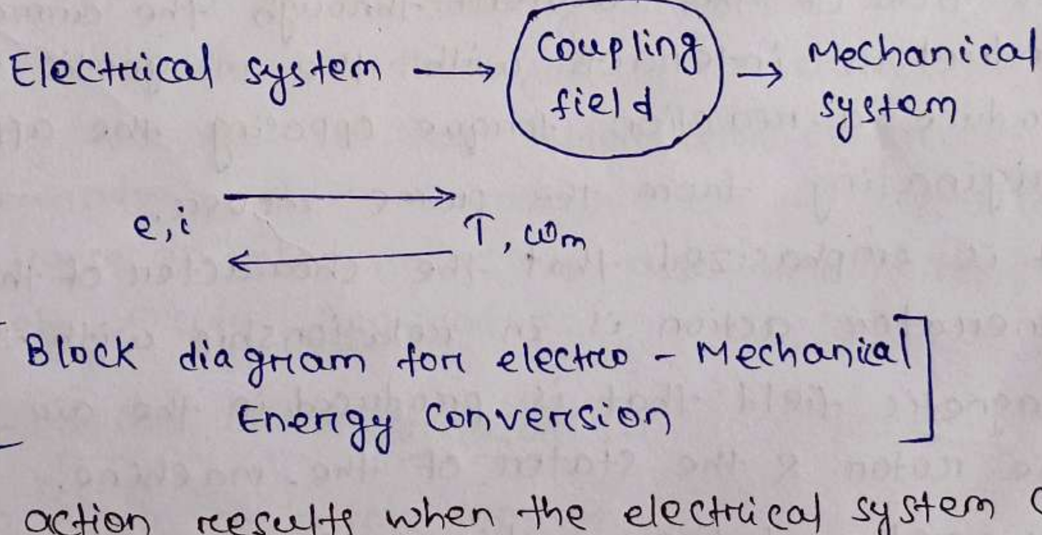
Unit-1

ALTERNATOR

Introduction tof Synchronous Generator :-

Introduction :-

- synchronous machines are electro - mechanical energy converts and involves the interchange of energy betⁿ an electrical and mechanical system.
- These machines are called synchronous machines because they operate at constant speeds & constant frequencies under steady state conditions.
- The primary quantities involved in the mechanical system are torque and speed.
- The analogues quantities with electrical system are voltage & current respectively, as shown in figure.



[Block diagram for electro - Mechanical Energy Conversion]

- Motor action results when the electrical system causes a current "i" to flow through the conductors that are placed in a magnetic field.
- A force is produced on each conductor so, that if the conductors are located on a structure that is free to rotate an electro-magnetic torque "T" results which in turn manifests it self as an angular velocity Wm.

- The development of this motor action the revolving conductors cut through the magnetic field, there by under going an electro - motive force 'e' which is really a reaction voltage analogues to the induced to the induced emf in the primary of a transformer.
- Note that the coupling field is involved in establishes the electromagnetic torque T as well as the reaction induced emf. 'e'.
- The reverse process takes place here the rotating member the 'rotor' is driven by a prime mover.
- The induced voltage 'e' to appear across the armature winding terminals.
- The current 'I' is made to flow, delivering electrical power to the load.
- The flow of this current through the armature conductors interacts with the magnetic field to produce a reaction torque opposing the applied torque originating from the prime mover.
- It is emphasized that the character of this motor-generator action is in relationship with the coupling magnetic field that is produced in the air gap betn the rotor & the stator of the machine.
- The most rotating machines, synchoronous machines are capable of operating as both motor & generator.

Introduction to alternator :-

→ An AC generating machine, is called an Alternator or AC generator.

→ It is used to generate alternating emf in accordance with the faraday's laws of electromagnetic induction.

→ When ever a conductor is rotated in a magnetic flux, then it cuts the magnetic lines of force, & an e.m.f. is induced in it.

→ The working principle of an alternator is the same as that of a D.C. Generator.

→ An alternator requires a magnetic flux, conductors and the mechanical power for generating the emf.

→ The emf generated by the alternator is obtained through slip-rings or directly from the stator windings, depending on the type of alternator used.

→ Generally the field of an alternator is excited with a D.C Generator, which is mounted on the alternator's shaft. Hence an alternator is also known as separately excited generator.

Classification of Alternator :-

- On the basic of prime mover

→ Water turbine alternator

→ Steam turbine alternator

→ Oil engine alternator.

- On the basic of phase

→ single phase alternator.

→ Three phase alternator.

- On the basis of rotor :-

→ Rotating armature alternator

→ Rotating field.

Types of alternator :-

On the basis of prime mover :-

ⓐ **Water turbine alternator :-**

→ In this alternator, the rotor is rotated with the force of water.

→ The water is stored in the form of a small lake, by making a barrage on a river or canal.

→ Then a water-fall is produced with the stored water, which rotates the turbine & which in turn rotates the rotor.

→ The speed of this alternator is low due to low water speed, & thus to obtain the required frequency, the number of poles in to be kept more.

(b) Steam turbine Alternator :-

→ The force produced by steam is greater than that produced by water.

→ The steam operates a steam-engine and the engine operates the alternator.

→ The speed of this alternator is high.

→ A 2-pole alternator can generate frequency of 50 c/s at 3000 R.P.M.

(c) Oil Engine Alternator :-

→ In this alternator, the rotor is rotated by a diesel or petrol operated engine. Since the system is expensive, therefore, it is used for such purposes where water or steam type alternators do not suit or for emergency purposes.

On the basis of phase :-

- Single phase alternator :-

→ A small alternator used to generate the emf upto 250 volts, for light & fan purposes, is usually single phase type.

- Three phase alternator :-

→ This alternator can generate 650 to 6600 volts or even more.

→ It is used for light & fan as well as for power purposes.

Rotating Armature alternator :-

→ It is similar to a generator in construction. It employs slip-rings in place of commutator.

→ The poles are kept stationary, & the armature rotates betn the poles.

→ The emf is obtained through the slip-rings. This alternator, usually has a low output capacity

Rotating field alternator :-

→ In this alternator, the rotor contains the magnetic poles while the armature is kept stationary. Hence, it can run at a high speed.

• → **Advantages of rotating field alternator:-**

→ Rotating field is comparatively light in weight & hence it can run at a high speed.

→ Two slip rings of low current capacity are sufficient for its field excitation circuit.

→ Higher voltages can be generated because of high speed of the rotor.

→ It is easier to insulate armature coils design to work at high voltages, because these are placed in the stator portion.

→ If the armature is kept rotating, then the high insulation of armature coils will make it bulky. Hence, it will not be able to rotate at a high speed.

→ The armature winding placed in star or delta system, can directly be connected to the distribution cables.

Advantages of polyphase alternator :-

→ Polyphase alternators are small in size & economical in comparision to the single phase alternators, having the same output, voltage & frequency.

→ A polyphase alternator has a constant armature reaction, while a single phase alternator has a pulsating armature reaction, under balanced load condition.

→ polyphase transmission lines require less copper, in comparision to single phase transmission lines.

→ The output power of a polyphase alternator is stable & non-pulsating for balanced load.

→ A Poly-Phase alternator has a greater efficiency in comparision to a single phase alternator.

Difference betn DC Generator & alternator :-

→ In case of a D.C Generator, besically the nature of the induced emf in the armature conductors is of alternating (A.C) type.

→ By using commutator & brush assembly it is converted to D.C & made available to the external CKT.

→ If commutator is removed from a DC generator and induced emf is collected with the help of slip rings & brushes from an armature directly outside to the external circuit, the nature of such emf will be alternating (A.C).

→ Such a machine with out commutator providing an A.C emf to ~~be~~ the external circuit is called as an alternator.

→ A Generator supplying an alternating circuit is known as alternator or AC generator.

PRINCIPLE OF OPERATION OF ALTERNATOR

(*) Working principle of synchronous generator :-

→ The alternators work on the principle of electro magnetic induction.

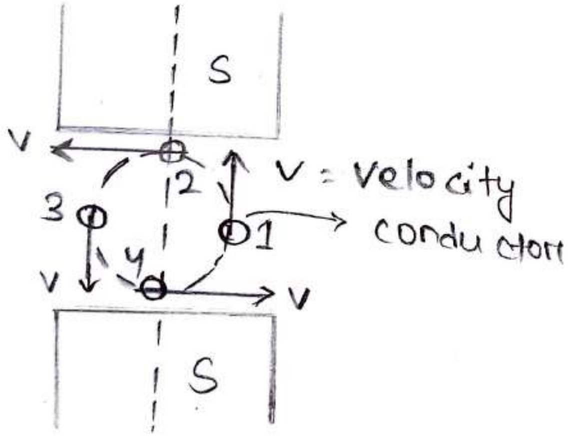
→ When there is a relative motor between the conductor and the flux, emf gets induced in the conductor.

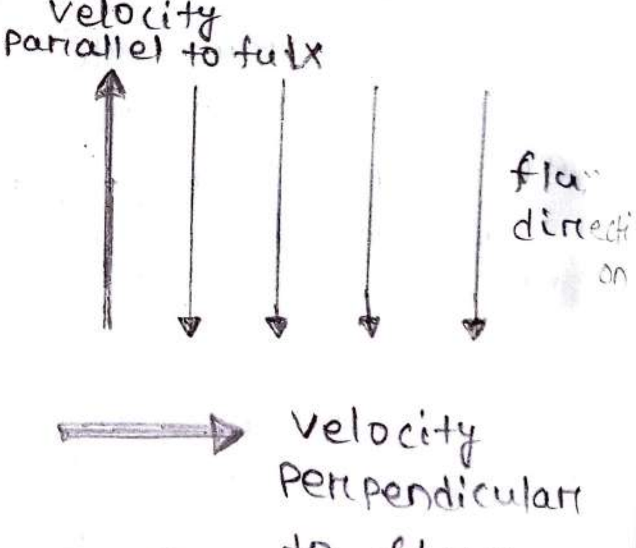
→ The DC Generators also work on the same principle.

→ The only difference in practical alternator and a d.c. generator is that in an alternator the conductor are stationary and field is rotating.

→ Consider a relative motion of a single conductor under the magnetic field produced by the two stationary poles.

→ The magnetic axis of the two poles produced by field is vertical, shown dotted in the figure.





[Two pole alternator]

→ let conductor starts rotating from position 1.

→ The entire velocity component is parallel to the flux lines. Hence there is no cutting of flux line by conductor.

→ The $\frac{d\phi}{dt}$ at this instant is zero and hence induced emf in the conductor is also zero.

→ The conductor moves from position 1 towords position 2.

→ The velocity component becomes perpendicular to the flux lines & proportional to that, emf gets induced in the conductor.

→ The magnitude of such an induced emf increase as the conductor moves from position 1 towords 2.

→ At position 2, the entire velocity component is perpendicular to the flux lines. Hence there exist maximum cutting of the lines.

→ The induced emf in the conductor is as its maximum.

→ The position of conductor changes from 2 towords 3.

→ The velocity perpendicular to the flux starts decreasing and hence induced emf magnitude also starts decreasing.

→ At position 3, again the entire velocity components is parallel to the flux lines & hence this instant induced emf in the conductor is zero.

→ The conductor moves from position 3 towords 4.

→ The velocity component perpendicular to the flux lines again starts increasing.

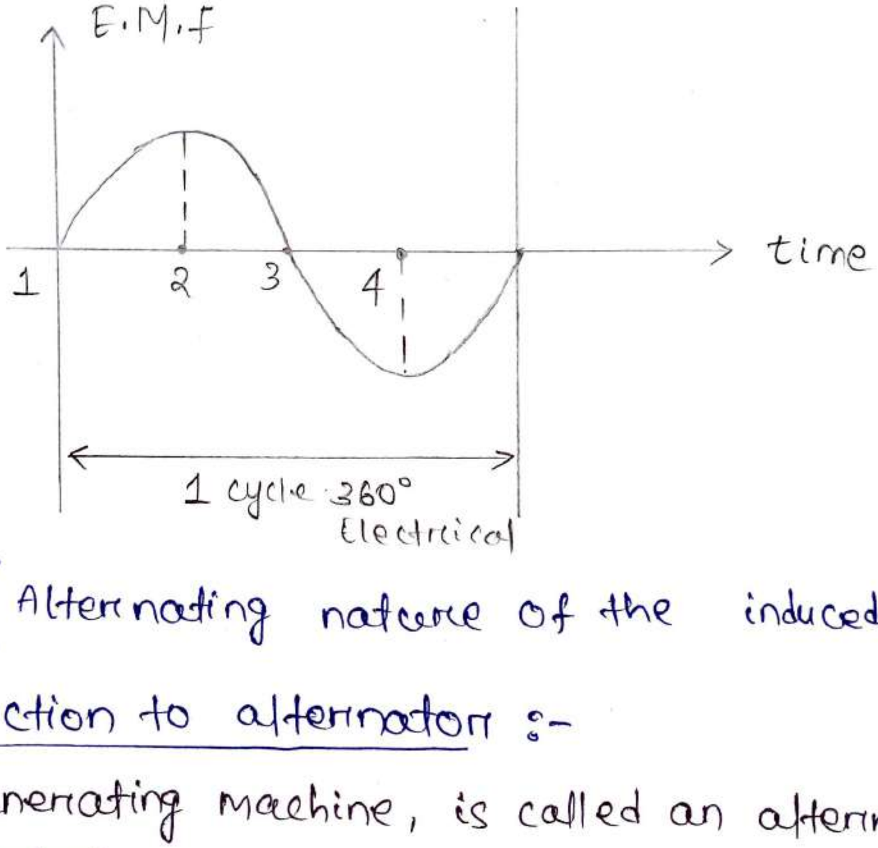
→ The direction of velocity component now is opposite to the direction of velocity component existing during the movement of the conductor from position 1 to 2.

→ The induced emf in the conductor increase but in the opposite direction.

→ At position 4, It achieves maxima in the opposite direction, as the entire velocity component becomes perpendicular to the flux lines.

→ The position 4 to 1 induced emf decrease & finally at position 1, again becomes zero. this cycle continues as conductor rotates at a certain speed.

→ The magnitudes of the induced emf against the time, we get an alternating nature of the induced emf as shown in the fig. This is the working principle of an alternator.



(Alternating nature of the induced emf)

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(iii) Oil engine alterantor

② On the basis of phase :-

(i) single phase alternator
(ii) Three phase alternator.

③ On the basis of rotor :-

(i) Rotating armature alternator.
(ii) Rotating field.

Frequency of Induced E.M.f :-

Let,

P = Number of poles

N = speed of rotor in R.P.M.

F = Frequency of the induced emf.

From the discussion, we can write

① one mechanical Revolution of Rotor
= $P/2$ cycle of emf electricity

② Thus there are $P/2$ cycles per revolution.

③ As speed in N R.P.M, in one second, rotor will completed $(N/60)$ revolution.

But,

cycles/sec. = Frequency (F)

∴ F = (Number of cycle / revolution) × (Number of revolution / sec.)

$$\therefore F = P/2 \times \frac{N}{60}$$

$$\therefore F = \frac{PN}{120} \text{ Hz (cycles/sec.)}$$

- So there exists a fixed relationship betn 3 quantities, the number of poles (P).
- The speed of the rotor N in r.p.m. & f frequency of an induced emf in HZ.

Synchronous Speed (N_s)

→ From the above expression, It is clear that for fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated emf constant at the required value. Such a speed is called synchronous speed of the alternator donated as Ns.

So,

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

Where,

f = Required frequency

P = No of poles

→ The frequency of an alternating emf is standard equal to 50 Hz To get 50 Hz.

→ The different number of poles, alternator must be driven at different speeds called synchronous speeds.

→ The following table gives that values of the synchronous speeds for the alternators having different number of poles.

Number of poles (P)	2	4	8	12	24
Synchronous speed Ns in r.p.m.	3000	1500	750	500	250

→ The minimum number of poles for an alternator can be two hence maximum value of synchronous speed is possible i.e. for frequency of 50 Hz is 3000 r.p.m.

Construction of alternator

Construction & classification of Alternator :-

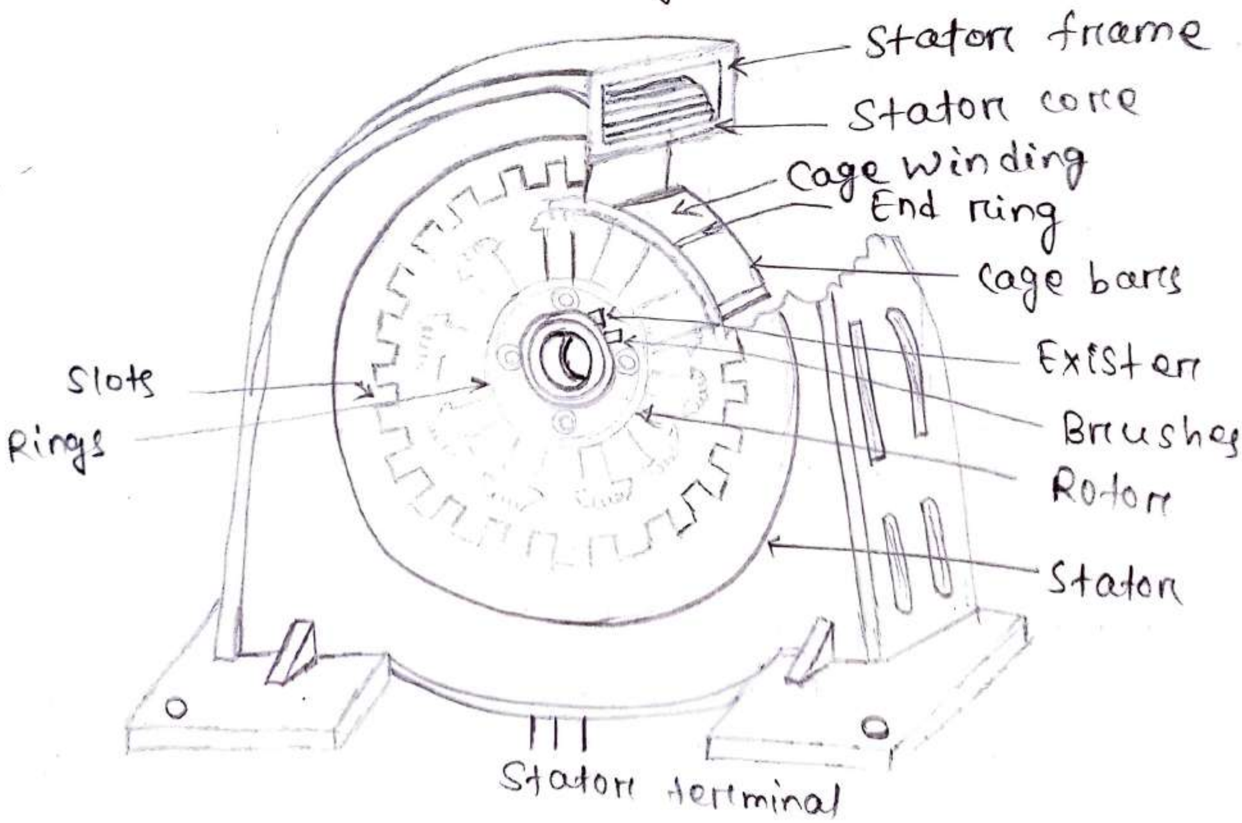
→ The electrical machine, which generates alternating current & hence voltage is known as alternator or A.C generator or synchronous generator.

→ The following are the major parts of an alternator.

Stator frame
Stator core
Stator winding
} stator or armature

magnetic poles & field windings
Slip rings
} field system

Brush & Brush holder
Spider
Exciter
Shaft and bearings
} Rotor



[ALTERNATOR]

→ small AC generators are commonly made with stationary field magnet system & revolving armature.

→ In large AC generators (Morden A.C generators) the arrangement is reverse i.e armature being stationary & field rotating.

- The advantages of stationary armature & that of the revolving field system are given below. :-

→ No difficulty is experienced in insulating the stationary armature winding for every high voltage. e.g. as high as 30,000 V or more.

→ The output current can be collected from fixed terminals on the armature or stator to the load.

→ Two slip-rings are required for the supply of D.C. to the rotor & since exciting current is to be supplied at low voltage, there is no difficulty in insulating them.

→ The armature windings can be more easily braced to prevent any deformation being produced by the mechanical stresses set up as a result of high centrifugal forces.

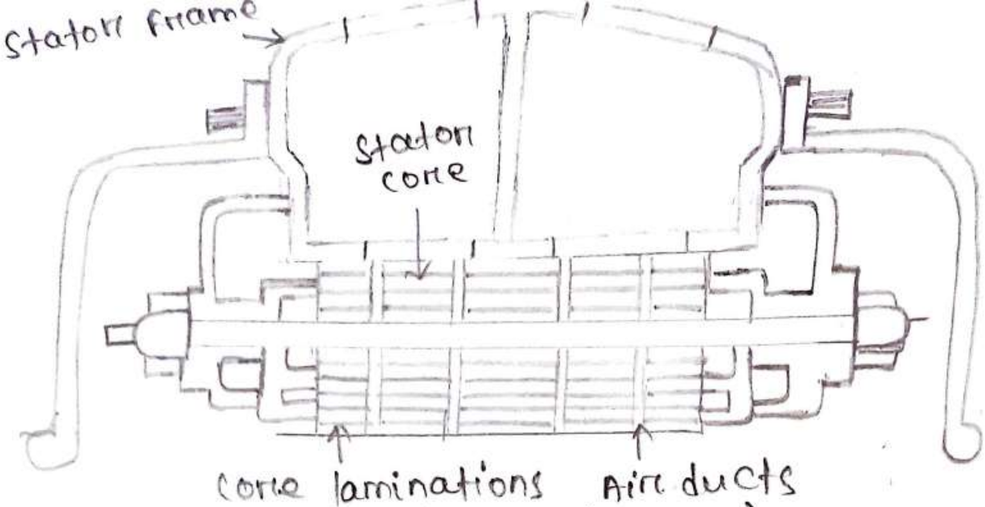
→ Rotating field comparatively light & can run with high speeds.

STATOR :-

(i) Stator frame :-

→ It is the outmost part of the machine, It is made of cast iron or cast stell or welded steel plates.

→ Its main function is to give the mechanical production to the entire machine and to hold the core in proper position.



(Stator frame)

(ii) Stator core :-

→ The stator core is laminated like a D.C armature core.

→ The laminations are formed of special magnetic iron or silicon steel having slots on its inner periphery to accommodate armature conductors.

→ The whole structure is held in a frame or stator frame as shown in figure.

→ Since the field rotates in the stator, so that flux of the rotating field cuts the core of the stator continuously and causes eddy current losses in the stator core.

→ To minimize the eddy current losses the stator core is laminated.

→ The laminations are stamped out in complete rings for smaller machines or in segments for larger machines & insulated from each other with varnish.

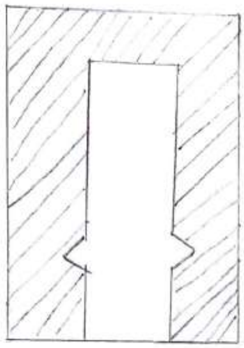
→ The stamping also have openings which make axial and radial ventilation ducts to provide efficient cooling.

→ Slots are provided on the inner periphery of the stator core.

→ These slots of 3 types.

(i) Open type or wide open :-

→ The open slots are used because the coils can be form wound & insulated prior to being placed in the slots giving least expenditure and more satisfactory winding Method.

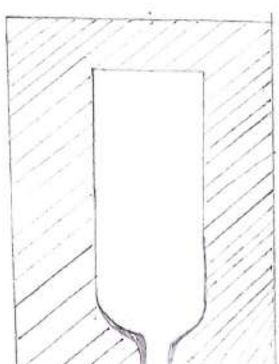


[Wide – open]

→ This type of slots also facilitates in removal & replacement of defactive coils. But this type of slots have disadvantages of distributing the air gap flux in to branches or tufts which tends to produce ripples in the emf wave.

(ii) Semi – closed type :-

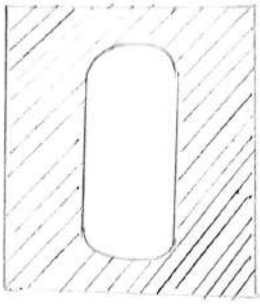
→ The semi closed type of slots are better in this respect but do not permit the use of form wound coils.



[Semi – closed]

(iii) Totally closed type :-

→ Totally closed slots are rarely used because of its increased winding cost etc.



(Closed)

Stator winding / Armature winding :-

→ The conductors placed in stator core slots & are connected in a particular fashion known as winding.

→ The emf's are induced in the winding. It is usually made of insulated copper or aluminium wire.

⊛ Rotor :-

→ The rotor is a rotating part of the alternator. It mainly used to house the magnetic poles & fixed winding.

→ The field excitation is usually provided from a small DC shunt or compound generator known as an exciter mounted on the same shaft of the alternator.

→ The exciting current is supplied to the rotor through two slip rings & brushes.

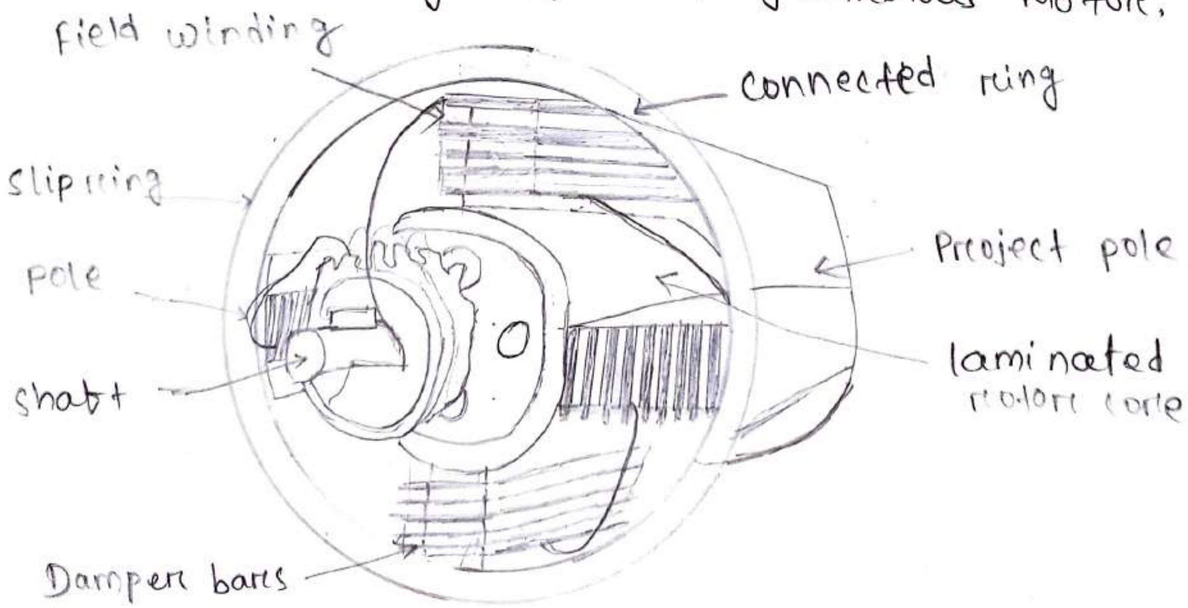
→ The power rating of exciter is ordinarily 0.3 to 1 % of power rating of the alternator.

→ Based on construction, rotors are classified in to two types as follows.

Rotors
→ salient pole type (or) projection pole type rotor (low speed, more number of poles, kaplan turbines)
→ Non salient pole type (or) smooth cylinderical type rotor (high speed (3000/1500 rpm), 2 or 4 poles, pelton wheel)

① Salient pole type rotor :-

→ It is used in low & medium - speed alternator.
→ It poles are made of steel laminations rivetted togather & are fixed to the rotor by a dove tail joint
→ The pole faces are usually provided with slots for damper winding (squirrel cage winding).
→ The damper bars are short - circuited at both ends by copper rings.
→ These dampers are used in preventing hunting & to provide starting torque in synchronous motor.



(Salient pole type rotor)

→ The field coils are placed on the pole-pieces as shown in figure and connected in series.

→ The ends of the field windings are connected to a D.C source through two slip-rings.

→ The salient pole type structure has the following special features.

(i) They have large diameter and short axial length.

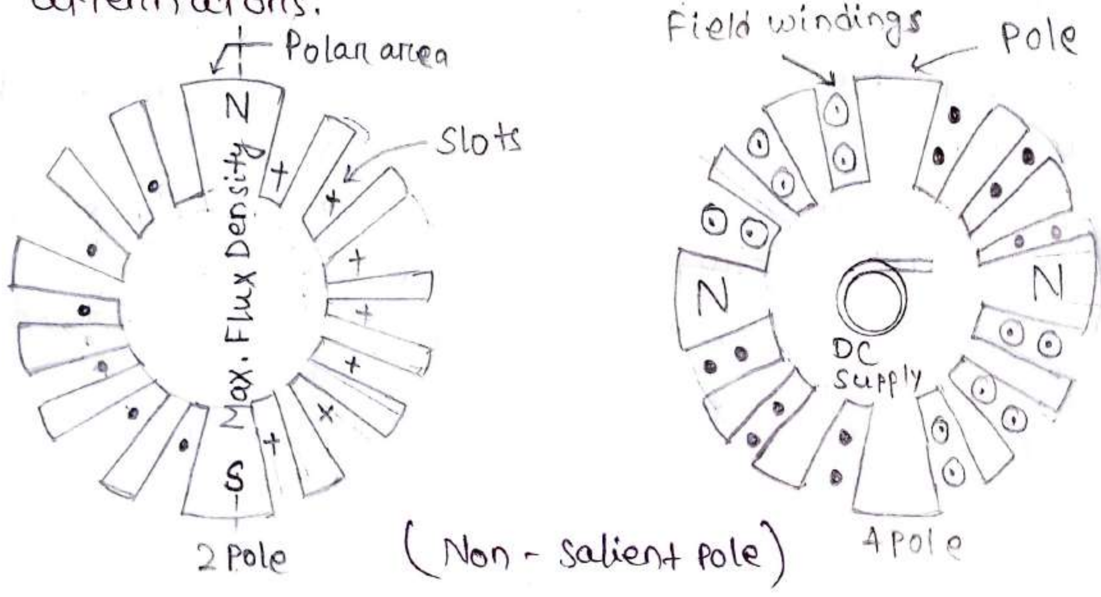
(ii) The pole shoes cover about 3 of pole pitch.

(iii) Poles are laminated to reduce eddy current losses.

(iv) These are employed with hydraulic turbines or diesel engines.

Non-Salient pole or Smooth cylindrical type :-

→ It is used in very high speed alternators usually driven by steam turbines also called turbo-alternators.



(Non-Salient Pole)

→ The rotor consists of a smooth solid forget steel cylinder having a number of slots on its outer periphery for accommodating field winding such rotors are design mostly for 2-Pole (or 4-pole) alternators running at 3000 r.p.m. (or 1500 r.p.m.).

→ The unslotted portions from pole faces as shown in figure.

→ General view of an assembly smooth cylindrical rotor is shown.

→ The non-salient pole type structure has the following special features.

(i) They are small diameter and of very long axial length. (to reduce periphery velocity).

(ii) less windage losses.

(iii) High speeds are obtained i.e. 3000 r.p.m (or 1500 r.p.m)

(iv) Better in dynamic balancing and quiter in operation.

Slip rings :-

→ usually hard drawn copper is used for manufacturing slip-rings.

→ The circular slip rings are mounted on the same shaft and is insulated from the shaft.

→ sliprings facilitate the DC supply to the field winding through brushes.

Brush & Brush holder :-

→ Brushes are made of carbon & are placed over the slip rings. It is a stationary part.

→ Brush and Brush holders are studied in D.C generators chapter, hence holds good here too.

SPIDER :-

→ It is like hub on which magnetic poles are fitted and its mounted on the shaft. It is made of either cast iron or cast steel.

EXCITER :-

→ In alternator, the field winding is always required to be excited by a separate D.C. supply. Hence all the alternators are necessary separately excited machines.

→ This is achieved by providing a small D.C generator called as an exciter mounted on the same shaft.

SHAFT & BEARINGS :-

→ The shaft is made of cast steel. It main function is to hold the rotor, slip rings & exciter in proper position. It is supported in bearings.

→ Depending upon the rating and position of the shaft (horizontal or vertical) bearings, roller bearings or thrust bearings are used.

⊛ DIFFERENCE Betn salient pole & Non-Salient pole rotor :-

Salient pole	Non Salient pole
(i) Poles are projected.	(i) Out surface is smooth. (Poles are not projected).
(ii) More number of poles are present.	(ii) Two or four poles are present.
(iii) large diameter (≃ 10 m) & small axial lengths (≃ 3 m).	(iii) small diameter (≃ 1 m) & large axial lengths (≃ 10 m).
(iv) Used for low and medium speed.	(iv) used for high speeds. (turbo) (3000 rpm or 1500 rpm only)
(v) Motor windage losses.	(v) less windage losses. (due to smooth surface).

Salient pole	Non salient pole
(vi) water turbines are preferred.	(vi) Steam turbines are preferred
(vii) Construction is difficult.	(vii) Construction is easy.
(viii) Perfectly not balanced.	(viii) Perfectly balanced.
(ix) Air gap is present in both poles	(ix) No air-gap in both poles.
(x) Flux is not uniform due to interpolar gap.	(x) Flux is uniformly distributed.

Advantages of stationary armature :-

- The following are the various advantages of alternator having stationary armature

→ It is easy to insulated stationary winding.
→ Stator winding voltage rating can be increased.
→ It needs only 2 slip rings on D.C side.
→ sparking at brushes is completely avoided.
→ Perfect mechanical balanced is obtained on stator winding.
→ It is easy to insulate slip-rings which are on D.C.
→ The rotor weight is less compared to stator weight.
→ They heavy bearings are not required since rotor is light weight.
→ Commutator is not present.

Alternator parts along with material :-

→ Table given below shows the various parts of alternator & material used for,

Name of the parts		Material used
① Stator frame	→	Cast iron or Cast steel
② stator core	→	silicon steel or sheet steel
③ Rotor core	→	silicon steel
④ Stator & rotor winding	→	Copper
⑤ Insulation	→	Varnish, paper, etc.
⑥ Slip rings	→	Hard drawn copper.
⑦ Brushes	→	Carbon
⑧ shaft	→	Mild steel or carbon steel.
⑨ End covers	→	Forged steel.

—x—

3 Phase winding in AC Machines

Armature winding :-

→ Winding is an orderly arrangement of insulated conductors in the slots of armature / stator cores with their end connection in a specified sequency.

→ Winding is mainly classified as

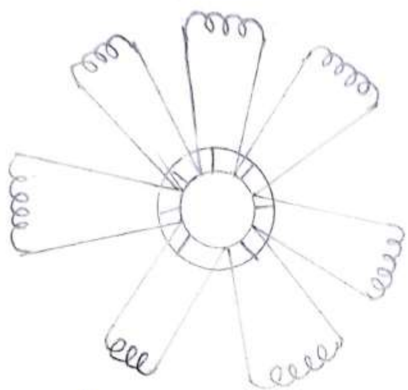
(i) closed coil winding.

(ii) open coil winding.

(i) Closed coil winding :-

→ It is also called D.C. armature winding, where in the coil ends are connected through the commutator segments to form the closed circuit.

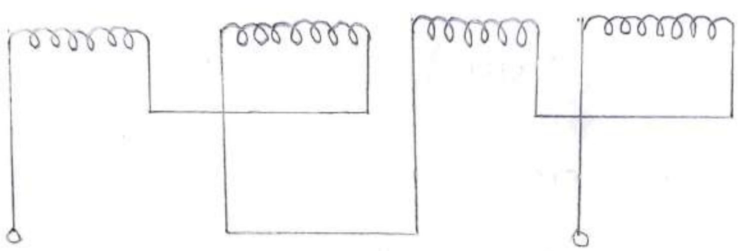
→ The end of the coil, after connecting through the other coils in the armature, finds it self connected to the commencement end of the starting coil as shown in the figure.



(Closed coil winding)

(ii) Open coil winding :-

→ It is also called A.C stator winding.



(Open coil winding)

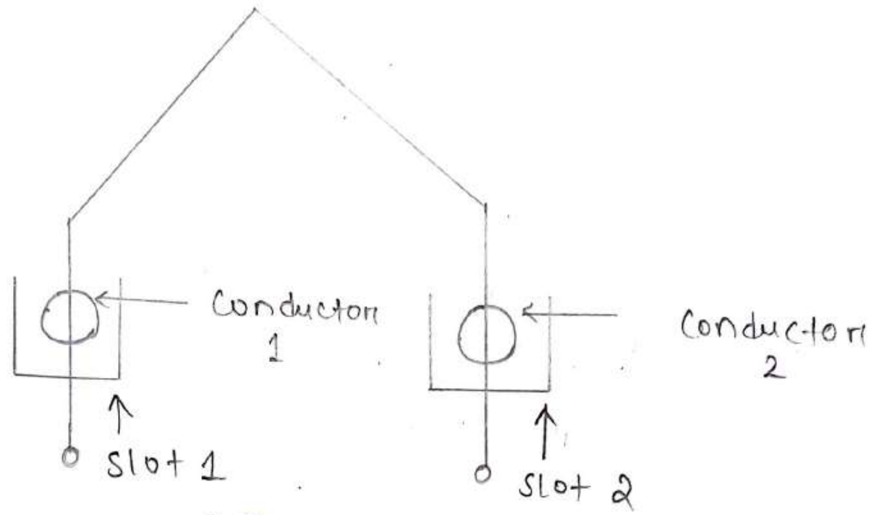
→ The end of the coil after connecting through other coils in the stator, is terminated as end lead, i.e, the starting end of the coil & the finishing end of the coil are kept on as shown. in fig.

(*) Conductor :-

→ The part of the wire which is under the influence of the magnetic field & responsible for the induced emf is called active length of the conductor. The conductors are placed in the armature slots.

Turn :-

→ A conductor is one slots when connected to a conductor in another slots forms a turn. So two conductor constitute a turn. This is shown in fig.

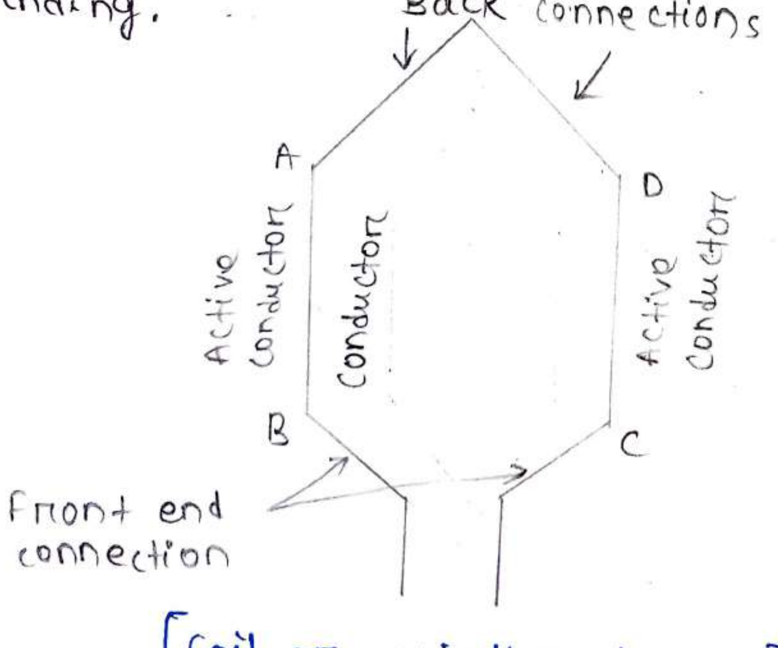


(Turn)

Coil or winding element :-

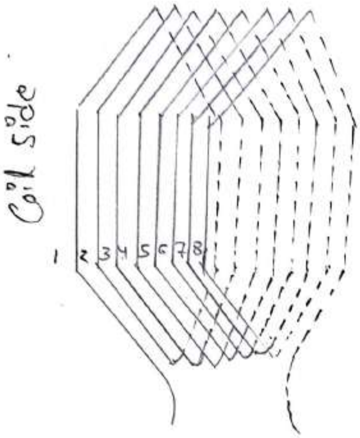
→ length of a wire lying in the magnetic field and in which an emf is induced is called an active conductor.

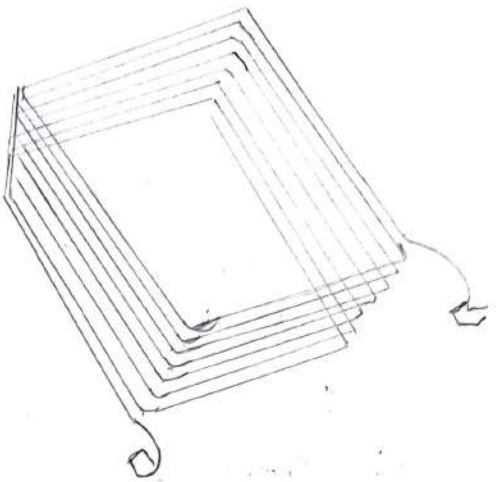
→ Referring to fig, we find the two active conductors AB & CD along with their end connections constitute on coil or winding element of the armature winding.



[Coil or winding element]

→ The coil may consist of a single turn only as shown in below figure 3 or multi turns as shown.



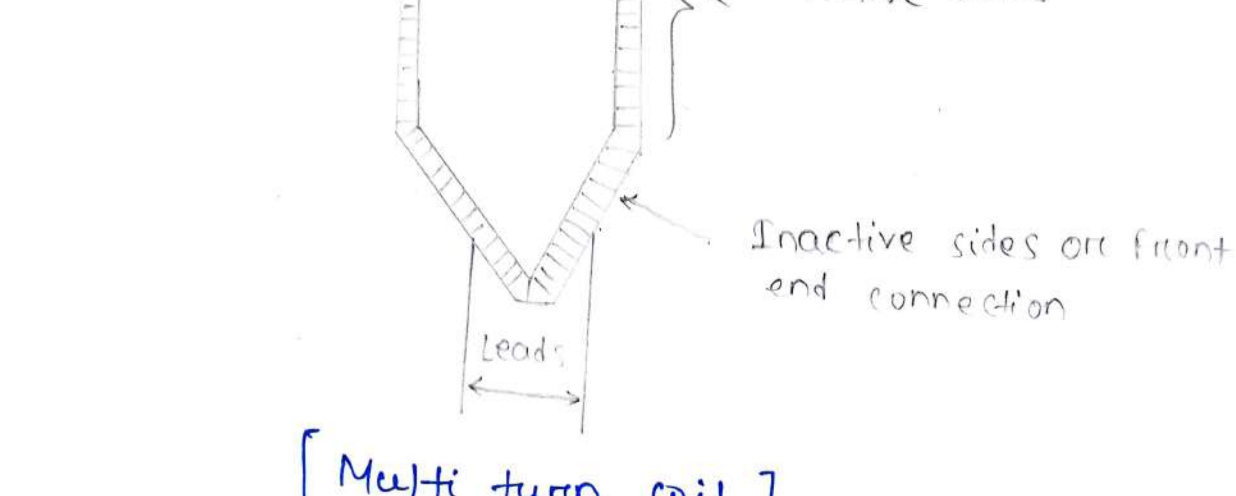


→ A single turn coil or winding element will have 2 conductors per coil side.

→ In fig. for example, each coil side has 8 conductore.

→ The group of conductores constituting a coil side of a multi turn coil is tied togather with a tape as a unit and is placed in the armature slot.

→ There are as many commutator bars as the number of winding element.



[Multi turn coil]

Active sides :-

- These are the side which lie with in the slots. They are also known as coil sides.
- The induction takes place only in the active sides of the coil while they move in the magnetic field.
- In winding calculation these active sides are considered as conductors.
- The coil has got two conductors irrespective of the number of turns.

Inactive Sides :-

- That part of a coil which does not lies in the slot is known as coil sides.
- No induction takes place in the inactive coils.
- Ex :- Back and front end connections.

Leads of coil :-

- The ends coming out from a coil are known as leads of a coil. Every coil has got two leads.

pole pitch :-

- It is centre to centre distance between the two adjacent poles. We have seen that for one rotation of the conductors, 2 poles are responsible for 360° electrical of emf, 4 poles are responsible for 720° electrical of emf and so on. So 1 pole is responsible for 180° electrical of induced emf. So 180° electrical is also called one pole pitch.
- Practically how many slots are under one pole which are responsible for 180° electrical, are measured to specify the pole pitch.

