01-08-10-2021 # ALTERNATER ch-1

Ac system has a number of advantages over d.c system like;

(i) The generation of A.c is cheaper than that of D.c.

(ii) A.c machines are simple & do not require much attention for their repair, maintanace during their use.

(iii) Ac can be easily be converted into Dc.

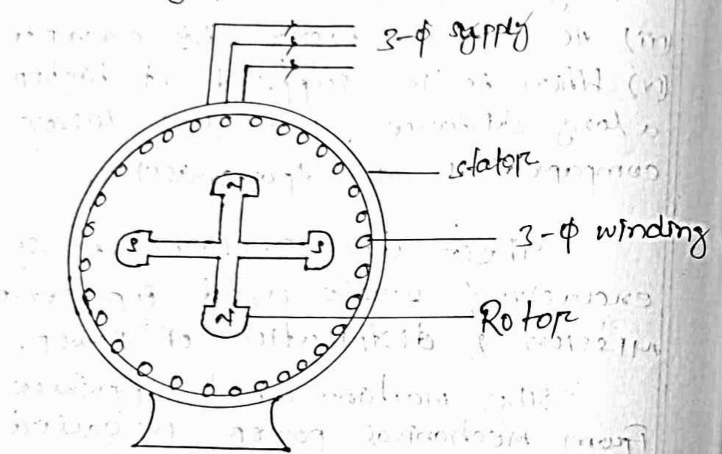
(iv) When Ac is supplied at higher voltage in a long distance, the line losses are small compared to Dc transmission.

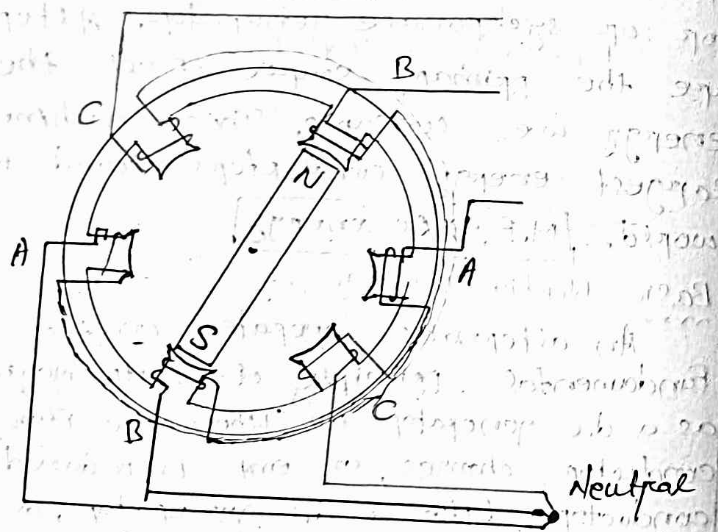
These days 3-phase ac system is being exclusively ~~unete~~ used for generation, transmission & distribution of power.

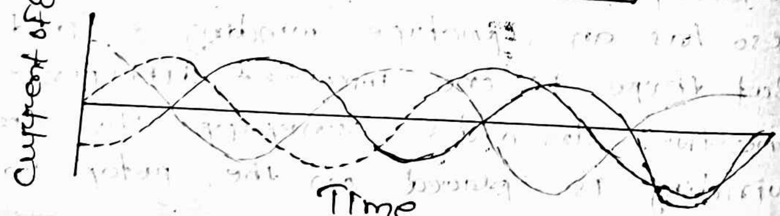
The machine which produce 3-phase power from mechanical power is called an alternator or sychronace generator. Alternators are the primary source of all the electrical energy we consume. These machines are the largest energy converters found in the world. M.E → AC energy

Basic Working principle :-

An alternator operates on the same fundamental principle of electro magnetic induction as a d.c generator i.e when the flux linking a conductor changes, an emf is induced in the conductor. Like a d.c generator, an alternator also has an armature winding & field winding. But there is one important difference betn the two. In a d.c generator the armature winding is placed on the rotor in order to provide a way of converting voltages generated on the winding to a direct voltage at the terminals through the use of rotating commutator. The field poles are placed on the stationary part of the machine. Since no commutator is required in the alternator. It is usually more convient & advantages to place the field winding on the rotating part (rotor) & armature winding on the stationary part (starter).







The starter consists of a cast iron frame which supports the armature core, having slots on its inner periphery for housing the armature conductors. The rotor is like a flywheel having alternate N & S poles fixed to its outer rim. The magnetic poles are excited (or magnetised) from direct current supplied by a dc source at 125 to 600 volts. In most cases necessary exciting current is obtained from a small dc shunt generator which is belted or mounted on the shaft of the alternator itself. Because the field magnets are rotating this current is supplied through two sliprings.

As the exciting voltage is relatively small the slip-rings & brush gear are of light constructions. Recently, brushless excitation system have been developed in which a 3-phase ac exciter & group of rectifiers ~~in which~~ supply d.c. to the alternator. Hence brushes, slip rings & commutator are eliminated.

When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux hence they have induced emf produced in them. Because the magnetic poles are alternately N & S they induce an emf & hence current in armature conductors, which first flows in one direction & then in the other.

Hence an alternating emf is produced in the stator conductors * whose frequency depends on the number of N & S poles moving past a conductor in one second & whose direction is given by Fleming's Right Hand Rule.

** Fleming's Right-Hand rule gives which direction the current flows. The right Hand is held with the thumb, index finger and middle finger mutually perpendicular to each other (at right angles), as The thumb is pointed in the direction of the motion of the conductor relative to the magnetic field.

Stationary Armature:-

The field winding of an alternator is placed on the rotor & is connected to dc supply through two slip ring. The 3-phase armature winding is placed on the stator. This arrangement has the following advantages;

(i) The output current can be led directly from fixed terminal on the stator (or armature winding) to the load circuit, without having to pass it through brush contacts.

(ii) It is easier to insulate stationary armature winding for high a.c voltages which may have as high a value of 30kv or more.

(iii) only two slip rings are required for d.c supply to the field winding on the rotor. since the exciting current is small, the slip ring and brush gear required are of light constructions.

iv) Due to simple in construction of the rotor higher speed of rotating d.c field is possible. This increases the output obtainable from a machine of given dimensions.

Construction of Alternator:-

An alternator has 3-phase winding on the stator & a d.c field winding on the rotor.

(1) Stator:-

It is the stationary part of the machine. In dc machine, the outer frame (Yoke) serves to carry the magnetic flux but in alternators, it is not meant for that purpose. Here it is used for holding the armature stampings & winding in positions: The armature core is supported by the stator & is build up of laminations of special magnetic iron or steel alloy. The core is laminated to minimise loss due to eddy currents. The laminations are stamped out in complete rings or in segments. The laminations are insulated from each other & have space between them for allowing the cooling air to pass through.

(a) Rotor:-

Two types of rotors are used in alternators
(i) Salient pole type.
(ii) Smooth - cylindrical type

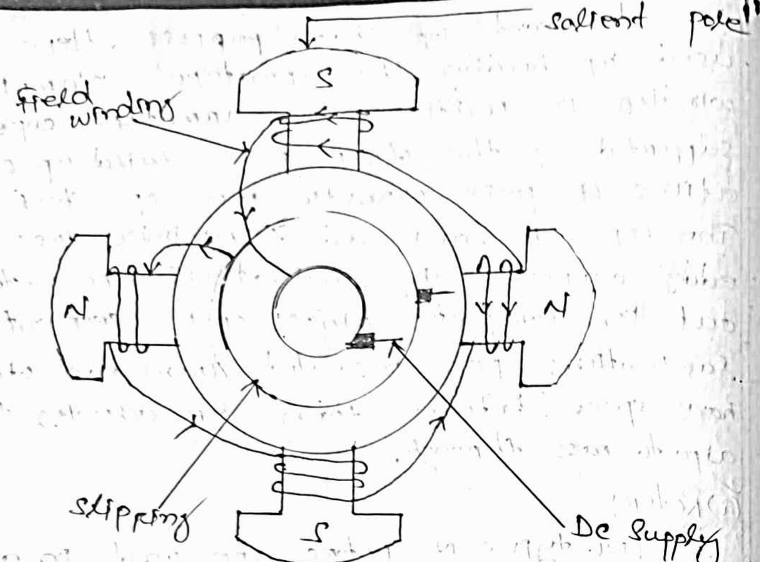
The rotor carries a field winding which is supposed with direct current through two slip rings by a separate d.c source.

(i) Salient pole type:-

In this type salient or projecting poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator. The individual field pole windings are connected in series in such a way that when the field winding is energised by the d.c exciter, adjecent poles have opposite polarities.

Low & medium - speed alternators (120-400 rpm) such as those driven by diesel engines or water turbines have salient pole type rotors due to the following reasons.

-> The salient field poles would cause an excessive windage loss if driven at high speed & would tend to produce noise.



→ Salient pole construction can not be made strong enough to withstand the mechanical stresses to which they may be subjected at higher speed.

Since a frequency of 50Hz is required, we must use a large no. of poles on the rotor of slow speed alternators. Low speed rotors always posses a large diameter to provide the necessary space for the poles. Consequently, salient pole type rotors have large diameter.

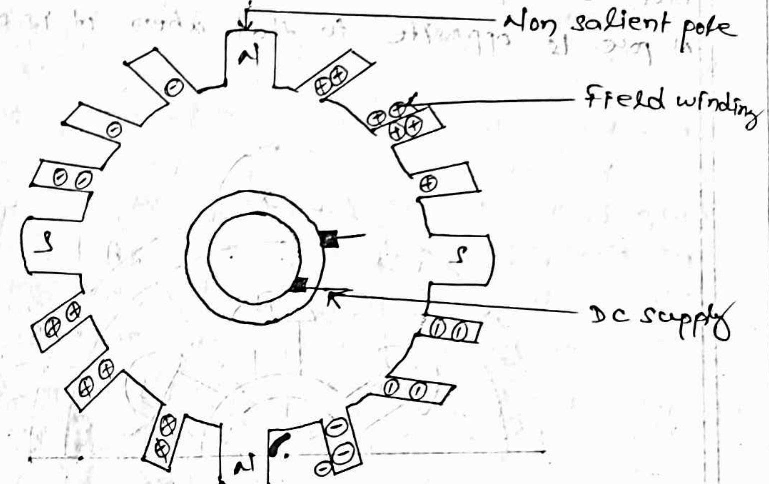
(ii) Smooth cylindrical type:-

In this type the rotor is made of smooth solid steel radial cylinder having a number of slots along the outer periphery. The field winding are embedded in these slots & are connected in series to slip rings through which they are energied by the d.c exciter.

High speed alternators (1500 or 3000 rpm) are driven by steam turbines & use non salient type rotors due to following reasons:-

→ This type of construction has mechanical robustness & gives noiseless operation at high speed.

→ The flux distribution around the periphery is nearly a sinewave & hence a better emf waveform is obtained than the salient pole type.



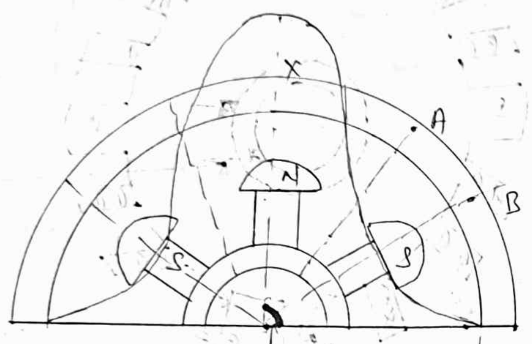
Since steam turbine run at high speed & a frequency of 50Hz is required, we need a small number of poles on the rotor of high speed alternator (also called turboalternators). We can use not less than 2 poles & this fixes the highest possible speed. For a frequency of 50Hz, it is 3000 rpm & the next lower speed is 1500 rpm for a 4 pole machine. Consequently turbo alternators possesses 2 or 4 pole & have small diameter.

Relation Between speed & frequency:-

In an alternator there exists a definite relationship between the rotational speed (N) of the rotor, the frequency (f) of the generated emf and the number of poles P.

Consider the armature conductor marked X situated at the centre of N-pole rotating in clockwise direction, the conductor being situated at the place of maximum flux density will have maximum emf induced in it. When the conductor is in the interpole gap as at A it has minimum emf induced emf because flux density is minimum there.

Again when it is at the centre of a 'S' pole it has maximum emf because flux density is maximum at B. But the direction of the emf when conductor is over N pole is opposite to that when it is over S-pole.



pole path

Obviously one cycle of emf is induced in a conductor when one pair of pole passes over it. In other word, the emf in an armature conductor goes through one cycle in angular distance equal to twice the pole pitch.

Let, p = total no. of magnetic poles.

N = speed of the rotor in r.p.m.

f = frequency of generated emf in Hz.

Since one cycle of emf is produced when a pair of poles passes past a conductor, the no. of cycles of emf produced in one revolution of the rotor is equal to the no. of pair of poles.

No. of cycles/revolution = P/2 & No. of revolution/sec = N/60

$$\text{frequency} = \frac{P}{2} \times \frac{N}{60}$$

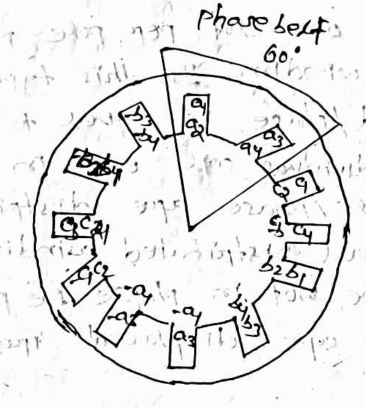
$$= \frac{PN}{120} \text{ Hz}$$

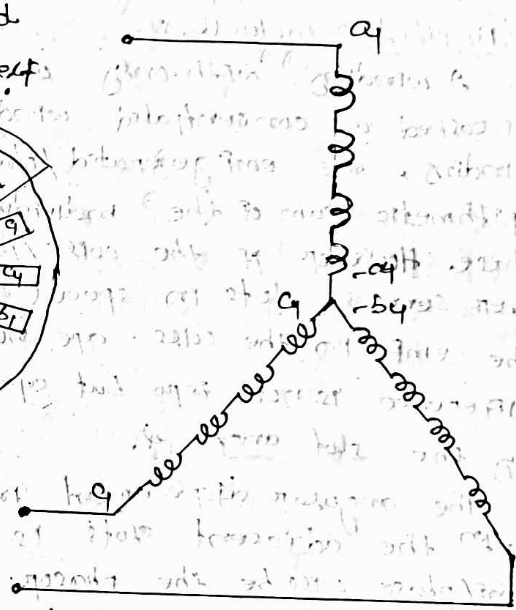
$$\boxed{F = \frac{PN}{120} \text{ Hz}}$$

N = Synchronous speed & generally represented by Ns. For a given alternator the no. of rotor pole is fixed & therefore the alternator must run at synchronous speed to give an output of desired frequency. For this reason an alternator is sometimes called synchronous generator.

Armature winding:-

The winding for an alternator are much simpler than that of a d.c machine because no commutator is used.





A 12pole, 3-phase, double layer of an alternator. There are 12 slots & each slot contain two coil sides that are placed in adjacent slots belong to the same shape such as a1, a3 or a2, a4 constitute a phase belt. Note that in a 3-phase machine, phase belt is always 60° electrical. There are 12 total coils & each phase has four coils.

The four coils in each phase are connected in series so that their voltage add. The three phase may be connected to for Y to Δ connection.

Winding Factors:-

The armature winding of an alternator is distributed over the entire armature. The distributed winding produces nearly a sine wave form & the heating is more uniform. The distribution & pitching of the coils affects the voltages induced in the coils. we shall discuss two winding factors:-

(i) Distribution factor (Kd) (Breadth factor)

(ii) pitch factor (kp) (chord factor)

i) Distribution factor (kd):-

A winding with only one slot per pole per phase is called a concentrated winding. In this type of winding, the emf generated/phase is equal to the arithmetic sum of the individual coil emf in that phase. However if the coils/phase are distributed over several slots in space (Distributed winding) the emf in the coils are not in phase i.e phase difference is not zero but are displaced from each by the slot angle α.

The angular displacement in electrical degrees betn the adjacent slots is called slot angle. The emf/phase will be the phasor sum of coil emfs.

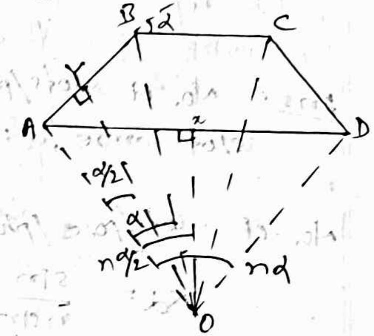
The Kd is defined as:

$$K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}} = \frac{\text{phasor sum of coil emf/phase}}{\text{Arithmetic sum of coil emf/phase}}$$

Let, α = slot angle = $\frac{180° \text{ electrical}}{\text{No. of slots/pole}}$

n = slots per pole per phase

Let $n=3$, the three coil emf as phasors AB, BC & CD each of which is a chord of circle with centre 'O' & subtends an angle α at O. The phasor sum of the coil emfs subtends an angle $n\alpha$ (Here $n=3$) at O. perpendicular bisectors of each chord such as OX, OY.



$$K_d = \frac{AD}{n \times AB} = \frac{2 \times Ax}{n \times (2Ay)} = \frac{Ax}{n \times Ay}$$

$$= \frac{OA \times \sin(n\alpha/2)}{n \times OA \times \sin(\alpha/2)}$$

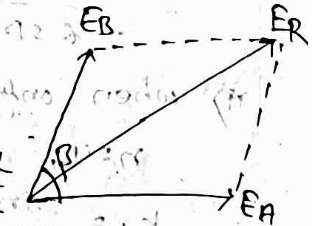
$$\boxed{K_d = \frac{\sin(n\alpha/2)}{n \sin(\alpha/2)}}$$

(ii) Pitch Factor:-

A coil whose sides are separated by one pole pitch is called a full pitch coil. with a full pitch coil the emf induced in the two coil sides are in phase with each other & the resultant emf is the arithmetic sum of the individual emfs. However, the waveform of the resultant emf can be improved by making the coil pitch less than a pole pitch such a coil is called short pitch coil. The factor by which emf per coil is reduced is called pitch factor kp.

$$K_p = \frac{\text{emf induced in short pitch coil}}{\text{emf induced in full pitch coil}}$$

The emf generated in the coils A & B differ in phase by an angle β & can be represented by phasor E_A & E_B respectively.



since $E_A = E_B$

$E_R = 2E_A \cos\beta/2$

$$K_p = \frac{\text{Emf induced in short pitch coil}}{\text{Emf induced in full pitch coil}} = \frac{2E_A \cos\beta/2}{2E_A} = \cos\beta/2$$

$$\boxed{K_p = \cos\beta/2}$$

Full pitch $k_p \leq 1$

short pitch $k_p < 1$

Q- Calculate the value of the distribution Factor for a 3-phase winding of a 4-pole alternator having 36 slots.

