Subject: Alternating Current Machines – 2 (26771)

Topic name: Understand the principle of alternator.

1.1 Define Alternator.
1.2 Explain the principle of alternator.
1.3 Differentiate between Alternator and DC generator.
1.4 Describe the methods of excitation of alternator.
1.5 Explain the rating of alternator.

Alternator :

An **alternator** is an electrical generator that converts mechanical energy to electrical energy in the form of alternating current. For reasons of cost and simplicity, most alternators use a rotating magnetic field with a stationary armature. Occasionally, a linear alternator or a rotating armature with a stationary magnetic field is used. In principle, any AC electrical generator can be called an alternator, Working principle:

Conductor moving relative to a magnetic field develops an electromotive force (EMF) in it (Faraday's Law). This EMF reverses its polarity when it moves under magnetic poles of opposite polarity. Typically, a rotating magnet, called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an induced EMF (electromotive force), as the mechanical input causes the rotor to turn.

The rotating magnetic field induces an AC voltage in the stator windings. Since the currents in the stator windings vary in step with the position of the rotor, an alternator is a synchronous generator.

The rotor's magnetic field may be produced by permanent magnets, or by a field coil electromagnet. Automotive alternators use a rotor winding which allows control of the alternator's generated voltage by varying the current in the rotor field winding. Permanent magnet machines avoid the loss due to magnetizing current in the rotor, but are restricted in size, due to the cost of the magnet material. Since the permanent magnet field is constant, the terminal voltage varies directly with the speed of the generator. Brushless AC generators are usually larger than those used in automotive applications.

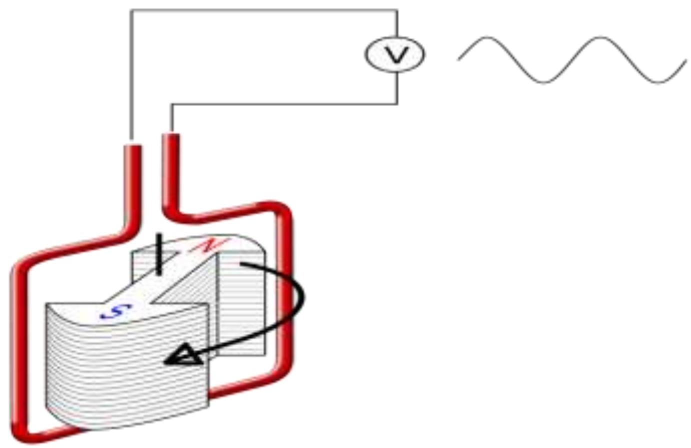


Diagram of a simple alternator with a rotating magnetic core (rotor) and stationary wire (stator) also showing the current induced in the stator by the rotating magnetic field of the rotor.

Difference Between Alternator & Generator

The major difference between the alternator and the generator is that in alternator the armature is stationary and the field system rotates whereas in the generator armature rotates and field is stationary. The armature of the alternator is mounted on the stationary element called stator and field winding on a rotating element. While the connection of a generator is just the reverse of it.

The generator induces both the alternating and direct current and the alternator produces only alternating current.

The rotor of the generator is placed inside the stationary magnetic field. The stationary magnetic field is produced by the magnetic poles. The rotor moves inside the magnetic field, intersects the magnetic line of force which induces the current in the wire.

Every half rotation of rotor changes the direction of the current which causes the alternating current. For getting the alternating current, the ends of the circuit is directly connected to the load. But for producing the direct current, the ends of the wire is connected to the commutator.

The commutator converts the alternating current into direct current.

Basis for Comparison	Alternator	Generator
Definition	A machine that converts the mechanical energy into AC electrical power.	A machine that changes mechanical energy into electrical energy (AC or DC).
Current	Induces alternating current	Generate both AC & DC.
Magnetic Field	Rotating	Stationary
Input Supply	Takes from stator.	Takes from rotor.
Armature	Stationary	Rotatory
Output EMF	Alternating	Constant
RPM (Rotation per minute)	Wide Range	Narrow Range
Dead Battery	Do not charge	charge
Output	Higher	Lower

Excitation System :

Definition:

The system which is used for providing the necessary field current to the rotor winding of the synchronous machine, such type of system is called an excitation system. In other words, excitation system is defined as the system which is used for the production of the flux by passing current in the field winding. The main requirement of an excitation system is reliability under all conditions of service, a simplicity of control, ease of maintenance, stability and fast transient response. The amount of excitation required depends on the load current, load power factor and speed of the machine.

The more excitation is needed in the system when the load current is large, the speed is less, and the power factor of the system becomes lagging.

The excitation system is the single unit in which the each alternator has its exciter in the form of generator. The centralised excitation system has two or more exciter which feeds the bus-bar. The centralised system is very cheap, but the fault in the system adversely affects the alternators in the power plant.

Rating of Alternator :

Power **rating** of an **alternator** is **defined** as the power which can be delivered by an **alternator** safely and efficiently under some specific conditions. ... Although losses of the **alternator** depend upon its KVA or MVA **rating**, actual output varies with electrical power factor.

For example :

KVA Rating: 5,88,000

Power Factor: 0.85 lag

Kilo Watt Rating: 5000

R.P.M: 3000

The table below shown a standard rating plate of alternator	
Make	……………
Kilo Watt Rating	5000
Power Factor	0.85 lag
KVA Rating	5,88,000
Stator Volt	21,000
Stator Ampere	16,200
Rotor Volt	340
Rotor Ampere	4040
R.P.M	3000
Hz	50
Phase	3
Armature Connection	Double Star
Coolant	Water & Hydrogen (Forced)
Gas Pressure	3.5 bar
Insulation Type	+ F
Type	……………
Specification	IS5422 & IEC34
Product Serial Number	……………
Manufacturing Year	

Lecture- 2 **Time: 50 min.**

2. Perceive the constructional features of alternators.

2.1 List the main parts of alternator.
2.2 Explain the advantages of stationary armature.
2.3 Describe the stator frame & stator core.
2.4 Classify rotor of alternator.
2.5 Describe salient pole type rotor and cylindrical type rotor.
2.6 Describe damper winding.

Main parts of alternator:

Alternators typically consist of front plate, back plate, stator, rectifier, rotor, front bearing, back bearing, pulley, and a regulator. These are the **main parts** of an **alternator**. The front and back plate of an **alternator** is used to enclose the **alternator** together. **An alternator has three main components, each playing a specific role to keep the car's battery fully charged.**

Rotor and Stator. The rotor and stator of an alternator are a belt-driven group of magnets inside copper wiring that creates a magnetic field. ...

Diode Assembly. ...

Voltage Regulator.

1. Stator 2. Rotor

Advantages of Stationary Armature:

1. It is easier to insulate stationary winding for high voltages for which the alternators are usually designed. It is because they are not subjected to centrifugal forces and also extra space is available due to the stationary arrangement of the armature.
2. The stationary 3-phase armature can be directly connected to load without going through large, unreliable slip rings and brushes.
3. Only two slip rings are required for d.c. supply to the field winding on the rotor. Since the exciting current is small, the slip rings and brush gear required are of light construction.

Due to the simple and robust construction of the rotor, the higher speed of rotating DC field is possible. This increases the output obtainable from a machine of given dimensions.

Salient Pole Rotor :

In **salient pole** type of rotor consist of large number of **projected poles** (salient poles) mounted on a magnetic wheel. **Construction of a salient pole rotor** is as shown in the figure at left. The projected poles are made up from laminations of steel. The rotor winding is provided on these poles and it is supported by pole shoes.

Salient pole rotors have large diameter and shorter axial length.

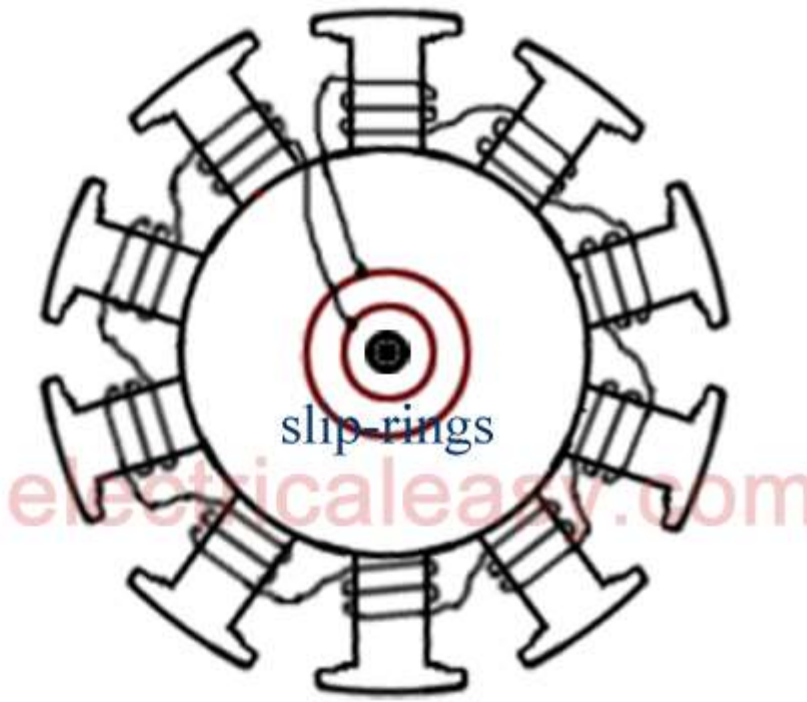
They are generally used in lower speed electrical machines, say 100 RPM to 1500 RPM.

As the rotor speed is lower, more number of poles are required to attain the required frequency. (Ns = 120f / P therefore, f = Ns*p/120 i.e. frequency is proportional to number of poles). Typically number of salient poles is between 4 to 60.

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



Salient Pole Rotor

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 above. 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.

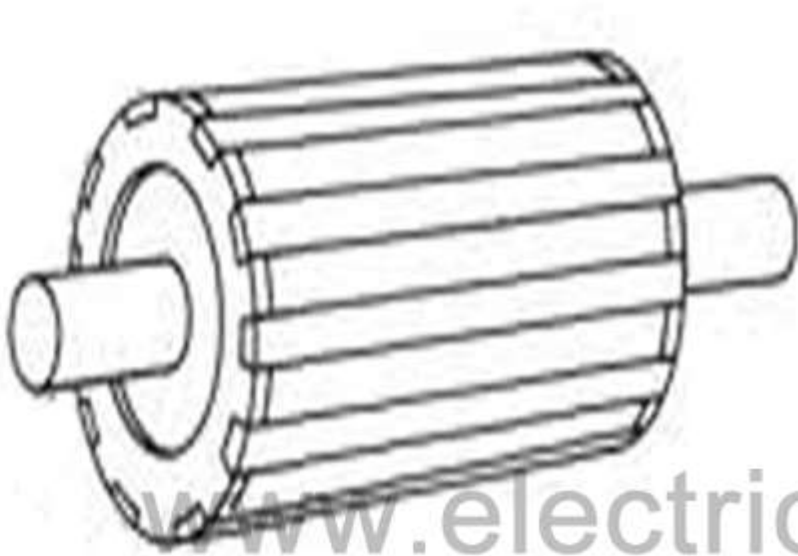
Their construction is robust as compared to salient pole rotors.

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.



Cylindrical rotor

Cross sectional view

Non-Salient Pole (Cylindrical) Rotor

Definition of **damper winding**. :

a short-circuited squirrel-cage **winding** placed in the pole faces and around the pole shoes of synchronous machines, the currents induced in the **winding** by the periodic variations in synchronous speed having the effect of a **damper**. — called also amortisseur. IMPACT OF **DAMPER WINDING** IN SYNCHRONOUS MACHINE **Damper windings** helps the synchronous motor to start on its own (self starting machine) by providing starting torque. ... These machines are made self starting by providing a special **winding** in the rotor poles, known as **damper winding** or squirrel cage **windings**.

The function of the **damper winding** in the synchronous generator is to suppress the negative sequence field and to dampen oscillation whereas it is used to provide starting torque and reduce effect of **hunting** to some extent in the synchronous motor.

Lecture- 3 **Time: 50 min.**

2.7 Describe three phase armature windings of single layer and double layer type.

2.8 Explain pitch factor and distribution factor.

2.9 Explain fractional pitch, full pitch, half coiled winding and whole coiled winding.

2.10 List the advantages of fractional pitch winding.

2.11 Solve problems related to pitch factor & distribution factor.

Click here to see the video of armature winding .

Single layer and double layer :

In a double layer winding, we have as many coils as number of slots. This is because each slot accommodates two coil sides.
The double layer winding is almost universally used in large motors and generators. This is primarily due to ease of winding. In a double layer winding, all coils have the same shape (unlike single layer winding) and winding is therefore easier. Thus, there is overall reduction in the cost of winding.

In a single layer winding, number of coils is half of the number of slots because each slot accommodates one coil side only.

Single layer winding has the advantage that it can use semi closed or closed slots. This results in quieter machine operation, lesser tooth loss and lesser ampere turns required to produce a given air gap flux. However, due to cumbersome winding process, single layer winding is popular with small machines only.

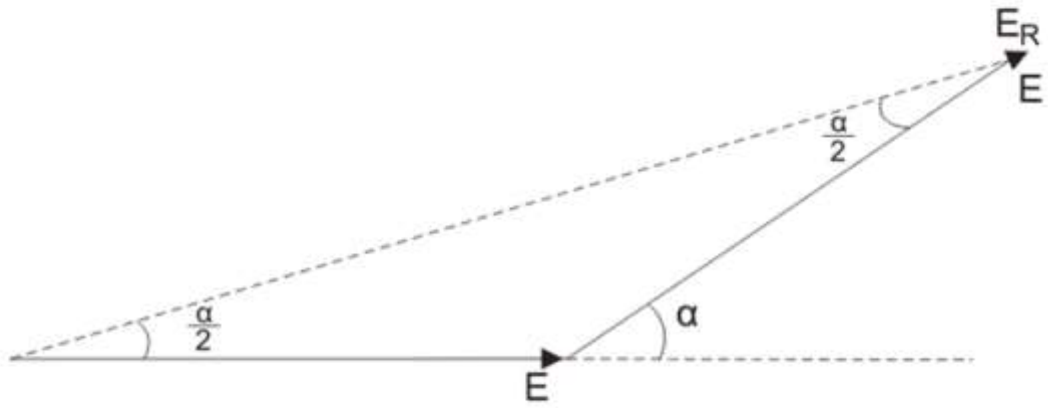
When each side of a coil occupies a slot completely without any other coil lying on top of it and the number of coils equals half the number of slots, the **winding** is known as single **layer winding** [1]. Concentric **winding** or chain **winding** types are common and in this type of **winding**, short-pitched coils cannot be used.

Pitch factor :

The **pitch factor** is the measure of resultant emf of a short**-pitched** coil in comparison with resultant emf of a full **pitched** coil. Hence, it must be the ratio of phasor sum of induced emfs per coil to the arithmetic sum of induced emfs per coil. Therefore, it must be less than unity. Hence, it must be the ratio of phasor sum of induced emfs per coil to the arithmetic sum of induced emfs per coil. Therefore, it must be less than unity.

Let us assume that, a coil is short pitched by an angle α (electrical degree). Emf induced per coil side is E. The arithmetic sum of induced emfs is 2E. That means, 2E, is the induced voltage across the coil terminals, if the coil would have been full pitched.

Now, come to the short pitched coil. From the figure below it is clear that, resultant emf of the short pitched coil



Now, as per **definition of pitched factor,**

$$K_p = \frac{Resultant\ emf\ of\ short\ pitched\ coil}{Resultant\ emf\ of\ full\ pitched\ coil}$$

$$= \frac{Phasor\ sum\ of\ coil\ side\ emfs}{Arithmetic\ sum\ of\ coil\ side\ emfs}$$

$$= \frac{2E\cos\frac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2}$$

Distribution Factor :

The **Distribution Factor** or the Breadth **Factor** is defined as the ratio of the actual voltage obtained to the possible voltage if all the coils of a polar group were concentrated in a single slot.
As per definition, distribution factor is a measure of resultant emf of a distributed winding in compared to a concentrated winding.
We express it as the ratio of the phasor sum of the emfs induced in all the coils distributed in some slots under one pole to the arithmetic sum of the emfs induced.

Derivation of Distribution factor is given below :

Let β be the value of angular displacement between the slots. Its value is

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

Let m = No. of slots/phase/pole

$m\beta$ = phase spread angle

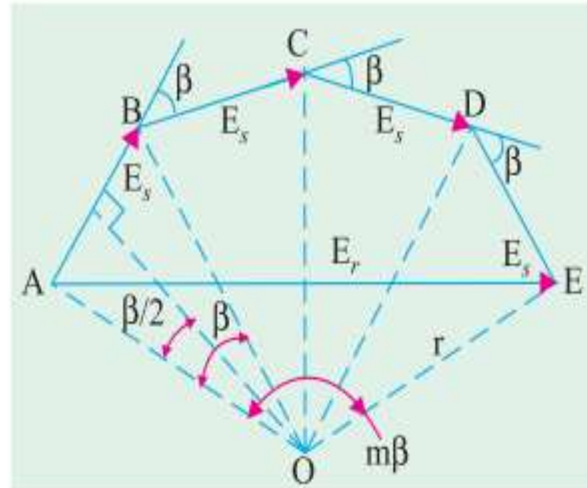


Fig. 37.21

Then, the resultant voltage induced in one polar group would be mE_S where E_S is the voltage induced in one coil side. Fig. 37.21 illustrates the method for finding the vector sum of m voltages each of value E_S and having a mutual phase difference of β (if m is large, then the curve $ABCDE$ will become part of a circle of radius r).

$$AB = E_S = 2r \sin \beta /2$$

$$\text{Arithmetic sum is } = mE_S = m \times 2r \sin \beta /2$$

$$\text{Their vector sum} = AE = E_r = 2r \sin m\beta /2$$

$$k_d = \frac{\text{vector sum of coils e.m.fs.}}{\text{arithmetic sum of coil e.m.fs.}}$$

$$= \frac{2r \sin m\beta /2}{m \times 2r \sin \beta /2} = \frac{\sin m\beta /2}{m \sin \beta /2}$$

Explain fractional pitch, full pitch, half coiled winding and whole coiled winding :

When the angular distance between the sides of a coil is less than the angular distance between the centers of adjacent field poles, the coil is termed to be a **fractional pitch** coil. An armature **winding** made up of **fractional pitch** coils is termed a **Fractional Pitch winding**.

Definition of full-pitch winding :

: the **winding** of an armature in which the two sides of the armature **coil** span a distance equal to the pole **pitch**.

It is a concentrated **winding** because all the **coils** of one phase are concentrated in the same slot under one pole. It is a **half-coil winding** because there is only one-**half** of a **coil** (one **coil** side) in each slot

whole coiled winding : The number of slot is equal to the number of coils. there are two **halves** of the **coil** (two **coil** sides) in each slot.

List the advantages of fractional pitch winding .

The advantages of short pitch winding are:

Waveform of induces EMF can be approximately made into a sine wave and losses due to harmonics can be totally reduced or eliminated.

Conductor material, copper, is saved in the back and in the front due to less copper span.

Fractional slot winding or fractional coils can /be used which in turn reduces losses due to the tooth ripple.

Mechanical strength of the coil is increased.

Problem:

In a 4 pole, 3 phase alternator, armature has 36 slots. It is using an armature winding which is short pitched by one slot. Calculate its coil span factor.

Solution :

n = Slots/pole = 36/4 = 9

$\beta = 180^o / = 20^o$

Now coil is shorted by 1 slot i.e. by 20^o to full pitch distance.

∴ α = Angle of short pitch = 20^o

∴ $K_c = \cos(\alpha/2) = \cos(10)$

$= 0.9848$

Example 37.8. *The stator of a 3-phase, 16-pole alternator has 144 slots and there are 4 conductors per slot connected in two layers and the conductors of each phase are connected in series. If the speed of the alternator is 375 r.p.m., calculate the e.m.f. inducted per phase. Resultant flux in the air-gap is 5×10^{-2} webers per pole sinusoidally distributed. Assume the coil span as 150° electrical.*

Solution. For sinusoidal flux distribution, $k_f = 1.11$; $\alpha = (180° - 150°) = 30°$ (elect)

$$k_c = \cos 30°/2 = 0.966^*$$

No. of slots / pole, $n = 144/16 = 9$;

$$\beta = 180°/9 = 20°$$

$$m = \text{No. of slots/pole/phase} = 144/16 \times 3 = 3$$

$$\therefore \quad k_d = \frac{\sin m\beta/2}{m \sin \beta/2} = \frac{\sin 3 \times 20°/2}{3 \sin 20°/2} = 0.96; \; f = 16 \times 375/120 = 50 \text{ Hz}$$

No. of slots / phase = 144/3 = 48; No of conductors / slot = 4

$\therefore$ No. of conductors in series/phase = 48 × 4 = 192

$\therefore$ turns / phase = conductors per phase/2 = 192/2 = 96

$$E_{ph} = 4\, k_f\, k_c\, k_d\, f \Phi\, T$$

$$= 4 \times 1.11 \times 0.966 \times 0.96 \times 50 \times 5 \times 10^{-2} \times 96 = \mathbf{988\ V}$$

Lecture- 4 **Time: 50 min.**

. Understand the principle of emf equation.

3.1 Describe emf equation.
3.2 Define Harmonics: fundamental, 3rd harmonic and 5th harmonic.
3.3 Explain the effect of pitch factor and distribution factor on harmonics.
3.4 Solve problems related to emf equation.

37.13. Equation of Induced E.M.F.

Let Z = No. of conductors or coil sides in series/phase

$= 2T$ — where T is the No. of coils or turns per phase (remember one turn or coil has two sides)

P = No. of poles

f = frequency of induced e.m.f. in Hz

Φ = flux/pole in webers

$$k_d = \text{distribution factor} = \frac{\sin m\beta/2}{m \sin \beta/2}$$

k_c or k_p = pitch or coil span factor $= \cos \alpha/2$

k_f = from factor = **1.11** —if e.m.f. is assumed sinusoidal

N = rotor r.p.m.

In one revolution of the rotor (*i.e.* in 60./N second) each stator conductor is cut by a flux of ΦP webers.

$$\therefore \quad d\Phi = \Phi P \text{ and } dt = 60/N \text{ second}$$

$$\therefore \quad \text{Average e.m.f. induced per conductor} = \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60}$$

Now, we know that $f = PN/120$ or $N = 120\, f/P$

Substituting this value of N above, we get

$$\text{Average e.m.f. per conductor} = \frac{\Phi P}{60} \times \frac{120 f}{P} = 2 f \Phi \text{ volt}$$

If there are Z conductors in series/phase, then Average e.m.f./phase $= 2f\Phi Z$ volt $= 4 f\Phi T$ volt

R.M.S. value of e.m.f./phase $= 1.11 \times 4f\Phi T = 4.44 f\Phi T$ volt*.

This would have been the actual value of the induced voltage if all the coils in a phase were (*i*) full-pitched and (*ii*) concentrated or bunched in one slot (instead of being distributed in several slots under poles). But this not being so, the actually available voltage is reduced in the ratio of these two factors.

$$\therefore \quad \text{Actually available voltage/phase} = 4.44\, k_c k_d f \Phi T = 4\, k_f k_c k_d f \Phi T \text{ volt.}$$

If the alternator is star-connected (as is usually the case) then the line voltage is $\sqrt{3}$ times the phase voltage (as found from the above formula).

Define Harmonics: fundamental, 3rd harmonic and 5th harmonic.

Harmonics are voltages or currents that operate at a frequency that is an integer (whole-number) multiple of the **fundamental** frequency. So given a 50Hz **fundamental** waveform, this means a 2nd **harmonic** frequency would be 100Hz (2 x 50Hz), a **3rd harmonic** would be 150Hz (**3** x 50Hz), a **5th** at 250Hz, a 7th at 350Hz and so on.

Explain the effect of pitch factor and distribution factor on harmonics.

37.14. Effect of Harmonics on Pitch and Distribution Factors

(*a*) If the short-pitch angle or chording angle is α degrees (electrical) for the fundamental flux wave, then its values for different harmonics are

for 3rd harmonic $= 3\alpha$; for 5th harmonic $= 5\alpha$ and so on.

∴ pitch-factor, $k_c = \cos \alpha/2$ —for fundamental

$= \cos 3\alpha/2$ —for 3rd harmonic

$= \cos 5\alpha/2$ —for 5th harmonic etc.

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

$$k_d = \frac{\sin m\beta/2}{m \sin \beta/2}$$ where *n* is the order of the harmonic

for fundamental, $n = 1$ $k_{d1} = \dfrac{\sin m\beta/2}{m \sin \beta/2}$

for 3rd harmonic, $n = 3$ $k_{d3} = \dfrac{\sin 3m\beta/2}{m \sin 3\beta/2}$

for 5th harmonic, $n = 5$ $k_{d5} = \dfrac{\sin 5m\beta/2}{m \sin 5\beta/2}$

(*c*) Frequency is also changed. If fundamental frequency is 50 Hz *i.e.* $f_1 = 50$ Hz then other frequencies are :

3rd harmonic, $f_3 = 3 \times 50 = 150$ Hz, 5th harmonic, $f_5 = 5 \times 50 = 250$ Hz etc.

Solve problems related to emf equation.

Example 37.5. *An alternator has 18 slots/pole and the first coil lies in slots 1 and 16. Calculate the pitch factor for* **(i)** *fundamental* **(ii)** *3rd harmonic* **(iii)** *5th harmonic and* **(iv)** *7th harmonic.*

Solution. Here, coil span is $= (16 - 1) = 15$ slots, which falls short by 3 slots.

Hence, $\alpha = 180° \times 3/18 = 30°$

(*i*) $k_{c1} = \cos 30°/2 = \cos 15° =$ **0.966** **(*ii*)** $k_{c3} = \cos 3 \times 30°/2 =$ **0.707**

(*iii*) $k_{c5} = \cos 5 \times 30°/2 = \cos 75° =$ **0.259** **(*iv*)** $k_{c7} = \cos 7 \times 30°/2 = \cos 105° = \cos 75° =$ **0.259.**

Example 37.13. *Calculate the R.M.S. value of the induced e.m.f. per phase of a 10-pole, 3-phase, 50-Hz alternator with 2 slots per pole per phase and 4 conductors per slot in two layers. The coil span is 150°. The flux per pole has a fundamental component of 0.12 Wb and a 20% third component.* **(Elect. Machines-III, Punjab Univ. 1991)**

Solution. Fundamental E.M.F.

$$\alpha = (180° - 150°) = 30°;\ k_{c1} = \cos\alpha/2 = \cos 15° = 0.966$$

$$m = 2\ ;\ \text{No. of slots/pole} = 6\ ;\ \beta = 180°/6 = 30°$$

$$\therefore \quad k_{d1} = \frac{\sin m\beta/2}{m \sin\beta/2} = \frac{\sin 2\times 30°/2}{2\sin 30°/2} = 0.966$$

$$Z = 10\times 2\times 4 = 80\ ;\ \text{turn/phase, } T = 80/2 = 40$$

$\therefore$ Fundamental E.M.F./phase $= 4.44\, k_c k_d f \Phi\, T$

$$\therefore \quad E_1 = 4.44\times 0.966\times 0.966\times 50\times 0.12\times 40 = 995\text{V}$$

Hormonic E.M.F.

$$K_{c3} = \cos 3\alpha/2 = \cos 3\times 30°/2 = \cos 45° = 0.707$$

$$k_{d3} = \frac{\sin mn\beta/2}{m\sin n\beta/2} \quad \text{where } n \text{ is the order of the harmonic } i.e.\ n = 3$$

$$\therefore \quad k_{d3} = \frac{\sin 2\times 3\times 30°/2}{2\sin 3\times 30°/2} = \frac{\sin 90°}{2\sin 45°} = 0.707,\ f_2 = 50\times 3 = 150\text{ Hz}$$

$$\Phi_3 = (1/3)\times 20\%\text{ of fundamental flux} = (1/3)\times 0.02\times 0.12 = 0.008\text{ Wb}$$

$$\therefore \quad E_3 = 4.44\times 0.707\times 0.707\times 150\times 0.008\times 40 = 106\text{ V}$$

$$\therefore \quad E\text{ per phase} = \sqrt{E_1^2 + E_3^2} = \sqrt{995^2 + 106^2} = \mathbf{1000\ V}$$

Lecture- 5 **Time: 50 min.**

4. Evaluate the effect of load and no load condition of an alternator.

4.1 Describe alternator on no load.

4.2 Describe the effect of resistance and leakage reactance on an alternator.

4.3 Explain the effect of armature reaction on emf of alternator.

4.4 Explain synchronous reactance and synchronous impedance.

4.5 Draw the vector diagram of a loaded alternator.

Explain synchronous reactance and synchronous impedance.

