wb}$$

Also, $$\phi = \frac{NI}{\dfrac{l}{\mu_0\mu_r a}} = \frac{NI}{s} \text{ wb}$$

According to the definition of reluctance,

$$S = \frac{N\,I}{\phi}$$



Thus, the denominator $\frac{1}{\mu a}$ or $\frac{1}{\mu_0 \mu_r a}$ is the reluctance of the circuit and is analogous to resistance in electric circuit

$$S = \frac{1}{\mu_0 \mu_r a}$$

$$\text{Flux} = \frac{\text{mmf}}{\text{reluctance}}$$

The above equation is also known as 'Ohm's' law of magnetic circuit' because its resembles a similar expression in electric circuits,

$$\text{Current} = \frac{\text{emf}}{\text{resistance}}$$

Comparison between electric and magnetic circuit

Sl. No.	Magnetic circuit	Electric circuit
1	Magnetic flux, φ webers	Electric current, I ampere
2	Magneto motive force, AT	EMF, E volts
3	Reluctance, S AT / Wb	Resistance, R ohm
4	$\varphi = \frac{\text{mmf}}{\text{reluctance}}$	$\text{Current} = \frac{\text{emf}}{\text{resistance}}$

Problems

.1 A toroidal air cored coil with 2000 turns has a mean radius of 25 cm, diameter of each turn being 6 cm. If the current in the coil is 10 *A*, find *MMF*, (b) flux and (c) flux density.

Solution:

$N = 2000$ turns; $I = 10$ Amps; $R_m = 25$ cm

dia. of each turn, $d = 6$ cm.

(a) $MMF = NI = 2000 \times 10 = 20{,}000$ Amperes

(b) Flux = MMF/Reluctance

Reluctance = $l/a\mu$

$$l = 2\pi R_m = 2\pi \times \frac{25}{100}\ \text{m} = 1.57\ \text{m}$$

$$a = \frac{\pi d^2}{4} = \frac{\pi}{4} \times (6 \times 10^{-2})^2 = 2.8 \times 10^{-3}\ \text{m}^2$$

$$\mu = \mu_0 \mu_r = 4\pi \times 10^{-7} \times 1$$

$\therefore$ Reluctance $= \dfrac{1}{a\mu}$

$$= \frac{1.57}{2.8 \times 10^{-3} \times 4\pi \times 10^{-7} \times 1}$$

$$= 4.46 \times 10^8\ \text{At/wb}$$

$$\text{Flux} = \frac{\text{mmf}}{\text{Reluctance}} = \frac{20{,}000}{3.47 \times 10^8}$$

$$= 4.48 \times 10^{-5}\ \text{wb}$$

$$\text{Flux density} = \frac{\text{Flux}}{\text{Area of cross section}} = \frac{4.48 \times 10^{-5}}{2.8 \times 10^{-3}}$$

$$= 1.6 \times 10^{-2}\ \text{wb/m}^2\ \text{(or) Tesla}$$

2 The flux produced in the air gap between two electromagnetic poles is 5×10^{-2} wb. If the cross sectional area of the air gap is 0.2 m^2 find (a) flux density, (b) magnetic field intensity, (c) reluctance, and (d) permeance of the air gap. Find also the mmf dropped in the air gap given the length of the air gap to be 1.2 cm.

Solution:

$$\phi = 5 \times 10^{-2} \text{ wb}$$

$$a = 0.2 \text{ m}^2$$

$$l_g = 1.2 \text{ cm} = 0.012 \text{ m}$$

$$\mu_r = 1$$

(a) Flux density (B) $\dfrac{\phi}{a} = \dfrac{5 \times 10^{-2}}{0.2} = 0.25$ wb/sq.m

(b) Magnetic field intensity (H) $= \dfrac{B}{\mu_0 \mu_r}$

$$= \frac{0.25}{4\pi \times 10^{-7} \times 1}$$

$$= 1.9894 \times 10^5 \text{ A/m}$$

(c) Reluctance (S) of the air gap $= \dfrac{l_g}{a\mu}$

$$= \frac{0.012}{0.2 \times 4\pi \times 10^{-7} \times 1}$$

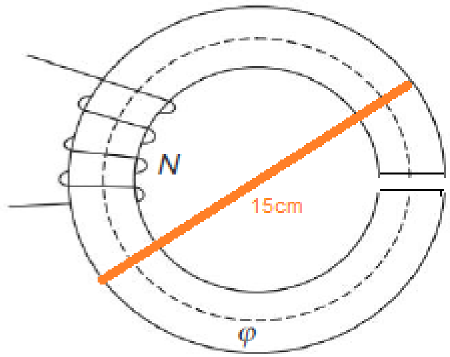
$$= 47746.48 \text{ A/wb}$$

(d) Permeance = 1/Reluctance = $\dfrac{1}{47746.48} = 2.0944 \times 10^{-5}$ wb/A

(e) mmf in the air gap = $\phi \times$ Reluctance = $5 \times 10^{-2} \times 47747 = 2387$ A.

3. A ring has mean diameter of 15 cm, a cross section of $1.7 cm^2$ and has a radial gap of 0.5 mm in it. It is uniformly wound with 1500 turns of insulated wire and a current of 1 A produces a flux of 0.1 mwb across the gap. Calculate the relative permeability of iron on the assumption that there is no magneticleakage.

Solution:



$$\phi = 0.1 \times 10^{-3} \text{ wb}$$

$$a = 1.7 cm^2 = 1.7 \times 10^{-4} \text{ m}^2$$

Total Reluctance = Reluctance of iron path+Reluctance of air gap

$$S_T = S_i + S_g$$

Total Reluctance $S_T = NI / \phi = 1500 \text{ X } 1 / 0.1 \times 10^{-3}$

$= 1,50,00,000$ A/Wb

Reluctance (S) of the air gap $=$ $S_g = \frac{l_g}{a\mu} = \frac{l_g}{a\mu_0\mu_r}$ $[\mu_r = 1 \text{ for air}]$

$= 0.5\text{x}10^{-3} /[1.7 \text{ x } 10^{-4} \text{ x } 4\pi \text{ x}10^{-7} \text{ x } 1]$

$= 23,40,513.8$ A/Wb

$$S_i = S_T - S_g$$

$$= 15000000 - 2340513.8$$

$$= 1,25,69,486.2 \text{ A/Wb}$$

$$S_i = \frac{l_i}{a\mu} = \frac{l_i}{a\mu_0\mu_r}$$

l_i, Length of iron path = Total length = l_g

$$l_i = (\pi d - l_g)m = (\pi \times 0.15 - 0.005)$$

$$= 0.466 \text{ m}$$

$$\mu_r = \frac{l_i}{a\mu_0 S_i}$$

$$= 174$$

4. An iron rod of 1 cm radius is bent to a ring of mean diameter 30 cm and wound with 250 turns of wire. Assume the relative permeability of iron as 800. An air gap of 0.1 cm is cut across the bent ring. Calculate the current required to produce a useful of 20,000 lines if (a) leakage is neglected and (b) leakage factor is 1.1.

Solution:

$$l_g = 0.1 \text{ cm}$$

$$\frac{d}{2} = 1 \text{ cm}$$

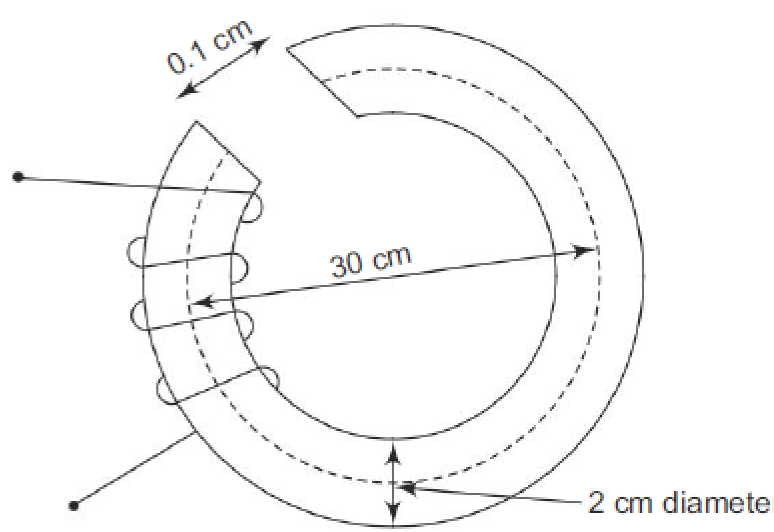
$$2R_m = 30 \text{ cm}$$

$$N = 250 \text{ turns}$$

$$\mu_r = 800$$

$$\phi = 20{,}000 \text{ lines}$$

$$= 20{,}000 \times 10^{-8} \text{ wb}$$



(a) Neglecting leakage:

$$\text{Total Reluctance} = \text{Reluctance of air gap} + \text{Reluctance of iron path}$$

$$\text{Reluctance of air gap} = \frac{l_g}{\mu_0 \mu_r a} = \frac{0.001}{(4\pi \times 10^{-7} \times 1 \times \pi \times 1 \times 10^{-4})}$$

$$= 2533029.59 \text{ A/wb}$$

$$l_i, \text{ Length of iron path} = \text{Total length} = l_g$$

$$l_i = (\pi d - l_g)m = (\pi \times 0.3 - 0.001)$$

$$\text{Reluctance of iron path} = \frac{(\pi \times 0.3 - 0.001)}{4\pi \times 10^{-7} \times 800 \times \pi \times 1 \times 10^{-4}}$$

$$= 2980988.896 \text{ A/wb}$$

$$\text{Total Reluctance} = 5514018.49 \text{ A/wb}$$

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

$$= 20{,}000 \times 10^{-8} \times 5514018.49 \text{ A/wb}$$

$$= 1102.8 \text{ Amp. turns}$$

$$\text{Current required} = \frac{1102.8}{\text{No. of turns}} = \frac{1120.8}{250}$$

$$\text{Current required} = 4.41 \text{ Amps.}$$

(b) Including leakage:

To have a useful flux of 20,000 lines in the air gap, the *MMF* required the air gap porition is

$$= \phi \times \text{Reluctance of air gap}$$

$$= 20{,}000 \times 10^{-8} \times 2533039.59$$

$$MMF \text{ for air gap} = 506.606 \text{ Amp}$$

For the iron path, the flux has to be more.

$$\text{The total flux in iron path} = \text{Leakage factor} \times \text{Useful flux}$$

$$= 1.1 \times 20000 \times 10^{-8} \text{ wb}$$

$$\text{Hence, } MMF \text{ for iron path} = 1.1 \times 20{,}000 \times 10^{-8} \text{ Reluctance of iron path}$$

$$= 655.82 \text{ Amp.}$$

$$\text{Total } MMF = 655.82 + 506.606 \text{ A} = 1162.426 \text{ A}$$

$$\text{Current required} = \frac{1162.426}{250} = 4.649 \text{ Amps.}$$

$$\text{Current required} = 4.649 \text{ Amps.}$$

LAW OF ELECTROMAGNETIC INDUCTION

1 Statement of Faraday's Law

Whenever the magnetic flux linking a circuit changes an emf is always induced in it. The magnitude of such an emf is proportional to the rate of change of flux linkages.

2 Lenz's Law

The law states that any induced emf will circulate a current in such a direction so as to soppose the cause producing it.

Thus, Lenz's law gives the nature of induced emfs.

INDUCED EMF

An emf is induced in a coil or conductor whenever there is a change in flux linkages
This change in flux linkages can be brought in the following two ways:
(i) The conductor is moved in a stationery magnetic field in such a way that there is a magnitude change in flux linkages. This kind of induced emf is known as dynamically induced emf (e.g generator).
(ii) The conductor is stationary and the magnetic field is moving or changing. This kind of induced emf is known as statically induced emf (e.g. transformer).

Statically Induced emf

In this case, the conductor is held stationary and the magnetic field varied. It may be self induced or mutually induced.

Self Induced emf If a single coil carries a current, a flux will be set up in it. If the current changes the flux will change. The change in flux will induce an emf in the coil. This kind of emf is known as "self induced emf".

The magnitude of this self-induced emf is $e = N\dfrac{d\phi}{dt}$

Mutually Induced emf It is the emf induced in one circuit due to change of flux linking it, the flux being produced by current in another circuit.

$$e_2 = N_2\frac{d\phi_{12}}{dt}$$

Where ϕ_{12} = 1 st coil flux linking 2 nd coil

SELF INDUCTANCE (L)

Definition

Self inductance of a circuit is the flux linkages per unit current in it. Its unit is Henry.

By definition, $L = \dfrac{N\phi}{I}$ Henry

Relationship between Self-Induced emf and Self Inductance

$$e = -L\frac{di}{dt}$$

MUTUAL INDUCTANCE (M)

Definition

Mutual inductance between two circuits is defined as the flux linkages of one circuit per unit current in the other circuit. Its unit is Henry.

$$M = \frac{N_2\phi_{12}}{I_1}$$

Where ϕ_{12} = 1 st coil flux linking 2 nd coil

or

$$M = \frac{N_1\phi_{21}}{I_2}$$

Where ϕ_{21} = 2 nd coil flux linking 1 st coil

Relationship between M and Induced emf

mutually induced emf in coil 2 due to change in current of coil 1 is,

$$e_{m,2} = -M\frac{di_1}{dt}$$

Similarly, mutually induced emf in coil 2 due to change in current of coil 2 is,

$$e_{m,1} = -M\frac{di_2}{dt}$$

COUPLING COEFFICIENT BETWEEN TWO MAGNETICALLY COUPLED CIRCUITS (K)

$$K = \frac{\phi_{12}}{\phi_1} \quad \text{or} \quad K = \frac{\phi_{21}}{\phi_2}$$

Where ϕ_{12} = 1 st coil flux linking 2 nd coil

Where ϕ_{21} = 2 nd coil flux linking 1 st coil

always $K \leq 1$.

