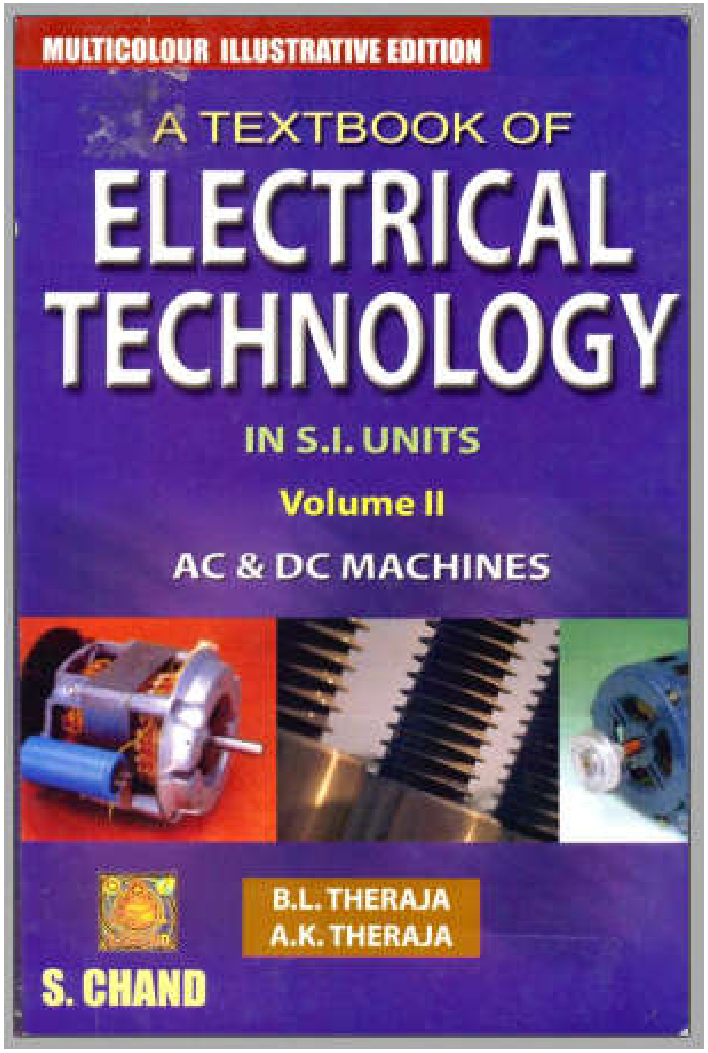
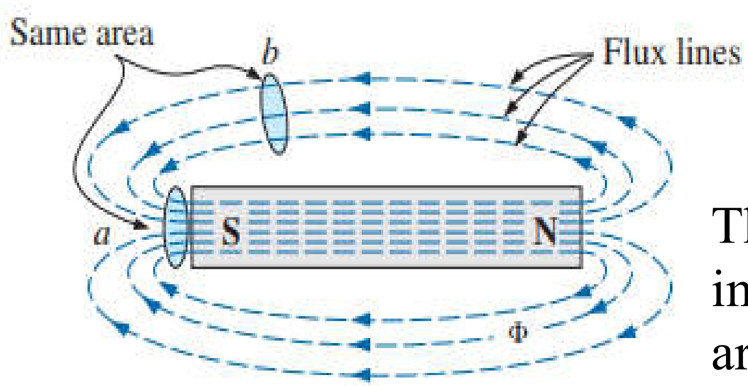
Electromagnetism
and
Fundamental Law's



Magnets

A magnet is a piece of metal that can **pull** certain types of metal toward itself.

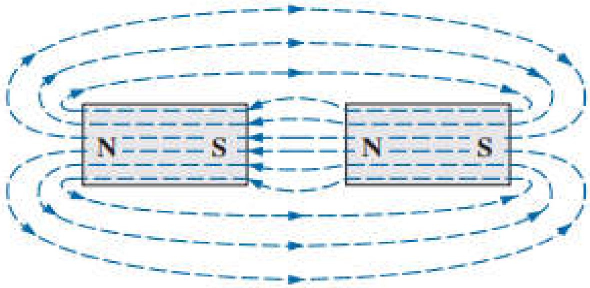
The force (which pulls the material) of magnets, called **magnetic field** or **magnetism**, is a basic force of nature, like gravity.



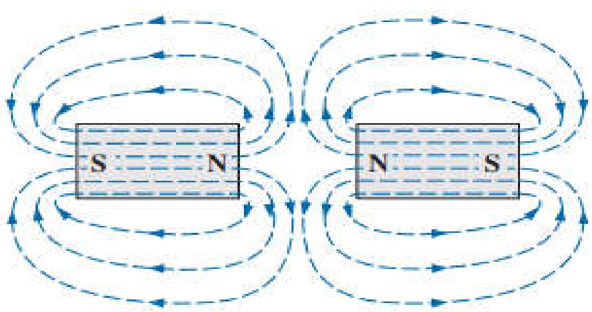
The magnetic field of magnet can be represented by imaginary lines (which is **invisible**) around magnet which are called **magnetic lines of force** or **lines of magnetic flux**.

The **magnetic lines of force** or **lines of magnetic flux** radiate from the north pole to the south pole, returning to the north pole through the metallic bar. That means, each flux line forms a **closed loop**.

If **unlike poles** of two magnets are brought together, the magnets **attract**.
If **like poles** of two magnets are brought together, the magnets **repel**.

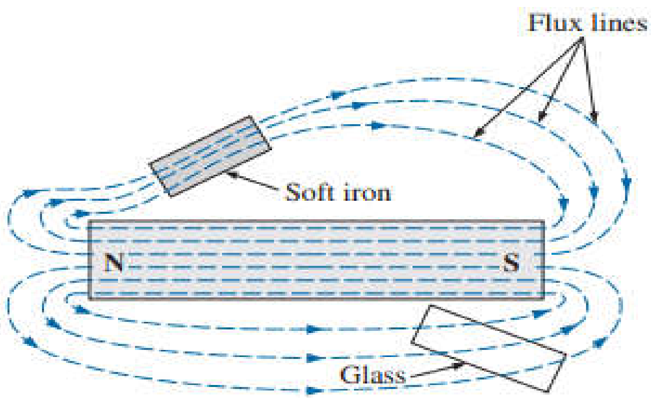


Flux distribution for two adjacent, opposite poles.



Flux distribution for two adjacent, like poles.

If a nonmagnetic material, such as glass or copper, is placed in the flux paths surrounding a magnet, an almost unnoticeable change occurs in the flux distribution.
If a magnetic material, such as soft iron, is placed in the flux path, the flux lines pass through the soft iron rather than the surrounding air because **magnetic flux lines pass with greater ease through magnetic materials than through air**.



Types or Classification of Magnets

Types of Magnet:

(***a***) **Permanent Magnet**:

(***i***) **Natural**: Obtained in a rock

(***ii***) **Artificial**: Made of a material that remains magnetized for long periods of time without the need for an external source of energy.

Diamagnetic: Materials that have permeabilities ($\mu = \mu_0\mu_r$ where $\mu_0 = 4\pi\times10^{-7}$ Wb/A-m) slightly less than that of free space are said to be diamagnetic [*Example*: *mercury, silver, carbon, copper etc.*].

Paramagnetic: Materials that have permeabilities slightly greater than that of free space are said to be paramagnetic [*Example*: *uranium, platinum, tungsten, aluminum, lithium etc.*].

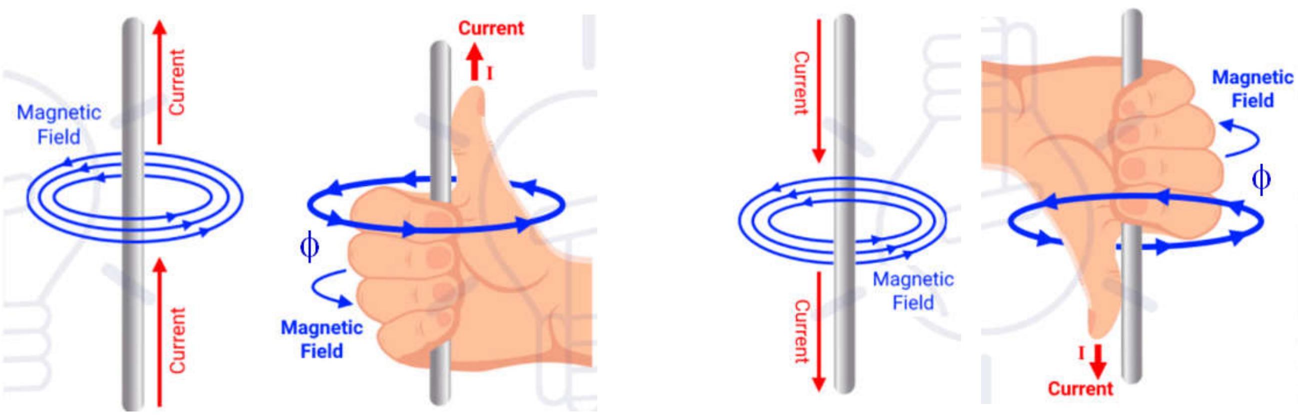
Ferromagnetic: Materials that have permeabilities is very high such as hundreds and even thousands of times that of free space are said to be ferromagnetic [*Example*: iron, nickel, steel, cobalt, and alloys of these metals].

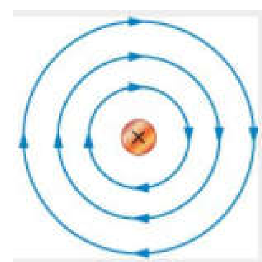
(***b***) **Electromagnet**: Perform same as magnet due to the flow of charge, or current in a conductor or coil or winding.

Electromagnetic Induction

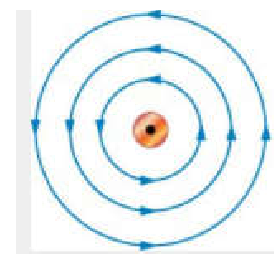
Electromagnet due to Straight Current Carrying Conductor:

When a straight conductor carries a current, a magnetic flux is produced around the conductor all along its length. The magnetic flux lines will be in the form of concentric circles around the conductor. The direction of the magnetic flux lines is conveniently obtained by the ***Right–Hand Thumb/Grip Rule***.



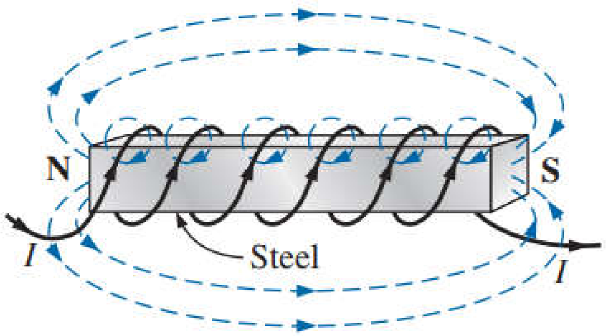


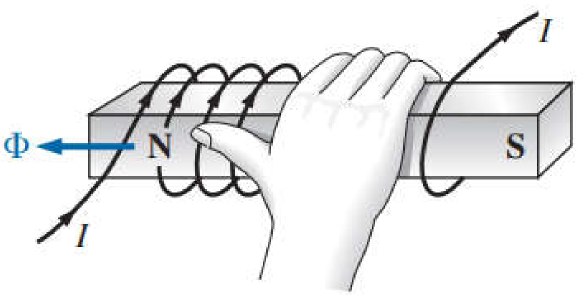
Current flowing away from viewer



Current flowing towards viewer

Right–Hand Thumb/Grip Rule: Suppose that a current carrying conductor is held in the right hand and the fingers are wrapped or curled around the conductor and the **thumb finger** is stretched in the **direction of current** flow. Then **wrapped or curled fingers** will give the **direction of circular magnetic flux line**.

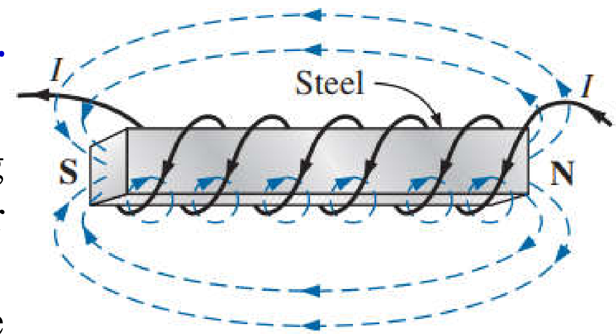


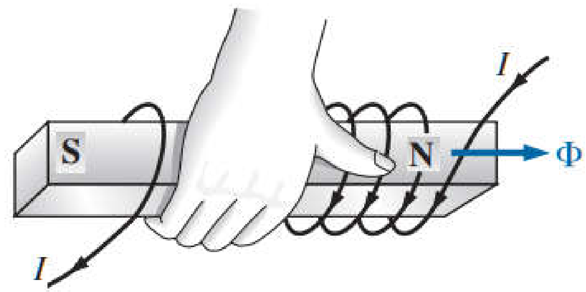


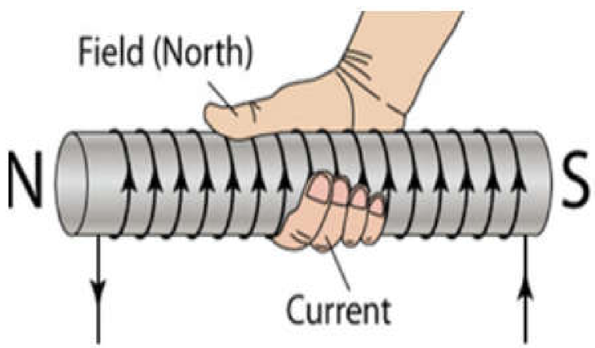
Electromagnet due to Circular Conductor (Coil) or Solenoid:

A **solenoid** is an arrangement in which long conductor is wound or wrapped with number of turns close together to form a coil.

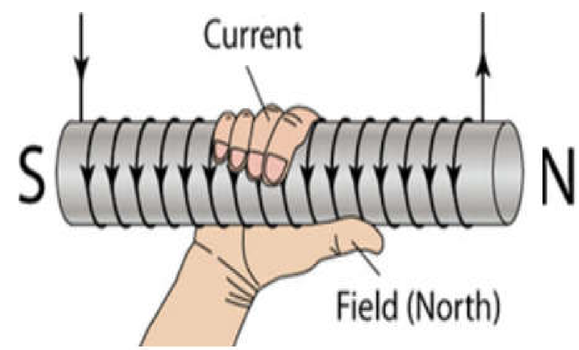
When a coil or solenoid is excited by the supply voltage so that it carries a current then it produces a magnetic field which acts through the coil along its axis and also around the solenoid. The direction of the magnetic flux lines is conveniently obtained by the ***Right–Hand Thumb/Grip Rule***.







