Unit IV Construction, Operation and Voltage Regulation of Synchronous generator

Construction of 3 Phase Alternator or Synchronous Generator

Alternator consists of two main parts, namely the stator and the rotor. The stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated. The output of the machine is taken from the stator. The rotor is the rotating part of the machine. The rotor produces the main field flux.

Stator Construction

The stationary part of the machine is called Stator. It includes various parts like stator frame, stator core, stator windings and cooling arrangement. They are explained below in detail.

Stator Frame

It is the outer body of the machine made of cast iron, and it protects the inner parts of the machine.

Stator Core

The stator core is made of silicon steel material. It is made from a number of stamps which are insulated from each other. Its function is to provide an easy path for the magnetic lines of force and accommodate the stator winding.

Stator Winding

Slots are cut on the inner periphery of the stator core in which 3 phase or 1 phase winding is placed. Enameled copper is used as winding material. The winding is star connected. The winding of each phase is distributed over several slots. When the current flows in a distributed winding it produces an essentially sinusoidal space distribution of EMF.

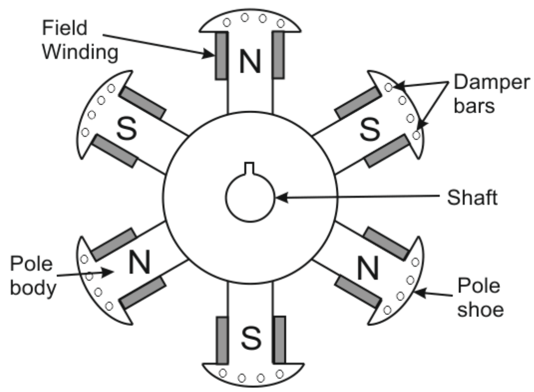
Rotor Construction

The rotating part of the machine is called Rotor. There are two types of rotor construction, namely the salient pole type and the cylindrical rotor type.

Salient Pole (Non cylindrical) Rotor

The term salient means projecting. Thus, a salient pole rotor consists of poles projecting out from the surface of the rotor core. Construction of a salient pole rotor is as shown in the figure. The projected poles are made up from laminations of steel.

- ✓ Salient pole rotors have large diameter and shorter axial length.
- ✓ They are generally used in lower speed electrical machines, say 100 RPM to 1500 RPM.

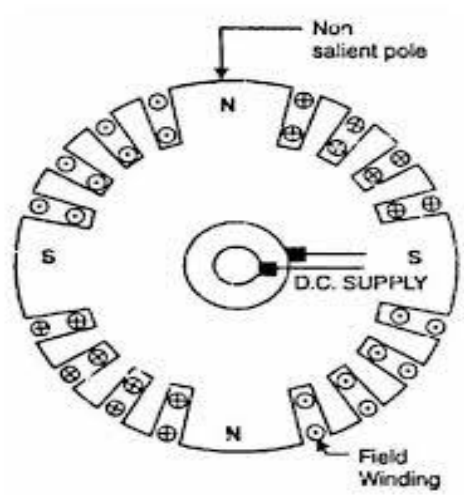


Six pole salient pole rotor

- ✓ Flux distribution is relatively poor than non-salient pole rotor, hence the generated EMF waveform is not as good as cylindrical rotor.
- ✓ Salient pole rotors generally need damper windings to prevent rotor oscillations during operation.
- ✓ Salient pole synchronous generators are mostly used in hydro power plants.

Non-salient pole (cylindrical) rotor

Non-salient pole rotors are cylindrical in shape having parallel slots on it to place rotor windings. It is made up of solid steel. The construction of non-salient pole rotor (cylindrical rotor) is as shown in figure below. Sometimes, they are also called as drum rotor.



- ✓ They are smaller in diameter but having longer axial length.
- ✓ Cylindrical rotors are used in high speed electrical machines, usually 1500 RPM to 3000 RPM.
- ✓ Windage loss as well as noise is less as compared to salient pole rotors.

- ✓ Their construction is robust as compared to salient pole rotors.
- ✓ Number of poles is usually 2 or 4.
- ✓ Damper windings are not needed in non-salient pole rotors.
- ✓ Flux distribution is sinusoidal and hence gives better EMF waveform.
- ✓ Non-salient pole rotors are used in nuclear, gas and thermal power plants.

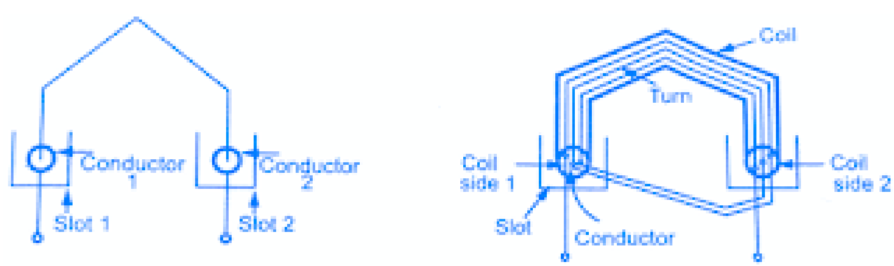
Armature Winding

Armature windings of alternators are different from that of DC machines. Basically, three phase alternators carry three sets of windings arranged in the slots in such a way that there exists a phase difference of 120° between the induced EMF in them. In a DC machine, winding is closed while in alternators winding is open i.e., two ends of each set of the winding are brought out.

In three phase alternators, the six terminals are brought out which are finally connected in star or delta and then the three terminals are brought out. Each set of windings represents winding per phase and induced EMF in each set is called induced EMF per phase denoted as $\mathbf{E_{ph}}$. All the coils used for one phase must be connected in such a way that their EMF helps each other. And overall design should be in such a way that the waveform of an induced EMF is almost sinusoidal in nature.

1) **Conductor:** The part of the wire, which is under the influence of the magnetic field and responsible for the induced EMF, is called active length of the conductor. The conductors are placed in the armature slots.

2) **Turn:** A conductor in one slot, when connected to a conductor in another slot forms a turn. So two conductors constitute a turn. This is shown in the below figure (a).



(a)Turn (b)Multiturn coil

3) **Coil:** As there are a number of turns, for simplicity the number of turns are grouped together to form a coil. Such a coil is called a multi-turn coil. A coil may consist of single turn called single turn coil. Figure (b) shows a multi-turn coil.

4) **Coil Side:** Coil consists of many turns. Part of the coil in each slot is called coil side of a coil as shown in the above figure (b).

5) **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

Key Point: **So 180° electrical is also called one pole pitch.**

Practically how many slots are under one pole which is responsible for 180° electrical, are measured to specify the pole pitch.

For example let us consider 2 poles, 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 for producing a phase difference of 180° between the EMFS induced in different conductors.

This number of **slots/pole** is denoted as **'n'**.

Pole pitch = 180° electrical = slots per pole (no. of slots/P) = **n**

6) **Slot angle (β)**: The phase difference contributed by one slot in degrees electrical is called slot angle As slots per pole contributes 180° electrical which is denoted as 'n', we can write,

$$1 \text{ slot angle} = 180°/n$$

$$\beta = 180°/n$$

In the above example,

$$n = 18/2 = 9, \qquad \text{while } \beta = 180°/n = 20°$$

Note: 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 in between 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.

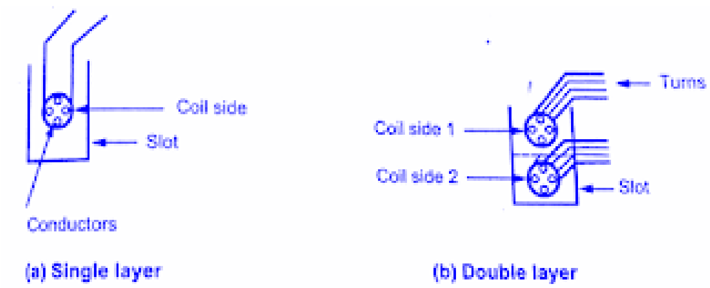
Types of Armature Windings in Alternator

The different types of armature windings in alternators are,

1) Single layer and double layer winding
2) Full pitch and short pitch winding
3) Concentrated and distributed winding

Single Layer and Double Layer Winding:

If a slot consists of only one coil side, winding is said to be a single layer. This is shown in figure (a). While there are two coil sides per slot, one, at the bottom and one at the top the winding is called double layer as shown in figure (b).A lot of space gets wasted in single layer hence in practice generally double layer winding is preferred.



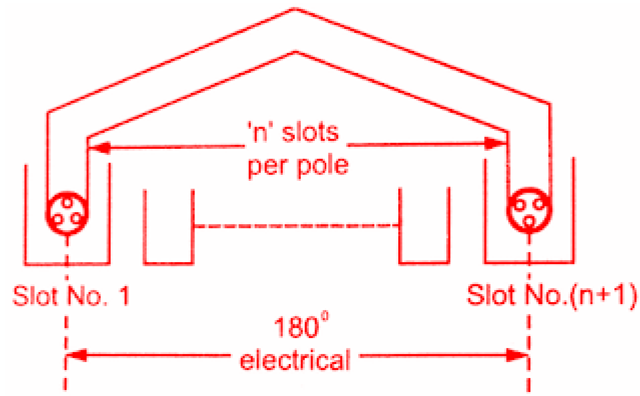
Full Pitch and Short Pitch Winding:

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 if coil side in one slot is connected to a coil side in another slot which is one pole pitch distance away from the first slot, the winding is said to be full pitch winding and coil is called full pitch coil. For example, in 2 poles, 18 slots alternator, the pole pitch is **n = 18/2 = 9 slots**. So if coil side in slot No. 1 is connected to coil side in slot No. 10 such that two slots No. 1 and No. 10 are one pole pitch or n slots or 180° electrical apart, **the coil is called full pitch coil**. Here we can define one more term related to a coil called coil span.

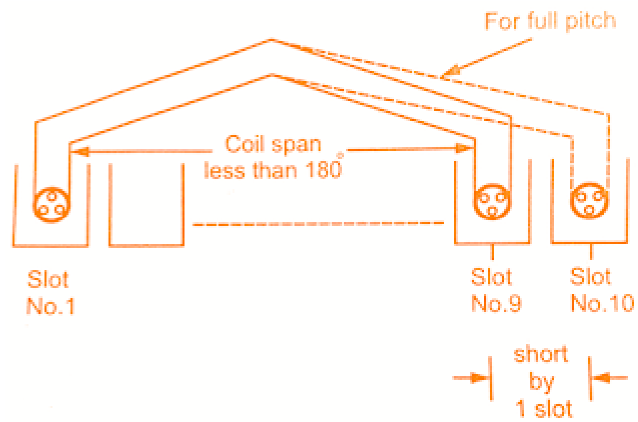
Coil Span:

It is the distance on the periphery of the armature, between two coil sides of a coil. It is usually expressed in terms of number of slots or degrees electrical. So if coil span is **'n' slots or 180°** electrical the coil is called **180° full pitch coil**. This is shown in the figure to left. As against this if coils are used in such a way that coil span is 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.



So in 18 slots, 2 pole alternator instead of connecting a coil side in slot No 1 to slot No.10, it is connected to a coil side in slot No.9 or slot No. 8, the coil is said to be short pitched coil and winding are called **short pitch winding**. This is shown in the below figure.



Advantages of Short Pitch Coils:

In actual practice, short pitch coils are used as it has following advantages,

- ✓ The length required for the end connections of coils is less i.e. the inactive length of winding is less and so less copper is required. Hence economical
- ✓ Short pitching eliminates high frequency harmonics which distort the sinusoidal nature of EMF Hence waveform of an induced EMF is more sinusoidal due to short pitching.
- ✓ As high frequency harmonics get eliminated, eddy current and hysteresis losses which depend on frequency also get minimized. This increases the efficiency

Concentrated and distributed winding:

In three phase alternators, we have seen that there are three different sets of windings, each for a phase. So depending upon the total number of slots and number of poles, we have certain slots per phase available under each pole. This is denoted as 'm'.

m = Slots per pole per phase = n/number of phases

= n/3 (generally no. of phases is 3)

For example in 18 slots, 2 pole alternator we have,

n = 18/2 = 9

Therefore m = 9/3

So we have 3 slots per pole per phase available. Now let 'x' number of conductors per phase are to be placed under one pole. And we have 3 slots per pole per phase available. But if all 'x' conductors per phase are placed in one slot keeping remaining 2 slots per pole per phase empty then the winding is called concentrated winding.

Key Point: So in a concentrated winding, all conductors or coils belonging to a phase are placed in one slot 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 per phase available under every pole, the winding is called distributed winding. So in distributed type of winding all the coils belonging to a phase are well distributed over the 'm' slots per phase, under every pole. Distributed winding makes the waveform of the induced EMF more sinusoidal in nature. Also in concentrated winding due to a large number of conductors per slot, heat dissipation is poor.

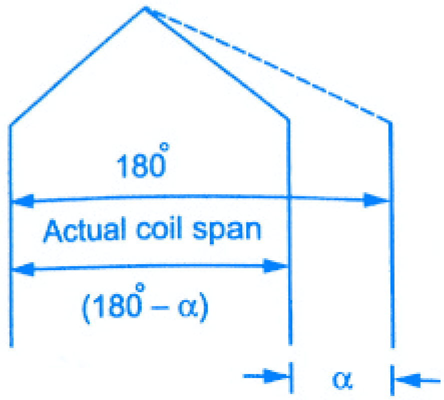
Key Point: So in practice, double layer, short pitched and distributed type of armature winding is preferred for the alternators.

Pitch Factor or Coil Span Factor (K_c):

In practice, short pitch coils are preferred. So 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.

Key Point: *The angle by which coils are short pitched is called angle of short pitch denoted as 'α'.*

α = Angle by which coils are short pitched.



Angle of short pitch

As coils are shorted in terms of the number of slots i.e. either by one slot, two slots and so on and slot angle is β then the angle of short pitch is always a multiple of the slot angle β.

α = β x Number of slots by which coils are short pitched

(or)

α = (180° - Actual coil span of the coils)

It is defined as the ratio of resultant EMF when the coil is short pitch to the result EMF when the coil is full pitched. It is always less than one.

$$K_c = \frac{E_R \text{ when coil is short pitched}}{E_R \text{ when coil is full pitched}} = \frac{2E\cos\left(\frac{\alpha}{2}\right)}{2E}$$

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

Where α = Angle of short pitch

Distribution Factor (K_d):

Similar to full pitch coils, concentrated winding is also rare in practice. Attempt made to use all the slots available under a pole for the winding which makes the nature of the induced EMF more sinusoidal. Such a winding is called distributed winding.

Consider 18 slots 2 pole alternator. So slots per pole i.e. n = 9.

m = Slots per pole per phase = 3

β = 180°/9 = 20°

The distribution factor is defined as the ratio of the resultant EMF when coils are distributed to the resultant EMF when coils are concentrated. It is always less than one.

$$K_d = \frac{E_R \text{ when coils are distributed}}{E_R \text{ when coils are concentrated}} = \frac{2R\sin\left(\frac{m\beta}{2}\right)}{2mR\sin\left(\frac{\beta}{2}\right)}$$

$$\boxed{K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m\sin\left(\frac{\beta}{2}\right)}}$$

Where m = Slots per pole per phase

β = Slot angle = 180°/n

n = Slots per pole

EMF Equation of Alternator

We know that Synchronous Generator or Alternator will generate an EMF. The following is the derivation of EMF equation of Synchronous Generator or Alternator.

Let Φ = Flux per pole, in Wb

P = Number of poles

N = Synchronous speed in RPM

f = Frequency of induced EMF in Hz

Z = Total number of conductors

Z_{ph} = Conductors per phase connected in series

Z_{ph} = Z/3 as number of phases = 3

Consider a single conductor placed in a slot.

The average value of EMF induced in a conductor = $d\Phi/dt$

For one revolution of a conductor,

E_{Avg} per conductor = (Flux cut in one revolution/Time taken for one revolution)

Total flux cut in one revolution is Φ x P.

Time taken for one revolution is $60/N_s$ seconds.

$\therefore$ E_{Avg} per conductor = $\Phi P / (60/N_s)$ …… (1)

$= \Phi P N_s/60$

But $f = PN_s/120$

Therefore $PN_s/60 = 2f$

Substation in (1),

E_{Avg} per conductor = 2 f Φ volts

Assume full pitch winding for simplicity i.e. this conductor is connected to a conductor which is 180° electrical apart. So there two EMFs will try to set up a current in the same direction i.e.

the two EMF are helping each other and hence resultant EMF per turn will be twice the EMF induced in a conductor.

∴ EMF per turn = 2 x (EMF per conductor)

$= 2 \times (2 f \Phi)$

$= 4 f \Phi$ volts

Let T_{ph} be the total number of turns per phase connected in series. Assuming concentrated winding, we can say that a are placed in single slot per pole per phase (So induced EMF's in all turns will be in phase as placed in a single slot. Hence net EMF per phase will be algebraic sum of the EMF'S per turn.

Average $E_{ph} = T_{ph}$ x (Average EMF per turn)

Average $E_{ph} = T_{ph} \times 4 f \Phi$

But in AC circuits RMS value of an alternating quantity is used for the analysis. The form factor is 1.11 of sinusoidal EMF

Form Factor, K_f = (R.M.S.)/Average = 1.11 .... for sinusoidal

∴ R.M.S. value of $E_{ph} = K_f$ x Average value

Therefore, the EMF equation of alternator is given by

$E = 4.44 \times f \Phi T_{ph}$ volts .... (2)

Note: This is the basic EMF equation for an induced EMF per phase for full pitch, concentrated type of winding.

