# Review Last Class

# Magnets

Magnetic field or magnetism, magnetic lines of force or lines of magnetic flux

Types or Classification of Magnets

Electromagnetic Induction [due to Straight Current Carrying Conductor and Coils or Solenoid]

Right–Hand Thumb/Grip Rule; Magnetic Flux, Flux Density

Magnetomotive Force (MMF) or Ampere-Turns, Absolute Permeability

Faraday's Law of Electromagnetic Induction, Lenz's Law

Nature of Induced EMF; Magnitude of Dynamic Induced EMF

Fleming's Right-Hand Rule and Fleming's Left-Hand Rule

Force on a Current Carrying Conductor in A Magnetic Field

How a Force and Torque are Produce on the Conductor?

Self Flux and Inductance, Leakage Flux and Inductance, and Mutual Flux and Inductance

# Transformer

Definition, Construction, Working Principle,

EMF Equation; Voltage Transformation Ratio

## 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 [$1.1 \text{ kV} \leq V_{HV} < 11$ 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

# Losses in a Transformer

There are two types of losses in a transform:
(***a***) Copper (or $I^2R$) losses, and (***b***) Iron (or Core) losses

**Copper (or $I^2R$) Losses**: These loss are due to the ohmic resistance of the transformer windings.

$$\textbf{Total Copper Loss}: \; P_{cu} = I_1^2 R_1 + I_2^2 R_2$$

**Core (or Iron) Losses**: These loss are due to the metallic body of core. There are two core loss:
(***a***) Hysteresis loss, and (***b***) Eddy current loss

**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.

$$\textbf{Hysteresis loss:} \quad W_h = k_h V B_{\max}^{1.6} f = P\, B_{\max}^{1.6} f$$

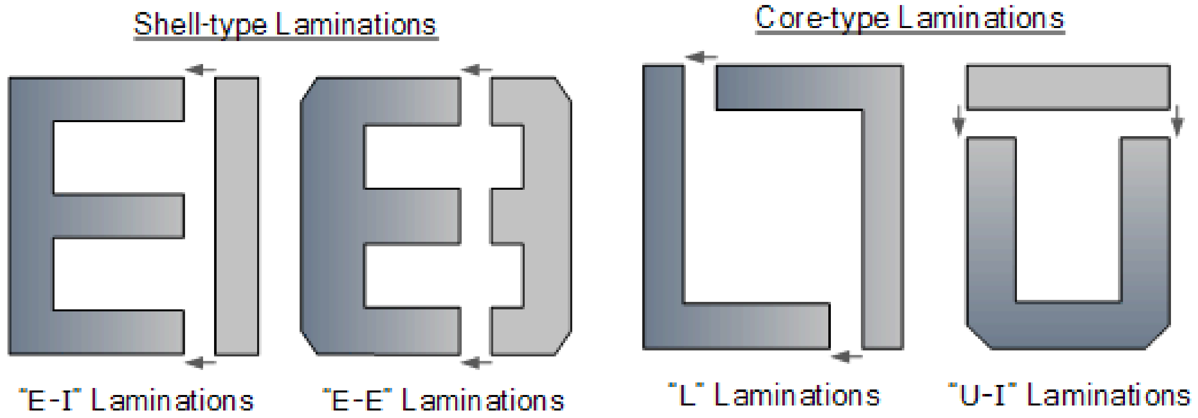
$P = K_h V$ is a constant; $K_h$ is constant depend on the characteristics of iron; $V$ is the volume of iron; $f$ is frequency; and $B_{\max}$ is the maximum flux density.

**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.

$$\textbf{Eddy-current loss:} \; W_e = k_e V t^2 B_{\max}^2 f^2 = Q B_{\max}^2 f^2$$

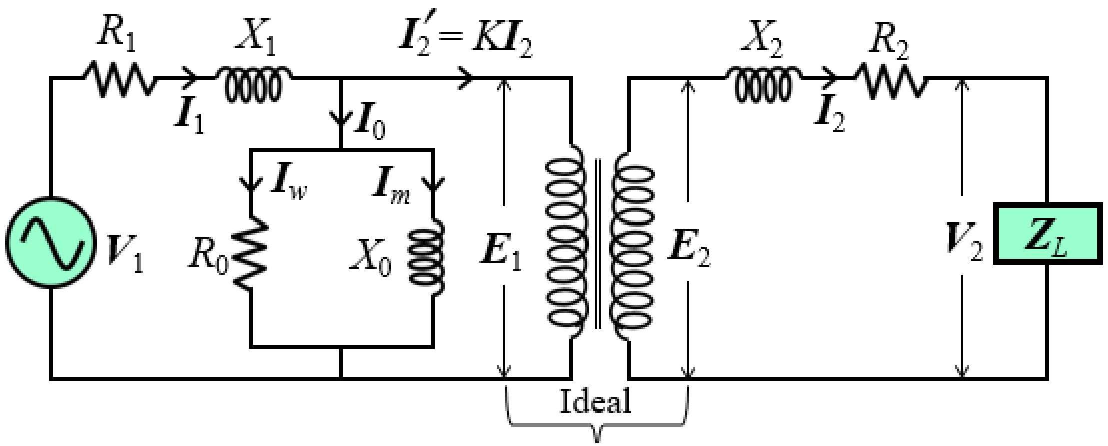
$Q = K_e V t^2$ is a constant; $K_e$ is constant depend on the characteristics of iron; $t$ is the thickness of lamination.

$$\textbf{Total Core Loss}: \; P_c = W_h + W_e$$



# Equivalent Circuit of a Transformer

The equivalent circuit of a transformer is shown in the following figure:




$\boldsymbol{V}_1$ and $\boldsymbol{V}_2$: Source and load voltages
$\boldsymbol{E}_1$ and $\boldsymbol{E}_2$: Primary and Secondary induced EMF
$\boldsymbol{I}_1$ and $\boldsymbol{I}_2$: Primary and Secondary currents
$\boldsymbol{I}_0$ and $I_m$ : No load and Magnetizing currents
$I_w$: Working or Active or Iron loss current
$R_1$ and $R_2$: Primary and Secondary windings resistance
$X_1$ and $X_2$: Primary and Secondary leakage reactance
$R_0$ and $X_0$: Core loss resistance and Mutual reactance
$\boldsymbol{Z}_L$ : Load impedance

# 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:

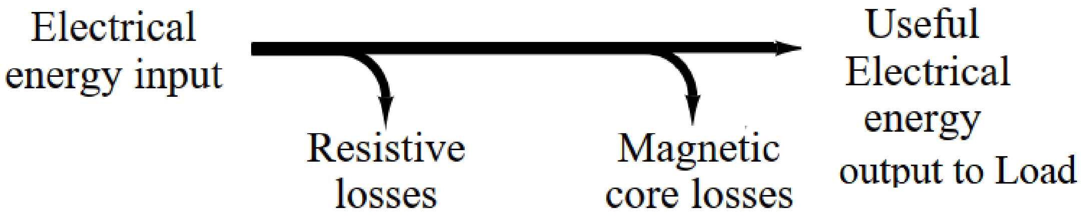
(***a***) **Open-Circuit Test**: Performing the open-circuit test, the core loss resistance ($R_0$) and magnetizing (or mutual) reactance ($X_0$) can be obtained.

(***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.