Ans - No. of slots/pole $= 36/4 = 9$

slot angle, $\alpha = \dfrac{180°}{\text{No. of slots/pole}} = \dfrac{180°}{9} = 20°$

No. of slots/pole/phase, $n = 9/3 = 3$

$$K_d = \frac{\sin(n\alpha/2)}{n\sin(\alpha/2)}$$

$$= \frac{\sin(3 \times 20°/2)}{3\sin(20°/2)}$$

$$= \frac{\sin 30°}{3\sin 10°} = 0.96 \quad \text{(Ans)}$$

Q- Calculate the distribution Factor for a single phase alternator having slots/pole (i) when all the slots are wound & (ii) when only four adjacent slots per pole are wound, the remaining slots being unwound.

ans

(i) when all the slots are wound.

$n = 6$, slot angle $\alpha = 180°/6 = 30°$

$$K_d = \frac{\sin(n\alpha/2)}{n\sin(\alpha/2)}$$

$$= \frac{\sin(6 \times 30°/2)}{6\sin(30°/2)} = \frac{\sin 90°}{6\sin 15} = 0.644$$

(ii) when only 4 adjacent slots per pole

$n = 4$, $\alpha = 30°$

$$K_d = \frac{\sin(n\alpha/2)}{n\sin(\alpha/2)}$$

$$= \frac{\sin(4 \times 30°/2)}{4\sin(30°/2)}$$

$$= \frac{\sin 60}{4\sin 15} = 0.837$$

EMF Equation of an Alternators:-

Let Z = No. of conductors or coils sides in series per phase.

ϕ = Flux per pole in webers.

P = Number of rotor poles

N = Rotor speed in r.p.m.

In one revolution (i.e $60/N$) sec. each stator conductor is cut by $P\phi$ wb. i.e

$$d\phi = P\phi \; ; \; dt = 60/N$$

Avg. emf induced in one stator conductor =

$$= \frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60} \text{ volts}$$

Since there are Z conductors in series per phase

$$\text{Avg emf/phase} = \frac{P\phi N}{60} \times Z$$

$$= \frac{P\phi Z}{60} \times \frac{120f}{P} \quad \left[N = \frac{120F}{P}\right]$$

$$= 2f\phi Z \text{ volts.}$$

Rms value of emf/phase = Avg value/phase × form factor

$$= 2F\phi Z \times 1.11$$

$$= 2.22F\phi Z \text{ volt}$$

$$\boxed{E_{rms}/\text{phase} = 2.22F\phi Z \text{ volts}}$$

If k_p & k_d are the pitch factor & distribution factor of the armature winding then

$$\boxed{E_{rms}/\text{phase} = 2.22\, k_p k_d f\phi Z \text{ volts}}$$

Sometimes the turns (T) per phase rather than conductor per phase are specified.

$$\boxed{E_{rms}/\text{phase} = 4.44\, k_p k_d F\phi T} \text{ volts}$$

Q- A 3-phase, 50Hz star connected alternator has 180 conductors per phase & Flux per pole is 0.0543 wb. Find (i) emf generated per phase (ii) emf bet? line terminals. Assume the winding to be full pitched & distributed factor to be 0.96.

Ans (i) Generated emf/phase, $E_{ph} = 2.22 k_p k_d Z f \phi$

$= 2.22 \times 1 \times 0.96 \times 180 \times 50 \times 0.0543$

$= 1041.5V$

(ii) Line voltage $E_L = \sqrt{3} E_{ph}$

$= \sqrt{3} \times 1041.5 = 1803.93V$

Q- The armature of an 8 pole, 3-phase, 50Hz alternator has 18 slots & 10 conductors/slot. A Flux of 0.04 wb is entering the armature from one pole. Calculate the induced emf/phase.

Ans - If k_p & k_d are not given assumed -1

Total no. of conductor $= 18 \times 10 = 180$

No. of conductor/phase, $Z = 180/3 = 60$

Induced emf/phase $= 2.22 \times k_p \times k_d \times Z \times f \times \phi$

$= 2.22 \times 1 \times 1 \times 60 \times 50 \times 0.04$

$= 266.4$ V (Ans)

Effect of Harmonics on pitch & Distribution factors:-

a) If the short pitch angle is α for the Fundamental flux wave, then its value for different harmonics are.

For 3rd Harmonics $= 3\alpha$

For 5th Harmonics $= 5\alpha$

Pitch Factor: $k_p = \cos \alpha/2$ ($\cos \beta/2$)

$= \cos 3\alpha/2$ ($\cos 3\beta/2$)

$= \cos 5\alpha/2$ ($\cos 5\beta/2$)

b) Similarly the distribution factor is also different for different harmonics. Its value becomes,

$k_d = \frac{\sin n\alpha/2}{n \cdot \sin \alpha/2}$

when 'n' is the order of the harmonices,

$n=1$; $k_d = \frac{\sin n\alpha/2}{n \sin \alpha/2}$

$n=3$; $k_d = \frac{\sin 3n\alpha/2}{3 \sin \alpha/2}$

$n=5$; $k_d = \frac{\sin 5n\alpha/2}{5 \sin \alpha/2}$

c) Frequency is also changed, $F_1 = 50Hz$, 3rd Harmonics, $F_3 = 3 \times 50 = 150$ Hz, 5th Harmonics, $F_5 = 5 \times 50 = 250Hz$

Q- A 3-phase, 16 pole alternator has a star connected winding with 144 slots & 10 conductors per slot. The Flux per pole is 0.03 wb sinusoidally distributed & the speed is 375 r.p.m. Calculate (i) the frequency & (ii) line induced emf.

Ans - (i) Line induced emf, $f = \frac{PN}{120}$

$= \frac{16 \times 375}{120} = 50$ Hz

(ii) slot angle, $\alpha = \frac{180°}{\text{No. of slots/pole}} = \frac{180}{144/16} = 20°$

No. of slots/pole/phase, $n = \frac{144}{16 \times 3} = 3$

Distribution factor, $k_d = \frac{\sin(n\alpha/2)}{n \sin(\alpha/2)}$

$= \frac{\sin(3 \times 20/2)}{3 \sin(20/2)}$

$= \frac{\sin 30}{3 \sin 10} = 0.96$

No. of turns/phase, $T = \frac{144 \times 10}{2 \times 3} = 240$

Assume pitch factor $k_p = 1$

Induced emF/ph, $E_{ph} = 4.44 k_p k_d T f \phi$

$= 4.44 \times 1 \times 0.96 \times 240 \times 50 \times 0.03$

$= 1534$ V.

Induced line voltage, $E_L = \sqrt{3}\, E_{ph}$

$= \sqrt{3} \times 1534$

$= 2657\ V$ (Ans)

Q- A 3-phase, star connected alternator on open ckt is required to generate a line voltage of 3600 V at 50Hz. When driven at 500 rpm. The stator has 3 slots per pole phase & 10 conductors per slots. Calculate
i) The no. of poles & (ii) use full flux per pole. Assume all the conductors per phase to be connected in series & the coils to be full pitch.

Ans-(i) $F = \frac{PN}{120} \Rightarrow 50 = \frac{500 \times P}{120} = 12$

ii) No. of slots/phase $= 3 \times 12 = 36$

No. of conductor/ph, $Z = 36 \times 10 = 360$

$EMF/ph = \frac{3600}{\sqrt{3}} = 2080V$

No. of slots/pole/ph, $n = 3$

$\alpha = \frac{180°}{No.\ of\ slots/pole} = \frac{180°}{3 \times 3} = 20°$

Distribution factor, $k_d = \frac{\sin(n\alpha/2)}{n \sin(\alpha/2)}$

$= \frac{\sin(30 \times 20/2)}{3 \sin(20/2)}$

$= \frac{\sin 30}{3 \sin 10} = 0.96$

Pitch factor, $k_p = 1$

$E_{ph} = 2.22\, k_p\, k_d\, Z f \phi$

$2080 = 2.22 \times 1 \times 0.96 \times 360 \times 50 \times \phi$

$\phi = 0.0543$ wb.

Q- An alternator has 90 slots per pole. If each coil span 80 slots pitches, what is the value of the pitch factor?

Ans- coil pitch $= \frac{8}{9} \times 180° = 160°$

coil is short pitch by $\beta = 180° - 160°$
$= 20°$

pitch factor, $k_p = \cos\beta/2$
$= \cos 20/2 = \cos 10 = 0.985$

Q- The stator of a 3-phase alternator has 9 slots per pole & carries a balanced 3-phase, double layer winding. The coils are short pitched & the coil pitch is 7 slots. Find the distribution factor & pitch factor

Ans slot angle $\alpha = \frac{180°}{No.\ of\ slots/pole}$

$= \frac{180°}{9} = 20°$

No. of slots/pole/ph, $n = 9/3 = 3$

coil pitch $= 7/9 \times 180$
$= 140°$

coil is short pitched by, $\beta = 180° - 140° = 40$

$k_d = \frac{\sin(n\alpha/2)}{n \sin(\alpha/2)}$

$= \frac{\sin(30 \times 20/2)}{3 \sin(20/2)} = \frac{\sin 30}{3 \sin 10} = 0.95$

$k_p = \cos\beta/2$

$= \cos 40/2 = \cos 20° = 0.939$

Q- Calculate the pitch factor for a winding having 24 stator slots when the coil span 5 slots.

Ans - winding having 24 stator slots [P=4]

pole pitch is 6 slots

coil pitch $= 5/6 \times 180° = 150°$

$\beta = 180° - 150° = 30°$

$k_p = \cos\beta/2$

$= \cos 30/2 = \cos 15°$

$= 0.96$.

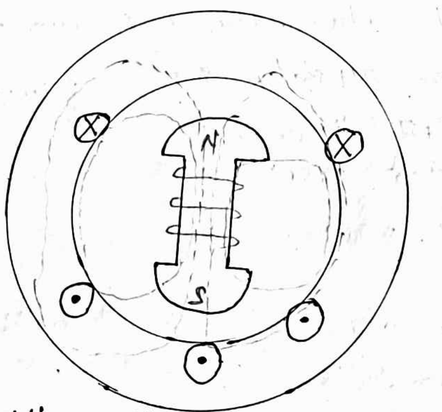
Armature Reaction In Alternator:-

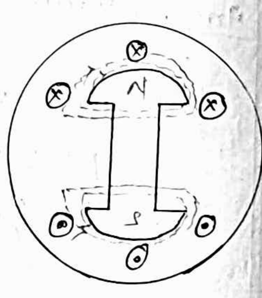
When an alternator is running at no load, there will be no current flowing through the armature winding. The flux produced in the air gap will be only due to the rotor armature. When the alternator is loaded, the air gap flux is changed from the no load condition.

The effect of armature flux on the flux produced by ampere turns (i.e rotor) is called armature Reaction.

Two things are worth noting about the armature Reaction in an alternator. First the armature flux & the flux produced by rotor ampere turn rotate at the same speed i.e synchronous speed in the same direction & the secondary the modification of the flux in the air gap due to armature flux depends on the magnitude of stator current & on the power factor of the load. It is the load power factor which determines whether the ampere flux distorts, opposes or helps the flux produced by the rotor-ampere turns. So we shall consider the three cases; i.e (i) When load power factor is unity (ii) When load power factor is zero lagging (iii) when load power factor is zero leading.

i) When load P.F is unity:-





When alternator is no load since the armature is open ckt, there is no stator current & Hence due to rotor current Distributed symmetrically i.e the air gap. Since the direction of the rotor is assumed clockwise, the generated emf in phase is at its maximum, no armature flux is produced since no current flows in the armature winding.

When a resistive load (unity P.F) is connected across the terminal of the alternator Acc. to right hand rule the current is 'in' the conductor under N-pole & 'out' in the conductor under S-pole. Therefore the armature flux is clockwise due to current in the top conductors & anticlockwise due to current in the bottom conductors. Armature flux is at 90° to the main flux & is behind the main flux. In this case the flux in the air gap is disterbated, but not weakend.

Therefore at unity P.F the effect of armature reaction is merely distered the main field.

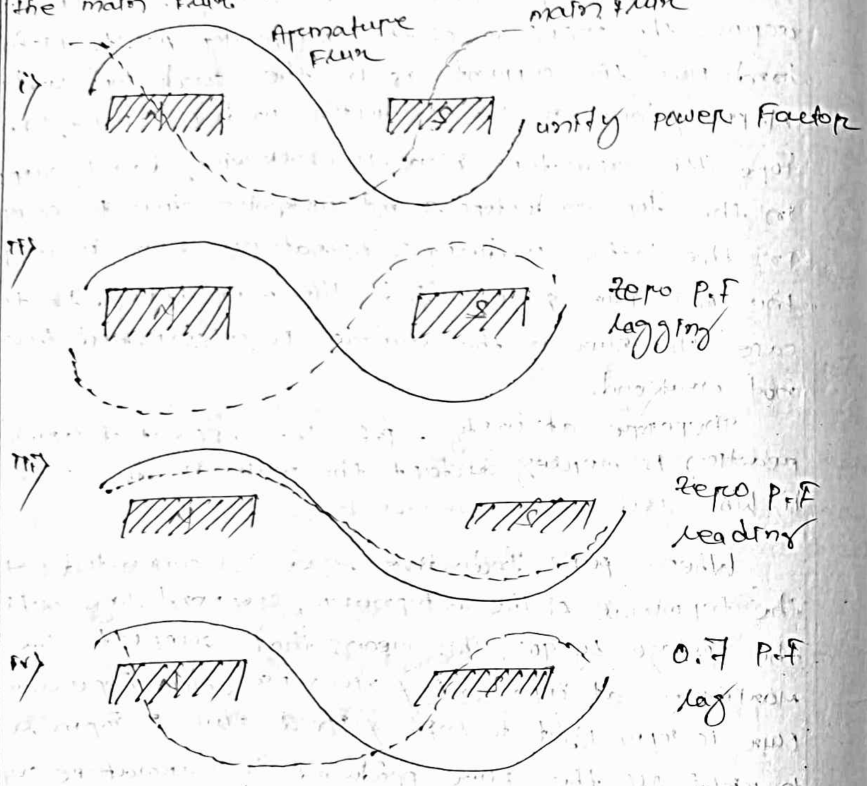
ii) When load P.F is zero lagging:-

When pure Inductive load is connected across the terminal of the alternator, current lags behind the voltage by 90°. This means that current will be maximum at zero emf & viceversa. Now here armature flux is form right to left & field flux is form left to right. All the flux produced by armature current (i.e armature flux) opposes the field flux & therefore weakens it. That means armature reaction is directly demagnetising. Hence at zero P.F lagging the armature reaction weakens the main flux. This cause a reduction in generated emf.

iii) When load P.F is zero leading:-

When a capacitive load (zero P.F leading) is connected across the terminal of the alternator the current in armature load the induced emf by 90°. Obviously the effect of armature reaction will be reverse that for pure inductive load. Thus armature

Flux now aids the main flux & the generated emf is increased. Here the armature flux is now in the same direction as the field flux & therefore strengthens it. This caused an incress in the generated voltage. Hence at zero p.f leading the armature reaction strengthens the main flux.



power factor values the effect of armature reaction is partically disterting & partially weakening for inductive load. For capactive load, the effect of armature reaction is partially disterting & partially strengtheing. so that loads are generally inductive.

Summary:-

a) When the load P.f is unity the effect of armature reaction is wholly distoting.

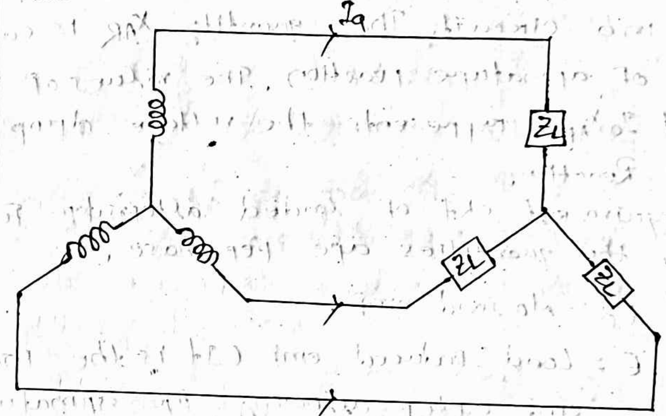
b) When the load p.f is zero lagging, the effect of armature reaction is wholly demagnetising.

c) When the load P.f is zero leading, the effect of armature reaction is wholly magnetising.

d) For intermediate value of load P.F the effect of armature reaction is partially distoring & partly weakening for Inductive load. For capacitive load the effect is partly distorting & partly strengthening.

* In pratice load on the alternater is generally inductive.

Alternator on Load:-



A Y connected alternator supplying inductive load (lagging P.F). When the load on the alternator is increased (i.e Ia in increased), the field excitation & speed being kept constant The terminal voltage 'V' of the alternator decreases.

This is due to;

i) Voltage drop I_aR_a where R_a is the armature resistance per phase.

ii) Voltage drop I_aX_L where X_L is the armature leakage reactance per phase.

iii) Voltage drop because of Armature Reaction.

→ Armature Resistance (R_a):- Since the armature has some resistances, there will be an I_aR_a drop when current (I_a) flow through it. The R_a is generally small so that I_aR_a drop is negligible.

→ **Armature leakage Reactance (X_L) :–** When current flows through armature winding flux is setup & it does not cross the air gap, so it gives the winding self inductance. This is called X_L. Therefore $I_a X_L$ drop which is also effective in reducing the terminal voltage.

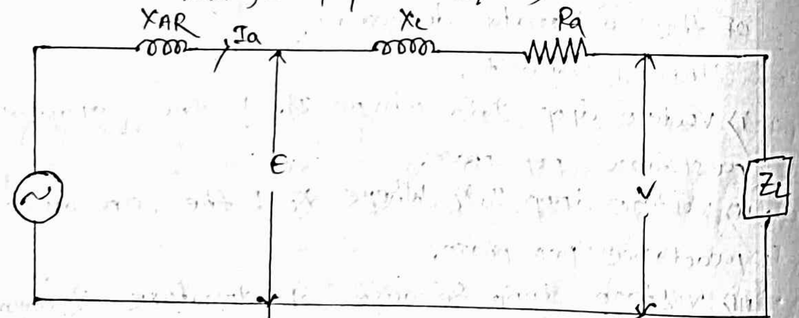
→ **Armature Reaction :–** The load is generally inductive & effect of armature reaction is to reduce the generated voltage. Since armature reaction results in a voltage effected in a circuit. The quantity X_{AR} is called reactance of armature reaction. The values of X_{AR} is such that $I_a X_{AR}$ represents the voltage drop due to armature Reaction.

The equivalent ckt of loaded alternator for one phase. All the quantities are per phase.

Here; E_0 = No load emf

E = Load induced emf (It is the induced emf after allowing for armature reaction. It is equal to phase difference of E_0 x $I_a X_{AR}$)

V = Terminal voltage (It is less than E by voltage drop in X_L & R_a)



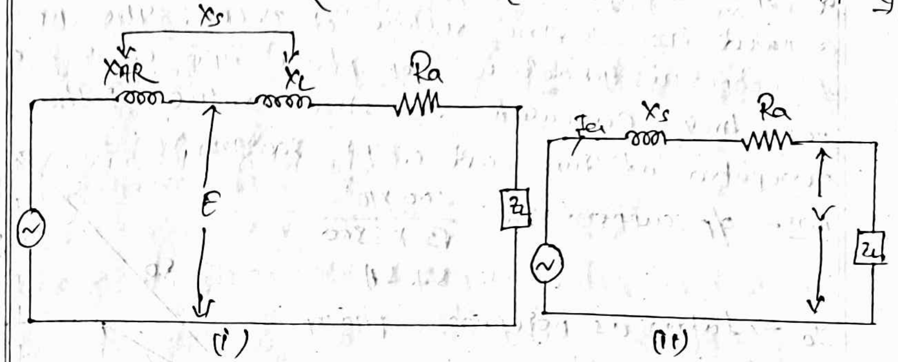
$E = V + I_a(R_a + jX_L)$,

$E_0 = E + I_a(jX_{AR})$

Sychronous Reactance (X_s) :–

The sum of armature reactance (X_L), & reactance of armature reaction (X_{AR}) is called synchronous reactance X_s.

