CONTENT

SUBJECT/SUBJECT CODE-4030410/ ELECTRICAL MACHINES II

1. **NOTES OF LESSON INDEX PAGE**
2. **NOTES OF LESSON (VIDEO LINK,PPTLINK ATTACHED IN THE INDEX PAGE)**

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NOTES OF LESSON –INDEX PAGE

YEAR	**SECOND YEAR**	**SEMESTER**	**IV SEMESTER**
SUBJECT/SUBJECT CODE	Electrical Machines – II /4030410	**SCHEME**	**N-SCHEME**

UNIT-I-ALTERNATOR PRINCIPLES AND CONSTRUCTION

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1	Basic principle of alternators – Types of alternators	A Textbook of Electrical Technology - Volume II B.L. Theraja	https://www.youtube.com/watch?v=YkHhFho6L2Y	NIL	NIL
2.	Stationary armature rotating field – advantages of rotating field – Construction details of alternator – Salient pole rotor, Cylindrical type rotor		https://www.youtube.com/watch?v=xRpWuYyUuyY		
3.	Types of A.C. armature windings		https://www.youtube.com/watch?v=wex3ZenASl0		
4.	Types of slots – Full pitch and short pitched windings		https://www.youtube.com/watch?v=rusquXYezNA		
5.	Phase spread angle and effect of distribution factor				
6.	pitch factor				
7.	relation between frequency, speed and number of poles				
8.	EMF equation – Problems	Electrical Technology Edward Hughes	https://www.youtube.com/watch?v=J85eybdH25k		
9.	methods of obtaining sine wave		https://www.youtube.com/watch?v=pnp-7146wSY		
10.	Critical speed of rotor				
11.	Ventilation of turbo alternators		https://www.youtube.com/watch?v=u0ShvEquaoA		
12.	advantages ofhydrogen cooling and its precaution – excitation and exciters.		https://www.youtube.com/watch?v=EVE4JK8zFbM		

UNIT-II-ALTERNATOR PERFORMANCE AND TESTING

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1.	Load characteristics of alternators – reason for change in terminal voltage	A Textbook of Electrical Technology - Volume II B.L. Theraja	NIL	NIL	E-BOOK
2.	Qualitative treatment of armature reaction for various power factor loads – effective resistance				
3.	leakage reactance – synchronous reactance, synchronous impedance				
4.	Voltage regulation				
5.	Determination of voltage regulation by synchronous impedance method (simple problems)-				
6.	MMFmethod – potier method				
7.	Necessity and conditions for parallel operation of alternators	Electrical Technology Edward Hughes			
8.	synchronizing by dark lamp method, bright lamp method				
9.	dark - bright lamp method and synchroscope method				
10.	synchronizing current, synchronizing power				
11.	synchronizing torque				
12.	load sharing of alternators, Infinite bus bar				

UNIT-III-THREE PHASE INDUCTION MOTOR

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1.	Rotating magnetic field	A Textbook of Electrical Technology - Volume II B.L. Theraja Electrical Technology Edward Hughes	NIL	NIL	E-BOOK
2.	Principle of operation of three phase induction motors				
3.	slip and slip frequency – comparison between cage and slip ring induction motors				
4.	slip-torque characteristics – stable and unstable region				
5.	no load test and blocked rotor test				
6.	development of approximate equivalent circuit				
7.	problems on the above topics				
8.	simplified circle diagram – determination of maximum torque, slip (problems not required)				
9.	starting torque and starting current expression				
10.	relationship between starting torque and full load torque				
11.	speed control of induction motors.				
12.	Starters of induction motors – direct on line starter				
13.	star delta starter				
14.	auto transformer starter -rotor resistance starter				
15.	cogging –crawling in induction motor				
16.	double cage induction motor-induction generator.				

UNIT-IV-SINGLE PHASE INDUCTION MOTOR & SYNCHRONOUS MOTOR

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1..	single phase induction motors not self starting methods of making it selfstarting construction,working principle –phasor diagram-slip torque characteristics- split phase motor capacitor motor	A Textbook of Electrical Technology -Volume II B.L. Theraja	https://www.youtube.com/watch?v=8QB0P9HWL7Q	NIL	NIL
2.	shaded pole motor		https://www.youtube.com/watch?v=Uity_1XDLZ4		
3.	repulsion motor - universal motor		https://www.youtube.com/watch?v=XlZo7YlP_D0 https://www.youtube.com/watch?v=1T_SQIO-1Xg		
4.	Operation of three phase motor with single phase supply		https://www.youtube.com/watch?v=mrC2NksYwcQ		
5.	Principle of operation –not self starting – methods of starting		https://www.youtube.com/watch?v=w7EW6_KjWxY https://www.youtube.com/watch?v=iOvlQ5BhZcI		
6.	effects of excitation on armature current and power factor	Electrical Technology Edward Hughes	https://www.youtube.com/watch?v=6zHlsyTm3oI		
7.	‘V’ curve and inverted ‘V” curve of synchronous motor		https://www.youtube.com/watch?v=SHk49rSvVp8		
8.	the phenomenon of hunting and prevention of hunting by damper winding		https://www.youtube.com/watch?v=ODXEsqUytDQ		
9.	comparison between synchronous motor and three phase induction motor - applications -problems on power factor improvement		https://www.youtube.com/watch?v=vh6lxv8jMrg		

UNIT-V- MAINTENANCE OF INDUCTION MOTORS AND STARTERS

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1.	BIS Publication Dealing with The Code of Practice of Induction Motors and Starters	A Textbook of Electrical Technology - Volume II B.L. Theraja	https://www.youtube.com/watch?v=TWUyWDydB-E	NIL	NIL
2.	Classification of Cage Motor .				
3.	Continuous Rating and Intermittent Rating		https://www.youtube.com/watch?v=t8PNGF5hsME		
4.	Various Types of Enclosures		https://www.youtube.com/watch?v=UFQiKO69lwM		
5.	Specifications of Motors – Selecting the Cable Rating		https://www.youtube.com/watch?v=2mrTZvZ8Yb0		
6.	Single Phase Prevention using Current Operated Relay		https://www.youtube.com/watch?v=bZ2NJ_WOswU		
7.	Commissioning - Annual Maintenance Selection of Starters of Induction Motor		https://www.youtube.com/watch?v=sQV92yBpIQQ https://www.youtube.com/watch?v=7UzGZpgQZwQ		
8.	Common Induction Motor Troubles and their Remedies	Electrical Technology Edward Hughes	https://www.youtube.com/watch?v=Zkbn62GALgI		
9.	Causes of Noise and Vibration Care of Bearings		https://www.youtube.com/watch?v=8RXu1f3Z9po		
10.	Static Balancing		https://www.youtube.com/watch?v=ZSvrbMCx6Lo		
11.	Degreasing – Vacuum Impregnation		https://www.youtube.com/watch?v=cj1rJ83VkFQ		
12.	Varnishing – Effect of Unbalanced Supply on the Performance of Induction Motor		https://www.youtube.com/watch?v=UYe-C_j4F9k		

UNIT-II

ALTERNATOR PERFORMANCE AND TESTING

2.1 Load characteristics of an alternators:

As the load of an alternator is varied, its terminal voltage is also found to vary. This variation in terminal voltage is due to the following reasons

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

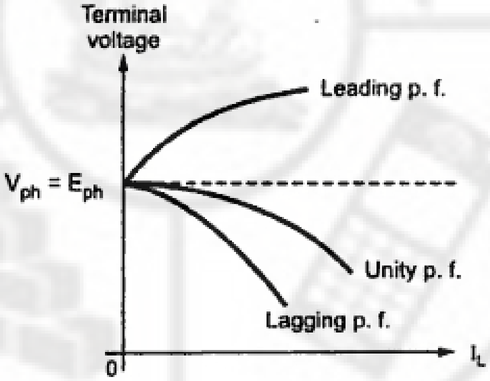


Fig: 2.1

A load characteristic of an alternator is the relation between the terminal voltage and the load current keeping the field excitation and speed as constant. The variation of terminal voltage also depends on the power factor of the load. With unity power factor load, there is a moderate voltage drop. But if there load has a lagging power factor this voltage drop is considerably increased. On the other hand, a load having a leading power factor has the reverse effect. If the load current leads the voltage by sufficient angle, the voltage drop may actually be converted into a voltage rise. The load characteristics curves for different power factors are shown in fig 2.1

2.2 Reason for change in terminal voltage or causes of voltage drop in alternators

When the armature current increases, the terminal voltage drops due to the following reasons.

- Voltage drop due to armature effective resistance (R_{eff}) of the armature winding.
- Voltage drop due to armature leakage reactance (X_L).
- Voltage drop due to armature reaction.

2.3 Armature reaction of alternators on load at various power factors

The armature winding of an alternator carries current only when the alternator is loaded. At no-load, there will be no current flowing through the armature winding. In alternators under loaded condition, there are two fluxes present in the air-gap. They are

- Flux due to the field ampere turns
- Flux due to the current flowing through the armature winding

That is, when the armature carries the load current, an armature flux (ϕ_a) is produced in the armature winding and is also present in the airgap. There is already another flux due to field current that is also present in the air-gap. Now there are two fluxes present in the air gap. But actually the machine needs only the fluxes due to field ampere turns only.

The effect of armature flux due to armature current over the main field flux is called armature reaction. This effect can be in the following forms.

They are

- The armature flux will produce a distortion over the field flux
- The armature flux will oppose the main field flux (or) will aid the main flux. The above said armature reaction effects depends upon the p.f of the load.

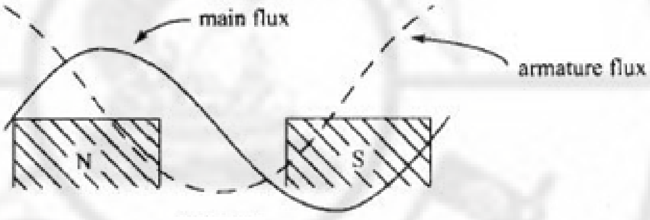


Fig 2.2 Unity p.f

Consider the load of the alternator as resistive and for which the p.f is unity. That is the load current is in phase with the terminal voltage V. at unity p.f, armature flux cross magnaetising. i..e at unity
p.f of the load, the main flux and the armature flux are as shown in Fig 2.2

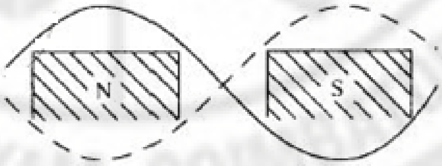


Fig 2.3 Zero p.f lagging

The result is that the flux at the leading pole tips of the pole is reduced. While it is increased at the trailing pole tips. Hence these two effects are more or less off set each other. Hence the filed strength is constant. Under unity p.f load, the armature reaction is distortional.

Consider the load of the alternator as pure inductive, and for which the p.f is zero lagging. That is the load current lags the terminal voltage by an angle 90^0 . At zero p.f lagging load, the armature flux is in direct opposition to the main flux as shown in Fig 2.3. So the main flux is decreased. For zero p.f lagging, the armature reaction is demagnetizing. It weakens the main flux. So less emf is generated. To keep the generated emf constant, field excitation has to be increased, in order to compensate the weaken flux.

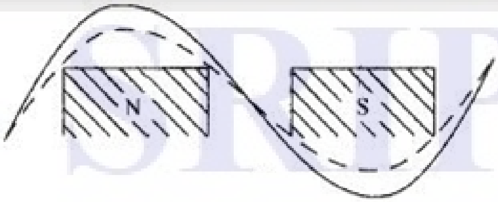


Fig 2.4 Zero p.f leading

Consider the load of the alternator is pure capacitive, and for which the p.f is zero leading. That is the load current leads the terminal voltage V by an angle 90^0. At zero p.f leading, the armature flux is in phase with the main flux as shown in Fig 2.4. The armature flux added with the main flux and hence the flux is increased. Here the armature reaction effect is magnetizing. Due to increasing of flux, the generated emf is increased. Hence to keep the generated emf constant, the field excitation has to be reduced in order to compensate the increasing flux.

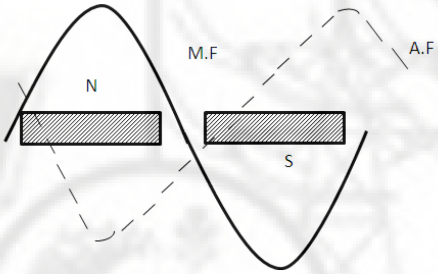


Fig 2.5 Intermediate power factor

If the p.f the load is intermediate (say 0.7 p.f lagging) the armature reaction effect is partly distortion and partly demagnetising. The effect is shown in Fig 2.5

2.4 Effective Resistance, R_{eff}:

The effective resistance of the armature is the resistance offered by the armature winding for a alternating current. It is greater than the D. C resistance due to skin effect. R_{eff} is usually assumed to be $1.6R_{DC}$. the voltage drop due to this resistance (IR_{eff}) is very low compared to other voltage drops.

2.4.1 Armature Resistance:

The armature resistance/phase Ra causes a voltage drop/phase of IRa which is in - phase with the armature current I. However, this voltage drop is practically negligible.

2.5 Armature Leakage Reactance:

When current flows through the armature conductors, fluxes are set up which do not cross the air- gap, but take different paths. Such fluxes are known as leakage fluxes. The leakage flux is practically independent of saturation, but is dependent on I and its phase angle with terminal voltage V. This leakage flux sets up an emf. of self-inductance which is known as reactance emf. and which is ahead of I by 90°.

Hence, armature winding is assumed to possess leakage reactance X_L (also known as Potier reactance X_P) such that voltage drops due to this equals IX_L. A part of the generated emf is used up in overcoming this reactance emf.

2.6 Synchronous Reactance X_S:

The synchronous reactance of an alternator is a fictitious reactance. It is equivalent to a reactance value, which is equal to the combined effects of the armature leakage reactance, X_L and a fictitious inductive reactance to represents the armature reaction X_a, synchronous reactance X_S is equal to $(X_L + X_a)$

2.7 Synchronous Impedance, Z_S :

The effective value of armature resistance R_{eff} and synchronous reactance combined together is called synchronous impedance, $Z_{S.}$ it is the vector sum of armature resistance and the synchronous reactance

Z_S = ohms.

2.8 Voltage Regulation:

It is clear that with change in load, there is a change in terminal voltage of an alternator. The magnitude of this change depends not only on the load but also on the load power factor.

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

$$\therefore \%\,\mathrm{Re}\,gulation\,'Up' = \frac{E_o - V}{V} \times 100$$

2.8.1 Determination of Voltage Regulation:

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

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

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

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

- Synchronous Impedance or E.M.F. Method
- The Ampere-turn or M.M.F. Method
- Zero Power Factor or Potier

Method All these methods require:

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

2.8.1 To find the Value of Ra:

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

2.8.2 Open circuit characteristics

The open –circuit characteristics or magnetization curve is really the B-H curve of the complete magnetic circuit of the alternator. But it is usual to plot the curve with exciting current in X-axis and the terminal voltage in Y-axis. The test is carried out on open circuit maintaining the speed of the machine at normal.

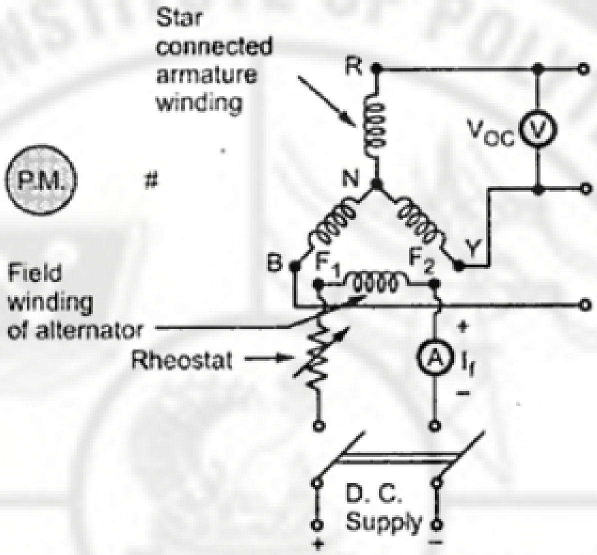


Fig 2.6

The connection in diagram for the open –circuit characteristics (O.C.C) is shown in fig.2.6 the armature terminals are left open circuited and a voltmeter is connected to show the induced emf . The ammeter connected shows the field excitation of the alternator. For various field current the induced emfs are noted and plotted the open-circuit characteristics as shown fig .2.7

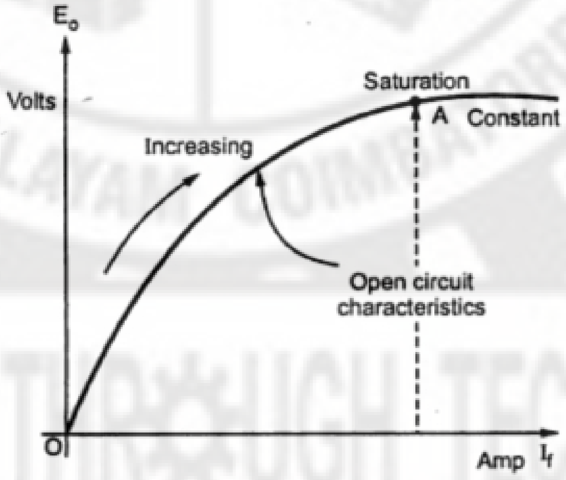


Fig 2.7

2.8.3 Short –circuit characteristics

The short –circuit characteristics, as its name implies, refers to the behavior of the alternator when its armature is short circuited. The connection diagram for conducting the short –circuit test is shown in fig 2.8. The armature terminals are short circuited through an ammeter to show the short circuit current. Another ammeter is connected in the field circuit of the alternator to show the field excitation.

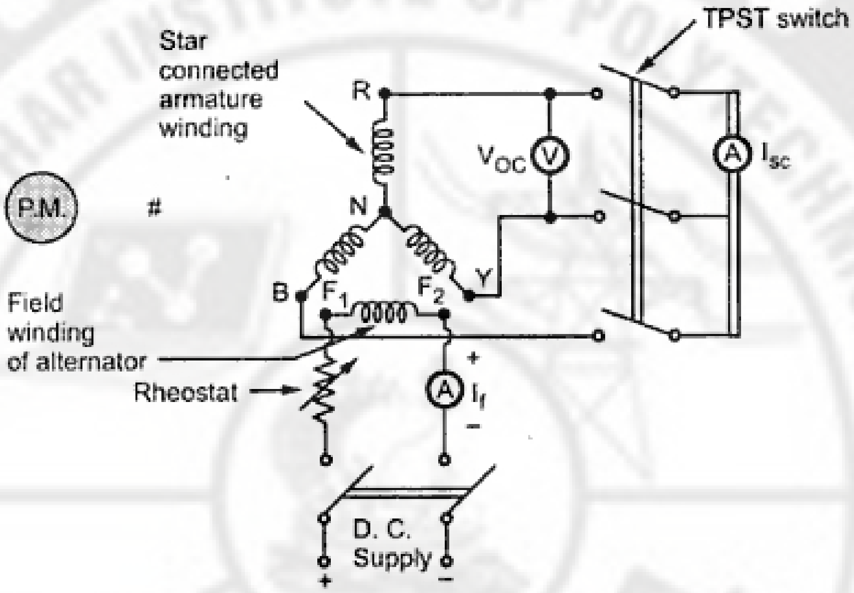


Fig: 2.8

The alternator is allowed to run at rated speed. The filed current is gradually increased till the armature current reaches its rated value. The small induced emf in the armature is equal to the voltage drop in the winding itself. This induced emf is required to circulate the short – circuit current through the armature windings.

The armature short- circuit current and the filed current are found to be proportional to each other over a wide range as shown in fig 2.9 .So the short –circuit characteristics (S.C.C) is a straight line.

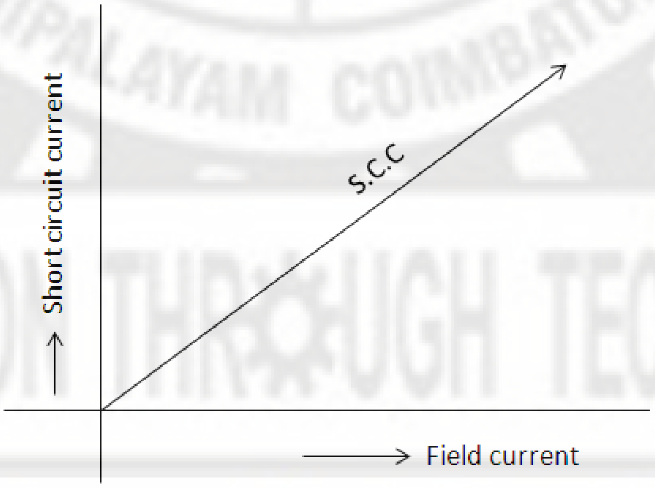


Fig: Short circuit characteristic

Fig: 2.9

2.9 Synchronous Impedance Method:

Following procedural steps are involved in this method:

1. O.C.C is plotted from the given data as shown in Fig. 2.10 (a).
2. Similarly, S.C.C. is drawn from the data given by the short-circuit test. It is a straight line passing through the origin. Both these curves are drawn on a common field-current base.

Consider a field current I_f. The O.C. voltage corresponding to this field current is E_1. When winding is short-circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short-circuit current I_1 against the synchronous impedance Z_S.

$$\therefore \quad E_1 = I_1 Z_S \qquad \therefore Z_S = \frac{E_1(\text{Open circuit})}{I_1(\text{Short circuit})}$$

3. Since Ra can be found as discussed earlier. $X_S = \sqrt{Z^2{}_s - R_a^2}$
4. Knowing R_a and X_S, vector diagram as shown in Fig. 2.10 (b) can be drawn for any load and any power factor.

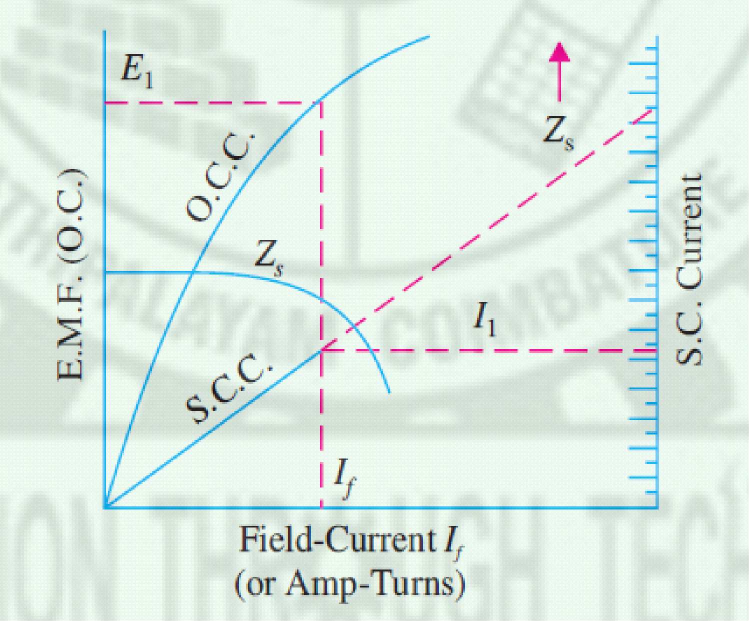


Fig.2.10 (a) OCC & SCC

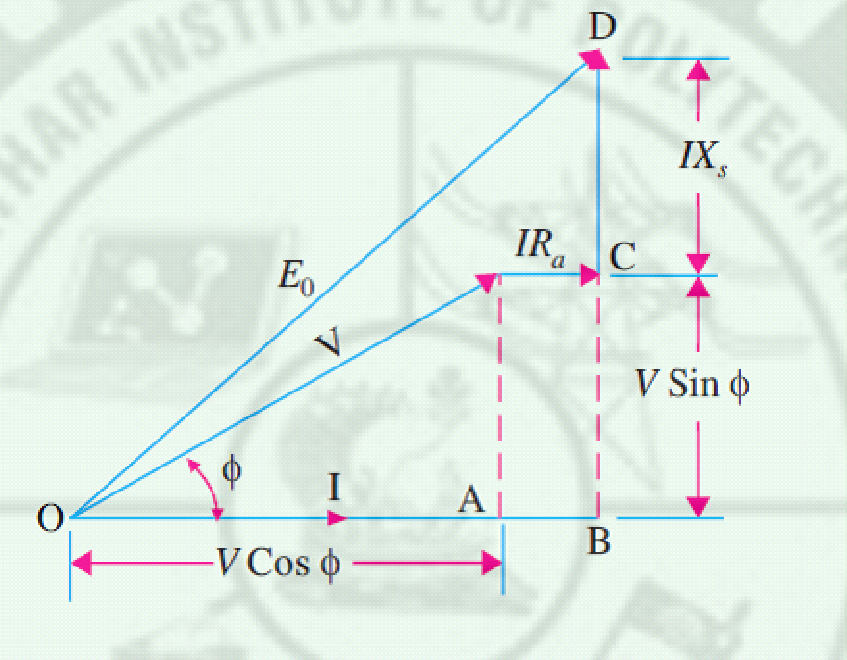


Fig.2.10 (b) Vector Diagram

Here $OD = E_O$ $\quad\quad \therefore E_O = \sqrt{\left(OB^2 + BD^2\right)}$

or $E_O = \sqrt{\left(V\cos\phi + IR_a\right)^2 + \left(V\sin\phi + IX_S\right)^2}$

$$\therefore \%\mathrm{Regulation}\,'Up' = \frac{E_o - V}{V} \times 100$$

This method is not accurate because the value of Z_S so found is always more than its value under normal voltage conditions and saturation. Hence, the value of regulation so obtained is always more than that found from an actual test. That is why it is called pessimistic method. The value of Z_S is not constant but varies with saturation.