## Efficiency of Transformer




$$\text{Input} = \text{Output} + \text{Losses}$$
$$= \text{Output} + \text{Cu Loss} + \text{Iron Losses}$$

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

$$\text{Output} = \text{Input} - \text{Losses}$$
$$= \text{Input} - \text{Cu Loss} - \text{Iron Loss}$$

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

## 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 $= 4762.5 \times \left(\frac{1}{2}\right)^2 = 1190.625\,\text{W}$

$$\text{Hence total loss on half load} = 1190.625 + 2500$$
$$= 3690.625\,\text{W or}$$
$$3.691\,\text{kW}$$

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

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,

$$\eta = \left[1 - \frac{\text{losses}}{\text{input power}}\right] \times 100\%$$
$$= \left[1 - \frac{3.691}{173.691}\right] \times 100\% = \mathbf{97.87\%}$$

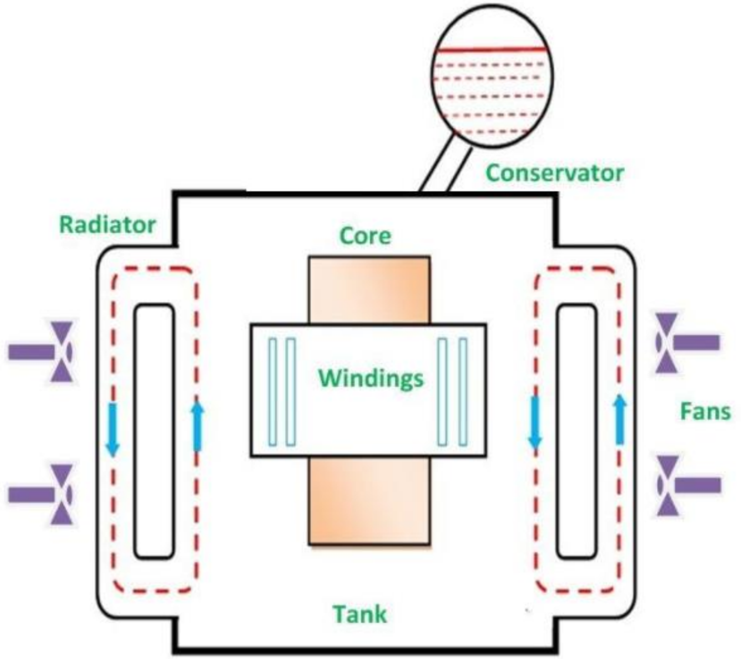
# Cooling of Transformer

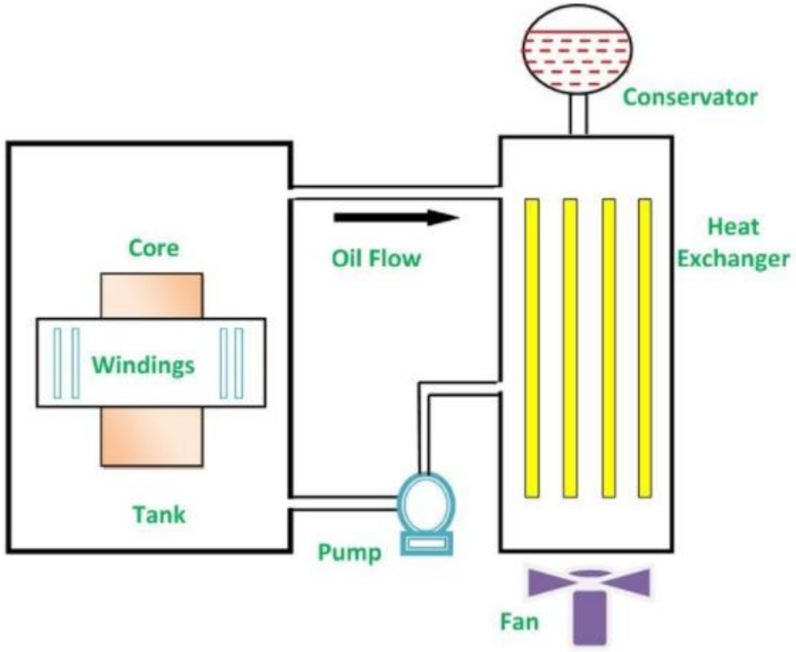
The losses of a transformer produce heat. To prevent undue temperature rise, this heat is removed by cooling.

(***i***) In small transformers (below 50 kVA), natural air cooling is employed *i.e.*, the heat produced is carried away by the surrounding air.

(***ii***) Medium size power or distribution transformers are generally cooled by housing them in tanks filled with oil. The oil serves a double purpose, carrying the heat from the windings to the surface of the tank and insulating the primary from the secondary.

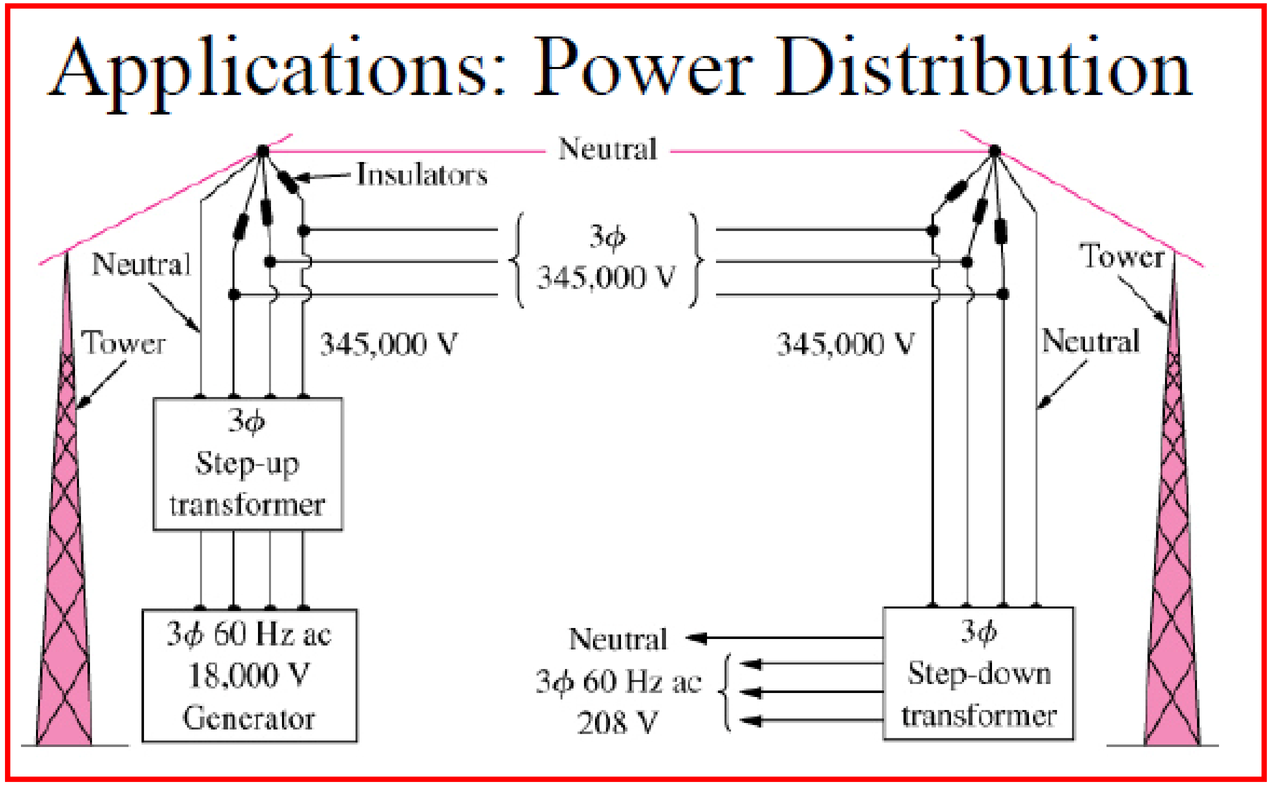
(***iii***) For large transformers, external radiators are added to increase the cooling surface of the oil filled tank. The oil circulates around the transformer and moves through the radiators where the heat is released to surrounding air. Sometimes cooling fans blow air over the radiators to accelerate the cooling process.