→ E.g consider 2 pole, 18 slots armature of an alternator. Then under 1 pole there are 18/2 i.e 9 slots. So pole pitch is 9 slots. or 180° Electrical. This means 9 slots are responsible to produce a phase difference of 180° between the e.m.f. s induced in different conductors.

This number of slots / pole is donated as 'n'

∴ Pole pitch = 180° electrical

= slots / pole (no of slots / P.)

= n

Slot angle (β) :-

→ The phase difference contributed by one slot in degrees electrical is called slot angle β.

→ As slots per pole contributes 180° electrical which is donated as 'n', we can write.

$$\therefore \quad 1 \text{ slots angle} = \frac{180}{n}$$

$$\therefore \quad \beta = \frac{180^\circ}{n}$$

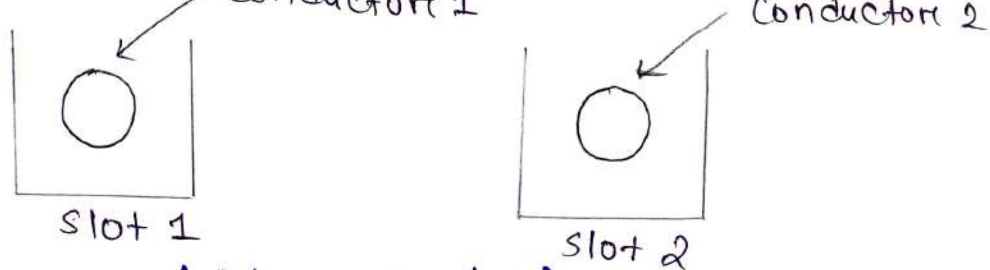
- In the above example,

$$n = \frac{18}{2} = 9$$

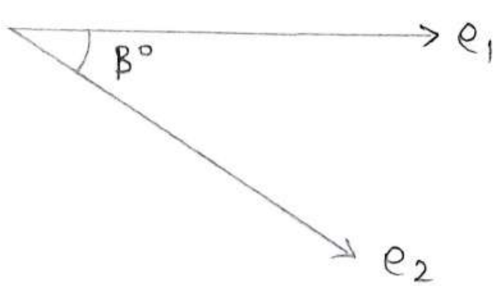
while,

$$\beta = \frac{180}{n} = 20^\circ$$

NOTE :-



(Adjacent slots)



e_1 = emf in conductor 1

e_2 = emf in conductor 2

(Indication of phase difference)

→ This means that if we consider an induced emf in the conductors which are placed in the slots which are adjacent to each other, there will exist a phase difference of β° in betn them. While if emf induced in the conductors which are placed in slots which are 'n' slots distance away, there will exist a phase difference of 180° in between them.

—x—

((Types of 3 ϕ windings))

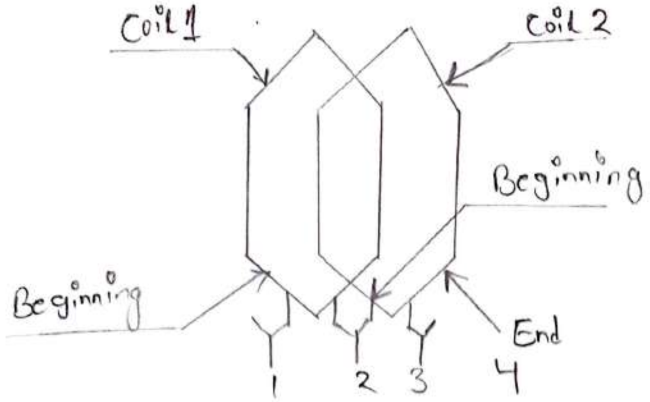
Types of armature windings :-

(i) Lap and wave winding :-

→ The armature windings are classified into two main groups, lap & wave windings.

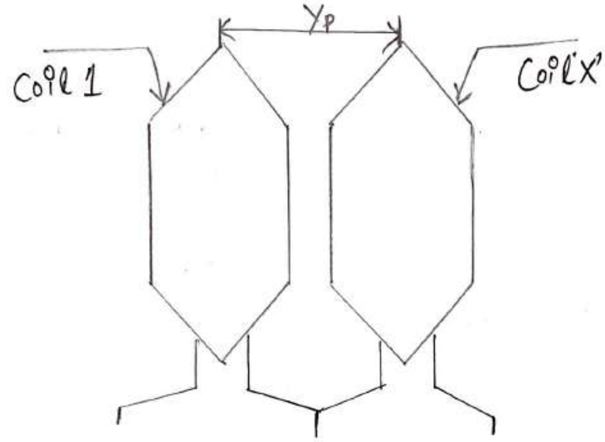
Simple lap winding :-

→ In a simplex lap winding the end lead of coil 1 is connected to the being lead of the adjacent (coil 2).



Simplex wave winding :-

→ In simplex wave winding, the end lead of the coil 1 is connected to the being of a coil placed at a distance equal to one pole pitch.



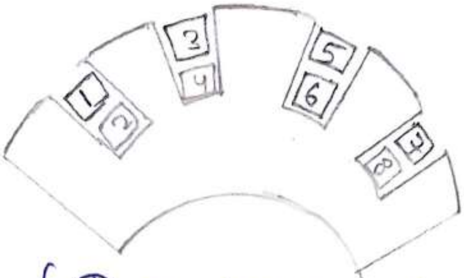
Single layer winding :-

→ A single layer winding is one in which only one coil side is placed in each armature slots as shown in fig. Such a winding is not used much.

Single layer winding

Two layer winding :-

→ In this type of winding, there are two conductors or coil sides per slot arranged in two layers as shown in fig.



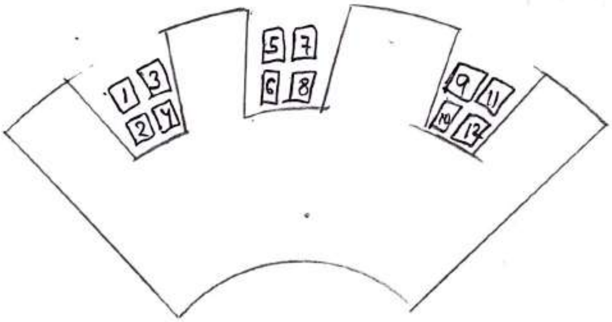
(Two-layer winding)

→ usually, one side of every coils lies in the upper half of one slot & the other sides of the same coils lies in the lower half some ..e other slot at a distance of one coil pitch away.

<u>Multi-coil winding :-</u>

→ Some time 4 or 6 or 8 coil side are used in each slot in several layers because it is not practicable to have too many slots.

→ The coil sides laying at the upper half of the slots are number odd, i.e, 1, 3, 5, 7 etc. while those at the lower half are numbered even i.e, 2, 4, 6, 8 etc.



<u>Multi-Coil winding</u>

<u>Full pitch & short pitch winding :-</u>

→ As seen earlier, one pole pitch is 180° electrical.

→ The value of 'n' slots per pole indicates how many slots are contributing 180° electrical phase difference.

→ So It coil side is one slots is connected to a coils side in another slot which is one pole pitch distance away from first slot, the winding is said to be full pitch winding and coil is called full pitch coil.

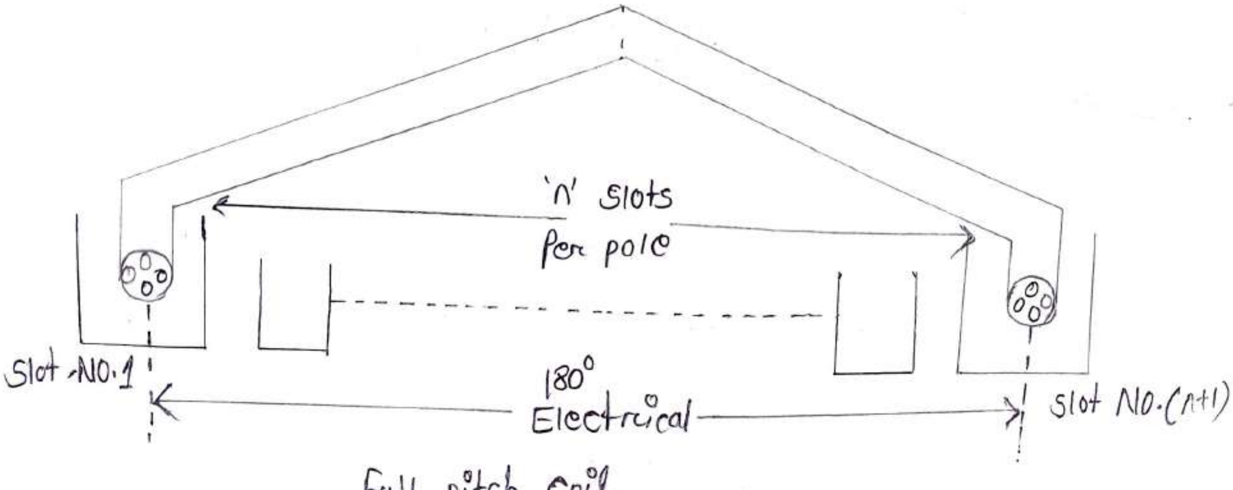
→ for example in 2 pole, 18 slots anothor, the pole pitch is $n = \frac{18}{2} = 9$ Slots. So it coil sides in slot no.1 is connected to coil side in slot no. 10 such that two slots no.1 & no. 10. are one pole pitch are n slots or 180° electrical a part, the coil is called full pitch coil. Here we can define one more term related to a coil called coil span.

⊛ Coil Span :-

→ It is the distance on the periphery of the armature betn two coil sides of a coil.

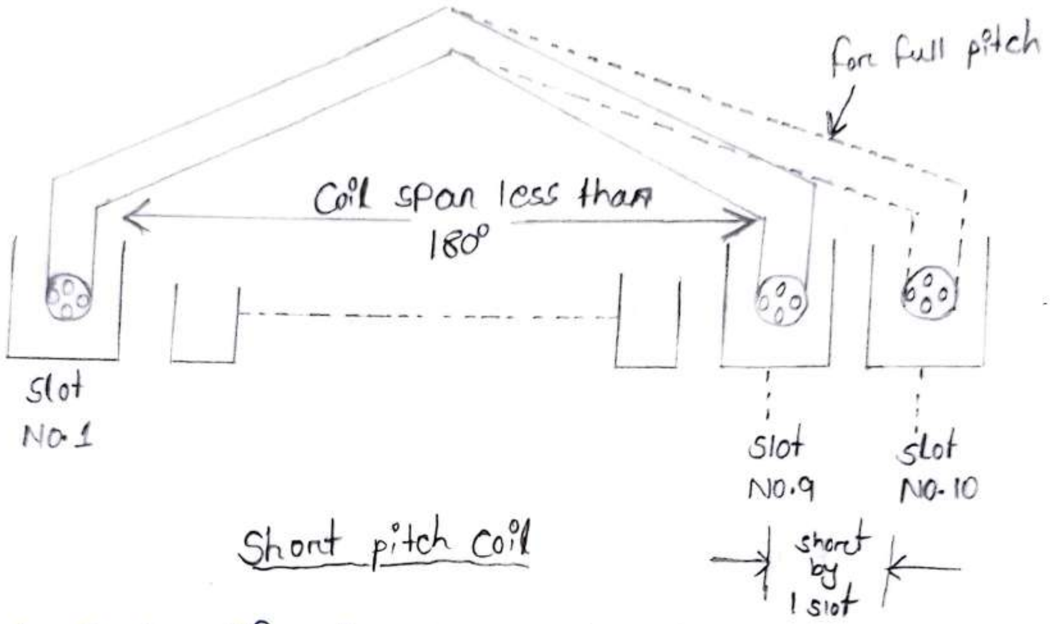
→ It is usually expressed in terms of number of slots or 180° electrical the coil is called full pitch coil. This is shown in the fig.

→ As against this It. coils are used in such a way that coil span in slightly less than a pole pitch i.e less than 180° electrical, the coils are called, short pitched coils or fractional pitched coils. Generally coils are shorted by one or two slots.



Full pitch Coil

→ So in 18 slots 2 pole alternator instead of connecting a coil side in slot No. 1 to slots No. 10, it's connected to a coil sides in slot No 9 or slots no. 8 coil is said to be short pitched coil & winding is called short pitch winding. This is shown in fig.



Short pitch coil

Advantages of short pitch coil :-

→ The length required for the end connections of coils is less. that is inactive length of winding is less. So, less copper is required. Hence economical.

→ Short pitching eliminates high frequency harmonics which distort the sinusodial nature of e.m.f Hence wave form of an induced emf is more sinusodial due to short pitching.

→ As high frequency harmonics get eliminated, eddy current and hysteresis lossed which depend on frequency also get minimised. This increases the efficiency.

Concentrated & distributed winding :-

→ In three phase alternators, we have seen that there are 3 different sets of windings, each for a phase.

→ So depending upon the total number of slots & number of poles, we have certain slots/phase available under each pole. This is donated as 'm'.

$$m = \text{Slots / pole / phase}$$
$$= n/\text{number of phases}$$
$$= n/3$$

for example in 18 Slots, 2 pole alternator we have,

$$n = \frac{18}{2} = 9$$

& $$m = \frac{9}{3} = 3$$

→ So we have 3 slots/pole/phase available. Now let 'x' number of conductors/phase are to be placed under one pole, & we have 3 slots/pole/phase available.

→ But of all 'x' conductors / phase & placed in one slots keeping remaining 2 slots / pole / phase empty then the winding is called concentrated winding. So in concentreated winding all conductors or coils belonging to a phase are placed in one slots under every pole.

→ But in practice, an attempt is always made to use all the 'm' slots per pole per phase available for distribution of the winding.

→ So, If 'x' conductors per phase are distributed amongst the 3 slots / phase available under every pole, the winding is called distributed winding.

Pitch factor or Coil span factor (K_c) :-

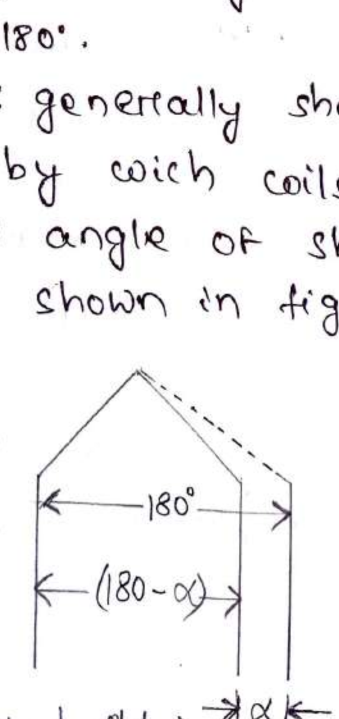
→ In actual practice, the winding used for the alternators is distributed and short pitch coil, hence emf induced slightly gets affected.

→ let us, see now the effect of short pitch type of winding on the emf equation.

→ In case of short pitch, coil is formed by connecting one coil side to another which is less than one pole × pitch away. So actual coil span is less than 180°.

→ The coil is generally shorted by one or two slots.

→ The angle by wich coils are short pitched is called as angle of short pitch donated as 'α'. This is shown in fig.



180° = Full pitch

$(180^\circ - \alpha)$ = Short pitch

(Angle of short pitch)

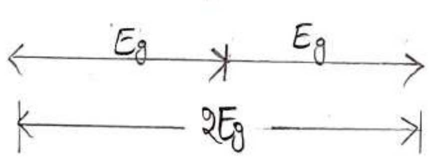
→ when the coils are full pitched, the resultant emf in a coils is the algebric sum of the emf induced in the 2 coils sides.

→ While when the coils are short pitched, due to short pitch angle α,

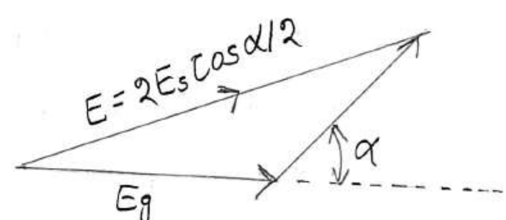
→ The resultant emf in a coils is the vector sum of the emfs induced in the two coil sides.

→ let E_s be the induced emf in each side of the coil.

→ If the coil were full pitched i.e if its two sides were one pole - pitch a part, then total induced emf in the coil would have been = $2E_s$. as shown in fig.



(a) Algebraic Sum (full pitched)



(b) Vector sum (short pitched)

(Algebraic Sum (full pitched) and)
(Vector Sum (short pitched))

→ Now the algebric sum is always more than the vector sum, So due to short pitching, the induced emf decreases by a factor called as coil span factor or pitch factor (K_c).

→ It is defined as the ratio of resultant emf (E_R) when coil is short pitch to the resultant emf when coil is full picthed. It is always less than one.

$$K_c = \frac{E_R \text{ when coil is short pitched}}{E_R \text{ when coil is full pitched}}$$

from the above figure,

$$K_c = \frac{2E_s \cos\left(\frac{\alpha}{2}\right)}{2E_s}$$

$$K_c = \cos\left(\frac{\alpha}{2}\right)$$

where,

α = Angle of short pitch.

Note :- The value of α will usually be given in the problem, if not, then assume $K_c = 1$

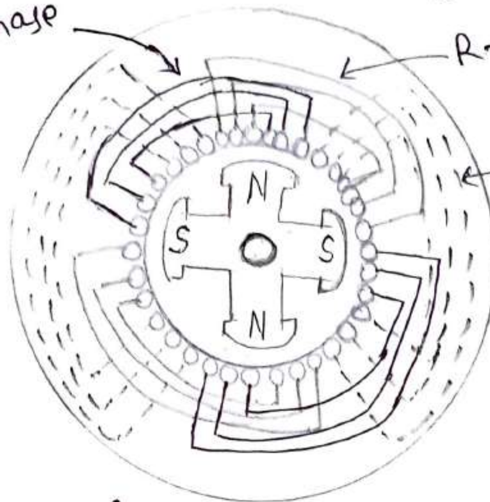
(*) Distribution or Breath factor or winding factor or spread factor. :-

→ It will be seen that in each phase, coil are not concentrated or bunched in one slot, but are distributed in a number of slots to form polar groups under each pole.

→ These coils / phase are displaced from each other by a certain angle. The result is that the EMF's induced in the coil sides constituting a polar group are not in phase with each other but differ by an angle equal to angular displacement of slots.

→ The following figure are shown the end connections of a 3-phase single layer winding for a 4-pole alternator. It has a total of 36 slots i.e, 9 slots / pole.

→ obviously there are 3 slots / phase / pole.
For ex :- Coil 1, coils 2 & 3 being to R phase.

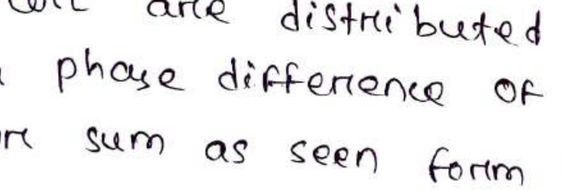


(Distribution factor)

→ Now these three coils which consitute one polar group are not bunched in one slot but in 3 different slots. Angular displacement betn any two adjacent slots = 180°/9 = 20° (electrical).

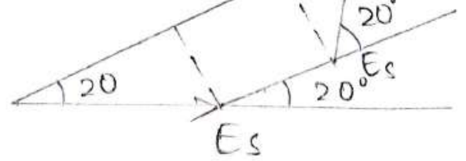
→ If 3 coils were bunched in one slots, then total emf induced in the three sides of the coil would be the arithmetic sum of the 3 emf's i.e, = 3 Es, where Es is the emf induced in one coil sides.

(a)



→ Since the coil are distributed, the individual emf have a phase difference of 20° with each other. Their vector sum as seen form fig.

(b)



$E = E_s \cos 20^\circ + E_s + E_s \cos 20^\circ$

$E = 2 E_s \cos 20^\circ$

$E = 2 E_s \times 0.9397 + E_s$

$E = 2.88 E_s$

The distribution factor (K_d) is defined as

$$= \frac{\text{EMf with distributed winding}}{\text{Emf with concentrated winding}}$$

In the present case,

$$K_d = \frac{\text{EMF with winding in 3 slots / pole / phase}}{\text{EMF with winding in 1 sots / pole / phase.}}$$

$$= \frac{E}{3E_s} = \frac{2.88 E_s}{3 E_s} = 0.96$$

$\therefore$ $K_d = 0.96$

General case :-

→ let β be the value of angular displacement betn the slots. Its value is

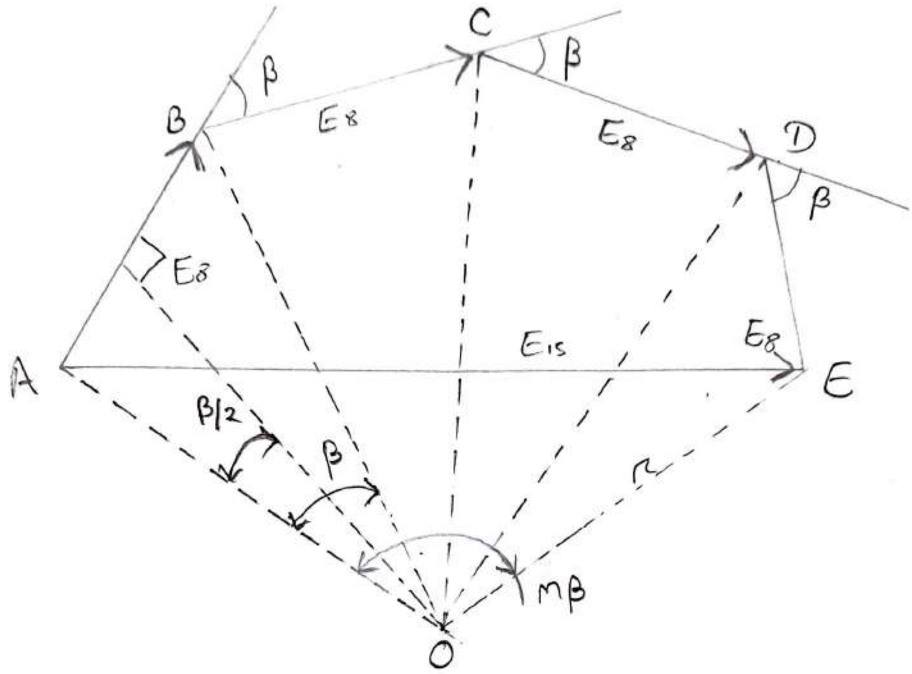
$$\beta = \frac{180}{\text{No of slots / pole}} = \frac{180^\circ}{n^\circ}$$

let m = No of slots / phase / pole.

$m\beta$ = phase spread angle.

→ Then the resultant voltage induced in one polar group would be mE_s, where E_s is the voltage induced in one coil sides.

→ The following figure illustrates the methods for finding the vector sum of m voltages each of value E_s & having a mutual phase difference of β.



$AB = E_s = 2r \sin β/2$

Arithmatic sum is $= mE_s = m \times 2r \sin β/2$

The vector sum is $= AE = E_s = 2r \sin mβ/2$

$$K_d = \frac{\text{Vector sum of coil e.m.fs}}{\text{Arithmatic sum of coil e.m.fs}}$$

$$K_d = \frac{2r \sin mβ/2}{m \times 2r \sin β/2}$$

$$K_d = \frac{\sin mβ/2}{m \sin β/2}$$

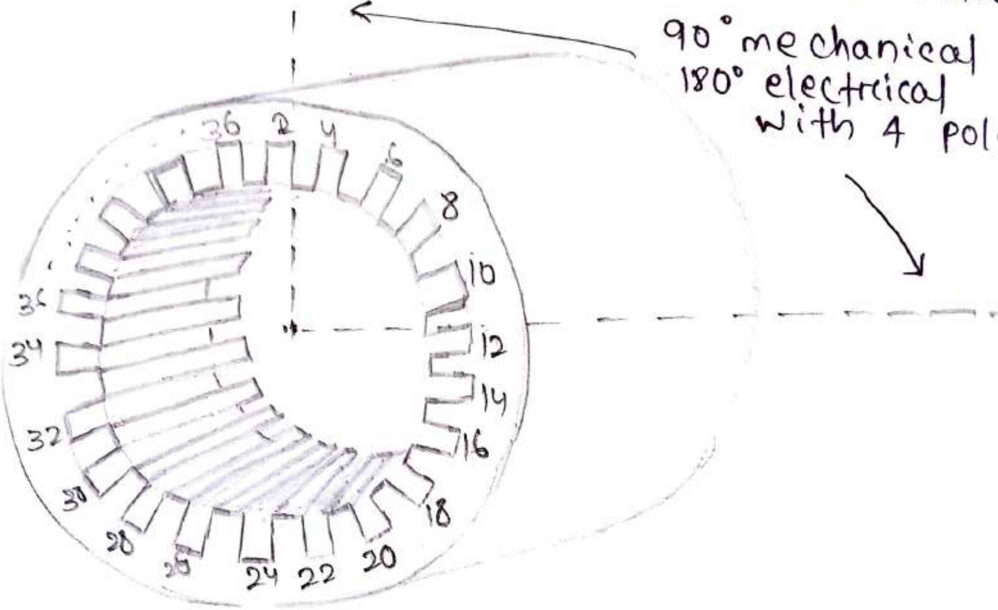
Chording of winding :-

→ Chording of the pole windings is one of the design factor.

→ The 36-slots, four pole machine, an individual coil enters slot 1 & comes back in slot 10, It will be spanned 90 mechanical degrees of the stator circular structure.

→ There are four poles, 90 mechanical degrees is 180 electrical degrees.

→ The two sides of the coil are in the same relative position on the adjacent north & south pole positions. This is a full-pitch coil construction.



(Four - pole AC stator with full pitch coil)

→ The more usual A.C machine coil will cover less of the periphery of the machine and is then said to be fractional pitch.

→ A typical situation might have a coil entre slot 1 & leave slot 7. This then covers six out of a possible nine slot pitches, & is a 6/9 or 66.7% pitch.

→ The majority of A.C machine coils are of fractional pitch type.

ADVANTAGES OF FRACTIONAL PITCH WINDING :-

→ The ends of the coil are shorted, which means less copper loss due to less total length.

→ The end coils can be formed more campactly. The end belts will need less winding space resulting in a shorter unit.

→ Improved wave form of the induced emf.

→ Fractional number of slots per pole can be used which in turn reduces tooth ripples.

→ Mechanical strength of the coils is increased.

→ The distinct reduction in machine harmonics due to cancellation of higher harmonics.

→ All ac equipment is designmed to operate on a pure sine wave, the generation of harmonics is to be avoided. This is especially so when the factor that achieves it is other wise desirable.

E.M.f Equation

let,

Z_{ph} = number of conductors or coil sides in series/phase

$Z_{ph} = 2T_{ph}$, where T_{ph} is the number of coils or turns/phase.

P = number of poles

ϕ = usefull flux/pole, weber

N = rotational speed of rotor, r.p.m

f = frequency, Hz

Kd = distribution factor

Kc = pitch factor or coil span factor

→ The alternator rotor move through one revolution in $t = (60/N)$ sec, the flux cut by the conductor

$= P\phi$ weber

The average emf induced in the conductor

$$E_{av} = \frac{d}{dt}(\text{flux}) \text{ volt}$$

$$= P \cdot \frac{\phi}{t}$$

$$= \frac{P\phi}{\frac{60}{N}}$$

$$\therefore E_{av} = \frac{P\phi N}{60}$$

we know that,

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

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

Substituting the value of N in equation 1, we get

$$E_{av} = \frac{P\phi \times 120 f}{60 \times P}$$

$$E_{av} = 2 f \phi \text{ volt/conductor}$$

Avarage emf / phase

$$E_{av}/\text{phase} = 2 f \phi \times 2 T_{ph}$$

$$E_{av}/\text{phase} = 4 f \phi T_{ph}$$

$$E_{rms}/\text{phase} = E_{av} \times \text{form factor}$$

$$E_{rms}/\text{phase} = 4 f \phi T_{ph} \times 1.11$$

$$E_{rms}/\text{phase} = 4.44 f \phi T_{ph} \text{ volt}$$

→ The above equation of emf induced / phase is true only.

→ The winding is concentrated in one slot but practically it is not true.

→ The winding for each phase under each pole is distributed and for such cases K_c & K_d must be considered.

→ Thus, emf induced / phase

$$E_{rms} / phase = 4.44 f \phi T_{ph} K_c K_d \text{ volt}$$

for full - pitched and concentrated winding.

$$K_p = 1 \quad , \quad K_d = 1$$

If the alternator is star - connected then the line voltage.

$$E_L = \sqrt{3} \, E_{rms} \text{ phase}$$

$$E_L = \sqrt{3} \times 4.44 f \phi T_{ph} K_c K_d \text{ volt}$$

Shape of the Emf wave :-

→ The instantaneous value of the induced emf in a conductor moving across the magnetic field is proportional to the rate of cutting the flux at that instant.

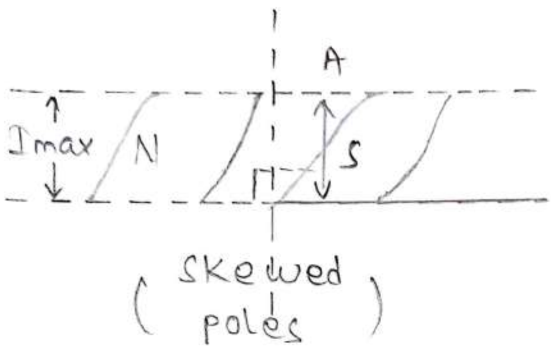
→ The wave form of the induced emf is similar to the wave of the magnetic flux in the air - gap.

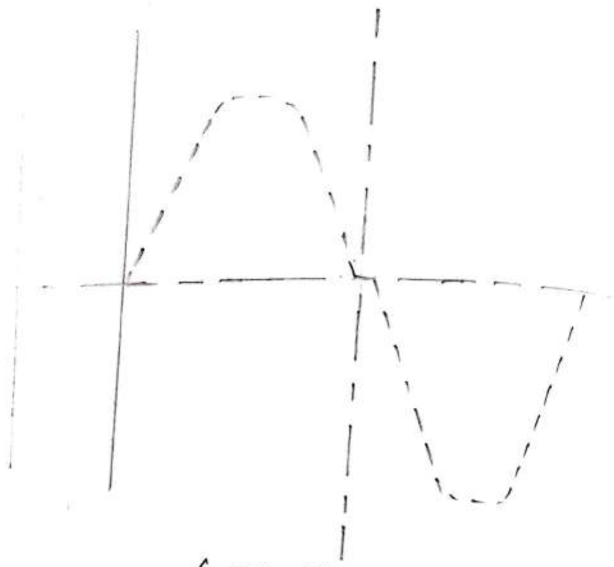
→ When the distribution of the flux in the air gap is sinusodial, the induced emf wave form will also be sinusodial. But the flux wave form in practice is never exactly sinusodial.

→ Further harmonics do creep up due to various causes. The pulsating flux tufts at the armature teeth also cause harmonics.

→ The following methods are employed to obtain emf wave whose shap is very close approximation to a sine wave.

→ The pole shoes are skewed. The field form due to a well designed skewed pole - shoe is shown in figure (b) while fig (a) shows a skewed pole.





(Field form)

(Fig - A)

→ This method of obtaining a very good shape for the emf wave is simple & interesting, since the value of emf induced in a conductor is given by the expression.

→ Since v (velocity) is assumed to be constant, either B (flux density) or I (active length of conductor) must very according to a sine law. How the active length I various is shown fig (a).

→ As the conductor moves relative to the poles, the length of conductor under the influence of a pole varies over a certain distance form instant to instant.

→ The pole - shoes should be given such a shape that the variation of the length I is according to a sine law.

→ The flux density under the gap can be made to vary according to a sine law if the gap length varies form the centre of the pole to the tips of the pole - shoes.

→ The increase in the gap length is made almost twice and the ratio $\frac{\text{Pole arc}}{\text{pole pitch}}$ is kept round about 0.67.

→ In turbo - alternators, where rotor is cylindrical in form the unslotted portion should be 0.3 times the pole pitch.

→ The field windings are accommodated in several points of slots, the windings of each pair contribute towords the total mmf.

→ The result gap density approaches very near to a sine wave low.

→

Problems - 1 :-

A 3 Φ, 16 pole alternator has a star - connected winding with 144 slots & the conductors per slot. The flux per pole is 0.03 wb. sinusodially distributed and the speed is 375 rpm. Find the frequency, phase & line voltages. Assume full - pitched coils.

Soln :-

Given Data,

No of poles (P) = 16

Synchronous speed (N_s) = 375 rpm

Flux/pole (Φ) = 0.03 wb

Number of slots = 144

Conductor / slots = 10

Full pitched coil (K_c) = 1

To find,

Frequency (f) = ?

phase voltage (E_{ph}) = ?

line voltage (E_L) = ?

Formula used,

$$\text{frequency}(f) = \frac{N_s P}{120}$$

$$\text{slot/pole}\ (n) = \frac{\text{Slot}}{\text{pole}}$$

$$\text{slot angle}\ (\beta) = \frac{180^\circ}{n}$$

m = slot/pole/phase

$$\text{Distribution factor}\ (K_d) = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\beta/2\right)}$$

No of conductor (Z) = Slots × conductor/slots

$$\text{Total number of turns/phase}\ (T_{ph}) = \frac{Z_{ph}}{2}$$

phase voltage (E_{ph}) = $4.44\, K_c K_d f \phi T_{ph}$

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

Soln

$$\text{frequency}\ (f) = \frac{P N_s}{120} = \frac{16 \times 375}{120} = 50\ \text{Hz}$$

$$\text{slot/pole}\ (n) = \frac{144}{6} = 9$$

$$\text{slot angle}\ (\beta) = \frac{180}{n} = \frac{180}{9} = 20^\circ$$

$$m = \frac{144}{16 \times 3} = 3$$

$$\text{Distribution factor}\ (K_d) = \frac{\sin 3\left(\frac{20}{2}\right)^{10}}{3 \sin \frac{20}{2}^{10}}$$

$K_d = 0.966$

$Z_{ph} = 144 \times \frac{10}{3} = 480$

$T = \frac{480}{2} = 240$

Full pitch winding $(K_c) = 1$

$E_{ph} = 4.44 \times 1 \times 0.96 \times 50 \times 0.03 \times 240$

$E_{ph} = 1534\ V$

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

$E_L = \sqrt{3} \times 1534$

$E_L = 2658\ V.$

∴ Frequency $(f) = 50\ Hz$

phase voltage $(E_{ph}) = 1534\ V$

line voltage $(E_L) = 2658\ V.$

Problem - 2 :-

→ A 3 Φ, star connected alternator has the following data; voltage required to be generated on open-ckT = 4000 V (at 50 Hz), speed = 500 RPM, stator slots/pole/phase = 3 conductors/slots = 12. calculate

(i) Number of poles

(ii) use ful flux/poles

Assume all conducts/phase to be connected in series & coil to be full pitch.

Given Data,

Generated open ckt voltage (E_L) = 4000V

synchronous speed (N_s) = 500 rpm

conductor / slot = 12

stator slots / pole / phase (m) = 3

Frequency (f) = 50 Hz

To find

Number of poles (P) = ?

Flux / pole (ϕ) = ?

Formula used

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

$$\phi = \frac{E_{ph}}{4.44 \, f \, T_{ph} \, K_c \, K_d}$$

Solution

$$\therefore P = \frac{120F}{N} = \frac{120 \times 50}{1500}$$

$$= 12 \text{ poles}$$

Pitch factor or coil span factor

$$K_c = 1$$

$$m = n/3$$

No of slots / pole (n) = 3×3 = 9

Angular displacement betn slots (β) $= \frac{180}{n}$

$$= \frac{180}{9}$$

$$= 20$$

$$\therefore K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \beta/2}$$

$$= \frac{\sin\left(\frac{3 \times 20}{2}\right)}{3 \sin \frac{20}{2}} = \frac{\sin 30}{3 \sin 10} = 0.96$$

Number of turns / phase

$$T_{ph} = \frac{Z_{ph}}{2}$$

$$\therefore Z_{ph} = \frac{Z}{3} = \frac{12 \times 9 \times 12}{3}$$

$$\therefore T_{ph} = \frac{12 \times 9 \times 12}{3 \times 2}$$

$$= 216$$

Now using the relative,

$$E_{ph} = 4.44\, \phi\, T_{ph}\, K_p\, K_d \text{ volts}$$

$$2309 = 4.44 \times 50 \times \phi \times 216 \times 1 \times 0.96$$

$$\phi = \frac{2309}{4.44 \times 50 \times 216 \times 1 \times 0.96}$$

$$= 0.05 \text{ wb}$$

$\therefore$ No. of poles (P) = 12 poles
flux / pole (ϕ) = 0.05 wb

<u>problem - 3 :-</u>

A 3ϕ, 10 pole alternator has 2 slots / pole / phase on its stator with 10 conductors / slot. The air gap flux is sinusoidally distributed & equals to 0.05 wb. The stator has double layer winding with a coil span of 150° electrical degrees. If the alternator is running at 600 rpm, calculate the emf generated / Phase at no load.

<u>Given Data :-</u>

Number of poles (P) = 10
Slots / pole / phase (m) = 2
conductor / slot (= 10
Coil span = 150° (Electrical)

Speed (N) = 600 rpm

To find

Emf generated / phase at no load (E_{ph}) = ?

Formula used

Phase voltage (E_{ph}) = $4.44 K_C K_d f \phi T_{ph}$

Solution

No of slots / pole (n) = 2 × 3 = 6

Angular displacement betn the slots

$$(\beta) = \frac{180}{n} = \frac{180}{6} = 30^\circ$$

Angle of chording (α) = $180^\circ - 150^\circ$

$= 30^\circ$

$$\therefore K_C = \cos\frac{\alpha}{2}$$

$$= \cos\frac{30}{2} = \cos 15^\circ$$

$$= 0.9659$$

$$\therefore K_d = \frac{\sin\left(\frac{q\beta}{2}\right)}{q\sin\left(\frac{\beta}{2}\right)} = \frac{\sin\frac{2 \times 30}{2}}{2\sin\frac{30}{2}}$$

$$= 0.9659$$

Number of conductors in series / phase

Z_{ph} = 10 × slots / phase

= 10 × (2 × 10)

= 200

Number of turns/phase $T_{ph} = \frac{Z_{ph}}{2}$

$$= \frac{200}{2} = 100$$

$$\therefore E_{ph} = 4.44 \times f \phi T_{ph} K_C K_d$$

$$= 4.44 \times 50 \times 0.05 \times 100 \times 0.9659 \times 0.9659$$

$$= 1035.6 \text{ V}$$

(Ans)

Problem - 4 :-

calculate the speed & open - CKT lines & phases voltages of a 4-pole, 3 phase, 50 Hz, star connected alternator with 36 slots & 30 conductors /slots. The flux /pole is 0.05 wb sinusoidally distributed.

Given data

No° of poles (P) = 4

frequency (f) = 50 Hz

No° of slots = 36

No° of conductor/slot = 30

flux per/pole (ϕ) = 0.05 wb.

To find

speed of alternator (Ns) = ?

open CKT line voltage (E_L) = ?

open CKT phase voltage (E_{ph}) = ?

Formula used

$$\text{Speed } (N_s) = \frac{120F}{P}$$

$$\text{phase voltage } (E_{ph}) = 4.44\, F \phi\, K_c K_d\, T_{ph}$$

Solution

$$N_s = \frac{120F}{P} = \frac{120 \times 50}{4}$$

$$= 1500 \text{ rpm}$$

Number of conductor connected in series /phase

$$Z_{ph} = \frac{\text{No° of slots} \times \text{No. of conductor/. slots}}{\text{No. of phases}}$$

$$= \frac{36 \times 30}{3}$$

$$= 360$$

No. of turns /phase (T_{ph}) = $\frac{Z_{ph}}{2}$

= $\frac{360}{2}$

= 180°

No. of slots / pole = n = $\frac{36}{4}$

= 9

No. of solts / pole / phase (m) = $\frac{9}{3}$ = 3

Angular displacement betn the slots

$(\beta) = \frac{180}{n} = \frac{180}{9} = 20$

∴ $K_d = \frac{\sin \frac{3 \times 20}{2}}{3 \sin \frac{20}{2}} = \frac{\sin 30}{3 \sin 10}$

= 0.96

pitch factor (K_c) = 1

open CKT phase voltage(E_{ph})

= $4.44 \times 50 \times 0.05 \times 180 \times 1 \times 0.96$

= 1918.1 V

open CKT line voltage (E_L) = $\sqrt{3}\, E_{ph}$

= $\sqrt{3} \times 1918.1$

= 3322.2 V.

∴ speed of alternator (N) = 1500 rpm.

open CKT phase voltage (E_{ph}) = 1918.1 V.

open CKT line voltage (E_L) = 3322.2 V.

Problem-5 :-

→ A 3 ϕ, 8 pole, 50 Hz, star connected alternator has 96 slots with 4 conductors / slot. The coil pitch is 10 slots. If the flux / pole is 6 mwb. find.

(i) The phase voltage

(ii) The line voltage

(iii) If each phase carrying 650 A, what is the KVA rating of the machine ?

~~(iv) If each phase carrying 650A,~~

Given Data :-

P = 8 poles

F = 50 Hz

ϕ = 60 mwb.

coil pitch = 10 slots

No of slots = 96

Solution

(n) = slots / pole = $\frac{96}{8} = 12$

slots angle (β) = $\frac{180^\circ}{12} = 15^\circ$

(m) slots / pole / phase = $\frac{12}{3} = 4$

coil pitch = 10 slots

= $10 \times \beta$

= 10×15

= 150° electrical

∴ Angle of short pitch

(α) = $180^\circ - 50^\circ$

= 30°

∴ $K_c = \frac{\cos\alpha}{2} = \cos 15^\circ = 0.9659$

$$\therefore K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\frac{\beta}{2}} = \frac{\sin\frac{4\times 15}{2}}{4\sin\frac{15}{2}}$$

$$= \frac{\sin 30}{4\sin\frac{15}{2}}$$

$$= 0.9576$$

Total number of conductors

= number of solts × conductor/slot

= 96 × 4

= 384

$\therefore$ Total turn = $\frac{384}{2}$ = 192

$\therefore T_{ph} = \frac{192}{3} = 64$

(i) The phase voltage =

$E_{ph} = 4.44\, K_C\, K_d\, \Phi\, f\, T_{ph}$

$= 4.44 \times 0.9659 \times 0.9576 \times 60 \times 50 \times 64$

$= 788.497$ V.

(ii) The line voltage

$E_{line} = \sqrt{3}\, E_{ph} = \sqrt{3} \times 788.497$

$= 1365.71$ V.

(iii) KVA Rating

$I_L = 650\text{ A} = I_{ph}$ = star connected

$\therefore$ KVA Rating $= \sqrt{3} \times E_{line} \times I_L$

$= \sqrt{3} \times 1365.71 \times 650$

$= 1537.56$ KVA.

Problem - 6 :-

A single phase 1500 r.p.m, 4 pole alternator has 8 conductors / slot with total of 24 slots. The winding is short pitched by 1/6 th of full pitch. Assume distributed winding with flux / pole as 0.05 wb. calculate the induced emf.

Given data :-

$N_s = 1500$

$P = 4$

slots = 24

conductor / slot = 50 Hz

solution :-

Note that the alternator is single phase & not the 3 ϕ

$$f = \frac{PN_s}{120} = \frac{4 \times 1500}{120} = 50 \text{ Hz}$$

$$n = \frac{\text{slots}}{\text{pole}} = \frac{24}{4} = 6$$

$m = n = 6$ as number of phases in one

$$\beta = \frac{180}{n} = \frac{180}{6} = 30^\circ$$

$$\therefore K_d = \frac{\sin\left(\frac{6 \times 30^\circ}{2}\right)}{6 \sin\left(\frac{30}{2}\right)} = 0.6439$$

full pitch = (n) = 6 slots

Coil short pitched by 1/6 th of full pitch i.e, by $\frac{1}{6} \times 6 = 1$ slots.

