4 Introduction to Electrical Machines

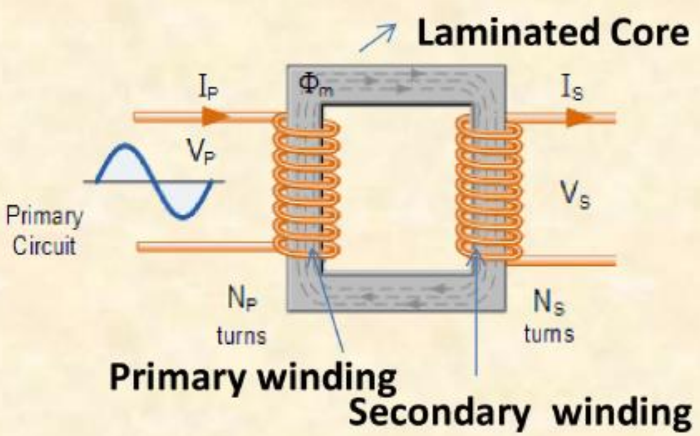
4.1 Single phase transformer : Construction and principle of working, emf equation of a transformer, losses in Transformer, Equivalent circuit of Ideal and practical transformer, and efficiency of transformer, (No numerical expected)

4.2 DC motors : Construction and working principle of DC motors such as series, shunt and compound, torque-speed characteristics, selection criteria and applications (no derivations and numerical expected)

4.3 Single phase induction motor: Construction, working principle, double field revolving theory, applications (no derivations and numerical expected)

Working Principle of Transformer

- Transformer is a static(or stationary) piece of apparatus by means of 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 with corresponding decrease or increase current (I). So the product VI remains constant.
- In its simplest form, transformer consists of two inductive coils (windings) which are electrically separated but magnetically linked through a path of low reluctance i.e. by laminated core as indicated below. The two coils posses high mutual inductance.



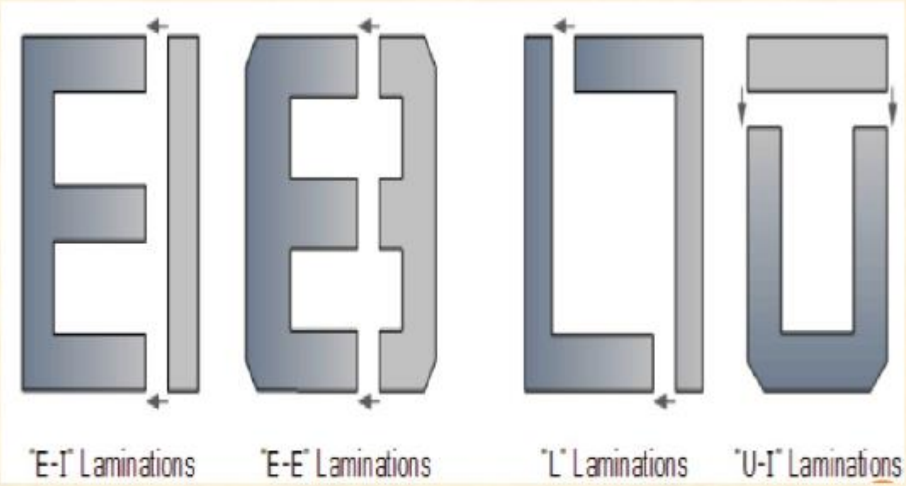
- The primary winding is connected to a source of alternating voltage, an alternating flux is set up in laminated core, most of which is linked with secondary winding in which it produces mutually induced e.m.f. according to Faradays law of electromagnetic induction($E=MdI/dt$).
- If the secondary winding circuit is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from first coil to the second coil.

Transformer construction

- Two basic of parts of transformer are
  1. Magnetic core
  2. Windings or coils

- **Magnetic core**

- The core of transformer either square or rectangular type in size.
- The vertical portion on which coils are wounds called limb while horizontal portion is called yoke.
- Core is made of laminated type constructions to minimize eddy current losses.



- Generally high grade silicon steel laminations (0.3 to 0.5mm) are used. The high silicon content and heat treated to ensure high permeability and low hysteresis at losses at usual flux densities.

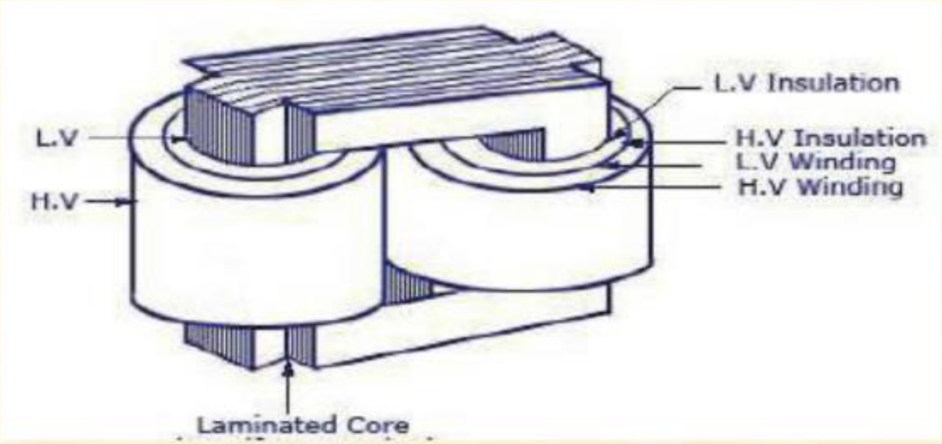
Transformer construction..

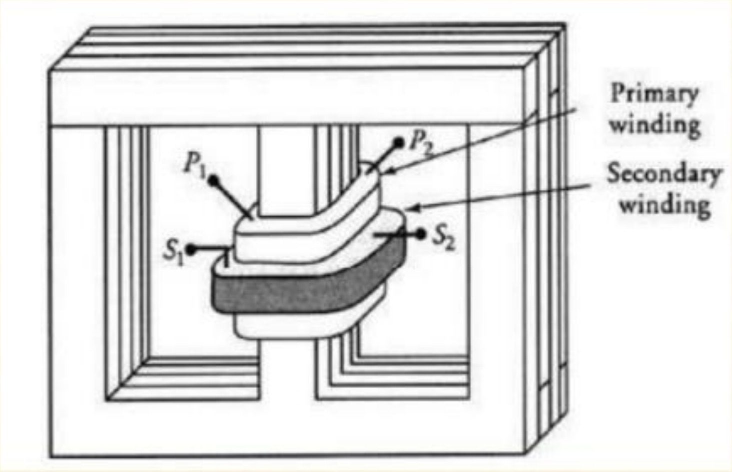
➢ Transformer winding or coils

- Conducting material such as copper is used in the winding of the transformer.
- The coils are used are wound on the limbs and insulated from each other.
- The leakage flux increases which affects the performance and efficiency of transformer. To reduce the leakage flux it is necessary that the windings should be very close to each other to have high mutual induction.

➢ Transformer classification based on construction

1. Core Type Transformer
2. Shell Type Transformer





Transformer construction..

1. Core Type

- In this type one magnetic circuit and cylindrical coils are used
- Normally L and T shaped laminations are used
- Commonly primary winding would on one limb while secondary on the other but performance will be reduce
- To get high performance it is necessary that other the two winding should be very close to each other

2. Shell Type

- In this type two magnetic circuit are used
- The winding is wound on central limbs
- For the cell type each high voltage winding lie between two voltage portion sandwiching the high voltage winding
- Sub division of windings reduces the leakage flux
- Greater the number of sub division lesser the reactance
- This type of construction is used for high voltage

Transformer classification

➢ In terms of number of windings

- Conventional transformer: two windings
- Autotransformer: one winding
- Others: more than two windings

➢ In terms of number of phases

- Single-phase transformer
- Three-phase transformer

➢ Depending on the voltage level at which the winding is operated

- Step-up transformer: primary winding is a low voltage (LV) winding
- Step-down transformer : primary is a high voltage (HV) winding

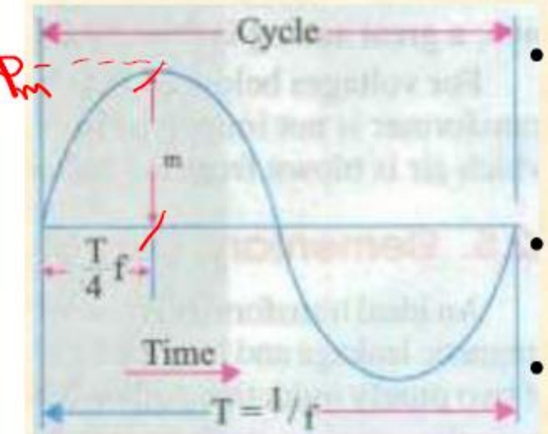
➢ Based on construction

- Core Type
- Shell Type

EMF Equation of Transformer

Let N_1= Number of turns in primary , N_2= Number of turns in secondary

Φ_m= Maximum flux in core in webers= Bm X A f= Frequency of a.c. input in Hz



$FF = \frac{V_m/\sqrt{2}}{2V_m/\pi} = \frac{\pi}{2\sqrt{2}}$

- Flux increases from zero value to maximum value Φ_m in 1/4f seconds.
- Average rate of change of flux= $\Phi_m/(1/4f)=4f\,\Phi_m$ wb/s or V
- As flux varies sinusoidally then rms value of induced emf is obtained by multiplying average value with form factor. since form factor= rms value/average value=1.11
- rms value of emf /turn= 1.11x 4 f Φ_m = 4.44 f Φ_m Volts

- **rms value of emf in whole primary = rms value of emf /turn X Number of turns**

  E1 = 4.44 f Φ_m X N_1= 4.44 f N_1 B_m A ……………….(i)

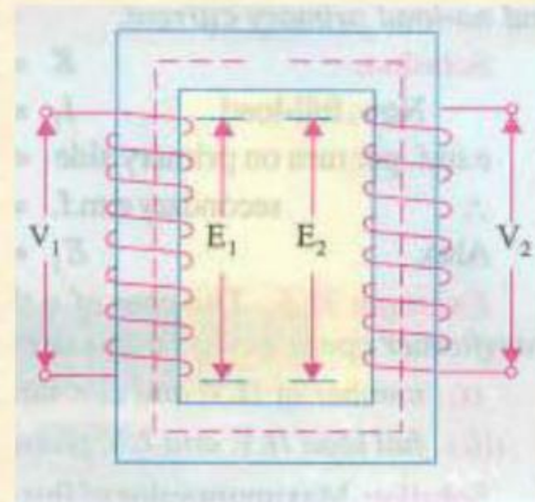
- **rms value of emf in whole secondary = rms value of emf /turn X Number of turns**

  E2 = 4.44 f Φ_m X N_2= 4.44 f N_2 B_m A ……………..(ii)

Transformation Ratio (K) of Transformer

From emf equation (i) and (ii) of the transformer

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



Where K is called transformation ratio.

- If $N_2 > N_1$ i.e. if $K>1$, then transformer is called step up transformer.
- If $N_2 < N_1$ i.e. if $K<1$, then transformer is called step down transformer.

For ideal transformer input VA= output VA

$$V_1 I_1 = V_2 I_2$$

$$\frac{\boldsymbol{I_2}}{\boldsymbol{I_1}} = \frac{\boldsymbol{V_1}}{\boldsymbol{V_2}} = \frac{\mathbf{1}}{\boldsymbol{K}}$$

Hence currents are in the inverse ratio the (voltage) transformation Ratio.

Losses in the Transformer

Core losses or Iron losses **Copper loss**

(i)Hysteresis loss (ii) Eddy current loss

- **Core losses or Iron losses:** Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**. These losses are independent of current does not change with load. Hence are called fixed losses.

(i) Hysteresis loss in transformer: Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz formula:

$$W_h=\eta B_{max}^{1.6} fV(\text{watts})$$

where,

f =frequency of supply

η=Steinmetz hysteresis constant

V = volume of the core in m^3

Losses in the Transformer

(ii) Eddy current loss in transformer:

In transformer, AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

- **Copper loss in transformer**

Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load, hence called variable losses.

Rating of the Transformer

➢ kVA Rating

- The copper losses in the transformer depends on the current and iron loss on voltage.

- Hence the transformer total loss depends on volt-ampere (VA) and not on phase angle between voltage and current i.e losses are independent of power factor.

- Hence the rating of transformer is described in volt-ampere or kilo Volt-ampere (kVA) and not as kW.

- $V_1I_1=V_2I_2$ defines the kVA rating.