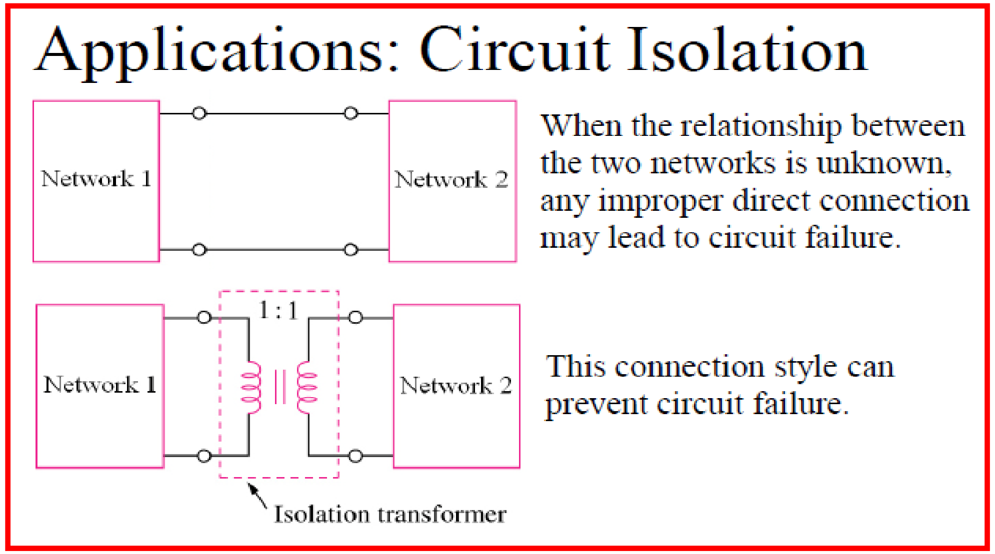



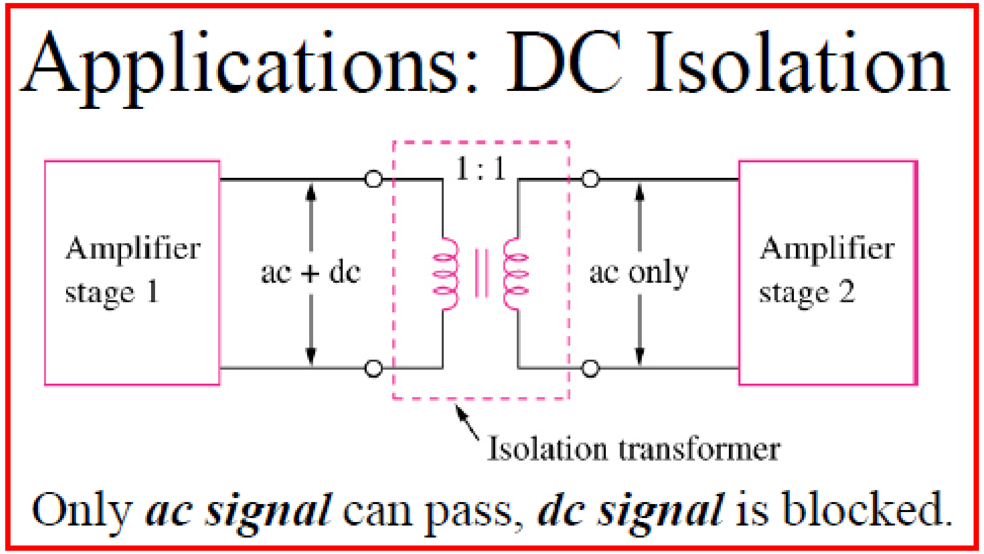
# Some Applications of Transformer

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

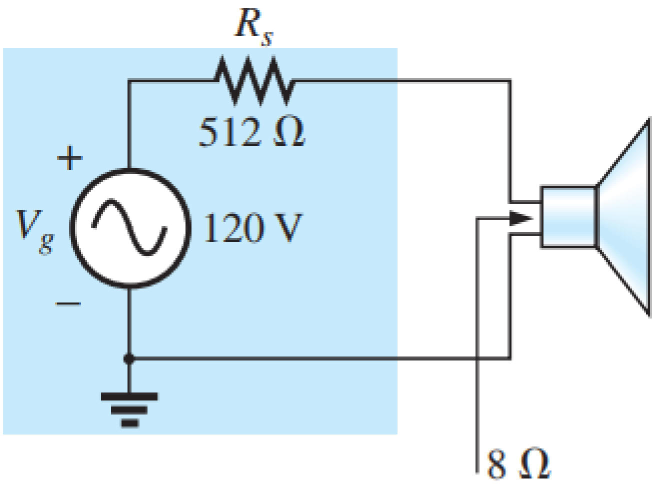


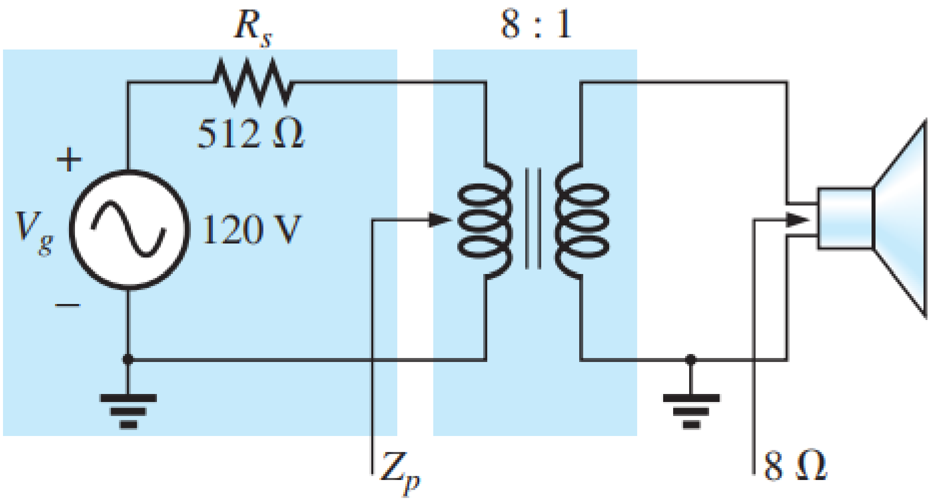

❖ To ***isolate*** one portion of a circuit from another.