Angle of short pitch = 1 slot angle

$$\alpha = \beta = 30^\circ$$

$$K_c = \cos\left(\frac{\alpha}{2}\right) = \cos\left(\frac{30}{2}\right)$$

$$= \cos 15 = 0.9659$$

$$\text{Total conductor} = \frac{\text{conductor}}{\text{slot}} \times \text{slots}$$

$$Z = 8 \times 24 = 192$$

But as number of phase = 1, $Z = Z_{ph} = 19$

$\therefore T_{ph} = \frac{Z_{ph}}{2} = \frac{192}{2} = 96$ [$\because$ 2 conductor = 1 turn

$\therefore E_{ph} = 4.44\, K_c K_d\, \phi f T_{ph}$

$= 4.44 \times 0.9659 \times 0.6438 \times 0.05 \times 50 \times 96$

$= 662.74$ V

(Ans)

ARMATURE REACTION & ITS EFFECT ON EMF AT DIFFERENT POWER FACTOR OF LOAD

Definition excitation :-

→ The field structure is the rotor & the DC voltage applied to the windings on the field rotor to produce magnetic flux is turned as the excitation.

Exciter :-

→ In A.C generators, D.C. supply to excide the magnetic poles provided on the rotor.

→ The magnetic poles become power full electromagnets and establish magnetic flux between rotor pole shoe & stator core. This D.C supply is obtained usually from a D.C generator know as exciter.

Types of exciter :-

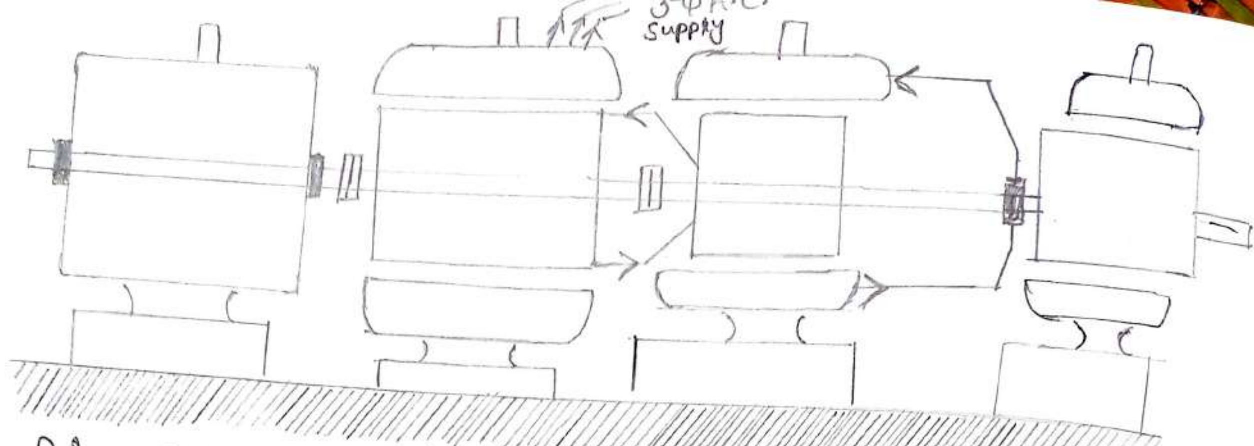
→ The exciter can be classified by 3 types namely,

(a) Main exciter
(b) pilot exciter
(c) Static exciter

(a) Main exciter :-

→ In operation an alternator requires its field current to be varied & this is usually obtained by varying the dc voltage of the main exciter.

→ This is turn, is obtained by varying the field current of main exciter. The location of exciter is shown in figure.



Location of exciter

(b) Pilot exciter :-

→ When the main exciter capacity is itself quite large variation of field current is obtained by changing the field current of a 'pilot exciter' whose armature supplies the field of the main exciter.

(C) Static excitation :-

→ Now a days D.C is produced by using electronic rectifiers rather than DC rotating machines.

→ The main exciter is replaced by a 3 - phase AC generator with a stationary D.C field.

→ This generator usually generates an A.C voltage which is converted to D.C by a 3 - phase bridge rectifier & then supplied to the rotor D.C field of the main alternator.

→ The exciting generator and rectifiers mounted on the main shaft & turn along with the rotor of the main alternator. Hence there is no need of slip rings & brushes.

→ The D.C excitation for the excitation generator is supplied by a pilot exciter which could be a rectified A.C. source.

Needs of exciter :-

- In alternator, the field winding is always required to be excited by a separate D.C. supply. Hence the alternators are necessarily separately excited machines.
- This is achieved by providing a small D.C generator called as an exciter mounted on the same shaft.
- This produces the required D.C voltage of the order of 110 V. to 250 V., when alternator is driven by the prime mover.
- This voltage is given to the field winding with the help of slip rings mounted on the same shaft between alternator & generator.

Armature reaction of alternators on load at various power factor :-

- The armature winding of an alternator carries current only when the alternator is loaded.
- At no load, there will be no current flowing through the armature winding.
- If alternators under loaded condition, there are two fluxes present in the air gap.
- Ther are,
  - Flux due to the field ampere turns
  - Flux due to the current flowing through the armature winding.
- There is already another flux due to field current, that is also present in the air gap.
- Now there are two fluxes present in the air gap.

But actually the machine need only the fluxes due to field ampere turns only.

→ The effect of armature flux due to armature current over the main field flux is called armature reaction.

→ When the armature carries the load current, a armature flux (ϕ_a) is produced in the armature winding and is also present in the air gap.

→ This effect can be in the following forms.

→ There are

- The armature flux will produce a distortion over the field flux.
- The armature flux will oppose the main field flux (or) will help the main field flux.

Power factors :-

① Unity power factor :-

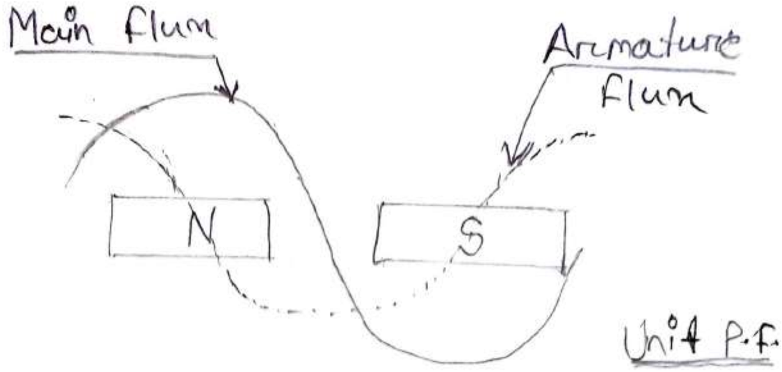
→ These punches are used to make witness marks on scribed lines.

→ The armature flux is cross magnetizing.

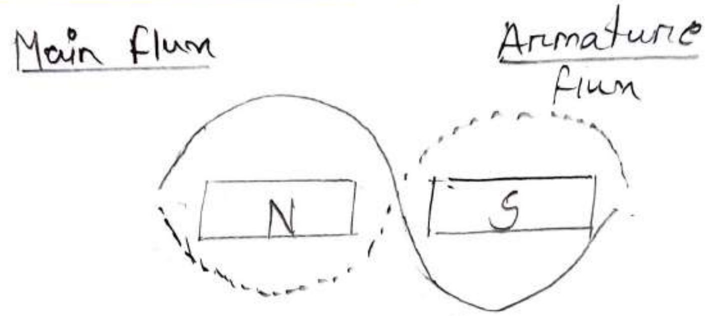
→ The result is that the flux (MMf waves) at the leading tips at the poles is reduced while at the trailing tips it is increased.

→ The two effects nearly off set each other, leaving the average field strength increased.

→ The armature reaction four unity power factor is distortional.



② Zero power factore lagging :-



Zero P.f. lagging

→ The armature flux is in direct opposition to the main flux.

→ The main flux is decreased.

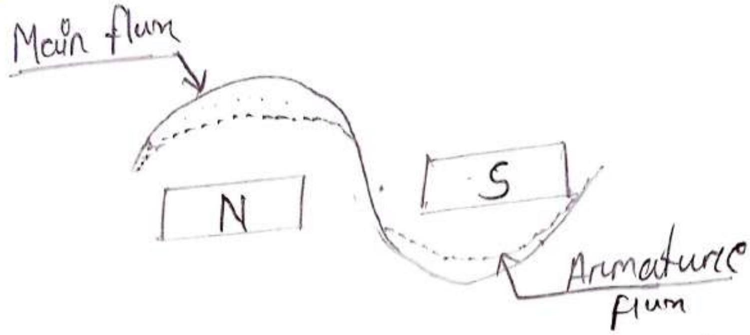
→ The armature reaction in this case is wholly de-magnetising, with the result that due to the weakening of the main flux, less emf is generated and hence the armature / output voltage will be lower.

→ To maintain the value of the generated emf / output voltage, at the desired level.

→ The field excitation current will have to be increased to compensate for this weaking of the main flux.

③ Zero power factor leading :-

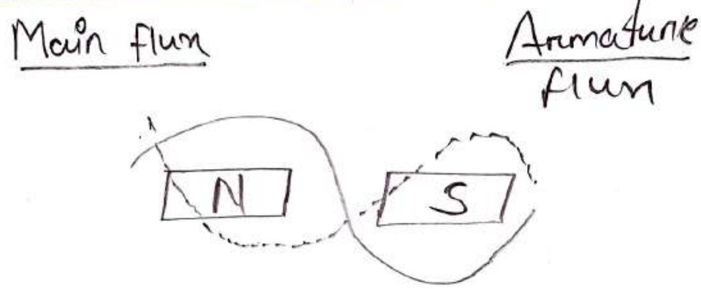
→ The armature flux wave has moved forword by 90°, so that it is in phase with the main flux. wave. This results an increased or added main flux.



→ The armature reaction is wholly magnetising which results in greater induced emf and the armature / out put voltage will be higher.

→ To maintain the generated emf / output voltage at the design level, the field excitation current will have to be reduced.

④ Other power factors lagging :-



0.7 P.F. lag

→ The effect is parity distortional and partly demagnetizing for other loads having lagging power factors of intermediate values.

→ Most load fall in this category in actual usage.

Alternator on load :-

→ The alternator load is varied, its terminal voltage 'V' is also found to vary as in D.C generators this variation in terminal voltage 'V' is due to the following reason.

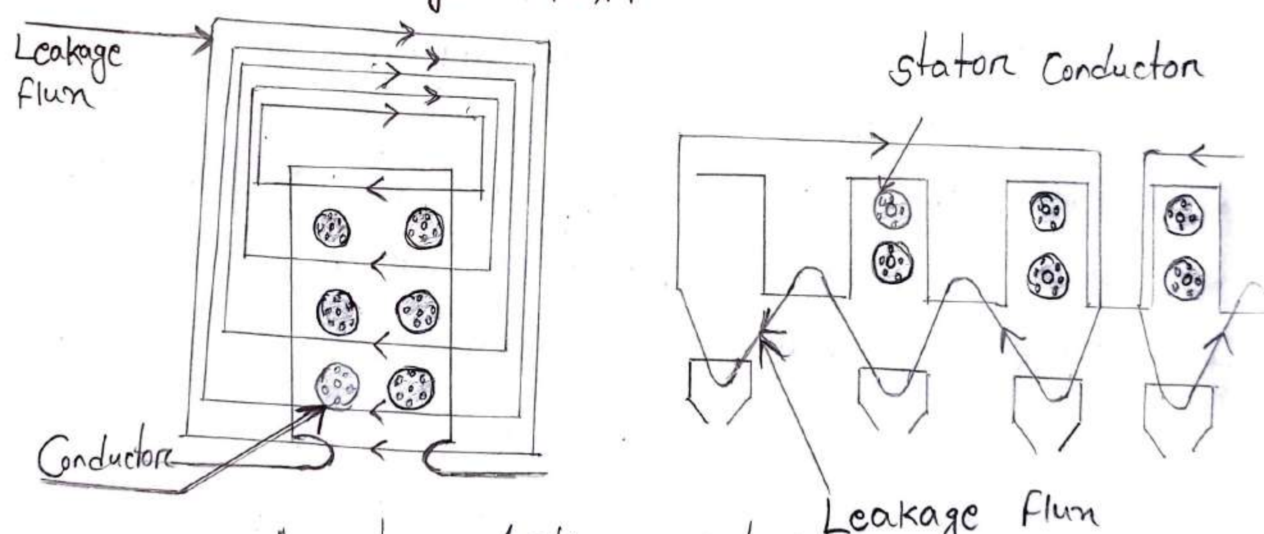
- Voltage drop due to armature resistance Ra,
- Voltage drop due to leakage reactance X_L.
- Voltage drop due to armature reaction.

→ Armature resistance / phase Ra, causes a voltage drop / phase of IRa, which is in phase with armature current I.

→ The voltage drop is practically negligible because Ra is very low resistance.

Aramature leakage reactance :-

→ When current flow through the armature conductors, fluxes are setup which do not cross the air gap, but take different paths. Such fluxes are known as leakage flux.

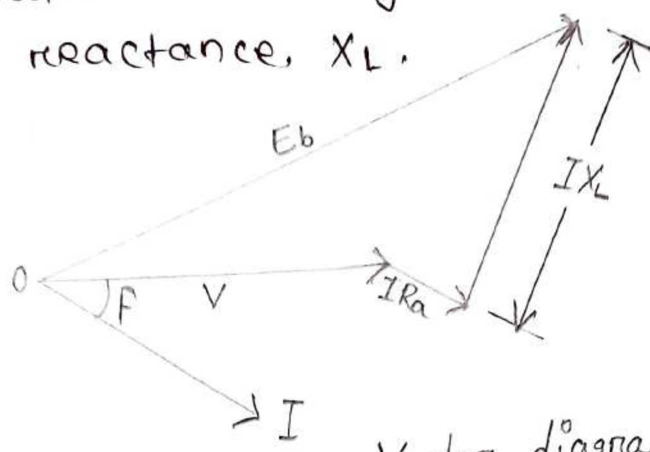


Armature leakage reactance

→ The leakage flux is practically independent of saturation, but is dependent on I & its phase angle with the terminal voltage V.

→ The leakage flux sets up an emf of self inductance which is known as reactance emf & which is ahead of I by 90°.

→ The armature winding is assumed to possess leakage reactance, X_L.



Vector diagram

→ A part of the generated emf is used up in over coming this reactance emf $= I X_L$

$$E = V + I (R_a + j X_L)$$

θ = The angle of twist (radians)

⊛ SYNCHRONOUS REACTANCE :-

→ The terminal voltage is decreased from its no load value E_0 to V (for a lagging power factor). This is because of

- Voltage drop due to armature resistance $= I R_a$
- Voltage drop due to leakage reactance $= I X_L$
- Voltage drop due to armature reaction $= I X_a$

→ The voltage drop due to armature reaction may be accounted for by assuming the presence of a fictitious reactance X_a in the armature winding.

→ The value of X_a is such that $I X_a$ represents the voltage drop due to armature reaction.

→ The leakage reactance X_L (or X_P) & the armature X_a may be combined to give synchronous reactance X_S.

→ Hence $X_S = X_L + X_a$

→ The ohmic value of X_a varies with the power factor, because armature reaction depends on the load power factor.

→ Therefore total voltage drop in an alternator on load is

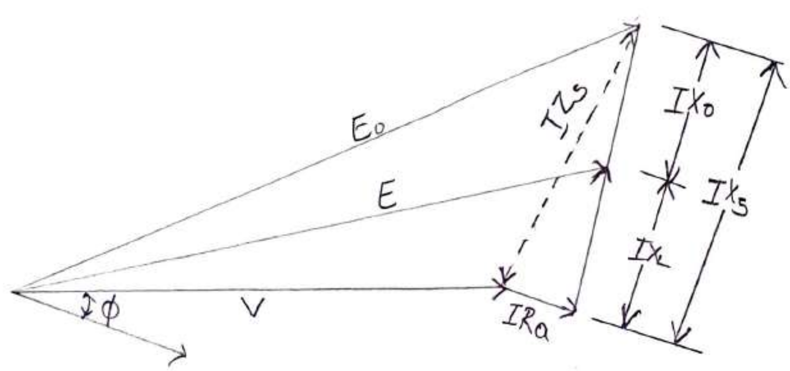
$$= IR_a + jIX_S = I(R_a + jX_S)$$
$$= IX_S$$
$$= IZ_S$$

where,

Z_S is known as the synchronous impedance of the armature.

→ The word "synchronous" is used for merely as an indication that it refers to the working conditions.

→ The vector difference between "No load" voltage E_0 & output / terminal voltage V is equal to IZ_S as shown figure.



Synchronous Reactance

SYNCHRONOUS IMPEDANCE :-

→ synchronous impedance may be defined as the vector sum of the armature resistance and synchronous reactance.

→ $$Z_s = \sqrt{R_a^2 + X_s^2}$$

Effect of synchronous impedance :-

→ Depending on load, synchronous impedance voltage drop is added vectorially to terminal voltage to get No load EMF.

→ Its impact is to change the excitation to the alternator.

→ Load conditions :-

(a) Purely resistive load :-

→ Current is in phase with voltage.

→ The armature reaction in to distort the main field.

→ Hence excitation remains unchanged.

(b) Purely inductive load :-

→ Current lags by 90° behind the voltage.

→ The armature reaction is to demagnetize the main field.

→ Hence excitation has to be increased.

(c) pure capacitive load :-

→ current leads by 900 a head the voltage.

→ The armature reaction in to magnetize the main field.

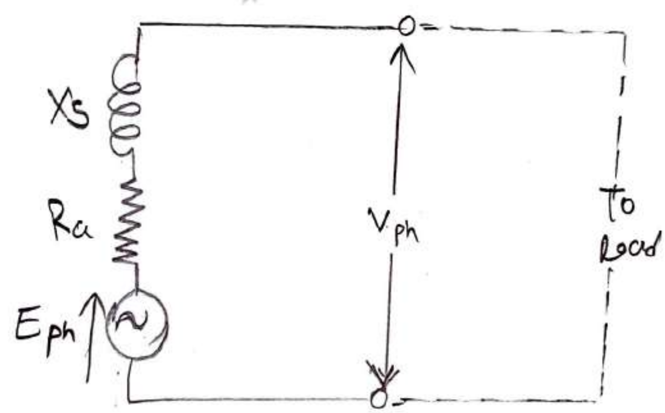
→ Hence excitation has to be decreased.

Reasons for voltage variation on-load :-

→ The D.C generator, we have seen that due to the armature resistance drop and brush drop it is not possible to have all the induced emf available across the load.

→ The voltage available to the load is called as terminal voltage.

→ The concept is same in case of alternators.



Equivalent Ckt

→ The entire induced emf cannot be made available to the load due to the various internal voltage drops.

→ So the voltage available to the load is called as terminal voltage donated as V_{ph}.

→ In case of 3 φ alternators as all the phases are idential, the equations & the phasor diagrams are expressed on pere phase basis.

→ So if E_{ph} is the induced emf / phase in the alternator, there are following voltage drops occours in an alternator.

→ The drop across the armature resistance, $I_a R_a$ (both I_a & R_a are per phase values)

→ The drop across synchronous resistance, $I_a X_s$ (both I_a & X_s are per phase values)

→ After supplying these drops, the remaining voltage of E_{ph} is available as the terminal voltage V_{ph}.

→ Now drop $I_a R_a$ is always in phase with I_a due to a resistive drop while current I_a lags by 90° with respect to drop $I_a X_s$ as it is drop across purely inductive reactance.

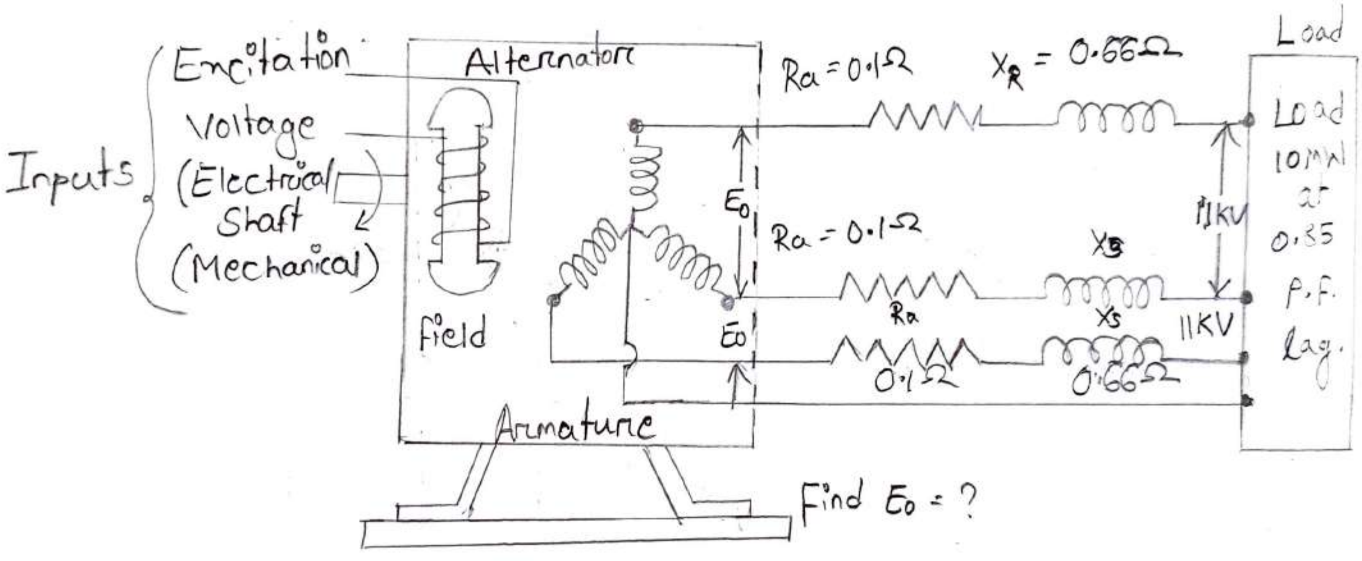
→ All these quantities can not be added or subtracted algebreaically but must be added or subtracted vectorially, considering their individual phases. But we can write a voltage equation in its phasor form as.

→ $$\bar{E}_{ph} = \bar{V}_{ph} + \bar{I}_a R_a + \bar{I}_a X_s$$

→ This is called as voltage equation of an alternator. The circuit for this is as shown in figure.

Worked example :-

→ A 3-ϕ, star-connected alternator supplies a load of 10 MW at P.f. 0.85 lagging and at 11 kV. Its resistance is 0.1 Ω per phase & synchronous reactance 0.66 Ω per phase. Calculate the line value of emf generated.



Circuit diagram

Solution :-

F.L output current $= \dfrac{10 \times 10^6}{\sqrt{3} \times 11000 \times 0.85}$

$= 618$ A

I.Ra drop $= 618 \times 0.1$

$= 61.8$ V

IX_s drop $= 618 \times 0.66$

$= 408$ V

Terminal voltage/phase $= \frac{11000}{\sqrt{3}}$

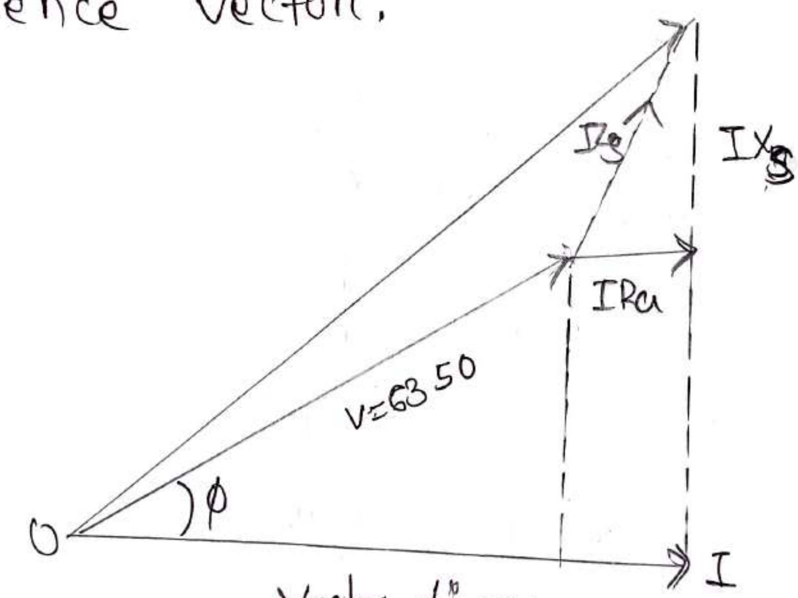
$= 6.350$ V.

$\phi = \cos^{-1}(0.85)$

$\Rightarrow \phi = 31.8^\circ$

$\Rightarrow \sin\phi = 0.527$

As seen from the vector diagram of where I gnstead of V has been taken along reberence vector.



Vector diagram

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

$= \sqrt{(6350 \times 0.85 \times 61.8)^2 + (6350 + 0.527 + 408)^2}$

$= 6625$ V

line e.m.f $= \sqrt{3 \times 6625} = 11486$ Volt

Vector diagram of alternators on load :-
(for lag, lead & unity power factor)

Let,

E_0 = No load emf / phase

V = Terminal voltage / phase

I = Load current / phase

Z_s = Synchronous impedance / phase

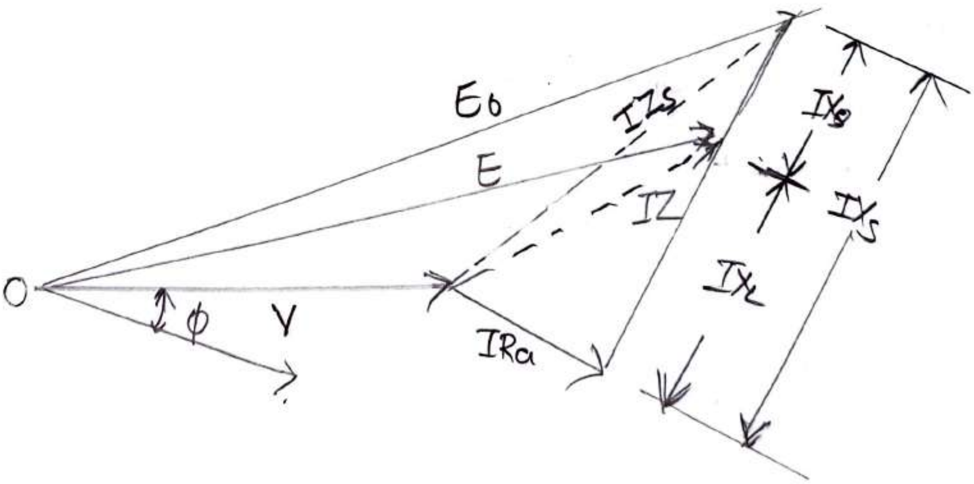
X_a = Fictitious reactance due to the armature reaction.

R_a = Effective armature resistance / phase

X_L = leakage reactance / phase

X_s = synchronous reactance / phase

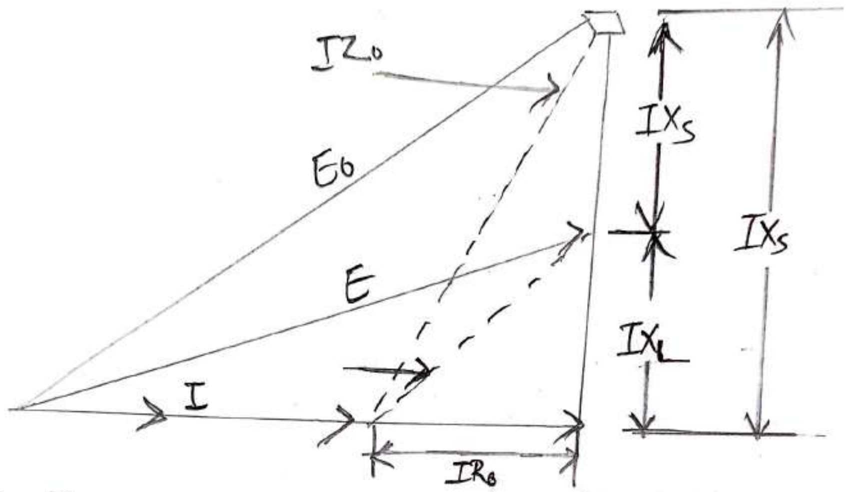
① Vector diagram for lagging power factor :-
(Inductive load) :-



→ The voltage drop due to armature reaction is equal to the voltage drop on fictitious reactance X_a. All the values are referred to phase values.

→ The phasor diagram for lagging power factor (Induc..., unity power factor (pure resistive) & leading power factor (capacitive).

② Vector diagram for unity power factor :-



→ In all the vector diagrams, the voltage taken as reference vector.

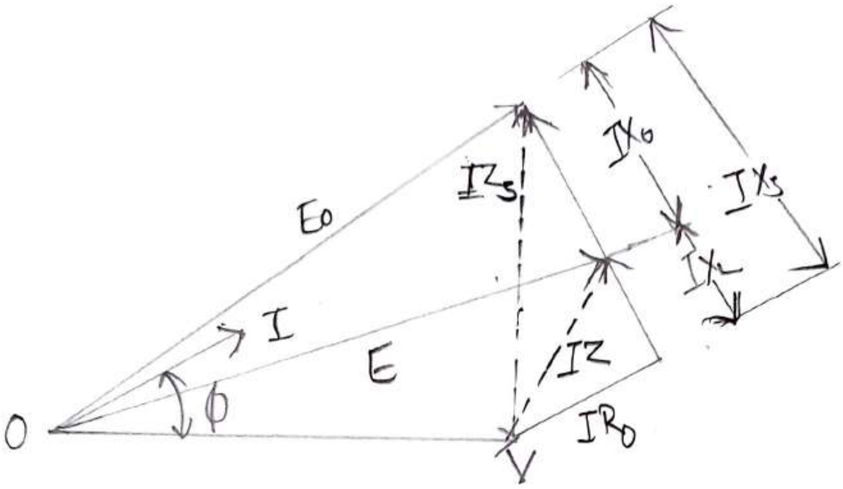
→ For unity power factor load, the voltage (V) is in phase with the load current (I) as shown in figure.

→ For lagging power factor load (I) lags the voltage by an angle θ shown in figure.

→ For leading power factor load, the load current (I) leads form the voltage by an θ angle shown in fig.

③ Vector diagram for leading power factor :-

→ In all the vector diagrams the voltage drop due to armature effective resistance IRa will be in phase with the current I.



→ The voltage drop due to leakage reactance IX_L & the voltage drop to armature reaction IX_a will be in quadrature (90°) with the load current I.

→ The NO load voltage E_0 is the vector sum of terminal voltage (V) & sum of above voltage drops i.e IZ_s.

where

Z_s is the synchronous impedance

Total voltage drop on load $= IR_a + j(IX_L + IX_a)$

$= I[R_a + j(X_L + X_a)]$

Total voltag drop on load $= IZ_s$

∴ Voltage on NO Load $E_0 = \bar{V} + \bar{I}\bar{Z}_s$

Voltage Regulation

Voltage regulation :-

→ The voltage regulation of an alternator is defined as the rise in voltage when full load is removed divided by the rated terminal/output voltage.

% regulation ('up')

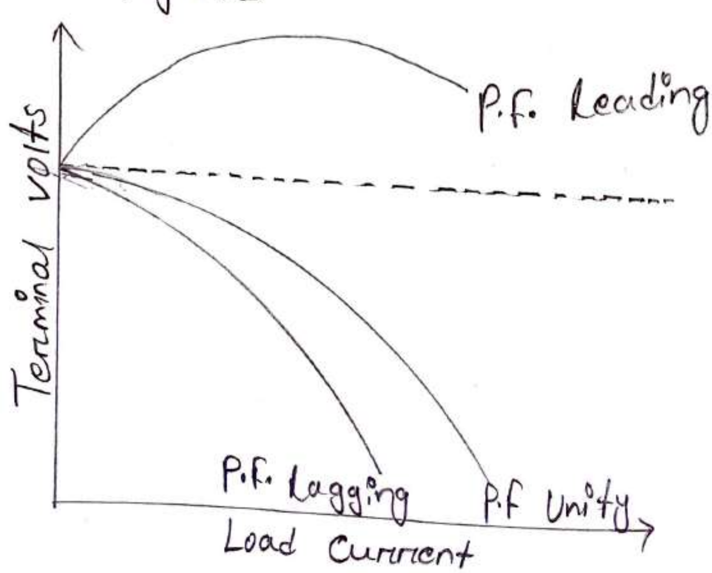
$$= \frac{E_0 - V}{V} \times 100$$

→ $E_0 - V$ is the arithmetical difference & not the vectorial one.

→ The leading load pf, terminal voltage will fall on removing the full load. Hence regulation is negative in that case.

→ The rise in voltage when full load is thrown off is not the same the fall in voltage when full load is applied.

→ Voltage characteristics of an alternator are shown in figure.



Voltage Regulation Curve

Determination of voltage regulation :-

→ The regulation may be found out by direct loading & the produce is as follows :

→ The terminal voltage is adjusted to its rated value 'V'.

→ The load is varied until the watt meter and ammeter indicate the rated values at the desired power factor.

→ The entire load thrown off while the speed & field excitation are kept constant.

→ The open circuit or no load voltage E_0 is read. Now regulation can be found from.

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

→ The large machines, the costs for finding the regulation by direct loading as for small machines becomes prohibitive.

→ It will be found that all these methods differ chiefly in the way the no load voltage E_0 is found in each case.

Regulation for large Machines :-

→ The following Methods are used for determination of regulation for large machines.

- Synchronous impedance or EMF Method. The method is due to the pioneering work by Behn eschenburg.
- The ampere turn or mmf method. This method is the contribution by Rothert.
- Zero power factor or potier method. This method is the work alone by potier.

Parameters Required :-

→ All the methods to determine the regulation for large machines require the following parameters of the machine/alternator.

→ These are,

- Armature (or stator) resistance.
- Open circuit/no load characteristics
- short circuit characteristics

EMF method or Alternator test :-

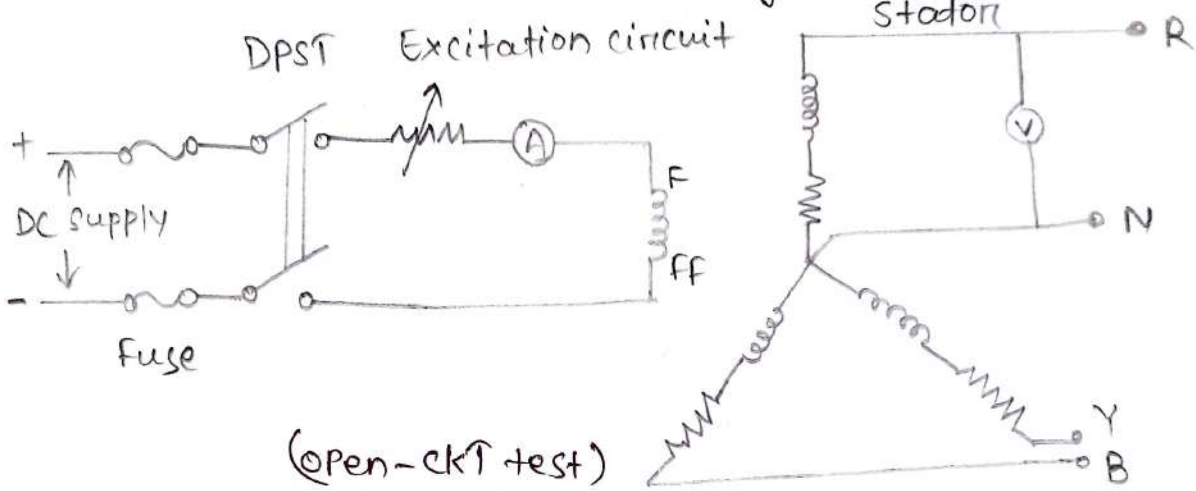
→ To determine the regulation of an alternator, the following tests are performed.

(a) open - circuit test.

(b) Short - circuit test.

(a) Open - circuit test :-

→ The machine is run on no-load & the induced e.m.f per phase is measured corresponding to various values of field current & a curve is drawn between induced emf per phase E_{ph} & field current I_F as shown in figure.



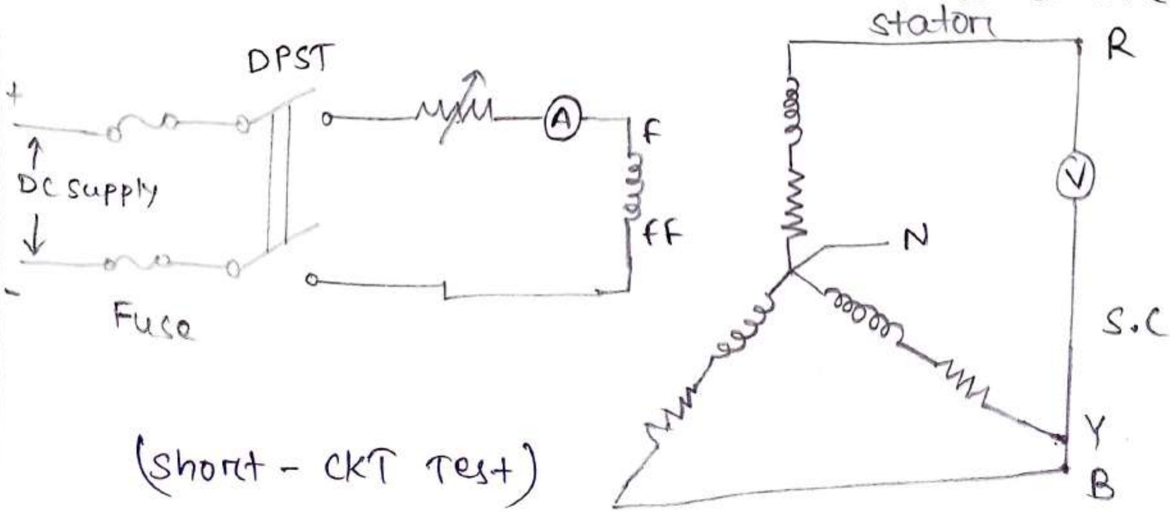
(Open-CKT test)

(b) Short - circuit test :-

→ In this test armature winding is short-circuited through a low resistance ameter as shown.

→ During this test the speed is kept constant & short-circuit current is measured corresponding to various values of field current.

→ The excitation is increased so as to give 1.5 to 2 times the value of the full-load current.



(Short - CKT Test)

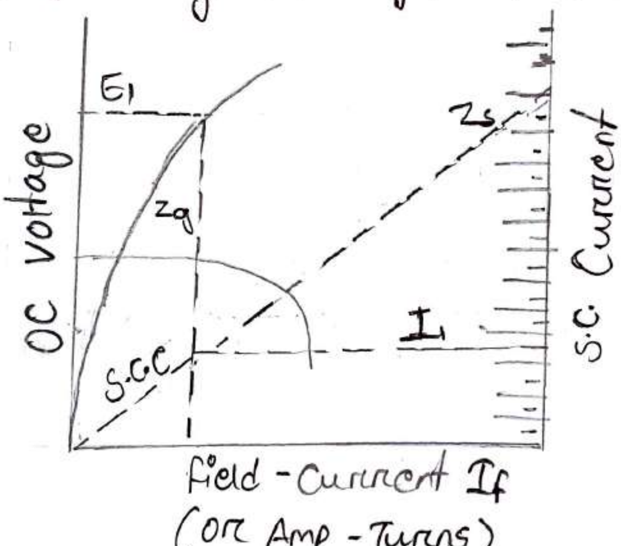
→ The short circuit characteristics is a curve drawn between short-circuit current I_{sc} & field current I_F as shown in figure.

Synchronous impedance method :-

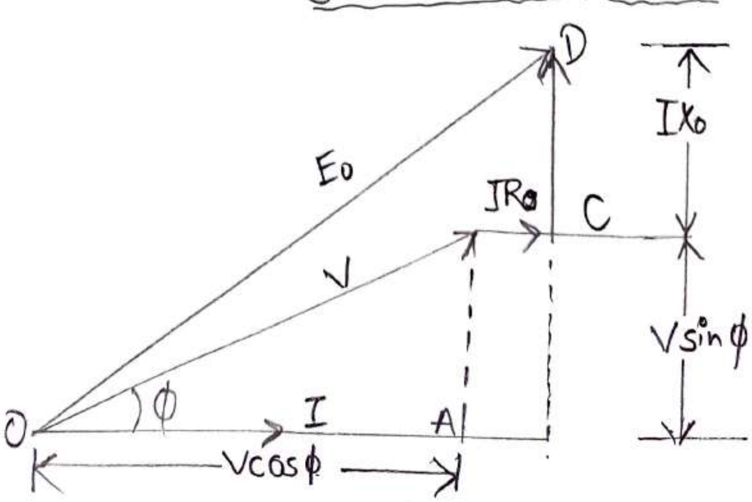
→ The following procedural steps are involved in this method.

→ The open circuit characteristics is plotted from given data as shown in figure.

→ The short circuit characteristics curve is drawn from the data of the short circuit test. It is a straight line passing through the origin.



Characteristic Curve



Vector diagram

→ Both these curves as drawn on a common field current base.

→ Consider a field current I_f.

→ The open circuit (OC) voltage for this field current is E_1.

→ When the winding is short circuited, the terminal voltage is zero. Hence it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short circuited current I_1, against the synchronous impedance Z_s.

There,

$$E_1 = I_1 Z_s$$

Where,

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

→ Ra can be found as discussed earlier,

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

→ Ra & X_s are known vector diagram shown in fig can be drawn for any load and any power factor.

→ Vector diagram OD = E_0,

$$\therefore \quad E_0 = \sqrt{OB^2 + BD^2}$$

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

There fore % regulation = $\frac{E_0 - V}{V} \times 100$

→ The value of regulation for unity power factor or leading power factor can also be found out in a similar way.

→ Note that this method of determining the voltage regulation has the following limitations.

- This method is not very accurate because the value of Z_s so found is always more than its value under normal voltage condition & saturation. Hence the value of regulation so found is always more than that found from an actual test. That is why this is called "pessimistic method".

- This value of Z_s is not constant but varies with "saturation" at low saturation its value is larger, because then the effect of a given armature ampere - turns is much more than at high saturation.

→ Now under short circuit condition, saturation is very low, because armature mmf is directly demagnetizing.

→ Different values of Z_s, corresponding to different values of field current are also plotted in figure.

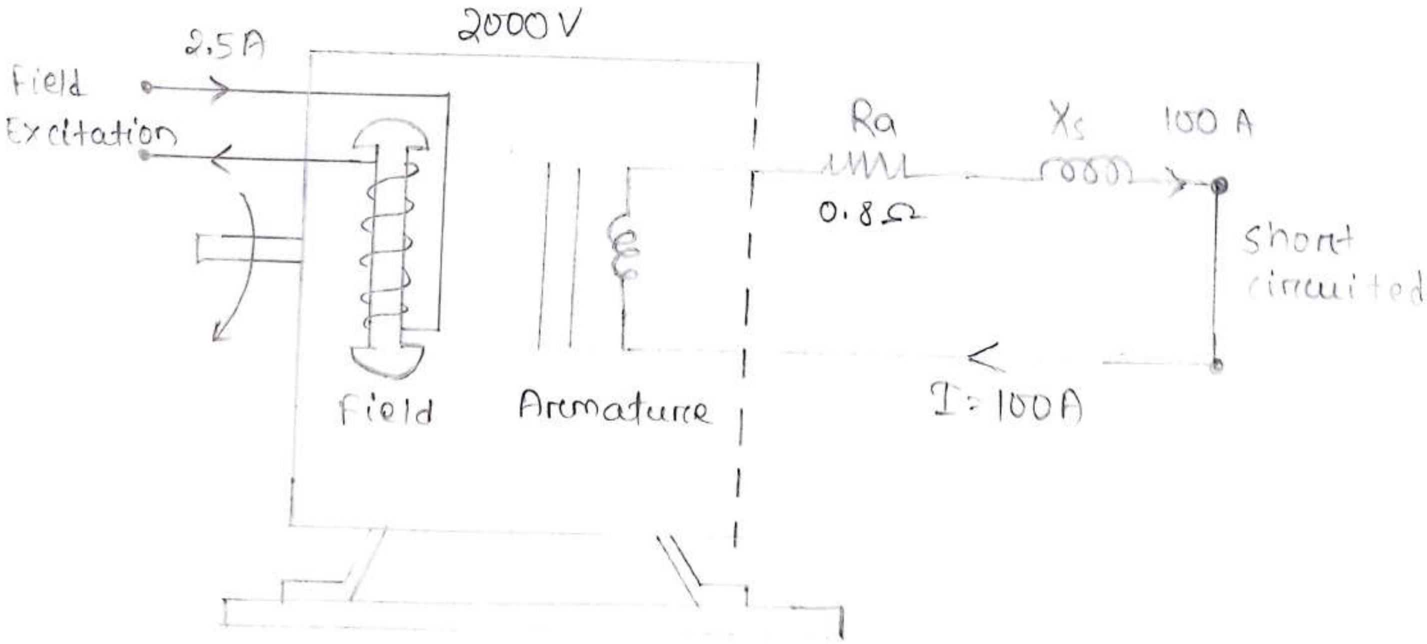
→ The value of Z_s usually taken is that obtained form full load current in the short circuit test.