Right–Hand Thumb/Grip Rule: Suppose that a current carrying coil or solenoid is griped such that the **curled fingers** in the **direction of current flow**. Then the **thumb finger** represents the **direction of flux** or the **North pole** of a magnet.



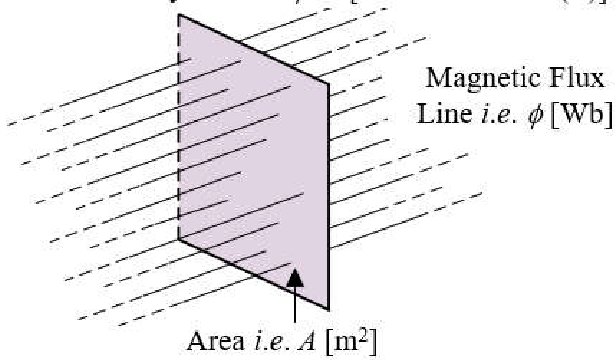
Some Definitions Related to Electromagnetic Induction

Magnetic Flux [Φ or ϕ]: The total number of magnetic lines of force existing in a particular magnetic field is called **magnetic flux**. The unit of magnetic flux is **weber** (Wb). It is denoted by Greek letter **Phi** (Φ for dc; ϕ for time varying case)

1 weber = 10^8 magnetic lines of force

Flux Density [B]: The magnetic flux [Φ or ϕ] per unit area (A) in a plane at right angles to the flux is known as **flux density**. The unit of magnetic flux is Wb/m^2 or Tesla [T]. It is denoted by B

Magnetic Flux density *i.e.* $B = \phi / A$ [Wb/m^2 or Tesla (T)]



Magnetic flux line crossing a surface or plane

Magnetomotive Force (MMF) **or Ampere-turns**: The product of number of turns of a coil and current is called **magnetomotive force** or **ampere-turns**.

$$\text{MMF} = NI \text{ [AT]}$$

Magnetic Field Strength or Magnetic Field Intensity or Magnetizing Force [H]: The magnetomotive force per unit length is called **magnetic field strength** or **magnetic field intensity** or **magnetizing force**.

$$H = \frac{\text{MMF}}{l} = \frac{NI}{l} \quad \text{[AT/m]}$$

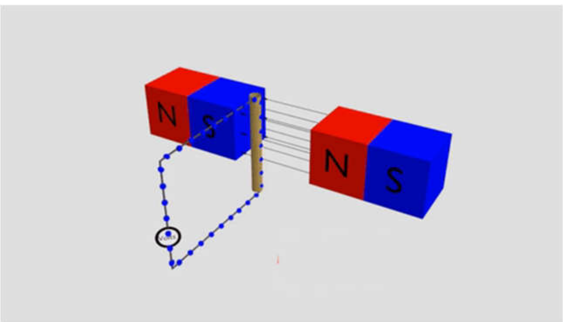
Absolute Permeability [μ]: The ratio of flux density (B) in a particular medium (other than vacuum or air) to the magnetic filed intensity (H) producing that flux is called **absolute permeability** of that medium.

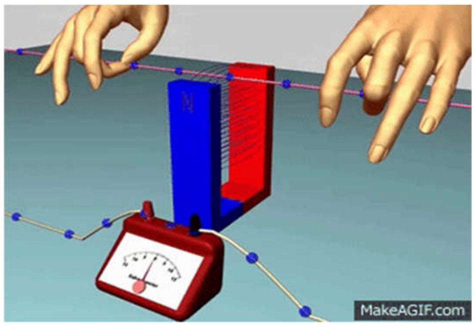
$$\mu = \frac{B}{H} \quad \text{[Henries/meter; H/m]}$$

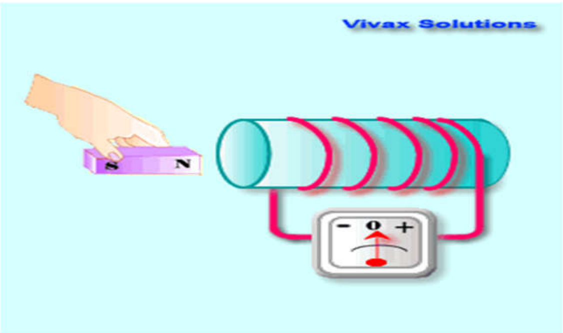
Faraday's Law of Electromagnetic Induction

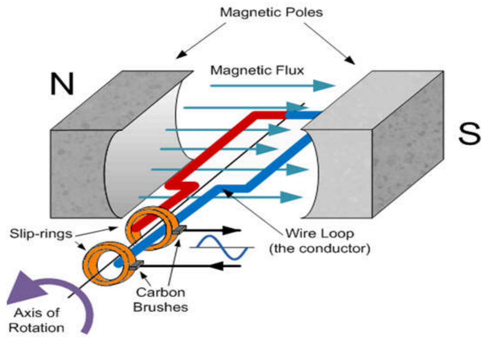
Statement of Faraday's Law 1: An induced emf is established in a conductor or circuit whenever the magnetic filed linking that conductor or circuit is changed.

Statement of Faraday's Law 2: The magnitude of induced emf is equal to the rate of change of flux linkages ($d\phi/dt$) with the coil.









Lenz's Law

To determine the polarity of induced emf, Lenz's law is applied.

Statement of Lenz's law: The direction of an induced emf produced by the electromagnetic induction is such that it sets up a current which always opposes the cause that is responsible for inducing the emf.

According Faraday's law 2 and to Lenz's law, an induced emf is mathematically expressed as follows:

$$e = -N\frac{d\phi}{dt} \quad [\mathrm{V}]$$

Nature of Induced EMF

EMF gets induced in a conductor, whenever there exists change in flux with that conductor, according to Faraday's law. Such change in flux can be brought about by the following methods:

(***a***) **Statically Induced EMF**:

By using a stationary conductor, a stationary electromagnet and varying the magnetic flux by supplying ac current to the electromagnet. This principle is used in **transformer**.

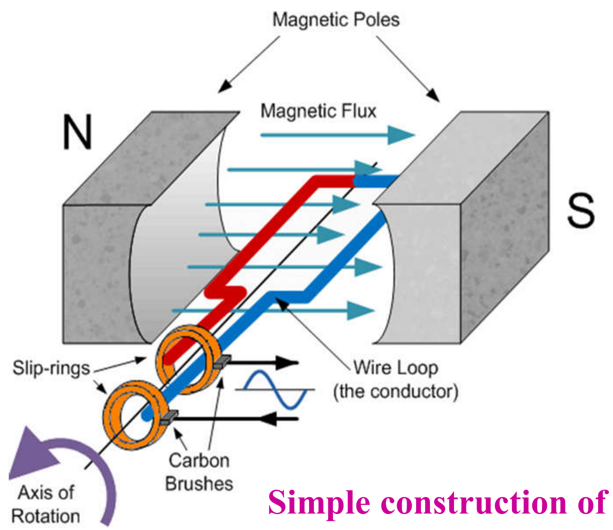
(***b***) **Dynamically Induced EMF**:

(***i***) By using a stationary permanent magnet (or an electromagnet fed by dc current) and a moving conductor. This principle is used in all **dc generators and motors**.

(***ii***) By using a stationary conductor, a rotating or moving permanent magnet (or an electromagnet). This principle is used in large **synchronous generators and motors**.

(***iii***) By using a stationary conductor which produced rotating or moving flux, a rotating or moving conductor with a relative speed between rotating flux and rotating conductor. This principle is used in an **induction generators and motors**.

Magnitude of Dynamic Induced EMF



Simple construction of a generator

Magnitude of Induced voltage or emf affected by **flux density** (B), the **effective length of conductor** (l), the **conductor velocity** (v) and sine of angle (α) between **flux line and the direction of motion of conductor**.

$$E = Blv\sin\theta \quad \text{[Volt, V]}$$

Fleming's Right-Hand Rule

Although the direction of induced emf could be determined by Lenz's law, it is found more convenient to use ***Fleming's Right-Hand Rule***.

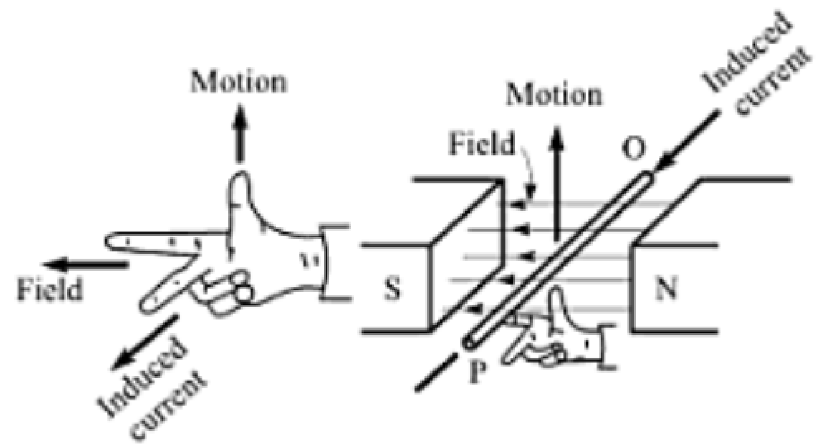


Illustration of Fleming's right-hand rule.

Statement of Fleming's Right-Hand Rule: Stretch the first (fore) finger, the second (middle) finger and the thumb finger of right hand in mutually perpendicular direction to each other. Arrange the right hand so that **first finger point in the direction of flux line** (North pole to south pole) and **thumb in the direction of motion of conductor** then the **middle finger will point in the direction of current (or emf)**.

Problem A conductor moves with a velocity of 15 m/s at an angle of (a) 90°, (b) 60° and (c) 30° to a magnetic field produced between two square-faced poles of side length 2 cm. If the flux leaving a pole face is 5 μWb, find the magnitude of the induced e.m.f. in each case.

Solution:

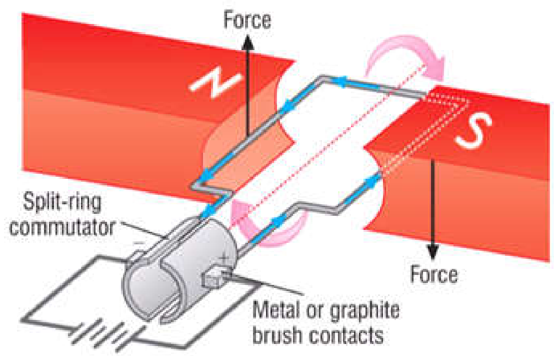
$v = 15\,\text{m/s}$; length of conductor in magnetic field, $l = 2\,\text{cm} = 0.02\,\text{m}$; $\quad A = 2 \times 2\,\text{cm}^2 = 4 \times 10^{-4}\,\text{m}^2$, $\Phi = 5 \times 10^{-6}\,\text{Wb}$

(a) $$E_{90} = Blv \sin 90^\circ = \left(\frac{\Phi}{A}\right) lv \sin 90^\circ = \frac{(5 \times 10^{-6})}{(4 \times 10^{-4})}(0.02)(15)(1) = \mathbf{3.75\ mV}$$

(b) $$E_{60} = Blv\ \sin 60^\circ = E_{90} \sin 60^\circ = 3.75 \sin 60^\circ = \mathbf{3.25\,mV}$$

(c) $$E_{30} = Blv\ \sin 30^\circ = E_{90} \sin 30^\circ = 3.75 \sin 30^\circ = \mathbf{1.875\,mV}$$

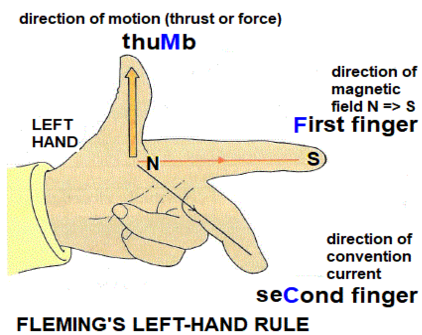
Force on a Current Carrying Conductor in A Magnetic Field



Lorentz or Electromagnetic Force: When a current-carrying conductor is placed in a magnetic field, a force is developed or produced or established on the conductor which is called *electromagnetic force,* or Lorentz force.

This force constitutes the basis of operation of motors.

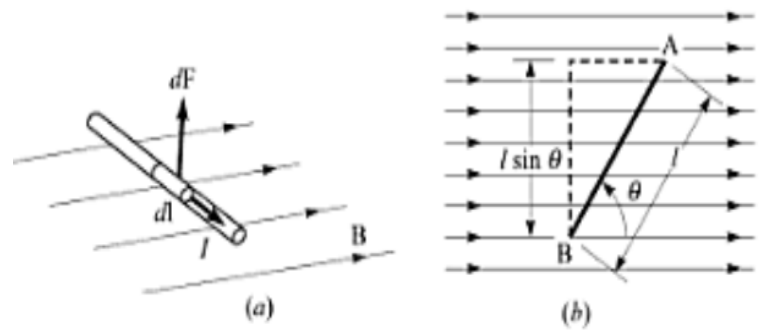
The direction of the magnetic flux lines is conveniently obtained by the **Fleming's Left-Hand Rule**.



Statement of Fleming's Right-Hand Rule: Stretch the first (fore) finger, the second (middle) finger and the thumb finger of right hand in mutually perpendicular direction to each other. Arrange the right hand so that **first finger point in the direction of flux line** (North pole to south pole) and the **middle finger to the direction of current** then **thumb will point in the direction of force of conductor**.

Magnitude of Force: Force on a current carrying conductor affected by **flux density** (B), the **effective length of conductor** (l), the **current** (v) and sine of angle (α) between **flux line and the direction of motion of conductor**.

$$\boxed{F = BlI\sin\theta \quad [\text{Newton, N}]}$$



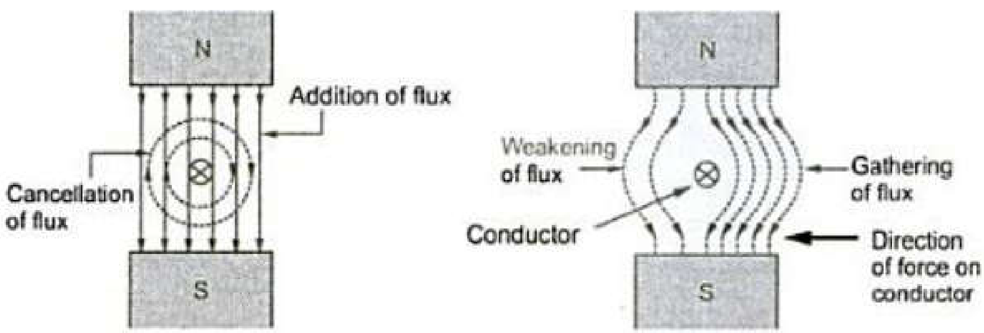
How a Force and Torque are Produce on the Conductor?