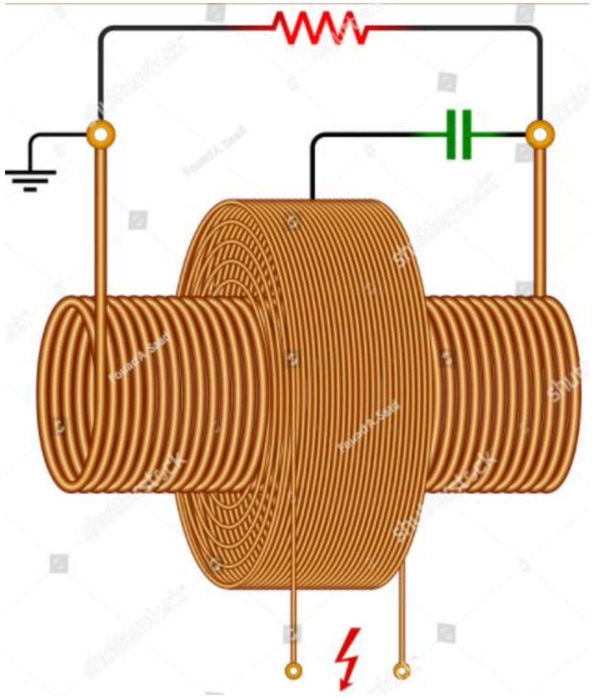



- As an ***impedance matching*** device for maximum power transfer.



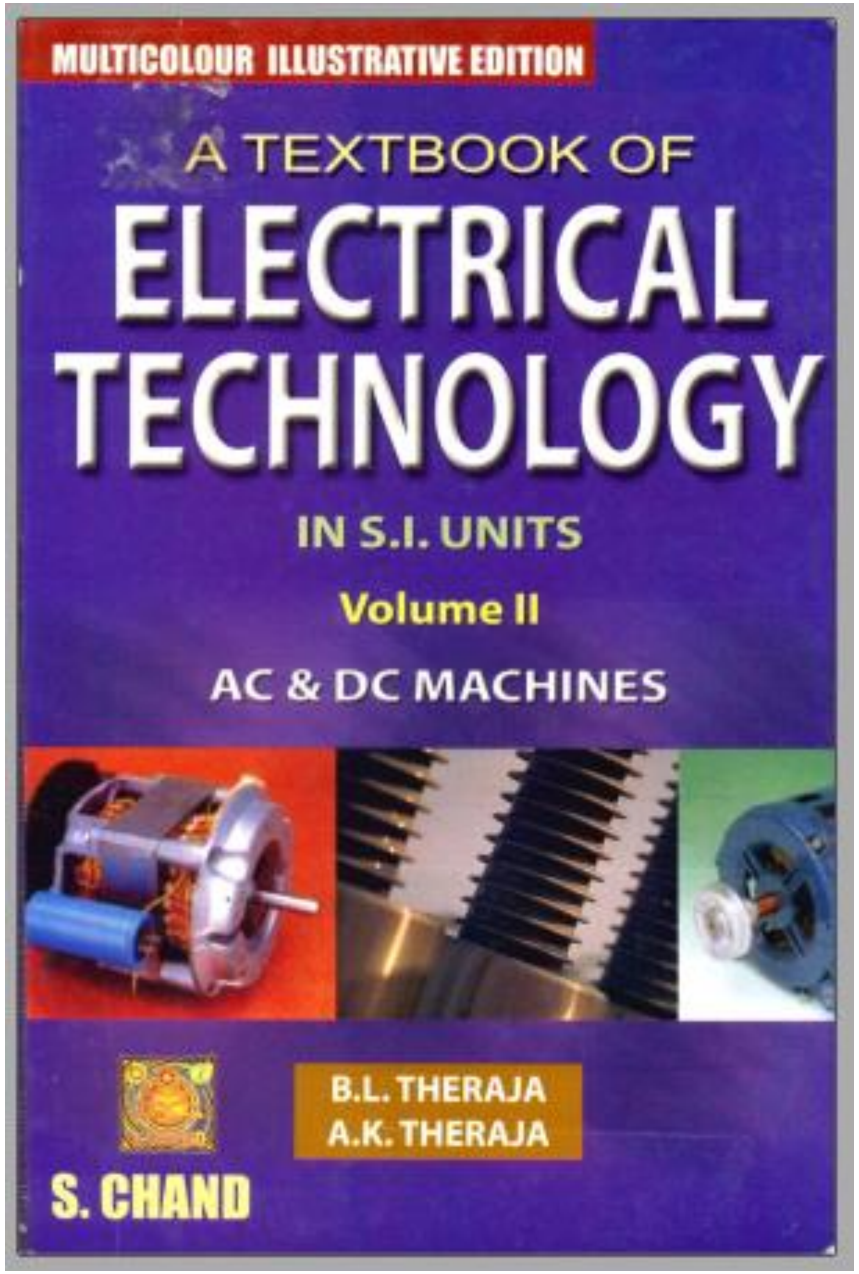




- ***Frequency-selective*** [**Resonance** or **Filter**] circuits.



# Basic of Electrical Machines

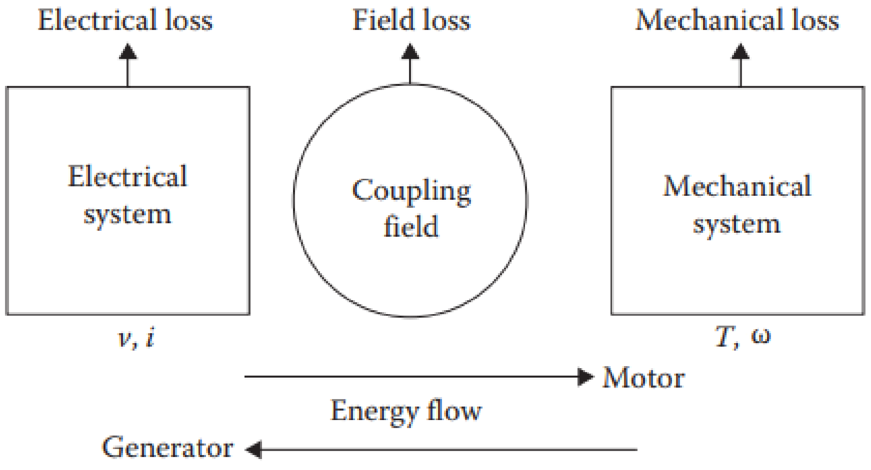
B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.



# Electromechanical Energy Conversion Principles

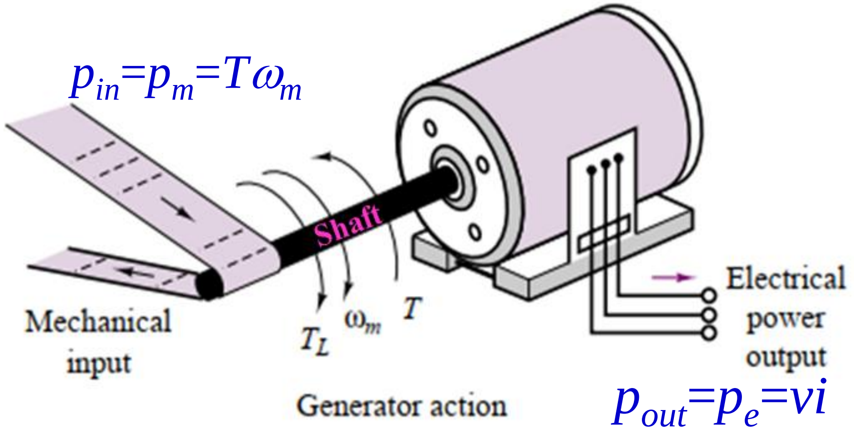
According to the **energy conversion principle**, *energy is neither created nor destroyed: it is simply changed in form*.