This leakage flux makes the armature winding inductive in nature. So winding possesses a leakage reacatnce, in addition to the resistance.

The effect of armature flux in an alternator depends on Magnitude of current flowing through the armature winding and Nature of power factor of the load connected to the alternator.

the synchronous reactance of an alternator is equal to Sum of leakage reactance and armature reaction reactance.

the **Synchronous Impedance** Z_S is a fictitious impedance employed to account for the voltage effects in the armature circuit produced by the actual armature resistance, the actual armature leakage reactance and the change in the air gap flux produced by the armature reaction.

Describe the effect of resistance and leakage reactance on an alternator.

The actual generated voltage consists of the summation of the two component voltages. One of these component voltages that would be generated if there were no armature reaction. It is the voltage that would be generated because of only the field excitation. This component of the generated voltage is called the **Excitation Voltage** (E_{exc}).
The other component of the generated voltage is known as the **Armature Reaction Voltage** (E_{AR}). Thus, the two voltages that are the armature reaction voltage and the excitation voltage are added to keep a check on the effect of armature reaction upon the generated voltage. The equation is shown below.

$$E_a = E_{exc} + E_{AR} \quad \dots\dots\dots (1)$$

The voltage in a circuit caused by the change in the flux by the current is a result of armature reaction. The nature of this effect is inductive reactance. Therefore, E_{AR} is equivalent to a voltage of inductive reactance and is given by the equation shown below.

$$E_{AR} = -jX_{AR}I_a \quad \dots\dots (2)$$

The Inductive Reactance X_{AR} is a fictitious reactance. As a result a voltage is generated in the armature circuit. Therefore, armature reaction voltage can be modeled as an inductor in series with the internally generated voltage.

In addition to the effects of armature reaction, the stator winding also has a self-inductance and resistance.

Let, L_a is the self-inductance of the stator winding

X_a is the self-inductive reactance of stator winding

R_a is the armature stator resistance.

The terminal voltage V is given by the equation shown below.

$$V = E_a - jX_{AR}I_a - jX_aI_a - R_aI_a \ldots\ldots (3)$$

R_aI_a is the armature resistance drop

X_aI_a is the armature leakage reactance drop

$X_{AR}I_a$ is the armature reaction voltage

The armature reaction effects and the leakage flux effects on the machine are both represented by inductive reactance. Therefore, all these combine to form a single reactance called **Synchronous Reactance** of the machine X_S.

$$X_S = X_a + X_{AR} \ldots\ldots (4)$$

Therefore,

The impedance Z_S in the above equation (7) is the **Synchronous Impedance**, and X_S is the **Synchronous Reactance.**

$$V = E_a - jX_S I_a - R_a I_a \quad \text{or}$$

$$V = E_a - (R_a + jX_S) I_a \quad \dots\dots\dots (5)$$

$$V = E_a - Z_S I_a \quad \dots\dots. (6)$$

Where,

$$Z_S = R_a + jX_S \quad \dots\dots. (7)$$

The impedance ZS in the above equation (7) is the Synchronous Impedance, and XS is the Synchronous Reactance.

Draw the vector diagram of a loaded alternator.

37.18. Vector Diagrams of a Loaded Alternator

Before discussing the diagrams, following symbols should be clearly kept in mind.

E_0 = No-load e.m.f. This being the voltage induced in armature in the absence of three factors discussed in Art. 37.16. Hence, it represents the maximum value of the induced e.m.f.

E = Load induced e.m.f. It is the induced e.m.f. after allowing for armature reaction. E is vectorially less than E_0 by IX_a. Sometimes, it is written as E_a (Ex. 37.16).

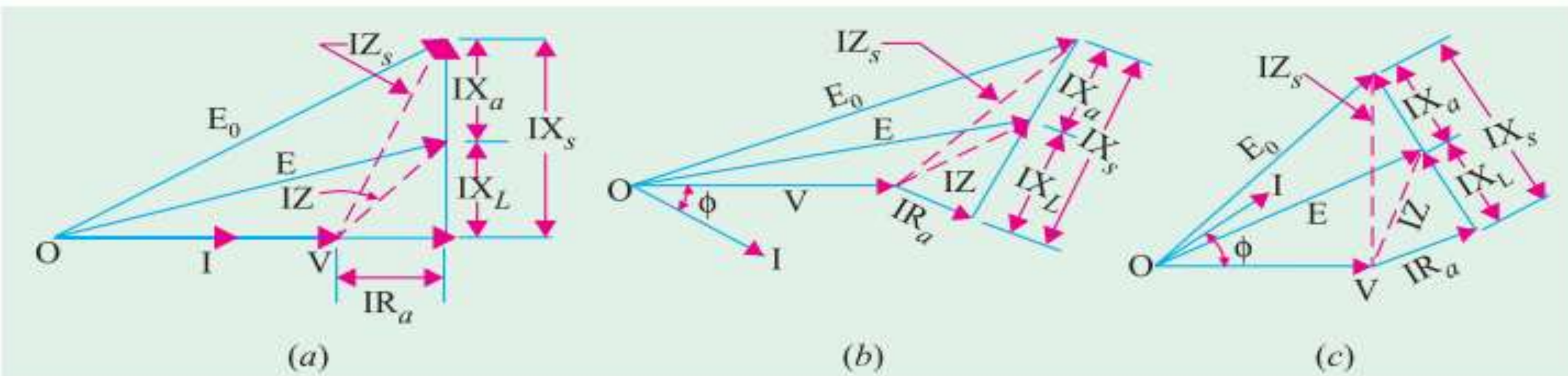


Fig. 37.27

V = Terminal voltage, It is vectorially less than E_0 by IZ_S or it is vectorially less than E by I_Z where

Z = $\sqrt{(R_a^2 + X_L^2)}$. It may also be written as Z_a.

I = armature current/phase and ϕ = load p.f. angle.

In Fig. 37.27 **(a)** is shown the case for unity p.f., in Fig. 37.27 **(b)** for lagging p.f. and in Fig. 37.27 **(c)** for leading p.f. All these diagrams apply to one phase of a 3-phase machine. Diagrams for the other phases can also be drawn similary.

Lecture- 6 **Time: 50 min.**

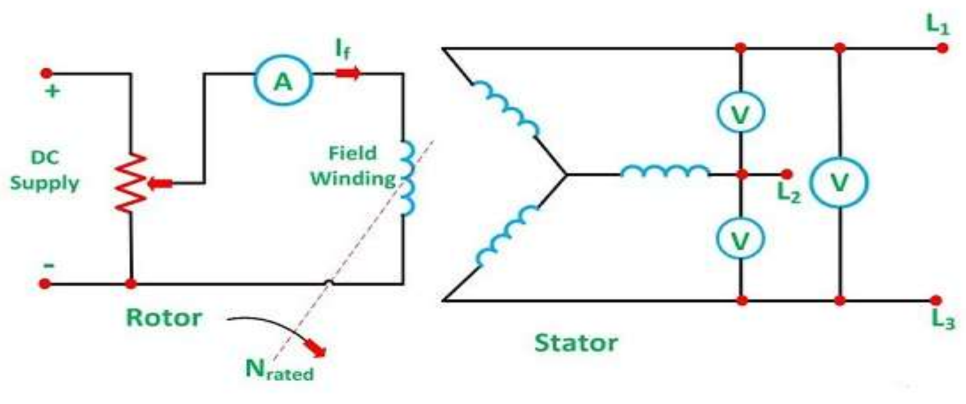
4.6 Describe resistance test, no-load lest / open circuit test and short circuit test of alternator.
4.7 Solve problems related to synchronous reactance and synchronous impedance.

Open Circuit Test and Short Circuit Test of Synchronous generator

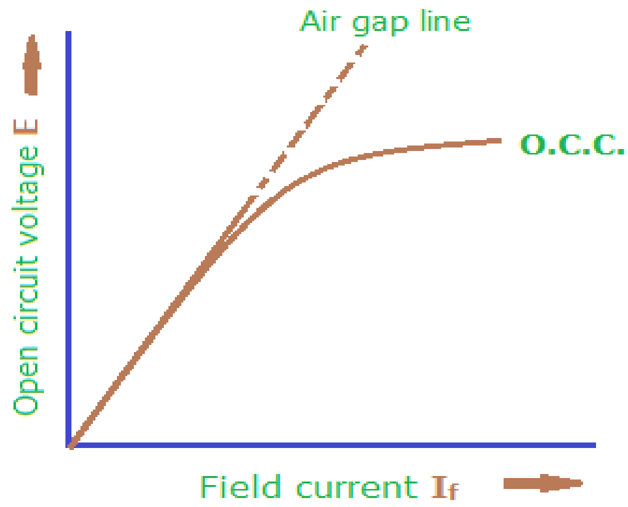
Open Circuit Test and Short Circuit Test are performed on a Synchronous Machine to find out the Synchronous impedance .
For Large Machine to Determine the voltage regulation

Open Circuit Test

the alternator is run at rated synchronous speed and the load terminals are kept open. That is, all the loads are disconnected. the field current is set to zero , this condition is called open circuit test condition.



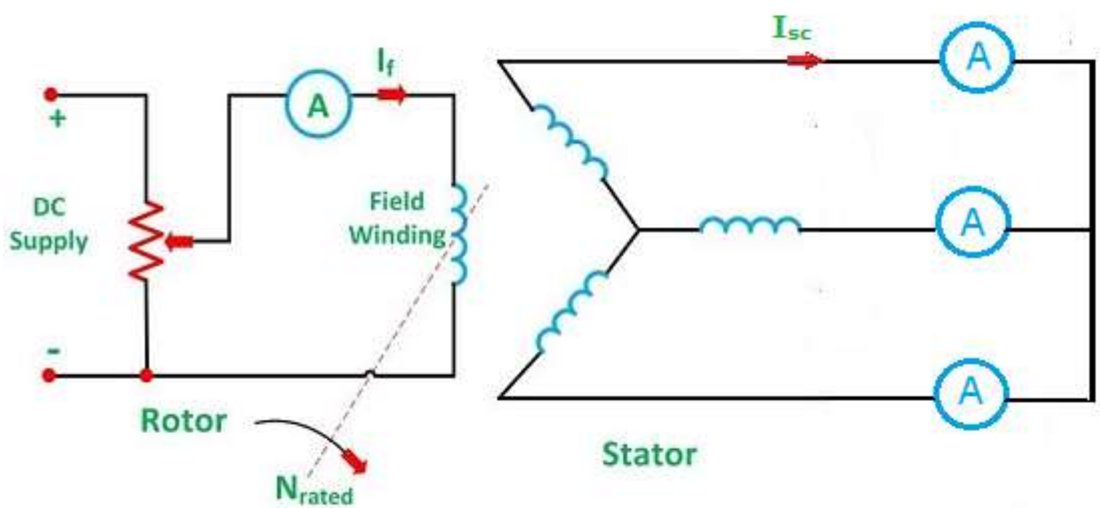
The field current is gradually increase in steps, and the terminal voltage Et is measure at each step, The excitation current may be increased to get 25% more than rated voltage of the alternator. A graph is plotted between the open circuit test voltage Ep and field excitation current If.



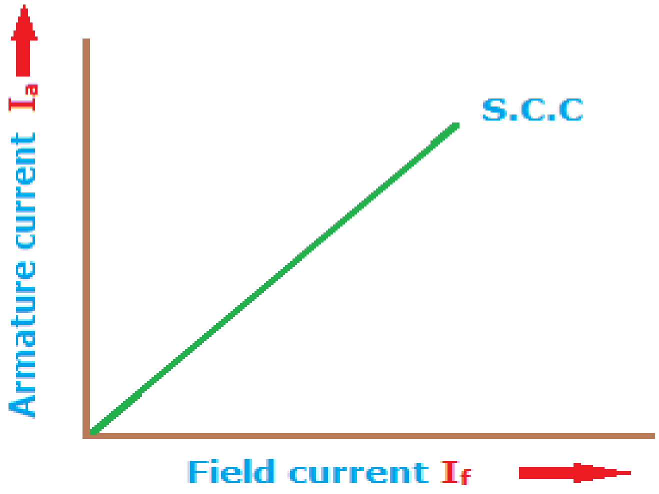
the characteristic curve so obtain is called open circuit characteristic (O.C.C.). it take the shape of a normal magnetization curve. the extension of linear portion of an O.C.C. is called the air gap line are show in figure

Short Circuit Test

The armature terminals are shorted through three ammeter. Care should we taken performing this test, and the field current should first decreased to zero before starting the alternator. Each ammeter should have range greater than the full rated value. the alternator run at synchronous speed. then the field current gradually increased in step, and the armature current is measured at each step.



The field current may be increased to get armature current up to 150% of the rated value. The field current If and the average of three ammeter reading at each step is taken.



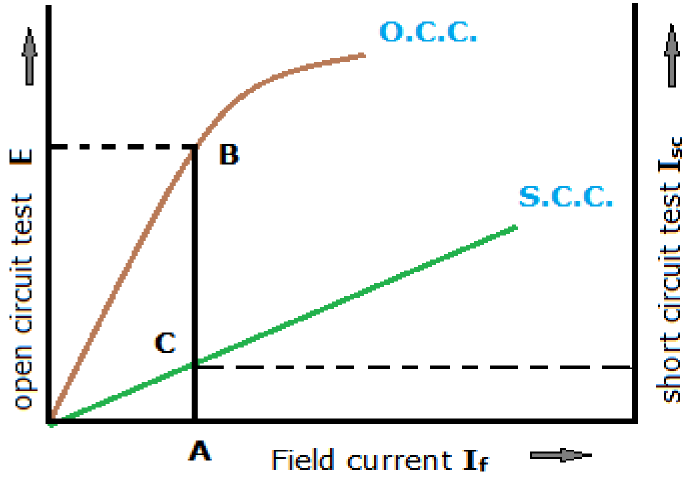
A graph is plotted between the armature current Ia and field current If. The characteristic so obtained is called short-circuit characteristic (SCC). the characteristic is a straight line as shown in figure.

Calculation of Zs

The open circuit characteristic (O.C.C.) and short circuit characteristic (S.C.C.) are drawn on the same curve sheet. Determine the value of Isc and field current that gives the rated alternator voltage per phase. the synchronous impedance Zs will then be equal to the open circuit voltage divided by the short circuit current at the field current which gives the rated e.m.f. per phase.

$$Z_s = \frac{\text{Open-circuit voltage per phase}}{\text{short-circuit armature current}}$$

For the same value of field current. The synchronous reactance is found as follows.



In figure , consider the field current *If* = OA that the produces rated alternator voltage per phase. corresponding to this field current the open circuit voltage is AB.

$$Z_s = \frac{AB \text{ (in volts)}}{AC \text{ (in amperes)}}$$

Example 37.32. *The open-and short-circuit test readings for a 3-ϕ , star-connected, 1000-kVA, 2000 V, 50-Hz, synchronous generator are :*

Field Amps ;	*10*	*20*	*25*	*30*	*40*	*50*
O.C. Terminal V	*800*	*1500*	*1760*	*2000*	*2350*	*2600*
S.C. armature current in A:	—	*200*	*250*	*300*	—	—

The armature effective resistance is 0.2 Ω per phase. Draw the characteristic curves and estimate the full-load percentage regulation at (a) 0.8 p.f. lagging (b) 0.8 p.f. leading.

Solution. The O.C.C. and S.C.C. are plotted in Fig. 37.51

The phase voltages are : 462, 866, 1016, 1155, 1357, 1502.

Full-load phase voltage $= 2000/\sqrt{3} = 1155$ V

Full-load current $= 1,000,000/2000 \times \sqrt{3} = 288.7$ A

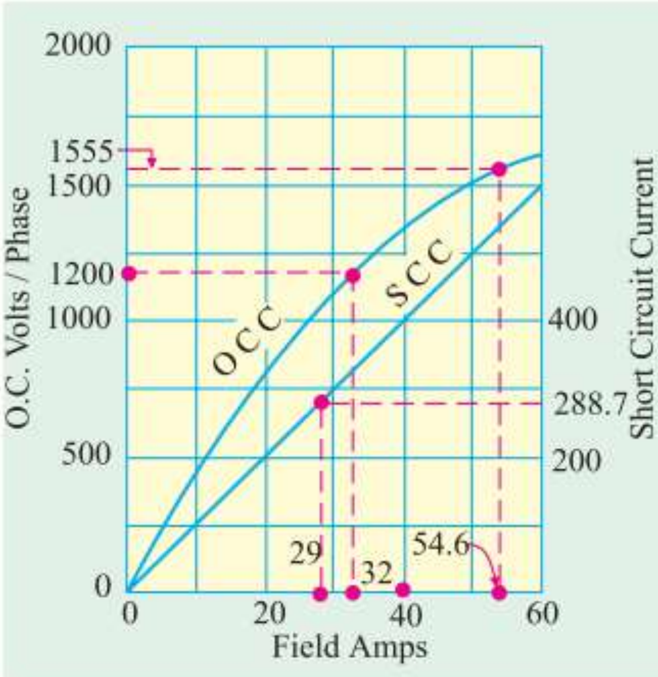


Fig. 37.51

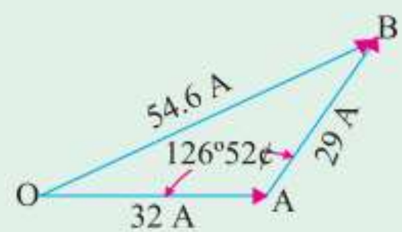


Fig. 37.52

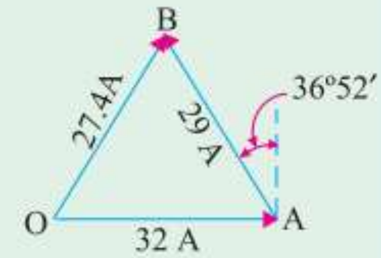


Fig. 37.53

Voltage/phase at full-load at 0.8 p.f. = $V + IR_a \cos\phi$ = 1155 + (288.7 × 0.2 × 0.8) = 1200 volt

Form open-circuit curve, it is found that field current necessary to produce this voltage = 32 A.

From short-circuit characteristic, it is found that field current necessary to produce full-load current of 288.7 A is = 29 A.

(*a*) $\cos\phi = 0.8, \phi = 36°52'$ (lagging)

In Fig. 37.52, *OA* = 32 A, *AB* = 29 A and is at an angle of (90° + 36°52′) = 126°52′ with *OA*. The total field current at full-load 0.8 p.f. lagging is *OB* = 54.6 A

O.C. volt corresponding to a field current of 54.6 A is = 1555 V

% regn. = (1555 − 1155) × 100/1155 = 34.6%

(*b*) In this case, as p.f. is leading, *AB* is drawn with *OA* (Fig. 37.53) at an angle of 90° − 36° 52′ = 53°8′. *OB* = 27.4 A.

O.C. voltage corresponding to 27.4 A of field excitation is 1080 V.

$$\% \text{ regn.} = \frac{1080 - 1155}{1155} \times 100 = \mathbf{-6.4\%}$$

Lecture- 7 **Time: 50 min.**

Understand the principle of voltage regulation and efficiency of alternator.

5.1 Define voltage regulation.

5.2 Explain voltage regulation at unity power factor, lagging power factor and leading power factor.

5.3 Solve problems related to voltage regulation of alternator.

37.20. Determination of Voltage Regulation

In the case of small machines, the regulation may be found by direct loading. The procedure is as follows :

The alternator is driven at synchronous speed and the terminal voltage is adjusted to its rated value V. The load is varied until the wattmeter and ammeter (connected for the purpose) indicate the rated values at desired p.f. Then the entire load is thrown off while the speed and field excitation are kept constant. The open-circuit or no-load voltage E_0 is read. Hence, regulation can be found from

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

In the case of large machines, the cost of finding the regulation by direct loading becomes prohibitive. Hence, other indirect methods are used as discussed below. It will be found that all these methods differ chiefly in the way the no-load voltage E_0 is found in each case.

1. ***Synchronous Impedance or E.M.F. Method.*** It is due to Behn Eschenberg.
2. ***The Ampere-turn or M.M.F. Method.*** This method is due to Rothert.
3. ***Zero Power Factor or Potier Method.*** As the name indicates, it is due to Potier.

All these methods require—

1. Armature (or stator) resistance R_a
2. Open-circuit/No-load characteristic.
3. Short-circuit characteristic (but zero power factor lagging characteristic for Potier method).

Now, let us take up each of these methods one by one.

(*i*) Value of Ra

Armature resistance R_a per phase can be measured directly by voltmeter and ammeter method or by using Wheatstone bridge. However, under working conditions, the effective value of R_a is increased due to 'skin effect'*. The value of R_a so obtained is increased by 60% or so to allow for this effect. Generally, a value 1.6 times the d.c. value is taken.

(*ii*) O.C. Characteristic

As in d.c. machines, this is plotted by running the machine on no-load and by noting the values of induced voltage and field excitation current. It is just like the *B-H* curve.

(*iii*) S.C. Characteristic

It is obtained by short-circuiting the armature (*i.e.* stator) windings through a low-resistance ammeter. The excitation is so adjusted as to give 1.5 to 2 times the value of full-load current. During this test, the speed which is not necessarily synchronous, is kept constant.

Example 37.18 (*a*). *In a 50-kVA, star-connected, 440-V, 3-phase, 50-Hz alternator, the effective armature resistance is 0.25 ohm per phase. The synchronous reactance is 3.2 ohm per phase and leakage reactance is 0.5 ohm per phase. Determine at rated load and unity power factor :*

***(a)** Internal e.m.f. E_a **(b)** no-load e.m.f. E_0 **(c)** percentage regulation on full-load **(d)** value of synchronous reactance which replaces armature reaction.*

(Electrical Engg. Bombay Univ. 1987)

Solution. **(*a*)** The e.m.f. E_a is the vector sum of (*i*) terminal voltage V **(*ii*)** IR_a and **(*iii*)** IX_L as detailed in Art. 37.17. Here,

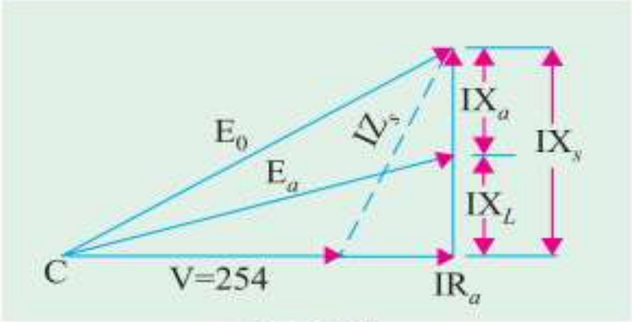


Fig. 37.31

$$V = 440/\sqrt{3} = 254 \text{ V}$$

F.L. output current at u.p.f. is

$$= 50{,}000/\sqrt{3} \times 440 = 65.6 \text{ A}$$

Resistive drop = 65.6 × 0.25 = 16.4 V

Leakage reactance drop $IX_L = 65.6 \times 0.5 = 32.8$ V

$$\therefore \quad E_a = \sqrt{(V + IR_a)^2 + (IX_L)^2}$$

$$= \sqrt{(254 + 16.4)^2 + 32.8^2} = 272 \text{ volt}$$

Line value $= \sqrt{3} \times 272 =$ **471 volt.**

(*b*) The no-load e.m.f. E_0 is the vector sum of **(*i*)** V **(*ii*)** IR_a and **(*iii*)** IX_S or is the vector sum of V and IZ_S (Fig. 37.31).

$$\therefore \quad E_0 = \sqrt{(V + IR_a)^2 + (IX_S)^2} = \sqrt{(254 + 16.4)^2 + (65.6 \times 3.2)^2} = 342 \text{ volt}$$

Line value $= \sqrt{3} \times 342 =$ **592 volt**

(*c*) % age regulation 'up' $= \dfrac{E_0 - V}{V} \times 100 = \dfrac{342 - 254}{254} \times 100 =$ **34.65 per cent**

(*d*) $X_a = X_S - X_L = 3.2 - 0.5 =$ **2.7 Ω** ...Art. 37.17

Lecture- 8 **Time: 50 min.**

5.4 List the losses occurred in alternator.
5.5 Explain the losses and efficiency of alternator.
5.6 Solve problems on losses and efficiency of alternator.

Alternator Losses

The following losses are occured in an alternator while its on working condition.

Copper Loss

Copper losses occur only in the armature winding and field winding.

Core Loss

The losses due to eddy current and hysteresis losses is said to be core loss.

Friction and Windage Losses

The loss due to the bearing and brush friction and to the power required to circulate the cooling air is known as friction and windage loss.

Load Loss

The load loss is due to the armature leakage flux which causes eddy currents and hysteresis in the iron surrounding the armature conductors.

Explain the losses and efficiency of alternator.

Whenever we convert one form of energy into another there are bound to be losses. No machine is perfect. Power is supplied to an alternator both in the form of electrical energy and in the form of mechanical energy. The electrical energy is supplied to the field coil. This energy is used to set up the main magnetic field. This field is constant. There is no energy taken from it in the generation of electricity. Therefore, since none of the power out comes from this energy, the power by the field must be counted as a loss. Most of the power comes from the prime mover. Some of this mechanical power is lost to the windings and friction of the alternator. The mechanical losses do not depend on the alternator's load.

To find these losses it is necessary to determine the overall mechanical losses then subtract the losses of the prime mover. Another class of losses that does not vary with load is the core losses. We are speaking here about the armature’s core. Since there is an alternating voltage generated, the core is continually becoming magnetized with one polarity, de-magnetized, then magnetized with the other polarity each cycle. All of this magnetic activity in the core causes eddy current and hysteresis losses.

These core losses depend on the alternator's voltage, not on load. As load current flows through the armature coils the resistance of the wire causes a power loss. This copper loss is proportional to the square of the current, P = I'R. Copper losses, therefore, increase rapidly with load. Percent efficiency is the ratio between the power out and the power in. % Eff. = Pout/pin x 100. If the load has unity power factor, Pout = E x I x 1.73. Regardless of load, Pin = Pout + losses

The alternator's efficiency from the equation: % Efficiency η = Power Out / Power Out + Losses x 100

Problem: An **alternator** is rated 25kVA, has a total loss of 2000W when it delivers rated kVA at 0.76 pf lagging. Calculate its **efficiency**.

A three-phase, 1200 HP, 2300 V, 60 Hz, RR synchronous machine has $R_s = 0.2\ \Omega$ and $X_s = 5.6\ \Omega$. When operated with the mechanical load disconnected with rated voltage and frequency, the field current is adjusted until line current has a minimum value. At this point, $I_a = 22.1\ \text{A}$, the measured input power is $P_T = 17.5\ \text{kW}$, and the measured field circuit values are $V_f = 276\ \text{V}$ and $I_f = 53.2\ \text{A}$. (*a*) Determine the rotational losses (core losses plus friction and windage) for this machine. (*b*) If the field current, frequency, and impressed terminal voltage are unchanged, but a mechanical load requiring 600 HP is attached, predict the power factor, line current, and efficiency.