Where T_{ph} = Number of turns per phase

$T_{ph} = Z_{ph}/2$ .... as 2 conductors constitute 1 turn

But as mentioned earlier, the winding used for the alternators is distributed and short pitch hence EMF induced slightly gets affected. Let us see now the effect of distributed and short pitch type of winding on the EMF equation.

So generalized expression for the derivation of EMF equation of Synchronous generator or Alternator can be written as

$$E_{ph} = 4.44 f \Phi T_{ph} K_c K_d \text{ volts}$$

But For full pitch coil, $K_c = 1$ and For concentrated winding $K_d = 1$

Armature Reaction in Synchronous Generator

When the load is connected to the alternator, the armature winding of the alternator carries a current. Every current carrying conductor produces its own flux so armature of the alternator also produces its own flux, when carrying a current. So there are two fluxes present in the air gap, one due to armature current while second is produced by the filed winding called main flux. The flux produced by the armature is called armature flux.

Note: So effect of the armature flux on the main flux affecting its value and the distribution is called armature reaction.

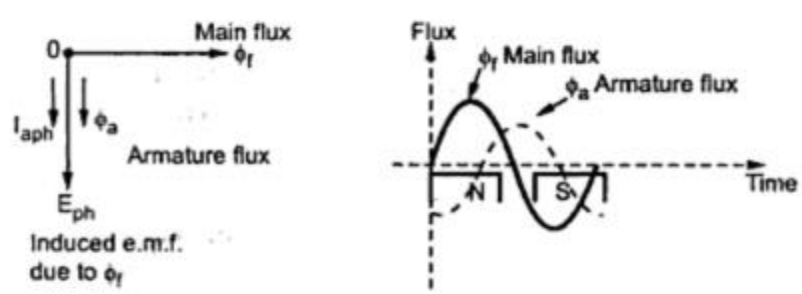
The effect of the armature flux not only depends on the magnitude of the current flowing through the armature winding but also depends on the nature of the power factor of the load connected to the alternator. Now we will study the effect of nature of the load power factor on the armature reaction.

Unity Power Factor Load

Consider a purely resistive load connected to the alternator, having unity power factor. As induced EMF. E_{ph} drives a current of I_{aph} and load power factor is unity, E_{ph} and I_{ph} are in phase with each other.

If Φ_f is the main flux produced by the field winding responsible for producing E_{ph} then E_{ph} lags Φ_f by 90^o. Now current through armature I_a, produces the armature flux say Φ_a. So flux Φ_a and I_a are always in the same direction.

This relation between Φ_f , Φ_a, E_{ph} and I_{aph} can be shown in the phasor diagram. (See Fig.)



It can be seen from the phasor diagram that there exists a phase difference of 90^o between the armature flux and the main flux. The waveforms for the two fluxes are also shown in the above Fig. From the waveforms it can be seen that the two fluxes oppose each other on the left half of each pole while assist each other on the right half of each pole. Hence average flux in the air gap remains constant but its distribution gets distorted.

Note : Hence such distorting effect of armature reaction under unity p.f. condition of the load is called cross magnetizing effect of armature reaction.

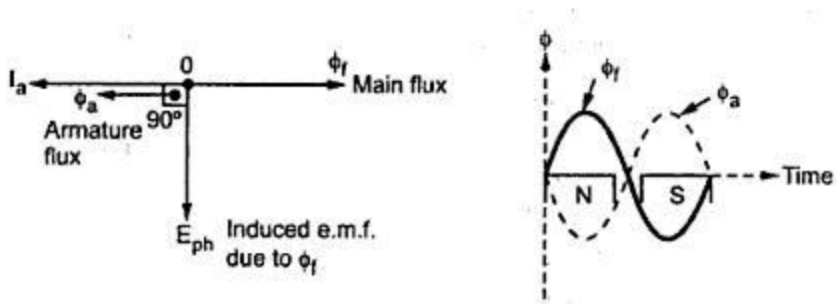
Due to such distortion of the flux, there is small drop in the terminal voltage of the alternator.

Zero Lagging Power Factor Load

Consider a purely inductive load connected to the alternator having zero lagging power factor. This indicates that I_{aph} driven by E_{ph} lags E_{ph} by 90^o which is the power factor angle Φ. Induced EMF E_{ph} lags main flux Φ_f by 90^o while Φ_a is in the same direction as that of I_a. So the phasor diagram and the waveforms are shown in the below Fig. It can be seen from the phasor diagram that the armature flux and the main flux are exactly in opposite direction to each other.

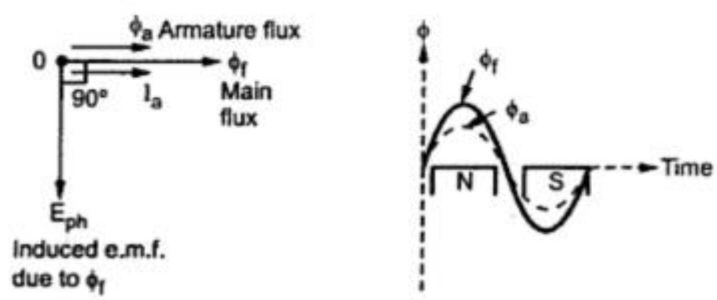
Note: So armature flux tries to cancel the main flux. Such an effect of armature reaction is called demagnetizing effect of the armature reaction.

As this effect causes reduction in the main flux, the terminal voltage drops. This drop in the terminal voltage is more than the drop corresponding to the unity p.f. load.



Zero Leading Power Factor Load

Consider a purely capacitive load connected to the alternator having zero leading power factor. This means that armature current I_{aph} driven by E_{ph}, leads E_{ph} by 90^o, which is the power factor angle Φ. Induced EMG=F E_{ph} lags Φ_f by 90^o while I_{aph} and Φ_a are always in the same direction. The phasor diagram and the waveforms are shown in the below Fig.



It can be seen from the phasor diagram and waveforms shown in the above Fig, the armature flux and the main field flux are in the same direction i.e. they are helping each other. This results into the addition in main flux.

Note : Such an effect of armature reaction due to which armature flux assists field flux is called magnetizing effect of the armature reaction.

As this effect adds the flux to the main flux, greater EMF gets induced in the armature. Hence there is increase in the terminal voltage for leading power factor loads.

For intermediate power factor loads i.e. between zero lagging and zero leading the armature reaction is partly cross magnetizing and partly demagnetising for lagging power factor loads or partly magnetizing for leading power factor loads.

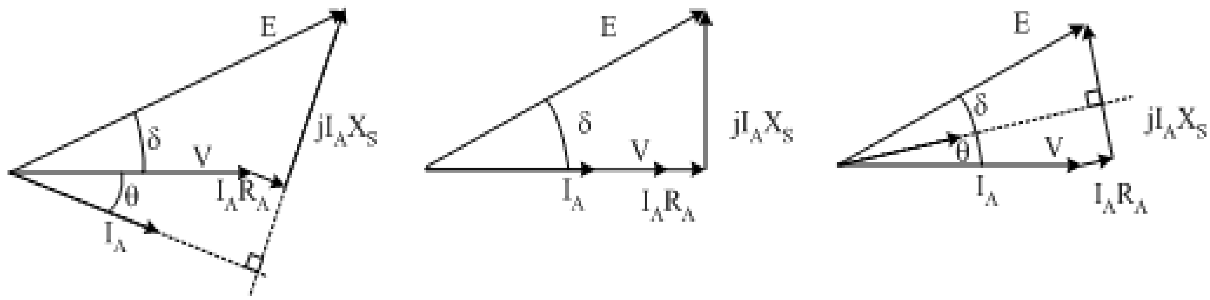
Armature Reaction Reactance (X_{ar})

In all the conditions of the load power factors, there is change in the terminal voltage due to the armature reaction. Mainly the practical loads are inductive in nature, due to demagnetizing effect of armature reaction; there is reduction in the terminal voltage. Now this drop in the voltage due to the interaction of armature and main flux. This drop is not across any physical element. But to quantify the voltage drop due to the armature reaction, armature winding is assumed to have a fictitious reactance. This fictitious reactance of the armature is called armature reaction reactance denoted as X_{ar} Ω/ph. And the drop due to armature reaction can be accounted as the voltage drop across this reactance as $I_{ar} X_{ar}$.

Note: The value of this reactance changes as the load power factor changes, as armature reaction depends on the load power factor.

Phasor Diagram of Synchronous Generator

The phasor diagram is a very significant factor of the power system analysis. As the output of the synchronous generator is alternating current, so it can easily be explained by the phasor diagrams. If we draw the output voltage and current in such a geometrically way that they show some relation among them, the resultant diagram called a phasor diagram.



Lagging Power Factor Phasor Diagram | Unity Power Factor Phasor Diagram | Leading Power Factor Phasor Diagram

In the electrical power system, there are three main types of load first one is resistive, the second one is capacitive and the third one is inductive. We will connect all these three loads with the synchronous generator and will see their effect and will draw their phasor diagram.

The given diagram shows the relation among the parameter like phase voltage (V), internal generated voltage (E), armature current (I_A), synchronous reactance (X_S) and some other factors by phasor diagram when the generator is working with the resistive load and have unity power factor (**Fig. 2**).

$$V = E - jX_sI_A - R_AI_A$$

We can observe from the above-given equation that internal generated voltage (E_A) are will be equal to the phase or terminal voltage of the generator if we deduct the voltage loss due to armature resistance and the synchronous reactance from it.

All these parameters and their facts are shown in an above-given diagram.

In a given diagram (**Fig. 1**), we have construed the phasor diagram of the synchronous generator when it relates to the inductive load, in this case, the power factor will be lagging. There is also a phasor diagram of the synchronous generator when it connected with the capacitive load, in this case, the power factor will be leading (**Fig. 3**).

If we compare the lagging and leading load phasor diagrams of the synchronous generator we can conclude that to get a specific value of the phase or terminal voltage and armature current we will require larger amount of internal generated voltage E for the inductive load (lagging) than the capacitive load (leading). So, we will have to provide a larger field current at the rotor in case of inductive load (lagging load) than the leading load to generates the same amount of the terminal voltage.

Two Reaction Theory / Analysis/ Blondel's Theory

We knew that in non-salient pole type alternators the air gap is uniform. Due to the uniform air gap, the field flux, as well as armature flux varies sinusoidally in the air gap. In non salient pole alternators, air gap length is constant and reactance is also constant. This two reaction theory was given by Professor Andre Blondel so it is named as Blondel two reaction theory.

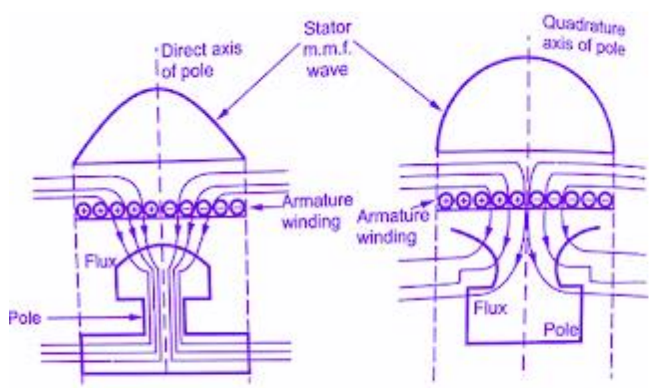
Due to this, the MMFs of armature and field act upon the same magnetic circuit all the time hence can be added vectorially. But in salient pole type alternators, the length of the air gap varies and the reluctance also varies. Hence the armature flux and field flux cannot vary sinusoidally in the air gap. The reluctances of the magnetic circuits on which MMFs act are different in the case of salient pole alternators.

Hence the armature and field MMFs are given special importance while given less importance in a non salient pole alternators. There are some disturbing factors in salient pole alternators which are analyzed below. The theory which gives the method of analysis of the disturbing effects caused by salient pole construction is called Two Reaction Theory.

According to this theory, the armature MMF can be divided into two components as,

1. Component acting along the pole axis called direct axis.
2. Component acting at right angles to the pole axis called quadrature axis.

The component which is acting along the direct axis can be magnetizing or demagnetizing. The component which is acting along quadrature axis is cross magnetizing. These components produce the effects of different kinds. The below figure shows the stator MMF wave and the flux distribution in the airgap along direct axis and quadrature axis of the pole



The reluctance offered to the MMF wave is lowest when it is aligned with the field pole axis. This axis is called the direct axis of pole i.e. d-axis. The reluctance offered is highest when the

MMF wave is oriented at 90° to the field pole axis which is called quadrature axis i.e. q-axis. The air gap is least in the centre of the poles and progressively increases, on moving away from the centre. Due to such shape of the pole-shoes, the field winding wound on salient poles produces the MMF wave which is nearly sinusoidal and it always acts along the pole axis which is direct axis.

Let F_f be the MMF wave produced by field winding, then it always acts along the direct axis. This MMF is responsible for producing an excitation EMF E_f which lags F_f by all angle 90°.

When armature carries current, it produces its own MMF wave $\mathbf{F_{AR}}$. This can be resolved into two components, one acting along d-axis (magnetizing or demagnetizing) and one acting along q-axis (cross-magnetizing). Similarly, armature current $\mathbf{I_a}$ also can in divided into two components, one along the direct axis and one along quadrature axis. These components are denoted as,

F_{AR}:

F_d = component along direct axis

F_q = component along quadrature axis

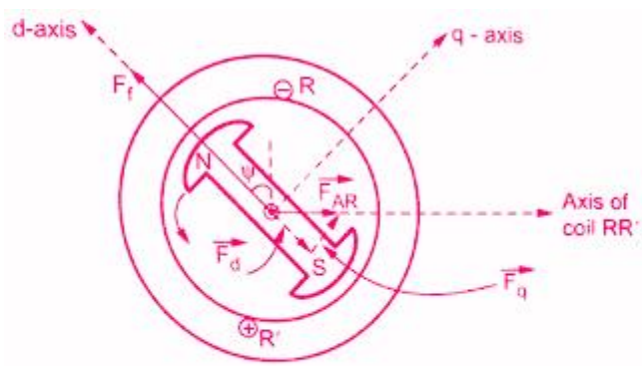
Ia :

I_d = component along direct axis

I_q = component along quadrature axis

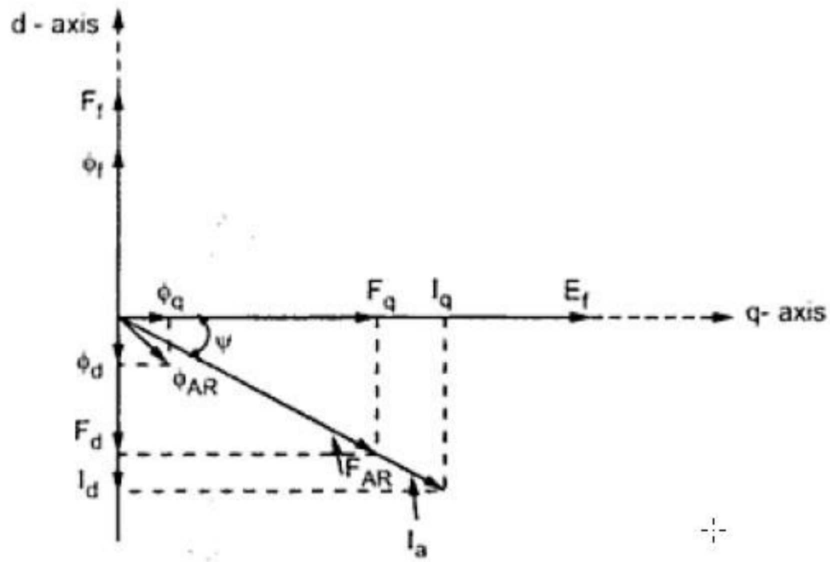
The positions of F_{AR}, F_d and F_q in space are shown in the below figure. The instant chosen to show these positions is such that the current in phase R is maximum positive and is lagging E_f by angle Ψ.

The phasor diagram of MMF wave positions in salient pole machine is shown below.



It can be observed from the figure that F_d is produced by Id which is at 90° to Ef while Fq is produced by I_q which is in phase with E_f. The flux components of Φ_{AR} which are Φ_d and Φ_q respectively are also shown in the below figure.

It can be noted that the reactance offered to flux along the direct axis is less than the reactance offered to flux along quadrature axis. Due to this, the flux Φ_{AR} is no longer along F_{AR} or I_a. Depending upon the reluctances offered along the direct and quadrature axis, the flux Φ_{AR} lags behind armature current I_a.