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



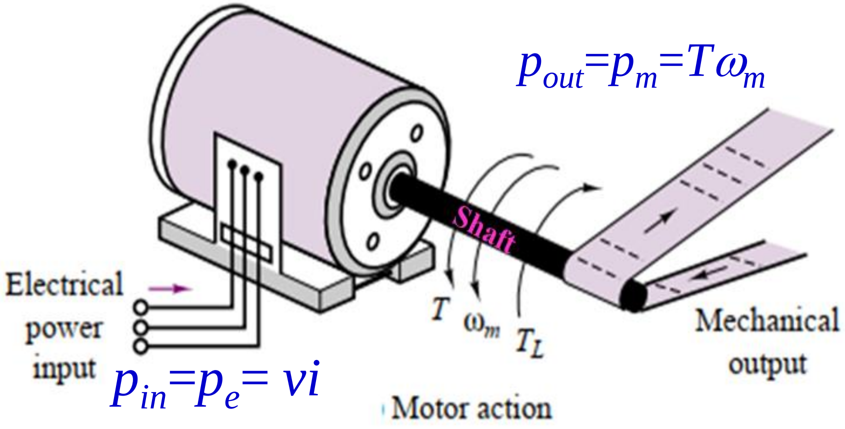

A representation of electromechanical energy conversion.

**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**: $P_e = vi \quad [\text{W}]$

**Mechanical Power**: $P_m = T\omega_m \quad [\text{W}]$

**Electrical Angular velocity ($\omega$) and Mechanical Angular velocity ($\omega_m$)**:

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

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

$T$ : 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:

Electrical are classified as follow:

(*a*) **DC (or Commutator) Machine**

(*b*) **AC (or Commutatorless) Machine**

(*i*) Synchronous Machine Induction Machine

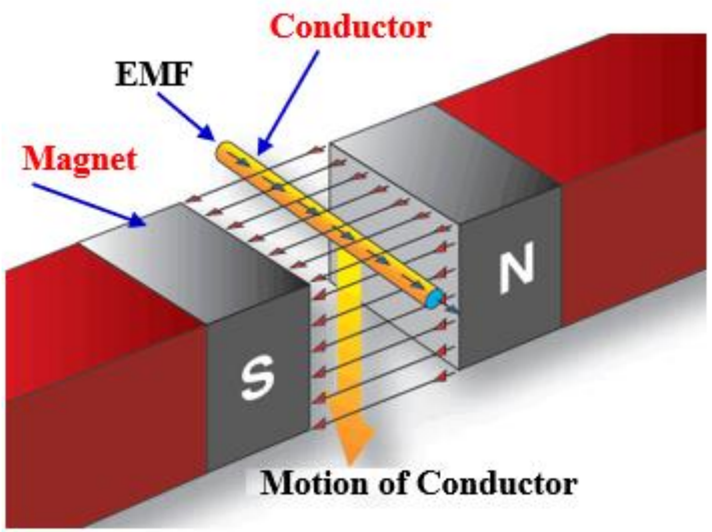
(*ii*) Single-phase Machine Three-phase Machine

(*c*) **Special Type Machine**

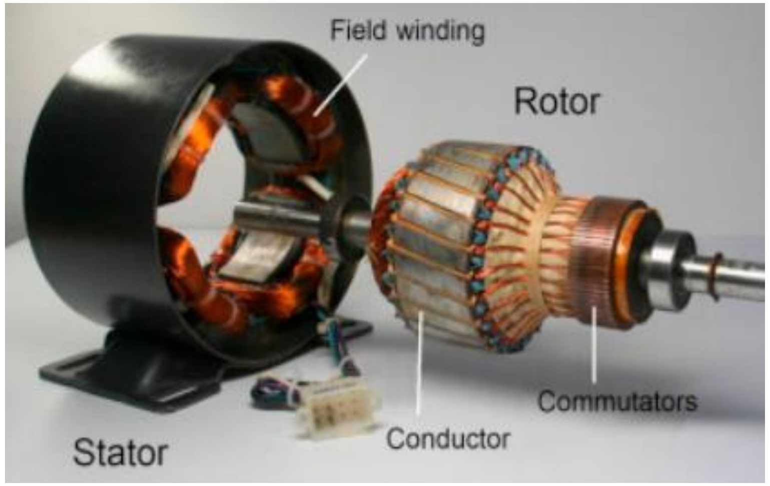
Universal Motor
Synchronous Reluctance Motor
Hysteresis Motor
Stepper Motor
Servo Motor
Linear Motor
Shaded-pole Motor
so on ……….

# Basic Elements and Parts 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.



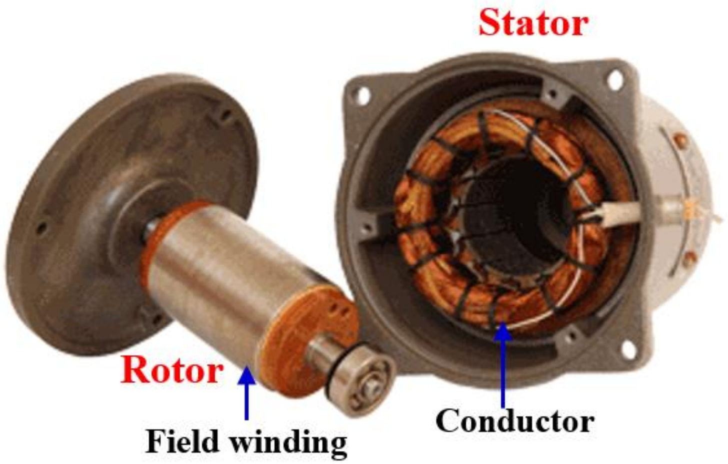

In broad sense, electrical machine has two major parts:
(*a*) **Stator**: The portion/part of electrical machine which is stationary is called stator.
(*b*) **Rotor**: The portion/part of electrical machine which is rotating is called rotor.




**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.

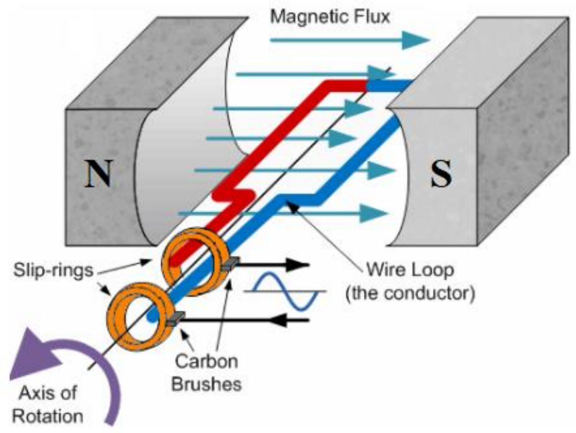



**AC machine**

# AC Generation and DC Generation

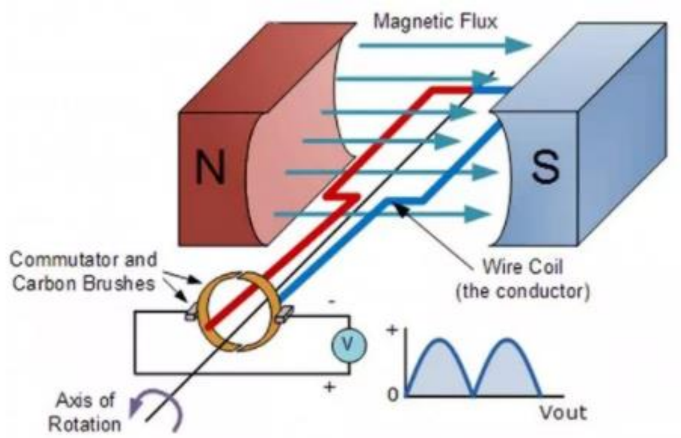
In a generator, an emf is induced in a conductor according to **Farady's law**.
The polarity of induced emf can be determined by **Flaming's Right Hand Rule**.
The induced emf in a rotating machine is changed sinusoidally because the direction of force of conductor is changed alternately from up–ward 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.