There is presence of two magnetic field. The force is created due to the interaction with each other.

Left side of conductor, conductor flux opposes the permanent magnet flux. Due to the interaction, the resultant left flux is **weakening**.

Right side of conductor, conductor flux assists with the permanent magnet flux. Due to the interaction, the resultant right flux is **strengthening/accumulating**.

Conductor experiences a force from high flux lines area towards low flux lines area i.e. from right to left.



Presence of the two fluxes

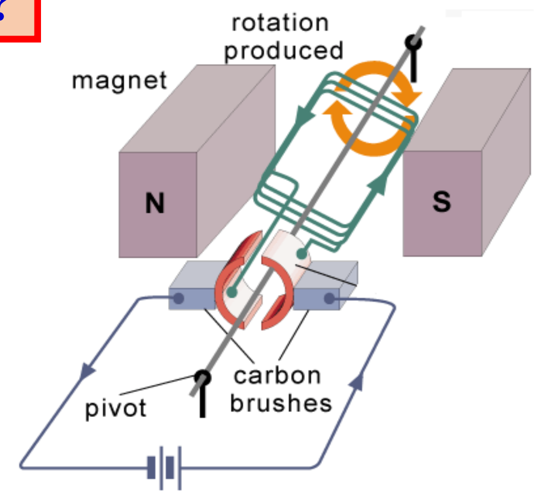
Resultant flux pattern

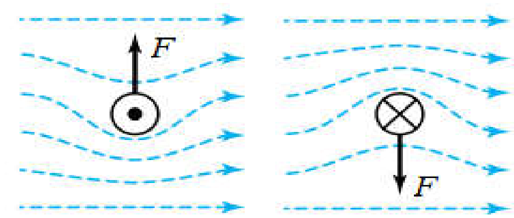
Interaction of the two flux lines

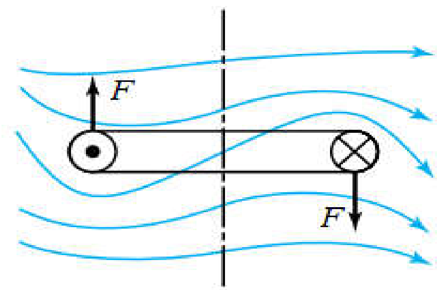
In an electrical machine, the direction of two conductor sides are different.

The developed forces in two sides are opposite direction.

The opposite direction of two sides forces are developed torque/rotation on shaft of electrical machine.







Example 3.5 : *Calculate the force experienced by the conductor of 20 cm long, carrying 50 amperes, placed at right angles to the lines of force of flux density 10×10^{-3} Wb/m^2.*

Solution : The force experienced is given by,

$F = BIl\sin\theta$ where $\sin(\theta) = 1$ as $\theta = 90$ degrees

B = Flux density = 10×10^{-3} Wb/m^2

l = Active length = 20 cm = 0.2 m

I = Current = 50 A

$F = 10\times10^{-3}\times50\times0.2 = \mathbf{0.1\ N}$

Problem A conductor 350 mm long carries a current of 10 A and is at right-angles to a magnetic field lying between two circular pole faces each of radius 60 mm. If the total flux between the pole faces is 0.5 mWb, calculate the magnitude of the force exerted on the conductor.

Solution:

$l = 350\,\text{mm} = 0.35\,\text{m}$; $I = 10\,\text{A}$;

Area of pole face $A = \pi r^2 = \pi(0.06)^2\,\text{m}^2$;

$\Phi = 0.5\,\text{mWb} = 0.5\times10^{-3}\,\text{Wb}$

Force $F = BIl$, and $B = \dfrac{\Phi}{A}$

hence force $F = \left(\dfrac{\Phi}{A}\right)Il$

$$= \frac{(0.5\times10^{-3})}{\pi(0.06)^2}(10)(0.35)\ \text{newtons}$$

i.e. force = 0.155 N

Losses of Electrical Machine

Losses of Electrical Machines:

(***a***) **Copper (Cu)/*I*²*R* Losses** (P_{Cu}):

Losses in different windings or coils

(***b***) **Stray Losses** (P_{st}):

(***I***) **Core or Iron Losses** (P_i):

(***i***) Eddy Current loss (P_e)

(***ii***) Hyteresis loss (P_h)

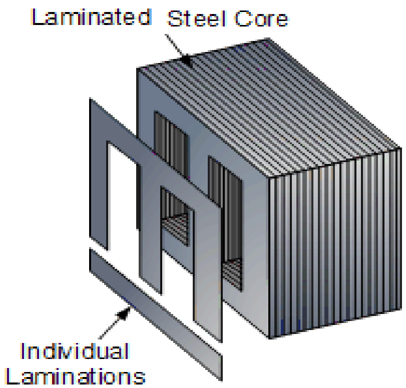
(***II***) **Mechanical Losses** (P_{mech}):

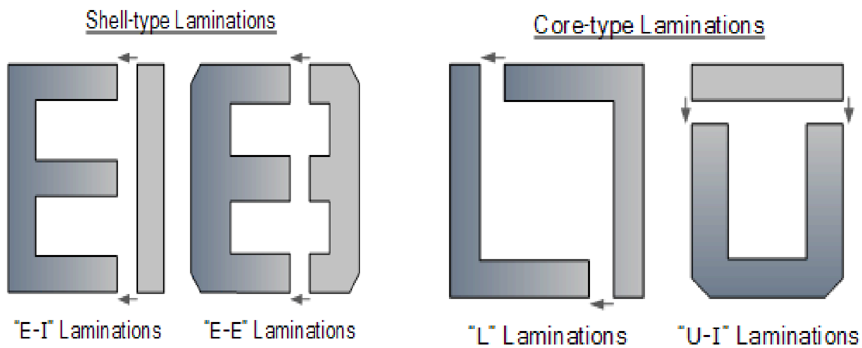
(***i***) Friction loss (P_f)

(***ii***) Windage loss (P_w)

Hysteresis Loss: Since the flux in a transformer core is alternating, power is required for the continuous reversals of the elementary magnets of which the iron is composed. This loss is known as hysteresis loss.

Eddy-Current Loss: Due to the alternating flux an emf is induced in core and current flows to the core due to this emf. This current is called ***eddy current***. The power loss due to the eddy current is called eddy current loss. By using thin laminations, insulated in core, a small portion of eddy current loss can be reduced.





Efficiency of Electrical Machine

$$\begin{aligned}\text{Input} &= \text{Output} + \text{Losses}\\ &= \text{Output} + \text{Cu Loss} + \text{Stray Losses}\end{aligned}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

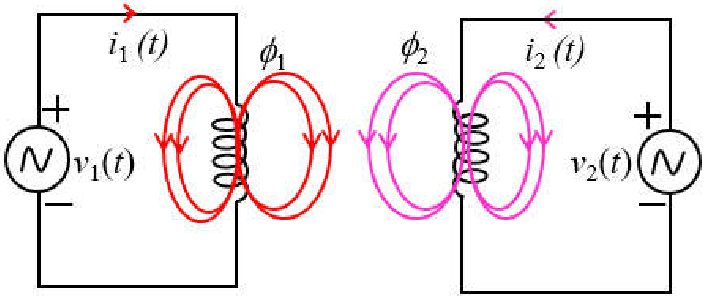
$$\begin{aligned}\text{Output} &= \text{Input} - \text{Losses}\\ &= \text{Input} - \text{Cu Loss} - \text{Stary Loss}\end{aligned}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{Losses}}{\text{Input}}$$

Self Inductance
Leakage Inductance
Mutual Inductance

Self Flux, Leakage Flux and Mutual Flux

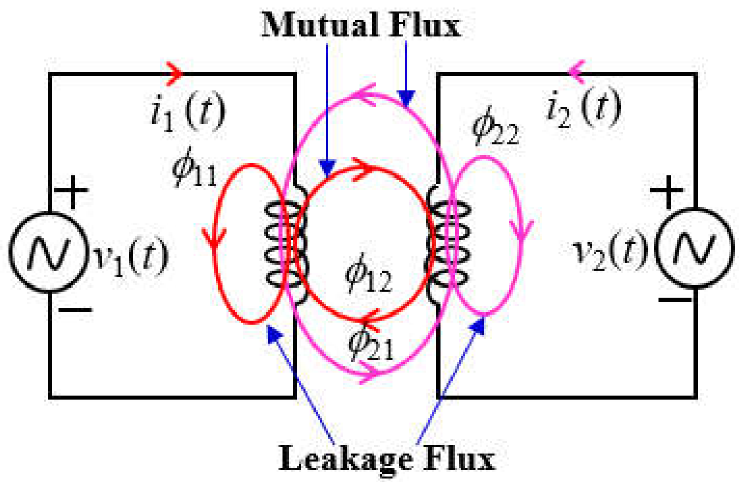
Self Flux: The total flux which is generated by a supplying current through a coil in an electromagnetic system is called self flux.



ϕ_1 is self-flux which is produced by the current i_1.
ϕ_2 is self-flux which is produced by the current i_2.

Leakage Flux: The portion of self-flux does not link with other coils is called leakage flux. (due to current i_1)
ϕ_{11} (due to current i_1) and ϕ_{22} (due to current i_2) are leakage flux.

Mutual Flux: The portion of self-flux links with other coils is called leakage flux.
ϕ_{12} (due to current i_1 and link to coil 2) and ϕ_{21} (due to current i_2 and link to coil 1) are mutual flux.



$$\phi_1 = \phi_{11} + \phi_{12} \qquad \phi_2 = \phi_{22} + \phi_{21}$$

Self Inductance, and Mutual Inductance

If a time-changing source [$v_1(t)$] as shown in ***Figure (a)*** is applied to a coil 1, the produced self–flux [$\phi_1(t)$] also will be time-changing. According to **Faraday's law of Electromagnetic Induction** an emf $e_1(t)$ [due to self–flux $\phi_1(t)$ since $\phi_1(t)$ links in coil 1] and an emf $e_{12}(t)$ [due to mutual flux $\phi_{12}(t)$ since $\phi_{12}(t)$ links in coil 2] are induced.

The induced emfs can be given by:

$$e_1(t) = N_1 \frac{d\phi_1(t)}{dt} = \left(N_1 \frac{d\phi_1(t)}{di_1(t)} \right) \frac{di_1(t)}{dt} = (L_1) \frac{di_1(t)}{dt}$$

$$e_{12}(t) = N_2 \frac{d\phi_{12}(t)}{dt} = \left(N_2 \frac{d\phi_{12}(t)}{di_1(t)} \right) \frac{di_1(t)}{dt}$$

$$= (M_{12}) \frac{di_1(t)}{dt}$$

N_1 and N_2: Number of turns of coil 1 and coil 2

L_1 and M_{12}: Self inductance of coil 1 and Mutual inductance due to current 1 in coil 2

Similarly, for **Figure (*b*)** we have:

$$e_2(t) = N_2 \frac{d\phi_2(t)}{dt} = \left(N_2 \frac{d\phi_2(t)}{di_2(t)} \right) \frac{di_2(t)}{dt} = (L_2) \frac{di_2(t)}{dt}$$

$$e_{21}(t) = -N_1 \frac{d\phi_{21}(t)}{dt} = -\left(N_1 \frac{d\phi_{21}(t)}{di_2(t)} \right) \frac{di_2(t)}{dt}$$

$$= -(M_{21}) \frac{di_2(t)}{dt}$$

L_2 and M_{21}: Self inductance of coil 2 and Mutual inductance due to current 2 in coil 1

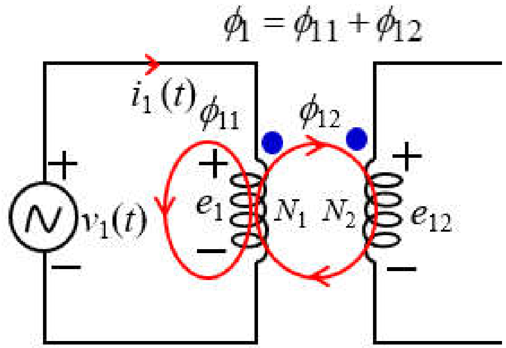


Figure (*a*)

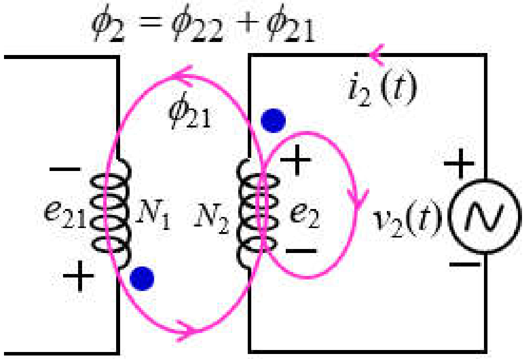


Figure (*b*)

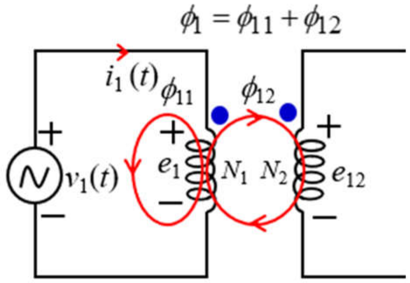


Figure (*a*)

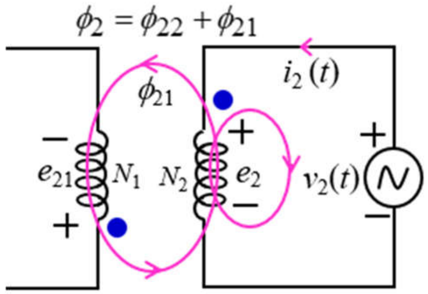


Figure (*b*)

M_{12} and M_{21} are equal if the medium of mutual fluxes of $\phi_{12}(t)$ and $\phi_{11}(t)$ are same, thus we have:

$$M_{12} = M_{21} = M$$

Polarity of induced emf due to mutual flux: The **dots** shown in the two figures indicate the polarity of the induced emf between the coils.

