EEEE Module 3 Short Notes

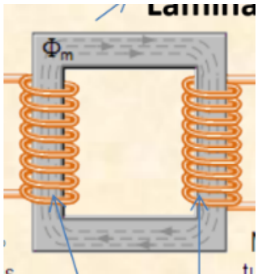
Transformer

- Definition: Transformer is a static piece of apparatus by which electric power in one circuit is transformed into electric power (of the same frequency) in another circuit.
- It can raise or lower the voltage (V) in a circuit but also decrease or increase current (I). So the product VI remains constant.
- Transformer consists of two inductive coils (windings) which are not in contact but magnetically linked through a path of low reluctance (laminated core). The two coils have a very high mutual inductance.
- The primary winding is connected to a source of alternating voltage, an alternating flux is set up in laminated core, most of which is linked with secondary winding in which it produces mutually induced e.m.f. according to Faraday's law of electromagnetic induction (E=MdI/dt). *When the secondary winding is a closed circuit, current flows through it. Electric energy is transferred magnetically from first winding to second.*

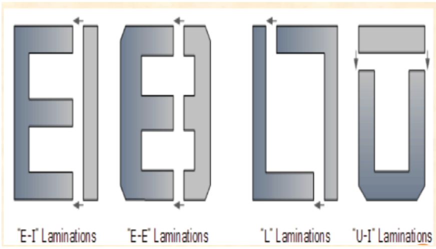
Transformer Construction

Two basic parts are there in a transformer.

Magnetic core



- Either square or rectangular
- Wherever the coil is wound is called limb, rest is called yoke. (limb is vertical here and yoke is horizontal)
- Core is laminated to minimise eddy current loss. (Wastage of energy in the form of heat during transforming)
- Types of laminations



- Most common lamination: high grade silicon steel.

Transformer coils/windings

- Most common material for windings: conducting materials like copper
- The coils are wound on limbs and insulated from each other

- There is a development of leakage flux and it badly affects the transformer efficiency. To minimise, we ensure that **the windings are super close together and have very high mutual inductance. (use an iron core, increase number of turns)**

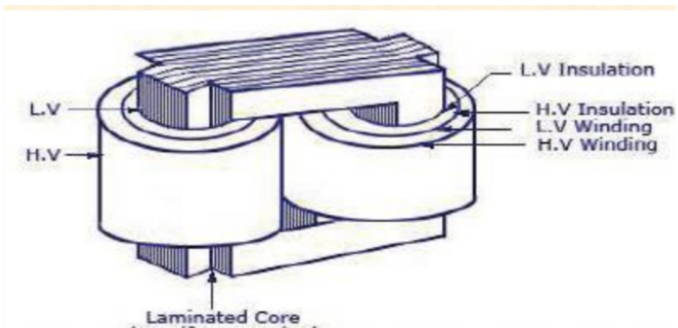
$$\mathbf{M}=\frac{N2 \cdot \Phi}{I1}$$

$$\mathbf{\Phi=BA\ cos}\theta$$

Transformer classification based on construction

Core Type

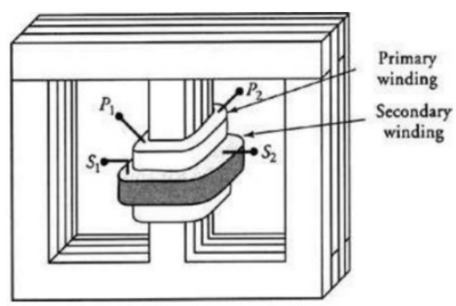
1. **One** magnetic circuit and cylindrical coils are used.
2. L and T type laminations are used
3. **Commonly primary winding is on one limb while secondary on the other**
4. Reduced performance since for efficiency, the windings need to be very close.
5. More economical



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

Shell type

1. **Two** magnetic circuits are used
2. Wounding is on the **central** limb
3. A high voltage winding is sandwiched between two low voltage windings. This design helps with insulation and proper voltage distribution.
4. Subdivision of windings reduce leakage of flux
5. Less subdivisions = less reactance
6. This is costlier but more efficient since the voltage is high