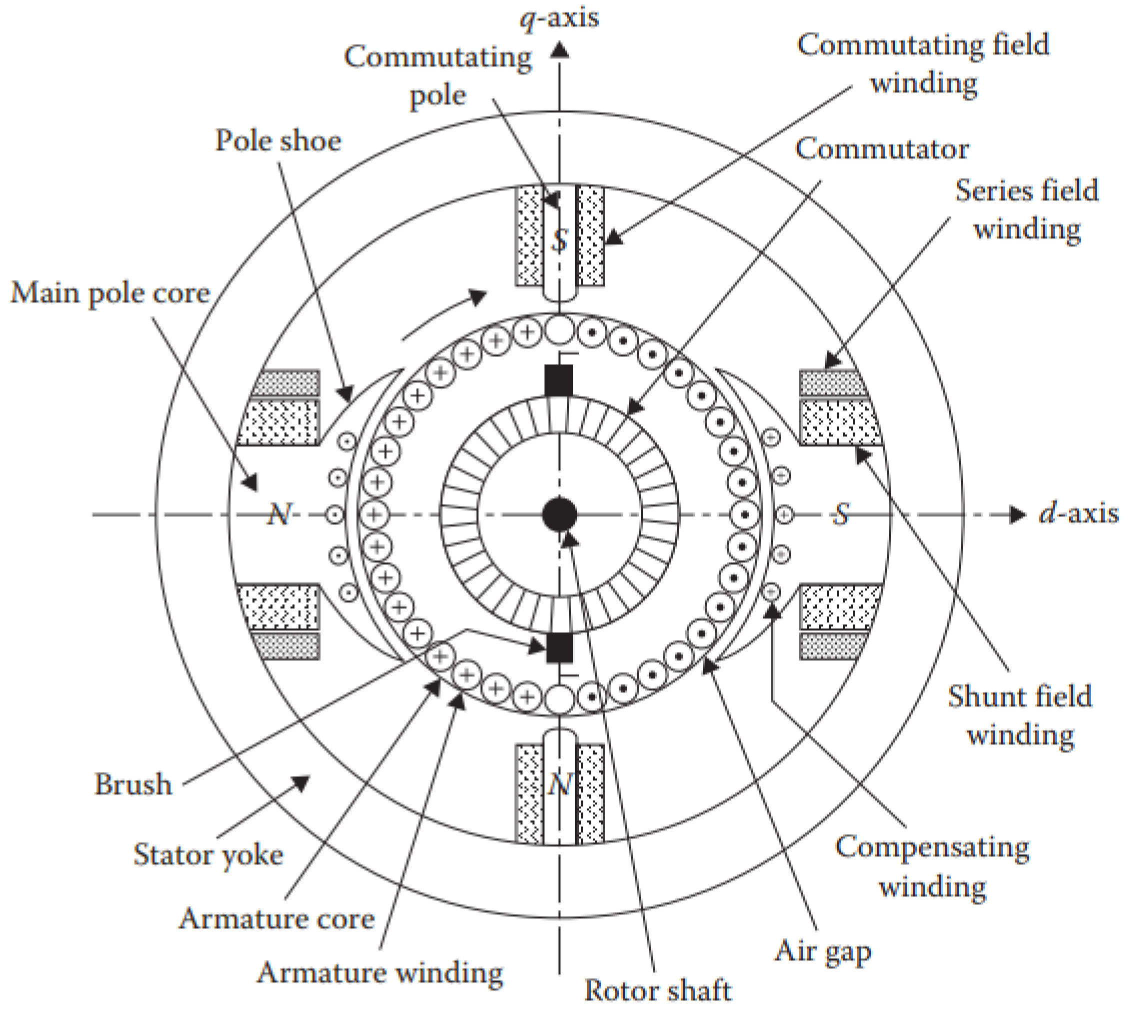

Commutator helps to convert ac induced emf to dc emf.
By increasing the number of conductors, the pulsation of dc voltage can be reduced

# DC Machines

# Chapters 26 and 29

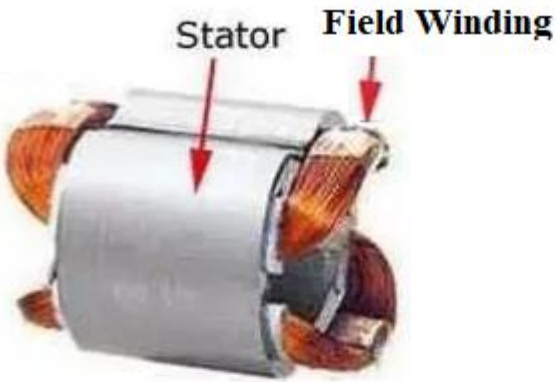
B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

# Construction of DC Machines



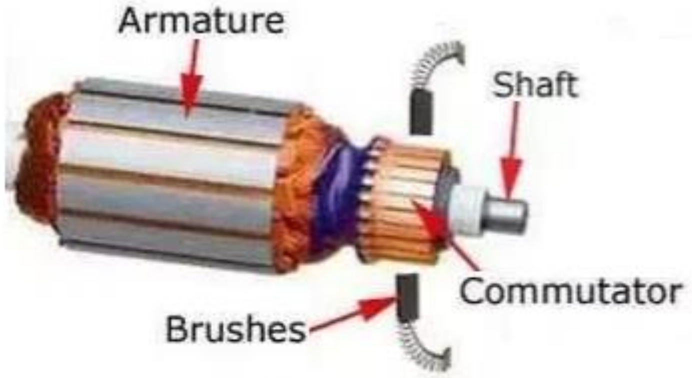

**Stator [Magnet]**

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

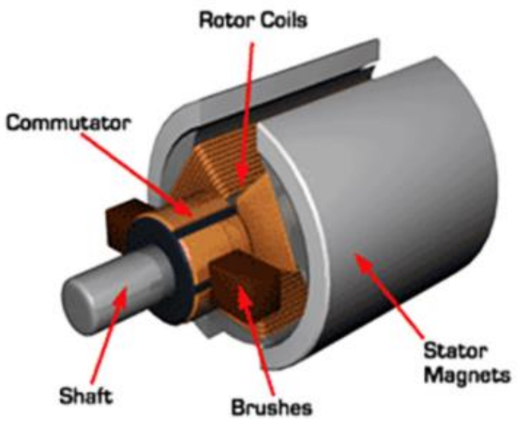
DC Machines are Classified as follows:

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

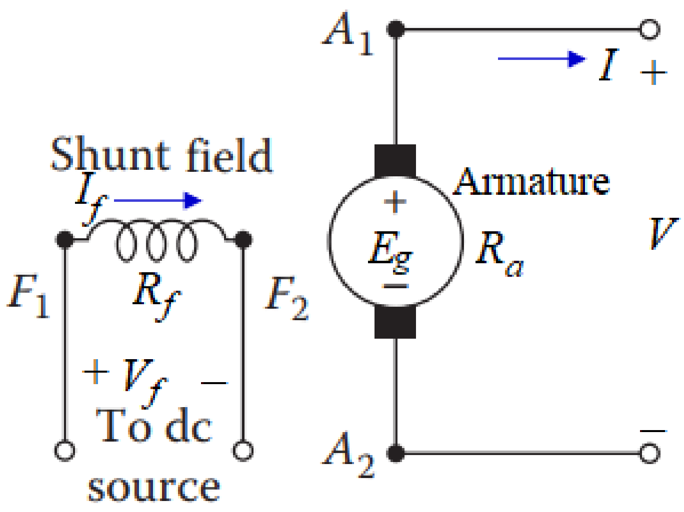
(**2**) **Electromagnetic based DC Machine**: Where electromagnet is used to produce magnetic flux. Mainly this type of DC machine has two field windings, the are called **shunt winding** and **series winding**.

