GANESH INSTITUTE OF ENGINEERING AND TECHNOLOGY (GIET)
Bidya Nagar, Jagannath Prasad, Andharua, Bhubaneswar

AC MACHINES AND SPECIAL ELECTRICAL MACHINES

(As per the 2025-26 syllabus of the SCTE&VT, Bhubaneswar, Odisha)

Fourth Semester

Electrical Engineering.

Prepared By: Er.Akshaya Kumar Samal

ENERGY CONVERSION-II

CHAPTER-WISE DISTRIBUTION OF PERIODS & MARKS

Sl. No.	Chapter/ Unit No.	Name of The Chapter/ Unit	Periods as per Syllabus	Expected Marks
01	03	3-PHASE INDUCTION MOTOR	14	15
02	04	1-PHASE INDUCTION MOTOR	08	05
03	01	ALTERNATOR(Synchronous Generator)	14	25
04	02	SYNCHRONOUS MOTOR	08	20
05	07	THREE PHASE TRANSFORMERS	05	20
06	05	COMMUTATOR MOTORS	06	20
07	06	SPECIAL ELECTRIC MOTOR	05	05
TOTAL			60	110

CHAPTER-1
ALTERNATOR

Learning Resources :

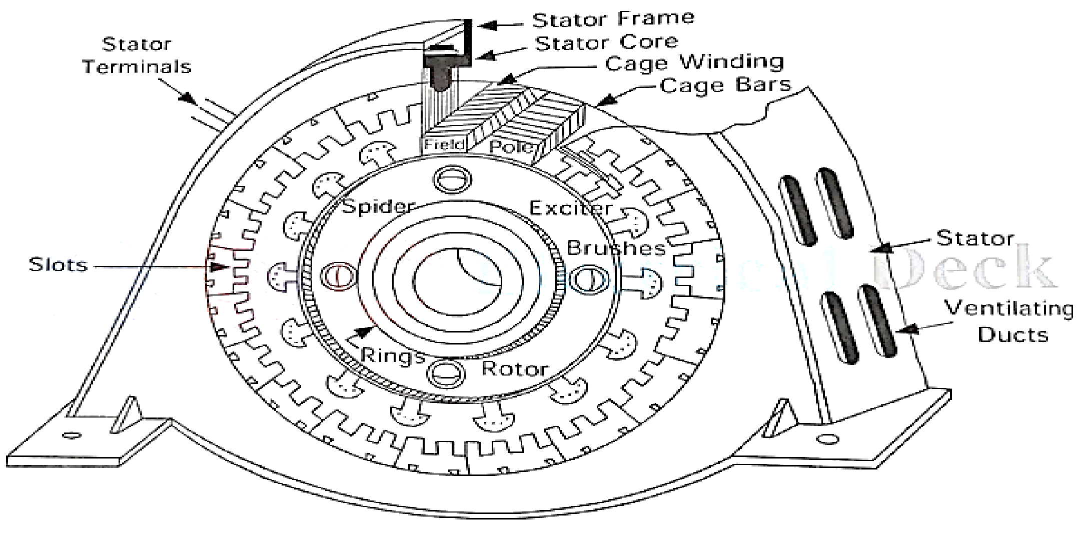
1.1. Types of alternator and their constructional features.
1.2. Basic working principle of alternator and the relation between speed and frequency.
1.3. Terminology in armature winding and expressions for winding factors (Pitch factor, Distribution factor).
1.4. Explain harmonics, its causes and impact on winding factor.
1.5. E.M.F equation of alternator. (Solve numerical problems).
1.6. Explain Armature reaction and its effect on emf at different power factor of load.
1.7. The vector diagram of loaded alternator. (Solve numerical problems)
1.8. Testing of alternator (Solve numerical problems)
1.8.1. Open circuit test.
1.8.2. Short circuit test.
1.9. Determination of voltage regulation of Alternator by direct loading and synchronous impedance method. (Solve numerical problems)
1.10. Parallel operation of alternator using synchro-scope and dark & bright lamp method.
1.11. Explain distribution of load by parallel connected alternators.

1.1. Types of alternator and their constructional features.

An alternator is defined as a machine which converts mechanical energy to electrical energy in the form of alternating current (at a specific voltage and frequency). Alternators are also known as synchronous generators.

A.C. generators or Alternators operate on the same fundamental principles of electro magnetic induction as D.C. generators. They also consist of an armature winding and a magnetic field. But there is one important difference between the two. In a D.C. generators, the armature rotates and the field system is stationary, the arrangement in alternators is just the reverse of it, i.e. armature winding mounted on a stationary element called stator and field windings on a rotating element called rotor.

CONSTRUCTION :



An alternator is made up of two main parts: Stator , Rotor and Exciter .

STATOR

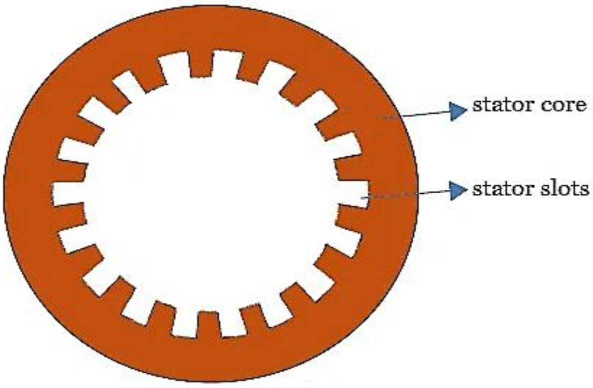
The stator consists of stator frame and stator core.

STATOR FRAME

- The stator frame is the outer most part of alternator and is used for holding the armature stampings and windings in position.
- Ventilation is maintained with the help of holes cast in the frame itself, which assist in cooling the alternator.
- It also provide protection to the machine.

STATOR CORE

- The armature core is supported by the stator frame and is built up of laminations of steel alloys or magnetic iron.
- The core is laminated to minimize the eddy current loss as it provide low reluctance path to magnetic flux.
- The laminations are insulated from each other and have spaces in between them for allowing the cooling air to pass through.
- The stator core is made up of number of slots on its inner periphery, as shown in the below figure.
- The slots are used for holding the armature winding.



ROTOR

There are mainly two types of rotors used in construction of alternator:

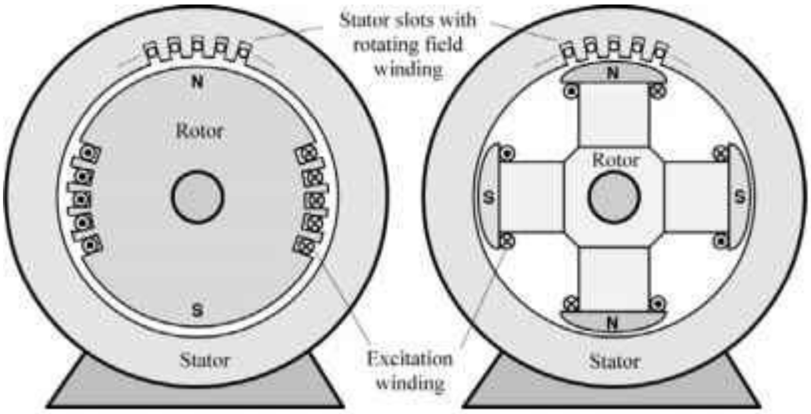
1. Salient pole type.
2. Cylindrical rotor type.

<u>Salient Pole Type</u>

- The term salient means protruding or projecting.
- The salient pole type of rotor is generally used for slow speed machines having large diameters and relatively small axial lengths.
- The poles, in this case, are made of thick laminated steel sections riveted together and attached to a rotor with the help of joint.
- They have a large horizontal diameter compared to a shorter axial length.
- The pole shoes covers only about $^2/_3$rd of pole pitch.
- Poles are laminated to reduce eddy current loss.
- The salient pole type motor is generally used for low-speed operations of around 100 to 400 rpm, and they are used in power stations with hydraulic turbines or diesel engines.
- Salient pole alternators driven by water turbines are called hydro-alternators or hydro generators.

Cylindrical Rotor Type

- The cylindrical rotor is generally used for very high speed operation and employed in steam turbine driven alternators like turbo-generators.
- The machines are built in a number of ratings from 10 MVA to over 1500 MVA.
- The cylindrical rotor type machine has a uniform length in all directions, giving a cylindrical shape to the rotor thus providing uniform flux cutting in all directions.
- The rotor, in this case, consists of a smooth solid steel cylinder, having a number of slots along its outer periphery for hosting the field coils.



Cylindrical Rotor **Salient Pole Rotor**

The field poles are made to rotate at synchronous speed $N_s = 120*f / P$ for effective power generation.

Where, f - Signifies the alternating current frequency and

P- Represents the number of poles.

The cylindrical rotor alternators are generally designed for 2-pole type giving very high speed of

$$N_s = \frac{(120 \times f)}{P} = \frac{(120 \times 50)}{2} = 3000\ rpm$$

Or 4-pole type running at a speed of

$$N_s = \frac{(120 \times f)}{P} = \frac{(120 \times 50)}{4} = 1500\ rpm$$

Where, f is the frequency of 50 Hz.

EXCITER :

- The exciter is generally a dc shunt or compound generator, whose voltage is up to 250 volts.
- DC in small alternator the exciter is mounted on the same shaft of the alternator.
- A variable resistance is connected in series with the shunt field of the exciter which varies the exciter voltage to vary the output voltage of the alternator.
- For high voltage alternator separately excited generator are used.

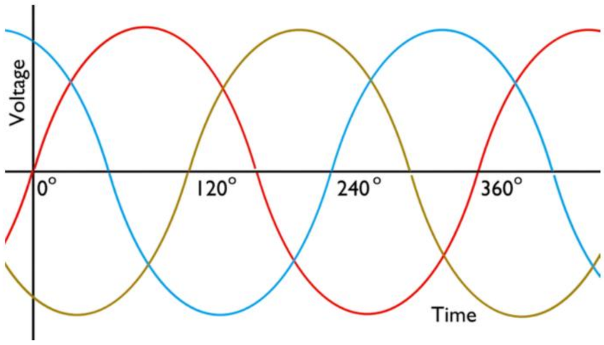
1.2. Basic working principle of alternator and the relation between speed and frequency.

The working principle of an alternator is very simple. It is just like the basic principle of DC generator. It also depends upon Faraday's law of electromagnetic induction which says the current is induced in the conductor inside a magnetic field when there is a relative motion between that conductor and the magnetic field.

In practical construction of alternator, armature conductors are stationary and field magnets rotate between them. The rotor of an alternator or a synchronous generator is mechanically coupled to the shaft or the turbine blades, which is made to rotate at synchronous speed N_s under some mechanical force results in magnetic flux cutting of the stationary armature conductors housed on the stator.

$$N_s = (120*f) / P$$

As a direct consequence of this flux cutting an induced emf and current starts to flow through the armature conductors which first flow in one direction for the first half cycle and then in the other direction for the second half cycle for each winding with a definite time lag of 120^o due to the space displaced arrangement of 120^o between them as shown in the figure below.



1.3. Terminology in armature winding and expressions for winding factors (Pitch factor, Distribution factor) :

Armature winding in an alternator may be either closed type open type. Closed winding forms star connection in armature winding of alternator**.**

There are some common properties of armature winding.

1. First and most important property of an armature winding is, two sides of any coil should be under two adjacent poles. That means, coil span = pole pitch.
2. The winding can either be single layer or double layer.
3. Winding is so arranged in different armature slots, that it must produce sinusoidal emf.

Types of Armature Winding of Alternator :

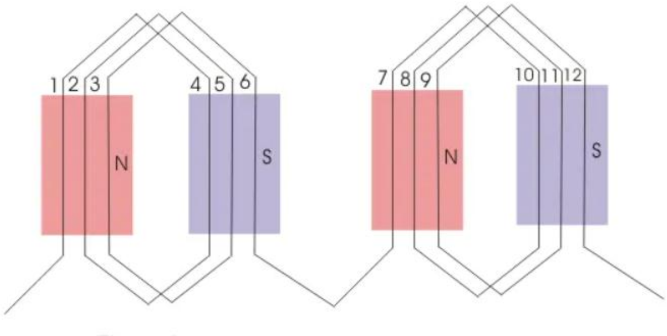
1. Distributed Armature Winding of Alternator :

For obtaining smooth sinusoidal emf wave from, conductors are placed is several slots under single pole. This armature winding is known as distributed winding. Although distributed armature winding in alternator reduces emf, still it is very much usable due to following reason.

1. It also reduces harmonic emf and so waveform is improved.
2. It also diminishes armature reaction.
3. Even distribution of conductors, helps for better cooling.
4. The core is fully utilized as the conductors are distributed over the slots on the armature periphery.

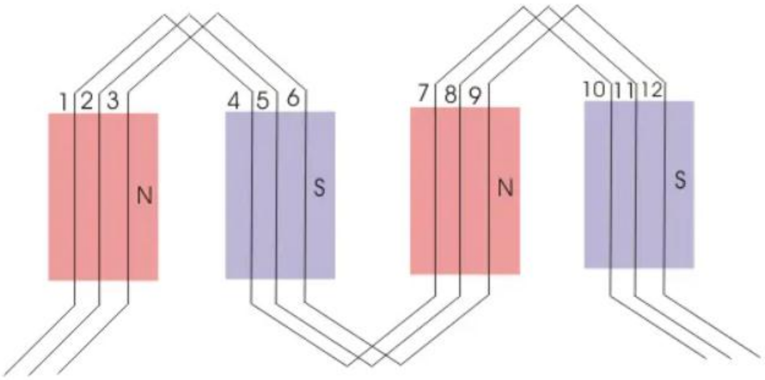
2. Lap Winding of Alternator :

The winding is completed per pair of the pole and then connected in series, Full pitched lap winding of 4 poles, 12 slots, 12 conductors (one conductor per slot) alternator is shown below.
The back pitch of the winding is equal to the number of conductors per pole, i.e., = 3 and the front pitch is equal to back pitch minus one.



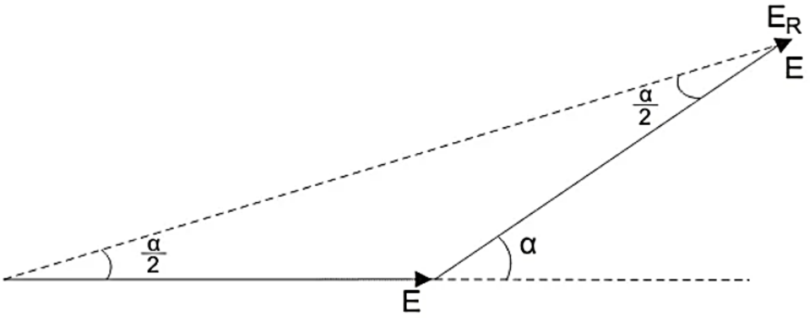
3. Wave Winding of Alternator

Wave winding of the same machine, i.e., four poles, 12 slots, 12 conductors is shown in the figure below. Here, back pitch and front pitch both equal to some conductor per pole.



Pitch Factor

The ratio of phasor sum of induced EMFs per coil to the arithmetic sum of induced EMFs per coil is known as pitch factor K_p or coil span factor K_c.
Its value is always less than unity.



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

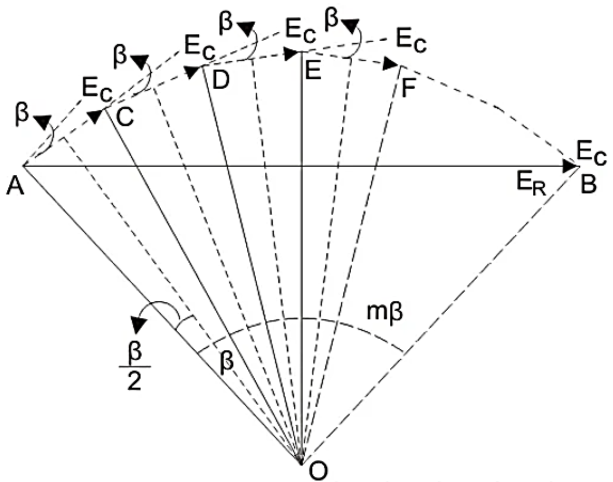
Now, as per **definition of pitched factor,**

$$\begin{aligned} K_p &= \frac{Resultant\ emf\ of\ short\ pitched\ coil}{Resultant\ emf\ of\ full\ pitched\ coil} \\ &= \frac{Phasor\ sum\ of\ coil\ side\ emfs}{Arithmetic\ sum\ of\ coil\ side\ emfs} \\ &= \frac{2E\cos\frac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2} \end{aligned}$$

If all the coil sides of any one phase under one pole are bunched in one slot, the winding obtained is known as concentrated winding and the total emf induced is equal to the arithmetic sum of the emfs induced in all the coils of one phase under one pole.

Distribution factor :

As per definition, distribution factor is ratio of EMF induced in distributed winding to the EMF induced in concentrated winding.



$$\begin{aligned} k_d &= \frac{EMF\ induced\ in\ distributed\ winding}{EMF\ induced\ if\ the\ winding\ would\ have\ been\ concentrated} \\ &= \frac{Phasor\ sum\ of\ component\ emfs}{Arithmetic\ sum\ of\ component\ emfs} \end{aligned}$$

As pitch factor, distribution factor is also always less than unity.

Let the number of slots per pole is n.

The number of slots per pole per phase is m.

Induced emf per coil side is E_c.

Angular displacement between the slots,

$$\beta = \frac{180^o}{n}$$

The resultant voltage induced in one pole group = mE_S
If m is larger, then the curve ABCDE will become part of a circle of radius r,
From above figure, AB = E_S = 2. r. Sinβ/2
Arithmetic sum = mE_S = 2.r. Sinβ/2
Vector sum = E_R = 2.r. Sin mβ/2

K_d= Sin mβ/2 / m.Sin β/2

1.4. Explain harmonics, its causes and impact on winding factor :

Harmonics are defined as an unwanted higher frequency component that is an integer multiple of the fundamental frequency. Harmonics create a distortion in the fundamental waveform.
Harmonics usually have a lower amplitude (volume) than the fundamental frequency.

Amplitude

The maximum value (positive or negative) of an alternating quantity is known as its amplitude.

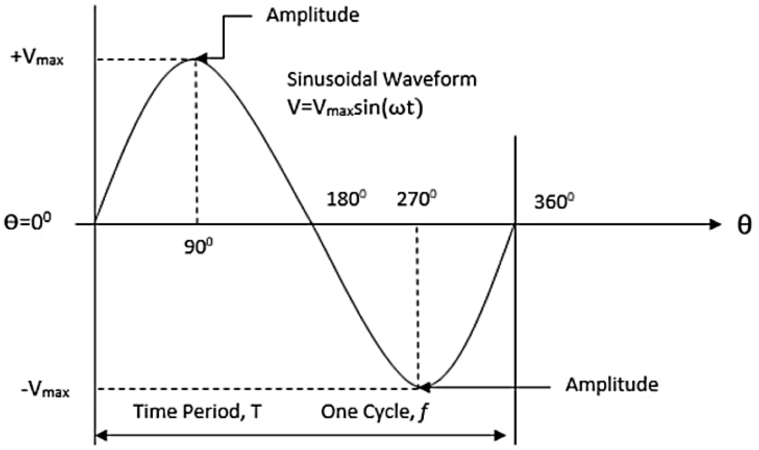
Sources of Harmonics

Harmonics are produced due to the non-linear loads such as an iron-cored inductor, rectifiers, electronic ballasts in fluorescent lights, switching transformers, discharge lighting, saturated magnetic devices and other such loads that are highly inductive in nature.

Effects of Harmonics :

- Harmonic frequencies in the power grid cause power quality problems.
- Harmonics in power systems result in increased heating in the equipment and conductors and create a pulsating torque in the motors.
- Harmonics cause increasing operating temperature and the iron losses (Hysteresis and Eddy current losses) in the AC motors and transformers because hysteresis loss is proportional to the frequency and eddy current loss is proportional to the square of the frequency.

Fundamental Frequency :

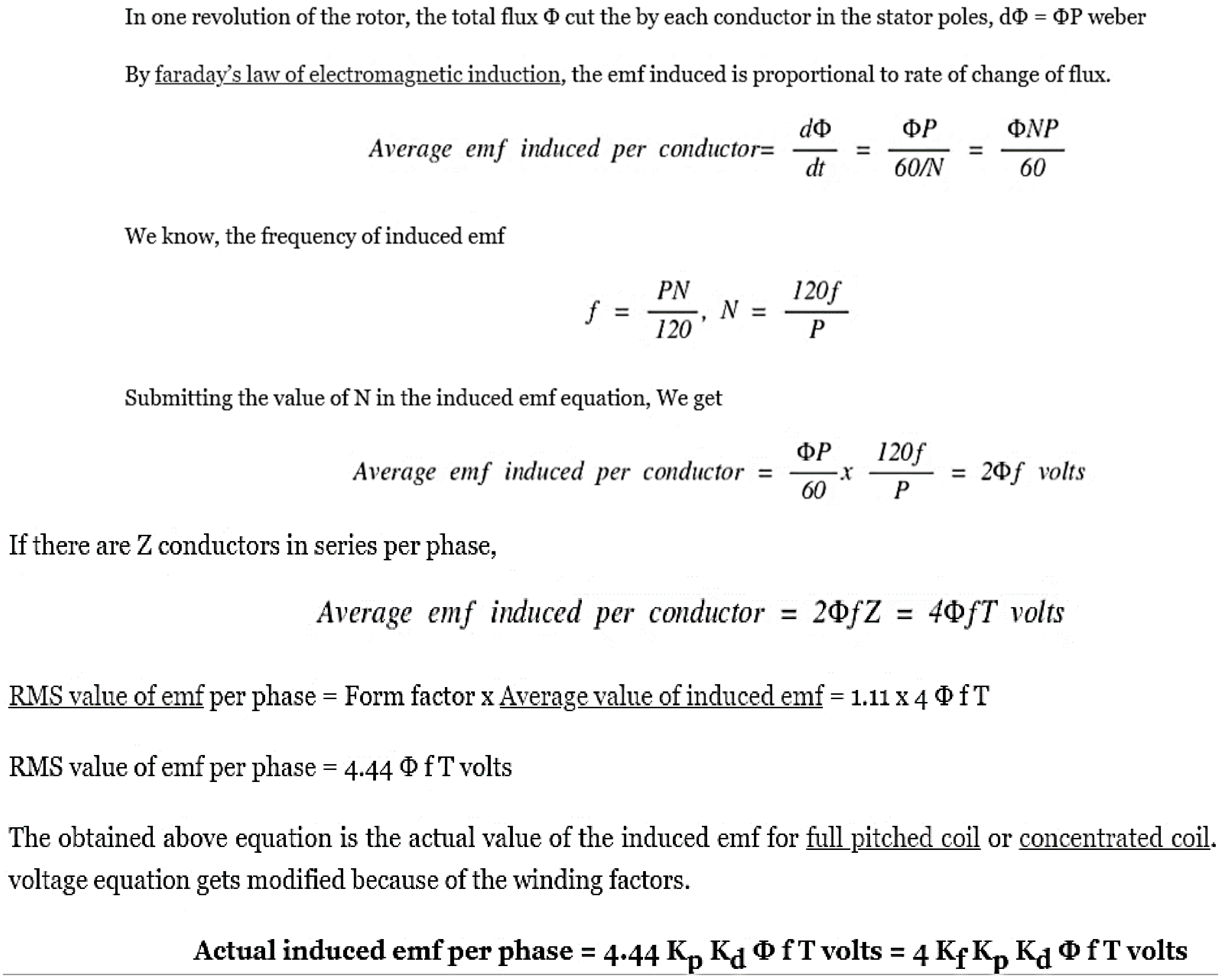


The lowest or base frequency produced by any particular instrument which we hear the sound at is known as the fundamental frequency. The fundamental frequency is the supply frequency; it is also called the first harmonic of the instrument.
The number of cycles completed by an alternating quantity per second is known as a frequency. It is denoted by f and expressed in hertz (Hz) or cycles/second.
Then other harmonics are , 2f, 3f, 4f, 5f,……….,nf, etc.
i.e if 50Hz fundamental is the first harmonic then 2nd harmonic would be 100Hz (250), a 3rd harmonic would be 150Hz (350), a 5th harmonic at 250Hz, a 7th at 350Hz and so on.

1.5. E.M.F equation of alternator :

The emf induced by the alternator or synchronous generator is three-phase alternating in nature.
Let us derive the mathematical equation of emf induced in the alternator.
Let,
Z = number of conductors in series per phase.
Z = 2T, where T is the number of coils or turns per phase. One turn has two coil sides or conductor as shown in the below diagram.
P = Number of poles.
f = frequency of induced emf in Hertz
Φ = flux per pole in webers.
K_p = pitch factor,
K_d = distribution factor,
K_f = Form factor
N = Speed of the rotor in rpm(revolutions per minute)
N/60 = Speed of the rotor in revolutions per second.
Time taken by the rotor to complete one revolution,

$$dt = 1/(N/60) = 60/N \text{ second}$$



In one revolution of the rotor, the total flux Φ cut the by each conductor in the stator poles, dΦ = ΦP weber

By faraday's law of electromagnetic induction, the emf induced is proportional to rate of change of flux.

$$Average\ emf\ induced\ per\ conductor = \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60}$$

We know, the frequency of induced emf

$$f = \frac{PN}{120},\ N = \frac{120f}{P}$$

Submitting the value of N in the induced emf equation, We get

$$Average\ emf\ induced\ per\ conductor = \frac{\Phi P}{60} x \frac{120f}{P} = 2\Phi f\ volts$$

If there are Z conductors in series per phase,

$$Average\ emf\ induced\ per\ conductor = 2\Phi f Z = 4\Phi f T\ volts$$

RMS value of emf per phase = Form factor x Average value of induced emf = 1.11 x 4 Φ f T

RMS value of emf per phase = 4.44 Φ f T volts

The obtained above equation is the actual value of the induced emf for full pitched coil or concentrated coil. voltage equation gets modified because of the winding factors.