$X_s = X_L + X_{AR}$ [∵ All are in per phase]



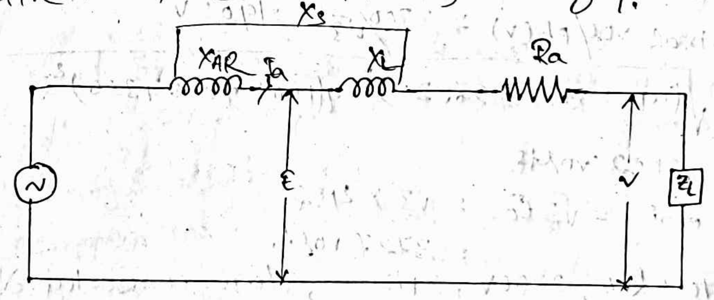
Sychronous Impedance, $Z_s = R_a + jX_s$

$E_0 = V + I_a Z_s$

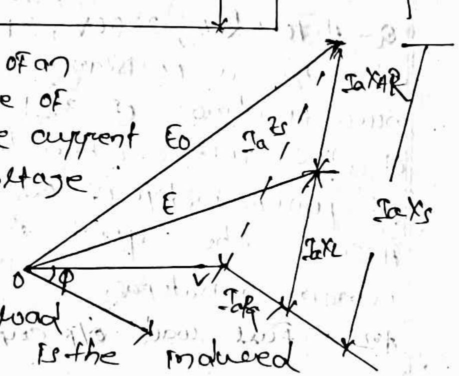
$= V + I_a(R_a + jX_s)$

Phasor Diagram of Loaded Alternator :–

Consider a Y-connected alternator supplying inductive load, the load p.f angle being ϕ.



The phasor diagram shows of an alternator for the usual case of inductive load. The armature current I_a lags the terminal voltage 'V' by p.f angle ϕ. The phasor sum of 'V' & drops $I_a R_a$ & $I_a X_L$ gives the load induced voltage E. It is the induced emf after allowing for armature reaction.

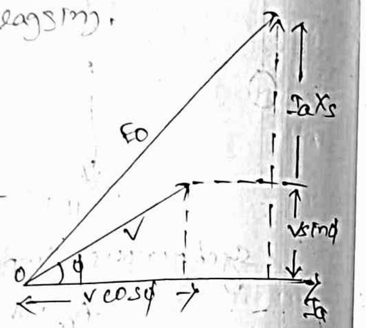


The phasor sum of E & $I_a X_{AR}$ gives the no-load emf E_0. Note that the phasor diagram either the terminal voltage (V) or armature current (I_a) may be taken as reference phasor.

Q- A 500 kVA, 3-phase, stator connected alternator has a rated line to line voltage of 3300V. The resistance & synchronous reactance per phase are 0.3 Ω & 4 Ω respectively. Calculate the line value of the emf generated at full load 0.8 pf lagging.

Ans- o/p current $I_a = \frac{500 \times 10^3}{\sqrt{3} \times 3300}$

$= 87.5 A$



I_a → taken as reference phasor

From phasor diagram:-

$E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$

Now, $\cos\phi = 0.8$

$\sin\phi = 0.6$

I_aR_a drop = $87.5 \times 0.3 = 26.25V$

$I_a X_s = 87.5 \times 4 = 350 V$

Terminal volt/ph(V) = $3300/\sqrt{3} = 1905 V$

$E_0 = \sqrt{(1905 \times 0.8 + 26.25)^2 + (1905 \times 0.6 + 350)^2}$

$= 2152$ volts

Line emf $= \sqrt{3} E_0 = \sqrt{3} \times 2152$

$= 3727$ volt.

Q- A 1000 kVA, 2300V, 3 phase, star connected alternator has a resistance of 0.309 Ω/phase & a synchronous reactance of 3.31 Ω/phase. Calculate the change of line voltage when the rated output of 1000 kVA at power factor of 0.8 lagging is switched off. Assume the speed & the exciting current to remain unilateral.

Ans - Full load o/p current $I_a = \frac{1000 \times 10^3}{\sqrt{3} \times 2300}$

$= 251 A$

$E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$

$\cos\phi = 0.8$, $\sin\phi = 0.6$

$I_aR_a = 251 \times 0.309 = 77.6V$

$I_aX_s = 251 \times 3.31 = 831$ volts

Terminal voltage, $V = 2300/\sqrt{3} = 1328 V$

$E_0 = \sqrt{(1328 \times 0.8 + 77.6)^2 + (1328 \times 0.6 + 831)^2}$

$= 1987$ volts.

Line voltage $= \sqrt{3} E_0$

$= \sqrt{3} \times 1987 = 3441$ volt

change in line voltage $= 3441 - 2300$

$= 1141$ volts.

Q- A 60 kVA, 220V, 50Hz, single phase alternator has effective resistance of 0.016 Ω & an armature leakage reactance of 0.07 Ω. Find the voltage induced in the armature when the alternator is delivering rated current at a load P.F. of (i) unity, (ii) 0.7 lagging, (iii) 0.7 leading.

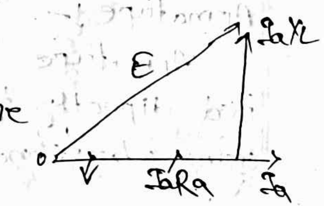
Ans- $I_a = \frac{60 \times 10^3}{220} = 272.72 A$

$V = 220 V$

$I_aR_a = 272.72 \times 0.016 = 4.3$ volts

$I_aX_L = 272.72 \times 0.07 = 19$ volts.

i) Unity P.F.:- current has been taken as the reference phasor



$E = \sqrt{(V + I_aR_a)^2 + (I_aX_L)^2}$

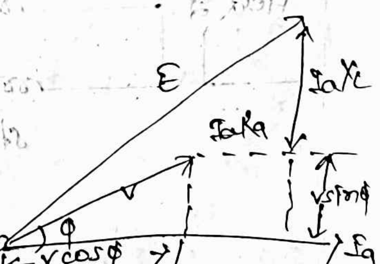
$= \sqrt{(220 + 4.3)^2 + (19)^2}$

$= 225$ volts

ii) 0.7 pf lagging

$\cos\phi = 0.7$

$\sin\phi = 0.7$



$$E = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_L)^2}$$

$$= \sqrt{(220 \times 0.7 + 4.3)^2 + (220 \times 0.7 + 19)^2}$$

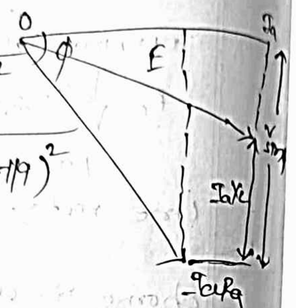
$= 234$ volts.

iii) 0.7 pf leading

$$E = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_L)^2}$$

$$= \sqrt{(220 \times 0.7 + 4.3)^2 + (220 \times 0.7 - 19)^2}$$

$= 205$ volts



Testing of Alternator:-

If $Z_s \rightarrow$ Synchronous Impedance

$R_e \rightarrow$ effective Resistance

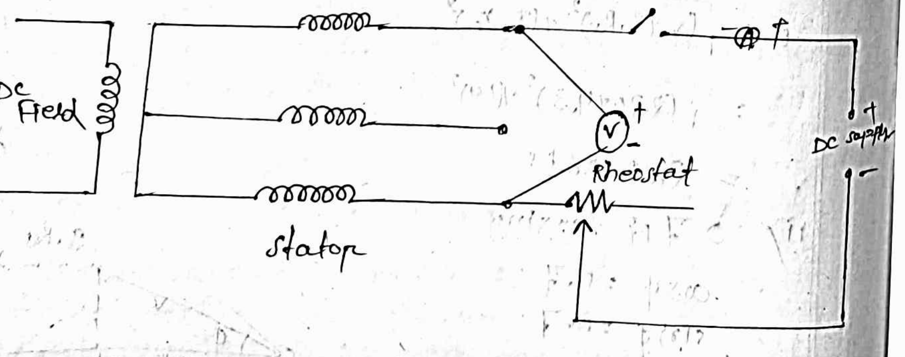
Due to Armature Reaction as already defined the sum of leakage reactance to acc. of voltage drop, the synchronous reactance X_s is given by

$$X_s = \sqrt{Z_s^2 - R_e^2}$$

Where Z_s is the synchronous impedance & R_e is the effective resistance.

Determination of effective Resistance of Armature:-

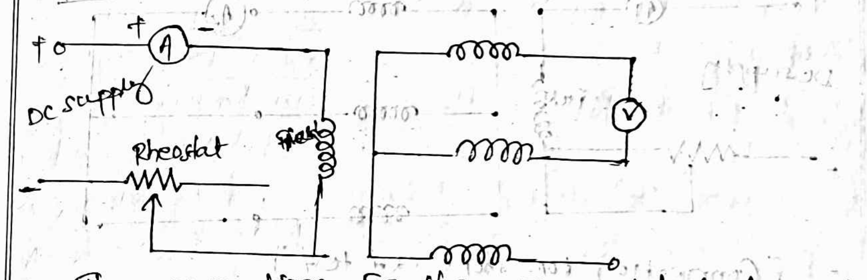
Armature resistance per phase can be measured directly by voltmeter-Ammeter method or by using wheatstone bridge.



DC resistance per phase can be measured directly by ammeter-voltmeter method as shown as fig.

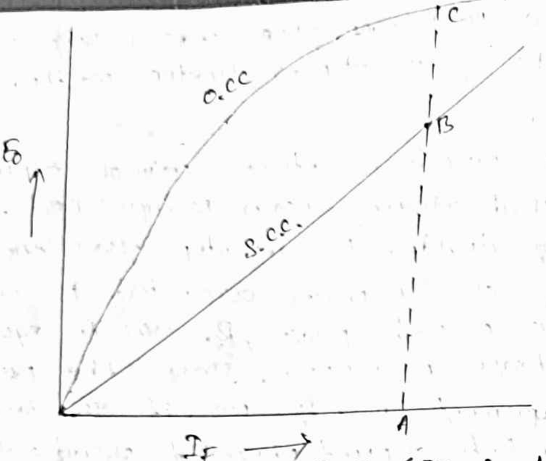
DC resistance between pair of terminal with the dc field winding open is measured. The voltmeter reading devided by ammeter gives the value of resistance of two phases connected is series, so resistance of each phase, R_a will be equal to half the resistance measured, since the resistance under measurement is very low, it will be necessary to use a high current rheostat of adjust the current to about rated value. Synchronous impedance is determined from the open circuit & short circuit tests.

1. Open circuit test:-



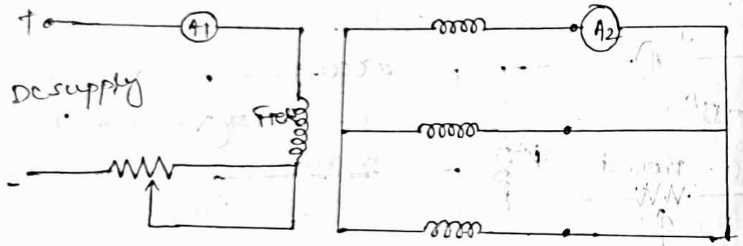
The connections for the open ckt test as shown in the above Figure. With the armature-winding circuit open, the machine is run at rated speed. The field is connected to a d.c source in series with a field rheostat & an ammeter so that the field current be adjusted & noted. The field current is raised in suitable steps until the voltage seen any pair of terminal of the armature winding is some what above rated emf & values of voltmeter indicating no-load line voltage are noted.

The open circuit voltages per phase E_0 are obtained by dividing the voltmeter reading by $\sqrt{3}$.



Now the curve is drawn betn E_0 & I_F is known as open circuit characteristic.

2. Short - circuit Test !-



[Connection for short ckt test]

All the three phases are shorted. Since the three currents will be equal, only one of them need be measured & so one ammeter is connected in any one of the three phase. Rheostat of sufficiently high ohmic value is inserted in the d.c field ckt to keep the current in the ckt very low. The machine is run at synchronous speed. The reading of the ammeters connected in the field ckt & armature ckt A_1 & A_2 are noted. The short ckt characteristic is determined by plotting a curve bet^n I_{sc} (short ckt current) & field current (I_F)

The S.C char. is normally a straight line.

If OA is the field current that gives the rated emf per phase represented by AC & AB gives the I_{sc}

that is $E_0 = I_{sc} Z_s$

$$Z_s = \frac{E_0}{I_{sc}} = \frac{AC \text{ (In volt)}}{AB \text{ (In Amp)}}$$

& $X_s = \sqrt{Z_s^2 - R_e^2}$

Q- The effective resistance of a 2200V, 440 kVA, 1-ϕ alternator is 0.5Ω. On short ckt a field current of 40A gives the full load current of 200A. The emf on open ckt with same field excitation 1160V. Calculate synchronous impedance & reactance.

Ans- short ckt current $I_{sc} = 200A$
open ckt voltage, $E_0 = 1160V$

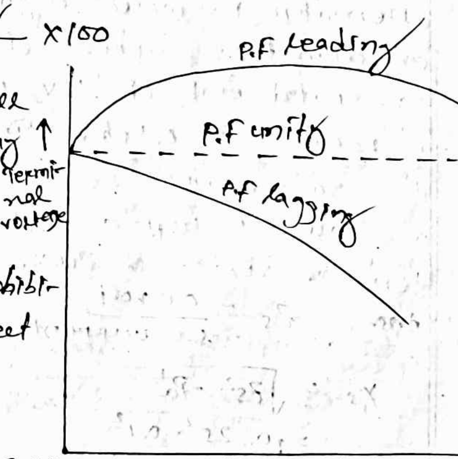
$$Z_s = \frac{\text{open ckt voltage}}{\text{short ckt current}} = \frac{1160}{200} = 5.8\Omega$$

$$X_s = \sqrt{Z_s^2 - R_e^2}$$
$$= \sqrt{5.8^2 - 0.5^2} = 5.778\Omega \text{ (Ans)}$$

Voltage Regulation !-

The voltage regulation of an alternator is defined as the rise in voltage when full load is removed (field excitation & speed remaining the same) divided by the rated terminal voltage.

$$\% \text{ Regulation} = \frac{E_0 - V}{V} \times 100$$



In the case of small machines, the regulation may be machines, the cost of finding the regulation by direct loading becomes prohibitive. Hence other indirect methods are used.

The methods are:-

→ Synchronous impedance or emf method.

→ The Ampere turn or MMF method.

→ Zero P.F method or potier method.

All these method Require:-

1) Armature Resistance
2) o.c characteristic
3) s.c characteristic.

Synchronous Impedance method :-

Consider a field current I_f. The o.c voltage corresponding to this field current is E_1. When winding is short circuited the voltage is zero.

$E_1 = I_1 Z_s$

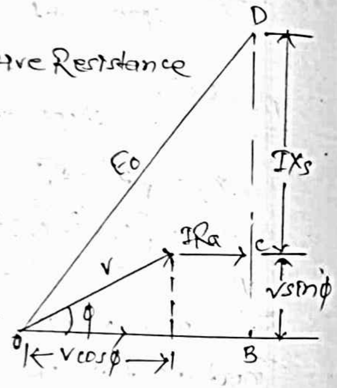
$\therefore Z_s = \frac{E_1 \text{ (open ckt)}}{I_1 \text{ (short ckt)}}$

since R_a can be used as effective Resistance

$\therefore X_s = \sqrt{Z_s^2 - R_a^2}$

Here $OD = E_0$

$E_0 = \sqrt{(OB)^2 + BD^2}$



$E_0 = \sqrt{[(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2]}$

$\% Reg = \frac{E_0 - V}{V} \times 100$

Q- Find the synchronous impedance & reactance of an alternator in which a given field current produces an armature current of 200A on short ckt & a generated emf of 50V on open ckt. The armature resistance is 0.1 ohm. To what induced voltage must the alternator be excited if it is to deliver a load of 100A a P.F of 0.8 lagging, with a terminal voltage of 200V.

Ans- $Z_s = \frac{\text{o.c volt}}{\text{s.c current}} = \frac{50}{200} = 0.25\Omega$

$X_s = \sqrt{Z_s^2 - R_a^2}$
$= \sqrt{0.25^2 - 0.1^2}$
$= 0.23\Omega$

$IR_a = 100 \times 0.1 = 100$

$IX_s = 100 \times 0.23 = 23V$

$\cos\phi = 0.8, \quad \sin\phi = 0.6$

$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

$= \sqrt{(200 \times 0.8 + 10)^2 + (200 \times 0.6 \times 23)^2}$

$= 222V.$

Q- From the following test results, determine the voltage Regulation of a 2000V, 1-φ alternator delivering a current of 100A at (i) unity P.F (ii) 0.8 leading P.F & (iii) 0.71 lagging P.F.

Test results : Full load current of 100A is produced on short ckt by a field excitation of 2.5A. An emf of 500V is produced on open ckt by the same excitation. The armature resistance is 0.8Ω.

Ans- G.t, $V = 2000$, o.c. volt $= 500V$ s.c current $I_{sc} = 100$

$Z_s = \frac{500}{100} = 5\Omega$

$X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{5^2 - 0.8^2} = 4.936\Omega$

$I_aR_a = 100 \times 0.8 = 80V$

$I_aX_s = 100 \times 4.936 = 494V.$

i) unity $E_0 = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$
$= \sqrt{(2000 + 80)^2 + (494)^2}$
$= 2138V$

$\% = \frac{E_0 - V}{V} = \frac{2138 - 2000}{2000} \times 100 = 7\%$

ii) 0.71 lagging-

$E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$
$= \sqrt{(2000 \times 0.71 + 80)^2 + (2000 \times 0.71 + 494)^2}$
$= \sqrt{(1500)^2 + (1914)^2} = 2432V$

$\% = \frac{E_0 - V}{V} = \frac{2432 - 2000}{2000} \times 100 = 21.6\%$

iii) 0.8 leading- $E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2}$
$= \sqrt{(2000 \times 0.8 + 80)^2 + (2000 \times 0.6 - 494)^2}$
$= \sqrt{(1680)^2 + (1706)^2}$
$= 1822$

$\% = \frac{E_0 - V}{V} \times 100 = \frac{1822 - 2000}{2000} \times 100 = -9\%$

Q- A Full load current of 100A requires an excitation current of 3amp, when a single phase 1200V alternator is short-circuited by an ammeter of resistance 0.01Ω, on o.c the same excitation produce 350V, The resistances of the armature is 0.5Ω, calculate the regulation of the alternator at 0.8 p.f leading.