At low saturation, its value is larger because then the effect of a given armature ampere-turns is much more than at high saturation. Now, under short-circuit conditions, saturation is very low, because armature m.m.f. is directly demagnetizing. Different values of Z_S corresponding to different values of field current are also plotted in Fig. 2.10 (a).

The value of Z_S usually taken is that obtained from full-load current in the short-circuit test. Here, armature reactance X_a has not been treated separately but along with leakage reactance X_L..

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

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

Example 2.1 The effective resistance of a 2200 V, 50Hz, 440KVA, single phase alternator is 0.5Ω. On short circuit, a field current of 40 A gives the full load current of 200 A .The emf on open circuit with the same field current excitation is 1160V. Calculate the synchronous impedance and reactance.

Solution:

Synchronous impedance, Zs = $\frac{open\ circuit\ voltage}{short\ circuit\ current}$

Synchronous impedance, Zs = $\frac{1160}{200} = 5.8\Omega$

Synchronous reactance, Xs = $\sqrt{Zs^2 - Ra^2}$

Xs = $\sqrt{5.8^2 - 0.5^2} = 5.78\Omega$

Example 2.2 The effective armature resistance and synchronous reactance of a 60 KVA, star connected. 440V, 3-phase, 50 Hz alternator are 0.2Ω and 3Ω per phase respectively. Determine the percentage voltage regulation on full load at unity power factor.

Solution:

Terminal voltage per phase = $\frac{440}{\sqrt{3}} = 254\ Volts$

Full load current = $\frac{60 \times 1000}{\sqrt{3} \times 440} = 78.72\ A$

Induced emf per phase, Eo = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

= $\sqrt{(254 \times 1 + 78.72 \times 0.2)^2 + (254 \times 0 + 78.72 \times}$

= 358.5 Volts

Percentage of voltage regulation $= \dfrac{E_o - V}{V} \times 100$

$= \dfrac{358.5 - 254}{254} \times 100 = 41\%$

Example 2.3 A 550V, 55 KVA, single phase alternator has an effective resistance of 0.2Ω. A field current of 10A produces an armature current of 200A on short circuit and an emf of 450V on open circuit. Calculate (1) the synchronous impedance and reactance (2) the full load regulation with 0.8 power factor lagging.

Solution:

Full load current $= \dfrac{55000}{550} = 100\ A$

Synchronous impedance, Zs $= \dfrac{open\ circuit\ voltage}{short\ circuit\ current} = \dfrac{450}{200} = 2.25\Omega$

Synchronous reactance, Xs $= \sqrt{Zs^2 - Ra^2}$

$Xs = \sqrt{2.25^2 - 0.2^2} = 2.24\Omega$

Induced emf per phase, $Eo = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

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

$=$ 720 volts

Percentage of voltage regulation $= \dfrac{E_o - V}{V} \times 100$

$= \dfrac{720 - 550}{550} \times 100 = 30.92\%$

Example 2.4 Determine the voltage regulation of a 2000V, single phase alternator giving a current of 100 A at 0.71 power factor lagging from the following test results.

Test Results: Full load current of 100 A is produced on short circuit by a field current of 2.5 A; an emf of 500V is produced on open circuit by the same excitation. Armature resistance is 0.8Ω.

Solution:

Synchronous impedance, Zs $= \dfrac{open\ circuit\ voltage}{short\ circuit\ current} = \dfrac{500}{100} = 5\Omega$

Synchronous reactance, Xs $= \sqrt{Zs^2 - Ra^2}$

$Xs = \sqrt{5^2 - 0.8^2} = 4.94\,\Omega$

Induced emf per phase, Eo $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

$= \sqrt{(2000 \times 0.71 + 100 \times 0.8)^2 + (2000 \times 0.71 + 100 \times}$

$=$ 2431.7 Volts

Percentage of voltage regulation $= \dfrac{E_o - V}{V} \times 100$

$= \dfrac{2431.7 - 2000}{2000} \times 100 = 21.58\,\%$

Example 2.5 A 60 KVA, 220V, 50Hz, 1- φ alternator has effective armature resistance of 0.016Ω and an armature leakage reactance of 0.07Ω . Compute the voltage induced in armature when the alternator is delivering rated current at a load power factor of (a) unity (b) ***0.7 lagging (c) 0.7 leading.***

Solution:

Full load current $= \dfrac{60000}{220} = 272.2\,A$

At unity power factor
Induced emf per phase, Eo $= \sqrt{(V + IR_a)^2 + (IX_L)^2}$

Eo $= \sqrt{(220 + 272.2 \times 0.016)^2 + (272.2 \times}$

$= 225$ V

At 0.7 lagging p.f Induced emf per phase, *Eo* $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + {}_L)^2}$

$= \sqrt{(220 \times 0.7 + 272.2 \times 0.016)^2 + (220 \times 0.7 + 272.2 \times}$

$=$ 235 Volts

At 0.7 leading p.f Induced emf per phase, *Eo* $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - {}_L)^2}$

$= \sqrt{(220 \times 0.7 + 272.2 \times 0.016)^2 + (220 \times 0.7 - 272.2 \times}$

$=$ 208 lts

Example 2.6 Find the synchronous impedance and reactance of an alternator in which a given field current produces an armature current of 200 A on short circuit and a generated emf of 50 V on open circuit. The armature resistance is 0.1Ω. To what induced voltage must the alternator be excited if it is to deliver a load of 100 A at a p.f. of 0.8 lagging. With terminal voltage of 200V

Solution:

Synchronous impedance, $Zs = \frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{50}{200} = 0.25\Omega$

Synchronous reactance, $Xs = \sqrt{Zs^2 - Ra^2}$

$Xs = \sqrt{0.25^2 - 0.1^2} = 0.23\,\Omega$

Induced emf per phase, *Eo* $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

$= \sqrt{(200 \times 0.8 + 100 \times 0.1)^2 + (200 \times 0.6 + 100 \times}$

= 222 lts

Example 2.7 Determine the voltage regulation of a 2000V, single phase alternator giving a current of 100 A at (i) unity p.f (ii) 0.8 leading p.f (iii) 0.71 lagging p.f from the following test results.

Test Results: Full load current of 100 A is produced on short circuit by a field current of 2.5 A; an emf of 500V is produced on open circuit by the same excitation. Armature resistance is 0.8Ω.

Solution:

Synchronous impedance, Zs $= \frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{500}{100} = 5\Omega$

Synchronous reactance, Xs $= \sqrt{Zs^2 - Ra^2}$

Xs $= \sqrt{5^2 - 0.8^2} = 4.94\,\Omega$

At unity power factor Induced emf per phase, *Eo* $= \sqrt{(V + IR_a)^2 + (IXs}$

$= \sqrt{(2000 + 100 \times 0.8)^2 + (100 \times}$

= 2140 V

At 0.71 lagging p.f Induced emf per phase, *Eo* $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + \ _s)^2}$

$= \sqrt{(2000 \times 0.71 + 100 \times 0.8)^2 + (2000 \times 0.71 + 100 \times}$

= 2432 Volts

At 0.8 leading p.f Induced emf per phase, *Eo* $= \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - \ _s)^2}$

$$= \sqrt{(2000\times 0.8+100\times 0.8)^2 + (2000\times 0.6-100\times}$$

$$= 1822 \text{ Volts}$$

At Unity p.f

Percentage of voltage regulation $= \frac{E_o - V}{V}\times 100$

$$= \frac{2140-2000}{2000}\times 100 = 7\%$$

At 0.8 leading p.f

Percentage of voltage regulation $= \frac{E_o - V}{V}\times 100$

$$= \frac{1820-2000}{2000}\times 100 = -9\%$$

At 0.71 lagging p.f

Percentage of voltage regulation $= \frac{E_o - V}{V}\times 100$

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

Example 2.8 A 100 KVA, 3000V, 50Hz, 3-phase star connected alternator has effective armature resistance of 0.2Ω. The field current of 40 A produces short circuit current of 200 A and an open circuit emf of 1040 V (line value). Calculate the full load voltage regulation at 0.8 ***p.f. lagging and 0.8 p.f leading.***

Solution:

Synchronous impedance, Z_s $= \frac{\text{open circuit voltage}}{\text{short circuit current}} = \frac{1040/\sqrt{3}}{200} = 3\Omega$

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

X_s $= \sqrt{3^2 - 0.2^2} = 2.99\Omega$

Full load current = $\frac{100000}{\sqrt{3} \times 3000} = 19.2\ A$

Voltage per phase = $\frac{3000}{\sqrt{3}} = 1732\ V$

(i) P.f 0.8 lagging = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$

At 0.8 lagging p.f Induced emf per phase , *Eo*

$= \sqrt{(1732 \times 0.8 + 19.2 \times 0.2)^2 + (1732 \times 0.6 + 19.2 \times}$

= 1770 Volts

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

$= \frac{1770 - 1730}{1730} \times 100 = 2.2\%$

(ii) At 0.8 leading p.f = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_s)^2}$

At 0.8 leading p.f Induced emf per phase, *Eo*

$= \sqrt{(1730 \times 0.8 + 19.2 \times 0.2)^2 + (1730 \times 0.6 - 19.2 \times}$

= 1701.31 Volts

At 0.8 leading p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

$$= \frac{1701 - 1730}{1730} \times 100 = -1.8\%$$

Example 2.9 A 3 –phase star connected alternator is rated at 1600 KVA, 13500 V. the armature resistance and synchronous reactance are 1.5Ω and 30Ω respectively per phase. Calculate the percentage regulation for a load of 1280 KW at 0.8 leading power factor.

Solution:

Load current $= \frac{1280 \times 10^3}{\sqrt{3} \times 13500 \times 0.8} = 68.4\ A$

Voltage per phase $= \frac{13500}{\sqrt{3}} = 7794\ V$

At 0.8 leading p.f Induced emf per phase, *Eo* $= \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi - \ {}_S)^2}$

$= \sqrt{(7794 \times 0.8 + 68.4 \times 1.5)^2 + (7794 \times 0.6 - 68.4 \times}$

= 6860 Volts

At 0.8 leading p.f Percentage of voltage regulation $= \frac{E_o - V}{V} \times 100$

$= \frac{6860 - 7795}{7795} \times 100 = -11.98\%$

Example 2.10 A 3-phase, 10 KVA, 400 V, 50Hz, Y-connected alternator supplies the rated load at 0.8 p.f lag. If armature resistance is 0.5Ω and synchronous reactance is 10 Ω. Find the voltage regulation.

Solution:

Full load current $= \frac{100000}{\sqrt{3} \times 400} = 14.4\ A$

Voltage per phase $= \frac{400}{\sqrt{3}} = 231\ V$

At 0.8 lagging p.f Induced emf per phase, *Eo* $= \sqrt{(V \cos \phi + IR_a)^2 + (V \sin \phi + \ {}_S)^2}$

= $\sqrt{(231\times 0.8+14.4\times 0.5)^2+(231\times 0.6+14.4\times}$

= 342 Volts

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V}\times 100$

= $\frac{342-231}{231}\times 100 = 48\ \%$

Example 2.11 The following test results are obtained from a 3-phase ,600 KVA, 6600V, star connected ,2 pole, 50 Hz turbo alternator:

With a field current of 125 A, the open circuit voltage is 8000 V at the rated speed. With the same field current and rated speed, the short- circuit current is 800 A. at the rated full load, the resistance drop is 3 percent. Find the regulation of the alternator on full load and at a power factor of 0.8 lagging.

Solution:

Synchronous impedance, Z_s = $\frac{\text{open circuit voltage}}{\text{short circuit current}} = \frac{8000/\sqrt{3}}{800} = 5.77\Omega$

Voltage per phase = $\frac{6600}{\sqrt{3}} = 3810.5\ V$

Resistive drop = 3% of 3810.5 V

= 114.3 V

Load current = $\frac{600\times 10\text{^}3}{\sqrt{3}\times 6600} = 52.5\ A$

IR_a = 114.3

R_a = 114.3/52.5 = 2.177Ω

Synchronous reactance, Xs = $\sqrt{Zs^2 - Ra^2}$

Xs = $\sqrt{5.77^2 - 0.218^2} = 5.3435\ \Omega$

At 0.8 lagging p.f Induced emf per phase, Eo = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + {}_S)^2}$

= $\sqrt{(3810 \times 0.8 + 525 \times 0.218)^2 + (3810 \times 0.6 + 525 \times}$

= 4073.23 Volts

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

= $\frac{4073 - 3810}{3810} \times 100 = 6.89\ \%$

Example 2.12 A 3-phase 50 Hz star connected 2000 KVA, 2300 V alternator gives a short circuit current of 600 A for a certain field excitation. With the same excitation, the open circuit voltage was 900 V. the resistance between a pair of terminals was 0.12Ω. Find full load regulation at (i) UPF (ii) 0.8 p.f lagging.

Solution:

Synchronous impedance, Zs = $\frac{open\ circuit\ voltage}{short\ circuit\ current} = \frac{900/\sqrt{3}}{600} = 0.866\Omega$

Full load current = $\frac{2000 \times 10\text{^}3}{\sqrt{3} \times 2300} = 502\ A$

Resistance between the terminals is 0.12Ω . it is the resistance of two phase

connected in series Resistance /phase = 0.12 / 2 = 0.06Ω

Effective resistance / phase = $1.5 \times Ra$

= $1.5 \times 0.06 = 0.09\,\Omega$

Synchronous reactance, Xs = $\sqrt{Zs^2 - Ra^2}$

Xs = $\sqrt{0.866^2 - 0.09^2} = 0.86\,\Omega$

Voltage per phase = $\frac{2300}{\sqrt{3}} = 1328\,V$

At unity power factor Induced emf per phase, *Eo* = $\sqrt{(V + IR_a)^2 + (IXs}$

= $\sqrt{(1328 + 502 \times 0.06)^2 + (502 \times}$

= 1425 V

Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

= $\frac{1425 - 1328}{1328} \times 100 = 7.3\%$

At 0.8 lagging p.f Induced emf per phase, *Eo* = $\sqrt{(V \cos\phi + IR_a)^2 + (V \sin\phi + {}_s)^2}$

= $\sqrt{(1328 \times 0.8 + 502 \times 0.06)^2 + (1328 \times 0.6 + 502 \times}$

= 1644 Volts

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V} \times 100$

= $\frac{1643 - 1328}{1328} \times 100 = 23.7\%$

Example 2.13 A 500 KVA, three phase, star connected alternator has a rated line to line terminal voltage of 3300V. The resistance and synchronous reactance per phase are 0.3Ω and **_4.0 Ω respectively. Calculate the voltage regulation at full load, 0.8 power factor lagging._**

Solution:

Full load current = $\frac{500000}{\sqrt{3}\times 3300} = 87.5\,A$

Voltage per phase = $\frac{3300}{\sqrt{3}} = 1905\,V$

At 0.8 lagging p.f Induced emf per phase, *Eo* = $\sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + {}_s)^2}$

= $\sqrt{(1905\times 0.8 + 87.5\times 0.3)^2 + (1905\times 0.6 + 87.5\times}$

= 2152 Volts/phase

At 0.8 lagging p.f Percentage of voltage regulation = $\frac{E_o - V}{V}\times 100$

= $\frac{2152 - 1905}{1905}\times 100 = 12.96\,\%$

Example 2.14 A 1200 KVA, 3300V, 50 Hz, three phase, star connected alternator has armature resistance of 0.25Ω per phase. A field current of 40 A produces a short –circuit current of 200 A and an open –circuit emf of 1100 V line to-line. Calculate the regulation on **_(a) full load 0.8 power factor lagging; (b) full load 0.8 leading power factor_**

Solution:

Full load current = $\frac{1200000}{\sqrt{3}\times 3300} = 210\,A$

Voltage per phase = $\frac{3300}{\sqrt{3}} = 1905\,V$

Synchronous impedance, Z_s = $\frac{\text{open circuit voltage}}{\text{short circuit current}} = \frac{1100/\sqrt{3}}{200} = 3.175\Omega$

Synchronous reactance, X_s = $\sqrt{Zs^2 - Ra^2}$

$X_s = \sqrt{3.175^2 - 0.25^2} = 3.165\ \Omega$

(*a*) At 0.8 lagging p.f Induced emf per phase, *Eo*

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

$$= \sqrt{(1905 \times 0.8 + 210 \times 0.25)^2 + (1905 \times 0.6 + 210 \times}$$

$= 2398$ Volts

At 0.8 lagging p.f Percentage of voltage regulation

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

$$= \frac{2398 - 1905}{1905} \times 100 = 25.9\%$$

(*b*) At 0.8 leading p.f Induced emf per phase, *Eo*

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

$$= \sqrt{(1905 \times 0.8 + 210 \times 0.25)^2 + (1905 \times 0.6 - 210 \times}$$

$= 1647$ Volts

At 0.8 leading p.f Percentage of voltage regulation

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

$$= \frac{1647 - 1905}{1905} \times 100 = -13.54\ \%$$

2.10 M.M.F. or Ampere-turn Method:

For determining the regulation of an alternator by Magneto Motive force (MMF) method, the open circuit test and short circuit test are to be conducted on the alternator.

In this method, the armature leakage reactance and the effect of armature reaction are treated as mmf

The following steps are followed in this method for calculating the regulation

1. MMF in terms of field currents are calculated.
2. Field current (MMF) for the voltage of the vector sum of terminal voltage (V) and IR_a drop is found out from the O.C.C . Let this field current be I_{f1}.

3. Rated armature current is known. Then from the S.C.C, the value of field current is found out in order to produce the rated full load armature current on short circuit. Let this filed current I_{f2}.
4. This is the field current or MMF necessary to send the rated current against the effect of armature leakage reactance and the armature reaction.
5. The vector sum of the two field currents I_{f1} and I_{f2} are found out and let this value be I_{fr}.
6. For this current I_{fr} ,the corresponding e.m.f . on the open circuit characteristics is found out. This e.m.f is the no load e.m.f of the alternator E.
7. Knowing the no load EMF E, the regulation can be calculated as

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

Fig 2.11 Shows the OC and SC characteristics and also the vector diagram for lagging p.f load. For lagging p.f load the I_{f2} is drawn from I_{f1} by an angle (90+θ) as shown in fig 2.12 (a). The vector sum of I_{f1} and I_{f2} is I_{fr} . For this current I_{fr} , the corresponding e.m.f on the open circuit characteristics is found out. This is no load emf (E)

Hence

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

Can be calculated for lagging p.f.

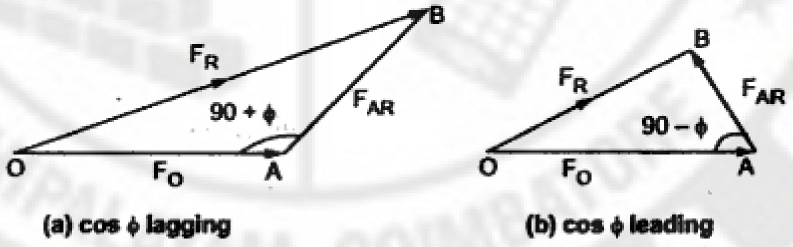


Fig 2.12

For leading p.f load , I_{f2} is drawn from I_{f1} by an angle (90-θ) as shown in Fig 2.12.(b) . the vector sum of I_{f1} and I_{f2} is I_{fr} . for this current I_{fr}, the corresponding e.m.f on open circuit characteristics is found out.

This e.m.f is no load e.m.f (E) . Then the

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

can be calculated for leading p.f

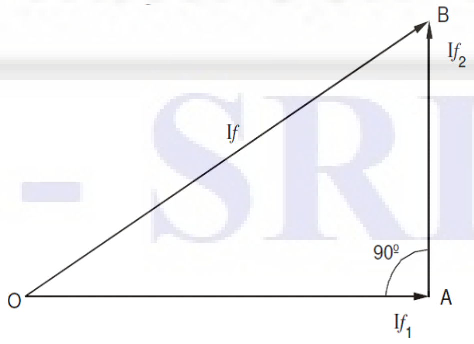


Fig 2.13

For unity p.f load ,I_{f2} is drawn 90^o from I_{f1} as shown in fig 2.13 the vector sum of I_{f1} and I_{f2} is I_{fr}. For this current I_{fr}, the corresponding e.m.f on O.C.C is found out. This e.m.f is no load e.m.f (E) . Then the

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

Can be calculated for unity p.f

2.11 Zero Power Factor or potier Method

This method gives more accurate results since it is based on the separation of armature leakage reactance drop and the armature reaction effects. The following experimental data is required in this method:

(i) No –load or open circuit curve
(ii) Full –load zero power factor curve (S.C.C)

The circuit diagram to conducting this test is shown in fig 2.14

From (ii) the reduction in voltage due to armature reaction is found out and volltage drop due to armature leakage reactance (also called potier reactance) X_L is found from both (i) and (ii). By combining the two, Eo can be calculated.

The above two curves are similar and displaced horizontally by the m.m.f due to armature reaction in terms of the field current.

Zero power factor test

To conduct zero power factor test, the switch 'S' is kept closed. Due to this, a purely inductive load is connected to the alternator through an ammeter. A purely inductive load has zero power factor lagging (i.e $\cos 90^o$). The machine speed is maintained constant at synchronous speed. Then by adjusting the field current such that the voltmeter reads rated voltage and by varying the inductance of the load, such that ammeter reads rated full load current.