Thus, coupling coefficient, $K = \dfrac{M}{\sqrt{L_1 L_2}}$

Problems

1. The number of turns in a coil is 250. When a current of 2 A flows in this coil, the flux in the coil is 0.3 m wb. When this current is reduced to zero in 2 milliseconds, the voltage induced in a coil lying in the vicinity of coil is 63.75 volts. If **K=0.75, Find** mutual inductance and number of turns in the second coil.

Solution: $N_1 = 250;\ I_1 = 2A:\ \phi_1 = 0.3$ wb

$dt = 2$ msec; $e_{m2} = 63.75$ V; $K = 0.75$

(a) Self inductance of first coil is

$$L_1 = N_1 \times \frac{\phi_1}{I_1}$$

$$= 250 \times \frac{0.3 \times 10^{-3}}{2}$$

$$= 37.5 \text{ mH.}$$

(b) Voltage in the second coil is

$$e_{m2} = M\frac{dI_1}{dt}$$

i.e. $$63.75 = M\frac{2-0}{2 \times 10^{-3}}$$

$$M = 63.75 \times 10^{-3} = 63.75 \text{ mH}.$$

we know that $$M = K\sqrt{L_1 L_2}$$

i.e. $$63.75 = 0.75\sqrt{3.75 \times L_2}$$

$$L_2 = 193 \text{ mH}.$$

(c) ϕ_{12} the flux in the second coil

$$\phi_{12} = k \times \phi_1$$

$$= 0.75 \times 0.3 \times 10^{-3}$$

$$= 0.255 \times 10^{-3}\ wb$$

$$e_2 = N_2\frac{d\phi_{12}}{dt}$$

$$63.75 = N_2\frac{0.255 \times 10^{-3}}{2 \times 10^{-3}}$$

$$N_2 = 500 \text{ turns}.$$

2. An air cored toroidal coil has 480 turns, a mean length of 30 cm and a cross-sectional area of 5 cm^2. Calculate (a) the inductance of the coil and (b) the average induced emf, if a current of 4 A is reversed in 60 millionseconds.

Solution:

$$l = 30 \text{ cm} = 0.3 \text{ m}$$

$$N = 450 \text{ turns}$$

$$a = 5 \text{ cm}^2 = 5 \times 10^{-4} \text{ m}^2$$

$$I = 4 \text{ Amps.}$$

$$dt = 60 \text{ m sec}$$

(a)
$$L = \frac{N^2}{(1/\mu_0 \mu_r a)}$$

$$= \frac{\mu_0 \mu_r a N^2}{l}$$

$$= \frac{4\pi \times 10^{-6} \times 1 \times 5 \times 10^{-4} \times (480)^2}{0.3} \text{ Henry} \quad (\because \mu_r = 1 \text{ for air})$$

$$= 483 \times 10^{-6}\, H$$

(b)
$$di = 4 - (-4) = 8 \text{ Amp}$$

$$dt = 60 \times 10^{-3} \text{ sec}$$

$$\text{Average induced emf } (E) = L\frac{di}{dt}$$

$$= 483 \times 10^{-6} \times \frac{8}{60 \times 10^{-3}}$$

$$= 0.064 \text{ V.}$$

3 The self inductance of a coil of 500 turns is 0.25 H. If 60% of the flux is linked with a second coil of 10500 turns, calculate (a) the mutual inductance between the two coils and (b) emf induced in the second coil when current in the first coil changes at the rate of 100 A/sec.

Solution:

$$L_1 = 0.25\ H$$

$$N_1 = 500 \text{ turns}$$

$$N_2 = 10500 \text{ turns}$$

$$\phi_{12} = \frac{60}{100}\phi_1 \,;\ \phi_{12} = 0.6\ \phi_1.$$

Where ϕ_{12} = 1 st coil flux linking 2 nd coil

$$\frac{di_i}{dt} = 100 \text{ A/sec}$$

Flux/ampere in the first coil

$$= \frac{\phi_1}{I_1} = \frac{0.25}{N_1} = \frac{0.25}{500} = 5 \times 10^{-4}$$

Flux linking the second coil $= \phi_{12} = 0.6\ \phi_1$

$$\frac{\phi_{12}}{I_1} = 0.6\ (\phi_1/I_1)$$

$$= 0.6 \times 5 \times 10^{-4}$$

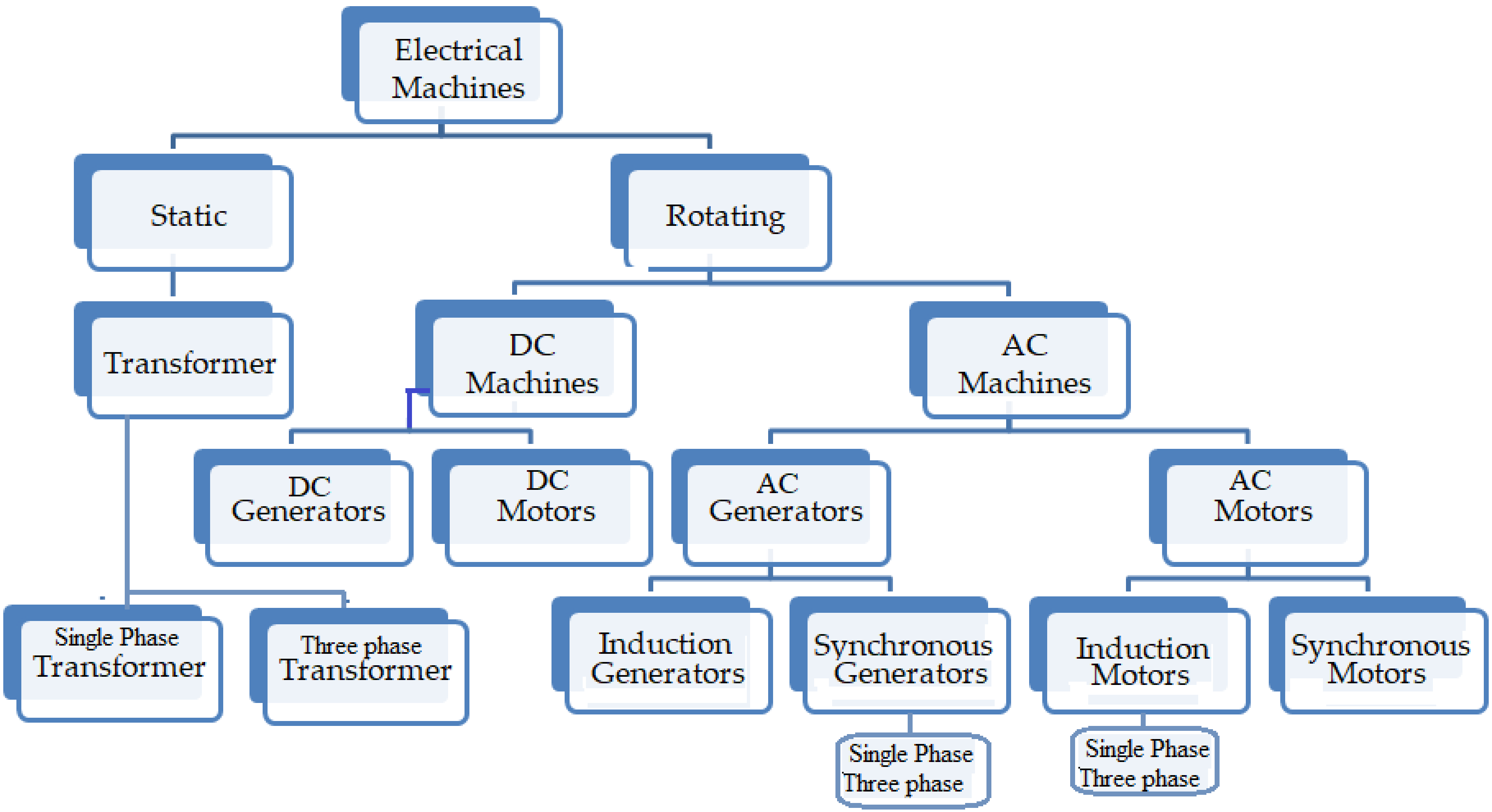
$$= 3 \times 10^{-4}$$

(a) $$M = N_2 \frac{\phi_{12}}{I_1} = 10500 \times 3 \times 10^{-4} = 3.15\ H$$

(b) $$e_m = M \frac{di_1}{dt} = 3.15 \times 100 = 315 \text{ V}$$

Electrical Machines

Classification of Electrical Machines

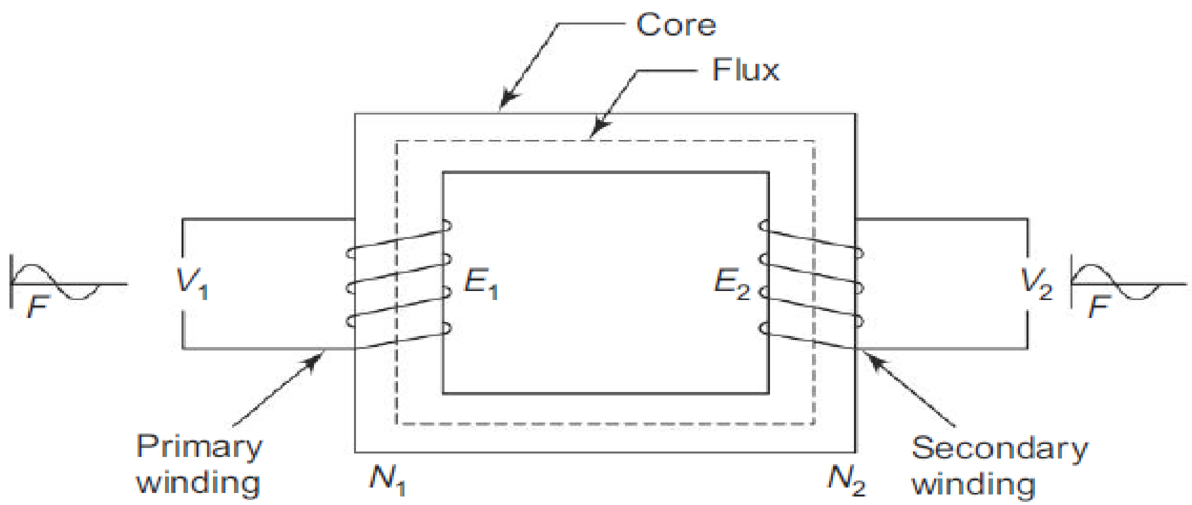


Single Phase Transformer

Principle of operation

The transformer works on the principle of electromagnetic induction. In this case, the conductors are stationary and the magnetic flux is varying with respect to time. Thus, the induced emf comes under the classification of statically induced emf.

The transformer is a static piece of apparatus used to transfer electrical energy
from one circuit to another. The two circuits are magnetically coupled. One of the circuits is energized by connecting it to a supply at specific voltage magnitude, frequency and waveform. Then, we have a mutually induced voltage available across the second circuit at the same frequency and waveform but with a change in voltage magnitude if desired. These aspects are indicated in Fig.



Construction

The following are the essential requirements of a transformer:

(a) A good magnetic core

(b) Two windings

(c) A time varying magnetic flux

The transformer core is generally laminated and is made out of a good magnetic material such as transformer steel or silicon steel. Such a material has high relative permeability and **low hysteresis loss**. In order to reduce the **eddy current loss**, the core is made up of laminations of iron. ie, the core is made up of thin sheets of steel, each lamination being insulated from others

Working

Let us say that a transformer has N_1 turns in its primary winding and N_2 turns in its secondary winding. The primary winding is connected to a sinusoidal voltage of magnitude V_1 at a frequency 'f' hertz. A working flux of ϕ webers is set up in the magnetic core. This working flux is alternating and sinusoidal as the applied voltage is alternating and sinusoidal. When this flux link the primary and the secondary winding, emfs are induced in them. The emf induced in the primary is the self induced emf and that induced in the secondary is the mutually induced emf. Let the induced voltages in the primary and the secondary be E_1 and E_2 volts respectively. These voltages will have sinusoidal waveform and the same frequency as that of the applied voltage. The currents which flow in the closed primary and the secondary circuits are respectively I_1 and I_2.

In any transformer, $K = \dfrac{N_2}{N_1}$, defines the transformation ratio.

Three categories of transformer action are possible:

$E_2 < E_1$ (i.e. $V_2 < V_1$) ... step down transformer

$E_2 > E_1$ (i.e. $V_2 > V_1$) ... Step up transformer

The induced emfs are proportional to the number of turns. In any transformer, the primary ampere turns equals the secondary ampere turns.