(*a*) Using the no-load data,

$$P_{FW} = P_T - 3I_a^2 R_s = 17{,}500 - 3(22.1)^2(0.2) = 17{,}793.05\ \text{W}$$

(*b*) Since the no-load current was a minimum value, the machine was operating at unity power factor. The excitation voltage corresponding to

$$\bar{E}_f = \bar{V}_{an} - \bar{I}_a(R_s + jX_s) = \frac{2300}{\sqrt{3}} - 22.1(0.2 + j5.6) = 1329.28\angle -5.34°\ \text{V}$$

Since the no-load current was a minimum value, the machine was operating at unity power factor. The excitation voltage corresponding to

$$\bar{E}_f = \bar{V}_{an} - \bar{I}_a(R_s + jX_s) = \frac{2300}{\sqrt{3}} - 22.1(0.2 + j5.6) = 1329.28\angle -5.34°\ \text{V}$$

Since $R_s \ll X_s$ little error is introduced if is neglected in calculation of the torque

for the loaded condition. From energy balance, $P_s + P_{FW} = \dfrac{3V_{an}E_f}{X_s}\sin\delta$

$$\delta = \sin^{-1}\left[\frac{(P_s + P_{FW})X_s}{3V_{an}E_f}\right] = \sin^{-1}\left[\frac{(600\times 746 + 17,793.05)(5.6)}{3\left(2300/\sqrt{3}\right)(1329.28)}\right] = 31.84°$$

Based on [7.36],

$$\bar{I}_a = \frac{\bar{V}_{an} - \bar{E}_f}{R_s + jX_s} = \frac{\frac{2300}{\sqrt{3}}\angle 0° - 1329.28\angle -31.84°}{0.2 + j5.6} = 130.07\angle -13.77°\text{ A}$$

Hence,

$$PF_{in} = \cos\left(\angle\bar{V}_{an} - \angle\bar{I}_a\right) = \cos(11.35°) = 0.97\text{ lagging}$$

The losses are

$$\text{Losses} = P_{FW} + 3I_a^2R_a + V_fI_f$$

$$\text{Losses} = 17,793.05 + 3(130.07)^2(0.2) + (276)(53.2) = 42,627.17\text{ W}$$

$$\eta = \frac{100P_s}{P_s + \text{losses}} = \frac{100(600\times 746)}{600\times 746 + 42,627.17} = 91.30\%$$

Lecture- 9 **Time: 50 min.**

6. Understand the principle of parallel operation and starting procedure of alternators.

6.1 Define the term synchronizing.

6.2 Describe the purposes of synchronizing alternators.

6.3 List the conditions for synchronizing.

6.4 Describe the dark & bright lamp methods of synchronizing there phase alternator.

Define the term synchronizing and the purposes of synchronizing alternators.

The operation of connecting an alternator in parallel with another alternator or with common bus-bars is known as ***synchronizing***. Generally, alternators are used in a power system where they are in parallel with many other alternators. It means that the alternator is connected to a live system of constant voltage and constant frequency. Often the electrical system to which the alternator is connected, has already so many alternators and loads connected to it that no matter what power is delivered by the incoming alternator, the voltage and frequency of the system remain the same. In that case, the alternator is said to be connected to ***infinite*** bus-bars.

The conditions for synchronizing:

It is never advisable to connect a stationary alternator to live bus-bars, because, stator induced e.m.f. being zero, a short-circuit will result. For proper synchronization of alternators, the following three conditions must be satisfied :

1. The terminal voltage (effective) of the incoming alternator must be the same as bus-bar voltage.

2. The speed of the incoming machine must be such that its frequency (= $PN/120$) equals bus-bar frequency.

3. 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 (or very near) the instant the two voltages have correct phase relationship.

Condition **(1)** is indicated by a voltmeter, conditions **(2)** and **(3)** are indicated by synchronizing lamps or a synchronoscope.

The dark & bright lamp methods of synchronizing there phase alternator:

In 3-ϕ alternators, it is necessary to synchronize one phase only, the other two phases will then be synchronized automatically. However, first it is necessary that the incoming alternator is correctly 'phased out' *i.e.* the phases are connected in the proper order of *R*, *Y*, *B* and not *R*, *B*, *Y* etc.

In this case, three lamps are used. But they are deliberately connected asymmetrically, as shown in Fig. 37.77 and 37.78.

This transposition of two lamps, suggested by Siemens and Halske, helps to indicate whether the incoming machine is running too slow. If 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 and R', L_2 between Y and B' (not Y and Y') and L_3 between B and Y' (and not B and B'), as shown in Fig. 37.78.

Voltage stars of two machines are shown superimposed on each other in Fig. 37.79.

Two sets of star vectors will rotate at unequal speeds if the frequencies of the two machines are different. If the incoming alternator is running faster, then voltage star *R′Y′B′* will appear to rotate anticlockwise with respect to the bus-bar voltage star *RYB* at a speed corresponding to the difference between their frequencies. With reference to Fig. 37.79, it is seen that voltage across L_1 is *RR′* and is seen to be increasing from zero, that across L_2 is *YB′* which is decreasing, having just passed through its maximum, that across L_3 is *BY′* which is increasing and approaching its maximum. Hence, the lamps will light up one after the other in the order 2, 3, 1 ; 2, 3, 1 or 1, 2, 3.

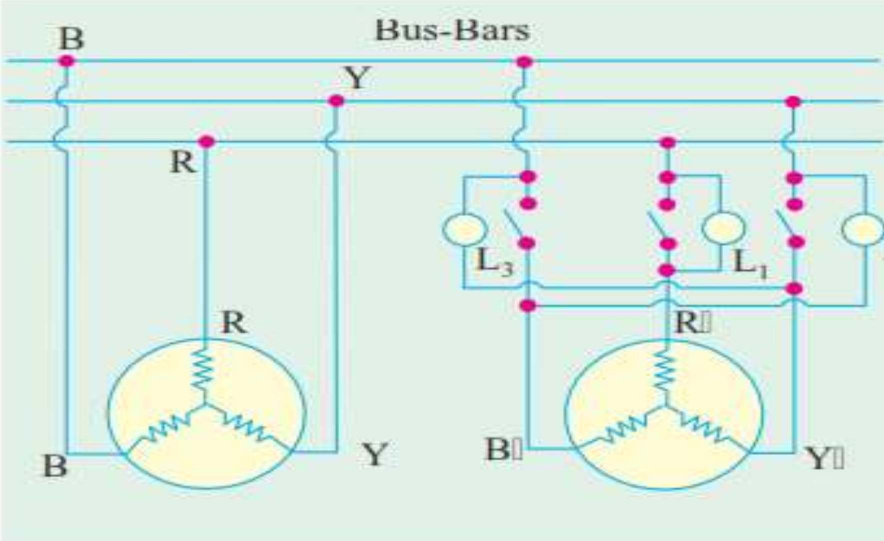


Fig. 37.77

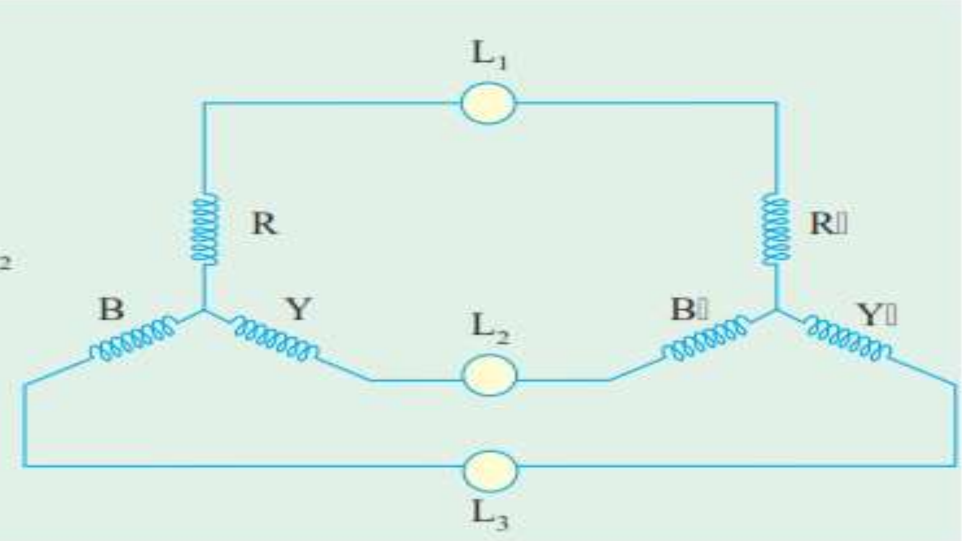


Fig. 37.78

Now, suppose that the incoming machine is slightly slower. Then the star R′Y′B′ will appear to be rotating clockwise relative to voltage star *RYB* (Fig. 37.80). Here, we find that voltage across L_3 *i.e. Y′B* is decreasing having just passed through its maximum, that across L_2 *i.e. YB′* is increasing and approaching its maximum, that across L_1 is decreasing having passed through its maximum earlier. Hence, 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. Usually, the three lamps are mounted at the three corners of a triangle and the apparent direction of rotation of light

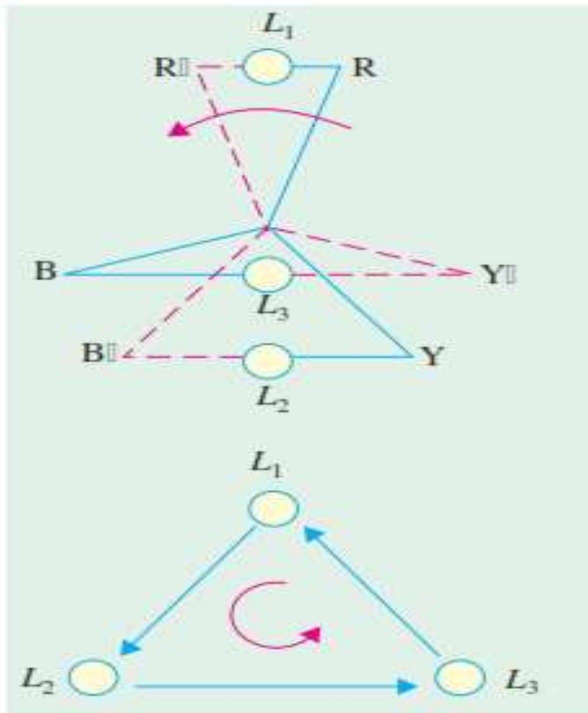


Fig. 37.79

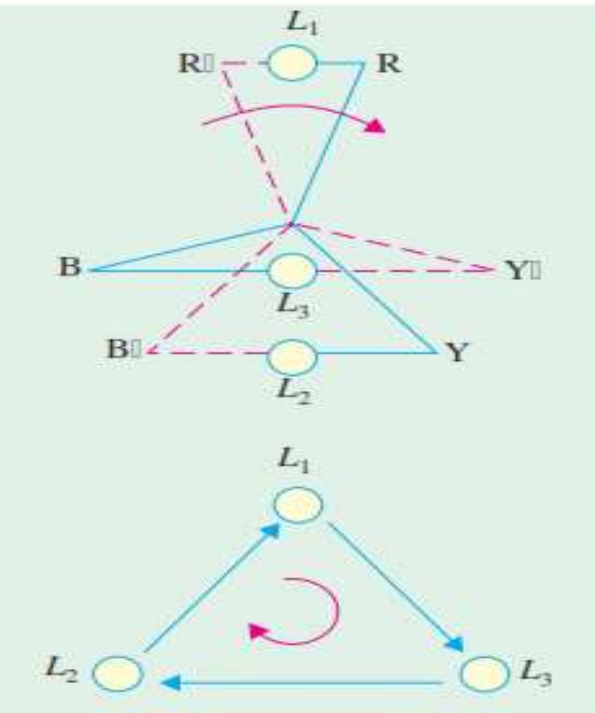


Fig. 37.80

indicates whether the incoming alternator is running too fast or too slow (Fig. 37.81). Synchronization is done at the moment the uncrossed lamp L_1 is in the middle of the dark period. When the alternator voltage is too high for the lamps to be used directly, then usually step-down transformers are used and the synchronizing lamps are connected to the secondaries.

It will be noted that when the uncrossed lamp L_1 is dark, the other two 'crossed' lamps L_2 and L_3 are dimly but equally bright. Hence, this method of synchronizing is also sometimes known as 'two bright and one dark' method.

It should be noted that synchronization by lamps is not quite accurate, because to a large extent, it depends on the sense of correct judgement of the operator. Hence, to eliminate the element of personal judgment in routine operation of alternators, the machines are synchronized by a more accurate device called a synchronoscope. It consists of 3 stationary coils and a rotating iron vane which is attached to a pointer. Out of three coils, a pair is connected to one phase of the line and the other to the corresponding machine terminals, potential transformer being usually used. The pointer moves to one side or the other from its vertical position depending on whether the incoming machine is too fast or too slow. For correct speed, the pointer points vertically up.

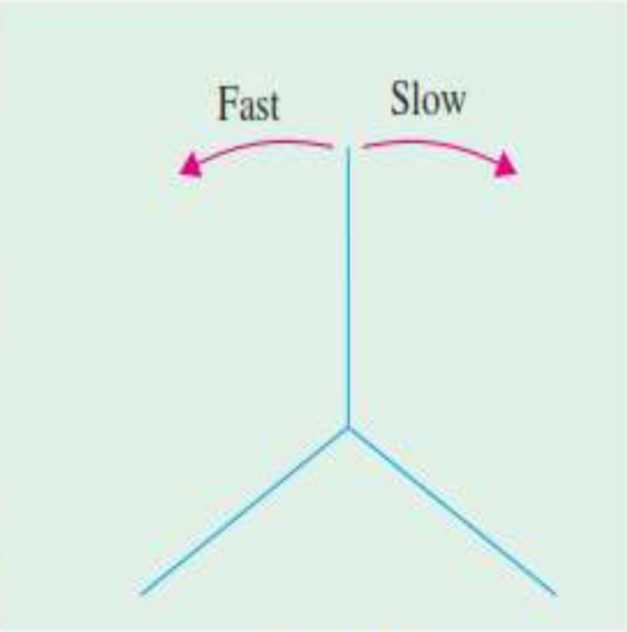
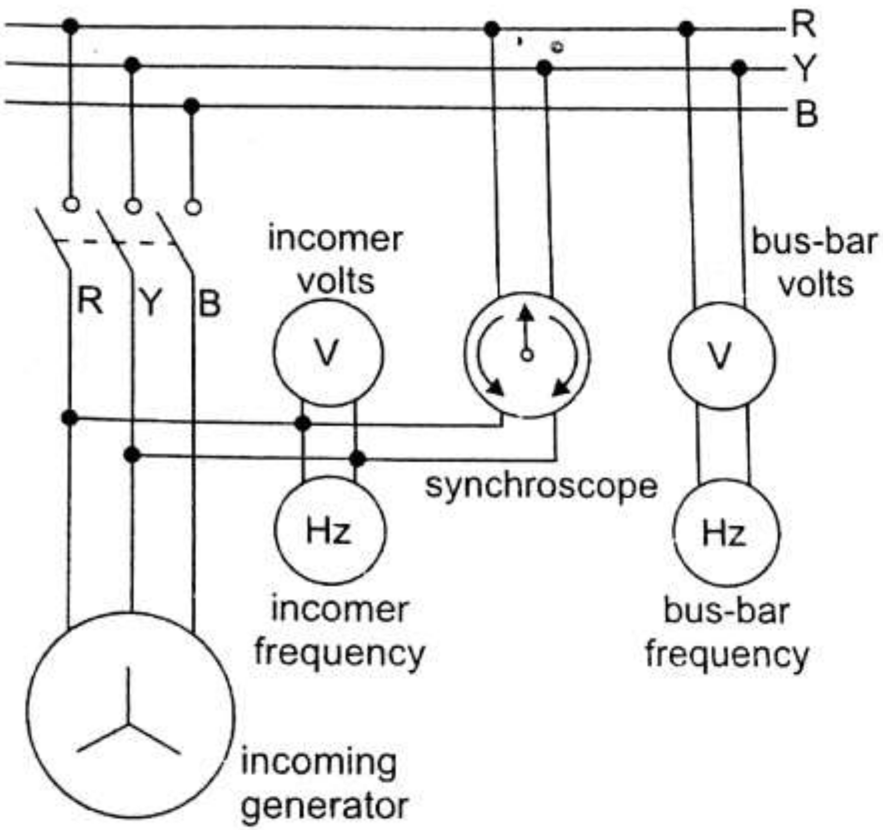


Fig. 37.81

Lecture- 10 **Time: 50 min.**

6.5 Explain the method of paralleling the alternators by synchroscope.
6.6 Explain synchronizing current and synchronizing power.
6.7 Explain the effect of unequal voltage on synchronizing two alternators.
6.8 Describe the distributions of load between two alternators in parallel.
6.9 Describe the steps of starting an alternator.

Explain the method of paralleling the alternators by synchroscope.
The incoming machine must have equal
1. **Line voltage 2. Frequency 3. Phase sequence 4. Phase angle 5. Waveform**
to that of the bus-bar which it is being synchronized.
The condition of the same waveform (all alternators should have the same sinusoidal waveform) and phase sequence (RYB terminals of an alternator outlet is connected with RYB of the main bus bar) is fixed by the construction of the alternator and can be checked by the phasing out test during the synchronizing of the alternator. So Voltage, Frequency & Phase angle must be controlled each time an alternator is to be connected to the bus-bar.


R
Y
B
R
Y
B
incomer
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synchroscope
bus-bar
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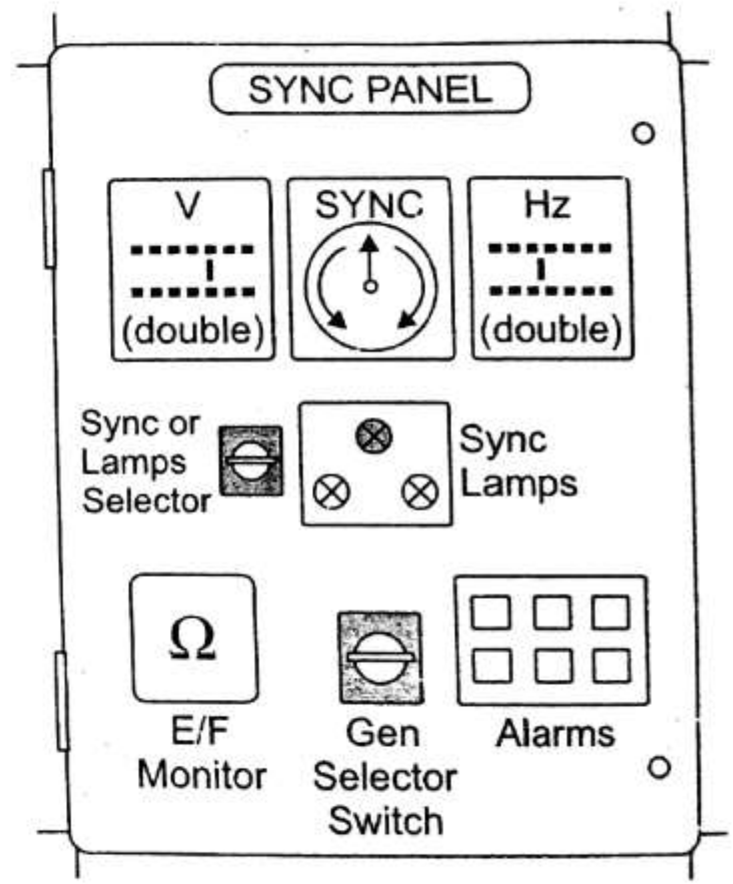
bus-bar
frequency
incoming
generator


SYNC PANEL
V
(double)
SYNC
Hz
(double)
Sync or
Lamps
Selector
Sync
Lamps
Ω
E/F
Monitor
Gen
Selector
Switch
Alarms

Working

The polarity of the poles will change alternatively in the north-south direction with the change in the phases of the incoming generator.

The rotating field will react with the poles by turning the rotor to either in clockwise or anticlockwise direction.

If the incoming machine field is strong (means running faster) then the rotor will move in clockwise direction.

If the incoming machine field is weaker (means running slower) then the rotor will move in an anticlockwise direction

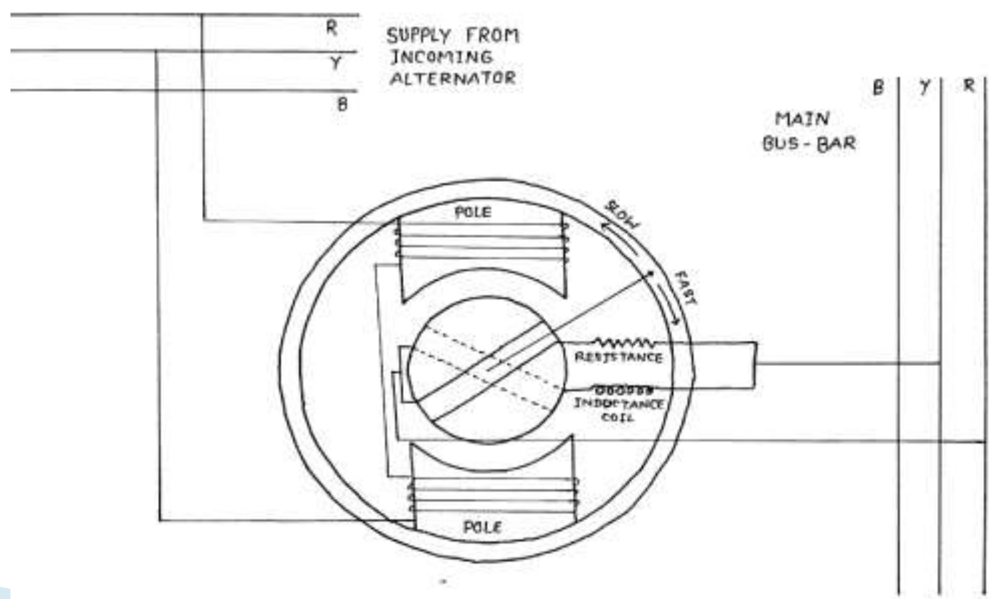
Generally, it is preferred to adjust the incoming machine slightly higher than the bus-bar which will move the pointer of the synchroscope in the clockwise direction. The breaker is closed just before the pointer reaches 12 o’clock position at which the incoming machine is in phase with the bus-bar.

Synchroscope :

Construction : Consists of a small motor with coils on the two poles connected across any two phases of the incoming machine and armature winding supplied from the same two phases of the switchboard bus bar

The bus bar circuit consists of an inductance coil and resistance connected in parallel. Inductor circuit delays the current by 90 degrees relative to the current in resistance.

These two currents are feed into the synchroscope with the help of slip rings to the armature winding which produces a rotating magnetic field



Once synchronized properly, two alternators continue to run in synchronism. Any tendency on the part of one to drop out of synchronism is immediately counteracted by the production of a synchronizing torque, which brings it back to synchronism.

When in exact synchronism, the two alternators have equal terminal p.d.'s and are in exact phase opposition, so far as the local circuit (consisting of their armatures) is concerned. Hence, there is no current circulating round the local circuit. As shown in Fig. 37.82 (*b*) e.m.f. E_1 of machine No. 1 is in exact phase opposition to the e.m.f. of machine No. 2 *i.e.* E_2. It should be clearly understood that the two e.m.f.s. are in opposition, so far as their local circuit is concerned but are in the same direction with respect to the external circuit. Hence, there is no resultant voltage (assuming $E_1 = E_2$ in magnitude) round the local circuit.

But now suppose that due to change in the speed of the governor of second machine, E_2 falls back* by a phase angle of α electrical degrees, as shown in Fig. 37.82 (*c*) (though still $E_1 = E_2$). Now, they have a resultant voltage E_r, which when acting on the local circuit, circulates a current known as synchronizing current. The value of this current is given by $I_{SY} = E_r / Z_S$ where Z_S is the synchronous impedance of the phase windings of both the machines (or of one machine only if it is connected to infinite bus-bars**). The current I_{SY} lags behind E_r by an angle θ given by $\tan\theta = X_S / R_a$ where X_S is the combined synchronous reactance of the two machines and R_a their armature resistance. Since R_a is negligibly small, θ is almost 90 degrees. So I_{SY} lags E_r by 90° and is almost in phase with E_1. It is seen that I_{SY} is generating current with respect to machine No.1 and motoring current with respect to machine No. 2 (remember when the current flows in the same direction as e.m.f., then the alternator acts as a generator, and when it flows in the opposite direction, the machine acts as a motor). This current I_{SY} sets up a synchronising torque, which tends to retard the generating machine (*i.e.* No. 1) and accelerate the motoring machine (*i.e.* No. 2).

Similarly, if E_2 tends to advance in phase [Fig. 37.82 (*d*)], then I_{SY}, being generating current for machine No. 2, tends to retard it and being motoring current for machine No. 1 tends to accelerate it. Hence, any departure from synchronism results in the production of a synchronizing current I_{SY} which sets up synchronizing torque. This re-establishes synchronism between the two machines by retarding the leading machine and by accelerating the lagging one. This current I_{SY}, it should be noted, is superimposed on the load currents in case the machines are loaded.

37.33. Synchronizing Power

Consider Fig. 37.82 (c) where machine No. 1 is generating and supplying the synchronizing power $= E_1 I_{SY} \cos \phi_1$ which is approximately equal to $E_1 I_{SY}$ ($\because \phi_1$ is small). Since $\phi_1 = (90° - \theta)$, synchronizing power $= E_1 I_{SY} \cos \phi_1 = E_1 I_{SY} \cos (90° - \theta) = E_1 I_{SY} \sin \theta \cong E_1 I_{SY}$ because $\theta \cong 90°$ so that

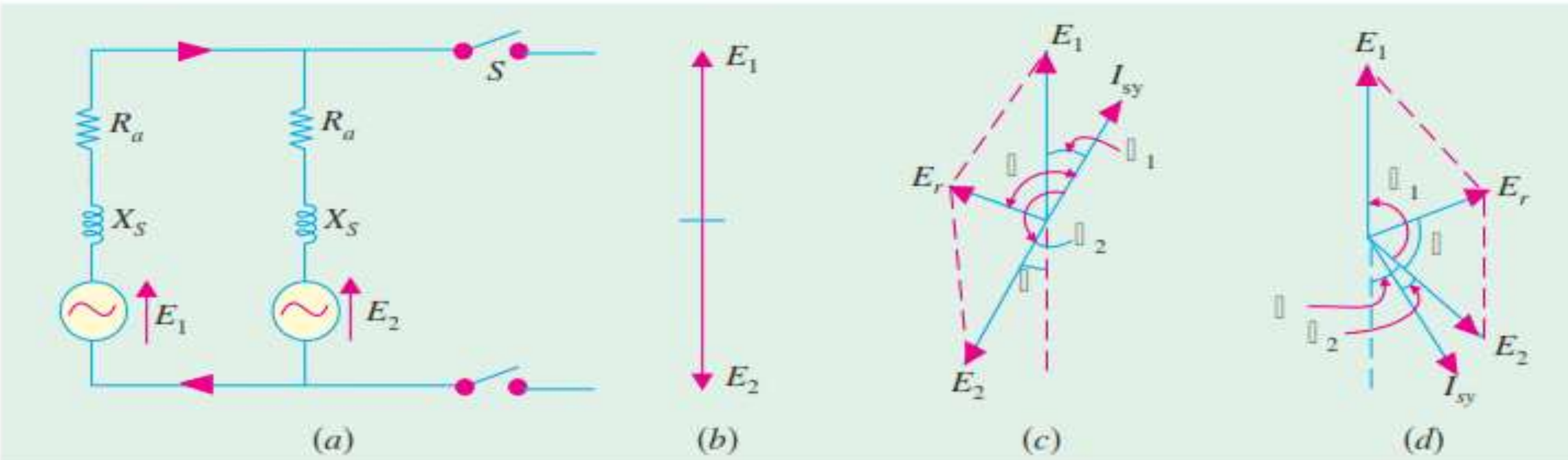


Fig. 37.82

$\sin \theta \cong 1$. This power output from machine No. 1 goes to supply (a) power input to machine No. 2 (which is motoring) and (b) the Cu losses in the local armature circuit of the two machines. Power input to machine No. 2 is $E_2 I_{SY} \cos \phi_2$ which is approximately equal to $E_2 I_{SY}$.

$\therefore \quad E_1 I_{SY} = E_2 I_{SY} + \text{Cu losses}$

Now, let $\quad E_1 = E_2 = E$ (say)

Then, $\quad E_r = 2E \cos [(180° - \alpha)/2]$*** $= 2E \cos [90° - (\alpha/2)]$

$$= 2E \sin \alpha/2 = 2E \times \alpha/2 = \alpha E \qquad (\because \alpha \text{ is small})$$

Here, the angle α is in electrical radians.