If the **dots** are at the same end of the coils, the voltage induced in coil 2 by a current in coil 1 has the same polarity as the voltage induced by the same current in coil 1; otherwise, the voltages are in opposition, as shown in **Figure (*b*)**. Thus, the presence of such dots indicates that magnetic coupling is present between two coils.

It should also be pointed out that if a current (and therefore a magnetic field) were present in the second coil as shown in **Figure (*c*)**, an additional voltage would be induced across coil 1. The voltage induced across a coil is, in general, equal to the sum of the voltages induced by self-inductance and mutual inductance. Thus, we have:

$$v_1(t) = e_1(t) + e_{21}(t) = L_1 \frac{di_1(t)}{dt} + M\frac{di_2(t)}{dt}$$

$$v_2(t) = e_2(t) + e_{12}(t) = L_2 \frac{di_2(t)}{dt} + M\frac{di_1(t)}{dt}$$

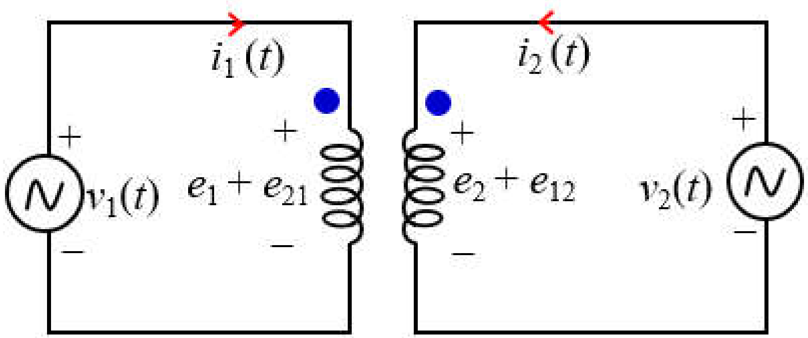


Figure (*c*)

Electric Machine

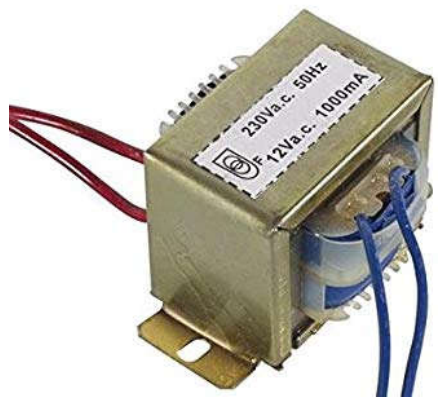
1. **Transformer**
2. **Generator**
3. **Motor**

Transformer

Chapter 21 [Text Book 1]

Chapter 32 [Text Book 2]

Transformer



Definition of Transformer

Transformer is a static device which transfers the electrical energy from one circuit to another circuit by raising or lowering the voltage without changing frequency.

Transformers are used in both communication and power circuits.

Construction of Transformer

There are two basic parts of a transformer:

(***a***) Windings, and (***b***) Magnetic cores

Windings: In a conventional transformer there have high voltage (**HV**) and low-voltage (**LV**) windings.

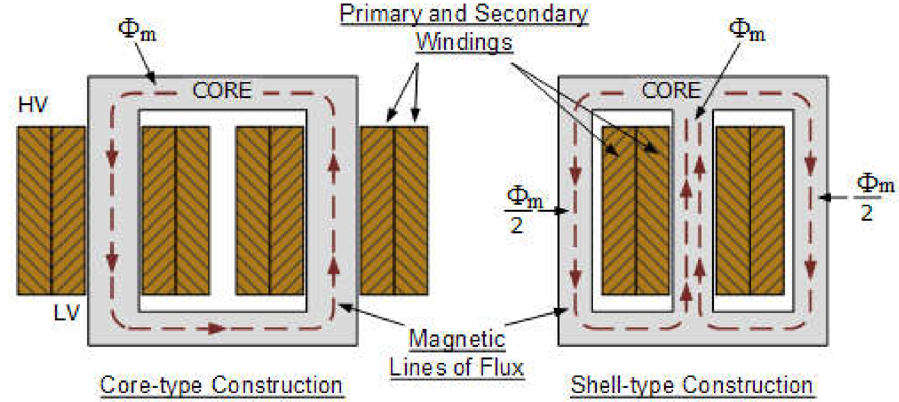
Primary (or ***driving***) winding/coil/side [either HV or LV]: The winding at which source is connected is called primary winding.

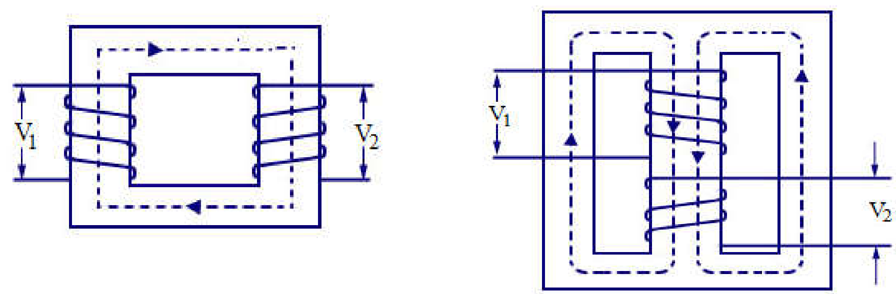
Secondary (or ***Receiving***) winding/coil/side [either HV or LV]: The winding at which load is connected is called primary winding.

Cores: There are two basic types of Magnetic cores:

(***a***) **Core Type**: the windings surround a considerable part of the core

(***b***) **Shell Type**: the core surrounds the considerable portion of the windings

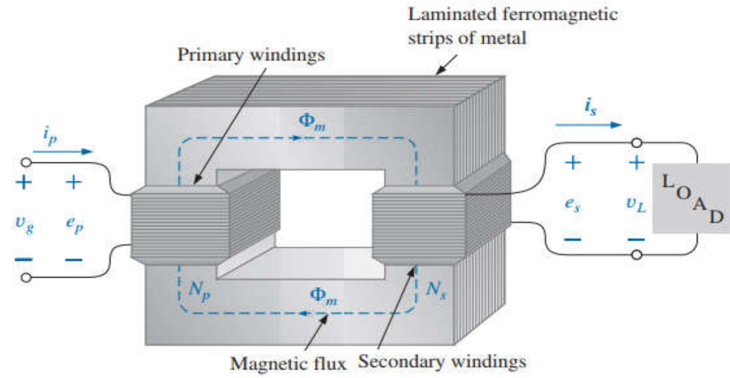


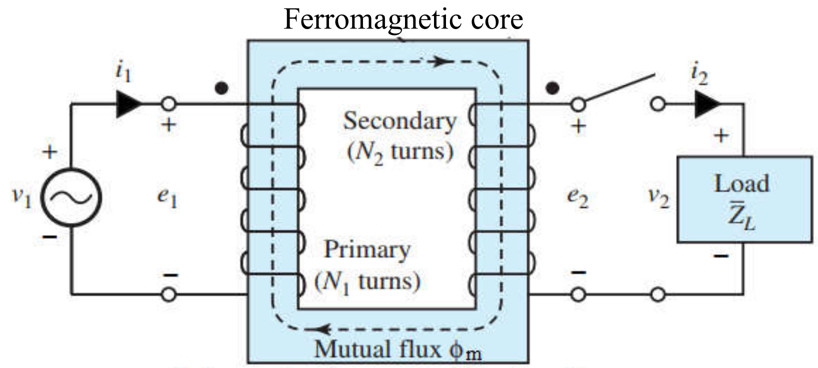


https://www.youtube.com/watch?v=XrIXioEn3yQ

Working Principle of Transformer

- When the primary winding is excited by an alternating voltage (v_g or v_1), an alternating current (i_p or i_1) starts to flow in primary side.
- The alternating current sets up an alternating flux
  $[\phi(t) = \Phi_m \sin(2\pi f)t = \Phi_m \sin\omega t$ Wb] in the core.
- The secondary winding is linked by most of this flux. According to ***Farady's Law of Electromagnetic Induction*** emfs in primary side (e_p or e_1) and secondary side(e_s or e_2)] are induced.
- According to ***Lenz's Law*** primary side emf (e_p or e_1) opposes the supply voltage (v_g or v_1). The primary side emf (e_p or e_1) is called back emf since it limits the flow of primary side current (i_p or i_1).
- If the secondary side circuit is closed, the secondary current (i_s or i_2) flows through the load. This is way energy is transferred from primary circuit to the secondary circuit through the medium of the magnetic field.
- When secondary current flows, it sets up a flux which is reduced the mutual flux. Then primary emf is reduced therefore primary current increases as well as primary fluxes is increased. Finally, the mutual flux will be back to its the previous values. So, the load current cannot change the mutual flux in the core.





Schematic of two-winding transformer.

Here,
v_L or v_2: Load voltage
N_p or N_1: Number of turns of primary side
N_s or N_2: Number of turns of secondary side
$\boldsymbol{Z}_L$: Load impedance

32.6 EMF Equation of a Transformer

Let, the expression of developed flux in core due the supply ac voltage (v_g or v_1) is:

$$\phi(t) = \Phi_m \sin \omega t$$

Based on the Faraday's Law, the expression induced voltage in primary side and secondary side can be obtained as follows:

$$e_1(t) = -N_1 \frac{d\phi(t)}{dt} = (2\pi f)N_1\Phi_m \sin(\omega t - 90°) \text{ V}$$

$$e_2(t) = -N_2 \frac{d\phi(t)}{dt} = (2\pi f)N_2\Phi_m \sin(\omega t - 90°) \text{ V}$$

The RMS Value of $e_1(t)$ and $e_2(t)$ are as follows:

$$E_1 = \frac{(2\pi f)N_1\Phi_m}{\sqrt{2}} = 4.44\, fN_1\Phi_m \qquad \text{(i)}$$

$$E_2 = \frac{(2\pi f)N_2\Phi_m}{\sqrt{2}} = 4.44\, fN_2\Phi_m \qquad \text{(ii)}$$

32.7 Voltage Transformation Ratio (K)

From the Eqs. (i) and (ii), we have:

$$\frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

This constant K is called ***voltage transformation ratio*** or ***transformation ratio*** or ***turns ratio***.

If the losses of a transformer are neglected, then

$$V_1 = E_1; \qquad V_2 = E_2 \text{ and}$$

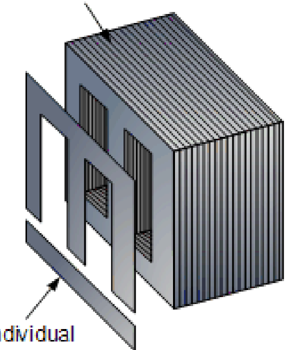
$$\text{input VA} = \text{output VA},$$

that means:

$$S_2 = S_1$$

$$V_2 I_2 = V_1 I_1$$

$$\frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{1}{K}$$



Hence, currents are the ***inverse ratio*** of the (voltage) transformation ratio.

Problem An ideal transformer has a turns ratio of 8:1 and the primary current is 3 A when it is supplied at 240 V. Calculate the secondary voltage and current.

Solution:

A turns ratio of 8:1 means $\frac{N_1}{N_2} = \frac{8}{1}$, i.e. a step-down transformer.

$\frac{N_1}{N_2} = \frac{V_1}{V_2}$ or secondary voltage

$$V_2 = V_1\left(\frac{N_2}{N_1}\right) = 240\left(\frac{1}{8}\right) = \mathbf{30\ volts}$$

Also, $\frac{N_1}{N_2} = \frac{I_2}{I_1}$; hence secondary current

$$I_2 = I_1\left(\frac{N_1}{N_2}\right) = 3\left(\frac{8}{1}\right) = \mathbf{24\ A}$$

Problem An ideal transformer, connected to a 240 V mains, supplies a 12 V, 150 W lamp. Calculate the transformer turns ratio and the current taken from the supply.

Solution:

$$V_1 = 240\text{ V},\ V_2 = 12\text{ V}, \qquad I_2 = \frac{P}{V_2} = \frac{150}{12} = 12.5\text{ A}$$

$$\text{Turns ratio} = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{240}{12} = \mathbf{20}$$

$\frac{V_1}{V_2} = \frac{I_2}{I_1}$, from which, $I_1 = I_2\left(\frac{V_2}{V_1}\right) = 12.5\left(\frac{12}{240}\right)$

Hence current taken from the supply, $I_1 = \frac{12.5}{20}$

$= \mathbf{0.625\ A}$

Problem A 5 kVA single-phase transformer has a turns ratio of 10:1 and is fed from a 2.5 kV supply. Neglecting losses, determine (a) the full load secondary current, (b) the minimum load resistance which can be connected across the secondary winding to give full load kVA and (c) the primary current at full load kVA.

Solution:

(a) $\frac{N_1}{N_2} = \frac{10}{1}$ and $V_1 = 2.5\,\text{kV} = 2500\,\text{V}$

Since $\frac{N_1}{N_2} = \frac{V_1}{V_2}$, secondary voltage

$$V_2 = V_1\left(\frac{N_2}{N_1}\right) = 2500\left(\frac{1}{10}\right) = 250\,\text{V}$$

The transformer rating in volt-amperes $= V_2 I_2$ (at full load), i.e. $5000 = 250 I_2$

Hence full load secondary current

$$I_2 = \frac{5000}{250} = \mathbf{20A}$$

(b) Minimum value of load resistance,

$$R_L = \frac{V_2}{I_2} = \frac{250}{20} = \mathbf{12.5\,\Omega}$$

(c) $\frac{N_1}{N_2} = \frac{I_2}{I_1}$, from which primary current,

$$I_1 = I_2\left(\frac{N_2}{N_1}\right) = 20\left(\frac{1}{10}\right) = \mathbf{2\,A}$$

Problem A 100 kVA, 4000 V/200 V, 50 Hz single-phase transformer has 100 secondary turns. Determine (a) the primary and secondary current, (b) the number of primary turns and (c) the maximum value of the flux.