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

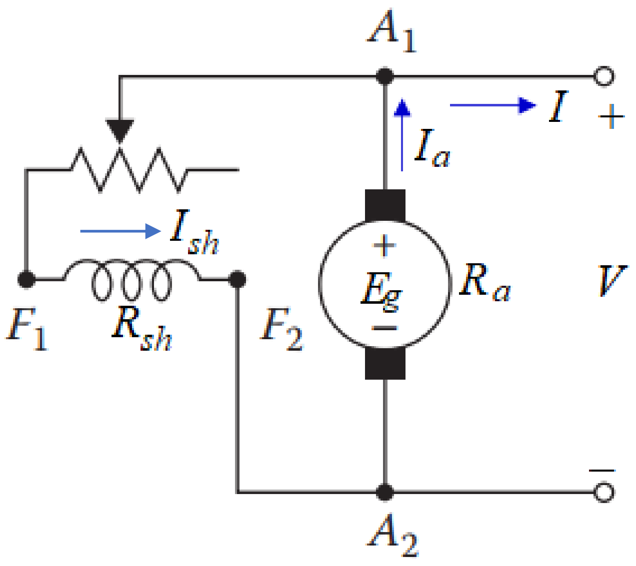
(***b***) **Self-exited DC Machine**: where the field winding receives its supply from the armature of its own machine.




**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:

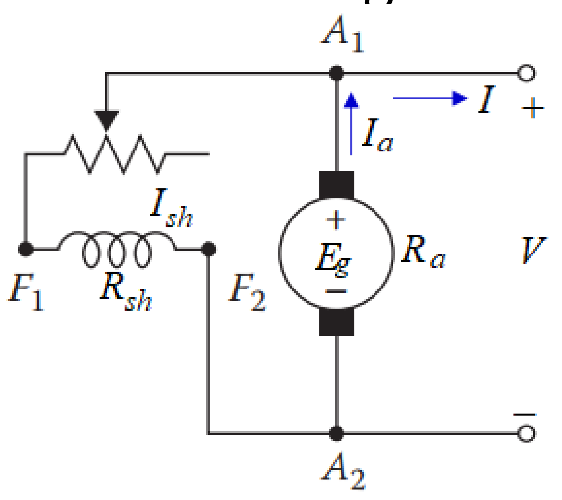
(*i*) **Shunt Wound DC Machine**: where the only shunt (parallel) field winding is connected in parallel with armature winding.

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

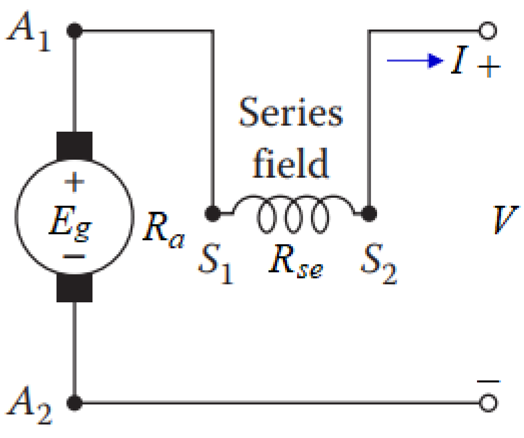
(*iii*) **Compound Wound DC Machine**: where the both shunt (parallel) and series field windings are connected.

(*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.

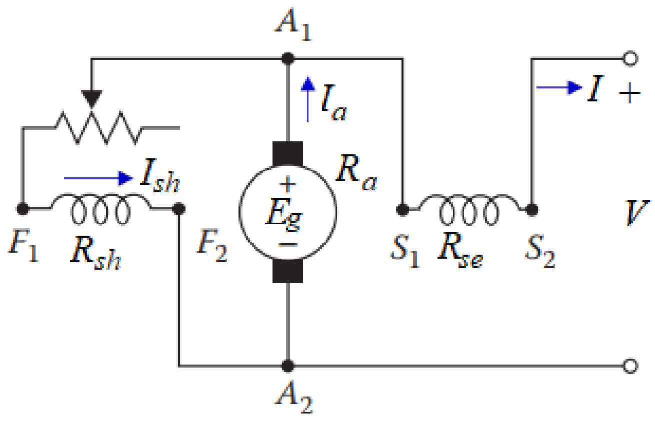
(*II*) **Short Shunt Wound DC Machine**: where series field winding is connected series with in combination of parallel connection of armature and shunt field winding.