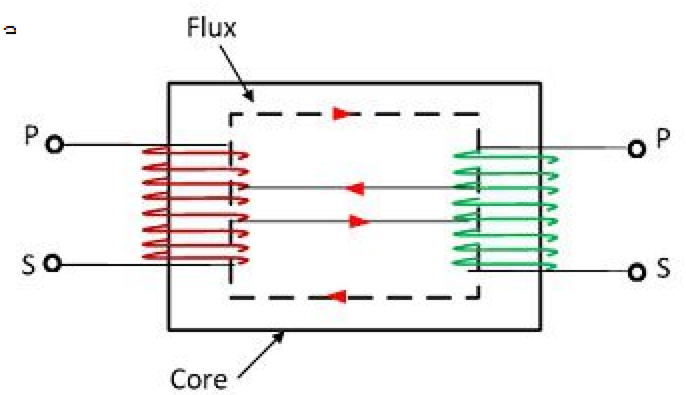
i.e. $$N_1 I_1 = N_2 I_2$$

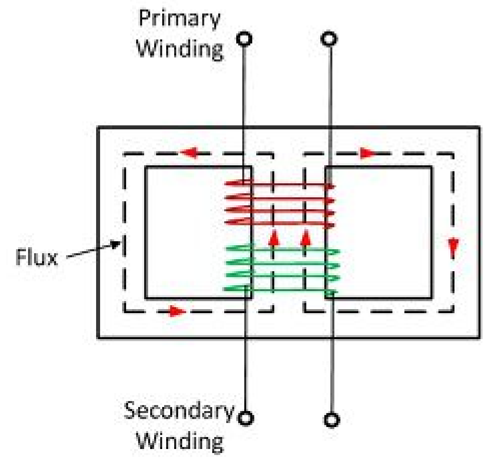
Thus, we have $$\frac{I_1}{I_2} = \frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = K$$

Whenever any load is put on the transformer (connected to secondary winding) the primary of the transmission draws the required amount of current in order to keep the working flux constant. Thus, the transformer works with a perfect static balance.

Basis for Comparison	Core Type Transformer	Shell Type Transformer

Da





Winding	In this type, winding surrounds the core	In this type, core surrounds the winding
Limbs	It has two limbs	It has three limbs
Copper requirement	Requires less	Requires more
Lamination	Laminations are usually in the form of alphabet letter L	Laminations are usually in the form of alphabet letter E and L
Flux distribution	Flux is equally distributed on the side limbs	Side limbs carry the half of the flux while the central one carries the whole flux

Windings position	Primary and secondary both windings are wound on the side limbs	Both windings are wound on the central limb
Magnetic circuit	Only one magnetic circuit	There are two magnetic circuits
Types	Cylindrical	Multilayer and Sandwich type
Cooling	Better cooling because more surface is exposed to external atmosphere	Natural cooling is not very effective so fans are used
Repair	Easy to repair because assembly can be dismantled easily	Difficult to repair because both windings are on the same limb
Output	Output is less because of more losses so less efficiency	Output is high because of less losses so efficiency is high in this type
Design	Easy in design and construction	Comparatively complex
Mechanical strength	Low because of non-bracing	Possesses high mechanical strength
Leakage reactance	Leakage reactance is not easily possible	In this type, leakage reactance is highly possible
Heat dissipation	Better heat dissipation from windings	Windings are surrounded by core so heat dissipation is not easy
Application	Used for high voltage application like power transformers,	Used for low voltage application like transformers in an electronic

32.6. E.M.F. Equation of a Transformer

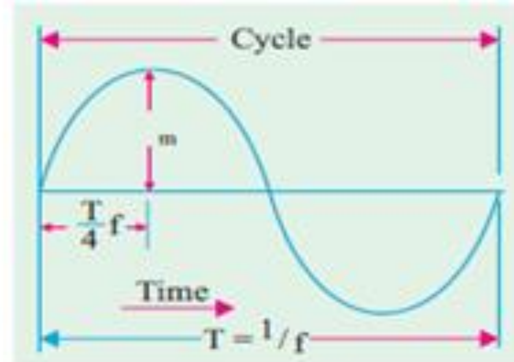


Fig. 32.14

Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

Φ_m = Maximum flux in core in webers

$= B_m \times A$

f = Frequency of a.c. input in Hz

As shown in Fig. 32.14, flux increases from its zero value to maximum value Φ_m in one quarter of the cycle *i.e.* in $1/4f$ second.

$$\therefore \quad \text{Average rate of change of flux} = \frac{\Phi_m}{1/4f}$$

$$= 4f\Phi_m \text{ Wb/s or volt}$$

Now, rate of change of flux per turn means induced e.m.f. in volts.

$$\therefore \quad \text{Average e.m.f./turn} = 4f\Phi_m \text{ volt}$$

If flux Φ varies *sinusoidally*, then r.m.s. value of induced e.m.f. is obtained by multiplying the average value with form factor.

$$\text{Form factor} = \frac{\text{r.m.s. value}}{\text{average value}} = 1.11$$

$$\therefore \quad \text{r.m.s. value of e.m.f./turn} = 1.11 \times 4f\Phi_m = 4.44f\Phi_m \text{ volt}$$

Now, r.m.s. value of the induced e.m.f. in the whole of primary winding

$$= (\text{induced e.m.f/turn}) \times \text{No. of primary turns}$$

$$E_1 = 4.44fN_1\Phi_m = 4.44fN_1B_mA \qquad \text{...(i)}$$

Similarly, r.m.s. value of the e.m.f. induced in secondary is,

$$E_2 = 4.44fN_2\Phi_m = 4.44fN_2B_mA \qquad \text{...(ii)}$$

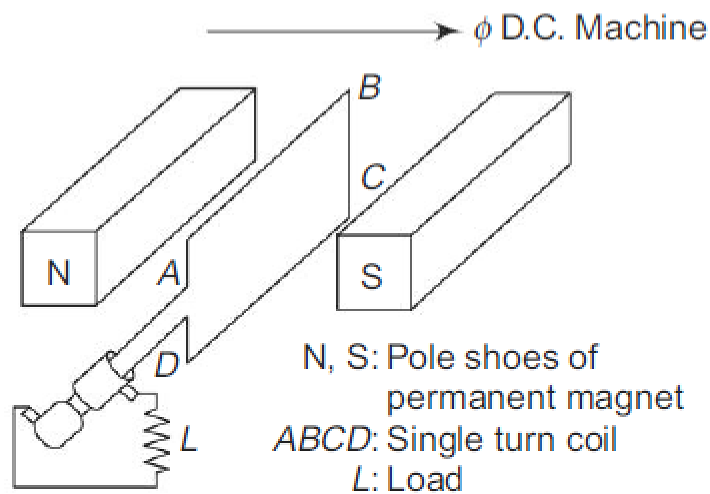
DC GENERATOR

Principle

The generator is a dynamic machine in which mechanical energy is converted into electrical energy. It operates on the principle based on the Faraday's Law of electro-magnetic induction. The emf generated is to be classified as dynamically induced emf. The basic requirements for the dynamically induced emf to exist are the following:

(i) A steady magnetic field
(ii) A conductor capable of carrying current
(iii) The conductor to move in the magnetic field

The working principle of a dc generator is illustrated in Fig. 6.1. It shows a steady magnetic field produced by the pole pieces of a magnet N and S. A single turn coil *ABCD* is placed in the field produced between the pole pieces. The coil is rotated by means of a prime mover. Thus, as per Faraday's law, an emf is induced in the coil. Such an emf is basically alternating. This bidirectional induced emf is made unidirectional using the commutator. Figure 6.2, illustrates the use of commutator.



Construction

For the satisfactory operation of a dc generator, it should consists of a stator and a rotor.

The stator accommodates the yoke, the main field system and the brushes. The rotor has the armature and the commutator as its main parts. Figure 6.3 shows these parts. Each of these parts is described as follows:

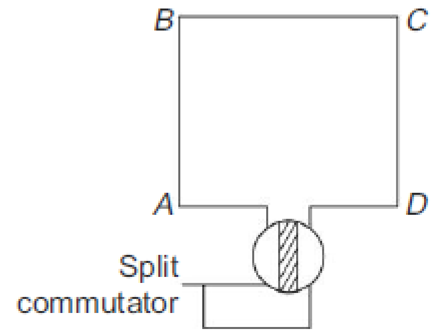
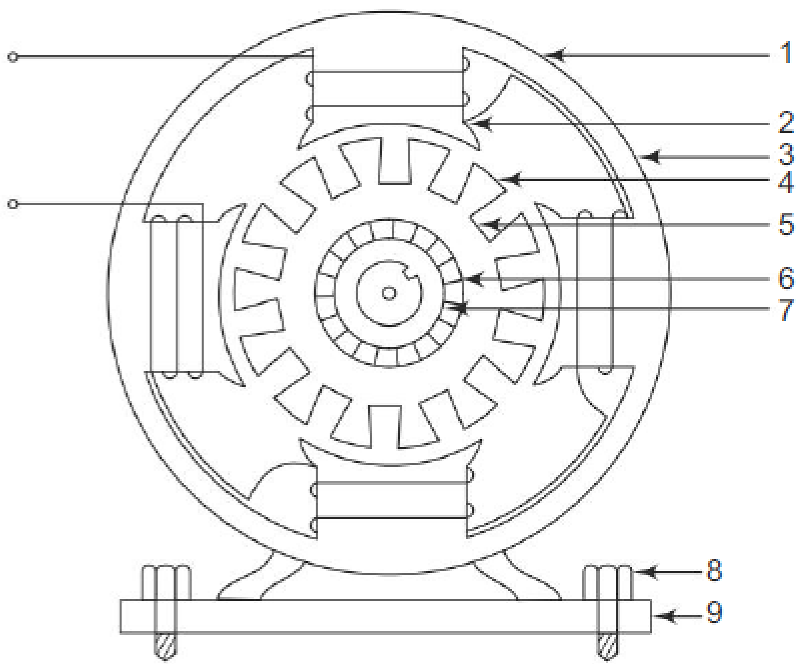


Fig. 6.2



1 Yoke or Frame
2 Main field pole
3 Field winding
4 Armature
5 Slot
6 Commutator
7 Shaft
8 Foundation bolt
9 Bed plate

Yoke or Frame It is the outermost solid metal part of the machine. It forms part of magnetic circuit and protects all the inner parts from mechanical damage.

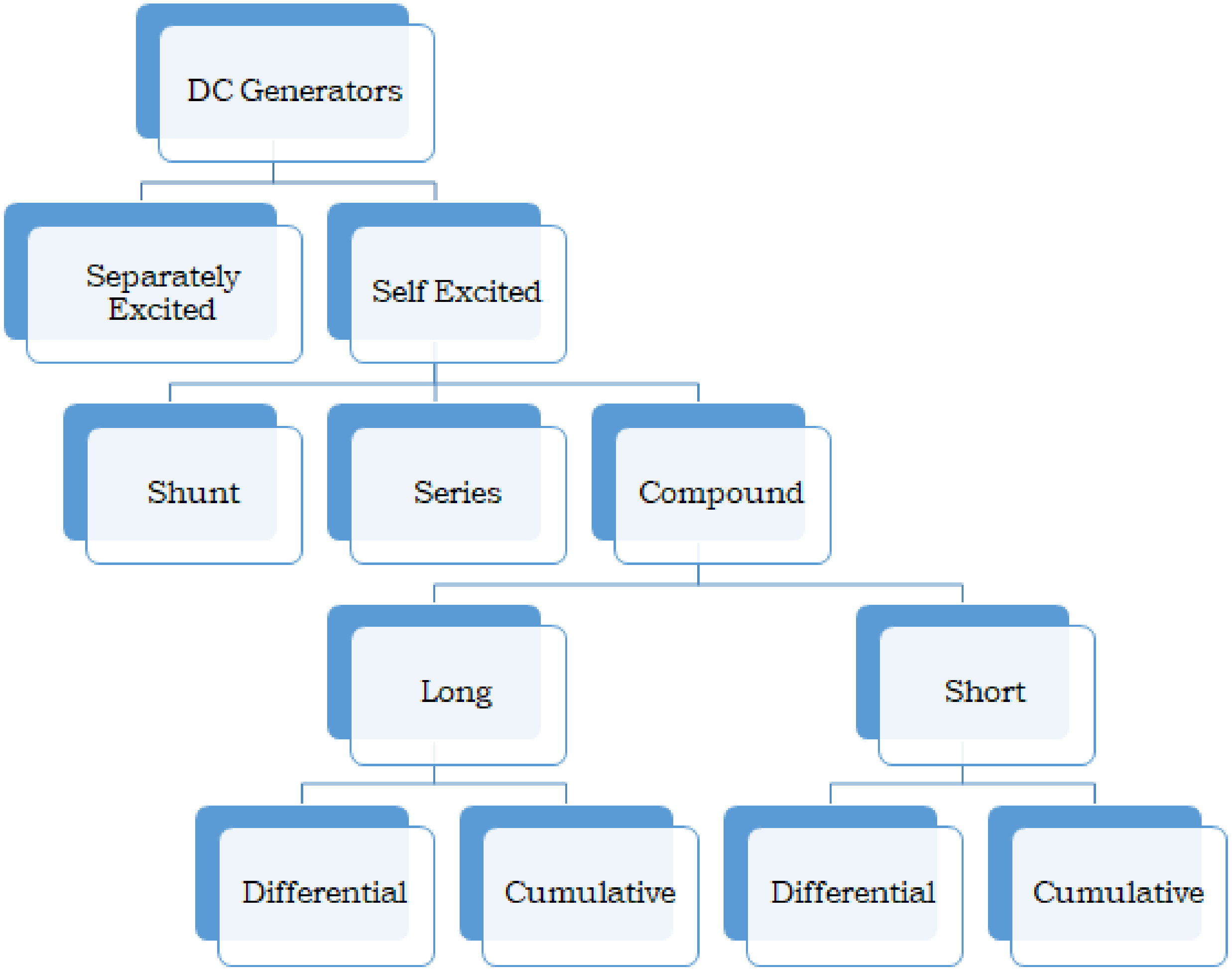
Field System This consists of main field poles and field winding. The field poles are made of laminations of a sutiable magnetic material. Such a magnetic material has very high relative permeability and very low hysteresis loss. The pole face is in the form of horse shoe so that a uniform flux distribution is obtained in the air gap between the poles and the rotating part. The field winding is placed over the each pole and all these are connected in series. Again the field winding is so arranged on the different poles that when a direct current is passed through this winding, the poles get magnetized to N and S polarities alternately. Thus, the field system is responsible for producing the required working flux in the air gap.