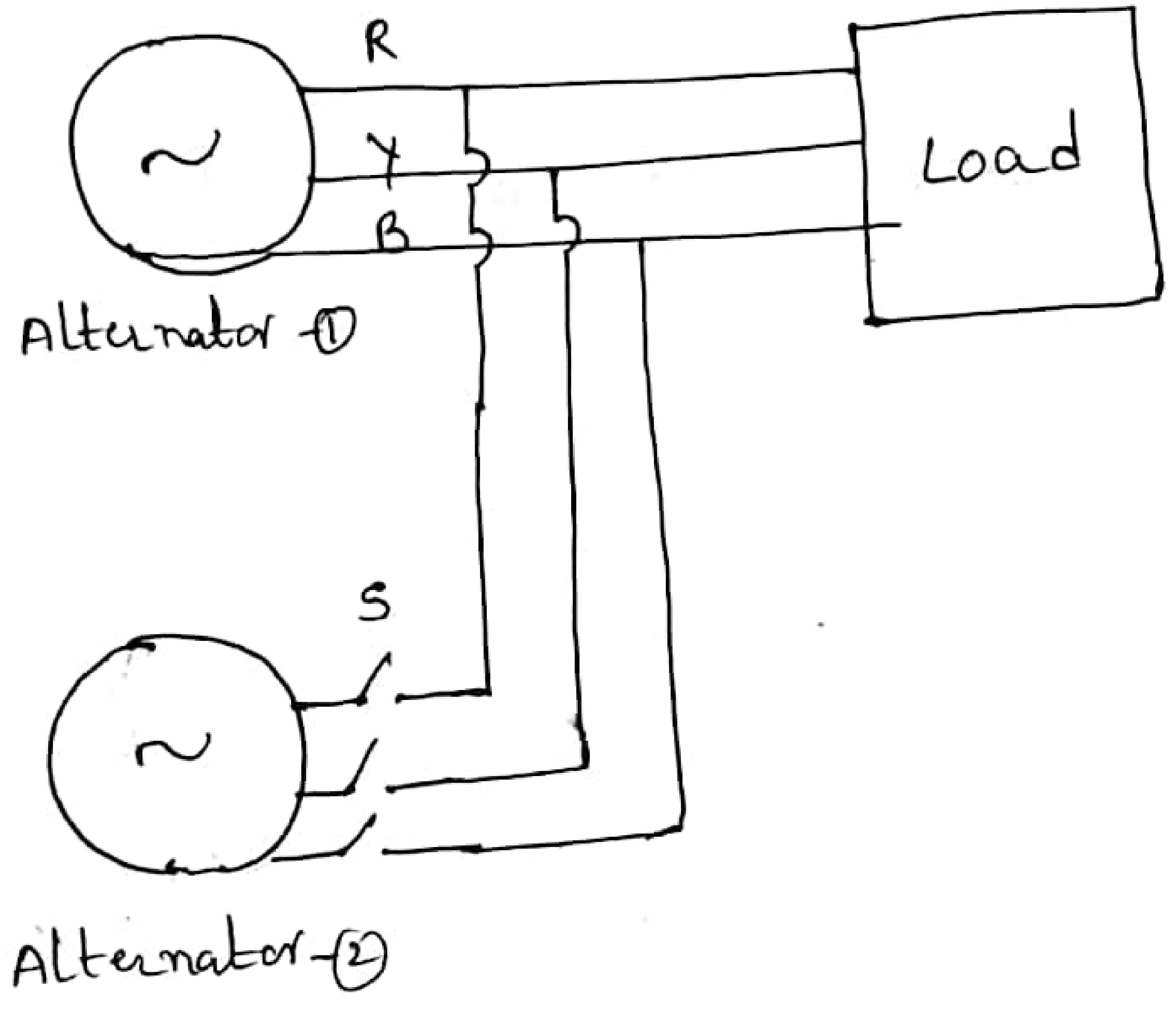
<u>**Determination of Voltage Regulation of Alternators**</u>

1. **EMF or Synchronous Impedence or Pessimistic method**
2. **MMF or Ampere turns or Optimistic method**
3. **ZPF or Potier triangle method**

FOR THE ABOVE TOPIC (EMF, MMF, ZPF) REFER CLASS NOTES

Parallel operation of Alternators

- The process of connecting one alternator in Parallel with another alternator is called Parallel operation (or) synchronisation.



Advantages of Parallel operation of alternators

1. By connecting two alternators in parallel the o/p increases (instead of single alternator).

- Economic cost is reduced
- Reliability of power systems increases
- continous power supply is possible

- load growth can be increased
- load sharing of alternators is possible.
- life span of alternators increases.

syn

Condition for parallel operation:

- The ratings of both Alternators should be Identical (or) similar
- the phase sequence of both Alternators should be same (or) similar
- The prime movers must be relatively similar.
- the terminal voltages of the incoming alternator must be same as the busbar voltages
- The frequency of the incoming Alternator must be same as the busbar frequency.
- Speed load droping characteristics of the speed governing system of the alternator should be similar.

Synchronization methods :-

Synchronization of alternator means connecting an alternator into grid in parallel with many other alternators, that is live system of constant voltage and constant frequency.

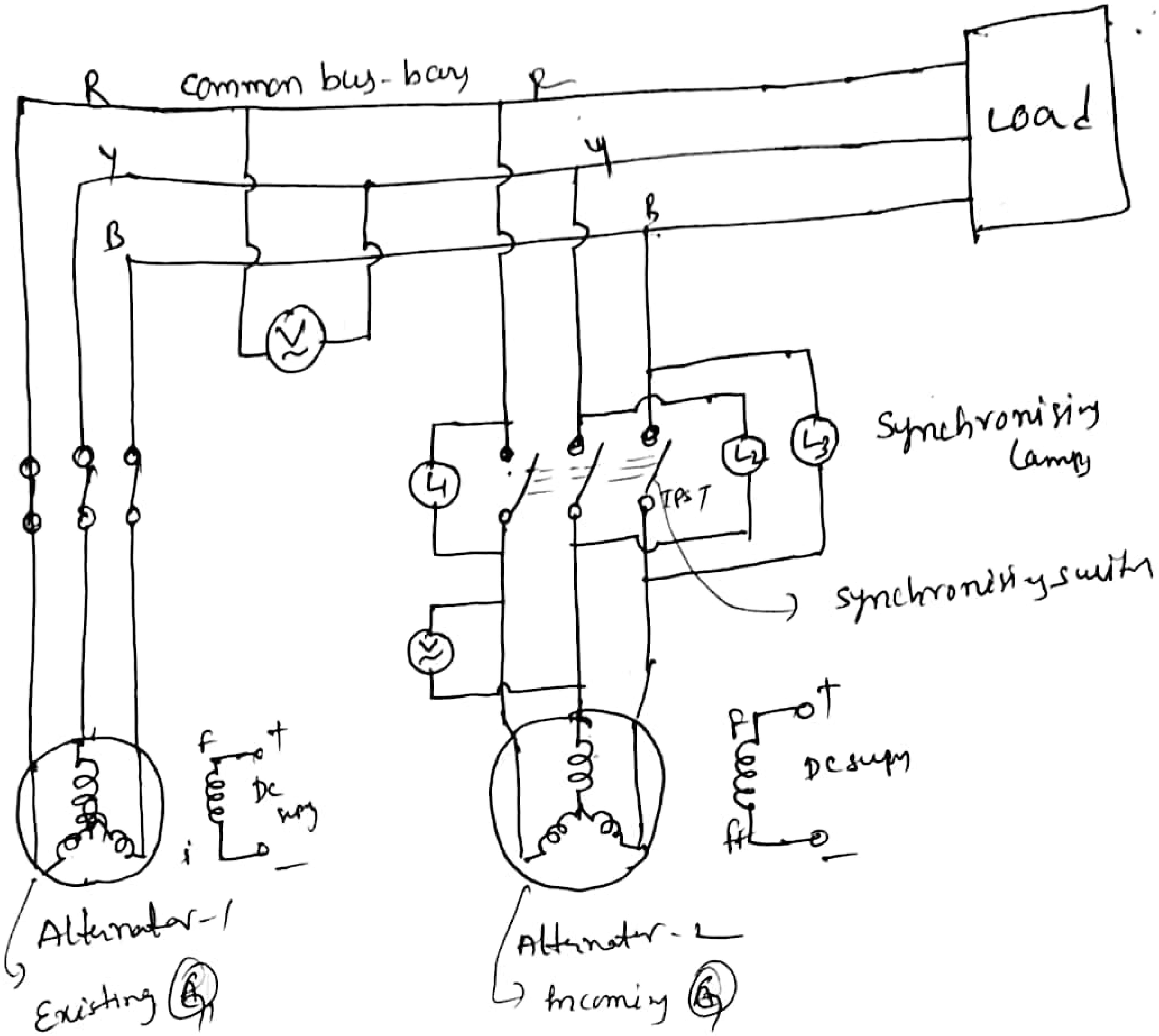
- the first condition of voltage equality can be satisfied by a voltmeter. To satisfy the conditions of equal frequency and identical phases, one of the following three methods can be used.

1. Three dark (or) Three bright lamp method
2. Two bright and one dark lamp method
3. Synchroscope method.

1. Three dark (or) Three bright lamp method:-

In order to connect two alternators in parallel it satisfy

1. Terminal voltage same
2. frequency same
3. phase sequence same.

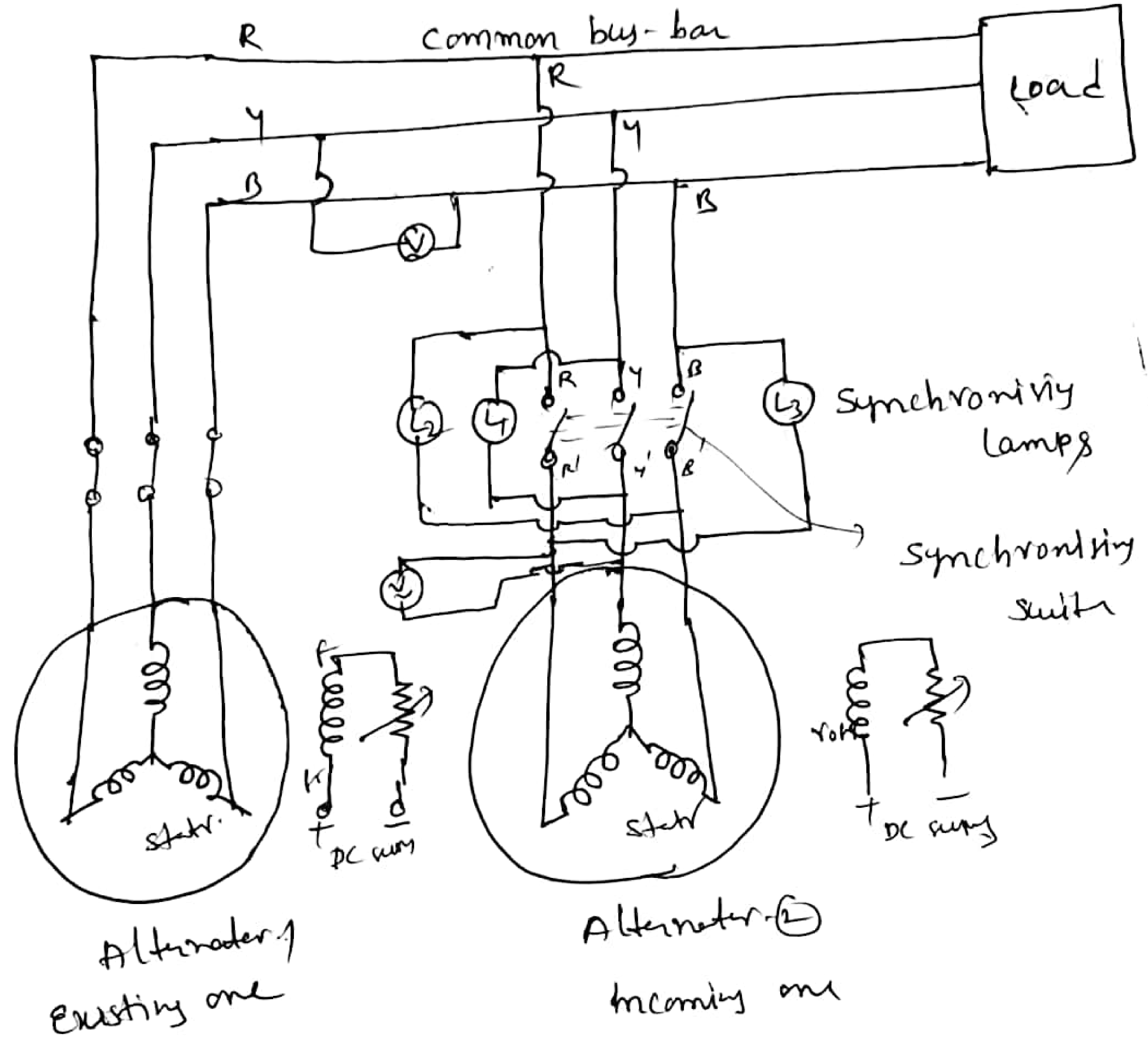


- the terminal voltages of Existing alternator and Incoming alternator must be same. It can be shown by voltmeter connected in above ckt
- Three lamps L_1, L_2, L_3 are connected across each phase as shown in fig.
- The bulbs are continously on & off then phase sequence is correct, in case the bulbs are not like that then reverse the two phases.
- If the bulbs are slowly on & off the frequency is same
If flikering is more the freq is not same then by adjusting field ~~...~~ set the same freq. Then close the TPST switch.

www.Jntufastupdates.com

Scanned with CamScanner

2. Two bright and one dark lamp method:



- This connection is called transposed manner
- L_1, L_2, L_3 are three lamps are connected 'L_1' is connected b/w Y & Y' and L_2 is connected b/w R & B' and 'L_3' is connected b/w B & R' as shown in above fig.
- The voltmeters are connected across two lines for existing (G) & incoming (G)

- If two voltmeters shows same value then it satisfy the first condition i.e terminal voltages must be same

- In this method phase sequence identification is not possible why because we are connected three lamps in transposed manner.

- This main drawback in this method i.e The phase sequency identification is not possible

- If the bulbs on and off slowly the flickering is less then frequency is same. If the bulbs on and off fastly then more flickering present then frequency is not same. If frequency is same for both alternators then only we can close the TPST switch other wise it is not possible to close the TPST switch.

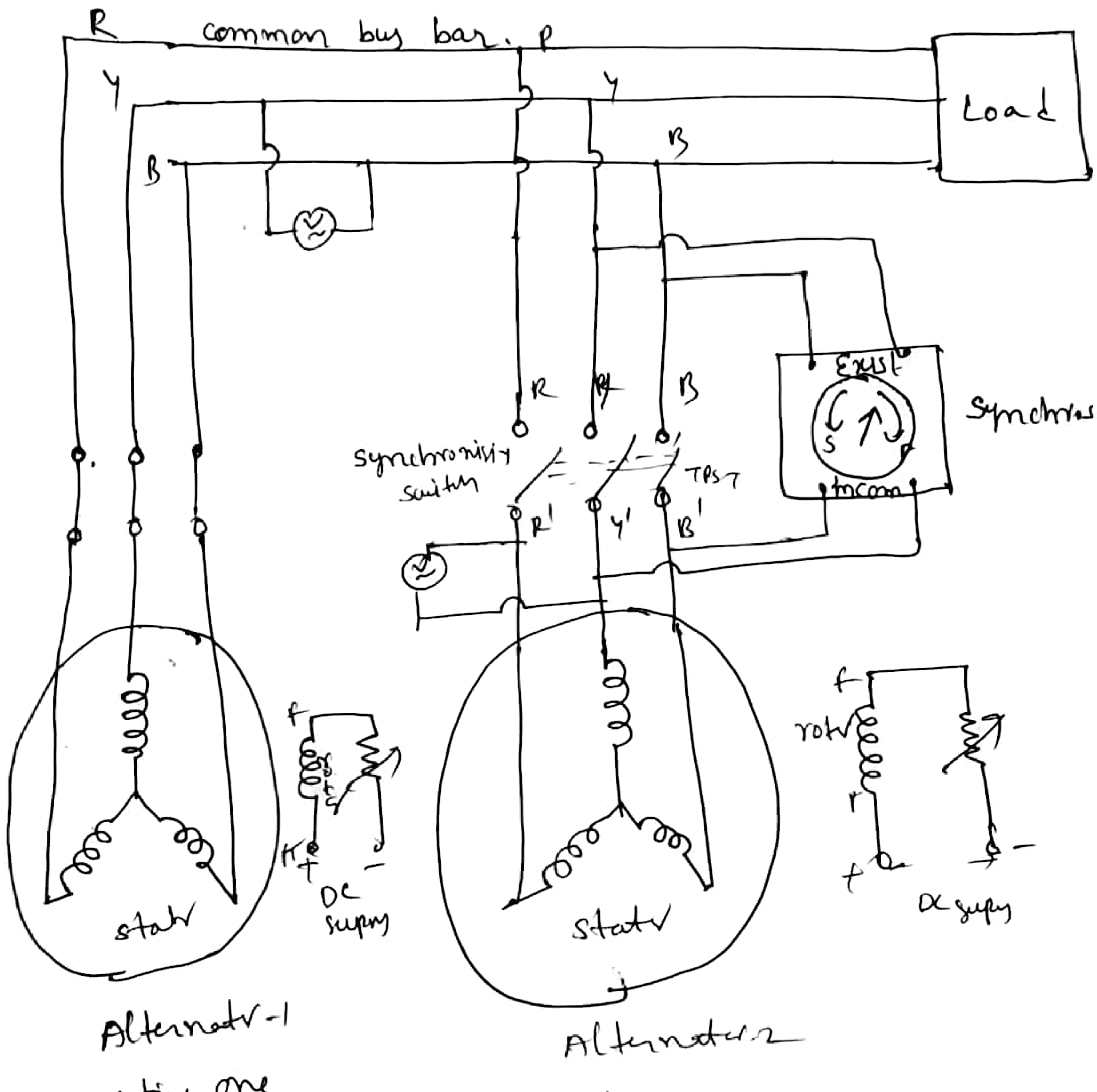
- for maintaining same frequency by changing the speed of alternator and set the same frequency

- the all the conditions satisfy then close the TPST switch.

www.Jntufastupdates.com

Scanned with CamScanner

3: synchroscope method :-



- first condition voltages are same by checking both voltmeter
- phase sequence is not applicable for power stations.
- If pointer shows ↑ direction then only close the TPST.