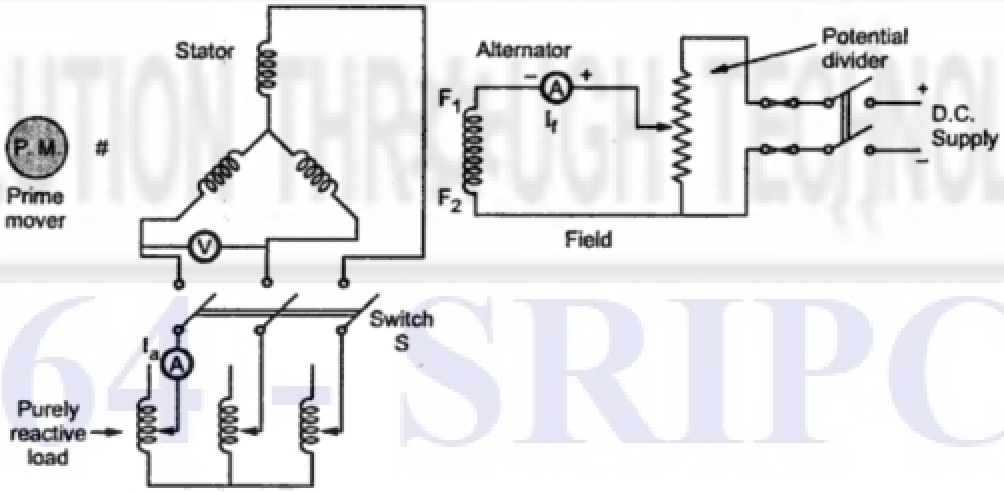


Fig 2.14

In this test there is no need to obtain number of points to obtain the curve. Only two points are enough to construct the zero power factor curve. This is the graph of terminal voltage against excitation when delivering full load zero power factor current.

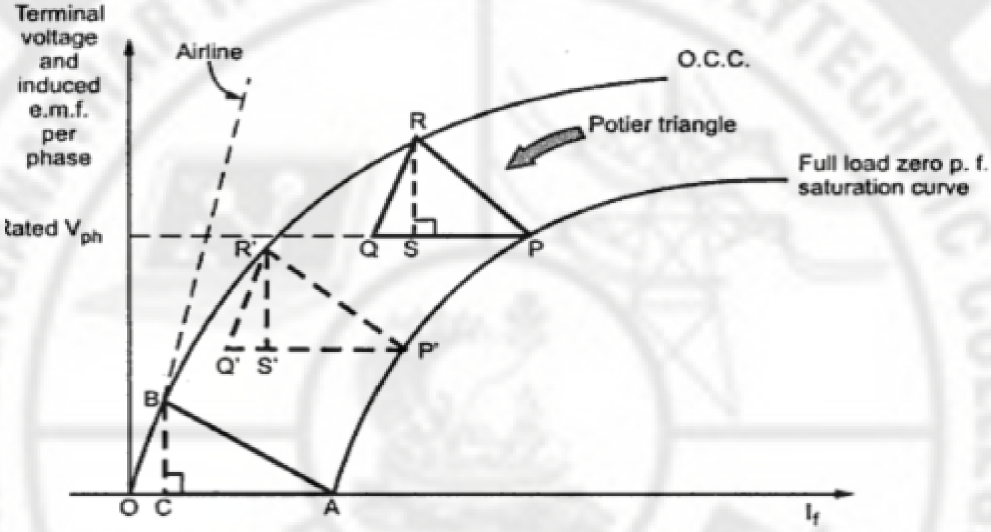


Fig 2.15

Zero power factor, full-load voltage excitation characteristics can be drawn by knowing two points A and P. point A is obtained from a short circuit test with full –load armature current. Hence OA represents field current (Excitation) required to overcome demagnetizing effect of armature reaction and to balance leakage reactance drop at full –load. Point P is obtained when full –load current flows through the armature and wattmeter reading is zero. Zero power factor curve may be drawn as follows:

(i) From P draw line PQ equal and parallel to OA.
(ii) Through point Q draw a line parallel to initial straight part of O.C.C (parallel to OB),cutting the O.C.C at R.
(iii) Join RQ and draw a perpendicular Line RS on PQ.
(iv) Impose the triangle PRS at various –points of O.C.C to obtain corresponding points on the zero power factor curve.

In triangle PRS

Length RS represents leakage reactance drop (IX_L)

Length PS represents armature reaction excitation. This shown in fig 2.15

Potier Regulation Diagram

Following is the procedure to draw potier regulation diagram:

(i) Draw OA horizontally to represent terminal voltage V on full load and OB to represent full load current (I) at a given power factor
(ii) Draw AC ($=IR_a$) ,voltage drop due to resistance (R_a) (if resistance is given)parallel to OB
(iii) Draw CD perpendicular to AC and equal to reactance drop IX_L. Now OD represents generated e.m.f E.
(iv) From O.C.C, find the field current I_1 corresponding to this generated e.m.f E and draw OF (equal to I_1) perpendicular to OD. Draw FG parallel to load current OB (i.e . I) to represent excitation (field current) equivalent to full load armature reaction.
OG gives total field current required.
(v) If the load is thrown off, then terminal voltage will be equal to generated e.m.f corresponding to field excitation OG. Hence e.m.f E_o may be obtained from

O.C.C corresponding to field excitation OG. Vector OJ will lag behind vector OG by 90^0 . DJ represents voltage drop due to armature reaction.

Now regulation may be obtained from the following relation:

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

2.12 Necessity for Parallel Operation of Alternators:

If the load on a single alternator at a power station becomes more than the rating of alternator, it becomes necessary to add another alternator in parallel to meet out the increasing load. For this reason, total output of a power station is supplied with a number of alternator connected in parallel to a common system of bus bars.

2.13 Condition for parallel operation:

- The terminal voltage of the incoming alternator must be the same as bus-bar voltage.
- The speed of the incoming machine must be such that its frequency (= PN/120) equals bus- bar frequency.
- The phase sequence of the alternator voltage must be identical with the phase sequence of the bus-bar voltage.

2.13.1 Advantages of Parallel operation:

- Increase the output capacity of a system beyond that of a single unit
- Serve as additional reserve power for expected demands
- Permit shutting down one machine and cutting in a standby machine without interrupting power distribution.

Methods of Synchronizing:

There are three methods of synchronizing for parallel operation

- Dark lamp Method
- Bright Lamp Method
- Synchroscope Method

2.14 synchronizing by Dark Lamp Method:

The connection for synchronizing a three phase alternator is shown in Fig 2.17 The alternator 1 is already connected with the bus-bar and is supplying power factor to the external circuit. The alternator 2 is the incoming alternator.

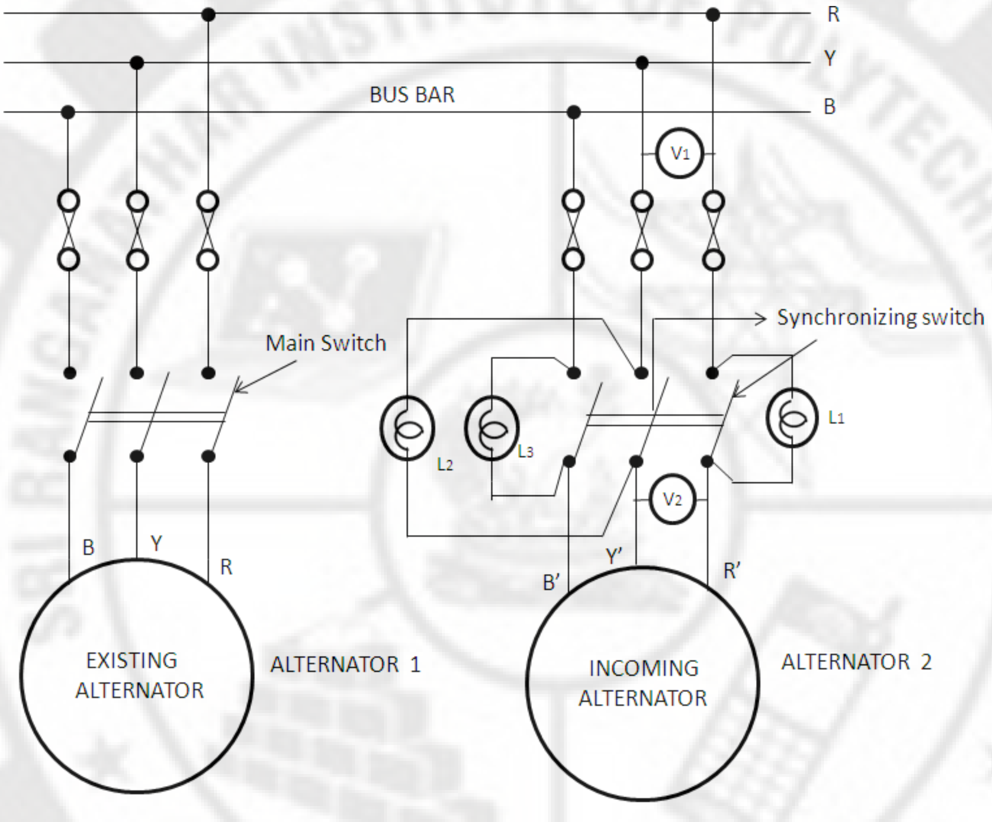


Fig : Dark lamp method

Fig 2.17

The incoming alternator started and its speed is adjusted to its rated value. Its excitation is also adjusted to generate its rated voltage. Voltmeter V_2 will indicate its voltage and voltmeter V_1 will indicate the bus-bar voltage. When the voltage V_1 and V_2 are equal, the condition 1 is satisfied.

The frequency of the incoming machine is adjusted to the bus-bar frequency by controlling the speed of the alternator 2. This fulfils the condition 2. The phase sequence also checked as mentioned above.

The synchronizing switch is closed at the middle of the lamps dark period. Now the incoming machine is connected to the bus-bar. At this stage, the generated emf of the incoming machine is just equal to the bus-bar voltage. It neither supply power nor receive power from the bus-bar, and the alternator 2 is said to be "floating on the bus-bar".

In dark lamp method, it is not possible to judge whether the incoming alternator is fast or slow. Also, the lamp can be dark even though a small value of voltage may present across its terminals. These are the disadvantages of dark lamp method. These disadvantage may not cause much in case of slow speed alternators or small capacity alternators. But it may cause harm and disturbance in case of high speed and large capacity alternators. The bright lamp method eliminates these difficulties.

2.15 Bright Lamp Method:

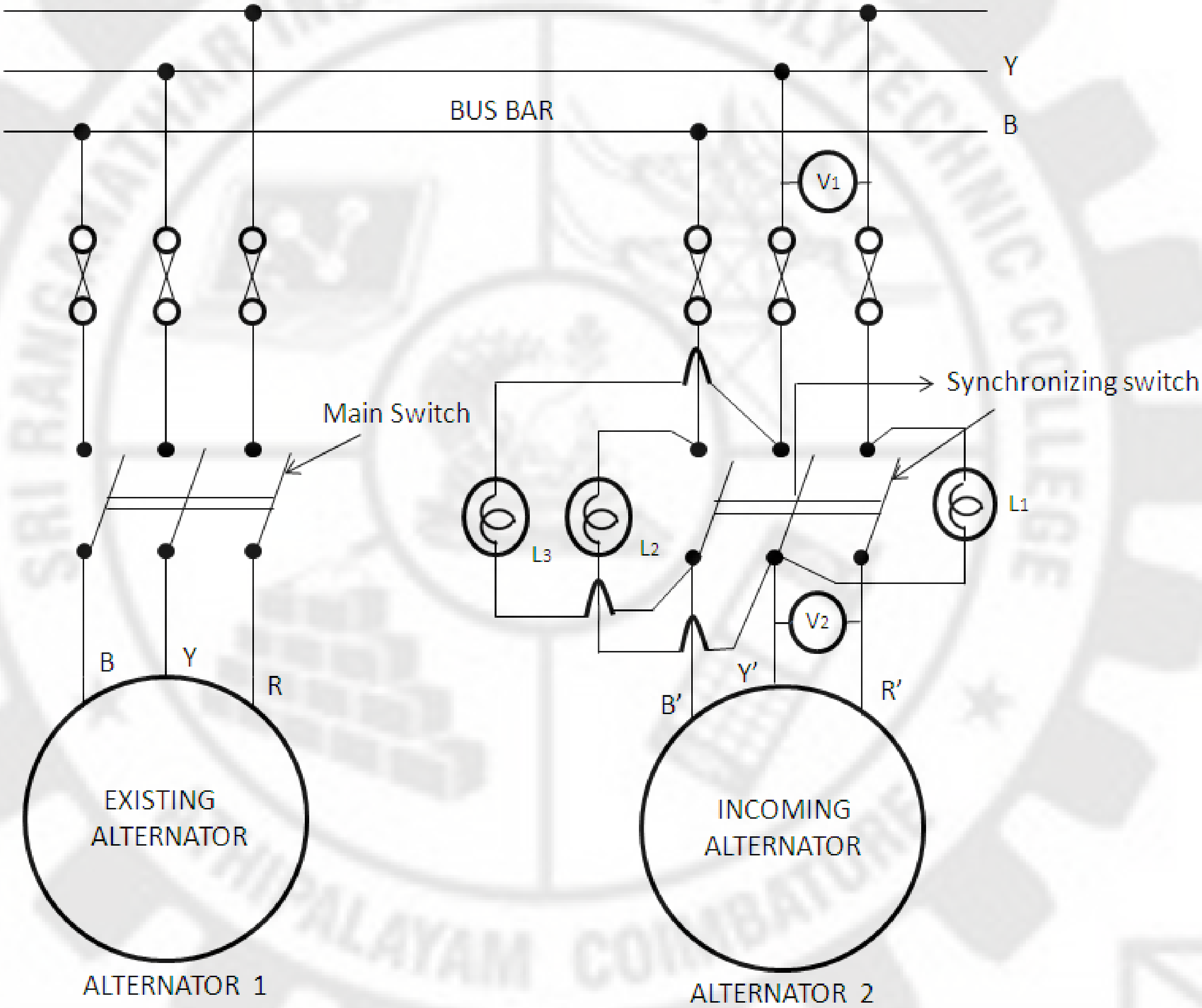


Fig : Bright lamp method

Fig 2. 18

In bright lamp method of synchronizing all three lamp connections have been reversed as shown in fig 2.18. AS in dark lamp method, the incoming machine is started, voltage and frequency are adjusted to bus-bar values. Phase sequence is checked by phase sequence indicator. Now the lamps are flickering proportional to the difference in frequencies of bus-bar and the incoming machine. The brightness of all the lamps are maximum when the voltages are in phase with the bus-bar. The synchronizing switch is closed at the middle period of the brightest period and thus the alternator is synchronized.

2.16 Two dark one bright Lamp method:

Fig 2.19 shows another method called the “rotating lamp method”, in which the lamp will flicker two bright, one dark, and two dark, one bright successively. The synchronizing switch is closed when the two lamps are bright and one lamp dark

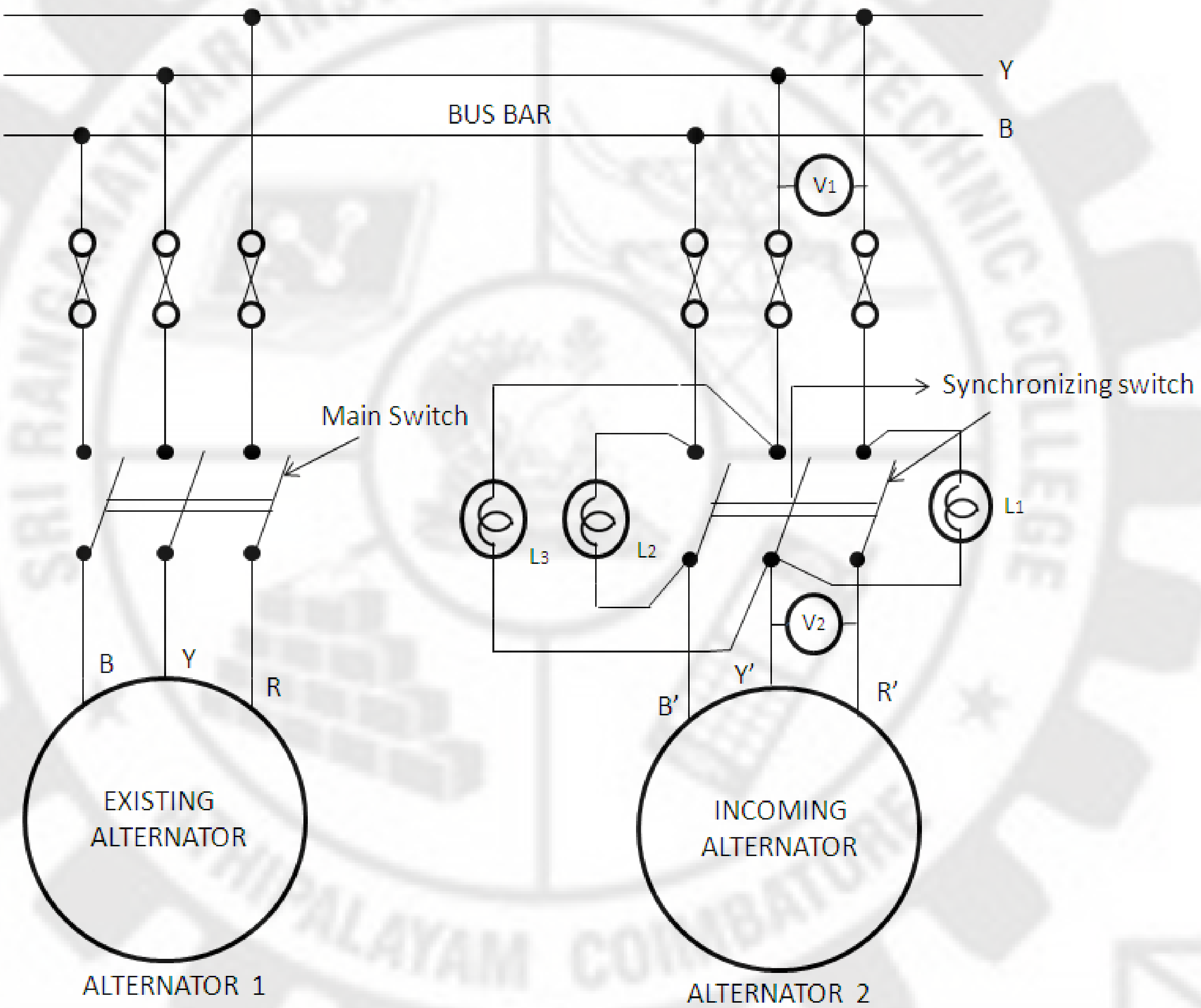


Fig : Rotating lamp method

Fig 2.19

2.17 Synchroscope Method:

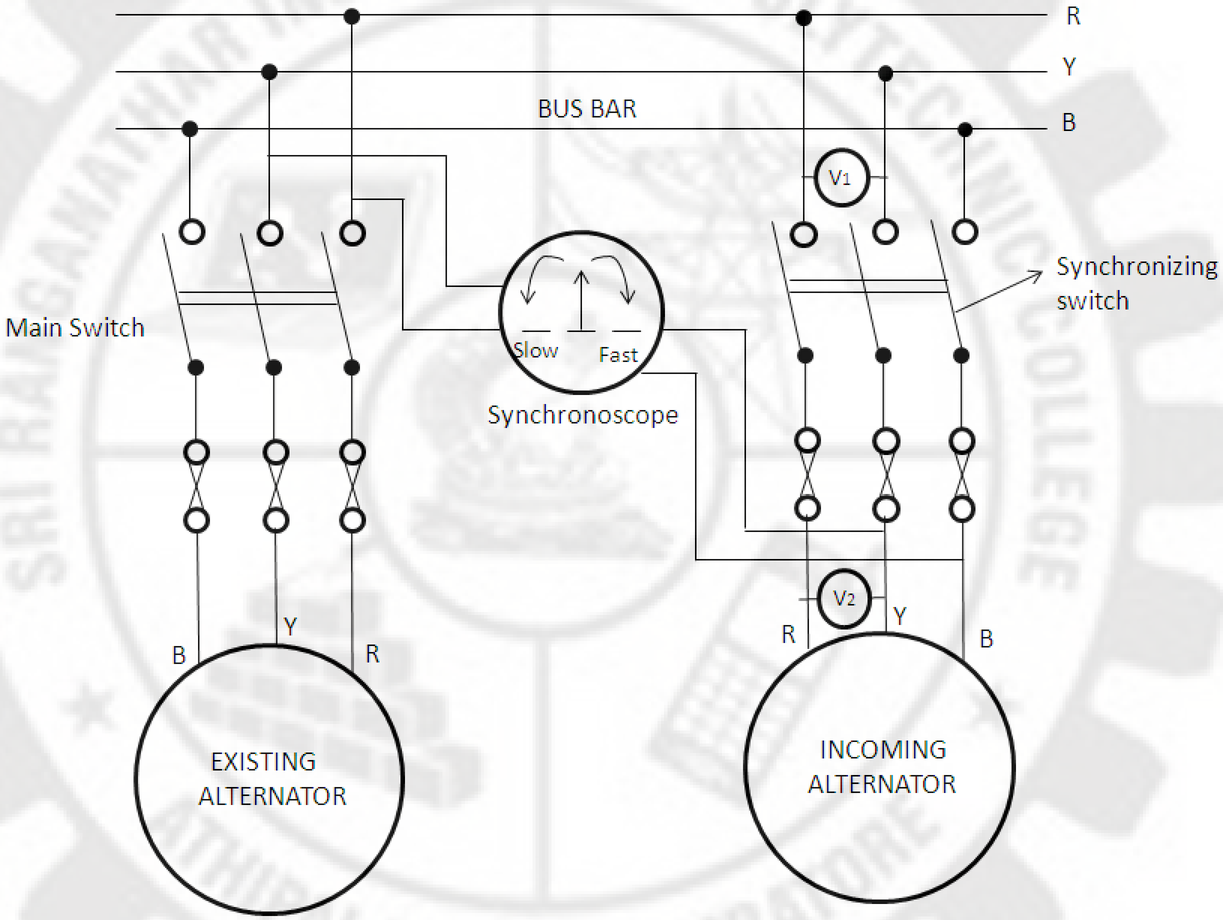


Fig : Synchroscope method

Fig 2.20

Synchronizing an alternator by using lamps is not very exact method, since it requires a correct judgment for closing the synchronizing switch. Therefore the lamps are replaced by a synchroscope. The synchroscope indicates not only the exact moment but also shows whether the incoming machine is fast or slow.

The synchroscope operates on the same principle as the power factor meter. It consist of a rotor and a stator. The rotor is connected to the incoming alternator, and the stator is connected to the bus- bar. A pointer is attached to the rotor. This pointer will indicate the correct time for closing the synchronizing switch. The correct time for synchronizing is the pointer points at 12^0 clock position.

Fig 2.20 shows the connection diagram for synchronizing the alternator by using synchroscope. In this case also, the phase sequence is checked by a phase sequence indicator or test lamp. After checking up the voltage and phase sequence as in previous cases, the incoming alternator is adjusted so that the pointer of the synchroscope rotates very slowly. If the frequencies are different values, the pointer will rotate. If the pointer rotates in the anticlockwise direction then the frequency of the incoming alternator is low. The clockwise direction of rotation of the pointer shows the frequency of the incoming alternator is higher than the frequency of the alternator 1 (Bus-bar). If the frequencies are equal, the pointer is at stationary position. The synchronizing switch is closed when the pointer is stationary at 12^0 clock position in the synchroscope. This is the correct instant for closing the switch. It is possible to parallel even the largest alternators without trouble.

2.18 Synchronizing Current:

Once a synchronous machine is synchronized, it will tend to remain in synchronism with the other alternators. Any tendency to depart from the condition of synchronism is opposed by a synchronizing torque produced due to circulating current flowing through the alternators.

When two alternators are in exact synchronism, the two alternators have equal induced emfs which are in exact phase opposition as shown in Fig.2.21 a, no circulating current flows round the local circuit.