Transformer classification based on other factors

1. Number of windings
    a. Conventional : 2 windings
    b. Autotransformer : 1 winding
    c. Other : 2+ windings
2. Number of phases
    a. Single phase transformers
    b. Three phase transformers
3. Voltage level at which windings are kept
    a. Step up transformer : primary winding is at low voltage

b. Step down transformers : primary winding is at high voltage

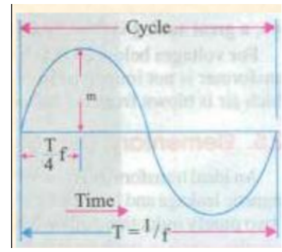
EMF equation of transformer

1. Flux increases from 0 to max value in ¼ time. = $\frac{1}{4f}$ where f is the frequency of the ac circuit
2. Average rate of change of flux = $\frac{\Delta\phi}{\Delta t} \;=\; \frac{\phi max - 0}{1/4f - 0} \;=\; \phi 4f$
3. Flux varies sinusoidally. The rms value of flux can be obtained by:

$$form\ factor \;=\; \frac{RMS\ value}{Average\ value}$$

$$RMS\ value \;=\; form\ factor \;*\; average\ value$$

4. Form factor is 1.11, so rms value (per turn) = 4.44fϕ volts
5. For total rms value, multiply with number of turns in each winding



Transformer ratio

$$\frac{e2}{e1} = \frac{n2}{n1} = k$$

When k>1, we have step up transformer
When k<1, we have step down transformer
For an ideal transformer, input VI = output VI

$$V^1 I^1 \;=\; V^2 I^2$$

$$\frac{i2}{i1} = \frac{v1}{v2} = \frac{1}{k}$$

Losses in Transformer

- Eddy current and hysteresis loss depends on the magnetic properties of core material. (hence the name). These are independent of current and are called fixed losses.
- **Hysteresis loss:**
  - Type of core loss
  - Due to reversal of magnetization in the core. Depending on volume and quality of iron, frequency of magnetic reversals (The magnetic field in a transformer changes direction because of the **alternating current**. AC voltage reverses direction regularly, causing the magnetic field to alternate as well), value of flux density.

$$W_h = \eta\ B_{max}^{1.6}\ f\ V(watts)$$

  - H is the Steinmetz constant and V is volume of core in m^3
- Eddy current loss
  - Type of core loss
  - When the ac current in primary winding links with secondary, it produces induced emf
  - Some part of this flux gets linked with other conducting parts of the system like the iron body or steel core. And thus, some induced emf is produced in these parts too. And then there are small circulating current in them. This current is called eddy current.

- ○ But this stray induced emf is useless to us. And the eddy current produces heat and all of this is lost energy.
- Copper loss
  - Type of winding loss
  - Due to the ohmic resistance of windings
  - For windings, copper loss = I^2R. where i and r are the current and resistance in THAT winding.
  - Copper loss is proportional to square of current and current depends on load. And load and current varies. So this loss is called variable loss.

Rating of a transformer

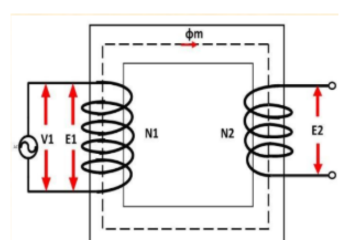
kVA rating

- Copper loss is dependent on current
- Core loss is dependent on voltage
- Total loss depends on VA and not on phase angle (Losses are independent of power factor)
- Thus the rating is described in VA or kVA not as KW (no role of power factor)
- V1*I1=V2*I2 = kVA : defines the kVA rating.

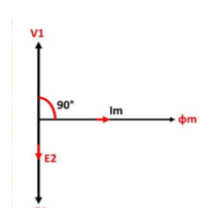
Ideal vs Practical Transformer

1. Definition of ideal transformer: Transformer free from all kinds of losses.
2. No core loss, no ohmic resistance, no leakage flux (flux from primary that is not linked with secondary and escaped the circuit)
3. Characteristics:
   a. Zero resistance in windings
   b. Infinite permeability in core, hence zero leakage flux
   c. 100% efficiency
4. Practical transformer: Has finite windings resistance, some leakage flux, and all losses.