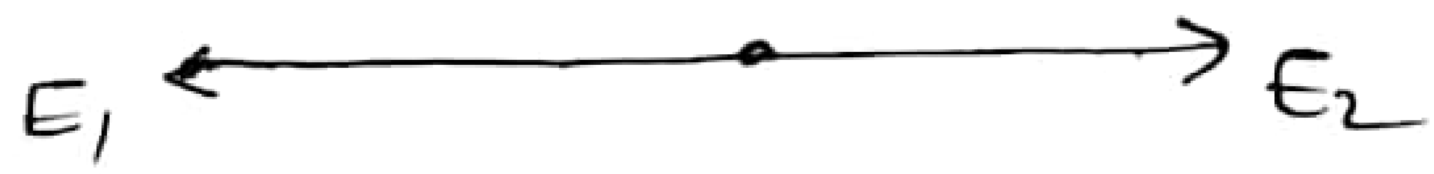
www.Jntufastupdates.com

Scanned with CamScanner

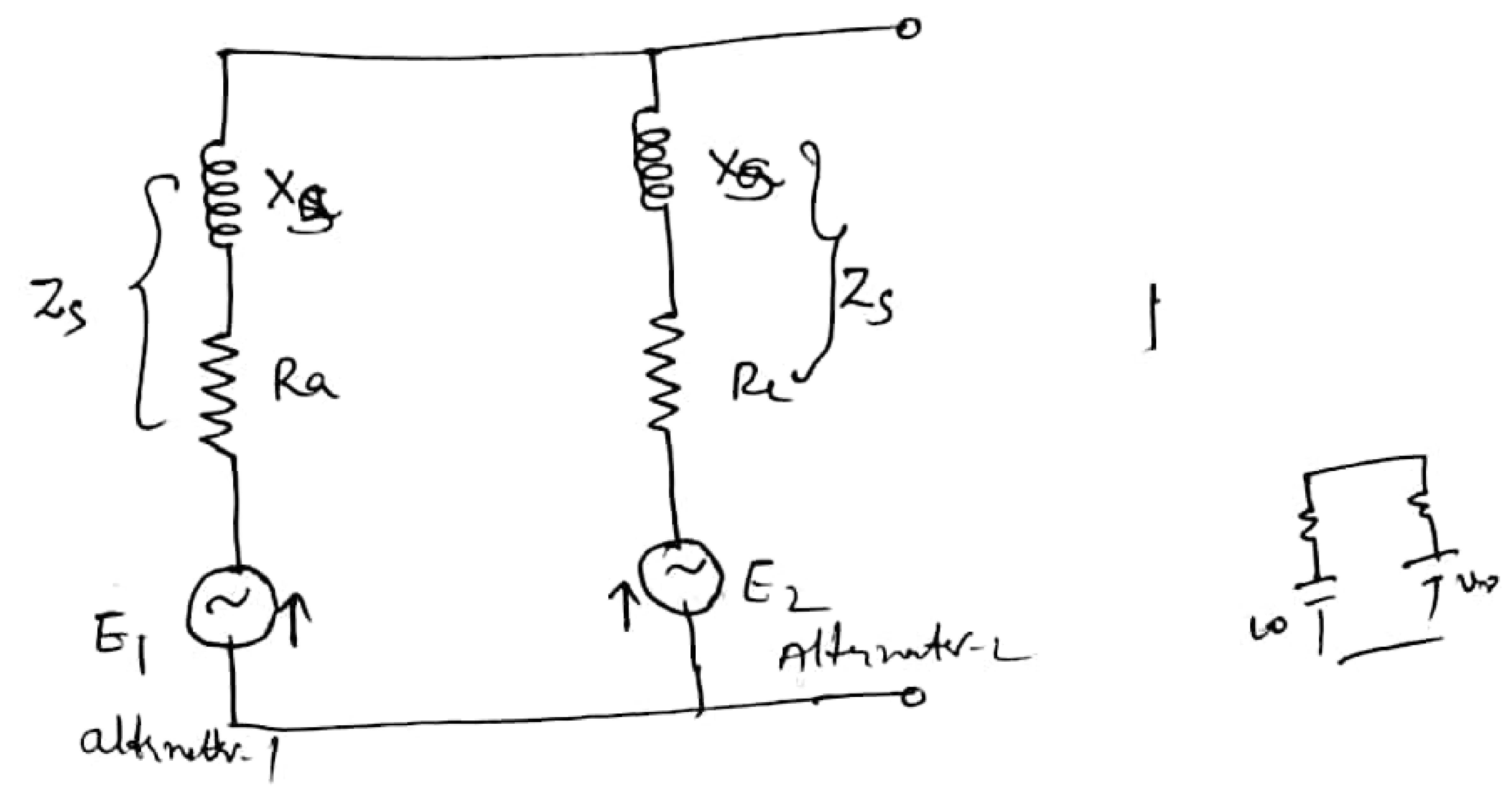
Synchronizing current and synchronizing Power and synchronizing Torque

After proper synchronization of alternators, They will run in synchronism. A synchronizing torque will be developed if any of The alternator drops out of synchronism and will bring it back to The synchronism.

- consider the two alternators shown in fig. which are in exact synchronism. Due to This They are having same terminal potential drop and with reference to Their local circuit They are in exact phase opposition.
- So there will not be any circulating current in The local circuit. The emf E_1 of alternator '1' is in exact phase opposition to That of alternator 'E_2'



- with respect to external load, The emf.s of The two alternators are in The same direction although They are in phase opposition with reference to local circuit. They will be no resultant voltage in The local circuit.



where E_1 be the e.m.f induced in Alternator-1

E_2 be the e.m.f induced in Alternator-2

Z_s be the synchronous impedence

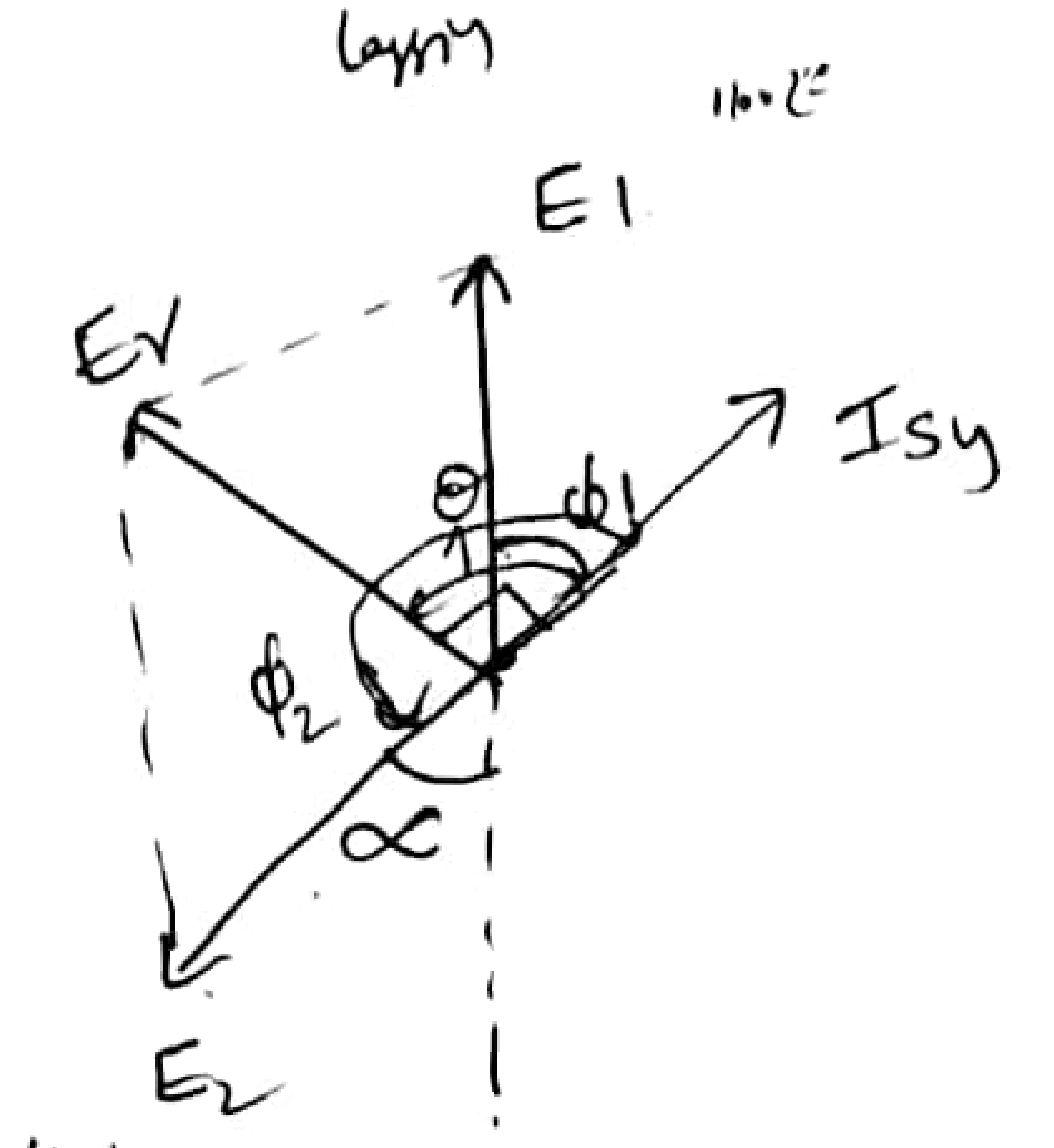
R_a armature resistance.

X_s be the synchronous reactance.

- Now assume that speed of alternator-2 is changed such that it's e.m.f 'E_2' falls by an angle 'α'.
  But E_1 & E_2 are equal in magnitude. The resultant voltage 'E_r' in this case will cause a current in the local circuit which is called synchronizing current.
  This circulating current is given by

$$I_{sy} = \frac{E_r}{Z_s} \quad \rightarrow (1)$$

where E_r = Resultant induced emf when both alternators are synchronized.



where. 'ϕ_1' is The angle b/w I_{sy} and E_1

'ϕ_2' is The angle b/w I_{sy} and E_2

'θ' is The angle b/w I_{sy} and E_r

'α' is shorted by 'E_2'

- from above phasor diagram. The phase angle of I_{sy} is given by angle 'θ' which can be computed as

$$\tan\theta = \frac{X_s}{R_a} \rightarrow (2)$$ This angle is almost 90°.

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$$

- Thus I_{sy} lags E_r almost 90° and approximately in phase with 'E_1'.

Let $E_1 = E_2 = E \longrightarrow (3)$

i.e both magnitudes of alternators equal

If two vectors having same magnitudes Then the resultant vector is given by.

$$E_r = 2E \cos\left(\frac{180-\alpha}{2}\right)$$

$$E_r = 2E \cos\left(90 - \frac{\alpha}{2}\right)$$

$$\therefore E_r = 2E \sin(\alpha/2) \rightarrow (4)$$

'α' is very small so that $\sin(\alpha/2) \simeq \alpha/2 \rightarrow (5)$

$$\therefore E_r = 2E \cdot \frac{\alpha}{2}$$

$$E_r = E\alpha \rightarrow (6)$$

$\therefore$ synchronizing power $P_{sy} = E_1 I_{sy} \rightarrow (7)$

$$= E \cdot I_{sy}$$

$$= E \cdot \left[\frac{E_r}{2Z_s}\right] \quad (\because \text{from } (1))$$

$$\therefore P_{sy} = E\left[\frac{E\alpha}{2Z_s}\right] \quad (\because \text{from } (6))$$

$$\therefore \boxed{P_{sy}/ph = \frac{\alpha E^2}{2Z_s}} \rightarrow (8)$$

synchronising power per three phase is

$$\boxed{P_{sy} \text{ for } 3\text{-}\phi = \frac{3\alpha E^2}{2Z_s}} \rightarrow (9)$$

www.Jntufastupdates.com

Scanned with CamScanner

Note:-

case-i) The Generalized synchronizing Power eq^n when both alternators are connected in parallel

$$P_{sy}/ph = \frac{\alpha E_1 E_2}{2Z_s}$$

case-ii) if armature resistance is neglected then

$E_1 = E_2 = E$

$$P_{sy}/ph = \frac{\alpha E_1 E_2}{2X_s} = \frac{\alpha E^2}{2X_s}$$

∴ for load condition

$$P_{sy}/ph = \frac{\alpha E_1 E_2}{2X_s} \quad (E_1 \neq E_2)$$

$$3P_{sy} = \frac{2\pi N_s T_{sy}}{60}$$

Torque (synchronizing torque) $T_{sy} = \dfrac{3P_{sy} \times 60}{2\pi N_s}$

- A 3000 kVA, 6-pole alternator runs at 1000 r.p.m. in parallel with other machines on 3,300V bus bars. The synchronous reactance is 25%. calculate the synchronizing power for one mechanical degree of displacement and the corresponding synchronizing torque

Sol

$$\text{voltage / phase} = 3300/\sqrt{3} = 1905V.$$

$$\text{full load current } I = \frac{KVA}{\sqrt{3}V_L} = \frac{3000 \times 1000}{\sqrt{3} \times 3300} = 525A$$

Now $IX_S = 25\% \, V_{ph}$

$$\therefore X_S = \frac{0.25 \times 1905}{525} = 0.9075\Omega$$

$$P_{sy} = \frac{3 \times \alpha E^2}{X_S}$$

$$\alpha = 1^\circ \text{ (mech)}.$$

$$\therefore \alpha(\text{elec}) = \frac{P}{2} \times \alpha(\text{mech}) = \frac{6}{2} \times 1 = 3^\circ$$

$$\therefore \alpha = \frac{3 \times \pi}{180} = \frac{\pi}{60} \text{ elec. radians}$$

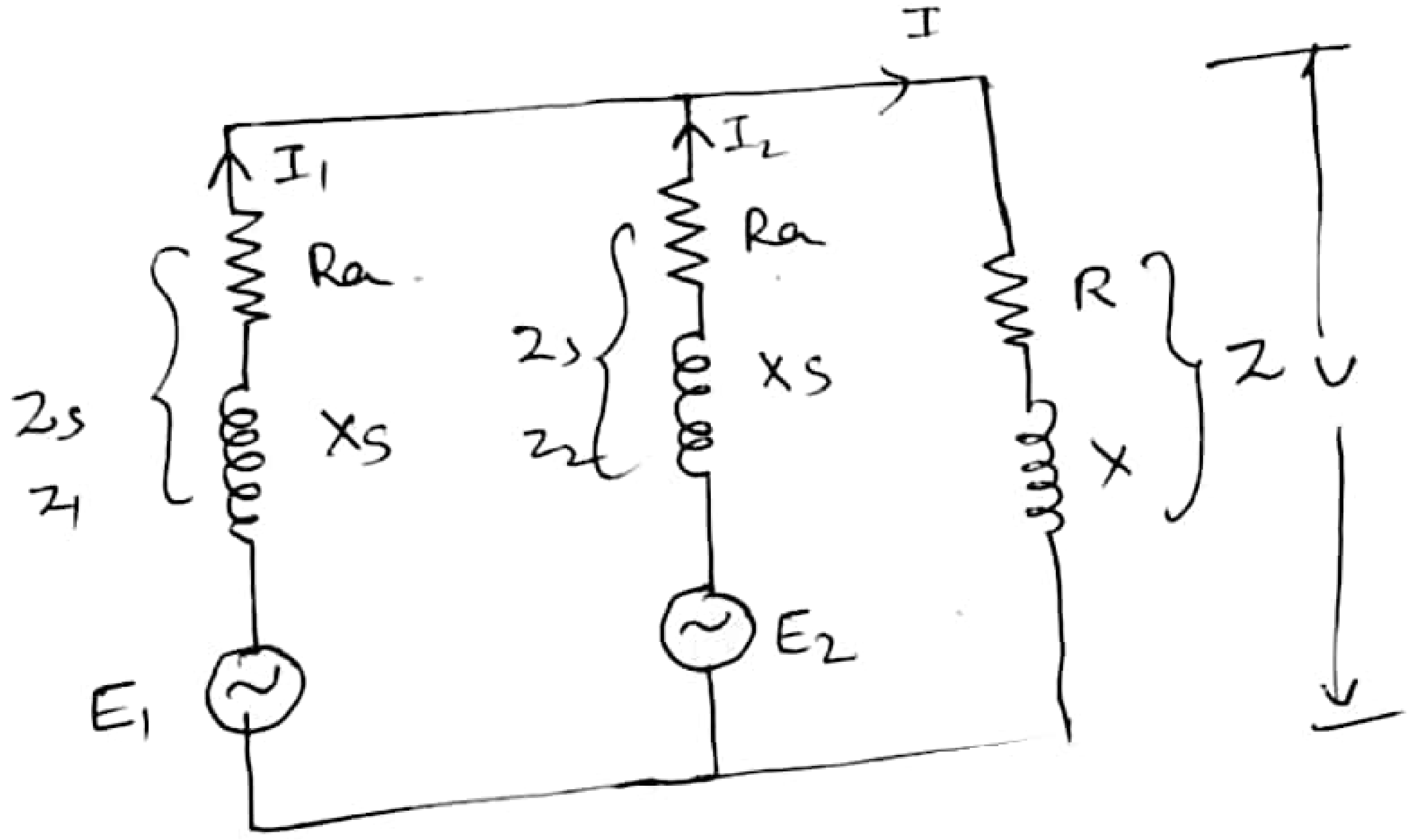
$$\therefore P_{sy} = \frac{3 \times \pi \times 1905^2}{60 \times 0.9075 \times 1000} = 628.4 \text{ kW}$$

$$\therefore T_{sy} = \frac{60 \times P_{sy}}{2\pi N_S} = 9.55 \times \frac{P_{sy}}{N_S} = 9.55 \times \frac{628.4 \times 10^3}{1000}$$

$$= 6000 \text{ N-m}$$

Load sharing of Alternators :

Let us consider two alternators of with same speed Load characteristics when connected in parallel is shown in below fig



Let E_1 = Generated emf in alternator -1

E_2 = Generated emf in alternator - 2

Z_1 = synchronous impedance of alternator - 1

Z_2 = Synchronous impedance of alternator -2

Z = ~~Syn~~ Equivalent impedance of both m/c's

I_1 = load current shared by alternator - 1

I_2 = Load current shared by alternator - 2

I = total current shared by both alternators.