Now,
$$I_{SY} = \frac{E_r}{\text{synch. impedance } Z_S} \cong \frac{E_r}{2X_S} = \frac{\alpha E}{2X_S}$$

—if R_a of both machines is negligible

Here, X_S represents synchronous reactance of one machine and not of both as in Art. 37.31 Synchronizing power (supplied by machine No. 1) is

$$P_{SY} = E_1 I_{SY} \cos \phi_1 = E\, I_{SY} \cos (90° - \theta) = EI_{SY} \sin \theta \cong EI_{SY}$$

Substituting the value of I_{SY} from above,

$$P_{SY} = E.\alpha E/2Z_S = \alpha E^2/2Z_S \cong \alpha E^2/2X_S \qquad \text{—per phase}$$

(more accurately, $P_{SY} = \alpha E^2 \sin \theta/2X_S$)

Total synchronizing power for three phases

$$= 3P_{SY} = 3\alpha E^2/2X_S \text{ (or } 3\alpha E^2 \sin \theta/2X_S)$$

This is the value of the synchronizing power when two alternators are connected in parallel and are on no-load.

Lecture- 11

7. Understand the principle of operation of synchronous motor.
7.1 Define synchronous motor.
7.2 Explain the principle of operation of synchronous motor.
7.3 Describe the effect of increase in load of synchronous motor with vector diagram.

Synchronous motor :

Synchronous motor is a **machine** whose rotor speed and the speed of the stator magnetic field is equal. **Synchronous motor** does not have slip.

Principle of operation of synchronous motor.:

In order to understand the principle of operation of a synchronous motor, let us examine what happens if we connect the armature winding (laid out in the stator) of a 3-phase synchronous machine to a suitable balanced 3-phase source and the field winding to a D.C source of appropriate voltage. The current flowing through the field coils will set up stationary magnetic poles of alternate North and South. (for convenience let us assume a salient pole rotor, as shown in Fig. 50). On the other hand, the 3-phase currents flowing in the armature winding produce a rotating magnetic field rotating at synchronous speed. In other words there will be moving North and South poles established in the stator due to the 3-phase currents i.e at any location in the stator there will be a North pole at some instant of time and it will become a South pole after a time period corresponding to half a cycle. (after a time =1/2f

, where f = frequency of the supply). Let us assume that the stationary South

pole in the rotor is aligned with the North pole in the stator moving in clockwise direction

at a particular instant of time, as shown in Fig. 50. These two poles get attracted and

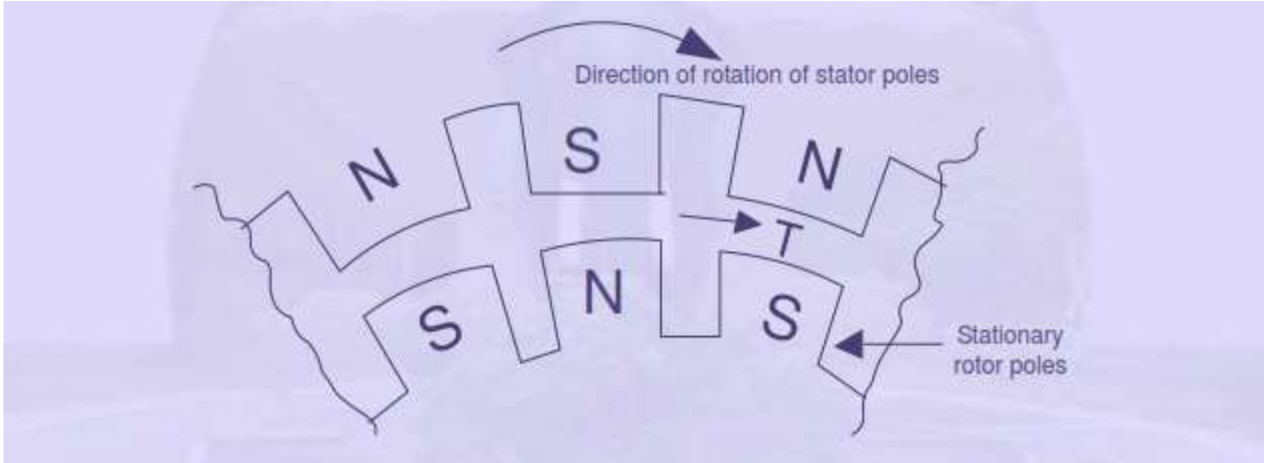


Figure 50: Force of attraction between stator poles and rotor poles - resulting in production of torque in clockwise direction

Figure 50 shows that Force of attraction between stator poles and rotor poles - resulting in production of torque in clockwise direction try to maintain this alignment (as per lenz's law) and hence the rotor pole tries to follow the stator pole as the conditions are suitable for the production of torque in the clockwise direction. However the rotor cannot move instantaneously due to its mechanical inertia, and so it needs sometime to move. In the mean time, the stator pole would quickly (a time duration corresponding to half a cycle) change its polarity and becomes a South pole.

So the force of attraction will no longer be present and instead the like poles experience a force of repulsion as shown in Fig. 51. In other words, the conditions are now suitable for the

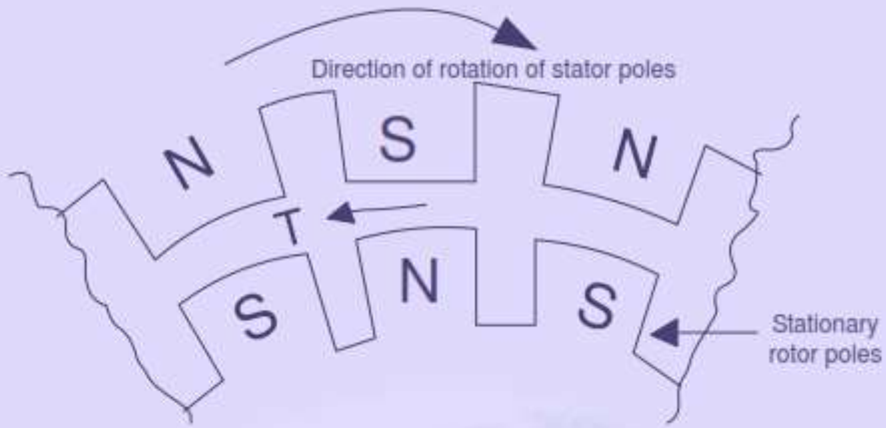


Figure 51: Force of repulsion between stator poles and rotor poles - resulting in production of torque in anticlockwise direction

Figure 51: Force of repulsion between stator poles and rotor poles - resulting in production of torque in anticlockwise direction production of torque in the anticlockwise direction. Even this condition will not last longer as the stator pole would again change to North pole after a time of 1/2f . Thus the rotor will experience an alternating force which tries to move it clockwise and anticlockwise at twice the frequency of the supply, i.e. at intervals corresponding to 1/2f seconds. As this duration is quite small compared to the mechanical time constant of the rotor, the rotor cannot respond and move in any direction. The rotor continues to be stationary only.

Describe the effect of increase in load of synchronous motor with vector diagram.

38.9. Effect of Increased Load with Constant Excitation

We will study the effect of increased load on a synchronous motor under conditions of normal, under and over-excitation (ignoring the effects of armature reaction). With normal excitation, $E_b = V$, with under excitation, $E_b < V$ and with over-excitation, $E_b > V$. Whatever the value of excitation, it would be kept *constant* during our discussion. It would also be assumed that R_a is negligible as compared to X_S so that phase angle between E_R and I_a *i.e.*, $\theta = 90°$.

(*i*) Normal Excitation

Fig. 38.15. (*a*) shows the condition when motor is running with light load so that (*i*) torque angle

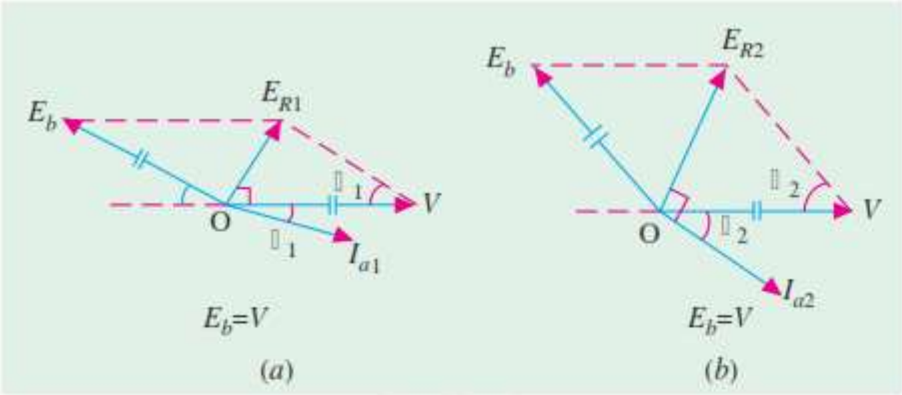


Fig. 38.15

α_1 is small (*ii*) so E_{R1} is small (*iii*) hence I_{a1} is small and (*iv*) ϕ_1 is small so that cos ϕ_1 is large.

Now, suppose that load on the motor is *increased* as shown in Fig. 38.15 (*b*). For meeting this extra load, motor must develop more torque by drawing more armature current. Unlike a d.c. motor, a synchronous motor cannot increase its I_a by decreasing its speed and hence E_b because both are constant in its case. What actually happens is as

1. rotor falls back ***in phase i.e.***, load angle increases to α_2 as shown in Fig. 38.15 (*b*),

2. the resultant voltage in armature is increased ***considerably*** to new value E_{R2},

3. as a result, I_{a1} increases to I_{a2}, thereby increasing the torque developed by the motor,

4. ϕ_1 increases to ϕ_2, so that power factor ***decreases*** from cos ϕ_1 to the new value cos ϕ_2.

Since increase in I_a is much greater than the ***slight*** decrease in power factor, the torque developed by the motor is *increased* (on the whole) to a new value sufficient to meet the extra load put on the motor. It will be seen that essentially it is by increasing its I_a that the motor is able to carry the extra load put on it.

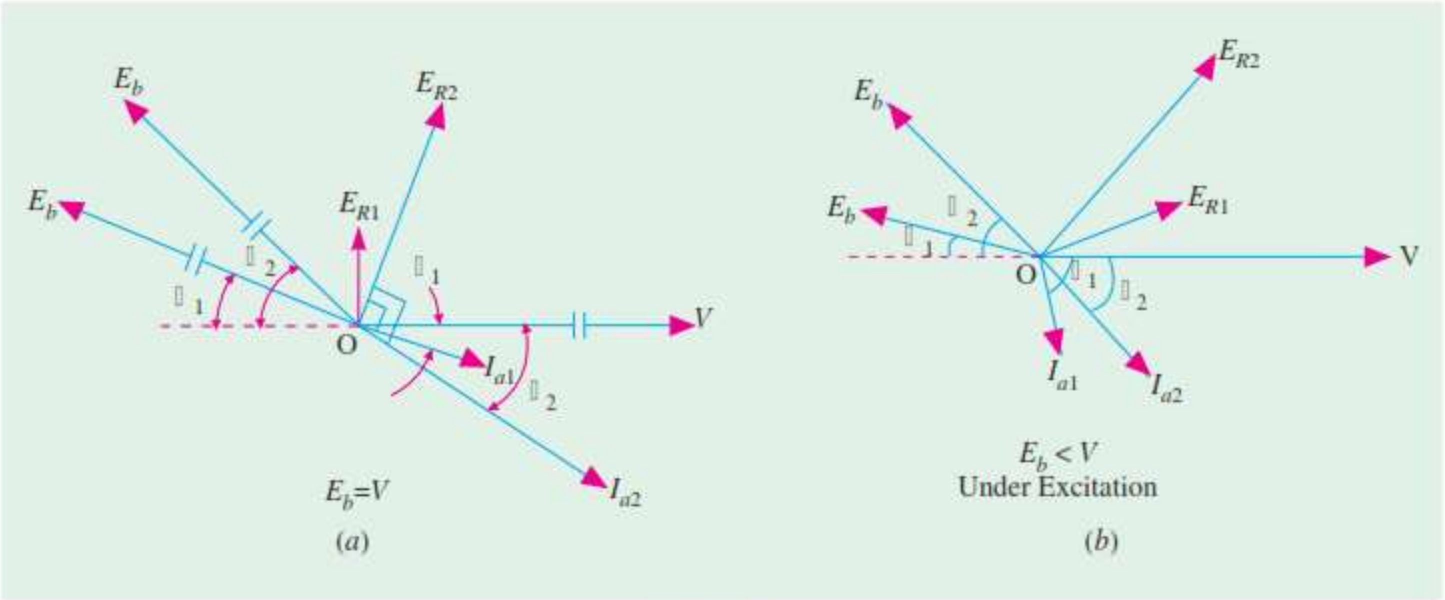


Fig. 38.16

A phase summary of the effect of increased load on a synchronous motor at ***normal excitation*** is shown in Fig. 38.16 (a) It is seen that there is a comparatively much greater ***increase*** in I_a than in ϕ .

(*ii*) Under-excitation

As shown in Fig. 38.16 (*b*), with a small load and hence, small torque angle α_1, I_{a1} lags behind V by a ***large*** phase angle ϕ_1 which means poor power factor. Unlike normal excitation, a much larger armature current must flow for developing the same power because of poor power factor. That is why I_{a1} of Fig. 38.16 (*b*) is larger than I_{a1} of Fig. 38.15 (*a*).

As load increases, E_{R1} increases to E_{R2}, consequently I_{a1} increases to I_{a2} and p.f. angle ***decreases*** from ϕ_1 to ϕ_2 or p.f. ***increases*** from cos ϕ_1 to cos ϕ_2. Due to increase both in I_a and p.f., power generated by the armature increases to meet the increased load. As seen, in this case, ***change in power factor is more than the change in*** I_a.

(*iii*) Over-excitation

When running on light load, α_1 is small but I_{a1} is comparatively larger and ***leads V*** by a larger angle ϕ_1. Like the under-excited motor, as more load is applied, the power factor improves and ***approaches*** unity. The armature current also increases thereby producing the necessary increased armature power to meet the increased applied load (Fig. 38.17). However, it should be noted that in this case, power factor angle ϕ decreases (or p.f. increases) at a faster rate than the armature current thereby producing the necessary increased power to meet the increased load applied to the motor.

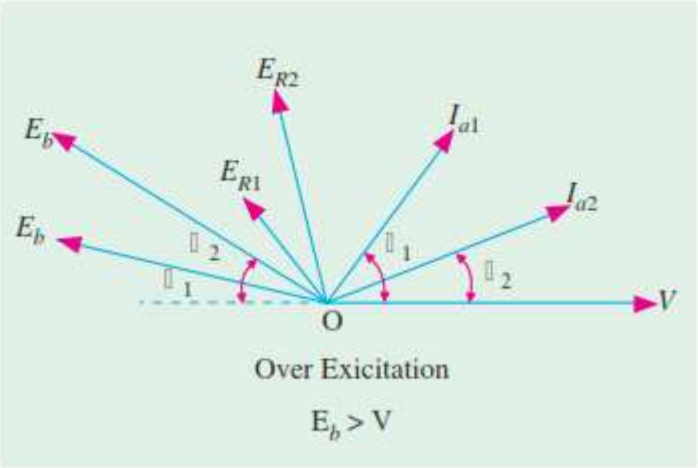


Fig. 38.17

Summary

The main points regarding the above three cases can be summarized as under :

1. As load on the motor increases, I_a ***increases regardless of excitation.***
2. For under-and over-excited motors, p.f. tends to approach unity with increase in load.
3. Both with under-and over-excitation, change in p.f. is greater than in I_a with increase in load.
4. With normal excitation, when load is increased change in I_a is greater than in p.f. which tends to become increasingly lagging.

Lecture- 12 **Time: 50 min.**

Understand the torques and excitation of a synchronous motor.

8.1 Describe different types of torque.

8.2 Explain the effect of excitation on armature current and power factor with vector diagram.

Effect of changes in field excitation on synchronous motor

38.8. Synchronous Motor with Different Excitations

A synchronous motor is said to have normal excitation when its $E_b = V$. If field excitation is such that $E_b < V$, the motor is said to be ***under-excited***. In both these conditions, it has a lagging power factor as shown in Fig. 38.12.

On the other hand, if d.c. field excitation is such that $E_b > V$, then motor is said to be ***over-excited*** and draws a leading current, as shown in Fig. 38.13 (*a*). There will be some value of excitation for which armature current will be in phase with V, so that power factor will become unity, as shown in Fig. 38.13 (*b*).

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* Strictly speaking, it should be $P_{in} = \frac{-E_b V}{X_S} \sin \alpha$

The value of α and back e.m.f. E_b can be found with the help of vector diagrams for various power factors, shown in Fig. 38.14.

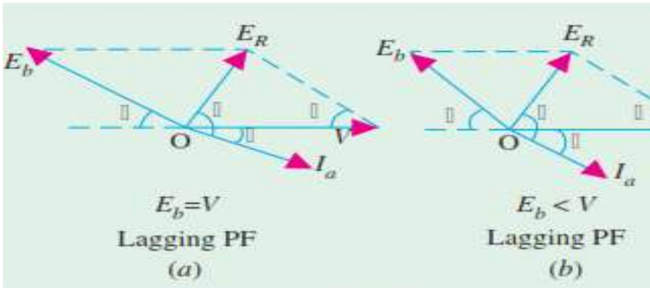


Fig. 38.12

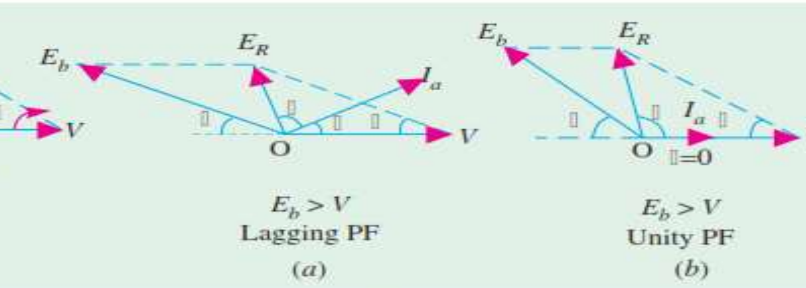


Fig. 38.13

(i) Lagging p.f. As seen from Fig. 38.14 (a)

$$AC^2 = AB^2 + BC^2 = [V - E_R \cos(\theta - \phi)]^2 + [E_R \sin(\theta - \phi)]^2$$

$$\therefore \quad E_b = \sqrt{[V - I_a Z_S \cos(\theta - \phi)]^2 + [I_a Z_S \sin(\theta - \phi)]^2}$$

Load angle $\quad \alpha = \tan^{-1}\left(\frac{BC}{AB}\right) = \tan^{-1}\left[\frac{I_a Z_S \sin(\theta - \phi)}{V - I_a Z_S \cos(\theta - \phi)}\right]$

(ii) Leading p.f. [38.14 (b)]

$$E_b = V + I_a Z_S \cos[180° - (\theta + \phi)] + j\, I_a Z_S \sin[180° - (\theta + \phi)]$$

$$\alpha = \tan^{-1}$$

(iii) Unity p.f. [Fig. 38.14 (c)]

Here, $\quad OB = I_a R_a$ and $BC = I_a X_S$

$$\therefore \quad E_b = (V - I_a R_a) + j\, I_a X_S; \quad \alpha = \tan^{-1}$$

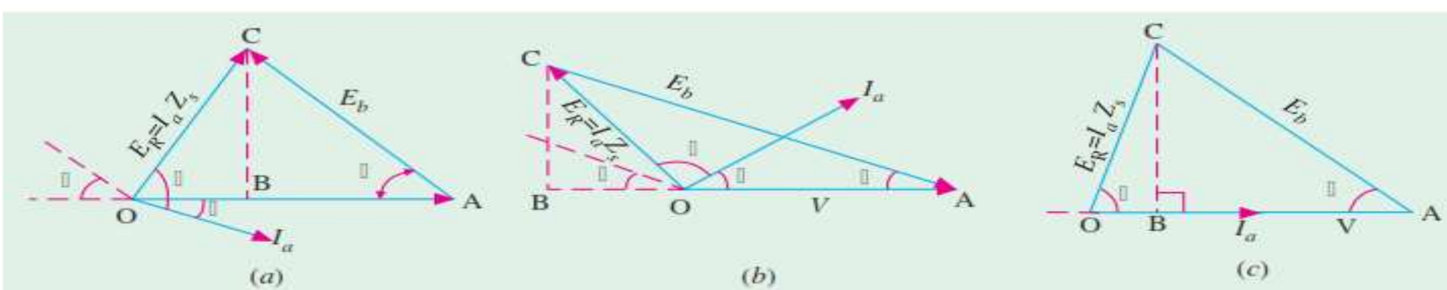


Fig. 38.14

8.1 Describe different types of torque.

38.11. Different Torques of a Synchronous Motor

Various torques associated with a synchronous motor are as follows:

1. starting torque
2. running torque
3. pull-in torque and
4. pull-out torque

(a) Starting Torque

It is the torque (or turning effort) developed by the motor when full voltage is applied to its stator (armature) winding. It is also sometimes called *breakaway* torque. Its value may be as low as 10% as in the case of centrifugal pumps and as high as 200 to 250% of full-load torque as in the case of loaded reciprocating two-cylinder compressors.

(b) Running Torque

As its name indicates, it is the torque developed by the motor under running conditions. It is determined by the horse-power and speed of the *driven* machine. The peak horsepower determines the maximum torque that would be required by the driven machine. The motor must have a break-down or a maximum running torque greater than this value in order to avoid stalling.

(*c*) Pull-in Torque

A synchronous motor is started as induction motor till it runs 2 to 5% below the synchronous speed. Afterwards, excitation is switched on and the rotor pulls into step with the synchronously-rotating stator field. The amount of torque at which the motor will pull into step is called the pull-in torque.

(*d*) Pull-out Torque

The maximum torque which the motor can develop without pulling out of step or synchronism is called the pull-out torque.

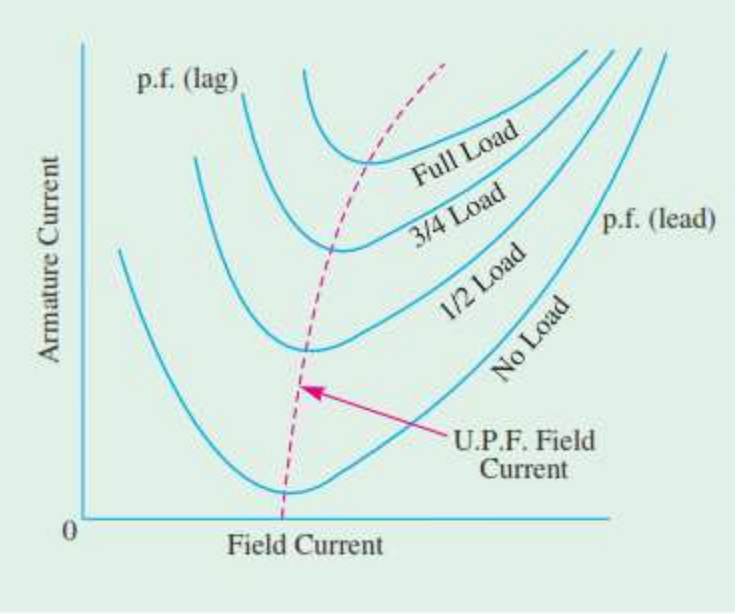
Normally, when load on the motor is increased, its rotor progressively tends to fall back *in phase* by some angle (called load angle) behind the synchronously-revolving stator magnetic field though it keeps running synchronously. Motor develops maximum torque when its rotor is retarded by an angle of 90° (or in other words, it has shifted backward by a distance equal to half the distance between adjacent poles). Any further increase in load will cause the motor to pull out of step (or synchronism) and stop.

Lecture- 13 **Time: 50 min.**

8.3 Construct V-curves.
8.4 Explain V-curves.
8.5 Describe the different point and position of V- curve in respect of power factor

38.19. Construction of V-curves

The *V*-curves of a synchornous motor show how armature current varies with its field current when motor ***input is kept constant***. These are obtained by plotting a.c. armature current against d.c.



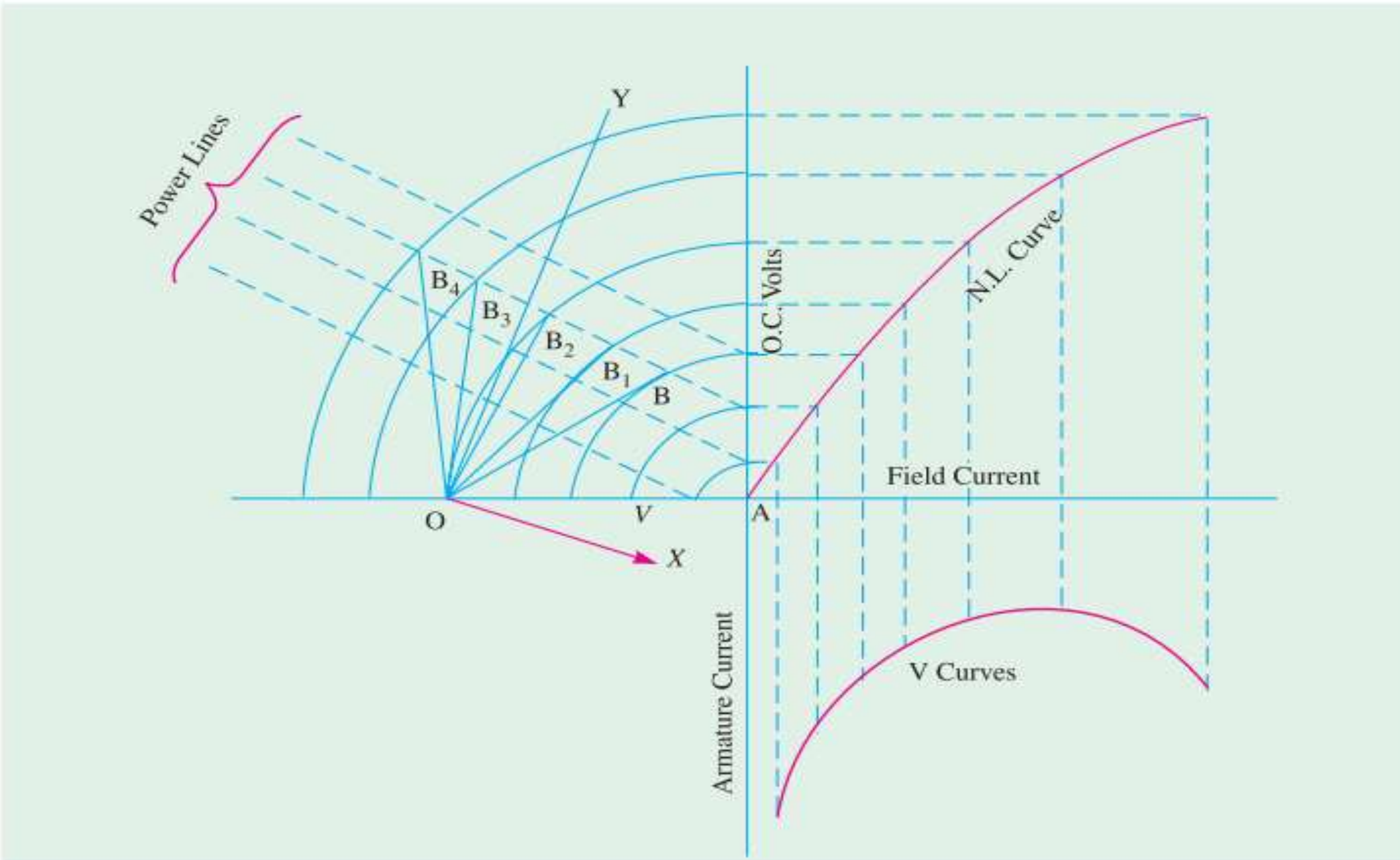
field current while motor input is kept constant and are so called because of their shape (Fig. 38.55). There is a family of such curves, each corresponding to a definite power intake.