Brushes A set of brushes made of carbon or graphic are fixed such that they are always in gentle touch with the revolving armature. The generator is connected to external circuits by means of these brushes. Thus, the brushes are used to tap the generated electrical energy off the rotating part of the generator.

Armature The armature of a dc generator is in the form of laminated slotted drum. Slots are provided over the entire periphery of the armature

Commutator The commutator is similar in shape to armature. But, it has less diameter than that of the armature. Required number of segments are provided over the complete periphery of the commutator. There is an electrical insulation between every pair of segments. A minimum of two conductors are connected to each segment. But, at the same time the two conductors making a single coil are connected to different commutator segments. The brushes are so placed that they are always keeping to such with the revolving commutator segments.

Types of DC Generator



1. Separately Excited DC Generator

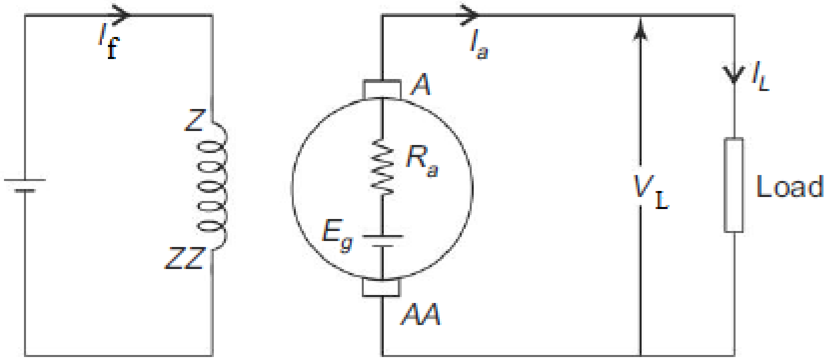
- Armature Current

  $I_a = I_L$

- Emf Equation

  $E_g = V_L + I_a R_a + V_b$

  V_b=brush drop for pair of brush



2.Self Excited DC Generator

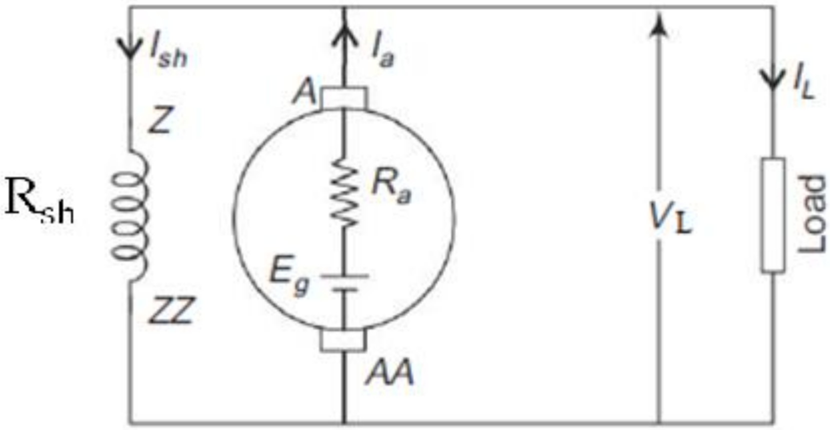
(i) DC Shunt Generator

- Armature Current

  $I_a = I_L + I_{sh}$

- Emf Equation

  $E_g = V_L + I_a R_a + V_b$



2.Self Excited DC Generator

(ii) DC Series Generator

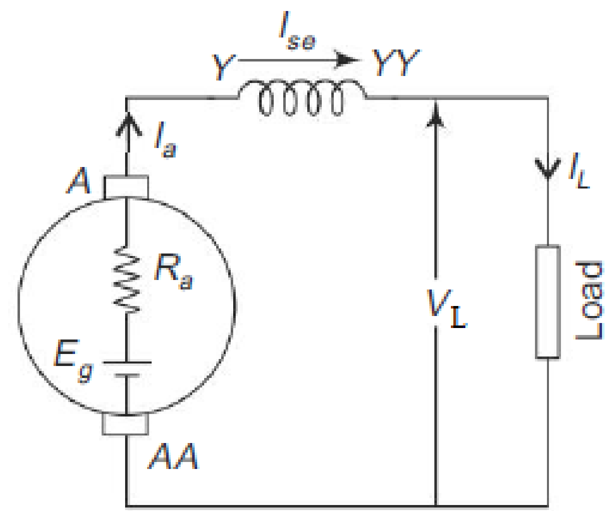
- Armature Current

  $I_a = I_L = I_{se}$

- Emf Equation

  $E_g = V_L + I_a R_a + I_{se} R_{se} + V_b$

  $E_g = V_L + I_a (R_a + R_{se}) + V_b$



2.Self Excited DC Generator
(iii)DC Compound Generator
(a)Long Shunt

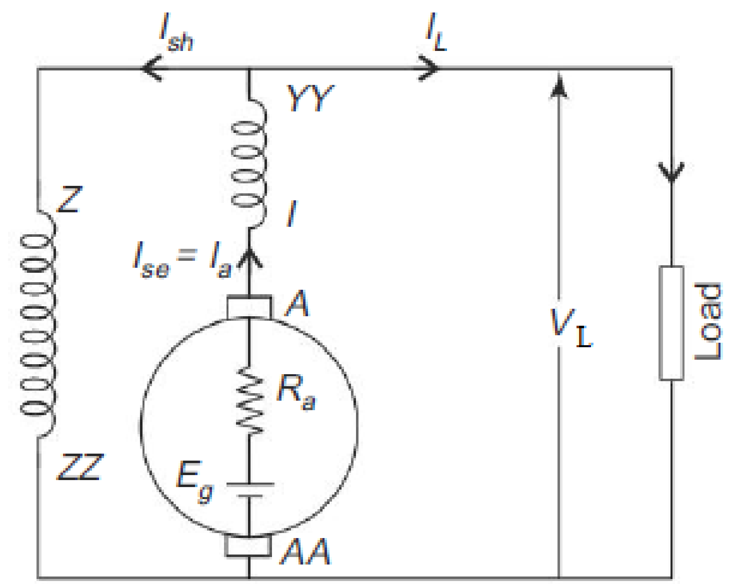
- Series Field Current

  $I_{se} = I_a$
- Armature Current

  $I_a = I_L + I_{sh}$
- Emf Equation

  $E_g = V_L + I_a R_a + I_{se} R_{se} + V_b$

  $E_g = V_L + I_a (R_a + R_{se}) + V_b$



2.Self Excited DC Generator

(iii)DC Compound Generator

(b)Short Shunt

- Series Field Current

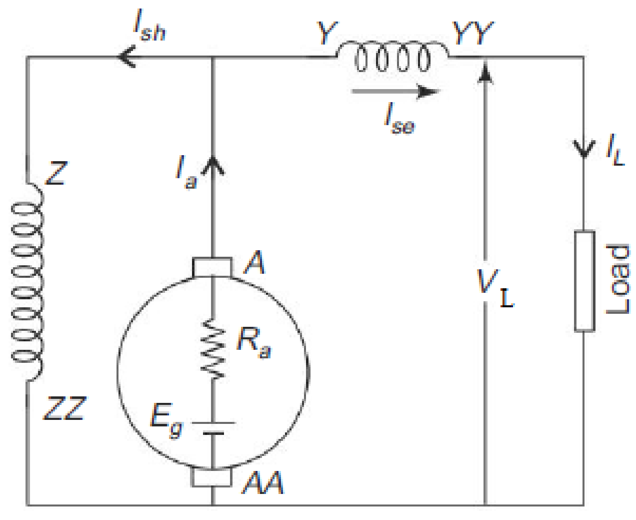
  $I_{se} = I_L$

- Armature Current

  $I_a = I_L + I_{sh}$

- Emf Equation

  $E_g = V_L + I_a R_a + I_{se} R_{se} + V_b$

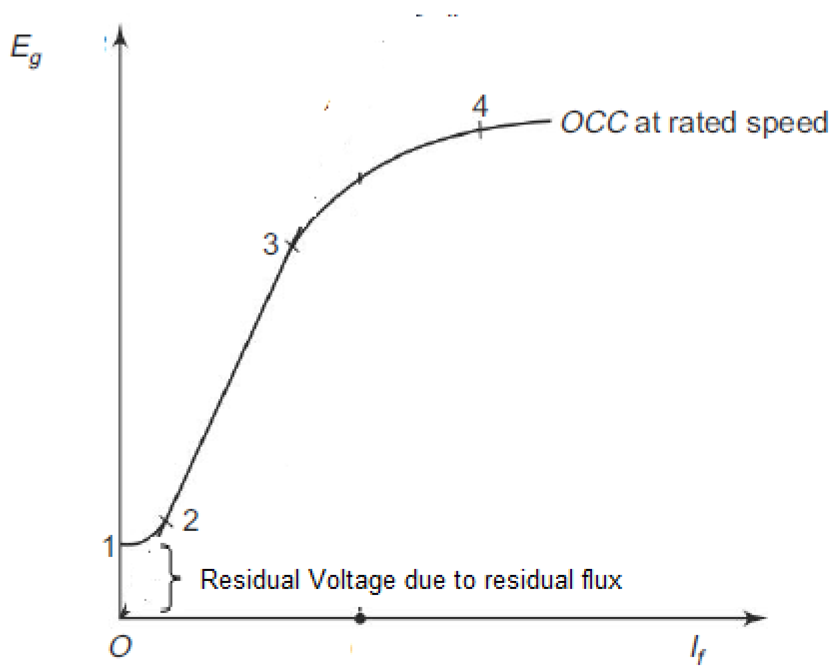


Characteristics of Generators

- Open Circuit Characteristics (I_f, E_{g0})
- Load Characteristics
  - Internal (I_a, E_g)
  - External (V_L, I_L)

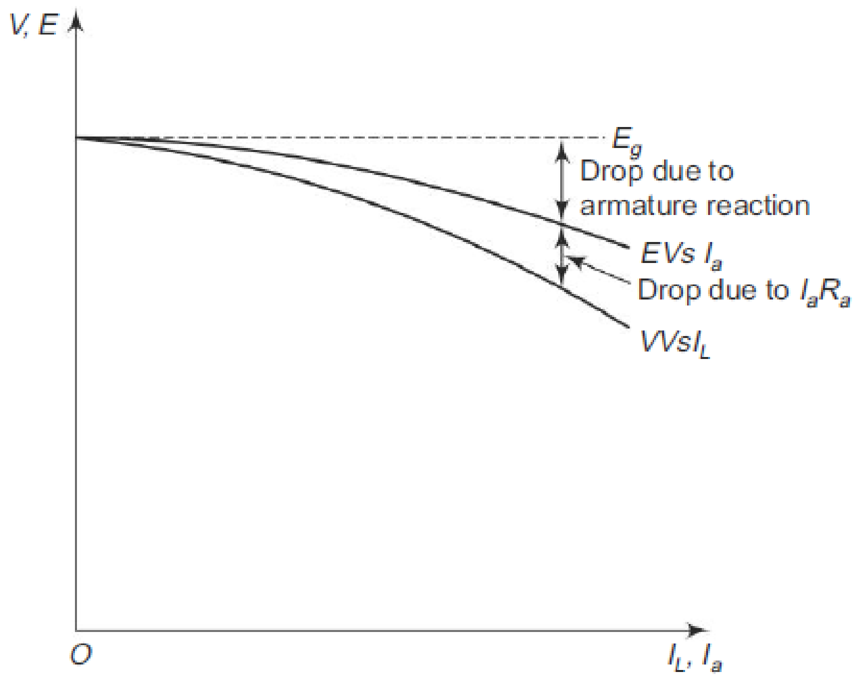
Separately Excited DC Generator and DC Shunt Generator - Characteristics [Both generators have same characteristics]

1. Open circuit characteristics (OCC) or No-load characteristics or magnetization characteristics. (I_f, E_{g0})



By removing the load connected , we obtain the no-load condition. When the generator is run at its rated speed with no-load, the terminal voltage appearing across the armature can be taken as the induced voltage. Thus, it is possible to obtain this open circuit voltage as a function of the field current. By varying the field current, we can obtain the variation in the no-load voltage. The curve thus obtained is known as open circuit characteristics. We can observe that the major portion of this characteristics (2-3) is linear. There are two non-linear portions namely 1-2 and 3-4. Beyond the operating point 4, we say that **saturation has occurred and so there will not be any appreciate increase in** the generated voltage even for large increase in field current. Because of the **residual flux in the magnetic poles there is a small amount of** induced voltage even when the field current is zero.