→ In this method, armature reactance, X_s has not been treated separately text along with leakage Reactance X_L.

Worked example using synchronous method/ EMF Method. :-

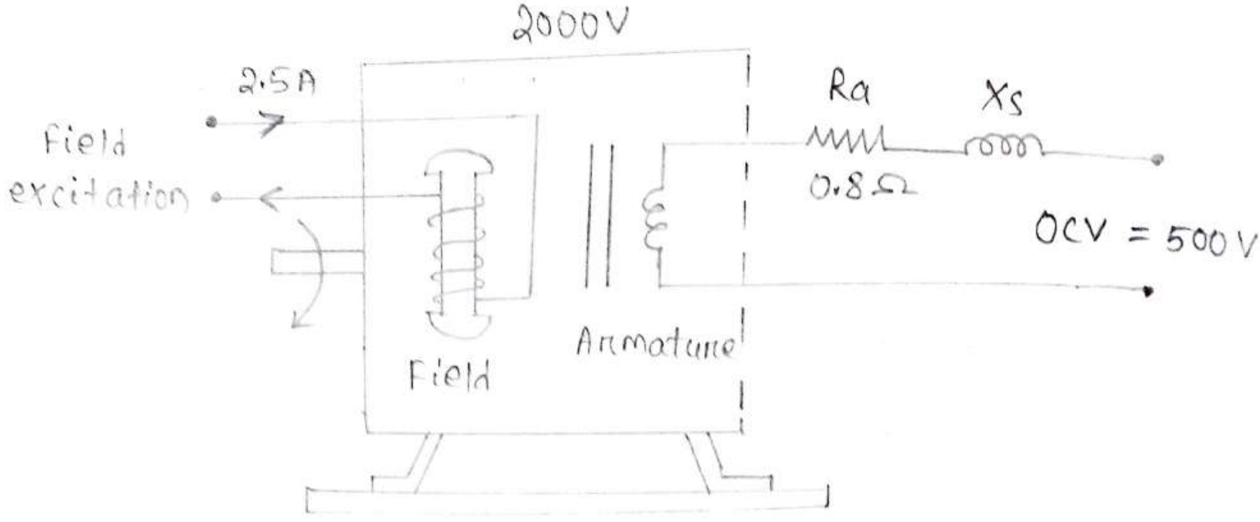
→ From the following test results, determine the voltage regulation of a 200 - V. I phases alternator delivering a current of 100 A at (i) unity p.f
(ii) 0.8 lagging p.f
(iii) 0.71 lagging p.f

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



[1 φ Alternator]

(Short circuited)



(1Φ Alternator)

(Open circuit)

Solution

For same excitation $Z_s = \dfrac{\text{O.C Volts}}{\text{S.C current}}$

$= 500/100$

$= 5\,\Omega$

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

$= \sqrt{5^2 - 0.8^2}$

$= 4.936\,\Omega$

Unity p.f :-

$IR_a = 100 \times 0.8$

$= 80\,V;$

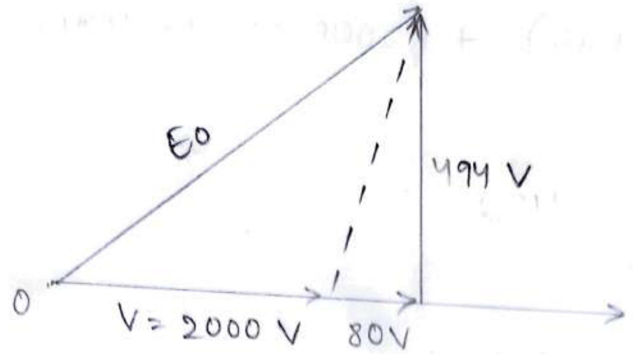
$IX_s = 100 \times 4.936$

$= 494\,V$

$E_o = \sqrt{(2000 + 80)^2 + 494^2} = 2140\,V$

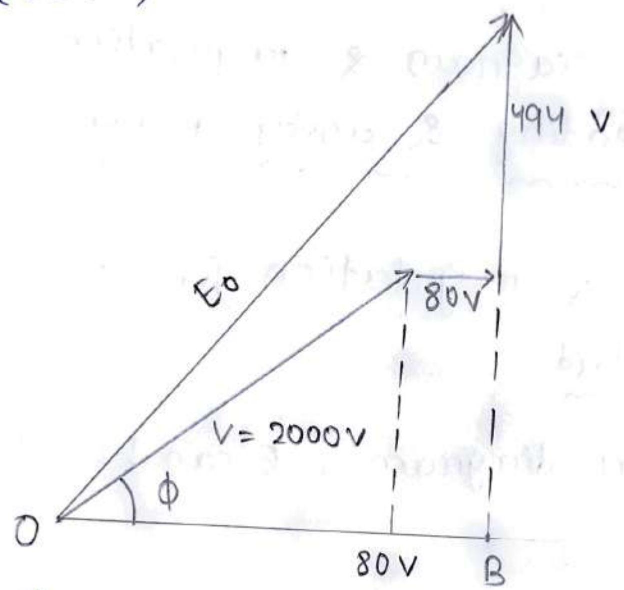
$\%\ \text{Regulation} = \dfrac{2140 - 2000}{200} \times 100$

$= 7\%$



(Unity Power factor) at

• P.F = 0.8 (Lead)



(Power factor at 0.8 leading)

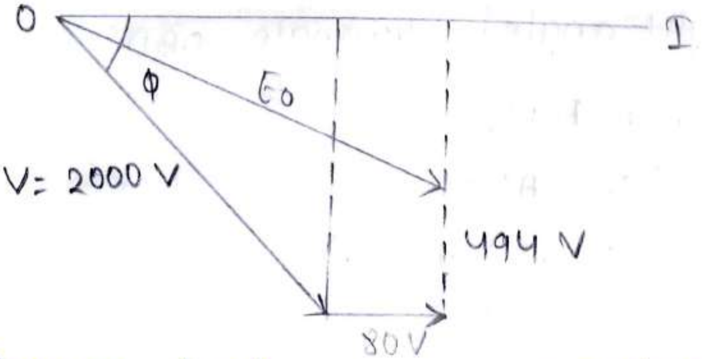
$$E_0 = \left[(2000 \times 0.8 + 80)^2 + (2000 \times 0.6 - 494)^2\right]^{\frac{1}{2}}$$

$= 1820$ V

$$\% \text{ regulation} = \frac{1820 - 2000}{2000} \times 100$$

$= -9\%$

• P.F = 0.71 (lag)



(Power factor at 0.71 lagging)

$$E_0 = \left[(2000 \times 7.1 + 80)^2 + (2000 \times 0.71 - 494)^2 \right]^{\frac{1}{2}}$$

$$= 2432 \text{ V}$$

$$\% \text{ regulation} = \frac{2432 - 2000}{2000} \times 100$$

$$= 21.6 \%$$

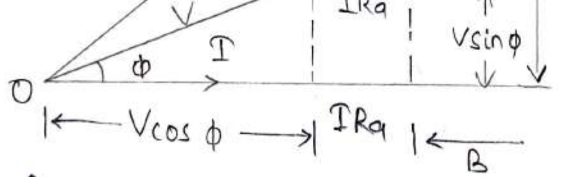
— x —

Vector diagram & regulation for lagging, leading & unity power factor load

(a) Vector diagram & regulation for lagging power factor load :-

- From the vector diagram, E can be found out

$OD = E$



(Vector diagram for lagging power factor)

- For the right angled triangle OBD

$$E = \sqrt{OB^2 + BD^2}$$

$$OB = (OA + AB)$$

$$OB = (V\cos\phi + IR_a)$$

$$BD = (BC + CD)$$

$$BD = (V\sin\phi + IX_s)$$

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

- By calculating E, the regulation can be calculated. Then,

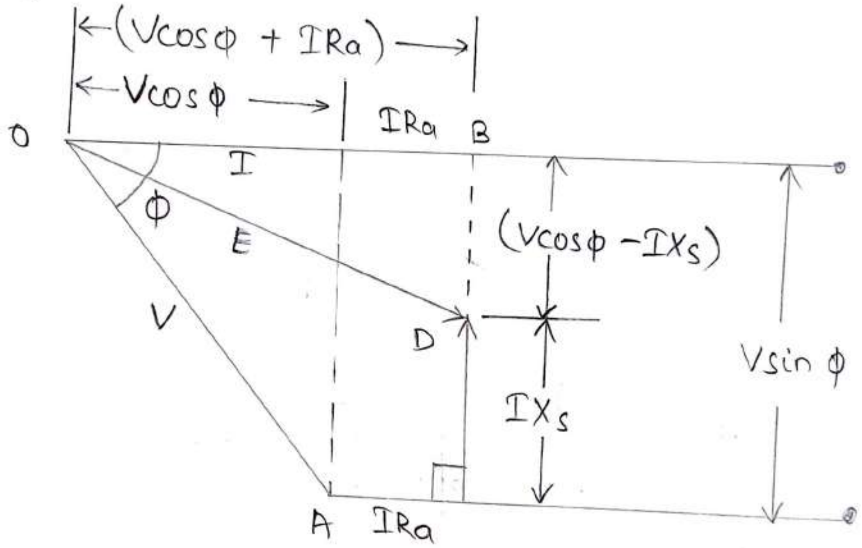
$$\% \text{ Regulation} = \frac{E - V}{V} \times 100$$

<u>Note</u> :- For lagging power factor load, the regulation is positive.

(b) Vector diagram for regulation for leading power factor load :-

- From the vector diagram E can be found out

$OD = E$



(Vector diagram for leading power factor)

→ From the right angled traingle OBD

$$E = \sqrt{OB^2 + BD^2}$$

$$OB = (OC + CB)$$

$$OB = (V\cos\phi + IR_a)$$

$$BD = (Ba - Da)$$

$$BD = (V\sin\phi - IX_s)$$

$$\therefore \; E = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_s)^2}$$

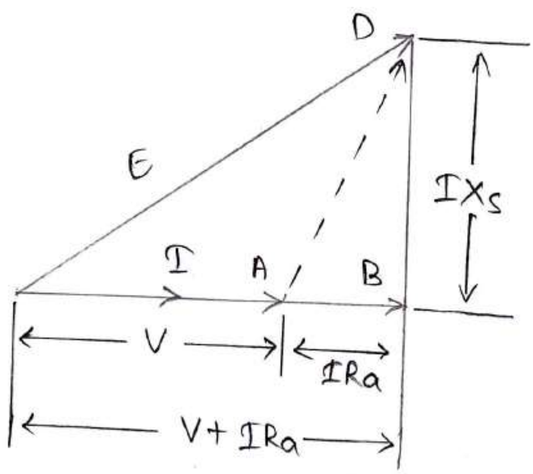
→ By calculating E, the regulation can be calculated.

Then, $\% \text{ regulation} = \dfrac{E - V}{V} \times 100$

∴ <u>Note</u> :- For leading power factor load the regulation is negative.

Vector diagram & Regulation for unity power factor load:-

→ From the vector diagram, E can be calculated as OD = E



(vector diagram for unity power factor)

$$\therefore \; E = \sqrt{OB^2 + BD^2}$$

$$OB = (OA + AB)$$

$$OB = (V + IR_a)$$

$$\therefore \; E = \sqrt{(V + IR_a)^2 + (IX_s)^2}$$

By calculating E, regulation can be calculated.

Then, % Regulation = $\frac{E-V}{V} \times 100$

General formula :-

→ For lagging & leading power factor load, the following expression is used for determining the value of E.

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

→ When load power factor is unity, then $\cos\phi = 1$

Then, & $\sin\phi = 0$

$$E = \sqrt{(V + IR_a)^2 + (IX_s)^2}$$

Problem -1 :-

A 3-ϕ star connected alternator is rated at 1600 KVA, 13.5 KV. The armature effective resistance are synchronous reactance & 1.5 Ω & 30 Ω respectively per phase. Calculate the percentage regulations for a load of 128 KW at p.f of 0.8 leading.

Given Data :-

Armature Resistance (R_a) = 1.5 Ω

Synchronous Reactance (X_s) = 30 Ω

Power factor ($\cos\phi$) = 0.8

To find :-

Percentage regulation = ?

Formula used :-

$$\% \text{ regulation} = \frac{E-V}{V}$$

$$V = 13.5\ KV\ \sqrt{3}$$

Solution :-

Let us first find the phase current of the star connected alternator for a load of 1280 KW at P.f of 0.8 leading

$$1280 \times 103 \times 13500 \times I_L \times 0.8$$

$$\Rightarrow I_L = 68.4\ A$$

Since the alternator is star connected, it also represents the phase current. Hence, armature phase current $I_a = 68.4\ A$

$$\therefore I_a R_a = 68.4 \times 1.5$$

$$= 103\ V$$

$$\therefore I_a X_s = 68.4 \times 30$$

$$= 2050\ V$$

$$V = 13500\ \sqrt{3}$$

$$\Rightarrow V = 7795\ V$$

$$\therefore E = \sqrt{(7795 \times 0.8 + 103)^2 + (7795 \times 0.6 - 2050)^2}$$

$$= 6910\ V$$

$$\% \text{ regulation} = \frac{6910 - 7795}{7795} \times 100$$

$$= -11.35\ \%$$ (Ans)

Problem - 2 :-

A 550 V , 55 KVA , single - phase alternator has an effective resistance of 0.2 Ω A field current of 10 A produces an armature current of 200 A on short circuit & an emf of 450 V on open circuit. Calculate

(a) the synchronous impedance and reactance

(b) the full - load regulation when the power factor is 0.8 lagging

Given data :-

Line voltage (V_L) = 550 V

Apparant power = 55 KVA

Armature resistance (Ra) = 0.2 Ω

Field current(I_f) = 10 A.

To find :-

(a) The synchronous impedance & reactance (Z_s)

(b) The full - load regulation when the power factor is 0.8 lagging.

Formula used :-

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

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

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

Solution :-

Synchronous impedance Z_s is,

$$Z_s = \frac{450\ V}{200\ A}$$

$$Z_s = 2.25\ \Omega$$

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

$$\Rightarrow X_s = \sqrt{(2.25)^2 - (0.2)^2}$$

$$= 2.241\ \Omega$$

Synchronous reactance, $(X_s) = 2.241\ \Omega$

Full load current is,

$$I_a = \frac{55 \times 10^3}{550}$$

$$= 100\ A.$$

$$E_0 = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi - I_a X_s)^2}$$

$$= \sqrt{(550 \times 0.8 + 100 \times 0.2)^2 + (550 \times 0.6 - 100 \times 2.241)^2}$$

$$= 720.16\ V$$

There fore,

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

$$= \frac{720.16 - 550}{550 \times 100} \times 100$$

$$= 30.94\ \%$$

∴ The synchronous impedance and reactance

$Z_s = 2.25\ \Omega$

∴ The full-load regulation when the power factor is 0.8 lagging $= 30.94\ \%$

Problem - 3 :-

A 50 - KVA , 415 V , 3-ϕ, 50 Hz alternator has an effective armature resistance of 0.25 Ω/phase. The synchronous reactance is 3.2 Ω/phase & leakage reactance is 0.5 Ω/phase. At u.p.f & rated load, determine the

(a) Internal emf (E_a)

(b) no - load emf (E_0)

(c) Percentage regulation on full load

(d) value of synchronous reactance which represents armature reaction.

Given data :-

Apparant power = 50 KVA

line voltage, V_L = 415 V

Phase = 3 ϕ

frequency (f) = 50 Hz

Armature resistance (R_a) = 0.25 Ω/phase

Synchronous reactance (X_s) = 3.2 Ω/phase

Armature reactance (X_a) = 0.5 Ω/phase

Used formula :-

$$E_a = \sqrt{(V + IR_a)^2 + (IX_L)^2}$$ (since it is u.p.f $V\sin\phi = 0$)

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

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

$$X_a = X_s - X_L$$

Solution :-

$\therefore V = \frac{415}{\sqrt{3}} = 239.6 \text{ V}$

$\therefore I_{FL} = \frac{50 \times 10^3}{\sqrt{3} \times 415}$

$= 69.56 \text{ A}$.

$\therefore IR_a = I_{FL} \times IR_a = 69.56 \times 0.25$

$= 17.39 \text{ V}$

$\therefore IX_a = I_{FL} \times X_a = 69.56 \times 0.5$

$= 34.78 \text{ V}$

$\therefore IX_s = I_F \times X_s$

$= 69.56 \times 3.2$

$= 222.592 \text{ V}$

(a) Internal emf $E_a = \sqrt{(V + IR_a)^2 + (IX_L)^2}$

$\Rightarrow E_a = \sqrt{(239.6 + 17.39)^2 + (34.78)^2}$

$\Rightarrow E_a = 259.33 \text{ V}$ (Ans)

(b) no-load emf (E_0)

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

$= \sqrt{(239.6 + 17.39)^2 + (222.592)^2}$

$= 340 \text{ V}$ (Ans)

(c) % regulation $= \frac{340 - 239.6}{239.6} \times 100$

$= 41.9 \%$ (Ans)

(d) value of synchronous reactance which represents armature reaction.

$$X_a = X_S - X_L$$

$$= 3.2 - 0.5$$

$$= \underline{2.7\ \Omega} \quad \text{(Ans)}$$

Problem - 4 :-

A 600 V, 60 KVA, single-phase alternator has an effective resistance of 0.2 Ω. A field current of 10A produces an armature current of 210 A on short circuit and an emf of 480 V on open - CKT.

(a) synchronous impedance & reactance.

(b) Regulation with 0.8 p.f lagging, unity & 0.6 p.f leading.

Given data :-

$V = 600\ V$

$I_{SC} = 210\ A$

$V_{OC} = 480\ V$

$I_F = 10\ A$

$R_a = 0.2\ \Omega$

Solution :-

The alternator is single phase

$$KVA = VI \times 10^{-3}$$

$$60 = 600 \times I \times 10^{-3}$$

$$I = 100\ A$$

$$= I_a \quad \text{(full load current)}$$

Now $Z_s = \frac{V_{oc}}{I_{sc}} \Big|_{\text{same } I_f}$

$= \frac{480}{210}$

$= 2.2857 \ \Omega$

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

$= \sqrt{(2.2857)^2 - (0.2)^2}$

$= 2.2769 \ \Omega$

Now $E = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi \pm I_a X_s)^2}$

+ve sign for lagging
-ve sign for leading

(i) $\cos\phi = 0.8$ lagging
$\sin\phi = 0.6$

$\Rightarrow E = \sqrt{(600 \times 0.8 + 100 \times 0.2)^2 + (600 \times 0.6 + 100 \times 2.2769)^2}$

$= 771.608 \ V$.

$\therefore$ % regulation $= \frac{E - V}{V} \times 100$

$= \frac{771.608 - 600}{600} \times 100$

$= 28.6\ \%$ (Ans)

(ii) $\cos\phi = 1$, $\sin\phi = 0$

$E = \sqrt{(600 \times 1 + 100 \times 0.2)^2 + (600 \times 0 + 100 \times 2.2769)^2}$

$\Rightarrow E = 660.486 \ V$.

$\therefore$ % regulation $= \dfrac{660.484 - 600}{600} \times 100$

$= 10.08\ \%$ (Ans)

(iii) $\cos\phi = 0.6$ (leading)
$\sin\phi = 0.8$

$$E = \sqrt{(600 \times 0.6 + 100 \times 0.2)^2 + (600 \times 0.8 - 100 \times 2.2769)^2}$$

$= 456.136\ V$

% regulation $= \dfrac{456.136 - 600}{600} \times 100$

$= -23.97$ (Ans)

Problem – 5 :-

A 3ϕ, star connected alternator is rated at 1600 KVA, 13500 Volts. The armature resistance & synchronous reactance are 1.5 Ω & 30 Ω respectively per phase. Calculate the percentage regulation for a load of 1280 KW at a P.f 0.8 lag, U.P.f 0.8 lead.

Given data :-

KVA = 1600 KVA

$V_L = 13500\ V$

$R_a = 1.5\ \Omega$

$X_s = 30\ \Omega$

$V_{ph} = \dfrac{V_L}{\sqrt{3}} = \dfrac{13500}{\sqrt{3}} = 7794.2286\ V$

(star connected)

Solution :-

case-1 :-

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

$P_{out} = \sqrt{3}\, V_L I_L \cos\phi$

$\therefore 1280 \times 10^3 = \sqrt{3} \times 13500 \times I_L \times 0.8$

$\Rightarrow I_L = 68.4266 \text{ A} = I_{aph}$

$\therefore E_{ph}^2 = (V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi + I_a X_s)^2$

$= (7794.2286 \times 0.8 + 68.426 \times 1.5)^2 + (7794.2286 \times 0.6 + 68.426 \times 30)^2$

$\Rightarrow E_{ph} = 9244.1772 \text{ V}.$

$\%\ \text{Regulation} = \dfrac{E_{ph} - V_{ph}}{V_{ph}} \times 100$

$= \dfrac{9244.1772 - 7794.2286}{7794.2286} \times 100$

$= 18.6\ \%$

Case-2 :-

$\cos\phi = 1$, $\sin\phi = 0$

$P_{out} = \sqrt{3}\, V_L I_L \cos\phi$

$\therefore 1280 \times 10^3 = \sqrt{3} \times 13500 \times I_L \times 1$

$\Rightarrow I_L = 54.7413 \text{ A} = I_{aph}$

$\therefore E^2_{ph} = (7794.2286 \times 1 + 54.7413 \times 1.5)^2 + (0 + 54.7413 \times 30)^2$

$E_{ph} = 8045.7249 \text{ V}$

$\% \text{ Regulation} = \dfrac{E_{ph} - V_{ph}}{V_{ph}} \times 100$

$= \dfrac{8045.7249 - 7794.2286}{7794.2286} \times 100$

$= 3.22 \%$

Case - 3 :-

$\cos\phi = 0.8$ lead

$\sin\phi = 0.6$

$P_{out} = \sqrt{3} V_L I_L \cos\phi$

As $\cos\phi = 0.8$, the current I_L is same as in case 1

$I_L = 68.426 \text{ A} = I_{aph}$

$\therefore E^2_{ph} = (7794.2286 \times 0.8 + 68.426 \times 1.5)^2 + (7794.2286 \times 0.6 - 68.426 \times 30)^2$

$= 6859.6372 \text{ V}$

$\% \text{ Regulation} = \dfrac{6859.6372 - 7794.2286}{7794.2286} \times 100$

$= -11.89 \%$

Necessity of parallel operation of Alternator

Parallel operation of alternator :-

→ The operation of connecting an alternator in parallel with another alterenator or with common bus-bars is known as synchronizing.

→ The alternators are used in a power system where they are in parallel with many other alternators.

→ The alternator is connected to a live system of constant voltage & constant frequency.

→ The electrical system to which the alternator is connected, has already so many alternators & loads connected to it that no matter what power is delivered by the incoming alternator.

→ The voltage & frequency of the system remains the same.

→ The alternator is said to be connected to infinite bus-bars.

→ The connecting of stationary alternator to live bus-bars, because, stator induced emf being zero, a short-circuit will result.

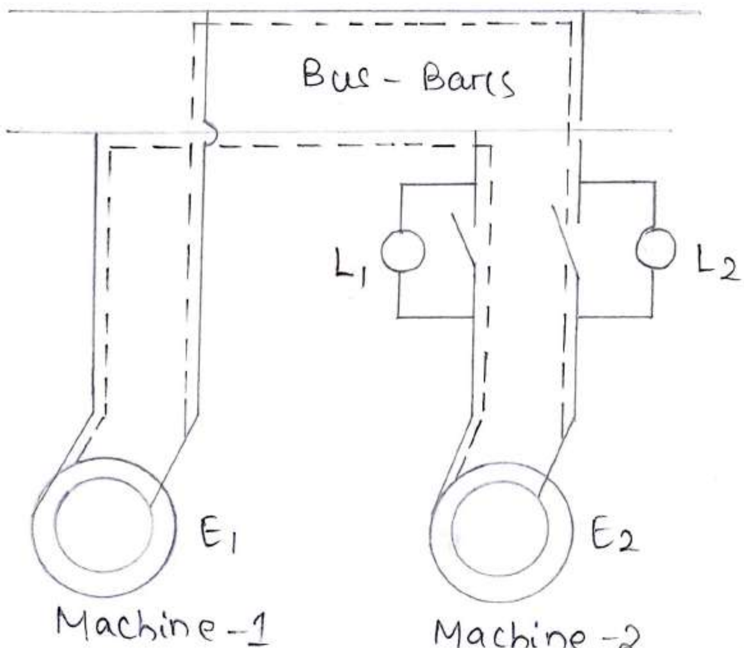
→ The proper synchronization of alternators, the following three conditions must be satisfied.

- The terminal voltage of the incoming alternators must be the same as bus-bars voltage.
- The speed of the incoming machine must be such that its frequency ($f = PN/120$) equals bus-bar frequency.
- The phase of the alternator voltage must be identical with the phase of the bus-bar voltage.
- It means that the switch must be closed at the instant the two voltages have correct phase relationship.

→ Condition 1 is indicated by a voltmeter, Condition 2 & 3 are indicated by synchronizing lamps or a synchronoscope.

Synchronizing of alternators :-

Single phase alternators :-



(Synchronizing of alternators)

→ The machine 2 is to be synchronized with or "put on" the bus-bars to which machine 1 is already connected.

→ This is done with the help of two lamps L_1 & L_2 connected as shown in figure.

→ The E_1 & E_2 are in-phase relative to the external circuit but are in direct phase opposition in the local circuit

→ The speed of the incoming machine 2 is not brought up to that of machine 1, then its frequency will also be different, hence there will be a phase-difference between their voltages.

→ The phase-difference will be continoausly changing with the changes in their frequencies.

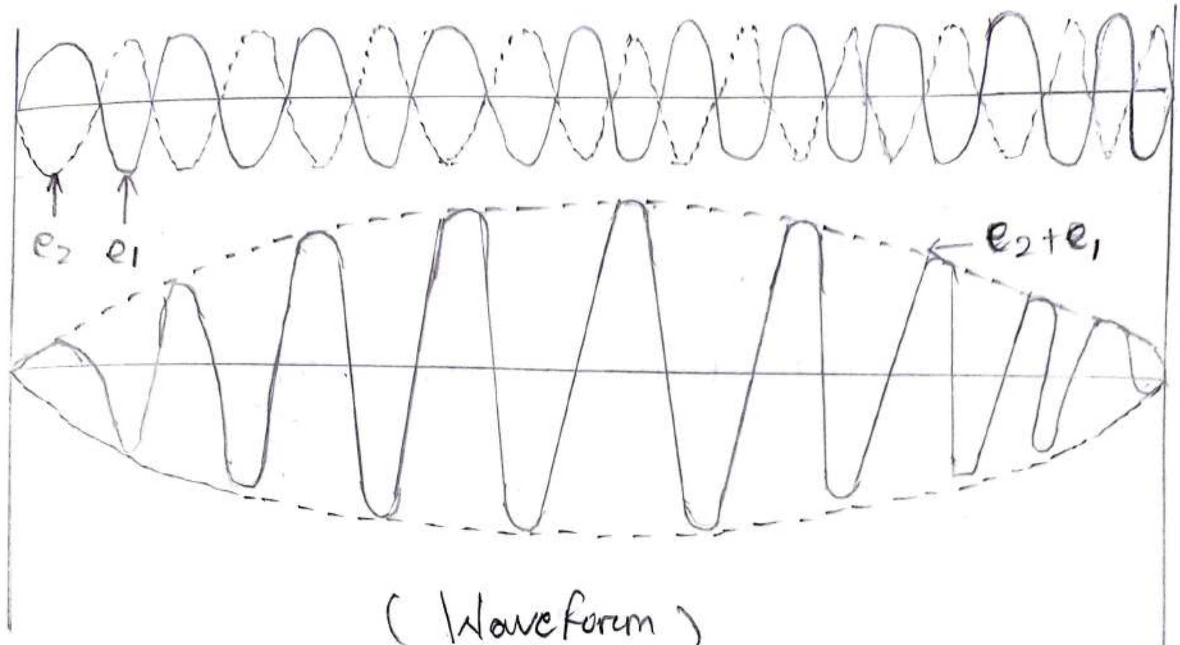
→ The result is that their resultant voltage will undergo changes similar to the frequency changes of beast produced.

→ When two sound source of nearly equal frequency are sounded together, as shown in figure.

→ The resultant voltage is maximum & some other times minimum.

→ The current is alternatingly maximum & minimum.

→ Due to this changing current through the lamps, a flicker will be produced.

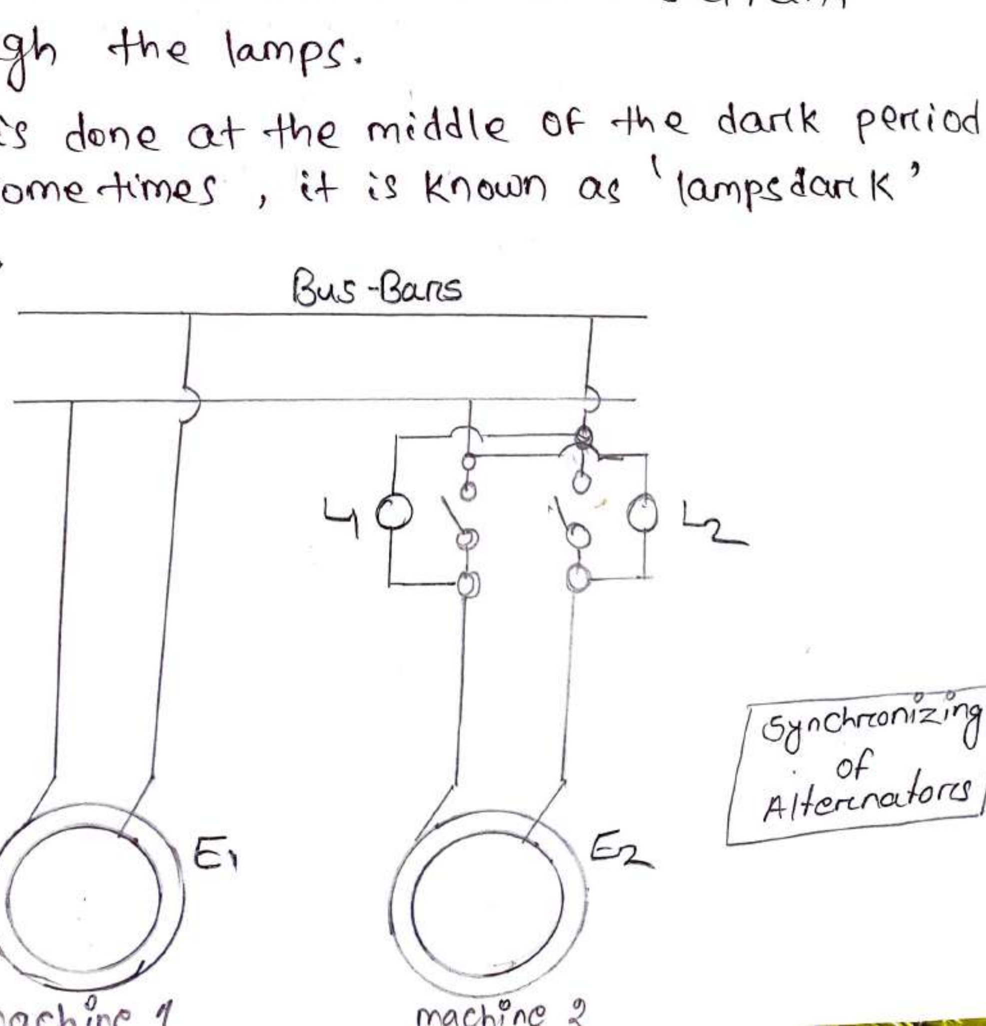


(Waveform)

→ The frequency of flicker being $(f_2 - f_1)$. lamps will dark out & glow up alternately.

→ Darkness indicates that the two voltages E_1 & E_2 are in exact phase opposition relative to the local circuit & hence there is no resultant current through the lamps.

→ Synchronizing is done at the middle of the dark period, That is why, sometimes, it is known as 'lamps dark' synchronizing.



→ The lamps will glow brightest when the two voltages are in-phase with the bus-bar voltage because then voltage across them is twice the voltage of each machine.

Necessity for parallel operation of alternators:

→ Alternators are operated in parallel for the following reasons.

(i) Several alternators can supply a bigger load than a single alternator.

(ii) One or more alternators may shut down during the period of light loads. Thus, the remaining alternator operates at near or full load with greater efficiency

(iii) When one machine is taken out of service for its scheduled maintenance and inspection the remaining machines maintain the continuity of the supply.

(iv) If there is a break down of the generator, there is no interruption of the power supply.

(v) Number of machines can be added with disturbing the initial installation according to the requirement to full fill the increasing future demand of the load.

(vi) Parallel operation of the alternator, reduces the operating cost of energy generation.

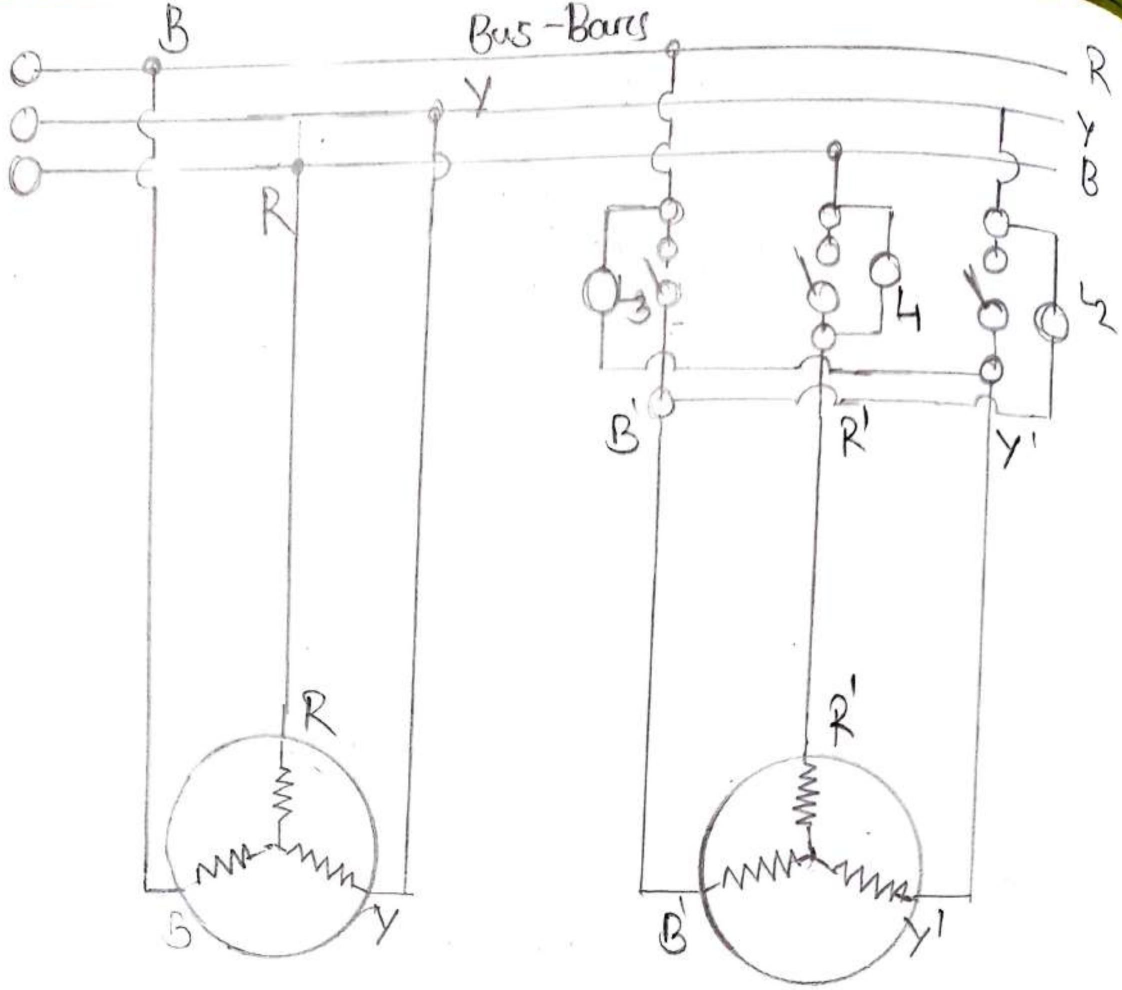
Requirement for parallel operation :-

The following conditions should be satisfied for parallel operation are as follows ;

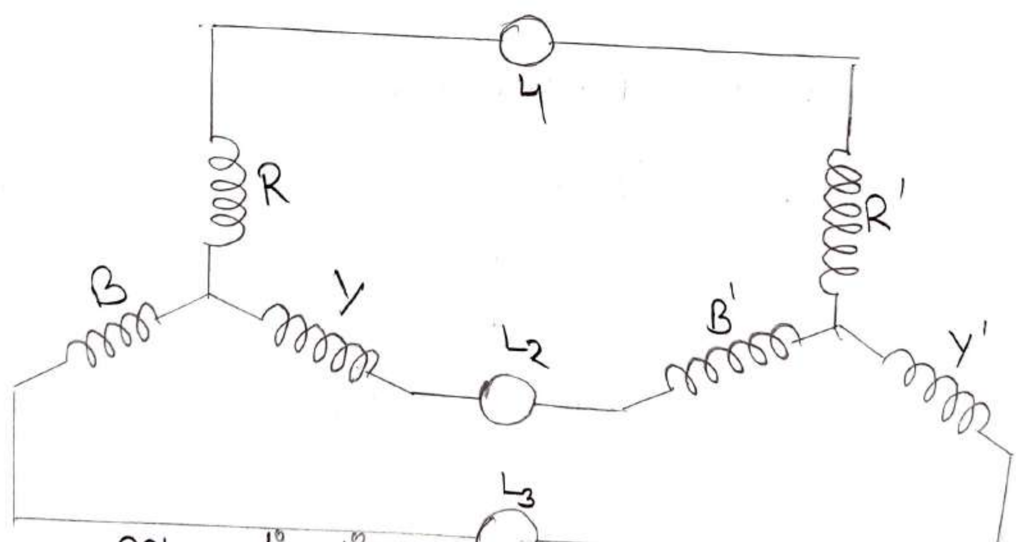
- The phase sequence of the Bus bar voltages & the incoming machine voltage must be the same.
- The Bus bar voltages and the incoming machine terminal voltage must be in phase.
- The terminal voltage of the incoming machine and the alternator which is to be connected in parallel or with the bus - bar voltage should be equal.
- The frequency of the generated voltage of the incoming machine & the frequency of the voltage of the Bus bar should be equal.

Three - phase Alternators :-

- Three-phase alternators, it is necessary to synchronize one phase only, the other two phases will then be synchronized automatically.
- First it is necessary that the incoming alternators is correctly 'phased out' i.e, the phases are connected in the proper order of R, Y, B & not R,Y, B etc.
- Three lamps are used. But they are deliberately connected asymmetrically, as shown in figures.



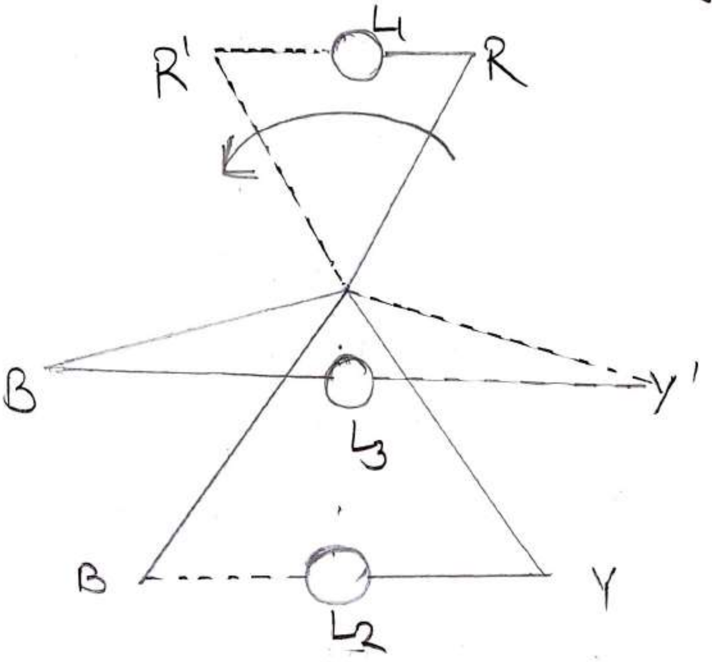
Asymmetrical Connection

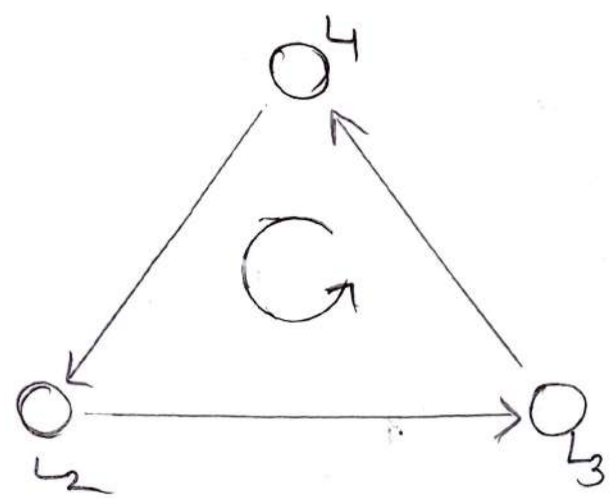


Schematic diagram

→ This transposition of two lamps, suggested by siemens and Halske, helps to indicated whether the incoming machine is running too slow.

- The lamps were connected symmetrically, they would dark out or glow up simultaneously (If the phase rotation is the same as that of the bus-bars).
- Lamp L_1 is connected between R & R', L_2 between Y & B' (not Y & Y') & L_3 between B & Y' (and not B & B') as shown in figure.
- Voltage stars of two machines are shown superimposed on each other in figure.





(Voltage stars of two machines)

→ Two sets of star vectors will rotate at unequal speeds if the frequencies of the two machines are different.

→ The incoming alternator is running faster, then voltage star R' Y' B' will appear to rotate anticlockwise with respect to the bus-bar.

→ The voltage star RYB at a speed corresponding to the difference between their frequencies.

→ The voltage across L_1 is RR' & is seen to be increasing from zero.

→ The voltage across L_1 is RR' and is seen to be increasing from zero.

→ The voltage across L_2 is YB' which is decreasing, having just passed through its maximum.

→ The voltage across L_3 is BY' which is increasing & approaching its maximum.

→ The lamps will light up one after the other in the order 2, 3, 1 ; 2, 3, 1 or 1, 2, 3.

→ The incoming machine is slightly slower.

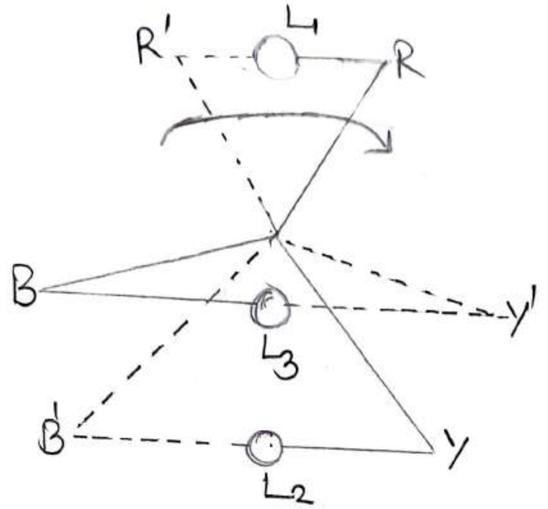
→ The star R'Y'B' will appears to be rotating clockwise relative to voltage star RYB.