Ans- Rated voltage, $V = 1200V$

$I = 100A$

$R_e = 0.5\Omega$

$$X_s = \sqrt{(R_e + \text{ammeter resistance})^2 + X_s^2}$$

(OR)

$$= \frac{\text{o.c volt}}{\text{s.c current}}$$

$$= \frac{350}{100} = 3.5\Omega$$

(OR)

$$X_s = \sqrt{3.5^2 - 0.5^2} = 3.5\Omega$$

at 0.8 leading p.f, $\cos\phi = 0.8$

$\sin\phi = -0.6$

$$E_0 = \sqrt{(V\cos\phi + IR_e)^2 + (V\sin\phi + IX_s)^2}$$

$$= \sqrt{(1200\times 0.8 + 100\times 0.5)^2 + (1200\times(-0.6) + 100\times 3.5)^2}$$

$= 1.07V.$

$$\text{voltage Regulation} = \frac{1077 - 1200}{1200} \times 100$$

$= -10.25\%$

Q- Find the synchronous impedance & reactance of a single phase alternator in which a given field current produces an armature current produces an armature current of 250A, on s.c & a generated emf of 1500V on open ckt. The armature resistance is 2.0Ω, calculate the terminal potential difference when a load of 250A at 6.6 kV at a lagging pf of 0.8 is switched off.

Ans $R_e = 2.0\Omega$

$$Z_s = \frac{\text{o.c voltage}}{\text{s.c current}}$$

$$= \frac{1500}{250} = 6\Omega$$

$$X_s = \sqrt{Z_s^2 - R_e^2}$$

$$= \sqrt{6^2 - 2^2} = 5.65\Omega$$

Load current $I = 250A$

$V = 6.6kV = 6600V$

$\cos\phi = 0.8$

$\sin\phi = 0.6$

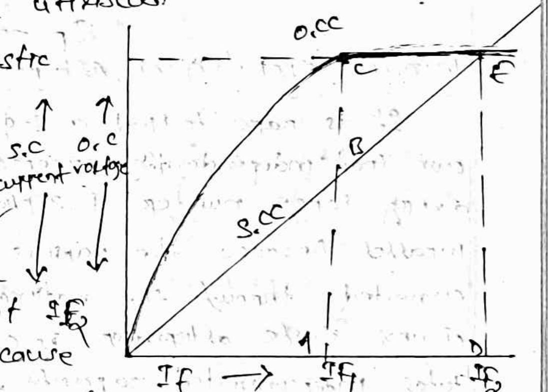
$$E_0 = \sqrt{(V\cos\phi + IR_e)^2 + (V\sin\phi + IX_s)^2}$$

$$= \sqrt{(6600\times 0.8 + 250\times 2)^2 + (6600\times 0.6 + 250\times 5.6)^2}$$

$= 7.89V$ (Ans)

Ampere turn (MMF) Method:-

In this method, the datas determined from open ckt test are utilised.

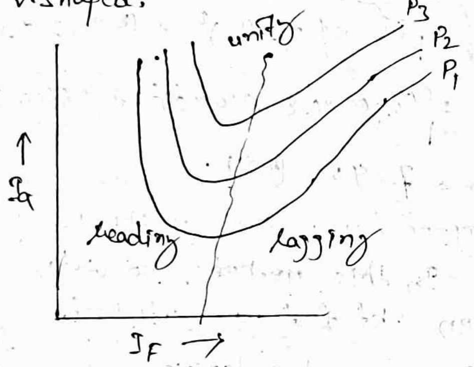


From the characteristic field current I_{f_1} is determined to give rated voltage 'V' on no load, neglecting armature resistance drop & field current I_{f_2} is determined to cause short ckt current equal to full load current on short circuit. On short ckt, the field excitation I_{f_2} balances the impedance drop in addition to armature rea^n on full load. But since R_e is usually very small & X_L is also small for low voltage on short ckt, so impedance drop can be neglecting. Hence p.f on short ckt is almost zero lagging & the field amp turn are used entirely to overcome the armature reaction.

This method of determination of synchronous impedance is known as optimistic method since it gives value lower than actual value. The reason of it is that the excitation to overcome armature reaction is determined on unsaturated part of saturation curve.

V curves for Alternator:-

The graph betn armature current (I_a) & field current (I_F) of an alternator for a constant output power is called its V-curve. The curve is so called because it is V-shaped.



Parallel operation of Alternator:-

It is rare to find a 3-φ alternator supplying its own load independently except test conditions. In practice a very large number of 3-phase alternators operate in parallel because the various power station are interconnected through the national grid. Therefores the o/p of any single alternator is small compared with the total interconnected capacity. For this reason the performance of a single alternator is unlikely to affect appreciable the voltage & current & frequency of the whole system.

An alternator connected to such a system is said to be connected to infinite bush bars. Such busbars are that they have constant voltage, constant frequency busbars. The operation of connecting an alternator to the infine busbar is known as paralleling with the infinite busbars.

Advantages of parallel operation of Alternators:-

→ Continuity of service:- If one alternator fails the continuity of supply can be maintained through the other healthy units. This will ensure uninterrupted supply to the consumers.

→ Efficiency:- The load on the power system varies during the whole day, being minimum during the late night hours. Since alternators operates most efficiently when delivering full load this permits the efficient operation of the power system.

→ Maintance & Repair:- It is often desirable to carry out routine maintance & repair of one or more units. For this purpose, the desired unit can be shunt down & the continuity of supply is maintained through the other units.

→ Load growth:- The load demand is increasing due to the increasing use of electrical energy. The load growth can be met by adding more unit without disturbing the original installation.

Conditions for paralleling alternator with infinite busbar

The proper method of connecting an alternator to the infinite busbars is called synchronising. In order to connect an alternator safely to the infinite busbar the following conditions are met:-

i) The terminal voltages (r.m.s value) of the incoming alternator must be same as busbars voltage.

ii) The frequency of the generated voltage of the incoming alternator must be equal to the busbar frequency.

iii) The phase of the incoming alternator voltage must be identical with the phase of the busbars voltage.

iv) The phase sequence of the voltage of the incoming alternator should be the same as that of the busbar.

Methods of synchronisation :-

The method of connecting an incoming alternator safely to the live busbar is called synchronising.

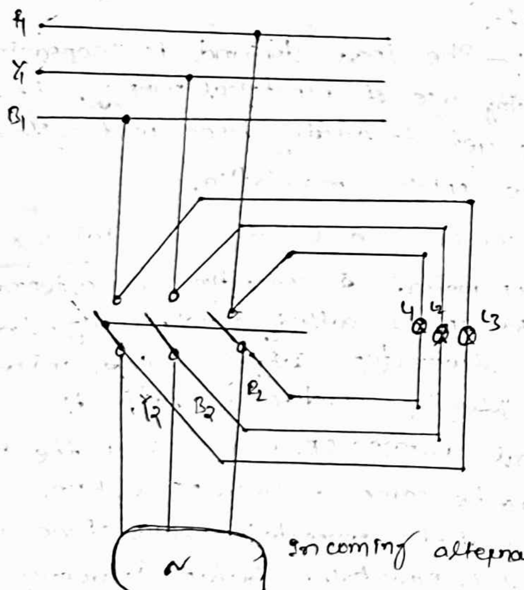
-> The equality of the voltage between the incoming alternator & the busbars can be easily checked by voltmeter.

-> The phase sequence of the alternator & the busbars can be checked by a phase sequence indicator.

-> Difference in frequency & phase of the voltage of the incoming alternator & busbar can be checked by two methods :-

(i) By three lamp method.
(ii) By synchroscope

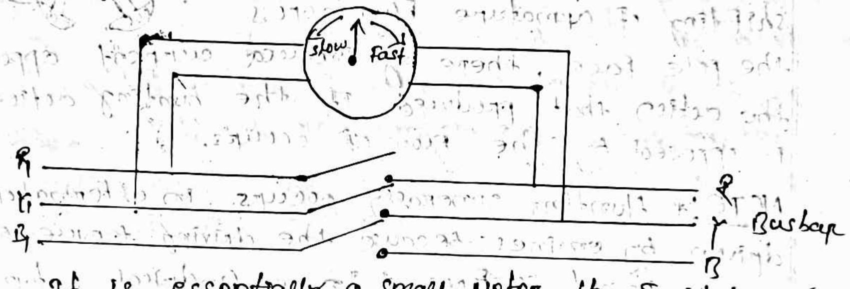
i) Three lamp method :-



In this method of synchronising three lamps L_1, L_2 & L_3 are connected as shown in above. The lamp L_1 is straight connected between the corresponding phase (R_1 & R_2) & the other two are cross-connected between the other two phases. The lamp L_2 is connected bet^n Y_1 & B_2 & lamp L_3 bet^n B_1 & Y_2. When the frequency & phase of the voltage of the busbars the straight connected lamp L_1 will be dark while cross connected lamps L_2 & L_3 will be equally bright so that it is also called one dark & two bright method. At this instant the synchronisation is perfect & the switch of the incoming alternator can be closed to connect it to the busbars. Thus incoming alternator can be closed to connect it to the busbars.

ii) Synchroscope :-

A synchroscope is an instrument that indicates by means of a revolving pointer the phase difference & frequency difference bet^n the voltage of the incoming alternator & the busbar.



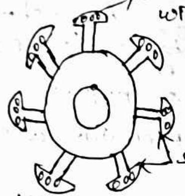
It is essentially a small motor, the field being supplied from the busbar through a potential half & the rotor from the incoming alternator. A pointer is attached to the rotor. When the incoming alternator is running fast frequency of the incoming alternator is higher than that of the busbars, the rotor & hence the pointer moves in the clockwise direction. When the alternator is running slow i.e the frequency of the alternator is lower than that of the busbar, the pointer moves anticlockwise direction. When the frequency of the alternator is equal to that of the busbar, no torque acts on the rotor & this pointer points vertically upward. It indicates the correct instant for connecting the alternator to the busbars. The synchoscope method is superior to the lamps method. Because is not only gives a true indication but the adjustment should there be bet^n the frequency of alternator & bus bar.

Hunting :-

Sometimes an alternator will not operate satisfactory with others due to hunting.

→ If the driving torque applied to an alternator is pulsating such that produced by diesel engine, the alternator rotor may be pulled periodically a head of or behind its normal position as it rotates. This oscillation action is called hunting. In salient pole machine, hunting is reduced by providing damper winding.

It consists of short ckt copper bars, embedded in the pole face.



When hunting occurs, there is shifting of armature flux across the pole face, there by induced current opposes the action that produced it the hunting action is opposed by the flow of occurs.

NOTE :* Hunting generally occurs in alternator driven by engines because the driving torque of engines is not conform. * In cylindrical rotor machines the damper winding are generally not used. It is because the considerable damping.

9/11/2021

Three phase Induction motors

Dt-08-11-21

Introduction

The 3-φ induction motors are the most widely used electric motors in industry. They run at essentially constant speed from no-load to full load.

3-φ induction motor :-

-> Like any electric motor, a 3-φ induction motor has a stator and a rotor.

-> The stator carries a 3-φ winding (called stator winding) while the rotor carries a short ckted winding (called rotor winding).

-> Only the stator winding is fed from 3-φ supply. The rotor winding derives its voltage and power from the externally energised stator winding through electromagnetic induction and hence the name.

-> The induction motor may be considered to be a transformer with a rotating secondary and it can, therefore, be described as a "transformer type" a.c. machine in which electrical energy is converted into mechanical energy.

Advantages :-

-> It has simple and rugged construction.

-> It is relatively cheap.

-> It requires little maintenance.

-> It has high efficiency and reasonably good power factor.

-> It has self - starting torque.

Disadvantages :-

-> It is essentially a constant speed motor and its speed cannot be changed easily.

-> Its starting torque is inferior to dc shunt motor.

Construction :-

-> A 3-φ induction motor has two main parts:-

(i) stator and (ii) Rotor

-> The rotor is separated from the stator by a small air-gap which ranges from 0.4mm to 4mm, depending on the power of the motor.

1) Stator:-

-> It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current loss.

-> A number of evenly spaced slots are provided on the inner periphery of the laminations.

-> The insulated conductors are placed in the stator slots and are suitably connected to form a balanced 3-ϕ star or delta connected circuit.

2) Rotor:- The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery.

(i) squirrel cage type (ii) Wound type

i) Squirrel cage type:-

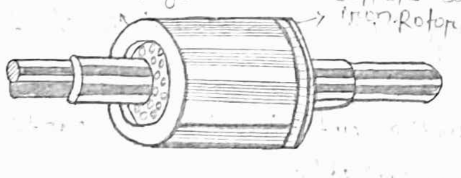
-> It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminium bar is placed in each slot.

-> All these bars are joined at each end by metal rings called end rings.

-> This forms a permanently short-ckted winding which is indestructible.

-> Those induction motors which employ squirrel cage are called squirrel cage induction motors.

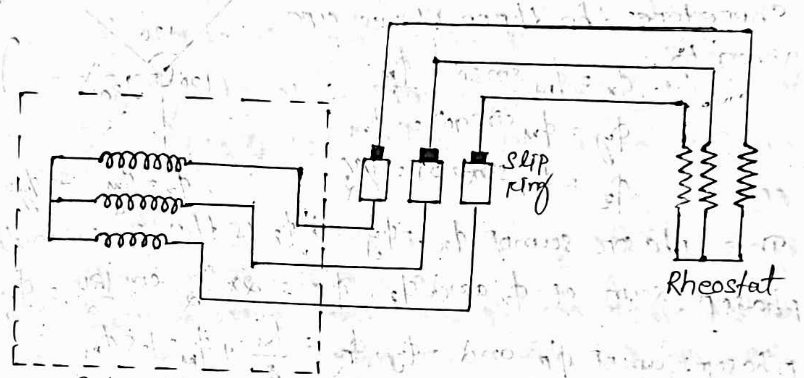
-> Motor of 3-ϕ induction motors use squirrel cage rotor as it has remarkably simple and robust construction enabling it to operate in the most adverse circumstances.



ii) Wound type Rotor:-

-> It consists of a laminated cylindrical core and carries a 3-ϕ winding similar to the one on the stator.

-> The rotor winding is uniformly distributed in the slots and is usually star-connected.

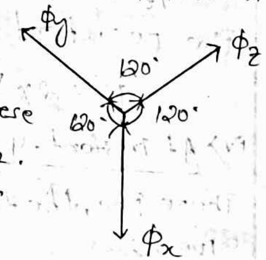


Rotor Winding

Rotating Magnetic Field Due to 3-ϕ Currents:-

-> When a 3-ϕ winding is energised from a 3-ϕ supply, a rotating magnetic field is produced.

-> This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating field.



-> The 3-ϕ X, Y and Z are energised from a 3-ϕ source and currents in these phases are indicated as I_x, I_y and I_z.

** Fluxes produced by these currents are given by:

$$\phi_x = \phi_m \sin\omega t$$
$$\phi_y = \phi_m \sin(\omega t - 120°)$$
$$\phi_z = \phi_m \sin(\omega t - 240°)$$

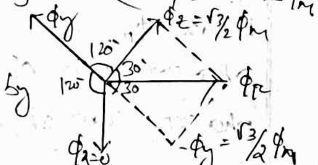
-> We shall now prove that this 3-ϕ supply produces a rotating field of constant magnitude equal to $1.5\phi_m$

1) At instant-1 $\omega t = 0°$

Therefore, the three fluxes are given by

$\phi_x = 0$; $\phi_y = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m$

$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$



The phasor sum of $-\phi_y$ and ϕ_z is the resultant flux ϕ_r.
It is clear that.

Resultant flux, $\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60^\circ}{2}$
$= 2 \times \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = 1.5\phi_m$

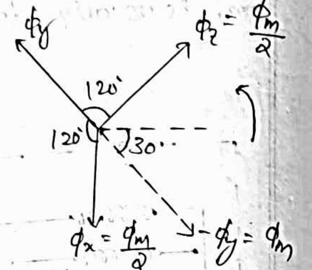
ii) **At instant-2** $\omega t = 30^\circ$

Therefore, the three fluxes are given by,

$\phi_x = \phi_m \sin 30^\circ = \frac{\phi_m}{2}$

$\phi_y = \phi_m \sin(-90^\circ) = -\phi_m$

$\phi_z = \phi_m \sin(-210^\circ) = \phi_m/2$



The phasor sum of ϕ_x, $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

phasor sum of ϕ_x and ϕ_z, $\phi'_r = 2 \times \frac{\phi_m}{2}\cos\frac{120^\circ}{2} = \frac{\phi_m}{2}$

phasor sum of ϕ'_r and $-\phi_y$, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\phi_m$

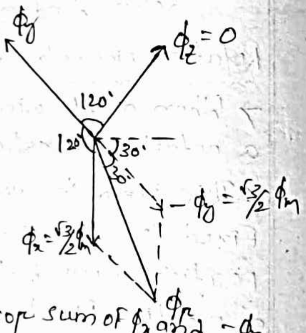
iii) **At instant-3** $\omega t = 60^\circ$

There, the three fluxes are given by,

$\phi_x = \phi_m \sin 60^\circ = \phi_m \sqrt{3}/2$

$\phi_y = \phi_m \sin(-60^\circ) = -\sqrt{3}/2\,\phi_m$

$\phi_z = \phi_m \sin(-180^\circ) = 0$



The resultant flux ϕ, is the phasor sum of ϕ_x and $-\phi_y$

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60^\circ}{2} = 1.5\phi_m \quad (\because \phi_z = 0)$$

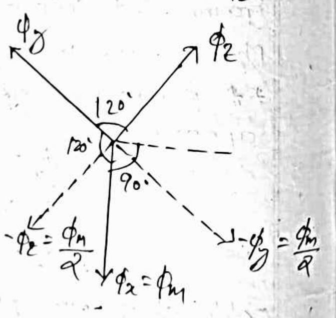
iv) **At instant-4** $\omega t = 90^\circ$

Therefore, the three fluxes are given by:

$\phi_x = \phi_m \sin 90^\circ = \phi_m$

$\phi_y = \phi_m \sin(-30) = -\frac{\phi_m}{2}$

$\phi_z = \phi_m \sin(-150^\circ) = -\frac{\phi_m}{2}$



The phasor sum of ϕ_x, $-\phi_y$ and $-\phi_z$ is the resultant flux ϕ_r.

phasor sum of $-\phi_z$ and $-\phi_y$, $\phi'_r = 2 \times \frac{\phi_m}{2}\cos\frac{120^\circ}{2} = \frac{\phi_m}{2}$

phasor sum of ϕ'_r and ϕ_x, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\phi_m$

Speed of Rotating Magnetic Field:-

-> The speed at which the rotating magnetic field revolves is called the synchronous speed (N_s).

-> During this one quarter cycle, the field has rotated through 90°.

-> In general, for 'P' poles the rotating field makes one revolution in P/2 cycles of current.

$\therefore$ cycles of current $= \frac{P}{2} \times$ revolutions of field.