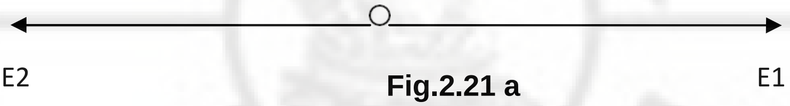


Fig.2.21 a

When the induced emfs of the two alternators are equal in magnitude but not in exact phase opposition as shown in fig.2.21 b, their resultant emf acts round the local circuit causes flow of current called the **synchronizing current, I_{sy}.**

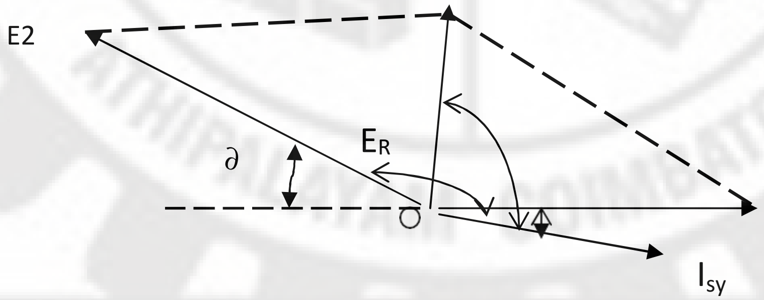


Fig.2.21b

If any alternator due to some disturbance tends to retard, E_2 falls back by a phase angle δ electrical degrees, as shown in fig.2.13b.

Now though their induced emfs E_1 and E_2 are in equal in magnitude but have a phase difference of $180^\circ - \delta$. Let each of the induced emfs E_1 and E_2 be equal to E.

Resultant emf, $E_R = 2E\cos\left[\frac{180^\circ - \delta}{2}\right] = 2E\cos\left(90 - \frac{\delta}{2}\right) = 2E\sin\frac{\delta}{2}$

$= 2E \times \frac{\delta}{2} = E\delta$ $\quad\therefore \delta$ is very small

Synchronizing Current, $I_{sy} = \frac{E_R}{Z_S} = \frac{E\delta}{Z_S}$

Where, Z_S is the combined synchronous impedance per phase of the two alternators

The synchronizing current I_{SY} lags behind the resultant emf E_R by an angle θ given by

$$\theta = \tan^{-1}\frac{X_S}{R_e}$$

Where, X_s is the combined synchronous reactance and R_e is the effective resistance of the two alternators. If resistance R_e is very small as compared to synchronous reactance Xs then,

Synchronizing Current, $I_{sy} = \frac{E\delta}{X_S}$ and lags behind E_R by 90°

2.19 Synchronizing Power:

In the parallel operation, machine no.1 supplies power equal to $E_1 I_{SY} \cos\phi_1$ and the machine no.2 receives power equal to $E_2 I_{SY} \cos(180^\circ - \phi_2)$.

The power supplied by the machine no.1= Power supplied to machine no.2 + copper loses.

The power supplied by the machine no.1 is called *synchronizing power* and is given by the expression

$$P_{SY} = E_1 I_{SY} \cos\phi_1 = E_1 I_{SY} = E \times \frac{E\delta}{X_S} = \frac{\delta E^2}{X_S} \quad \because E_1 = E \text{ and } \phi \text{ is very small}$$

Total synchronizing power for 3 phases = $3P_{sy} = \frac{3\delta E^2}{X_S}$

2.20 Synchronizing Torque:

If T_{sy} be the synchronizing torque in Nm, then the total synchronizing power $3P_{sy} = T_{SY} \times \frac{2\pi N_S}{60}$

Or synchronizing torque, $T_{SY} = \frac{3P_{SY} \times 60}{2\pi N}$

s

2.21 Load Sharing Between Two Alternators:

Consider two machines with identical speed –load characteristics running in parallel with a common terminal voltage of V volts and load impedance Z.

Let the generated emfs of the two machines1 and 2 operating in parallel be E1 and E2 respectively and synchronous impedance per phase be Zs_1 and Zs_2 respectively.

$$Terminal\,Voltage\,of\,Machines1, \boldsymbol{V} = E_1 - I_1 Z_{s1} ----------(1)$$

Similarly

$$Terminal\,Voltage\,of\,Machines2, \boldsymbol{V} = E_2 - I_2 Z_{s2} --------(2)$$

Also

$$\boldsymbol{V} = IZ = (I_1 + I_2)Z ------------------(3)$$

From Equation (1) and (2), we have

$$I_1 = \frac{E_1 - V}{Z_{s1}} ---------------(4)$$

And

$$I_2 = \frac{E_2 - V}{Z_{s2}} ------------(5)$$

Adding equation (4) and (5) and we have

$$I_1 + I_2 = \frac{E_1 - v}{Z_{s2}} + \frac{E_2 - V}{Z_{s2}}$$

or

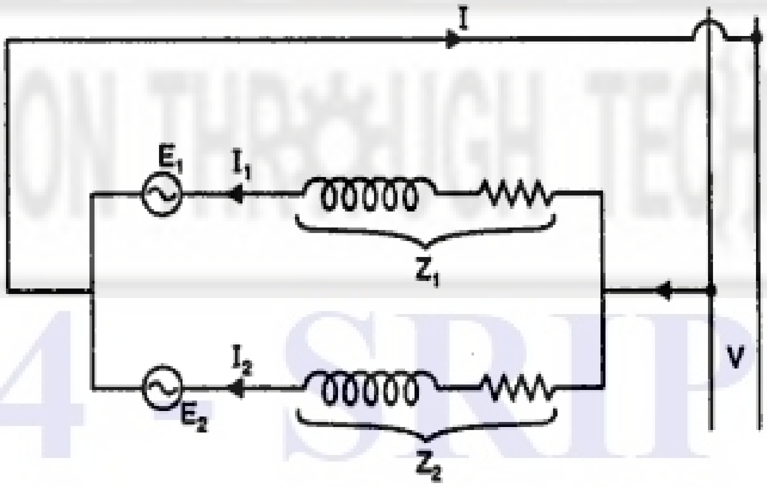


Fig.2.22 Equivalent circuit for two alternators in parallel

$$\frac{V}{Z} = \frac{E_1 - V}{Z_{s1}} + \frac{E_2 - V}{Z_{s2}}$$

From Equation (3)

$$I_1 + I_2 = \frac{V}{Z}$$

or

$$V\left(\frac{1}{Z_{s1}} + \frac{1}{Z_{s2}} + \frac{1}{Z}\right) = \frac{E_1}{Z_{s1}} + \frac{E_2}{Z_{s2}}$$

or

$$V = \frac{\frac{E_1}{Z_{s1}} + \frac{E_2}{Z_{s2}}}{\frac{1}{Z_{s1}} + \frac{1}{Z_{s2}} + \frac{1}{Z}} -------------(6)$$

2.22 Infinite Bus Bar:

It is the general practise to operate a number of alternators in parallel in the generating stations. A power system with a large number of alternators connected in parallel is called Infinite bus bar.

When large number of alternators are connected in parallel to an infinite bus-bar, the synchronous impedance of the system is reduced to a very small value.(Since all the alternators are connected in parallel). Irrespective of the changes or variations of the electrical loads on the system, the terminal voltage and the bus-bar frequency are constant in an infinite bus-bar system.

Unit - 3

THREE PHASE INDUCTION MOTORS

3.1 INTRODUCTION

In the year 1821 British scientist Michael Faraday explained the conversion of electrical energy into mechanical energy by placing a current carrying conductor in a magnetic field which resulted in the rotation of the conductor due to torque produced by the mutual action of electrical current and magnetic field. Based on his principle the most primitive of machines a DC (Direct Current) machine was designed by another British scientist William Sturgeon in the year 1832. But his model was overly expensive and wasn't used for any practical purpose. Later in the year 1886 the first electrical motor was invented by scientist Frank Julian Sprague, that was capable of rotating at a constant speed under a varied range of load, and thus derived motoring action.

3.1.1 Types of AC motor

- **Classification Based On *Principle Of***

Operation*: *(a) Synchronous Motors.

1. Plain

2. Super

(b) Asynchronous Motors.

1. Induction Motors:

(a) Squirrel Cage

(b) Slip-Ring (external resistance).

2. Commutator Motors:

(a) Series

(b) Compensated

(c) Shunt

(d) Repulsion

(e) Repulsion-start induction

(f) Repulsion induction

- Classification ***Based On no of phases:***

1. Single Phase

2. Three Phase

- Classification Based On ***<u>Speed Of Operation:</u>***

1. Constant Speed.
2. Variable Speed.
3. Adjustable Speed.

- Classification Based On ***<u>Structural Features:</u>***

1. Open
2. Enclosed
3. Semi-enclosed
4. Ventilated
5. Pipe-ventilated
6. Riveted frame-eye etc..

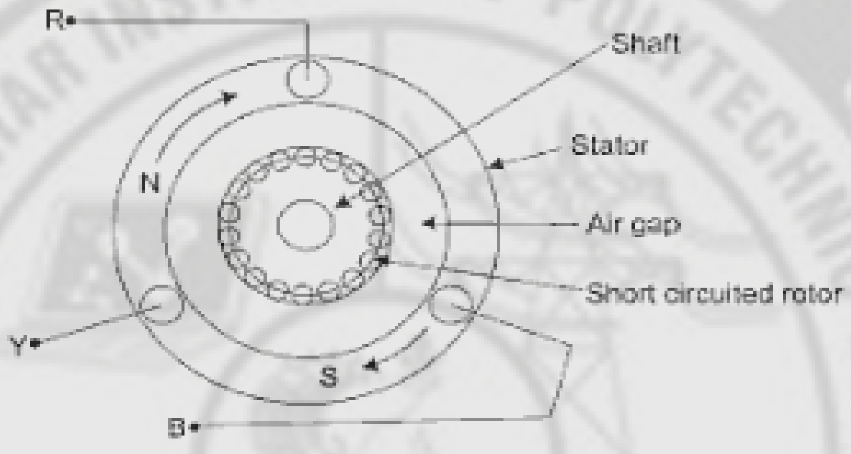
3.2 General principle of operation

Conversion of electrical power into mechanical power takes place in the rotating part of an electrical motor .In dc motor the electrical power is conducted directly to the armature through brushes and commentator hence in this sense a dc motor can be called as conduction motor. However in ac motor the rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary that is why such motor are know as induction motors .infact a induction motor can be treated as a rotating transformer i.e. one in which primary winding is stationary but the secondary as free to rotate.

3.2.1 Principles of operation of three phase induction motor:

Why a 3-Ø Induction motor is self-starting? How the rotor does rotate?

i. When a 3-Ø stator winding having a space displacement of 120° electrical is energized from a 3- Ø supply having 120° time displacement a rotating magnetic field is setup in the stator.
ii. This rotating magnetic field rotates with synchronous $N_s = \frac{120f}{P}$ with respect to speed stationary in the air gap
iii. This rotating field passes through the air gap and cuts the stationary rotor conductors
iv. Due to the relative speed between the rotating flux and the stationary rotor EMFs are induced in the rotor conductors



3-ɸ Induction motor (shorted rotor) (two pole)

Fig 3.1

v. If the rotor conductors are short circuited, currents start flowing in the rotor conductor

vi. According to Len's law the direction of the induced current is such that it opposes the cause.

vii. Cause is the relative speed between the rotating field and stationary rotor

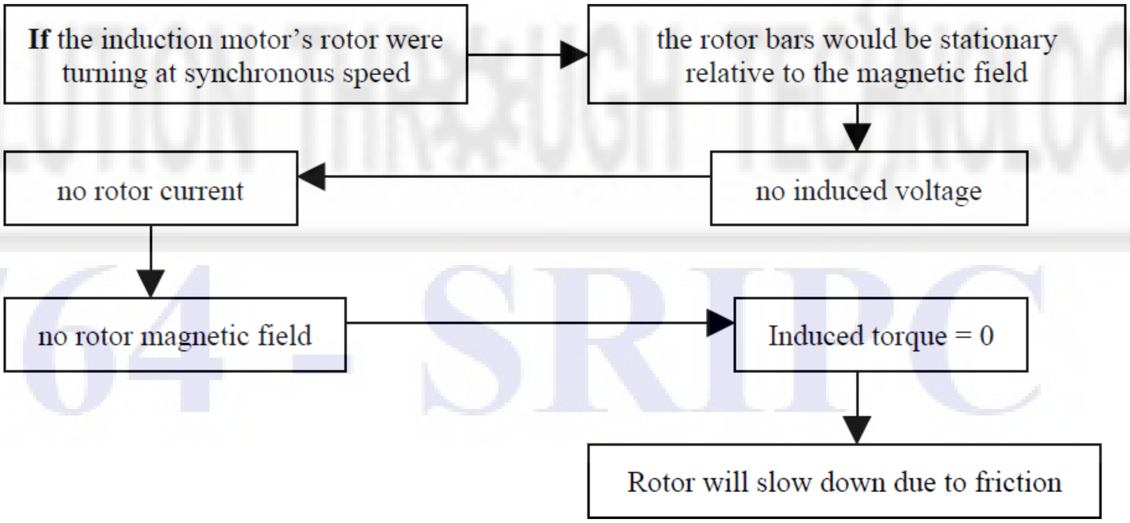
viii. Hence, a rotor has a tendency to reduce the relative speed

ix. So rotor begins to move in the direction of rotating field and continues towards synchronous speed and the machine runs at a speed near but below synchronous speed depending upon load on shaft

x. As the speed of rotor reaches to synchronous speed (speed of field) relative speed is zero. Hence no emf, no current and therefore no torque at synchronous speed. Hence rotor never reaches to synchronous speed.

xi. At synchronous speed current is zero in rotor conductor hence no force acting on rotor conductor and slip back, somewhat less speed than synchronous speed.

Why 3phase induction motor does not run at synchronous speed?



An induction motor can thus speed up to near synchronous speed but it can never reach synchronous speed.

Advantages

Thus the three phase induction motor is:

- Self-starting.
- Less armature reaction and brush sparking because of the absence of commutators and brushes that may cause sparks.
- Robust in construction.
- Economical.
- Easier to maintain.

Disadvantages

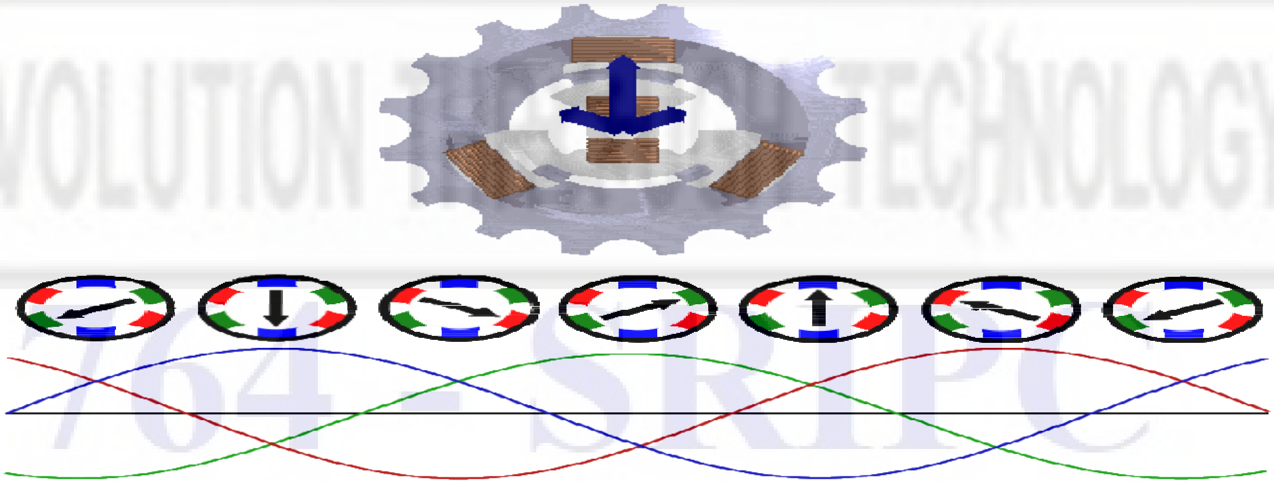
- Its speed cannot be varied without sacrificing some of its efficiency.
- Just like a dc shunt motor its speed decreases with increase in load.
- Its starting torque is somewhat inferior to that of a dc shunt motor.

3.3 Rotating Magnetic Field

The fundamental principle of operation of AC machines is the **generation of a rotating magnetic field**, which causes the rotor to turn at a speed that depends on the speed of rotation of the magnetic field.

Production of Rotating Magnetic Field

The stator of the motor consists of overlapping winding offset by an electrical angle of 120°. When the primary winding or the stator is connected to a 3 phase AC source, it establishes a rotating magnetic field which rotates at the synchronous speed.



Rotating 3-phase magnetic field

Fig 3.2

3.3.1 Rotating magnetic field produced by Three phase:

It will now be shown that when three-phase windings displaced in space by 120º, are fed by three phase currents, displaced in time by 120º, they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

The principle of a 3-phase, two-pole stator having three identical windings placed 120 space degrees apart is shown in Fig. 3.4 The flux (assumed sinusoidal) due to three-phase windings is shown in Fig 3.3

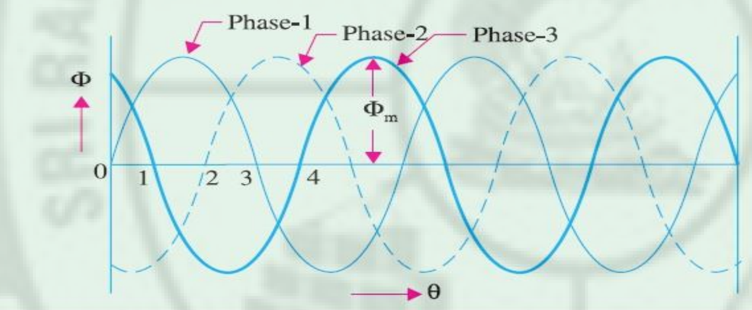


Fig.3.3

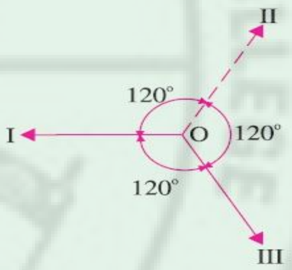


Fig.3.4

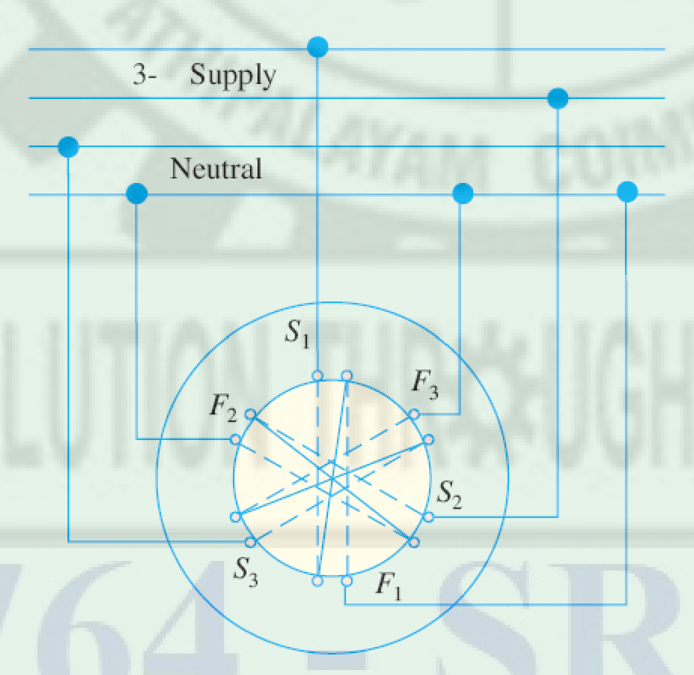


Fig 3.5

The assumed positive directions of the fluxes are shown in Fig 3.3. Let the maximum value of flux due to any one of the three phases be Φ_m.

The resultant flux Φ_r, at any instant, is given by the vector sum of the individual fluxes, Φ_1, Φ_2 and Φ_3 due to three phases. We will consider values of Φ_r at four instants 1/6th time-period apart corresponding to points marked 0, 1, 2 and 3 in Fig. 3.3.

When $\theta = 0^\circ$ i.e corresponding to point 0 in Fig.3.6. Here $\Phi_1 = 0, \Phi_2 = -\frac{\sqrt{3}}{2}\Phi_m, \Phi_3 = \frac{\sqrt{3}}{2}\Phi_m$

The vector for Φ_2 in fig 4.8 (i) is drawn in a direction opposite to the direction assumed in Fig.3.4

$$\therefore \Phi_r = 2 \times \frac{\sqrt{3}}{2}\Phi_m \cos\frac{60^\circ}{2} = \sqrt{3} \times \frac{\sqrt{3}}{2}\Phi_m = \frac{3}{2}\Phi_m$$

(i) When $\theta = 60^\circ$ i.e corresponding to point 1 in Fig.3.3.

Here $\Phi_1 = \frac{\sqrt{3}}{2}\Phi_m$ ……… drawn parallel to OI of Fig.3.4 as shown in Fig.3.6 (ii)

$\Phi_2 = -\frac{\sqrt{3}}{2}\Phi_m$ ……… drawn in opposition to OI of Fig.3.4

$\Phi_3 = 0$

$$\therefore \Phi_r = 2 \times \frac{\sqrt{3}}{2}\Phi_m \times \cos 30^\circ = \frac{3}{2}\Phi_m$$

It is found that the resultant flux is $\frac{3}{2}\Phi_m$ but has rotated clockwise through an angle of 60º again

(ii) When $\theta = 120^\circ$ i.e corresponding to point 2 in Fig.3.3

Here, $\Phi_1 = \frac{\sqrt{3}}{2}\Phi_m$, $\Phi_2 = 0$, $\Phi_3 = -\frac{\sqrt{3}}{2}\Phi_m$

It can be again proved that $\Phi r = \frac{3}{2}\Phi_m$

So that resultant is again of the same value, but has further rotated clockwise through an angle of 60° [Fig.3.6 (iii)]

(iii) When $\theta = 180^\circ$ i.e corresponding to point 3 in Fig.3.3

$\Phi_1 = 0$, $\Phi_2 = \frac{\sqrt{3}}{2}\Phi_m$, $\Phi_3 = -\frac{\sqrt{3}}{2}\Phi_m$

The resultant is $\Phi r = \frac{3}{2}\Phi_m$ and has rotated clockwise through an additional angle 60° or through an angle of 180◦ from the start.

ence, we conclude that

1. The resultant flux is of constant value = $\frac{3}{2}\Phi_m$ i.e. 1.5 times the maximum value of the flux due to any phase.

2. The resultant flux rotates around the stator at synchronous speed given by $N_s = 120\, f/P$.

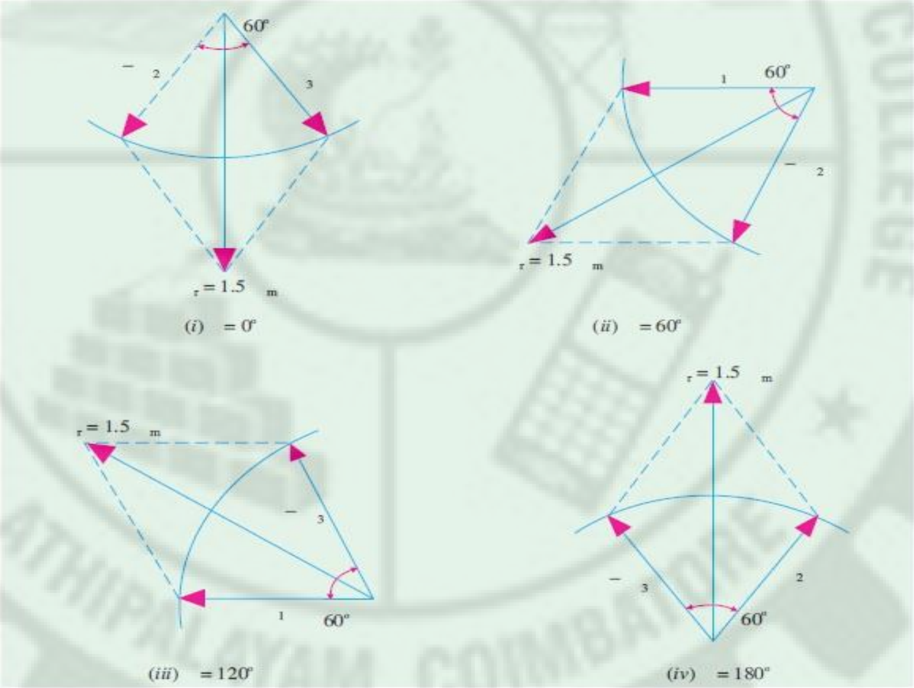


Fig.3.6

Fig. 3.7 (*a*) shows the graph of the rotating flux in a simple way. As before, the positive directions of the flux phasors have been shown separately in Fig. 3.7 (*b*).