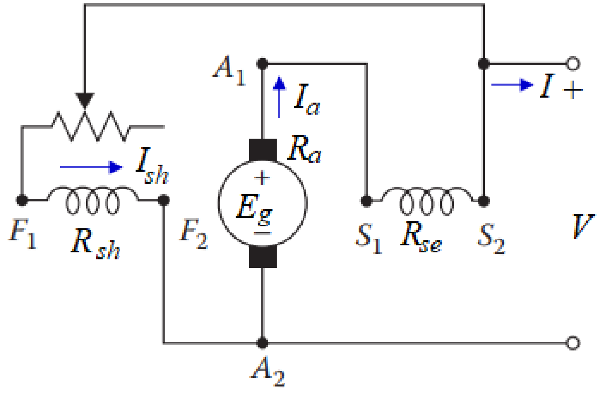

**Shunt Wound**




**Series Wound**




**Short Shunt**

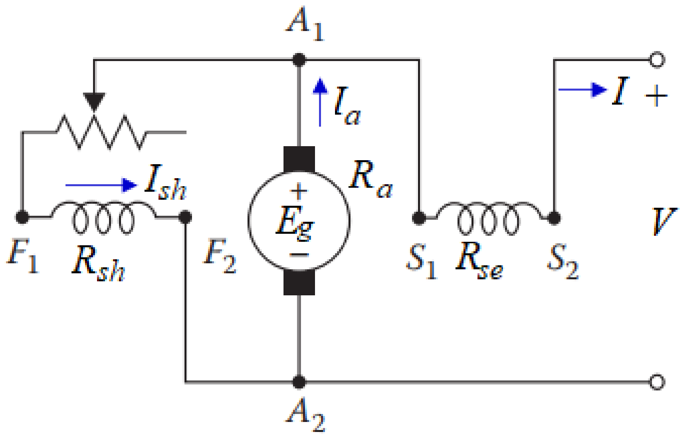



**Long Shunt**

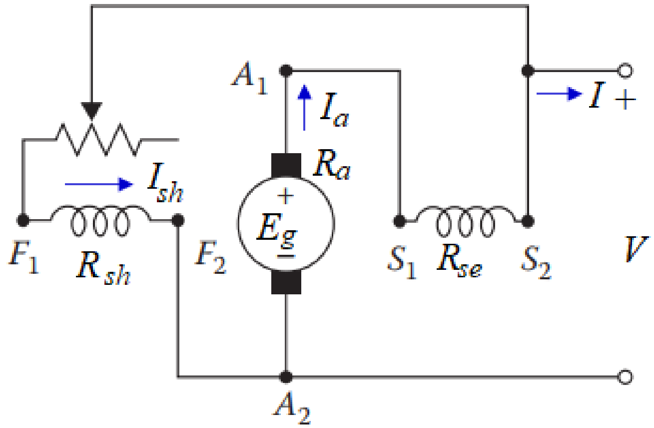
**Compound Wound**

**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.

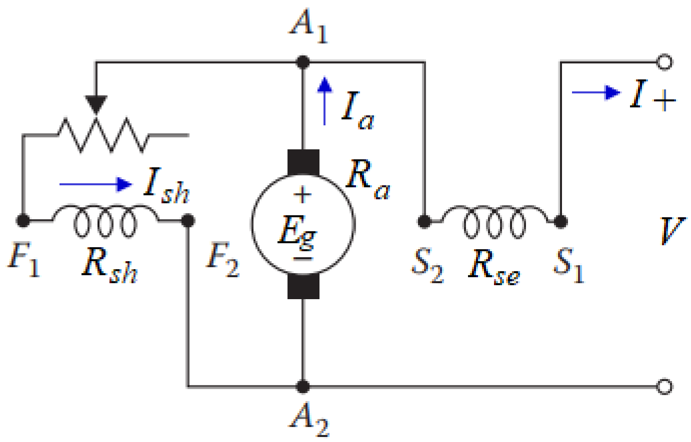



**Short Shunt Cumulative Compound DC Machine**

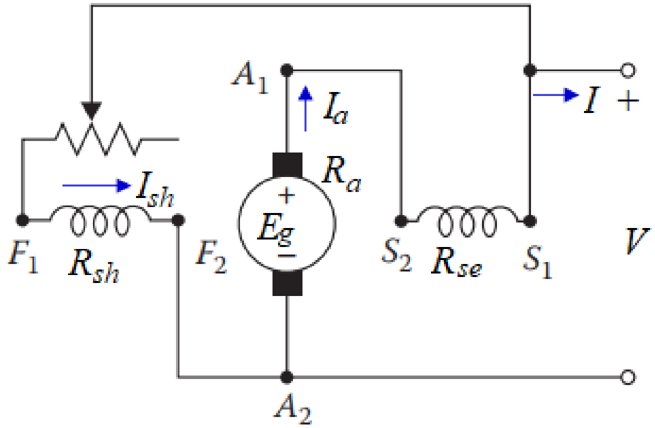



**Long Shunt Cumulative Compound DC Machine**

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




**Short Shunt Differential Compound DC Machine**



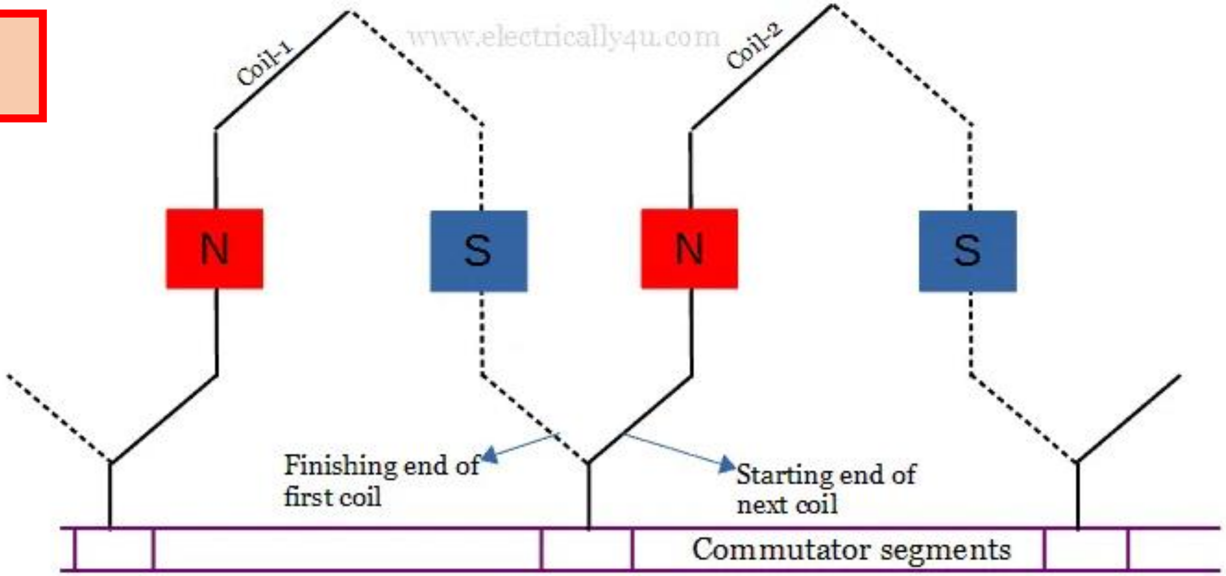

**Long Shunt Differential Compound DC Machine**

# Armature Winding of DC Machine

Armature windings can be divided into two groups, depending on how the wires are joined to the commutator. These are called:

(*a*) **Wave windings** and

(*b*) **Lap windings**



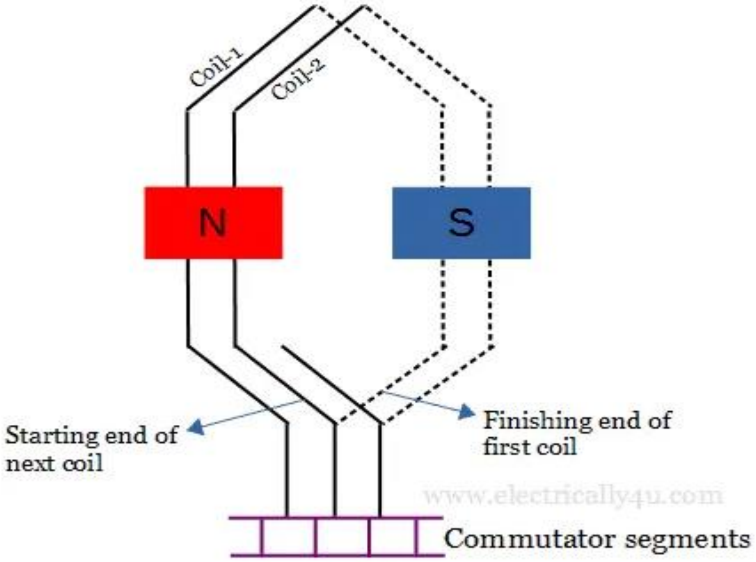

*Wave winding*

(*a*) In **wave windings** there are **two paths in parallel**, irrespective of the number of poles, each path supplying half the total current output. Wave wound generators produce high-voltage, low-current outputs.

**Parallel path (*A*) = 2**

(*b*) In **lap windings** there are as many paths in parallel as the machine has poles. The total current output divides equally between them. Lap-wound generators produce high-current, low-voltage output.

**Parallel path (*A*) = number of magnetic pole (P)**




*Lap winding*