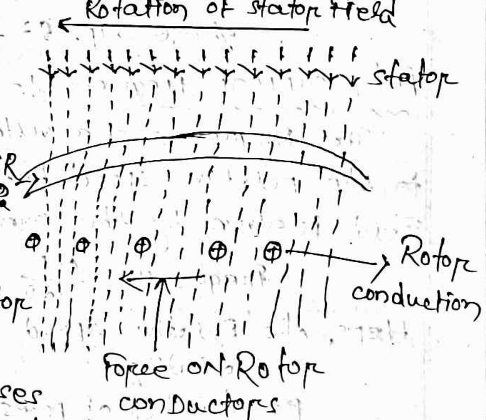
$$\therefore f = \frac{P}{2} \times \frac{N_s}{60} = \frac{N_s P}{120}$$

$$N_s = \frac{120f}{P}$$

Principle of Operation:-

-> consider a portion of 3-ϕ induction motor as

-> The operation of the motor can be explained as under:-



i) When 3-ϕ stator winding is energised from a 3-ϕ supply, a rotating magnetic field is setup which rotates around the stator at synchonous speed $N_s (= 120f/P)$

ii) The rotating field passes through the air gap and cuts the rotor conductors, which as yet, are stationary. Due to the relative speed between the rotating flux and the stationary rotor, emfs are induced in the rotor conductors. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.

iii) The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently mechanical forces acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque which tends to move the rotor in the same direction as the rotating field.

iv) The fact that rotor is urged to follow the stator field (i.e rotor moves in the direction of stator field) can be explained by Lenz law. According to this law, the dirⁿ of rotor currents will be such that they tend to oppose the cause producing them. Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors. Hence to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.

Slip:-

The difference between the synchronous speed N_s, of the rotating stator field and the actual rotor speed N is called * slip. It is usually expressed as a percentage of synchronous speed. i.e,

$$\text{\% age slip}, s = \frac{N_s - N}{N_s} \times 100$$

Rotor current Frequency:-

The frequency of a voltage or current induced due to the relative speed between a winding and a magnetic field is given by the general formula:

$$\text{Frequency} = \frac{NP}{120}$$

Here, N = Relative speed betⁿ magnetic field and the winding.

P = Number of poles.

For a rotor speed N, the relative speed between the rotating flux and the rotor is $N_s - N$. Consequently, the rotor current frequency f' is given by;

$$f' = \frac{(N_s - N)P}{120}$$

$$= \frac{s N_s P}{120} \qquad \left[\because s = \frac{N_s - N}{N_s}\right]$$

$$= sf \qquad \left[\because f = N_s P/120\right]$$

i.e Rotor current frequency = Fractional slip × Supply frequency.

i) When the rotor is at stand still or stationary (i.e $s=1$), the frequency of rotor current is the same as that of supply frequency. ($f' = sf = 1 \times f = f$)

ii) As the rotor picks up speed, the relative speed betⁿ the rotating flux and the rotor decreases. Consequently, the slip s and hence rotor current frequency decreases.

Example-1 A 6-pole, 3-φ induction motor is connected to 50Hz supply. If it is running at 970 r.p.m. Find the slip.

Solⁿ - Synchronous speed, $N_s = 120f/P = 120 \times 50/6 = 1000$ r.p.m

$$\text{Slip}, s = \frac{N_s - N}{N_s} \times 100 = \frac{1000 - 970}{1000} \times 100 = 3\% \text{ or } 0.03$$

Example-2 A 3-φ induction motor is wound for 4 poles and is supplied from 50Hz system. Calculate (i) the synchronous speed (ii) the speed of the motor when slip is 4% and (iii) the rotor current frequency when the motor runs at 600 r.p.m.

Solⁿ → (i) Synchronous speed, $N_s = 120f/P = 120 \times 50/4 = 1500$ r.p.m

(ii) $\text{Slip}, s = \frac{N_s - N}{N_s} \times 100$

$$4 = \frac{1500 - N}{1500} \times 100$$

$$N = 1440 \text{ r.p.m}$$

(iii) When $N = 600$ r.p.m, $s = \frac{1500 - 600}{1500} = 0.6$

∴ Rotor current frequency, $f' = sf = 0.6 \times 50 = 30Hz$

Effect of slip on the Rotor circuit:-

→ When the rotor is stationary, $s=1$. Under these conditions, the per phase rotor emf. E_2 has a frequency equal to that of supply frequency f.

→ At any slip s, the relative speed between stator field and the rotor is decreased.

→ At the same time, per phase rotor reactance X_2, being frequency dependent, is reduced to sX_2.

(i) The relative speed betⁿ stator flux and the rotor is now only 40 r.p.m. Consequently, rotor emf/phase is reduced to:

$$* \; E_2 \times \frac{40}{1000} = 0.04E_2 \text{ or } sE_2$$

ii) The frequency is also reduced in the same ratio to:

$$50 \times \frac{40}{1000} = 50 \times 0.4 \text{ or } sf$$

iii) The per phase rotor reactance X_2 is likewise reduced to:

Thus at any slip s,

Rotor emf/phase $= sE_2$

Rotor reactance/phase $= sX_2$

Rotor frequency $= sf$

where E_2, X_2 and f are the corresponding values at stand still.

Example- A 3-ϕ, 6-pole induction motor is connected to a 60Hz supply. The voltage induced in the rotor bars is 4.0V when the rotor is at stand still. Calculate the voltage and frequency induced in the rotor bars at 300 r.p.m.

Soln Synchronous speed, $N_s = 120f/P = 120 \times 60/6 = 1200$ r.p.m

slip, $s = \frac{N_s - N}{N_s} = \frac{1200-300}{1200} = 3/4$

corresponding to this slip, we have,

Induced voltage $= 4 \times s = 4 \times 3/4 = 3V$

Frequency $= f \times s = 60 \times 3/4 = 45Hz$

Starting Torque (T_s)

E_2 = Rotor emf per phase at stand still

X_2 = Rotor reactance per phase at stand still

R_2 = Rotor resistance per phase

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$

Rotor current/phase, $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2+X_2^2}}$

Rotor P.F, $\cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2+X_2^2}}$

starting torque, $T_s = kE_2 I_2 \cos\phi_2$

$$= kE_2 \times \frac{E_2}{\sqrt{R_2^2+X_2^2}} \times \frac{R_2}{\sqrt{R_2^2+X_2^2}}$$

$$= \frac{kE_2^2 R_2}{R_2^2+X_2^2}$$

$$\therefore T_s = \frac{k_1 R_2}{R_2^2+X_2^2} = \frac{k_1 R_2}{Z_2^2}$$

$$\therefore T_s = \frac{3}{2\pi N_s} \times \frac{E_2^2 R_2}{R_2^2+X_2^2}$$

Condition for Maximum Starting Torque :-

$$T_s = \frac{k_1 R_2}{R_2^2+X_2^2} \quad \text{--- (1)}$$

Differentiating eqn (1) w.r.t R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = k_1 \frac{d}{dR_2}\left(\frac{R_2}{R_2^2+X_2^2}\right) = 0$$

$$= \frac{(R_2^2+X_2^2).1 - R_2 . 2R_2}{(R_2^2+X_2^2)} = 0$$

$$= R_2^2 + X_2^2 - 2R_2^2 = 0$$

$$= X_2^2 - R_2^2 = 0$$

$$\Rightarrow X_2^2 = R_2^2$$

$$\Rightarrow X_2 = R_2$$

Effect of change of supply voltage :-

$$T_s = \frac{kE_2^2 R_2}{R_2^2+X_2^2}$$

since $E_2 \propto$ supply voltage V.

$$\therefore T_s = \frac{k_2 V^2 R_2}{R_2^2+X_2^2}$$

Starting Torque of 3-ϕ Induction Motors :-

-> The rotor circuit of an induction motor has low resistance and high inductance.

-> At starting, the rotor frequency is equal to the stator frequency (i.e 50Hz) so that rotor reactance is large compared with rotor resistance.

-> Therefore, rotor current lags that rotor emf by a large angle, the power factor is low and consequently the starting torque is small.

i) Squirrel-cage motors:-

→ Squirrel cage motors have starting torque of 1.5 to 2 times the full-load value with starting current of 5 to 9 times the full-load current.

ii) Wound rotor motors:-

→ By inserting the proper value of external resistance (so that $R_2 = X_2$), max^m starting torque can be obtained.

→ As the motor accelerates, the external resistance is gradually cut out until the rotor circuit is short-ckted on itself for running conditions.

Torque under Running conditions:-

Let the rotor at standstill have perphase induced emf E_2, reactance X_2 and Resistance R_2. Then under running conditions at slip's,

$$\text{Rotor emf/phase, } E_2' = sE_2.$$

Max^m Torque under Running conditions:-

$$T_r = \frac{k_2 s R_2}{R_2^2 + s^2 X_2^2} \quad \text{—— (1)}$$

In order to find the value of rotor resistance that gives maximum torque under running conditions, Differentiate exp. (i) w.r.t 's' and equate the result to zero

i.e $$\frac{dT_r}{ds} = k_2\left[\frac{d}{ds}\left(\frac{sR_2}{(R_2^2 + s^2X_2^2)}\right)\right] = 0$$

$$= \left[\frac{(R_2^2 + s^2X_2^2)\frac{d}{ds}k_2 sR_2 - k_2 sR_2 \frac{d}{ds}(R_2^2 + s^2X_2^2)}{R_2^2 + s^2X_2^2}\right] = 0$$

$$= \left((R_2^2 + s^2X_2)k_2R_2 - k_2 sR_2(0 + 2sX_2^2)\right) = 0$$

$$= k_2R_2\left[(R_2^2 + s^2X_2^2) - (2s^2X_2^2)\right] = 0$$

$$= \left[R_2^2 - s^2X_2^2\right) = 0$$

$$\Rightarrow R_2^2 = s^2X_2^2$$

$$\Rightarrow \boxed{R_2 = sX_2}$$

Thus for max^m torque (T_M) under running conditions:

Rotor resistance/phase = Fractional slip × standstill rotor reactance/phase

$$T_r \propto \frac{sR_2}{R_2^2 + s^2X_2^2} \quad \text{—— From eq}^n\text{(1) above.}$$

For maximum torque, $R_2 = sX_2$ putting $R_2 = sX_2$ in the above expression, the max^m torque T_M is given by:-

$$T_M \propto \frac{1}{2X_2}$$

Slip corresponding to maximum torque, $s = \frac{R_2}{X_2}$.

It can be shown that;

$$T_M = \frac{3}{2\pi N_s} \times \frac{E_2^2}{2X_2} \text{ N-m} \quad \text{— } N_s \text{ in r.p.s}$$

It is evident from the above equations that:

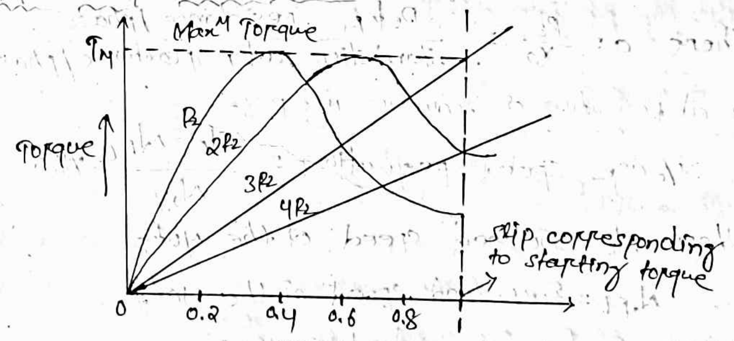
i) The value of Rotor resistance does not alter the value of the maximum torque but it only changes the value of the slip at which it occurs.

ii) The max^m torque varies inversely as the standstill reactance. Therefore, it should be kept as small as possible

iii) The max^m torque varies directly with the square of the applied voltage.

iv) To obtain max^m torque at starting (s=1), the rotor resistance must be made equal to rotor reactance at standstill.

Torque-slip characteristics:-



The following points may be noted carefully:

i) At s=0, T=0 so that torque-slip curve starts from the origin.

ii) At normal speed, slip is small so that s^2X_2 is negligible as compared to R_2.

$$T \propto s/R_2$$
$$T \propto s \quad \rightarrow \text{as } R_2 \text{ is constant.}$$

Hence torque-slip curve is a straight line from zero slip to a slip that corresponds to full-load.

Full-Load, Starting And Max^m Torques:-

$$T_f \propto \frac{sR_2}{R_2^2+(sX_2)^2}$$

$$T_s \propto \frac{R_2}{R_2^2+X_2^2}$$

$$T_M \propto \frac{1}{2X_2}$$

Note that 's' corresponds to Full-load slip.

i) $\therefore \frac{T_M}{T_f} = \frac{R_2^2+(sX_2)^2}{2sR_2X_2}$

Dividing the numerator and denominator on R.H.S by X_2^2, we get,

$$\frac{T_M}{T_f} = \frac{(R_2/X_2)^2+s^2}{2s(R_2/X_2)} = \frac{a^2+s^2}{2as}$$

Where, $a = \frac{R_2}{X_2} = \frac{\text{Rotor resistance / phase}}{\text{Stand still rotor reactance / phase}}$

ii) $\frac{T_M}{T_s} = \frac{R_2^2+X_2^2}{2R_2X_2}$

Dividing the numerator and denominator on R.H.S by X_2^2 we get

$$\frac{T_M}{T_s} = \frac{(R_2/X_2)^2+1}{2(R_2/X_2)} = \frac{a^2+1}{2a}$$

Where $a = \frac{R_2}{X_2} = \frac{\text{Rotor resistance / phase}}{\text{Standstill rotor reactance / phase}}$

Speed Regulation of Induction Motors:-

$$\%\text{age speed regulation} = \frac{N_0 - N_{F.L}}{N_{F.L}} \times 100$$

Where, N_0 = no-load speed of the motor

$N_{F.L}$ = Full-load speed of the motor

Power Factor of Induction Motor:-

$$\text{power factor, } \cos\phi = \frac{\text{Active component of current } (I\cos\phi)}{\text{Total current } (I)}$$

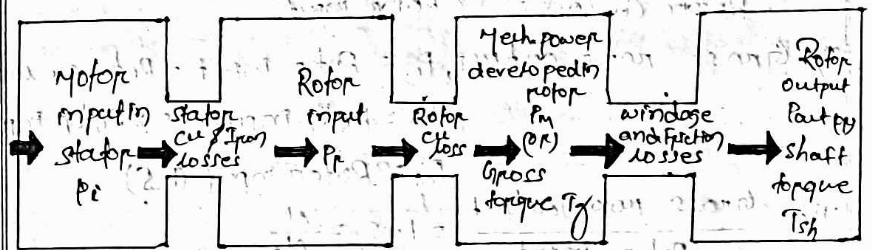
Power stages In an Induction Motor:-

1) Fixed losses:-

(i) Stator Iron loss (ii) Friction and windage loss.

2) Variable losses:-

(i) Stator copper loss (ii) Rotor copper loss.



Induction Motor Torque:-

The Mechanical power 'P' available from any electric motor can be expressed as:-

$$P = \frac{2\pi NT}{60} \text{ watts}$$

Here, N = speed of the Motor in R.P.M

T = torque developed in N-M

$$\therefore T = \frac{60}{2\pi}\frac{P}{N} = 9.55\frac{P}{N} \text{ N-M}$$

If the gross output of the rotor of an induction motor is P_M and its speed is N r.p.m, then gross torque T_g developed is ~~given by~~:

$$T_g = 9.55\frac{P_M}{N} \text{ N-M}$$

Similarly $T_{sh} = 9.55\frac{P_{out}}{N}$ N-M

Note- Since windage and friction loss is small, $T_g = T_{sh}$. This assumption leads to any significant error.

Rotor output:-

If T_g newton-metre is the gross torque developed and N r.p.m is the speed of the rotor, then,

$$\text{Gross rotor output} = \frac{2\pi NT_g}{60} \text{ watts}$$

If there were no copper losses in the rotor, the output would equal rotor input and the rotor would run at synchronous speed N_s,

$\therefore$ Rotor input $= \frac{2\pi N_s T_g}{60}$ watts

$\therefore$ Rotor Cu loss = Rotor input − Rotor output

$= \frac{2\pi T_g}{60}(N_s - N)$

i) $\frac{\text{Rotor Cu loss}}{\text{Rotor input}} = \frac{N_s - N}{N_s} = s$

$\therefore$ Rotor Cu loss = s × Rotor input.

ii) Gross rotor output, P_M = Rotor input − Rotor cu loss

P_M = Rotor input − s × Rotor input

P_M = Rotor input (1−s)

iii) $\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s = \frac{N}{N_s}$

iv) $\frac{\text{Rotor Cu loss}}{\text{Gross rotor output}} = \frac{s}{1-s}$

Induction Motor Torque Equation

The gross T_g developed by an induction motor is given by:

$T_g = \frac{\text{Rotor input}}{2\pi N_s}$ — N_s in r.p.s

$= \frac{60 \times \text{Rotor input}}{2\pi N_s}$ — N_s in r.p.m

Now, Rotor input $= \frac{\text{Rotor Cu loss}}{s} = \frac{3(I_2')R_2}{s}$ —①

Under running conditions,

$I_2' = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} = \frac{sKE_1}{\sqrt{R_2^2 + (sX_2)^2}}$

Where, K = Transformation ratio

$= \frac{\text{Rotor turns/phase}}{\text{stator turns/phase}}$

$\therefore$ Rotor input $= 3 \times \frac{s^2 E_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{1}{s}$

$= \frac{3sE_2^2 R_2}{R_2^2 + (sX_2)^2}$ [Putting the value of I_2' in eqn ①]

Also, Rotor input $= 3 \times \frac{s^2 K^2 E_1^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{1}{s}$

$= \frac{3sK^2E_1^2R_2}{R_2^2 + (sX_2)^2}$ [Putting the value of I_2' in eqn (1)]

$\therefore T_g = \frac{\text{Rotor input}}{2\pi N_s} = \frac{3}{2\pi N_s} \times \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$ [In terms of E_2]

$= \frac{3}{2\pi N_s} \times \frac{sK^2E_1^2R_2}{R_2^2 + (sX_2)^2}$ [In terms of E_1]

Example - A 3-φ, 60 Hz, 4-pole, star-connected induction motor having a nominal rating of 75 kW is excited by a 600V source. The two-wattmeter method shows a total power consumption of 70 kW and an ammeter indicates a line current of 78 A. Precise measurements gives a rotor speed of 1763 r.p.m. The following char. of the motor are known:

Stator Iron loss = 2 kW

Windage and friction loss = 1.2 kw

Resistance betn two stator terminals = 0.34 Ω

Calculate (i) power supplied to the rotor (ii) Rotor cu losses (iii) Motor output (iv) efficiency (v) gross torque

Soln. power input to stator = 70 kW

(i) stator resistance/phase, $R_1 = 0.34/2 = 0.17\,\Omega$

Stator cu loss $= 3I_1^2 R_1 = 3(78)^2 \times 0.17 = 3.1$ kW

Stator Iron loss = 2 kW (given)

Total stator losses = 3.1 + 2 = 5.1 kW

power supplied to rotor, P_r = 70 − 5.1 = 64.9 kW

ii) Motor slip, $s = \frac{N_s - N}{N_s} = \frac{1800 - 1763}{1800} = 0.0205$

$\therefore$ Rotor Cu loss $= sP_r = 0.0205 \times 64.9 = 1.33$ kW

(iii) Mech power developed is given by:

$P_M = P_r$ − Rotor Cu loss

= 64.9 − 1.33 = 63.5 kW.