'V' is called common terminal voltage.

from the above Equivalent ckt.

$$V = E_1 - I_1 Z_1 = E_2 - I_2 Z_2 \rightarrow (1)$$

$$E_1 - E_2 = I_1 Z_1 - I_2 Z_2 \rightarrow (2)$$

$$I = I_1 + I_2 \longrightarrow (3)$$

$$V = IZ \longrightarrow (4)$$

where $V = (I_1 + I_2) Z \longrightarrow (5)$

from Eq^n (1) $\quad E_1 - I_1 Z_1 = V$

$$E_1 - I_1 Z_1 = (I_1 + I_2) Z$$

$$E_1 = (I_1 + I_2) Z + I_1 Z_1 \rightarrow (6)$$

similarly $\quad E_2 = (I_1 + I_2) Z + I_2 Z_2 \longrightarrow (7)$

from Eq^n (6) $\Rightarrow (I_1 + I_2) Z = E_1 - I_1 Z_1$

$$I_2 Z = E_1 - I_1 Z_1 - I_1 Z$$

$$\boxed{I_2 = \frac{E_1 - I_1 (Z_1 + Z)}{Z}} \rightarrow (8)$$

sub eq^n (8) in Eq^n (2)

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

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

$$I_1 Z_1 = E_1 - E_2 + \frac{E_1 Z_2 - I_1 Z_1 Z_2 - I_1 Z Z_2}{Z}$$

$$= \frac{E_1 Z - E_2 Z + E_1 Z_2 - I_1 Z_1 Z_2 - I_1 Z Z_2}{Z}$$

$$I_1 Z_1 Z = E_1 Z - E_2 Z + E_1 Z_2 - I_1 Z_1 Z_2 - I_1 Z Z_2$$

$$I_1 Z_1 Z + I_1 Z_1 Z_2 + I_1 Z Z_2 = E_1 Z - E_2 Z + E_1 Z_2$$

$$I_1 (Z Z_1 + Z_1 Z_2 + Z Z_2) = E_1 Z - E_2 Z + E_1 Z_2$$

$$\therefore \quad I_1 = \frac{Z(E_1 - E_2) + E_1 Z_2}{Z(Z_1 + Z_2) + Z_1 Z_2} \longrightarrow (9)$$

from eq^n (7) $\quad (I_1 + I_2) Z = E_2 - I_2 Z_2$

~~$E_1 = I_1 Z_1 - I_1 Z$~~

$$I_1 Z = E_2 - I_2 Z_2 - I_2 Z$$

$$\therefore \quad I_1 = \frac{E_2 - I_2(Z_2 + Z)}{Z} \longrightarrow (10)$$

sub eq^n (9) in eq (2)

$$E_1 - E_2 = \left[\frac{E_2 - I_2(Z_2 + Z)}{Z}\right] Z_1 - I_2 Z_2$$

$$E_1 - E_2 = \left[\frac{E_2 Z_1 - I_2 Z_2 Z_1 - I_2 Z_1 Z - I_2 Z_2 Z}{Z}\right]$$

$$E_1 Z - E_2 Z = E_2 Z_1 - I_2\left[Z_2 Z_1 + Z_1 Z + Z_2 Z\right]$$

$$E_2 Z_1 - E_1 Z + E_2 Z = I_2\left[Z(Z_1 + Z_2) + Z_1 Z_2\right]$$

$$I_2 = \frac{(E_2 - E_1)Z + E_2 Z_1}{Z[Z_1 + Z_2] + Z_1 Z_2} \longrightarrow (11)$$

∴ from Eqn (3)

$$I = I_1 + I_2$$

$$I = \frac{(E_1 - E_2)Z + E_1 Z_2}{Z[Z_1 + Z_2] + Z_1 Z_2} + \left[\frac{[E_2 - E_1]Z + E_2 Z_1}{Z[Z_1 + Z_2] + Z_1 Z_2}\right]$$

$$\therefore I = \frac{E_1 Z - E_2 Z + E_1 Z_2 + E_2 Z - E_1 Z + E_2 Z_1}{Z[Z_1 + Z_2] + Z_1 Z_2}$$

$$\therefore I = \frac{E_1 Z_2 + E_2 Z_1}{Z[Z_1 + Z_2] + Z_1 Z_2} \longrightarrow (12)$$

$$\therefore V = IZ = \left[\frac{E_1 Z_2 + E_2 Z_1}{Z[Z_1 + Z_2] + Z_1 Z_2}\right] \cdot Z \longrightarrow (13)$$

- Two single phase alternators operating in parallel have induced e.m.f.s on open circuit of $220\angle0^\circ$ and $220\angle10^\circ$ V and respective reactances of $j3\Omega$ and $j4\Omega$. calculate i) terminal voltage ii) currents and iii) power delivered by each of the alternators to a load impedance is 6Ω.

Sol

Given data:-

Impedance of alternator-1 $(\bar{Z}_1)$ = $j3\Omega$

Impedance of alternator-2 $(\bar{Z}_2)$ = $j4\Omega$

$\bar{E}_1 = 220\angle0^\circ$ volts

$\bar{E}_2 = 220\angle10^\circ$ volts

$\bar{Z} = 6\Omega$

current I_1 is given by

$$\bar{I}_1 = \frac{(\bar{E}_1 - \bar{E}_2)\bar{Z} + \bar{E}_1\bar{Z}_2}{\bar{Z}(\bar{Z}_1+\bar{Z}_2) + \bar{Z}_1\bar{Z}_2}$$

$$\bar{I}_1 = \frac{[(220+j0) - (216.65+j38.20)]6 + (220\angle0^\circ \times j4)}{6[j3+j4] + (j3\times j4)}$$

$$\therefore I_1 = \frac{6[3.35 - j38.20] + (0+j880)}{j42-12}$$

$$\bar{I}_1 = \frac{(20.1 - j229.2) + (0 + j880)}{-12 + j42}$$

$$\bar{I}_1 = \frac{20.1 + j650.8}{-12 + j42} = \frac{651.11 \angle 88.23^\circ}{43.68 \angle 105.94^\circ}$$

$$\therefore \bar{I}_1 = 14.90 \angle -17.71^\circ \, A$$

$$\therefore \bar{I}_2 = \frac{(\bar{E}_2 - \bar{E}_1)\bar{Z} + \bar{E}_2 \bar{Z}_1}{\bar{Z}(\bar{Z}_1 + \bar{Z}_2) + \bar{Z}_1 \bar{Z}_2}$$

$$\bar{I}_2 = \frac{[220\angle 10^\circ - 220\angle 0^\circ]6 + 220\angle 10^\circ \times (j4)}{6[j3 + j4] + (j3 \times j4)}$$

$$= \frac{6[(216.65 + j38.20) - (220 + j0)] + [(220\angle 10^\circ \times 3\angle 90^\circ)]}{j42 - 12}$$

$$= \frac{6[-3.35 + j38.20] + (660\angle 100^\circ)}{-12 + j42}$$

$$= \frac{(-20.1 + j229.2) + (-114.60 + j649.97)}{-12 + j42}$$

$$= \frac{-134.7 + j879.17}{-12 + j42} = \frac{889.42 \angle 98.71}{43.68 \angle 105.94^\circ}$$

$$\therefore I_2 = 20.36 \angle -7.23^\circ \, A$$

$\therefore \bar{I} = \bar{I}_1 + \bar{I}_2$

$\bar{I} = [14.90\angle{-17.71} + 20.36\angle{-7.23}]$

$= [14.19 - j4.53 + 20.19 - j2.56]$

$= [34.38 - j7.09]$

$\therefore \bar{I} = 35.10\angle{-11.65^\circ}$

$\therefore$ Now voltage $\bar{V} = \bar{I}\bar{Z} = (35.10\angle{-11.65})\, 6\angle{0^\circ}$

$\bar{V} = 210.6\angle{-11.65^\circ}$ volts

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

$P_1 = 210.6 \times 14.90 \times \cos 17.71$

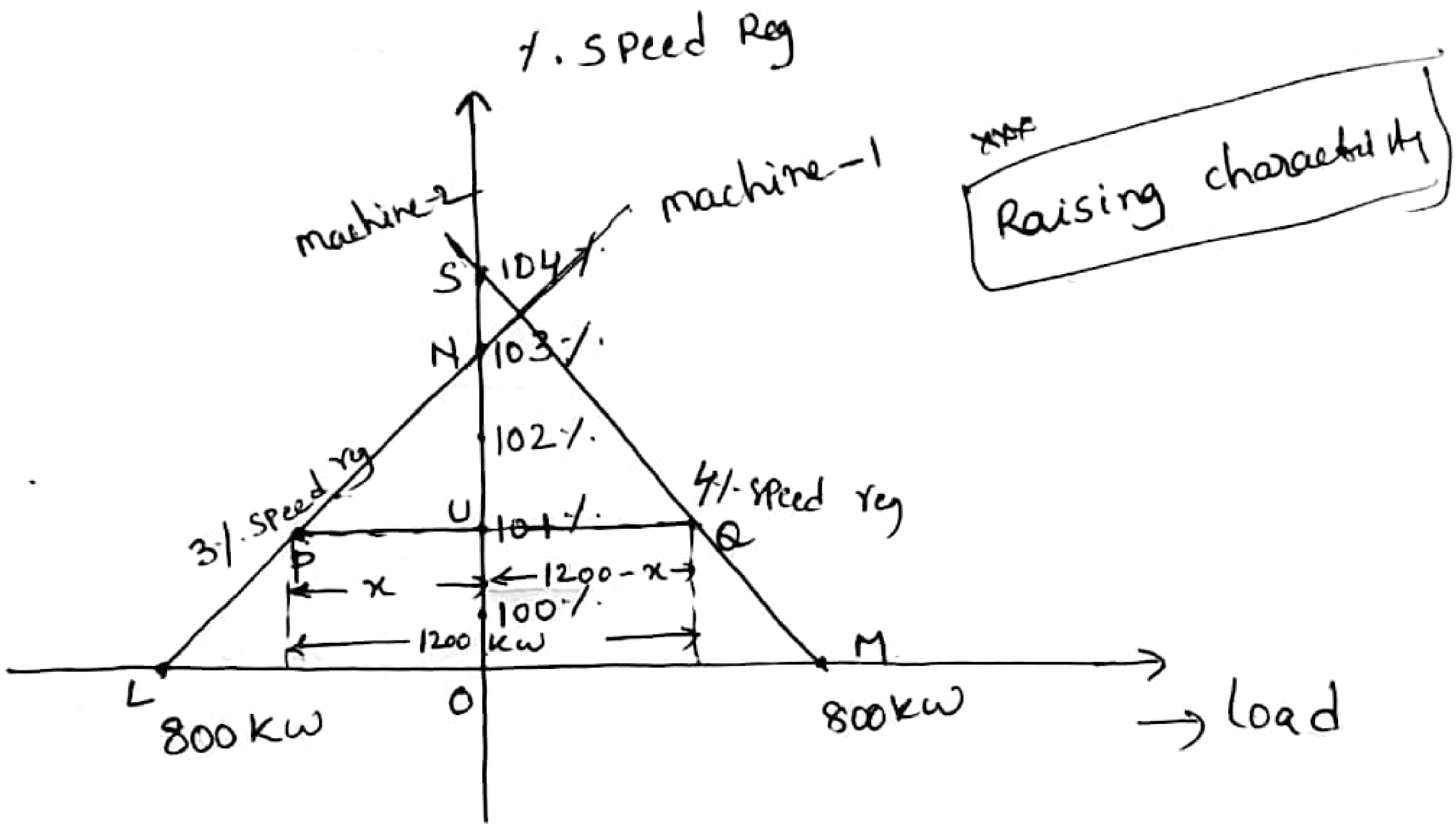
$\therefore P_1 = 2989.22$ watts

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

$= 210.6 \times 20.36 \times \cos 7.23^\circ$

$\therefore P_2 = 4253.72$ watts

-2. A 2 800 KW Alternators are operated in Parallel the speed regulation of one set is 100% to 103% from full load to No-load and the other set is 100% to 104%. How will these two alternators will share a total load of 1200 kw.



Draw a PQ line which passes through some point 'U' such That PQ = 1200 KW (i.e PQ be the total load)

Speed regulation of machine-1 = 100% to 103% = 3%

Speed regulation of machine-2 = 100% to 104% = 4%

'LN' represents the speed load characteristics of machine-1

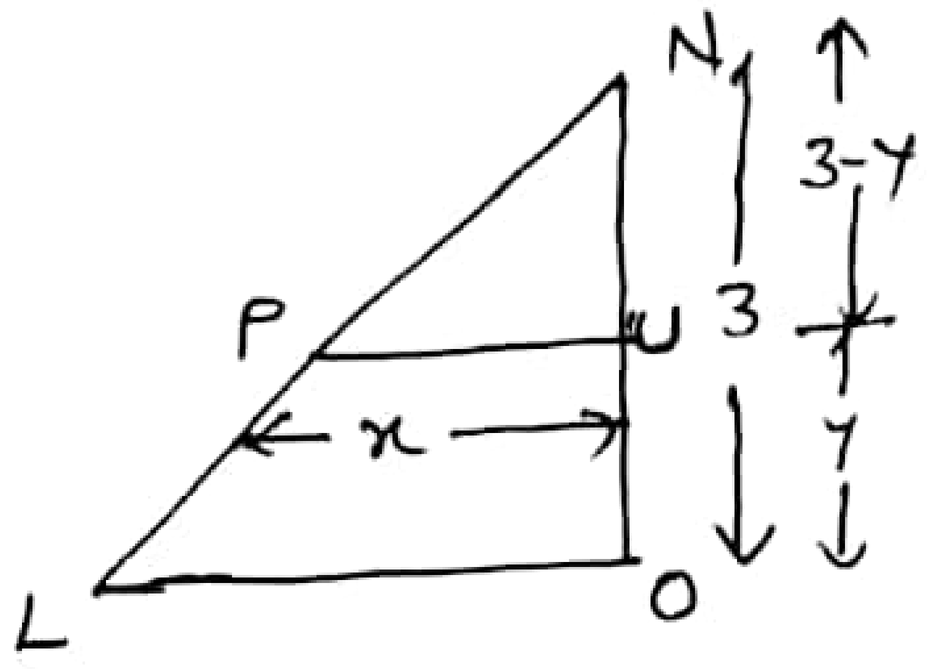
'MS' represents the speed load characteristics of machine-2

Let us consider left hand side triangle i.e OLN:

x - load shared by alternator - 1

from the similar triangle properties, we have.

$$\frac{OL}{PU} = \frac{NO}{NU}$$



$$\frac{800}{x} = \frac{3}{3-y}$$

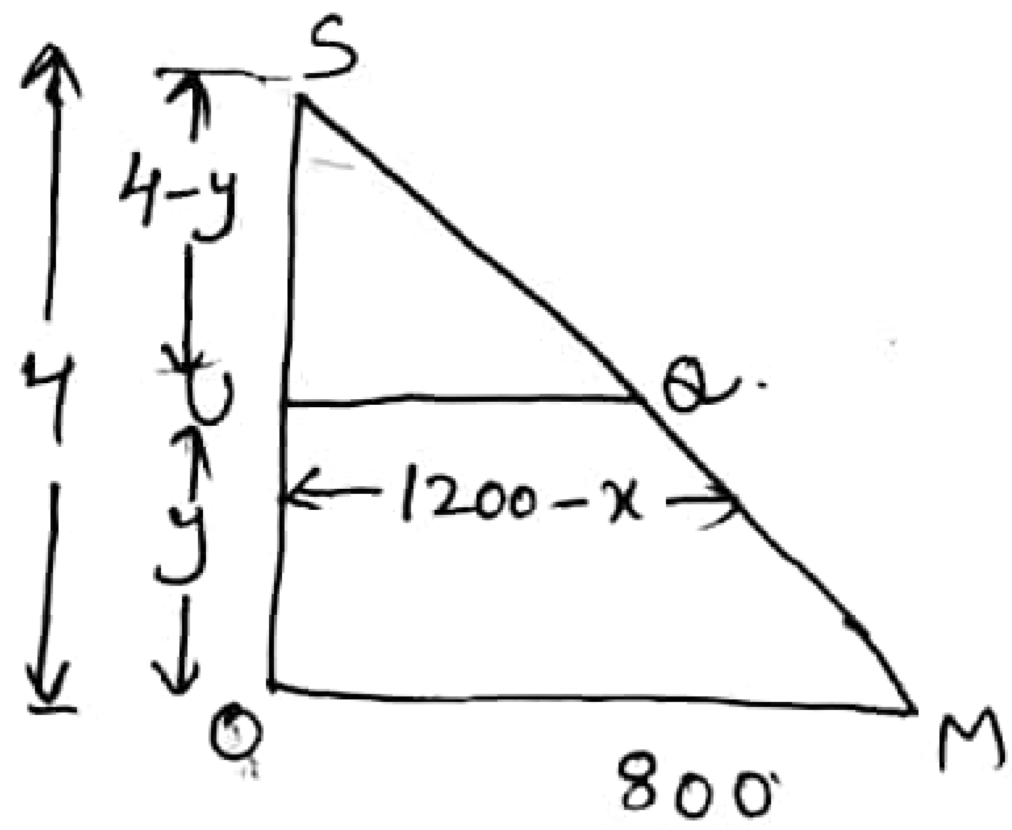
$$3x = 2400 - 800y$$

$$3x + 800y = 2400$$

$$x + 266.6y = 800 \longrightarrow (1)$$

Let us consider Right hand side triangle i.e OMS:

$$\frac{OM}{UQ} = \frac{SO}{SU}$$



$$\frac{800}{1200-x} = \frac{4}{4-y}$$

$$3200 - 800y = 4800 - 4x$$

$$4x - 800y + 3200 - 4800 = 0 \Rightarrow 4x - 800y - 1600 = 0$$

$$\therefore x - 200y = 400 \longrightarrow (2)$$

solving eq (1) x (2)

$$x + 266.64y = 800$$
$$x - 200y = 400$$
$$466.6y = 400 \Rightarrow y = \frac{400}{466.6} \Rightarrow y = 0.857$$

and $x = 400 + 200y \Rightarrow 400 + 200 \times 0.857$

$\therefore x = 571.4$ kw

Therefore alternator-1 is shared by a

load of $x = 571.4$ kW

and alternator-2 is shared by a load of 'UQ'

$\therefore UQ = PQ - PU$

$= 1200 - x$

$= 1200 - 571.4$

$= 628.6$ kW.