In order to draw these curves experimentally, the motor is run from constant voltage and constant-frequency bus-bars. Power input to motor is kept constant at a definite value. Next, field current is increased in small steps and corresponding armature currents are noted. When plotted, we get a *V*-curve for a particular constant motor input. Similar curves can be drawn by keeping motor input constant at different values. A family of such curves is shown in Fig. 38.55.

Detailed procedure for graphic construction of *V*-curves is given below :

1. First, constant-power lines are drawn as discussed in Art. 38.14.
2. Then, with *A* as the centre, concentric circles of different radii AB, AB_1, AB_2, etc. are drawn where AB, AB_1, AB_2, etc., are the back e.m.fs corresponding to different excitations. The intersections of these circles with lines of constant power give positions of the working points for specific loads and excitations (hence back e.m.fs). The vectors OB, OB_1, OB_2 etc., represent different values of E_R (and hence currents) for different excitations. Back e.m.f. vectors AB, AB_1 etc., have not been drawn purposely in order to avoid confusion (Fig. 38.56).

3. The different values of back e.m.fs like AB, AB_1, AB_2, etc., are projected on the magnetisation and corresponding values of the field (or exciting) amperes are read from it.
4. The field amperes are plotted against the corresponding armature currents, giving us 'V' curves.



Lecture- 14 **Time: 50 min.**

9. Predicted the hunting or phase swinging of synchronous motor.

9.1 Explain hunting or phase swinging.

9.2 List the disadvantages of hunting.

9.3 Explain the disadvantages

9.4 Remedies of hunting.

38.20. Hunting or Surging or Phase Swinging

When a synchronous motor is used for driving a varying load, then a condition known as hunting is produced. Hunting may also be caused if supply frequency is pulsating (as in the case of generators driven by reciprocating internal combustion engines).

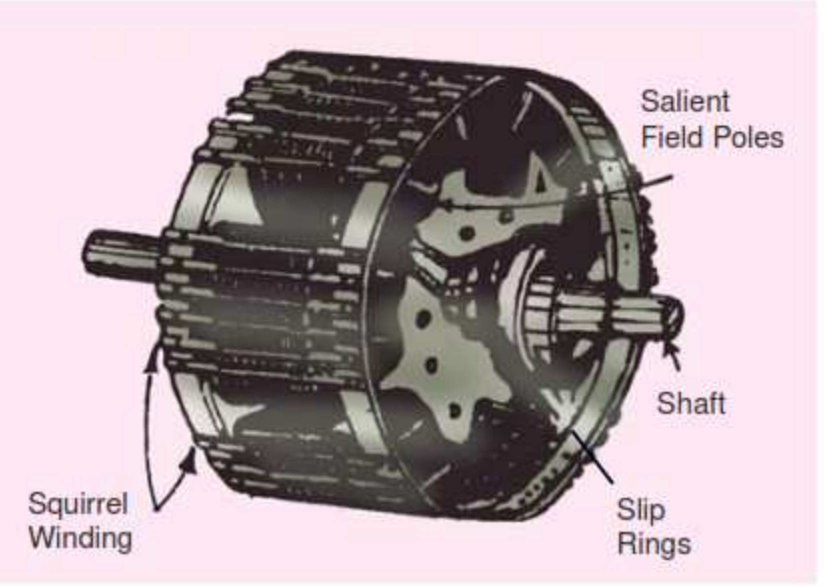


Fig. 38.57

We know that when a synchronous motor is loaded (such as punch presses, shears, compressors and pumps etc.), its rotor falls back in phase by the coupling angle α. As load is progressively increased, this angle also increases so as to produce more torque for coping with the increased load. If now, there is sudden decrease in the motor load, the motor is immediately pulled up or advanced to a new value of α corresponding to the new load. But in this process, the rotor overshoots and hence is again pulled back. In this way, the rotor starts oscillating (like a pendulum) about its new position of

Salient - poled squirrel eage motor

equilibrium corresponding to the new load. If the time period of these oscillations happens to be equal to the natural time period of the machine (refer Art. 37.36) then mechanical resonance is set up. The amplitude of these oscillations is built up to a large value and may eventually become so great as to throw the machine out of synchronism. To stop the build-up of these oscillations, dampers or damping grids (also known as squirrel-cage winding) are employed. These dampers consist of short-circuited Cu bars embedded in the faces of the field poles of the motor (Fig. 38.57). The oscillatory motion of the rotor sets up eddy currents in the dampers which flow in such a way as to suppress these oscillations.

But it should be clearly understood that dampers do not completely prevent hunting because their operation depends upon the presence of some oscillatory motion. Howover, they serve the additional purpose of making the synchronous motor self-starting.

Lecture- 15 **Time: 50 min.**

Perceive the starting method and uses of synchronous motor.

10.1 List the methods of starting synchronous motor.

10.2 Describe the procedures of starting a synchronous motor.

As seen earlier, synchronous motor is not self starting. It is necessary to rotate the rotor at a speed very near to synchronous speed. This is possible by various method in practice. The various methods to start the synchronous motor are,

1. Using pony motors
2. Using damper winding
3. As a slip ring induction motor
4. Using small d.c. machine coupled to it.

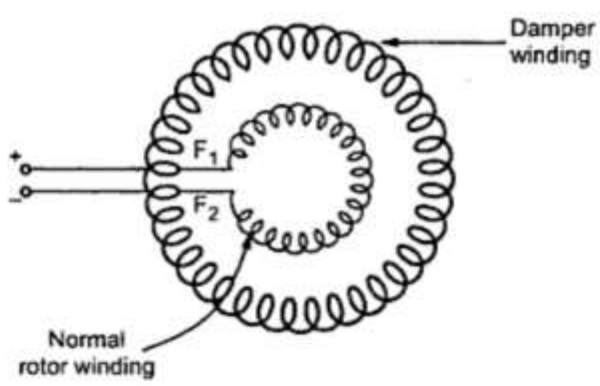
<u>1. Using pony motors</u>

In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. Such an external device is called 'pony motor'.

Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled. The motor then continues to rotate as synchronous motor.

2. Using Damper Winding

In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings. Such an additional winding on the rotor is called damper winding. This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor. The schematic representation of such damper winding is shown in the Fig.1.

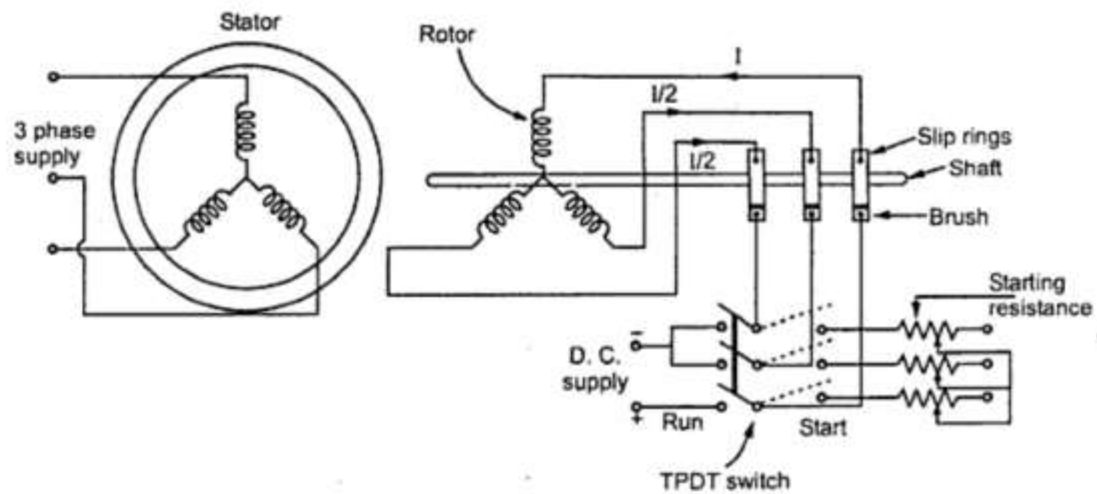


Once the rotor is excited by a three phase supply, the motors starts rotating as an induction motor at sub synchronous speed. Then d.c. supply is given to the field winding. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed. As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero. Hence when motor is running as synchronous motor, there can not be any induced e.m.f. in the damper winding. So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards it is out of the circuit. As damper winding is short circuited and motor gets started as induction motor, it draws high current at start so induction motor starters like star-delta, autotransformer etc. used to start the synchronous motor as an induction motor.

As a Slip Ring Induction Motor

The above method of starting synchronous motor as a squirrel cage induction motor does not provide high starting torque. So to achieve this, instead of shorting the damper winding, it is designed to a form a three phase star or delta connected winding. The three ends of this winding are brought out through slip rings. An external rheostat then can be introduced in series with the rotor circuit. So when stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque. The resistance is then gradually cut off, as motor gathers speed. When motor attains speed near synchronous. d.c. excitation is provided to the rotor, then motors gets pulled into synchronism ans starts rotating at synchronous speed. The damper winding is shorted by shorting the slip rings. The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a motor resistance starter.

The synchronous motor started by this method is called a slip ring induction motor is shown in the Fig.1(b).



Starting as a slip ring I.M.

It can be observed from the Fig. 1(b) that the same three phase rotor winding acts as a normal rotor winding by shorting two of the phases. From the positive terminal, current 'I' flows in one of the phases, which divides into two other phases at start point as 1/2 through each, when switch is thrown on d.c. supply side.

Using Small D.C. Machine

Many a times, a large synchronous motor are provided with a coupled d.c. machine. This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed. Then the excitation to the rotor is provided. Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter. The field of the synchronous motor is then excited by this exciter itself.

Lecture- 16 **Time: 50 min.**

10.3 Compare synchronous motor with induction motor.
10.4 Mention the field of application of synchronous motor.

A **synchronous motor** is a doubly excited **machine**, whereas an **induction motor** is a single excited **machine**. In case of **Synchronous motor** its armature winding is energized from an AC source and its field winding from a DC source, whereas in case of **Induction motor** its stator winding is energized from an AC source.

Synchronous motor	Induction motor
Construction is complicated	Construction is simpler , particularly in case of cage rotor
Not self starting	Self starting
Separate DC source is required for rotor excitation	Rotor gets excited by the induced e.m.f so separate source is not necessary
The speed is always synchronous irrespective of the load	The speed is always less than synchronous but never synchronous
Speed control is not possible	Speed control is possible though difficult
As load increases, load angle increases, keeping speed constant at synchronous	AS load increases , the speed keeps on decreasing
By changing excitation , the motor p.f can be changed from lagging and leading	It always operates at lagging p.f and p.f control is not possible
It can be used as synchronous condenser for p.f improvement	It can not be used as synchronous condenser
Motor is sensitive to sudden load changes and hunting results	Phenomenon of hunting is absent
Motor is costly and requires frequent maintenance	Motor is cheap , especially cage rotors and maintenance free

The various classes of service for which synchronous motors are employed may be classified as:

Power factor correction

Voltage regulation

Constant speed constant load drives

Applications:

Synchronous motors are used in generating stations and in substations connected to the busbars to improve the power factor. For this purpose they are run without mechanical load on them and in over-excited condition.

These machines when over excited delivers the reactive power to grid and helps to improve the power factor of the system. The reactive power delivered by the synchronous motors can be adjusted by varying the field excitation of the motor.

These motors used for power factor correction applications can also be termed as "synchronous condensers".

Advantage of synchronous condensers compared to shunt capacitors is that shunt capacitors generate constant reactive power whereas on the other hand synchronous condensers can able to deliver different reactive power levels by varying the excitation of machine.

Because of the higher efficiency compared to induction motors they can be employed for loads which require constant speeds.

Some of the typical applications of high speed synchronous motors are such drives as fans, blowers, dc generators, line shafts, centrifugal pumps, compressors, reciprocating pumps, rubber and paper mills.

Synchronous motors are used to regulate the voltage at the end of transmission lines

In textile and paper industries synchronous motors are employed to attain wide range of speeds with variable frequency drive system .

Lecture- 17 **Time: 50 min.**

Understand the principle of power factor corrections.

11.1 Define synchronous condenser.

11.2 Distinguish between synchronous motor and synchronous condenser.

11.3 Explain the methods of power factor corrections with the help of synchronous motor and synchronous condenser.

A **synchronous condenser** or a **synchronous** compensator is a **synchronous** motor running without a mechanical load. It can generate or absorb reactive volt-ampere (VAr) by varying the excitation of its field winding. It can be made to take a leading current with over-excitation of its field winding

The only **difference between** a **synchronous motor** and a **synchronous condenser** is **the synchronous condenser** shaft is not connected to anything—it simply spins unimpeded. **The** sole purpose of a **synchronous condenser** is to adjust conditions (power factor) on **the** electric power transmission grid.

2. Synchronous condenser. A synchronous motor takes a leading current when over-excited and, therefore, behaves as a capacitor. An over-excited synchronous motor running on no load is known as *synchronous condenser.* When such a machine is connected in parallel with the supply, it takes a leading current which partly neutralises the lagging reactive component of the load. Thus the power factor is improved.

Fig 6.5 shows the power factor improvement by synchronous condenser method. The 3ϕ load takes current I_L at low lagging power factor cos ϕ_L. The synchronous condenser takes a current I_m which leads the voltage by an angle ϕ_m*. The resultant current I is the phasor sum of I_m and I_L and lags behind the voltage by an angle ϕ. It is clear that ϕ is less than ϕ_L so that cos ϕ is greater than cos ϕ_L. Thus the power factor is increased from cos ϕ_L to cos ϕ. Synchronous condensers are generally used at major bulk supply substations for power factor improvement.

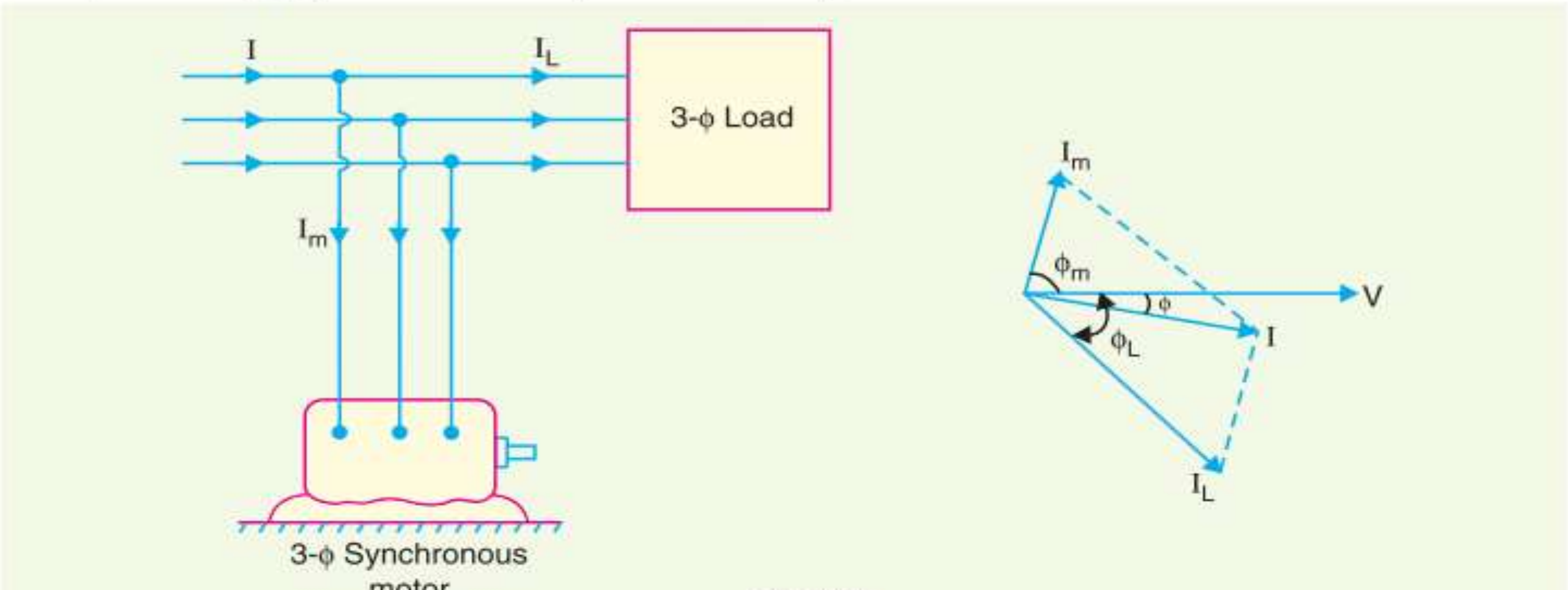


Fig. 6.5

Advantages

(*i*) By varying the field excitation, the magnitude of current drawn by the motor can be changed by any amount. This helps in achieving stepless † control of power factor.

(*ii*) The motor windings have high thermal stability to short circuit currents.

(*iii*) The faults can be removed easily.

Disadvantages

(*i*) There are considerable losses in the motor.

(*ii*) The maintenance cost is high.

(*iii*) It produces noise.

(*iv*) Except in sizes above 500 kVA, the cost is greater than that of static capacitors of the same rating.

(*v*) As a synchronous motor has no self-starting torque, therefore, an auxiliary equipment has to be provided for this purpose.

6.7 Calculations of Power Factor Correction

Consider an inductive load taking a lagging current I at a power factor $\cos\phi_1$. In order to improve the power factor of this circuit, the remedy is to connect such an equipment in parallel with the load which takes a leading reactive component and partly cancels the lagging reactive component of the load. Fig. 6.6 (*i*) shows a capacitor connected across the load. The capacitor takes a current I_C which leads the supply voltage V by 90°. The current I_C partly cancels the lagging reactive component of the load current as shown in the phasor diagram in Fig. 6.6 (*ii*). The resultant circuit current becomes I' and its angle of lag is ϕ_2. It is clear that ϕ_2 is less than ϕ_1 so that new p.f. $\cos\phi_2$ is more than the previous p.f. $\cos\phi_1$.

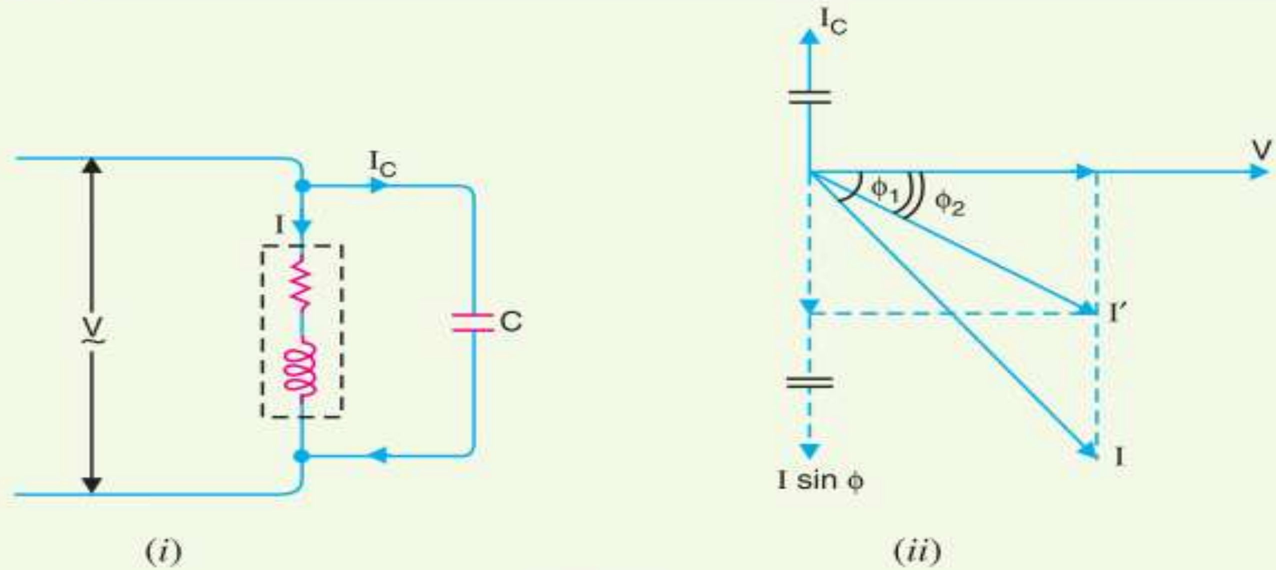


Fig. 6.6

From the phasor diagram, it is clear that after p.f. correction, the lagging reactive component of the load is reduced to $I'\sin\phi_2$.

Obviously, $I'\sin\phi_2 = I\sin\phi_1 - I_C$

or $I_C = I\sin\phi_1 - I'\sin\phi_2$

∴ Capacitance of capacitor to improve p.f. from $\cos\phi_1$ to $\cos\phi_2$

$$= \frac{I_C}{\omega V} \qquad \left(\because X_C = \frac{V}{I_C} = \frac{1}{\omega C}\right)$$

Power triangle. The power factor correction can also be illustrated from power triangle. Thus referring to Fig. 6.7, the power triangle *OAB* is for the power factor $\cos\phi_1$, whereas power triangle *OAC* is for the improved power factor $\cos\phi_2$. It may be seen that active power (*OA*) does not change with power factor improvement. However, the lagging kVAR of the load is reduced by the p.f. correction equipment, thus improving the p.f. to $\cos\phi_2$.

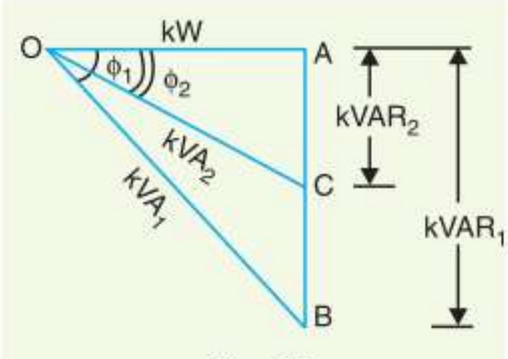


Fig. 6.7

Leading kVAR supplied by p.f. correction equipment

$$= BC = AB - AC$$
$$= \text{kVAR}_1 - \text{kVAR}_2$$
$$= OA\,(\tan\phi_1 - \tan\phi_2)$$
$$= \text{kW}\,(\tan\phi_1 - \tan\phi_2)$$

Knowing the leading kVAR supplied by the p.f. correction equipment, the desired results can be obtained.

Lecture- 18 **Time: 50 min.**

11.4 Solve problems on power factor correction related to synchronous condenser.

Example 6.1 *An alternator is supplying a load of 300 kW at a p.f. of 0·6 lagging. If the power factor is raised to unity, how many more kilowatts can alternator supply for the same kVA loading ?*

Solution :

$$\text{kVA} = \frac{\text{kW}}{\cos\phi} = \frac{300}{0\cdot 6} = 500 \text{ kVA}$$

$$\text{kW at } 0\cdot6 \text{ p.f.} = 300 \text{ kW}$$

$$\text{kW at 1 p.f.} = 500 \times 1 = 500 \text{ kW}$$

$\therefore$ Increased power supplied by the alternator

$$= 500 - 300 = \mathbf{200\ kW}$$

Note the importance of power factor improvement. When the p.f. of the alternator is unity, the 500 kVA are also 500 kW and the engine driving the alternator has to be capable of developing this power together with the losses in the alternator. But when the power factor of the load is 0·6, the power is only 300 kW. Therefore, the engine is developing only 300 kW, though the alternator is supplying its rated output of 500 kVA.

Example 6.2 *A single phase motor connected to 400 V, 50 Hz supply takes 31·7A at a p factor of 0·7 lagging. Calculate the capacitance required in parallel with the motor to rais power factor to 0·9 lagging.*

Solution : The circuit and phasor diagrams are shown in Figs. 6.8 and 6.9 respectively. motor M is taking a current I_M of 31·7A. The current I_C taken by the capacitor must be such that combined with I_M, the resultant current I lags the voltage by an angle ϕ where cos ϕ = 0·9.

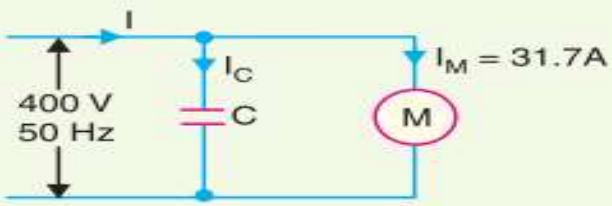


Fig. 6.8

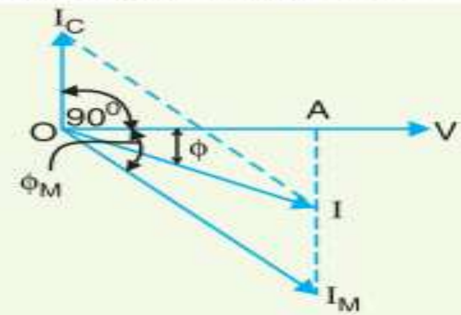


Fig. 6.9

Referring to the phasor diagram in Fig. 6.9,

$$\text{Active component of } I_M = I_M \cos\phi_M = 31{\cdot}7 \times 0{\cdot}7 = 22{\cdot}19\text{A}$$

$$\text{Active component of } I = I\cos\phi = I \times 0{\cdot}9$$

These components are represented by OA in Fig. 6.9.

$$\therefore \quad I = \frac{22\cdot19}{0\cdot9} = 24{\cdot}65\text{A}$$

$$\text{Reactive component of } I_M = I_M \sin\phi_M = 31{\cdot}7 \times 0{\cdot}714^* = 22{\cdot}6\text{A}$$

$$\text{Reactive component of } I = I\sin\phi = 24{\cdot}65\sqrt{1-(0\cdot9)^2}$$

$$= 24{\cdot}65 \times 0{\cdot}436 = 10{\cdot}75 \text{ A}$$

It is clear from Fig. 6.9 that :

$$I_C = \text{Reactive component of } I_M - \text{Reactive component of } I$$

$$= 22{\cdot}6 - 10{\cdot}75 = 11{\cdot}85\text{A}$$

But
$$I_C = \frac{V}{X_C} = V \times 2\pi fC$$

or
$$11{\cdot}85 = 400 \times 2\pi \times 50 \times C$$

$$\therefore \quad C = 94{\cdot}3 \times 10^{-6}\text{ F} = \mathbf{94{\cdot}3\ \mu F}$$

* $\sin\phi_M = \sqrt{1-\cos^2\phi_M} = \sqrt{1-(0\cdot7)^2} = 0{\cdot}714$

Example 6.9. *A synchronous motor improves the power factor of a load of 200 kW from 0.8 lagging to 0.9 lagging. Simultaneously the motor carries a load of 80 kW. Find (i) the leading kVAR taken by the motor (ii) kVA rating of the motor and (iii) power factor at which the motor operates.*

Solution.

Load, $P_1 = 200$ kW ; Motor load, $P_2 = 80$ kW

p.f. of load, $\cos\phi_1 = 0{\cdot}8$ lag

p.f. of combined load, $\cos\phi_2 = 0{\cdot}9$ lag

Combined load, $P = P_1 + P_2 = 200 + 80 = 280$ kW

In Fig. 6.12, Δ *OAB* is the power triangle for load, Δ *ODC* for combined load and Δ *BEC* for the motor.