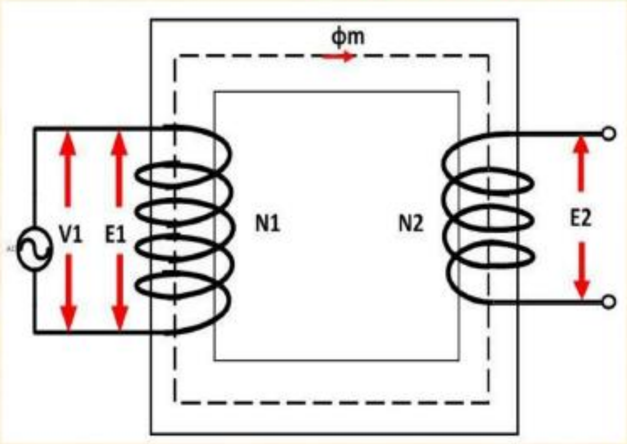
Ideal Vs Practical Transformer

- **The transformer which is free from all types of losses is known as an ideal transformer.** It is an imaginary device which has no core loss, no ohmic resistance and no leakage flux. The ideal transformer has the following important characteristic.

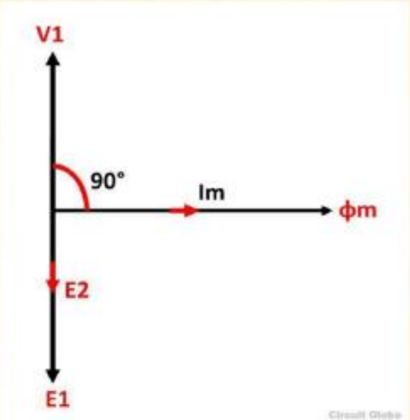
- The resistance of their primary and secondary winding is zero.
- The core of the ideal transformer has infinite permeability. The infinite permeable means less magnetising current requires for magnetising their core.
- The leakage flux of the transformer becomes zero, i.e. the whole of the flux induces in the core of the transformer links with their primary and secondary winding.
- The ideal transformer has 100 percent efficiency, i.e., the transformer is free from hysteresis and eddy current loss.

While the practical transformer has finite windings resistance , some leakage flux and has all kind of losses.

Phasor Diagram of Ideal transformer



- The voltage source V_1 is applied across the primary winding of the transformer. Their secondary winding is kept open. The N_1 and N_2 are the numbers of turns of their primary and secondary winding.
- The current I_m is the magnetizing current flows through the primary winding of the transformer. The magnetizing current produces the flux ϕ_m in the core of the transformer. As the permeability of the core is infinite the flux of the core link with both the primary and secondary winding of the transformer.
- The flux link with the primary winding induces the emf E_1 because of self-induction. The direction of the induces emf is inversely proportional to the applied voltage V_1. The emf E_2 induces in the secondary winding of the transformer because of mutual induction.



← The phasor diagram of the ideal transformer is shown in the figure below.

As the coil of the primary transformer is purely inductive the magnetising current induces in the transformer lag 90° by the input voltage V_1. The E_1 and E_2 are the emf induced in the primary and secondary winding of the transformer. The direction of the induced emf opposite to the applied voltage as per Lenz's Law.

Theory of Practical Transformer

Practical Transformer on No Load

1. Consideration of Non-Zero Core and copper losses

- There is iron loss in the core and copper loss in both primary and secondary windings and these losses are not negligible.

- Even when transformer secondary is open (No Load), the primary input current is not purely reactive. The primary input current under no load condition has to supply

  (i) iron losses (hysteresis and eddy current) in the core

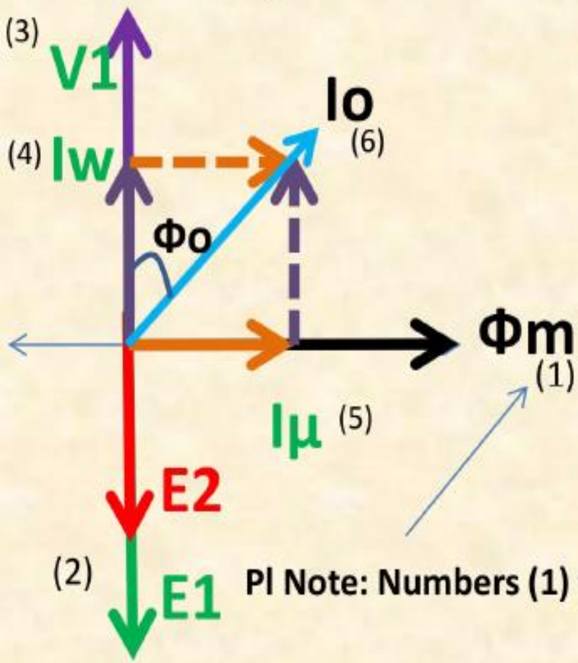
  (ii) very small copper loss in the primary (since secondary is open so no copper loss in secondary).

- Hence the no load input primary current does not lag 90^o behind the applied voltage V1 but lags behind $\Phi o < 90^o$.

Theory of Practical Transformer ..

Practical Transformer on No Load

Phasor Diagram of Practical Transformer on NO load:



- As seen from the phasor diagram , the primary current (Io) has two components. (i) I_W which is in phase with V1, is known as active, working or loss component because is mainly supplies iron loss plus very small copper loss Iw=Io cos(Φ_0).

- (ii) The other component Iμ in quadrature with V1 is known as magnetising component because its function is sustain alternating flux in the core. Iμ=Io sin(Φ_0)

Pl Note: Numbers (1) to (6) in the phasor diagram indicates steps /sequence to draw various quantities.

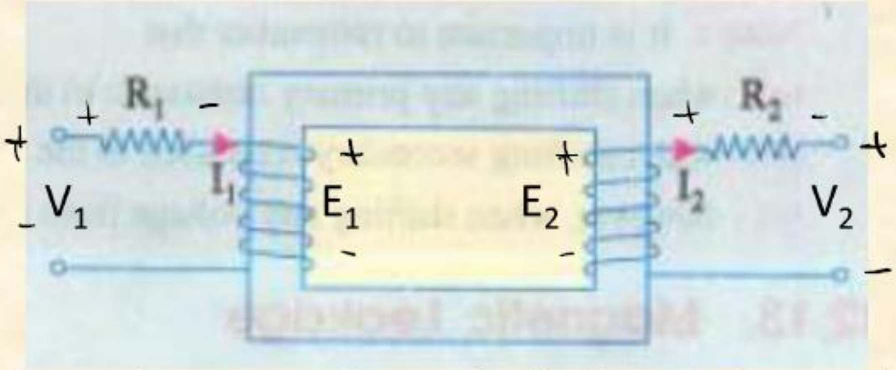
Important Points about the no load Primary current (Io):

- The No load primary current (**Io)** is very small compared to full load (**IF**)current. Io=1 % of IF.
- Since Io is very small and also the copper loss is negligible , hence the primary input current at no load is practically equal to iron loss of the transformer.
- Since the iron loss is responsible for the shift in Io current vector hence the angle Φ_0 is known as hysteresis angle of advance.

Theory of Practical Transformer ..

2. Consideration of primary and secondary winding resistance

- An ideal transformer has zero winding resistance however the practical transformer has always a finite resistance of primary and secondary windings.



- Due to this resistance there is finite voltage drop in the two windings. The results is that

  (i) The secondary terminal voltage V_2 is vectorically less than secondary induced emf E_2 by an amount I_2R_2 where R_2 is resistance of secondary.

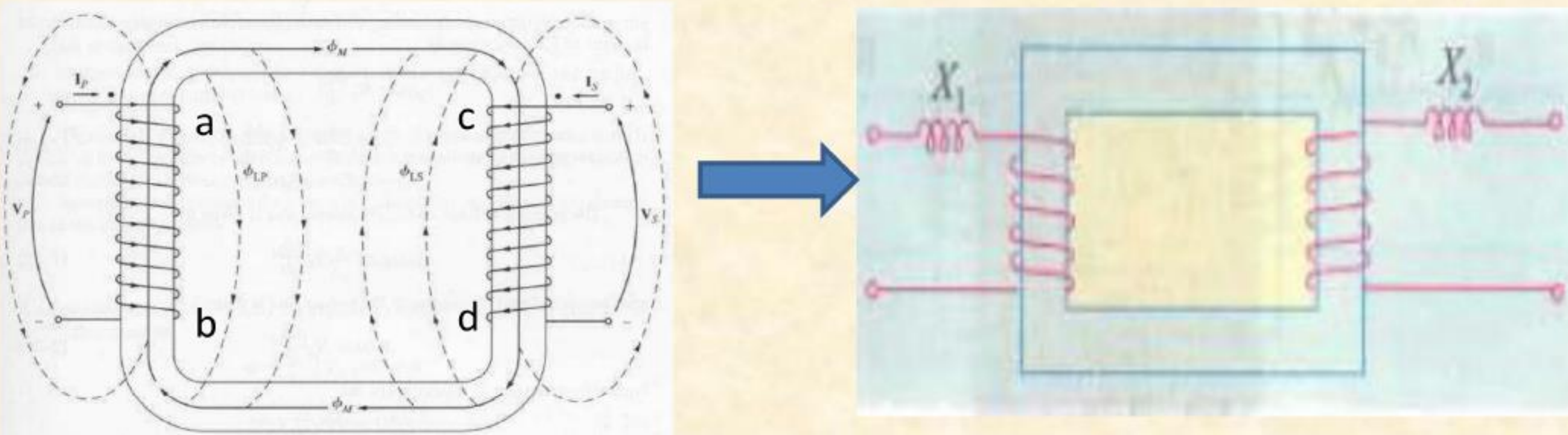
  $\bar{V}_2 = \bar{E}_2 - \overline{I_2R_2}$ ---------------------------(note its vector difference)

  (ii) Similarly, the primary induced emf E_1 is vectorically less an applied voltage V_1 by an amount I_1R_1 where R_1 is resistance of primary.

  $\bar{E}_1 = \bar{V}_1 - \overline{I_1R_1}$ ---------------------------(note its vector difference)

Theory of Practical Transformer ..

3. Consideration of magnetic Leakage at primary and secondary



- All the flux linked with primary does not link with secondary but part of it i.e. Φ_{L1} completes it magnetic circuit by passing through air rather than through core. This leakage flux is produced when the m.m.f due to primary ampere-turns existing between points a and b acts along leakage path. Hence this flux is known as primary leakage flux and is proportional to primary ampere-turns alone and because secondary turns do not link magnetic circuit of $\Phi_{L1.}$ The flux Φ_{L1} is in phase with $I_1$and it induces emf e_{L1} in Primary.

- Similarly secondary ampere-turns existing between points c and d set up flux Φ_{L2} . The flux Φ_{L2} is in phase with $I_2$and it induces emf e_{L2}in secondary .

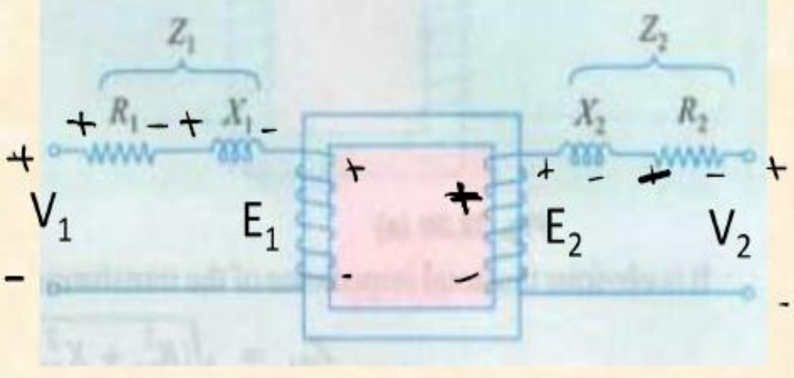
- The leakage flux induces emf in respective winding hence the leakage fluxes are represented by a small inductive coil in series with each winding .
  As indicated in diagram reactances $X_1= e_{L1}/I_1$ and $X_2= e_{L2}/I_2$

Theory of Practical Transformer ..

3. Consideration of magnetic Leakage at primary and secondary..

Important points about leakage reactance:

- The leakage flux links one or the other winding but not both, hence it in no way contributes to the transfer of energy from primary to secondary.
- The primary voltage V_1 will have to supply reactive drop I_1X_1 in addition to I_1R_1. Similarly E_2 will have to supply I_2X_2 in addition to I_2R_2 .
- The primary and secondary windings are placed close to reduce leakage flux.



- The primary and secondary impedances Z_1 and Z_2
  $Z1 = \sqrt{R1^2 + X1^2}$ $\quad Z2 = \sqrt{R2^2 + X2^2}$
- The resistance and leakage reactance are responsible for voltage drops in each winding.