Motor output, $P_{out} = P_M$ − windage and friction loss

= 63.5 − 1.2

= 62.3 kw

iv) Motor efficiency, $\eta = \frac{62.3}{70} \times 100$

$= 89\%$

v) Gross torque, $T_g = 9.55 \times \frac{P_m}{N} = 9.55 \times \frac{62.5 \times 10^3}{1763} = 344\,Nm$

Plugging of an Induction motor:-

-> In some Industrial applications, it is desired to bring the running induction motor to a rapid stop.

-> This can be done by simply interchanging the two stator leads.

-> This process is called plugging. When we interchange two stator leads, the revolving field suddenly turns in the opposite direction to the rotor.

-> During the plugging period, the motor acts as a brake. It absorbs kinetic energy from the still revolving field, causing its speed to fall.

-> The mech power associated with the rotor is entirely dissipated as heat in the rotor.

-> Unfortunately, the rotor also continues to receive power from the stator which is also dissipated as heat.

-> Consequently, plugging produces I^2R losses in the rotor which even exceed those when the rotor is locked.

Induction Generator:-

-> If an induction motor whose stator windings are connected to a 3-ϕ line is driven by a primemover at a speed higher than synchronous speed, it acts as a generator.

-> It converts the mechanical energy it receives from the prime-mover into electrical energy and electrical energy is supplied to the mains.

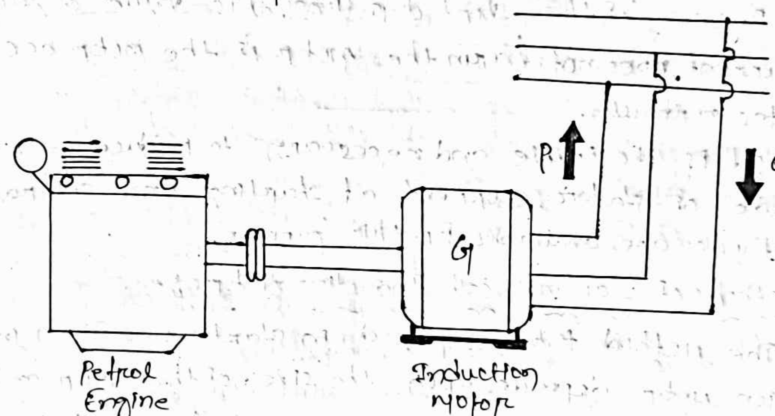
-> Such a machine is called an induction generator or a synchronous generator.

-> When speed of the induction motor exceeds the synchronous speed, the slip (s) becomes negative.

-> Therefore, the relative motion betn the rotor conductors and the rotating flux is reversed and as a result, the directions of rotor emf and rotor currents will also be reversed.

-> The petrol engine is the prime-mover. As soon as the engine speed exceeds the synchronous speed, the motor becomes a generator, delivering active power P (kW) to the electrical systems to which is connected.

-> However, to create its magnetic field, the motor has to absorb relative power Q (kVAR). This power can only come from the supply lines.



-> The active power P(kW) delivered is directly proportional to the slip above synchronous speed.

-> Thus, a higher engine speed produces a greater output. However, the rated output is reached at very small slip, generally less than 3%.

Applications of Induction Generators:-

-> The most important use of the principle of the induction generator lies in automatic dynamic braking.

-> The motor speed exceeds the synchronous speed and the machine automatically becomes an induction generator and produces a braking torque, returning the energy of the descending load to the supply.

Starting of 3-ϕ Induction motors:-

-> The induction motor is fundamentally a transformer in which the stator is the primary and the rotor is short-ckted secondary.

-> At starting the voltage induced in the induction motor rotor is maximum ($\because s=1$).

-> Since the rotor impedance is low, the rotor current is excessively large.

-> This large rotor current is reflected in the stator because of transformer action.

-> This results in high starting current (4 to 10 times the full load current) in the stator at * low power factor and consequently the value of starting torque is low.

-> Because of the short duration, this value of large current does not harm the motor if the motor accelerates normally.

-> It is desirable and necessary to reduce the magnitude of stator current at starting and several methods are available for this purpose.

Methods of starting 3-ϕ Induction motors :-

-> The method to be employed in starting a given induction motor depends upon the size of the motor and the type of the motor. The common methods used to start induction motors are :-

(i) Direct-on-line starting
(ii) stator resistance starting
(iii) Autotransformer starting.
(iv) star-delta starting.
(v) Rotor resistance starting.

Methods of starting squirrel-cage motors :-

i) Direct-on-line starting :-

-> This method of starting is just what the name implies - the motor is started by connecting it directly to 3-ϕ supply.

-> The impedance of the motor at standstill is relatively low and when it is directly connected to the supply system, the starting current will be high and at a low power factor.

-> Consequently, this method of starting is suitable for relatively small (upto 7.5 kW) machines.

ii) stator resistance starting :-

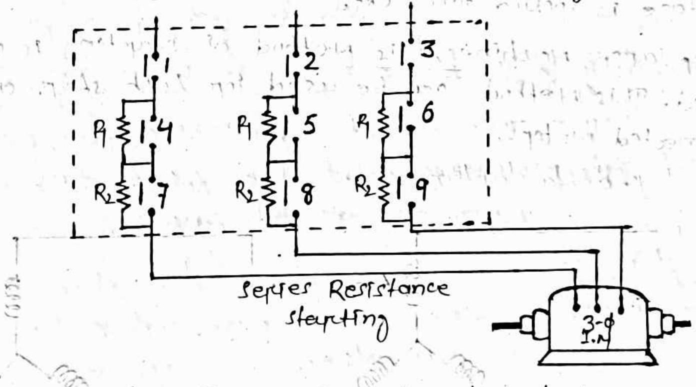
-> The external resistances are connected in series with each-ϕ of stator winding during starting.

-> This causes voltage drop across the resistances so that voltage available across motor terminals is reduced and hence the starting current.

-> The resistances are gradually cut out in steps from the stator ckt. as the motor picks up speed.

-> When the motor attains rated speed, the resistances are completely cut out and full line voltage is applied to the motor.

Start : close 1-2-3
Next : close 4-5-6
Finally : close 7-8-9



Series Resistance starting

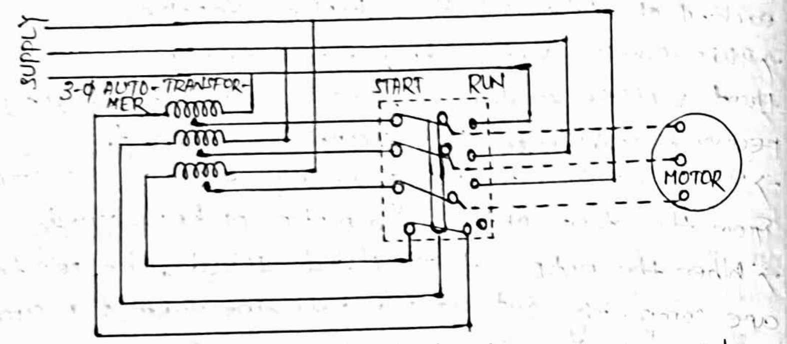
-> This method suffers from two drawbacks. First, the reduced voltage applied to the motor during the starting period * lowers the starting torque and hence increases the accelerating time.

-> Secondly, a lot of power is wasted in the starting resistances.

iii) Autotransformer starting :-

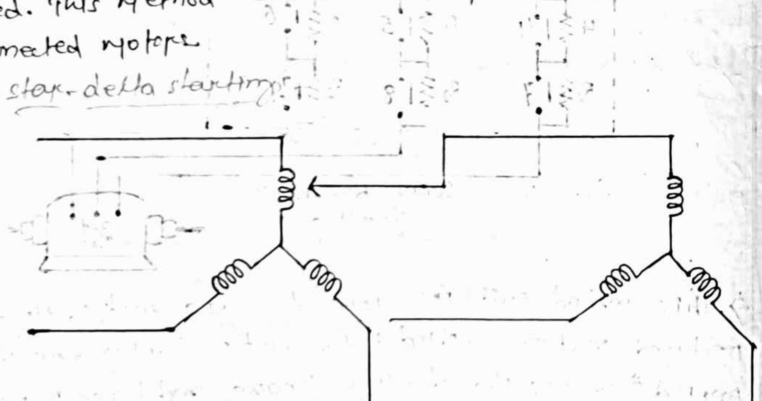
-> This method also aims at connecting the induction motor to a reduced supply at starting and then connecting it to the full voltage as the motor picks up sufficient speed.

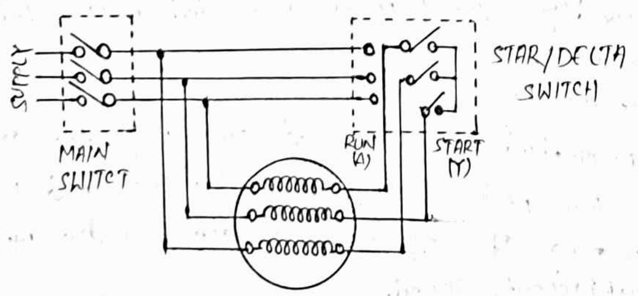
-> The tapping on the autotransformer is so set that when it is in the ckt, 65% to 80% of line voltage is applied to the motor.



-> At the instant of starting, the change-over switch is thrown to 'start' position.
-> This puts the autotransformer in the ckt and thus reduced voltage is applied to the ckt.
-> For large machines, this method of starting is often used. This method can be used for both star and delta connected motors.

v) star-delta starting:





-> The stator winding of the motor is designed for delta operation and is connected in star during the starting period.
-> When the machine is up to speed, the connections are changed to delta. The ckt arrangement for star-delta starting.
-> The six leads of the stator windings are connected to the change-over switch.
-> At the instant of starting, the change-over switch is thrown to "start" position which connects the stator winding in star.
-> Therefore, each stator phase gets $V/\sqrt{3}$ volts where 'V' is the line voltage.
-> This reduces the starting current. When the motor picks up speed change over switch is thrown to run position which connects the stator winding in delta.
-> Now each stator phase gets full line voltage V. The disadvantages of this method are:

a) With star-connection during starting, stator phase voltage is $1/\sqrt{3}$ times the line voltage.
Consequently, starting torque is $(1/\sqrt{3})^2$ or $1/3$ times the value it would have with Δ-connection. This is rather is large reduction in starting torque.

b) The reduction in voltage is fixed.
This method of starting is used for medium-size machines (upto 25 h.p)

Induction motor rating:-
-> The name plate of 3-φ induction motor provides the following information:-
(i) Horse power (ii) Line voltage
(iii) Line current (iv) Speed
v) Frequency (vi) Temp. rise.

Introduction :-

-> All electric machines have the same basic principle of operation, special purpose machines have some features that distinguish them from conventional machines.

-> For example:- a stepper motor rotates by a specific number of degrees (eg. 2°, 2.5°, 5° or 7.5°) in response to an input electrical signal and is widely used in digital control systems.

Stepper Motor :-

-> Stepper motors are also known as stepping motors or step motors. A stepper motor is an electromagnetic motor that rotates by a specific number of degrees in response to an input electrical signal

-> Typical step sizes are 2°, 2.5°, 7.5° and 15° for each electrical pulse. Note that there is no continuous energy conversion (electrical to mechanical) so that the rotor does not rotate continuously as in a conventional electric power.

-> The stepper motor converts electrical pulses into proportionate mechanical movement. Each revolution of the stepper motor is made up of a series of definite individual steps.

-> A step is defined as the angular rotation of the motor each time it receives the electrical pulse, such a step control is required in many applications.

-> Each time the controller receives an input electrical signal, the paper is driven to a certain incremental distance.

-> Stepper motors are relatively cheap and simple in construction and can be made to rotate in steps in either direction.

-> These motors are excellent candidates for such application as electric typewriters, control of floppy disc drives, numerical control of machine tools etc.

The two most popular types of stepper motors are :

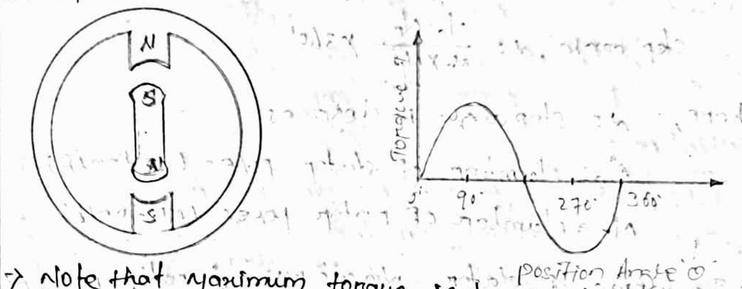
(i) Permanent magnet (PM) stepper motor.

(ii) Variable reluctance (VR) stepper motor.

(i) PM stepper motor :-

-> A 2-pole, single phase permanent magnet (PM) stepper motor. When the stator is energised, the excitation torque acts on the rotor (permanent magnet).

-> The rotor will move to a position where the excitation torque is zero i.e the rotor will be aligned (parallel) with the stator field.

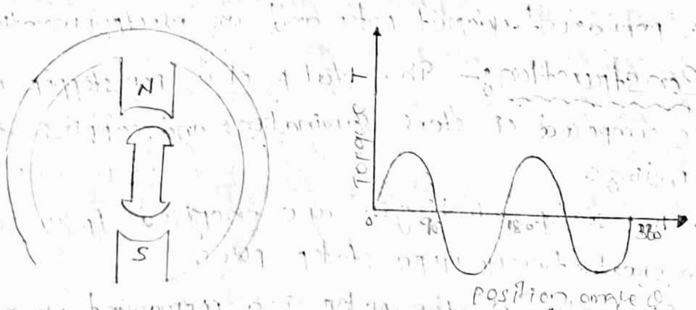


-> Note that maximum torque is developed when the rotor is developed when the rotor is displaced from the stator field by either 90° or 270°. However, the torque is zero when the rotor is aligned (parallel) with the stator field.

ii) VR Stepper motor :-

-> A 2-pole, simple phase variable-reluctance (VR) stepper motor. When the stator energised, reluctance torque acts on the rotor (soft-iron material).

-> The rotor will move to a position where reluctance is minimum and air-gap flux is max^m. This means that rotor teeth will align with the energised stator poles.



-> With the rotor at 0° or 90°, no torque is developed. max^m torque is developed at 45° and 135° which is the position where reluctance torque forces the rotor to move to position of minimum reluctance.

Step angle:-

-> The angle through which the motor shaft rotates for each command pulse is called step angle.

-> It can be shown that for any PM or VR stepper motor, the step angle can be found from the following two relations:

i) In terms of stator poles (N_s) and rotor poles (N_r), the step angle (α) is given by:

$$\text{step angle}, \alpha = \frac{N_s - N_r}{N_s \times N_r} \times 360°$$

Where, α = step angle in degrees

N_s = Number of stator poles (or teeth)

N_r = Number of rotor poles (or teeth)

ii) In terms of stator phases (M) and rotor poles (N_r), the step angle is given by:

$$\text{Step angle}, \alpha = \frac{360°}{M N_r}$$

Where, α = step angle in degrees

M = Number of stator phases

N_r = Number of rotor poles (or teeth)

Permanent-magnet (PM) stepper motor

-> A permanent magnet (PM) stepper motor is a popular type of stepper motor.

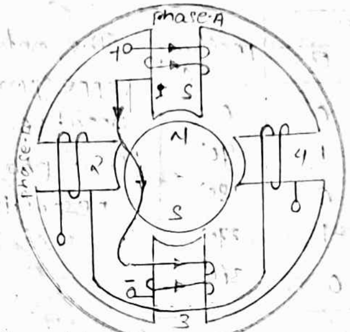
-> It operates on the principle of interaction between a permanent-magnet rotor and an electromagnetic field.

Construction:- The stator of a PM stepper motor is composed of steel laminations and carries stator windings.

-> The stator windings are energised from a d.c source to create two or more stator poles.

-> The rotor of the motor is a permanent magnet made of high-retentivity steel alloy.

-> The rotor has even no. of poles. The motor has two rotor poles. The stator coils are grouped to form 2-phase ~~2-pole PM~~ winding i.e phase-A winding and phase-B winding. The phase winding terminals are brought out for d.c. excitation.



Operation:- For this PM stepper motor, the number of rotor poles, $N_r = 2$ and number of phases, $M = 2$

$$\therefore \text{step angle}, \alpha = \frac{360°}{M N_r} = \frac{360°}{2 \times 2} = 90°/\text{step}.$$

i) When only phase-A winding is excited by a constant current as shown in Fig. Stator tooth-1 becomes south pole. This makes the north pole of the PM rotor to align (parallel) with the south pole (stator tooth 1) of the stator. The rotor will remain locked in the position. Under this condition, step angle $\alpha = 0°$.

ii) If phase-A winding is de-energised and phase-B winding is energised, stator tooth 2 becomes south pole. As a result, the north pole of the PM rotor ~~angles~~ aligns (parallel) with the south pole (stator tooth 2) of the stator. Thus the rotor has displaced 90° in the anticlockwise direction.

iii) If phase-B winding is de-energised and phase-A is excited with reverse current it is opposite to the case in, the rotor will further rotate 90° in anticlockwise direction.

iv) So far the rotor has completed one-half revolution. However, if we continue the appropriate switching.

We can change the step angle (α) of a PM stepper motor by changing number of * rotor poles (N_r) and the number of phases (M). Thus for a 3-phase, 24-pole PM stepper motor, the step angle $\alpha = \frac{360°}{MN_r} = \frac{360°}{3 \times 24} = 5°$/step.

TRUTH TABLE

cycle	Phase A	Phase B	position $\alpha°$
+	1	0	0
	0	1	90°
-	-1	0	180°
	0	-1	270°
+	1	0	360°

The notation, 1, -1, 0 correspond to positive, negative and zero current in a phase winding respectively.

Limitations:-

i) It is difficult to make a small PM rotor with a large no. of poles. Therefore, PM stepper motors are restricted to large step angles in the range of 30° to 90°.

ii) The PM stepper motors have high inertia because of the permanent-magnet rotor. Therefore, these motors have slow acceleration. The maximum step rate (stepping frequency) is 300 steps/second.

iii) The PM stepper motors have high rotational speed because of large stepping angle. Therefore, motor torque for a given power is low.

Variable-Reluctance (VR) stepper motor:-

-> The variable-Reluctance (VR) stepper motor operates on the same principle as the reluctance motor.

-> That is, when a piece of ferromagnetic material, free to rotate, is placed in a magnetic field, torque acts on the material to bring it to the position of minimum reluctance to the path of magnetic flux.

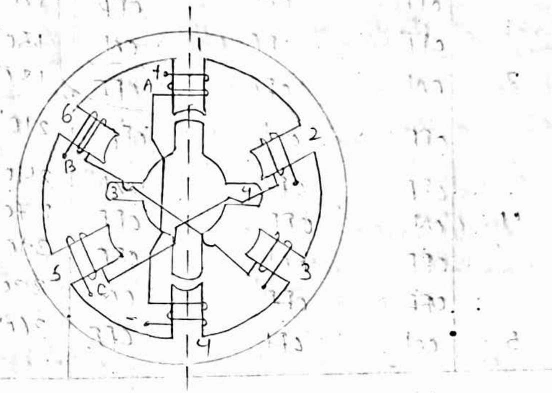
Construction:- The stator construction of a VR stepper motor is the same as that of a PM stepper motor. The stator place winding are wound on each stator tooth. The rotor is made of soft steel with teeth and slots.