Phasor Diagram of Ideal transformer



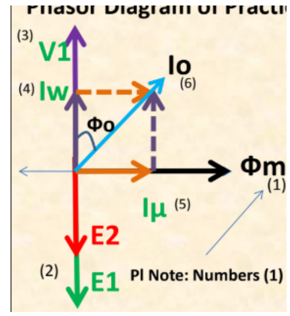
1. V1 is applied across primary winding
2. Secondary is kept open
3. N1 and N2 are number of turns
4. I_m is the magnetizing current. It flows through the primary winding. It produces flux φ_m in the core
5. As the permeability of the core is infinite, flux of the core is linked with both primary and secondary winding
6. The flux linked with primary winding induces E1 due to self induction
7. Direction of induced emf is opposite to v1
8. E2 is induced in secondary winding by primary due to mutual induction



9. The core is purely inductive, the magnetizing current lags 90º behind v1. The e1 and e2 are emf. Direction of the induced emf is opposite to applied as per Lenz's law

Practical Transformer

No Load Connected to Secondary Windings



1. There is iron loss in the core and copper loss in the windings
2. These losses are not negligible
3. Even when the secondary windings are open(no load), the primary current is not purely reactive (not all of it is conserved).
4. This current at no load accounts for
   a. Iron loss of hysteresis and eddy current
   b. Copper loss in primary windings
5. The no-load input current (io) lags behind by some angle less than 90. (blue line)
6. Iw and iu are components of input current io
7. Iw is in phase with v1 and is known as active, working or loss component as it compensates for the various losses.
8. Iu is 90^0 behind v1 (in quadrature) and is called the magnetizing component as it sustains the alternating flux in the core.

Important points:

- No load primary current (io) is 1% of full load current (when secondary winding is not open)
- Io is practically equal to iron loss of transformer; as copper loss is negligible
- Φ_0 (diagram) is called **hysteresis angle of advance** as the iron loss(io) is responsible for the shift in Io from 90 to Φ_0 .

Primary and Secondary winding resistance: Load

- Practical transformer always has a finite resistance in windings
- Thus, there is a finite **voltage drop** in both windings.
- V_2 is therefore less than e_2 by an amount of i_2r_2 (vector difference) and the same is for v_1.

$$V_2 = E_2 - I_2R_2$$

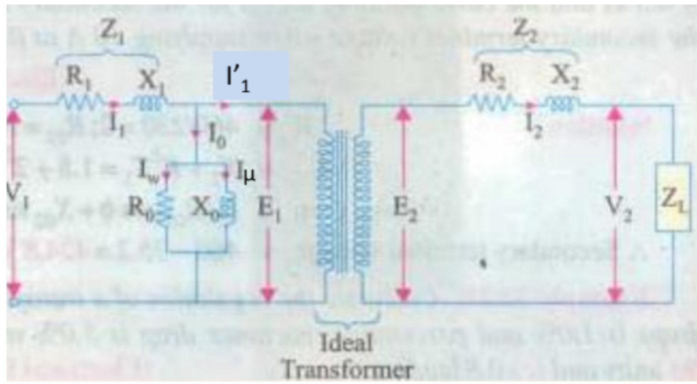
Magnetic Leakage: Load

- All the flux linked with the primary coil does not link with the secondary coil. Part of it passes through the air rather than through the core.
- This leakage is produced when mmf (magnetomotive force) follows a path that does not link it to the secondary winding.
- This flux is called primary leakage flux and is proportional to primary I1*N1 alone. This flux is in phase with i1 and induces emf e_{L1} in the primary coil due to self induction.
- Same thing happens in the secondary coil. Induced emf = e_{L2}
- X1= e_{L1} /I_1 and X2= e_{L2} /I_2 where x is the leakage reactance of the windings.

- The primary voltage v1 will have to supply i1x1 ALONG with i1r1. This is to make up for the induced emf earlier.
- Solution: keep primary and secondary windings superclose to avoid/reduce leakage flux.
- $z1 \ = \ \sqrt{r1^2 \ + \ x1^2}$ and similarly for z2. R and X are responsible for voltage drops in each winding. Source voltage has to provide more to compensate.
- V1 = e1 + i_1 (r1+jx1) [vector addition] and same for secondary
- v1=e1 mostly but to overcome losses, we need to add r and x factors too.