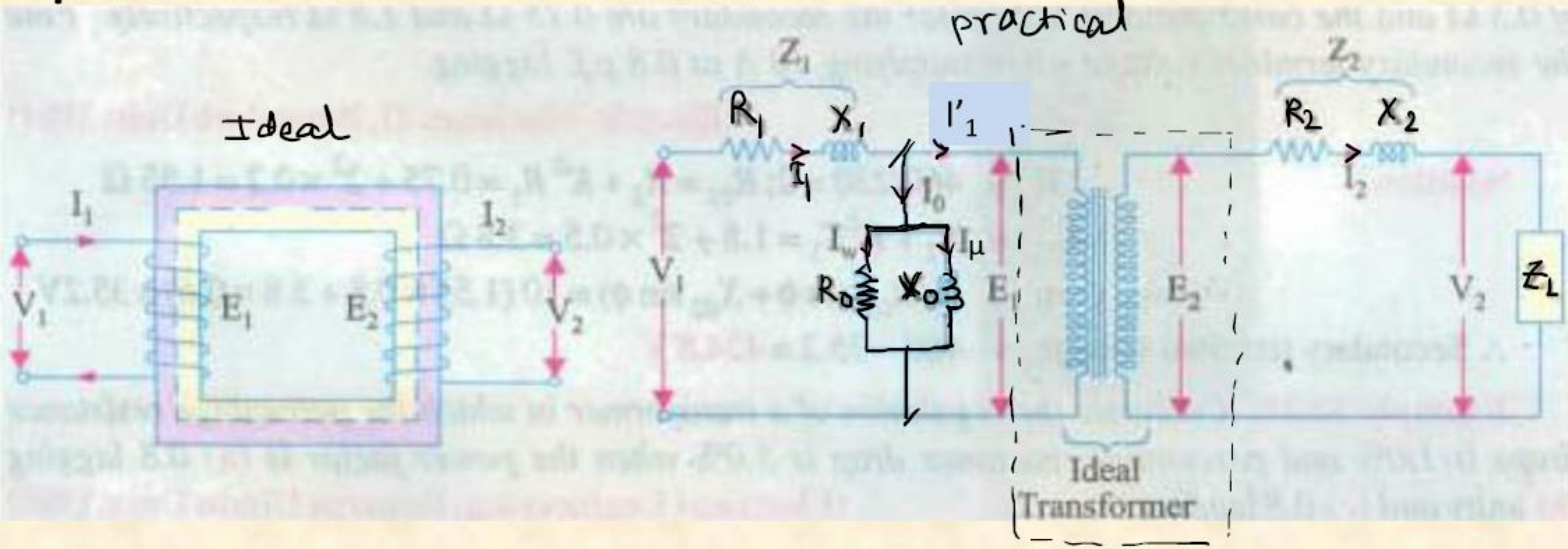
$$\bar{V}_1 = \bar{E}_1 + \bar{I}_1 (R_1 + jX_1) = \bar{E}_1 + \overline{I_1 Z_1}$$ ....note its vector addition)

Similarly, there are I_2R_2 and I_2X_2 drops in secondary which combine with V_2 to give E_2.

$$\bar{E}_2 = \bar{V}_2 + \bar{I}_2 (R_2 + jX_2) = \bar{V}_2 + \overline{I_2 Z_2}$$ ....note its vector addition)

Theory of Practical Transformer ..

Equivalent Circuit of the Transformer



- The exact equivalent circuit is shown above where the winding resistance and leakage reactance of the winding are drawn in series with respective winding and are imagined to be external to the winding.
- The no load primary current Io is simulated by a pure inductance Xo taking the magnetising component Iμ and non inductive resistance Ro taking working component Iw, connected in parallel across primary circuit.
- The value of E_1 and V_2 are obtained by vector subtractions as $\overline{E}_1 = \overline{V}_1 - \overline{I_1 Z_1}$ and $\overline{V}_2 = \overline{E}_2 - \overline{I_2 Z_2}$

i.e. $\vec{E_1} = \vec{V_1} - \overrightarrow{I_1 Z_1}$ and $\overrightarrow{V2} = \vec{E_2} - \overrightarrow{I_2 Z_2}$

- E1 and E2 are related as E2/E1= N2/N1=K

Theory of Practical Transformer ..

Efficiency of Transformer:

efficiency of a transformer can be defined as the output power divided by the input power.

$$\text{efficiency, } \eta = \frac{\text{Output Power}}{\text{Input Power}} \times 100\%$$

$$= \frac{\text{Input Power - Losses}}{\text{Input Power}} \times 100\%$$

$$= \left(1 - \frac{\text{Losses}}{\text{Input Power}}\right) \times 100\%$$

Condition for maximum efficiency:

Copper loss = $I_1^2R_1$ and Iron loss = Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

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

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{\cancel{V_1I_1^2\cos\Phi_1}} = \frac{W_i}{\cancel{V_1I_1^2\cos\Phi_1}}$$

When Copper loss =iron loss the efficiency of the transformer is maximum.

$$I_1^2R_1 = W_i$$

Theory of Practical Transformer ..

ALL-DAY EFFICIENCY:

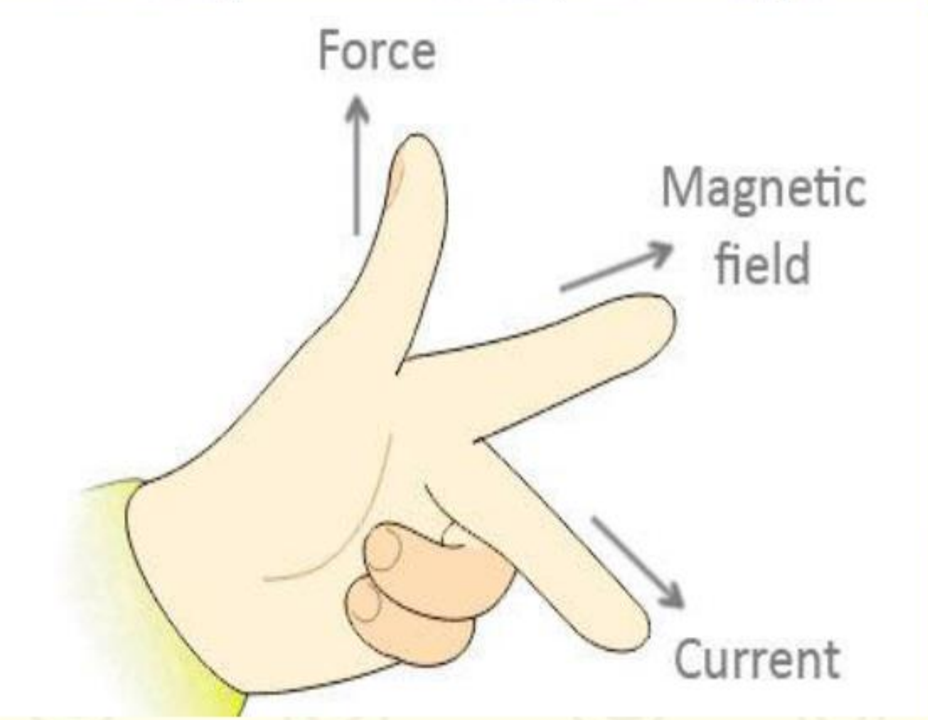
It is defined as the ratio of the energy (kilowatt-hours) delivered by the transformer in a 24-hour period to the energy input in the same period of time. To determine the all-day efficiency, it is necessary to know how the load varies from hour to hour during the day.

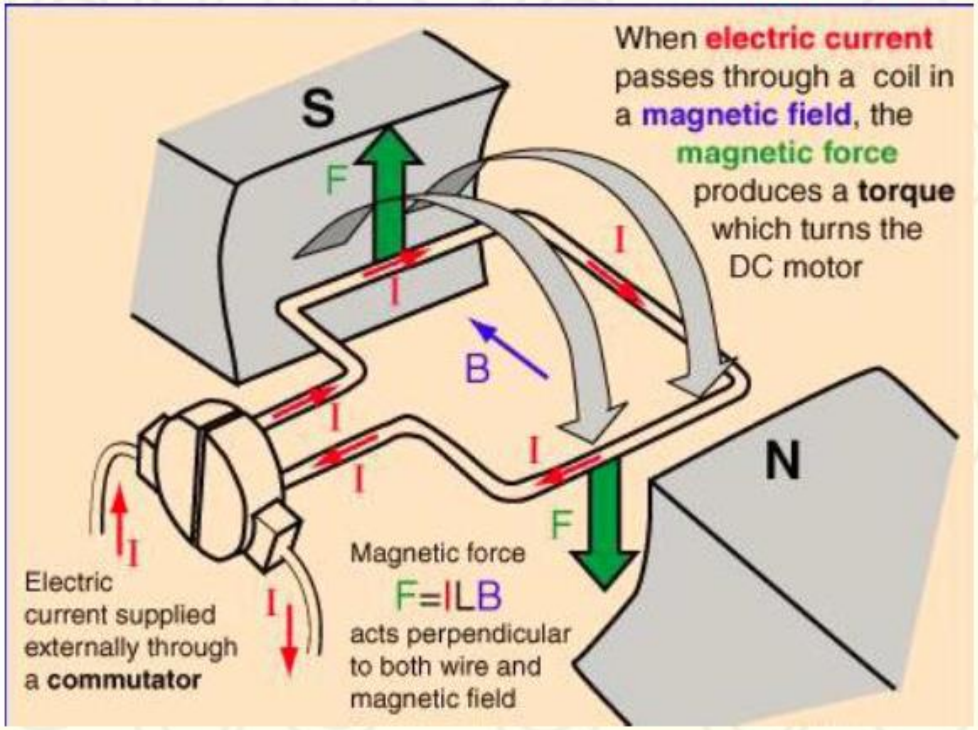
$$\text{All day efficiency} = \frac{\text{output (in kWh)}}{\text{input (in kWh)}} \quad \text{(for 24 hours)}$$

All day efficiency of a transformer is always less than ordinary efficiency of it.

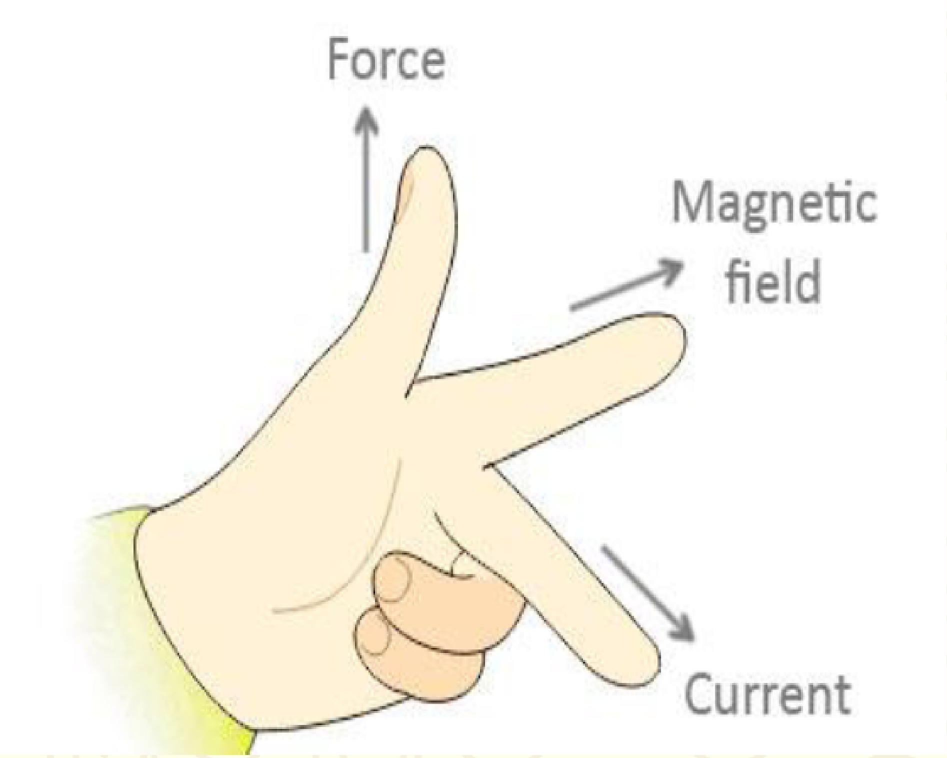
Working Principle of DC motors

- An electric motor is a machine which converts electric energy into mechanical energy.
- Its action is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force. The direction of force is given by Fleming's left hand rule and magnitude is $F=BIL$ Newton, where B is flux density wb/m^2, I is current through conductor, L is length of conductor.