Actual induced emf per phase = 4.44 K_p K_d Φ f T volts = 4 K_f K_p K_d Φ f T volts

Numerical problems

Q.1 A 3 phase, 16 pole alternator has a star-connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.02 Wb, sinusoidally distributed and the speed is 375 rpm. Find the frequency of the induced emf, phase emf and line emf. Assume the coil as full pitched.

Given parameters: P = 16, slots = 144 , Z = 10 conductors per slot,

Φ = 0.02 wb, N = 375 rpm, for full pitch coil,

$K_p = 1$.

To find : f, E_{ph}, E_L

Solution:

f= PN/120 = 16 x 375/120, So f = 50 Hz

The emf equation of alternator is given by, $E_{ph} = 4.44\, K_p\, K_d\, \Phi\, f\, T$ volts

Here, m = no. of slots/pole/phase = 144/16/3 = 3

where n=no. of slots/pole = 144/16 = 9

Z = 10 conductors per slot per phase = 10 x 144/3 = 480

T = Z/2 = 480 /2 = 240

$E_{ph} = 4.44 \times 1 \times 0.96 \times 0.02 \times 50 \times 240 = 1022.97$ V

$$E_L = \sqrt{3}\, E_{ph} = \sqrt{3} \times 1022.97 = 1771.83 \ V$$

1.6. Explain Armature reaction and its effect on emf at different power factor of load.

According to Faraday’s law of electromagnetic induction there would be an emf induced in the armature. Thus, as soon as the load is connected with armature terminals, there is a current flowing in the armature coil.

As soon as current starts flowing through the armature conductor there is one reverse effect of this current on the main field flux of the alternator (or synchronous generator). This reverse effect is referred as armature reaction in alternator or synchronous generator**.**

In other words, the effect of armature (stator) flux on the flux produced by the rotor field poles is called armature reaction.

It has two undesirable effects, either it distorts the main field, or reduces the main field flux or both. They deteriorate the performance of the machine. When the field gets distorted, it is known as a cross magnetizing effect. And when the field flux gets reduced, it is known as the demagnetizing effect.

Armature reaction in alternator

In an alternator like all other synchronous machines, the effect of armature reaction depends on the power factor i.e the phase relationship between the terminal voltage and armature current. Reactive power (lagging) is the magnetic field energy, so if the generator supplies a lagging load, this implies that it is supplying magnetic energy to the load. Since this power comes from excitation of synchronous machine, the net reactive power gets reduced in the generator.

Hence, the armature reaction is demagnetizing. Similarly, the armature reaction has magnetizing effect when the generator supplies a leading load (as leading load takes the leading VAR) and in return gives lagging VAR (magnetic energy) to the generator. In case of purely resistive load, the armature reaction is cross magnetizing only.

The armature reaction of alternator or synchronous generator, depends upon the phase angle between, stator armature current and induced voltage across the armature winding of alternator.

1. Armature Reaction of Alternator at Unity Power Factor

At unity power factor, the angle between armature current I and induced emf E, is zero. That means, armature current and induced emf are in same phase. But we know theoretically that emf induced in the armature is due to changing main field flux, linked with the armature conductor.

As the field is excited by DC, the main field flux is constant in respect to field magnets, but it would be alternating in respect of armature as there is a relative motion between field and armature in the alternator. If main field flux of the alternator in respect of armature can be represented as

$$\phi_f = \phi_{fm} sin\omega t \cdots\cdots\cdots (1)$$

Then induced emf E across the armature is proportional to, $d\varphi_f/dt$.

$$Now,\ \frac{d\phi_f}{dt} = -\omega\phi_{fm} cos\omega t \cdots\cdots\cdots (2)$$

Hence, from these above equations (1) and (2) it is clear that the angle between, φ_f and induced emf E will be 90^o. Now, armature flux φ_a is proportional to armature current I. Hence, armature flux φ_a is in phase with armature current I.

Again at unity electrical power factor I and E are in same phase. So, at unity power factor, φ_a is phase with E. So at this condition, armature flux is in phase with induced emf E and field flux is in quadrature with E. Hence, armature flux φ_a is in quadrature with main field flux φ_f.

As this two fluxes are perpendicular to each other, the armature reaction of the alternator at unity power factor is purely distorting or cross-magnetising type. As the armature flux pushes the main field flux perpendicularly, distribution of main field flux under a pole face does not remain uniformly distributed. The flux density under the trailing pole tips increases somewhat while under the leading pole tips it decreases.

2. Armature Reaction of Alternator at Lagging Zero Power Factor

At lagging zero electrical power factor, the armature current lags by 90^o to induced emf in the armature. As the emf induced in the armature coil due to main field flux thus the emf leads the main field flux by 90^o. From equation (1) we get, the field flux,

$$\phi_f = \phi_{fm} sin\omega t$$

$$Therefore,\ induced\ emf\ E \propto -\frac{d\phi_f}{dt}$$

$$\Rightarrow E \propto -\omega\phi_{fm} cos\omega t$$

Hence, at $\omega t = 0$, E is maximum and φ_f is zero.
At $\omega t = 90^o$, E is zero and φ_f has maximum value.
At $\omega t = 180^o$, E is maximum and φ_f zero.
At $\omega t = 270^o$, E is zero and φ_f has negative maximum value.

Here, φ_f got maximum value 90^o before E. Hence φ_f leads E by 90^o.

Now, armature current I is proportional to armature flux φ_a, and I lags E by 90^o. Hence, φ_a lags E by 90^o. So, it can be concluded that, field flux φ_f leads E by 90^o.

Therefore, armature flux and field flux act directly opposite to each other. Thus, armature reaction of the alternator at lagging zero power factor is a purely demagnetising type.
That means, armature flux directly weakens main field flux.

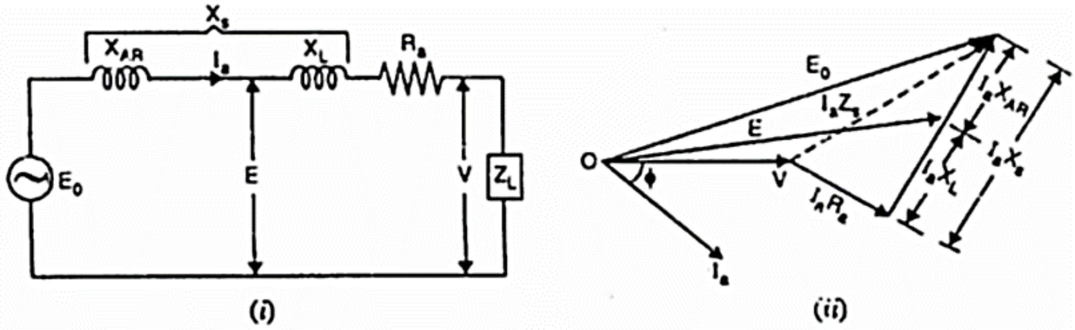
3. Armature Reaction of Alternator at Leading Power Factor

At leading power factor condition, armature current “I” leads induced emf E by an angle 90^o. Again, we have shown just, field flux φ_f leads, induced emf E by 90^o.

Again, armature flux φ_a is proportional to armature current I. Hence, φ_a is in phase with I. Hence, armature flux φ_a also leads E, by 90^o as I leads E by 90^o.

As in this case both armature flux and field flux lead, induced emf E by 90^o, it can be said, field flux and armature flux are in the same direction. Hence, the resultant flux is simply arithmetic sum of field flux and armature flux. Hence, at last, it can be said that armature reaction of alternator due to a purely leading electrical power factor is the magnetizing type.

1.7. The vector diagram of loaded alternator :



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

Fig. (i) shows the equivalent circuit of the alternator per phase. All quantities are per phase.Fig. (ii) shows the phasor diagram of an alternator for the usual case of inductive load.

The armature current I_a lags the terminal voltage V by p.f. angle Φ.

The phasor sum of V and drops I_aR_a and I_aX_L gives the load induced voltage E. It is the induced e.m.f. after allowing for armature reaction. The phasor sum of E and I_aX_{AR} gives the no-load e.m.f. E_0. The phasor diagram for unity and leading p.f. is left as an exercise for the reader. Note that in drawing the phasor diagram either the terminal voltage (V) or armature current (I_a) may be taken as the reference phasor.

In the last article, we have derived the equation for EMF induced in the alternator. The equation for per-phase induced emf E_{ph} in an alternator is given as,

$$E_{ph} = 4\ K_f\ K_c\ K_d\ f\ \varphi\ T \text{ volt}$$

When an alternator is loaded the whole induced emf doesn't appear across the output terminals. As the load on the alternator is varied, its terminal voltage V_{ph} also varies due to the following drops,

- Voltage drop I_aR_a due to armature resistance R_a.
- Voltage drop I_aX_s due to armature leakage reactance X_L.
- Voltage drop due to armature reaction.

The induced emf in the alternator has to supply the above drops while supplying the load. Therefore the equation for terminal voltage of an alternator is given as,

$$E_{ph} = V_{ph} + I_aR_a + I_aX_s \text{ volt}$$

From the above voltage equation, let us draw the phasor diagram of a synchronous generator operating at different load power factors. The relation between terminal voltage and current for power factor analysis can be done by the phasor diagram.

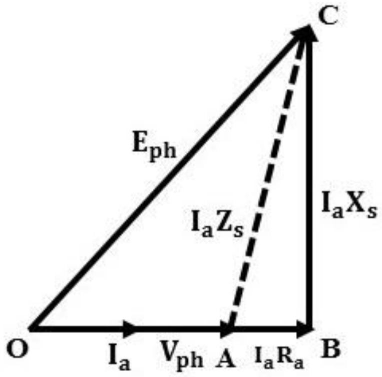
Let,

- E_{ph} = Induced emf on load per phase.
- V_{ph} = Terminal voltage per phase
- I_a = Armature current
- φ = Phase angle between I_a and V_{ph} (i.e., p.f.)
- R_a = Armature resistance per phase
- X_s = Synchronous reactance (leakage reactance + armature reaction reactance)

Taking V_{ph} as the refernce phasor. The phase relationship between armature induced emf E due to field flux φ_f and the current flowing through the armature I_a depends upon the power factor of the load. Phasor Diagram at Unity Power Factor Load :

When the alternator is driving a unity power factor load (resistive) i.e., cos φ = 1.

The armature current I_a will be in phase with V_{ph} as shown below.



From the triangle OBC, the expression for induced emf E_{ph} is given as,

$$OC^2 = OB^2 + BC^2$$

$$E_{ph}{}^2 = (OA + AB)^2 + BC^2$$

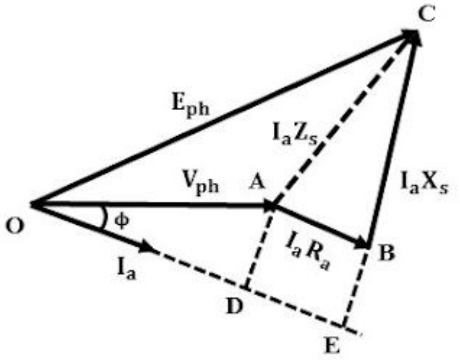
$$E_{ph} = \sqrt{\left(V_{ph}\cos\phi + I_aR_a\right)^2 + \left(V_{ph}\sin\phi + I_aX_s\right)^2}$$

At unity power factor cos φ = 1 and sin φ = 0. The equation is modified as,

$$E_{ph} = \sqrt{\left(V_{ph} + I_aR_a\right)^2 + (I_aX_s)^2}$$

Phasor Diagram at Lagging Power Factor Load :

For lagging power factor loads the current I_a will lag the terminal voltage V_{ph} with an angle φ. At zero lagging power factor (pure inductive) the current I_a lags the voltage V_{ph} exactly by 90°. The below shows the phasor diagram for the lagging power factor.



The armature resistance drop I_aR_a is due to armature current I_a. Hence it always lies in phase with current I_a i.e., DE. Therefore, from the triangle OCE,

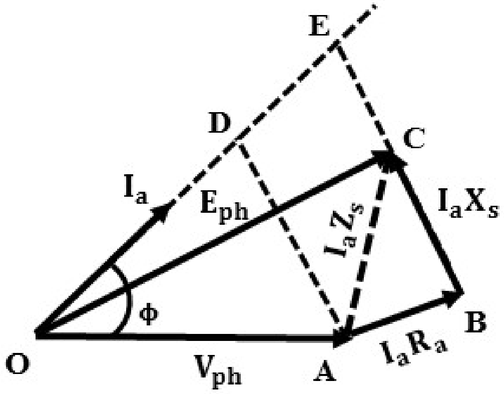
$$OC^2 = OE^2 + EC^2$$

$$E_{ph}{}^2 = (OD + DE)^2 + (EB + BC)^2$$

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

Phasor Diagram at Leading Power Factor Load :

Similar to the lagging power factor the current I_a leads the voltage V_{ph} by φ at leading power factor loads as shown below. At zero leading power factor (pure capacitive) current I_a lead V_{ph} exactly by 90°.



From triangle OCE,

$$OC^2 = OE^2 + EC^2$$

$$E_{ph}{}^2 = (OD + DE)^2 + (BE - BC)^2$$

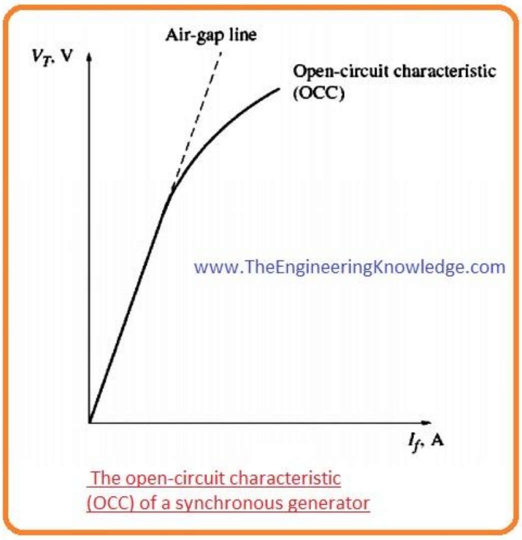
$$E_{ph} = \sqrt{\left(V_{ph}\cos\phi + I_aR_a\right)^2 + \left(V_{ph}\sin\phi - I_aX_s\right)^2}$$

1.8 Testing of alternator :

1.8.1. OPEN CIRCUIT TEST OF THE SYNCHRONOUS GENERATOR

- To accomplish this test the generator should move at its rated speed, no-load should be at its terminals, and the value of the field winding current should be 0.
- After following these steps, we will vary the field current step by step and calculate the terminal voltage at each step.

- As there is no load at the output terminals of the generator, so there will be zero armature current.
- Hence the internal generated voltage E_A will equal to the phase voltage $V_ø$.
- By using this data, we can construct the curve among the internally generated voltage that equals the terminal voltage and the field current.
- This graph between E_A and the field current is known as the **open-circuit characteristic** (OCC) of the synchronous generator.

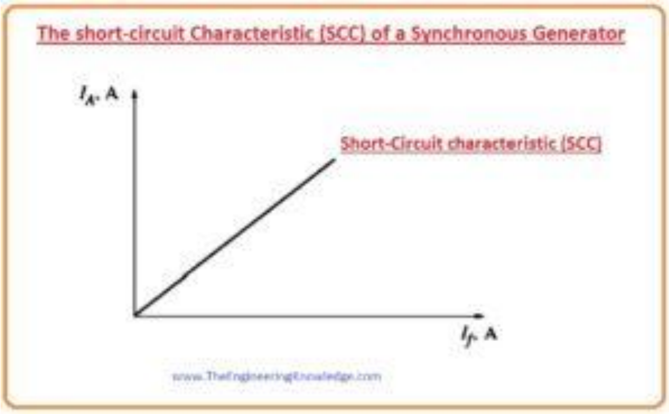


The open-circuit characteristic (OCC) of a synchronous generator

1.8.2. SHORT CIRCUIT TEST OF SYNCHRONOUS GENERATOR

- To do a short circuit test first of set the value of field current at 0 and connect the output terminals of the generator by the ammeter.
- After that find the value of the armature current (I_A) by changing the field current.
- This graph among the field current and the armature current known as the short-circuit characteristic (SCC).

The short-circuit Characteristic (SCC) of a Synchronous Generator



-
-

1.9 Determination of voltage regulation of alternator by direct loading and synchronous impedance method :

Voltage Regulation:

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to acertain extent, and the amount of this variation determines the regulationofthemachine. When thealternator is loaded the terminal voltage decreases as the drops in the machine stars increasing andhence it will always be different than theinduced emf.Voltage regulation of an alternator is defined as the change in terminalvoltage from no load to fulload expressed as a percentage of rated voltagewhen the load at a given power factor is removed without change in speed and excitation. Or The numerical value of the regulation is defined as thepercentage rise in voltage whenfull load at the specified power-factor is switched off with speed andfield current remaining unchanged expressed as a percentage of rated voltage.Hence regulation canbe expressed as

% Regulation = (Eph – Vph / Vph) x 100
where Eph = induced emf /phase, Vph = rated terminal voltage/phase
Methods of finding Voltage Regulation: The voltage regulation of an alternator can be determined bydifferent methods. In case of small generators it can be determined by direct loading whereas in caseof large generators it can not determined by direloadingbut will be usually predetermined bydifferent methods. Following are the different methods used for predetermination of regulation ofalternators.

1. Direct loading method
2. EMF method or Synchronous impedance method
3. MMF method or Ampere turns method
4. ASA modified MMF method
5. ZPF method or Potier triangle method

All the above methods other than direct loading are valid for nonsalient pole machines only. As thealternators are manufactured in large capacity direct loading of alternators is not employed
determination of regulation. Other methods can be employed for predetermination of regulation.
Hence the other methods of determination of regulations will be discussed in the following sections.

EMF method: This method is also known as synchronous impedance method. Here the magnetic
circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator
are replaced by their equivalent emf, and hence called emf method.
To predetermine the regulation by this method the following informations are to be determined.
Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the
alternator.

(Synchronous impedance method)

Tests:

Conduct tests to find

OCC (upto 125% of rated voltage) **SCC** (for rated current)

Armature resistance (per phase)

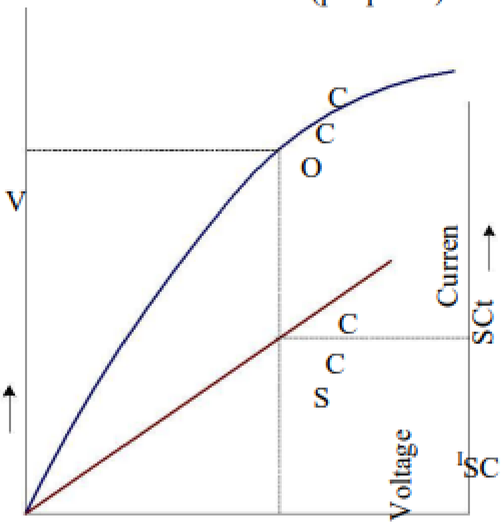


Fig 4.1

V = rated phase voltage

I_{sc} = short circuit current corresponding to the field current producing the rated voltage

Synchronous impedance per phase,

$$Z_S = V / I_{sc}$$

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

For any load current I and phase angle Φ, find E_0 as the vector sum of V, IR_a and IX_s

For lagging power factor

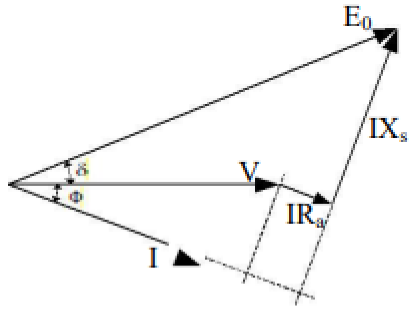


Fig 4.2

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

For unity power factor

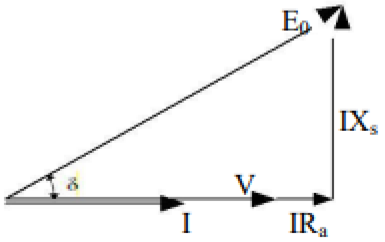


fig 4.3

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

For leading power factor

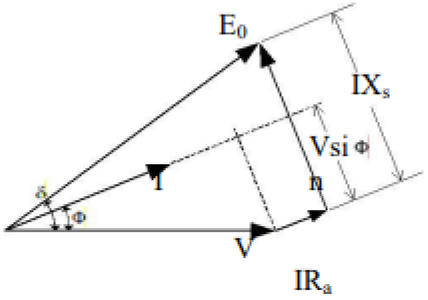
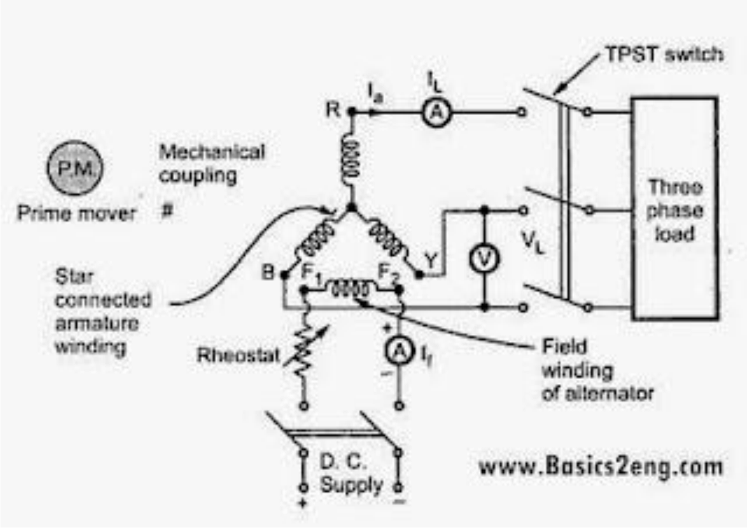


fig 4.4

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

Voltage Regulation of alternator by Direct Loading method:

The below figure shown is three phase alternator on which Direct Loading test is conducted. A three phase load is connected to star connected armature with the help of TPST [Triple Pole Single Throw] switch.By using an external D.C supply, the field winding is excited. A rheostat is connected in series with the field winding, to control the flux i.e. current in the field winding.In the below figure, the prime mover shown is used to drive the alternator at Synchronous speed.



Voltage Regulation of Alternator

Direct loading method Procedure:

By using prime mover, the alternator is driven at Synchronous speed [Ns].

Now Eph is proportional to Iph

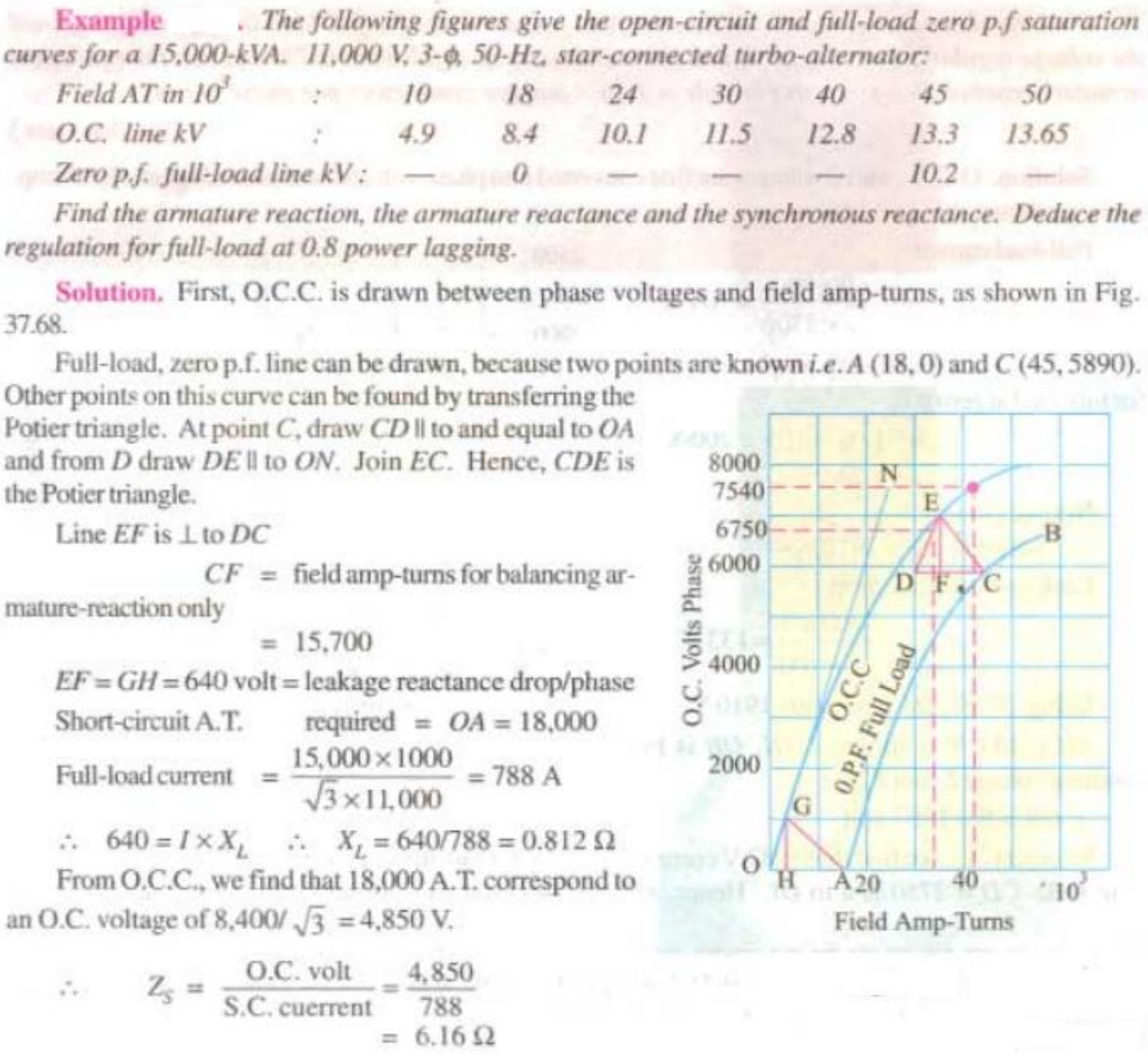
After giving the D.C supply to the field winding, the field current is adjusted in order to adjust flux so that rated voltage appears across the terminals. This is observed on a voltmeter connected across the terminals.