(*i*) Leading kVAR taken by the motor

$= CE = DE - DC = AB - DC$ [$\because AB = DE$]

$= P_1 \tan\phi_1 - P^* \tan\phi_2$

$= 200 \tan(\cos^{-1} 0{\cdot}8) - 280 \tan(\cos^{-1} 0{\cdot}9)$

$= 200 \times 0{\cdot}75 - 280 \times 0{\cdot}4843$

= **14·4 kVAR**

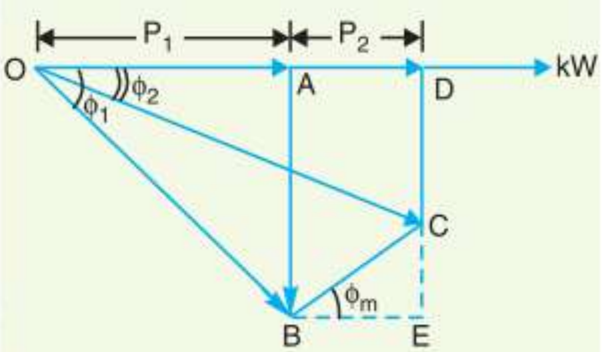


Fig. 6.12

(*ii*) kVA rating of the motor $= BC = \sqrt{(BE)^2 + (EC)^2} = \sqrt{(80)^2 + (14\cdot4)^2}$ = **81·28 kVA**

(*iii*) p.f. of motor, $\cos\phi_m = \dfrac{\text{Motor kW}}{\text{Motor kVA}} = \dfrac{80}{81\cdot28}$ = **0·984 leading**

Lecture- 19 **Time: 50 min.**

12. Understand the principle of operation of AC commutator motor.

12.1 Describe the principle of operation of Schrage (poly phase commutator motor) motor.

12.2 Application of Schrage motor.

12.3 Mention the advantages and disadvantages of Schrage motor .

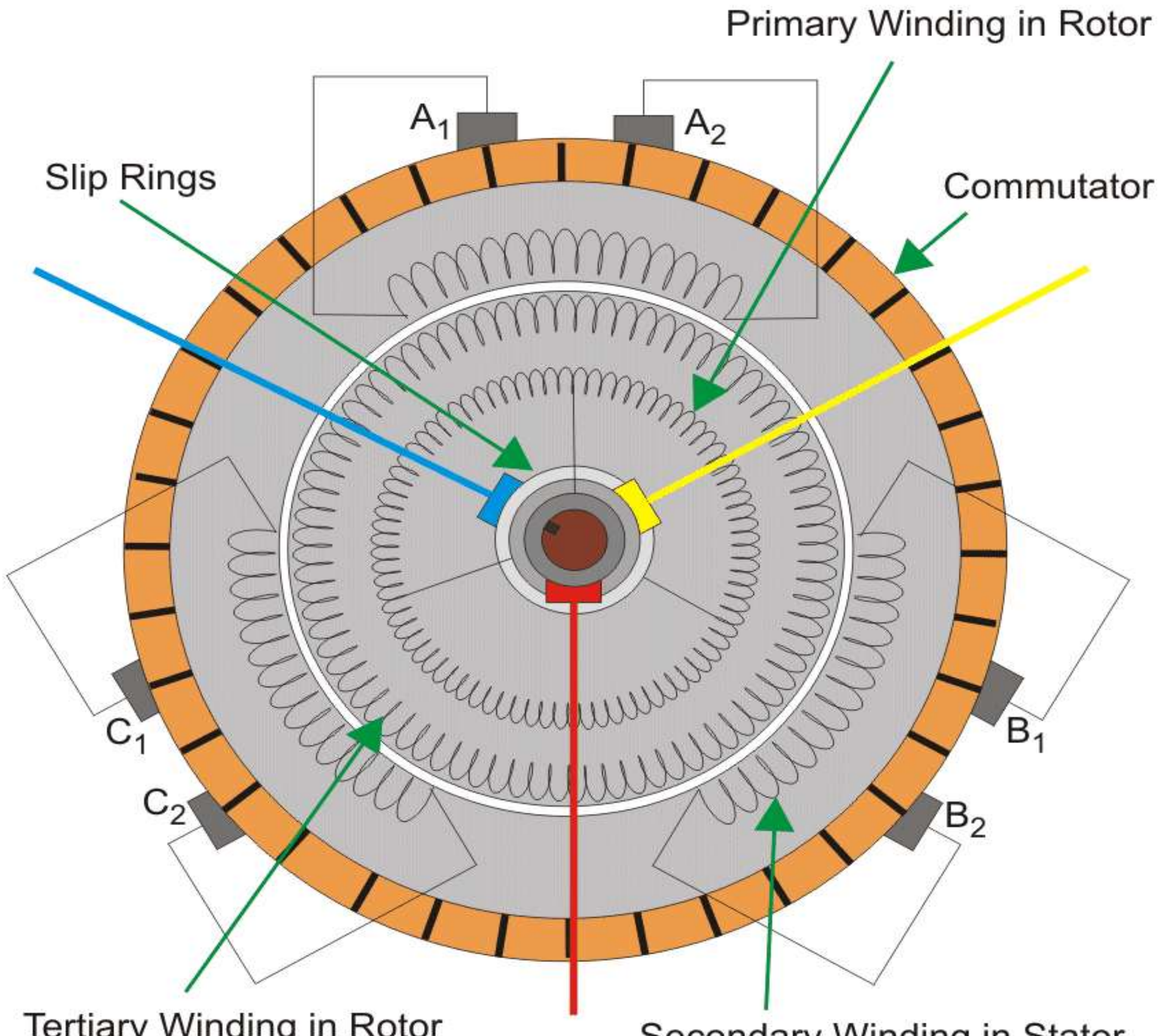
Schrage motor is essentially a combination of wound rotor induction motor and frequency convertor. Schrage motor can be treated as an inverted poly phase induction motor. Unlike induction motor the primary winding of Schrage motor is on the rotor. Three phase supply is given to the primary with the help of 3 slip rings. The secondary winding is on the stator. Apart from primary and secondary there is a third type of winding called as tertiary winding which is connected to the commutator .

Description :

The primary and tertiary are housed in the same rotor slots and are mutually coupled. The secondary winding terminals are connected to the commutator via three sets of movable brushes A_1A_2, B_1B_2 and C_1C_2. The brush position can be changed by a wheel provided at the back of motor. The angular displacement between the brushes determines the injected emf into the secondary winding which is required for speed and power factor control.

Operation Principle of Schrage Motor

At standstill conditions due to three phase currents flowing in the primary winding a rotating field is produced. This rotating field cuts the secondary with a synchronous speed n_s. Therefore according to Lenz's law the rotor will rotate in a direction so as to oppose the cause i.e. to induce slip frequency emfs into secondary. Therefore the rotor rotates opposite to the direction of rotation of synchronously rotating field. Now air gap field is rotating at slip speed $n_s - n_r$ with respect to secondary. Therefore the emf collected by the stationary brushes is at slip frequency and hence suitable for injection into secondary.


Primary Winding in Rotor
A1
A2
Slip Rings
Commutator
C1
C2
B1
B2
Tertiary Winding in Rotor
Secondary Winding in Stator

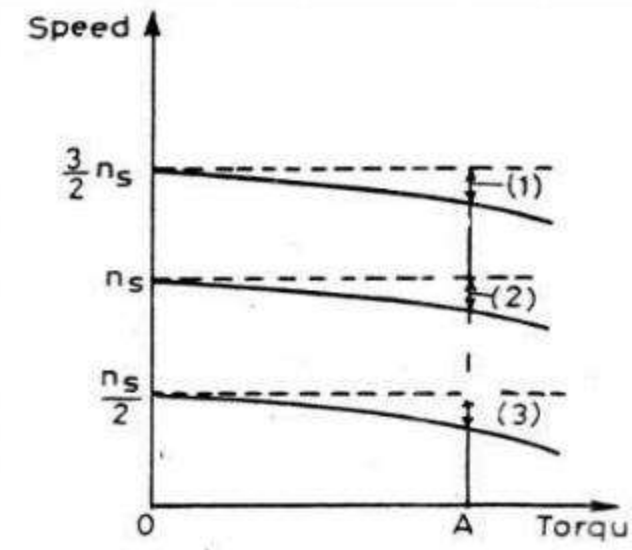
Speed Torque Characteristics

Same reveals that the Schrage Motor is almost
a constant speed motor. (SHUNT CHARACTERISTICS)

Applications

Can be applied to any individual drive requiring Variable speed. Especially in

(i) Hoisery knitting & Ring spinning m/cs.
(ii) Cranes & Hoists
(iii) Fans & Centrifugal Pumps
(iv) Printing Machinery
(v) Conveyors, Packing machinery & Paper Mills



ADVANTAGES:

- Wide variation of speed ranges are obtained.
- Speed control is simpler.
- P.F can be adjusted easily.

DISADVANTAGES:

- Complicated structure.
- More losses.
- Efficiency is less.

USES OF SCHRAGE MOTOR:

- Paper mills
- Spinning mills
- Cranes
- Hoists
- Boiler drought fans
- Textile machinery

Lecture- 20 **Time: 50 min.**

13. Understand the principle of operation of single phase motor.

13.1 Explain why single phase motor is not self starting.

13.2 Describe double revolving field theory and cross magnetizing field theory.

Why single phase induction motor is not self starting?

In induction machine a rotating magnetic field is required to produce torque.

A rotating magnetic field can produced if we have balanced three phase supply and each phase is electrically spaced 120 to each other OR we have required minimum two phase BUT in single phase induction motor there is single phase supply to the stator of motor. A SINGLE PHASE SUPPLY CAN NOT PRODUCE A ROTATING MAGNETIC FIELD BUT IT PRODUCE A PULSATING MAGNETIC FIELD WHICH DOES NOT ROTATE.

Due to this pulsating magnetic field torque can not produce so motor is not self starting.

Double Revolving Field Theory of Single Phase Induction Motor

Consider two magnetic fields represented by quantities OA and OB of equal magnitude revolving in opposite directions as shown in fig:b

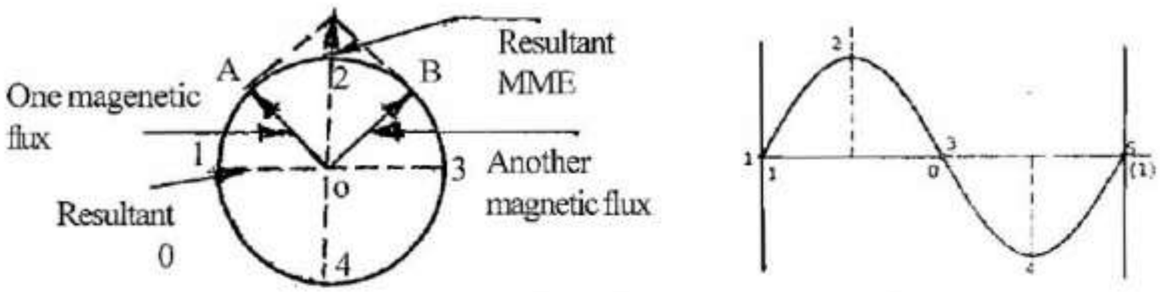


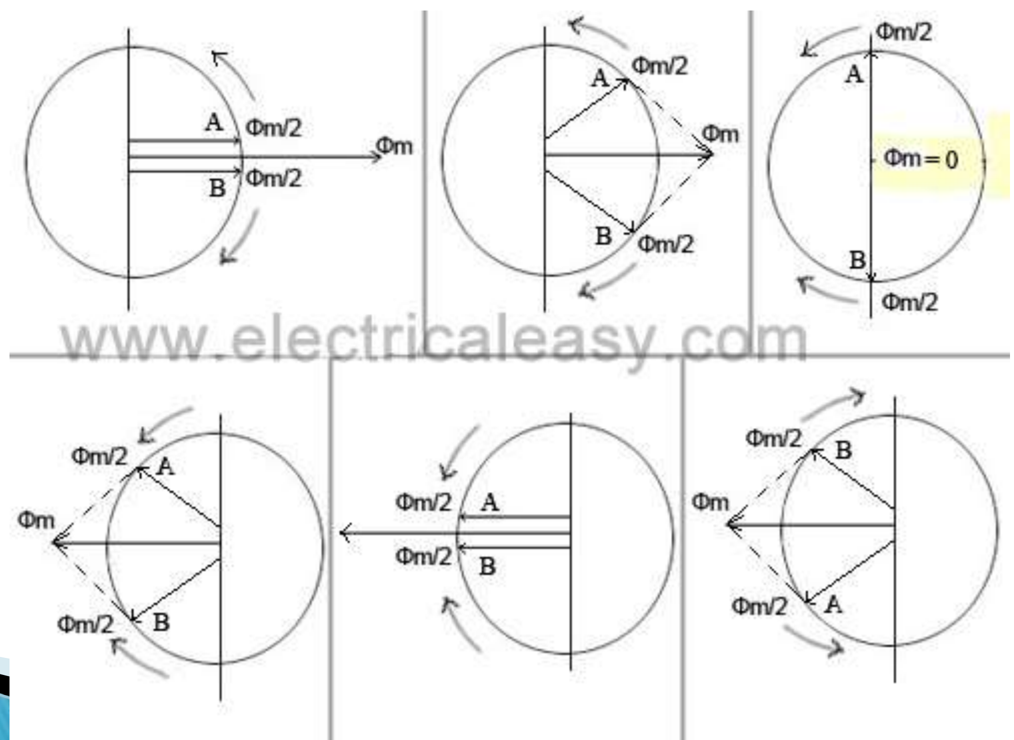
Fig: (b)

The resultant of the two fields of equal magnitude rotating in opposite directions is alternating. Therefore an alternating current can be considered as having two components which are of equal in magnitude and rotating in opposite directions. From the above, it is clear that when a single phase alternating current is supplied to the stator of a single phase motor, the field produced will be of alternating in nature which can be divided into two components of equal magnitude one revolving in clockwise and other in counter clockwise direction.

Double-Field Revolving Theory

The double-field revolving theory states that, any alternating quantity (here, alternating flux) can be resolved into two components having magnitude half of the maximum magnitude of the alternating quantity, and both these components rotating in opposite direction.

Following figures will help you understanding the double field revolving theory.



Why Single Phase Induction Motor Is Not Self Starting?

The stator of a single phase induction motor is wound with single phase winding. When the stator is fed with a single phase supply, it produces alternating flux (which alternates along one space axis only). Alternating flux acting on a squirrel cage rotor can not produce rotation, only revolving flux can. That is why a single phase induction motor is not self starting.

How To Make Single Phase Induction Motor Self Starting?

As explained above, **single phase induction motor is not self-starting**. To make it self-starting, it can be temporarily converted into a two-phase motor while starting. This can be achieved by introducing an additional 'starting winding' also called as auxillary winding.

Hence, stator of a single phase motor has two windings: (i) Main winding and (ii) Starting winding (auxillary winding). These two windings are connected in parallel across a single phase supply and are spaced 90 electrical degrees apart. Phase difference of 90 degree can be achieved by connecting a capacitor in series with the starting winding.

.

Hence the motor behaves like a two-phase motor and the stator produces revolving magnetic field which causes rotor to run. Once motor gathers speed, say upto 80 or 90% of its normal speed, the starting winding gets disconnected form the circuit by means of a centrifugal switch, and the motor runs only on main winding.

If a stationary squirrel cage rotor is kept in such a field equal forces in opposite direction will act and the rotor will simply vibrate and there will be no rotation.

But if the rotor is given a small jerk in any direction in this condition, it will go on revolving and will develop torque in that particular direction. It is clear from the above that a single phase induction motor when having only one winding is not a self-starting. To make it a self-starting anyone of the following can be adopted.

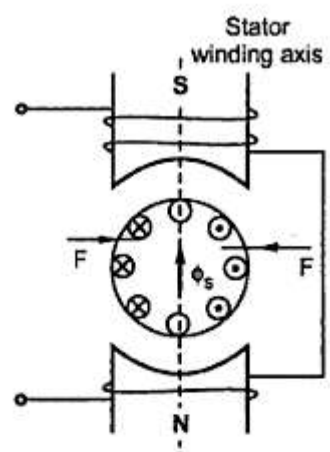
(i) Split phase starting.
(ii) Repulsion starting.
(iii) Shaded pole starting.

Lecture- 21 **Time: 50 min.**

13.3 List the methods of making single phase motor self starting.
13.4 Describe standard split phase motor

Cross magnetizing field theory :

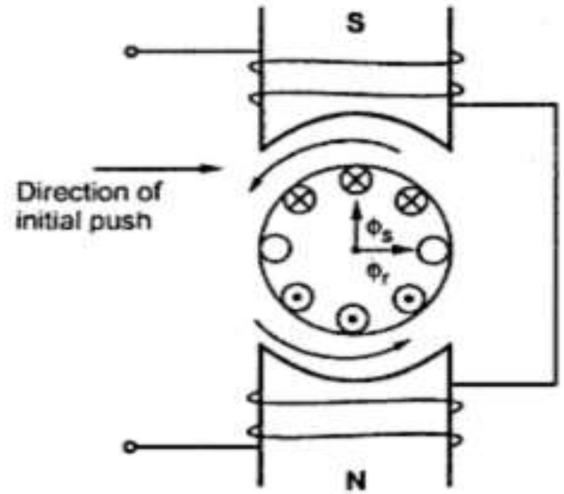
Consider a single phase induction motor with standstill rotor as shown in the Fig. 1. The stator winding is excited by the single phase a.c. supply. This supply produces an alternating flux Φ_s which acts along the axis of the stator winding. Due to this flux, e.m.f., gets induced in the rotor conductors due to transformer action. As rotor is closed one, this e.m.f. circulates current through the rotor conductors. The direction of the rotor current is as shown in the Fig. 1. The direction of rotor current is so as to oppose the cause producing it, which is stator flux Φ_s.



Now Fleming's left hand rule can be used to find the direction of the force experienced by the rotor conductors. It can be seen that when Φ_s acts in upward direction and increasing positively, the conductors on left experience force from left to right while conductors on right experience force from right to left. Thus overall, the force experienced by the rotor is zero. Hence no torque exists on the rotor and rotor can not start rotating.

We have seen that there must exist two fluxes separated by some angle so as to produce rotating magnetic field. According to cross field theory, the stator flux can be resolved into two components which are mutually perpendicular. One acts along axis of the stator winding and other acts perpendicular to it.

Assume now that an initial push is given to the rotor anticlockwise direction. Due to the rotation, rotor physically cuts the stator flux and dynamically e.m.f. gets induced in the rotor. This is called speed e.m.f. or rotational e.m.f. The direction of such e.m.f. can be obtained by Flemung's right hand rule and this e.m.f. in phase with the stator flux Φ_s. The direction of e.m.f. is shown in the Fig. 2. This e.m.f. us denoted as E_{2N}. This e.m.f. circulates current through rotor which is I_{2N}. This current produces its own flux called rotor flux Φ_r. This axis of Φ_r is at 90^o to the axis of stator flux hence this rotor flux is called cross-field.



Due to very high rotor reactance, the rotor current I_{2N} and Φ_r lags the rotational e.m.f. by almost 90^o .

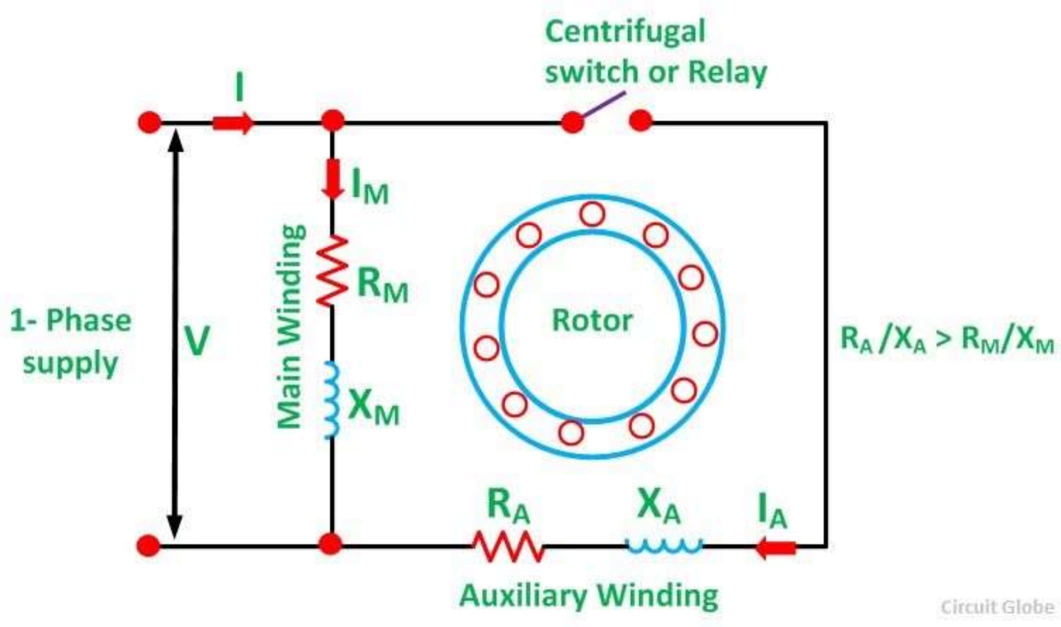
Thus Φ_r is in quadrature with Φ_s in space and lags Φ_s by 90^o in time phase. Such two fluxes produce the rotating magnetic field.

The direction of this rotating magnetic field will be same as the direction of the initial push given. Thus rotor experiences a torque in the same direction as that of rotating magnetic field i.e. the direction of initial push. So rotor accelerates in the anticlockwise direction under the case considered and attains a subsynchronous speed in the steady state.

we can make single phase induction motor self start by split single phase supply into two phase supply with the help of auxiliary winding.

Split Phase Induction Motor :

The **Split Phase Motor** is also known as a **Resistance Start Motor**. It has a single cage rotor, and its stator has two windings known as main winding and starting winding. Both the windings are displaced 90 degrees in space. The main winding has very low resistance and a high inductive reactance whereas the starting winding has high resistance and low inductive reactance . The Connection Diagram of the motor is shown below.

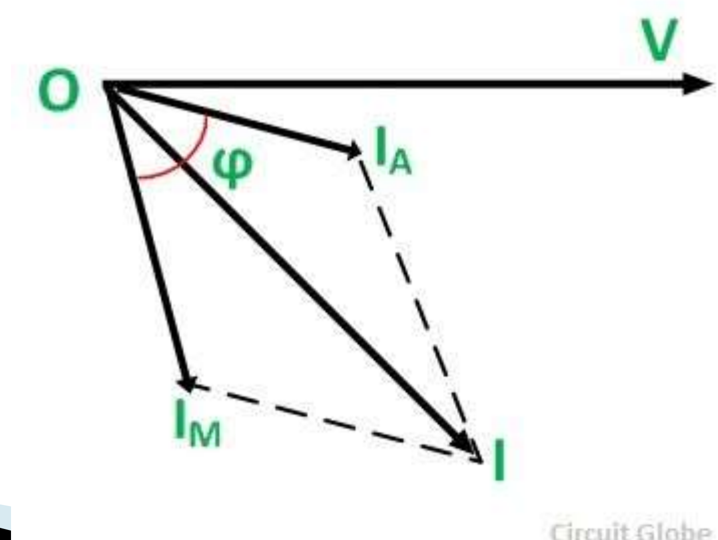


A resistor is connected in series with the auxiliary winding. The current in the two windings is not equal as a result the rotating field is not uniform. Hence, the starting torque is small, of the order of 1.5 to 2 times of the started running torque. At the starting of the motor both the windings are connected in parallel.

As soon as the motor reaches the speed of about 70 to 80 % of the synchronous speed the starting winding is disconnected automatically from the supply mains. If the motors are rated about 100 Watt or more, a centrifugal switch is used to disconnect the starting winding and for the smaller rating motors relay is used for the disconnecting of the winding.

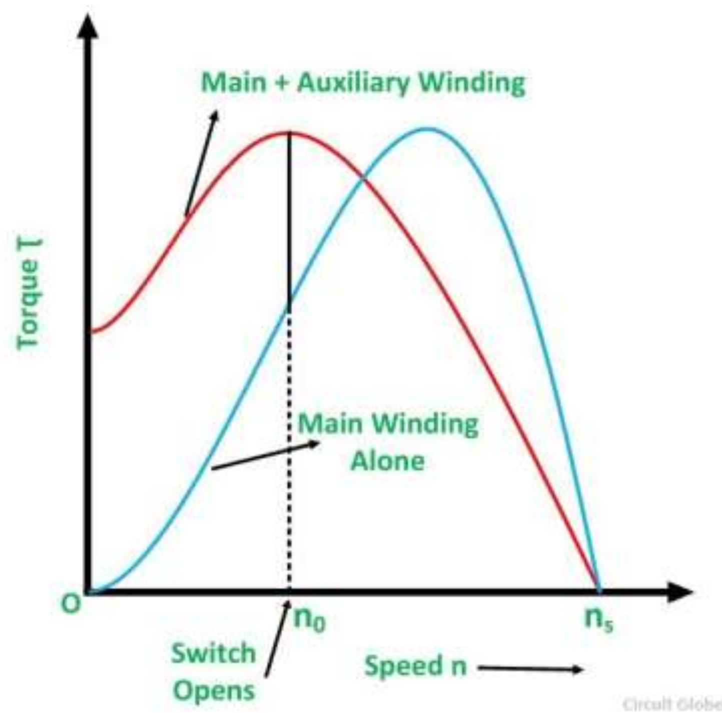
A relay is connected in series with the main winding. At the starting, the heavy current flows in the circuit, and the contact of the relay gets closed. Thus, the starting winding is in the circuit, and as the motor attains the predetermined speed, the current in the relay starts decreasing. Therefore, the relay opens and disconnects the auxiliary winding from the supply, making the motor runs on the main winding only.

The phasor diagram of the Split Phase Induction Motor is shown below.



The current in the main winding (I_M) lag behind the supply voltage V almost by the 90-degree angle. The current in the auxiliary winding I_A is approximately in phase with the line voltage. Thus, there exists the time difference between the currents of the two windings. The time phase difference ϕ is not 90 degrees, but of the order of 30 degrees. This phase difference is enough to produce a rotating magnetic field.

The **Torque Speed Characteristic** of the Split Phase motor is shown below.



Here, n_0 is the point at which the centrifugal switch operates. The starting torque of the resistance start motor is about 1.5 times of the full load torque. The maximum torque is about 2.5 times of the full load torque at about 75% of the synchronous speed. The starting current of the motor is high about 7 to 8 times of the full load value.

The direction of the Resistance Start motor can be reversed by reversing the line connection of either the main winding or the starting winding. The reversal of the motor is possible at the standstill condition only.

Lecture- 22 **Time: 50 min.**

13.5. Describe capacitor motor and double capacitor motor.
13.6 Describe shaded pole motor & repulsion motor.

Start capacitor AC induction motors

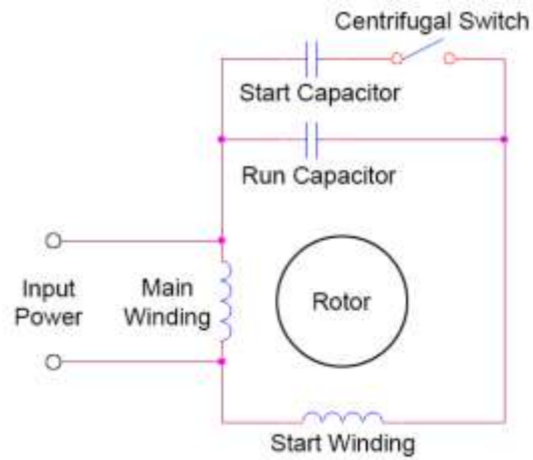
One way to improve on the single coil design is by using an auxiliary coil in series with a motor starting capacitor. The auxiliary coil, also called starting coil, is used to create an initial rotating magnetic field. In order to create a rotating magnetic field, the current flowing through the main winding must be out of phase in respect to the current flowing through the auxiliary winding.

The role of the starting capacitor is to lag the current in the auxiliary winding, bringing these two currents out of phase. When the rotor reaches sufficient speed, the auxiliary coil is disconnected from the circuit by means of a centrifugal switch, and the motor remains powered by a single coil creating a pulsating magnetic field. In this sense, the auxiliary coil in this design can be regarded as a starting coil, since it is only used during motor startup.

Start/run capacitor AC induction motors (Double Capacitor).

Another way to further improve on the single-coil single-phase induction motor design is to introduce an auxiliary coil, which remains powered not only during the motor startup phase, but also during normal operation. As opposed to an AC motor using only a motor start capacitor, which creates a pulsating magnetic field during normal operation, AC motors using a motor start capacitor and a motor run capacitor create a rotating magnetic field during normal operation.

The function of the motor start capacitor remains the same as in the previous case – it gets disconnected from the circuit after the rotor reaches a predetermined speed by means of a centrifugal switch. After that point, the auxiliary winding remains powered through a motor run capacitor. The figure below describes this type of design.



Motor start and motor run capacitors

Start capacitors

Motor start capacitors are used during the motor startup phase and are disconnected from the circuit once the rotor reaches a predetermined speed, which is usually about 75% of the maximum speed for that motor type. These capacitors usually have capacitance values of over 70 µF. They come in various voltage ratings, depending on the application they were intended for.