---

3) A Two 50MW, 3-ϕ alternators operate in Parallel. The settings of governors are such that the rise in speed from full load to no load is 2% in one machine and 3% in other machine. If each machine is fully loaded when the total load is 100 MW. what could be the load on each machine when the total load is 60MW

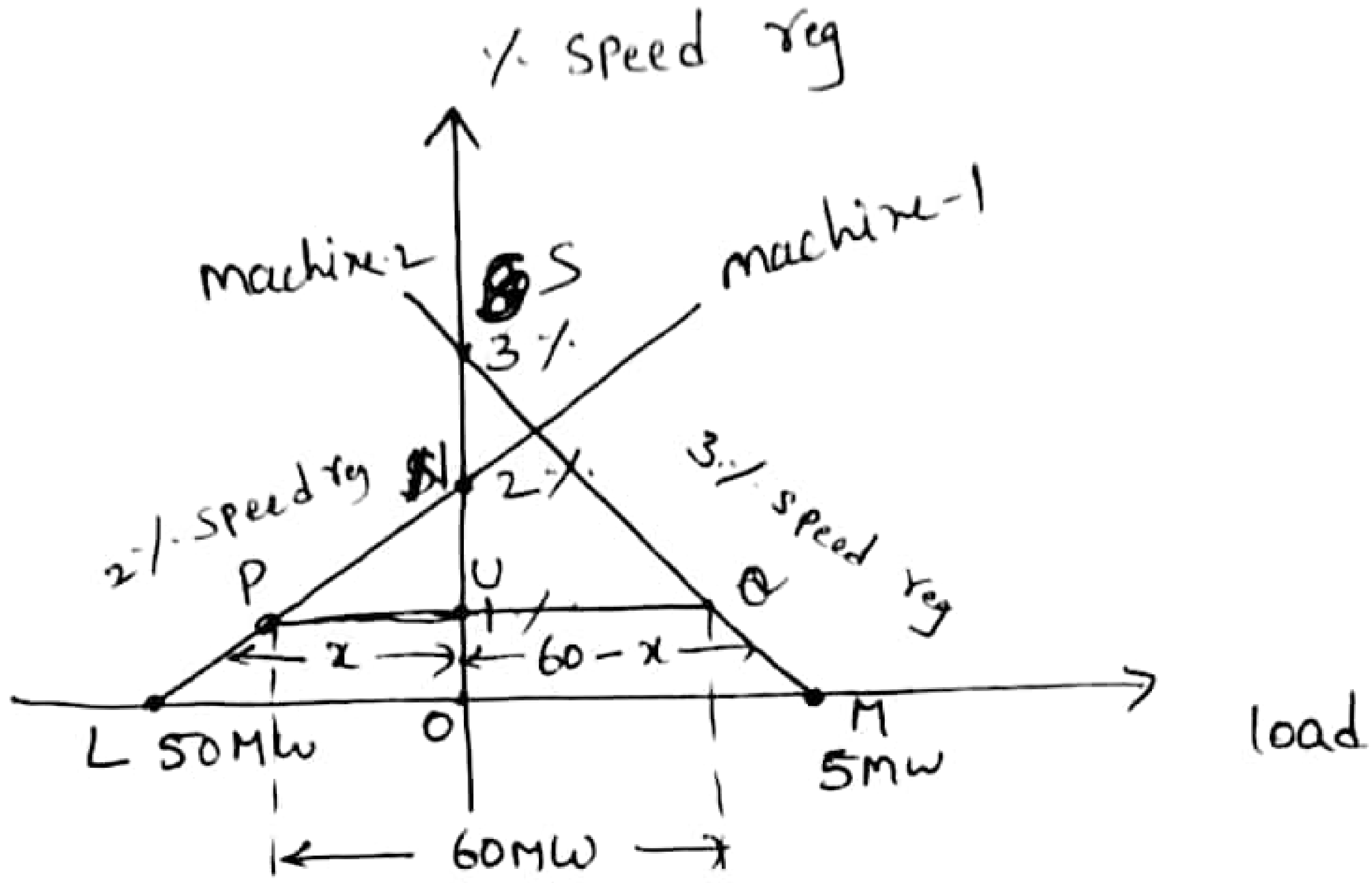
Sol

speed regulation of machine-1 = 2%.

speed regulation of machine-2 = 3%

PQ = 60 kW (total load)

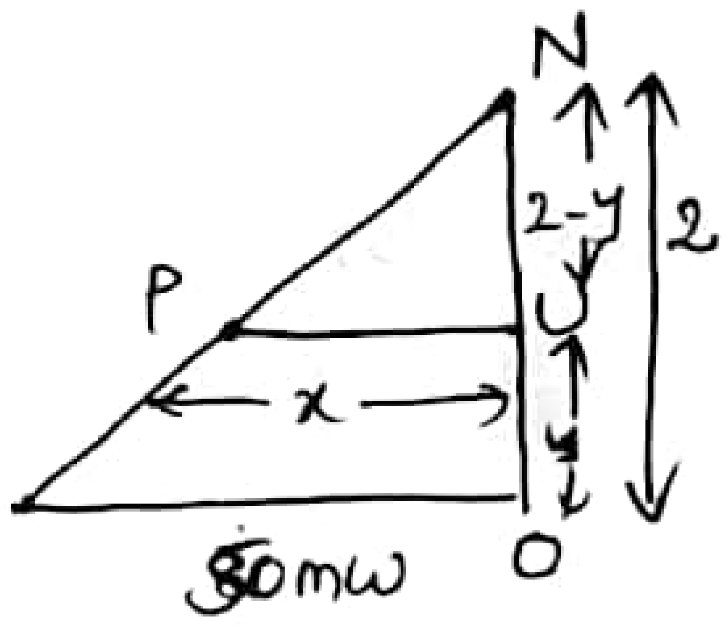
each alternator is of 50 MW load



Draw a PQ line which passes through some point 'U' such that PQ = 60MW (i.e total load)

From R.H.S triangle OLN :-

∴ from triangle properties

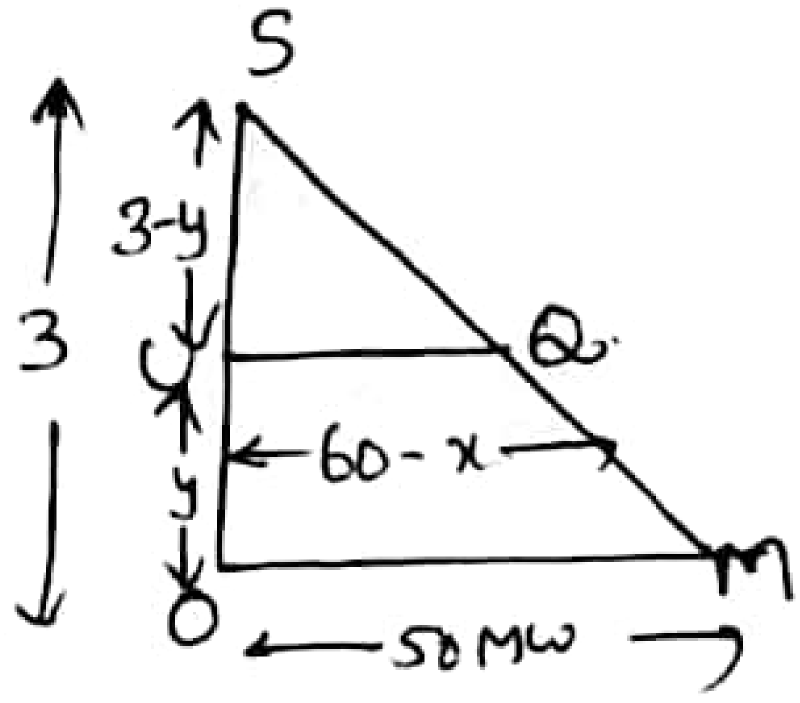


$$\frac{OL}{PU} = \frac{NO}{NU}$$

$$\frac{50}{x} = \frac{2}{2-y} \Rightarrow 2x - 50y + 100 = 0$$

$$\therefore \quad x + 25y = 50 \longrightarrow (1)$$

From R.H.S triangle OMS :-



$$\therefore \frac{OM}{UQ} = \frac{SO}{SU}$$

$$\frac{50}{60-x} = \frac{3}{3-y}$$

$$150 - 50y = 180 - 3x$$

$$3x - 50y = 180 - 150 \Rightarrow$$

$$x - 16.66y = 10 \longrightarrow (2)$$

solving Eq (1) & (2)

$$x + 25y = 50$$

$$x - 16.66y = 10$$

$$41.66y = 40 \Rightarrow y = \frac{40}{41.6} = 0.96$$

from Eq (1)

$$\therefore \quad x = 50 - 25y$$

$$x = 50 - 25 \times 0.96$$

$$x = 26 \text{ MW}$$

$\therefore$ load shared by alternator-1 $\Rightarrow x = 26$ MW

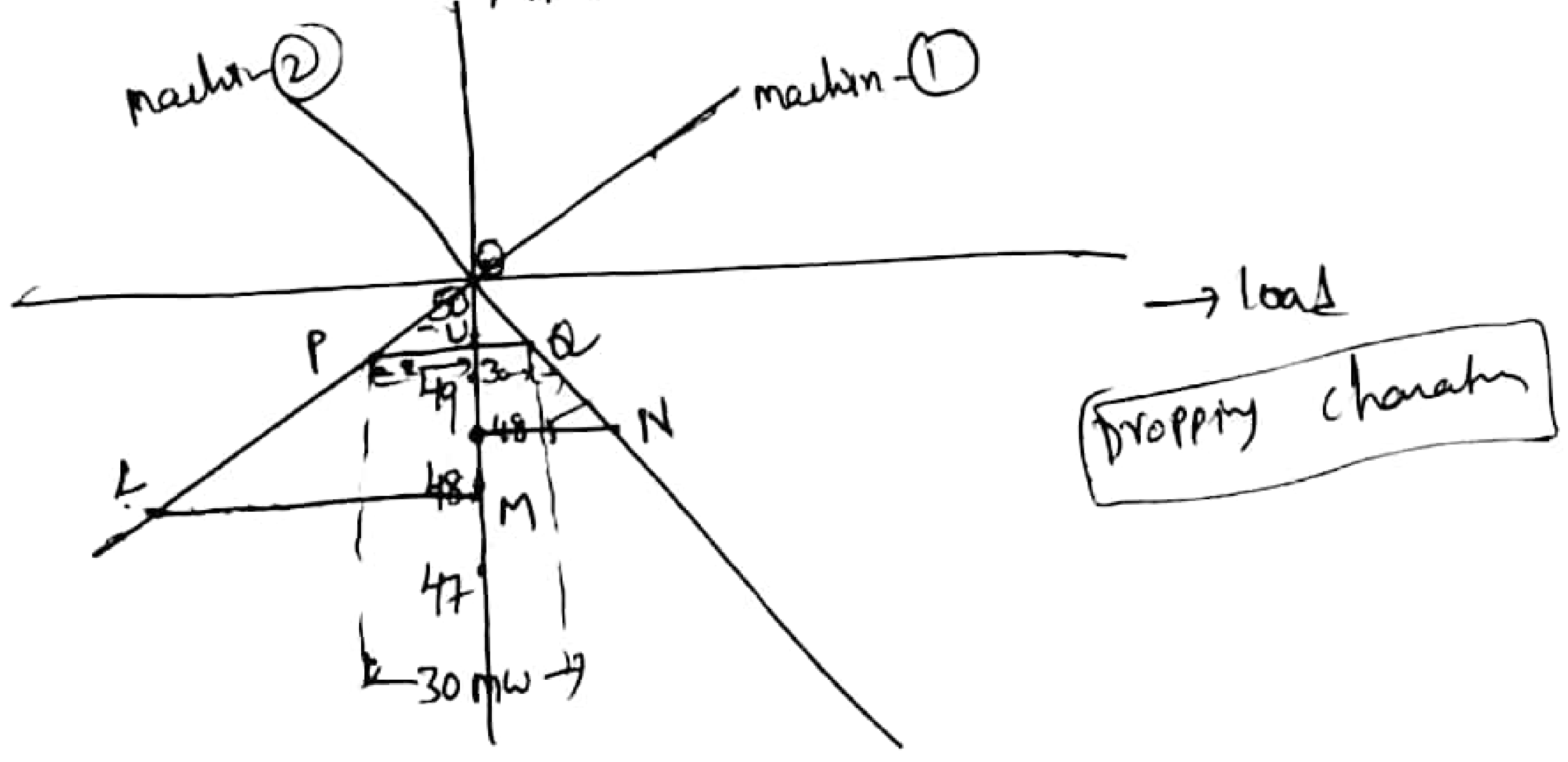
load shared by alternator-2 $\Rightarrow 60 - x$

$\therefore \quad 60 - 26 = 34$ MW

---

3) Two exactly similar turbo alternators are rated at 25MW each. They are running in parallel. The speed-load characteristics of the driving turbines are such that the frequency of alternator-1 drops uniformly from 50Hz on no load to 48 Hz on full load. and the other alternator from 50Hz to 48.5 Hz. How will there two alternator will share a load of 30MW

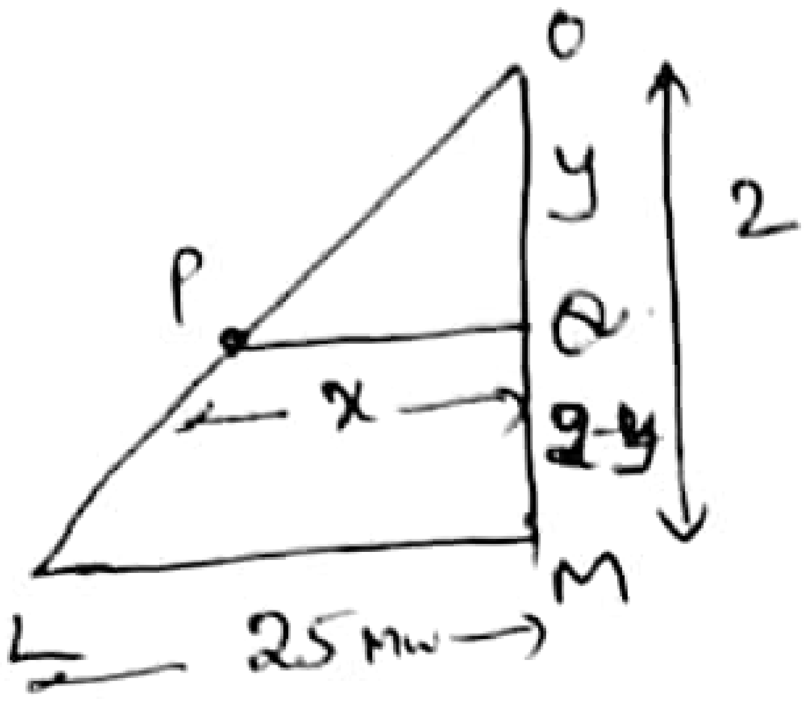
Sol The characteristics obtained here are of dropping characteristics



www.Jntufastupdates.com

Scanned with CamScanner

from L.H.S triangle OLM:



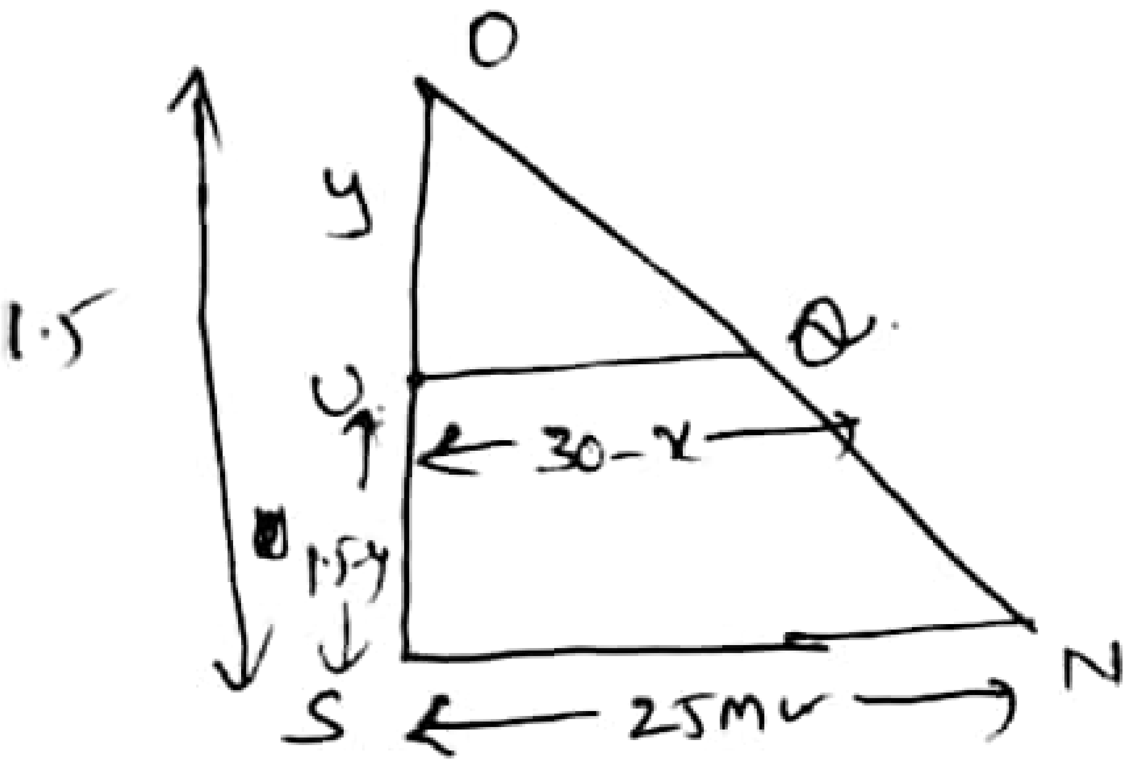
$$\frac{LM}{PQ} = \frac{OM}{OQ}$$

$$\frac{25}{x} = \frac{2}{y}$$

$$2x = 25y$$

$$x = 12.5y \rightarrow (1)$$

from R.H.S triangle OSN



$$\frac{SN}{UQ} = \frac{OS}{OU}$$

$$\frac{25}{30-x} = \frac{1.5}{y}$$

$$25y = 45 - 1.5x \rightarrow (2)$$

Sub (1) value in Eq (2)

$$25y = 45 - 1.5(12.5y)$$

$$25y = 45 - 18.75y$$

$$25y + 18.75y = 45$$

$$\therefore y = \frac{45}{43.75} = 1.028$$

$$\therefore x = 12.5y \Rightarrow 12.5 \times 1.028 = 12.85 \text{ MW}$$

$\therefore$ load shared by alternator-1 = x = 12.85 MW

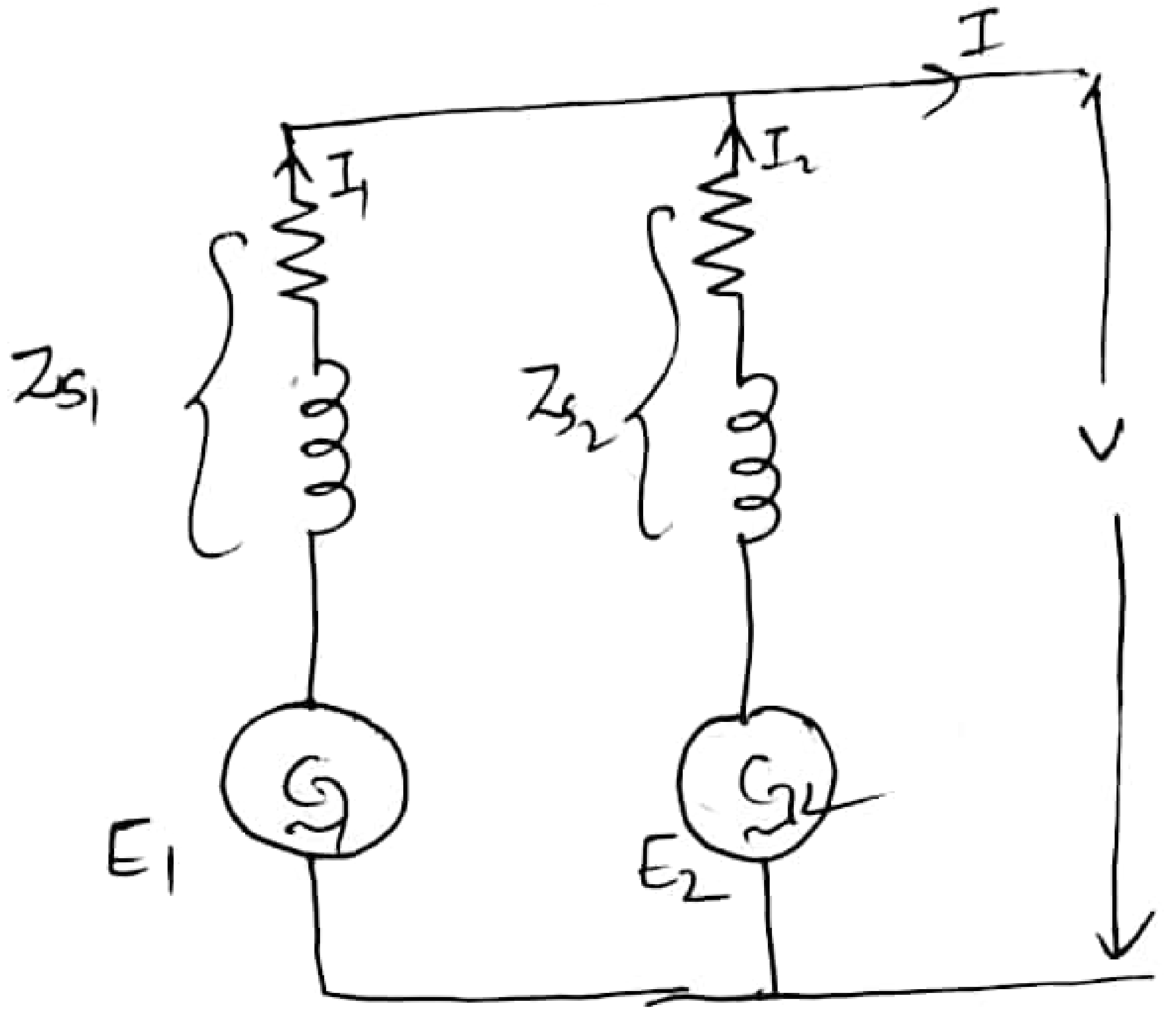
Load shared by alternator-2 → 30 - x

$$= 30 - 12.85$$

$$= 17.15 \text{ MW}$$

Effect of change in Excitation:-

Let us condider two alternators connected in Parallel as shown in below fig.



where Z_{S_1} be The impedance of G_1

Z_{S_2} be the impedance of G_2

'E_1' emf induced in Generator-1

'E_2' be the emf induced in Generator-2

'I_1' be The load current of G_1

'I_2' be The load current of G_2

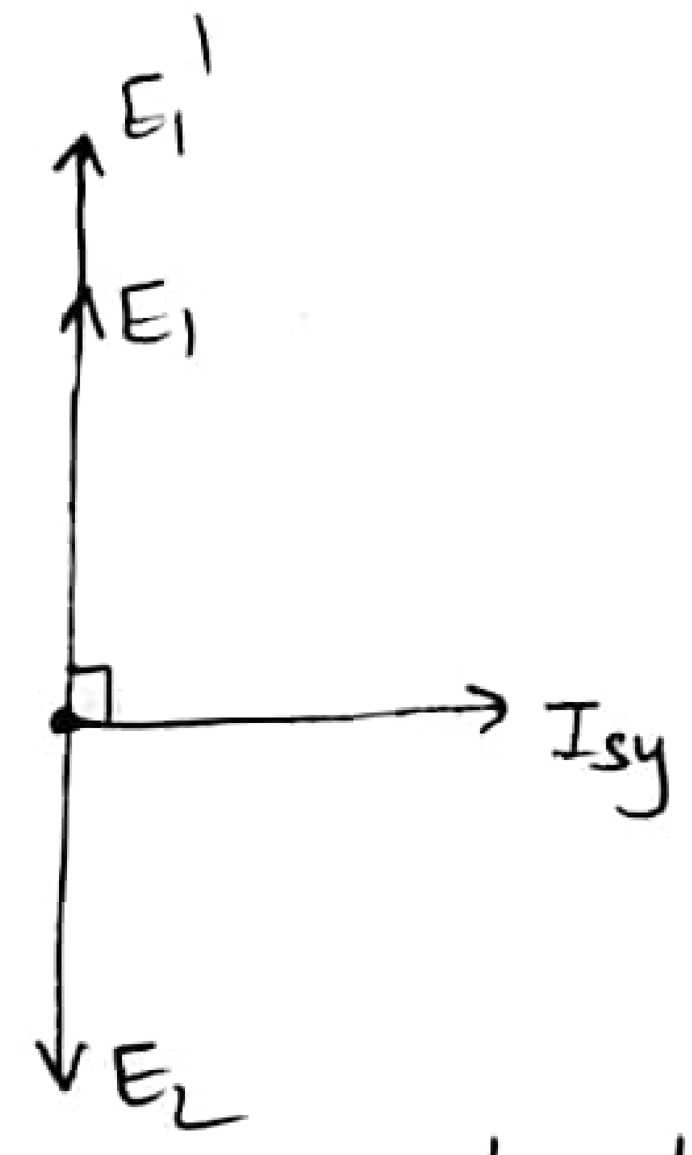
'I' be The total load current of both generators

'V' be terminal voltage.

at normal Excitation The e.m.f Induced in both generators are equal i.e $E_1 = E_2 = E$, i.e both are in opposite direction. In this case there is no circulating currents because the voltage potential drop zero.

$$E_1 \longleftarrow \bullet \longrightarrow E_2$$

If generator-1 Excitation is increased Then the e.m.f Induced in generator-1 is increased i.e E_1 becomes E_1'. $E_1' > E_1$



because of the difference b/w Induced voltage E_1' & E_2 There will be a circulating current produced 'I_{sy}'.

I_{sy} - ~~circulated~~ synchronising current

E_{sy} - synchronizing voltage $= E_1' - E_2$

The I_{sy} lags E_1' by 90° because The resistance value is very small then only Inductance act.

The I_{sy} leads E_2 by 90°

- . I_y lagging E_1' then here de-magnetizing effect present due to this effect the emf induced in generator-1 is increased because flux decreased.
- I_y leads E_2 then here magnetizing effect present due to this effect the flux increased in (G_2) then E_2' value will be increased

$$I_{sy} \rightarrow \text{demagnetise } m/c\text{-}1 \longrightarrow E_1' \downarrow$$
$$I_{sy} \rightarrow \text{magnetise } m/c\text{-}2 \longrightarrow E_2 \uparrow$$
$\Big\}\ V \uparrow$

$$\therefore \quad I_{sy} = \frac{E_1' - E_2}{Z_{s1} + Z_{s2}} = \frac{E_{sy}}{Z_{s1} + Z_{s2}}$$

I_{sy} lag E_1 ($\wedge E_1'$) lags $90°$

∴ The machine-(1) operates at zero p.f lag

The machine (2) operates at zero p.f leads

∴ Synchronizing power

active power

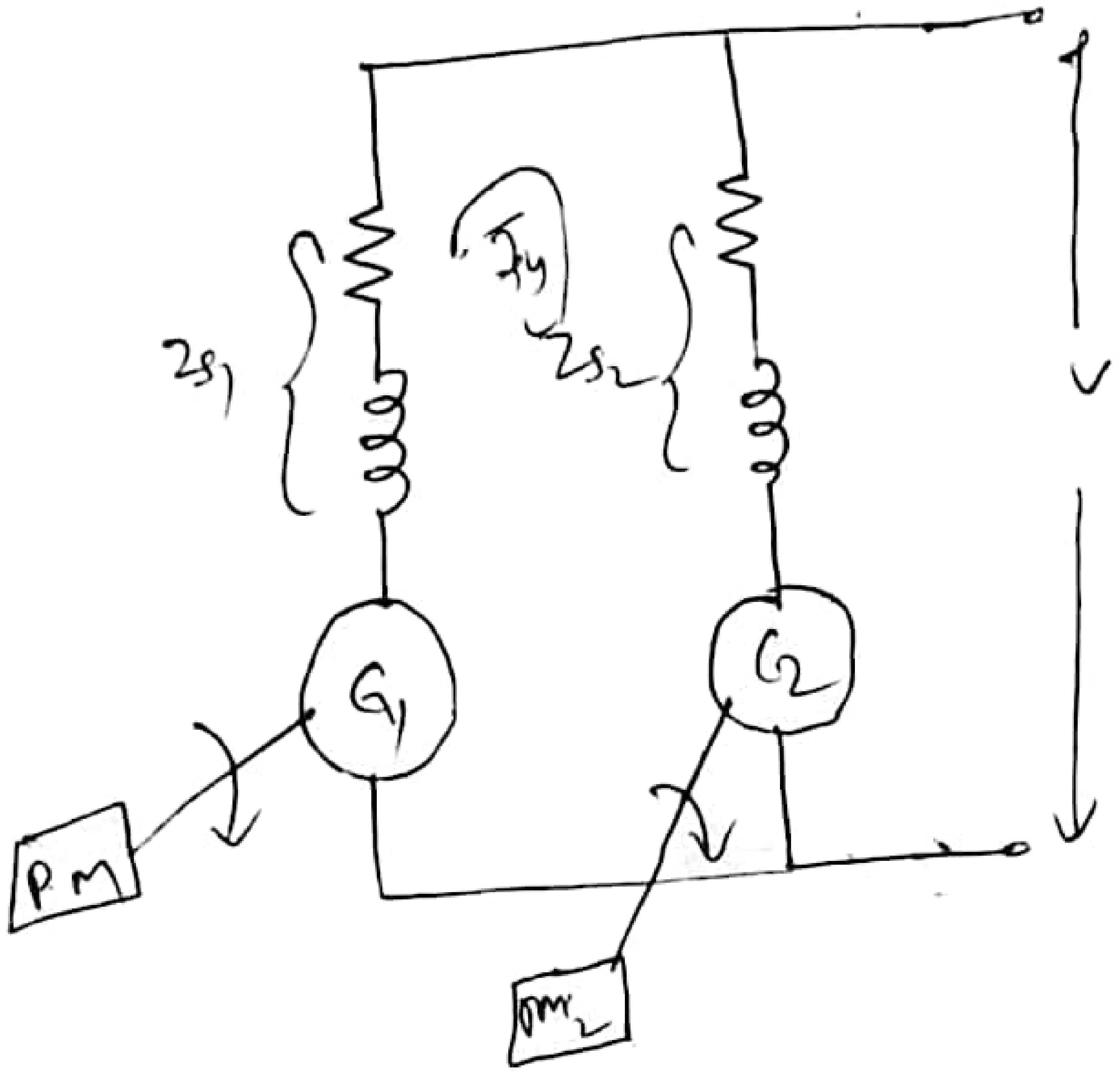
$$P_{s1} = E_1' I_{sy} \cos(90°) = 0$$
$$P_{s2} = E_2 I_{sy} \cos(90°) = 0$$
$\Big\}$ active power zero

Reactive power

$$Q_{s1} = E_1' I_{sy} \sin 90 = E_1' I_{sy}$$
$$Q_{s2} = E_2 I_{sy} \sin(-90) = -E_2 I_{sy}$$
$\Big\}$ → +ve for m/c-1, → -ve for m/c-2

Effect of change in mechanical input (or) Steam input.