Next load is connected by using the TPST switch. The load is increased in steps so that ammeter reads rated current. This is the full condition of the alternator. Again adjust the voltage to its rated value by field excitation using the rheostat.

Then disconnect the entire load by opening TPST switch, keeping the speed and field excitation constant. As load is disconnected there will be no armature current and associated drops. Now the voltmeter shows a reading which is the actual value of internally induced e.m.f called no load terminal voltage.

$$\%Reg = [Eph - Vph]/Vph * 100$$

The value of regulation of alternator or synchronous generator obtained by this Direct loading method is accurate because a particular load at required power factor is actually connected to note down the readings



Example . *The following figures give the open-circuit and full-load zero p.f saturation curves for a 15,000-kVA. 11,000 V, 3-φ, 50-Hz, star-connected turbo-alternator:*

Field AT in 10^3	:	10	18	24	30	40	45	50
O.C. line kV	:	4.9	8.4	10.1	11.5	12.8	13.3	13.65
Zero p.f. full-load line kV	:	—	0	—	—	—	10.2	—

Find the armature reaction, the armature reactance and the synchronous reactance. Deduce the regulation for full-load at 0.8 power lagging.

Solution. First, O.C.C. is drawn between phase voltages and field amp-turns, as shown in Fig. 37.68.

Full-load, zero p.f. line can be drawn, because two points are known *i.e.* A (18, 0) and C (45, 5890). Other points on this curve can be found by transferring the Potier triangle. At point C, draw $CD \parallel$ to and equal to OA and from D draw $DE \parallel$ to ON. Join EC. Hence, CDE is the Potier triangle.

Line EF is $\perp$ to DC

CF = field amp-turns for balancing armature-reaction only

= 15,700

$EF = GH$ = 640 volt = leakage reactance drop/phase

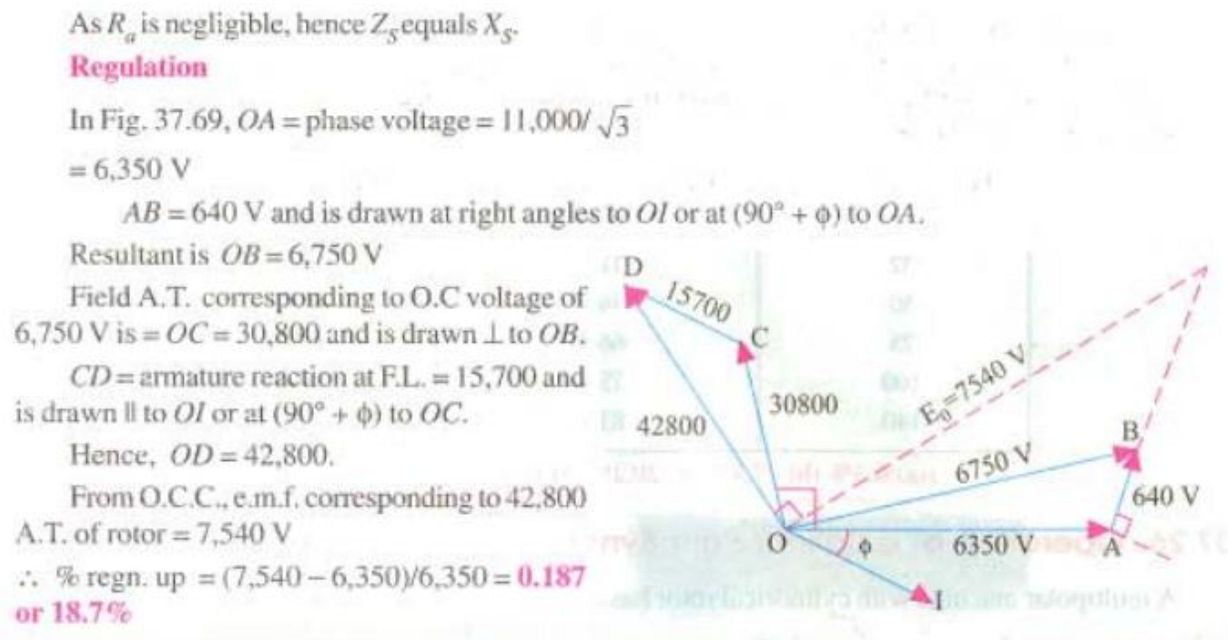
Short-circuit A.T. required = OA = 18,000

$$\text{Full-load current} = \frac{15,000 \times 1000}{\sqrt{3} \times 11,000} = 788 \text{ A}$$

$$\therefore \quad 640 = I \times X_L \quad \therefore \quad X_L = 640/788 = 0.812\ \Omega$$

From O.C.C., we find that 18,000 A.T. correspond to an O.C. voltage of $8,400/\sqrt{3} = 4,850$ V.

$$\therefore \quad Z_S = \frac{\text{O.C. volt}}{\text{S.C. cuerrent}} = \frac{4,850}{788} = 6.16\ \Omega$$



As R_a is negligible, hence Z_S equals X_S.

Regulation

In Fig. 37.69, OA = phase voltage = $11,000/\sqrt{3}$

= 6,350 V

AB = 640 V and is drawn at right angles to OI or at (90° + ϕ) to OA.

Resultant is OB = 6,750 V

Field A.T. corresponding to O.C voltage of 6,750 V is = OC = 30,800 and is drawn $\perp$ to OB.

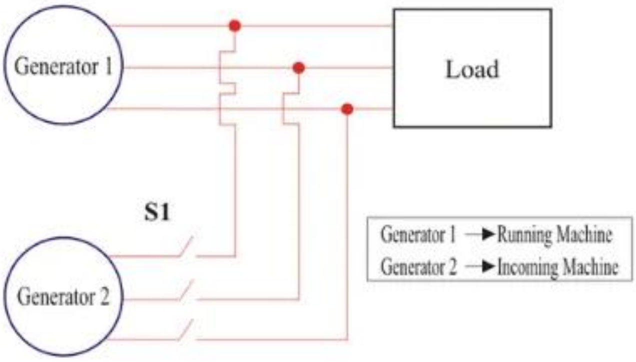
CD = armature reaction at F.L. = 15,700 and is drawn $\parallel$ to OI or at (90° + ϕ) to OC.

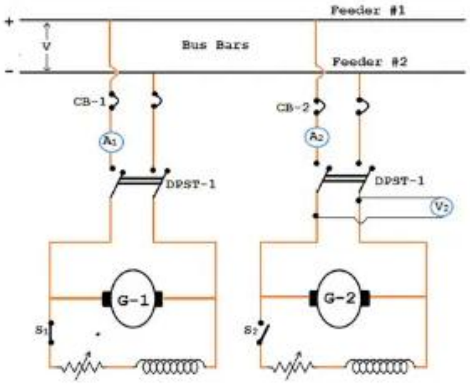
Hence, OD = 42,800.

From O.C.C., e.m.f. corresponding to 42,800 A.T. of rotor = 7,540 V

$\therefore$ % regn. up = (7,540 − 6,350)/6,350 = **0.187 or 18.7%**

1.10. Parallel operation of alternator :





Alternator is really an AC generator. In alternator, an EMF is induced in the stator (stationary wire) with the influence of rotating magnetic field (rotor) due to Faraday's law of induction. Due to the synchronous speed of rotation of field poles, it is also known as synchronous generator.

Here, we can discuss about parallel operation of alternator**.** When the AC power systems are interconnected for efficiency, the alternators should also have to be connected in parallel. There will be more than two alternators connected in parallel in generating stations.

Condition for Parallel Operation of Alternator:

There are some conditions to be satisfied for parallel operation of the alternator**.** Before entering into that, we should understand some terms which are as follows.

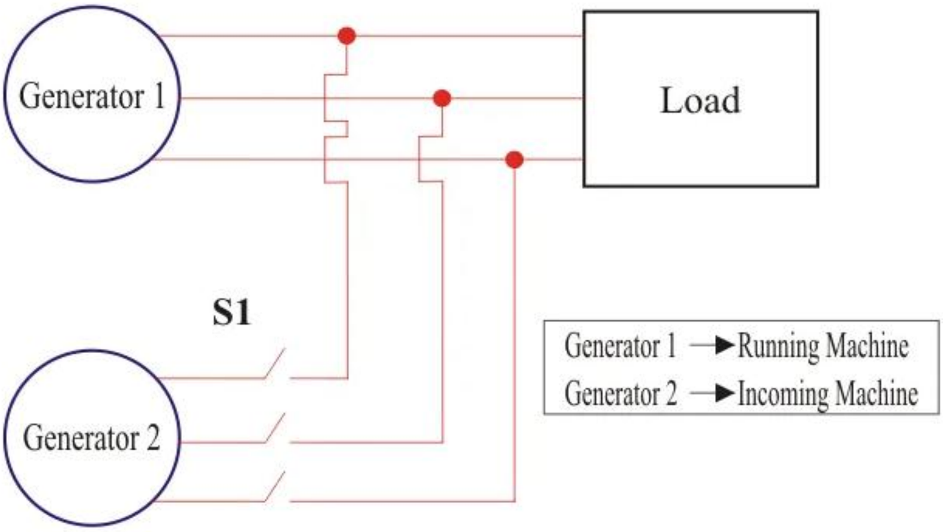
- The process of connecting two alternators or an alternator and an infinite bus bar system in parallel is known as synchronizing.
- Running machine is the machine which carries the load.
- Incoming machine is the alternator or machine which has to be connected in parallel with the system.

The conditions to be satisfied are

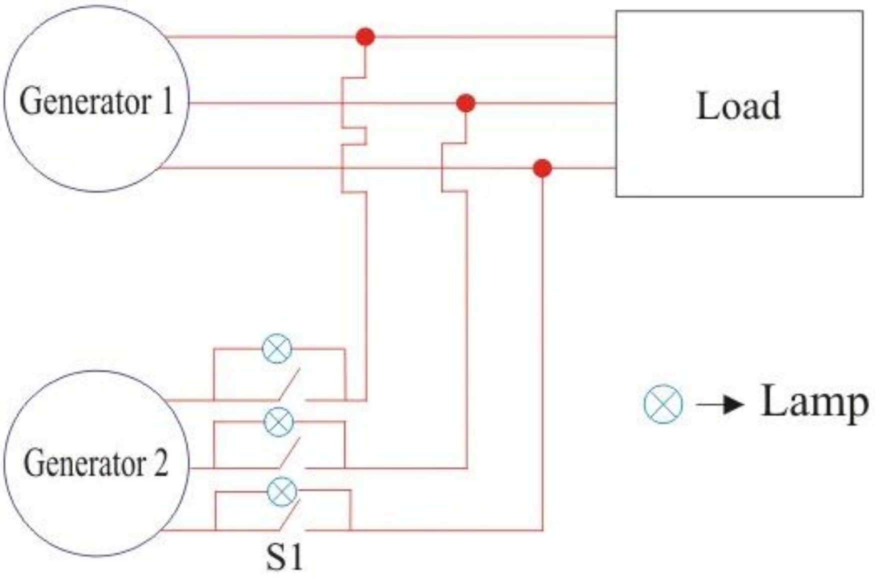
1. The phase sequence of the incoming machine voltage and the bus bar voltage should be identical.
2. The RMS line voltage (terminal voltage) of the bus bar or already running machine and the incoming machine should be the same.
3. The phase angle of the two systems should be equal.
4. The frequency of the two terminal voltages (incoming machine and the bus bar) should be nearly the same. Large power transients will occur when frequencies are not nearly equal.

GENERAL PROCEDURE FOR PARALLELING ALTERNATORS

The figure below shows an alternator (generator 2) being paralleled with a running power system (generator 1). These two machines are about to synchronize for supplying power to a load. Generator 2 is about to parallel with the help of a switch, S1. This switch should never be closed without satisfying the above conditions.



1. To make the terminal voltages equal. This can be done by adjusting the terminal voltage of incoming machine by changing the field current and make it equal to the line voltage of running system using voltmeters.
2. There are two methods to check the phase sequence of the machines. They are as follows
    - First one is using a Synchroscope. It is not actually check the phase sequence but it is used to measure the difference in phase angles.
    - Second method is three lamp method . Here we can see three light bulbs are connected to the terminals of the switch, S1. Bulbs become bright if the phase difference is large. Bulbs become dim if the phase difference is small. The bulbs will show dim and bright all together if phase sequence is the same. The bulbs will get bright in progression if the phase sequence is opposite. This phase sequence can be made equal by swapping the connections on any two phases on one of the generators.



3. Next, we have to check and verify the incoming and running system frequency. It should be nearly the same. This can be done by inspecting the frequency of dimming and brightening of lamps.
4. When the frequencies are nearly equal, the two voltages (incoming alternator and running system) will alter the phase gradually. These changes can be observed and the switch, S1 can be made closed when the phase angles are equal.

Advantages of Parallel Operating Alternators

- When there is maintenance or an inspection, one machine can be taken out from service and the other alternators can keep up for the continuity of supply.
- Load supply can be increased.
- During light loads, more than one alternator can be shut down while the other will operate in nearly full load.
- High efficiency.
- The operating cost is reduced.
- Ensures the protection of supply and enables cost-effective generation.
- The generation cost is reduced.
- Breaking down of a generator does not cause any interruption in the supply.
- Reliability of the whole power system increases.

1.11. Distribution of load by parallel connected alternator :

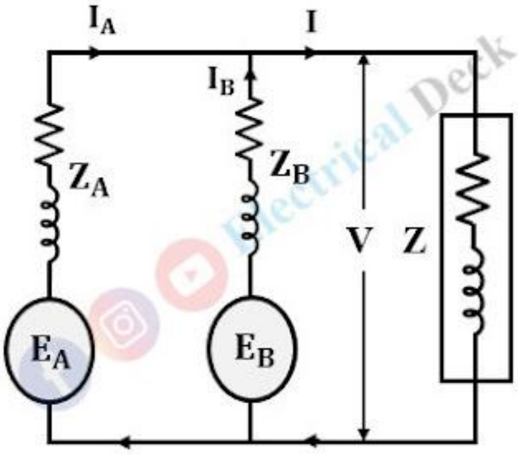
When an incoming alternator is synchronized for parallel operation with other alternators. The alternator floats on the bus-bar i.e., it doesn't share any load or doesn't supply any load current. let us see how to make the alternator to share the load, in parallel operation depending upon its kVA rating.

In parallel operation of dc generator when an incoming dc generator is connected to share load the machine starts floating on the bus-bar. This is because the induced emf in the incoming dc generator is equal to the bus-bar voltage. To eliminate this floating condition in dc generator the induced emf is made greater than the bus-bar voltage by varying field excitation. Thus the generator starts sharing the load with other generators.

Load Sharing Between Two Alternators :

Consider two alternators with identical speed-load characteristics running in parallel with a common terminal voltage of V volt and load impedance Z.

- E_A & E_B = Induced EMFs of alternators A and B respectively,
- I_A & I_B = Respective currents, and
- Z_A & Z_B = Respective phase impedances.



The terminal voltage V is given by,

$$V = E_A - I_A Z_A$$

$$= E_B - I_B Z_B$$

Load current I, is given by,

$$I = I_A + I_B$$

$$I_A = \frac{E_A - V}{Z_A},\ I_B = \frac{E_B - V}{Z_B}$$

$$E_A - E_B = I_A Z_A - I_B Z_B$$

From the above diagram, the terminal V is equal to IZ i.e., V = IZ. Therefore, the emf E_A induced in the alternator A is,

$$E_A = V + I_A Z_A$$

$$= IZ + I_A Z_A$$

$$= (I_A + I_B)\, Z + I_A Z_A$$

$$= I_A\,(Z_A + Z) + I_B Z$$

Similarly, the emf E_B induced in the alternator B is,

$$E_B = V + I_B Z_B$$

$$= I_B\,(Z_B + Z) + I_A Z$$

Short questions with answer :

1. **What Is Meant By Synchronising The Alternators?**
   Answer :
   The process of connecting two or more alternators in parallel for supplying a common load is called synchronising.
2. **What Are The Conditions To Be Satisfied For Proper Synchronising Of Alternators?**
   Answer :
   - The terminal voltage of the incoming alternator must be the same as bus-bar voltage.
   - The speed of the incoming alternator must be such that its frequency equals to the bus-bar frequency
   - The phase sequence of the incoming alternator must be the same as that of the other alternators or busbars.
3. **What Are The Advantages Of Parallel Operation Of Alternators?**
   Answer :
   - It ensures continuity of power supply to consumers in case of breakdown of an alternator in an generation station.
   - This is economical and improves the efficiency of the generating station.
   - When the demand of power increases, new alternators can be installed to operate in parallel.
   - It is not possible to built single large size alternator to meet the requirement.
4. **What Are Types Of Rotors Used In Alternators?**
   Answer :
   There are two types of rotors used in alternators namely

   - Salient pole rotor
   - Smooth cylindrical type rotor
5. **What Are The Advantages Of Providing Damper Winding?**
   Answer :
   The damper winding is useful in preventing the hunting (momentary speed fluctuations) in generators.

   The damper winding also used to maintain balanced 3 phase voltage under unbalanced load conditions.
6. **What Are The Various Methods To Determine The Voltage Regulation Of The Large Alternators?**
   Answer :
   In case of small machines, the regulation can be found by direct loading.

   For large alternators, to find the voltage regulation indirect methods are used. They are

   - Synchronous Impedance Method.
   - The Ampere-turn method.
   - Zero power factor or Pointer Method.
7. **What Is The Basic Principle Of Alternators?**
   Answer :
   Alternators is noting but a AC generators. They operate on the fundamental principle of electromagnetic induction as dc generators.

   ie, when the rotor rotates, the emf is induced in the stator.
8. **Which Type Of Rotor Is Suitable For Low Speed Alternators? Salient Pole Type Or Cylindrical Type Rotor?**
   Answer :
   Salient pole type alternators are suitable for low and medium speed alternators. It has large number of projecting poles. It has large diameters and short axial lengths.

9. **What Is Meant By Turbo Alternators?**

Answer :

High speed alternators are called as Turbo alternators.

As it runs at very high speed, salient pole rotors are not used. Smooth cylindrical type rotor is suitable for turbo alternators.

LONG QUESTIONS

Q1. What do you mean by parallel operation of alternator and how it works ?

Q2. Describe the construction and working principle of alternator ?

Q3. What do you mean by Voltage regulation of an alternator ?

CHAPTER-2

(SYNCHRONOUR MOTOR)

Learning Resources :

2.1. Constructional feature of Synchronous Motor.
2.2. Principles of operation, concept of load angle
2.3. Derive torque, power developed.
2.4. Effect of varying load with constant excitation.
2.5. Effect of varying excitation with constant load.
2.6. Power angle characteristics of cylindrical rotor motor.
2.7. Explain effect of excitation on Armature current and power factor.
2.8. Hunting in Synchronous Motor.
2.9. Function of Damper Bars in synchronous motor and generator.
2.10. Describe method of starting of Synchronous motor.
2.11. State application of synchronous motor.

2.1. Constructional feature of Synchronous Motor :

The most common type of 3 phase motors are synchronous motors and induction motors. When three-phase electric conductors are placed in certain geometrical positions (i.e. in a certain angle from one another) – an electrical field is generated. The rotating magnetic field rotates at a certain speed known as the synchronous speed**.**

Synchronous motors run at synchronous speed. The synchronous speed is

$$N_S = (120*f)/P$$

Where, N_s = synchronous speed,
f = supply frequency,
P = number of poles.

Definition:

The motor which runs at synchronous speed is known as the synchronous motor. The synchronous speed is the constant speed at which the motor generates the electromotive force. The synchronous motor is used for converting the electrical energy into mechanical energy.

CONSTRUCTION

The construction of a synchronous motor is very similar to the construction of an alternator. Both are synchronous machines where one we use as a motor and the other as a generator. Just like any other motor, the synchronous motor also has a stator and a rotor.

Stator of Synchronous Motor

The main stationary part of the machine is stator. The stator consists of the following parts.

Stator Frame : The stator frame is the outer part of the machine and is made up of cast iron. It protects the enter inner parts of the machine.

Stator Core : The stator core is made up of thin silicon laminations. It is insulated by a surface coating to minimize hysteresis and eddy current losses. Its main purpose is to provide a path of low reluctance for the magnetic lines of force and accommodate the stator windings.

Stator Winding : The stator core has cuts on the inner periphery to accommodate the stator windings. The stator windings could be either three-phase windings or single phase windings.

Enamelled copper is used as the winding material. In the case of 3 phase windings, the windings are distributed over several slots. This is done to produce a sinusoidal distribution of EMF.

Rotor of Synchronous Motor

The rotor is the moving part of the machine. Rotors are available in two types:

- **Salient Pole Type**
- **Cylindrical Rotor Type**

The salient pole type rotor consists of poles projecting out from the rotor surface. It is made up of steel laminations to reduce eddy current losses.

A salient pole machine has a non-uniform air gap. The gap is maximum between the poles and is minimum at the pole centres. They are generally used for medium and low-speed operations as they have a large number of poles. They contain damper windings which are used for starting the motor.

A cylindrical rotor is made from solid forgings of high-grade nickel chrome molybdenum steel forgings of high-grade nickel chrome molybdenum steel. The poles are created by the current flowing through the windings. They are used for high-speed applications as they have less number of poles. They also produce less noise and windage losses as they have a uniform air gap. DC supply is given to the rotor windings via slip-rings. Once the rotor windings are excited, they act like poles.

Types of Synchronous Motor

Depending upon the method of magnetization of the rotor, there are two types of synchronous motors –

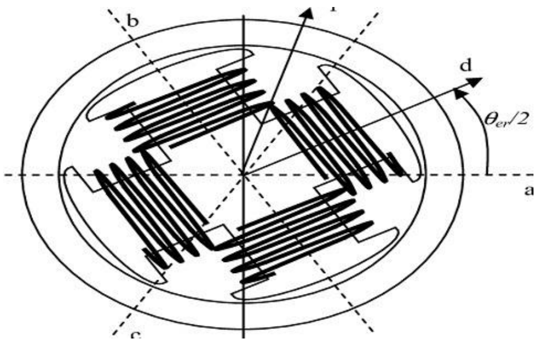
- Non-excited.
- Direct current Excited.

Non-excited Motor

In these motors, the rotor is magnetized by the external stator field. The rotor contains a constant magnetic field. High retentive steel such as cobalt steel is used to make the rotor. These are classified as a permanent magnet, reluctance, and hysteresis motors.

DC Current Excited Motor

Here the rotor is excited using the DC current supplied directly through slip rings. AC induction and rectifiers are also used. These are usually of large sizes such as larger than 1 horsepower etc.



DC Current Excited Motor

2.2. Principles of operation, concept of load angle:

Working of synchronous motors depends on the interaction of the magnetic field of the stator with the magnetic field of the rotor. The stator contains 3 phase windings and is supplied with 3 phase power. Thus, stator winding produces a 3 phased rotating Magnetic- Field. DC supply is given to the rotor.

The rotor enters into the rotating Magnetic-Field produced by the stator winding and rotates in synchronization. Now, the speed of the motor depends on the frequency of the supplied current.

Speed of the synchronous motor is controlled by the frequency of the applied current. The speed of a synchronous motor can be calculated as

Ns= 120*f/p

where, f = frequency of the AC current (Hz)
P = total pair number of poles per phase.