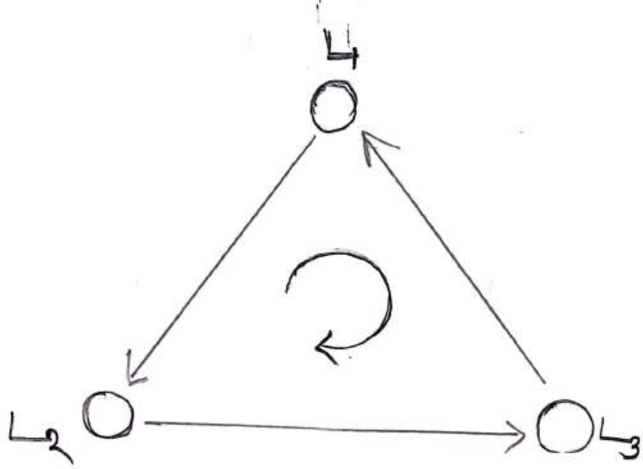
→ The voltage across L_3 i.e, Y'B is decreasing having just passed through its maximum.

→ The voltage across L_2 i.e YB' is increasing & approaching its maximum.

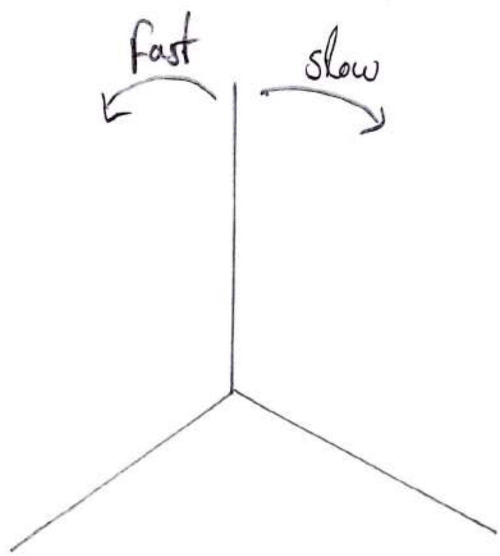
→ The voltage across L_1 is decreasing having passed through its maximum.

→ The lamps will light up one after the other in the order 3, 2, 1 ; 3, 2, 1 etc. which is just the reverse of the first order.





Voltage stars of two machines



Mounting of three lamps

→ The three lamps are mounted at the 3 corners of a traingle & the apparent direction of rotation of light indicates whether the incoming alternator is running too fast or too slow.

→ Synchronization is done at the moment the uncrossed lamp L_1 is in middle of the dark period.

→ When the alternator voltage is too high for the lamps to be used directly.

→ The step-down T/F s are used & the synchronizing lamps are connected to the secondaries.

→ When the uncrossed lamp L_1 is dark, the other two 'crossed' lamps L_2 & L_3 are dimly but equally bright.

→ Hence, this method of synchronizing is also sometimes known as "two bright & one dark" method.

→ The synchronization by lamps is not quite accurate, because to a large extent, it depends on the sense of correct judgment of the operator.

→ To eliminate the element of personal judgment in routine operation of alternators.

→ The machines are synchronized by a more accurate device called a synchronoscope.

→ The 3 stationary coil & a rotating iron vane which is attached to a pointer.

→ Out of three coils, a pair is connected to one phase of the line & the other to the corresponding machine terminals, potential transformer being usually used.

→ The pointer moves to one side or the other forms its vertical position depending on whether the incoming machine is too fast or too slow.

→ For correct speed, the pointer points vertically up.

Condition for parallel operation of Alternator

Parallel operation of Alternators :-

→ The process of connecting two or more alternators in parallel to share a common load is called operation of Alternators.

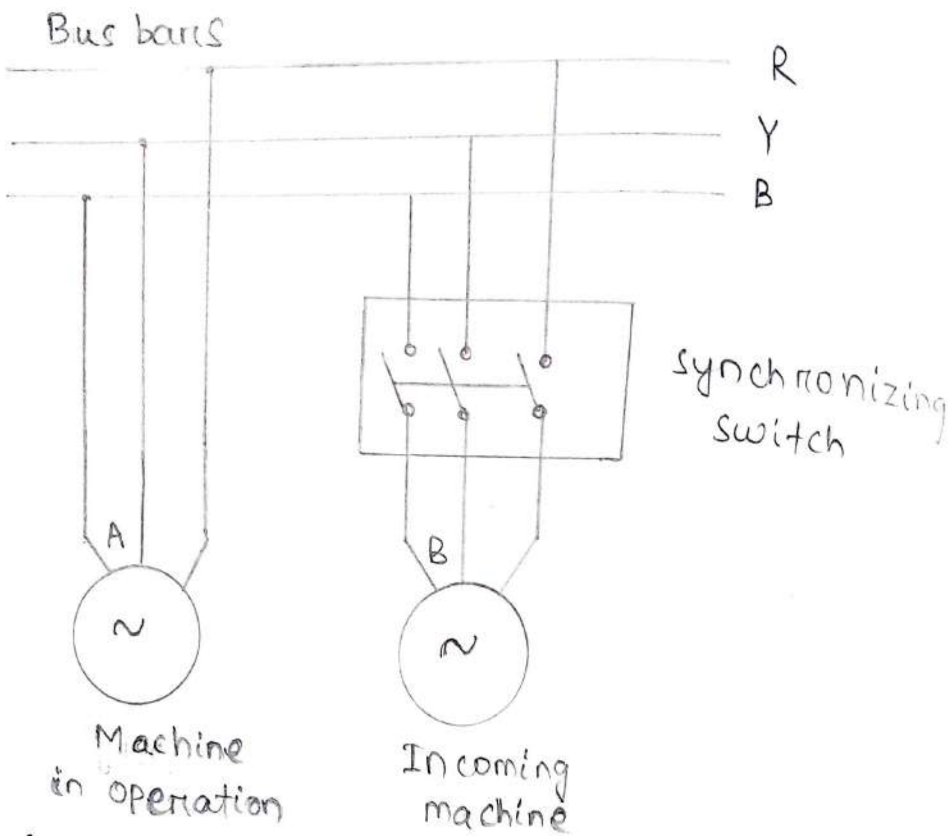
Conditions for parallel operation of Alternators :-

→ let us see the condition for parallel operation of alternators one by one,

Condition - 1 :-

→ Equal terminal voltages :-

- This is obtained by adjustment of the incoming generator's field strength.

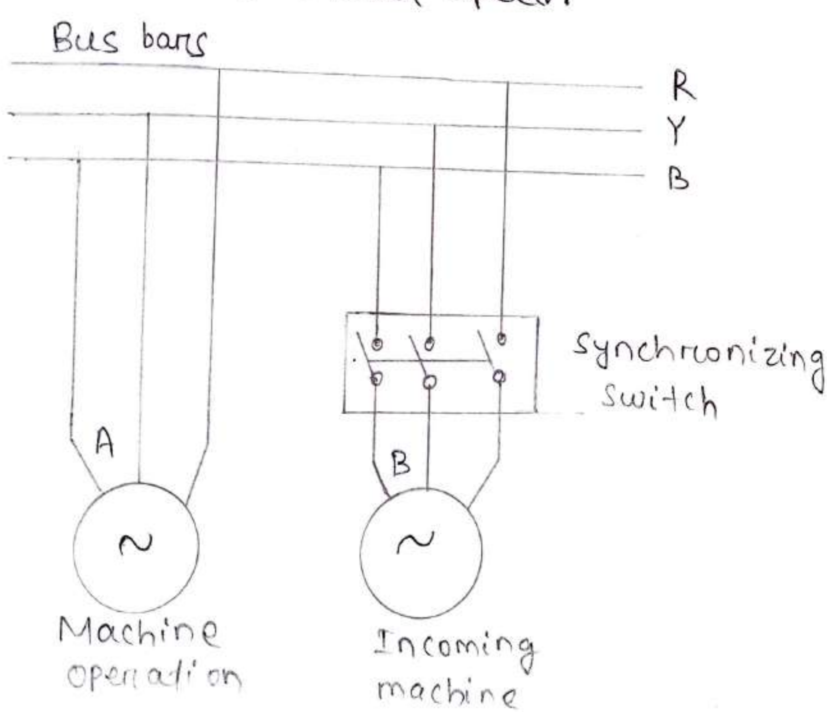


(Synchronization of alternators)

Condition -2 :-

→ Equal frequencies :-

This is obtained by adjusting the incoming generator's prime - mover speed.

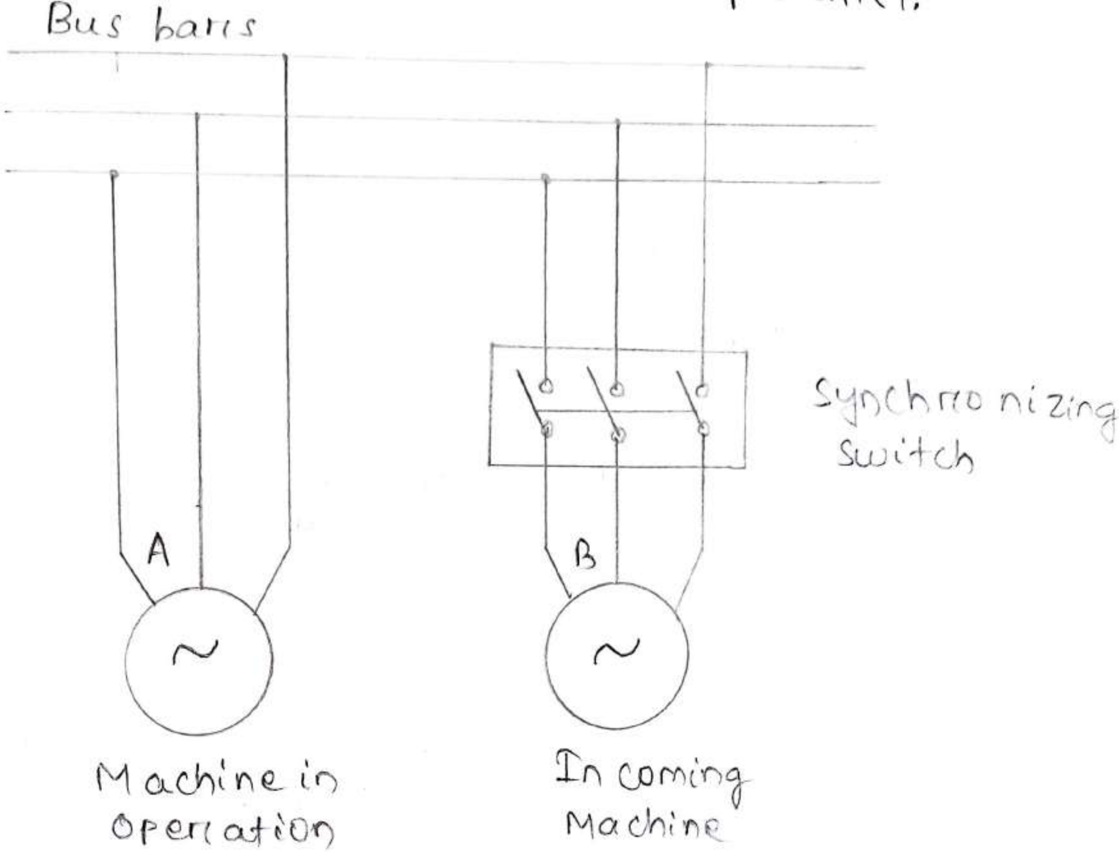


(synchronization of Alternators)

Condition - 3 :-

same phase sequence :-

- This is obtained by adjusting the conditions of the alternators which connect in parallel.



(synchronization of Alternators)

Synchronization :-

→ This is the term which is frequently used in parallel operation of alternators.

→ The method of connecting the alternators in parallel is known as synchronization.

Synchroscope

* Synchroscope 4 methods are here :-
  - (i) Dark lamp method
  - (ii) Bright lamp method
  - (iii) Dark & bright lamp method
  - (iv) Synchroscope method.

① Dark lamp method :-

→ In dark lamp method of synchonising, three lamps are connected as shown in figure.

→ The alternator 1 is already connected with the busbar & is supplying power to the load.

→ The alternator 2 is the incoming alternator.

→ Incoming alternator (2) is started & its speed is adjusted to its rated value.

→ The voltage & frequency of the system remain the same.

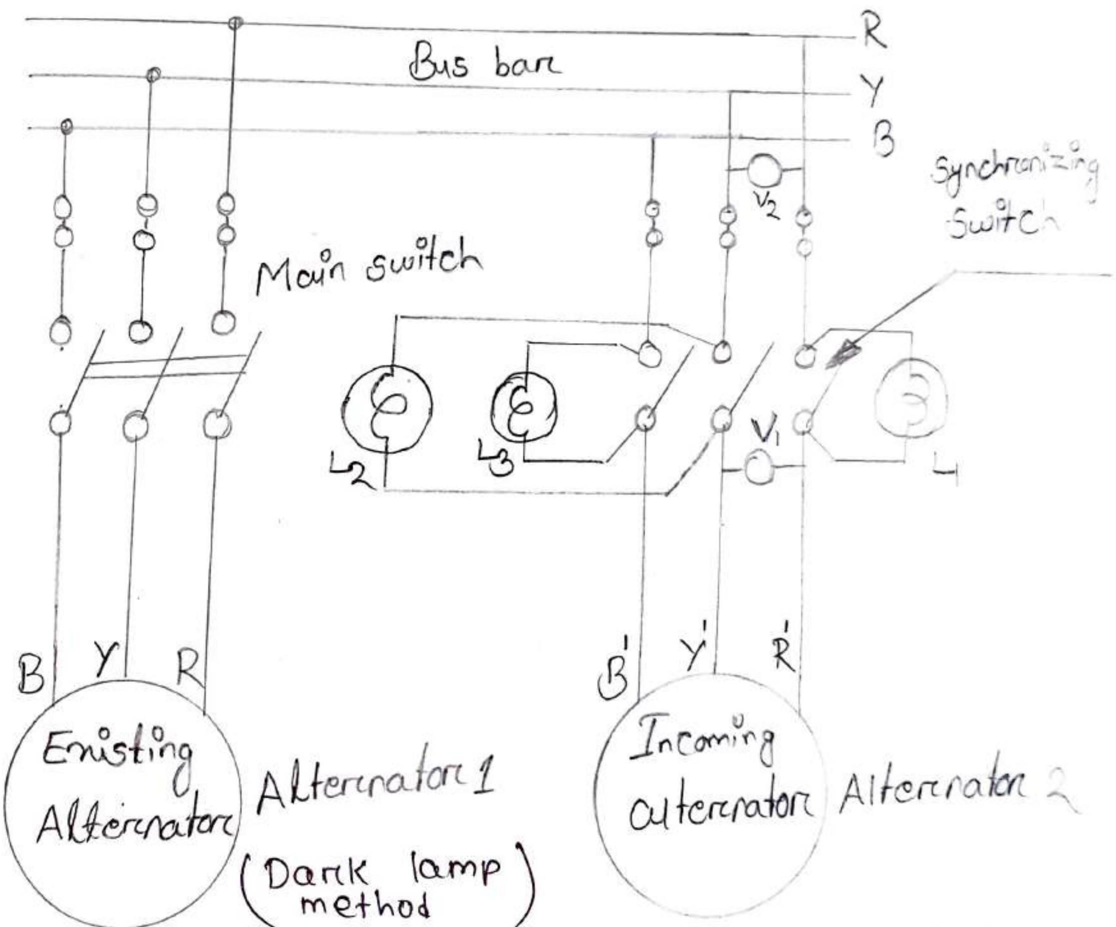
→ The excitation of incoming alternator is adjusted to generate its rated voltage.

→ Voltmeters V_1 will indicate the generated voltage of existing alternator voltage.

→ Voltmeter V_2 will indicate the generated voltage of incoming alternator.

→ To verify the condition 1, for synchronisation, voltage indicated by the voltmeter V_1 & V_2 are observed.

- When the voltages V_1 & V_2 are equal, condition 1 is satisfied.
- The phase sequence of the incoming alternator & existing alternator can be chocked by using phase sequence indicator.
- The 3 lamps in the circuit are glowing uniformly togather & becomes dark togather, then it indicates that the phase sequence is correct.



(Dark lamp method)

- The sequence of the incoming alternator is same as that of existing alternator, the synchronising lamps will start flickering in uniform.
- The output terminals of the incoming alternator changed properly.

→ There is any difference in frequency, of the alternators, the lamp will be bright & dark alternatively.

→ The speed of alternators 2 is adjusted properly so that flickering of lamps is slower in rate.

→ The lamps flicker at a very slow rate, It indicates that the frequencies of the two alternators are almost equal.

→ At this condition the synchronising switch is closed at the middle of all the 3 dark lamps.

→ When the synchronizing switch is closed, the alternator 2 is just connected to the bus bar.

→ At this stage generated emf of the incoming alternator is just equal to the bus bar voltage.

→ It neither supplies power nor receives the power form the bus bar and the alternator 2 is said to be "floating on the busbar".

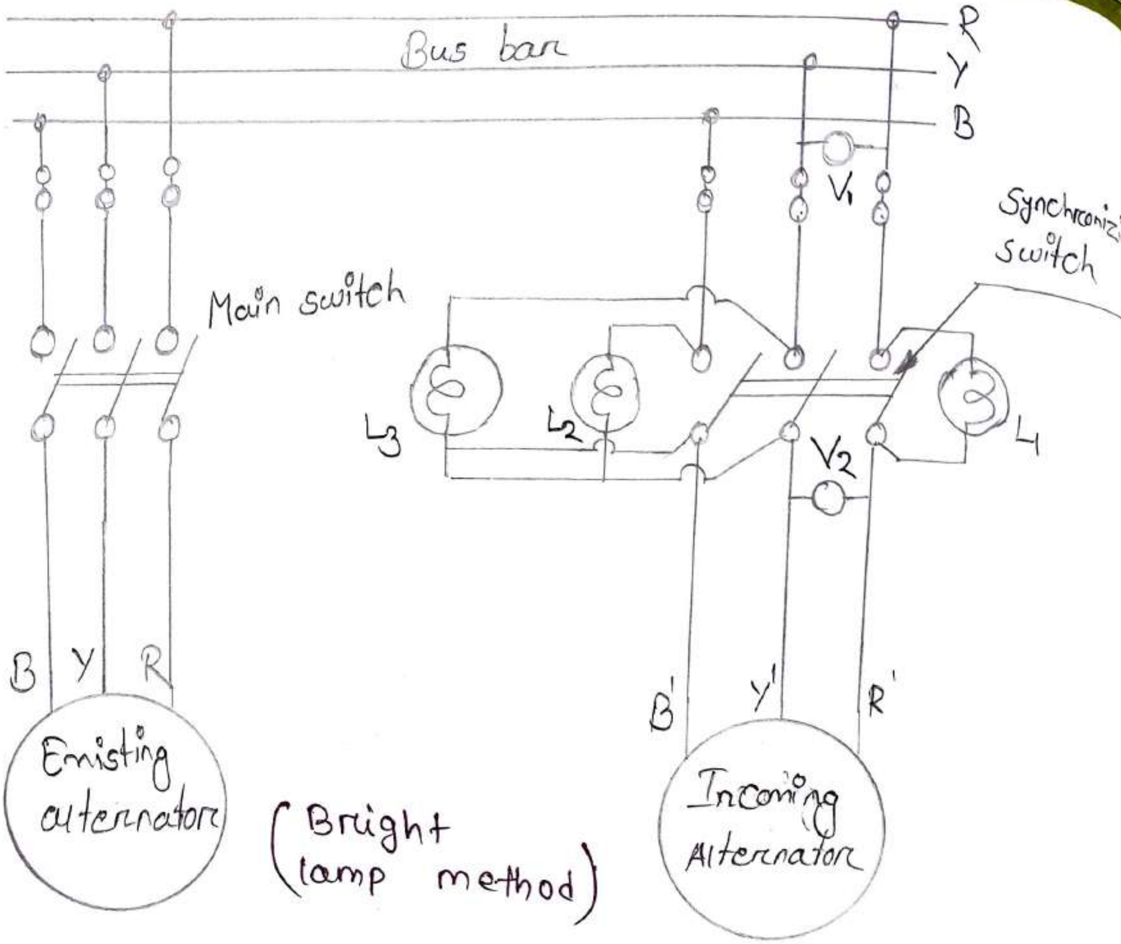
Demerits :-

→ It is not possible to judge whether the incoming alternator is fast or slow.

→ The lamps can be dark even through a small value of voltage may present across its terminals. The bright lamp method eliminates these disadvantages.

② Bright lamp method :-

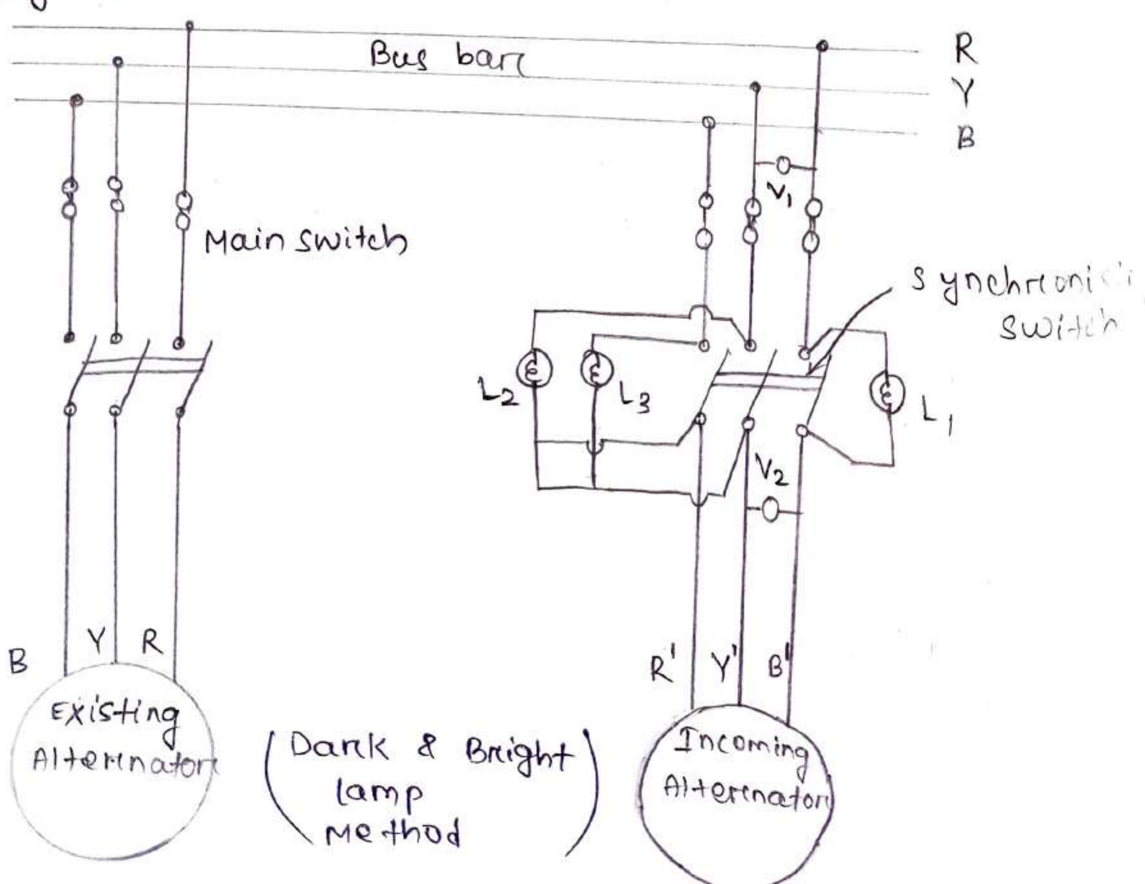
- In bright lamp method of synchronising all the 3 lamps are cross connected as shown if figure.
- The lamps will glow the brightest when the two voltages are in phase, because the voltage across the lamp is twice the voltage of each alternators.
- Now the incoming alternator is started and its speed is adjusted to its rated speed.
- Field excitation is also adjusted to generate the rated voltage.
- When the voltage V_1 & V_2 are equal the condition 1 is satisfied.
- The phase sequence is checked by the use of phase sequence indicator or using 3 lamps.
- If the sequence of the incoming alternator is same as that of existing alternator, the synchronising lamps will start flickering in uniform.
- If not so, the output terminals of the incoming alternator will be changed properly.
- The frequency of the incoming machine is adjusted to the existing alternator frequency by adjusting the speed of the incoming alternator.
- The synchronising switch is closed at the middle of the brightest period of the lamps & thus the alternator is synchronised.



(Bright lamp method)

③ Dark & Bright lamp method :-

→ In this method, 3 lamps are connected as shown in figure.



(Dark & Bright lamp Method)

→ First the incoming alternator is allowed to run at its rated speed.

→ Its generated e.m.f is adjusted to a value equal to the existing alternator voltage by varying the field excitation of incoming alternator.

→ The phase sequence is checked with the help of a phase sequence indicator.

→ When the voltage V_1 & V_2 are equal the condition 1 is satisfied.

→ In this method, the voltage across the lamps is different and thus the lamps will not flicker in uniform.

→ Depending upon the frequency of incoming alternator, the order of brilliance of the lamps may be varied.

→ If f_1 is the frequency of existing alternator and f_2 is the frequency of the incoming alternator.

Condition for incoming machine :-

→ For the condition the incoming machine is slower, i.e, f_1 is greater than f_2 ($f_1 > f_2$), now lamp L_1 is dying out, lamp L_2 has already passed its point of maximum brilliance & lamp L_3 is approaching maximum brilliance.

→ The order of brilliance of the lamps is L_2, L_3 & L_1 i.e, L_1, L_2, L_3.

→ For the condition the incoming machine, is faster i.e, ($f_2 > f_1$) the order of brilliance of the lamps is L_1, l_3 & l_2.

→ Synchronising switch is closed during dark period of the lamp L_1.

→

④ Synchroscope :-

→ The synchroscope is an instrument for indicating difference of phase & frequency between two voltages & at the same time it also indicates whether alternator is running slow or fast.

→ It is a motor having a pointer fixed at one end of the motor's shaft which rotates over a circular scale fixed at the end of the shaft.

Principle of synchroscope :-

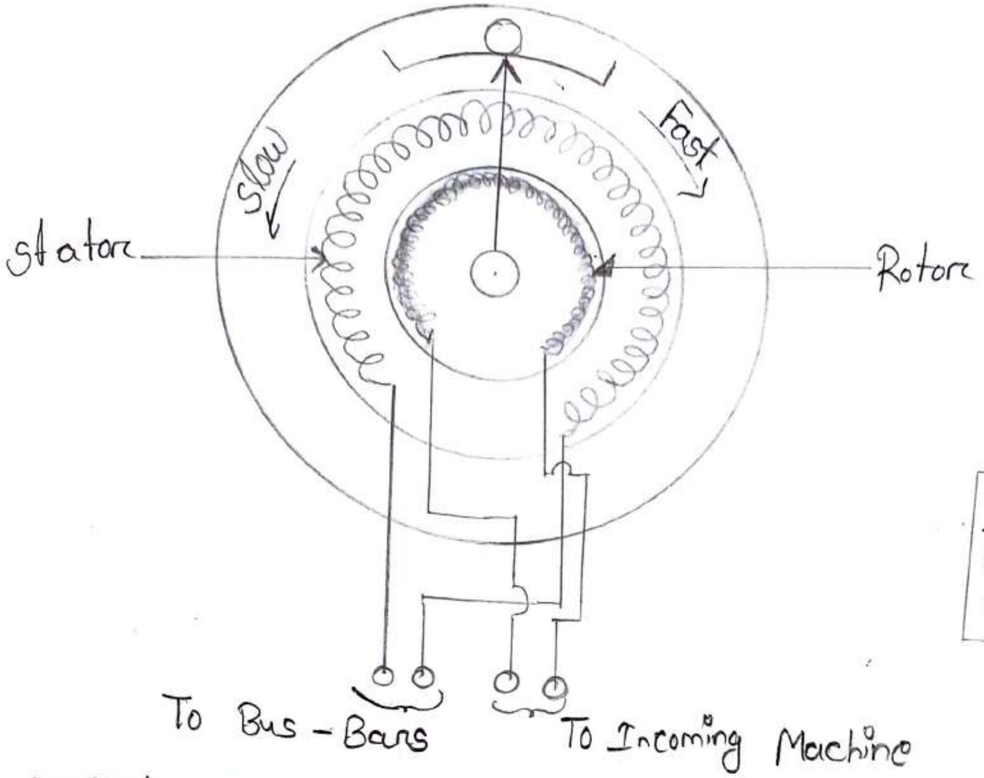
→ The synchroscope works on the principle of rotating magnetic field.

→ Constructional details of synchroscope :-

→ It consists of a rotor & stator wound for two phase system.

→ The rotor & stator is supplied from two phase supply from the alternators to be connected in parallel.

→ If the two phases are synchronized, then the third phase will automatically be synchronized.



Internal Connection of Synchroscope

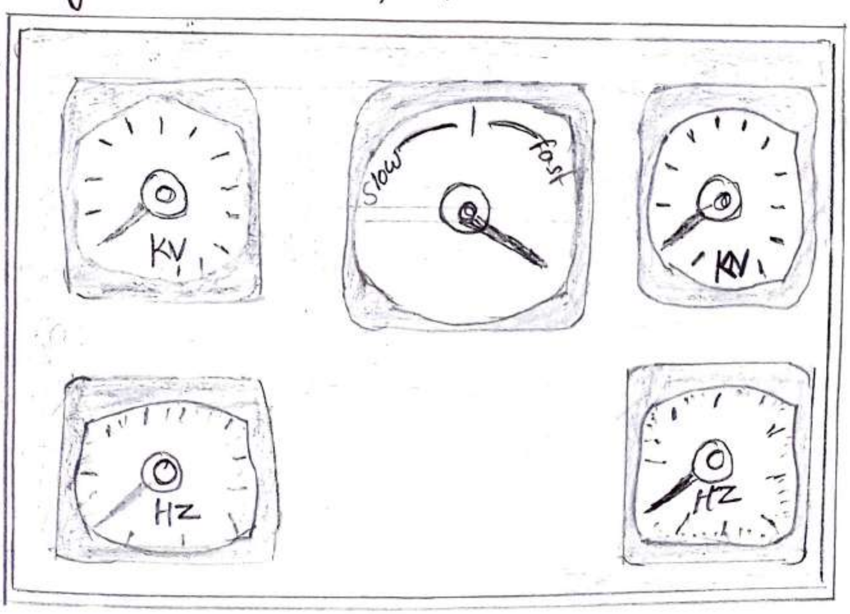
→ The supply to stator of synchroscope is given by existing alternator.

→ The supply to rotor of synchroscope is given by incoming alternator.

Functions of synchroscope :-

→ It indicates difference in phase & frequencies of alternators which are to be connected in parallel.

→ It also indicates whether the coming alternator is running slow or fast.



Synchroscope

Working of synchroscope :-

→ The working of the synchronscope depends upon the difference in frequency of alternators which are to be connected in parallel.

→ If there is no difference in Frequency of rotor & Stator supply then the rotor remains stand-still.

→ If there difference in frequencies of rotor & stator supply, the rotor will rotated.

→ If the difference in frequencies is greater, The rotor speed to be greter.

→ If the difference in frequencies is less, the rotor speed will be less.

Synchroscope method :-

→ Synchroscope of an alternator by using lamps is not very exact method. since it requires a correct judgement for closing the synchronizing switch.

→ If there is a small angle of phase displacement, It causes disturbance to the alternators.

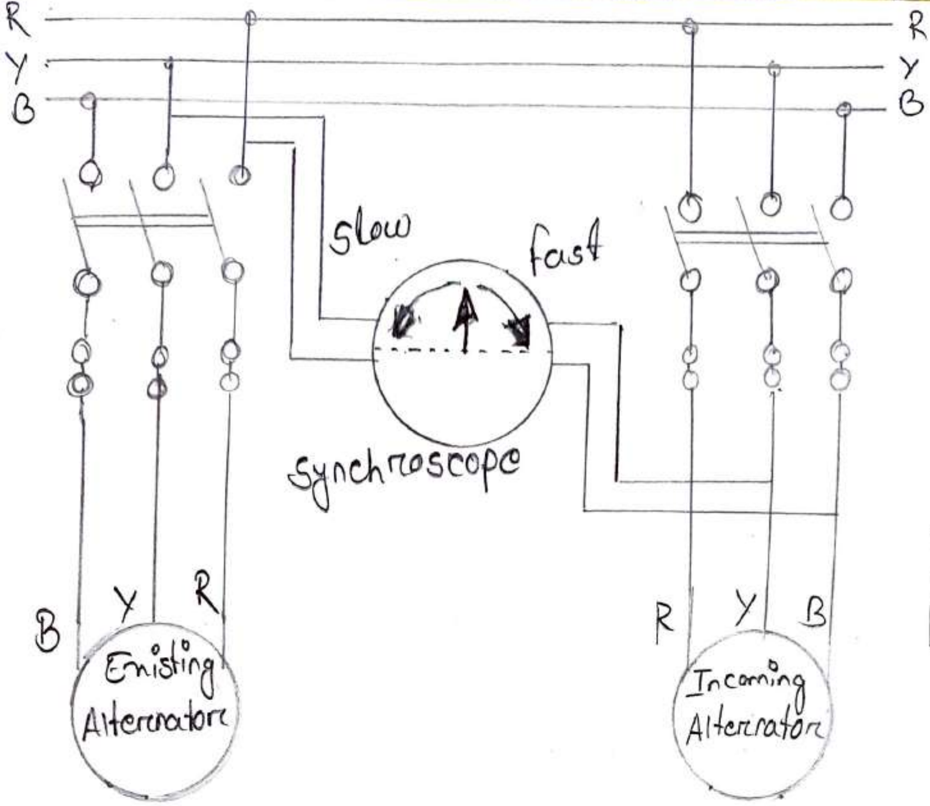
→ In this method, synchroscope is used instead of lamps.

→ The synchroscope indicates the instant of synchronism more correctly.

→ The synchroscope is connected as shown in figure.

→ The synchroscope consists of a rotor and a stator.

→ The rotor or the moving coils is connected to the incoming alternator & the stator or the fixed coil is connected to the existing alternator, or the bus bars.



Synchroscope method

- In the synchroscope, a pointer is attached to the rotor.
- This pointer will indicate the correct time for closing the synchronising switch.
- The correct time for synchronising is when the pointer in the synchroscope is stationary at 12'0 clock position.
- If frequencies are different values, the pointer will rotate.
- It the pointer indicates in the anti-clockwise direction, the frequencies of the incoming alternator is low.
- The Clockwise direction of rotation of the pointer Shows the frequency of the incoming alternator as higher than the frequency of the alternator 1.
- In this method also the voltages are checked first by providing voltmeters.
- The field rheostat of incoming alternators is adjusted such that the two alternators voltage must be equal.

→ Then the phase sequence is checked by using phase sequence indicator on the test circuit.

→ If the voltage values & the phase sequence is correct, the speed of the incoming alternator is adjusted in such a way the pointer of the synchroscope rotates very slowly.

→ If the frequencies are equal, the pointer is at stationary position.

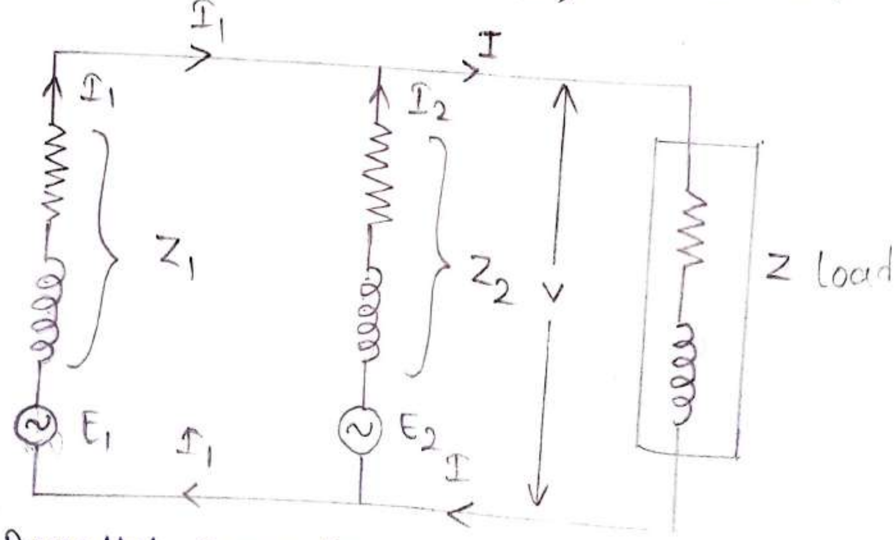
→ The synchronising switch of the incoming alternator is closed, when the pointer is stationary at 12' O clock position in the synchroscope.

→ This is the correct instant for closing the synchronising switch.

(Synchronising Current, Synchronsising power)

Parallel operation of two alternators :-

let us assume that the two alternators with identical speed - load characteristics running in parallel with a common terminal voltage (V) Volts & load impedance (Z) as shown in figure.



(Parallel operation of two alternators)

→ Assume the generated emf of two machines 1 & 2 are E_1 & E_2 respectively & the synchronous impedance per phase Z_1 & Z_2 respectively.

→ $$V = E_1 - I_1 Z_1$$

$$V = E_2 - I_2 Z_2$$

where,

E_1 = induced emf alternator 1

E_2 = induced emf alternator 2

I_1 = Alternator current I_1

I_2 = Alternator current I_2

$$\therefore \quad E_1 - E_2 = I_1 Z_1 - I_2 Z_2$$

Also, $$I = I_1 + I_2 \quad \& \quad V = IZ$$

$$\therefore \quad E_1 = I_1 Z_1 + IZ$$

$$\Rightarrow E_1 = I_1 (Z + Z_1) + I_2 Z$$

$$\therefore \quad E_2 = I_2 Z_2 + IZ$$

$$\Rightarrow E_2 = I_2 (Z + Z_2) + I_1 Z$$

$$\therefore \quad I_1 = \frac{(E_1 - E_2) Z + E_1 Z_2}{Z(Z_1 + Z_2) + Z_1 Z_2}$$

$$\therefore \quad I_2 = \frac{(E_2 - E_1) Z + E_2 Z_1}{Z(Z_1 + Z_2) + Z_1 Z_2}$$

$$I = \frac{E_1 Z_2 + E_2 Z_1}{Z(Z_1 + Z_2) + Z_1 Z_2}$$

$$\therefore \quad V = IZ$$

$$\Rightarrow V = \frac{E_1 Z_2 + E_2 Z_1}{Z_1 + Z_2 + (Z_1 Z_2 / Z)}$$

$$I_1 = \frac{E_1 - V}{Z_1}$$

The circulating current under no-load condition

$$I_c = \frac{(E_1 - E_2)}{(Z_1 + Z_2)}$$

Problem - 1 :-

Two single phase alternators operating in parallel have induced emf s an open circuit of $230\angle 0°$ & $230\angle 10°$ volt & respective reactance of $j2\,\Omega$ & $j3\,\Omega$.

Calculate (i) Current

(ii) Terminal Voltage

(iii) power delivered by each of the alternators to a load of impedance 6Ω. (respective)

Sol^n

Given data :-

$Z_1 = j2\,\Omega$

$Z_2 = j3\,\Omega$

$Z = j6\,\Omega$

$E_1 = 230\angle 0°\,V$

$E_2 = 230\angle 10°\,V$

To find :-

$I_1, I_2 = ?$

$V = ?$

$P_1, P_2 = ?$

Solution :-

$E_1 = 230\angle 0°\,V$

$E_2 = 230\angle 10°\,V$

$E_2 = 230\,(0.985 + j\,0.175)$

$\Rightarrow E_2 = (226.5 + j\,39.9)\,V$

(i) $\therefore I_1 = \dfrac{((E_1 - E_2)Z + E_1 Z_2)}{(Z(Z_1 + Z_2) + Z_1 Z_2)}$

$= \dfrac{(230 + j10) - (226.5 + j39.9) \times 6 + (230 \times j3)}{6(j2 + j3) + j2 \times j3}$

$= (14.3 - j3.56)$

$= 14.73 \angle -14° \text{ A}$

$\therefore I_2 = \dfrac{((E_2 - E_1)Z + E_2 Z_1)}{(Z(Z_1 + Z_2) + Z_1 Z_2)}$

$= (22.8 - j1.2)$

$= 22.83 \angle -3.4$

$\therefore I = I_1 + I_2$

$= 37.1 - j4.7$

$= 37.4 \angle -7.3°$

$\therefore V = IZ$

$= (37.1 - j4.7) \times 6$

$= 222.6 - j28.2$

$= 224 \angle -7.3°$

$\therefore P_1 = V I_1 \cos \phi_1$

$= 224 \times 14.73 \times \cos 14$

$= 3201 \text{ W}$

$\therefore P_2 = V I_2 \cos \phi_2$

$= 224 \times 22.83 \times \cos 3.4$

$= 5105 \text{ W.}$

Load sharing

load sharing between two alternators :-

- When an alternator is synchronized, the load can be shifted from the existing alternator to the incoming alternator which is to be connected in parallel.
- load sharing between the alternators can be changed by altering the mechanical input to the prime movers.

Condition for load sharing between two alternators depends on :-

→ synchronous generators running in parallel must run at same frequency.

→ Speed power characteristics of the prime movers during driving the two alternators in parallel decides the load division between the two.

→ The electrical power of the alternator in parallel is determined by mechanical input.

→ The electrical power output of alternator in parallel is determined by mechanical input.

→ Changes in excitation of the alternators results in change of voltage but the division of active power remains almost unaffected.

Control of active load (KW) & reactive load (KVAR)

- The reactive load (KVAR) supplied by each alternator operating in parallel is controlled by controlling the excitation of it.
- When the excitation of one of the alternators is increased, the reactive power (KVAR) supplied by that alternators will be increased.
- When the excitation of on of the alternator is decreased, the reactive power (KVAR) supplied by that alternator will be decreased.
- The change of excitation does not make any change in the active power (KW) supplied by the alternator.
- The active load (KW) supplied by each alternator operating in parallel is controlled by controlling the input power applied to it.
- When the input power of one of the alternators is increased, the active power (KW) supplied by that alternatores will be increased.
- When the input power of one of the alternators is decreased, the active power (KW) supplied by that alternatores will be decreased.

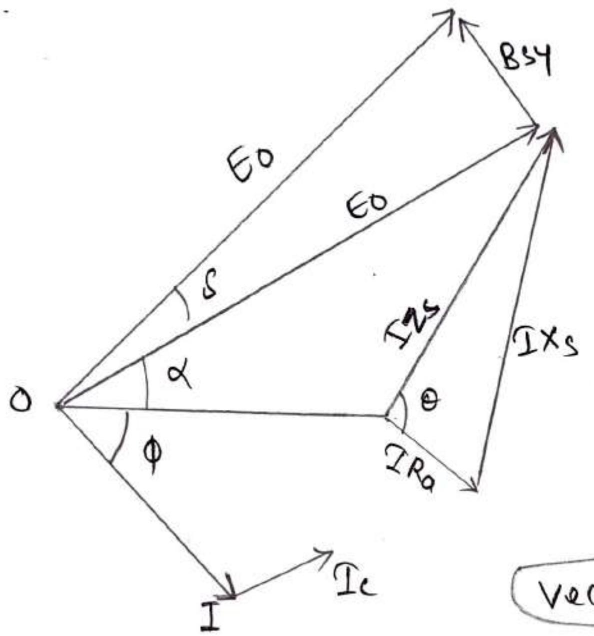
Infinite bus bar :-

- Alternator generally feed power into power system.
- Power system consists of a large number of alternators interconnected.