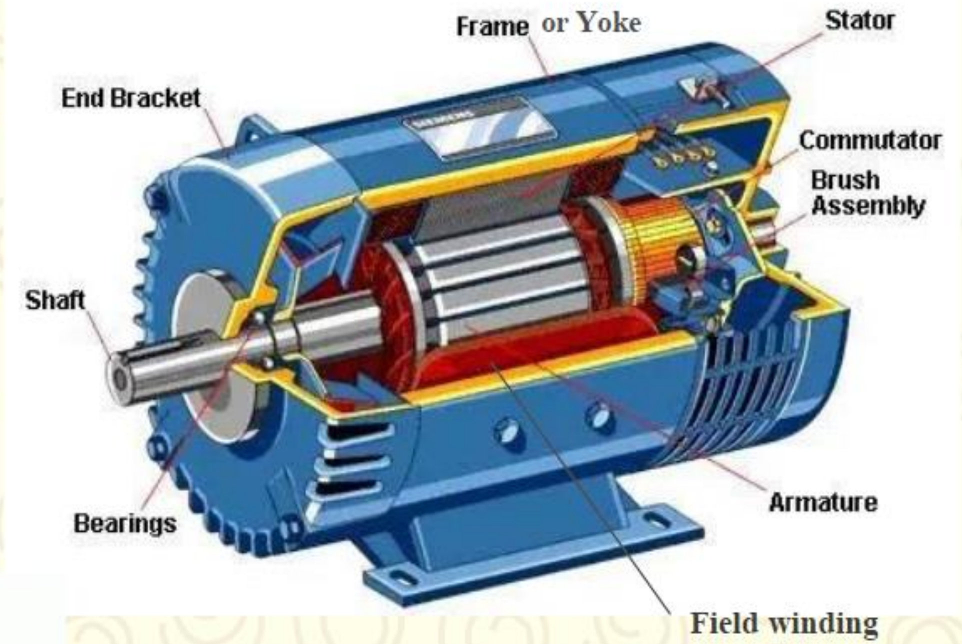
Fleming's left hand rule

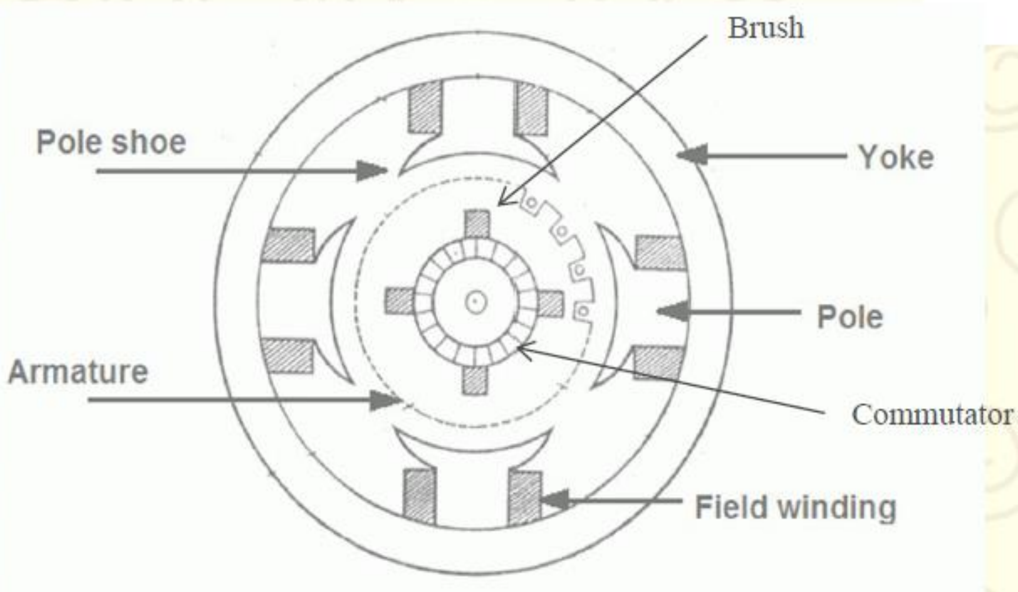


According to **Fleming's left hand rule**, if the thumb, fore-finger and middle finger of the left hand are stretched to be perpendicular to each other as shown in the illustration at left, and if the fore finger represents the direction of magnetic field, the middle finger represents the direction of current, then the thumb represents the direction of force. Fleming's left hand rule is applicable for motors.

Construction of DC motors

The main parts used in the construction of a DC motor are the yoke, poles, field winding, Armature, commutator, carbon brushes, bearings





Construction of a DC Motor

Construction of DC motors…

- **Yoke/Frame:**

The yoke acts as the outer cover of a DC motor and it is also known as the frame. The yoke is an iron body, made up of low reluctance magnetic material such as cast iron, silicon steel, rolled steel etc. Yoke serve two purposes, firstly it provides mechanical protection to the outer parts of the machine secondly it provides low reluctance path for the magnetic flux.

- **Poles and Pole Shoe**

The pole and pole shoe are fixed on the yoke by bolts. These are made of thin cast steel or wrought iron laminations which are riveted together. Poles produce the magnetic flux when the field winding is excited. Pole shoe is an extended part of a pole. Due to its shape, the pole area is enlarged and more flux can pass through the air gap to the armature.

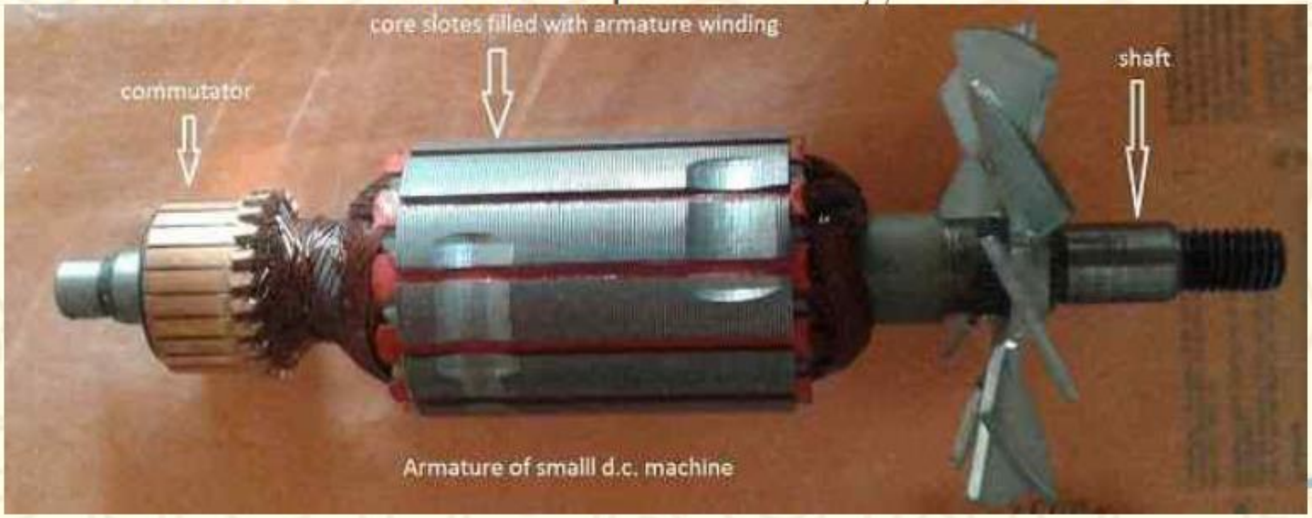
Construction of DC motors…

- **Field Winding**

The coils around the poles are known as field (or exciting) coils and are connected in series to form the field winding. Copper wire is used for the construction of field coils. When the DC current is passed through the field windings, it magnetizes poles which produce magnetic flux.

- **Armature Core**

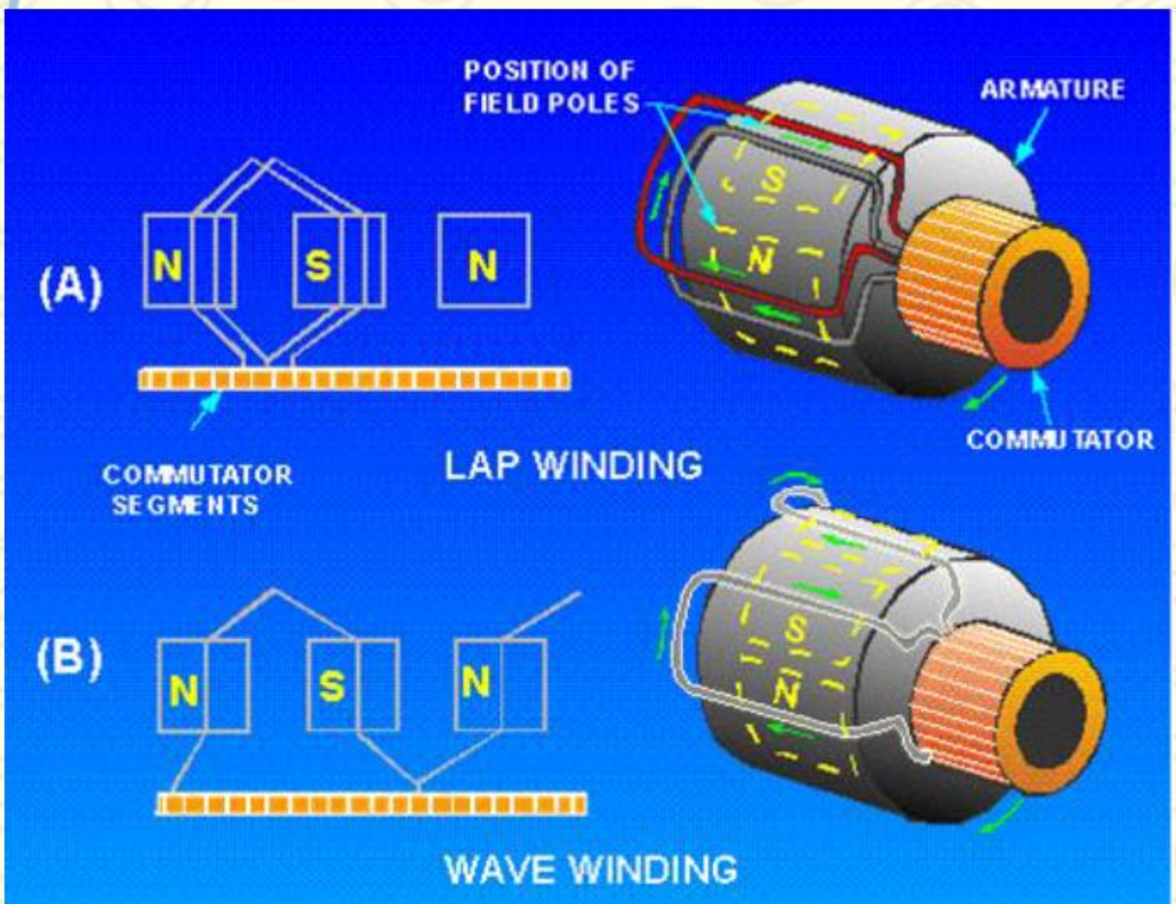
It is a cylindrical drum and keyed to the rotating shaft. A large number of slots are made all over its periphery, which accommodates the armature winding. Low reluctance, high permeability material such as cast iron and cast steel are used for armature core. The laminated construction is used to produce the armature core to minimize the eddy current losses. The air holes are also provided on the armature core for the air circulation which helps in cooling the motor.



Construction of DC motors…

- **Armature Winding**

The armature winding plays very important role in the construction of a DC motor because the conversion of power takes place in armature winding. On the basis of connections, there are two types of armature windings named: Lap winding & Wave Winding



Construction of DC motors…

- **Commutator**

The commutator connects the rotating armature conductor to the stationary external circuit through carbon brushes. It converts alternating torque into unidirectional torque produced in the armature.

Carbon Brushes

The current is conducted from voltage source to armature by the carbon brushes which are held against the surface of commutator by springs. They are made of high-grade carbon steel and are rectangular in shape.

Bearings

The ball or roller bearings are fitted in the end housings. The friction between stationary and rotating parts of the motor is reduced by bearing. Mostly high carbon steel is used for making the bearings as it is very hard material.

Back E.M.F in DC Motor

When the armature winding of a DC motor rotates in the magnetic field produced by the field winding, it cuts the magnetic flux. Hence an EMF is induced in the armature winding according to the Faradays law of electromagnetic induction. And as per Lenz's law, this induced EMF acts in opposite direction to the armature supply voltage. Therefore, this EMF is known as the back EMF and it is denoted by E_b.