-> In the ckt, the rotor is shown with fewer teeth than the stator. This ensures that only one set of stator and rotor teeth will parallel at any given instant.

-> The stator has six teeth and the rotor has four teeth. The stator has three phases - A, B, C with teeth, 1 & 4, 3 & 6, 2 & 5 respectively.

Step angle, $\alpha = \frac{N_s - N_r}{N_s N_r} \times 360° = \frac{6-4}{6 \times 4} \times 360° = 30°$/step.

∴ the rotor will turn 30° each time a pulse is applied.



Operation:-

i) The position of the rotor when phase A is energised with a constant current. As long as phase A is energised, the rotor will be held stationary. Note that in this condition, the rotor teeth 1 and 2 are aligned with the energised stator teeth 1 and 4. The stepper angle $\alpha = 0°$.

ii) When phase A is switched off and phase 'B' is energised, the rotor will turn 30° clockwise so that the rotor teeth 3 and 4 align with the energised stator teeth 6 and 3.

iii) The effect of de-energising phase B and energising phase 'C'. In this ckt, the rotor has further moved 30° clockwise so that rotor teeth 1 and 2 align with energised stator teeth 2 and 5.

iv) After the rotor has displaced 60° (clockwise) from its starting point, the step sequence has completed one cycle.

The direction of rotation will be ~~ene~~ reversed if the switching sequence is in the order of A, C and B. For this particular motor, applied voltage must have at least five cycles for one revolution.

Truth table

cycle	phase A	B	C	position
1	ON	OFF	OFF	0°
	OFF	ON	OFF	30°
	OFF	OFF	ON	60°
2	ON	OFF	OFF	90°
	OFF	ON	OFF	120°
	OFF	OFF	ON	150°
3	ON	OFF	OFF	180°
	OFF	ON	OFF	210°
	OFF	OFF	ON	240°
4	ON	OFF	OFF	270°
	OFF	ON	OFF	300°
	OFF	OFF	ON	330°
5	ON	OFF	OFF	360°

HYBRID stepper motor :-

-> As the name implies, the* hybrid stepper motor combines the features of the PM and the VR stepper motors. The torque developed by this motor is greater than that of the PM or VR types.

Construction:- The basic construction of a hybrid stepper motor. The stator construction is similar to that of a VR or a PM motor. However the rotor construction combines the design of the rotors of a VR and a PM stepper motor.

-> The rotor of a hybrid stepper motor consist of two identical stacks of soft iron as well as an axially magnetised round permanent magnet.

-> Soft iron stacks are attached to the north and south poles of the permanent magnet.

-> The rotor teeth are machined on the soft iron stacks. Thus the rotor teeth on one end become the north pole and those at the other and become the south pole.

-> This rotor teeth of both north and south poles are displaced in angle for the proper aligned of the rotor pole with that of the stator.

Operation:- The operating mode of the hybrid stepper motor is very similar to that of a PM or VR stepper motor.

-> The phase windings are energised in proper sequence and the rotor rotates in steps.

-> Unlike the PM or VR stepper motors, the step angle of a hybrid stepper motor is independent of the number of stator phase and depends only on the number of rotor teeth (N_r) is given by:

$$\text{step angle } \alpha = \frac{90°}{N_r} \text{ in degrees.}$$

For a hybrid stepper motor having 5 rotor teeth, the step angle $\alpha = \frac{90°}{N_r} = 90/5 = 18°/\text{step}$. It means that for each change of stator excitation, the rotor will turn by a step of 18°.

-> It may be noted that a hybrid stepper motor operates under the combined principles of the permanent magnet and variable reluctances stepper motors.

-> Therefore, the hybrid motor develops both excitation torque and reluctance torque.

-> Consequently, the resultant torque developed by the hybrid stepper motor is greater than that of the PM or VR stepper motor.

Q- A hybrid stepper motor has 50 variable-reluctance rotor teeth. Calculate the step angle in degrees.

Sol^n^ step angle, $\alpha = \frac{90°}{N_r} = \frac{90°}{50} = 1.8°/\text{step}$.

Application of stepper motor:-

Commercially, stepper motor are used in floppy disk drives, flatbed scanners, computer printers plotters, slot machines, image scanners, computer disc drives, intelligent lighting, camera lenses, cnc machines and 3D printer.

22/11/2021

Dt-16-11-21 Three Phase Transformer ch-7

A three-phase system is used to generate and transmit electric power. Three-phase voltages are raised or lowered by means of three phase transformers. A three-phase transformer can be built in two ways (i) by suitably connecting a bank of three single-phase transformer (ii) by constructing a three-phase transformer on a common magnetic structure. The windings may be connected in Y-Y, Δ-Δ, Y-Δ or Δ-Y.

i) Bank of three single-phase transformers:-

-> Three similar single-phase transformers can be connected to form a three-phase transformer.

-> The primary and secondary windings may be connected in star (Y) or delta (Δ) arrangement.

-> The primary windings are connected in star and the secondary windings are connected in delta.

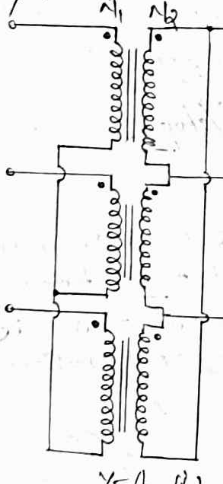
-> The primary and secondary windings shown parallel to each other belong to the same single transformer.

-> The ratio of secondary phase voltage to primary phase voltage is the phase transformation ratio K.

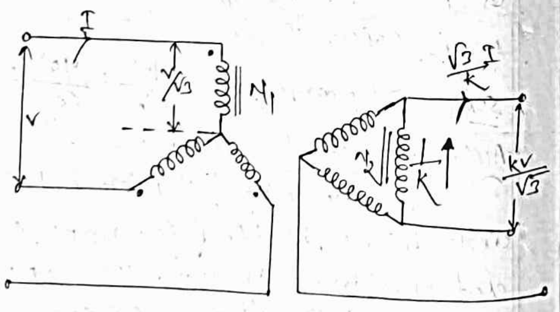
phase transformation ratio, $K = \frac{\text{secondary phase voltage}}{\text{primary phase voltage}}$

$= \frac{N_2}{N_1}$

-> The phase transformation ratio is $(K = N_2/N_1)$.



Y-Δ (i)



(ii)

ii) Three-phase Transformer:-

-> A three phase transformer can be constructed by having three primary and three secondary windings on a common magnetic circuit.

-> The basic principle of a 3-ϕ transformer is in below.

-> The three single-phase core type transformers, each with windings (primary and secondary) on only one leg have their unwound legs combined to provide a path for the returning flux.

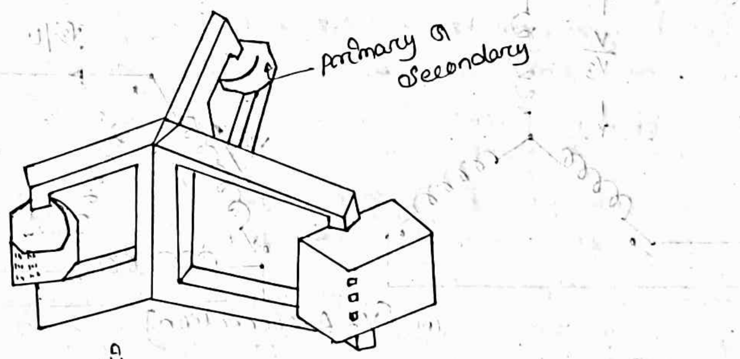
-> The primaries as well as secondaries may be connected in star or delta.

-> If the primary is energised from a 3-ϕ supply, the central limb (unwound limb) carries the fluxes produced by the 3-ϕ primary winding.

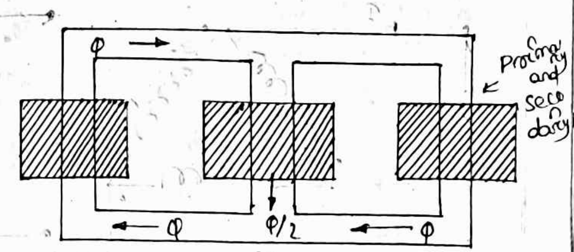
-> Since the phasor sum of three primary currents at any instant is zero, the sum of three fluxes passing through the central limb must be zero.

-> Hence no flux exists in the central limb and it may, therefore be eliminated. This modification gives a three leg core-type 3-ϕ transformer.

-> In this case, any two legs will act as a return path for the flux in the third leg.



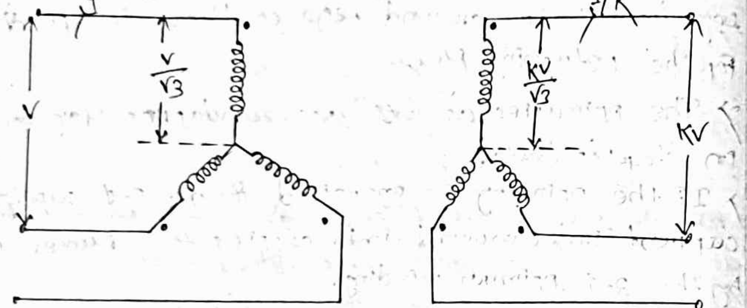
(i)



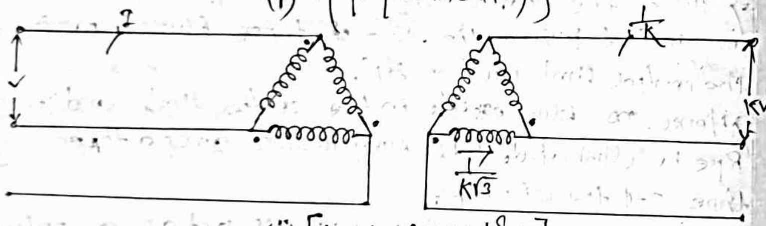
Three-phase transformer connections

-> A three-phase transformer can be built by suitably connecting a bank of three single-phase transformers or by one three-phase transformer.

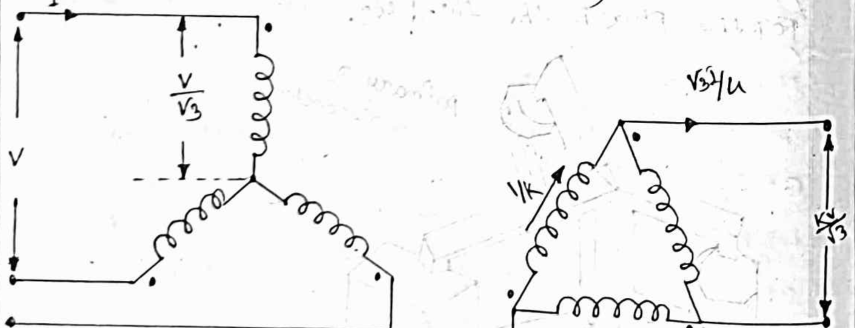
-> The primary or secondary winding may be connected in either star (Y) or delta (Δ) arrangement. The four most common connections are (i) Y-Y (ii) Δ-Δ (iii) Y-Δ and (iv) Δ-Y.



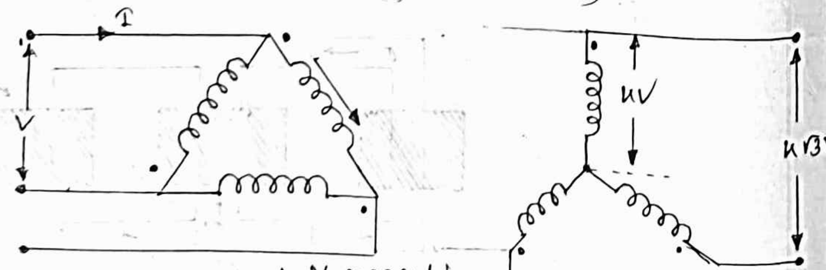
(i) [Y-Y connection]



(ii) [Δ-Δ connection]



(iii) [Y-Δ connection]



Δ-Y connection

$$K = \frac{\text{Secondary phase voltage}}{\text{primary phase voltage}} = \frac{N_2}{N_1}$$

i) Y-Y Connection :- In the Y-Y connection show in Fig. (i), 57.7% (or $1/\sqrt{3}$) of the line voltage is impressed upon each winding but full line current flows in each winding. power ckts in their immediate vicinity. Because of this and other disadvantages, the Y-Y connection is seldom used.

ii) Δ-Δ Connection :- The Δ-Δ connection is often used for moderate voltages. An advantage of this connection is that if one transformer gets damaged or is removed from service, the remaining two can be operated in what is known as the open-delta or V-V connection.

iii) Y-Δ Connection :- The Y-Δ connection is suitable for stepping down a high voltage. In this case, the primaries are designed for 57.7% of the high tension line voltages.

iv) Δ-Y Connection :- The Δ-Y connection is commonly used for stepping up to a high voltage.

Three-phase transformation with two single-phase transformers :-

-> It is possible to transform three-phase power by using two single-phase transforms.

i) The connection of two identical single-phase transformers in open delta (or V-V connection)

ii) The T-T connection (or scott connection) of two non identical single-phase transformers.

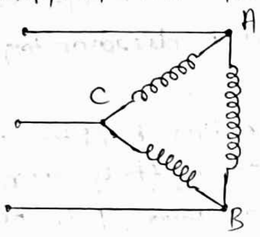
Open-Delta OR V-V connection :-

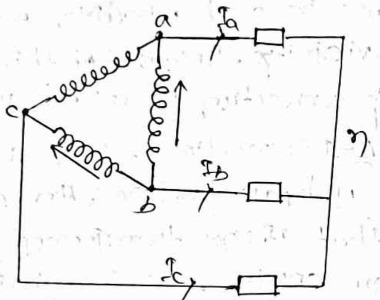
-> If one transformer breaks down in a star-star connected system of 3-single-phase transformers, three-phase power cannot be supplied until the defective transformer has been replaced or repaired.

-> To eliminate this undesirable condition, single-phase transformers are generally connected in Δ-Δ.

-> In this case, if one transformer breaks down, it is possible to continue supplying three-phase power with the other two transformers because this arrangement maintains correct voltage and phase relations on the secondary.

→ However, with two transformers, the capacity of the bank is reduced to 57.7% of what it was with all three transformers in service.





Applications of open-Delta OR V-V connection

→ The V-V ckt has a no. of features that are advantages are given below by way of illustration :-

i) The ckt can be employed in an emergency situation when the one transformer in a complete Δ-Δ ckt must be removed for repair and continuity of service is required.

ii) Upon failure of the primary or secondary of one transformer of a complete Δ-Δ ckt, the system can be operated as V-V circuit and can deliver 3-φ power (with reduced capacity) to a 3-φ load.

Scott connection OR T-T connection :-

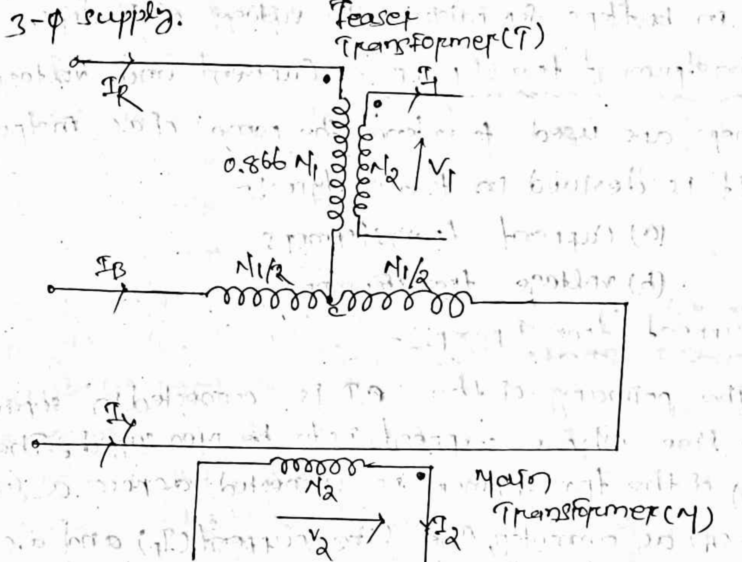
→ Although there are now no 2-phase transmission and distribution systems, a 2-phase supply is sometimes required.

→ We can convert 3-phase supply into 2-phase supply through scott or T-T connection of two single-phase transformers.

→ One is called the main transformer M which has a centre tapped primary; the centre tap being C. The primary of this transformer has N_1 turns and is connected betⁿ the terminals B and Y of the 3-phase supply.

→ The other transformer is called teaser transformer T and its primary has $0.866 N_1$ turns.

→ One [illegible]
centre tap C and the other end to the terminal R of the 3-φ supply.



Parallel operation of 3-phase transformers :-

i) The secondaries of all transformers must have the same phase sequence.

ii) The phase displacement betⁿ primary and secondary line voltages must be the same for all transformers which are to be operated in parallel.

iii) The secondaries of all transformers must have the same magnitude of line voltage.

Applications of transformer :-

i) Power transformers :- They are designed to operate with an almost constant load which is equal to their rating. The maxᵐ efficiency is designed to be at full-load. This means that full-load winding copper losses must be equal to the core losses.

ii) Distribution transformers :- These transformers have variable load which is usually considerably less than the full-load rating. Therefore, these are designed to have their maxᵐ efficiency at between ½ and ¾ of full load.

iii) Autotransformers :- An autotransformers has only one winding and is used in cases where the ratio of step-up or step-down differs little from 1. For the same output and voltage ratio, an autotransformers are used for starting induction motors and in boosters for raising the voltage of feeders.

iv) Instrument transformers:- Current and voltage transformers are used to extend the range of a.c instruments.

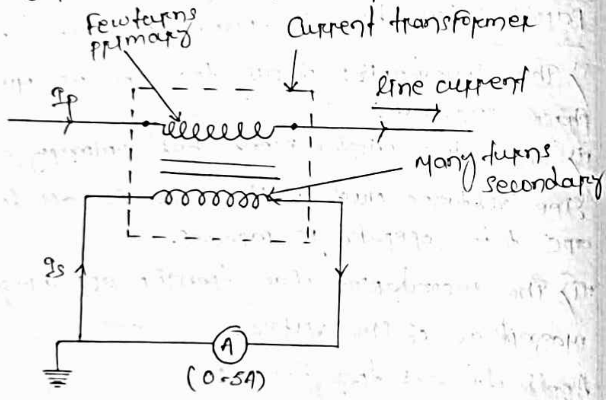
-> It is devided in to two types:-

(a) Current transformers

(b) voltage transformers.

a) Current transformers:-

-> The primary of the C.T is connected in series with the line whose current is to be measured. The secondary of the transformer is connected across a low-range (0-5A) ac ammeter. The line current (I_p) and a.c ammeter current (I_s).



$N_p I_p = N_s I_s$

$\Rightarrow \frac{I_p}{I_s} = \frac{N_s}{N_p}$

-> The primary to secondary current ratio (i.e I_p/I_s) is called C.T ratio.