- The size of the system is very large. Hence removing of an alternator or adding an alternator with the system does not affect the system voltage & frequency.
- The very large system working at constant voltage & frequency is called an infinite bus bar system.
- The behaviour of the infinite bus bar system is same as a large generator having zero internal impedance ($Z_s/\infty = 0$).
- The speed of an alternator connected to an infinite bus bar is fixed corresponding to the system frequency.
- If an alternator is to be shut down from the infinite bus bars, the KW loads must be removed first by reducing the input power to the alternator.
- The reactive load must be removed reducing the excitation.
- when there is no real load & load reactive load on the alternators, it flots on the bus bars neither taking current nor delivering current.
- The alternator can be disconnected from the bus bars when it floats.

Alternative expression for synchronizing power

→ let V & E be the terminal voltage & induced emf per phase of the rotor. Then, taking $V = V\angle 0^\circ$, the load current supplied by the alternator.



Vector diagram

→ $$I = \frac{E - V}{Z_s}$$

$$\Rightarrow I = \frac{E\angle\alpha - V\angle 0^\circ}{Z_s \angle 0^\circ}$$

$$\Rightarrow I = \frac{E}{Z_s}\angle\alpha - \theta - \frac{V}{Z_s}\angle -\theta$$

$$\Rightarrow I = \frac{E}{Z_s}\left[\cos(\theta - \alpha) - j\sin(\theta - \alpha)\right]$$

$$\Rightarrow I = -\frac{V}{Z_s}(\cos\theta - j\sin\theta)$$

$$\Rightarrow I = \left[\frac{E}{Z_s}\cos(\theta - \alpha) - \frac{V}{Z_s}\cos\theta\right] - j\left[\frac{E}{Z_s}\sin(\theta - \alpha) - \frac{V}{Z_s}\sin\theta\right]$$

→ These components represent the $I \cos \phi$ & $I \sin \phi$ respectively. The power P converted internally is given be the sum of the product of corresponding components of the current with $E \cos \alpha$ & $E \sin \alpha$.

$$\therefore P = E \cos\alpha \left[\frac{E}{Z_s}\cos(\theta-\alpha) - \frac{V}{Z_s}\cos\theta\right] - E \sin\alpha$$

$$\left[\frac{E}{Z_s}\sin(\theta-\alpha) - \frac{V}{Z_s}\sin\theta\right]$$

$$\Rightarrow P = E\left[\frac{E}{Z_s}\cos\theta\right] - E\left[\frac{V}{Z_s}\cos(\theta+\alpha)\right]$$

$$\Rightarrow P = \frac{E}{Z_s}\left[E\cos\theta - V(\cos\theta+\alpha)\right] \text{ per phase}$$

→ Now, let, for some reason, angle α be changed to $(\alpha \pm \delta)$. since V is held rigidly constant due to displacement $\pm\delta$, an additional emf of divergence i.e, $I_{sy} = E_{sy}/Z_s$. The internal power will become.

$$P' = \frac{E}{Z_s}\left[E\cos\theta - V\cos(\theta+\alpha\pm\delta)\right]$$

The difference between P' & P gives the synchronizing power.

$$\therefore P_{sy} = P' - P = \frac{EV}{Z_s}\left[\cos(\theta+\alpha) - \cos(\theta+\alpha\pm\delta)\right]$$

$$\Rightarrow P_{sy} = \frac{EV}{Z_s}\left[\sin\delta\sin(\theta+\alpha) \pm 2\cos(\theta+\alpha)\sin^2\delta/2\right]$$

→ If δ is very small, then $\sin^2(\delta/2)$ is zero, hence Psy per phase

$$P_{sy} = \frac{EV}{Z_s} \sin(\theta + \alpha) \sin \delta$$

→ In large alternators, Ra is negligible, hence $\tan \theta = X_s/R_a = \infty$, so that $\theta = 90°$.

There fore, $\sin(\theta + \alpha) = \cos \alpha$

$$\therefore P_{sy} = \frac{EV}{Z_s} \cos \alpha \sin \delta \text{ per phase}$$

$$= \frac{EV}{X_s} \cos \alpha \sin \delta \text{ per phase}$$

→ Consider the case of synchronizing an unloaded machine on to a constant-voltage bus-bars. For proper operation, $\alpha = 0$ so that E coincides with V. In that case $\sin(\theta + \alpha) = \sin \theta$.

$$\therefore P_{sy} = \frac{EV}{Z_s} \sin \theta \sin \delta \quad \text{From (i) above}$$

since δ is very small, $\sin \delta = \delta$

$$\therefore P_{sy} = \frac{EV}{Z_s} \delta \sin \theta$$

$$\therefore P_{sy} = \frac{EV}{X_s} \delta \sin \theta$$

Usually, $\sin \theta \simeq 1$, hence

$$\therefore P_{sy} = \frac{EV}{Z_s} \delta$$

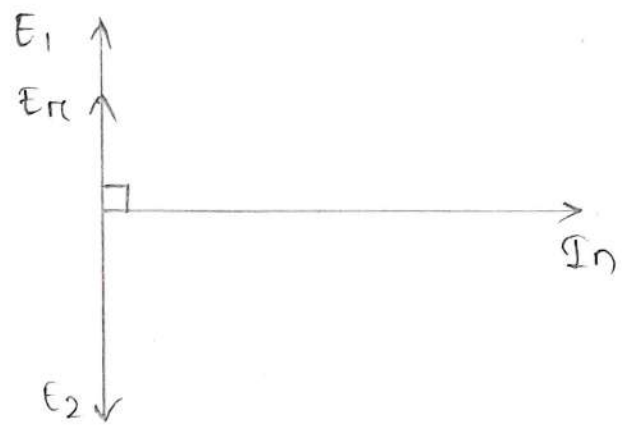
$$\Rightarrow P_{sy} = V\left(\frac{E}{Z_s}\right) \delta$$

$\Rightarrow P_{sy} = V\left(\frac{E}{X_s}\right)\delta$

$\Rightarrow P_{sy} = VI_{sc}\,\delta$ per phase

EFFECT OF UNEQUAL VOLTAGES :-

→ Consider two alternators, which are running exactly in-phase but which have slightly unequal voltages, as shown in figure.



(Effect of unequal voltages)

→ If E_1 is greater than E_2, then their resultant is $E_r = (E_1 - E_2)$ & is in-phase with E_1. Their E_r or E_{sy} set up a local synchronizing current I_{sy} which is almost 90° behind E_{sy} & hence behind E_1 also.

→ The lagging current produces demagnetising effect on the first machine, hence E_1 is reduced.

→ The other machine runs as a synchronous motor taking almost 90° leading current. hence its field is strengthened due to magnetising effect of armature reaction. This tends to increase E_2.

- The two effects act togather & hence lesson the inequalities between the two voltages & tend to establish stable conditions.

Distribution of load :-

- The amount of load taken up by an alternator running, in parallel with other machines, is solely determined by its driving torque. i.e, by the power input to its prime mover.
- Any alternation in its excitation merely changes its KVA output, but not its KW output.
- In other words, it merely changes the power factor at which the load is delivered.

Effect of change in excitation :-

- The initial operating conditions of the two parallel alternators are indentical i.e, each alternator supplies one half of the active load (KW) & one half of the reactive load (KVAR), the operating power factors thus being equal to the load p.f.
- The active & reactive powers are divided equally there by giving equal apparent power triangles for the two machines as shown in figure.
- The each alternator supplies a load current I so that output current is 2I.

→ The excitation of alternator No. 1 be increased, so that E_1 becomes greater than E_2.

→ The difference between the two e.m.f s set up a circulating current $I_c = I_{sy} = \frac{(E_1 - E_2)}{2}$ zs which is confined to the local path through the armatures and round the bus-bars. This current is superimposed on the original current distribution.

→ I_c is vectorially added to the load current of alternator No. 1 and subtracted from that of No 2.

→ The two machines now deliver load currents I_1 & I_2 at respective power factors of $\cos \phi_1$ & $\cos \phi_2$.

→ The change in load currents lead to changes in power factors, such that $\cos \phi_1$ is reduced, where as $\cos \phi_2$ is increased. Effect on the KW loading of the two alternators is negligible, but $KVAR_1$ supplied by alternator No. 1 is increased whereas $KVAR_2$ supply by alternator No. 2 is correspondingly decreased, as shown by the KVA triangles of figure.

→ Effect on the KW loading of the alternators is negligible, but $KVAR_1$ supplied by alternator No. 1 is increased, whereas $KVAR_2$ supplied by alternator 2. is correspondingly decreased, as shown by the KVA triangles of figure.

Effect of change in steam supply :-

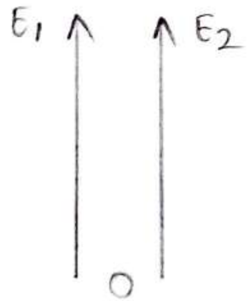
→ Now, suppose that excitations of the two alternators are kept the same but steam supply to alternator No. 1 is increased i.e, power input to its prime mover is increased.

→ The speed of the two machines are tied togather by their synchronous bond, machine No 1. can not overrun machine No 2.

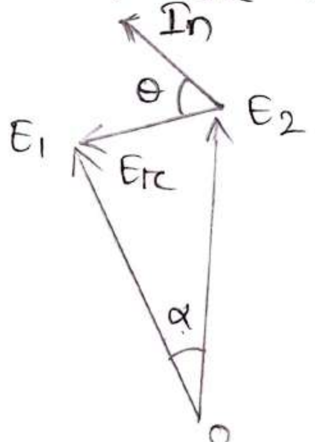
→ Alternatively, it utilizes its increased power input for carrying more load than No 2

→ It can be made possible only when rotor no. 1 advances its angular position with respect to No. 2 as shown in figure. where E_1 is shown advanced ahead of E_2 by an angle α,

→ Consequently, resultant voltage E_r is produced which, acting on the local circuit sets up a current I_{sy} which lags by almost 90° behind E_r but is almost in phase with E_1.

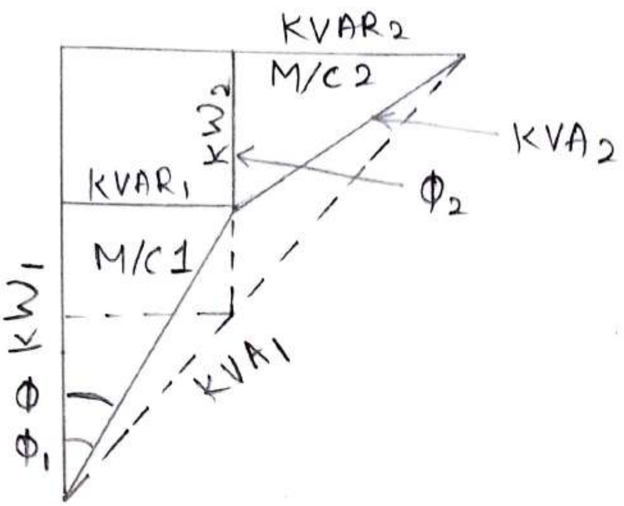


Equal excitations
Equal steam supply
Equal speeds



Equal excitation
steam supply - 1 > steam supply - 2
equal speeds

(Effect of change in steam supply)



(Effect of change in steam supply)

→ Hence power per phase of No. 1 is increased by an amount = $E_1 I_{sy}$ where as that of No. 2 is decreased by the same amount.

→ I_{sy} has no appreciable reactive component, the increase in steam supply does not disturb the division of reactive power, but it increases the active power output of alternator No 1. and decreases that of No 2 load division, when steam supply to alternator No. 1. increased, is shown in figure.

→ It is found that by increasing the input to its prime mover, an alternator can be made to take a greater share of the load, through at a different power factor.

→ The points worth remembering are
(i) The load taken up by an alternators directly depends upon its driving torque or in other words, upon the angular advance of its rotor.

(ii) The excitation merely changes the p.f at which the load is delivered with out affecting the load so long as steam supply remains unchanged.

(iii) If input to the prime mover of an alternator is kept constant, but its excitation is changed, then KVA components of its output is changed, Not KW.

Problems on load sharing

Problem -1 :-

To identical, 3 phase star connected alternators operating in parallel, share equally to total load of 750 KW of 6000 V. and pf 0.8. The synchronous reactance & resistance of each machine are respectively 50 Ω & 2.5 Ω per phase.
The field of the first alternators is excited so that the armature current is 40 A. lagging.

Find :-

(i) The armature current of the second alternator
(ii) The power factor of each machine.

Given Data :-

Total load = 750 KW

load voltage = 600 V

load p.f = 0.8 lagging

$X_s/ph = 50\,\Omega$

$R_a/ph = 2.5\,\Omega$

$I_1 = 40\,A$

To find :-

$I_2 = ?$

$\cos\phi_2 = ?$

load current $(I_L) = \dfrac{750 \times 10^3}{(\sqrt{3} \times 6000 \times 0.8)}$

$= 90.21$ A

Active component of $I_L = 90.21 \times 0.8$

$I_L = 72.168$ A

Reactive component of $I_L = 90.21 \times 0.6$

$= 54.126$ A

The power supply is unchanged

Active component of both the machine remains the same. $= \dfrac{72.168}{2}$

$= 36.084$ A

Due to variation in excitation of 1st machine the reactive component of load would vary due to Change in excitation.

There fore, Reactive component of 1st machine after changing excitation $= 40^2 - (36.084)^2$

$= 17.261$ A

Reactive component of 2nd machine

$= 54.126 - 17.261$

$= 36.865$ A

$\therefore I_2 = \sqrt{(36.084)^2 + (36.865)^2}$

$= 51.585$ A.

$\therefore \cos\phi_1 = \dfrac{36.084}{40}$

$= 0.9021$ lag.

$\therefore \cos\phi_2 = \dfrac{36.084}{51.585}$

$= 0.699$ lag

Problem - 2 :-

Two 20 MVA, 3ϕ alternators operate in paralle to supply a load of 35 MVA at 0.8 p.f lagging. If the output of one machine is 25 MVA at 0.9 lagging, what is the output and p.f of the other machine ?

Given Data :-

$P_1 = 25$ MVA

Power factor 1 = 0.9 lagging.

Rating of alternators = 20 MVA

No of alternators = 2

Total load = 35 MVA

Load p.f = 0.8 lagging

To find :-

$P_2 = ?$

Power factor 2 = ?

Solcetion :-

load MW = 35 × 0.8

= 28

lad MVAR = 35 × 0.6

= 21

From first machine data,

$\cos\phi_1$ = 0.9 lagging

$\sin\phi_1$ = 0.436 lagging

MVA_1 = 25

we obtain,

$MW_1 = 25 \times 0.9$

$= 22.5$

$MVAR_1 = 25 \times 0.436$

$= 10.9$

From second machine data,

we find,

$MW_2 = MW - MW_1$

$= 28 - 22.5$

$= 5.5$

$MVAR_2 = MVAR - MVAR_1$

$= 21 - 10.9$

$= 10.1$

$MVA_2 = \sqrt{(MW_2)^2 + (MVAR_2)^2}$

$= \sqrt{(5.5)^2 + (10.1)^2}$

$= 11.5$

$\cos\phi_2 = \frac{5.5}{11.5} = 0.478$ (lag.) (Ans)

* **Introduction to synchronous motor :-**

- A synchronous motor is a machine which converts electrical energy in to mechanical energy that rotate at a constant speed equal to synchronous speed.
- An alternator can run as a synchronous motor If A.C supply is given to armature winding and D.C supply is given to the field winding such type of motor is known a synchronous motor.

→ **Some important feature of synchronous motor are given below.**

- It runs either synchronous or not at all
- It runs at constant speed.
- The only way to change the synchronous speed is to change the supply frequency (Since $N_s = \frac{120f}{P}$) where N_s is synchronous speed
- It can not be self stated.

→ **Synchronous motor - General :-**

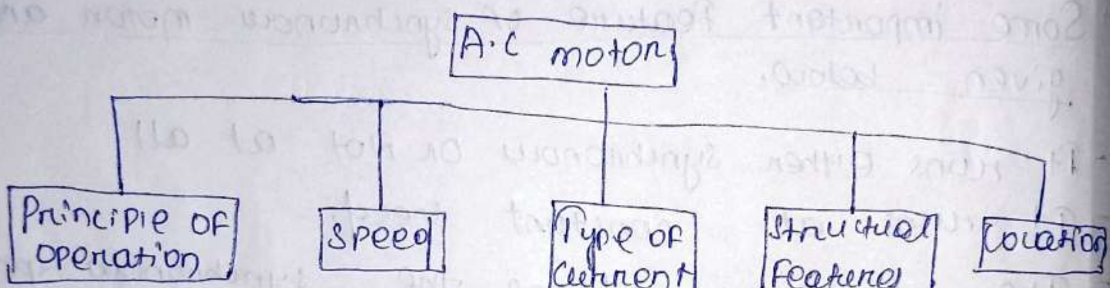
- A synchronous motor figure is electrically identical with an alternator or A.C generator.
- The given synchronous machine may be used, atleast theoretically as an alternator, when driven mechanically or as a motor, when driven electrically, Just as in the case of d.c machines.
- Most Synchronous motor are rated between 150kW to 15MW and run at speed ranging form 150 to 1800 r.p.m.

→ **Some characteristic features of a synchronous motor are worth noting :-**

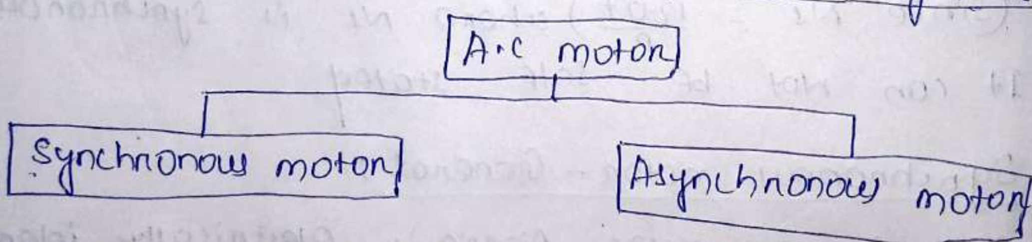
- It runs either at synchronous speed or not at all i.e, while running it maintain a constant speed.
- The only way to change its speed is to vary the supply frequency (because $N_s = \frac{120f}{P}$)
- It is not inherently self starting. it has to be run up to synchronous speed by some means before it can be synchronized to the supply.

→ **Classification of A.C Motors :-**

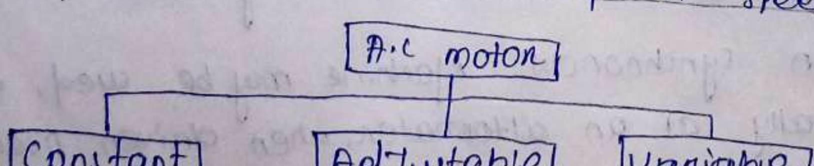
A.C motor are classified based on diffrent factors such as



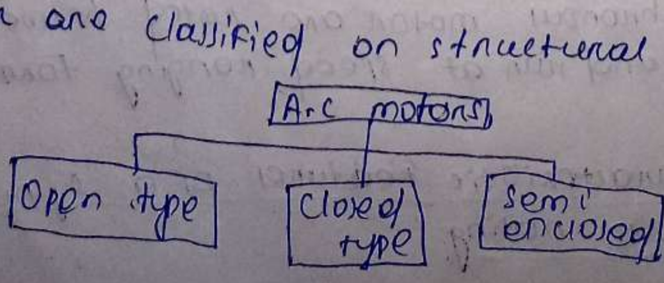
- A.C motor are clissified based on working principle



- A.C motor are classified based in speed.



- A.C motor are classified on structural features.



Classification according to location

- A.C motor
  - Surface type
  - Submersible type

Advantage of synchronous motor :-

- Speed is constant and independent of load.
- power factor can be controlled easily
- motor can work at lagging, leading and unity power factor

Disadvantage :-

- It is not a self starting motor
- It requires D.C ~~excitation~~ excitation.
- Initial cost is very high
- It can not be used for variable speed drives.
- It has a tendency to hunt.

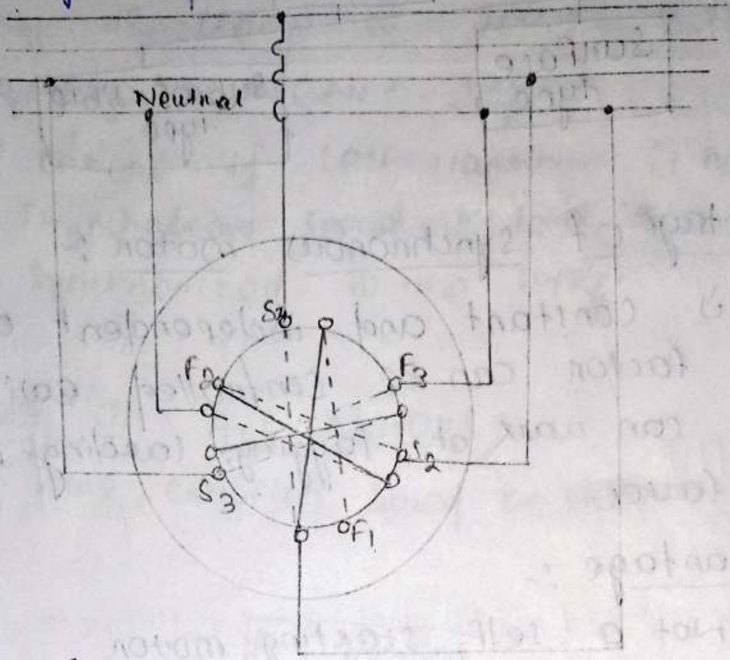
Application of synchronous motor :-

- Constant speed application like clocks, air compressors, centrifugal pumps blower, paper mill and teleprinter.
- Improving voltage regulation of long transmission line.
- Frequency changers.

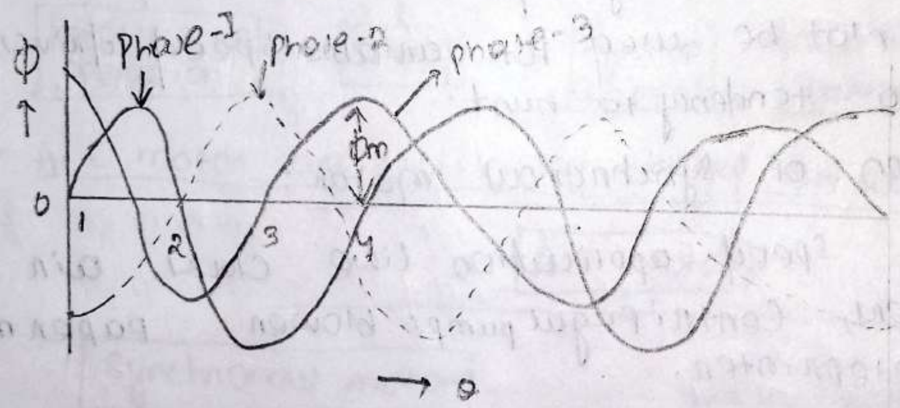
* Production of rotating Magnetic field :-

- The stator of the induction motor has 3-ϕ winding on the inner periphery and are spread be accommodate d in all the slots of the stator.
- The 3-ϕ winding when feed with 3-ϕ current displace in time by 120° they produce a resultant magnetic flux which rotate in a space as through actual magnetic pole where being rotated mechanically, inside the stator.

- A 3-ϕ 2 pole stator having 3 Identical winding placed 120° space degree apart is show in figure

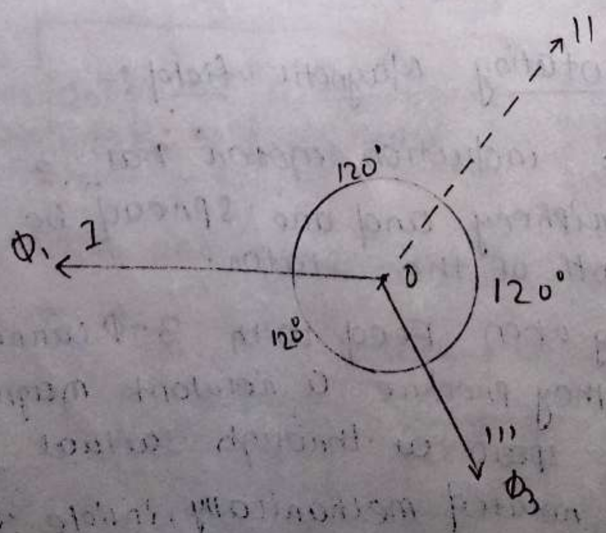


(Three phase 2-pole stator winding)



(Three phase waveform)

- The assumed positive direction of Flux :-



(Vector digram)

- Let the maximum value of flux due to any one the 3ϕ be a ϕ_m
- The resultant flux ϕ_R at any instant is given by the vector sum of the individual flux ϕ_1 and ϕ_2, ϕ_3 due to each of the 3-ϕ at that instant.
- Consider the value of ϕ_R at 4 instant 1/6 time-period apart, corresponding to point marked 0, 1, 2, and 3 shown

when

$$\theta = 0^\circ$$

$$\phi_1 = 0 \quad \phi_2 = \frac{\sqrt{3}}{2}\phi_m, \quad \phi_3 = \frac{\sqrt{3}}{2}\phi_m$$

- The vector for ϕ_2 in a direction opposite to the direction assumed +ve.
- at instant $\theta = 0$ phase 2 is Negative.

Hence,

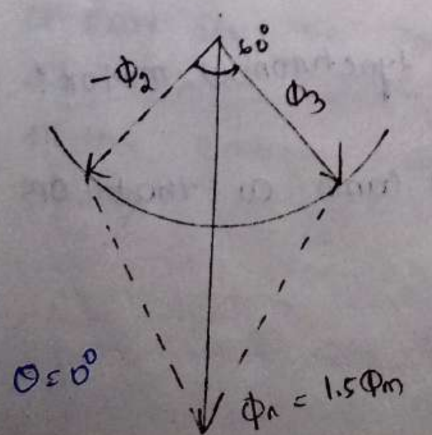
$$\phi_R = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60^\circ}{2}, \quad \phi_R = \sqrt{3} \times \frac{\sqrt{3}}{2}\phi_m = \frac{3}{2}\phi_m$$

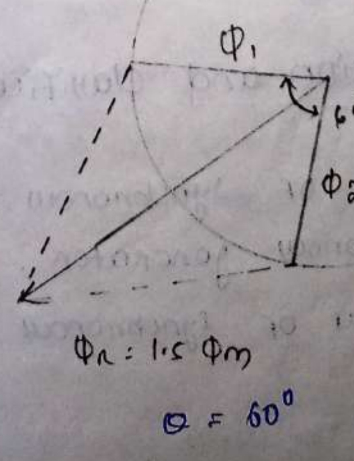
when $\theta = 60^\circ$ point 1 $\quad \phi_{m1} = \frac{\sqrt{3}}{2}\phi_m$

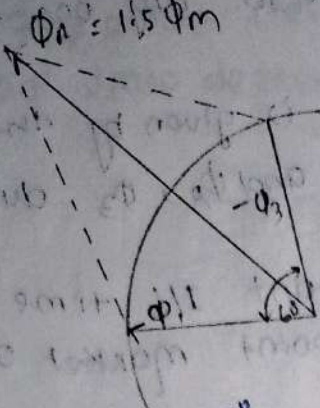
$$\phi_2 = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_R = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos 30^\circ = \sqrt{3} \times \frac{\sqrt{3}}{2}\phi_m = \frac{3}{2}\phi_m$$

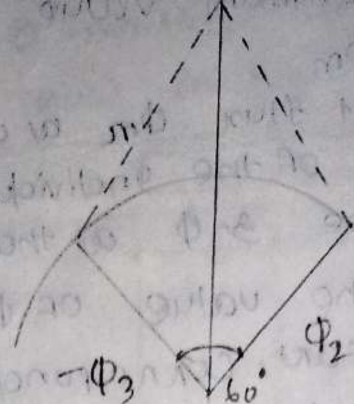
- It is found that resultant flux ϕ_R again has a magnitude $\frac{3}{2}\phi_m$
- But has rotated clockwise through an angle 60°







$\theta = 120°$



$\theta = 180°$

when,

$\theta = 120°$ i.e, corresponding to point 2

$$\phi_1 = \frac{\sqrt{3}}{2}\phi_m, \ \phi_2 = 0, \ \phi_3 = -\frac{\sqrt{3}}{2}\phi_m$$

Proceeding on the same line as for I and II above it can found that.

$\phi_r = \frac{3}{2}\phi_m$ here again resultant flux ϕ_r is the same magnitude.

But has further rotate clockwise through an angle of 60°

$\theta = 180°$ corresponding to point 3

$\phi_1 = 0, \ \phi_2 = \frac{\sqrt{3}}{2}\phi_m, \ \phi_3 = -\frac{\sqrt{3}}{2}\phi_m$ here again resultant flux ϕ_r is the same.

magnitude $\frac{3}{2}\phi_m$

And has rotated clockwise through an additional angle of 60° or through an angle of 180° form the state at $\theta = 0°$

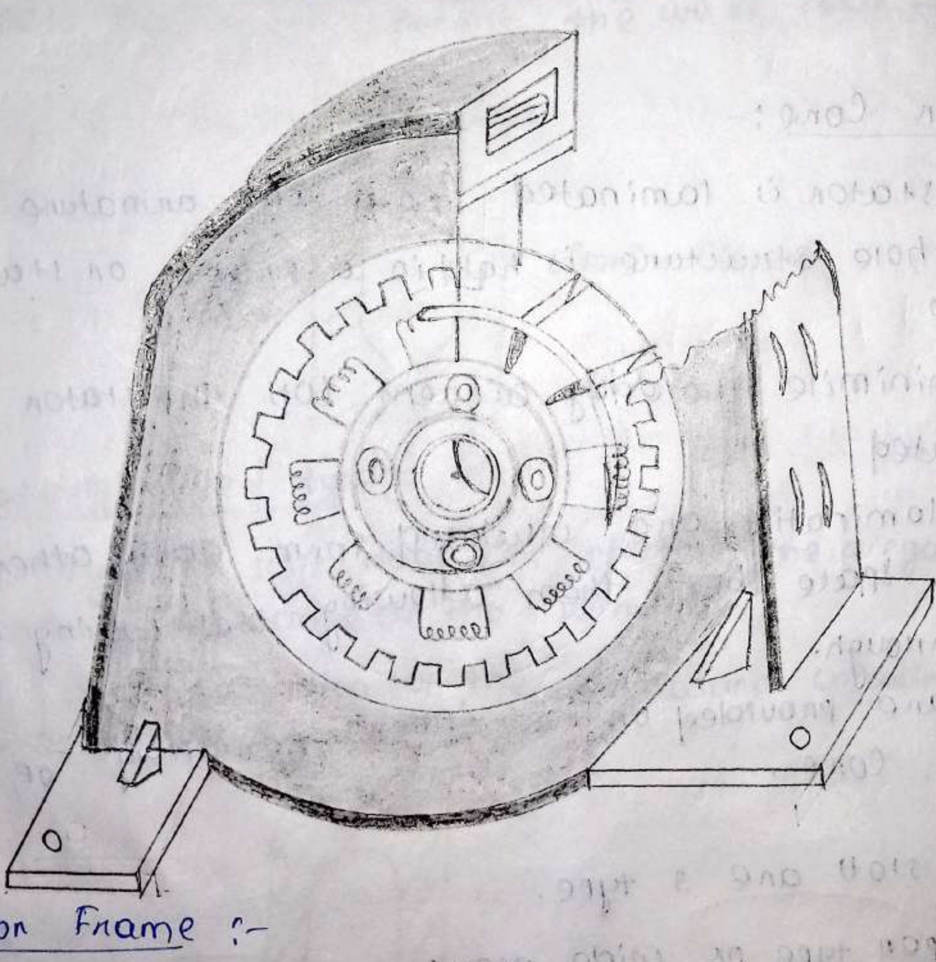
→ Construction and classification of synchronous motor :-

- Construction of synchronous motor is same as that of the synchronous generator
- Major part of synchronous motor.

Staton Frame
Staton Cone
staton winding
] Staton on Anmature.

Magnetic pole and field winding } Field system
Slip ring

Brush and Brush holder
Spider
Exciter
Shaft and bearing
] Rotor



· Staton Frame :-

- It is the outer most part of the machine. It is made of cast iron or cast steel or welded steel plate.
- It is main function is to give mechanical protection to the entire machine and to hold the core in proper position.

Staton Cone :-

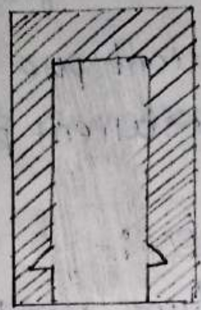
- The staton is laminated like a d.c armature Cone
- The hole structure is held in a frame on staton frame
- To minimise the eddy current loss the staton Cone is laminated
- The lamination are insulated form each other and have space bet^n them allowing the colling air pass through.
- slots are provided on the inner periphery of the staton cone,

These slots are 3 type.

1- Open type or wide open :-

- The open slots are used belowe coil can be form wound and insulated
- The type of slots also facilitate in removal and replacement of defective coil.
- Disadvantage of distributing the air gap flux in to branches of tufts which tend to produce reple

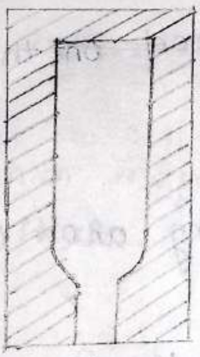
the emf wave.



wide - open type

2. Semi closed type :-

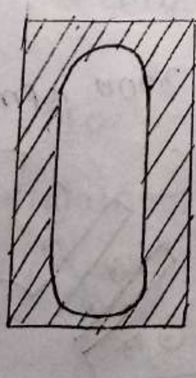
This semi closed type of slots are better in this respect but do not permit the use of form wound coil.



Semi - Closed.

3. Totally closed type:-

- This Type of slots does Not disturb the airgap flux.
- Increase Inductance of the winding.
- The end connection of the armature winding is also complicated.



Totally colsed.

* Rotor :-

- The rotor is a rotating part of alternator. It is mainly used howe the magnetic pole and field winding
- The field excitation is usually provided form a small

Dc. shunt on compound generator.

Rotor classified in to 2 type

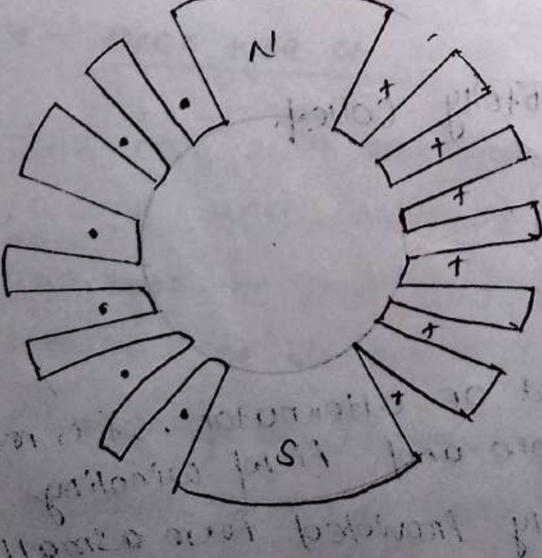
Rotor → Salient pole type
Rotor → NON salient pole type.

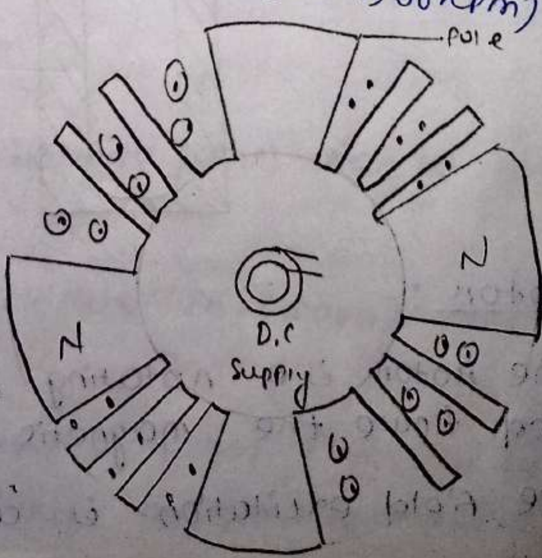
→ Salient pole type rotor :-

- It is used low medium speed alternator.
- The pole are made of steal lamination rivetted togather and are fixed to the rotor. by a dove tail Joint.
- The damper bars are short circuited at both ends by copper ring.
- The field coil are placed on the pole pices as shown in figure.
- The end of field winding are connected to DC source through 2 slip ring.

→ NON-Salient pole or smooth cylindrical type :-

- It is used in very high speed alternator usally driven by steem turbines also called turbo alternator.
- There are of small dyameter and of very long axial length
- less windage loss.
- High spread are optained 3000 rpm (or 1500 rpm)





Slip rings :-

- Usally hand drawn copper is used for manufacturing slip ring.
- The circuit slip ring are mounted on the same shaft.
- Slip ring facilitate the D.C supply to the field winding through brushes.

Brush and brush holder :-

- Brushes are made of carbon and are placed over the slip ring, it is a stationary part.
- brush and brush holder are studied in D.c generator

Spider :-

It is like hub on which magnetic pole are fitted and mounted on the shaft.

Exciter :-

- In alternator the field winding is always required to be excied by a separate D.c supply.

Shaft and bearings :-

- The shaft is made of cast steel.
- Main function is hold the rotor.
- It is support in bearing.

Advantage of stationary armature :-

- It is eary to insulate stationary winding.
- stator winding is Not subjected to centrifugnal forces.
- It needs only 2 slip rings on D.c side.
- The rotor weight is less when compared to stator weight.
- Commutator is Not present.

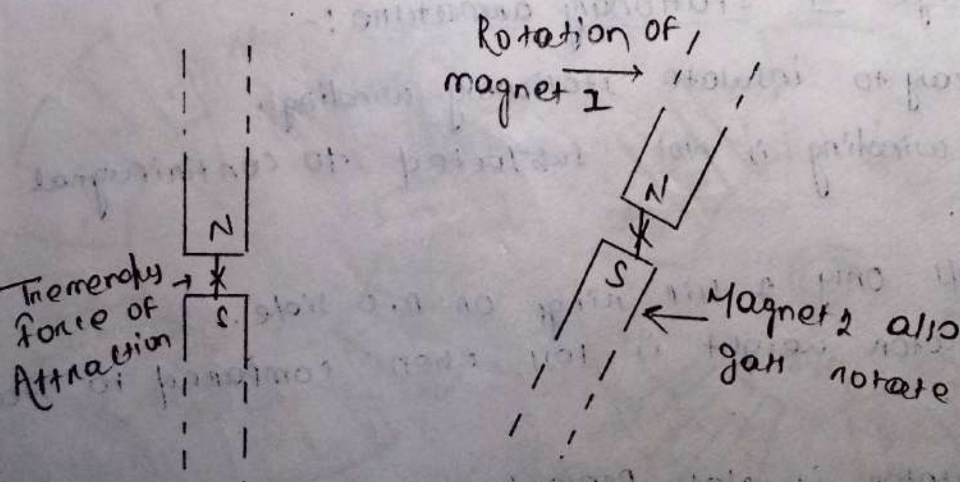
Armature part along with material :-

Sl.No	Name of the part	Material used.
1	Stator frame	cast iron cast steel
2	stator core	Silicon steel or sheet steel,
3	Rotor core	silicon steel
4	stator and rotor winding	Copper
5.	insulation	varnish, paper
6	Slip rings	Hand drawn copper
7	Brushes	Carbon
8	shaft	Mild steel or Carbon steel
	End cover.	Forged steel

Principle of operation

Magnetic locking :-

- Synchronous motor works on the principle of the magnetic locking.
- The 2 unline poles are brought near each other, if the magnet are strong there exist a tremendous force of attraction between those two poles.
- In such condition the two magnets are said to be magnetically locked. due to magnetic locking condition.



- So have the magnetic locking condition, there must exist two unlike pole.

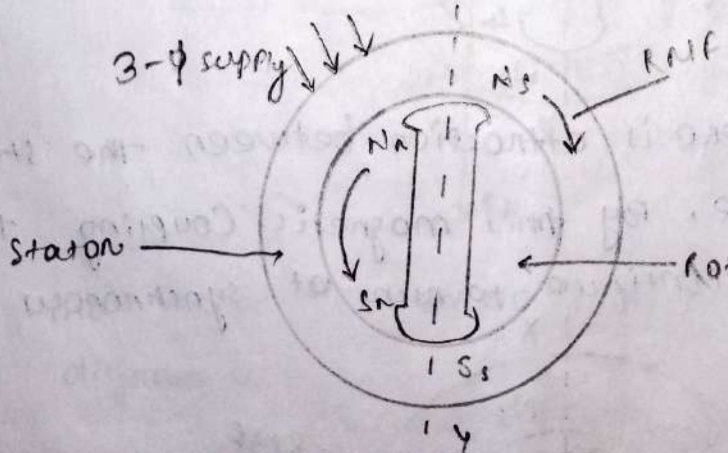
→ Principle operation of synchronous motor :-

- when a balanced 3-ϕ A.C supply is given to a 3 phase stator winding of synchronous motor it produce a rotating magnetic field (RMF)
- The speed of Rotating magnetic field is synchronous speed

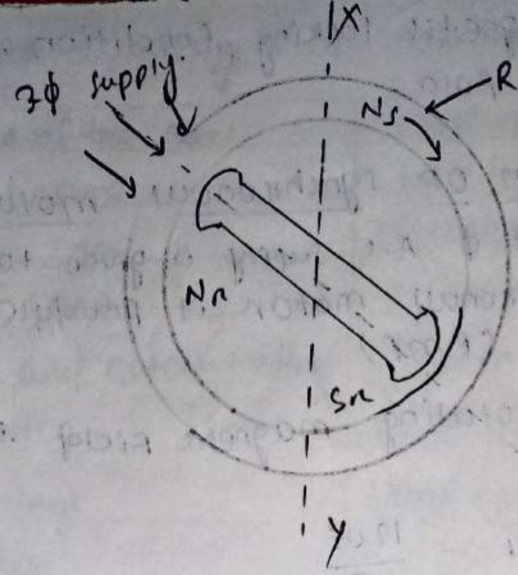
$$N_s = \frac{120f}{P}$$

where
f = supply frequency
P = No of pole in the stator

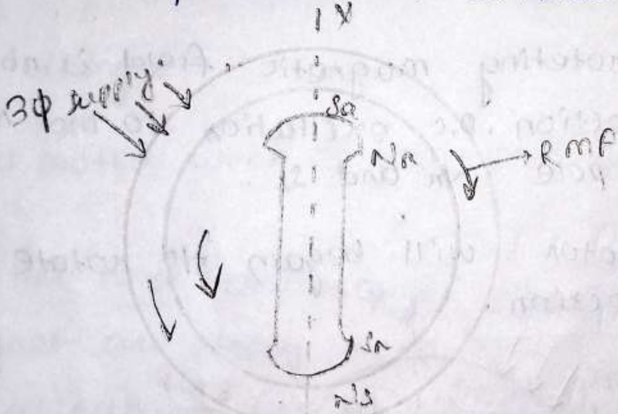
- This rotating field can be considered as a North (N_s) and south pole (S_s) at the stator.
- Assume the rotating magnetic field is rotated in clockwise direction. D.C excitation to the rotor also form rotor pole N_r and S_r.
- Now the rotor will begain to rotate in the anti-clockwise direction.