This back EMF induced in a DC motor can be expressed mathematically as,

$$E_b = \frac{\Phi ZNP}{60\ A}$$

Where P = number of poles

Φ = flux per pole in Wb

N = speed of motor in RPM

Z = number of armature conductors

A = number of parallel paths

Torque equation of a DC motor

- When armature conductors of a DC Motor carry current in the presence of stator field flux, a mechanical torque is developed between the armature and the stator.
- Torque is given by the product of the force and the radius at which this force acts.
  Torque $\boldsymbol{T = F \times r}$ ***(N-m)*** …where, F = force and r = radius of the armature
- Work done by this force in once revolution = Force × distance = $F \times 2\pi r$ (where, $2\pi r$ = circumference of the armature)
- Net power developed in the armature = word done / time = (force × circumference × no. of revolutions) / time = $(F \times 2\pi r \times N) / 60$ (Joules per second) …..(A)
- But, $F \times r = T$ and $2\pi N/60$ = angular velocity ω in radians per second. Putting these in the above equation (A)
- Net power developed in the armature = $P = T \times \omega$ (Joules per second)

Torque equation of a DC motor…

Armature torque (Ta)

- The power developed in the armature can be given as, $Pa = Ta \times \omega = Ta \times 2\pi N/60$. The mechanical power developed in the armature is converted from the electrical power,

- Therefore, mechanical power = electrical power

i.e $Ta \times 2\pi N/60 = Eb.Ia$

We know, $Eb = P\Phi NZ / 60A$

- Therefore, $Ta \times 2\pi N/60 = (P\Phi NZ / 60A) \times Ia$

Rearranging the above equation,

$Ta = (PZ / 2\pi A) \times \Phi.Ia$ (N-m)

- The term $(PZ / 2\pi A)$ is practically constant for a DC machine.
- **Thus, armature torque is directly proportional to the product of the flux and the armature current i.e. $Ta \propto \Phi.Ia$**

Power Equation of a D.C. Motor

- The voltage equation of a d.c. motor is given by,

  $V = E_b + I_a R_a$

- Multiplying both sides of the above equation by I_a we get,

  $V I_a = I_a E_b + I_a^2 R_a$,

  This equation is called power equation of a d.c. motor.

$V I_a$ = Net electrical power input to the armature measured in watts.

$I_a^2 R_a$ = Power loss due to the resistance of the armature called armature copper loss.

So difference between $V I_a$ and $I_a^2 R_a$ i.e. input – losses gives the output power.

So $E_b I_a$ is called electrical equivalent of gross mechanical power developed by the armature. This is denoted as P_m.

Gross mechanical power developed in the armature = Power input to the armature – Armature copper loss

Power Equation of a D.C. Motor

Condition for Maximum power

For a motor from power equation it is known that

$Pm = VIa - I^2a\ Ra$

For maximum gross mechanical power so $\frac{dPm}{dIa} = 0$

$V - 2\ Ia\ Ra = 0$

$Ia\ Ra = V/2$

But $V = Eb + Ia\ Ra = Eb + V/2$

So $Eb = V/2$ is condition for maximum power.

Classification of DC Motors

(A). DC Motor (Electromagnet)

- Separately excited DC motors
- Self excited DC motors
  - Shunt Motor
  - Series Motor
  - Compound Motor
    - Cumulative compound
    - Differential compound

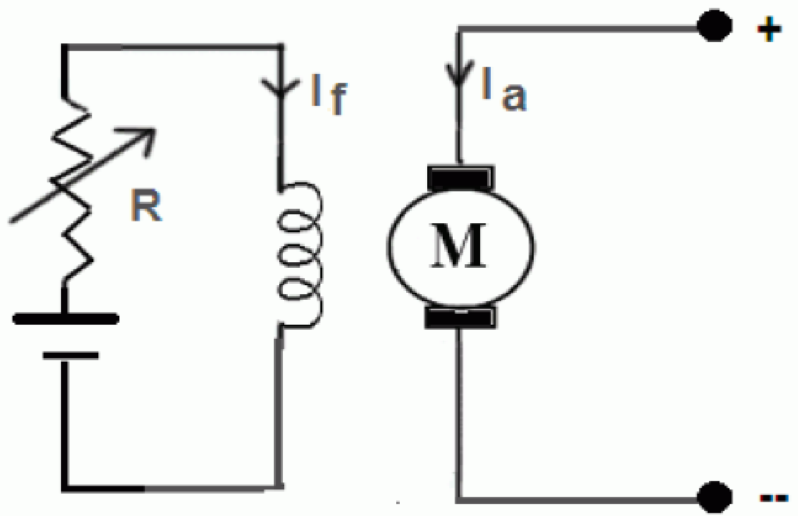
(B). Permanent Magnet DC Motor

In these motors, the magnetic field is produced by small magnets. These motors are made in very small sizes and ratings. These motors are used where very small driving torque is required like toys.

Classification of DC Motors…

- **Separately Excited DC Motor**

In these motors, the armature and field coils are fed from different supply sources.



Circuit diagram of separately excited motor

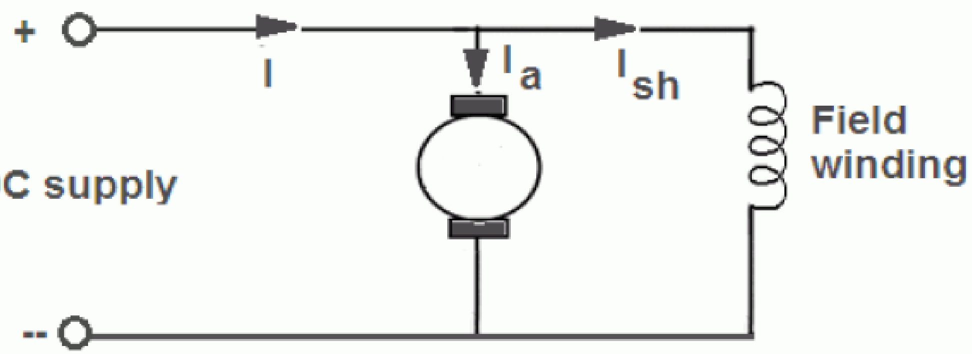
Very accurate speed control can be obtained by these motors.
These motors are best suited for the applications where speed variation is required from very low value to high value.

Classification of DC Motors…

Self excited motors

DC Shunt Motor

In the DC shunt motor , the armature and field winding are connected in parallel as shown in the figure.

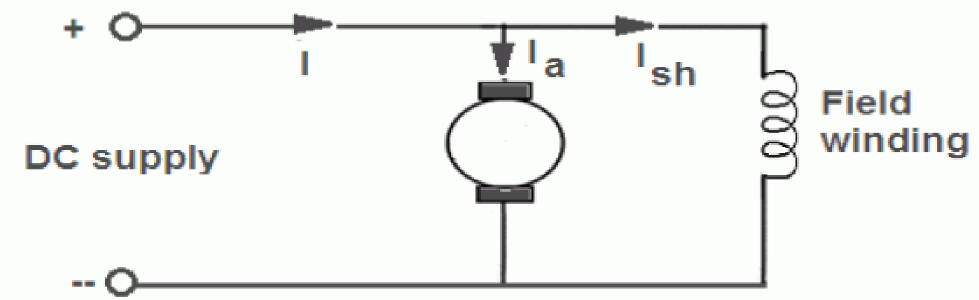


Circuit diagram of shunt motor

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.

Classification of DC Motors…

DC Shunt Motor



Circuit diagram of shunt motor

Voltage and Current Relations for DC Shunt Motor

Total current drawn from the voltage source $I = I_a + I_{sh}$ Where I_a = armature current, I_{sh} (field current) = V/R_{sh}

Since the applied voltage (V) and the field resistance (R_{sh}) are almost constant, therefore field current (I_{sh}) remains constant. As the field current is responsible for flux generation so the flux produced in the shunt motor also remains constant. This is why **shunt motor is also known as constant flux motors**.

Therefore **flux, $\varphi \propto I_{sh}$ (constant)**

Supply voltage $\mathbf{V = E_b + I_a R_a}$,

Where E_b = back EMF, R_a = armature resistance.

Classification of DC Motors…

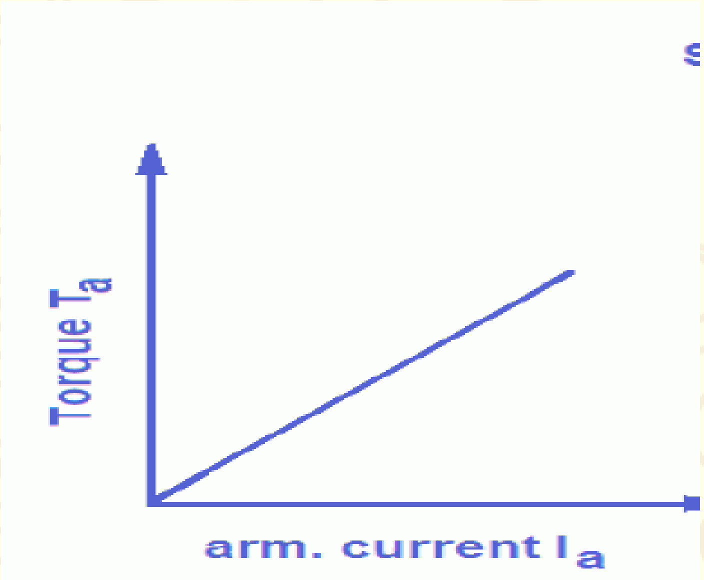
DC Shunt Motor Characteristics and Applications

A. Torque – Current Characteristics (T v/s I_a)

We know that, $T \propto I_a \varphi$

But flux of a shunt motor is practically constant. Therefore, $T \propto I_a$

Therefore, torque current characteristics of a shunt motor is a straight line passing through the origin. Although the field current remains practically constant, yet the field flux becomes slightly weaker at heavy loads, due to armature reaction, hence the curve bends slightly bends at heavy loads.



Classification of DC Motors…

DC Shunt Motor Characteristics and Applications

B. Speed Current Characteristic (N v/s I_a)

Back EMF of shunt motor is given by $E_b = V - I_aR_a = (P\varphi NZ)/60A$

Because P, N, Z and A are constant Therefore

$E_b \, \alpha \, N\varphi$, or $V - I_aR_a \, \alpha \, N\varphi$ or $N \, \alpha \, (V - I_aR_a)/\varphi$ …….(1)

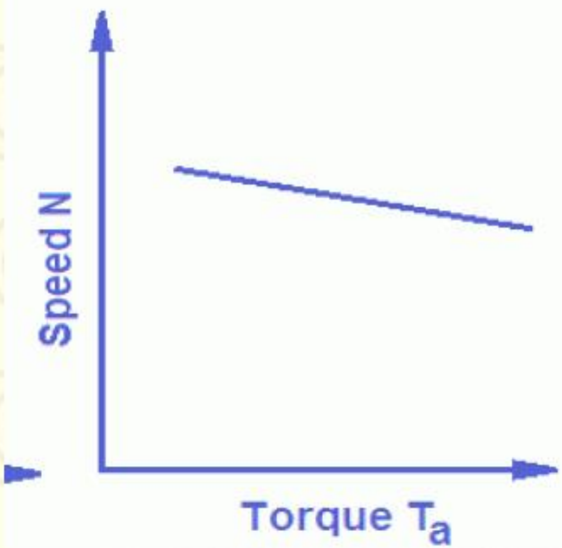
The field flux of shunt motor is almost constant. Therefore, the numerator of RHS of equation (1) decreases with increase in load (or I_a). So there is a little fall in speed with the increase in load, hence the curve bends slightly as the load is increased due to increased I_aR_a voltage drop.

Classification of DC Motors…

DC Shunt Motor Characteristics and Applications

C. Speed – Torque Characteristics (N v/s T)

The speed torque characteristics are similar to speed current characteristics.

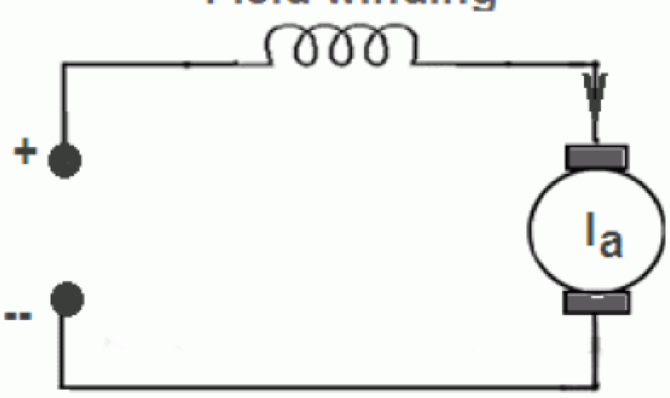


Because there is no appreciable change in the speed of a shunt motor from no-load to full-load, it may be connected to loads which are totally and suddenly thrown off without any fear of excessive speed resulting. Due to the constancy of their speed, shunt motors are suitable for driving shafting, machine tools, lathes, wood-working machines and for all other purposes where an approximately constant speed is required.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

In the DC series motor, the armature and field windings are connected in series with each other. The field winding of DC series motor consists of few turns of thick wire. Therefore, the resistance of the series field winding(R_s) is much smaller as compared to that of the armature resistance.