Solution:

$V_1 = 4000\,\text{V},\ V_2 = 200\,\text{V},\ f = 50\,\text{Hz},\ N_2 = 100$ turns

(a) Transformer rating $= V_1 I_1 = V_2 I_2 = 100\,000$ VA

Hence primary current, $I_1 = \dfrac{100\,000}{V_1} = \dfrac{100\,000}{4000}$ $= \mathbf{25\ A}$

and secondary current, $I_2 = \dfrac{100\,000}{V_2} = \dfrac{100\,000}{200}$ $= \mathbf{500\ A}$

(b) From equation (3), $\dfrac{V_1}{V_2} = \dfrac{N_1}{N_2}$

from which, primary turns,

$$N_1 = \left(\frac{V_1}{V_2}\right)(N_2) = \left(\frac{4000}{200}\right)(100)$$

i.e. $\boldsymbol{N_1 =}$ **2000 turns**

(c) From equation , $E_2 = 4.44 f \Phi_m N_2$

from which, maximum flux Φ_m

$$= \frac{E_2}{4.44 f N_2} = \frac{200}{4.44(50)(100)}$$

(assuming $E_2 = V_2$)

$= \mathbf{9.01 \times 10^{-3}\ Wb}$ or **9.01 mWb**

Classification of Transformer Based on Voltage Level

Based on the voltage level in primary side and secondary side transformer are two types:

Step-up Transformer: If secondary side voltage (V_2) is ***greater*** than the primary side voltage (V_1) that means ***K*>1** then transformer is called step up transformer.

Step-down Transformer: If secondary side voltage (V_2) is ***smaller*** than the primary side voltage (V_1) that means ***K*<1** then transformer is called step up transformer.

Others Classification of Transformer

According to Service Conditions:

(***a***) Power transformer
(***b***) Distribution transformer
(***c***) Instrument Transformer
    (***i***) Current transformer (CT)
    (***ii***) Potential transformer (PT or VT)

According to Winding:

(***a***) Single-phase transformer
(***b***) Three phase transformer
(***c***) Auto Transformer

According to Volt-Ampere and Voltage Ratings:

(***a***) Low voltage transformer [$V_{HV} < 1.1$ kV]
(***b***) Medium voltage transformer [1.1 kV $\leq V_{HV} < 11$ kV]
(***c***) High voltage transformer [$V_{HV} \geq 11$ kV]

According to Type of Cooling:

(a) Natural cooled: natural air cooled and oil immersed natural cooled
(***b***) **Forced cooled**: air blast cooled and oil immersed air blast cooled
(***c***) **Water cooled**: oil immersed water cooled

Transformer Test

The performance of a transformer can be calculated on the basis of its equivalent circuit. The parameters of equivalent can easily be determined by two tests:

(***a***) **Open-Circuit Test**: Performing the open-circuit test, the core loss resistance (R_0) and magnetizing (or mutual) reactance (X_0) can be obtained.

(***b***) **Short-Circuit Test**: Performing the short-circuit test, the windings resistance (R_1 and R_2) and the leakage reactances (X_1 and X_2) can be obtained.

Why Transformer Rating is kVA?

From the two test it is seen that, the Cu loss of a transformer depends on current and core loss on voltage. Hence total transformer loss depends on volt-ampere (VA) and not depends on the phase difference between voltage and current *i.e.* it is independent of load power factor. That is why rating of transformer is in kVA and not kW.

Regulation of Transformer

When the secondary of a transformer is loaded, the secondary terminal voltage, V_2, falls.
As the power factor decreases, this voltage drop increases. This is called the **regulation of the transformer** and it is usually expressed as a percentage of the secondary no-load voltage, E_2. For full-load conditions:

$$\text{Regulation} = \left(\frac{E_2 - V_2}{E_2}\right) \times 100\%$$

The fall in voltage, $(E_2 - V_2)$, is caused by the resistance and reactance of the windings.
Typical values of voltage regulation are about 3% in small transformers and about 1% in large transformers.

Problem A 400 kVA transformer has a primary winding resistance of 0.5 Ω and a secondary winding resistance of 0.001 Ω. The iron loss is 2.5 kW and the primary and secondary voltages are 5 kV and 320 V, respectively. If the power factor of the load is 0.85, determine the efficiency of the transformer (a) on full load, and (b) on half load.

Solution:

(a) Rating $= 400\,\text{kVA} = V_1 I_1 = V_2 I_2$

$$I_1 = \frac{400 \times 10^3}{V_1} = \frac{400 \times 10^3}{5000} = 80\,\text{A}$$

$$I_2 = \frac{400 \times 10^3}{V_2} = \frac{400 \times 10^3}{320} = 1250\,\text{A}$$

$$\text{Total copper loss} = I_1^2 R_1 + I_2^2 R_2$$
$$= (80)^2(0.5) + (1250)^2(0.001)$$
$$= 3200 + 1562.5 = 4762.5\,\text{watts}$$

$$\text{On full load, total loss} = \text{copper loss} + \text{iron loss}$$
$$= 4762.5 + 2500 = 7262.5\,\text{W} = 7.2625\,\text{kW}$$

$$\text{Total output power on full load} = V_2 I_2 \cos\phi_2$$
$$= (400 \times 10^3)(0.85) = 340\,\text{kW}$$

$$\text{Input power} = \text{output power} + \text{losses}$$
$$= 340\,\text{kW} + 7.2625\,\text{kW} = 347.2625\,\text{kW}$$

$$\text{Efficiency, } \eta = \left[1 - \frac{\text{losses}}{\text{input power}}\right] \times 100\%$$
$$= \left[1 - \frac{7.2625}{347.2625}\right] \times 100\%$$
$$= \mathbf{97.91\%}$$

(b) Since the copper loss varies as the square of the current, then total copper loss on half load $= 4762.5 \times \left(\frac{1}{2}\right)^2 = 1190.625\,\text{W}$

Hence total loss on half load $= 1190.625 + 2500$

$= 3690.625\,\text{W}$ or

$3.691\,\text{kW}$

Output power on half full load $= \frac{1}{2}(340) = 170\,\text{kW}$

Input power on half full load

$= \text{output power} + \text{losses}$

$= 170\,\text{kW} + 3.691\,\text{kW} = 173.691\,\text{kW}$

Hence efficiency at half full load,

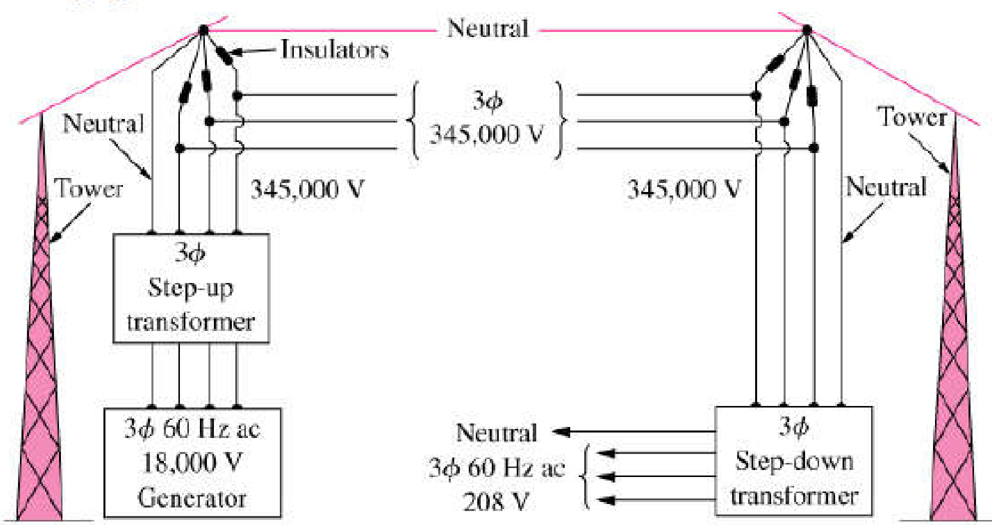
$$\eta = \left[1 - \frac{\text{losses}}{\text{input power}}\right] \times 100\%$$

$$= \left[1 - \frac{3.691}{173.691}\right] \times 100\% = \mathbf{97.87\%}$$

Some Applications of Transformer

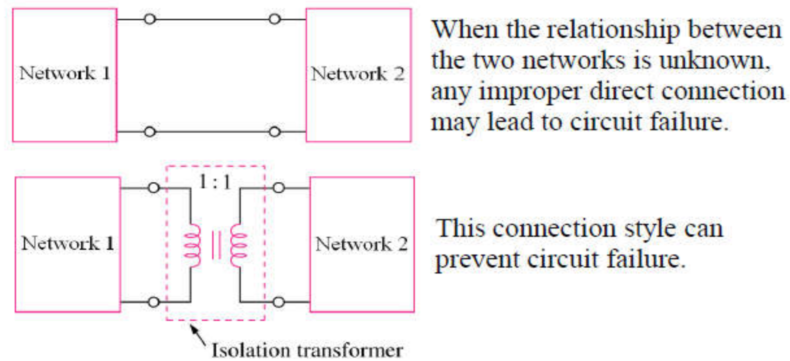
❖ To ***step up*** or ***step down*** voltage and current (useful for power transmission and distribution).

Applications: Power Distribution

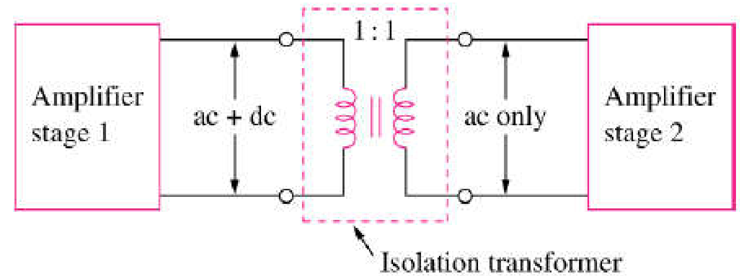


❖ To ***isolate*** one portion of a circuit from another.

Applications: Circuit Isolation

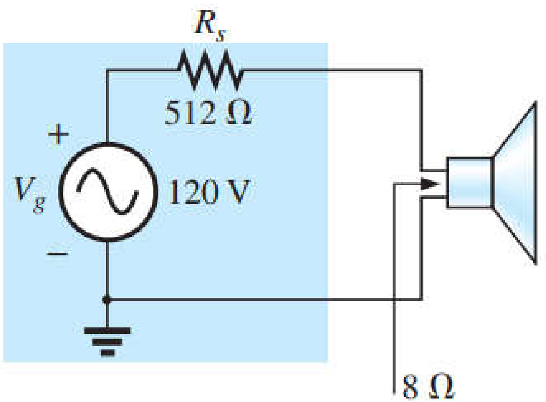


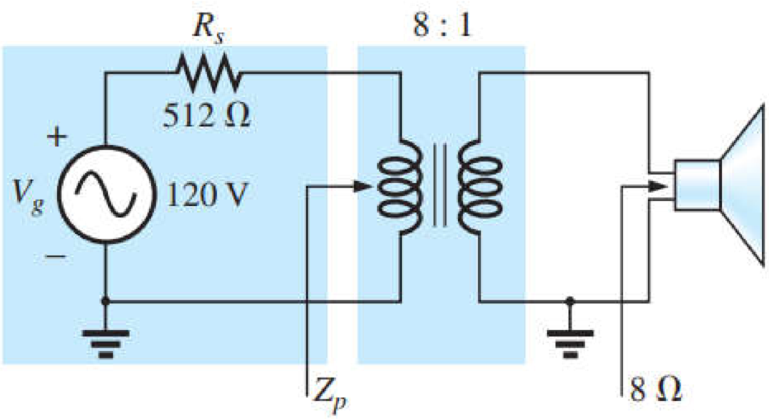
Applications: DC Isolation



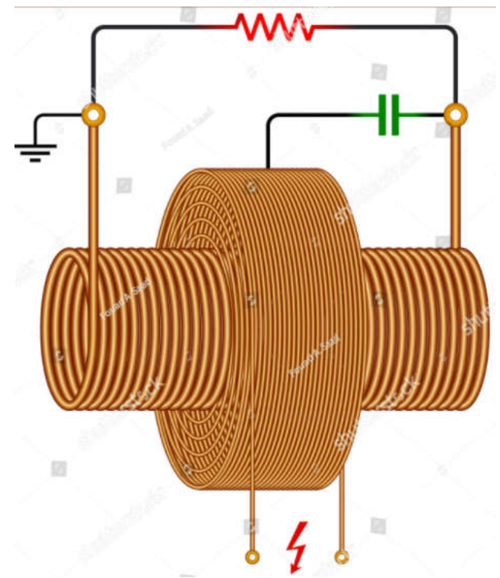
Only ***ac signal*** can pass, ***dc signal*** is blocked.

❖ As an ***impedance matching*** device for maximum power transfer.



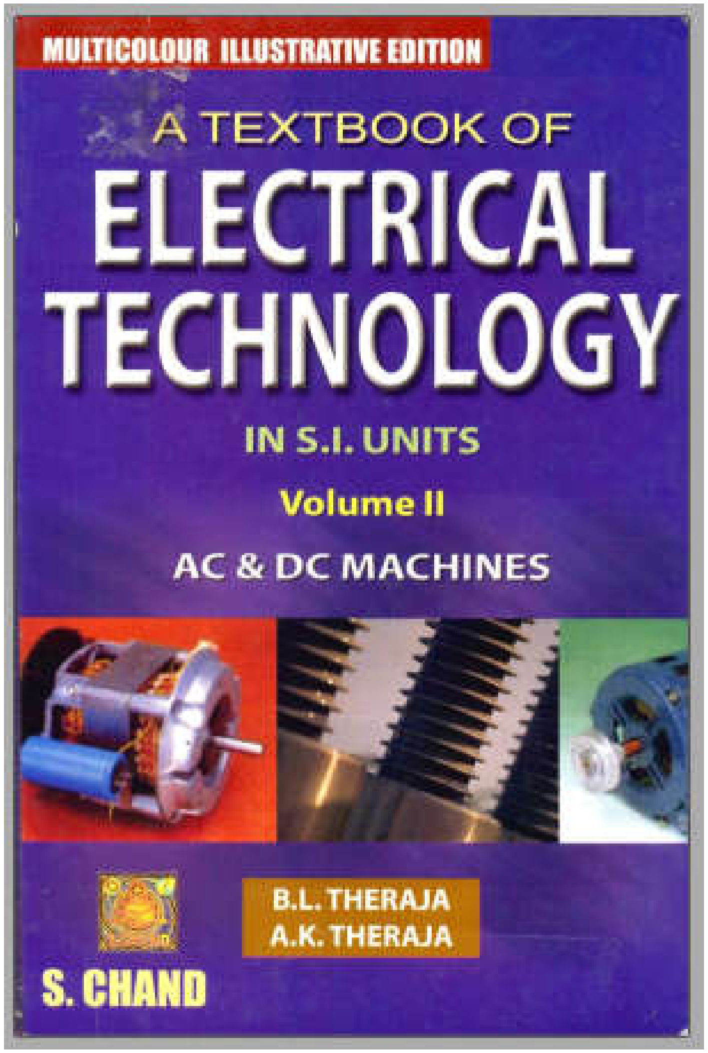


❖ ***Frequency-selective*** [**Resonance** or **Filter**] circuits.