2.Internal (Ia, Eg) Characteristics
3.External (VL, IL) Characteristics



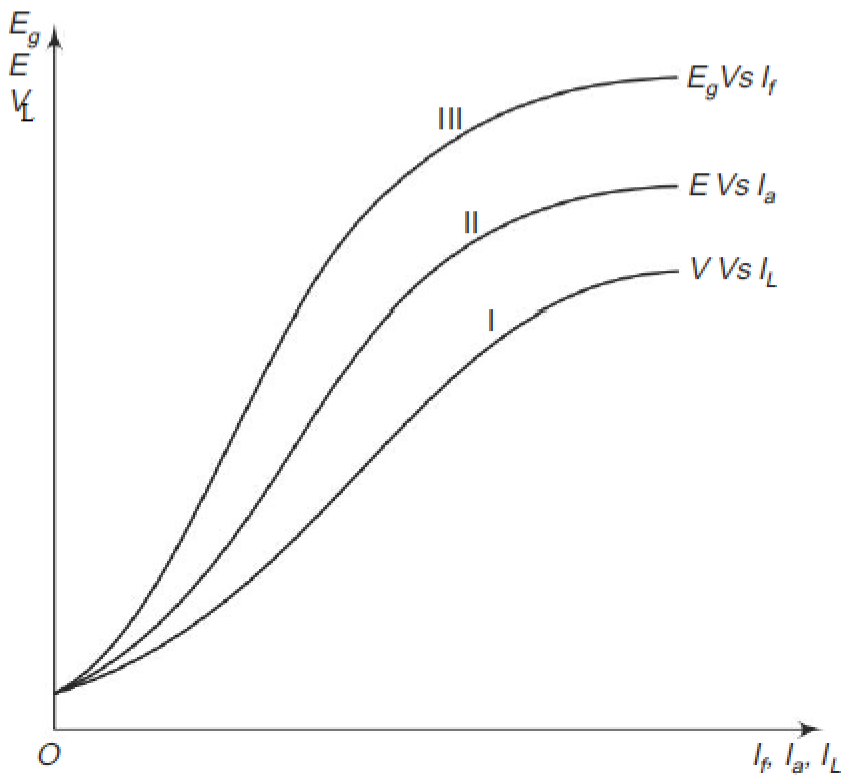
The generators should be made to run at its rated speed. The generator field current should be adjusted so that rated voltage is built up at no-load. Now by varying the load, the terminal voltage V as a function of load current I_L can be obtained as shown in Fig

The terminal voltage of the generator decreases on loading. This is because of (i) voltage drop due to armature resistance, Ra (ii) voltage drop due to armature reaction. So the generated emf and the terminal voltage go on decreasing.

External characteristics Variation of load terminal voltage with respect to the load current [i.e. V vs I_L]. These two quantities are external quantities and they can be measured directly. Hence the name external characteristics.

Internal characteristics Variation of induced voltage in loaded condition as a function of the armature current [i.e. E vs Ia]. These two quantities are internal quantities for the generation and E cannot be measured directly, but it can be estimated. Hence the name internal characteristics.

DC Series Generator- Characteristics [All 3 Characteristics]



The **OCC** of series generator can be obtained with the help of the no load and shape of OCC is similar and same as that for DC shunt generator.

The load characteristics is rising characteristics. The difference between curves I and II represents the voltage drop due to internal resistance of the generator, i.e. Ra (Ra + Rse) drop. The difference between curves II and III represents the drop due to armature reaction. If the load goes on increasing, then the terminal voltage may become zero because of heavy armature reaction.

Armature Reaction

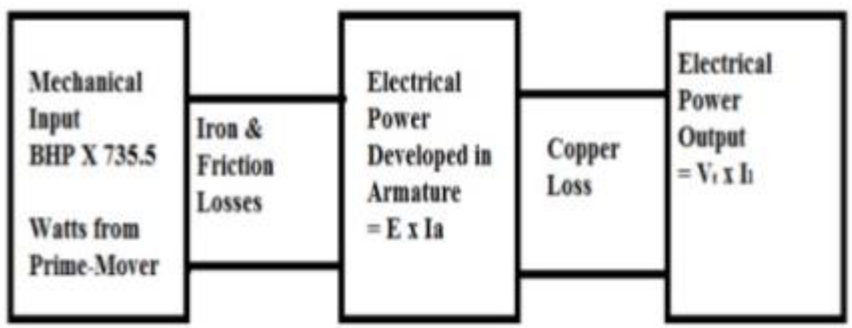
By armature reaction is meant the effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator. The armature magnetic field has two effects :

(*i*) ***It demagnetises or weakens the main flux*** and

(*ii*) ***It cross-magnetises or distorts it.***

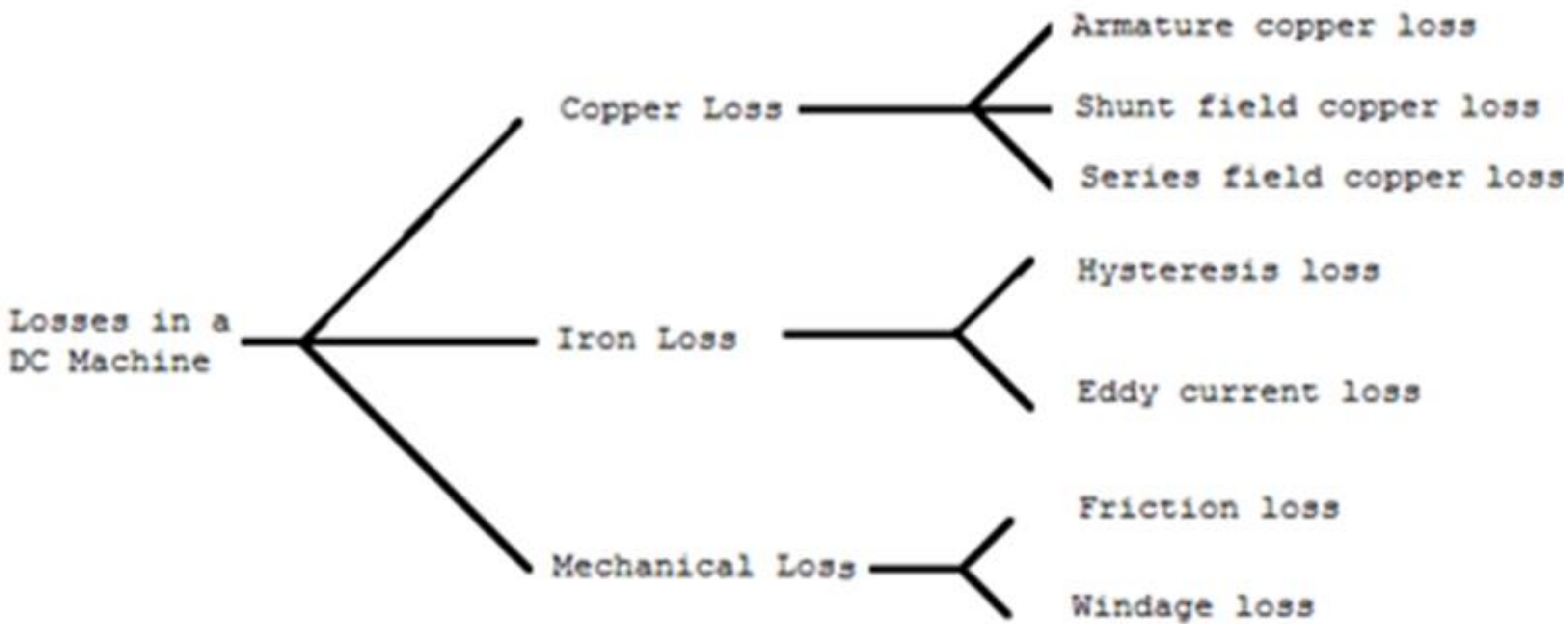
The first effect leads to reduced generated voltage and the second to the sparking at the brushes.

Power Stages in D.C. Generator



Stage A Stage B Stage C

Losses in DC Generator



Applications of DC Generators

DC Shunt Generator

1. Separately excited generators are preferred where the characteristics of dc shunt generators is not upto the expected level.
2. They can be used to excite the field magnets of ac generators.
3. A s the drop in voltage is very small, these generators can be used for supplying loads needing constant voltage.
4. They are used as source for battery charging purpose.
5. These generators are used for electroplating and electrolytic purpose.

DC Series Generators

1. They are used for series arc lighting.
2. They are used for series incandescent lighting.
3. They are used as booster, for the purpose of compensating the drop in voltage in the lines on loading.
4. Used for regenerative braking of dc locomotives.

Compound Generators

1. By means of compound generators it is possible to give constant voltage at the line by proper compounding.
2. Differentially compounded generator may be used for welding purposes.
3. They are used to supply power to railway circuits, incandescent lamps, elevator motors, etc.

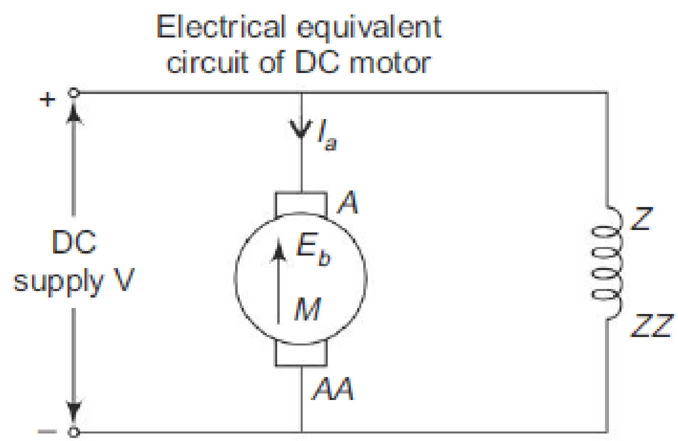
DC MOTOR

Principle

Whenever a current carrying conductor is kept in a stationery magnetic field an electromagnetic force is produced. This force is exerted on the conductor and hence the conductor is moved away from the field. This is the principle used in d.c. motors.

Construction

The construction of dc motor is exactly similar to dc generators. The salient parts of a dc motor are yoke or frame, main field system, brushes, armatures and commutator.



Working

In a dc motor, both the armature and the field windings are connected to a dc supply. Thus, we have current carrying armature conductors placed in a stationery magnetic field. Due to the electromagnetic torque on the armature conductors, the armature starts revolving. Thus, electrical energy is converted into mechanical energy in the armature. When the armature is in motion, we have revolving conductors in a stationery magnetic field. As per Faraday's Law of electromagnetic induction, an emf is induced in the armature conductors. As per Lenz's law, this induced emf opposes the voltage applied to the armature. Hence, it is called the counter or back emf. There also occurs a potential drop in the armature circuit due to its resistance. Thus, the applied voltage has to overcome the back emf in addition to supplying the armature circuit drop and producing the necessary torque for the continuous rotation of the armature.

Figure gives the electrical circuit of a d.c. shunt motor where

E_b = back EMF

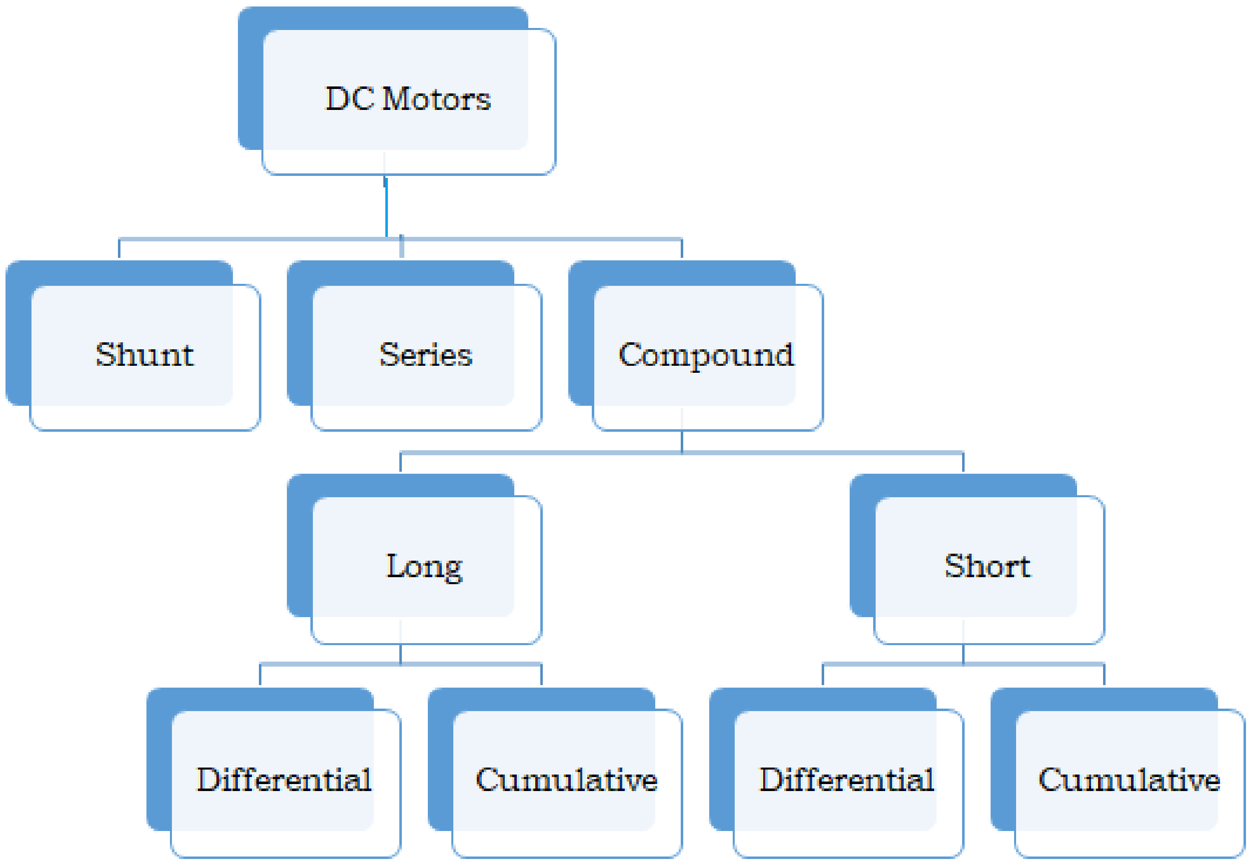
I_a = current flowing in the armature circuit

R_a = resistance of armature circuit

V = applied voltage

Thus, the characteristics equation of a dc motor is $V = E_b + I_a R_a$, where $I_a R_a$ represents the potential drop in the armature circuit.