If the load greater than breakdown load is applied, the motor gets desynchronized. The 3 phase stator winding gives the advantage of determining the direction of rotation. In case of single-phase winding, it is not possible to derive the direction of rotation and the motor can start in either of the direction. To control the direction of rotation in these synchronous motors, starting arrangements are needed.

2.3. Derive torque, power developed :

Motor Torque

Gross torque, T =9.55 Pm/Ns N-M

where Pm = Gross motor output in watts = Eb.Ia. cos(ϴ - ϕ)

Ns = Synchronous speed in r.p.m.

Shaft torque, Tsh = 9.55 Psh_{out} /Ns N-M

It may be seen that torque is directly proportional to the mechanical power because rotor speed (i.e., Ns) is fixed.

Mechanical Power Developed

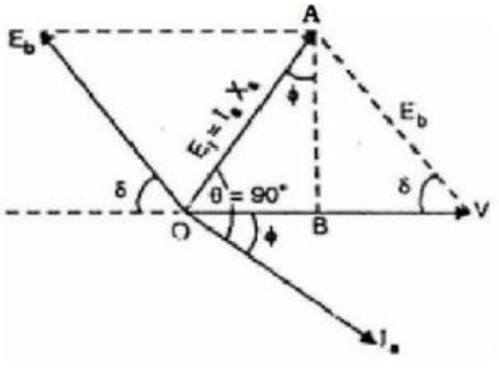
Neglecting the armature resistance the phasor diagram of an under-excited synchronous motor driving a mechanical load. Since armature resistance Ra is assumed zero. tan ϴ = Xs/Ra = infinite and hence ϴ =90°.

Input power/phase = V Ia cos ϕ

Since Ra is assumed zero, stator Cu loss (I Ra)2 will be zero.

Hence input power is equal to the mechanical power Pm developed by the motor.

Mechanical power developed/ phase, Pm = V Ia cos ϕ, referring to the phasor diagram in below figure,



$$AB = E_r \cos\phi = I_a X_s \cos\phi$$

$$AB = E_b \sin\delta$$

$$E_b \sin\delta = I_a X_s \cos\phi$$

$$I_a \cos\phi = \frac{E_b \sin\delta}{X_s}$$

Substituting the value of $I_a \cos\phi$ in exp. (i) above.

$$P_m = \frac{VE_b}{X_s} \quad \text{per phase}$$

$$= \frac{VE_b}{X_s} \quad \text{for 3-phase}$$

It is clear from the above relation that mechanical power increases with torque angle (in electrical degrees) and its maximum value is reached when $\delta = 90°$ (electrical).

$$P_{max} = \frac{VE_b}{X_s} \quad \text{per phase}$$

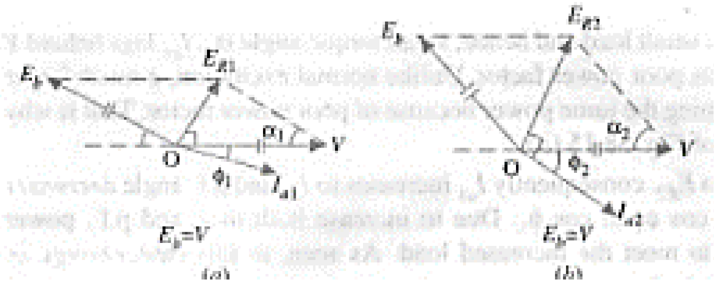
Under this condition, the poles of the rotor will be mid-way between N and S poles of the stator.

2.4. Effect of varying load with constant excitation :

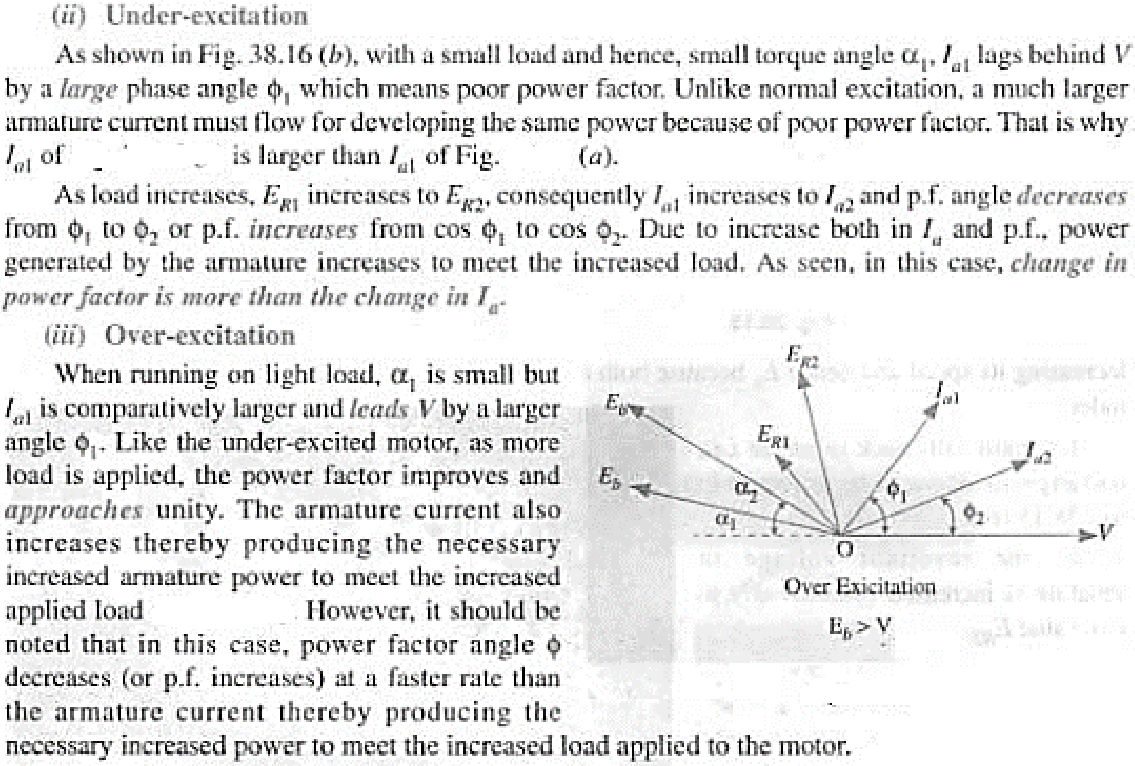
We will study the effect of increased load on a synchronous motor under conditions of normal, under and over-excitation (ignoring the effects of armature reaction). With normal excitation, $E_b = V$, with under excitation, $E_b < V$ and with over-excitation, $E_b > V$. Whatever the value of excitation, 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

. (*a*) shows the condition when motor is running with light load so that (*i*) torque angle α_1 is small (*ii*) so E_{R1} is small (*iii*) hence I_{a1} is small and (*iv*) ϕ_1 is small so that $\cos\phi_1$ 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.



(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 is larger than I_{a1} of Fig. (*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 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.

Over Exicitation

$E_b > V$

2.5. Effect of varying excitation with constant load :

(i) Under excitation

The motor is said to be under-excited if the field excitation is such that Eb < V. Under such conditions, the current Ia lags behind V so that motor power factor is lagging as shown in Fig:

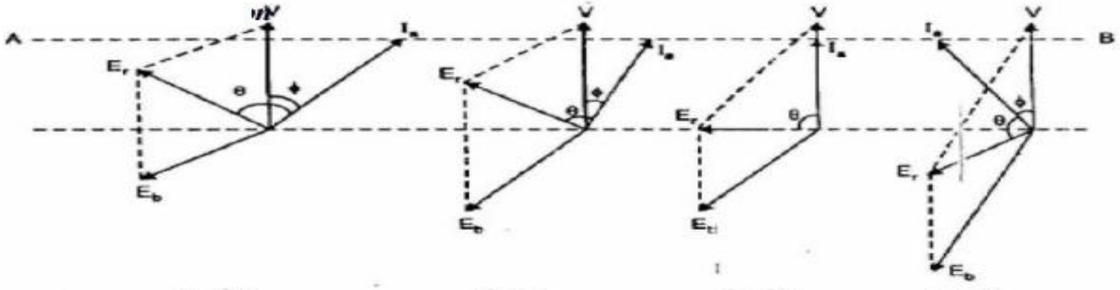
(i). This can . be easily explained. Since Eb < V, the net voltage Er is decreased and turns clockwise. As angle (δ δ = 90°) between Er and Ia is constant, therefore, phasor Ia also turns clockwise i.e., current Ia lags behind the supply voltage. Consequently, the motor has a lagging power factor.

(ii) Normal excitation

The motor is said to be normally excited if the field excitation is such that Eb = V.

Note- that the effect of increasing excitation (i.e., increasing Eb) is to turn the phasor Er and hence Ia in the anti-clockwise direction i.e., Ia phasor has come closer to phasor V. Therefore, p.f. increases though still lagging. Since input power (=3 V*Ia *cos ϕ) is unchanged, the stator current Ia must decrease with increase in p.f. Suppose the field excitation is increased until the current Ia is in phase with the applied voltage V, making the p.f. of the synchronous motor unity. For a given load, at unity p.f. the resultant Er and, therefore, Ia are minimum.

(iii) Over excitation



$E_b < V$
Under excitation
(i)

$V = E_b$
Normal excitation
(ii)

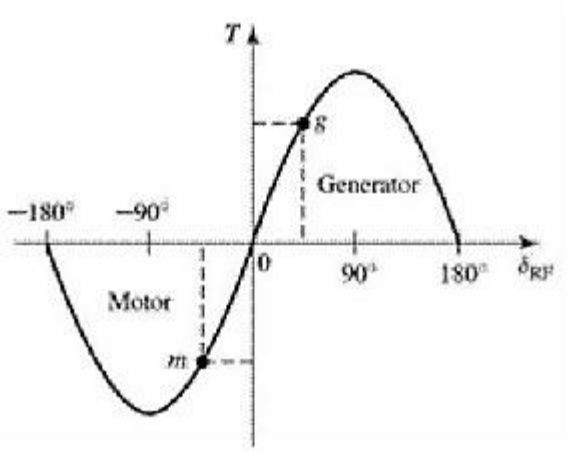
$E_b > V$
Unity p.f.
(iii)

$E_b > V$
Over-excitation
(iv)

The motor is said to be overexcited if the field excitation is such that Eb > V. Under-such conditions, current Ia leads V and the motor power factor is leading as shown in Fig: (iv).

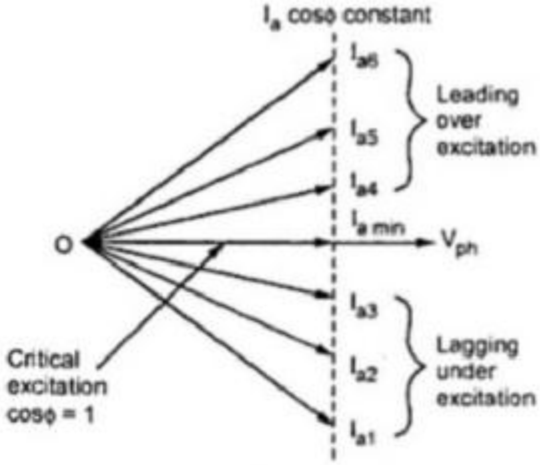
2.6. Power angle characteristics of cylindrical rotor motor :

The variation of power with respect to power-angle is plotted in Fig below. The power versus load angle characteristic curve has a sinusoidal shape and is usually called power-angle characteristic of the cylindrical-rotor synchronous machine. The power P, for generator is taken as positive and therefore, for motor as negative.



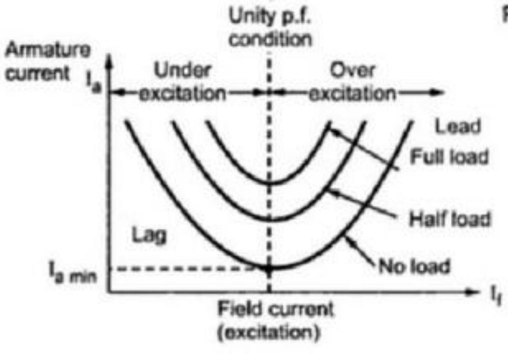
2.7. Explain effect of excitation on Armature current and power factor:

It is clear from above discussion that if excitation is varied from very low (under excitation) to very high (over excitation) value, then current Ia decreases, becomes minimum at unity p.f. and then again increases. But initial lagging current becomes unity and then becomes leading in nature. This can be shown as in the Fig below.

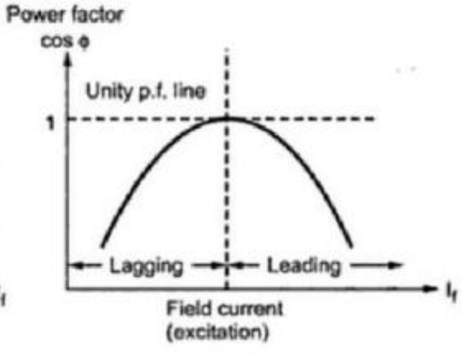


Excitation can be increased by increasing the field current passing through the field winding of synchronous motor. If graph of armature current drawn by the motor (Ia) against field current (I_f) is plotted, then its shape looks like an english alphabet V. If such graphs are obtained at various load conditions we get family of curves, all looking like V. Such curves are called V-curves of synchronous motor. These are shown in the Figure.

As against this, if the power factor (cos ɸ) is plotted against field current (If), then the shape of the graph looks like an inverted V. Such curves obtained by plotting p.f. against If, at various load conditions are called Inverted V-curves of synchronous motor. These curves are shown in the Fig:b.



(a)



(b)

2.8. Hunting in Synchronous Motor.

Unloaded synchronous machine has zero degree load angle. On increasing the shaft load gradually load angle will increase. Let us consider that load P_1 is applied suddenly to unloaded machine shaft so machine will slow down momentarily. Also load angle (δ) increases from zero degree and becomes δ_1. During the first swing electrical power developed is equal to mechanical load P_1. Equilibrium is not established so rotor swings further. Load angle exceeds δ_1 and becomes δ_2. Now electrical power generated is greater than the previous one. Rotor attains synchronous speed. But it does not stay in synchronous speed and it will continue to increase beyond synchronous speed. As a result of rotor acceleration above synchronous speed the load angle decreases. So once again no equilibrium is attained. Thus rotor swings or oscillates about new equilibrium position. This phenomenon is known as hunting or phase swinging.

Hunting occurs not only in synchronous motors but also in synchronous generators upon abrupt change in load.

Causes of Hunting in Synchronous Motor

1. Sudden change in load.
2. Sudden change in field current.
3. A load containing harmonic torque.
4. Fault in supply system.

Effects of Hunting in Synchronous Motor

1. It may lead to loss of synchronism.
2. Produces mechanical stresses in the rotor shaft.
3. Increases machine losses and cause temperature rise.
4. Cause greater surges in current and power flow.
5. It increases possibility of resonance.

Reduction of Hunting in Synchronous Motor

Two techniques should be used to reduce hunting. These are –

- Use of Damper Winding: It consists of low electrical resistance copper / aluminum brush embedded in slots of pole faces in salient pole machine. Damper winding damps out hunting by producing torque opposite to slip of rotor. The magnitude of damping torque is proportional to the slip speed.
- Use of Flywheels: The prime mover is provided with a large and heavy flywheel. This increases the inertia of prime mover and helps in maintaining the rotor speed constant.
- Designing synchronous machine with suitable synchronizing power coefficients.

2.9. Function of Damper Bars in synchronous motor and generator.

The damper winding is used in the synchronous motor to provide starting torque. We know that the synchronous motor is not self-starting. So to start the synchronous motor we follow various methods of starting. The method of starting using the damper winding is one of them.

Suppose a synchronous motor has damper winding. Initially, when the motor is off, the rotator is constant. When we give the main power supply to the stator winding of the synchronous motor, it creates a rotating magnetic field. Now the stator flux will cut the damper winding conductor and an emf will be induced in the damper winding as the induction motor principle.

So, initially, the synchronous motor will start as an induction motor and it will continue running after giving the auxiliary dc supply to the main field winding. When the rotor catches the synchronous speed there will be no relative speed between the stator and rotor and the damper winding will stop inducing emf. So it is clear that the damper winding works only starting time of the motor.

The damper winding is used in the synchronous alternator to suppress or eliminate hunting. When in an alternator load is sudden changes then the rotor hunts and it tries to go a new equilibrium position.

2.10. Describe method of starting of Synchronous motor.

Below are the techniques used for starting a synchronous motor**:**

1) Starting a Synchronous Motor Using an Induction Motor

We need to bring the rotor of the synchronous motor to synchronous speed before we switch on the motor. For that reason, we directly couple a small induction motor (pony motor) with the synchronous motor.

Note here, that the number of poles of the induction motor should be less than the synchronous motor else it will never be able to achieve the synchronous speed of the synchronous motor. This is because an induction motor always has a speed less than the synchronous speed and for it to become equal to the synchronous speed of the synchronous motor, its own speed has to be increased.

2) Starting a Synchronous Motor Using a DC Machine

It is similar to above method with a slight difference between the two. A DC machine is coupled to the synchronous motor. The DC machine works like a DC motor initially and brings the synchronous motor to synchronous speed. Once it achieves the synchronous speed, the DC machine works like a DC generator and supplies DC to the rotor of the synchronous motor. This method offers easy starting and better efficiency than the earlier method.

3) Starting a Synchronous Motor Using Damper Windings

In this method, the motor is first started as an induction motor and then starts running as a synchronous motor after achieving synchronous speed. For this, damper windings are used. Damper windings are additional windings consisting of copper bars placed in the slots in the pole faces. The ends of the copper bars are short-circuited. These windings behave as the rotor of an induction motor. When 3 phase power is supplied to the motor, the motor starts running as an induction motor at a speed below synchronous speed. After some time DC supply is given to the rotor. The motor gets pulled into synchronism after some instant and starts running as a synchronous motor.

4) Starting a Synchronous Motor Using Slip Ring Induction Motor

Here we connect one external rheostat in series with the rotor. The motor is first started as a slip ring induction motor. The resistance is gradually cut-off as the motor gains speed. When it achieves near synchronous speed, DC excitation is given to the rotor, and it is pulled into synchronism. Then it starts rotating as a synchronous motor.

2.11. State application of synchronous motor :

Due to constant speed characteristics, it is used in machine tools, motor generator sets, synchronous clocks, stroboscopic devices, timing devices, belt driven reciprocating compressors, fans and blowers, centrifugal pumps, vacuum pumps, pulp grinders, textile mills, paper mills line shafts, rolling mills, cement mills etc.

The synchronous motors are often used as a power factor correction device, phase advancers and phase modifiers for voltage regulation of the transmission lines. This is possible because the excitation of the synchronous motor can be adjusted as per the requirement.

The disadvantages of synchronous motor are their higher cost, necessity of frequent maintenance and a need of d.c. excitation source, auxiliary device or additional winding provision to make it self starting. Overall their initial cost is very high.

Short questions with answer :

1. What does hunting of synchronous motor mean?

When the load applied to the synchronous motor is suddenly increased or decreased, the rotor oscillates about its synchronous position with respect to the stator field. This action is called hunting

2. What is the function of damper bars? (Win-2016)

Ans : Damper bar is given for starting of synchronous motor.

3. What is synchronous condenser?

An over-excited synchronous motor under no load used for the improvement of power factor is called as synchronous condenser because, like a capacitor it takes a leading current.

4. Write the applications of synchronous motor. (Win-2020)

a. Used for power factor improvement in sub-stations and in industries. b. Used in industries for power applications.

c. Used for constant speed drives such as motor-generator set, pumps and compressors.

5. What is an inverted 'V' curve? (Sum-2018)

Ans :V curving synchronous motor is a graph plotted between field current and armature current, taking load constant.

.**7. If load angle of a 4 pole synchronous motor is 8 degrees electrical, what is its mechanical degree ?**

Ans : 1 electrical degree = (P/2) Mechanical degree

So, mechanical degree = (2/P)* Electrical Degree

= (2/4) * 8 degrees = 4 degree

Long questions :

Q1. Write the procedure for starting of synchronous motor?

Q2. Explain the V curve and inverted V curve of a 3 Phase synchronous motor?

Q3.Describe the effect of Variable excitation with constant load?

Q4. What is hunting, explain it? **(Sum-2019 (N))**

Q5. Explain the effect of excitation on armature current and power factor in synchronous motor in details. **(Win-2020)**

CHAPTER NO.- 03

THREE PHASE INDUCTION MOTOR

Learning Objectives:

3.1. Production of rotating magnetic field.

3.2. Constructional feature of Squirrel cage and Slip ring induction motors.

3.3. Working principles of operation of 3-phase Induction motor.

3.4. Define slip speed, slip and establish the relation of slip with rotor quantities.

3.5. Derive expression for torque during starting and running conditions and derive conditions for maximum torque. (solve numerical problems)

3.6. Torque-slip characteristics.

3.7. Derive relation between full load torque and starting torque etc. (solve Numerical problems)

3.8. Establish the relations between Rotor Copper loss, Rotor output and Gross Torque and relationship of slip with rotor copper loss. (solve numerical problems)

3.9. Methods of starting and different types of starters used for three phase Induction motor.

3.10. Explain speed control by Voltage Control, Rotor resistance control, Pole changing, frequency control methods.

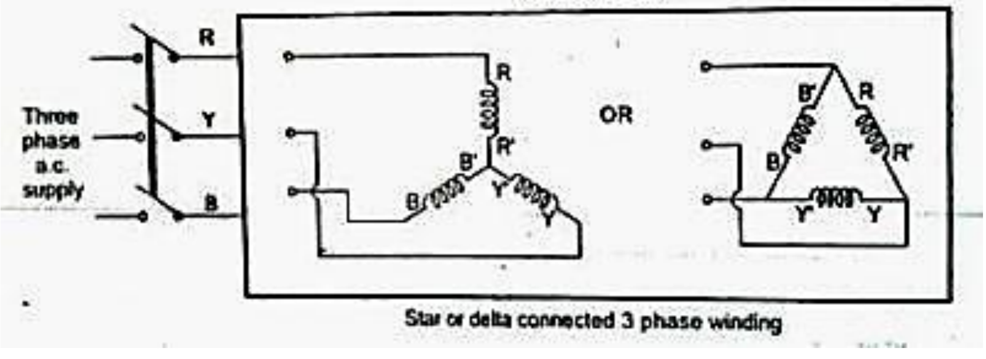
3.11. Plugging as applicable to three phase induction motor.

3.12. Describe different types of motor enclosures.

3.13. Explain principle of Induction Generator and state its applications.

3.1 PRODUCTION OF ROTATING MAGNETIC FIELD :

When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating field.



Star or delta connected 3 phase winding

The three-phase windings are displaced from each other by 120°.

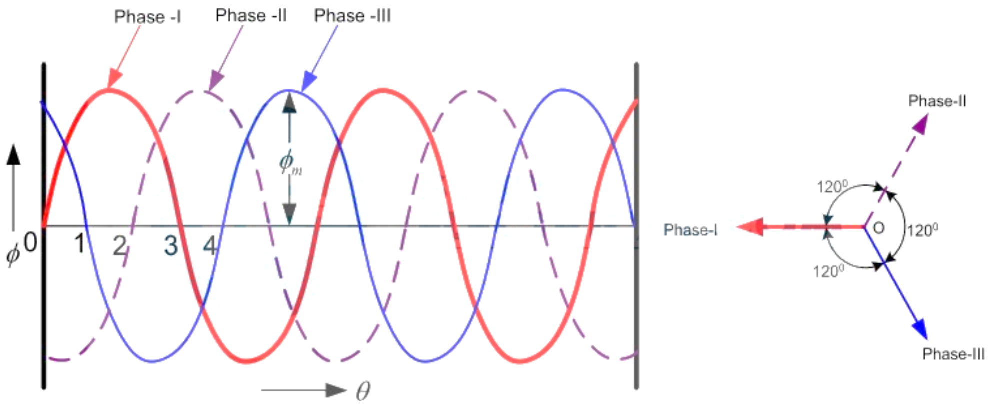
If the phase sequence of the windings is R-Y-B, then mathematical equations for the instantaneous values of the three fluxes Φ_R , Φ_Y ,Φ_B can be written as,

$$\Phi_R = \Phi m \sin(\omega t)$$

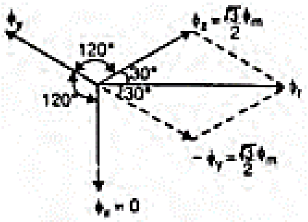
$$\Phi_Y = \Phi m \sin(\omega t - 120)$$

$$\Phi_B = \Phi m \sin(\omega t - 240)$$

As windings are identical and supply is balanced, the magnitude of each flux is Φm .
Here Φm is the maximum flux due to any phase.