Equivalent circuit of the Transformer

- Winding resistance and leakage reactance is in series with respective windings.
- No load primary current I_O is simulated by X_o, along with magnetic component I_u and by R_o, working component I_w. This is connected in parallel as shown.
- $v_1=e_1 + i_1r_1$
- $v_2 = e_2 - i_2r_2$



Operation of the Transformer on Load Condition

- When the load is connected to the secondary winding of the transformer, i2 flows through the secondary winding. I_2 induces magnetomotive force n_2i_2 on the secondary winding. This force sets up flux φ2 in the core. φ2 opposes φ, per Lenz's law.
- This opposition reduces the overall flux in the core, which in turn, lowers the induced EMF e1 in the primary winding.
- To restore the situation and maintain the original flux, the primary voltage v1 must supply **extra current** to counterbalance the opposing flux.
- The **primary counterbalancing current** i1′ helps cancel out the opposing flux ϕ2 and brings the core's flux back to its original value.
- This additional counterbalancing current produces magnetomotive force n1i1'. This force will set up another flux ϕ'1. It cancels out ϕ2 thus completing our purpose. And N1I1' = N2I2

$$I1' \ = \ \frac{n2}{n1} i2 \ = \ k2$$

- The phasor difference between v1 and i1 gives a power factor.
- The power factor of the secondary side (between v2 and i2) depends on the type of load connected to the transformer. If load is **inductive**, power factor is **lagging** and if it is **capacitive**, the pf is **leading**.
- $I_1 = I^o + I_1$` (vector sum)
- Thus, I_1 is the sum of current in primary winding at no load I^o and current in primary winding when load is attached. I_1`

[PHASOR DIAGRAM DRAWING METHOD FROM SLIDES]

Efficiency

$$\eta = \frac{Output\ power}{Input\ power} \times 100\%$$

$$\eta = \frac{Input\ power - losses}{Input\ power} \times 100\%$$

Condition for max efficiency ; Copper loss = iron loss
Copper loss = $i_1^2 r_1$ (formula for energy, as copper loss is heat dissipation)
W_1 = Iron loss in watts
All day efficiency = $\frac{output\ in\ kWH}{input\ in\ kWh} for\ 24\ hours$
Definition: ratio of energy delivered by transformer in 24 hours to the energy input.
All day efficiency is always less than ordinary efficiency

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2 R_1 + W_i}{V_1 I_1 \cos\Phi_1}$$

$$\eta = 1 - \frac{I_1 R_1}{V_1 \cos\Phi_1} - \frac{W_i}{V_1 I_1 \cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1 \cos\Phi_1} + \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

η will be maximum at $\frac{d\eta}{dI_1} = 0$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1 \cos\Phi_1} = \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

$$\frac{I_1^2 R_1}{V_1 I_1^2 \cos\Phi_1} = \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

$$I_1^2 R_1 = W_i$$

Voltage regulation

Definition: The change in secondary terminal voltage when transformer loading is maximum is called voltage regulation. (full load is applied and primary voltage is constant).
Benefit: Determines voltage drop when load is high (higher load will demand more current as i2 and thus, higher copper and iron losses) and efficiency is affected.
It is expressed as a percentage or per unit of the no-load voltage (as voltage drop at full load / no load rated secondary voltage)
$voltage\ regulation = \frac{E2(no\ load\ voltage) - V2(full\ load\ voltage)}{E2}$ and multiply by 100 for percentage voltage regulation.
At no load, the secondary rated voltage = E2.
Upon substituting formulae

$$\%\ \text{regulation} = \frac{I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}{E_2} 100$$

- \+ For lagging power factor
- \- For leading power factor

Three Phase Induction Motors

Construction

Stator

- The stator is a steel frame with a hollow cylindrical core made of thin silicon-steel laminations.
- It has several stampings to receive windings.
- The stator carries a 3-phase winding and is powered by a 3-phase supply.
- When a 3 phase ac supply is given, a rotating magnetic field is produced that induces currents in the rotor by electromagnetic induction.

Rotor

The rotor is a **hollow laminated core** mounted on a shaft. It has slots on its outer periphery, where windings are placed.