Types of Motor



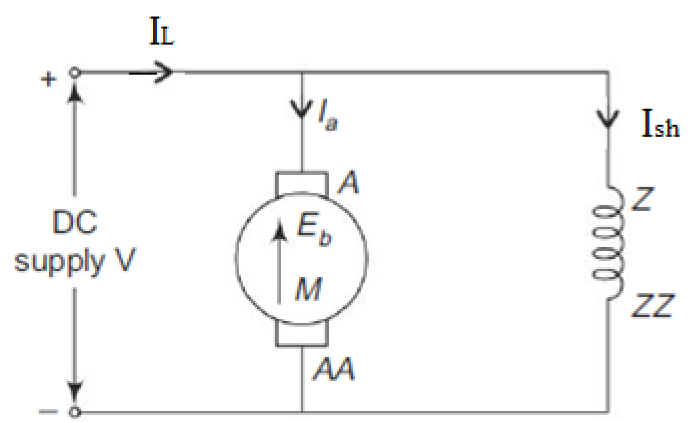
1. DC Shunt Motor

- Line Current

  $I_L = I_a + I_{sh}$ Where I_{L} = Line or supply current

- Emf Equation

  $V = E_b + I_a R_a + V_b$



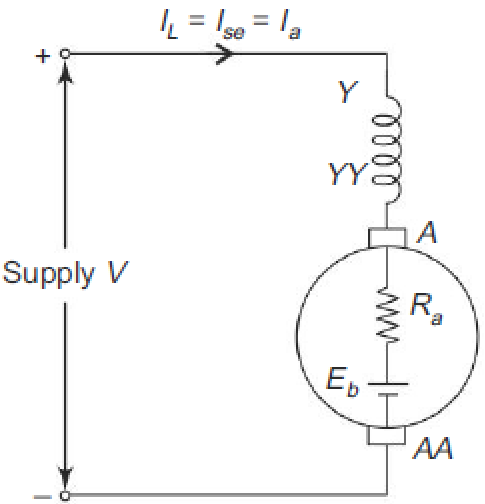
2. DC Series Motor

- Line Current

  $I_L = I_a = I_{se}$

- Emf Equation

  $V = E_b + I_a R_a + I_{se} R_{se} + V_b$



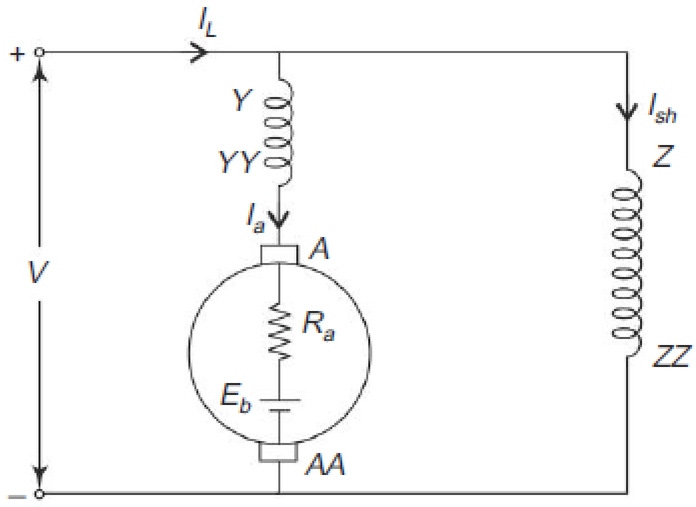
3. DC Compound Motor-Long Shunt

- Line Current

  $I_L = I_a + I_{sh}$
- Series Field Current

  $I_a = I_{se}$
- Emf Equation

  $V = E_b + I_a R_a + I_{se} R_{se} + V_b$



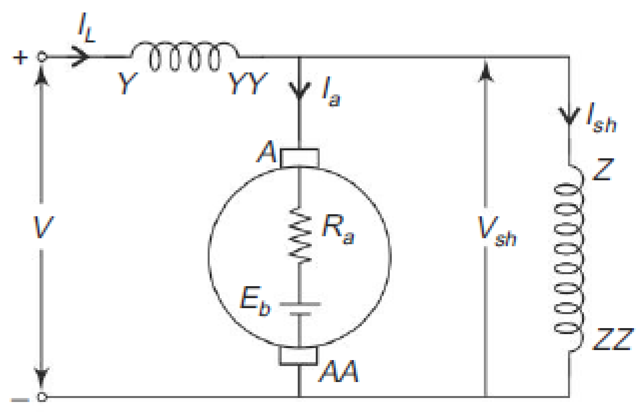
4. DC Compound Motor-Short Shunt

- Line Current

  $I_L = I_a + I_{sh}$
- Series Field Current

  $I_L = I_{se}$
- Emf Equation

  $V = E_b + I_a R_a + I_{se} R_{se} + V_b$



Torque and Speed Equations DC Motor

Armature Torque T_a of Motor $T_a \,\alpha\, \phi I_a$

Speed Equation $N \alpha \frac{E_b}{\phi}$

Characteristics of DC Motors

The characteristics of dc show the relationship between the following quantities.

(i) Torque and armature current (T vs I_a). It is also known as the electrical characteristic.

(ii) Speed and armature current (N vs I_a).

(iii) Speed and armature torque (N vs T_a). It is also known as mechanical characteristics.

The above characteristics can be obtained for all types of motors with the help torque and speed equations.

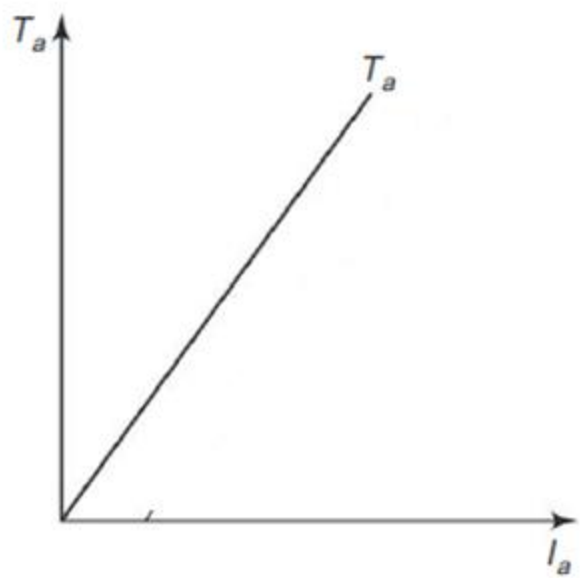
1. Characteristics DC Shunt Motor

(i) T_a Vs I_a

(i) T_a vs I_a Characteristics The flux, ϕ reduces slightly on heavy loads only. Thus, flux can be considered to remain constant.

$$T_a \, \alpha \, I_a$$

So, T_a vs I_a characteristics is a straight line characteristics as shown in Fig.



1. Characteristics DC Shunt Motor

(ii) N Vs I_a

(ii) N vs I_a Characteristic

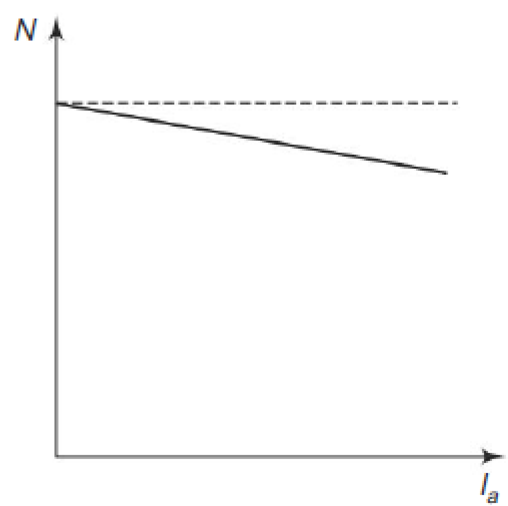
$$N \,\alpha\, \frac{Eb}{\phi} \qquad (1)$$

For shunt motor ϕ is almost constant on load $\therefore N \,\alpha\, E_b$

$$N \,\alpha\, V - I_a R_a \qquad (2)$$

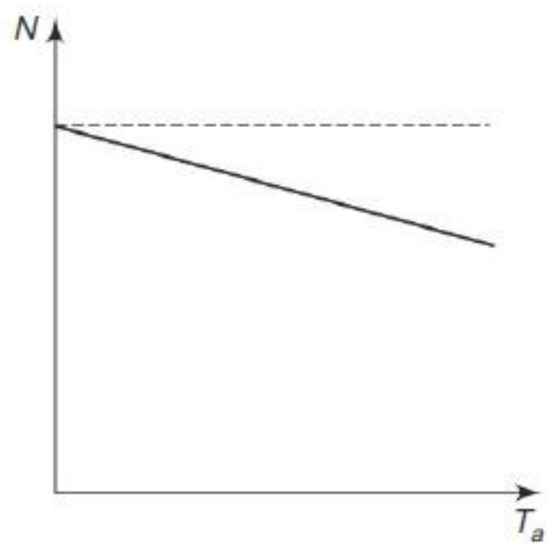
As load increases, I_a increases, but the drop $I_e R_a$ is very small as R_e is very small. So there will be a small change in speed from no-load to full load as shown in Fig. The drop in speed from no-load to full-load is 5 to 10% of no-load speed.

Shunt motor is a constant speed motor



1. Characteristics DC Shunt Motor
(iii) N Vs Ta

(iii) N vs T_a Characteristics This can be deduced from the above two characteristics and is shown in Fig. 6.24.



2. Characteristics DC Series Motor

(i) Ta Vs Ia

(i) T_a vs I_a Characteristics

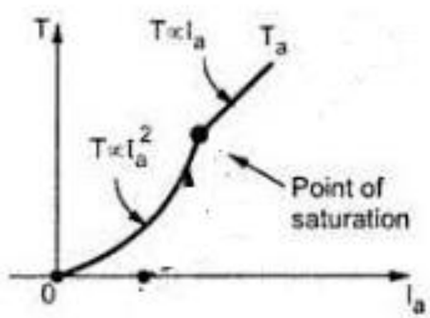
$$T_a \, \alpha \, f \, I_a;$$

In series motor $\phi \, \alpha \, I_{Se}$ and $I_{Se} = I_a$

At light loads, $T_a \, \alpha \, I_a^2$ (prior to saturation of field poles)

At heavy loads, $T_a \, \alpha \, I_a$ (after saturation of magnetic poles, ϕ is constant for any value of I_a)

So, T_a vs I_a characteristics is a parabola prior to saturation, and it is a straight line after saturation, as shown in Fig. . On heavy loads, the series motor exerts higher starting torque as $T_a \, \alpha \, I_a^2$ prior to saturation.



2. Characteristics DC Series Motor

(ii) N Vs Ia

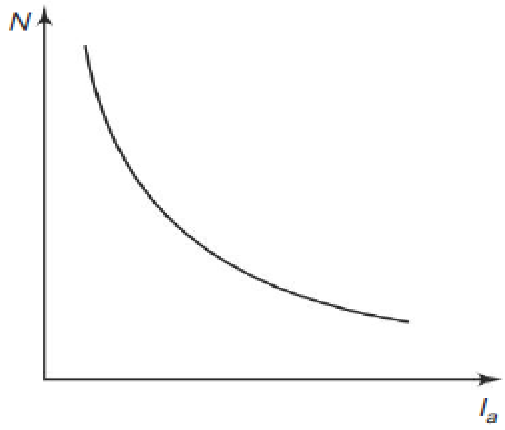
(ii) N vs I_a Characteristic

$$N \alpha \frac{E_b}{\phi}; \qquad (1)$$

$$E_b = V - I_a (R_a + R_{se}) \text{ and } \phi \, \alpha \, I_{se} (I_{se} = I_a) \qquad (2)$$

Change in E_b is very small with changes in load. So it can be regarded as constant on all loading

$$\therefore \qquad N \alpha 1/\phi \quad \text{or} \quad N \alpha 1/I_a \qquad (3)$$

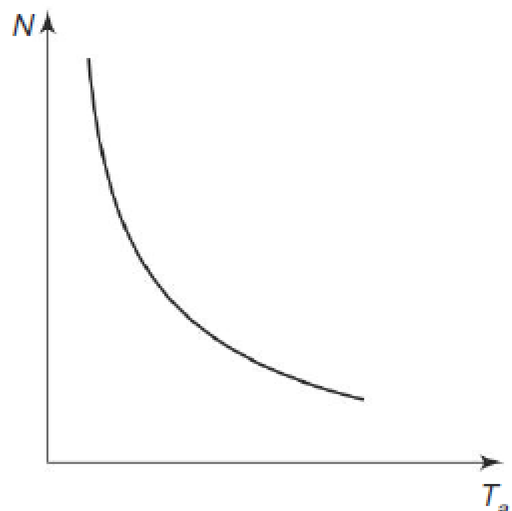


The speed-armature current characteristic is a regular parabola as shown in Fig. 6.26. On light load or no-load, the armature current I_a is very small, and so the motor will run at dangerously high speeds. So, series motor should always be started with some load on it. Series motor is a variable speed motor.