Circuit diagram of DC series motor

Voltage and Current Relations

As armature and the field winding are in series, therefore,

$\boldsymbol{I} = \boldsymbol{I}_a = \boldsymbol{I}_s$

Where $\boldsymbol{I}$ = total current drawn by the motor

$\boldsymbol{I}_a$ = armature current

$\boldsymbol{I}_s$ = series field current

Total supply voltage V is given by,

$\mathbf{V = E_b + \boldsymbol{I}_a(R_a + R_s)}$

E_b = back EMF

$\boldsymbol{I}_a$ = armature current

R_a = armature resistance

R_s = series field resistance.

In the DC motors flux produced is proportional to the field current. But in the series motor, the field current is same as the armature current. Thus the armature current ($\boldsymbol{I}_a$) and hence field current is load dependent. So with the increase in load flux also increases. Therefore, **DC series motor is a variable flux motor**.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

A. Torque – Current characteristics (T v/s I_a)

For a series motor,

Torque α Armature current x Field flux

$T \propto I_a \varphi$

Before saturation, $\varphi \propto I_a$, Therefore, $T \propto I_a^2$

After magnetic saturation of core, flux (φ) is independent of I_a i.e. flux does not increase with increase in armature current. Therefore after saturation, $T \propto I_a$

Therefore, on light loads, the torque produced by the series motor is proportional to the square of armature current and hence curve drawn between torque and armature current up to magnetic saturation is a parabola. But after magnetic saturation flux φ is independent of excitation current and so torque is proportional to I_a and hence characteristics become a straight line.

B. **Speed – Current Characteristics (N v/s I_a)**

We know that $E_b = (P\varphi NZ)/60A$ or $N = (60AE_b)/P\varphi Z$

In above equation, all quantities are constant except E_b and φ.

$N \propto E_b / \varphi$

also $E_b = V - I_a R_a$

Classification of DC Motors…

DC Series Motor Characteristics and Applications

A. Torque – Current characteristics (T v/s I_a)

For a series motor,

Torque α Armature current x Field flux

$T \propto I_a \varphi$

Before saturation, $\varphi \propto I_a$, Therefore, $T \propto I_a^2$

After magnetic saturation of core, flux (φ) is independent of I_a i.e. flux does not increase with increase in armature current. Therefore after saturation, $T \propto I_a$

Therefore, on light loads, the torque produced by the series motor is proportional to the square of armature current and hence curve drawn between torque and armature current up to magnetic saturation is a parabola. But after magnetic saturation flux φ is independent of excitation current and so torque is proportional to I_a and hence characteristics become a straight line.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

B. Speed – Current Characteristics (N v/s I_a)

We know that $E_b = (P\varphi NZ)/60A$

or $N = (60AE_b)/P\varphi Z$

In above equation, all quantities are constant except E_b and φ.

$N \alpha E_b / \varphi$

also $E_b = V - I_a R_a$ Therefore, $N \alpha (V - I_a R_a) / \varphi$

In a DC series motor, initially the field flux φ rises in proportion to the current but after saturation, it is independent of armature current. Consequently, speed N is roughly proportional to the current. The speed may become dangerously high if load reduces to a small value.

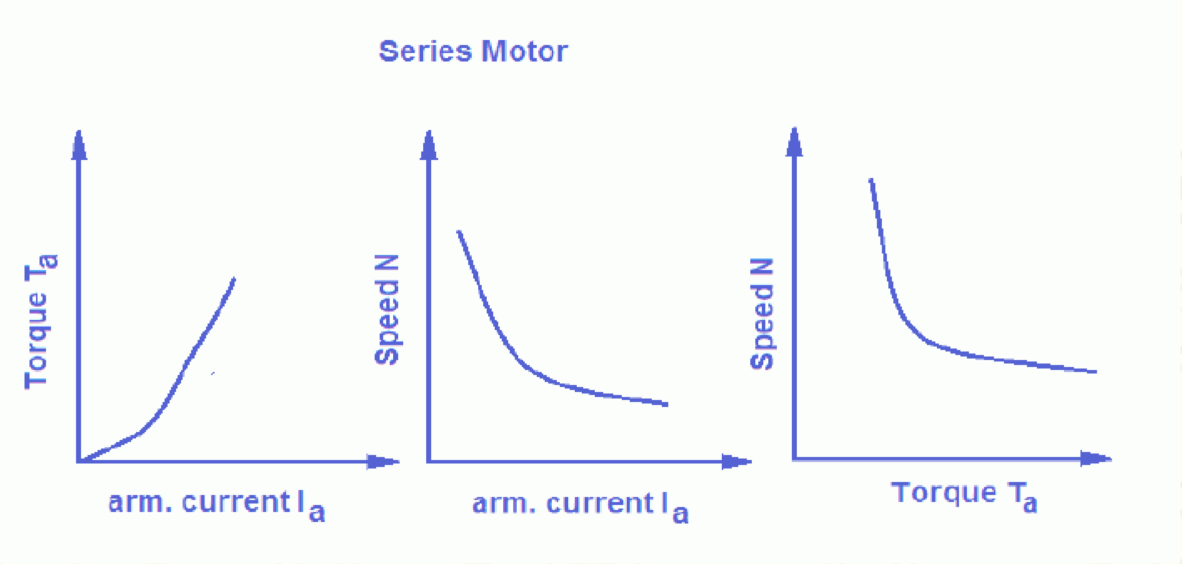
When load is heavy, I_a is large. Hence, speed is low (this decreases E_b and allows more armature current to flow). But when load current and hence I_a falls to a small value, speed becomes dangerously high. Hence, a series motor should never be started without some mechanical (not belt-driven) load on it otherwise it may develop excessive speed and get damaged due to heavy centrifugal forces so produced. It should be noted that series motor is a variable speed motor.

Classification of DC Motors…

DC Series Motor Characteristics and Applications

C. Speed – Torque Characteristics (N v/s T)

Since a series motor develops high starting torques at low speeds and low torque at high speeds, therefore, speed – torque characteristics of a DC series motor is a hyperbola. **High starting torque enables, even a small series motor to start a heavy load.**



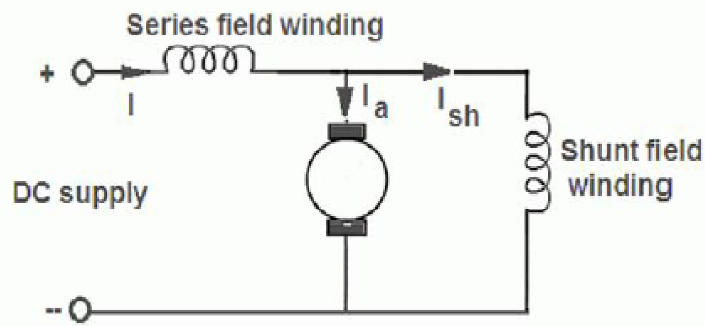
Application of DC Series Motor

DC series motors are used where high starting torque is required like hoists, cranes, electrical locomotives, elevators etc.

Classification of DC Motors…

DC Compound Motors

Shunt and series, both the field windings are present in compound motors. In these motors, a part of the field winding is connected across the armature and remaining field winding is connected in series with the armature. These compound motors are further subdivided into two types, namely, cumulative compound and differential compound.



cumulative compound motor circuit diagram

- 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 i.e. series field flux strengthens the field due to shunt field winding.

Differential Compound Motor

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 i.e. series field flux weakens the field due to shunt field winding.

Classification of DC Motors…

DC Compound Motor Characteristics and Applications

A. Torque – Current Characteristics

In the case of a cumulative compound motor, as the armature current increases, the series flux increases, so flux per pole increases.

But T α Iaφ

Consequently torque also increases; however, this increase in torque is greater than that of the shunt motor.

Whereas in the case of a differential compound motor, series field opposes the shunt field so the total flux of such motor decreases with increase in current (i.e. load). Hence in a differential compound motor, torque increases with increase in current.

B. Speed – Current Characteristics

In cumulative compound motor, series field aids the shunt field, so flux per pole increases as the armature current increase and hence speed decreases.

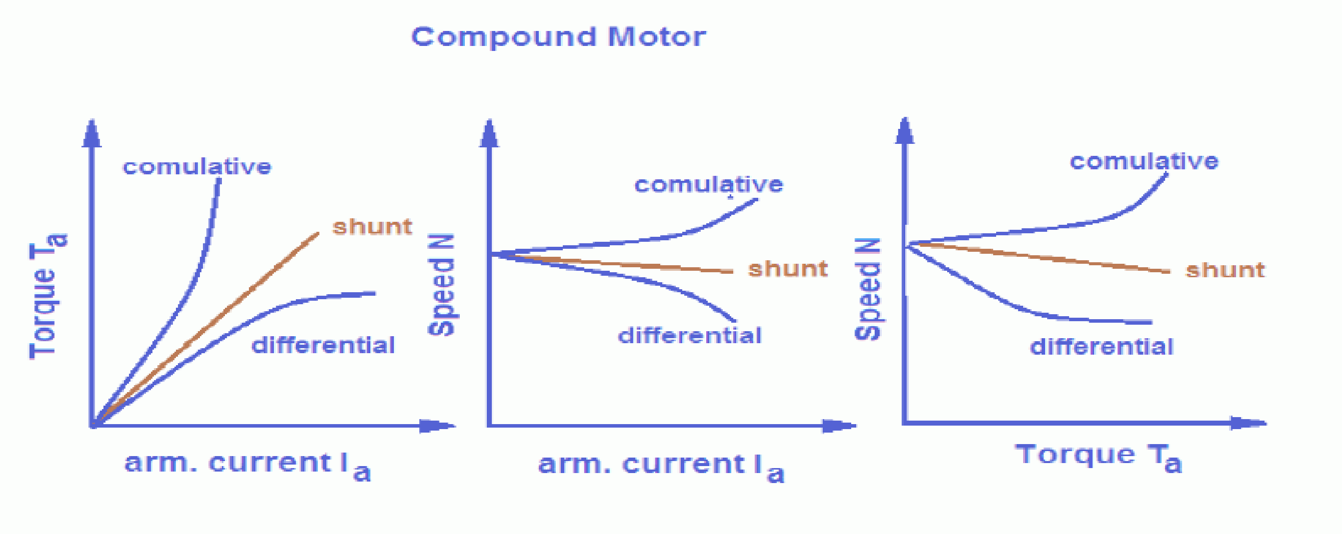
Whereas in a differential compound motor, series field opposes the shunt field, so flux per pole decreases as the armature current increase and hence speed increases.

Classification of DC Motors…

DC Compound Motor Characteristics and Applications

Speed – Torque Characteristics

In a cumulative compound motor, the series excitation helps the shunt excitation hence speed decreases with increase in torque whereas torque increases very slightly with the speed.



Applications of DC Compound Motor

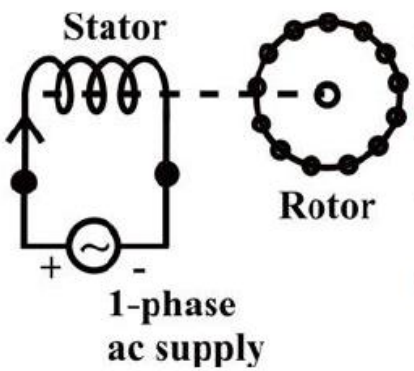
A cumulative compound motor has a fairly constant speed and good starting torque. Such motors are used where series characteristics are required and the load is likely to be removed totally. These motors are used in driving machines which are subject to the sudden application of heavy loads; they are used in rolling mills, punching and shearing machines, mine-hoists etc.

In a differential compound motor, the motor speed will increase with an increase in the load, which leads to an unstable operation. Therefore, a differential compound motor is rarely used for any practical application.

Single phase induction motor Construction

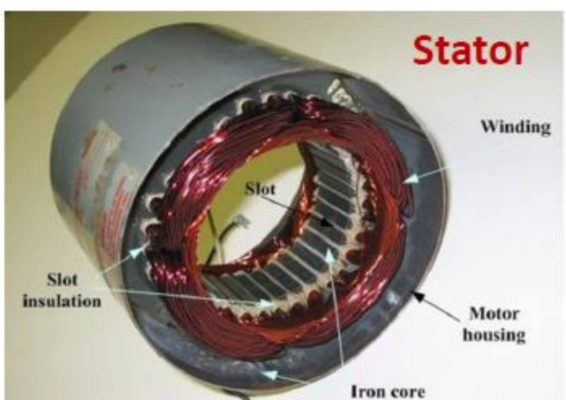
→ Single phase motors are designed to operate on single phase supply. These motors are fractional kWatts small size motors.