Basic of Electrical Machines

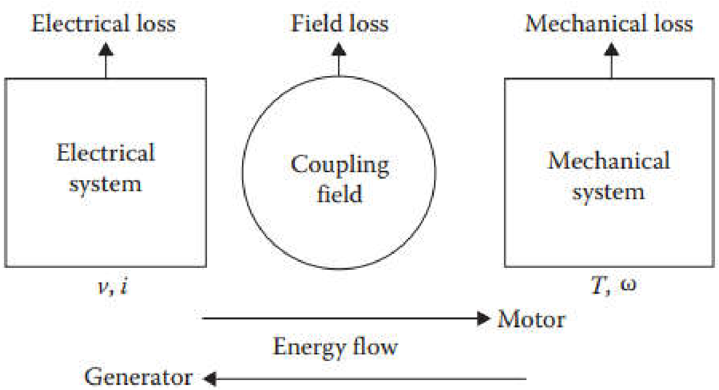
B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.



Electromechanical Energy Conversion Principles

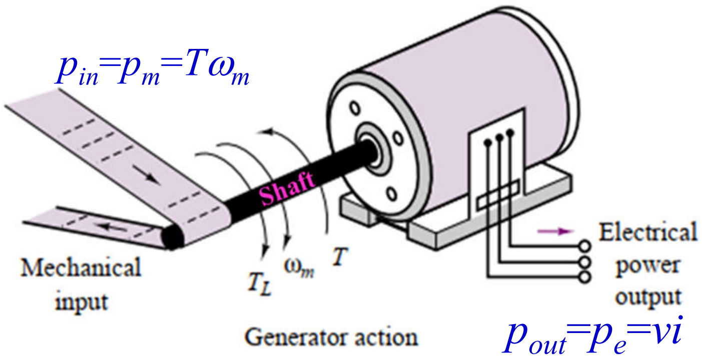
According to the **energy conversion principle**, *energy is neither created nor destroyed: it is simply changed in form*.

A **rotational electromagnetic machine** (also called **electrical machine**) converts energy from mechanical to electrical form, or vice versa.



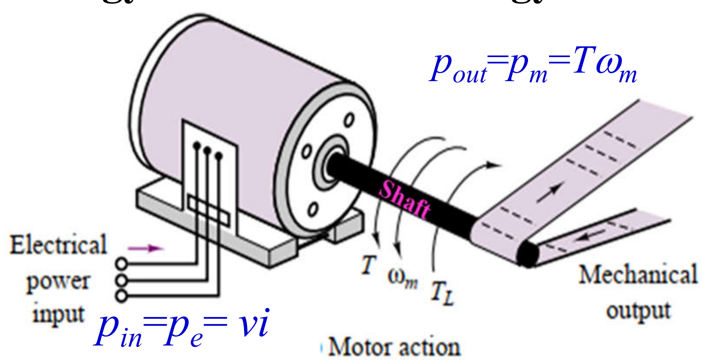
A representation of electromechanical energy conversion.

Generator: The electrical machine which converts **form mechanical energy to electrical energy** is called generator.



EMF or voltage is induced according to Faraday's law since conductor is moved inside magnetic field.

Motor: The electrical machine which converts **form electrical energy to mechanical energy** is called motor.



According to Lorentz Force theory, rotation is obtained due to the developed force in the current carrying conductors inside a magnetic field.

Some Basic Mathematical Relation of Electrical Machines

Electrical Power: $P_e = vi \quad [\mathrm{W}]$

Mechanical Power and Torque: $P_m = T\omega_m [\mathrm{W}]$ $\qquad T = \dfrac{P_m}{\omega_m} \quad [\mathrm{Nm}]$

Electrical Angular velocity (ω) and Mechanical Angular velocity (ω_m):

$$\omega = \frac{P}{2}\omega_m \qquad \omega_m = \frac{2\omega}{P}$$

Speed : $N = \left(\dfrac{60}{2\pi}\right)\omega_m = \left(\dfrac{60}{2\pi}\right)\left(\dfrac{2\omega}{P}\right) = \dfrac{120f}{P}$ [rev/m or rpm]

T : Torque in N–m
f : Frequency in Hz
P : Number of magnetic pole always in even number

Classification of Electrical Machines

Electrical Machines Broadly Classy as Follows:

(A) DC (or Commutator) Machine

(B) AC (or Commutatorless) Machine

(**a**) Based on the number of phase:

(*i*) Single-phase Machine

(*ii*) Three-phase Machine

(**b**) Based on the running speed:

(*i*) Synchronous Machine

run at synchronous speed

(*ii*) Induction (*Asynchronous*) Machine

run at below synchronous speed

(C) Special Type Machine

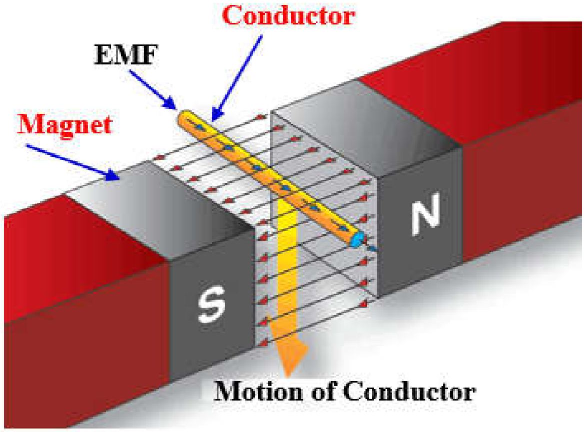
Universal Motor
Shaded-pole Motor
Synchronous Reluctance Motor
Hysteresis Motor
Stepper Motor
Servo Motor
Linear Motor
so on ……….

Basic Elements and Parts of Electrical Machine

In an electrical machine must have the followings two basic essential parts:

(*a*) **Armature** or **Conductor** where emf is induced or voltage is supplied.

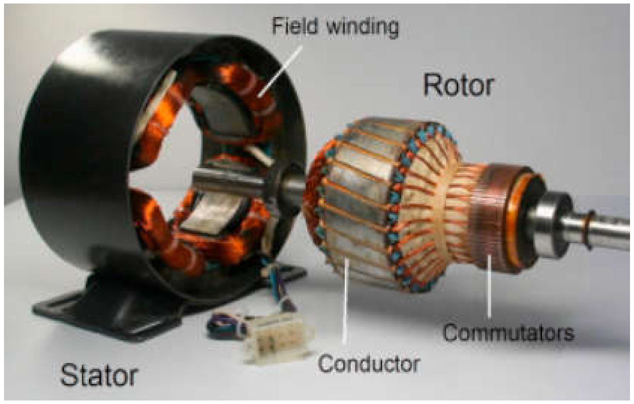
(*b*) **Magnet** either permanent magnet or electromagnet where force/rotation is established.



In broad sense, electrical machine has two major parts:

(*a*) **Stator**: The portion/part of electrical machine which is stationary is called stator.

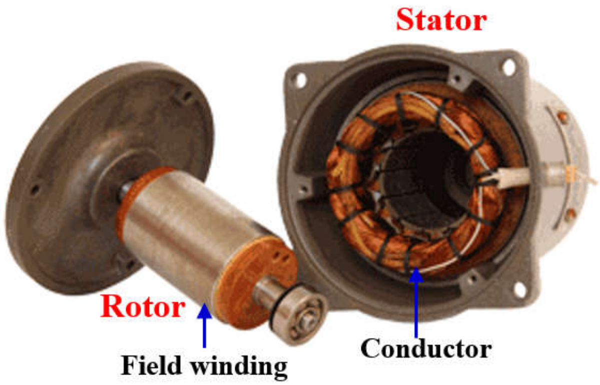
(*b*) **Rotor**: The portion/part of electrical machine which is rotating is called rotor.



DC machine

In a DC machine, Magnet is in stator and armature is in rotor.

In an AC machine, Armature is in stator and magnet is in rotor.

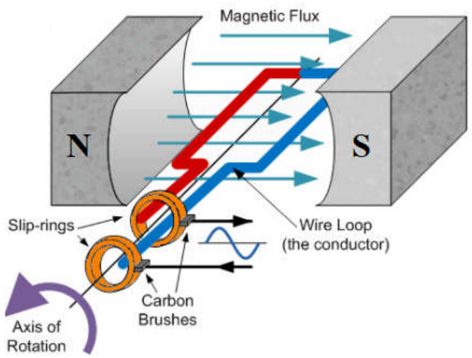


AC machine

AC Generation and DC Generation

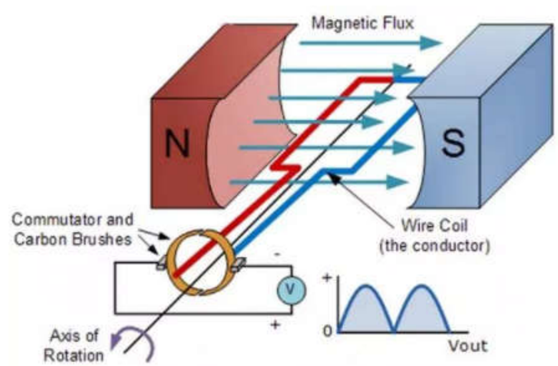
In a generator, an **emf** is induced in a conductor according to **Farady's law**.
The **polarity of induced emf** can be determined by **Flaming's Right Hand Rule**.
The induced emf in a rotating machine is changed sinusoidally because the direction of force of conductor is changed alternately from up–ward to down –ward or down –ward to up –ward.
The load cannot be connected directly to load. Loads are connected through brushes. Brushes are in contact continuously with **slip-rings** (to get **ac** output) or **commutator segments** (to get **dc** output).

Slip-rings are used to supply current to load for ac voltage. Here, both slip-rings and brushes are fixed. A conductor is always in touch with slip ring.



So, the output voltage across a load is ac since the induced emf in the conductor is sinusoidal.

Commutator-segments are used to supply current to load for dc voltage. Here, commutator is rotating with conductor and brushes are fixed. One brush is collected current from the positive induced voltage. On other hand, another brush is collected current from the negative induced voltage.

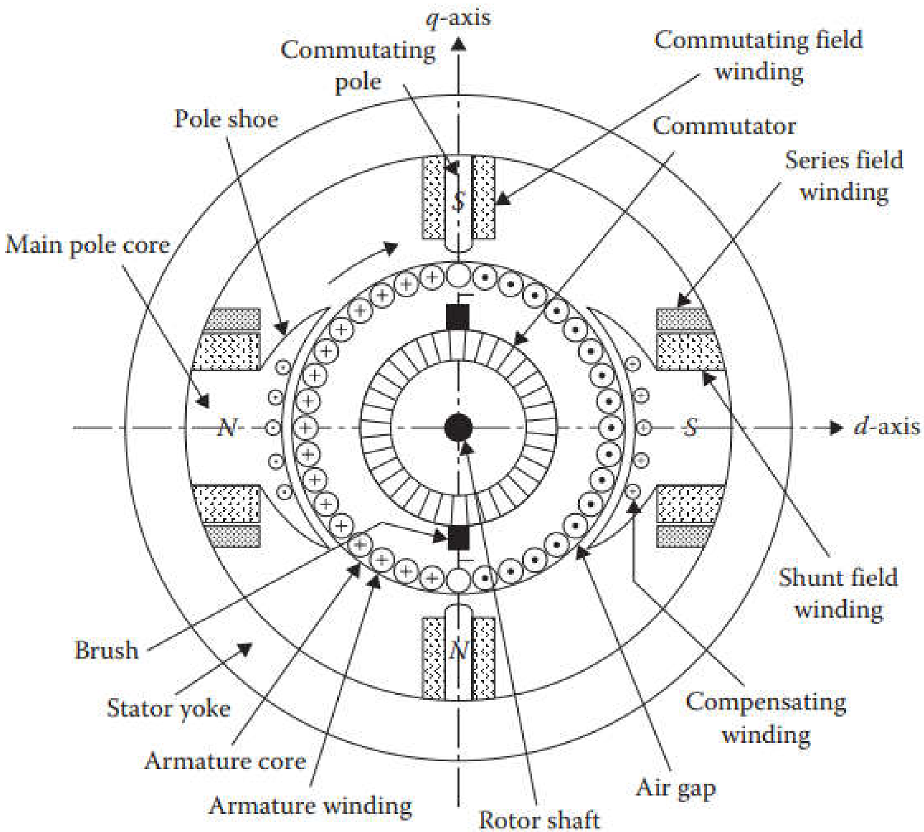


Commutator helps to convert ac induced emf to dc emf.
By increasing the number of conductors, the pulsation of dc voltage can be reduced

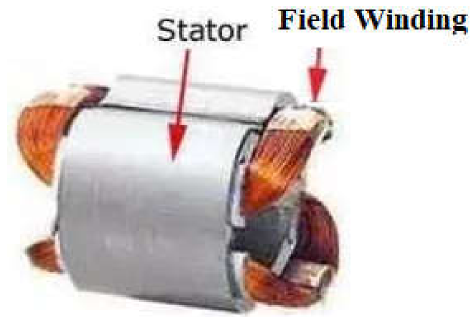
DC Machines
Chapters 26 and 29

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

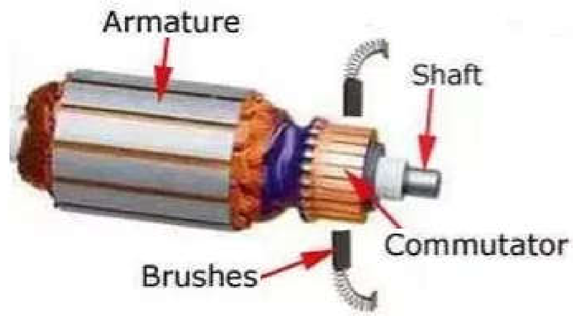
Construction of DC Machines



Stator [Magnet]
Magnetic pole core and pole shoe
Frame or Yoke
Field (Shunt and series) winding
Interpole or Commutating pole
Compensating
Terminal box



Rotor [Conductors or Armature]
Armature Core
Armature Slots
Armature winding
Bearing and Shaft
Commutator and Brushes



Classification of DC Machines

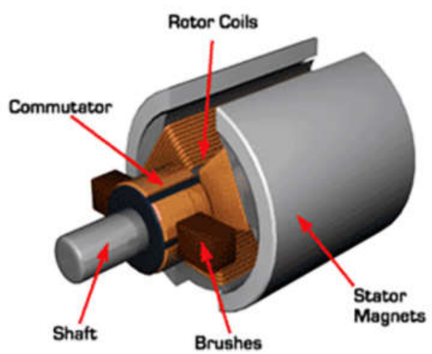
DC Machines are Classified as follows:

(**1**) **Permanent Magnet DC Machine**: Where permanent magnet is used for magnetic flux.