2. Characteristics DC Series Motor

(iii) N Vs Ta

(iii) N vs T_a Characteristics From the above two characteristics, this characteristics can be deduced, as shown in Fig. 6.27.

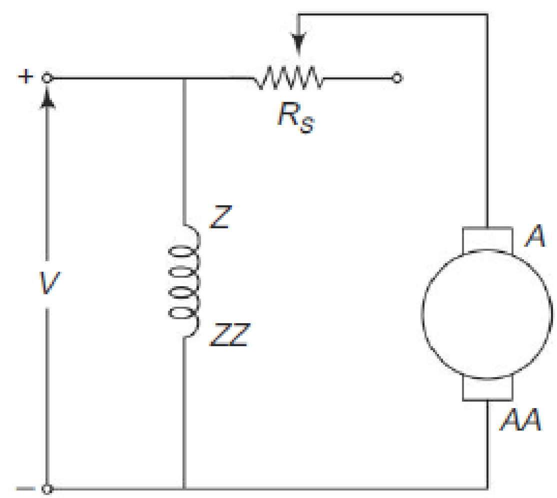


STARTERS

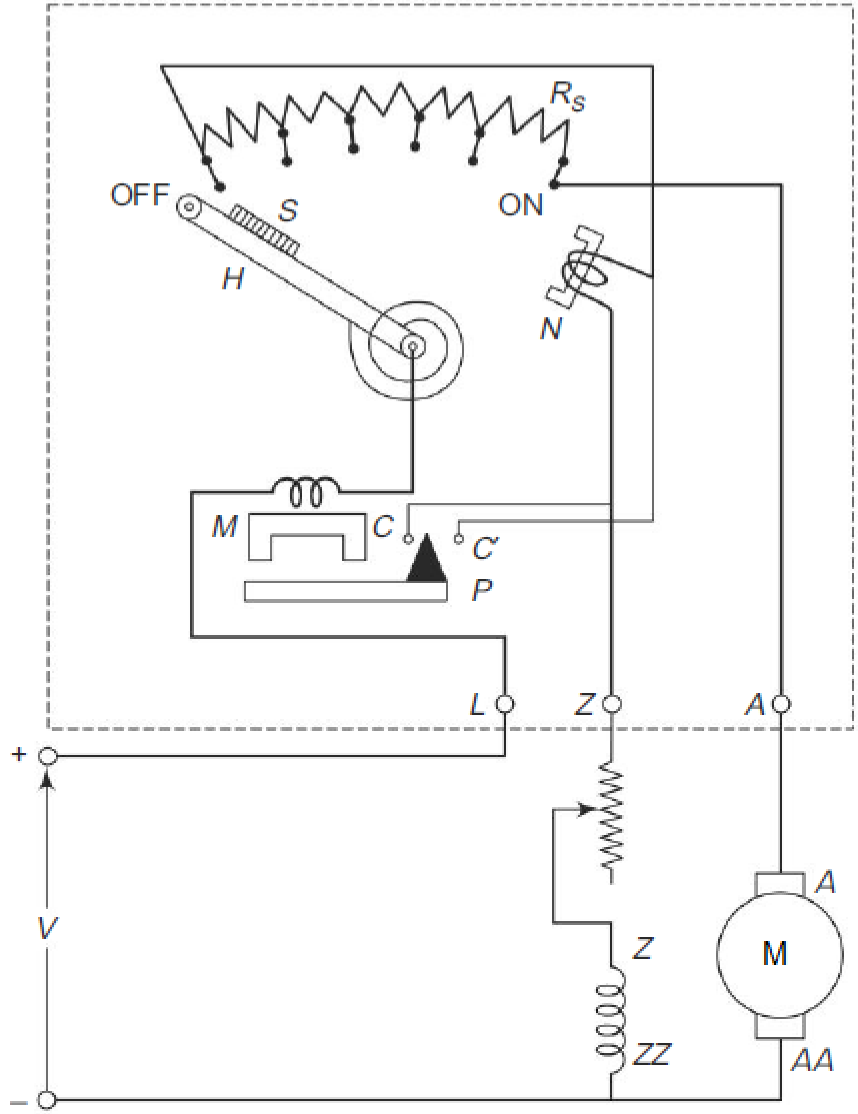
Starting of D.C. Motors

If the motor is directly switched on to the supply, the current drawn by the motor will be many times its full load current. This is because at the moment of switching on, there is no back emf developed by the motor. So, the current drawn by the motor is controlled by its internal resistance which is very small in value. This current is $I_a = \frac{V}{R_a}$ which is sometimes around 25 to 30 times of full load current of motor. This starting current will affect the power system supply quality. Specifically, there will be a heavy drop in system voltage momentarily. So, the starting current has to be limited. This can be achieved by connecting a resistance in the armature circuit. Once the motor picks up speed the back emf is developed and so the external resistance can be gradually cut out from the circuit. This is shown in Fig. 6.40. This resistance can be called as starting resistance.

To start the dc motor a device called starter can be used. The main function of the starter is to control the starting current drawn by the motor. The main component of a starter is resistance R_s. In addition to this they have protective devices like no-voltage release coil and overload release coil. There are 2-point starters meant for starting dc series motors 3-point and 4-point starters which are used for starting dc shunt and compound motors. The construction and working of a 3-point starter alone is discussed here.



3-POINT STARTER



DC 3-point Starter The components and the internal wiring of a 3-point starter is shown in Fig.

When the starter handle is moved from OFF position to stud (1) of R_s, the armature circuit of motor is closed through the starting resistance R_s and the overload release coil [OLR coil], thereby the starting current is controlled. Field circuit of motor is also closed through the voltage coil [NVC]. The motor starts running and back emf develops. Now the starter handle can be moved gradually from one stud to another and finally to ON.

The starter handle should be moved against the restraining force offered by the spring mounted in the starter handle. Once the starter handle comes to ON position, the NVC holds the starter handle firmly, i.e. the electromagnetic attracts the soft iron piece attached to the starter handle.

Whenever supply fails, the NVC gets de-energised and the electromagnetic N is demagnetized. Because of spring "force, the starter" handle comes to OFF position. When the motor is over loaded, electromagnetic force offered by the OLR coil is sufficient to attract the iron strip *P*. The contacts *CC* are bridged which results in short circuiting of NVC. So in this case also the electromagnet. "*N*" is demagnetized and the starter handle comes to OFF position. In this way the motor is protected against failure of supply and against overloading.

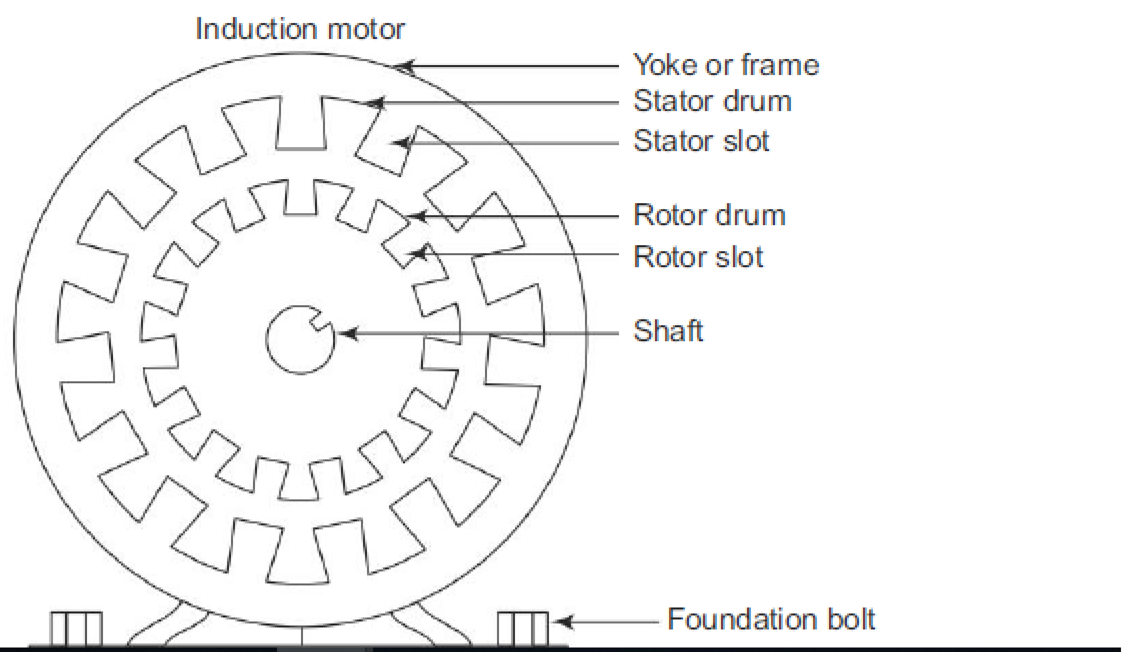
THREE PHASE INDUCTION MOTOR

Principle

When a three phase balanced voltage is applied to a three phase balanced winding, a rotating magnetic field is produced. This field has a constant magnitude and rotates in space with a constant speed. If a stationary conductor is placed in this field, an emf will be induced in it. By creating a closed path for the induced current to flow, an electromagnetic torque can be exerted on the conductor. Thus, the conductor is put in rotation.

Construction

The important parts of a three phase induction motor are schematically represented in Fig. 6.47. Broadly classified, they are stator and rotor. Each of these is described below.



Stator This is the stationary part of the motor. It consists of an outer solid circular metal part called the yoke or frame and a laminated cylindrical drum called the stator drum. This drum ash number of slots provided over the entire periphery of it. Required numbers of stator conductors are embedded in the slots. These conductors are electrically connected in series and are arranged to form a balanced three phase winding. The stator is wound to give a specific number of poles. The stator winding may be star or delta connected.

Rotor This is the rotating part of the induction motor. It is also in the form so slotted cylindrical structure. The air gap between stator and rotor is as minimum as mechanically possible. There are two types of rotors—squirrel cage rotor and slip-ring or wound rotor.

Working

A three phase balanced voltage is applied across the three phase balanced stator winding. A rotating magnetic field is produced. This magnetic field completes its path through the stator, the air gap and the rotor. In this process, the rotor conductors, which are still stationary, are linked by the time varying stator magnetic field. Therefore, an emf is induced in the rotor conductors. When the rotor circuit forms a closed path, a rotor current is circulated. Thus, the current carrying rotor conductors are placed in the rotating magnetic field. Hence, as per the law of interaction, an electromagnetic force is exerted on the rotor conductors. Thus, the rotor starts revolving.

According to Lenz's law, the nature of the rotor induced current is to oppose the cause producing it. Here the cause is the rotating magnetic field. Hence, the rotor rotates in the same direction as that of the rotating magnetic field.

In practice, the rotor speed never equals the speed of the rotating magnetic field (called the synchronous speed). The difference in the two speeds is called slip. The current drawn by the stator is automatically adjusted whenever the motor is loaded.

SINGLE PHASE INDUCTION MOTORS

Single phase induction motors are widely used in domestic, industrial and machine tool applications. The capacity of this motor varies from fractional horse power to 5 HP. Fractional horse power motors are used in variety of applications.

Construction and Non-Self Starting of 1-phase Induction Motor

The construction of 1-phase is similar to 3-phase induction motors. The starter has a single winding. The rotor is squirrel cage type as in 3-phase induction motor. When starter winding is energised with single phase supply an alternating flux is set up, but it is not a revolving field as in 3-phase induction motor. This alternating flux when acting on stationery motor cannot produce rotation. Only a revolving starting. However if the rotor is given an initial start by hand or by other means, then motor may start and run.

To make the single phase induction motors self starting, the following type of 1-phase induction motors were developed.