Arrows on these flux phasors are reversed when each phase passes through zero and becomes negative.

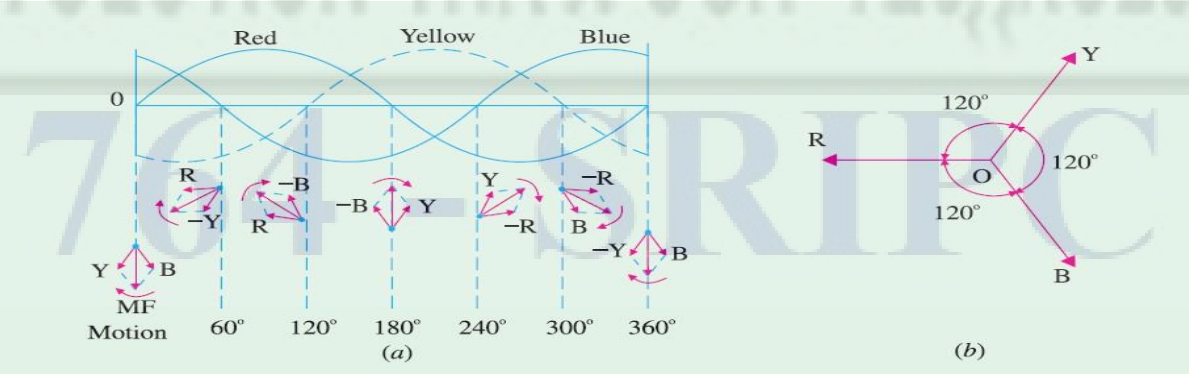


Fig.3.7

3.3.2 Construction of Three Phase Induction:

An Induction motor consists of mainly two parts:

(a) Stator **(b)**

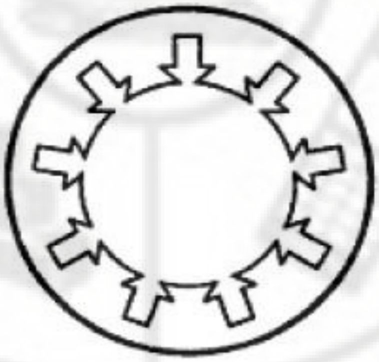
Stator:

(i) Stator core is made of laminated steel stampings and has slots and teeth on its inner periphery to house stator windings. The stampings are 04.to 0.5 mm thick.

(ii) Stator carries a 3-phase winding having space displacement of 120° electrical

(iii) The 3-phase winding is either star or delta connected and is fed from 3-phase supply

(iv) The radial ventilating ducts are provided along the length of the stator core



Stator Stamping

Rotor:

i. Rotor comprises a cylindrical laminated iron core, with slots on outer periphery
ii. Like stator, rotor lamination are punched in one piece for small Machine
iii. In larger machine the lamination are segmented
iv. If there are ventilating ducts on the stator core, an equal number of such ducts is provided on rotor core

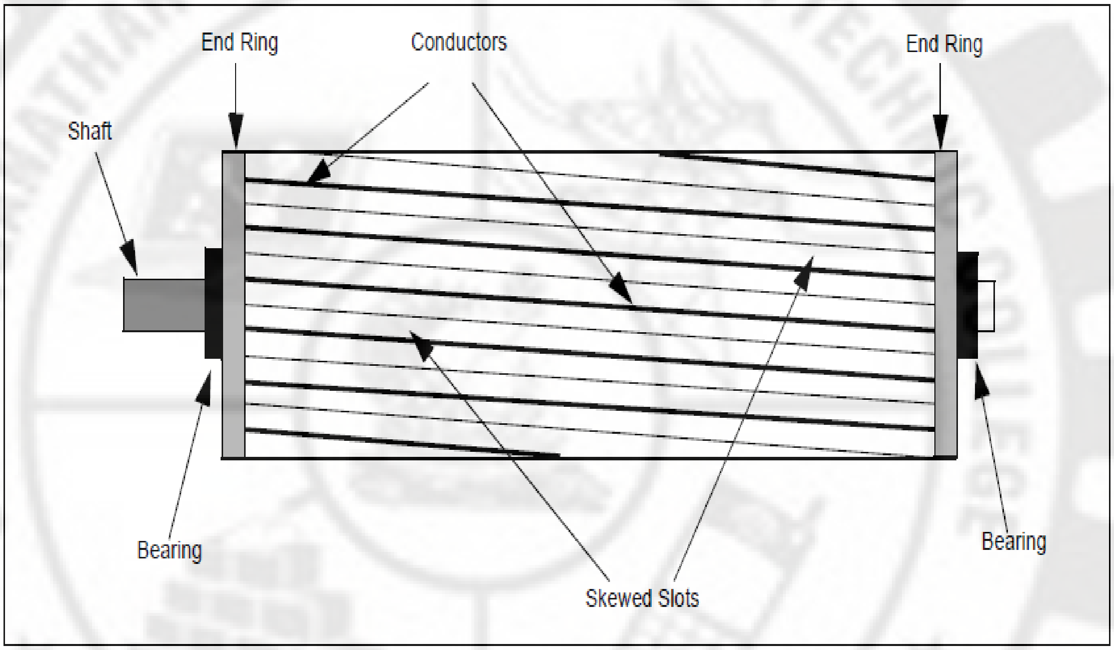
According to windings rotor are of two types:

a) Squirrel cage rotor
b) Slip ring or wound rotor

Squirrel Cage Rotor:

i. This rotor consists of a cylindrical laminated core with parallel slots
ii. Rotor slots are usually not quite parallel to the shaft but for reducing the magnetic hum and locking tendency rotor slots are slight skew
iii. In rotor slots heavy copper, aluminum or alloy bars are housed

iv. Rotor bars are permanently short circuited at the ends. This limits that no external resistance insertion is possible



Squirrel cage rotor

Advantages of squirrel cage induction rotor-

- Its construction is very simple and rugged.
- As there are no brushes and slip ring, these motors requires less maintenance.

Applications:

- Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

3.4 Slip Ring or Wound Rotor:

i. The rotor is wound for the same number of poles and number of phase as that of stator

ii. Rotor winding is either star or delta but star connection is preferred

iii. The three star terminals are connected to three brass slip ring mounted on rotor shaft

iv. These slip rings are insulated from rotor shaft

v. Slip rings connected with brushes and three brushes can further be connected externally to 3- variable rheostats

vi. This makes possible introduction to additional resistance in the rotor circuit during starting period

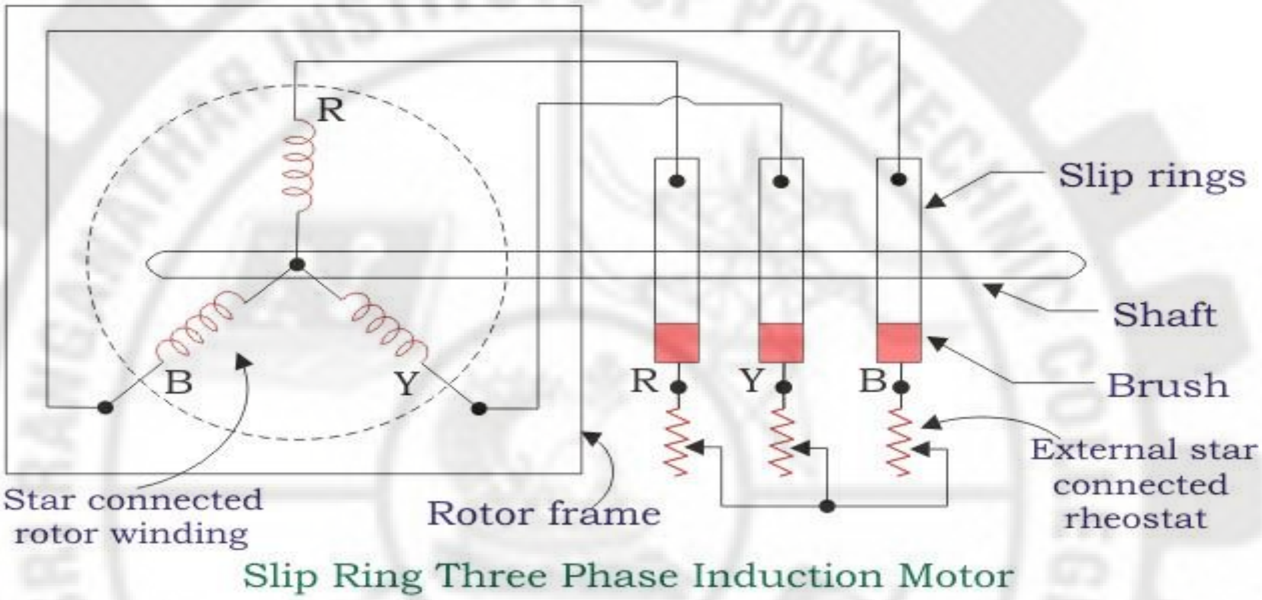


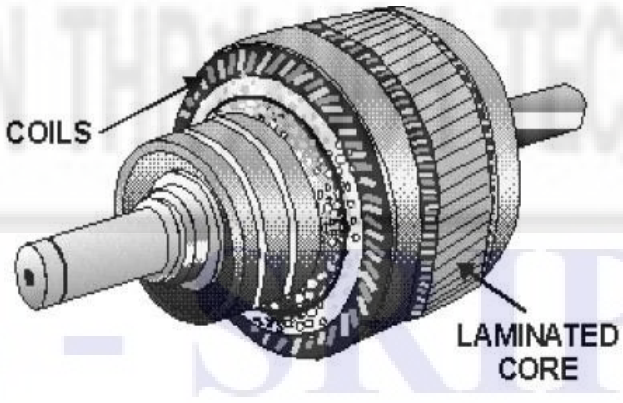
Fig.3.8 Wound rotor

Advantages of slip ring induction motor -

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

Application:

- Slip ring induction motor are used where high starting torque is required i.e. in hoists, cranes, elevator etc.



3.5 Difference between Slip Ring and Squirrel Cage Induction Motor

Slip ring or phase wound Induction motor	***Squirrel cage induction motor***
Construction is complicated due to presence of slip ring and brushes	Construction is very simple
The rotor winding is similar to the stator winding	The rotor consists of rotor bars which are permanently shorted with the help of end rings
We can easily add rotor resistance by using slip ring and brushes	Since the rotor bars are permanently shorted, it's not possible to add external resistance
Due to presence of external resistance high starting torque can be obtained	Staring torque is low and cannot be improved
Slip ring and brushes are present	Slip ring and brushes are absent
Frequent maintenance is required due to presence of brushes	Less maintenance is required
The construction is complicated and the presence of brushes and slip ring makes the motor more costly	The construction is simple and robust and it is cheap as compared to slip ring induction motor
This motor is rarely used only 10 % industry uses slip ring induction motor	Due to its simple construction and low cost. The squirrel cage induction motor is widely used
Rotor copper losses are high and hence less efficiency	Less rotor copper losses and hence high efficiency
Speed control by rotor resistance method is possible	Speed control by rotor resistance method is not possible
Slip ring induction motor are used where high starting torque is required i.e in hoists, cranes, elevator etc	Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

3.6 Slip and Slip frequency:

The relative speed between the rotating magnetic field (n_s) and rotor (n_r) is called slip speed.

$$slip\ speed = n_s - n_r \quad rps$$

Slip :

Percentage change in slip speed is called as slip

$$slip = \frac{n_s - n_r}{\quad}\times 100 \Rightarrow$$

$$n_s n_r = n_s(1 - s)$$

When rotor is stationary $n_r = 0$, s=1 or 100%

Typical values of slip between no load and full load are about 4 to 5 percent for small motor and 1.5 to 2 percent for large motor

When the rotor is stationary, rotor emf having same frequency as stator emf

$$E_S = \sqrt{2}\pi f \quad N_1\Phi \qquad E_r = \sqrt{2}\pi f N_2\Phi$$

$$\text{Frequency} = \frac{Poles \times relativespeed\ orslipspeed}{120}$$

Frequency of the rotor induced emf

$$f_r = \frac{P(n_s - n_r)}{120}$$

but

$$s = \frac{n_s - n_r}{n_s} \Rightarrow sn_s = n_s - n_r$$

So

$$f_r = \left(\frac{Psn_s}{n_r}\right), f_{stator} = \frac{Pn_s}{120}$$

$$f_r = sf_s$$

As rotor picks up speed hence rotor current frequency decreases. When rotor is rotating

$$E_{stator} = \sqrt{2}\pi f_s N_1 \Phi k_w \text{ and } f_r = s f_{stator}$$

$$E_{rotor} = \sqrt{2}\pi f_r N_2 \Phi k_w$$

$$E_r = S E_S$$

Rotor EMF:

When the rotor is at standstill, the motor is equivalent to a 3-phase transformer with secondary short circuited. So induced emf per phase E_2 in the rotor, when it is at standstill i.e. at the instant of starting is given by

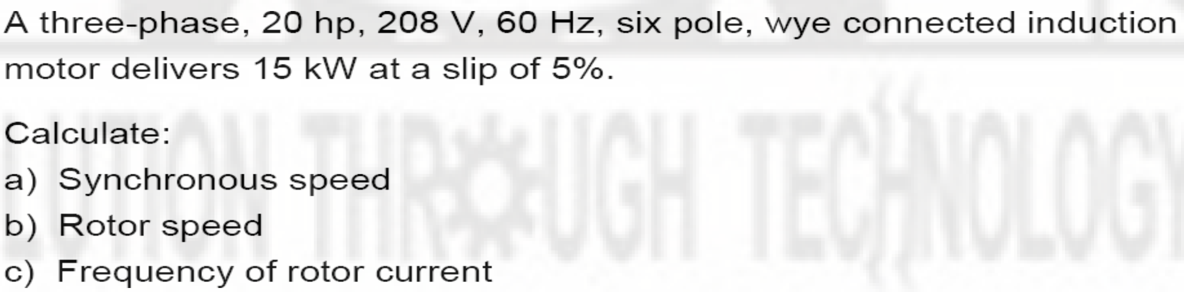
$$E_2 = E_1 \times \frac{N_2}{N_1}$$

Where E_1 is applied voltage per phase to primary i.e. stator winding, N_2 and N_1 are the number of turns per phase on rotor and stator respectively.

When the rotor starts running, the relative speed of the rotor with respect to stator flux i.e. slip s drops in direct proportion with the relative speed or slip s is given by sE_2

Hence for slip s, the induced emf in the rotor is s times the induced emf in the rotor at standstill.

Example 1



A three-phase, 20 hp, 208 V, 60 Hz, six pole, wye connected induction motor delivers 15 kW at a slip of 5%.

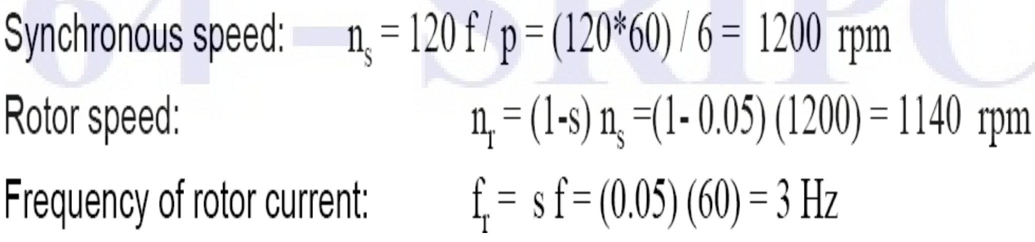
Calculate:

a) Synchronous speed

b) Rotor speed

c) Frequency of rotor current

Solution:



Synchronous speed: $n_s = 120\,f / p = (120{*}60) / 6 = 1200$ rpm

Rotor speed: $n_r = (1-s)\, n_s = (1-0.05)(1200) = 1140$ rpm

Frequency of rotor current: $f_r = s\,f = (0.05)(60) = 3$ Hz

3.7 Phasor Diagram of Induction Motor

The phasor diagram of loaded induction motor is similar to the loaded transformer. The only difference is the secondary of induction motor is rotating and short circuited while transformer secondary is stationary and connected to load. The load on induction motor is mechanical while load on transformer is electrical. Still by finding electrical equivalent of mechanical load on the motor, the phasor diagram of induction motor can be developed.

Let Φ = Magnetic flux links with both primary and

There is self induced e.m.f. E_1 in the stator while a mutually induced e.m.f. E_{2r} in the rotor.

Let R_1 = Stator resistance per

X_1 = Stator reactance per phase

The stator voltage per phase V_1 has to counter balance self induced e.m.f. $E_1$and has to supply voltage drops $I_1 R_1$ and $I_1 X_1$. So on stator side we can write,

$$\overline{V_1} = -\overline{E_1} + \overline{I_1R_1} + j\,\overline{I_1X_1} = \overline{E_1} + \overline{I_1}\,(R_1 + j\,X_1) = -\overline{E}_1 + \overline{I}_1\overline{Z}_1$$

The rotor induced e.m.f. in the running condition has to supply the drop across impedances as rotor short circuited.

$$\therefore \quad \overline{E}_{2r} = \overline{I_{2r}R_2} + j\overline{I_{2r}X_2} = \bar{I}_{2r}\,(R_2 + jX_2) = \overline{I_{2r}}\ \overline{Z_{2r}}$$

The value of E_{2r} depends on the ratio of rotor turns to stator turns.

The rotor current in the running condition is I_{2r} which lags E_{2r} by rotor p.f. angle Φ_{2r}.

The reflected rotor current I_{2r}' on stator side is the effect of load and is given by,

$I_{2r}' = K\, I_{2r}$

The induction motor draws no load current I_o which is phasor sum of I_c and I_m. The total stator current drawn from supply is,

$\bar{I}_1 = \bar{I}_o + \bar{I}_{2r}'$

The Φ_1 is angle between V_1 and I_1 and cos Φ_1 gives the power factor of the induction motor.

Thus using all above relations the phasor diagram of induction motor on load can be obtained.

The steps to draw phasor diagram

are, 1. Takes Φ as reference phasor.

2. The induced voltage E_1 lags Φ by

90°. 3. Show - E_1 by reversing voltage

phasor.

4. The phasor E_{2r} is in phase with E_1. So I_{2r} show lagging E_{2r} i.e. E_1 direction by Φ_{2r}.

5. Show $I_{2r} R_2$ in phase with I_{2r} and $I_{2r} X_{2r}$ leading the resistive drop by 90^o, to get exact location of. 6. Reverse I_{2r} to get I_{2r}'.

7. I_m is in phase with Φ while Ic is at leading with. Add I_m and Ic to get I_o. 8. Add I_o and I_{2r}' to get I_1.

9. From tip of - E_1 phasor, add $I_1 R_1$ in phase with I_1 and I_1X_1 at 90^o leading to I_1 to V_1 get phasor. 10. Angle between V_1 and I_1 is Φ_1.

The phasor diagram is shown in the Fig. 1.

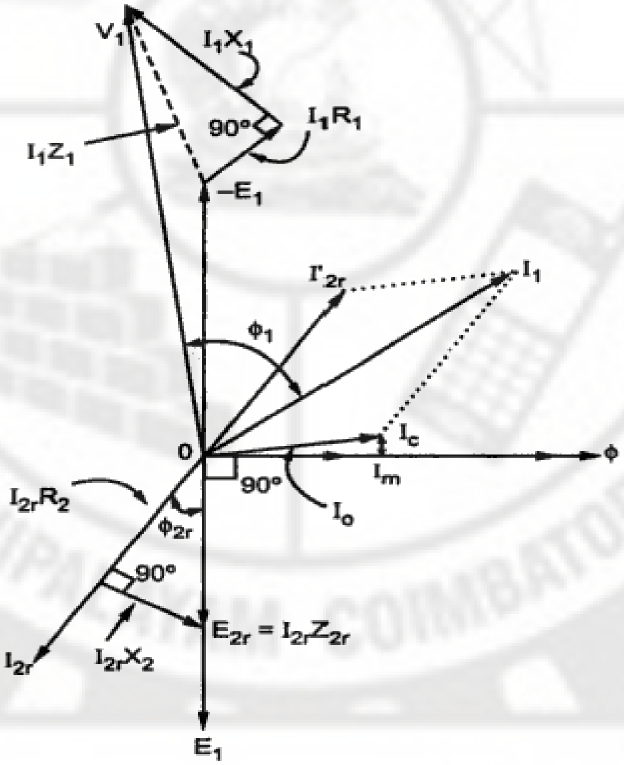


Fig. 3.9 On load phasor diagram of induction motor

3.7.1Torque Equation of Three Phase Induction Motor

The torque produced by three phase induction motor depends upon the following three factors:Firstly the magnitude of rotor current, secondly the flux which interact with the rotor of three phase induction motor and is responsible for producing emf in the rotor part of induction motor, lastly the power factor of rotor of the three phase induction motor.

Combining all these factors together we get the equation of torque as-

$$T \propto \phi I_2 \cos\theta_2$$

Where, T is the torque produced by induction motor,

φ is flux responsible for producing induced emf, I_2 is rotor current,

$\cos\theta_2$ is the power factor of rotor circuit.

The flux φ produced by the stator is proportional to stator emf E1.

i.e. $\varphi \propto E_1$

We know that transformation ratio K is defined as the ratio of secondary voltage (rotor voltage) to that of primary >voltage (stator voltage).

$$K = \frac{E_2}{E_1}$$

$$or,\ K = \frac{E_2}{\phi}$$

$$or,\ E_2 = \phi$$

Rotor current I_2 is defined as the ratio of rotor induced emf under running condition , sE_2 to total impedance, Z_2 of rotor side,

$$i.e\ I_2 = \frac{sE_2}{Z_2}$$

and total impedance Z_2 on rotor side is given by ,

$$Z_2 = \sqrt{R_2^2 + (sX_2)^2}$$

Putting this value in above equation we get,

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

s= slip of Induction motor

We know that power factor is defined as ratio of resistance to that of impedance. The power factor of the rotor circuit is

$$\cos\theta_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Putting the value of flux φ, rotor current I_2, power factor $\cos\theta_2$ in the equation of torque we get,

$$T \propto E_2 \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

Combining similar term we get,

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

Removing proportionality constant we get,

$$T = KsE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$This\ constant\ K = \times \frac{3}{R_2^2 + (sX_2)^2} \frac{}{2\pi n_s} \times \frac{3}{2\pi n_s} N - m$$

Where ns is synchronous speed in r. p. s, ns = Ns / 60. So, finally the equation of torque becomes,

$$T \quad sE_2^2 \qquad R_2$$

Derivation of K in torque equation.