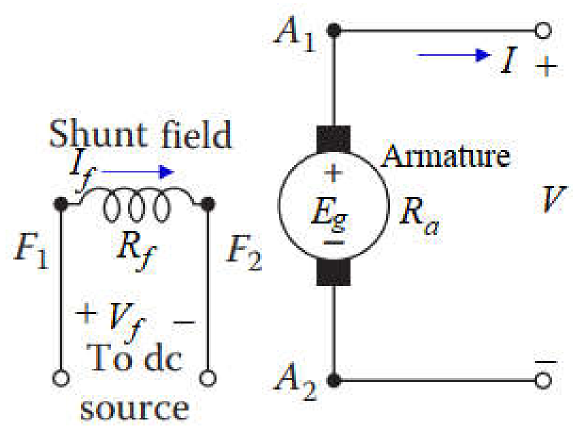
(**2**) **Electromagnetic based DC Machine**: Where electromagnet is used to produce magnetic flux. Mainly this type of DC machine has two field windings, the are called **shunt winding** and **series winding**.

(***a***) **Separately Exited DC Machine**: where the field winding is connected to a source of supply other than the armature of its own machine

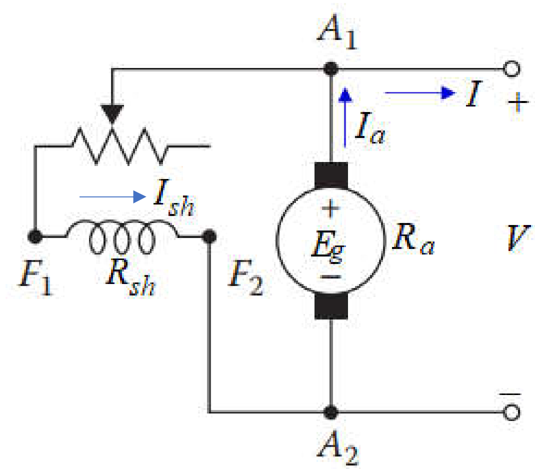
(***b***) **Self-exited DC Machine**: where the field winding receives its supply from the armature of its own machine.



Permanent Magnet DC Machine



Separately excited DC Machine

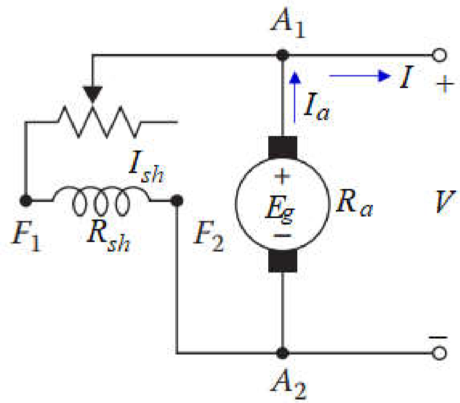


Self-excited DC Machine

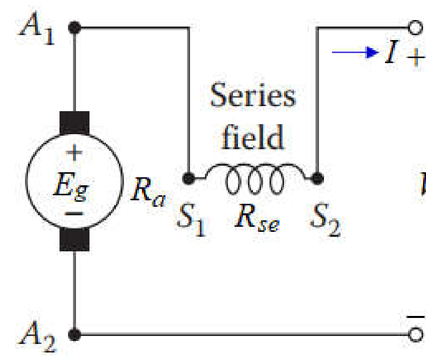
Self-Exited DC Machine are three types based on field winding connection with armature:

(*i*) **Shunt Wound DC Machine**: where the only shunt (parallel) field winding is connected in parallel with armature winding.

(*ii*) **Series Wound DC Machine**: where the only series field winding is connected in series with armature winding.



Shunt Wound

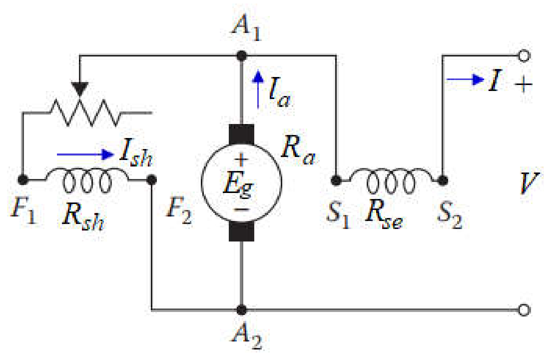


Series Wound

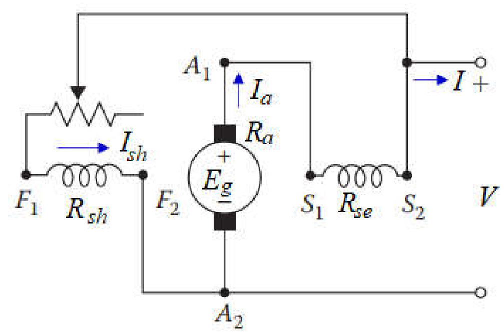
(*iii*) **Compound Wound DC Machine**: where the both shunt (parallel) and series field windings are connected.

(***I***) **Long Shunt Wound DC Machine**: where shunt field winding is connected parallel with in combination of series connection of armature and series field winding.

(***II***) **Short Shunt Wound DC Machine**: where series field winding is connected series with in combination of parallel connection of armature and shunt field winding.



Short Shunt

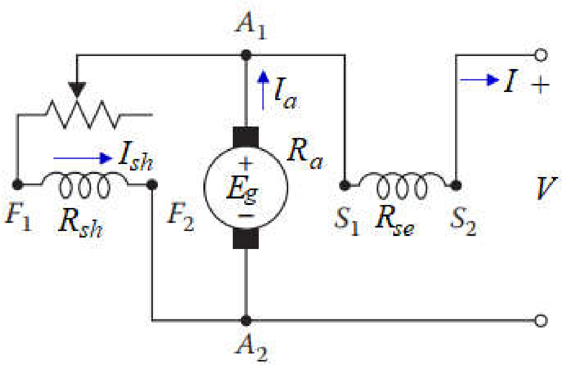


Long Shunt

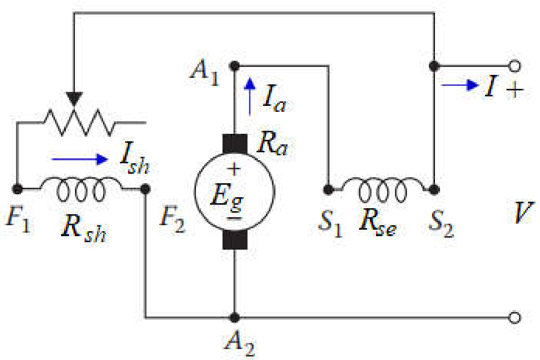
Compound Wound

Compound Wound DC Machine is two types based on the relative shunt flux and series flux:

(***a***) **Cumulative Compound DC Machine**: where series field flux ***aids*** with shunt field flux.

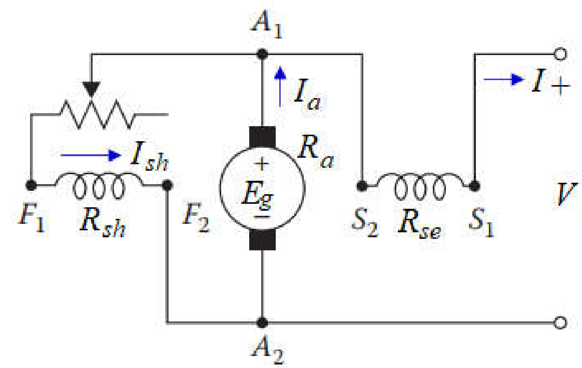


Short Shunt Cumulative Compound DC Machine

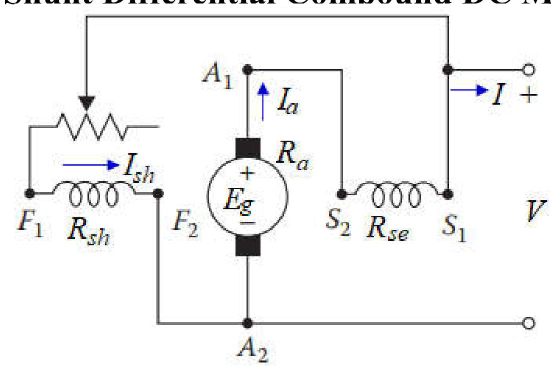


Long Shunt Cumulative Compound DC Machine

(***b***) **Differential Compound DC Machine**: where series field flux ***opposes*** with shunt field flux.



Short Shunt Differential Compound DC Machine



Long Shunt Differential Compound DC Machine

Example 26.3. *A shunt generator delivers 450 A at 230 V and the resistance of the shunt field and armature are 50 Ω and 0.03 Ω respectively. Calculate the generated e.m.f.*

Solution. Generator circuit is shown in Fig. 26.46.

Current through shunt field winding is

$$I_{sh} = 230/50 = 4.6 \text{ A}$$

Load current $I = 450$ A

∴ Armature current $I_a = I + I_{sh}$

$$= 450 + 4.6 = 454.6 \text{ A}$$

Armature voltage drop

$$I_a R_a = 454.6 \times 0.03 = \mathbf{13.6\ V}$$

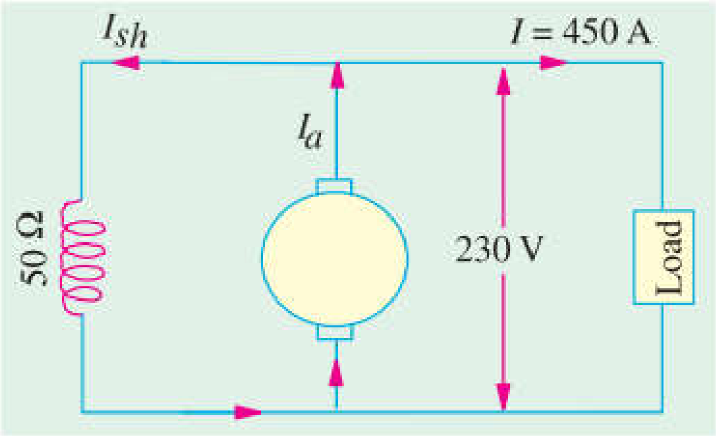


Fig. 26.46

Now E_g = terminal voltage + armature drop

$$= V + I_a R_a$$

∴ e.m.f. generated in the armature

$$E_g = 230 + 13.6 = \mathbf{243.6\ V}$$

Example 26.4. *A long-shunt compound generator delivers a load current of 50 A at 500 V and has armature, series field and shunt field resistances of 0.05 Ω, 0.03 Ω and 250 Ω respectively. Calculate the generated voltage and the armature current. Allow 1 V per brush for contact drop.*

Solution. Generator circuit is shown in Fig. 26.47.

$$I_{sh} = 500/250 = 2 \text{ A}$$

Current through armature and series winding is

$$= 50 + 2 = 52 \text{ A}$$

Voltage drop on series field winding

$$= 52 \times 0.03 = 1.56 \text{ V}$$

Armature voltage drop

$$I_a R_a = 52 \times 0.05 = 2.6 \text{ V}$$

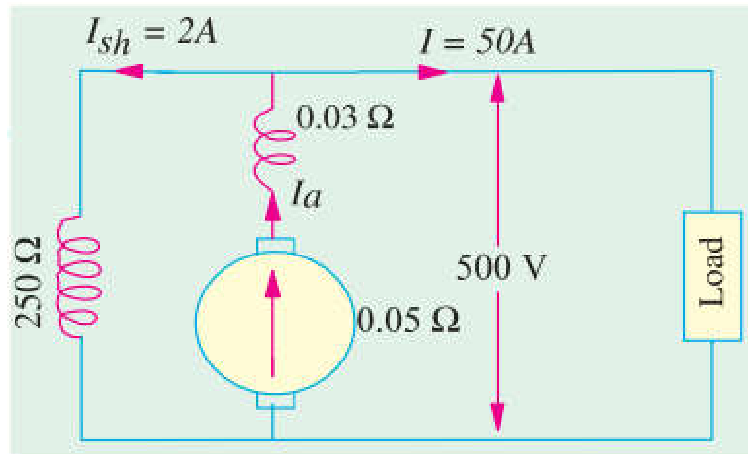


Fig. 26.47

Drop at brushes = 2 × 1 = 2 V

Now, $E_g = V + I_a R_a$ + series drop + brush drop

$$= 500 + 2.6 + 1.56 + 2 = \mathbf{506.16 \text{ V}}$$

DC Generator
Chapters 29

B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

Working Principle of a DC Generator

- Let, a coil is rotating clock-wise direction having two sides *AB* and *CD* (**Fig. 26.2**). As the coil cuts the magnetic field, according to Faraday's law of electromagnetic induction an emf is induced in it which is proportional to the rate of change of flux ($e = Nd\phi/dt$).
- When the coil side ***AB*** is at position 1, it produces zero **EMF** because ***the flux linked with the coil is maximum*** but ***rate of change of flux is zero***.
- As it moves in the clockwise direction, the rate of change of flux increases so does the **EMF**.
- When the conductor portion is at position 2, it produces maximum **EMF** because ***the flux linked with the coil is minimum*** but ***rate of change of flux is maximum***.
- At position 3, the **EMF** is zero, at position 4 negative maximum and at position 5 zero again.
- The wave shape of the generated **EMF** which is shape is sinusoidal is given in **Fig. 26.3**.
- The sinusoidal voltage is converted to dc voltage by using commutator segment.