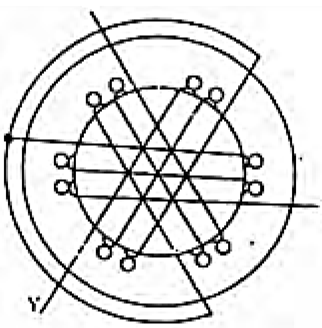
(i) At instant 1 [See Fig. ((ii)) and (iii))], the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 ϕ_m as proved under:



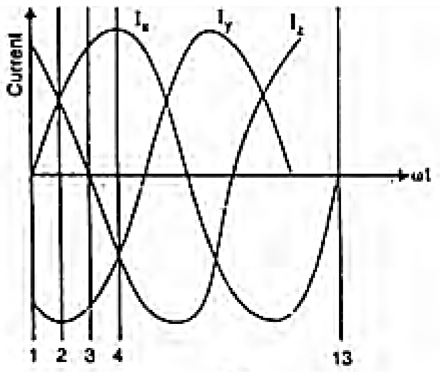
At instant 1, ωt = 0°. Therefore, the three fluxes are given by;

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

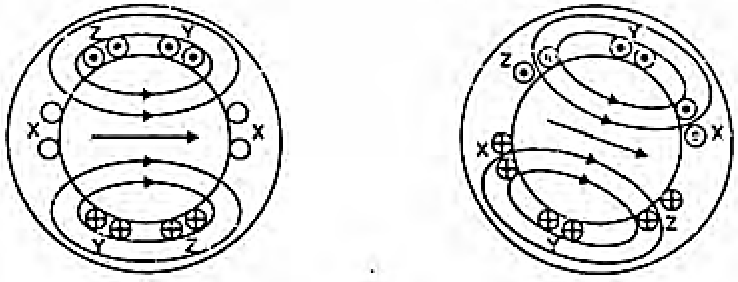
$$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$



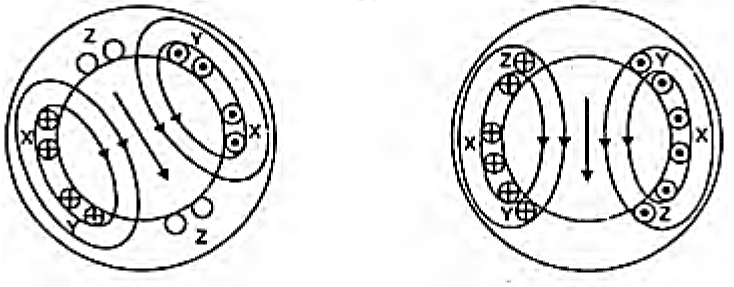
(i)



(ii)



(1) (iii) (2)

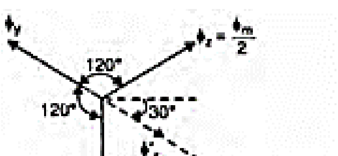


(3) (iii) (4)

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

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

(ii) At instant 2, the current is maximum (negative) in ϕ_y phase Y and 0.5 maximum (positive) in phases X and Y. The magnitude of resultant flux is 1.5 ϕ_m as proved under:



At instant 2, ωt = 30°. Therefore, the three fluxes are given by;

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

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

$$\phi_z = \phi_m \sin(-210^\circ) = \frac{\phi_m}{2}$$

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

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

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

3.2 CONSTRUCTIONAL FEATURE OF SQUIRREL CAGE AND SLIP RING INDUCTION MOTORS

The stator carries a 3-phase winding (called stator winding) while the rotor carries a short-circuited winding (called rotor winding).

The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power of the motor. The main body of the Induction Motor comprises of two major parts as shows in fig-1.

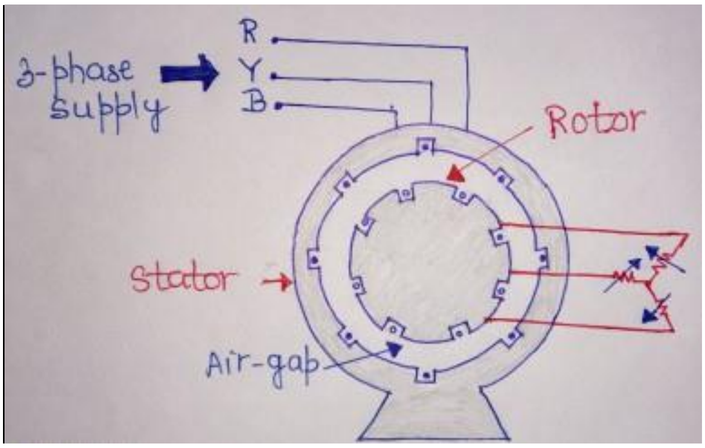


Figure 1: Stator and Rotor

STATOR

Stator is made up of number of stampings in which different slots are cut to receive 3 phase winding circuit which is connected to 3 phase AC supply.

The windings are wound for a definite number of poles depending upon the speed requirement, as speed is inversely proportional to the number of poles, given by the formula:

$N_s = 120f/p$ Where N_s = synchronous speed
f = Frequency
p = no. of poles

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

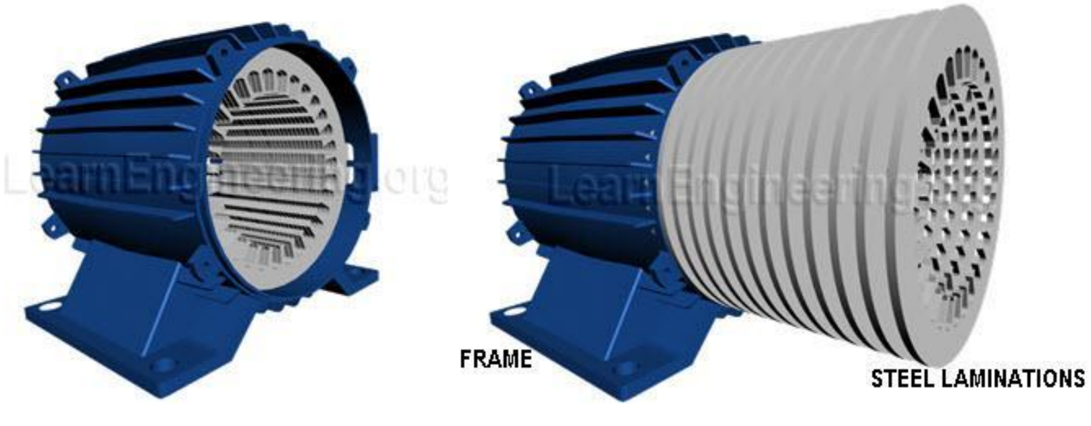


Figure-2 : Stator core

- The insulated connected to form a balanced 3-phase star or delta connected circuit. When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced.
- This rotating field induces currents in the rotor by electromagnetic induction.

Stator Winding or Field Winding

The slots on the periphery of stator core of the motor carries three phase windings. This three phase winding is supplied by three phase ac supply. The winding wound is also called field winding which produces a rotating magnetic.

- The squirrel cage motor is mostly started by star-delta stator and hence the stator of squirrel cage motor is delta connected.
- The slip ring three phase induction motor are started by inserting resistances so, the stator winding of slip ring induction can be connected either in star or delta.

ROTOR

The rotor is a rotating part of IM. The rotor is connected to the mechanical load through the shaft. Rotor consists of cylindrical laminated core with parallel slots that carry conductor bars. Conductors are heavy copper or aluminum bars which fits in each slots. These conductors are brazed to the short circuiting end rings.

- The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed for the following reason.
    - They reduces magnetic hum or noise.
    - They avoid stalling of motor.

The winding placed in these slots (called rotor winding) may be one of the following two types: Squirrel cage type and Wound type.

A. SQUIRREL CAGE ROTOR

The rotor of the squirrel cage three phase induction motor is cylindrical in shape and have slots on its periphery. The squirrel cage rotor consists of aluminum, brass or copper bars. These aluminum, brass or copper bars are called rotor conductors and are placed in the slots on the periphery of the rotor as shown in fig-3.

Figure-3

- The rotor conductors are permanently shorted by the copper or aluminum rings called the end rings.
- As the bars are permanently shorted by end rings, the rotor resistance is very small and it is not possible to add external resistance as the bars are permanently shorted.
- The absence of slip ring and brushes make the construction of Squirrel cage three phase induction motor very simple and robust
- Most of 3-phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction enabling it to operate in the most adverse circumstances with less maintenance.

However, it suffers from the disadvantage of a low starting torque

Applications:

Used in lathes, drilling machine, fan, blower printing machines etc.

B. SLIP RING OR WOUND ROTOR

In this type of three phase induction motor the rotor is wound for the same number of poles as that of stator, carries star or delta winding similar to that of stator winding.

The rotor consists of numbers of slots and rotor winding are placed inside these slots. The three end terminals are connected together to form star connection.

The three ends of three phase windings are permanently connected to these slip rings.

The brushes are used to carry current to and from the rotor winding. These brushes are further connected to three phase star connected resistances. At starting, the resistance are connected in rotor circuit and is gradually cut out as the rotor pick up its speed

ADVANTAGES OF SLIP RING INDUCTION MOTOR:

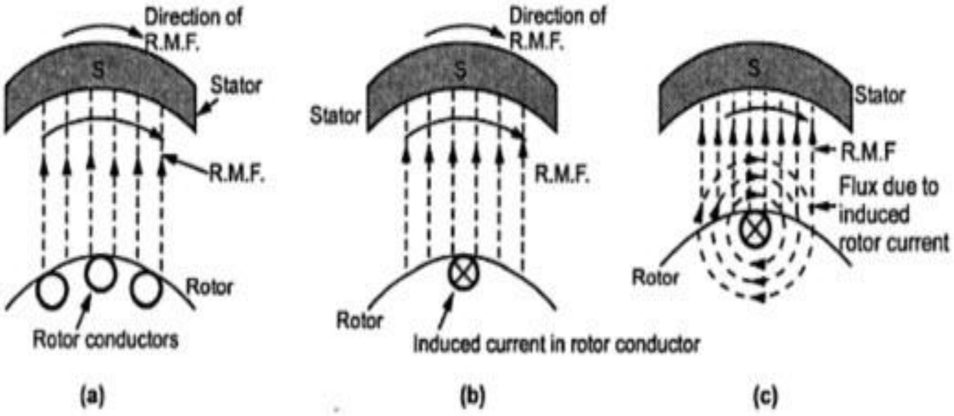
A. It has high starting torque and low starting current.
B. Possibility of adding additional resistance to control speed.

Application:

Used where high starting torque is required i.e in hoists, cranes, elevator etc.

3.3 WORKING PRINCIPLES OF OPERATION OF 3-PHASE INDUCTION MOTOR

When the motor is excited with a three-phase supply, three-phase stator winding produces a rotating magnetic field with 120 displacements at a constant magnitude which rotates at synchronous speed.



This changing magnetic field cuts the rotor conductors and induces a current in them according to the principle of Faraday’s laws of electromagnetic induction. As these rotor conductors are shorted, the current starts to flow through these conductors.

- In the presence of the magnetic field of the stator, rotor conductors are placed, and therefore, according to the Lorenz force principle, a mechanical force acts on the rotor conductor. Thus, all the rotor conductors force, i.e., the sum of the mechanical forces produces torque in the rotor which tends to move it in the same direction of the rotating magnetic field.

- This rotor conductor’s rotation can also be explained by Lenz’s law which tells that the induced currents in the rotor oppose the cause for its production, here this opposition is rotating magnetic field. This result the rotor starts rotating in the same direction of the stator rotating magnetic field.

3.4 DEFINE SLIP SPEED, SLIP AND ESTABLISH THE RELATION OF SLIP WITH ROTOR QUANTITIES.

The speed at which the rotating magnetic field revolves is called the synchronous speed (Ns).

In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor.

The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the stator field speed (Ns). This difference in speed depends upon load on the motor.

SLIP

The ratio of difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N to N_S is called slip.
It is usually expressed as a percentage of synchronous speed

i.e. % age slip $S = \frac{Ns-N}{Ns} * 100$

(i) The quantity Ns − N is sometimes called slip speed.
(ii) When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.
(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1%to 3% so that it is essentially a constant-speed motor.

SLIP SPEED

The speed at which the induction motor work is known as the slip speed. The difference between the synchronous speed and the actual speed of the rotor is known as the slip speed.

3.5 DERIVE EXPRESSION FOR TORQUE DURING STARTING AND RUNNING CONDITIONS AND DERIVE CONDITIONS FOR MAXIMUM TORQUE.

Torque of a three phase induction motor is proportional to flux per stator pole, rotor current and the power factor of the rotor.

$T \propto \phi I_2 \cos\phi_2$ OR $T = k \phi I_2 \cos\phi_2$.
where, ϕ = flux per stator pole,
I_2 = rotor current at standstill,
ϕ_2 = angle between rotor emf and rotor current,
k = a constant.
Now, let E_2 = rotor emf at standstill
we know, rotor emf is directly proportional to flux per stator pole, i.e. $E_2 \propto \phi$.
therefore, $T \propto E_2 I_2 \cos\phi_2$
Or, $T = k_1 E_2 I_2 \cos\phi_2$.

STARTING TORQUE

The torque developed at the instant of starting of a motor is called as starting torque. Starting torque may be greater than running torque in some cases, or it may be lesser.

We know, $T = k_1 E_2 I_2 \cos\phi_2$.

let, R2 = rotor resistance per phase

X2 = standstill rotor reactance

$$Z_2 = \sqrt{(R_2^2 + X_2^2)} \quad = \text{rotor impedence per phase at standstill}$$

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$$

Therefore, starting torque can be given as,

$$Tst = k_1 E_2 \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \times \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}} = \frac{k_1 E_2^2 R_2}{R_2^2 + X_2^2}$$

The constant k1 = 3 / 2πNs

$$Tst = \frac{3}{2\pi Ns} \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Condition For Maximum Starting Torque

If supply voltage V is kept constant, then flux ϕ and E_2 both remains constant. Hence,

$$Tst = k_2 \frac{R_2}{R_2^2 + X_2^2}$$

Hence, it can be proved that maximum starting torque is obtained when rotor resistance is equal to standstill rotor reactance. i.e. $R_2^2 + X_2^2 = 2R_2^2$.

TORQUE UNDER RUNNING CONDITION

$T \propto \phi\ I_r \cos\phi_2$.

where, E_r = rotor emf per phase under running condition = sE_2. (s=slip)

I_r = rotor current per phase under running condition

reactance per phase under running condition will be = sX_2 ,therefore,

$$I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{(R_2^2 + (sX_2)^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

$$T = \frac{k\,\phi\, sE_2\, R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

as, $\phi \propto E_2$.

$$T = \frac{k_1 sE_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi Ns} \frac{sE_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Maximum Torque Under-Running Condition:

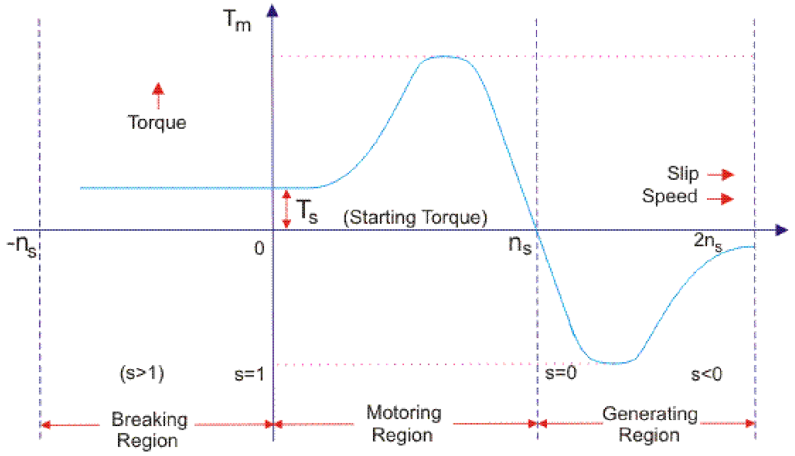
Torque under running condition is maximum at the value of slip (s) which makes rotor reactance per phase equal to rotor resistance per phase.

At standstill, **ce/Phase=RotorReactance/Phaseatstandstill**

Under the condition of maximum starting torque, the rotor power factor angle $\phi_2 = 45°$ and the rotor power factor is 0.707 lagging.

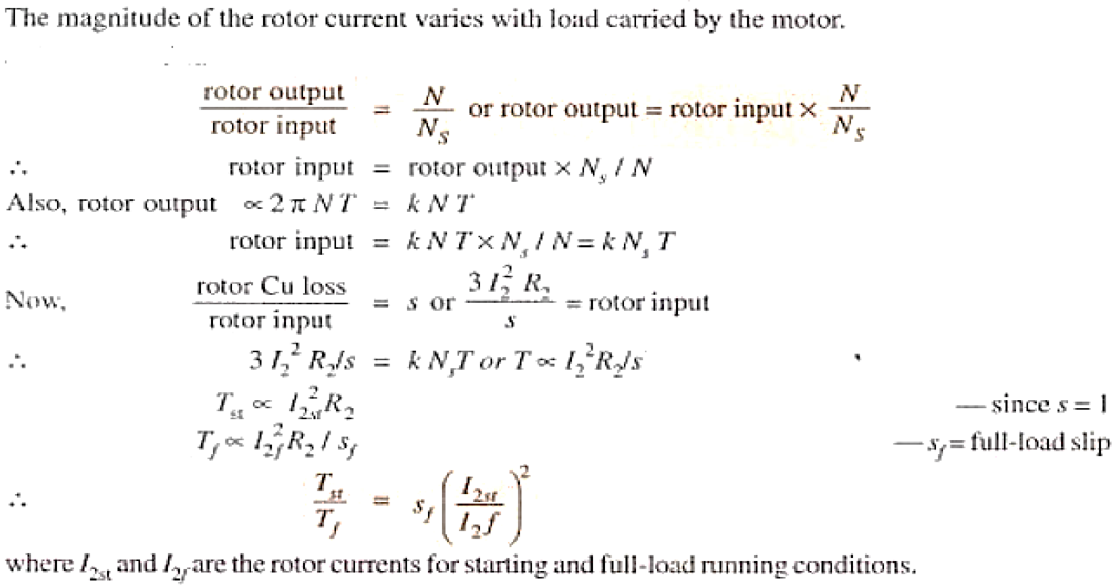
3.6 TORQUE SLIP CHARACTERISTICS

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary. The curve can be described in three modes of operation-



Torque Slip Curve for Three Phase Induction Motor

3.7 DERIVE RELATION BETWEEN FULL LOAD TORQUE AND STARTING TORQUE



The magnitude of the rotor current varies with load carried by the motor.

$$\frac{\text{rotor output}}{\text{rotor input}} = \frac{N}{N_S} \text{ or rotor output} = \text{rotor input} \times \frac{N}{N_S}$$

$$\therefore \quad \text{rotor input} = \text{rotor output} \times N_s / N$$

$$\text{Also, rotor output} \propto 2\pi N T = k N T$$

$$\therefore \quad \text{rotor input} = k N T \times N_s / N = k N_s T$$

$$\text{Now,} \quad \frac{\text{rotor Cu loss}}{\text{rotor input}} = s \text{ or } \frac{3 I_2^2 R_2}{s} = \text{rotor input}$$

$$\therefore \quad 3 I_2^2 R_2/s = k N_s T \text{ or } T \propto I_2^2 R_2/s$$

$$T_{st} \propto I_{2st}^2 R_2 \qquad \text{— since } s = 1$$

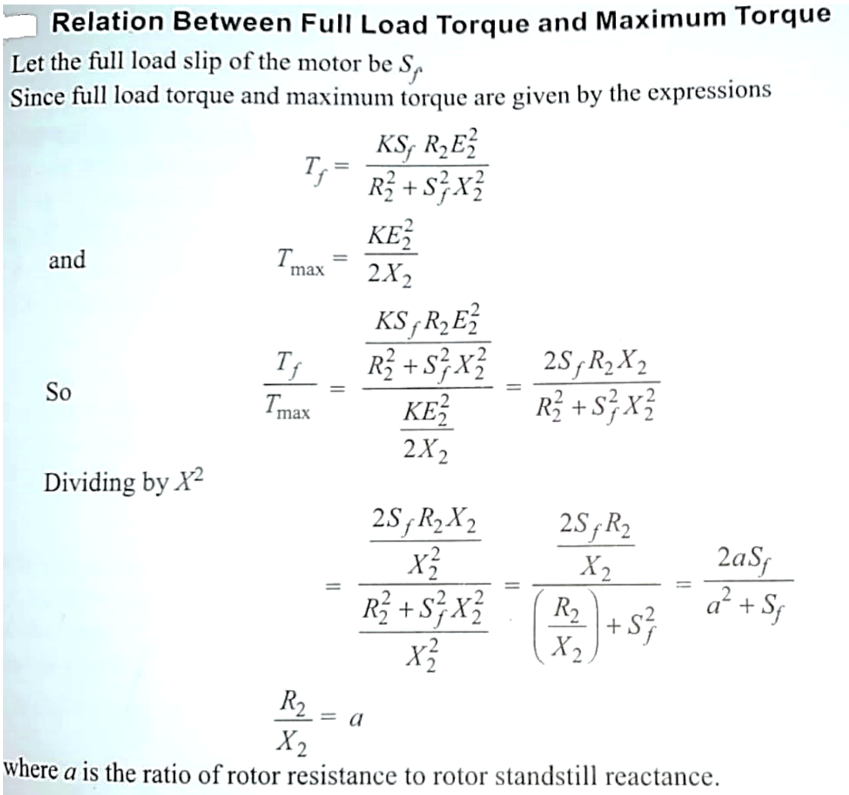
$$T_f \propto I_{2f}^2 R_2 / s_f \qquad \text{— } s_f = \text{full-load slip}$$

$$\therefore \quad \frac{T_{st}}{T_f} = s_f \left(\frac{I_{2st}}{I_2 f} \right)^2$$

where I_{2st} and I_{2f} are the rotor currents for starting and full-load running conditions.

Important –

- Starting Torque of Squirrel Cage Motors – For the squirrel cage motors, the starting torque is very low about 1.5 to 2 times of the full-load value.
- Starting Torque of Wound Rotor Motors – In case of slip ring induction motors, the resistance of the rotor circuit can be increased by inserting external resistance. By adding the proper value of the external resistance (i.e., $R_2 = X_2$), maximum starting torque can be obtained.



Relation Between Full Load Torque and Maximum Torque

Let the full load slip of the motor be S_f

Since full load torque and maximum torque are given by the expressions

$$T_f = \frac{KS_f R_2 E_2^2}{R_2^2 + S_f^2 X_2^2}$$

and
$$T_{\max} = \frac{KE_2^2}{2X_2}$$

So
$$\frac{T_f}{T_{\max}} = \frac{\dfrac{KS_f R_2 E_2^2}{R_2^2 + S_f^2 X_2^2}}{\dfrac{KE_2^2}{2X_2}} = \frac{2S_f R_2 X_2}{R_2^2 + S_f^2 X_2^2}$$

Dividing by X^2

$$= \frac{\dfrac{2S_f R_2 X_2}{X_2^2}}{\dfrac{R_2^2 + S_f^2 X_2^2}{X_2^2}} = \frac{\dfrac{2S_f R_2}{X_2}}{\left(\dfrac{R_2}{X_2}\right) + S_f^2} = \frac{2aS_f}{a^2 + S_f}$$

$$\frac{R_2}{X_2} = a$$

where a is the ratio of rotor resistance to rotor standstill reactance.

PROBLEM

A 100 kW, 3 kV, 50 Hz, 8-pole, star connected induction motor has a star connected slip ring rotor with a turn ratio of 2.5 (stator/rotor). The rotor resistance is 0.2 Ω/phase and its per phase leakage inductance is 4 mH. The stator impedance may be neglected. Find the starting torque on rated voltage with short circuited slip rings?

Solution:

$$K = \frac{\text{Rotor turns/phase}}{\text{Stator turns/phase}} = \frac{1}{2.5} = 0.4$$

$$\text{Rotor resistance/phase referred to stator, } R'_2 = \frac{R_2}{K_2} = \frac{0.2}{0.4^2} = 1.25\Omega$$

The reactance of the rotor circuit is,

$$X_2 = 2\pi fL = 2\pi \times 50 \times (4 \times 10^{-3}) = 1.256\Omega;$$

Rotor reactance/phase referred to stator,

$$X'_2 = \frac{X_2}{K^2} = \frac{1.256}{0.4^2} = 7.85\Omega$$

Now, supply voltage/phase,

$$E_1 = \frac{3000}{\sqrt{3}} = 1732\text{V}$$

Therefore, the starting torque of the motor is,

$$\tau_s = \frac{KE_2^2R_2}{(R_2^2+X_2^2)} = \frac{3}{2\pi N_s} \times \frac{E_1^2R_2'}{(R'_2)^2+(X'2)^2}$$

Where,

$$N_s = \frac{120f}{P} = \frac{120\times 50}{8} = 750\text{RPM} = 12.5\text{rps}$$

And,

$$K = \frac{3}{2\pi N_s}; \text{and} E2 \propto E1$$

$$\therefore \tau_s = \frac{3}{2\pi N_s} \times \frac{E_1^2R_2'}{(R'_2)^2+(X'2)^2}$$

$$= (\frac{3}{2\pi\times 12.5}) \times (\frac{(1732)^2\times 1.25}{1.252+7.85^2})$$

$$= 2267\text{Nm}$$

3.8 ESTABLISH THE RELATIONS BETWEEN ROTOR COPPER LOSS, ROTOR OUTPUT AND GROSS TORQUE AND RELATIONSHIP OF SLIP WITH ROTOR COPPER LOSS.