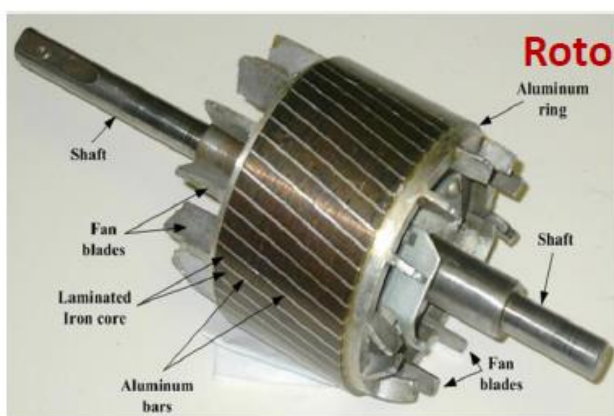
→ The single-phase induction machine is the most frequently used motor for refrigerators, washing machines, clocks, drills, compressors, pumps etc.

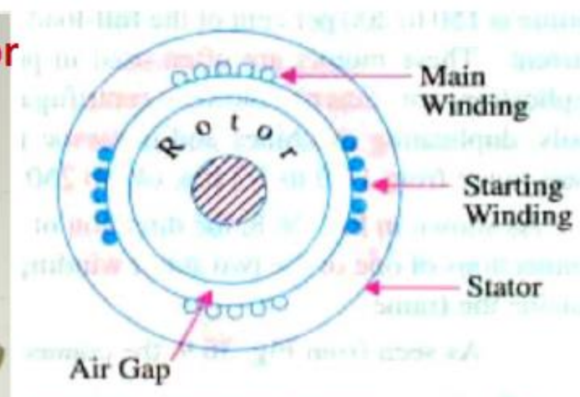


→ The winding used normally in the stator of the single-phase induction motor is a distributed one.

→ The rotor is of squirrel cage type, which is a cheap one







Single phase induction motor: Operation

- As the stator winding is fed from a single-phase supply, the flux in the air gap is alternating only, not a synchronously rotating one produced by a poly-phase motors.

- This type of alternating field cannot produce a torque, if the rotor is stationery. So, a single-phase IM is not self-starting, unlike a three-phase one.

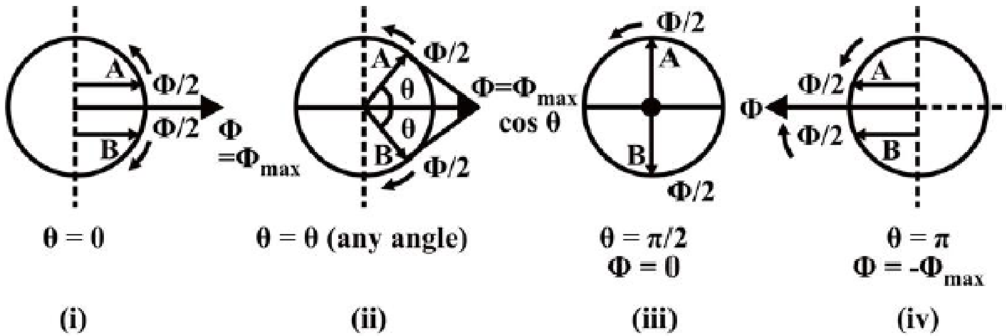
- However, if the rotor is initially given some torque in either direction, then immediately a torque is produced in the motor. The motor then accelerates to its final speed, which is lower than its synchronous speed.

- This is explained using double field revolving theory

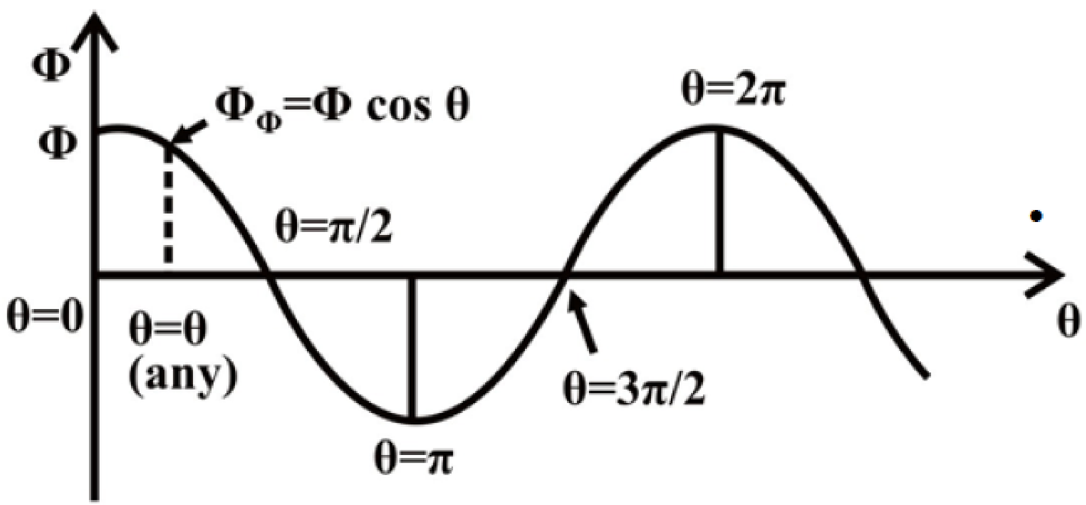
Single phase induction motor: Operation

→ Why single phase induction motor is not self starting?

Double field revolving theory



Position of the pulsating and rotating in fluxes with change in angle (θ)



Pulsating (sinusoidal) flux as a function of space angle (θ)

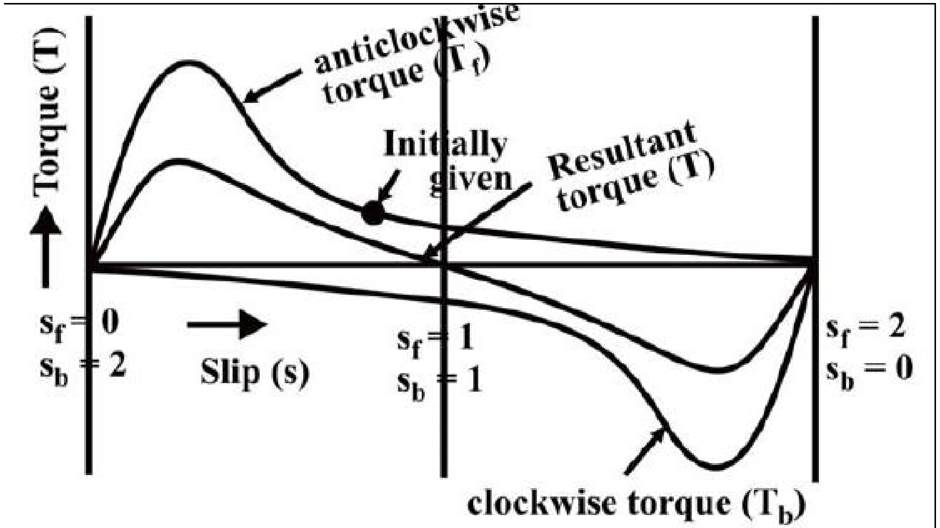
- When the stator winding carries a sinusoidal current being fed from a single-phase supply, a sinusoidal space distributed mmf, whose peak or maximum value pulsates (alternates) with time, is produced in the air gap.
- This sinusoidally varying flux (ϕ) is the sum of two rotating fluxes or fields, the magnitude of which is equal to half the value of the alternating flux (ϕ/2), and both the fluxes rotating synchronously at the speed, (*ns=2f/p*) in opposite directions.
- The resultant sum of the two rotating fluxes or fields, as the time axis (angle) is changing from θ=0 to 180°. The alternating or pulsating flux (resultant) varying with time or angle.

Single phase induction motor: Operation

→ Why single phase induction motor is not self starting?

Double field revolving theory

Slip of IM $S = \frac{N_s - N}{N_s} \times 100$



Speed-torque characteristics of single phase induction motor

- The flux or field rotating at synchronous speed, say, in the anticlockwise direction, i.e. the same direction, as that of the motor (rotor) taken as positive, induces emf (voltage) in the rotor conductors. The rotor is a squirrel cage one, with bars short circuited via end rings. The current flows in the rotor conductors, and the electromagnetic torque is produced in the same direction as given above, which is termed as positive (+ve).
- The other part of flux or field rotates at the same speed in the opposite (clockwise) direction, taken as negative. So, the torque produced by this field is negative (-ve), as it is in the clockwise direction, same as that of the direction of rotation of this field.
- Two torques are in the opposite direction, and the resultant (total) torque is the difference of the two torques produced.
- If the rotor is stationary, the slip due to forward (anticlockwise) rotating field is Sf=1.0. Similarly, the slip due to backward rotating field is also Sb=1.0 .

The two torques are equal and opposite, and the resultant torque is 0.0 (zero). So, there is no starting torque in a single-phase IM.

Single phase induction motor: Operation

→ Why single phase induction motor is not self starting?

Double field revolving theory

- But, if the motor (rotor) is started or rotated somehow, say in the anticlockwise (forward) direction, the forward torque is more than the backward torque, with the resultant torque now being positive. The motor accelerates in the forward direction, with the forward torque being more than the backward torque. The resultant torque is thus positive as the motor rotates in the forward direction.
- The motor speed is decided by the load torque supplied, including the losses (specially mechanical loss).

Single phase induction motor: Operation

→ Why single phase induction motor is not self starting?

Double field revolving theory

- Mathematically, the mmf, which is distributed sinusoidally in space, with its peak value pulsating with time, is described as ($F=F_{peak}\cos\theta$) where θ (space angle) measured from the winding axis.
- Now, $F_{peak}= F_{max}\cos\omega t$. So, the mmf is distributed both in space and time, i.e.

$$F= F_{max}\cos\omega t\cos\theta$$

This can be expressed as

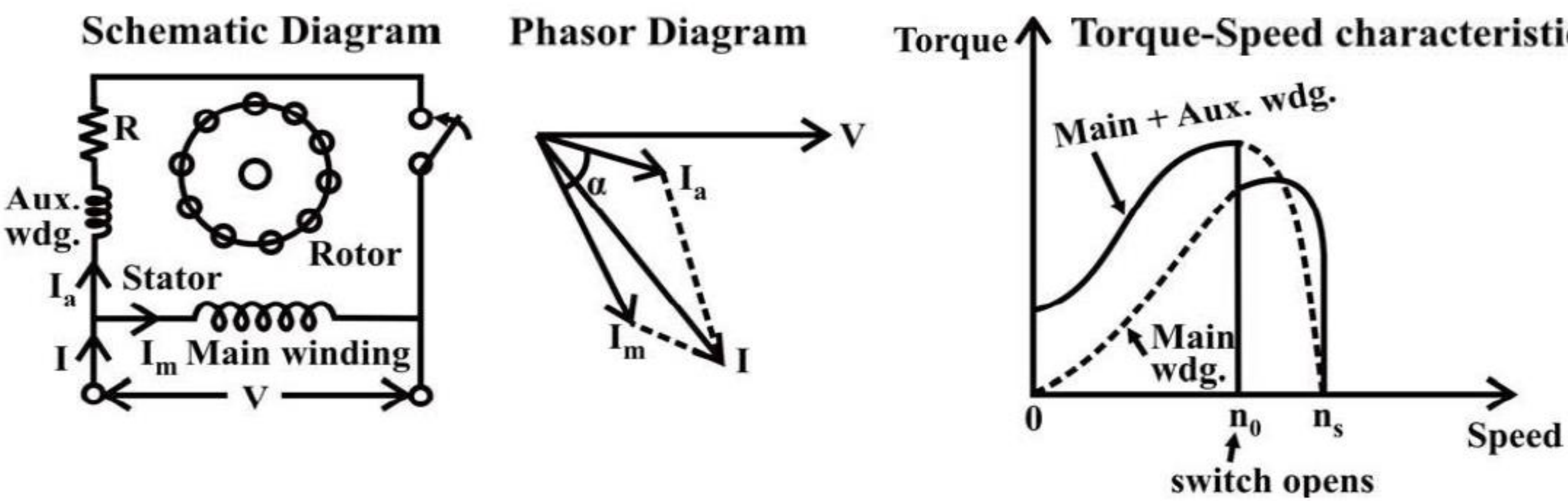
$$F = (F_{\max}/2)\cdot\cos(\theta-\omega t)+(F_{\max}/2)\cdot\cos(\theta+\omega t)$$

which shows that a pulsating field can be considered as the sum of two synchronously rotating fields ($\omega_s = 2\pi n_s$). The forward rotating field is, $F_f = (F_{\max}/2)\cdot\cos(\theta-\omega t)$, and the backward rotating field is, $F_b = (F_{\max}/2)\cdot\cos(\theta+\omega t)$. Both the fields have the same amplitude equal to $(F_{\max}/2)$, where $F_{\max}$ is the maximum value of the pulsating mmf along the axis of the winding.