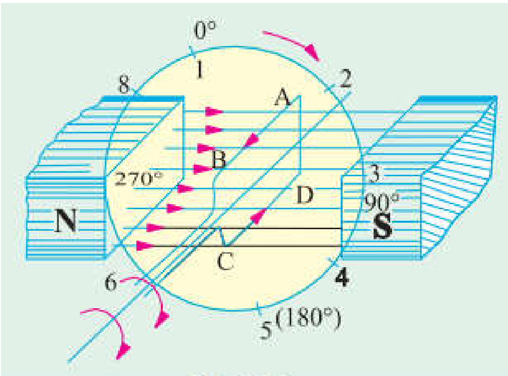


Fig. 26.2

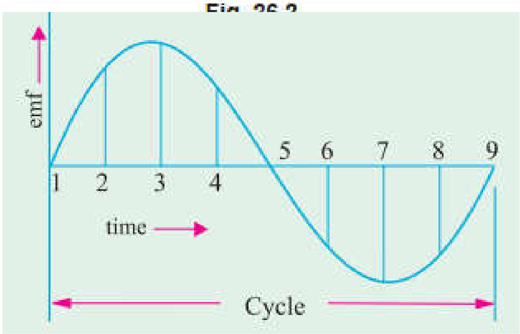
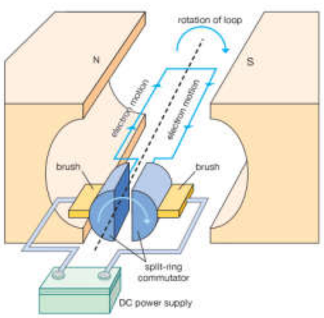
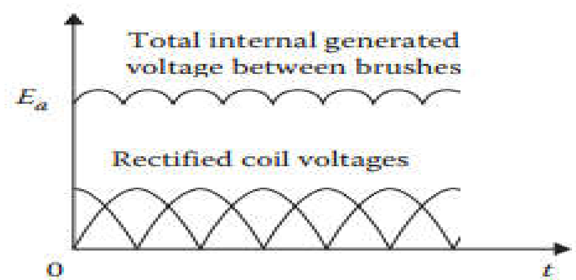


Fig. 26.3





EMF Equation of DC Generator

The developed emf (E_g) per parallel path of a DC generator is given by:

$$E_g = E_a = \frac{\Phi PN}{60}\left(\frac{Z}{A}\right) = \frac{\Phi P\omega_m}{2\pi}\left(\frac{Z}{A}\right) \qquad (26.1)$$

For a given DC machine, Z, P, A are constant, thus Eq. (26.1) can be written as follows:

$$E_g = K_n \Phi N = K_\omega \Phi \omega_m \qquad (26.2)$$

For an electromagnetic system flux is proportional to field current i.e. $\Phi \propto I_f$. So, Eq. (26.2) can be written as follows:

$$E_g = K_1 I_f N = K_2 I_f \omega_m \qquad (26.2)$$

K_1 and K_2 are constant

$I_f = I_{sh}$ for shunt wound DC motor

$= I$ for series wound DC motor

Φ = Flux/pole [Wb]

Z = Total number of armature conductor

= Number of Slots × (Number of conductor/slot)

= 2 × Number of turns

P = Number of generator poles

N = Armature rotation in revolution per minute (rpm)

ω_m = Armature rotation in rad/s

A = Number of parallel paths in armature

= 2 for wave winding

= P for lap winding

E_g or E_a = EMF induced in any of the parallel paths

$$K_n = \frac{PZ}{60A}$$

$$K_\omega = \frac{PZ}{2\pi A}$$

Example 26.8. *A four-pole generator, having wave-wound armature winding has 51 slots, each slot containing 20 conductors. What will be the voltage generated in the machine when driven at 1500 rpm assuming the flux per pole to be 7.0 mWb ?*

Solution. Here, $\Phi = 7 \times 10^{-3}$ Wb, $Z = 51 \times 20 = 1020$, $A = 2$, $P = 4$, $N = 1500$ r.p.m.

$$E_g = \frac{\Phi Z N}{60}\left(\frac{P}{A}\right) \text{ volts}$$

$$\therefore \quad E_g = \frac{7 \times 10^{-3} \times 1020 \times 1500}{60}\left(\frac{4}{2}\right) = \mathbf{178.5\ V}$$

Example 26.11(*a*). *An 8-pole d.c. shunt generator with 778 wave-connected armature conductors and running at 500 r.p.m. supplies a load of 12.5 Ω resistance at terminal voltage of 50 V. The armature resistance is 0.24 Ω and the field resistance is 250 Ω. Find the armature current, the induced e.m.f. and the flux per pole.*

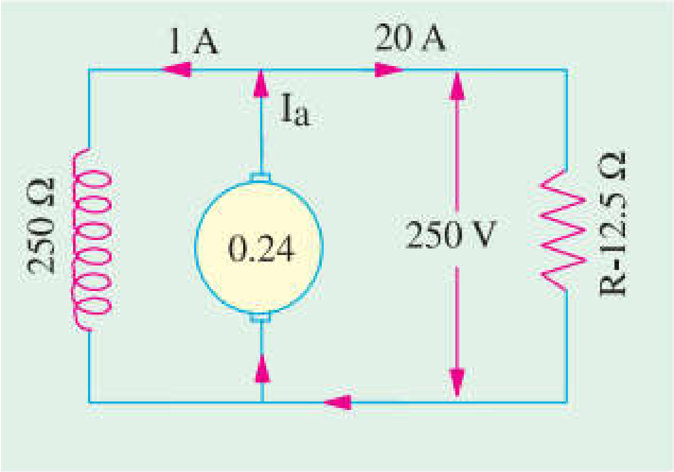


Fig. 26.53

Solution. The circuit is shown in Fig. 26.53

Load current = $V/R = 250/12.5 = 20$ A

Shunt current = $250/250 = 1$ A

Armature current = $20 + 1 =$ **21 A**

Induced e.m.f. = $250 + (21 \times 0.24) =$ **255.04 V**

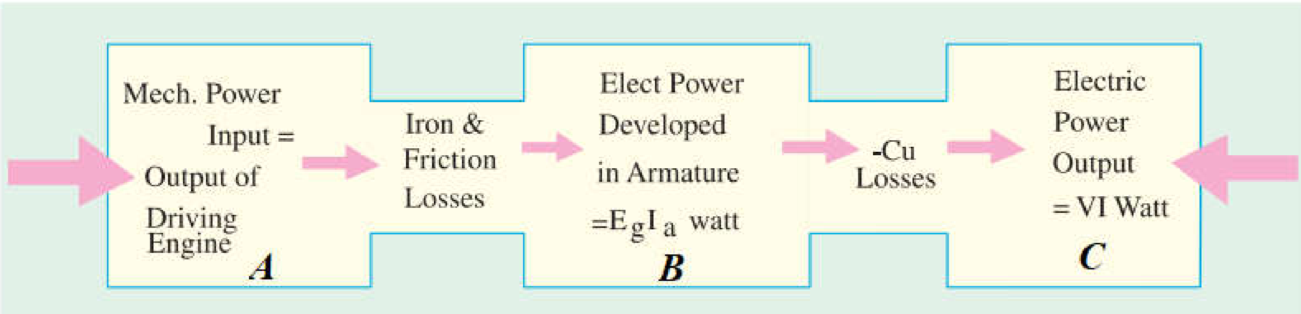
Now, $$E_g = \frac{\Phi Z N}{60} \times \left(\frac{P}{A}\right)$$

$$\therefore \quad 255.04 = \frac{\Phi \times 778 \times 500}{60}\left(\frac{8}{2}\right)$$

$$\therefore \quad \Phi = \mathbf{9.83\ mWb}$$

Power Stages of a DC Generator

The various power stages in a DC generator are represented diagrammatically in Figure below.



Mechanical Efficiency

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{output of driving engine}}$$

A – B = Iron and Friction Losses

Electrical Efficiency

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

B – C = Copper (Cu) Losses

Overall or Commercial Efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

Applications of DC Generator

Separately Excited DC Generators	• Primarily used in laboratory and commercial testing • Speed regulation Tests • Supplying power to the DC motors, whose speed being to be controlled
Series wound DC Generators	○ Voltage boosting in the feeders in the various types of distribution systems ○ Used to provide high voltage DC power transmission at constant load current ○ In supplying field excitation current in DC locomotives for regenerative breaking ○ Arc lightening
Shunt wound DC Generators	❑ Battery charging applications ❑ Lighting and power supply purposes ❑ Excitation to the alternators
Compound wound DC Generators	• Over compounded generators are used in supplying loads through long transmission lines. • Cumulative compound generators are used for supplying power to DC motors and for lighting, power supply purposes and for heavy power services, etc. • The differential compound generators are used for arc welding purposes where a large voltage drop and constant current is required.

DC Motor
Chapters 29

B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

Working Principle of a DC Motor

Consider a part of a DC. motor as shown in **Figure DCM 01**. When the terminals of the motor are connected to DC supply:

(***i***) the field magnets are excited developing alternate *N* and *S* poles.

(***ii***) the armature conductors carry currents. All conductors under *N*-pole carry currents in one direction while all the conductors under *S*-pole carry currents in the opposite direction.

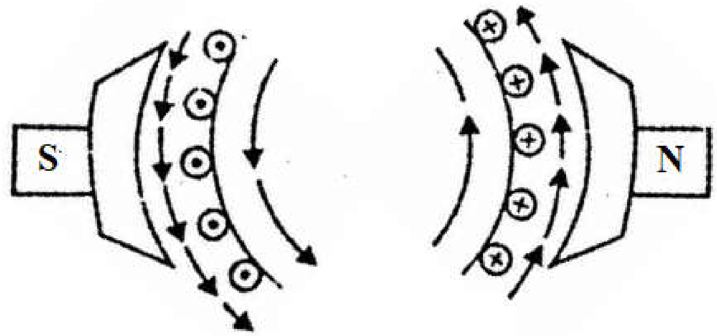


Figure DCM 01

Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force (*F*) Developed on it as shown in **Figure DCM 02**.

Referring to Figure DCM 01 and Figure DCM 01 and applying ***Fleming's left hand rule***, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction.

Force of individual conductor add together to produce a driving torque which sets the armature rotating.

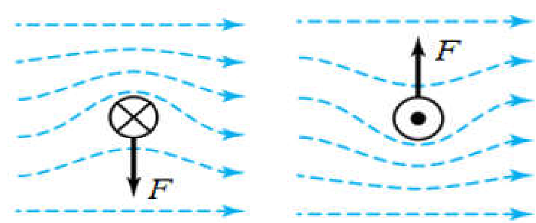


Figure DCM 02

Back or Counter EMF

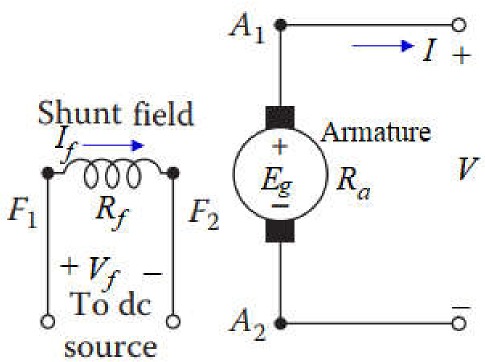
When the armature conductor of a DC. motor rotates through the magnetic field an emf is induced (Faraday's Law). The induced emf acts in opposite direction to the applied voltage (Lenz's law) and in known as back or counter emf which is given by:

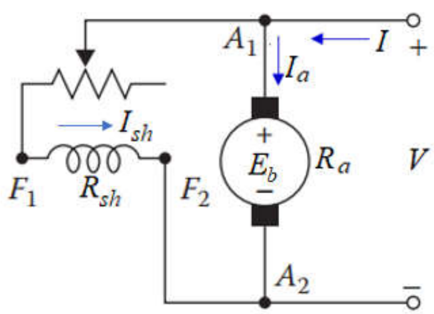
$$E_b = K_n \Phi N = K_\omega \Phi \omega_m = K_2 I_f \omega_m \qquad (29.1.1)$$

$$E_b = V - I_a R_a \qquad (29.1.2)$$

From Eq. (29.1), we have:

$$I_a = \frac{V - E_b}{R_a} \qquad (29.2)$$





Electromagnetic Torque Equations

The product $E_b I_a$ known as the electromagnetic power (P_{em}) (which is developed in armature) being converted, is related to the electromagnetic torque by the relation:

$$P_{em} = E_g I_a = T_e \omega_m \qquad (29.3)$$

Combining Eq. (29.1) and Eq. (29.3) the electromagnetic torque can be written as follows:

$$T_e = \frac{E_b I_a}{\omega_m} = K_\omega \Phi I_a \qquad (29.4)$$

For an electromagnetic system flux is proportional to field current i.e. $\Phi \propto I_f$. So, Eq. (29.3) can be written as follows:

$$T_e = K_1 I_f I_a \qquad (29.5)$$

K_1 = Constant

$I_f = I_{sh}$ for shunt wound DC motor

$= I$ for series wound DC motor

Applications of DC Motor

Types of Motor	Characteristics	Applications
Shunt wound DC Generators	Approximately Constant Speed Adjustable Speed Medium starting torque	○ For driving constant speed line shafting lathes ○ Centrifugal and Reciprocating pumps ○ Machine tools ○ Blowers and fans
Series wound DC Generators	Variable Speed Adjustable varying Speed High starting torque	○ For Traction work *i.e.* Electrical locomotives ○ Rapid transit systems ○ Trolley, cars etc. ○ Cranes and hoists ○ Conveyors
Compound wound DC Motors	Variable Speed Adjustable varying Speed High starting torque	○ For intermittent high torque loads ○ For sheares and punches ○ Elevators, Conveyors, Heavy planers ○ Rolling mils, Ice machines ○ Printing process, Air compressor

EXAMPLE: A 200V d.c. shunt-wound motor has an armature resistance of 0.4 and at a certain load has an armature current of 30 A and runs at 1350 rev/min. If the load on the shaft of the motor is increased so that the armature current increases to 45 A, determine the speed of the motor, assuming the flux remains constant.

Solution: There are two cases.

In case 1: I_{a1} = 301 A, N_1 = 1350 rpm
In case 2: I_{a2} = 45 A, N_2 = ?

$$\text{In Case 1: } E_1 = V - I_{a1}R_a = 220 - 30 \times 0.4 = K_2 I_f \omega_m = 188 \text{ V}$$

$$\text{In Case 2: } E_2 = V - I_{a2}R_a = 220 - 40 \times 0.4 = K_2 I_f \omega_m = 182 \text{ V}$$

Since flux is remain constant: $E \propto N$, thus we have $\frac{E_2}{E_1} = \frac{N_2}{N_1}$

$$\therefore \quad N_2 = \frac{E_2}{E_1} N_1 = \frac{182}{188} \times 1350 = \mathbf{1307\ rpm}$$