Stator input=P_1 =stator output + stator losses

The stator output is transferred entirely inductively to the rotor circuit.

P_m =Rotor input – Rotor copper losses

This rotor output is converted into mechanical energy and give rise to gross torque Tg.

Out of this gross torque developed, some is lost due to windage and friction losses in the rotor and the rest appears as the use full or shaft torque Tsh.

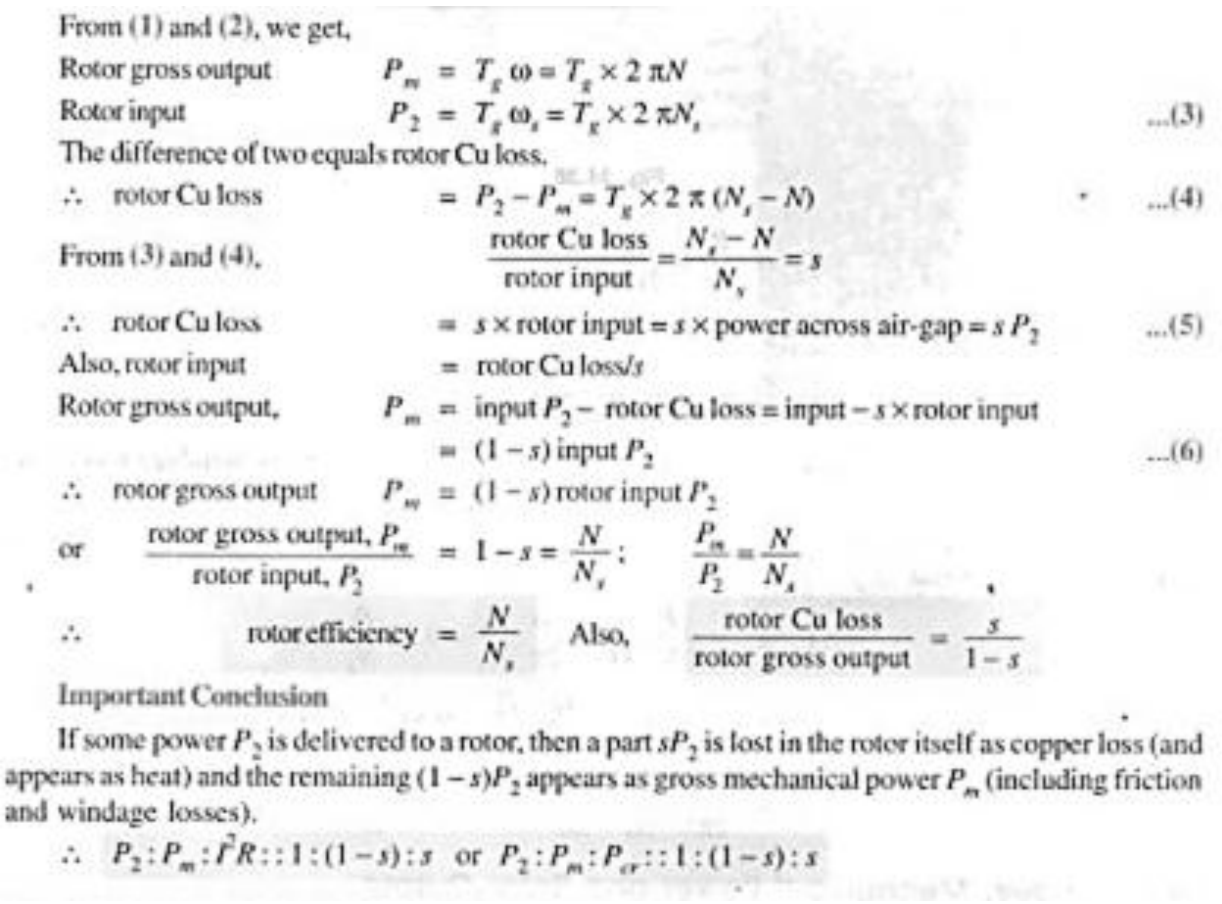
Let Nrps be the actual speed of the rotor and if Tg is in N-m , then

$T_g * 2\pi N$=rotor gross output in watts x Pm

T_g = (rotor gross output in watt x Pm) / 2πN …….N-m …………….(1)

If there were no copper loss in the rotor , then rotor output will equal rotor input and the rotor will run at synchronous speed.

Tg = rotor input P_2 / $2\pi N_s$ .... (2)



From (1) and (2), we get,

Rotor gross output $P_m = T_g \omega = T_g \times 2\pi N$

Rotor input $P_2 = T_g \omega_s = T_g \times 2\pi N_s$ ...(3)

The difference of two equals rotor Cu loss.

$\therefore$ rotor Cu loss $= P_2 - P_m = T_g \times 2\pi (N_s - N)$ ...(4)

From (3) and (4), $\dfrac{\text{rotor Cu loss}}{\text{rotor input}} = \dfrac{N_s - N}{N_s} = s$

$\therefore$ rotor Cu loss $= s \times$ rotor input $= s \times$ power across air-gap $= s P_2$ ...(5)

Also, rotor input = rotor Cu loss/s

Rotor gross output, P_m = input $P_2 -$ rotor Cu loss = input $- s \times$ rotor input

$= (1 - s)$ input P_2 ...(6)

$\therefore$ rotor gross output $P_m = (1 - s)$ rotor input P_2

or $\dfrac{\text{rotor gross output, } P_m}{\text{rotor input, } P_2} = 1 - s = \dfrac{N}{N_s}$; $\dfrac{P_m}{P_2} = \dfrac{N}{N_s}$

$\therefore$ rotor efficiency $= \dfrac{N}{N_s}$ Also, $\dfrac{\text{rotor Cu loss}}{\text{rotor gross output}} = \dfrac{s}{1-s}$

Important Conclusion

If some power P_2 is delivered to a rotor, then a part sP_2 is lost in the rotor itself as copper loss (and appears as heat) and the remaining $(1 - s)P_2$ appears as gross mechanical power P_m (including friction and windage losses).

$\therefore$ $P_2 : P_m : I^2R :: 1 : (1 - s) : s$ or $P_2 : P_m : P_{cr} :: 1 : (1 - s) : s$

Rotor torque:

The torque = force x Radius i.e. T = F . r
For one revolution (2π) i.e. T = 2π.F.r
The power (P) = T x N i.e. P = $2\pi . F . r . N$

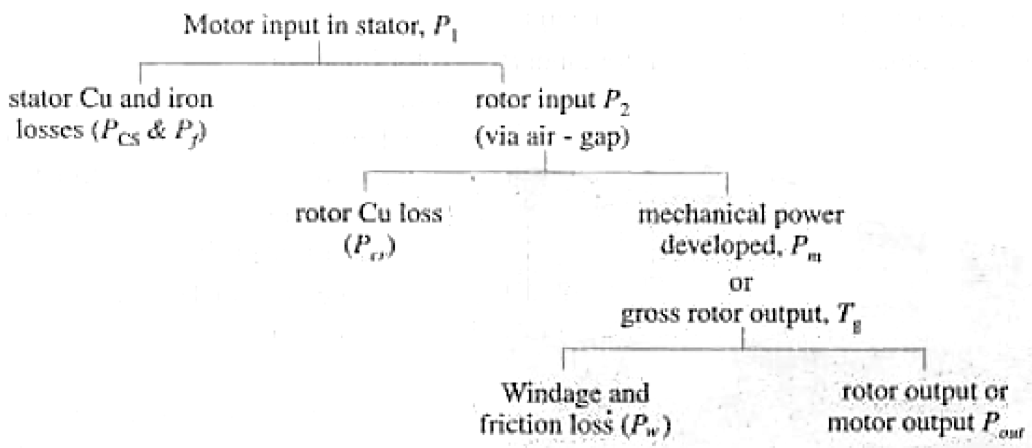
$$P = T.\omega$$

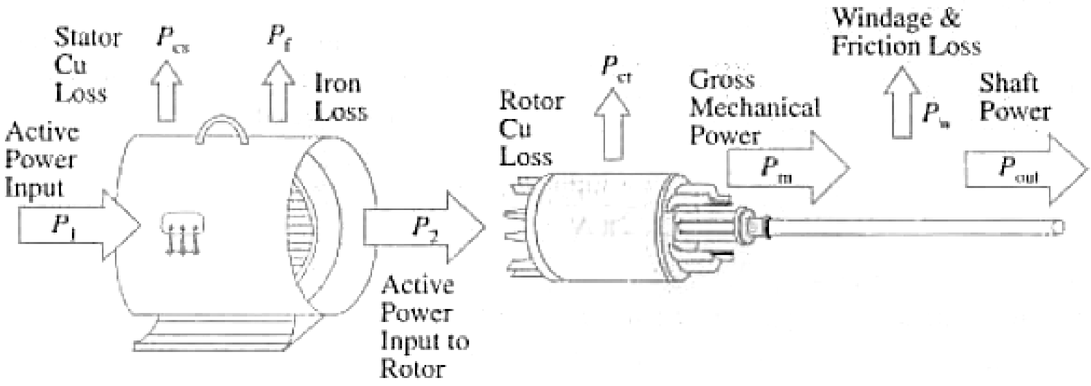
$$T = \frac{P}{\omega} \quad \text{where } P = E.I\,COS\theta$$

$$\text{i.e. } T = \frac{1}{\omega} E.I.COS\theta$$

$$\text{For three phase } T = 3.\frac{1}{\omega} E.I.COS\theta$$

Power Stage Diagram





$$T_g = \frac{P_m}{\omega} = \frac{P_m}{2\pi N}$$ ... in terms of rotor output

The shaft torque T_{sh} is due to output power P_{out} which is less than P_m because of rotor friction and windage losses.

$$\therefore \qquad T_{sh} = P_{out}/\omega = P_{out}/2\pi N$$

The difference between T_g and T_{sh} equals the torque lost due to friction and windage loss in the motor.

In the above expressions, N and N_s are in r.p.s. However, if they are in r.p.m., the above expressions for motor torque become

$$T_g = \frac{P_2}{2\pi N_s/60} = \frac{60}{2\pi}\cdot\frac{P_2}{N_s} = 9.55\frac{P_2}{N_s} \text{ N-m}$$

$$= \frac{P_m}{2\pi N/60} = \frac{60}{2\pi}\cdot\frac{P_m}{N} = 9.55\frac{P_m}{N} \text{ N-m}$$

$$T_{sh} = \frac{P_{out}}{2\pi N/60} = \frac{60}{2\pi}\cdot\frac{P_{out}}{N} = 9.55\frac{P_{out}}{N} \text{ N-m}$$

PROBLEM- *A 400 V, 4-pole, 3-phase, 50-Hz induction motor has a rotor resistance and reactance per phase of 0.01 Ω and 0.1 Ω respectively. Determine (a) maximum torque in N-m and the corresponding slip (b) the full-load slip and power output in watts, if maximum torque is twice the full-load torque. The ratio of stator to rotor turns is 4.*

Solution. Applied voltage/phase $E_1 = 400/\sqrt{3} = 231$ V

Standstill e.m.f. induced in rotor, $E_2 = KE_1 = 231/4 = 57.75$ V

(*a*) Slip for maximum torque, $s_m = R_2/X_2 = 0.01/0.1 = 0.1$ or 10%

$$T_{max} = \frac{3}{2\pi N_S} \times \frac{E_2^2}{2\,X_2}$$

$$N_s = 120 \times 50/4 = 1500 \text{ r.p.m.} = 25 \text{ r.p.s.}$$

$$\therefore \quad T_{max} = \frac{3}{2\pi \times 25} \times \frac{57.75^2}{2 \times 0.1} = 320 \text{ N-m}$$

(*b*)

$$\frac{T_f}{T} = \frac{2as_f}{a^2 + s^2} = \frac{1}{2}; \text{ Now, } a = R_2/X_2 = 0.01/0.1 = 0.1$$

$$\therefore \quad 2 \times 0.1 \times s_f/(0.1^2 + s_f^2) = 1/2 \qquad \therefore\ s_f = 0.027 \text{ or } 0.373$$

Since $s_f = 0.373$ is not in the operating region of the motor, we select $s_f = 0.027$.

Hence, $s_f = 0.027.$ $N = 1500\,(1 - 0.027) = 1459.5$ r.p.m.

Full-load torque $T_f = 320/2 = 160$ N-m

F.L. Motor output $= 2\,\pi\,N\,T_f/60 = 2\,\pi \times 1459.5 \times 160/60 = 24{,}454$ W

PROBLEM- *A 6-pole, 50-Hz, 3-phase, induction motor running on full-load with 4% slip develops a torque of 149.3 N-m at its pulley rim. The friction and windage losses are 200 W and the stator Cu and iron losses equal 1,620 W. Calculate (a) output power (b) the rotor Cu loss and (c) the efficiency at full-load.*

Solution. $N_s = 120 \times 50/6 = 1{,}000$ r.p.m; $N = (1 - 0.04) \times 1{,}000 = 960$ r.p.m.

Out put power $= T_{sh} \times 2\,\pi N = 2\,\pi \times (960/60) \times 149.3 = 15$ kW

Now, output $= 15{,}000$ W

Friction and windage losses $= 200$ W ; Rotor gross output $= 15{,}200$ W

$$\frac{P_m}{P_2} = \frac{N}{N_S} \quad \therefore \text{ rotor input } P_2 = 15{,}200 \times 1{,}000/960 = 15{,}833 \text{ W}$$

(*b*) $\therefore$ rotor Cu loss $= 15{,}833 - 15{,}200 = 633$ W

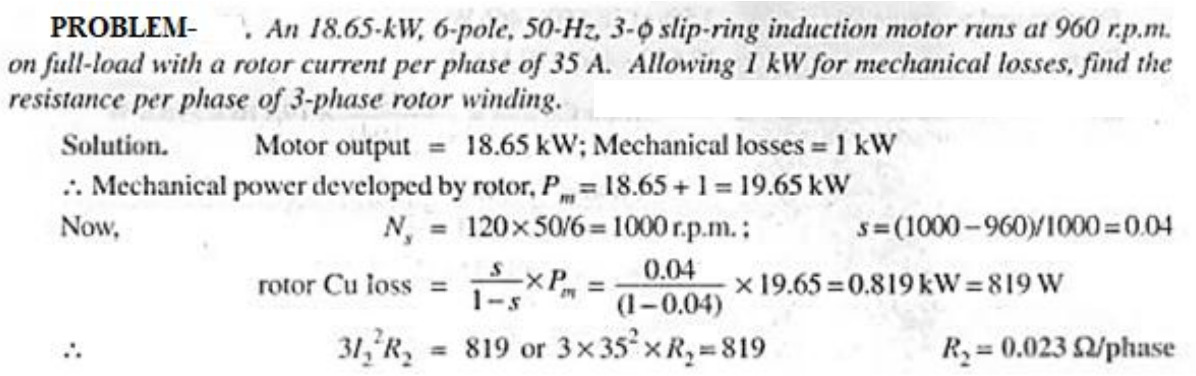
$$\left(\text{rotor Cu loss is given by : } \frac{\text{rotor Cu loss}}{\text{rotor output}} = \frac{s}{1-s}\right)$$

(*c*) stator output $=$ rotor input $= 15{,}833$ W

Stator Cu and iron losses $= 1{,}620$ W

$\therefore$ Stator input $P_1 = 15{,}833 + 1{,}620 = 17{,}453$ W

overall efficiency, $\eta = 15{,}000 \times 100/17{,}453 = 86\%$



PROBLEM- . *An 18.65-kW, 6-pole, 50-Hz, 3-φ slip-ring induction motor runs at 960 r.p.m. on full-load with a rotor current per phase of 35 A. Allowing 1 kW for mechanical losses, find the resistance per phase of 3-phase rotor winding.*

Solution. Motor output = 18.65 kW; Mechanical losses = 1 kW

∴ Mechanical power developed by rotor, $P_m = 18.65 + 1 = 19.65$ kW

Now, $N_s = 120\times 50/6 = 1000$ r.p.m. ; $s = (1000-960)/1000 = 0.04$

rotor Cu loss $= \frac{s}{1-s}\times P_m = \frac{0.04}{(1-0.04)}\times 19.65 = 0.819$ kW = 819 W

∴ $3I_2^2R_2 = 819$ or $3\times 35^2\times R_2 = 819$ $R_2 = 0.023\ \Omega$/phase

3.9 METHODS OF STARTING AND DIFFEERENT TYPES OF STATER USED FOR 3 PHASE INDUCTION MOTOR :

A 3-phase induction motor is theoretically self-starting. But in case 3-phase induction motors employ a starting method not to provide a starting torque at the rotor, but because of the following reasons;

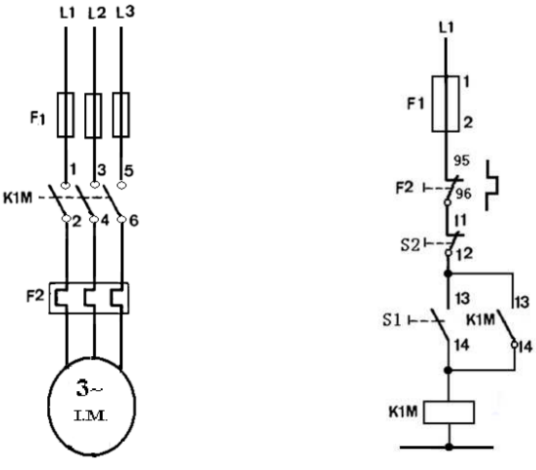
1) Reduce heavy starting currents and prevent motor from overheating.
2) Provide overload and no-voltage protection.

There are many methods in use to start 3-phase induction motors:

i. Direct On-Line Starter (DOL)
ii. Star-Delta Starter
iii. Auto Transformer Starter
iv. Rotor Impedance Starter

DIRECT ON-LINE STARTER (DOL)

The Direct On-Line (DOL) starter is the simplest and the most inexpensive of all starting methods and is usually used for squirrel cage induction motors. It directly connects the contacts of the motor to the full supply voltage. The starting current is very large, normally 6 to 8 times the rated current. In order to avoid excessive voltage drops in the supply line due to high starting currents, the DOL starter is used only for motors with a rating of less than 5KW. There are safety mechanisms inside the DOL starter which provides protection to the motor as well as the operator of the motor.



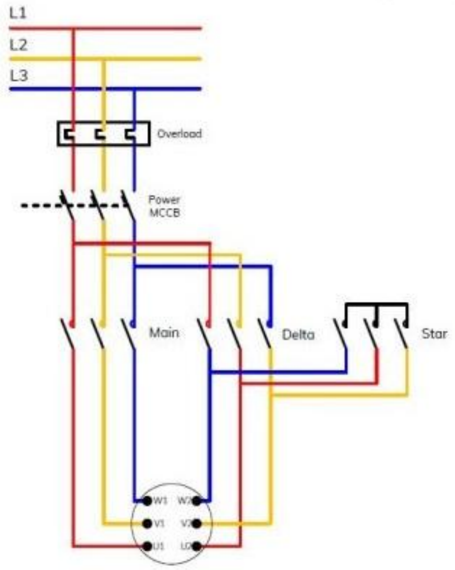
Power Circuit Control Circuit

Figure: power and control circuits of three phase induction motor with DOL starter.

STAR-DELTA STARTER

The star delta starting is a very common type of starter and extensively used, compared to the other types of the starters. This method used reduced supply voltage in starting. Figure shows the connection of a 3 phase induction motor with a star-delta starter. The method achieved low starting current by first connecting the stator winding in star configuration, and then after the motor reaches a certain speed, throw switch changes the winding arrangements from star to delta configuration

In case of star Connection, $V_{ph} = \frac{V_L}{\sqrt{3}}$

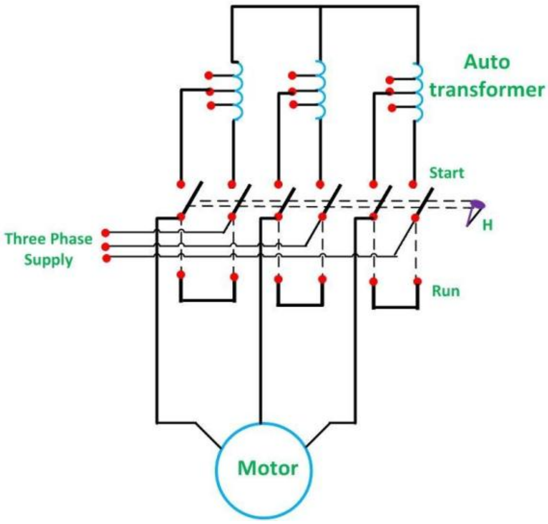


(Fig : STAR-DELTA STASTER)

AUTO TRANSFORMER STARTER

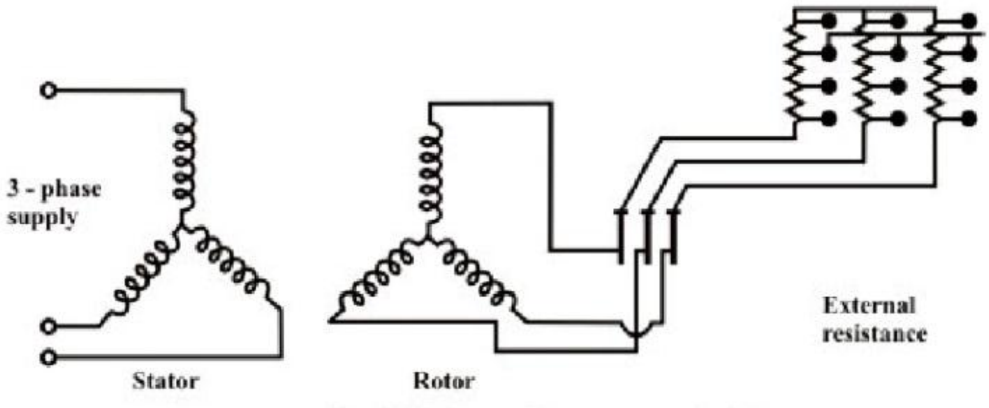
The operation principle of auto transformer method is similar to the star delta starter method. The starting current is limited by (using a three phase auto transformer) reduce the initial stator applied voltage.

The auto transformer starter is more expensive, more complicated in operation and bulkier in construction when compared with the star – delta starter method. But an auto transformer starter is suitable for both star and delta connected motors, and the starting current and torque can be adjusted to a desired value by taking the correct tapping from the auto transformer.



ROTOR RESISTANCE STARTERS

The easiest method of starting wound rotor (slip-ring) induction motors is to connect some extra resistance in the rotor circuit as shown in fig. Connection of extra resistance in the rotor circuit decreases the starting current and at the same time increases the starting torque. As the motor starts rotating the extra resistance is gradually cut out.



Rotor resistance Starter

3.10 EXPLAIN SPEED CONTROL BY VOLTAGE CONTROL, ROTOR RESISTANCE CONTROL, POLE CHANGING, FREQUENCY CONTROL METHODS:

1. V / f control or frequency control –

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed. In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \text{ or } V = 4.44\phi K.T.f \text{ or } \phi = \frac{V}{4.44KTf}$$

Where K is the winding constant,
T is the number of turns per phase
f is frequency.

Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , φ constant and it is only possible if we change voltage .

i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/ f as constant. Hence its name is V/ f method.

2. Controlling supply voltage:

The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX)^2$ is very very small as compared to R_2 . So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

Since rotor resistance, R_2 is constant so the equation further reduces to

$$T \propto sE_2^2$$

We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$.

From the equation above it is clear that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increases the motor will run at reduced speed .

3. Rotor resistance speed control

If the resistance of the motor is increased, this method of speed control is very simple. It is possible to have a large starting torque, low starting current, and large values of the pullout torque at a small value of slip.

The major disadvantage of the rotor resistance control method is that the efficiency is low because of the additional losses present in the resistors connected within the rotor circuit.

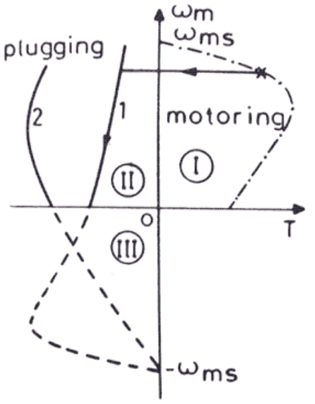
4. Pole Changing Method

This method of controlling the speed by pole changing is used mainly for cage motor only because the cage rotor automatically develops a number of poles, which is equal to the poles of the stator winding.

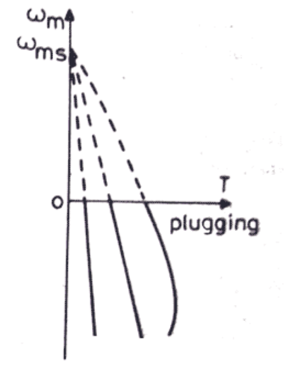
3.11. PLUGGING AS APPLICABLE TO THREE PHASE INDUCTION MOTOR :

- Plugging is the method of inducing negative torque in the rotor of an induction motor to rapidly bring its speed of rotation to zero.
- This is done by reversing the supply connection at the stator terminals.
- Reverses the current flow and the magnetic field in the armature which tends to generate a torque in the reverse direction thereby slowing the motor down, stopping it and forcing it to rotate in the reverse direction.
- During plugging the slip is (2 – s), if the original slip of the running motor is s, then it can be shown in the following way.

$$S_n = \frac{-\omega_{ms} - \omega m}{-\omega_{ms}} = 2 - s$$



(a) 1: natural characteristic
2: with external resistance in rotor



(b) Plugging in IV quadrant with large external resistance in rotor

3.12. DESCRIBE DIFFERENT TYPES OF MOTOR ENCLOSURES

Open-protected type

The enclosure provides free access to air and also provides sufficient mechanical protection. This type of enclosure is suitable where there is no unusual exposure to dust particles or dampness.