Squirrel Cage Rotor

A squirrel cage rotor has a laminated cylindrical core with parallel slots. Copper or aluminum bars are placed in each slot and connected by end rings, forming a short-circuited winding. The rotor is not connected to the supply but receives current from the induced current of the stator by transformer action.

Current is induced in the rotor through electromagnetic induction from the stator. When a 3-phase current flows through the stator windings, it creates a rotating magnetic field. This magnetic field passes through the rotor and induces an electric current in it. Since the bars are permanently short-circuited by end rings, extra resistance can't be added.

https://www.youtube.com/watch?v=JGrkP9lO4W4

Wound rotor

Laminated cylindrical core. Carries a 3 phase winding. The rotor winding is distributed in the slots (like bars in squirrels but they're just three in number) and is star connected. The open ends of the rotor windings are brought out and insulated with slip rings. The "brushes" or end points from each of the three windings are connected to an external resistance. External resistances are included in the rotor circuit and give a large starting torque. Slowly this is reduced to zero as the motor picks up speed. When the normal speed is attained, the brushes are short circuited to mimic squirrel cage rotor.

Rotating Magnetic Field Produced by 3 phase AC Machines

When a 3-phase winding is fed by a 3-phase supply, it creates a set of rotating magnetic fields.

$$\phi 1 \ = \ \phi m \ sin \ \theta$$

$$\phi 2 = \phi m \sin(\theta - 120)$$
$$\phi 3 = \phi m \sin(\theta - 240)$$
$$\phi r = \frac{3}{2}\phi m \text{ when theta } 0,60,120,180$$

Synchronous Speed N_s:
Definition: Speed at which revolving flux rotates at the stator.

$$Ns = \frac{120 * frequency}{P} \text{ ; P is the number of poles}$$

Principle of Operation of Three Phase Induction Motor <recap>

- When a three phase stator winding is fed from a 3 phase supply, a rotating magnetic field is set up.
- The field passes through the air gap, cutting the rotor conductors.
- EMF is induced according to Faraday's laws. $E=N.d\Phi/dt$
- Due to this emf, a current starts flowing in the rotor conductors (bars in squirrel and windings in wound) I = E/R
- There is emf, there is current, so there will be force that starts acting on the rotor conductors. $F=B \cdot I \cdot L \cdot \sin(\theta)$
- The force produces a torque which moves the rotor in the same direction as the field.
- Induction motors are self starting motors.

Concept of Slip

Speed of rotor is always less than that of stator. This difference is essential to create induced rotor current and torque. This difference in speed depends on load on the motor.
Slip: Difference between synchronous speed NS and rotor speed N is called slip.

$$Slip\ s = \frac{Ns - N}{Ns} \times 100$$

Ns - N is sometimes called slip speed. When rotor is not moving, s = 100%

Applications

Three-phase induction motors are widely used due to their simplicity, reliability, and efficiency.

1. **Pumps** – For water, oil, or chemical pumping.
2. **Fans and Blowers**
3. **Compressors** – For refrigeration and air compression.
4. **Conveyor Belts** – In factories and production lines.
5. **Elevators** – For vertical transportation in buildings

Single-Phase Induction Motor

1. Construction:

- **Stator:** Laminated core with slots for winding; connected to single-phase AC supply.
- **Rotor:** Squirrel cage rotor with short-circuited bars made of aluminum or copper.
- **Frame:** Provides structural support.
- **Bearings and Shaft:** Allow smooth rotor rotation.

Classification:

- Split phase motors
- Capacitor phase motors
- Shaded pole motors

2. Working Principle:

- When a single-phase AC supply is applied to the stator, it produces a pulsating magnetic field.
- Polarity reverses but there is no rotation
- This pulsating field induces currents in the rotor, producing torque.
- **Not self-starting**: Requires an external push.