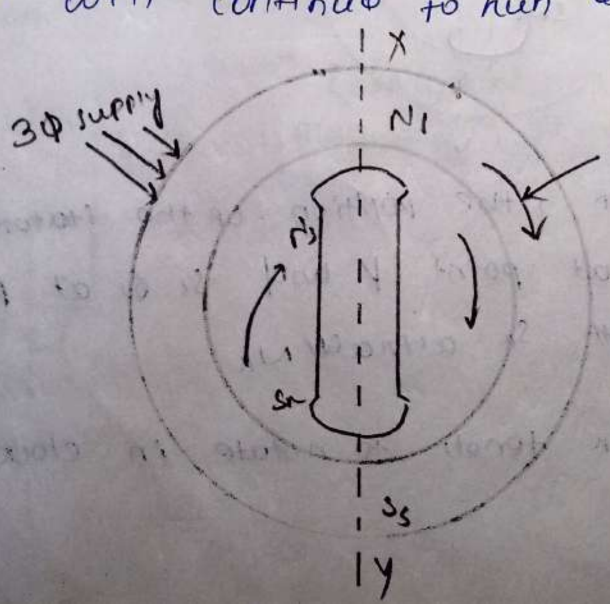
- Half a cycle later, the position of the stator pole increased N_s is at point Y and S_s is at point X
Now N_s attracts S_r attracts N_r
- Hence the rotor tends to rotate in clock wise direction



- Since the repulation and attraction take place in every half a cycle alternatively, the rotor is stationary
- Therefore synchronous motor is not starting.
- Now letus consider the position of stator, rotor
- The stator and rotor pole attracts each other.
-



- Now also there is attraction between the stator and rotor pole. By this magnetic Coupling the motor will continue to run at synchronous speed



Vector digram of synchronous motor

Vector digram of synchronous motor on No load and load

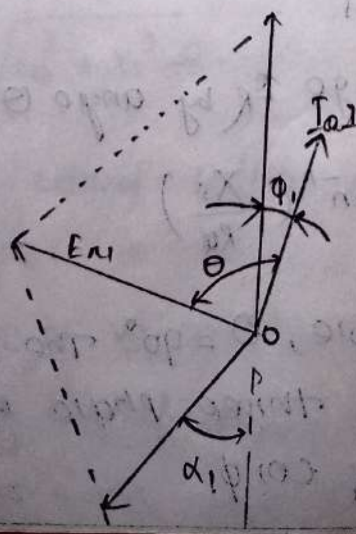
- when the synchronous motor is running on a supply voltage V, back emf is setup in the armature (stator) which oppose the applied voltage.
- This Back e.m.f depends on excitation only as the speed is constant.
- The result voltage in the armature is the vector diff rance of v and Eb.
- The armature current current drawn by the motor $\bar{I}_a = \frac{\bar{V} - E_b}{Z_s}$.

where

Z_s - synchronous Impedance / phase.

- when the motor is running on No load and if it is assumed then the power taken is zero.

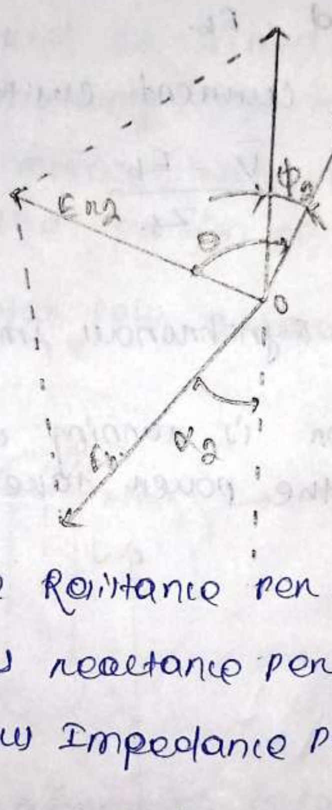
- If the motor is on No load, with its losses, then the digram is



- The vector E_b falls back by a creation angle α_1, so a resultant voltage E_{r1} is produced and hence a current I_{a1} flow through the armature and this current make up the no load -losses.

- If now the motor loaded then its rotor will further falls back by an angle α_2 called the load angle

- Now there resultant voltage E_{r1} is increased to E_{r2} and hence motor draws increased armature current I_{a2}.



Let R_a = Armature Resistance per phase.

X_s = Synchronous reactance per phase.

Z_s = Synchronous Impedance per phase.

Stator Armature Current / phase $I_a = \frac{E_R}{Z_s}$

$$I_a = \frac{V - E_b}{Z_s}.$$

I_a lags the voltage E_R by angle θ.

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$$

- If R_a is Negligible, $\theta = 90°$ The power input for a star connected three phase motor

$$= \sqrt{3}\, V_L I_a \cos\phi.$$

where ϕ is angle between v and I_a.

Analysis of phasor digram:

- Consider a phaser digram with normal excitation i.e such a current through field winding which will produce flux that will adjust magnatude of E_{bph} same as V_{ph}
- Let α be the load angle corresponding to the lode on the motor so form the exact oppositing position of E_{bph} with respect to V_{ph}. E_{bph} gate displaced by angle α.
- Vector difference of E_{bph} and V_{ph} give the phaser with represent $I_a Z_s$ called E_{Rph}.

Now,

$$Z_s = R_a + jX_s \ \Omega$$

$$Z_s = |Z_s| \angle \theta \ \Omega$$

where R_a = Resistance of stator / phase

X_s = synchronous reactance of stator / phase.

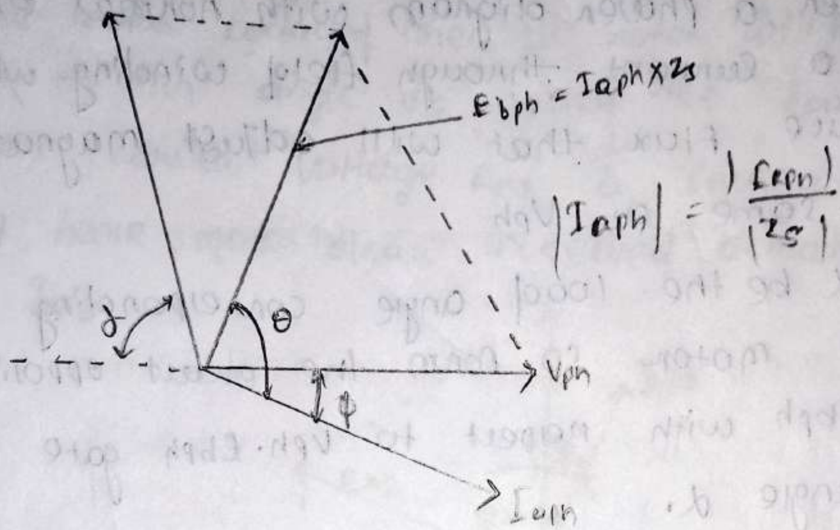
i.e $\theta = \tan^{-1} \frac{X_s}{R_a}$.

and $|Z_s| = \sqrt{R_a^2 + X_s^2} \ \Omega$

- This angle θ is called initial machine angle or an Impedance angle.
- The significance of θ is that it tails that phaser I_{aph} lag behind E_{Rph} i.e; $I_a Z_s$ by angle θ

- Current always lags in inductive impedance with respect to voltage drop across the impedance.

- Practically Ra is very small compared to Xa and hence θ tends to 90°



$\phi = V_{ph} \wedge I_{aph}$

φ = Power Factor Angle.

and

cos φ = power factor at which motor is working

- The nature of this P.F is lagging if Iaph lags Vph angle φ. while it's leading If Iph lead Vph by angle φ. Phasor diagram indicating all the details

→ <u>phasor digram of under excited synchronous motor on load</u>

- The emf induced in the armature Eb.

V = supply voltage

Eb = Back EMF

ER = Resultant V of Eb and V

Ra = Armature Resistance per phase in ohm

Xs = Synchronous reactance per phase in ohm

Synchronous impedance $|Z| = \sqrt{R_a^2 + X_s^2}$

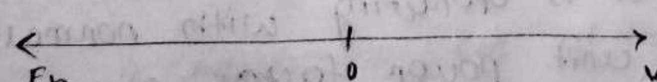
- The armature current I_a lags behind the resultant voltage E_R by an angle θ.

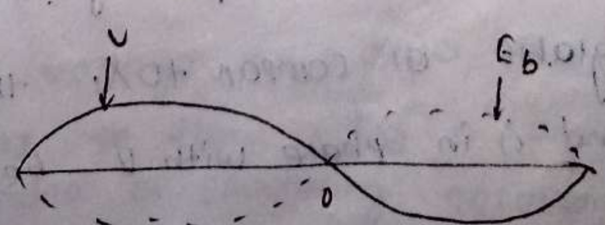
* **Effect of varying load with constant Excitation**

- Before considering as to what goes on inside a synchronous motor it is worthwhile to refer briefly to the d.c motor.
- we have seen that when d.c motor is running on a supply of say, V on rotating a back emf E_b is setup in it armature conductor.
- The resultant voltage across the armature is $(V - E_b)$
  Armature Current $= (V - E_b)/R_a$ flow where R_a is armature ckt resistance.
- The value of depends among other factor. on speed of the rotating armature.
- Motor is Running on No load and has no losses

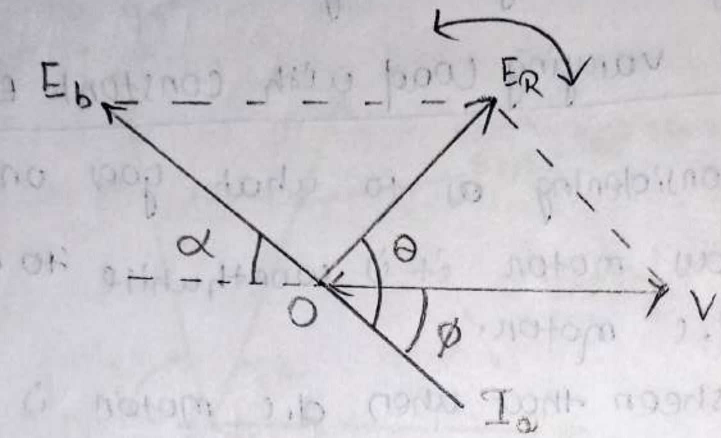
$$E_b = V$$

- It is seen that vector diff of E_b and V is zero. Armature current motor takes (0) zero.

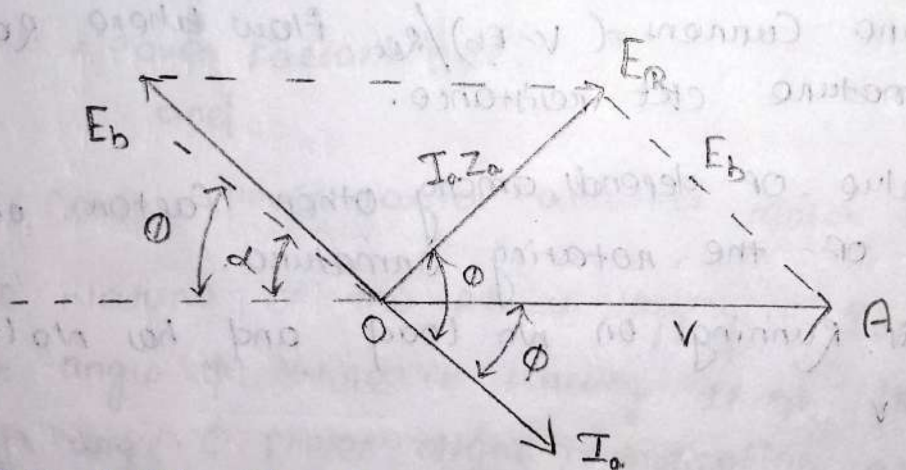




- If motor is on no-load but it has losses vector for E_b falls back.



- If now the motor is loaded its then rotor will further fall back in phase in by a greater value of angle α in the load angle coupling angle

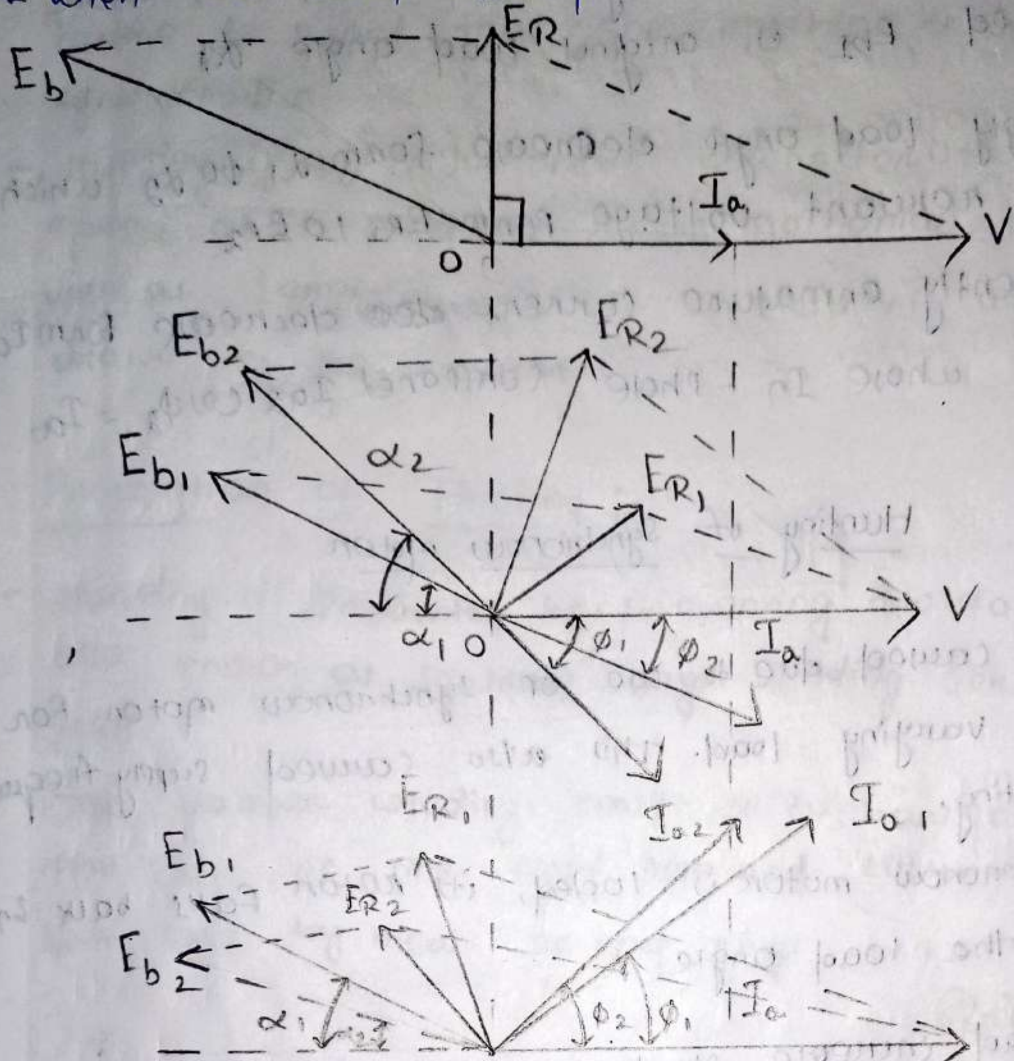


* Effect of changing excitation on constant load

- Synchronous motor is operating with normal excitation ($E_b = V$) at unit power factor given load.
- If Ra is negligible as compare to X_s then Ia lags ER by 90° and is in phase with V because P.F is unity
- The armature is drawing a power of V.Ia per phase which is enough to meet the mechanical load.

on the motor.

- when the load applied the motor remain constant.



Excitation decreased:-

- Back emf is reduce to E_{b1} at the same load angle. α_1

- The resultant voltage E_{R1} cause a lagging armature current I_{a1} to flow. I_{a1} is larger than I_a in magnitude incapable of producing necessary power VI_a for carrying the constant load belowe $I_{a1}\cos\phi_1$ component is less than I_a so that $VI_{a1}\cos\phi_1 < VI_a$

Excitation Increased :-

- The effect of increasing field excitation where increased E_{b1} is original load angle α_1

- Accordingly load angle decrease form α_1 to α_2 which decrease resultant voltage form E_{R1} to E_{R2}

- Consequently armature current decrease form I_{a1} to I_{a2} whose In-phase componed $I_{a2} \cos\phi_2 = I_a$

→ **Hunting of synchronous motor**

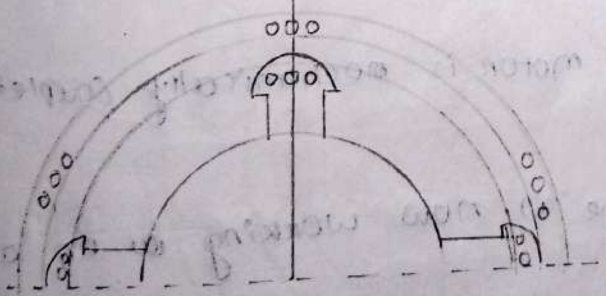
- Hunting is caused due to use of synchronous motor for driving a varying load. This also caused supply frequency is pulsating.
- when synchronous motor is loded, its rotor falls back in phase by the load angle α.
- when load increase slowly angle α also increase so that torque produce is more.
- If Now load in the motor decreases suddenly then α also change corresponding New load.
- But in this process rotor overshoots.
- Due to this rotor start oscillating like a pendulum about its New equilibrium position.
- Like this motor is hunting for the right position when load on the motor changes.
- This also called as phase swinging (or) surging.
- If this frequency of oscillation is equal to the Natural frequency then mechanical resonance

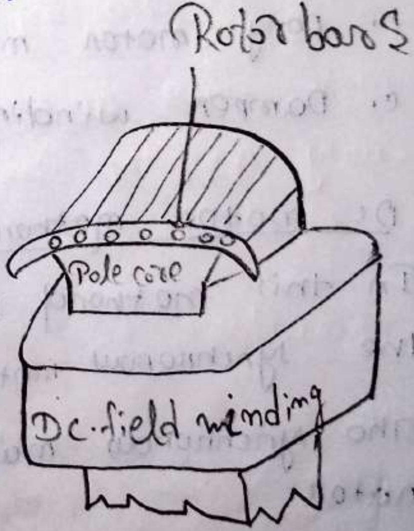
is setup and the amplitude of the swing of the rotor pole relative to the pole of rotating field become so great that the machine thrown out of synchronouism.

- Hunting is an objectionable characteristic of synchronous motor, as it produces severe mechanical stresses as well as large variation in current and power drawn by the motor.

Prevention of Hunting :-

- Hunting is prevented by preventing the damper winding also known as squirrel cage winding (or) damper grids.
- The damper winding consist of cu bars embeded in the face of the field pole and circuited at the both end by means of end rings.





- when the motor is operating at exactly synchronous speed, there is no relative motion betn the rotor and the stator rotating field and so no current is induced in this winding.
- But when hunting takes place, there is a relative motion exist and therefore eddy current are setup

In this winding which flow in such a way to suppress on damp out the oscillation.

- The dampers can not prevent hunting completely because their operation depends upon the presence of oscillation motion.

- However, the damper winding also serves to make the synchronous motor self starting.

Methods of starting :-

Starting methods of synchronous motor :-

- There are the methods for used starting the synchronous motor.

  a. D.C. motor method
  b. pony motor method
  c. Damper winding method.

a. DC motor method :-

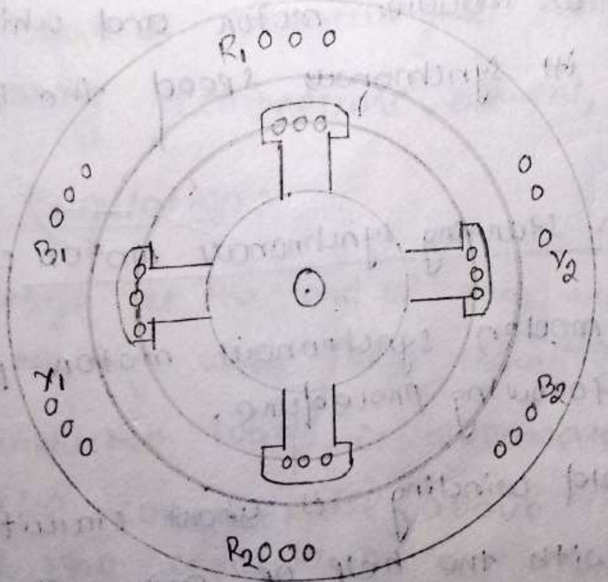
- In this method D.C motor is mechanically coupled to the synchronous motor.
- The synchronous machine is now working as an alternator.
- Its excitation in increase till the e.m.f developed is equal to 3-ϕ supply voltage at the busbar.
- Then the synchronous machine is synchronised with the bus bar.
- At this stages, the D.C. supply to the D.C. motor is

switch off. Now the synchronous machine run as a synchronous motor.

b. Pony motor method :-

- This machine by using a separate small induction motor.
- The small induction motor is called pony motor.
- The help of induction motor to run at the synchronous speed of the synchronous motor.
- To start the synchronous motor the induction motor stated first.
- D.C. supply given to the field winding of synchronous motor.
- The synchronous motor to run at synchronous speed. Tho cut off the supply to the induction motor.

c. Damper winding method :-



- Synchronous motor has salient pole rotor.
- The slots are made on the pole faces.
- copper or aluminium bars are inserted in the slots.

- The bars are short circuited at both ends by copper rings.
- A 3-ϕ supply given to the ~~supply~~ stator.
- The synchronous provided with a damper winding start as induction motor. this will run at a speed near the synchronous speed.
- For this purpose reduce voltage may be applied by an auto T/F

Starting of synchronous motor

- The synchronous motor are required with dampers or squirrel cage winding considering of cu bars embeded in the pole shoes and shortcircuited at both end.
- This motor start readily, acting as an induction motor during the starting period.
- motor starts an as induction motor and while it reachs nearly 95% of its synchronous speed the D.C field is excited.

Procedure for starting synchronous motor :-

- while starting a moden synchronous motor provide with damper winding following procedure.

a. First main field winding is short circuited.

b. Reduce voltage with the help of auto T/F is applied cross stator terminal. The motor startup.

c. Full supply voltage is applied across stator terminal by cutting out the auto T/F.

Synchronous motor application:-

- Synchronous motor find extensive applicatio of follo wing vari of service.

- power factor connecition.
- constant speed, constant load drives.
- voltage regulation.

Power factor Connecition:-

- overexcited synchronous motor having leading power factor are widely used for improving power factor of those factor of those power system which employ a large no of induction motor lagging power factor such as welders and fluorescent light etc.

Constant-speed application:-

- Because of their high efficiency and high speed
- synchronous motor (above 600 r.p.m) are well suited for load where constant speed is required such as centrifugal pump, belt, driven. reciprocating compressors, blowers, line shafts.

Voltage Regulation:-

- The voltage at the end of long transmission line varies greatly especially when large inductive load are present.
- when an inductive load is disconnected suddenly voltage tends to rise considerable above its normal value because of line capacitance.
- By installing a synchronous motor with a field regulator (for varying its excitation) this voltage rises controlled.

- when line voltage decreases due to inductive load motor excitation is increased thereby raising its P.F which compensates for the line drop.
- If on the other hand, line voltage rise due to line capacitive effect, motor excitation is decreased thereby making its P.F lagging which helps to maintain the line voltage at Normal value.

Three phase induction Motor

Introduction :-

→ The induction motor is the most commonly used electrical motor.

→ Induction motor is considered to be the working horse of the industry. More than 85% of industrial motor in use today are induction motor.

→ It is an electro-mechanical energy converter & involves the interchange of energy between an electrical & mechanical system.

→ The primary quantities involved in the mechanical system are torque and speed, while, the analogous quantities with electrical system are voltage and current respectively. as shown fig

Electrical system — Coupling field — Mechanical system

e, i. — T, ωm

e = voltage
i = current

T = Torque
ωm = Speed

(electromechanical energy conversion)

→ The convertion of electrical power to mechanical power takes place in the rotating ... part of electric motor called the rotor.

(1) Why DC motor is called as a conduction motor?

→ In DC motor the electrical power is conducted directly to the armature through brushes & commutator.

(2) Why it is called as Induction motor?

→ In induction motor, rotor does n't recieve power by conduction. But by induction in exctly the same way as the secondary of a two winding T/F receives its power from the primary.

→ An induction motor can be treated as rotating T/F. That is one in which the primary winding is stationary but the secondary winding is free to rotate.

ADVANTAGES OF INDUCTION MOTOR :-

(i) It is very simple & construction & reliable in operation.

(ii) It is self starting.

(iii) It is very rugged, especially cage type. It is requires minimum maintenance.

(iv) Its efficiency is high & power factor is reasonably good.

(v) It is quite cheap in cost.

DISADVANTAGES

(i) Speed decreases with increase in load.

(ii) Starting torque is inferior to that of dc shunt motor.

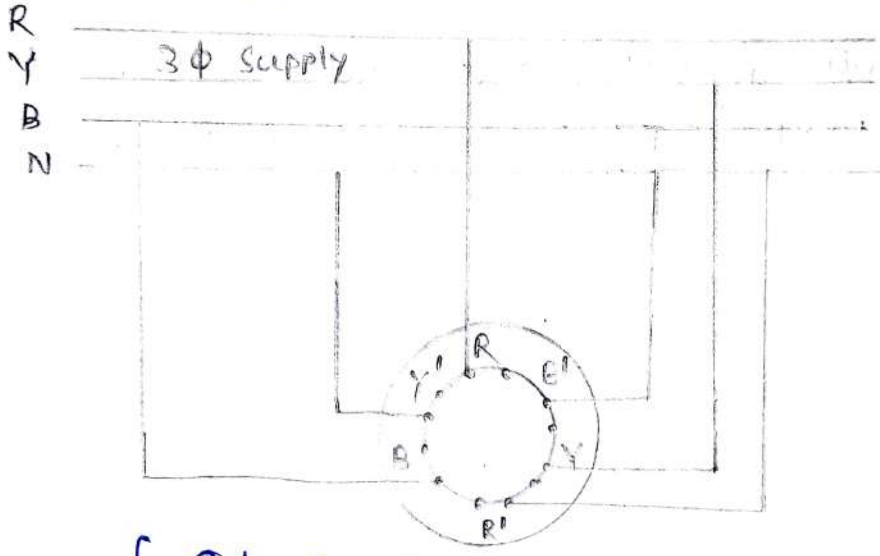
(iii) Methods of its speed control involve more cost.

Production of rotating magnetic field :-

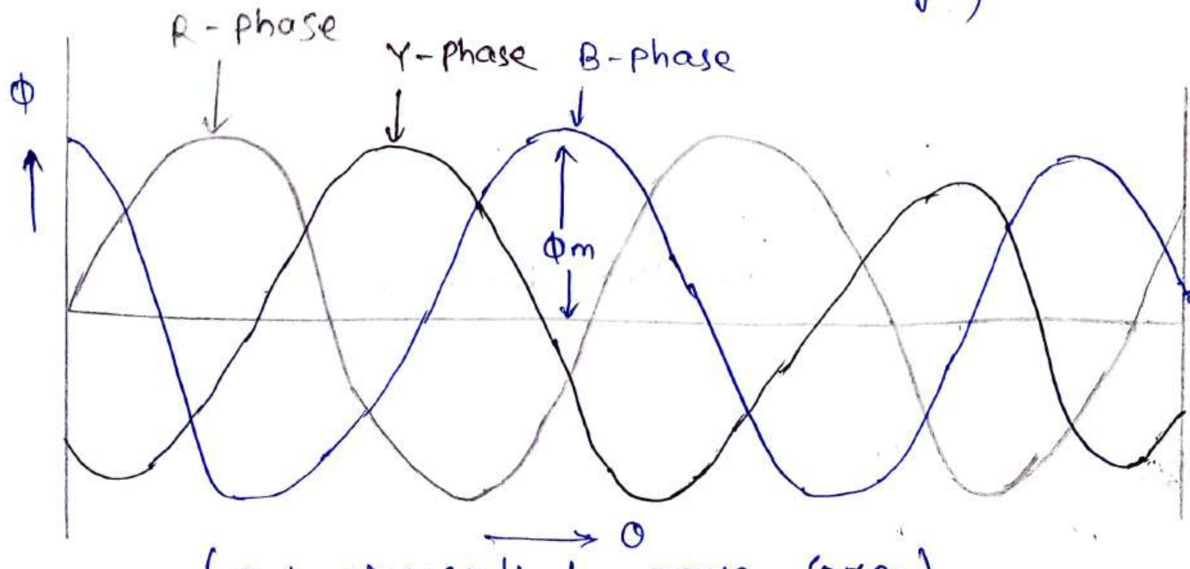
→ The stator of the induction motor has 3 ϕ winding on the inner periphery & are spread to be a accommodated in all the slots of the stator.

→ The 3ϕ winding when fed with 3 ϕ current displaced in time by 120°, they produce a resultant magnetic flux, which rotates in space as thought actual magnetic poles where being rotated mechanically, inside the stator.

→ The 3 ϕ, 2 pole stator having 3 identicall windings placed 120° space degrees a part is show in fig. due to 3 ϕ windings is shown. in bellow fig.



(3ϕ 2 pole stator winding)



(3 ϕ sinusodial wave form)

→ If the phase sequence of the windings is RYB, then mathematically equations for the instaneous values of the 3 fluxes ϕ_R, ϕ_Y & ϕ_B can be wirlitten as

$$\phi_R = \phi_m \sin \omega t$$

$$\phi_Y = \phi_m \sin(\omega t - 120)$$

$$\phi_B = \phi_m \sin(\omega t - 240)$$

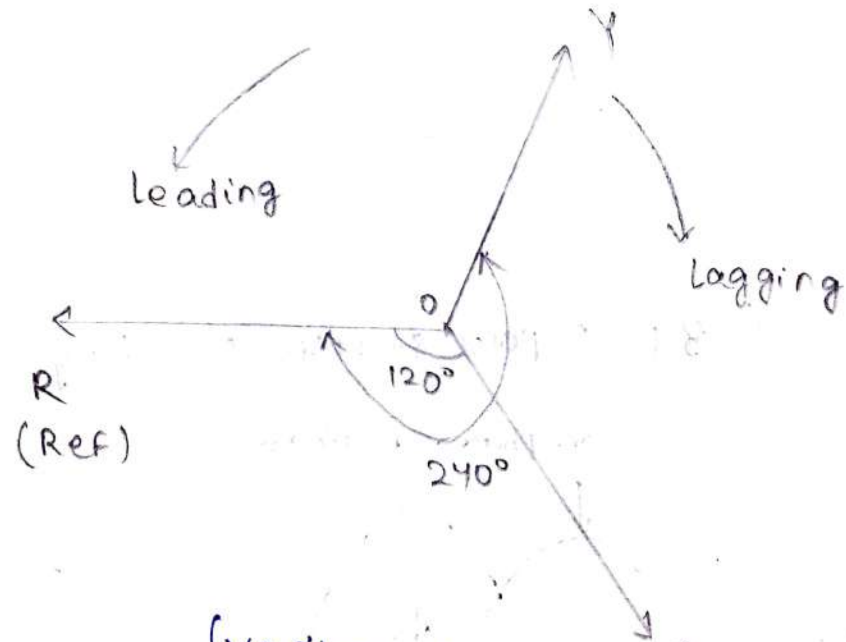
Hence $(\because \omega t = 0)$

$$\phi_R = \phi_m \sin \theta$$

$$\phi_Y = \phi_m \sin(0 - 120^\circ)$$

$$\phi_B = \phi_m \sin(0 - 240^\circ)$$

→ As windings are identical & supply is balanced the magnitude of each flux is ϕ_m.



(vector diagram)

→ Due to phase sequence R-Y-B flux, ϕ_Y lags behind ϕ_R by 120° & ϕ_B lags ϕ_y by 120°. So ϕ_B ultimately lags ϕ_R by 240°.

→ The flux ϕ_R is taken as reference while writing the equation.

→ let ϕ_R, ϕ_y & ϕ_B be the instaneous value of three fluxes. The resultant flux ϕ_r is the phasor addition of ϕ_R, ϕ_y & ϕ_B.

$$\overline{\phi_r} = \overline{\phi_R} + \overline{\phi_y} + \overline{\phi_B}$$

→ let us find ϕ_r at the instant 1, 2, & 3 & 4 as shown in figure which represented the values of θ as 0°, 60°, 120°, 180° respectively.

→ The phasor addition can be performed by obtaining the values of ϕ_R, ϕ_y & ϕ_B by substituting values of θ in the following equations.

$$\phi_R = \phi_m \sin\theta \quad \text{--- (1)}$$

$$\phi_Y = \phi_m \sin(\theta - 120°) \quad \text{--- (2)}$$

$$\phi_B = \phi_m \sin(\theta - 240°) \quad \text{--- (3)}$$

<u>Case - 1 : $\theta = 0°$:-</u>

substituing $\theta = 0°$ in eq^n 1, 2, 3 we get

Eq^n (1) $\phi_R = \phi_m \sin 0°$

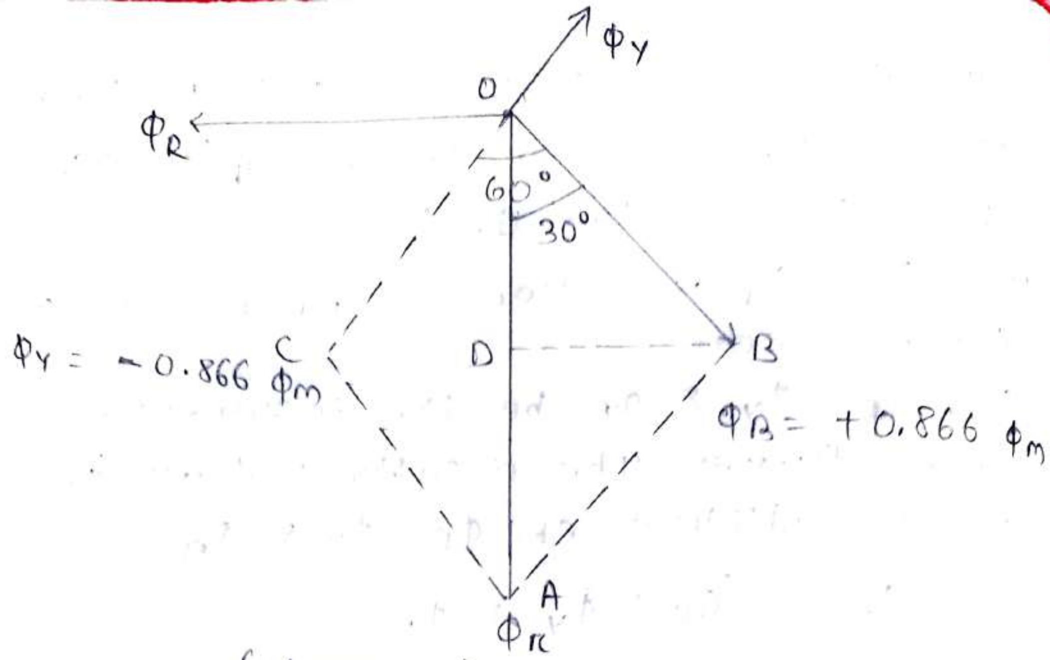
$$\boxed{\phi_R = 0}$$

Eq^n (2)

$$\phi_Y = \phi_m \sin(0 - 120)$$

$$\phi_Y = \phi_m \sin(-120°)$$

$$\boxed{\phi_Y = -0.866\ \phi_m}$$



(Case - 1)

Eqn (3) = $\phi_B = \phi_m \sin(\theta - 240°)$

$\phi_B = \phi_m \sin(-240°)$

$$\boxed{\phi_B = +0.866\,\phi_m}$$

from the above vector diagram $\phi_r = 2 \times OD$ —— (4)

From Δ ODB

$\therefore\ OD = OB \times \cos\theta \quad \left(\because \cos\theta = \frac{OD}{OB}\right)$

$OD = 0.866\,\phi_m \times \cos 30°$

$= 0.75\,\phi_m$ —— (5)

Substituting equation 5 in 4

$\phi_r = 2 \times 0.75\,\phi_m$

$$\boxed{\phi_r = 1.5\,\phi_m}$$

so magnitude of ϕ_r is $1.5\,\phi_m$ & its position is vertically upwords at $\theta = 0°$

Case - 2 : $\theta = 60°$:-

substituting $\theta = 60°$ in eqn 1, 2, 3 we get

Eq-1 $\Rightarrow \phi_R = \phi_m \sin 60°$

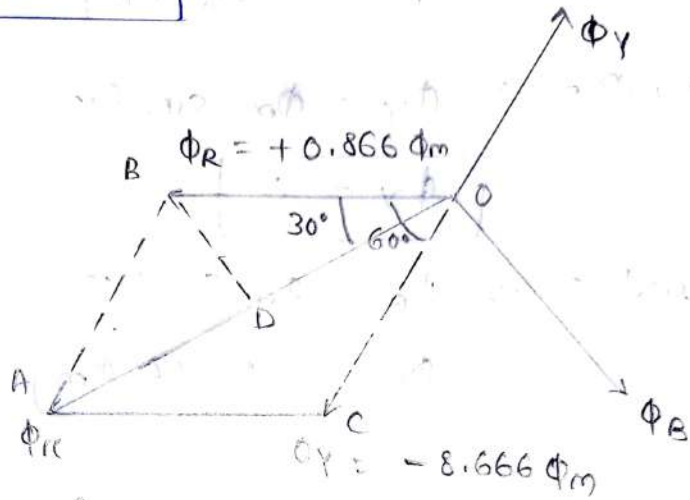
$$\boxed{\phi_R = +0.8666\,\phi_m}$$

$Eq^n\ 2 \Rightarrow \quad \phi_Y = \phi_m \sin(60 - 120)$

$$\boxed{\phi_Y = -0.866\ \phi_m}$$

$Eq^n\ 3 \Rightarrow \quad \phi_B = \phi_m \sin(60^\circ - 240^\circ)$

$$\boxed{\phi_B = 0}$$



(case - 2)

From above vector diagram,

$\phi_R = 2 \times OD$ ——— (6)

From Δ ODB

$\therefore OD = OB \times \cos\theta \qquad \left(\because \cos\theta = \frac{OD}{OB}\right)$

$= 0.866\ \phi_m \times \cos 30^\circ$

$$\boxed{OD = 0.75\ \phi_m} \quad \text{——— (7)}$$

Substitute equ^n 7 in 6

$\phi_R = 2 \times 0.75\ \phi_m$

$$\boxed{\phi_R = 1.5\ \phi_m}$$

- It can be seen that through its magnitude is $1.5\ \phi_m$ it has rotated ~~to~~ through 60° in space, in clockwise direction, from its previous position.

Case - 3 : $\theta = 120°$

Substituting $\theta = 120°$ in equ^n 1, 2, & 3 we g

Equn :- 1 = $\phi_R = \phi_m \sin 120°$ in the equ^n

$$\phi_R = \phi_m \sin 120°$$

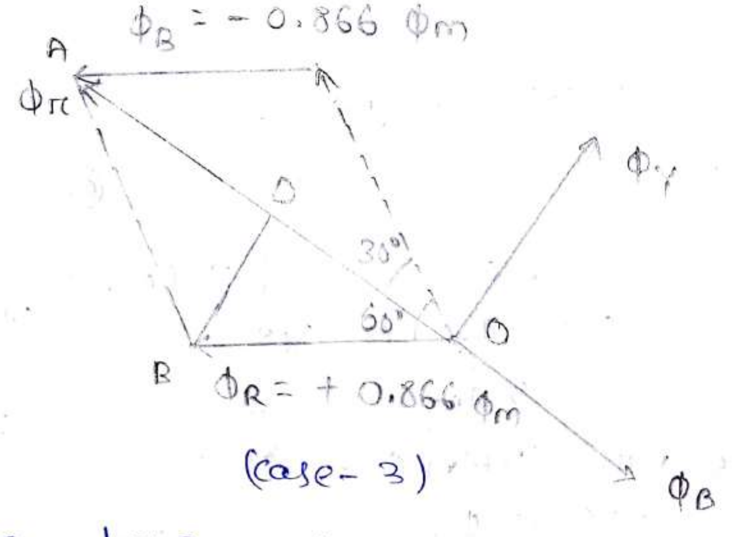
$$\boxed{\phi_R = 0.866\ \phi_m}$$

Equ^n 2 ⇒ $\phi_Y = \phi_m \sin(120° - 120°)$

$$\boxed{\phi_Y = 0}$$

Equ^n 3 ⇒ $\phi_B = \phi_m \sin(120 - 240)$

$$\boxed{\phi_B = -0.866\ \phi_m}$$



(case- 3)

From above vector diagram,

$$\phi_r = 2 \times OD \quad \text{———} (8)$$

From Δ ODB

$\therefore OD = OB \times \cos\theta$ $\quad \left(\because \cos\theta = \frac{OD}{OB}\right)$

$= 0.866\,\phi_m \times \cos 30°$

$OD = 0.75\ \phi_m \quad \text{———} (9)$

substitute equ^n 9 in 8

$$\phi_r = 2 \times 0.75\ \phi_m$$

$$\boxed{\phi_r = 1.5\ \phi_m}$$

The position of ϕ_r is such that it has rotated further through 60° from its perivious position in clock wise direction & from its position at $\theta = 0°$, it has rotated through 120° in space in clock wise direction.

<u>case-4</u> :- $\theta = 180°$

substituting $\theta = 180°$ in equation 1, 2, 3 we get

Equn = 1 $\Rightarrow$ $\phi_R = \phi_m \sin 180°$

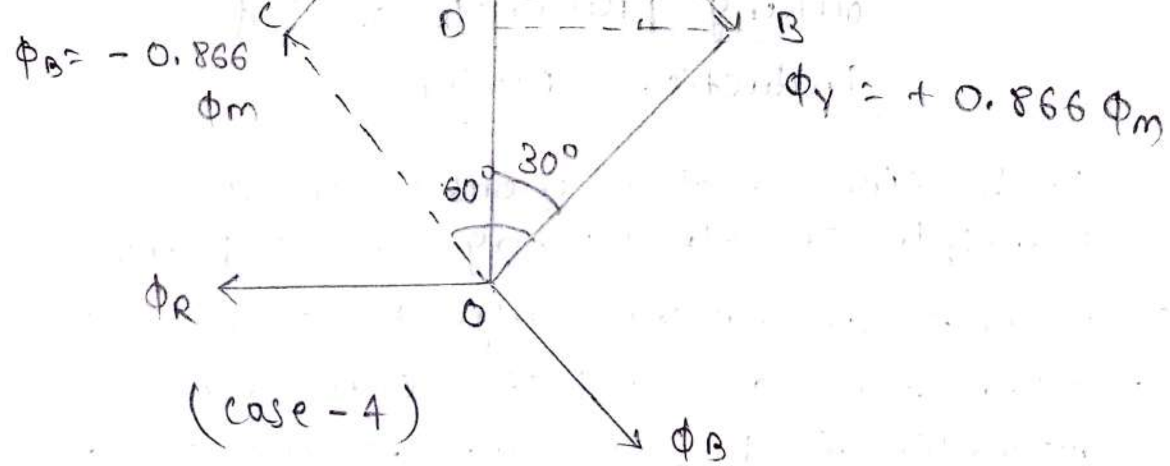
$$\boxed{\phi_R = 0°}$$

Equn = 2 $\Rightarrow$ $\phi_Y = \phi_m \sin(180° - 120°)$

$$\boxed{\phi_Y = +0.866\,\phi_m}$$

Equn 3 $\Rightarrow$ $\phi_B = \phi_m \sin(180° - 240)$

$$\boxed{\phi_B = -0.866\,\phi_m}$$



(case-4)

From above vector diagram,

$$\phi_r = 2 \times OD \quad \text{------} \quad (10)$$

From Δ ODB

$\therefore$ $OD = OB \times \cos\theta$ $\left(\cos\theta = \frac{OD}{OB}\right)$

$OD = 0.866\,\phi_m \times \cos 30$ ——— (11)

$OD = 0.75\,\phi_m$

substitute equation 11 in 10

$\phi_r = 2 \times 0.75\,\phi_m$

$$\boxed{\phi_r = 1.5\,\phi_m}$$

→ So for an electrical half cycle of 180°, the resultant ϕ_r has also rotated through 180°. This is applicable for the winding wound for 2 poles.

Conclusion :-

→ The resultant flux is of constant magnitude $\frac{3}{2}\phi_m$ i.e, 1.5 times the maximum value of the flux due to any phase.

→ The resultant flux rotates around the stator at synchronous speed given by Ns

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

Working principle of 3 ϕ Induction Motor

→ Induction motor works on the principle of electromagnetic induction.

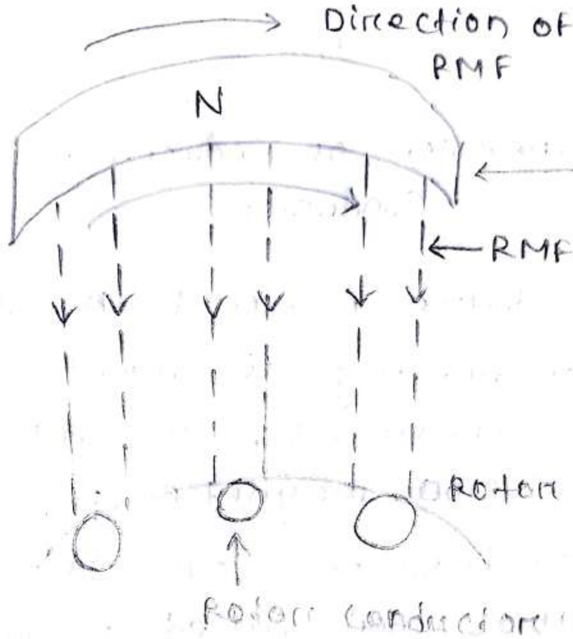
(Q) What is an electromagnetic induction?