Run capacitors

Some single phase AC motor designs use motor run capacitors, which are left connected to the auxiliary coil even after the start capacitor is disconnected by the centrifugal switch. These designs operate by creating a rotating magnetic field. Motor run capacitors are designed for continuous duty, and remain powered whenever the motor is powered, which is why electrolytic capacitors are avoided, and low-loss polymer capacitors are used instead. The capacitance value of run capacitors is usually lower than the capacitance of start capacitors, and is often in the range of 1.5 µF to 100 µF.

Choosing a wrong capacitance value for a motor can result in an uneven magnetic field, which can be observed as uneven motor rotation speed, especially under load. This can cause additional noise from the motor, performance drops and increased energy consumption, as well as additional heating, which can cause the motor to overheat.

Lecture- 23 **Time: 50 min.**

13.6 Describe shaded pole motor & repulsion motor.

Shaded pole motor :

Introduction

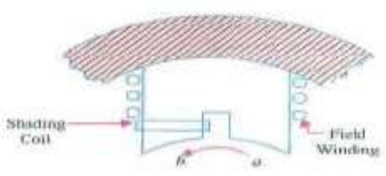
Shaded pole motor is one of the types of single phase induction motors, which are used for producing a rotating stator flux in order to make the single phase induction motor a self starting one. Let us discuss the constructional details, diagrams and working of shaded pole motors in detail.

Shaded-Pole Single-Phase Motors

Like any other motors the shaded pole induction motor also consists of a stator and rotor. The stator is of salient pole type and the rotor is of squirrel cage type.

The poles of shaded pole induction motor consist of slots, which are cut across the laminations. The smaller part of the slotted pole is short-circuited with the help of a coil. The coils are made up of copper and it is highly inductive in nature. This coil is known as shading coil. The part of the pole which has the coil is called the shaded part and the other part of the pole is called unshaded part.

Now let us consider that an alternating current is passed through the excited winding which surrounds the pole. Due to the presence of shading coil, the axis of the pole shift from unshaded part to shaded part. This shifting effect is equivalent to the physical movement of the poles, which is nothing but the rotation of poles. So the rotor starts rotating in the direction of the shift from unshaded part to shaded part.



Why Magnetic Axis Shift Takes Place?

Now let us discuss why the axis shift occurs when current is passed through the winding and how the shading coil aids in producing the shift.The current carried by stator winding produces alternating flux. The distribution of flux through the poles is greatly influenced by the shading coils.

When the alternating current through the coil increases, it induces a current in the shading coil. The direction of current in shading coil is such as to oppose the cause producing it (from Lenz law). The cause is the alternating current. So the flux in the shading coil decreases and it opposes the main flux. Hence the flux mostly crowds or shifts towards the unshaded part of the pole. So the magnetic axis lies along the middle of the unshaded part.It is denoted as NC in the picture below.

Now consider that the alternating current has reached its peak (or) somewhere near the peak. Here the rate of change of current is low, as it has already reached the peak (or) it is very close to peak value. Since the change is current is so small, the induced current at shading ring is also small and negligible. So the shading ring does not affect the distribution of main flux. The flux is distributed uniformly and the magnetic axis lies at the center of pole face . The magnetic axis is denoted as ND in the picture.

The alternating current, after reaching the peak starts to decrease rapidly and in turn decreases the main flux. The change in current induces a current in shading coil. According to Lenz law the direction of this current is so as to oppose the cause producing it (the decreasing alternating current). So the flux in shading coil opposes the decrease in main flux and strengthens it. This increases the strength of main flux in the shaded part. SO the magnetic axis shifts itself to the middle part of shaded pole.The magnetic axis denoted as NE in the picture below.

So it is quite clear that during the positive half cycle of the alternating current, North Pole shifts from unshaded part to shaded part and during the negative half cycle, the South Pole shifts along from unshaded part to shaded part. This effect is nothing but the rotation of poles from left to right.

Thus shaded coils aids in producing the rotating flux and thus the single phase Induction motor is converted into self starting one using the Shading coil. Due to fixed of position of shading coils, the direction of rotation of such motors cannot be changed.

Advantages, Disadvantages and Applications

The various **advantages** of Shaded pole motors includes

Very cheap and reliable. Easy to construct. Extremely rugged in nature

Disadvantages includes

Low efficiency

Low starting torque

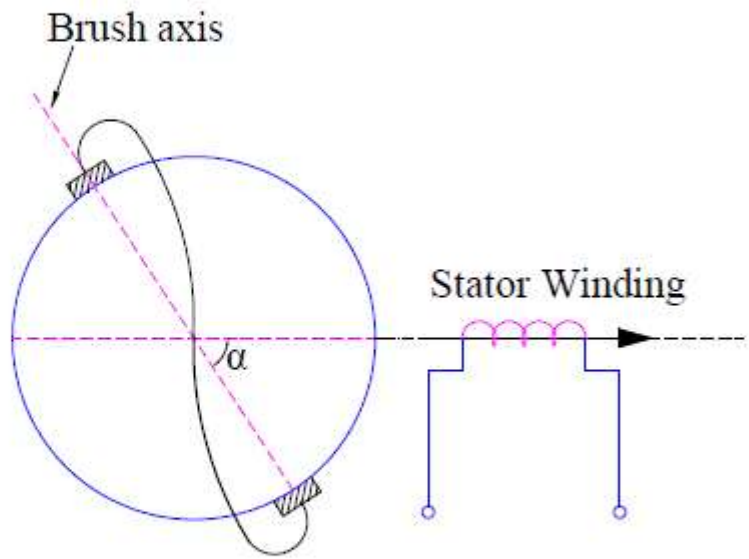
Since the shading coil is made of copper, the copper loss is high.

Uses

Due to their low starting torques they are mostly employed in small instruments, toys, small fans, electric clocks, hair dryers, ventilators, circulators etc.

Construction of Repulsion Motor:

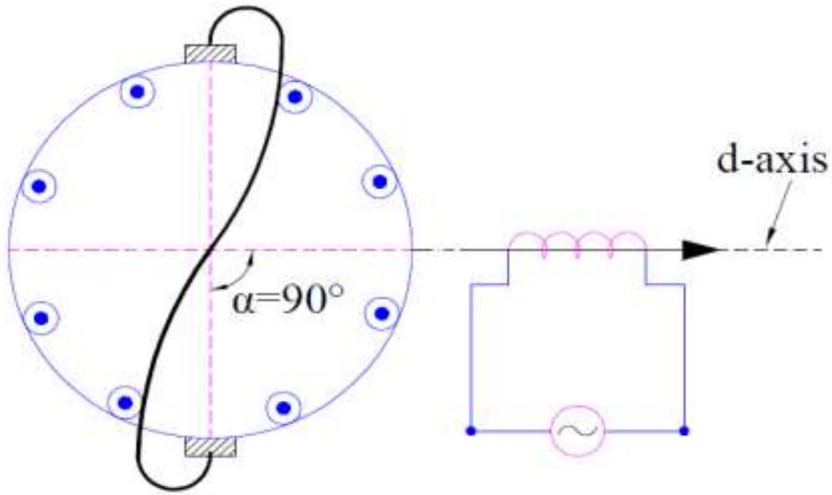
The main components of repulsion motor are stator, rotor and commutator brush assembly. The stator carries a single phase exciting winding similar to the main winding of single phase induction motor. The rotor has distributed DC winding connected to the commutator at one end just like in DC motor. The carbon brushes are short circuited on themselves.



In the above figure, the stator winding have single phase AC winding which produces the working mmf in the air gap. The brushes on rotor are shown to be shorted. As the rotor circuit is shorted, the rotor receives power from stator by transformer action.

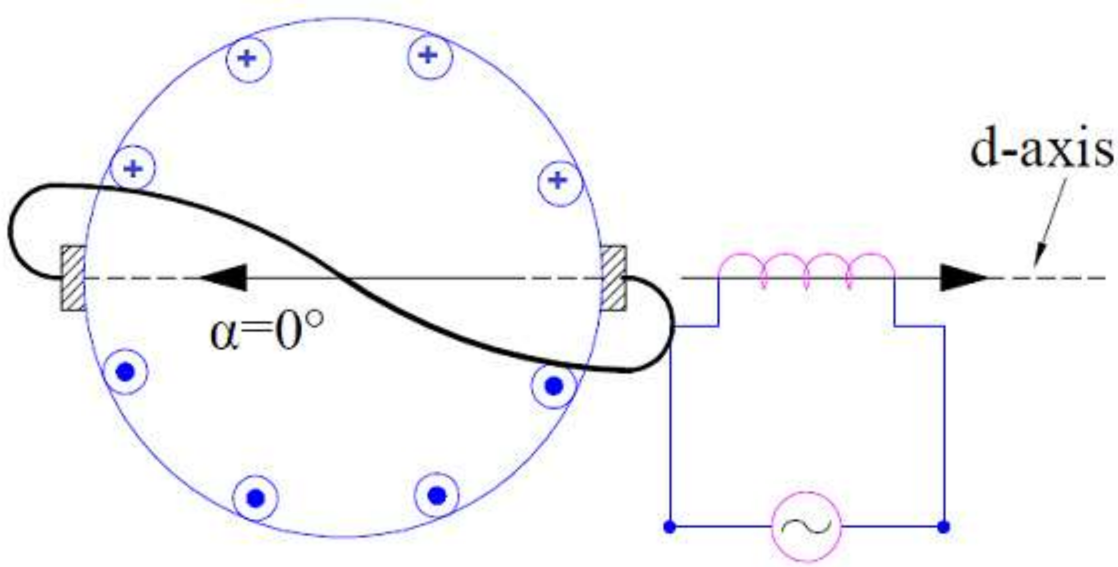
Working principle of Repulsion Motor:

The basic principle behind the working of repulsion motor is that "similar poles repel each other." This means two North poles will repel each other. Similarly, two South poles will repel each other. When the stator winding of repulsion motor is supplied with single phase AC, it produces a magnetic flux along the direct axis as shown in figure above by arrow mark. This magnetic flux when link with the rotor winding, creates an emf. Due to this emf, a rotor current is produced. This rotor current in turn produces a magnetic flux which is directed along the brush axis due to commutator assembly. Due to the interaction of stator and rotor produced fluxes, an electromagnetic torque is produced. Let us discuss this aspect in detail.



In the above figure, the angle α between the stator produced field and brush axis is 90°. This means, the brush axis is in quadrature with the direct. Under this condition, there will not be any mutual induction between the stator and rotor windings. Therefore, no emf and hence no rotor current is produced. Thus no electromagnetic torque is developed.

This means that motor will not run when α = 90°. As the stator produced flux is unaffected by the zero rotor mmf, this condition is similar to the open circuit transformer. This is the reason, the brush position of α = 90° is called open-circuit, no-load, high impedance or neutral position.

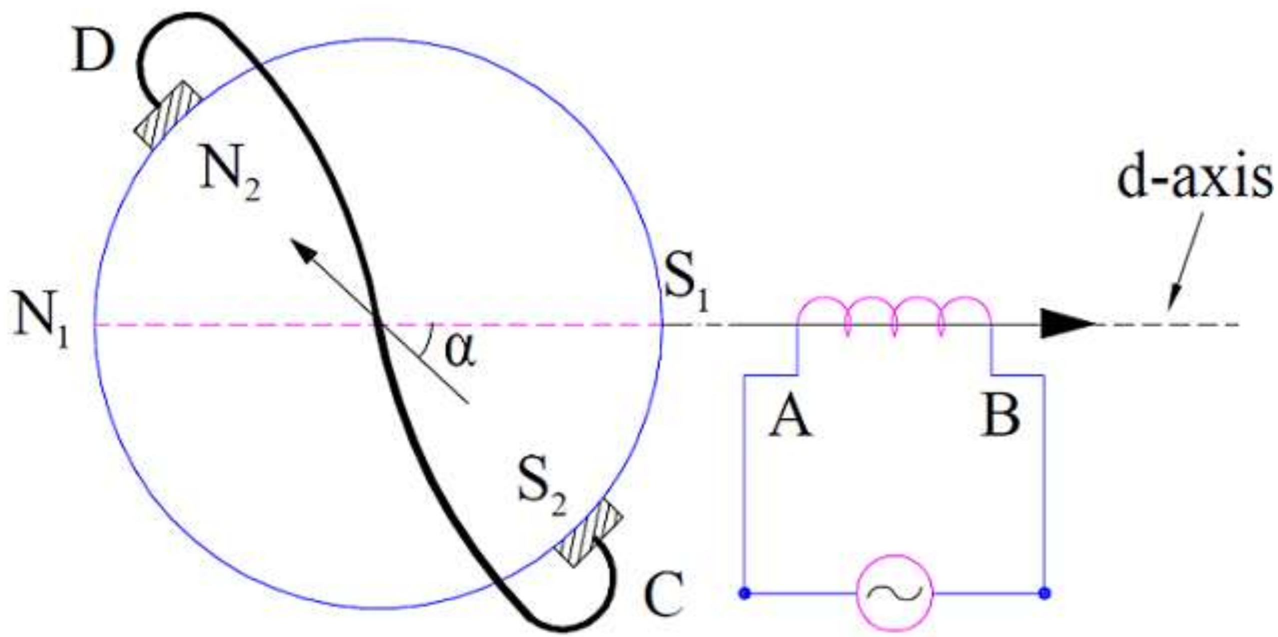


In this condition, a maximum emf is induced across the brushes. This is because, the rotor and stator magnetic flux coincides and hence there is a perfect mutual coupling between them. Since the electromagnetic torque T is given as

T_e = k (Stator Field Strength) (Rotor Field Strength) Sinα
where is k is a constant.

No electromagnetic torque is developed as α = 0°. Thus in repulsion motor, no electromagnetic torque is developed when the angle between the stator and rotor magnetic flux axis is either 0 or 90°.

But actually the brush axis occupies a position somewhere in between α = 0° and α = 90° as shown in figure below.



If the stator produced flux is assumed to be directed from A to B, then rotor produced flux must also have a component in a direction opposite to stator produced flux. This is just because of Lenz's Law. Therefore the rotor flux will be directed from C to D. Notice that it cannot be directed from D to C otherwise it will have a flux component directed toward A to B which is violation of Lenz's Law.

Since stator flux is toward A to B, South Pole (S1) is generated at A. Similarly South Pole (S2) is generated on rotor at C. Since similar poles repel each other, S1 will repel S2. Due to this repulsion between the like poles, motor will rotate in clockwise direction. ***This is the reason; this motor is called Repulsion Motor***. It is clear from the above figure and discussion that, the direction of rotation of repulsion motor can be reversed by simply changing the brush axis to the other side of filed winding (stator winding).

Following points regarding must be noted from the above curve:

Rotor current is maximum when the brush axis and direct axis coincides.

Rotor current is zero when the brush occupies a position in quadrature with the direct axis.

Maximum torque in repulsion motor is achieved when stator and rotor field axis are 45° apart.

Uses:

Repulsion motor is used for loads requiring high starting torque such as hoists, lifts etc.

Lecture- 24 **Time: 50 min.**

13.7 Describe hysteresis motor, universal motor, reluctance motor & AC series Motor

Hysteresis Motor

The operation of hysteresis motor depends upon effect of hysteresis. It is a type of single phase motor.

The rotor magnetic field lags behind by the stator magnetizing force in this motor.

Construction

Stator

The stator slots consists of main winding and auxiliary winding.

These two winding generate rotating magnetic field due to single phase supply.

This type of construction is called as Split phase construction.

If the operation of the hysteresis motor depends upon effect of shaded pole, it is called as shaded pole hysteresis motor.

Rotor

The rotor is made of chrome steel or alnico type hard material.

It does not consist any winding.

Its hysteresis loop area must be high in order to high hysteresis loss.

The rotor of the hysteresis motor is shown in the Figure A.

It consists of two or more rings at outer side and cross bars.

The rotor is made by heat treatment of hard steel material.

When a stator magnetic field cuts rotor, torque produces due to hysteresis effect and rotor starts to rotate.

.

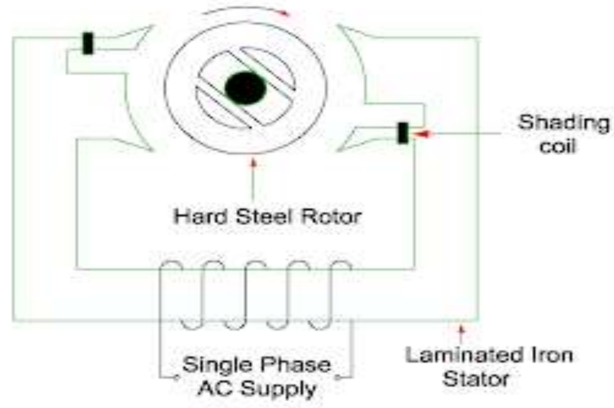
When the rotor speed increases up to synchronous speed, flux gets low reluctance path due to low reluctance.

This will result in creation of rotor poles in the rotor. The rotor continues to rotate at synchronous speed. The rotor is made of smooth cylindrical as shown in the Figure A.

The hysteresis ring is made of chrome, cobalt or alnico material.

The resistivity of rotor material is kept high in order to reduce eddy current in the rotor.

The output of the motor reduces as the thickness of the ring increases



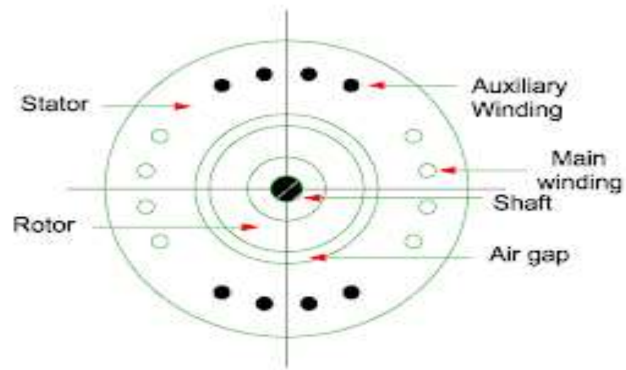


FIG A : CONSTRUCTION OF HYSTERESIS MOTOR

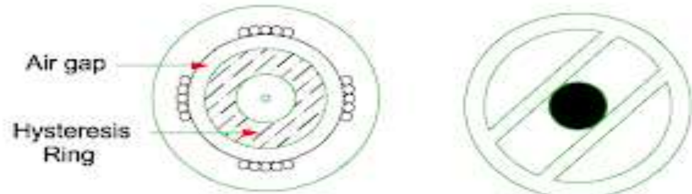


FIG B : TYPES OF ROTOR

Working

When a single phase supply is given to the main winding and running winding, a stator magnetic field is produced.

When a rotor cuts stator magnetic field, rotor starts to rotate due to eddy current torque and hysteresis torque.

When a rotor speed approaches synchronous speed, stator and rotor magnetic field locked with each other.

The eddy current torque becomes zero due to relative speed between stator and rotor magnetic becomes zero.

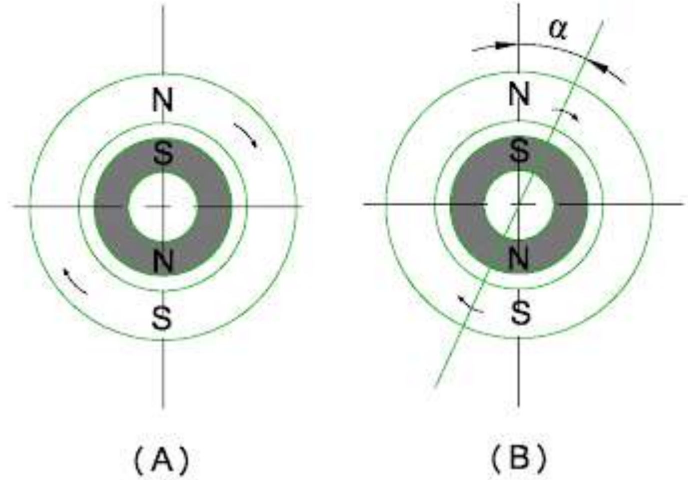


FIG C : (A) ROTOR POLES INDUCED IN THE ROTOR

FIG C : (B) TORQUE DEVELOPED IN THE ROTOR

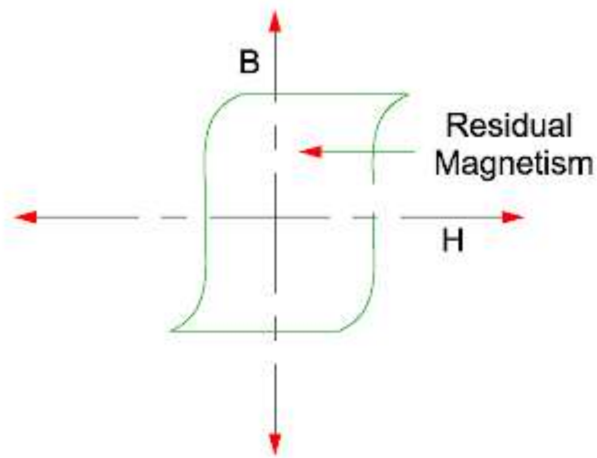


FIG C : (C) HYSTERESIS LOOP OF ROTOR MATERIAL

•The rotor poles create when a rotor rotates at synchronous speed.

•The rotor poles always lags behind stator poles due to hysteresis effect.

•When a load is applied, a torque acts on rotor is called as hysteresis torque.

•This torque remains constant at all speed. The polarity of rotor poles do not change as the resistivity of rotor material is high.

•The mechanical power developed in the rotor

$P_m = (1 – s) / s$ ……….(1)

Where P_m = Hysteresis loss and

s = Slip

Universal motor (AC series Motor) :

A **universal motor** is a special type of motor which is designed to run on either DC or single phase AC supply. These motors are generally series wound (armature and field winding are in series), and hence produce high starting torque (See characteristics of DC motors here). That is why, **universal motors** generally comes built into the device they are meant to drive. Most of the universal motors are designed to operate at higher speeds, exceeding 3500 RPM. They run at lower speed on AC supply than they run on DC supply of same voltage, due to the reactance voltage drop which is present in AC and not in DC.

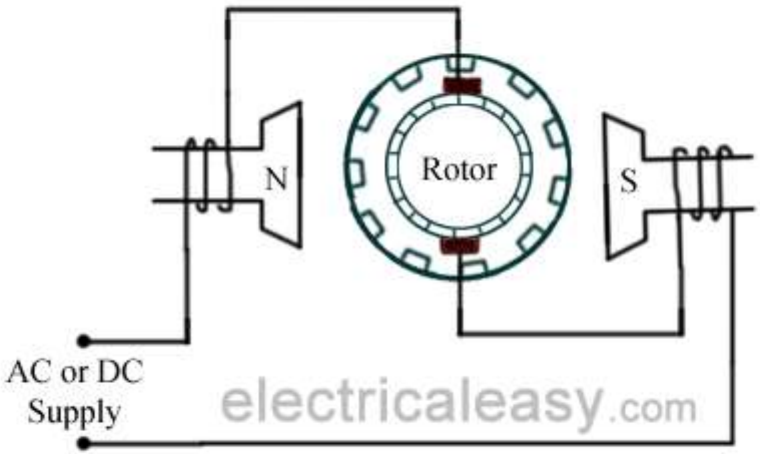
There are two **basic types of universal motor** : (i)compensated type and (ii) uncompensated type

Construction Of Universal Motor :

Construction of a universal motor is very similar to the construction of a DC machine. It consists of a stator on which field poles are mounted. Field coils are wound on the field poles. However, the whole magnetic path (stator field circuit and also armature) is laminated. Lamination is necessary to minimize the eddy currents which induce while operating on AC.

The rotary armature is of wound type having straight or skewed slots and commutator with brushes resting on it. The commutation on AC is poorer than that for DC. because of the current induced in the armature coils. For that reason brushes used are having high resistance.

Working Of Universal Motor :



A universal motor works on either DC or single phase AC supply. When the universal motor is fed with a DC supply, it works as a DC series motor. (see working of a DC series motor here). When current flows in the field winding, it produces an electromagnetic field. The same current also flows from the armature conductors. When a current carrying conductor is placed in an electromagnetic field, it experiences a mechanical force. Due to this mechanical force, or torque, the rotor starts to rotate. The direction of this force is given by Fleming's left hand rule.

When fed with AC supply, it still produces unidirectional torque. Because, armature winding and field winding are connected in series, they are in same phase. Hence, as polarity of AC changes periodically, the direction of current in armature and field winding reverses at the same time.
Thus, direction of magnetic field and the direction of armature current reverses in such a way that the direction of force experienced by armature conductors remains same. Thus, regardless of AC or DC supply, universal motor works on the same principle that DC series motor works.

Applications Of Universal Motor

Universal motors find their use in various home appliances like vacuum cleaners, drink and food mixers, domestic sewing machine etc.

The higher rating universal motors are used in portable drills, blenders etc.

Construction & Working principle of Reluctance Motor - Applications

Machines

Construction of Reluctance Motor:

We know about different types of synchronous motors, apart from all these motor works based on reluctance. So it is called **Reluctance Motor**. Here we will discuss **construction and working principle of Reluctance Motor**. The reluctance motor has basically two main parts called stator and rotor. the stator has a laminated construction, made up of stampings.

The stampings are slotted on its periphery to carry the winding called stator winding. The stator carries only one winding. This is excited by single-phase a.c. supply. The laminated construction keeps iron losses to a minimum. The stampings are made up of material from silicon steel which minimises the **hysteresis loss**. The stator winding is wound for certain definite number of poles.

The rotor has a particular shape. Due to its shape, the air gap between stator and rotor is not uniform.No d.c supply is given to the rotor. The rotor is free to rotate. The reluctance i.e., the resistance of the magnetic circuit depends on the air gap. More the air gap, more is the reluctance and vice-versa. Due to the variable air gap between stator and rotor, when the rotor rotates, reluctance between stator and rotor also changes. The stator and rotor are designed in such a manner that the variation of the inductance of the windings is sinusoidal with respect to the rotor position.

The **construction of Reluctance Motor** is shown in figure(a) while the practical rotor of **Reluctance Motor** is shown in figure(b) below.

Working Principle of Reluctance Motor:

The stator consists of a Single Winding called main winding. But single winding cannot produce rotating magnetic field. So for production of rotating magnetic field, there must be at least two windings separated by the certain phase angle. Hence stator consists of an additional winding called auxiliary winding which consists of a capacitor in series with it.

Thus there exists a phase difference between the currents carried by the two windings and corresponding fluxes. Such two fluxes react to produce the rotating magnetic field. The technique is called split phase technique of production of the rotating magnetic field. The speed of this field is the synchronous speed which is decided by the number of poles for which stator winding is wound. The rotor carries the short-circuited copper or aluminium bars and it acts as a squirrel-cage rotor of an **induction motor**. If an iron piece is placed in a magnetic field, it aligns itself in a minimum reluctance position and gets locked magnetically. Similarly, in the **reluctance motor**, rotor tries to align itself with the axis of rotating magnetic field in a minimum reluctance position. But due to rotor inertia, it is not possible when the rotor is standstill.

So rotor starts rotating near synchronous speed as a **squirrel cage induction motor**. When the rotor speed is about synchronous, stator magnetic field pulls rotor into synchronism i.e. minimum reluctance position and keeps it magnetically locked. Then rotor continues to rotate with a speed equal to synchronous speed. Such a torque exerted on the rotor is called the reluctance torque. Thus finally the **reluctance motor** runs as a synchronous motor. The resistance of the rotor must be very shall and the combined inertia of the rotor and the load should be small to run the motor as a synchronous motor.

Applications of Reluctance Motor:

Reluctance motor is used in

Signalling Devices , Control Apparatus , Automatic regulators , Recording Instruments , Clocks , All timing devices , Teleprinters , Gramophones .

Lecture- 25 **Time: 50 min.**

13.8 Explain the losses and efficiency of single phase motor.
13.9. Understand the working principle of stepper motor.
13.10 Explain Types, advantages and application of stepper motor

There are two types of losses occur in three phase induction motor. These losses are,

Constant or fixed losses,

Variable losses.