3. Double Field Revolving Theory:

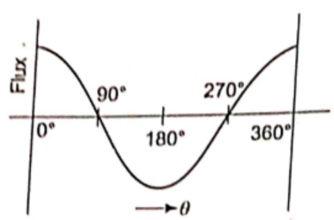
- The pulsating magnetic field can be considered as two rotating magnetic fields of equal magnitude but opposite directions.
- Only the forward rotating field interacts with the rotor to produce net torque.
- After time t, component fluxes will have rotated through an angle. The resultant flux is $\phi m \,.\, cos\theta$ where ϕm is the maximum flux.
- After half cycle, resultant flux is -ϕm
- After ¾ cycle, resultant flux = 0
- 

Fig. 6.10 variation with cos theta

4. Starting Methods:

1. **Split-Phase Motor:**
    - Uses an **auxiliary winding** with high resistance for starting. AW is placed 90 deg from main winding. Connected in parallel.
    - AW is low resistance high reactance

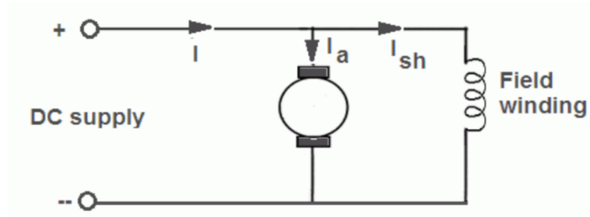
    - MW is low reactance high resistance
    - Make AW's resistance high by connecting R in series w it.
    - Phase angle between main winding current and auxiliary winding current is as large as possible.
    - The auxiliary winding is disconnected by a centrifugal switch once the motor gains 75% synchronous speed.
    - When disconnected, motor works as single phase motor and during the starting, it works as a double phase motor.
    - Self starting
2. **Capacitor Start Motor:**
    - A **capacitor** is added in series with the **auxiliary winding** to provide higher starting torque.
    - Centrifugal cuts out aw and capacitor here too at reaching 75% synchronous speed.
    - Phase difference between iA and iM is larger, about 80 as compared to 30 in split phase.
    - Very large starting torque
3. **Shaded Pole Motor:**
    - A portion of each of the stator pole is surrounded by a copper ring (called shading coil), creating a phase shift for weak starting torque.
    - Used for low-power applications.

5. Applications:

- Fans, blowers, water pumps, washing machines, compressors, and small household appliances.

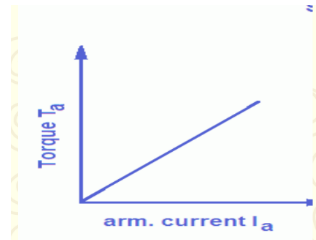
DC motors

Shunt Motor

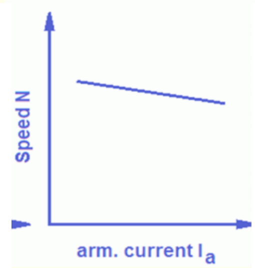


Circuit diagram of shunt motor

The field winding consists of a large number of turns of fine wire. The cross-sectional area of the wire used for field winding of shunt motor is always smaller than that of the wire used for the armature winding. Therefore, the resistance of field winding is more than that of the armature winding. More current passes through the armature winding.
V = Ish.Rsh
Since v and r are constant, iSH is constant. Thus, flux is constant.
Supply voltage V = Eb + IaRa



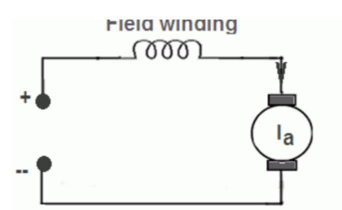
T α Iaφ but φ is constant so we get linear relationship between torque and Ia



From the back emf formula, we can obtain that **N is directly proportional to -Ia**. So there's a small fall in speed with increasing Ia. But essentially speed remains constant. This is why shunt motors can be used in lathes, wood working machines etc where speed constancy is required.