→ when ever a conductor cuts across the magnetic field, an emf is induced in a conductor.

Production of Rotating magnetic field :-

→ When a 3 Φ supply is given to the three phase stator winding, a rotating magnetic field of constant magnitude is produced.

→ let direction of Rotation of this RMS is clock wise.



(RMF Produced by stator)

→ The speed of the RMF is known as synchronous speed.

→ It is denoted as Ns in RPM.

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

where,

N_s = Speed of RMF

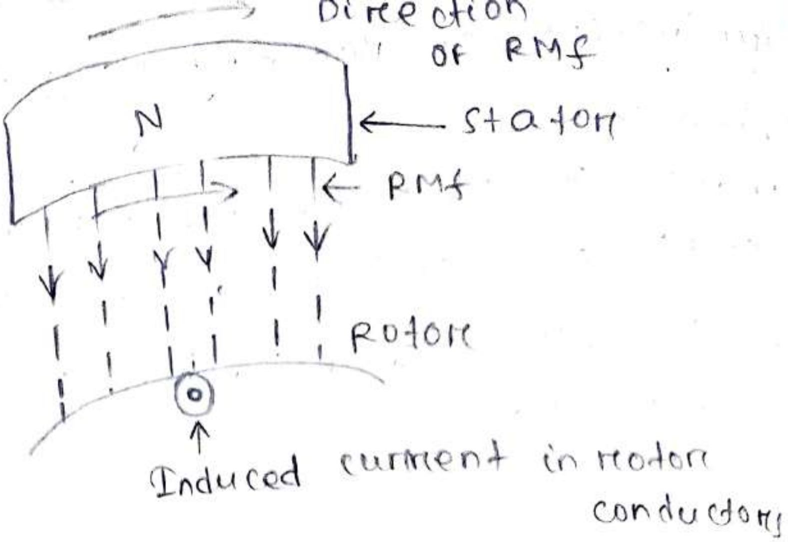
P = Number of poles for which stator winding is wound.

f = Supply frequency

Induced emf in Rotor :-

→ At this instant, rotor is stationary & stator flux is rotating.

→ Now stator flux passes through the air gap sweeps past the rotor surface and so cut the rotor conductor.

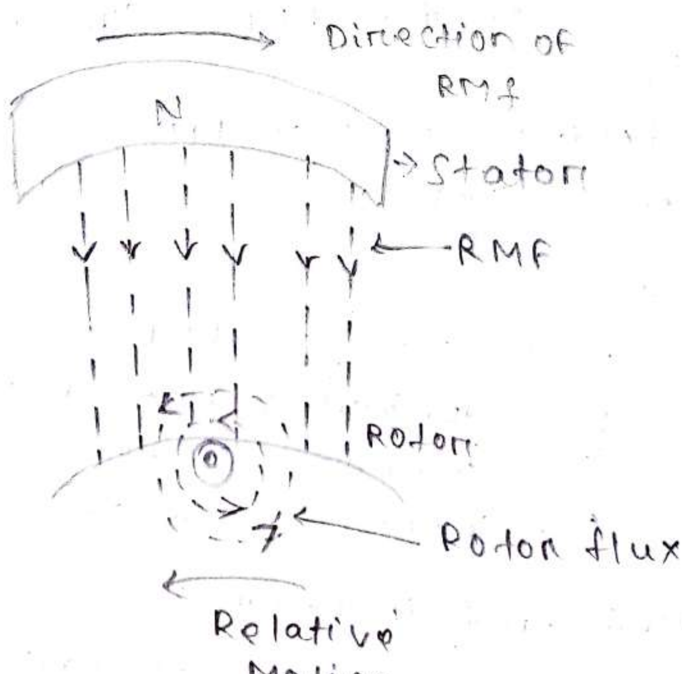


[Direction of induced emf in Rotor Conductor]

→ Due to relative motion betn the rotating flux & stationary conductors, an emf induced in rotor conductors, according to Faraday law of electro magnetic induction.

→ The induced emf circulates the current through the rotor called rotor current.

To Find direction of Rotor flux :-



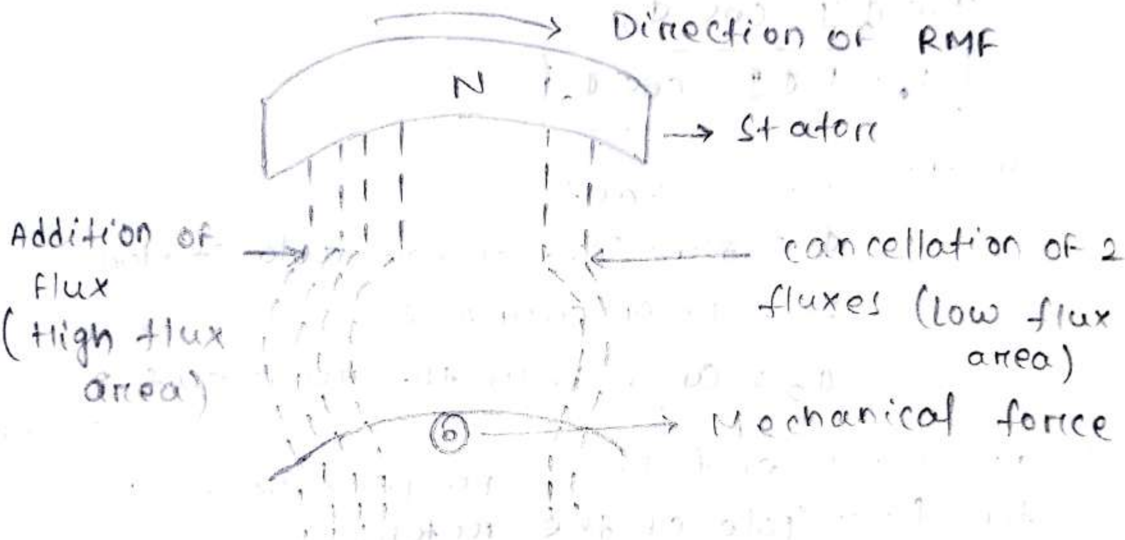
(Direction of Rotor flux)

→ By applying Flemings right hand rule, the direction of induced emf in the rotor is found to following outword.

→ Any current carrying conductor produces its own flux. So rotor produce its own flux is called rotor flux

The setting up torque for the rotating rotor

→ Both the RMF & rotor fluxes interact with each as shown,



(Interaction of two fluxes)

→ On the left of Rotor conductor, two fluxes are in same direction hence add up to get high flux density area.

→ On right side, two fluxes cancel each other to produce low flux density area.

→ As resultant field lines act as a stretched rubber band, high flux density resion exerts a force on conductor two world low density Region, i.e clock wise direction.

→ The direction of force can also be found by flemings left hand rule.

Torque of 3 ϕ Induction Motor :-

Torque equation :-

→ The torque of a 3 ϕ induction motor depends upon three factors namely flux per pole of stator, rotor current & the rotor p.f.

→ The torque in 3 ϕ induction motor is proportional to the product of above parameters.

→ $T \propto \phi I_2 \cos \phi_2$

$$\boxed{T = K \phi I_2 \cos \phi_2}$$

where,
- K = constant
- ϕ = flux / pole of the ~~roto~~ stator
- I_2 = Rotor current
- ϕ_2 = angle betn the rotor emf & rotor current.

→ The rotor emf E_2 is proportional to the flux / pole of the rotor.

Substituting $\phi \propto E_2$ on the equation 1

$$\therefore T \propto E_2 I_2 \cos \phi_2$$

→ $T = K_1 E_2 I_2 \cos \phi_2$ which is of induction motor torque equation.

→ From the above equation it is under stood that, when ϕ_2 increases $\cos \phi_2$ decrease & therefore the torque decrease.

→ When ϕ_2 decrease, $\cos \phi_2$ increase & therefore torque increases.

Starting torque of 3 ϕ induction motor

Assume,

E_2 = Rotor emf / phase at stand still

R_2 = Rotor resistance / phase

X_2 = Rotor reactance / phase

$$Z_2 = \sqrt{R_2^2 + X_2^2}$$

Z_2 = Rotor impedance / phase at stand still

$$I_2 = \frac{E_2}{Z_2}$$

Rotor current at stand still (I_2)

$$I_2 = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

Rotor power factor,

$$\cos\phi_2 = \frac{R_2}{Z_2}$$

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

Starting torque $T_s = K_1 E_2 I_2 \cos\phi_2$

∴ substitute the value of I_2 & $\cos\phi_2$ on the equation 1

Starting torque (T_s)

$$T_s = K_1 E_2 \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$= \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2}$$

$$= \frac{K_1 E_2^2 R_2}{Z_2^2}$$

→ When the voltage applied to the motor is constant, then ϕ is constant & there by E_2 is constant.

Hence starting torque $T_s = K_2 \frac{R_2}{Z_2^2}$

→ When K_2 is another constant. Here the starting torque of induction motor is directly properetional to rotor resistance.

Starting current I_s :-

let, E_2 = rotor emf / phase at stand still

R_2 = rotor resistance / phase at stand still

X_2 = rotor reactane / phase at stand still

Z_2 = rotor impedane / phase at stand still

$$Z_2 = \sqrt{R_2^2 + X_2^2}$$

At starting rotor current (I_2)

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

Condition to obtain maximum starting torque

we know,

starting torque,

$$T_s = K_2 \frac{R_2}{Z_2^2}$$

$$T_s = K_2 \frac{R_2}{R_2^2 + X_2^2} \quad (\text{since } Z_2^2 = R_2^2 + X_2^2)$$

→ To obtain maximum starting torque, differentiate the torque w.r.t R_2 & equating to zero.

$$\therefore \frac{dT_s}{dR_2} = \frac{d}{dR_2} K_2 \left(\frac{R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow K_2 \left[\frac{(R_2^2 + X_2^2) - R_2 (2R_2)}{(R_2^2 + X_2^2)^2}\right] = 0$$

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

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

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

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

$$\Rightarrow \boxed{R_2 = X_2}$$

→ Hence the maximum starting torque, the rotor resistance is equal to rotor reactance.

Torque of Induction motor under running condition :-

$T \propto E_r I_r \cos\phi_r$ (since $E_r \propto \phi$)

(or) $T \propto \phi_r I_r \cos\phi_r$ ——— ①

Where,

E_r = Rotor induced emf / phase under running condition

$E_r = SE_2$

I_r = rotor current / phase under running condition

$$I_r = \frac{E_r}{Z_r} \quad \text{——— ②}$$

$$Z_r = \sqrt{R_2^2 + (SX_2)^2}$$

Put Z_r & E_r value on Equⁿ ②

$$I_r = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$\therefore \Rightarrow \cos\phi_r = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

∴ under running condition, the equation 1 becomes.

$$T \propto \phi \frac{S E_2}{\sqrt{R_2^2 + (S X_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (S X_2)^2}}$$

∴ By introducing constant K

$$\therefore T = \frac{K \phi S E_2 R_2}{R_2^2 + (S X_2)^2}$$

But $E_2 \propto \phi$

∴ Hence,

$$T = \frac{K_1 S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

Where,

K_1 is another constant $= \frac{3 \times 60}{2\pi N_s}$

(where N_s = syn. speed in rpm)

<u>Condition for maximum torque at Running condition :-</u>

The torque under running condition is

$$T_r = \frac{K_1 S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

→ To get maximum torque, differentiate the torque w.r.t slip & equating to zero.

$$\therefore \frac{d}{ds}\left(\frac{K_1 S E_2^2 R_2}{R_2^2 + (S X_2)^2}\right) = 0$$

$$\Rightarrow \frac{K_1 R_2 E_2^2 \left\{\left[R_2^2 + (S X_2)^2\right] 1 - S X_2^2 \cdot (2S)\right\}}{\left[R_2^2 + (S X_2)^2\right]}$$

$$\Rightarrow R_2^2 + (S X_2)^2 - 2S^2 X_2^2 = 0$$

$$\Rightarrow R_2^2 - S^2 X_2^2 = 0$$

$$\Rightarrow R_2^2 = S^2 X_2^2 \quad \Rightarrow \boxed{R_2 = S X_2}$$

Problem - 1

A 50 Hz, 8 pole induction motor has a full load slip of 4%. The rotor resistance & reactance are 0.01 Ω & 0.01 Ω/phase respectively. Find the ratio of maximum to full load torque & speed at which in maximum torque occours.

Solution :-

No of poles (P) = 8

Frequency (f) = 50 Hz

Synchronous Speed $(N_s) = \frac{120f}{P}$

$= \frac{120 \times 50}{8} = 750$ RPM

Full load slip $S_F = 4\%$

$\Rightarrow S_F = 0.04$

Rotor resistance $(R_2) = 0.01\Omega$/phase

Stand still rotor reactance $(x_2) = 0.01\Omega$/phase

The ratio of max^m to full load torque

$$\frac{T_{max}}{T_{FL}} = \frac{a^2 + S_F^2}{2aS_F}$$

where,

$$a = \frac{R_2}{X_2} = \frac{0.01}{0.01} = 1$$

$$\therefore \frac{T_{max}}{T_{FL}} = \frac{1^2 + (0.04)^2}{2 \times 1 \times 0.04}$$

$= 12.52$

Slip for maximum torque $S_m = a = \frac{R_2}{X_2} = 1$

speed at maximum torque $N_m = N_s(1 - S_m)$

$N_m = 750(1-1) = 0$

$N_m = 0$ (Ans)

Problem - 2 :-

The rotor resistance & stand still reactance per phase of a 3 phase slip ring induction motor are 0.02 Ω & 0.01 Ω respectively. What should be the value of the external resistance per phase to be inserted in the rotor circuit to give maximum torque at starting.

Solution :-

Rotor resistance (R_2) = 0.02 Ω/phase

stand still rotor reactance (X_2) = 0.1 Ω/phase

starting torque $(T_{st}) = T_{max}$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2} = 1$$

$$a^2 - 2a + 1 = 0$$

$$\Rightarrow a = 1$$

let be r the external resistance then $(R_2 + r)$ will be the total resistance.

$$a = \frac{R_2 + r}{X_2} = 1$$

$$r = X_2 - R_2$$

$$= 0.1 - 0.2$$

$$= 0.08 \ \Omega/\text{phase}$$

External resistance to be added

$r = 0.08$ Ω / phase.

Slip torque characteristics of 3 ϕ Induction Motor :-

→ The torque 'T' of a 3 ϕ induction motor is given by

$$T = \frac{K \phi S E_2 R_2}{R_2^2 + (S X_2)^2}$$

where,

ϕ = flux

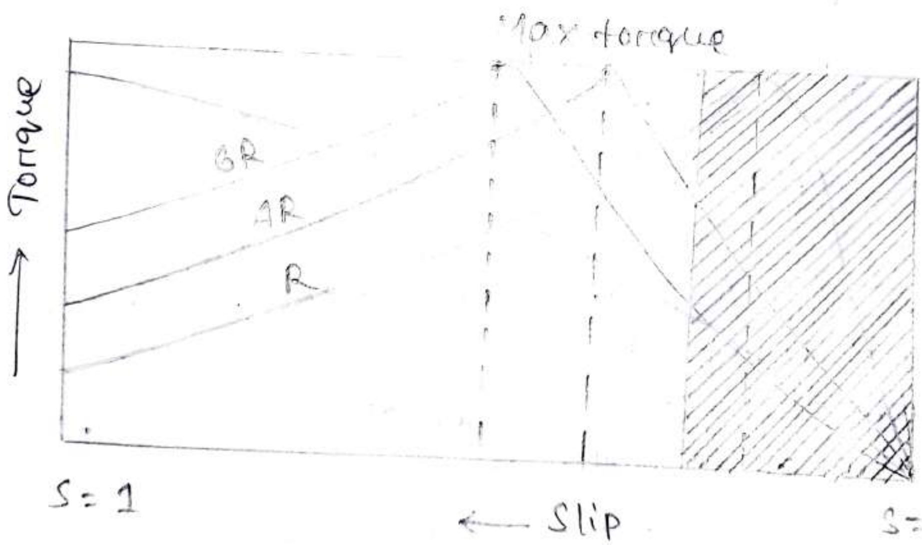
S = slip

E_2 = Rotor induced emf / phase at stand still

R_2 = Rotor resistance / phase

X_2 = Rotor Reactance / phase at stand still

K = a constant



spee

[Speed Torque characteristics of 3 ϕ Induction Motor]

→ The slip torque curve for various ranges of slip with R_2 are drawn.

→ For slip values ranging from 0 to 1 these curve are drawn.

→ Using the above relation, the following cases are considered.

Case-1 :-

→ From the above relation, when $S=0$ then the torque T is also zero. Therefore the curves start from origin (0, 0) as shown in figure.

Case-2 :-

→ When the speed of the rotor is near the synchronous speed, then the slip S value is very small. Therefore the term SX_2 is small.

→ On comparing this value with R_2 the value SX_2 is negligible. Hence the torque eqn becomes

$$T = \frac{K \phi S E_2 R_2}{R_2^2}$$

$$\Rightarrow T \propto \frac{S}{R_2}$$

→ Since ϕ, E_2 are constants. or ; $T \propto S$, If R_2 is constant.

→ From this it is understood that at low value of the slip the torque - slip curve, is more on less a straight line,

Case-3 :-

→ When the load on the motor increases the rotor speed falls down. Then the slip values increases.

→ From the above relation it is seen that when slip 'S' increases the torque 'T' also increases.

→ The torque will attain a maximum value at $s = (R_2/X_2)$. This torque is called pull out or break down or stalling torque.

→ Further increases in load on the motor cause the slip to increase still more.

→ For higher values slip, the term (sX_2) is more in value. Hence at higher values of slip R_2 is negligible as compared to (sX_2)

→ Then the torque equⁿ becomes :-

$$T \propto \frac{K \phi s E_2}{(sX_2)^2}$$

$$T \propto \frac{s}{(sX_2)^2}$$ (since ϕ, E_2 are constant i.e, X_2 is constant)

$$T \propto \frac{1}{s}$$

→ There force for higher of slips the torque slip curve is a rectangular hyperbola.

→ For various values, of R, the family of torque slip curve is as shown in fig.

→ from these curve it is clear that beyond the point of max^m torque, the increased load on the motor results in a decrease in torque developed.

→ Any further more increase in load on the motor results, the motor slowing down & it finally stops.

→ The speed of the motor comes to zero, when the slip reaches to 1.

→ If the load on the motor is too much, the rotor speed comes to zero & it stops. Then slip,

$$s = \frac{N_s - 0}{N_s}$$ & equals to 1.

→ The stable operating region of the motor lies for the slips value s=0 & that corresponding to maximum torque.

→ The operating region is hatched are shown in the figure.

→ The unstable operating region of motor lies for the slip s = 1 that corresponding to maximum torque.

→ From the torque-slip curves, the following points are noticed :-

→ Maximum torque T_{max} remains same & is independent of the rotor resistance.

→ The slip for maximum torque increases with increase in rotor resistance.

→ Starting torque increases with increase in Rotor Resistance.

Construction of 3 Φ Induction Motor :-

→ An induction motor consists of two main parts namely,
(a) stator (b) rotor

rotor consists of two types.
(i) squirrel cage rotor
(ii) phase wound or slip ring motor.

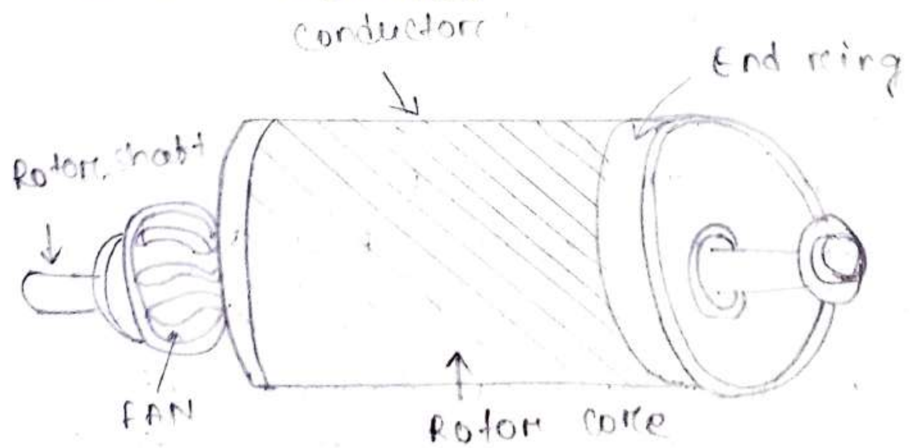
→ The stator construction is same for both the type of induction motor. The difference in both the type of motor is only in the construction of the rotor.

Construction of squirrel cage induction motor :

Motor employing this type of rotor is called squirrel cage induction motor.

squirrel cage rotor :-

→ Almost 90% of induction motors have the squirrel cage type rotors.
→ The rotor is simplest, rugged construction & indestructible.



(squirrel cage rotor)

→ The parts of squirrel cage rotor are
(a) Rotor core
(b) Rotor bars
(c) End ring.

(a) Rotor core :-

→ The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductions.
→ Rotor core is made up of high quality low-loss silican steel laminations & flash enamelled on both sides.

(b) Rotor bars :-

→ The rotor conductors are not wires but they consist of heavy bars of copper, alluminium or an alloy.
→ One bar is placed in each slot.
→ These rotor bars are brazed, electrically welded or bolted to two heavy & stout short circuiting end rings thus giving a rotor that will look like a squirrel cage. Hence the name is squirrel cage motor.

(c) End ring :-

→ All the ends of the copper bars of each sides are short ckted by cu. end rings to form a closed circuit.
→ Hence in this type of rotors, it is not possible to add any external resistance in series with the rotor circuit for starting or speed control.

(ii) <u>Phase wound or slip ring rotor :-</u>

→ The structural details of 3 Φ wound rotor as follows.

(a) rotor core & winding

(b) slip ring

(c) starting resistance.

(a) <u>rotor core & winding :-</u>

→ A wound rotor has a laminated core with slots on its outer surface.

→ These slots carry 3 phase rotor winding which is similar to the stator winding.

→ Both the stator & rotor windings are designed for the same number of poles.

→ The 3 Φ rotor winding is usually star connected.

(b) <u>Slip ring :-</u>

→ The 3 ends of the rotor winding are connected to the slip rings mounted on the motor shaft.

→ So in this type of rotor, the external resistance can be added with the help of brushes & slipring arrangement in series with each phase of the rotor winding.

(c) <u>Starting resistance :-</u>

→ At the time of starting, additional resistance in the rotor CKT is induced to have higher starting torque.

→ When the motor is in running condition the slip rings are short circuited by means of a metal collar which is pushed along the shaft & connects all the slip ring togather,

⇒ At a same time, brushes are also lifted form the slip rings to reduce wear & tear of the brushes due to friction.

Applications of slip ring motor :-

→ High starting torque of induction motor is perferred for

→ Hoists
→ Cranes
→ campress
→ lifts
→ Elevators

Application of squirrel cage motors :-

→ → Blower
→ water pumps
→ Printing machines
→ Drilling machines
→ lathe machines
→ Grinders
→ Driving fans

Slip & slip speed

slip speed :-
The slip speed is defined as the difference between the synchronous speed (Ns) & the actual speed of the motors. (N)

$$\text{slip speed} = N_s - N$$

Slip :-
The slip is defined as the difference betn the synchronous speed (Ns) & the actual speed of the motor (N), expressed as a fractional of synchronous speed.

$$\text{Slip}, S = \frac{N_s - N}{N_s}$$

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

At running condition :-

The actual speed of the motor can be expressed as

$$S = \frac{N_s - N}{N_s}$$

$$\Rightarrow S N_s = N_s - N$$

$$\Rightarrow N = N_s - S N_s$$

$$\Rightarrow N = N_s (1 - S)$$

At start (or) stand still condition $N = 0$

$$\therefore \text{Slip}, S = \frac{N_s - N}{N_s}$$

$$\Rightarrow S = \frac{N_s - 0}{N_s}$$

$$\Rightarrow S = \frac{N_s}{N_s} = 1$$

$\Rightarrow S = 1$ (This is Maximum value of slip)

slip can not be zero :-

when, $S = 0$

$$\Rightarrow S = \frac{N_s - N}{N_s}$$

$$\Rightarrow 0 = \frac{N_s - N}{N_s}$$

$\Rightarrow N_s = N$ (& The torque is zero (0))

Problem :-

A slip ring induction motor runs at 290 rpm at full load when connected to 50 Hz supply. Determine the number of poles & slip.

Soln Given Data

$f = 50 Hz$

full load speed of Motor $N = 290$ rpm

To find :-

Number of poles (P) = ?

Slip (s) = ?

Solution :-

Assume synchronous speed $N_s = 300$ rpm.

Number of poles $(P) = \frac{120f}{N_s}$

$= \frac{120 \times 50}{300}$

$\Rightarrow P = 20$

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

$= \frac{300 - 290}{300} \times 100$

$= \frac{1000}{300}$

$= 3.33\%$

Result

$P = 20$

$S = 3.33\%$

Relationship between rotor input, rotor copper losses & rotor output :-

let P_2 = Rotor i/p

P_c = Rotor copper losses

P_m = Gross mechanical power developed or rotor O/P

T_g = Gross torque developed by the rotor in N-m.

→ The actual torque available at the shaft called as shaft Torque or usefull Torque T_{sh}.

Shaft Torque (T_{sh}) = T_g (Gross Torque) − Torque loss due to friction loss.

→ Now i/p to the rotor is through the air gap with the help of rotating magnetic field which is rotating at a speed of 'N_s' rpm.

→ To rotor i/p can be expressed in terms of gross torque T_g & speed as

$$P_2 = \frac{2\pi N_s T_g}{60} \text{ watts} \quad \text{——} \ (1)$$

→ Now torque developed remains same, but the rotor O/P which is gross mechanical power developed, P_m is at a speed 'N' RPM. So from O/P side we can write

$$P_m = \frac{2\pi N T_g}{60} \text{ watt} \quad \text{——} \ (2)$$

we know that rotor copper losses

$$P_c = P_2 - P_m = \frac{2\pi T_g}{60}(N_s - N) \quad \text{———} \quad (3)$$

Dividing equation 3 by 1, we get

$$\therefore \frac{P_c}{P_2} = \frac{\frac{2\pi T_g}{60}(N_s - N)}{\frac{2\pi T_g}{60} \times N_s}$$

$$\Rightarrow \frac{P_c}{P_2} = \frac{N_s - N}{N_s}$$

$$\Rightarrow \frac{P_c}{P_2} = \text{slip}(s)$$

$$\Rightarrow P_c = S P_2 \quad \text{———} \quad (4)$$

So rotor cu. loss are slip times the rotor i/p.

→ Now gross mechanical power delivered

$$P_m = P_2 - P_c$$

$$\Rightarrow P_m = P_2 - S P_2$$

$$\Rightarrow P_m = (1-s) P_2 \quad \text{———} \quad (5)$$

→ So gross mechanical power developed is $(1-s)$ times rotor i/p.

Dividing equn 4 by 5 we get

$$\frac{P_c}{P_m} = \frac{s}{1-s} \quad \text{———} \quad (6)$$

From the above, it can be concluded that

$$P_2 : P_c : P_m = 1 : s : 1-s$$

Problem

The power i/p to a 3 ϕ induction motor is 60 KW. The total stator losses is 1 Kw. Find the rotor copper loss / phase if the motor is running with slip (s) of 3%.

Solution

Rotor i/p or Stator i/p (Pin) = 60 KW

Total stator losses = 1 KW

slip (s) = 3% = 0.03

Rotor i/p

P_2 = Stator i/p − Stator losses

$\Rightarrow P_2 = 60 - 1$

$\Rightarrow P_2 = 59$ KW

$\Rightarrow P_2 = 59 \times 10^3$ W

Rotor copper losses

$P_C = sP_2$

$\Rightarrow P_C = 0.03 \times 59 \times 10^3$

$= 1170$ W

Rotor copper loss / phase = $\frac{1170}{3} = 590$ W.

Problem :-

The rotor emf of a 3 ϕ, 6 pole, 400 V, 50 Hz induction motor alternaties at 3 Hz. Compute the speed & % slip of the motor. Find the rotor copper loss / phase if the full i/p to the rotor has 111.9 KW.

Solution :-

No. of Poles $(P) = 6$

frequency $(f) = 50 Hz$

synchronous speed $(N_s) = \frac{120f}{P}$

$\Rightarrow N_s = \frac{120 \times 50}{6}$

$\Rightarrow N_s = 1000$ RPM

Rotor frequency $(f_r) = 3 Hz$

Slip $(s) = \frac{f_r}{f} = \frac{3}{50} = 0.06$

% slip = 6%

Motor speed $(N) = N_s(1-s)$

$\Rightarrow N = 1000(1-0.06)$

$\Rightarrow N = 940$ RPM

Rotor i/p

$P_2 = 111.9$ KW

Rotor copper loss

$P_c = sP_2$

$\Rightarrow P_c = 0.06 \times 111.9$

$\Rightarrow P_c = 6.714$

Rotor cu loss /phase $= \frac{6.714}{3}$

$= 2.238$ KW

Rotor cu loss / phase 2.238 KW.

Starting Methods of 3 ϕ induction Motor :-

Starting of induction Motor :-

→ The plain induction Motor is similar in action to a polyphase T/F with a short - CKTed rotating secondary.

→ The normal supply voltage is applied to the stationary motor, then as in the case of a T/F , a very large initial current is taken by the primary, at least for a short while.

→ The exactly similar conditions exist in the case of a D.C motor. If it is thrown directly across the supply lines.

→ Induction motors, when directly switched takes five to seven times their full load current & developed only 1.5 to 2.5 times their full load torque.

→ The initial excessive current is objectionable because it will produced large line voltage drop that it turns, will affect the operation of other electrical equipment connected to the same lines . Hence, It is not advisable to line start motors of rating above 25 KW to 40 KW.

→ The starting torque of an induction motor can be improved by increasing the resistance of the rotor circuit.

→ This can be easily feasible in the case of slip ring motors but not in the case of squirrel cage motor.

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→ The starting torque of an induction motor can be improved by increasing the resistance of the rotor circuit.

→ This can be easily feasible in the case of Slip ring motors but not in the case of squirrel cage motor.

→ The initial inrush of current is controlled by applying a reduced voltage to the stator during the starting period, full normal voltage being applied when the motor has run up to speed.

Direct switching or line starting of induction motor :-

It has been shown earlier that

Rotor i/p $= 2\pi N_s T$

$= KT$

Also,

rotor cu. loss = s × rotor input

$\therefore \quad 3 I_2^2 R_2 = s \times KT$

$\therefore \quad T \propto I_2^2 / s$ (if R_2 is the same)

Now $I_2 \propto I_1$

$\therefore \quad T \propto I_1^2 / s$ (or) $T = K I_1^2 / s$

→ At starting moment :-

$s = 1$

$\therefore \quad T_{st} = K I_{st}^2$

where,

I_{st} = starting current

s_f = full load slip

If, I_f = normal full-load current

Then,

$T_f = K I_f^2 / s_f$

$$\therefore \frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 s_f$$

→ When motor is direct - switched on to normal voltage, then starting current is the short-circuit current I_{sc}.

$\therefore \dfrac{T_{st}}{T_F} = \left(\dfrac{I_{sc}}{I_F}\right)^2 S_f$

$\Rightarrow \dfrac{T_{st}}{T_F} = a^2 S_f$

Where, $a = I_{sc}/I_F$

Suppose in a case

$I_{sc} = 7 I_f$

$S_f = 4\%$

$S_f = 0.04$

Then,

$T_{st}/T_F = 7^2 \times 0.04$

$\Rightarrow T_{st}/T_F = 1.96$

$\therefore$ Starting torque = 1.96 × full - load Torque

→ We find that with a current as greate as seven times the full - load current, the motor develops a starting torque which is only 1.96 times the full - load value.

Types of Stator :-

→ The expression of rotor current it can be seen that the current at start can be controlled by reducing E_2 which is possible by supplying reduced voltage at start or by increasing the rotor resistance R_2 at start.

→ The second method is possible only in case of slip ring induction motors.

→ The various types of starter based on the above two methods of reducing the starting current.

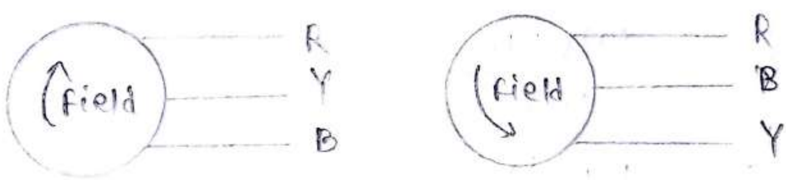
(i) Stator resistance starter starter.
(ii) Auto Transformer starter starter.
(iii) Start - delta starter.
(iv) Rotor - resistance starter.
(v) Direct on line starter.

Plugging in 3 ϕ Inductor Motor :-

→ plugging or reverse current braking condition is achieved by reversing the direction of the field.

→ The direction of rotation of the field in the air gap depends on the phase sequence connections of the stator windings.

→ Effect of ϕ sequence on direction of rotation

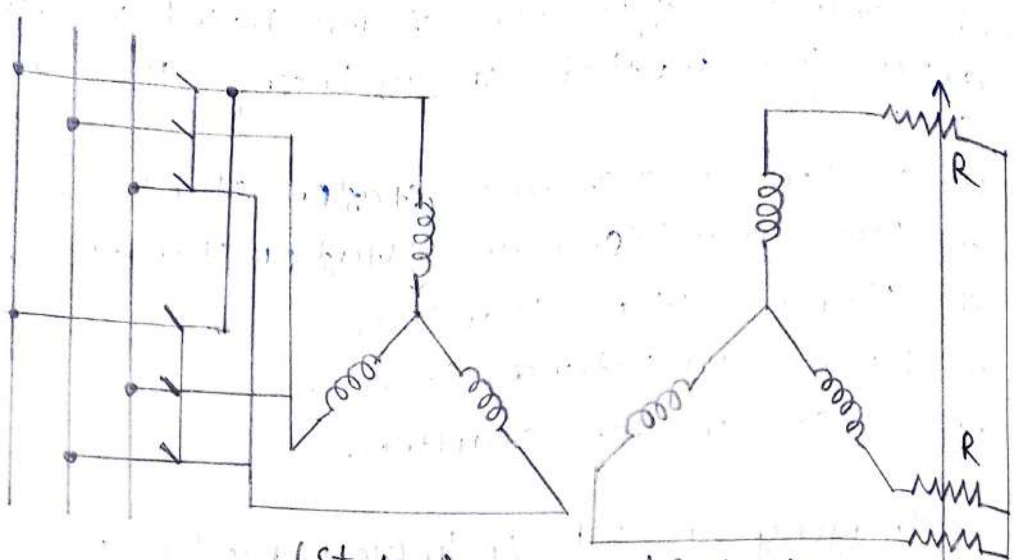


[Effect of ϕ sequence on direction of rotation air gap field]

→ When the 3 ϕ stator windings are connected in the RYB sequence, the air gap field rotate in one direction at synchronous speed.

→ When the sequence of the stator winding is change in RBY the field reverse its direction.

→ The inter changing the supply of any two terminal of the motor as shown fig.



(Connections for plugging of a 3 ϕ induction motor)

→ The rotor & stator magnetic field rotate in opposite directions. Then the slip of the motor is given by:

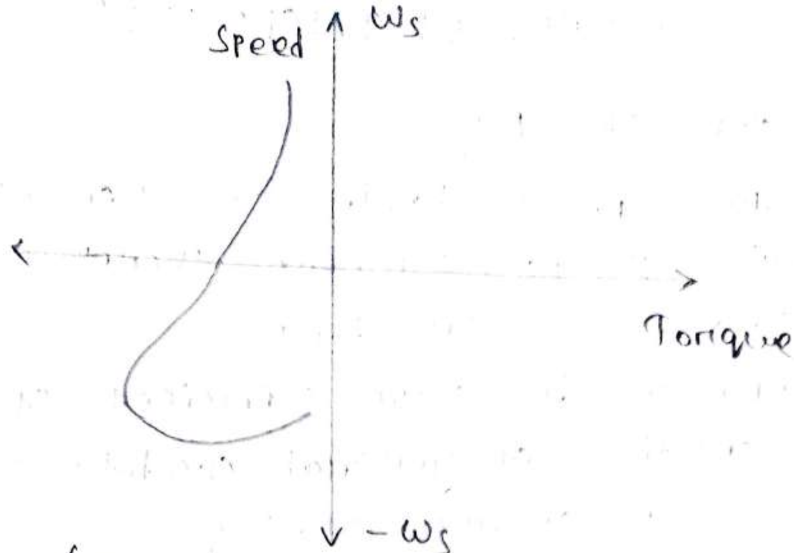
$$S = \frac{\omega_s - (-\omega_s)}{\omega_s}$$

$$\Rightarrow S = \frac{\omega_s + \omega}{\omega_s}$$

$$\Rightarrow S = 1 + \frac{\omega}{\omega_s}$$

→ The slip is more than 1 & full speed it is nearly equal to 2.

→ The speed torque characteristics of the motor during plugging is shown in fig.



(Speed torque characteristics for plugging)

→ The direction of torque developed is reversed and the motor begins to slow down till its speed becomes 'zero'.

→ The motor is disconnected from the supply at this instant, Otherwise the motor will accelerate in the reverse direction in the motoring condition.

→ Plugging is also known Counter current braking.

ADVANTAGES :-

→ Simple control scheme, except for the requirement of a relay to stop the motor.

→ Uniform current loading of all the 3 ϕ during the process of braking.

DIS ADVANTAGES :-

→ Energy loss is high.

→ Increased heating of the machine.

→ Possibility of the motor running in reversed direction in case of malfunctioning of the relay used to stop the motor.

→ Appearance of very high voltages at the slip rings.

TYPES OF ENCLOSURE

(i) Open protected type :-

→ These type are suitable for all ordinary commerical purposes where there is no usual exposure of dust or damp.

→ The end shields have sufficient openings for inspection of general conditions, brushe commutator or the winding.

(ii) Screen protected enclosure :-

→ A motor is said to be totally enclosed when it is so closed in all respect as to prevent air circulation between the inside & outside the case.

→ The figure show the generical view of one such encloser.

(iii) Screen protected encloser :-

→ These are ventilated enclosures having openings in the frame but are protected with a wire screen or with an expended metal or other suitable perforated cover

→ The area of each aperture in the screen or cover would be sufficient for cooling & protection.

→ The figure shows the general view of one such enclosure.

Speed control of 3 ϕ induction motor :-

① **Supply voltage control ;-**

→ We know that $T \propto \dfrac{sE_2^2R_2}{R_2^2+(sX_2)^2}$

Now E_2 the rotor induced emf at stand still depends on the supply voltage V.

$\therefore E_2 \propto V$

Also for low slip region, which is operating region of the induction motor $(sX_2)^2 << R_2$ & hence can be neglected.

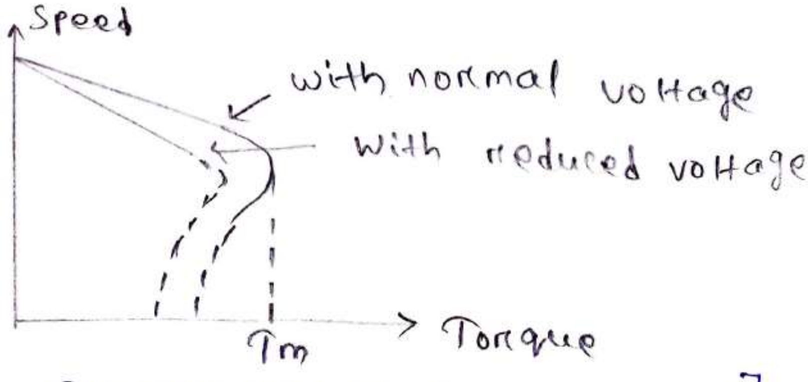
$\therefore T \propto \dfrac{sV^2R_2}{R_2^2} \propto sV^2$ for constant R_2

→ The supply voltage is reduced below rated value, as per equation torque produced also decreases.

→ To supply the same load it necessary to devlop same torque hence value of slip increases so that torque produced remains same.

→ Slip increases means motor reacts by running at lower speed, to decreases in supply voltage so motor produced the required load torque at a lower speed.

→ The speed torque characteristics for the motor using supply voltage control are shown in fig.



[Speed - Torque curves for motor with voltage control]

- In this method, due to reduction in voltage, current draw by the motor increase.
- large change in voltage for small changes in speed is required is the biggest disadvantage. Due to increased current, the motor may get over head.
- Additional voltage changing equipment is necessary. Hence this method is rarely used in practice.

② **Supply frequency control Method :-**

The synchronous speed is given.

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

- Thus by controlling the supply frequency smoothly the synchronous speed can be controlled over a wide range. This given smooth speed control of an induction motor.

But the expression for the air gap flux is given,

$$\phi_g = \frac{1}{4.44\,K_1 T_{ph1}}\left(\frac{V}{f}\right)$$

This is according to the emf equation of a T/F.

Where K_1 = Stator winding

T_{ph1} = Stator turns / phase.

V = supply Voltage

f = Supply frequency.

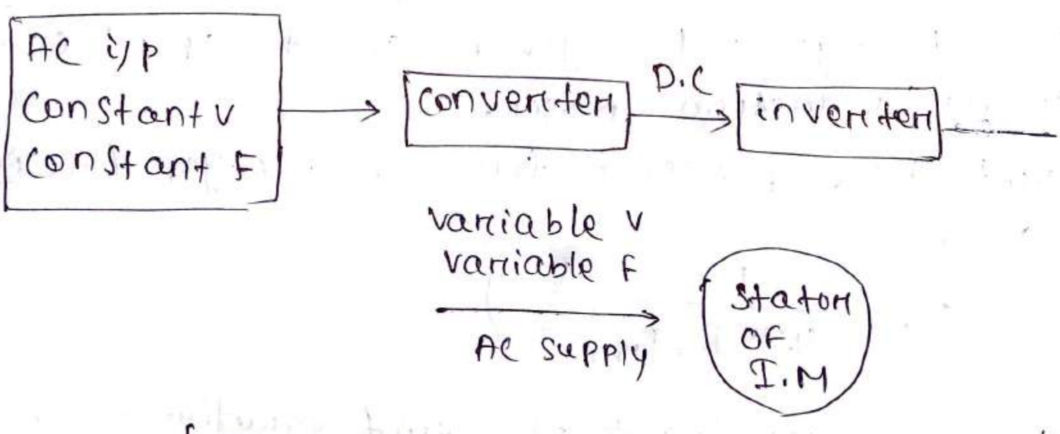
- It can be seen form the supply frequency (f) is changed. The value of air gap flux also gets affected.

→ This may result saturation of stator & rotor cores. Such a saturation leads to sharp increased in the no. load current of the motor.

→ It is necessary to maintain air gap flux constant when supply frequency (f) is change.

→ To achieve this, it can be seen form the above expression that along with f, V also must be changed so as keep (V/F) ratio constant.

→ In this method the supply to the induction motor required is variable voltage variable frequency supply & can be achieve by an electronic scheme using conveter & inverter circuity. This is shown in the figure.



(Electronic scheme for V/F control)

→ The normal supply available is constant voltage constant frequency AC supply. The converter converts this supply in to a D.C supply. This DC supply is then given to the inverter.

→ The inverter is a device which converts DC supply to variable voltage, variable frequency

AC supply which is required to keep V/f ratio constant.

- By selecting the proper frequency & maintaining V/f constant, smooth speed control of the induction motor is possible.

- If f is the normal working f. then the fig. shows the torque slip characteristics for the frequency $f_1 > f$ & $f_2 < f$ i.e, for frequencies above the blow the normal frequency.

- Another disadvantages of this method is that supply obtained can not be used to supply other devices which require constant voltage. Hence an individual scheme for a separate motor is required which makes it costly.