In case of three phase induction motor, there occur copper losses in rotor. These rotor copper losses are expressed as

$$P_c = 3I_2^2R^2$$

We know that rotor current,

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

Substitute this value of I_2 in the equation of rotor copper losses, Pc. So, we get

$$P_c = 3R_2 \left(\frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \right)^2$$

$$On\ simplifying\ P_c = \frac{3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

The ratio of P_2 : Pc : Pm = 1 : s : (1

- s) Where, P_2 is the rotor input,

Pc is the rotor copper losses,

Pm is the mechanical power developed.

$$\frac{P_c}{P_m} = \frac{s}{1-s}$$
$$or \quad P_m = \frac{(1-s)P_c}{s}$$

Substitute the value of Pc in above equation we get,

$$P_m = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

On simplifying we get,

$$P_m = \frac{(1-s)3R_2 s E_2^2}{R_2^2 + (sX_2)^2}$$

The mechanical power developed Pm = Tω,

$$\omega = \frac{2\pi N}{60}$$

$$or\ P_m = T\frac{2\pi N}{60}$$

Substituting the value of Pm

$$\frac{1}{s} \times \frac{(1-s)\,3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2} = T\frac{2\pi N}{60}$$
$$\frac{1}{s} \times \frac{(1-s)\,3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2}$$

$$or\ T = \quad \times \frac{60}{2\pi N}$$

We know that the rotor speed N = Ns(1 - s)

Substituting this value of rotor speed in above equation we get,

$$T = \frac{1}{s} \times \frac{(1-s)3R_2 s^2 E_2^2}{R_2^2 + (sX_2)^2} \times \frac{60}{2\pi N_s(1-s)}$$

Ns is speed in revolution per minute (rpm) and ns is speed in revolution per sec (rps) and the relation between the two is

$$\frac{N_s}{60} = n_s$$

Substitute this value of Ns in above equation and simplifying it we get

$$Toeque,\ T = \frac{s\ E_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi N_s}$$

$$or,\ T = KsE_2^2 \frac{R_2}{R_2^2 + (sX_2)^2}$$

Comparing both the equations, we get, constant K = 3 / 2πns

3.7.2 Equation of Starting Torque of Three Phase Induction Motor

Starting torque is the torque produced by induction motor when it is started. We know that at start the rotor speed, N is zero.

$$So,\ slip\ s = \frac{N_s - N}{N_s}\ becomes\ 1$$

So, the equation of starting torque is easily obtained by simply putting the value of s = 1 in the equation of torque of the three phase induction motor,

$$T = \frac{E_2^2 R_2}{R_2^2 + X_2^2} \times \frac{3}{2\pi n_s}\ N - m$$

The starting torque is also known as standstill torque

3.7.3 Maximum Torque Condition for Three Phase Induction Motor

In the equation of torque,.

$$T = \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \times \frac{3}{2\pi n_s}$$

The rotor resistance, rotor inductive reactance and synchronous speed of induction motor remains constant . The supply voltage to the three phase induction motor is usually rated and remains constant so the stator emf also remains the constant. The transformation ratio is defined as the ratio of rotor emf to that of stator emf. So if statoremf remains constant then rotor emf also remains constant.

If we want to find the maximum value of some quantity then we have to differentiate that quantity with respect to some variable parameter and then put it equal to zero. In this case we have to find the condition for maximum torque so we have to differentiate torque with respect to some variable quantity which is slip, s in this case as all other parameters in the equation of torque remains constant.

So, for torque to be maximum

$$\frac{dT}{ds} = 0$$

$$T = KsE_2^2\frac{R_2}{R_2^2 + (sX_2)^2}$$

Now differentiate the above equation by using division rule of differentiation. On differentiating and after putting the terms equal to zero we get,

$$s^2 = \frac{R_2^2}{X_2^2}$$

Neglecting the negative value of slip we get

$$s^2 = \frac{R_2^2}{X_2^2}$$

So, when slip $s = R_2 / X_2$, the torque will be maximum and this slip is called maximum slip Sm and it is defined as the ratio of rotor resistance to that of rotor reactance.

NOTE: At starting S = 1, so the maximum starting torque occur when rotor resistance is equal to rotor reactance.

Equation of Maximum

Torque The equation of

torque is

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

The torque will be maximum when slip $s = R_2 / X_2$

Substituting the value of this slip in above equation we get the maximum value of torque as,

$$T_{max} = K\frac{E_2^2}{2X_2}N - m$$

In order to increase the starting torque, extra resistance should be added to the rotor circuit at start and cut out gradually as motor speeds up.

From the above equation it is concluded that

The maximum torque is directly proportional to square of rotor induced emf at the standstill. The maximum torque is inversely proportional to rotor reactance.

The maximum torque is independent of rotor resistance.

The slip at which maximum torque occur depends upon rotor resistance, R_2. So, by varying the rotor resistance, maximum torque can be obtained at any required slip.

3.7.4 Torque/Speed Curve:

The torque developed by a conventional 3-phase motor depends on its speed but the relation between the two cannot be represented by a simple equation.

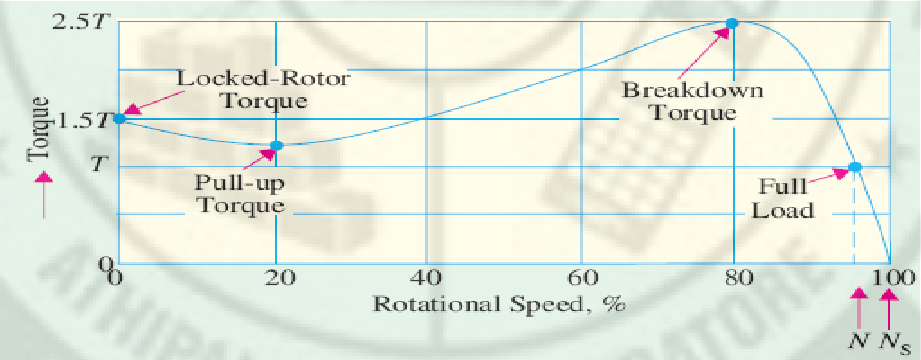


Fig.3.10

It is easier to show the relationship in the form of a curve (Fig. 3.10). In this diagram, *T* represents the nominal full-load torque of the motor. As seen, the starting torque (at *N* = 0) is 1.5 *T* and the maximum torque (also called breakdown torque) is 2.5 T

At full-load, the motor runs at a speed of *N*. When mechanical load increases, motor speed decreases till the motor torque again becomes equal to the load torque.

As long as the two torques are in balance, the motor will run at constant (but lower) speed. However, if the load torque exceeds 2.5 *T*, the motor will suddenly stop.

3.8 Determination of Equivalent Circuit Constants by Conducting No load Test and Blocked Rotor Test:

The various constants of the equivalent circuit of an induction motor is shown in fig.3.13

3.8.1 No-load Test:

The Connection diagram for no load test on three phase induction motor is shown in Fig.3.11

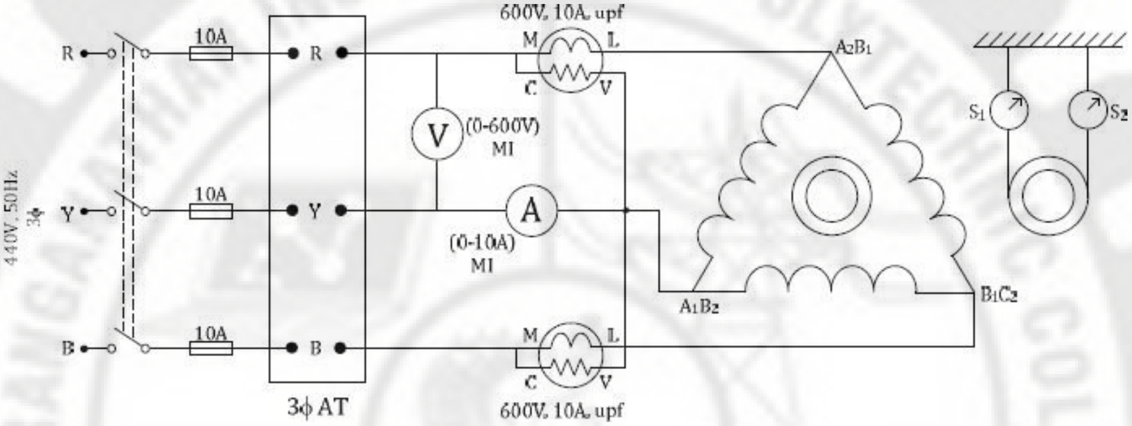


Fig.3.11

Rated voltage is given to the stator windings and the motor is allowed to run on no-load. The no load current Io, the applied voltage Vo and no load input power Po are noted. At no load, the input power is supplied to meet out losses. The various losses are

1. Stator winding loss (= $3I_{01}^{2}R$)
2. Core Loss ($3\frac{V^{2}}{R}$)
3. Friction and Wind age loss

The core loss, friction and windage losses totally are called constant losses (Fixed Loss)

No load power factor $Cos\Phi_0 = \frac{P_0}{\sqrt{3}V_0}$

Where ,P_0 is no load power, V_o is no load voltage

No load current per phase $= \frac{I}{\sqrt{3}}$ (Since Stator winding is delta connected)

No load Resistance $R_0 = \frac{V_0}{I_W}$ ohm , I_W is watt -full current, $I_W = \frac{I_o}{\sqrt{3}}\cos\Phi_0$

No load Reactance $X_0 = \frac{V_0}{I_m}$ ohm , I_m is magnetizing current, $I_m = \sqrt{I_0^2 - I_W}$

3.8.2Blocked Rotor Test:

This test is called locked rotor test (or) short circuit test. The connection diagram for blocked rotor test is shown in Fig.3.12

In this method, the rotor is locked. In case of slip ring induction motor the rotor windings are short circuited at slip rings. Reduced voltage is allowed to the stator winding by an autotransformer to flow rated full load current.

Now the voltage applied V_{SC} the short circuit current I_{SC} and the power taken by the motor P_{SC} are noted.

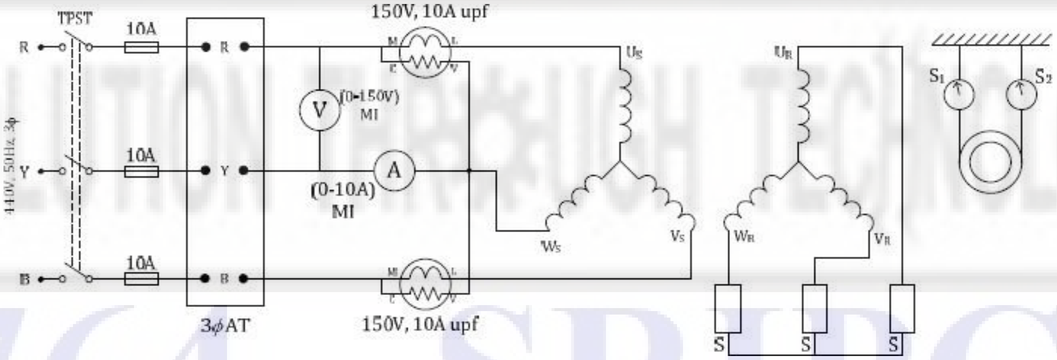


Fig.3.12

Short circuit Impedance $Z = \frac{V_{SC}}{I_{SC}}$ ohm , Where V_{SC} is short circuit voltage, I_{SC} is short circuit current

Resistance/ phase referred to stator $R_{01} = \frac{P_{SC}}{I_{SC}^2}$ ohm

Reactance/ phase referred to stator $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$ ohm

3.9 Equivalent Circuit of Induction Motor:

The rotor current is given by $I_2 = \frac{\text{rotor emf}}{\text{rotor impedance}}$

$$I_2 = \frac{sE_2}{\sqrt{R_2^2 + s^2X_2^2}}$$

If n is stator to rotor turns ratio then stator current,

$$I_1 = \frac{I_2}{n}$$

or

$$I_1 = \frac{sE_2}{n\sqrt{R_2^2 + s^2X_2^2}}$$

To produce I_1 current in the stator there is a requirement of voltage. i.e. $E_1 = nE_2$ so that the rotor impedance referred in stator winding

$$= \frac{E_1}{I_1} = \frac{E_1}{\frac{I_2}{n}} = nE_2 \times \frac{n\sqrt{R_2^2 + s^2X_2^2}}{sE_2} = \frac{n^2}{s}\sqrt{R_2^2 + s^2X_2^2}$$

$$= \sqrt{\left(\frac{n^2R_2}{s}\right)^2 + (n^2X_2)^2}$$

The rotor resistance $\left(\frac{n^2R_2}{s}\right)$ can be divided as series combination of two resistances n^2R_2 and $n^2R_2\left(\frac{1}{s} - 1\right)$.

The n^2R_2 part remains constant and represents physical rotor resistance referred to stator side.

i.e. R'_2 . But $n^2R_2\left(\frac{1}{s} - 1\right)$.k varies from zero to infinite as s changes from unity to zero and represents the rotor output in the form of power in this resistance. The equivalent circuit referred to stator side is shown in fig.3.13

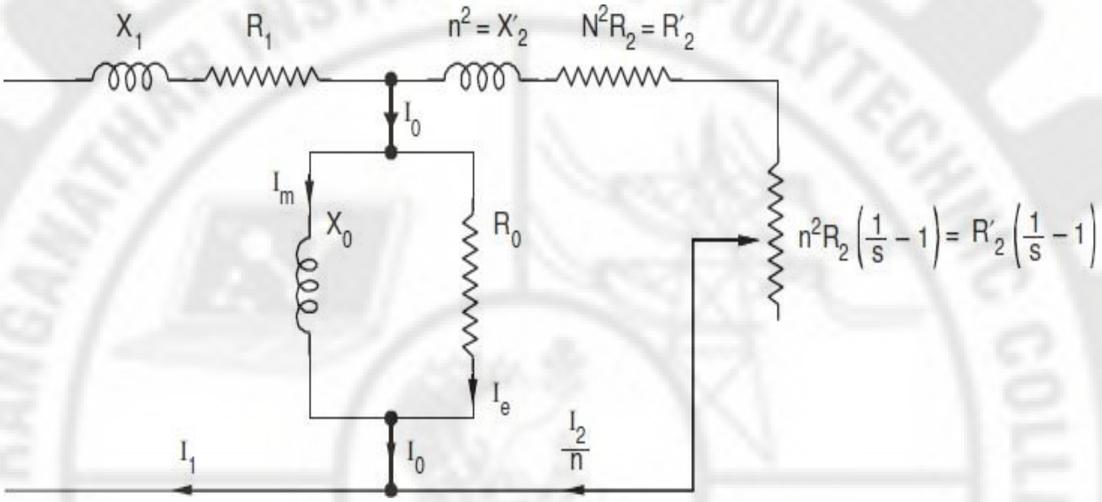


Fig. 3.13 Equivalent circuit of Induction Motor

3.10 Circle Diagram of an Induction Motor:

By using the data obtained from the no load test and the blocked rotor test, the circle diagram can be drawn using the following steps :

Step 1: Take reference Phasor V as vertical (Y-axis).

Step 2: Select suitable current scale such that diameter of circle is about 20 to 30 cm.

Step3: From no load test, I_o and are Φ_o obtained. Draw vector I_o, lagging V by angle Φ_o. This is the line OO' as shown in the Fig. 3.14

Step 4: Draw horizontal line through extremity of I_o i.e. O', parallel to horizontal axis.

Step 5: Draw the current I_{SN} calculated from I_{sc} with the same scale, lagging V by angle Φ_{sc}, from the origin O. This is Phasor OA as shown in the Fig. 3.14

Step 6: Join O'A is called output line.

Step 7: Draw a perpendicular bisector of O'A. Extend it to meet line O'B at point C. This is the centre of the circle.

Step 8: Draw the circle, with C as a centre and radius equal to O'C. This meets the horizontal line drawn from O' at B as shown in the Fig.3.14

Step 9: Draw the perpendicular from point A on the horizontal axis, to meet O'B line at F and meet horizontal axis at D.

Step 10: Torque line.

The torque line separates stator and rotor copper losses.

Note that as voltage axis is vertical, all the vertical distances are proportional to active components of currents or power inputs, if measured at appropriate scale.

Thus the vertical distance AD represents power input at short circuit i.e. W_{SN}, now which consists of core loss and stator, rotor copper losses.

Now FD = O'G

= Fixed loss

Where O'G is drawn perpendicular from O' on horizontal axis. This represents power input on no load i.e. fixed loss.

Hence AF α Sum of stator and rotor copper losses Then point E can be located as,

AE/EF = Rotor copper loss / Stator copper loss

The line O'E under this condition is called torque line.

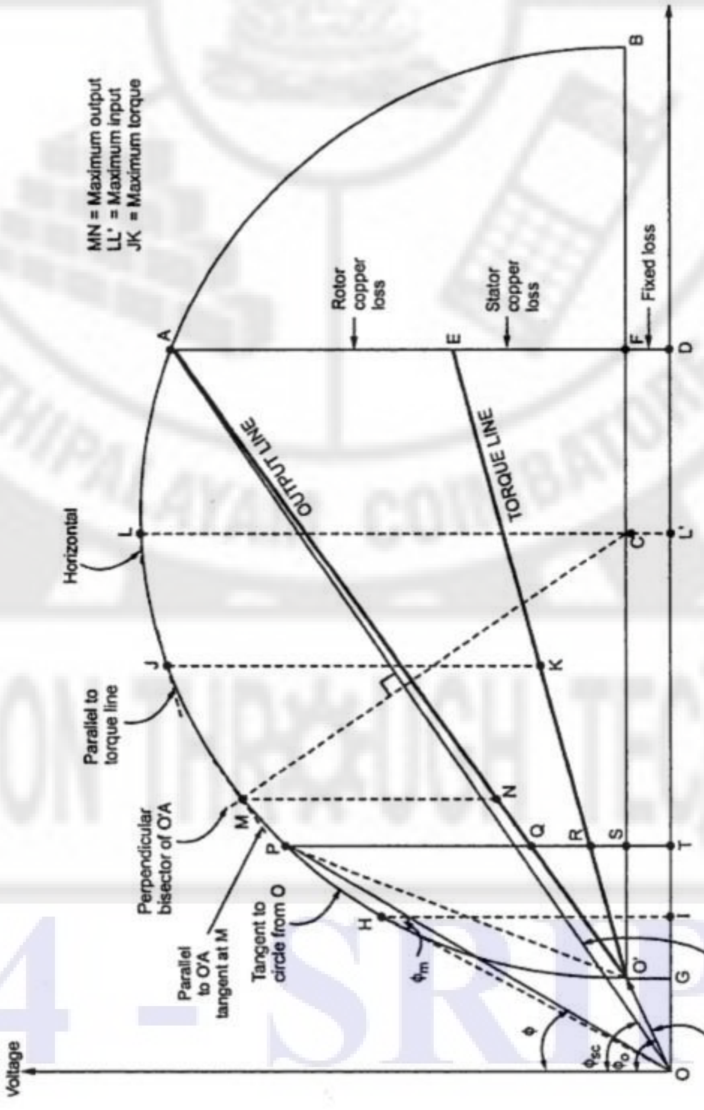


Fig.3.14 Circle Diagram of an Induction Motor

Power scale:

As AD represents W_{SN} i.e. power input on short circuit at normal voltage, the power scale can be obtained as,

Power scale = $W_{SN}/l(AD)$ W/cm

where $l(AD)$ = Distance AD in cm

Location of Point E :

In a slip ring induction motor, the stator resistance per phase R_1 and rotor resistance per phase R_2 can be easily measured. Similarly by introducing ammeters in stator and rotor circuit, the currents I_1 and I_2 also can be measured.

$\therefore$ $K = I_1/I_2$ = Transformation ratio

Now AF/EF = Rotor copper loss / Stator copper loss = $(I_2^2R_2)/(I_1^2R_1) = (R_2/R_2)(I_2^2/I_1^2) = (R_2/R_2).(1/K^2)$ But $R_2' = R_2/K^2$ = Rotor resistance referred to stator

$\therefore$ $AE/EF = R_2'/R_1$

Thus point E can be obtained by dividing line AF in the ratio R_2' to R_1

In **a squirrel cage motor**, the stator resistance can be measured by conducting resistance test.

$\therefore$ Stator copper loss = $3I_{SN}^2 R_1$ where I_{SN} is phase value.

Neglecting core loss, W_{SN} = Stator Cu loss + Rotor Cu loss

$\therefore$ Rotor copper loss = $W_{SN} - 3I_{SN}^2 R_1$

$\therefore$ $AE/EF = (W_{SN} - 3I_{SN}^2 R_1)/(3I_{SN}^2 R_1)$

Dividing line AF in this ratio, the point E can be obtained and hence O'E represents torque line.

Predicting Performance from Circle Diagram:

Let motor is running by taking a current OP as shown in the Fig. 3.15. The various performance parameters can be obtained from the circle diagram at that load condition.

Draw perpendicular from point P to meet output line at Q, torque line at R, the base line at S and horizontal axis at T.

We know the power scale as obtained earlier.

Using the power scale and various distances, the values of the performance parameters can be obtained as,

Total motor input = PT x Power scale

Fixed loss = ST x power scale

Stator copper loss = SR x power scale

Rotor copper loss = QR x power scale

Total loss = QT x power scale

Rotor output = PQ x power scale

Rotor input = PQ + QR = PR x power

scale Slip s = Rotor Cu loss = QR/PR

Power factor cos = PT/OP

Motor efficiency = Output / Input = PQ/PT

Rotor efficiency = Rotor output / Rotor input =

PQ/PR Rotor output / Rotor input = 1 - s = N/N_s =

PQ/PR The torque is the rotor input in

synchronous watts.

Maximum Quantities from Circle Diagram

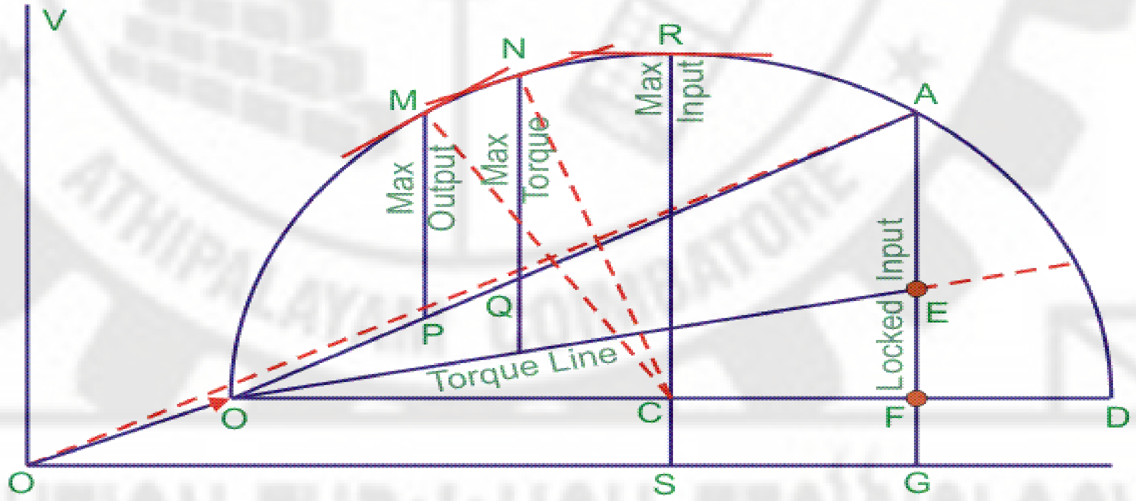


Fig 3.15

Maximum Output Power

When the tangent to the circle is parallel to the line then output power will be maximum. That point M is obtained by drawing a perpendicular line from the center to the output line and extending it to cut at M.

Maximum Torque

When the tangent to the circle is parallel to the torque line, it gives maximum torque. This is obtained by drawing a line from the center in perpendicular to the torque line AD and extending it to cut at the circle. That point is marked as N.