Semi-enclosed type or screen protected type

In order to give additional protection to the motor, metal grids or perforated covers are provided as shown in the figure. This will prevent particles from being drawn inside which may cause a short circuit or another type of damage to the motor.

Totally enclosed type

In the totally closed type motor enclosure design, there will be no free circulation of air between the inside and outside of the motor. However, the enclosure is not necessarily “airtight”. A totally closed type motor enclosure is shown in the figure. This type of enclosure is used in motors installed in mill and factories where there are dust and moisture in the environment.

Totally-enclosed fan-cooled type

In a totally-enclosed machine, an efficient method of cooling can be provided by a fan, driven by the motor itself, blowing external air over the cooling surfaces and through the cooling passages. This type of enclosure is used in a dirty, dusty, and corrosive environment.

Pipe-ventilated or duct-ventilated type

In this type of enclosure, there is a continuous supply of fresh ventilating air. The frame I so arranged that ventilating are conveyed to and from the machine through pipes or ducts attached to the enclosing case as shown in the figure.

3.13. EXPLAIN PRINCIPLE OF INDUCTION GENERATOR AND STATE ITS APPLICATIONS

An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce electric power.

Induction generators operate by mechanically turning their rotors faster than synchronous speed. A regular AC induction motor usually can be used as a generator, without any internal modifications.

Applications

Because they can recover energy with relatively simple controls, induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure.

Limitations

When the load current exceeds the capability of the generator to supply both magnetization reactive power and load power the generator will immediately cease to produce power.

Induction generators are particularly suitable for wind generating stations as in this case speed is always a variable factor. Unlike synchronous motors, induction generators are load-dependent and cannot be used alone for grid frequency control.

SHORT QUESTIONS WITH ANSWER

Q1.What is slip of a 3 phase IM ? (2019-S)

Ans – Slip of a 3 phase IM is defined as the ratio between slip speed and synchronous speed .

It is calculated in percentage

Mathematically Percentage of Slip= ((Ns-N) / Ns) * 100

Q2. Why do you mean by is called asynchronous speed ?

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

$$N_S = \frac{120*f}{P}$$

Q3.Why rotor slots of squirrel cage IM are skewed slightly ? (2011-W)

Ans- The rotor slot of S.C.I.M are skewed slightly in order to reduce magnetic harmonics. It also helps in reducing locking tendency of the rotor.

Q4. How can the direction of rotation of 3 phase IM be reversed ? (2012/2018-W)

Ans- The direction of rotion of 3 phase IM can be reversed by inter changing any two of the line terminals.

Q5.What do you mean by single phasing of an 3 phase IM ? (2012-W)

Ans- Single phasing of an 3 phase IM is defined as the opening of one wire or terminal or phase of 3 phase circuit.

LONG QUESTIONS

Q1. Explain the torque slip characteristics of a 3 phase IM. (2019-S(N))

Q2. Describe Plugging applicable to Three Phase IM. (2019-S(N))

Q3.A 20 KW, 4 pole , 50 Hz , 3 Phase IM has friction and windage loss of 3 percent of the Output. The full load speed of the motor is 1440 rpm. Find for full load, (2014-W)

(a) The rotor copper loss.
(b) The rotor input.
(c) Shaft torque.
(d) Gross electromagnetic torque

Q4. Derive an expression for starting torque of a slip ring IM. Find the condition for maximum torque. (2019-W)

CHAPTER-4
SINGLE PHASE INDUCTION MOTOR

Learning Objectives:

4.1. Explain Ferrari's principle.
4.2. Explain double revolving field theory and Cross-field theory to analyze starting torque of 1-phase induction motor.
4.3. Explain Working principle, Torque speed characteristics, performance characteristics and application of following single phase motors.
4.3.1. Split phase motor.
4.3.2. Capacitor Start motor.
4.3.3. Capacitor start, capacitor run motor.
4.3.4. Permanent capacitor type motor.
4.3.5. Shaded pole motor.
4.4. Explain the method to change the direction of rotation of above motors.

4.1 EXPLAIN FERRARIE'S PRINCIPLE:

Galileo Ferraris, (Italy), Italian physicist who established the basic principle of the induction motor, which is now the principal device for the conversion of electrical power to mechanical power.

Ferraris devised a motor using electromagnets at right angles and powered by alternating currents that were 90° out of phase, thus producing a revolving magnetic field. The direction of the motor could be reversed by reversing the polarity of one of the currents. The principle made possible the development of the asynchronous, self-starting induction motor that is widely used today.

4.2 EXPLANATION OF DOUBLE REVOLING FIELD THEORY & CROSS FIELD THEORY :

According to double field revolving theory, we can resolve any alternating quantity into two components. Each component has a magnitude equal to the half of the maximum magnitude of the alternating quantity, and both these components rotate in the opposite direction to each other.

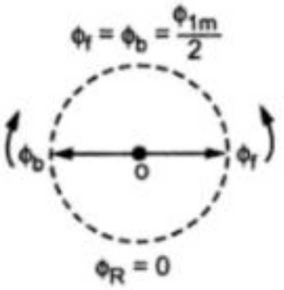
For example – a flux, φ can be resolved into two components

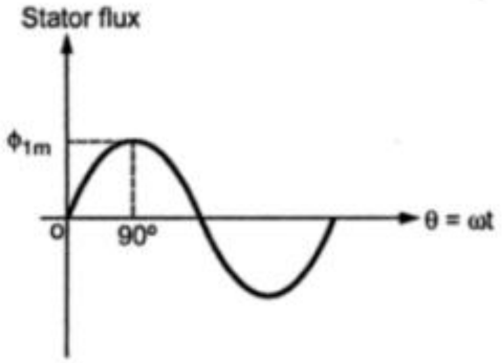
$$\frac{\phi_m}{2} \; and \; -\frac{\phi_m}{2}$$

According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude $\varphi_m/2$. Each of these components will rotate in the opposite direction, with the synchronous speed, N_s.

Let us call these two components of flux as forwarding component of flux, φ_f and the backward component of flux, φ_b. The resultant of these two components of flux at any instant of time gives the value of instantaneous stator flux at that particular instant.

$$i.e. \phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \; or \; \phi_r = \phi_f + \phi_b$$





Now at starting condition, both the forward and backward components of flux are exactly opposite to each other. Also, both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at the starting condition is zero. So, the single phase induction motors are not self-starting motors.

If the rotor is given an initial rotation by some auxiliary means in either directions, then the torque due to the rotating magnetic field acting in the either direction of initial rotation will be more than the torque due to the other rotating magnetic field. Thus, the motor develops a net torque in the same direction as the initial rotation. Therefore, the motor will keep running in the same direction of the initial rotation.

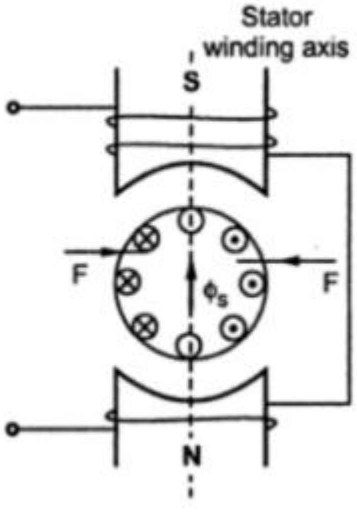
CROSS FIELD THEORY

Consider a single phase induction motor with standstill rotor as shown in following figure. The direction of the rotor current is as shown in the Fig. The direction of rotor current is so as to oppose the cause producing it, which is stator flux ϕs.

Now Fleming's left hand rule can be used to find the direction of the force experienced by the rotor conductors.

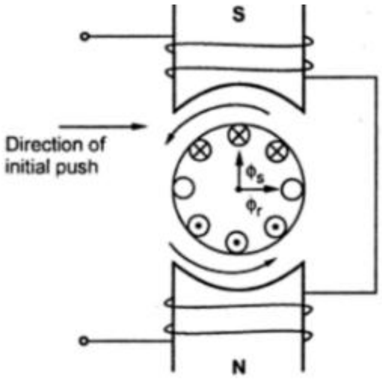
It can be seen the conductors on left experience force from left to right while conductors on right experience force from right to left. Thus overall, the force experienced by the rotor is zero.

Hence no torque exists on the rotor and rotor cannot start rotating.



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 in 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 Fleming's right hand rule and this e.m.f. is in phase with the stator flux ϕs. The direction of e.m.f. is shown in following figure.



This e.m.f. is denoted as E_2. This e.m.f. circulates current through rotor which is I_2. This current produces its own flux called rotor flux ϕr. This axis of ϕr is at 90° to the axis of stator flux hence this rotor flux is called cross-field. Due to very high rotor reactance, the rotor current I_2 and ϕr lags the rotational e.m.f. by almost 90 degree. Thus ϕr is in quadrature with ϕs in space and lags ϕs by 90 degree in time phase. Such two fluxes produce the rotating magnetic field.

4.3. EXPLAIN WORKING PRINCIPLE, TORQUE SPEED CHARACTERISTICS, PERFORMANCE CHARACTERISTICS AND APPLICATION OF FOLLOWING SINGLE PHASE MOTORS:

When we apply a single phase AC supply to the stator winding of single phase induction motor, the alternating current starts flowing through the stator or main winding. This alternating current produces an alternating flux called main flux.

This main flux also links with the rotor conductors and hence cut the rotor conductors.

According to the Faraday's law of electromagnetic induction, emf gets induced in the rotor.

As the rotor circuit is closed one so, the current starts flowing in the rotor. This current is called the rotor current.

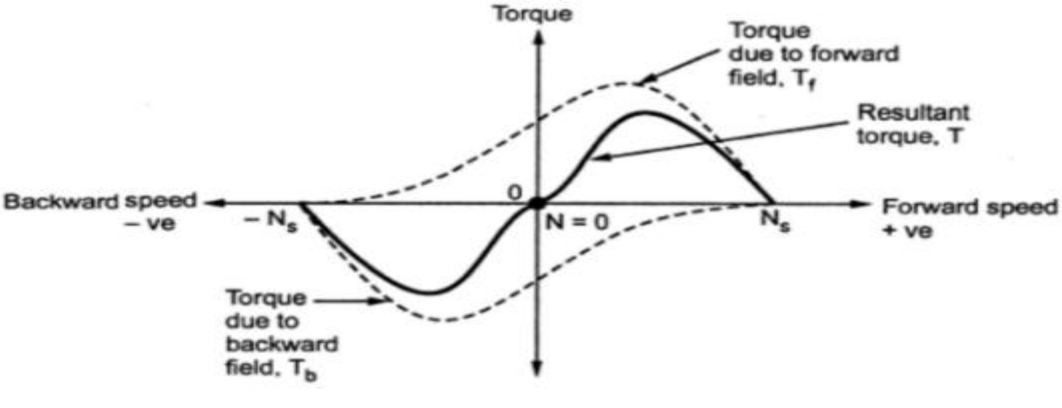
This rotor current produces its flux called rotor flux. Since this flux is produced due to the induction principle so, the motor working on this principle got its name as an induction motor. Now there are two fluxes one is main flux, and another is called rotor flux. These two fluxes produce the desired torque which is required by the motor to rotate.

TORQUE SPEED CHARACTERISTICS

The two oppositely directed torques and the resultant torque can be shown effectively with the help of torque-speed characteristics. It is shown in following figure.

It can be seen that at start N = 0 and at that point resultant torque is zero.

So single phase motors are not self starting. However if the rotor is given an initial rotation in any direction, the resultant average torque increases in the direction in which rotor is initially rotated. And motor starts rotating in that direction. But in practice it is not possible to give initial torque to rotor externally hence some modifications are done in the construction of single phase induction motors to make them self starting.



METHODS FOR MAKING SINGLE PHASE INDUCTION AS SELF STARTING MOTOR:

A single-phase induction motors are not self-starting because the produced stator flux is alternating in nature and at the starting, the two components of this flux cancel each other and hence there is no net torque. The solution to this problem is that if we make the stator flux rotating type, rather than alternating type, which rotates in one particular direction only. Then the induction motor will become self-starting.

Depending upon the methods for making a motor as Self Starting Motor, there are mainly four **types of single phase induction motor** namely,

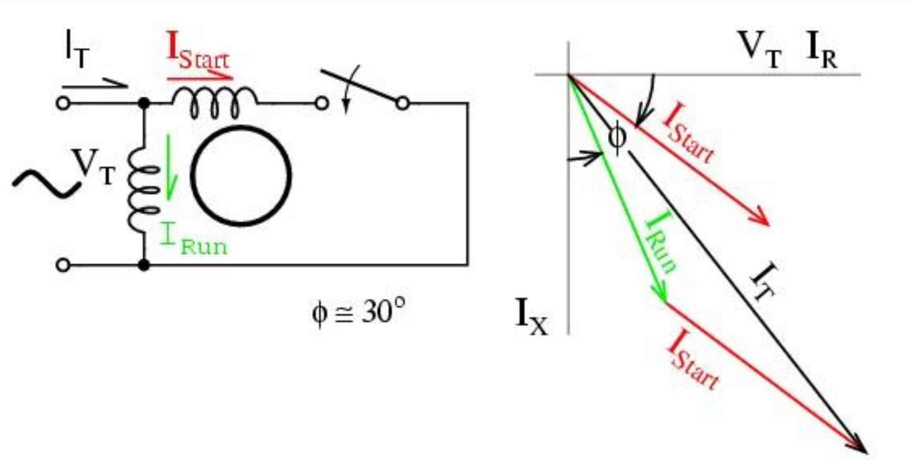
1. Split phase induction motor,
2. Capacitor start inductor motor,
3. Capacitor start capacitor run induction motor,
4. Shaded pole induction motor.

4.3.1. SPLIT PHASE INDUCTION MOTOR :

In addition to the main winding or running winding, a single-phase induction motor's stator carries another winding called auxiliary winding or starting winding. A centrifugal switch is connected in series with auxiliary winding. This switch aims to disconnect the auxiliary winding from the main circuit when the motor attains a speed up to 75 to 80% of the synchronous speed.

- I_{run} is the current flowing through the main or running winding,
- I_{start} is the current flowing in starting winding,
- V_T is the supply voltage.

The starting winding is highly resistive so, the current flowing in the starting winding lags behind the applied voltage by a very small angle and the running winding is highly inductive in nature so, the current flowing in running winding lags behind applied voltage by a large angle.



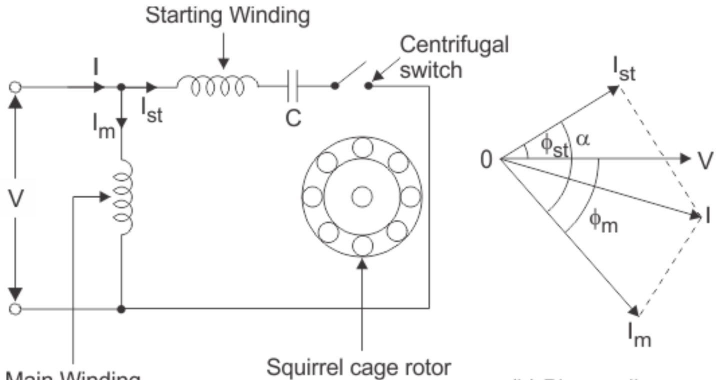
The resultant of these two current is I_T—the resultant of these two current produce rotating magnetic field which rotates in one direction. In a split-phase induction motor**,** the starting and main current get split from each other by some angle, so this motor got its name as a split-phase induction motor.

Applications of Split Phase Induction Motor :

These motors are used in fans, blowers, centrifugal pumps, washing machines, grinders, lathes, air conditioning fans, etc. These motors are available in size ranging from 1/20 to 1/2 KW.

4.3.2. Capacitor Start IM /
4.3.3 Capacitor Start IM & Capacitor Start Capacitor Run IM :

The working principle of capacitor-start inductor motors is almost the same as capacitor-start capacitor-run induction motors.



(b) Phasor diagram

In capacitor start inductor motor **and** capacitor start capacitor run induction motor, we are using two winding, the main winding, and the starting winding.

With starting winding, we connect a capacitor, so the current flowing in the capacitor, i.e., I_{st} leads the applied voltage by some angle, φ_{st}. The running winding is inductive in nature so, the current flowing in running winding lags behind applied voltage by an angle, φ_m.

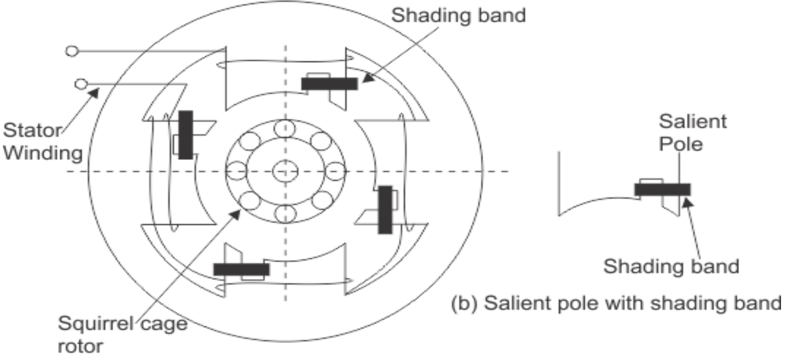
In the case of capacitor start induction motor, the centrifugal switch is provided to disconnect the starting winding when the motor attains a speed up to 75 to 80% of the synchronous speed but in the case of capacitor start capacitors run induction motor, there is no centrifugal switch.

Application of Capacitor Start IM and Capacitor Start Capacitor Run IM :

These motors have high starting torque; hence they are used in conveyors, grinders, air conditioners, compressors, etc. They are available up to 6 kW.

4.3.5. SHADED POLE SINGLE PHASE INDUCTION MOTORS :

The stator of the shaded pole single-phase induction motor has salient or projected poles. These poles are shaded by a copper band or ring, which is inductive in nature.
The poles are divided into two unequal halves. The smaller portion carries the copper band and is called the shaded portion of the pole.
When a single-phase supply is given to a shaded pole induction motor's stator, an alternating flux is produced. This change of flux induces emf in the shaded coil.



(b) Salient pole with shading band

(a) 4-pole shaded pole construction

Since this shaded portion is short-circuited, the current is produced in it in such a direction to oppose the main flux.
The flux in the shaded pole lags behind the flux in the unshaded pole. The phase difference between these two fluxes produces resultant rotating flux.

The advantages of shaded pole induction motor are :

1. Very economical and reliable.
2. Construction is simple and robust because there is no centrifugal switch.

The disadvantages of shaded pole induction motor are :

1. Low power factor.
2. The starting torque is very poor.
3. The efficiency is very low as the copper losses are high due to the presence of the copper band.
4. The speed reversal is also difficult and expensive as it requires another set of copper rings.

Applications of Shaded Pole Motor :

Due to their low starting torques and reasonable cost, these motors are mostly employed in small instruments, hairdryers, toys, record players, small fans, electric clocks, etc. These motors are usually available in a range of 1/300 to 1/20 KW.

4.4 EXPLAIN THE METHOD TO CHANGE THE DIRECTION OF ROTATION OF ABOVE MOTORS :

To reverse rotation on a single phase capacitor start motor, you will need to reverse the polarity of the starter winding. This will cause the magnetic field to change directions, and the motor will follow.

The motor consist of two windings namely main winding and starter winding. These two windings produces rotating magnetic field when connected to power supply. So to reverse the direction of rotation we have to change the direction of rotating magnetic field. This can be done by changing polarity of supply voltage of either main winding or starting winding but not both.

SHORT QUESTIONS WITH ANSWER:

Q1.What type of rotor used in a single phase I.M.?

Ans: In a single Phase IM squirrel cage type rotor is used.

Q2.How a single phase IM is made self-starting ?

Or, why sta ting winding is needed for single phase IM ? (W-2011) (W-2016) (W-2020)

Ans- A starting winding is needed for single phase IM due to following reason,

(a) With one winding , a single phase IM creates pulsating torque for which resultant torque become zero.
(b) Since this starting winding maes 90 degree angle with the running winding , so two filed which are created by two windings will also flow with 90 degree apart.

Q3.Is a single phase induction motor is self-starting?

Ans: No, a single phase IM is not self-starting.

Q3. In which direction does a shaded pole induction motor run?

Ans: A shaded pole motor runs from unshaded region to shaded region.

Q4.How can we reverse the direction of rotation of a capacitor start induction motor? (W-2019)

Ans: We can reverse the direction of rotation of a capacitor start induction motor by reversing either the starting or running leads, but both should not be reversed.

LONG QUESTIONS :

Q1. Which winding has more resistance in a single phase IM Explain in brief ? (W-2012)

Q2. Why single phase Induction Motor is not self-starting ? Explain it by using any theory you have studied ? (W-2012/2014)

Q3. Explain with vector diagram how a rotating field is created by a single phase stator winding ? (W-2014)

Q4. Explain Ferrari’s principle for Single Phase IM. (W-2017)

Q5. Write short notes on shaded pole type motor. (W-2018)

CHAPTER- 5

(COMMUTATOR MOTOR)

Learning Resources :

5.1. Construction, working principle, running characteristic and application of single phase series motor.

5.2. Construction, working principle and application of Universal motors.

5.3. Working principle of Repulsion start Motor, Repulsion start Induction run motor, Repulsion Induction motor.

5.1. Construction, working principle, running characteristic and application of single phase series motor :

AC commutator motors, like comparable DC motors, have higher starting torque and higher speed than AC induction motors.

The series motor operates well above the synchronous speed of a conventional AC motor. AC commutator motors may be either single-phase or poly-phase. The single-phase AC version suffers a double line frequency torque pulsation, not present in the poly phase motor.

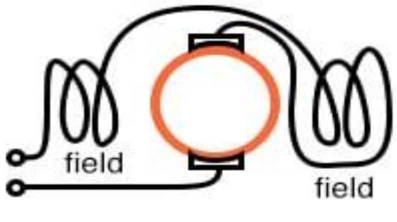
Since a commutator motor can operate at a much higher speed than an induction motor, it can output more power than a similar size induction motor. However, commutator motors are not as maintenance-free as induction motors, due to brush and commutator wear.

SINGLE PHASE SERIES MOTOR

If a DC series motor equipped with a laminated field is connected to AC, the lagging reactance of the field coil will considerably reduce the field current. While such a motor will rotate, the operation is marginal.

While starting, armature windings connected to commutator segments shorted by the brushes look like shorted transformer turns to the field. This results in considerable arcing and sparking at the brushes as the armature begins to turn.

This is less of a problem as speed increases, which shares the arcing and sparking between commutator segments The lagging reactance and arcing brushes are only tolerable in very small uncompensated series AC motors operated at high speed. Series AC motors smaller than hand drills and kitchen mixers may be uncompensated. (Figure below)

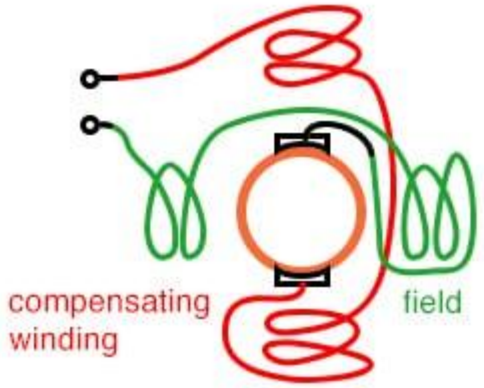


Compensated Series Motor

The arcing and sparking is mitigated by placing a *compensating winding* the stator in series with the armature positioned so that its magnetomotive force (mmf) cancels out the armature AC mmf.

A smaller motor air gap and fewer field turns reduce lagging reactance in series with the armature improving the power factor. All but very small AC commutator motors employ compensating windings.

Motors as large as those employed in a kitchen mixer, or larger, use compensated stator windings.



5.2. Construction, working principle and application of Universal motors.

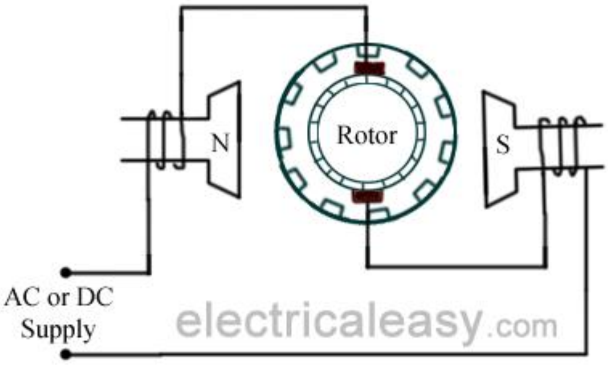
It is possible to design small (under 300 watts) *universal motors* which run from either DC or AC. Very small universal motors may be uncompensated. Larger higher speed universal motors use a compensating winding.