Constant or Fixed Losses

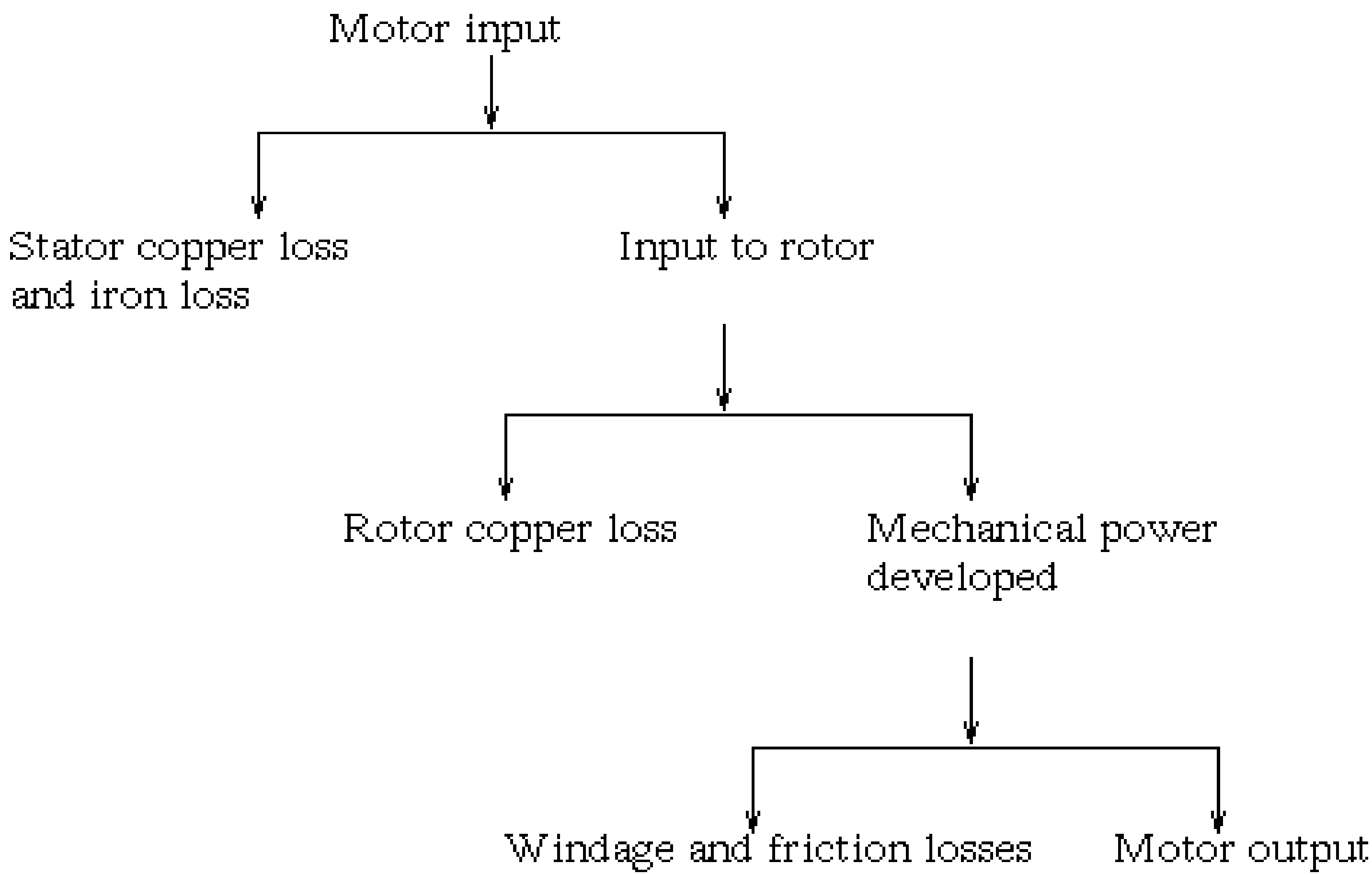
Constant losses are those losses which are considered to remain constant over normal working range of induction motor. The fixed losses can be easily obtained by performing no-load test on the three phase induction motor. These losses are further classified as-

Iron or core losses,

Mechanical losses,

Brush friction losses.

Variable Losses



Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta = \frac{output}{input}$$

Rotor efficiency of the single phase induction motor ,

$$= \frac{rotor\ output}{rotor\ input}$$

induction motor efficiency,

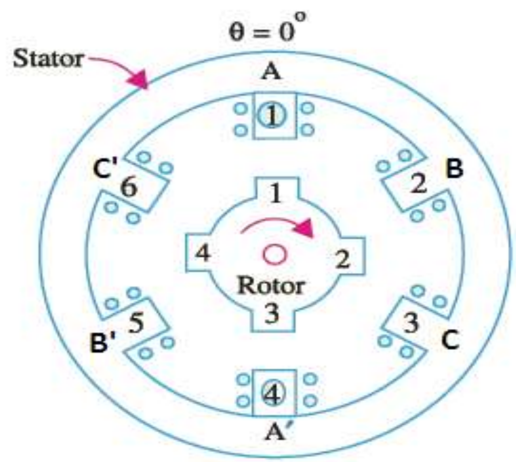
$$= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

$$\eta = \frac{P_{out}}{P_{in}}$$

a stepper motor is a device which converts digital pulses into precise angular movement.

Stepper Motor Working Principle

A stepper motor is a D.C. motor with field placed on the rotor in the form of permanent magnets with two, three or four sets of coils called phases, placed in the stator around the rotor. The windings are connected to an external logic driver which delivers voltage pulses to the windings sequentially. The motor responds to these pulses and performs start, stop, and reverse operations under command.

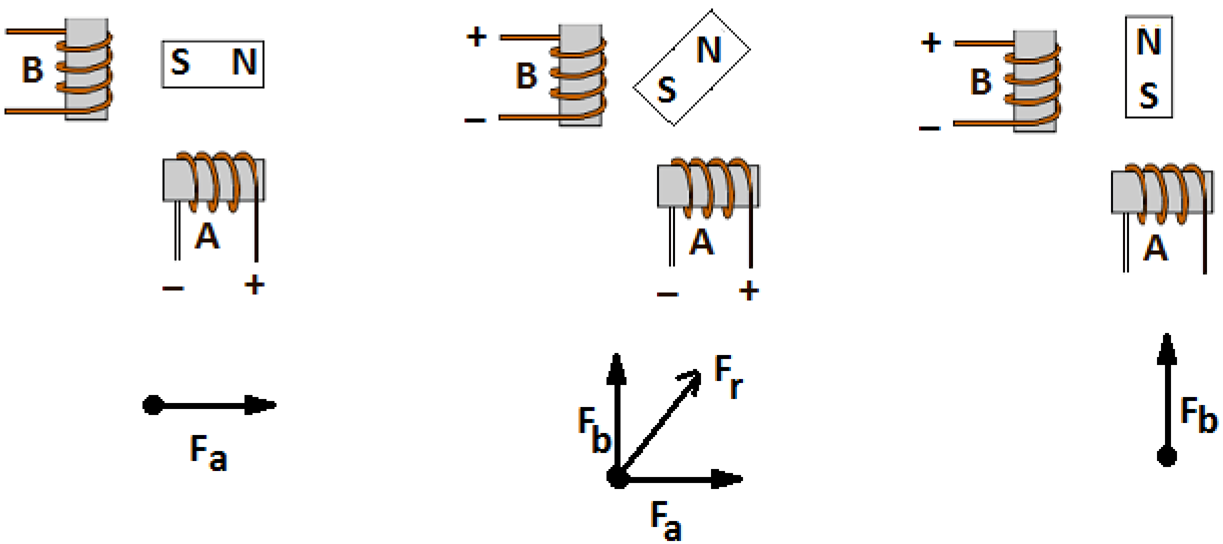


Stepper Motor

Both the rotor and stator have a definite number of teeth to suit the designed step angle. The step angle is defined as the angular displacement of the rotor in response to each pulse. The rotor position depends upon the step angle and the number of pulses. The speed of rotation depends upon the rate of pulses (and not supply voltage) are precisely controlled; thus making the stepper motor an ideal drive for operations involving precise positioning. Unlike control and servo motors, no feedback control winding is required to close the loop and monitor the position and speed of the rotor.

The **stepper motor working principle** is explained in Figure. The rotor takes a position as per excitation of winding:

In position (a) only winding **A** is energized.
In position (b) both the windings, **A** and **B** are energized.
In position (c), winding **B** is energized and so on.



Position (a) Position (b) Position (c)

From the above illustration, you can understand easily that we can rotate the rotor in steps by supplying current to stator coils in a specific sequence. This is what we do in stepper motors. For detailed information about working of the stepper motor, you can refer to my next article.

Holding torque is the maximum load torque that can be overcome by the motor without causing the rotor to slip from its stable equilibrium position.

The operation of a stepper motor is accurate and precise over a wide range of speed. Accuracy tolerance is the maximum deviation from nominal values of each rotor displacement in response to input pulse under no-load condition. The accuracy tolerance is usually in the range of 3 to 5% and this error is non-cumulative. A stepper motor system must accelerate and deaccelerate at a rate that allows the motor to overcome the system inertia. For this reason, rotors are constructed with less diameter and longer lengths. If a stepper motor is dynamically overloaded, it will slip phase. These motors are best suited for applications where loads are well within the capacity of the motor.

Types of Stepper Motors

There are three basic **categories of stepper motors**, namely

Permanent Magnet Stepper Motor

Variable Reluctance Stepper Motor

Hybrid Stepper Motor

Advantages of Stepper Motor

At standstill position, the motor has full torque. No matter if there is no moment or changing position.

It has a good response to starting, stopping and reversing position.

As there is no contact brushes in the stepper motor, It is reliable and the life expectancy depends on the bearings of the motor.

The motor rotation angle is directly proportional to the input signals.

It is simple and less costly to control as motor provides open loop control when responding to the digital input signals.

The motor speed is directly proportional to the input pulses frequency, this way a wide range of rotational speed can be achieved.

When load is coupled to the shaft, it is still possible to realize the synchronous rotation with low speed.

The exact positioning and repeatability of movement is good as it has a 3-5% accuracy of a step where the error is non cumulative from one step to another.

Stepper motors are safer and low cost (as compared to servo motors), having high torque at low speeds, high reliability with simple construction which operates at any environment.

Applications of Stepper Motors

Stepper motors are used in automated production equipments and automotive gauges and industrial machines like packaging, labeling, filling and cutting etc.

It is widely used in security devices such as security & surveillance cameras.

In medical industry, stepper motors are widely used in samples, digital dental photography, respirators, fluid pumps, blood analysis machinery and medical scanners etc.

They are used in consumer electronics in image scanners, photo copier and printing machines and in digital camera for automatic zoom and focus functions and positions.

Stepper motors also used in elevators, conveyor belts and lane diverters.

Lecture- 26 **Time: 50 min.**

Interpret Starting and Speed Control of Single Phase Induction Motor.

14.1 Understand the principle of speed control of single phase motor.

14.2 List the methods of speed control of single phase motor.

14.3 Describe the methods of speed control of single phase motor.

14.4 Describe the method of reversing the direction of rotation of single phase induction motor using timers and relays.

An induction motor or a synchronous motor is a type of alternating current motor where power is supplied to the rotor by means of electromagnetic induction. An electric motor turns because of magnetic force exerted between a stationary electromagnet called the stator and a rotating electromagnet called the rotor. In an induction motor, by contrast, the current is induced in the rotor without contacts by the magnetic field of the stator, through electromagnetic induction.

The speed of an induction motor is dependent upon its terminal voltage and operating frequency. The operating frequency of an induction motor is varied by using PWM.

We know that the speed of an induction motor is dependent upon the voltage and frequency. If voltage and frequency is changed then the speed of induction motor is changed.

List the methods of speed control of single phase motor .

The two primary ways to **control** the **speed** of a **single-phase** AC **motor** is to either change the frequency of the line voltage the **motor** sees or by changing the voltage seen by the **motor**, thereby changing the rotational **speed** of the **motor**

Lecture- 27 **Time: 50 min.**

Paraphrase the Starting and Speed Control of Three Phase Induction Motor.

15.1 Describe the operation of three phase induction motor by auto-transformer action using relay and timer.

15.2 Describe the methods of reversing the direction of rotation of three phase induction motor using relay and timer.

Autotransformer starters are used generally with star connected AC squirrel cage motors. As high voltage AC squirrel cage motors are connected in star to reduce the voltage strain on the winding insulation. In that case, we can not use the star-delta starters.

So, to limit the starting current or to decrease the starting strain on those motors, autotransformer starters are used. Such starters consist of an auto-transformer, with necessary arrangements.

Autotransformer Starter Working Principle

To reduce the voltage across the motor terminals during the starting period, an autotransformer-type starter generally has two autotransformers connected in open delta. In this method of connection, only two windings are used and connected as shown in Figure.

This arrangement is generally used, because it is cheaper, although the currents are unbalanced during starting period. This is, however, not much objectionable, because the current imbalance is about 15 percent and balance is restored as soon as running conditions are attained.

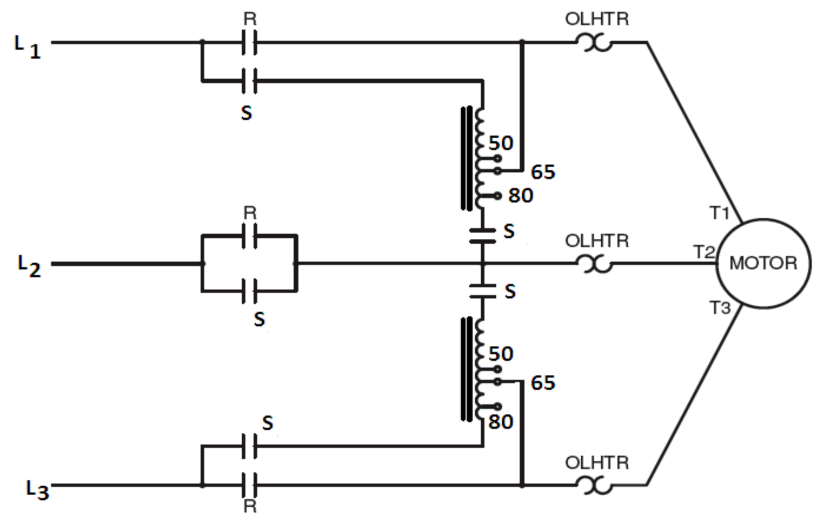
The auto-transformer starters can be used for both star and delta connected motors. Most of the auto-starters are provided with 3 sets of taps, so as to reduce the voltage to 80, 65 or 50 percent of the line voltage, to suit the local conditions of supply.

Most squirrel cage induction motors can be successfully started at 65 percent of line voltage. Where this fraction of line voltage does not provide sufficient starting torque, the 80 percent tap can be used.

Where 50 percent tap creates excessive voltage dip, the 65 percent taps can be used.

At the time of starting, a reduced voltage is applied across the motor terminals. With the lower starting voltage, the motor draws less current and develops less starting torque than if it were connected to the full line voltage When the motor attains 80% of its normal speed, auto-transformers are cut out and the full supply voltage is applied to the motor. The switch making these changes from ‘start’ to ‘run’ may be airbreak (for small motors) or may be oil-immersed (for large motors) to reduce sparking.

Autotransformer Starter Working



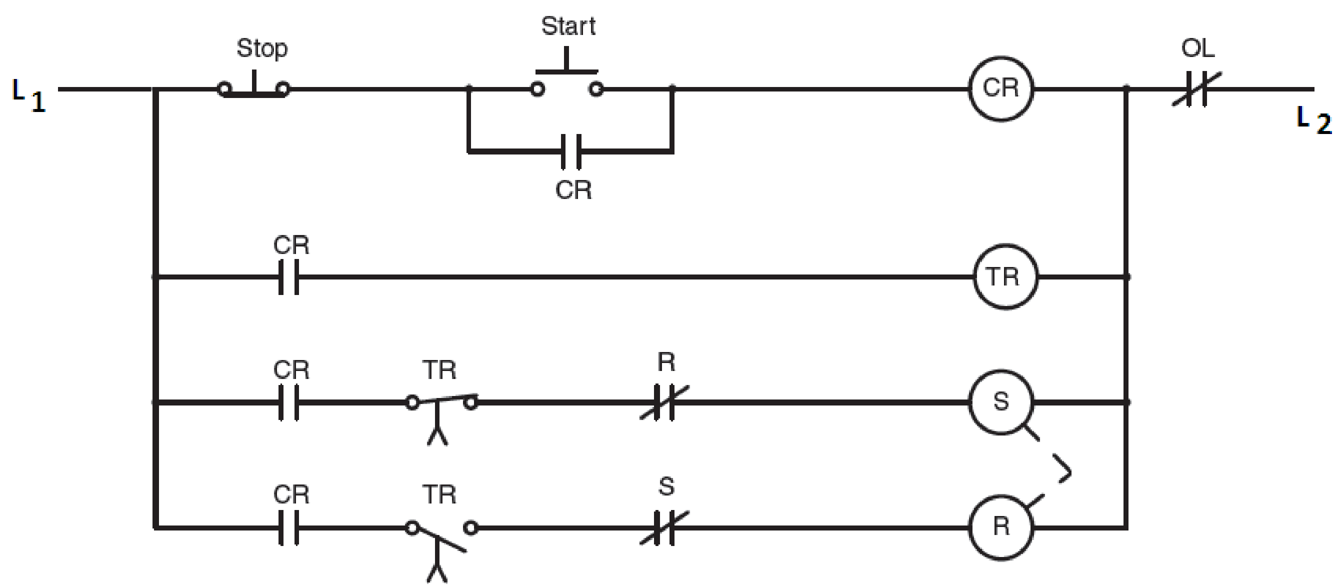
Power circuit and control circuit for a two coil autotransformer starter is shown in Figure. The working of the starter is as under:

When the start-button is pressed a circuit is completed to the coil of control relay CR, causing all CR contacts to close.

When the coil of S contactor energizes, all S contacts change position. The normally closed S contact connected in series with R coil opens to prevent both S and R contactors from being energized at the same time.

When the S load contacts close, the motor is connected to the power line through the autotransformers and 65% of the supply voltage is applied to the motor.

When the time sequence for TR timer is completed, both TR contacts change position.

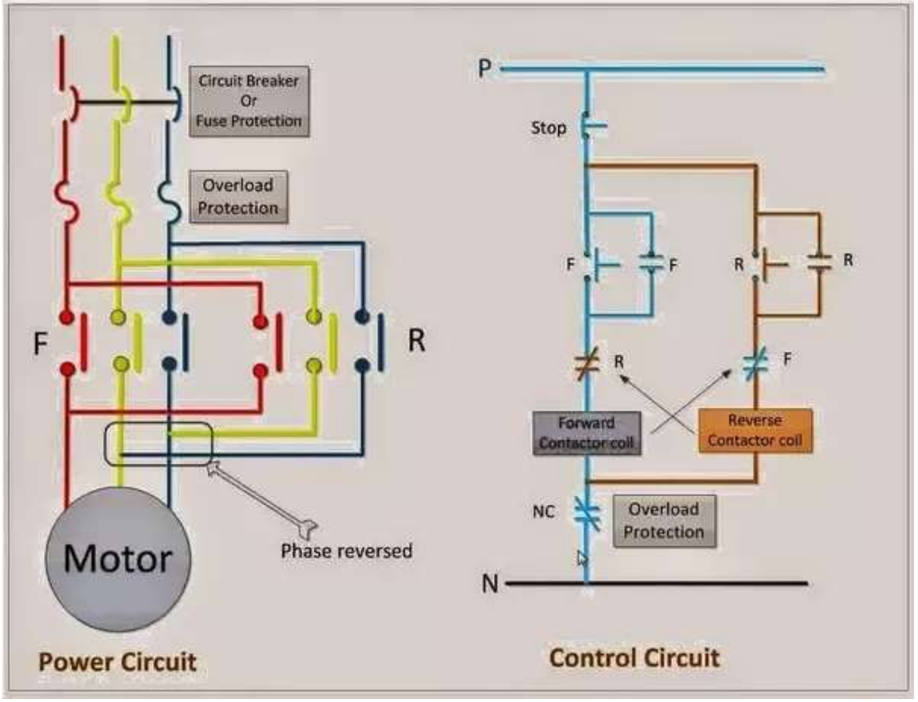


The normally closed TR contact opens and disconnects contactor S from the line causing all S contacts to return to their normal position.
The normally open TR contact closes and supplies power through the now closed S contact to coil R.

When contactor R energizes, all R contacts change position.
The normally closed R contact connected in series with S coil opens to provide interlocking for the circuit.

The R load contacts closed and connect the motor to full voltage.
When the stop-button is pressed, control relay CR de-energizes and opens all CR contacts. This disconnects all other control components from the power line and the circuit returns to its normal position.

The forward reverse motor control is used in a system where forward and backward or upward and downward movement in the operation are needed. Forward and Reverse Operation of motor can be obtained by interchanging any two of its three terminals.



In the Circuit both the Forward & Reverse Contactor interlocked in a way that only one contactor should be in closed condition while the other is in open condition.

Lecture- 28 **Time: 50 min.**

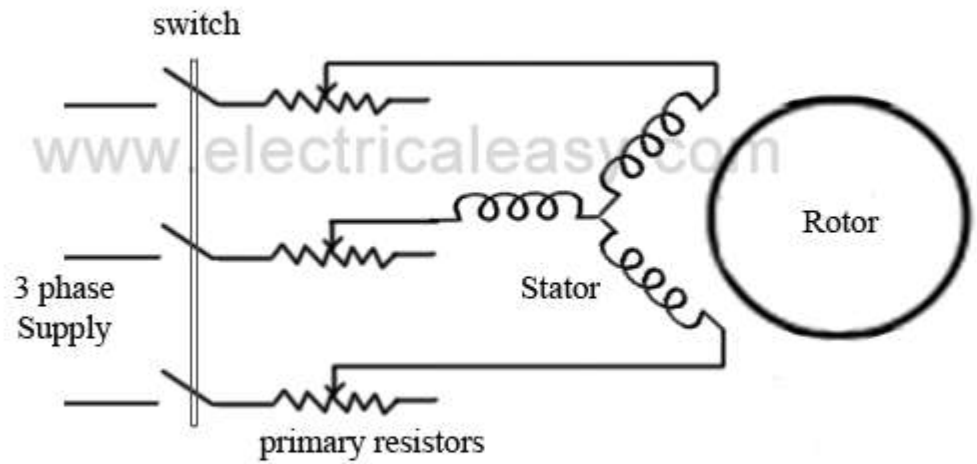
15.3 Describe the methods of controlling speed of three phase induction (squirrel cage) motor by reduced voltage method using relays and timers.

15.4 Describe the methods of controlling speed of three phase induction (wound rotor) motor by inserted resistance.

Starting Of Squirrel Cage Motors
Starting in-rush current in squirrel cage motors is controlled by applying reduced voltage to the stator. These methods are sometimes called as **reduced voltage methods for starting of squirrel cage induction motors**. For this purpose, following methods are used:

By using primary resistors
Autotransformer
Star-delta switches

Using Primary Resistors:

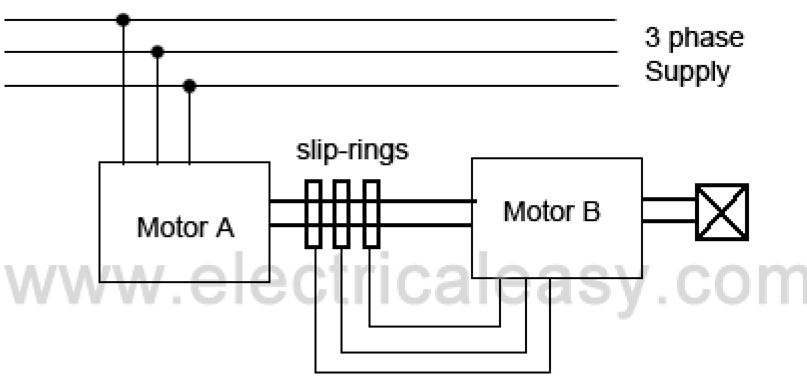


Obviously, the purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%. Then according to the Ohm's law (V=I/Z), the starting current will also be reduced by the same percentage. From the torque equation of a three phase induction motor, the starting torque is approximately proportional to the square of the applied voltage. That means, if the applied voltage is 50% of the rated value, the starting torque will be only 25% of its normal voltage value. This method is generally used for a **smooth starting of small induction motors**. It is not recommended to use primary resistors type of starting method for motors with high starting torque requirements.

Resistors are generally selected so that 70% of the rated voltage can be applied to the motor. At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up. When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

2. Cascade Operation

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following figure.



Motor A is called the main motor and motor B is called the auxiliary motor.

Let, N_{s1} = frequency of motor A

N_{s2} = frequency of motor B

P_1 = number of poles stator of motor A

P_2 = number of stator poles of motor B

N = speed of the set and same for both motors

f = frequency of the supply

Now, slip of motor A, $S_1 = (N_{s1} - N) / N_{s1}$.

frequency of the rotor induced emf in motor A, $f_1 = S_1 f$

Now, auxiliary motor B is supplied with the rotor induce emf

therefore, $N_{s2} = (120f_1) / P_2 = (120S_1 f) / P_2$.

now putting the value of $S_1 = (N_{s1} - N) / N_{s1}$

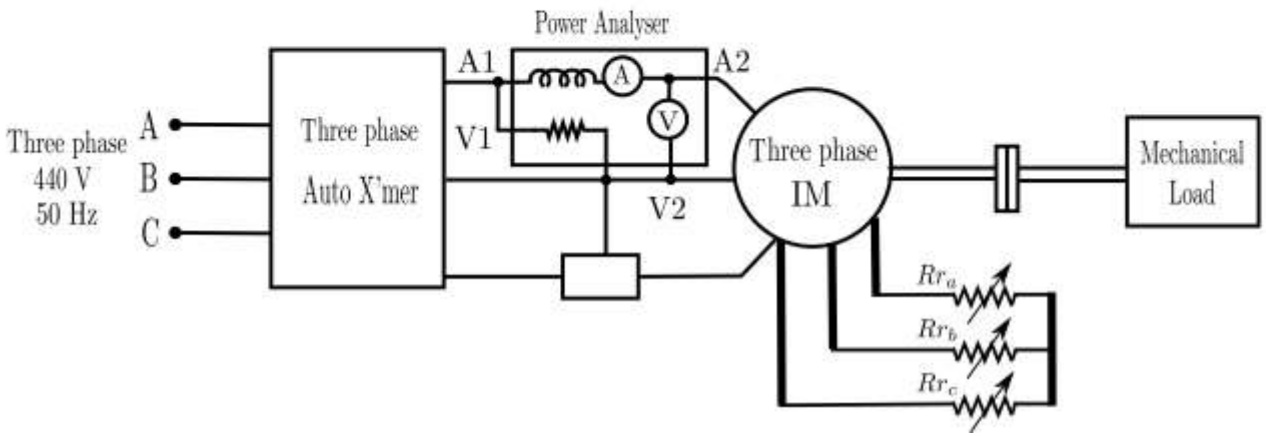
$$N_{s2} = \frac{120f(N_{s1} - N)}{P_2 N_{S1}}$$

At no load, speed of the auxiliary rotor is almost same as its synchronous speed.
i.e. $N = N_{s2}$. from the above equations, it can be obtained that

$$N = \frac{120f}{P_1 + P_2}$$

With this method, four different speeds can be obtained
1. when only motor A works, corresponding speed = .Ns1 = 120f / P_1
2. when only motor B works, corresponding speed = Ns2 = 120f / P_2
3. if commulative cascading is done, speed of the set = N = 120f / (P_1 + P_2)
4. if differential cascading is done, speed of the set = N = 120f (P_1 - P_2)

Speed Control Of Wound Rotor Induction Motor Using Rotor Resistance Control



A. Note down the machine ratings and calculate rated current of the machine if not available

B. Connect a rheostat in each of the rotor phases brought out via the terminal box mounted on top of the machine. Keep the rheostats at the maximum positions

C. With the rheostats in maximum resistance position, slowly apply the three-phase input voltage to the stator terminals using the three-phase variac.