(a) Split-phase induction motors

(i) Resistance-start motor

(ii) Capacitor-start motor

1 Split Phase Resistance Start 1-Phase Induction Motor

In addition to the main winding of the motor, an auxillary winding is also placed in the starter. Both these windings are uniformly distributed in the stator slots. The two windings are displaced by 90° (electrical) in space. The main winding is called running winding and the auxillary winding is called the starting winding. The arrangement of these two windings in stator is shown in Fig. 6.53. The main winding is

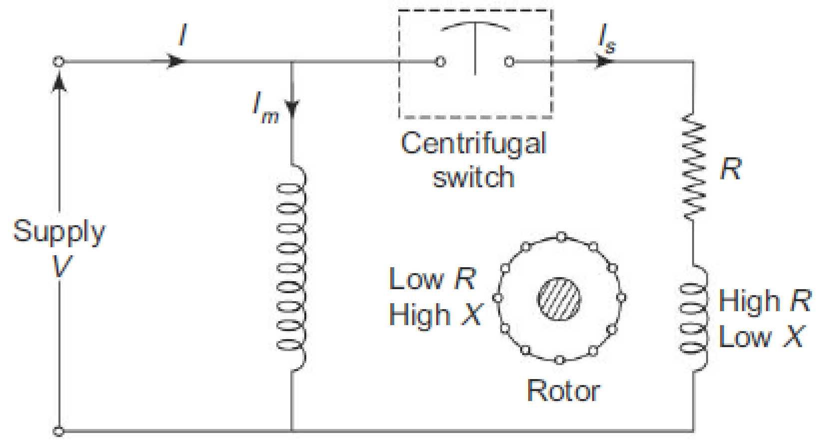
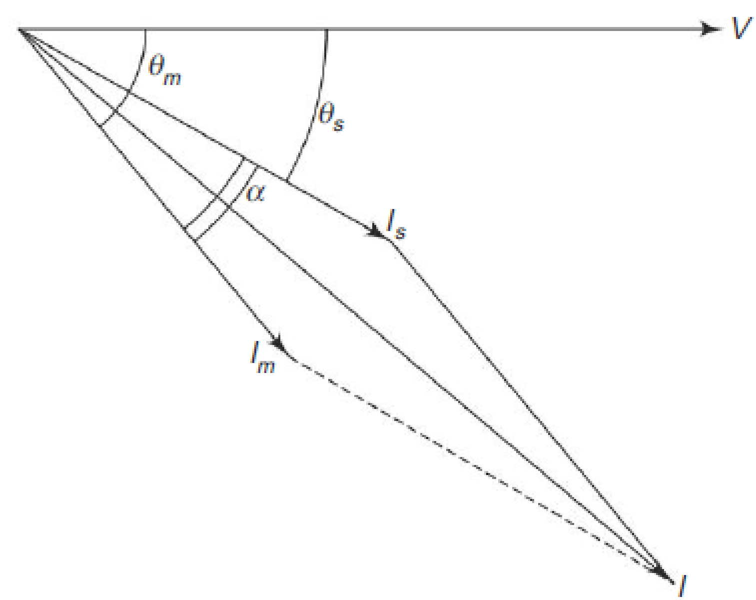


Fig. 6.53

highly inductive and the auxillary winding should be highly resistive. For this purpose, the auxiliary winding is provided with less number of turns. To make it highly resistive external resistance can be used in the auxiliary winding circuit. A centrifugal switch placed in the auxiliary winding circuit. The switch is in closed condition when the motor is at rest.

The 1-phase supply is given to the two windings, which are I parallel across the supply. The currents through the main winding and starting winding are displaced by an angle α as shown in Fig. 6.54. This angle α should be kept nearer to 90° by proper design of starting winding. The starting torque developed is proportional to sin α. When the motor attain 75% of rated speed, the centrifugal switch is opened and hence starting winding is disconnected from the supply. The starting torque developed is 150 to 200% full load torque of the motor.

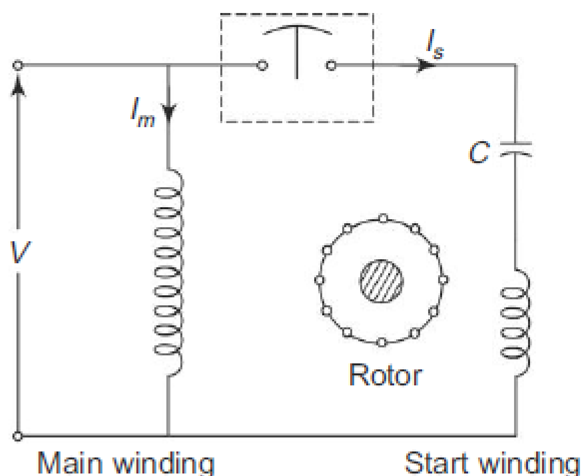
This type of motor is used in oil burns, machine tools, grinders, dish washes, washing machines, airblowers and air compressors.

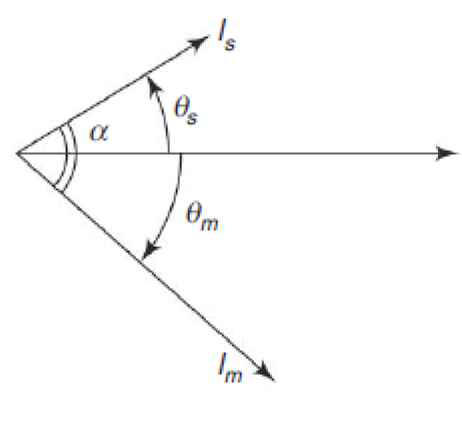


2. Split Phase Capacitor Start Induction Run Single Phase Induction Motor

The single phase supply given to the stator winding, can be split into two phases by connecting a suitable capacitor in series with the starting winding, as shown in Fig. 6.55 (i). The value of capacitance should be such that the phase angle α between I_s and I_m should be nearer to 90°. Then the fluxes due to this current is also displaced by the same angle α. This causes revolving field. The starting torque developed depends on sin α. The starting torque developed is about 300 to 450% of full load torque. This is more as compared to the previous type motor as α is more here. The value of α in the previous type motor is around 40° only. When the motor attains 75% of rated speed, the centrifugal switch opens and the starting winding is isolated from the circuit.

This motor is used where high starting torque is needed under loaded condition. They are used for pumps, refrigerations units, air-conditioners, large size washing machines, etc.





3-PHASE AC GENERATOR OR ALTERNATOR

An alternator works on the principle of electromagnetic induction. If a conductor is placed in a moving magnetic field an emf is induced in the stationery conductor as per Faraday's first law of electromagnetic induction.

Construction

The two important parts of AC generators are stator and rotor. The construction of ac generator showing all main parts is given in Fig. 6.56.

Stator The stator consists of a cast iron or mild steel frame, which supports the armature core. This frame acts as an enclosure and provides a closed path for the magnetic flux. The armature core is made of laminated sheets. The material for armature core may be special magnetic iron or steel alloys. The inner periphery of

the armature core is slotted, in order to accommodate the armature winding. The armature winding may be single layer or double layer. The 3-phase armature winding should be a balanced one. The number of turns and size of wire should be same for all the 3-phase winding and the 3-phase winding are displaced in space by 120° (electrical) between them. The three ends of three phase winding are connected together to make the starprint, and the other three terminals of the three phase windings are brought out of the generator.

Rotor The rotor is like a flywheel having alternate N and S poles on its outer periphery. These electromagnets are magnetised by means of low dc voltage of 125 or 250 V. As rotor and hence the field magnets are rotating, this dc excitation voltage is given through slip rings which are fixed on the frame.

There are two types of rotors used in ac generators.

(i) *Salient or projecting pole type* It is used for engine driven generators, which are run at low and medium speed. The rotor has even number of projecting poles, whose cores are boiled to a heavy magnetic wheel of cast iron. The axial length of rotor is short and the diameter is large.

(ii) *Smooth cylindrical type* It is used for steam turbine driven generators or turbo alternators which are run at high speed. The rotor is made up of cast iron and cylindrical in shape. The outer periphery of the rotor is slotted to receive the field windings. The field windings are wound, such that N and S poles occur alternately. The number of field poles may be two or four. The axial length of rotor is large and its diameter is less.

Working of Alternator

The field magnets are magnetised by applying 125 volts or 250 volts through slip rings. The field windings are connected such that, alternate N and S poles are provided. The rotor and hence the field magnets are driven by the prime movers (steam driven turbine or engine driven). As the rotor rotates, the armature conductors are cut by the magnetic flux. Hence emf is induced in the armature conductors. As the magnetic poles are alternately N and S pole, the emf acts in one direction and then in the other direction. Hence an alternating emf induced in the stator conductors. The frequency of induced emf is depends on the number of N and S poles moving past an armature conductor in one second. The frequency of induced emf is given by,

$$f = \frac{P\,N}{120};\ \text{P} \rightarrow \text{No. of magnetic poles}$$

$$N \rightarrow \text{Speed of rotor in rpm.}$$

The direction of induced emf can be obtained by Fleming's Right hand rule.

SYNCHRONOUS MOTOR

Synchronous motor runs only at synchronous speed, $N_s = \frac{120 f}{P}$ on no-load and loaded conditions. It maintains speed while running. The only way to change the speed is by varying the supply frequency. It is not a self starting motor. This motor has to run upto its synchronous speed by some method, and then it can be synchronised.

Construction

The construction of synchronous motor is same as that of 3-phase ac generator. A synchronous machine may be run as synchronous motor and as synchronous generator.

Working Principle of Operation

When a 3-phase balanced winding is supplied with a balanced 3-phase supply, a rotating magnetic field of constant magnitude and synchronous speed is produced. Let the motor stator have 2-poles marked as N_s and S_s as shown in Fig. 6.57. The stator poles are rotating at synchronous speed. Let us assume that it moves in clockwise direction. The rotor is positioned as shown in Fig. 6.58 initially with reference to the position AB marked. As like poles repel, the rotor will tend to move in anticlockwise direction. At the end of first half cycle of supply, the rotor poles occupy the position as shown in Fig. 6.58 with respect to the reference plane AB. Now, because of attractive force between the unlike poles, the rotor will tend to move in the opposite, i.e. clockwise direction. So, with rapid movement of the stator poles, the rotor is subjected to a torque which is also rapidly reversing. But because of the inertia of the rotor, it will not respond to such a rapid reversing torque. So, the rotor remains stationary, which shows that it is not a starting motor.

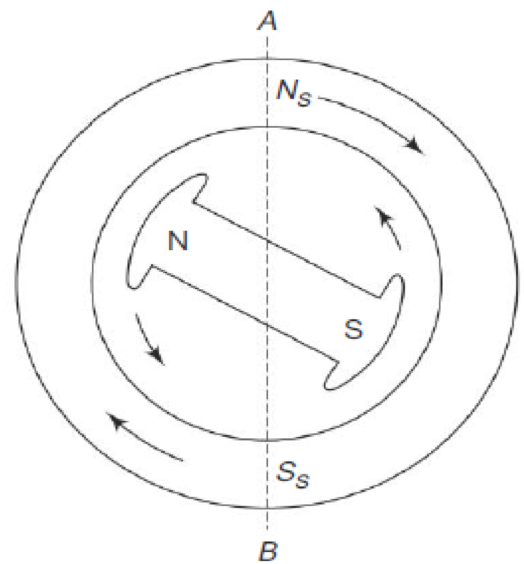


Fig. 6.57

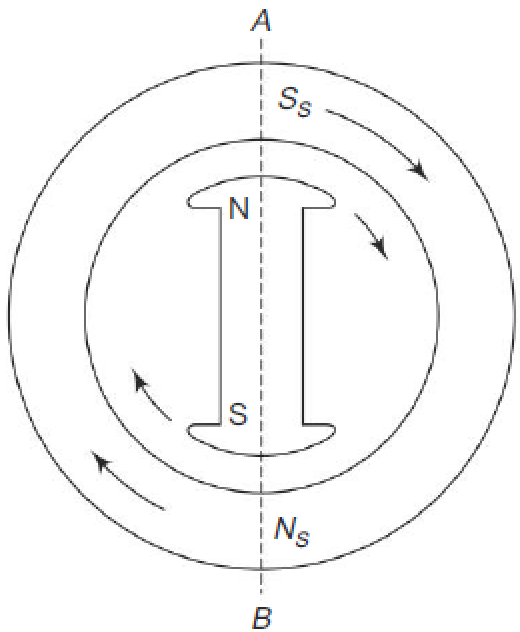


Fig. 6.58

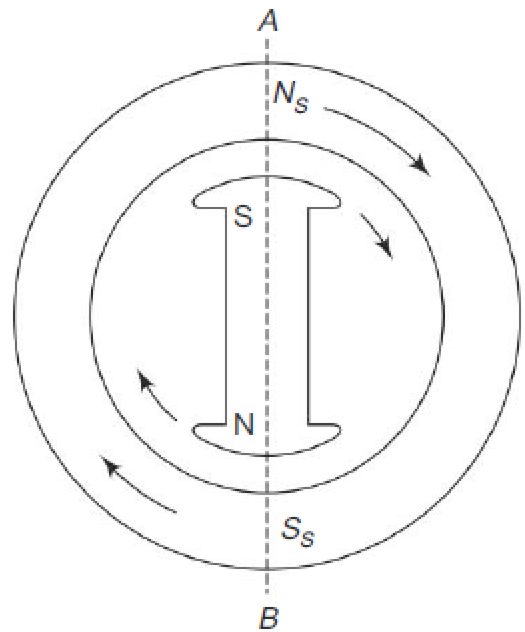


Fig. 6.59

Now consider the position of the rotor as shown in Fig. 6.59. The stator and rotor poles attract each other. Let the rotor also be rotating in clockwise direction at synchronous speed as that of stator field. So, the stator and rotor poles attract each other, at any instant, which results in unidirectional torque production, in clockwise direction in this case.

Sychronous Motor Starting Method

The methods for starting synchronous motor are:

(i) A dc motor coupled to the synchronous motor shaft: (discussed above)

(ii) Using the damper windings as a squirrel cage induction motor.

(iii) Using the field excited generator as a dc motor [similar to method (i)].

Synchronous Motor-application

(i) It is used in power house and in major substations to improve the power factor.

(ii) Used in textile mills, rubber mills, mining and other big industries for power factor improvement purpose and to maintain the facility of system voltage.

(iii) It is used to drive continuously operating and constant speed equipments like fans, blowers, centrifugal pumps, air comparators, etc.