Maximum Input Power

It occurs when tangent to the circle is perpendicular to the horizontal line. The point is the highest point in the circle diagram and drawn to the center and extends up to

S. That point is marked as R.

Example

A 480 V, 50 hp, three phase induction motor is drawing 60 A at 0.85 pf lagging. The stator copper losses are 2 kW and the rotor copper losses are 700 W. The friction loss is 600 W and the core losses are 1800 W, find:

- The air gap power.
- The converted power.
- The output power.
- The efficiency of the motor.

Solution

$$\text{a) } n_s = \frac{120f}{P} = \frac{(120)(60)}{4} = 1800\,\text{rpm}$$

$$n_m = (1-s)n_s = (1-.022)(1800) = 1760\,\text{rpm}$$

$$\text{b) } Z_{total} = \left\{ \left(\frac{R_2}{s} + jx_2\right) \| (jx_m) \right\} + (R_1 + jx_1) = 14.0$$

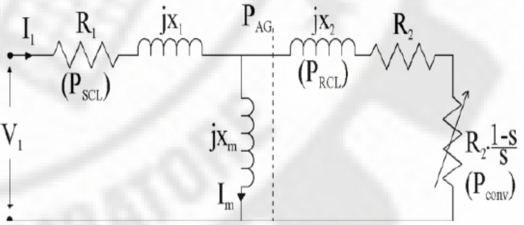
$$I_1 = \frac{V_{phase}}{Z_{total}} = 18.88\angle -33.6$$

$$\text{c)} p.f. = \cos(33.6) = 0.833\,lagging$$

$$\text{d)} P_{in} = \sqrt{3}(480)(18.88)(0.833) = 12.53\,\text{kW}$$

$$P_{SCL} = 3I_1^{\,2}R_1 = 3(18.88)^2(0.641) = 685\ \text{W}$$

$$P_{AG} = P_{in} - P_{SCL} = 12{,}530 - 685 = 11.845\text{kW}$$



3.11 Speed Control of Induction Motor

3.11.1 Induction Motor Speed Control From Stator Side

1. By Changing the Applied Voltage:

From the torque equation of induction motor,

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

Rotor resistance R_2 is constant and if slip s is small then $(sX_2)^2$ is so small that it can be neglected. Therefore, T ∝ sE_2^2 where E_2 is rotor induced emf and $E_2 \propto V$ Thus, $T \propto sV^2$, which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases. This method is the easiest and cheapest, still rarely used, because

1. large change in supply voltage is required for relatively small change in speed.
2. large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

2. By Changing the supply Frequency

Synchronous speed of the rotating magnetic field of an induction motor is given by,

$$Ns = \frac{120\,f}{P} \quad (RPM)$$

where, f = frequency of the supply and P = number of stator poles. Hence, the synchronous speed changes with change in supply frequency. Actual speed of an induction motor is given as N = Ns (1 - s). However, this method is not widely used. It may be used where, the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance. And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

3. Constant V/F Control Of Induction Motor

This is the most popular method for controlling the speed of an induction motor. As in above method, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux will tend to saturate. This will cause excessive stator current and distortion of the stator flux wave. Therefore, the stator voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of the stator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, by keeping V/F constant, the developed torque remains approximately constant. This method gives higher run-time efficiency. Therefore, majority of AC speed drives employ constant V/F method (or variable voltage, variable frequency method) for the speed control. Along with wide range of speed control, this method also offers 'soft start' capability.

4. Changing the Number Of Stator Poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots. For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.

For supply frequency of 50 Hz

i) synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM

ii) synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

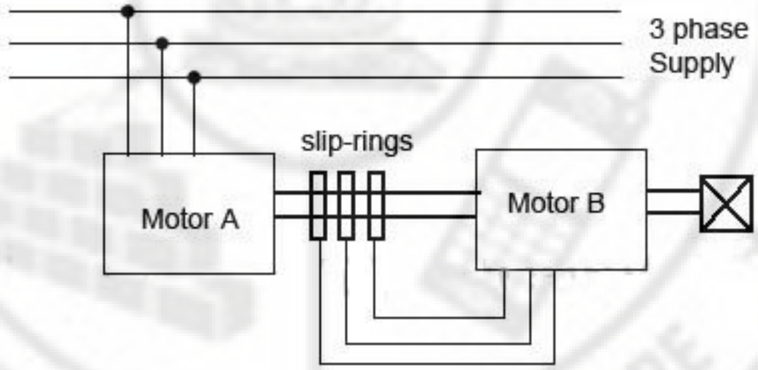
3.11.2 Speed Control from Rotor Side:

1. Rotor Rheostat Control

This method is similar to that of armature rheostat control of DC shunt motor. But this method is only applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cage motors is notpossible.

2. Cascade Operation

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



Motor A is called the main motor and motor B is called the auxiliary
motor. Let, Ns1 =synchronous speed of motor A
Ns2 =synchronous speed of motor
B P1 =number of poles stator of
motor A P2 =number of stator
poles of motor B
N=speed of the set and same for both
motors f = frequency of the supply
Now, slip of motor A, S1 = (Ns1 - N) / Ns1.
frequency of the rotor induced emf in motor A, f1 = S1f
Now, auxiliary motor B is supplied with the rotor induce
emf

therefore, Ns2 =(120f1) / P2 = (120S1f) /

P2. now putting the value of S1 = (Ns1 - N)

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

/ Ns1

At no load, speed of the auxiliary rotor is almost same as its synchronous speed.
i.e. N = Ns2.
from the above equations, it can be obtained that

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

With this method, four different speeds can be obtained

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

5. By Injecting EMF In Rotor Circuit

In this method, speed of an induction motor is controlled by injecting a voltage in rotor circuit. It is necessary that voltage (emf) being injected must have same frequency as of the slip frequency. However, there is no restriction to the phase of injected emf. If we inject emf which is in opposite phase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is in phase with the rotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed can be controlled. The main advantage of this method is a wide range of speed control (above normal as well as below normal) can be achieved. The emf can be injected by various methods such as Kramer system, Scherbius system etc.

3.12 *Various starting methods of induction motors*

An induction motor is similar to a poly-phase transformer whose secondary is short circuited. Thus, at normal supply voltage, like in transformers, the initial current taken by the primary is very large for a short while. Unlike in DC motors, large current at starting is due to the absence of back emf. If an induction motor is directly switched on from the supply, it takes 5 to 7 times its full load current and develops a torque which is only 1.5 to 2.5 times the full load torque. This large starting current produces a large voltage drop in the line, which may affect the operation of other devices connected to the same line.

3.12.1 *Direct-On-Line (DOL) Starters*

Small three phase induction motors can be started direct-on-line, which means that the rated supply is directly applied to the motor. But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current. The starting torque is likely to be 1.5 to 2.5 times the full load torque. Induction motors can be started directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipment such as a circuit breaker. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons. When the start push button is pressed, the contactor gets energized and it closes all the three phases of the motor to the supply phases at a time. The stop push button de-energizes the contactor and disconnects all the three phases to stop the motor.

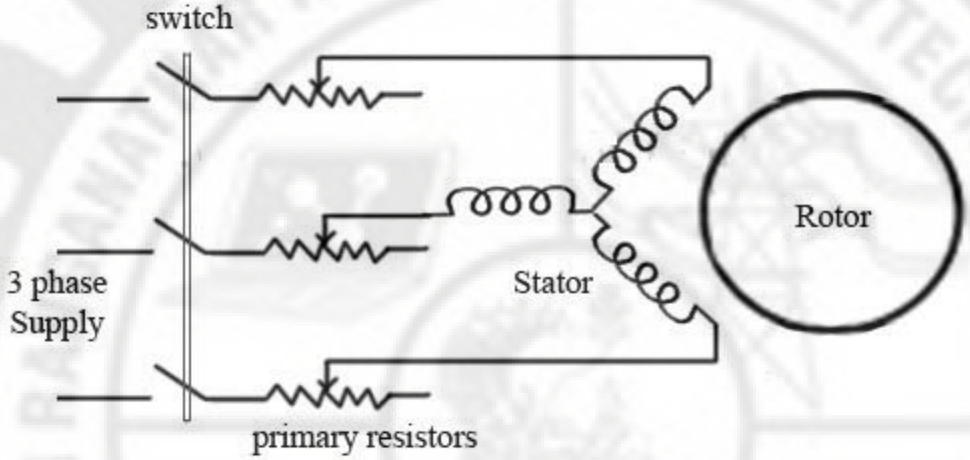
In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used for motors that are rated below 5kW.

Starting Of Squirrel Cage Motors

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

1. By using primary resistors
2. Autotransformer
3. Star-delta switches

1. Using Primary Resistors:



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

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

2. Auto-Transformers:

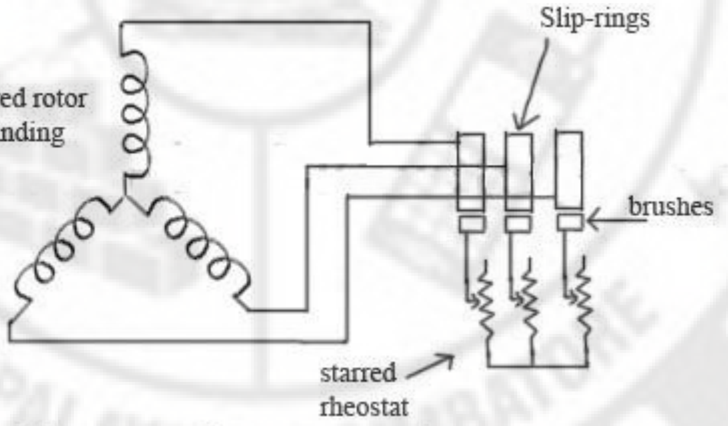
Auto-transformers are also known as auto-starters. They can be used for both star connected or delta connected squirrel cage motors. It is basically a three phase step down transformer with different taps provided that permit the user to start the motor at, say, 50%, 65% or 80% of line voltage. With auto- transformer starting, the current drawn from supply line is always less than the motor current by an amount equal to the transformation ratio. For example, when a motor is started on a 65% tap, the applied voltage to the motor will be 65% of the line voltage and the applied current will be 65% of the line voltage starting value, while the line current will be 65% of 65% (i.e. 42%) of the line voltage starting value. This difference between the line current and the motor current is due to transformer action. The internal connections of an auto-starter are as shown in the figure. At starting, switch is at "start" position, and a reduced voltage (which is selected using a tap) is applied across the stator. When the motor gathers an appropriate speed, say upto 80% of its rated speed, the auto-transformer automatically gets disconnected from the circuit as the switch goes to "run" position. The switch changing the connection from start to run position may be air-break (small motors) or oil- immersed (large motors) type. There are also provisions for no-voltage and overload, with time delay circuitsonanautostarter.

3. Star-Delta Starter:

This method is used in the motors, which are designed to run on delta connected stator. A two way switch is used to connect the stator winding in star while starting and in delta while running at normal speed. When the stator winding is star connected, voltage over each phase in motor will be reduced by a factor 1/(sqrt. 3) of that would be for delta connected winding. The starting torque will 1/3 times that it will be for delta connected winding. Hence a star-delta starter is equivalent to an auto-transformer of ratio 1/(sqrt. 3) or 58% reduced voltage.

3.12.2*Starting Of Slip-Ring Motors*

Rotor resistance starter



Phase wound rotor connections

Slip-ring motors are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings. A star connected rheostat is connected in series with the rotor via slip-rings as shown in the fig. Introducing resistance in rotor current will decrease the starting current in rotor (and, hence, in stator). Also, it improves power factor and the torque is increased. The connected rheostat may be hand-operated or automatic. As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load. The external resistance introduced is only for starting purposes, and is gradually cut out as the motor gathers the speed.

3.12.3*Crawling And Cogging In Induction Motors*

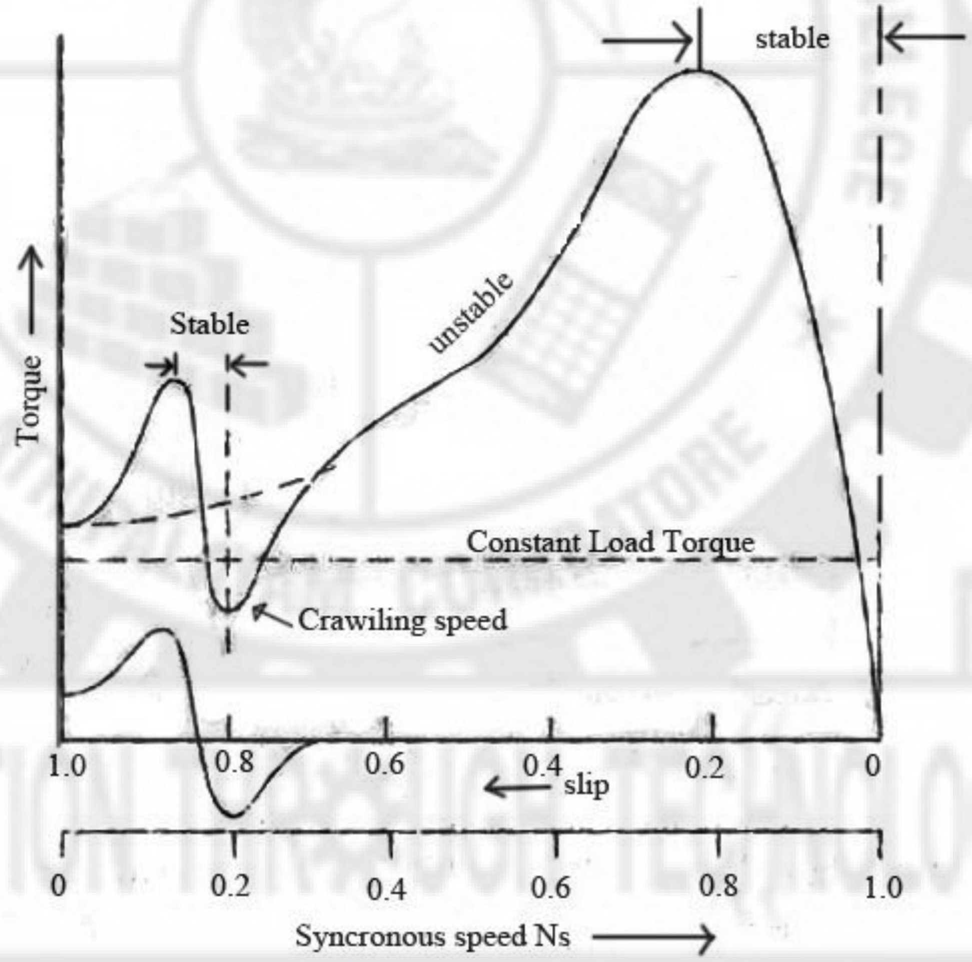
crawling and cogging both are particularly related to squirrel cage induction motors.

Crawling

Sometimes, a squirrel cage induction motor exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as **crawling of an induction motor**.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque.

3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).



Now, 5th harmonic currents will have phase difference of 5 X 120 = 600° =2 X 360 - 120 = -120°. Hence the revolving speed set up will be in reverse direction with speed Ns/5. The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of 7 X 120 = 840° = 2 X 360 +120 = + 120°. Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7th harmonic torque reaches its maximum positive value just before1/7th of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the motor may fall below this load torque. In this case, motor will not accelerate up to its normal speed, but it will run at a speed which is nearly 1/7th of of its normal

speed. This phenomenon is called as **crawling in induction motors.**

3.12.4 Cogging (Magnetic Locking Or Teeth Locking)

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum, that is why the rotor tends to remain fixed. This phenomenon is called cogging or **magnetic locking of induction motor**.

3.12.5 Double Squirrel Cage Motor / Deep Bar Double Cage Induction Motor

Why starting torque is poor in squirrel cage induction motor?

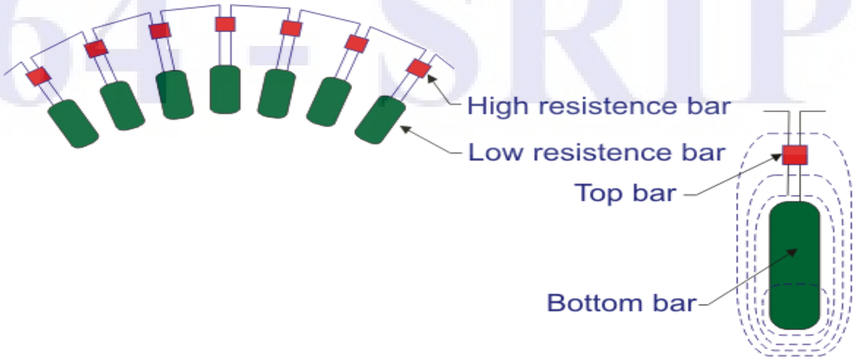
The resistance cannot be varied in squirrel cage rotor as it is possible in slip ring induction motor. The fixed resistance of the rotor of the squirrel cage induction motor is very low. At the starting moment, the induced voltage in the rotor has same frequency as the frequency of the supply. Hence the starting inductive reactance gets higher value at stand still condition. The frequency of the rotor current gets same frequency as the supply frequency at standstill. Now the case is that the rotor induced current in spite of having higher value lags the induced voltage at a large angle. So this causes poor starting torque at the stand still condition. This torque is only 1.5 times of the full load torque though the induced current is 5 to 7 times of the full load current. Hence, this squirrel cage single bar single cage rotor is not being able to apply against high load. We should go for deep bar double cage induction motor to get higher starting torque

3.12.6 Construction of Deep Bar Double Cage Induction Motor

In deep bar double cage rotor bars are there in two layers.

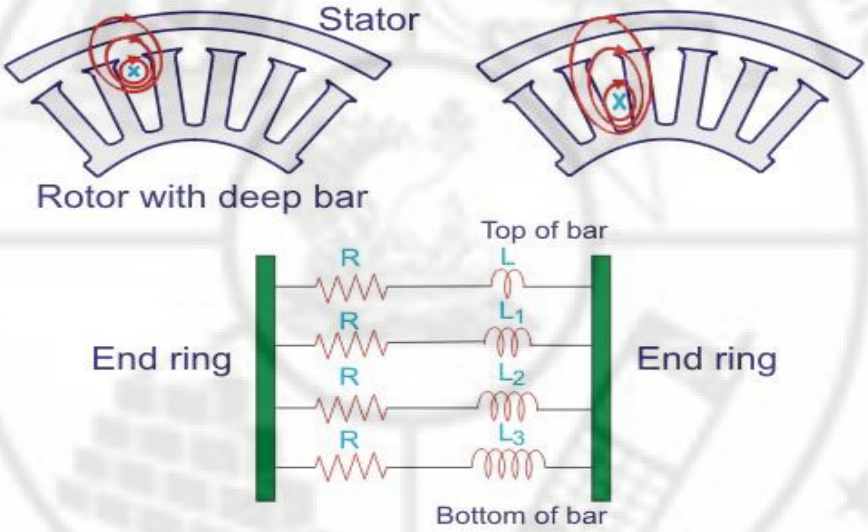
Outer layer has the bars of small cross sections. This outer winding has relatively large resistance. The bars are shorted at the both ends. The flux linkage is thus very less. And hence inductance is very low. Resistance in outer squirrel cage is relatively high. Resistance to inductive reactance ration is high.

Inner layer has the bars of large cross section comparatively. The resistance is very less. But flux linkage is very high. The bars are thoroughly buried in iron. As flux linkage is high the inductance is also very high. The resistance to inductive reactance ration is poor.



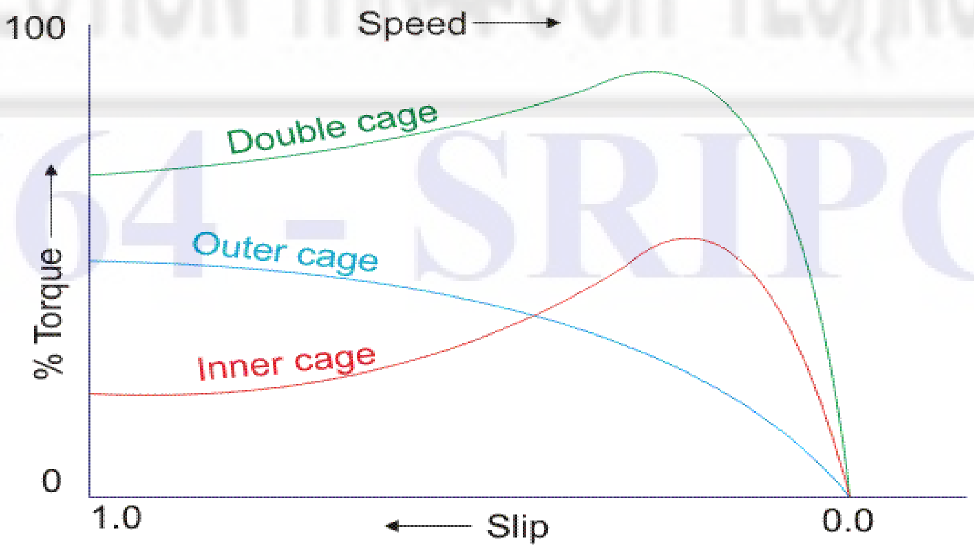
3.12.7 Operational Principle and Construction of Deep Bar Double Cage Induction Motor

At the stand still condition the inner and outer side bars get induced with voltage and current with the same frequency of the supply. Now the case is that the inductive reactance ($X_L = 2\pi fL$) is offered more in the deep bars or inner side bars due to skin effect of the alternating quantity i.e. voltage and current. Hence the current tries to flow through the outer side rotor bars.



The outer side rotor offers more resistance but poor inductive reactance. The ultimate resistance is somewhat higher than the single bar rotor resistance. The higher valued rotor resistance results more torque to be developed at the starting. When the speed of the rotor of the deep bar double cage induction motor increases, the frequency of the induced EMF and current in the rotor gets gradually decreased. Hence the inductive reactance (X_L) in the inner side bars or deep bars gets decreased and the current faces less inductive reactance and less resistance as a whole. Now no need for more torque because the rotor already has arrived to its full speed with running torque.

Speed Torque Characteristics of Deep Rotor IM



where R_2 and X_2 are the rotor resistance and inductive reactance at starting

respectively, E_2 is the rotor induced EMF and $k = \frac{3}{2\pi N_s}$ N_s is the RPS speed of synchronous stator flux and S is the slip of the rotor speed. The above speed-torque graph shows that the higher valued resistance offers higher torque at the stand still condition and the max torque will be achieved at higher valued slip. Comparison between single cage and double cage motors:

1. A double cage rotor has low starting current & high starting torque. Therefore, it is more suitable for direct on line starting.
2. Since effective rotor resistance of double cage motor is higher, there is larger rotor heating at the time of starting as compared to that of single cage rotor.
3. The high resistance of the outer cage increases the resistance of double cage motor. So full load copper losses are increased & efficiency is decreased.
4. The pull out torque of double cage motor is smaller than single cage motor.
5. The cost of double cage motor is about 20-30 % more than that of single cage motor of same rating.

3.13 Induction generator

Induction machine is sometimes used as a generator. It is also called Asynchronous Generator. What are the conditions when the poly phase (here three phase) induction machine will behave as an induction generator? The following are conditions when the induction machine will behave as an induction generator are written below:

(a) Slip becomes negative due to this the rotor current and rotor emf attains negative value.

(b) The prime mover torque becomes opposite to electric torque.