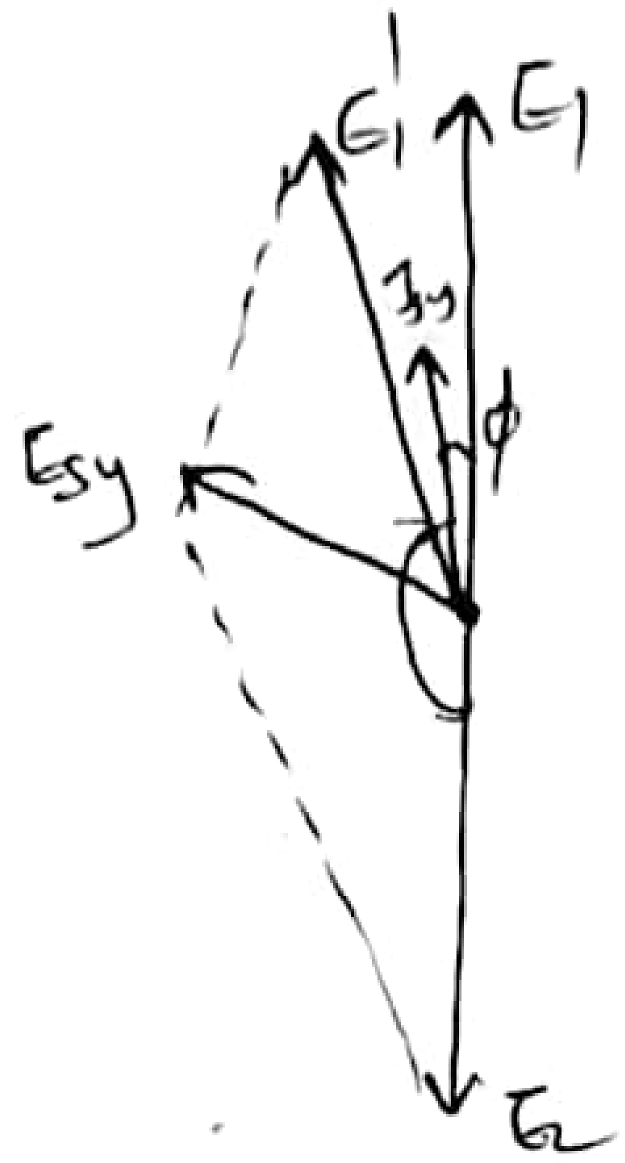
Let us consider two alternators connected in parallel as shown in fig.



- Initially both alternators are running with 1500 rpm.
- There Generator-1 & Generator-2 both are having mechanical input as a prime movers as shown in fig
- If mechanical input to machine-1 is increased then speed of the machine increased if speed is increased then frequency of Generator-1 increased.

speed $\propto$ frequency

If two alternators are running with same mechanical input then E_1 & E_2 are same in phase but opposite direction



∴ The I_{sy} lead E_{sy} by 90°

$$I_{sy} = \frac{E_1' - E_2}{Z_{s1} + Z_{s2}} = \frac{E_{sy}}{Z_{s1} + Z_{s2}}$$

- where the angle b/w E_1' & I_{sy} is nearly '0'

∴ syn. power is active power

$$P_{s1} = E_1' I_{sy} \cos(0)$$

$$= E_1 I_{sy} \longrightarrow \text{for generating}$$

$$P_{s2} = E_2 I_{sy} \cos(180)$$

$$= -E_2 I_{sy} \longrightarrow \text{for motoring.}$$

Reactive power:

$$Q_{s1} = E_1 I_{sy} \sin 0 = 0$$

$$Q_{s2} = E_2 I_{sy} \sin(180) = 0$$

∴ The syn power is not reactive. it is active power

m/c-1 speed↓ Then speed of m/c-2 ↑↑

Conclusion :-

case (i): If mechanical input and Excitation both are changes then the p.f of the load changes.

Note:- The excitation always depends on KVAR (or) p.f and KVAR is controlled by controlling the field current value (I_f)

- The mechanical input (or) steam supply always depends upon active power component i.e 'kw'. And it will not have any effect on 'KVAR' output. This mechanical input is always controlled by controlling the steam input.

case ii):- If excitation is changed and mechanical input is kept constant then KVAR (or) output 'Q' is changed but not kw o/p (P)

so Therefore

$$kw_1 = kw_2$$

and

$$KVAR_1 > KVAR_2$$

$$KVA_1 > KVA_2$$

$$\Rightarrow \phi_1 > \phi_2$$

$$\Rightarrow \cos\phi_1 < \cos\phi_2$$

case iii): If excitation is kept constant and mechanical input is changed then the kw output (P) is changed but not KVAR o/p (Q).

$$\therefore kw_1 > kw_2$$

and

$$KVAR_1 = KVAR_2$$

But

$$KVA_1 < KVA_2$$

$$\rightarrow \phi_1 < \phi_2$$

$$\rightarrow \cos\phi_1 > \cos\phi_2$$

Example 17.5. A 2-pole, 50 Hz, 3-ϕ, turbo-alternator is excited to generate the bus-bar voltage of 11 kV on no load. Calculate the synchronising power per degree of mechanical displacement of the rotor and the corresponding synchronising torque. The machine is star-connected and the short-circuit current for this excitation is 1,200 amperes.

Solution: EMF per phase, $E = \dfrac{11{,}000}{\sqrt{3}} = 6{,}350$ V

Rotor displacement,

$$\delta = 1 \times \frac{P}{2} = 1 \times \frac{2}{2} = 1 \text{ electrical degree or } \frac{\pi}{180} \text{ elec. radian}$$

Synchronous speed,

$$N_s = \frac{120 f}{P} = \frac{120 \times 50}{2} = 3{,}000 \text{ rpm}$$

Synchronous reactance,

$$X_s = \frac{E}{I_{sc}} = \frac{6{,}350}{1{,}200} = 5.292\ \Omega \text{ (neglecting resistance)}$$

Total synchronising power for 3-phases,

$$3\,P_{sy} = \frac{3\delta E^2}{X_s} = \frac{3 \times \pi \times (6.350)^2}{180 \times 5.592}$$

$$= 3{,}77{,}655 \text{ W or } 377.655 \text{ kW } \textbf{Ans.}$$

Synchronising torque,

$$T_{sy} = \frac{3P_{sy} \times 60}{2\pi N_s} = \frac{3{,}77{,}655 \times 60}{2\pi \times 3{,}000} = 1{,}202 \text{ N-m } \textbf{Ans.}$$

Example 17.17. Two identical, 3-phase, star-connected generators operating in parallel, share equally a total load of 750 kW at 6,000 V and power factor 0.8 lagging. The synchronous reactance and resistance of each machine are respectively 50 Ω and 2.5 Ω per phase. The field of the first generator is excited so that the armature current is 40 A (lagging). Find (*i*) the armature current of the second alternator (*ii*) the pf of each machine.

[*J.N. Technological Univ. Electrical Machines-III, May-2013*]

Solution: Total load supplied by the two generators,

$$I_L = \frac{P}{\sqrt{3}\, V_L \cos\phi} = \frac{750 \times 1{,}000}{\sqrt{3} \times 6{,}000 \times 0.8} = 90.21 \text{ A}$$

$$\mathbf{I}_L = I_L \angle -\text{Cos}^{-1} 0.8 = 90.21 \angle -36.87^\circ = (72.168 - j\,54.126) \text{ A}$$

Load supplied by generator $G_1 = \frac{P}{2} = \frac{750}{2} = 375$ kW

Power factor of load supplied by generator G_1,

$$\text{Cos}\,\phi_1 = \frac{P/2}{\sqrt{3} V_L I_{a1}} = \frac{375 \times 1{,}000}{\sqrt{3} \times 6{,}000 \times 40} = 0.90211 \text{ (lagging)}$$

Thus armature current,

$$\mathbf{I}_{a_1} = I_{a_1} \angle -\cos^{-1} 0.90211 = 40 \angle -25.56^\circ \text{ A}$$

$$= (36.084 - j\,17.258) \text{ A}$$

Armature current of generator G_2,

$$\mathbf{I}_{a_2} = \mathbf{I}_L - \mathbf{I}_{a_1} = (72.168 - j\,54.126) - (36.084 - j\,17.258)$$

$$= (36.084 - j\,36.868) = 51.588 \angle -45.62^\circ \text{ A}$$

(*i*) Armature current of the second generator, $I_{a_2} = 51.588$ A

(*ii*) Generator G_1 operates at pf of 0.90211 (lagging) **Ans.**

Generator G_2 operates at pf of cos (–45.62°) = 0.6995 (lagging) **Ans.**

PROBLEM

3. Two 3ϕ alternators operated in parallel have induced emf's $230\angle 0^\circ$ and $230\angle 10^\circ$ respectively. The reactances are $j2\Omega$ and $j3\Omega$ respectively. Calculate

(i) terminal voltage

(ii) currents

(iii) power delivered by each of the alternator to a load of impedance 6Ω resistive

Given:

$E_1 = 230\angle 0^\circ = 230\,V$

$E_2 = 230\angle 10^\circ = 226.5 + j\,39.93\,V$

$Z_1 = j2\Omega = 2\angle 90^\circ\,\Omega$

$Z_2 = j3\Omega = 3\angle 90^\circ\,\Omega$

$Z = 6\Omega$

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

$$= \frac{[230 - (226.5 + j39.93)]\,6 + 230 \times 3\angle 90^\circ}{6\,(j2 + j3) + 2\angle 90^\circ \times 3\angle 90^\circ}$$

$$= \frac{[3.5 - j39.93]\,6 + 690\angle 90^\circ}{j30 + 6\angle 180^\circ}$$

$$= \frac{21 - j\,239.58 + j\,690}{j30 + (-6 + 0j)}$$

$$= \frac{21 + j\,450.42}{-6 + j30}$$

$$= \frac{450.91\angle 87.33}{30.59\angle 101.31}$$

$$= 14.74\angle -13.98^\circ\,A$$

$$= 14.74\angle -14^\circ\,A$$

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

$$= \frac{(226.5 + j39.93 - 230)6 + 230\angle 10^\circ \times 2\angle 90^\circ}{30.59\angle 101.31^\circ}$$

$$= \frac{(-3.5 + j39.93)6 + 460\angle 100^\circ}{30.59\angle 101.31^\circ}$$

$$= \frac{-21 + j239.58 + (-79.87 + j453.01)}{30.59\angle 101.31^\circ}$$

$$= \frac{-100.87 + j692.59}{30.59\angle 101.31^\circ}$$

$$= \frac{699.89\angle 98.28^\circ}{30.59\angle 101.31^\circ}$$

$$= 22.87\angle -3.03^\circ \text{ A}$$

$$I = I_1 + I_2$$

$$= 14.74\angle -14^\circ + 22.87\angle -3.03^\circ$$

$$= 14.30 - j3.56 + 22.83 - j1.208$$

$$= 37.13 - j2.35$$

$$= 37.20\angle -3.62^\circ \text{ A}$$

$$V = IZ$$

$$= 37.20\angle -3.62^\circ \times 6$$

$$= 223.2 \text{ V}$$

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

$$= 223.2 \times 14.74 (\cos 14^\circ)$$

$$= 3192.24 \text{ W} = 3.19 \text{ kW}$$

Power delivered by alternator-2 $= P_2 = V I_2 \cos\phi_2$

$$= 223.2 \times 22.87 \times \cos(3.03)$$

$$= 5097.44 \text{ W}$$

$$= 5.09 \text{ kW}$$

PROBLEM

1) Two alternators working in parallel supplied a lighting load of 3000 kW and a motor load aggregates to 5000 kW at 0.72 pf lagging. What is the load and power factor of the other machine?

lighting load = 3000 kW.

let the pf of lighting load be unity pf. (since not mentioned)

Motor load = 5000 kW.

pf of motor load = 0.72 pf lagging.

load of machine-1 = 5000 kW (at 0.8 pf lagging)

Phase angle of the motor load $\phi_m = \cos^{-1}(0.72)$

$= 43.94°$

KVAR (Q) of load $= P \times \tan\phi_m$

$= 5000 \times \tan(43.94°)$

$= 4819.26$ KVAR.

KVAR (Q) of lighting load $= P \times \tan\phi$

$= 300 \times \tan(0)$

$= 0$.

The total KVAR of the loads = Motor load + lighting load

$= 4819.26 + 0$

$= 4819.26$ KVAR

∴ Total load in kW = Motor + lighting loads.

$= 5000 + 3000$

$= 8000$ kW

load supplied by machine-1 = 5000 kw

KVAR of the machine-1 = $P \times \tan\phi_1$ 5

$\phi_1 = \cos^{-1}(0.8)$

$= 5000 \times \tan(36.86)$

$= 3750$ KVAR.

∴ Total load = load supplied by machine-1 + load supplied by machine

8000 = 5000 + load supplied by machine-2.

→ ∴ load supplied by machine-2 in kw = 8000 - 5000

= 3000 kw

KVAR of machine-2 = total KVAR − KVAR of machine-1

= 4819.26 − 3750.

= 1069.26 KVAR.

∴ tan (phase angle of m/c-2) = $\frac{Q}{P}$

$= \frac{1069.26}{3000}$

$= 0.356$.

$\therefore \phi_{m/c-2} = \tan^{-1}(0.356)$

$= 19.61°$

→ pf of machine-2 = $\cos(19.61)$

= 0.94

www.Jntufastupdates.com

Scanned with CamScanner

PROBLEM

1. A 6600V, 1200 KVA, 3ϕ alternator is delivering full load at 0.8 pf lagging. Its reactance is 25% and resistance is negligible. By changing the excitation the emf is increased by 30% at this load. Calculate the new values of current and pf. This machine is connected in infinite bus bar.

Given: $V_L = 6600V$

$\therefore V_{ph} = \frac{6600}{\sqrt{3}} = 3810.51V$

$\therefore I_{a_1} = \frac{Q}{\sqrt{3}V_L} = \frac{1200 \times 10^3}{\sqrt{3} \times 6600} = 104.97 A$

$\therefore I_{a_1}X_s = 25\% V_{ph}$

$\Rightarrow 104.97 X_s = \frac{25}{100}(3810.51)$

$\Rightarrow 104.97(X_s) = 952.6275$

$X_s = 9.07\Omega$

Given $R_a = 0$ (negligible)

[E = ~~Vph + j IXs~~

= ~~3810.51~~ + j]

$E_{ph_1} = \sqrt{(V_{ph}\cos\phi + I_aR_a)^2 + (V_{ph}\sin\phi + I_aX_s)^2}$

$= \sqrt{[3810.51 \times 0.8 + 104.97 \times 0]^2 + (3810.51 \times 0.6 + 104.97 \times 9.07)^2}$

$= \sqrt{9292791.334 + 10487130.28}$

$= 4447.46 V$

Machine-2 Emf is increased by 30%.

$\Rightarrow E_{ph_2} = E_{ph_1} + \frac{30}{100}\%(E_{ph_1})$

$= 4447.46 + \frac{30}{100}(4447.46)$

$= 4447.46 + 1334.238$

$= 5781.69 V$

When the machines are connected in parallel, then

$V_{ph_1} I_{a_1} \cos\phi_1 = V_{ph_2} I_{a_2} \cos\phi_2$ But $V_{ph_1} = V_{ph_2}$

$\Rightarrow I_{a_1}\cos\phi_1 = I_{a_2}\cos\phi_2 \Rightarrow I_{a_2}\cos\phi_2 = 104.97 \times 0.8 = 83.976$ — ①

Also we have $E_{ph_2} = \sqrt{(V_{ph_2} + \cos\phi_2 I_{a_2} R_a)^2 + (V_{ph_2} \pm \sin\phi_2 I_{a_2} X_s)^2}$

(or) use ... formulae $\Rightarrow E_{ph_2} = \sqrt{(3810.51 + 0)^2 + [3810.51 \pm \sin\phi_2 I_{a_2} 9.07]^2}$

$\Rightarrow (5781.69)^2 = (3810.51)^2 + (3810.51 \pm \sin\phi_2 I_{a_2} 9.07)^2$

$\Rightarrow 18907952.8 = (3810.51 \pm \sin\phi_2 I_{a_2} 9.07)^2$

$\Rightarrow 3810.51 \pm \sin\phi_2 I_{a_2}(9.07) = \sqrt{18907952.8} = 4348.33$

$\Rightarrow \pm \sin\phi_2 I_{a_2}(9.07) = 537.82$

$\Rightarrow \pm \sin\phi_2 I_{a_2} = 59.29$ — ②

$\therefore$ from ① and ②.

$I_{a_2} = \sqrt{(I_{a_2}\cos\phi_2)^2 + (I_{a_2}\sin\phi_2)^2}$

$= \sqrt{(83.976)^2 + (59.29)^2}$

$= 102.79\text{ A}$ $\Rightarrow \boxed{I_{a_2} = 102.79\text{ A}}$

From eq ① $\Rightarrow I_{a_2}\cos\phi_2 = 83.976$

$\Rightarrow 102.79(\cos\phi_2) = 83.976$

$\Rightarrow \cos\phi_2 = 0.8169$

$\Rightarrow \boxed{\cos\phi_2 = 0.816}$

$E_{ph} = V_{ph} + jI_a \cdot X_s$

$= V_{ph}\angle 0^\circ + jI_a\angle{-\phi} \cdot X_s = I_a\angle{-\phi}\angle 90 \cdot X_s$

$= V_{ph}(\cos\theta + j\sin\theta) + I_a\angle 90-\phi \cdot X_s$

$= V_{ph}\cos\theta + jV_{ph}\sin\theta + I_a X_s(\cos(90-\phi) + j\sin(90-\phi))$

$= V_{ph} + \ldots$

$= (V_{ph} + I_a X_s \sin\phi + jI_a X_s \cos\phi)$

$E_{ph_2} = (V_{ph_2} + I_{a_2} X_s \sin\phi_2 + jI_{a_2} X_s \cdot \cos\phi_2)$

$= \sqrt{(V_{ph_2} + I_{a_2} X_s \sin\phi_2)^2 + (I_{a_2} X_s \cos\phi_2)^2}$

Prbm②. 6.6 kV, 1 MVA, reactance is 20%, Emf is ↑ by 25%.

Ans: $I_{a_2} = 190.51\text{ A}$

$\cos\phi_2 = 0.369$