How to make Single phase induction motor self starting?

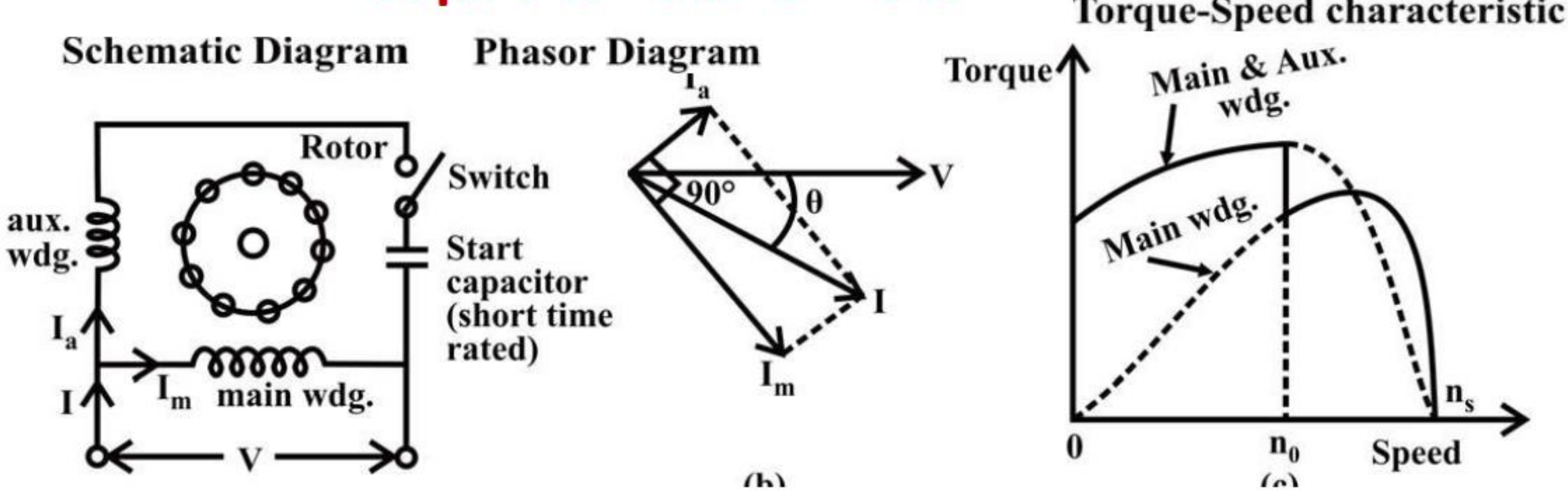
- So, in a single-phase IM, if an auxiliary winding is introduced in the stator, in addition to the main winding, but placed at a space angle of 90^0(electrical), starting torque is produced.
- The currents in the two (main and auxiliary) stator windings also must be at an angle of 90^0 , to produce maximum starting torque.
- Thus, rotating magnetic field is produced in such motor, giving rise to starting torque. The various starting methods used in a single-phase IM.

1. Resistance Split-phase Motor



How to make Single phase induction motor self starting?

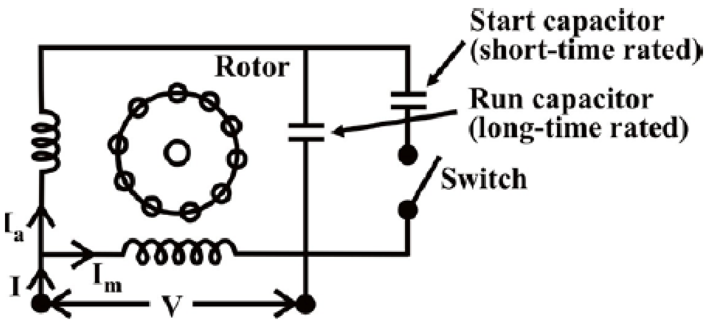
2. Capacitor start Motor

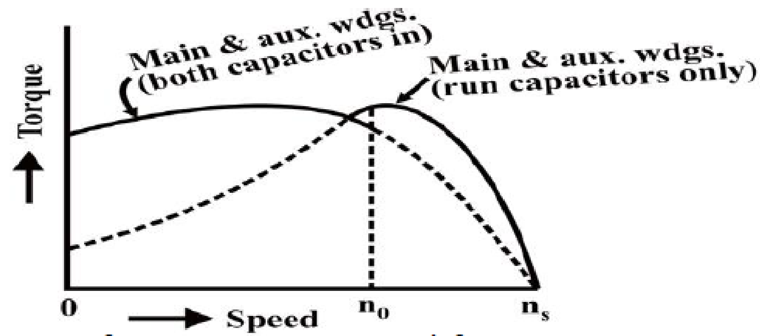


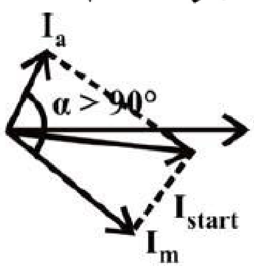
- To get high starting torque, the phase difference required is 90° when the starting torque will be proportional to the product of the magnitudes of two currents.
- As the current in the main winding is lagging by ϕm, the current in the auxiliary winding has to lead the input voltage by ϕa, with (ϕm + ϕa=90°). ϕa is taken as negative (-ve), while ϕm is positive (+ve). This can be can be achieved by having a capacitor in series with the auxiliary winding, which results in additional cost, with the increase in starting torque.
- A capacitor along with a centrifugal switch is connected in series with the auxiliary winding.
- This motor is used in applications, such as compressor, conveyor, machine tool drive, refrigeration and air-conditioning equipment, etc.

How to make Single phase induction motor self starting?

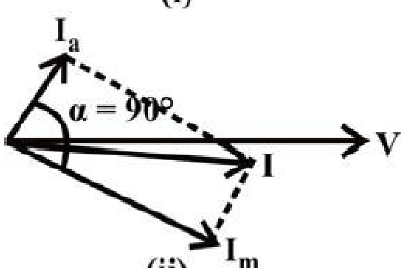
3. Capacitor-start and Capacitor-run Motor







(i)

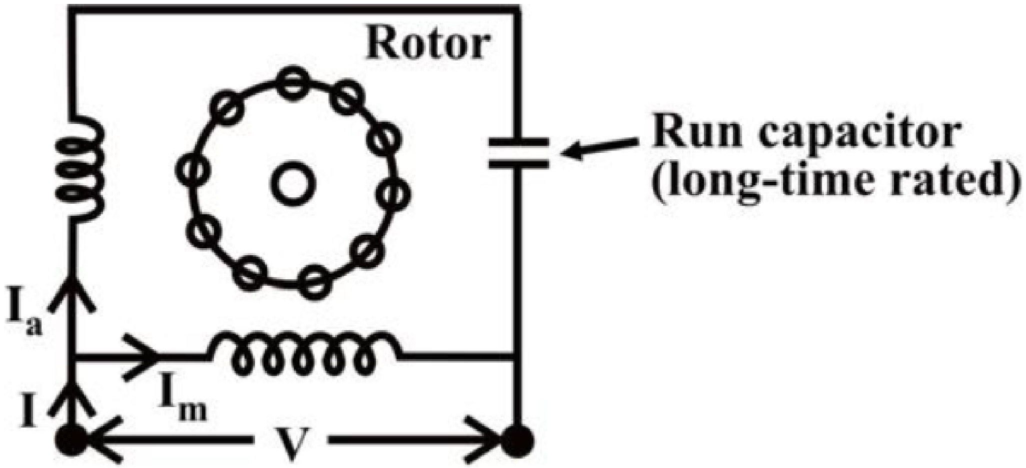


(ii)

- Two capacitors – for starting Cs, and for running Cr, are used.
- The first capacitor is rated for intermittent duty, being used only for starting. A centrifugal switch is also needed here.
- The second one is to be rated for continuous duty, as it is used for running.
- The phasor diagram of two currents in both cases, and the torque-speed characteristics with two windings having different values of capacitors.
- The phase difference between the two currents is ($\phi m + \phi a > 90^{o}$) in the first case (starting), while it is for second case (running).
- In the second case, the motor is a balanced two phase one, the two windings having same number of turns and other conditions as given earlier, are also satisfied. So, only the forward rotating field is present, and the no backward rotating field exists.
- The efficiency of the motor under this condition is higher. Hence, using two capacitors, the performance of the motor improves both at the time of starting and then running. This motor is used in applications, such as compressor, refrigerator, etc.

How to make Single phase induction motor self starting?

4. Capacitor-run Motor

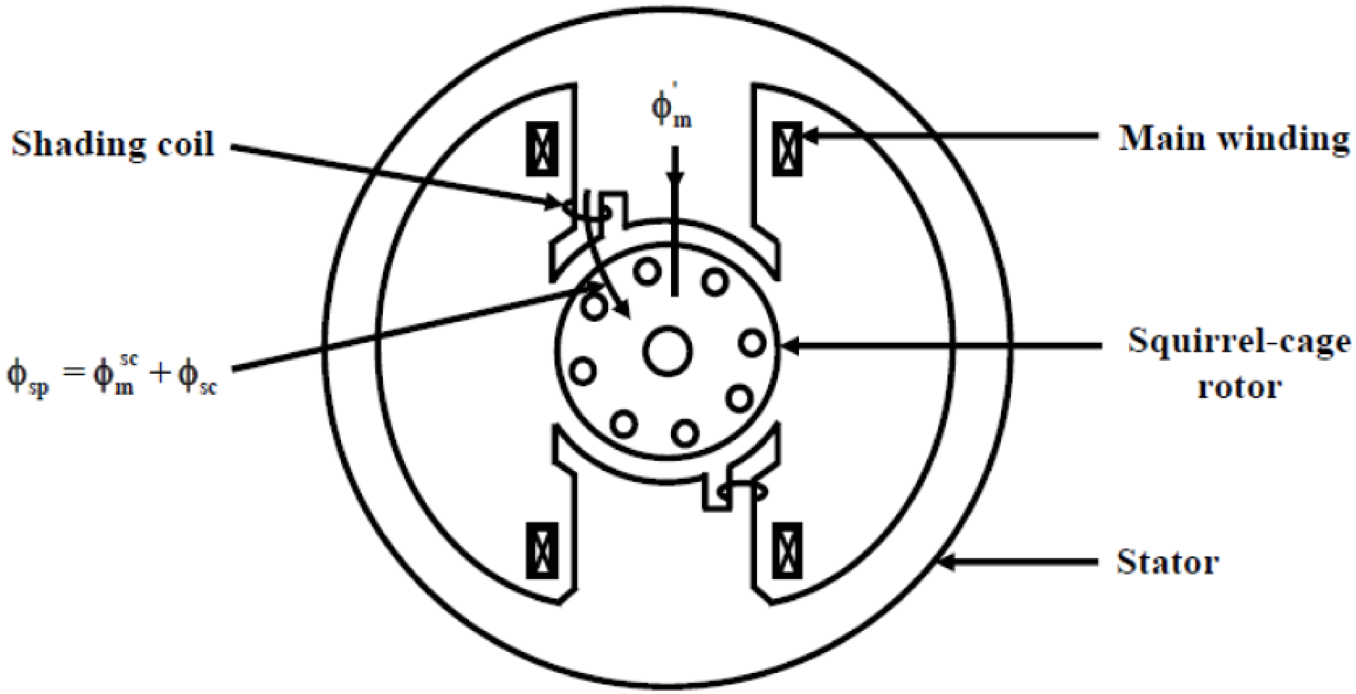


Schematic Diagram of Capacitor-run Induction Motor

- A Permanent Capacitor Motor with the same capacitor being utilized for both starting and running, is also used.
- The power factor of this motor, when it is operating (running), is high. The operation is also quiet and smooth.
- This motor is used in applications, such as ceiling fans, air circulator, blower, etc.

How to make Single phase induction motor self starting?

5. Shaded-pole Motor



- This is a single-phase induction motor, with main winding in the stator.
- A small portion of each pole is covered with a short-circuited, single-turn copper coil called the shading coil.
- The sinusoidally varying flux created by ac (single-phase) excitation of the main winding induces emf in the shading coil.
- As a result, induced currents flow in the shading coil producing their own flux in the shaded portion of the pole.

THANK YOU !