A motor will run slower on AC than DC due to the reactance encountered with AC. However, the peaks of the sine waves saturate the magnetic path reducing total flux below the DC value, increasing the speed of the "series" motor.

Thus, the offsetting effects result in a nearly constant speed from DC to 60 Hz. The small line operated appliances, such as drills, vacuum cleaners, and mixers, requiring 3000 to 10,000 rpm use universal motors.

Though, the development of solid-state rectifiers and inexpensive permanent magnets is making the DC permanent magnet motor a viable alternative.

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 cunt 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.

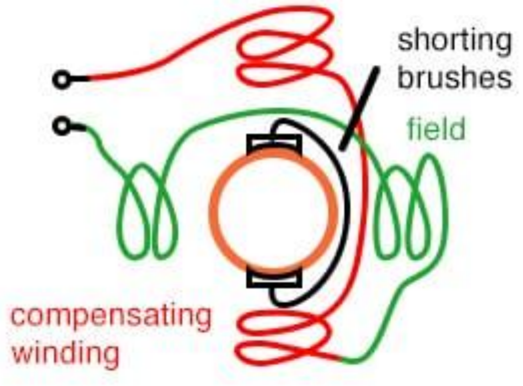
Applications Of Universal Motor

- 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

5.3. Working principle of Repulsion start Motor, Repulsion start Induction run motor, Repulsion Induction motor :

A repulsion motor consists of a field directly connected to the AC line voltage and a pair of shorted brushes offset by 15°to 25° from the field axis. The field induces a current flow into the shorted armature whose magnetic field opposes that of the field coils.

Speed can be controlled by rotating the brushes with respect to the field axis. This motor has superior commutation below synchronous speed, inferior commutation above synchronous speed. The low starting current produces high starting torque.



Repulsion AC motor

Repulsion Start Induction Motor

When an induction motor drives a hard starting load like a compressor, the high starting torque of the repulsion motor may be put to use. The induction motor rotor windings are brought out to commutator segments for starting by a pair of shorted brushes.

At near running speed, a centrifugal switch shorts out all commutator segments, giving the effect of a squirrel cage rotor. The brushes may also be lifted to prolong brush life. Starting torque is 300% to 600% of the full speed value as compared to under 200% for a pure induction motor.

Repulsion Motor Applications

The applications of repulsion motors include the following.

Film winding machines, Hoists, Machines in Textile , Machines for floor maintenance , Printing presses, Air compressors, Pumps & Fans ,Laundry equipment, High-speed lifts, Mixing machines, Machine tools, Air pump , Mining tools, Petrol pumps, Drive compressors etc.

Short questions with answer :

Q1. Can a dc series motor run when single phase ac supply is given to it?

Ans: Yes, a dc series motor can run when single phase ac supply is given to it but not satisfactory as dc supply given to it.

Q2. Write the application of universal motor? (Win-14)

Ans: An universal motor is used in domestics purpose like

1) Vacuum cleaner

2) Food processor

3) Electric shaver

Long questions :

Q1. Explain the working of an ac commutator motor with neat figure? (Win-15)

Q2. Explain the working principle of universal motor and its application? (Win-17)

Q3. Write short note on ac servo motor.

Q3.Explainthe single phase on or full step operation in variable reluctance stepper motor briefly ? (Win-2020)

CHAPTER- 6

(SPECIAL ELECTRICAL MACHINE)

Learning Resources :

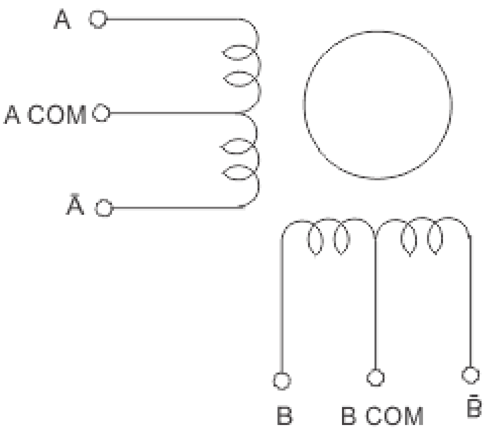
6.1. Principle of Stepper motor.
6.2. Classification of Stepper motor.
6.3. Principle of variable reluctant stepper motor.
6.4. Principle of Permanent magnet stepper motor.
6.5. Principle of hybrid stepper motor.
6.6. Applications of Stepper motor.

6.1. Principle of Stepper motor :

A stepper motor is an electromechanical device it converts electrical power into mechanical power. Also, it is a brushless, synchronous electric motor that can divide a full rotation into an expansive number of steps.

The motor's position can be controlled accurately without any feedback mechanism, as long as the motor is carefully sized to the application. Stepper motors are similar to switched reluctance motors.

The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided. The stator has eight poles, and the rotor has six poles. The rotor will require 24 pulses of electricity to move the 24 steps to make one complete revolution. Another way to say this is that the rotor will move precisely 15° for each pulse of electricity that the motor receives.
A stator is another part which is in the form of winding. In the diagram below, the centre is the rotor which is surrounded by the stator winding. This is called as four phase winding.



Stepper Motor

WORKING PRINCIPLE

The stepper motor working principle is Electro-Magnetism. It includes a rotor which is made with a permanent magnet whereas a stator is with electromagnets. Once the supply is provided to the winding of the stator then the magnetic field will be developed within the stator. Now rotor in the motor will start to move with the rotating magnetic field of the stator. So this is the fundamental working principle of this motor.

6.2. Classification of stepper motor :

There are three main types of stepper motors, they are:

- Permanent magnet stepper
- Hybrid synchronous stepper
- Variable reluctance stepper

6.3. Principle of variable reluctance stepper motor :

Variable reluctance (VR) motors have a plain iron rotor and operate based on the principle that minimum reluctance occurs with minimum gap, hence the rotor points are attracted toward the stator magnet poles.

The stepper motor like variable reluctance is the basic type of motor and it is used for the past many years. As the name suggests, the rotor's angular position mainly depends on the magnetic circuit's reluctance that can be formed among the teeth of the stator as well as a rotor.

6.4. Principle permanent magnet stepper motor :

Permanent magnet motors use a permanent magnet (PM) in the rotor and operate on the attraction or repulsion between the rotor PM and the stator electromagnets.

This is the most common type of stepper motor as compared with different types of stepper motors available in the market. This motor includes permanent magnets in the construction of the motor. This kind of motor is also known as tin-can/can-stack motor. The main benefit of this stepper motor is less manufacturing cost. For every revolution, it has 48-24 steps.

6.5. Principle of hybrid stepper motor :

Hybrid stepper motors are named because they use a combination of permanent magnet (PM) and variable reluctance (VR) techniques to achieve maximum power in small package sizes. The most popular type of motor is the hybrid stepper motor because it gives a good performance as compared with a permanent magnet rotor in terms of speed, step resolution, and holding torque. But, this type of stepper motor is expensive as compared with permanent magnet stepper motors. This motor combines the features of both the permanent magnet and variable reluctance stepper motors. These motors are used where less stepping angle is required like 1.5, 1.8 & 2.5 degrees.

Advantages :

The advantages of stepper motor include the following.

- Ruggedness
- Simple construction
- Can work in an open-loop control system
- Maintenance is low
- It works in any situation
- Reliability is high
- The rotation angle of the motor is proportional to the input pulse.
- The motor has full torque at standstill.
- Excellent response to starting, stopping, and reversing.
- Very reliable since there are no contact brushes in the motor. Therefore the life of the motor is simply dependant on the life of the bearing.

Disadvantages :

The disadvantages of stepper motor include the following.

- Efficiency is low
- The Torque of a motor will declines fast with speed
- Accuracy is low
- Feedback is not used for specifying potential missed steps
- Small Torque toward Inertia Ratio
- Extremely Noisy
- If the motor is not controlled properly then resonances can occur
- Operation of this motor is not easy at very high speeds.
- The dedicated control circuit is necessary
- As compared with DC motors, it uses more current

6.6. Application of stepper motor :

The applications of stepper motor include the following.

1. **Industrial Machines** – Stepper motors are used in automotive gauges and machine tooling automated production equipment.
2. **Security** – new surveillance products for the security industry.
3. **Medical** – Stepper motors are used inside medical scanners, samplers, and also found inside digital dental photography, fluid pumps, respirators, and blood analysis machinery.
4. **Consumer Electronics** – Stepper motors in cameras for automatic digital camera focus and zoom functions.

Short questions with answer:

Q1. What is step angle? (Win-2019 / Win-2020)
Ans: The angle through which the motor shaft rotates for each command pulse as step angle.

Q2.What is the function of compensated winding in compensated repulsion motor? (Win-2020)

Ans :
1) To improve power factor.
2) To provide better speed regulation.

Q3. Write down the uses of universal motor? (Win-2019)
Ans: Sewing machine,
Grinder,
Hair dries,
Blowers,
Kitchen application.

Q4. What is stepper motor?
Ans: Stepper motor is defined as an electro mechanical machine which converts electrical pulses in to angular rotation.

Long questions :

Q1.Explainprinciple and application of a hybrid stepper motor?

Q2. Write short notes on Universal motor. (Win-2018 (N))

Q3.Explain construction, working principle and application of universal motor? (Win-2019)

Q4.Explain principle and operation of permanent magnet stepper motor? (Win-2016)

CHAPTER-7

3-PHASE TRANSFORMER

Learning Objectives:

7.1. Explain Grouping of winding, Advantages.

7.2. Explain parallel operation of the three phase transformers.

7.3. Explain tap changer (On/Off load tap changing)

7.4. Maintenance Schedule of Power Transformers.

DEFINATION,PRINCIPLE AND CONSTRUCTION OF 3 PHASE TRANSFORMER :

DEFINATION

As known, a single-phase transformer is a device that is capable of transferring electrical energy from one circuit to one or more circuits based on the concept of mutual induction. It comprises two coils – a primary and a secondary coil, which helps to transform the energy. The primary coil is connected to a single-phase supply, while the secondary is connected to a load.

Similarly, a three-phase transformer consists of three primary coils and three secondary coils and is represented as 3-phase or 3ϕ. A three-phase system can be constructed using three individual identical single-phase transformers, and such a 3-phase transformer is known as the bank of three transformers. On the other hand, the three-phase transformer can be built on a single core. The windings of a transformer can be connected in either delta or wye configurations. The working of the 3-phase system is similar to a single-phase transformer, and they are normally employed in power generation plants.

PRINCIPLE

A transformer works on the principle of mutual induction. Mutual induction is the phenomenon by which when the amount of magnetic flux linked with a coil changes, an E.M.F. is induced in the neighbouring coil.

THREE-PHASE TRANSFORMER CONSTRUCTION

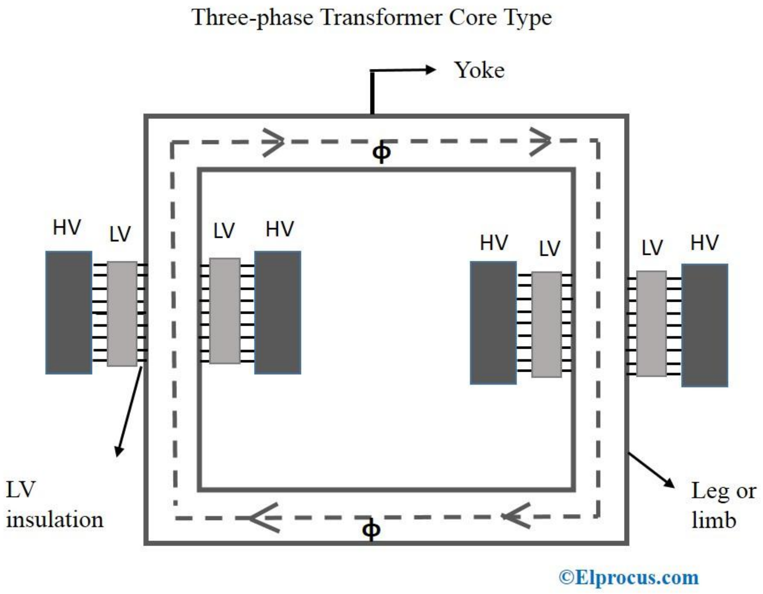
The diagram of a three-phase transformer is shown in the figure below.

Three Phase Transformer Diagram

A three-phase transformer of a single unit is used widely because it is lighter, cheaper and occupies less space than the bank of three single-phase transformers. The three-phase transformer construction is of two types: Core type and Shell type.

CORE TYPE CONSTRUCTION

In this type of construction, there are three cores and two yokes. Each core has both primary and secondary windings wounded spirally as shown in the figure. Each leg of the core carries high voltage as well as low voltage windings. The core is laminated to minimize eddy current losses on core and yoke. As it is easier to laminate low voltage (LV) winding than the high voltage (HV) winding. The LV windings are positioned near the core with appropriate insulation and oil ducts in between them whereas, the HV windings are placed above the LV windings with appropriate insulation and oil ducts between them.



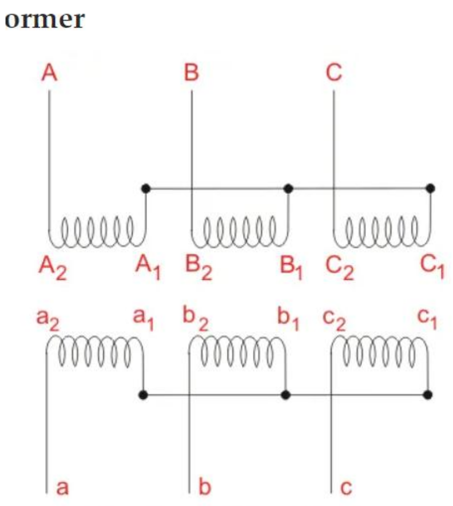
Core Type Transformer

SHELL TYPE TRANSFORMER

The three-phase shell type transformer is generally constructed by stacking three individual single-phase transformers. Three phases of a shell-type transformer are independent than the core-type transformer, while each phase has an individual magnetic circuit. These magnetic circuits are parallel to each other and flux induced by each winding is in phase. Shell type transformer is highly preferred as the voltage waveforms are less distorted.

7.1. Explain Grouping of winding, Advantages.

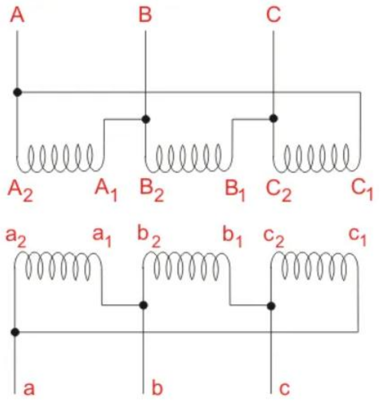
Star-star transformer is formed in a 3 phase transformer by connecting one terminal of each phase of individual side, together. The common terminal is indicated by suffix 1 in the figure below. If terminal with suffix 1 in both primary and secondary are used as common terminal, voltages of primary and secondary are in same phase. That is why this connection is called zero degree connection or 0^o – connection.



Star-Star Three Phase Transformer

Delta-Delta Transformer

In **delta-delta transformer**, 1 suffixed terminals of each phase primary winding will be connected with 2 suffixed terminal of next phase primary winding.

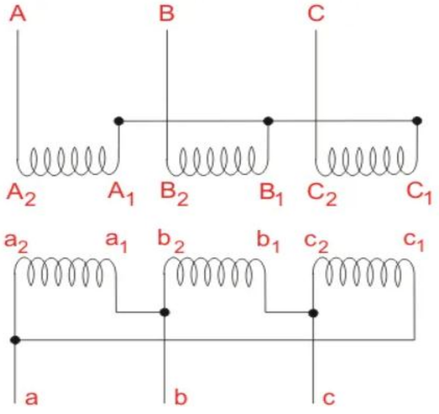


Delta-Delta Three Phase Transformer

If primary is HV side, then A_1 will be connected to B_2, B_1 will be connected to C_2 and C_1 will be connected to A_2. Similarly in LV side 1 suffixed terminals of each phase winding will be connected with 2 suffixed terminals of next phase winding. That means, a_1 will be connected to b_2, b_1 will be connected to c_2 and c_1 will be connected to a_2.

Star-Delta Transformer

Here in **star-delta transformer**, star connection in HV side is formed by connecting all the 1 suffixed terminals together as common point and transformer primary leads are taken out from 2 suffixed terminals of primary windings.

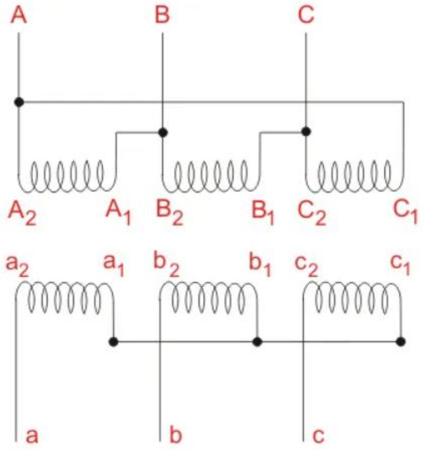


Star-Delta Three Phase Transformer

It is also observed from the phasor diagram that, phase to neutral voltage (equivalent star basis) on the delta side lags by − 30^o to the phase to neutral voltage on the star side; this is also the phase relationship between the respective line to line voltages. This star delta transformer connection is therefore known as − 30^o-connection.

Delta-Star Transformer

Delta-star transformer connection of three phase transformer is similar to star – delta connection. If any one interchanges HV side and LV side of star-delta transformer in diagram, it simply becomes delta – star connected 3 phase transformer. That means all small letters of star-delta connection should be replaced by capital letters and all small letters by capital in delta-star transformer connection.



Delta-Star Three Phase Transformer

Advantages

A single 3 phase transformer costs around 15 % less than a bank of three single phase transformers. Again former occupies less space than later. For a very big transformer, it is impossible to transport a large three-phase transformer to the site and is instead easier to transport three single-phase transformers, which are erected separately to form a three-phase unit.
Another advantage of using a bank of three single phase transformers is that, if one unit of the bank becomes out of order, then the bank can be run as an open delta transformer.

7.2 EXPLAIN PARALLEL OPERATION OF THE THREE PHASE TRANSFORMERS :

Parallel operation of three phase transformer is very common in three phase power generation, transmission and distribution. It is advantageous to use two or more Transformer units in parallel instead of using a single large unit. This offers flexibility for maintenance as well as operation.

Advantage of Parallel Operation of Three Phase Transformers

- It increases the reliability of supply system.
- The size of transformer increases with the increase of its rating. Therefore, a larger transformer will be bigger in size. Therefore, its transportation form manufacturer to the Site will be difficult. Whereas, transportation and installation of small sized transformers are comparatively easy.
- The maintenance opportunity in case of parallel operation is increases. One or more transformers may be taken under maintenance while the remaining transformers will supply the load at reduced power.

Condition for Parallel Operation of Three Phase Transformers :

Following are the necessary conditions for parallel operation of 3 phase transformers:

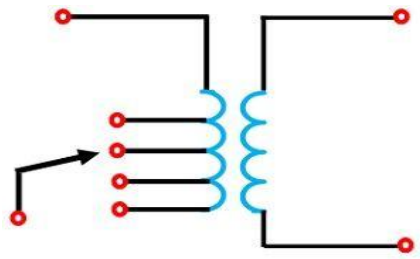
- The line voltage ratio of the transformers must be same.
- The transformers should have equal per unit leakage impedance. (You may read per unit system)
- The ratio of equivalent leakage reactance to equivalent resistance should be same for all the transformers.
- The transformers should have the same polarity.
- The relative phase displacement between the secondary line voltages of all transformers should be zero. This means that transformers to be connected in parallel must belong to same Group number like Yy0 and Dd0 belong to same group number viz. Group 1.
- The phase sequence of secondary line voltages of all the transformers should be same.

7.3. Explain tap changer (On/Off load tap changing) :

The change of voltage is affected by changing the numbers of turns of the transformer provided with taps. For sufficiently close control of voltage, taps are usually provided on the high voltage windings of the transformer. There are two types of tap-changing transformers.

Off-load tap-changing transformer

In this method, the transformer is disconnected from the main supply when the tap setting is to be changed. The tap setting is usually done manually. The off load tap changing transformer is shown in the figure below

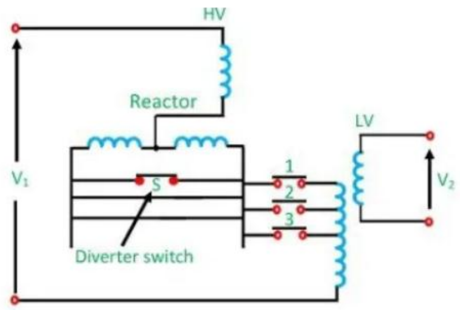


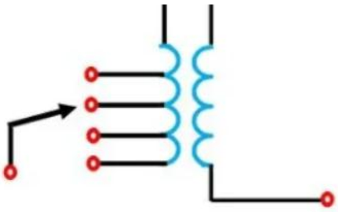
Off-load tap-changing transformer

On-load tap-changing transformer

In order that the supply may not be interrupted, on-load tap changing transformer are sued. Such a transformer is known as a tap-changing under load transformer. While tapping, two essential conditions are to be fulfilled.

- The load circuit should not be broken to avoid arcing and prevent the damage of contacts.
- No parts of the windings should be short–circuited while adjusting the tap.





7.4. Maintenance Schedule of Power Transformers.

Daily Basis Maintenance Testing and Checking

Here are 3 maintenance tests you should run on your transformer on a daily basis:

Oil levels of MOG (Magnetic Oil Gauge) of the main tank and conservator tank. Always maintain to keep oil filled up to the desired level in MOG.

1. Replace the silica gel if its color changes to pink.
2. If any leakage is detected seal it.

Transformer Maintenance Checks on a Monthly Basis

1. Oil level in the oil cap must be checked on a monthly basis so that it doesn't drop below a fixed limit and hence avoid damage due to it.
2. Keep the breathing holes in the silica gel breather clean to ensure proper breathing action at all times.
3. If your electrical transformer has oil filling bushing, make sure that the oil is filled up to the correct level.

Annual Transformer Maintenance Schedule

The air fans, oil pumps along with other items that are used to cool down a transformer and control circuit must be inspected annually.

1. Make sure that you clean all the bushings of your electrical transformer with only soft cotton cloth annually.
2. Oil condition of OLTC should be carefully examined on an annual basis. For that take an oil sample from drain valve and test it for moisture content (PPM) and dielectric strength (BDV). If the BDV value is found low and the PPM value high, then the oil needs to be replaced.
3. Make sure to clean out the inside of all of the marshalling boxes annually. Check proper functioning of the space and illumination heaters. All of the terminal connections of control and relay wiring need to be tightened at least once a year.
4. All the control switches, alarms and relays along with their circuits, Remote Tap Changer Control Panel and Relay and Control Panel have to be cleaned with a proper cleaning agent.
5. Examine all the pockets for the Winding Temperature Indicator and Oil Temperature Indicator if they have the necessary level of oil and make sure to top it up if required.
6. The proper function of Buchholz and Press Release Device relay need to be checked on a yearly basis.
7. Make sure to measure the resistive value of the earth connection with a clamp on the earth resistance meter.

SHORT QUESTIONS WITH ANSWER

Q1. What is the angle between any two adjacent core of a 3 phase transformer?
Answer : The angle between two adjacent core of a transformer is 120 degree.

Q2. What is the phase shift angle between the primary and secondary winding of star delta transformer ?
Answer : The phase shift angle is 30 degree.

Q3. Why transformer rating in KVA ? (W-2014)
Answer:Since nature of load connected to the transformer is not known and is not fixed, so it is generally rated in apparent power (KVA). In other word there are two losses in a transformer, such as iron loss and copper loss. We know that iron loss depends upon voltage whereas copper loss depends upon currents , that is why it is expressed in KVA.

Q4.What Are Power Transformer?
Answer : Power transformer is used for the transmission purpose at heavy load, high voltage greater than 33 KV & 100% efficiency.
It is big in size as compared to distribution transformer, it used in generating station and Transmission substation. It is generally rated above 200MVA

Q5. What Are Distribution Transformer?
Answer :
The distribution transformer is used for the distribution of electrical energy at low voltage as less than 33KV in industrial purpose and 440v-220v in domestic purpose. It works at low efficiency at 60-70%, small size, easy in installation, having low magnetic losses & it is not always fully loaded.

Q6. What are the difference between power and distribution transformer ? (W-2016)
Answer :
Distribution transformer is designed for maximum efficiency at 60% to 70% load as it normally doesn’t operate at full load all the time. Its load depends on distribution demand. Whereas power transformer is designed for maximum efficiency at 100% load as it always runs at 100% load being near to generating station.

LONG QUESTIONS

Q1. Explain the constructional details of a three phase transformer ?

Q2. Describe different connection of 3 phase transformer ? (W-2014)

Q3. Discuss various vector groups of 3 phase transformer ?

Q4. What is parallel operation ? Why it is needed ? State the necessary condition for parallel operation of three phase transformer ? (W-2014/15/16/19)

Q5. Write short notes on maintenance of power transformer ? (W-2016/19)