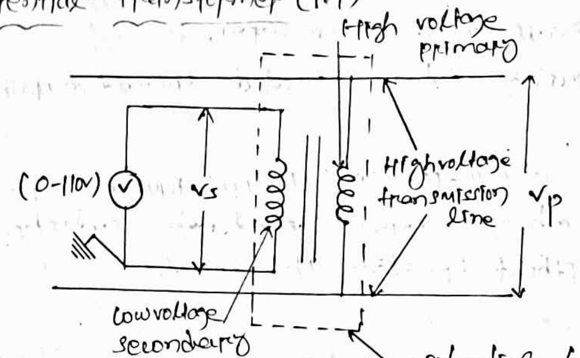
$\therefore \frac{I_p}{I_s} = C.T\ ratio$

(or) $I_p = I_s \times C.T\ ratio$

i.e line current (I_p) = A.C. ammeter reading × C.T ratio

Thus if the reading of a.c ammeter is 1A and the C.T ratio is 100 : 1 (or 100/1), then line current = 1×100 = 100A.

b) Potential transformer (P.T)



-> A P.T is used to measure high alternating potential difference (voltage) in a power system.

-> The primary of this transformer has many turns while the secondary has few turns. It is clear a P.T is simply a well-designed step-down transformer.

-> The stepped down voltage is measured with a low range a.c voltmeter. The magnetic core of a P.T usually has a shell-type construction for better accuracy.

-> In order to provide adequate protection to the operator one end of the secondary winding is usually grounded.

-> The primary of the P.T is connected across the high voltage line whose voltage is to be measured.

-> A low-range (0-110 v) a.c voltmeter is connected across the secondary. The line voltage (V_p) and a.c voltmeter voltage (V_s) are related as:-

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

-> The primary to secondary voltage ratio (V_p/V_s) is called P.T ratio.

$\therefore \frac{V_p}{V_s} = P.T\ ratio$

$V_p = V_s \times P.T\ ratio$

Advantages of Instrument Transformers:-

i) The errors due to stray inductance and capacitance in shunts, multipliers and their leads are eliminated.

ii) we can use low-range and accurate a.c instruments.

iii) The length of the connecting leads from the transformer to the instrument is of lesser importance and leads may be of small cross-sectional area.

iv) The measuring ckt is isolated from the mains by the transformer.

v) By using a clip-on type of transformer core, the current in a heavy-current ~~the heavy~~ conductor can be measured without breaking the circuit.

Tap changer:-

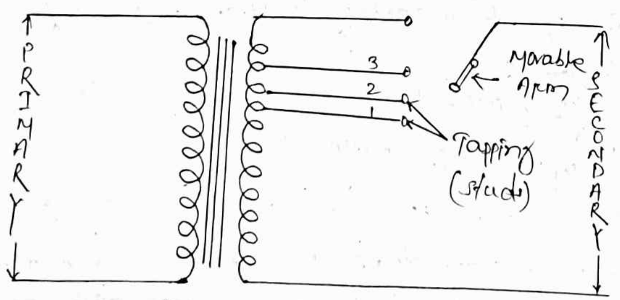
-> In transmission and distribution systems there can be voltage fluctuation (i.e increase or decrease in voltage levels) when the load on the system varies. These fluctuation can also be caused due to a voltage in the distribution system. Sometimes these variation in voltage levels can result in quite unsatisfactory performance.

-> In order to maintain a constant voltage or to maintain within the prescribed limits transformer tap-changing is used.

-> There are two types of tap changing transformer:-

1) OFF load Tap changing Transformer:-

-> The below fig. shows the off load tap changing transformer provided with tapping (1 or 5) on the secondary winding. The position of the movable arm on the first stud will give min^m secondary voltage and on the fifth stud will give max^m voltage across secondary

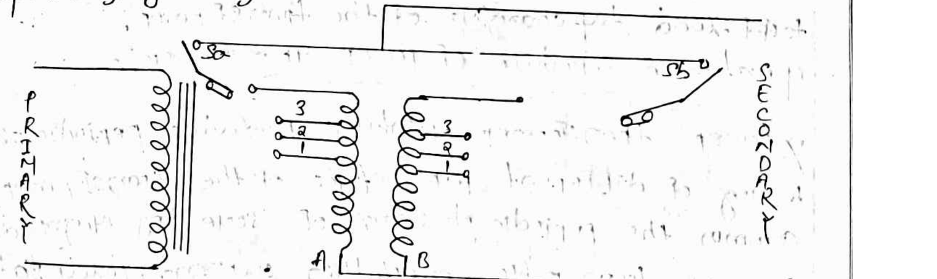


-> During the light load period, the movable arm is placed on the first stud and with an increase in load, the movable arm is taken to a stud (2,3,4,5) giving higher turns-ratio so that voltage drop in the line is compesated and the o/p secondary voltage is maintained.

-> The disadvantage of this scheme is whenever the tapping, is to change load must be disconnected first from the transformer thus it is referred to as off-load tap-changing. This type of tap-changing cannot be used where continuity of the supply to the load is the main priority and it is limited where there will be a need for only slight changing in the turn ratio.

ON-Load Tap-changing Transformer:-

-> The drawback of off-load tap chaning can be overcome by using a special arrangement to coil connection to the transformer known as ON-load tap-changing of the transformer. The transformer connection for ON-load tap-changing is given below.



-> Here the coil of the winding in which tappings are to be done are divided into two parallel section with equal tapping on both section of the coil. This forms the two winding A & B as shown above.

-> Under normal operating conditions both the switches (Sa and Sb) are in the closed (S.C) condition with identical tapping (i.e 1 and 1'). As the winding is divided into parallel sections the total current will be the sum of the current in winding A and B.

-> When the tapping are to be changed to maintain the continuity of the supply the tap-changing process is made in such a way that. At first, any one of the winding (either A or B) from the parallel section is to be disconnected by open the respective switch.

-> Now, the tapchanging is to be done to the disconnected winding. At this instant, the full load current will pass through the connected winding.

-> After changing the tapping to the disconnected winding is reconnected by closing the switch. At this moment there will be an unequal share of the load on both winding due to their different turn ratio.

-> Now the other winding is disconnected and tapping is to be changed (which is equal to the tapping of previously disconnected winding).

-> So that there will be an equal amount of load share on both the windings (A and B)

-> In this way, the continuity of the supply is maintaining and more turn-ratio of tapchanging can possibly compare to off-load tap changing of the transformer.

Maintenance schedule of power Transformer:-

-> power transformer maintain includes periodic electrical testing of different parameters of the transformer, being common the periodic checking of some key magnitudes such as turn ratio, excitation current, polarization index, insulation resistance, winding resistance S.C impedance etc.

13/12/23

Ch-4 Single-phase Motors

Introduction:-

Single phase motors are the most familiar of all electric motors because they are extensively used in home appliances shops, offices etc.

-> It is true that single-phase motors are less efficient substitute for 3-ϕ motors but 3-ϕ power is normally not available in large commercial and industrial establishments.

Types of single-phase motors

1) Single-phase induction motors:

a) Split-phase type

b) capacitor type

c) shaded-pole type

2) A.C. series motor/ universal motor.

3) Repulsion motors:

a) Repulsion-start induction run-motor

b) Repulsion-induction motor

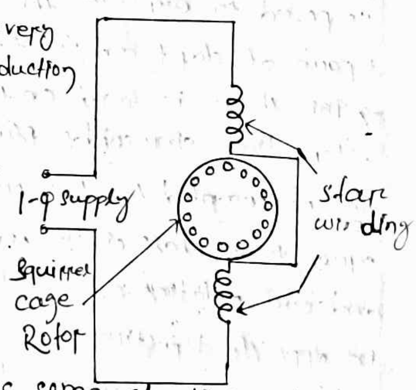
4) Synchronous motors.

a) Reluctance motor

b) Hysteresis motor

Single-phase induction motors

-> A single phase induction motor is very similar to a 3-ϕ squirrel cage induction motor.



-> It has (i) a squirrel-cage rotor identical to a 3-ϕ motor and (ii) a single-ϕ winding on the motor.

-> Unlike a 3-ϕ induction motor, a single-phase induction motor is not self-starting but requires some starting means.

-> The single-phase stator winding produces a magnetic field that pulsates in strength in a sinusoidal manner.

-> The field polarity reverse after each half cycle but the field does not rotate. Consequently, the alternating flux cannot produce rotation in a stationary squirrel cage rotor

-> However, if the rotor of a single-phase motor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation.

-> As a matter of fact, the rotor quickly accelerates until it reaches a speed slightly below the synchronous speed.

-> Once the motor is running at this speed, it will continue to rotate even through single-phase current is flowing through the stator winding.

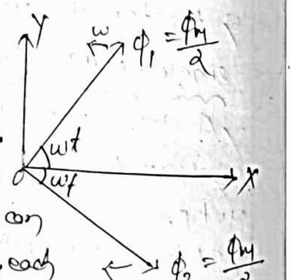
-> This method of starting is generally not convenient for large motors. Nor can it be employed for a motor located at some inaccessible spot.

-> Such a motor inherently does not develop any starting torque and, therefore, will not start to rotate if the stator winding is connected to single-phase a.c supply.

-> However, if the rotor is started by auxiliary means, the motor will quickly attain the final speed.

-> This strange behaviour of single-phase induction motor can be explained on the basis of double-field revolving theory.

Double-Field Revolving Theory :-



-> The double-field revolving theory is proposed to explain this dilemma of no torque at start and yet torque once rotated.

-> This theory is based on the fact that an alternating sinusoidal flux ($\phi = \phi_m \cos\omega t$) can be represented by two revolving fluxes, each equal to one-half of the max^m value of alternating flux (i.e. $\phi_m/2$) and each rotating at synchronous speed ($N_s = \frac{120f}{P}$) ($\omega = 2\pi f$) in opposite directions.

$$\phi = \phi_m \cos\omega t$$

-> Consider two rotating magnetic fluxes ϕ_1 and ϕ_2, each of magnitude $\phi_m/2$ and rotating in opposite directions with angular velocity 'ω'.

-> Let the two fluxes start rotating from OX axis at t=0.

-> After time 't' seconds, the angle through which the flux vectors have rotated is ωt.

-> Resolving the flux vectors along X-axis and Y-axis, we have,

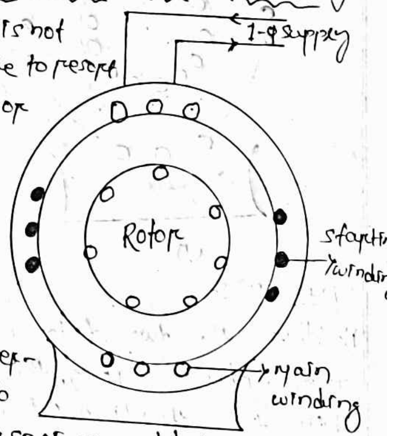
$$\text{Total X-component} = \frac{\phi_m}{2}\cos\omega t + \frac{\phi_m}{2}\cos\omega t$$
$$= \phi_m \cos\omega t.$$

$$\text{Total Y-component} = \frac{\phi_m}{2}\sin\omega t - \frac{\phi_m}{2}\sin\omega t = 0$$

$\therefore$ Resultant flux, $\phi = \sqrt{(\phi_m \cos\omega t)^2 + 0^2} = \phi_m \cos\omega t.$

Thus the resultant flux vector is $\phi = \phi_m \cos\omega t$ along X-axis. Therefore an alternating field can be replaced by two rotating fields of half its amplitude rotating in opposite directions at synchronous speed.

Making Single-phase Induction motor self-starting



-> The single-phase induction motor is not self starting and it is undesirable to resort to mechanical spinning of the shaft or pulling a belt to start it.

-> To make a single-phase induction motor self-starting, we should somehow produce a revolving stator magnetic field.

-> This may be achieved by converting a single-phase supply into two-phase supply through the use of an additional winding.

-> When the motor attains sufficient speed the starting means (i.e. additional winding) may be removed depending upon the type of the motor.

-> As a matter of fact, single-phase induction motors are classified and named according to the method employed to make them self starting.

1) Split-phase motors :- started by two phase action through the use of an auxiliary or starting winding.

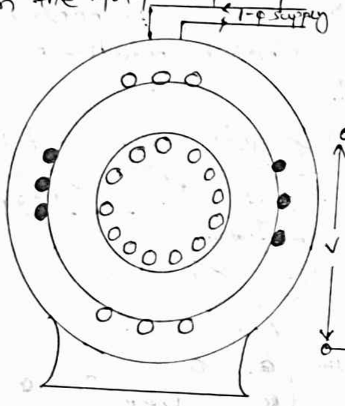
2) Capacitor motors :- Started by two-phase motor action through the use of an auxiliary winding and a capacitor.

5) Shaded-pole motors :- started by the motion of the magnetic field produced by means of a shading coil around a portion of the pole structure.

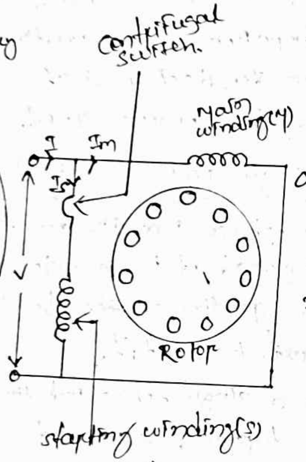
Split-phase Induction motor :-

-> The stator of a split-phase induction motor is provided with an auxiliary or starting winding S in addition to the main or running winding M.

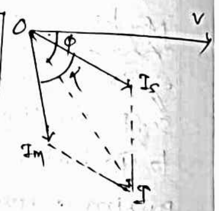
-> The starting winding is located 90° electrical from the main winding and operates only during the brief period when the motor starts up.



(1)



(2)



(3)

Operation :-

i) When the two stator windings are energised from a single-phase supply, the main winding carries current I_m while the starting winding current I_s.

ii) Since main winding is made highly inductive while the starting winding highly resistive, the currents I_m & I_s have a reasonable phase angle α (25° to 30°) between them.

iii) When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the ckt of the starting winding. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

Characteristics :-

i) The starting torque is 1.5 to 2 times the full-load torque and the starting current is 6 to 8 times the full load current.

ii) Due to their low cost, split-phase induction motors are most popular single-phase motors in the market.

iii) An important characteristic of these motors is that they are essentially constant-speed motors. The speed variation is 2-5% from no-load to full-load.

iv) These motors are suitable where a moderate starting torque is required and where starting periods are infrequent. e.g. to drive:

a) fans (b) washing machines (c) oil burners (d) small machine tools etc.

-> The power rating of such motors generally lies between 60W and 250W.

Capacitor-start motor :-

-> The capacitor-start motor is identical to a split-phase motor except that the starting winding has as many turns as the main winding.

-> Moreover, a capacitor 'C' is connected in series with the starting winding.

-> The value of capacitor is so chosen that I_s leads I_m by about 80° (i.e. α = 80°) which is considerably greater than 25° found in split-phase motor.

-> Consequently, starting torque ($T_s = k I_m I_s \sin\alpha$) is much than that of a split-phase motor.

-> Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed.

-> The motor than operates as a single-phase induction motor and continues to accelerates till it reaches the normal speed.

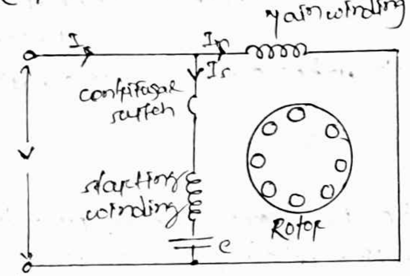
characteristics

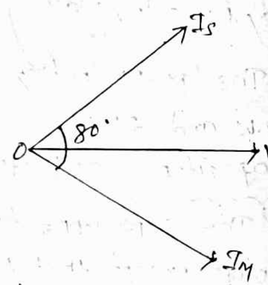
-> Although starting characteristics of a capacitor-start motor are better than those of a split-phase motor, both machines possess the same running characteristics because the main winding are identical.

-> Capacitor-start motors are used where high starting torque is required and where the starting period may be long. e.g., to drive:-

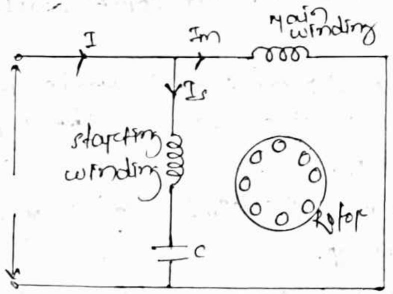
a) compressors
b) large fans
c) pumps
d) High inertia loads.

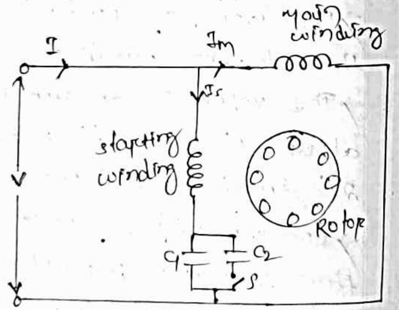
-> The power rating of such motors lies betn 120 w and 7.5 kW. (Capacitor is used to maintain the phase difference betn I_s & I_m)





Capacitor-start capacitor-Run motor





-> This motor is identical to a capacitor-start motor except that starting winding is not opened after starting, so that both the windings remain connected to the supply when running as well as at starting.

Two designs are generally used.

i) In one design, a single capacitor 'C' is used for both starting and running.

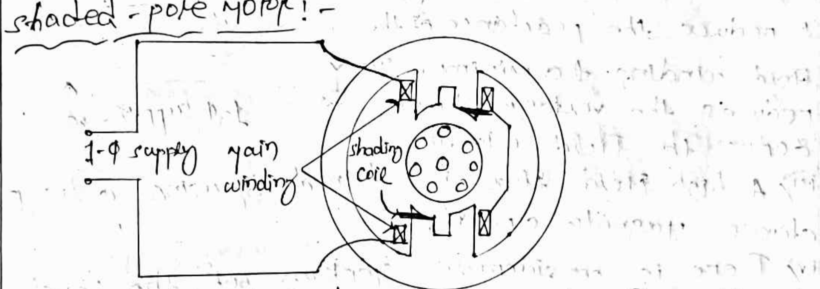
ii) In the other design, two capacitor C_1 and C_2 are used in the starting winding. The smaller capacitor C_1 required for optimum running conditions is permanently connected in series with the starting winding. The much larger capacitor C_2 is connected in parallel with C_1 for optimum starting and remains in the ckt during starting. The motor then runs as a single-phase induction motor.

characteristics :-

a) The starting winding and the capacitor can be designed for perfect 2-phase operation at any load. The motor then produces a constant torque and not a pulsating torque as in other single-phase motors.

b) Because of constant torque, the motor is vibration free and can be used in:
i) Hospitals (ii) studios and (iii) other places where silence is important.

shaded-pole motor :-



-> The shaded-pole motor is very popular for ratings below 0.05 hp. (≃ 40W) because of it's extremely simple construction.

-> It has salient poles on the stator excited by single-phase supply and a squirrel-cage rotor.

-> A portion of each pole is surrounded by a short-circuited turn of copper strip called shaded coil.

characteristics:-

i) The salient features of this motor are extremely simple construction and absence of centrifugal switch.

ii) Since starting torque, efficiency and power factor are very low, these motors are only suitable for low power applications. e.g. to drive :- (a) small fans, (b) toys (c) hairdriers (d) desk fans

-> The power rating of such motors is upto about 30 W.