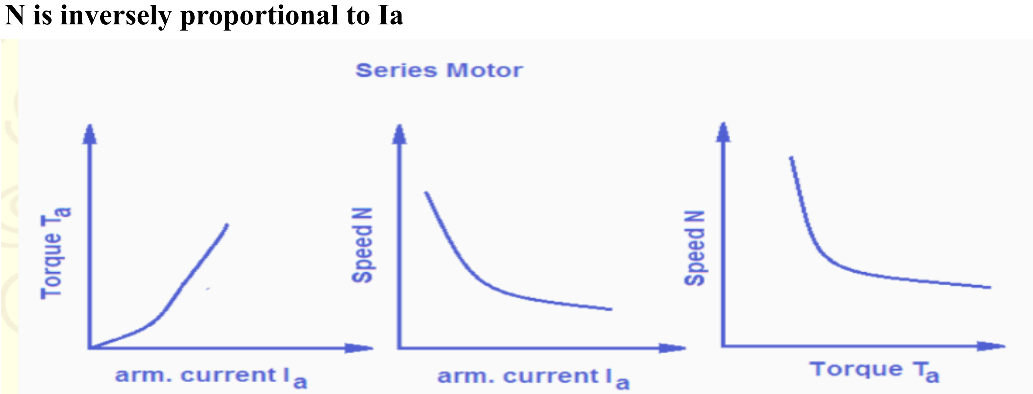
DC Series Motor

I = Ia = Is
V = Eb + Ia (Ra + Rs)
DC series motor is a variable flux motor.
Flux is proportional to Is
T α Iaφ
T α I^2 as flux is directly proportional to I till a limit, after that φ attains maxima and graph is T α I a straight line.



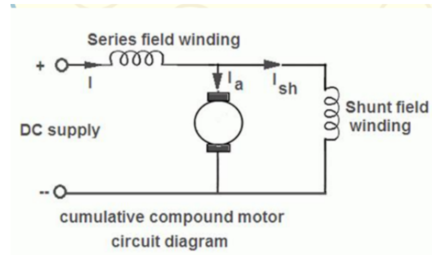
Circuit diagram of DC series motor

N α (V – IaRa) / φ
N is inversely proportional to Ia

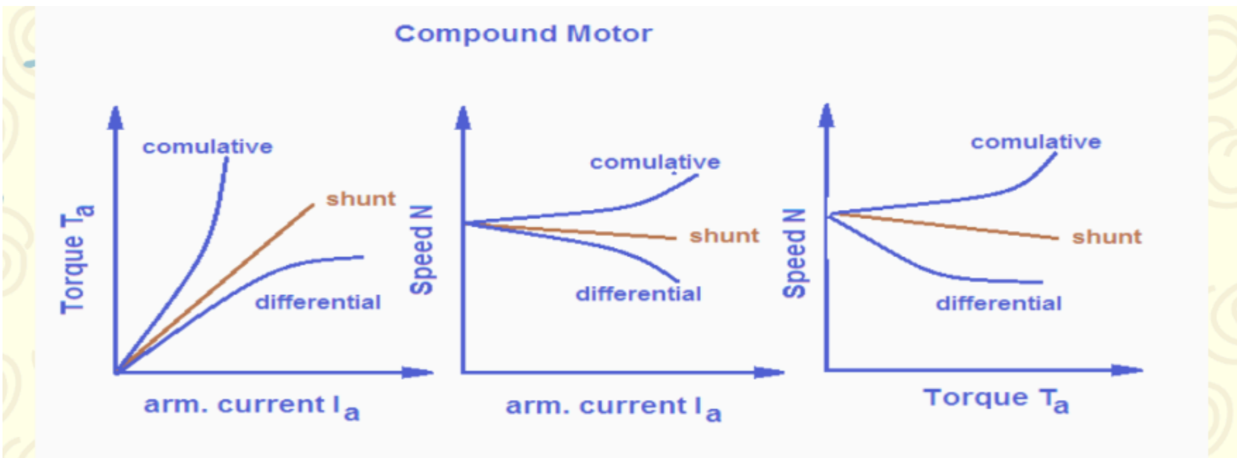


Applications:
Wherever high starting torque is needed. (small motor can start heavy loads)
Example: hoists, cranes, electrical locomotives, elevators etc.

DC Compound Motor



Shunt and series, both the field windings are present in compound motors.

- In the **cumulative** compound motor, shunt and series field winding is connected in such a way that the direction of flow of current is same in both the field windings.
- In the **differential** compound motor, shunt and series field winding is connected in such a way that the direction of flow of current is opposite in both the field windings
- 

Cumulative	Differential
T α Iaφ	T ∝ Iaφ but weaker due to opposing flux
N α T	N α 1/ T
These motors are used in driving machines which are subject to the sudden application of heavy loads; they are used in rolling mills, punching and shearing machines, mine-hoists etc.	A differential compound motor is rarely used for any practical application.