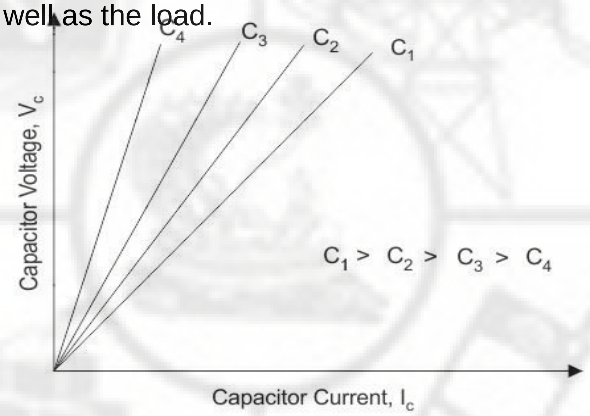
Now let us discuss how we can achieve these conditions. Suppose that an induction machine is coupled with the prime mover whose speed can be controlled. If the speed of the prime mover is increased such that the slip becomes negative (i.e. speed of the prime mover becomes greater than the synchronous speed).Due to this, all the conditions that we have mentioned above will become fulfilled and machine will behave like an induction generator. Now if the speed of the prime mover is further increased such that it exceeds the negative maximum value of the torque produced then the generating effect of the generator vanishes. Clearly the speed of the induction generator during the whole operation is not synchronous, therefore the induction generation is also called a synchronous generator.

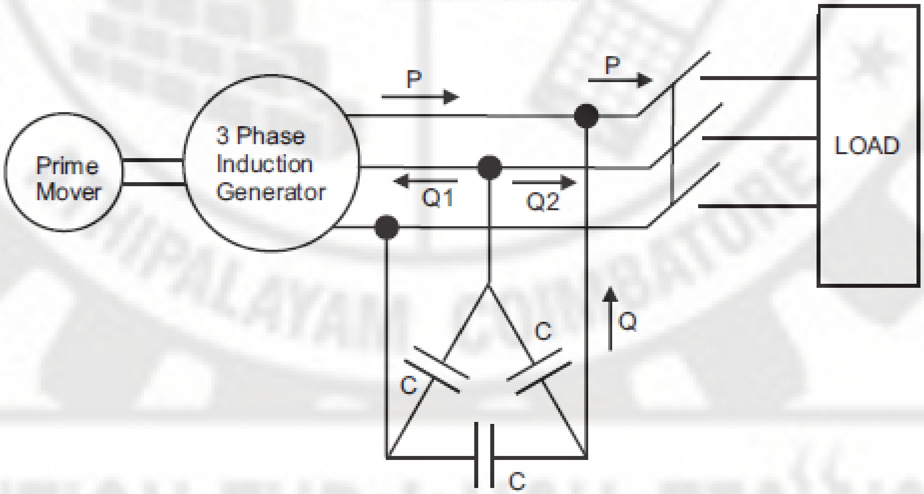
Induction generator is not a self excited machine therefore in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The induction generator obtains its magnetizing current and reactive power from the various sources like the supply mains or it may be another synchronous generator. The induction generator can’t work in isolation because it continuously requires reactive power from the supply system. However we can have a *self excited or isolated induction generation* in one case if we will use capacitor bank for reactive power supply instead of AC supply system. So let us discuss **isolated induction generator** in detail,

3.14 Isolated Induction Generator

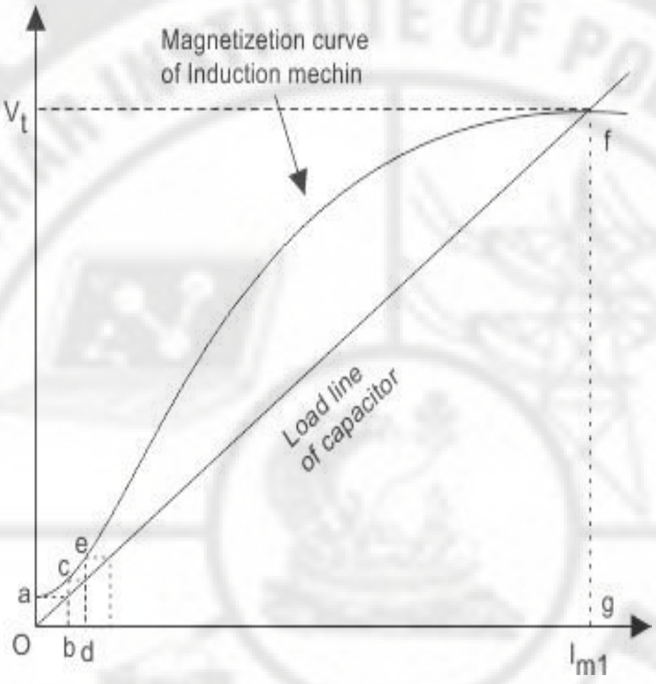
This type of generator is also known as self excited generator. Now why it is called self excited? It is because it uses capacitor bank which is connected across its stator terminals as shown in the diagram given below,

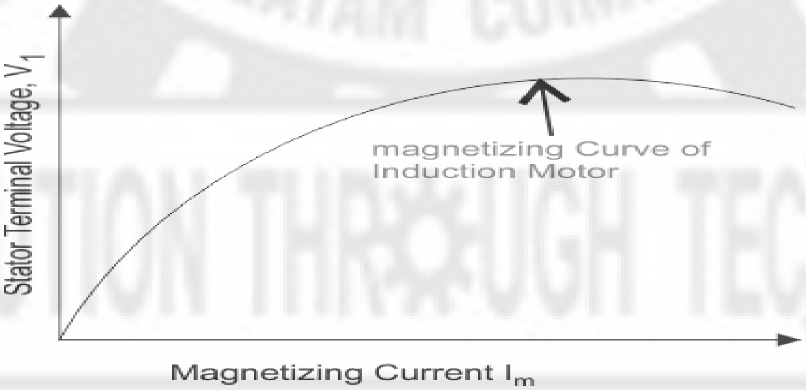
The function of the capacitor bank is to provide the lagging reactive power to the induction generator as well as load. So mathematically we can write total reactive power provided by the capacitor bank is equals to the summation of the reactive power consumed by the induction generator as well as the load.





There is generation of small terminal voltage oa (as in figure given below) across the stator terminal due the residual magnetism when the rotor of the induction machine runs at the required speed. Due to this voltage oa the capacitor current ob is produced. The current bc sends current od which generates the voltage de. The cumulative process of voltage generation continues till





the saturation curve of the induction generator cuts the capacitor load line at some point. This point is marked as f in the given curve.

3.14.1*Application of Induction Generator*

Let us discuss **application of induction generator**: We have two types of **induction generator** let us discuss the application of each type of generator separately: Externally excited generators are widely used for regenerative breaking of hoists driven by the three phase induction motors.

Self-excited generators are used in the wind mills. Thus this type of generator helps in converting the unconventional sources of energy into electrical energy. Now let us discuss some disadvantages of externally excited generator:

- The efficiency of the externally excited generator is not so good.
- We cannot use externally excited generator at lagging power factor which major drawback of this type of generator.
- The amount of reactive power used to run these types of generator required is quite large.

As an example, consider the use of a 10 hp, 1760 r/min, 440 V, three-phase induction motor as an asynchronous generator. The full-load current of the motor is 10 A and the full-load power factor is 0.8.

Required capacitance per phase if capacitors are connected in delta:

Apparent power $S = \sqrt{3}\, E\, I = 1.73 \times 440 \times 10 =$
7612 VA Active power $P = S \cos \theta = 7612 \times 0.8 =$
6090 W Reactive power $Q = \sqrt{(S^2 - P^2)} = 4567$ VAR

For a machine to run as an asynchronous generator, capacitor bank must supply minimum 4567 / 3 phases = 1523 VAR per phase. Voltage per capacitor is 440 V because capacitors are connected in delta.

Capacitive current $I_c = Q/E = 1523/440 =$
3.46 A Capacitive reactance per phase $X_c =$
$E/I_c = 127\ \Omega$

Minimum capacitance per phase:

$C = 1 / (2 \cdot \pi \cdot f \cdot X_c) = 1 / (2 \cdot 3.141 \cdot 60 \cdot 127) = 21$ microfarads.

If the load also absorbs reactive power, capacitor bank must be increased in size to

compensate. Prime mover speed should be used to generate frequency of 60 Hz:

Typically, slip should be similar to full-load value when machine is running as motor, but negative (generator operation):

if $N_s = 1800$, one can choose $N = N_s + 40$ rpm
Required prime mover speed $N = 1800 + 40 = 1840$ rpm.

3.14.2 Advantages of Induction Generator

1. It has robust construction requiring less maintenance. Also it is relatively cheaper.
2. It has small size per KW output power.
3. It runs in parallel without hunting
4. No synchronization to the supply line is required like a synchronous generator.

Limitations It cannot generate reactive voltamperes. It requires reactive voltamperes from the supply line to furnish its excitation.

Problems

Ques1: A 3 φ 4 pole 50 hz induction motor runs at 1460 r.p.m. find its %age slip.

Solution
N_s = 120f/p = 120*50/4 = 1500r.p.m.
Running speed of motor = n=
1460r.p.m.
Slip S=(N_s–N)/ N_s*100 =(1500-1460) x 100 / 1500 = 2.667%

Ques2: A 12 pole 3 φ alternator driver at speed of 500 r.p.m. supplies power to an 8 pole 3 φ induction motor. If the slip of motor is 0.03p.u, calculate the speed.

Solution
Frequency of supply from alternator, f=PN/120
=12*500/120 = 50hz

where P= no of poles on
alternatev N=alternator speed
is r.p.m.
Synchronous speed of 3 φ induction
motor N=120f/Pm
=120*50/8 = 750 r.p.m.
Speed of 3 φ induction motor N=Ns (1-s)
=750(1-0.03) = 727.5 r.p.m.

Ques3: A motor generates set used for providing variable frequency ac supply consists of a 3-φ synchronous and 24 pole 3 φ synchronous generator. The motor generate set is fed from 25hz, 3 φ ac supply. A 6 pole 3 φ induction motor is electrically connected to the terminals of the synchronous generator and runs at a slip of 5%. Find

i) the frequency of generated voltage of synchronous generator
ii) the speed at which induction motor is running

Solution
Speed of motor generator set
N_s=(120*f_1(supply freq))/(no of pole on syn motor)
=120*25/10=300 r.p.m.

(1) frequency of generated voltage
f_z=speed of motor gen set voltage *no of poles on syn gen/120
= 300*24/120 = 60hz
(2) Speed of induction motor , N_m=N_s(1-s)
=120 f_z /P_m(1-s) = 120*60/6(1-0.05) = 1140r.p.m.

Ques4: A 3-φ 4 pole induction motor is supplied from 3φ 50Hz ac supply. Find
(1) synchronous speed
(2) rotor speed when slip is 4%
(3) the rotor frequency when runs at 600r.p.m.

Sulution
1) N_s =120f/p
=120*50/4 = 1500 r.p.m.

2) speed when slip is 4% or
.04 N=N_s (1-s)

=1500(1-0.04) = 1440 r.p.m.
3) slip when motor runs at 600
r.p.m. $S'=(N_s - N)/N_s$
=(1500-600)/1500 = 0.6

Rotor frequency f' = S'f = 0.6*50 = 30Hz.

Ques5: A 12 pole 3-φ alternator is coupled to an engine running at 500r.p.m. If supplied a 3φ induction motor having full speed of 1440r.p.m.
Find the %age slip, frequency of rotor current and no of poles of rotor.

Ans
Frequency of supply from alternator $f=P_a*N_a/120$
=12*500/120 = 50Hz

Full load speed N_f =1440 r.p.m.
The no of poles (nearest to and higher than full load speed of motor =1440) should be in even nos. P=120f/n = 120*50/1440 = 4
$N_s = 120f/P_m$ = 120*50/4 = 1500 r.p.m.
% Slip s = $(N_s-N)/N_s$ x 100 =(1500-1440) x 100 / 1500 = 4%

Rotor frequency f' = sf = 0.04*50 =

2Hz No A poles of the motor = 4

Ques6: The rotor of 3φ induction motor rotates at 900r.p.m. when states is connected to 3φ supply .find the rotor frequency.
Solution N_r =980 r.p.m., f=50Hz,
N_s=120f/p When P=2,
N_s=3000r.p.m.,P=4, N_s=1500

P=6, Ns=1000, P=8, Ns=750r.p.m.

As we know that synchronous speed is slightly greater than rotor

speed. N_s=1000 r.p.m. P=6

Fr=Sf=(Ns-N)/Ns*f=Sf = (1000-980) x 50 / 1000

Ques7: A 3 φ 50Hz induction motor has a full load speed of 960 r.p.m
(a) find slip
(b) No of poles
(c) Frequency of rotor induced e.m.f
(d) Speed of rotor field w.r.t. rotor structure
(e) Speed of rotor field w.r.t. Stator structure
(f) Speed of rotor field w.r.t. stator field

Solution:
Given f = 50 Hz(supply
frequency) N = 960r.p.m
The no. of pole will be 6 only(because at P=6, Ns = 1000 which is nearer nad greater then 960 r.p.m.)

(a) Slip, S = $(N_s-N)/N_s$ * 100 = (1000 – 960) / 1000 * 100 = 4%
(b) No of poles = 6
(c) Frequency of rotor induced emf = f_r = SF = .04 * 50 = 2Hz

(d) Speed of rotor field w.r.t rotor structure = $120f_r/p$ = 120*2/6 = 40 r.p.m.
(e) Speed of rotor field w.r.t. stator structure os actually the speed of stator filed w.r.t stator structure, N_s = 1000r.p.m
(f) Speed of rotor field w.r.t stator field is zero

Ques8: A 3 φ, 400V wound rotor has delta connected stator winding and star connected rotor winding. The stator has 48 turns/phase while rotor has 24 turns per phase. Find the stand still or open circuited voltage across the slip rings

Solution

Stator e.m.f/phase E1 =
400V Statur turns/phase
N1 = 48 Rotor turns/phase
N2 = 24 K= N2/N1 = 24/48
= 1/2

Rotor e.m.f/phase = KE_1 = 1/2 * 400 = 200V
Voltage between slip rings = Rotor line voltage = √ 3 x 200 = 346 volt

Ques9: A 6 pole 3 φ 50Hz induction motor is running at full load with a slip of 4%. The rotor is star connected and its resistance and stand still reactance are 0.25 ohm and 1.5 ohm per phase. The e.m.f between slip ring is 100V. Find the rotor current per phase and p.f, assuming the slip rings are short circuited.

Solution

Rotor e.m.f./phase at stand still E_2 = 100√3 = 57.7V
Rotor e.m.f./phase at full load = sE_2 = 0.04 * 57.7 = 2.31
V Rotor reactance/phase at full Load = SX_2 = .04 * 1.5 =
.06 ohm
Rotor impedance/phase at full load = $\sqrt{((0.25)^2 + (0.06)^2)}$ = .257
ohm Full load Rotor current/phase = 2.31/0.257 = 9A
Rotor P.f = 0.25/0.257 = 0.97 lag

Quest10: A 50 Hz, 8 pole induction motor has full load slip of 4%. The rotor resistance and stand still reactance are 0.01 ohm and 0.1 ohm per phase respectively. Find:
i) The speed at which maximum torque occurs
ii) The ratio of maximum torque to full load torque

Solution:

Synchronous speed N_s = 120f/P = 120*50/8 = 750r.p.m.
Slip at which maximum torque occurs = R_2/X_2 = 0.01/0.1 = 0.1
Rotor speed at maximum torque = (1-0.1) N_s = (1- 0.1) 750 = 675 r.p.m. $T_m/T_f = (a^2 + s^2)/2as$ Where s = Full load slip = 0.04

a = R_2/X_2 = 0.01/0.1 = 0.1
$T_m/Tf = ((0.1)^2 + (0.04)^2)/(2*0.1*0.04)$ = 1.45

Ques 11: An 8 pole 3 φ, 50 Hz induction motor has rotor resistance of 0.025 ohm/phase and rotor standstill reactance of 0.1ohm/phase. At what speed is the torque maximum? What proportion of maximum torque is the starting torque?

Solution

N_s = 120f/P = 120*50/8 = 750 r.p.m.
$R_2 = SX_2$------------for maximum torque
S = R_2/X_2 = 0.025/0.1 = 0.25
Corresponding speed N = (1-s)Ns = (1 – 0.25)750 = 562.5

r.p.m. ii) $T_s/T_m = 2a/(a^2+1) = 0.47$ where $a = R_2/X_2 =$

0.025/0.1 = 0.25

Ques12: A 500 V, 3 φ, 50 Hz induction motor develops an output of 15 KW at 950 r.p.m. If the input p.f. is 0.86 lagging, Mechanical losses are 7.30 W and stator losses 1500W, Find
i) the slip
ii) the rotor Cu loss
iii) the motor input
iv) the line current

Solution:

VL = 500V, motor output Pr =
15KW N = 950 r.p.m. P.f. = cos Ø
= 0.86lags Mech. Loss = 730 W
Stator loss = 1500 W
Ns = 120f/P = 120 * 50/6 = 1000r.p.m.
i) S = (Ns-N)/Ns * 100 = (1000 – 960)/1000 *100 = 0.05*100 = 5%
ii) Rotor output = Motor output + Mechanical output = 15 + .730 watt = 15.73
KWatt There fore (Rotor Cu loss)/(Rotor output) = s/(s-1)
Or Rotor Cu loss = 15.73 * (0.05)/(1-0.05) = 827.89

watt Power flow diagram for finding the motor input

Motor input = 15kw + 730 + 1500 + 827.89 = 18.058KW
Line Current = $\sqrt{3}V_2I_2\text{Cos}\varphi$
I2 = 24.25A

Ques13: A 6 pole 3φ induction motor develops 30hp including 2 hp mechanical losses at a speed of 950 r.p.m. on 550V, 50Hz Mains. The P.F. is 0.88 lagging. Find:
1) Slip
2) Rotor Cu loss
3) Total input if stator losses are 2kw
4) η
5) Line current

Solution

N_s = 120f/P = 120 * 50/6 = 1000 r.p.m.
1) S = (N_s – N)/N_s = (1000 – 950)/1000 = 0.05
Rotor output P_{mech} = 30hp = 30 * 735.5 = 22065 watt
Power input to rotor = P_{mech}/(1-S) = 22065/(1-0.05) = 23,226
2) Rotor Cu loss = s * rotor input = 0.05 * 23226 = 1161 Watt
3) Total input = Power input to rotor + stator losses = 23226 + 2000 = 25226 Watt

Motor output = Rotor output – Mech loss = 30 – 2 = 28 HP = 28 * 735.5 = 20594 Watt
4) η = (Motor output)/(Motor input) * 100 =
81.64% 5) I_L = (Motor Input)/(√3 * 550 * 0.88) =
30A

Ques14: A 4 pole 50 Hz 3 φ induction motor running at full load, develops a torque of 160N-m, when rotor makes 120 complete cycles per minute, find what power output

Solution

Supply frequency f = 50Hz

Rotor e.m.f. frequency = f = 120/60 =
2Hz Slip S = f'/f = 2/50 = 0.04
N_s = 120f/p = 120 *50/4 = 1500 r.p.m.
Shaft power output = T_{sh} * 2πN/160 = 160 * 2 π * 1440/60 = 24127W

Ques15: The power input to a 500V 50Hz, 6 pole, 3 φ squirrel case inductor motor running at 975 r.p.m. is 40kw. The stator losses are 1 kw and friction and windage losses are 2kw. Find:

1) Slip
2) Rotor Cu loss
3) Brake hp

Solution:

i) N_s = 120f/P = 120*50/6 = 1000 r.p.m.
S= (N_s – N)/N_s = (1000 – 975)/1000 = 0.025
Power input to station P_1 = 40Kw
Stator output power = P_1 – stator losses = 40 -1 =
39kw Power input to rotor P_2 = Stator output
power = 39 KW
ii) Rotor Cu loss = sP_2 = 0.025 * 39 =
0.975KW P_{mech} = P_2 – P_{cu} = 39 – 0.975 =
38.025
iii) Motor output = P_{mech} – friction and windage loss = 38.025 – 2 = 36.025KW

Ques16: A 480V, 60 Hz, 6-pole, three-phase, delta-connected induction motor has the following parameters:

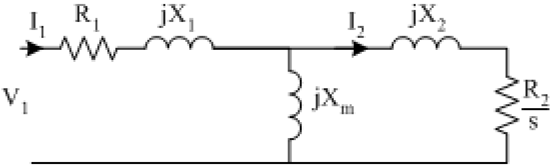
R_1=0.461 Ω, R_2=0.258 Ω, X_1=0.507 Ω, X_2=0.309 Ω, X_m=30.74 Ω

Rotational losses are 2450W. The motor drives a mechanical load at a speed of 1170 rpm. Calculate the following information:

i. Synchronous speed in rpm
ii. slip
iii. Line Current
iv. Input Power
v. Airgap Power
vi. Torque Developed
vii. Output Power in Hp
viii. Efficiency

Solution

This machine has no iron loss resistance, so the equivalent circuit is as follows:



i. Synchronous speed is given by:

$$n_s = \frac{120 f_e}{p}$$

Therefore

$n_s = 1200$ rpm

ii. Slip is given by

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{n_s - n_m}{n_s}$$

Using the rpm equation,

$s = (1200-1170)/1200 = 0.025$

iii. Now, phase current is given by

$$I_1 = \frac{V_1}{Z_{in}}$$

where phase impedance is given by

$$Z_{in} = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2}{s} + jX_2\right)}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}$$

Using the above equation, $Z_{in} = 9.57 + j3.84\ \Omega$
And noting that the machine is delta connected, $V_1 = V_{LL} = 480V$

$I_1 = 43.1 - j17.4$ A. $|I_1| = 46.6$ A, $\theta = -21.9°$
Therefore $I_L = \sqrt{3} \times 46.6 = 80.6$ A

iv. Input power is given by:

$$P_{in} = \sqrt{3} V_{LL} I_L \cos\theta = 3 V_1 I_1 \cos\theta$$

Therefore:

$P_{in} = 62.2$ kW

v. To find airgap power, There are two possible approaches:

   a. Airgap power is the input power minus stator losses. In this case the core losses are grouped with rotational loss. Therefore

$$P_{gap} = P_{in} - 3 I_1^2 R_1$$

$P_{gap} = 62.2\text{ kW} - 3 \times 46.6^2 \times 0.461$
$P_{gap} = 59.2$ kW

b. Airgap Power is given by

$$P_{gap} = \frac{3I_2^2R_2}{s}$$

This approach requires rotor current to be found. With no core loss resistance:

$$\mathbf{I}_2 = \frac{jX_m}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}\mathbf{I}_1$$

$$I_2 = \left|\frac{jX_m}{\frac{R_2}{s} + j\left(X_2 + X_m\right)}\right| I_1$$

Giving $I_2 = 43.7\ A$. Substituting into the power equation

$P_{gap} = 59.2kW$

vi. Torque developed can be found from

$$\tau = \frac{P_{gap}}{\omega_s}$$

where synchronous speed in radians per second is given by

$$\omega_s = \frac{4\pi f_e}{p}$$

giving

$\tau = 471\ Nm$

vii. Output power in horsepower is the output power in Watts divided by 746. (there are 746 W in one Hp).

$$P_{out} = P_{conv} - P_{rotational}$$

and

$$P_{conv} = \left(1 - s\right)P_{gap}$$

Therefore output power in Watts is:P_{out} =

$55.3kW$ $P_{out} = 74.1\ Hp$

viii. Efficiency is given by

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

Therefore

$\eta = 55.3/62.2 = 88.9\%$

Ques17: A three-phase, 6-pole, 10 HP, 400 Hz induction motor has a slip of 3% at rated output power. Friction and windage losses are 300 W at rated speed. The rated condition total core losses are 350 W. $R_1 = R'_2 = 0.05\ \Omega$. $X_1 = X'_2 = 0.15\ \Omega$. If the motor is operating at rated output power, speed, and frequency, find (*a*) rotor speed, (*b*) frequency of rotor currents, (*c*) total power across the air gap, (*d*) efficiency, and (*e*) applied line voltage. Use the approximate equivalent circuit for analysis.

(*a*)

$$n_s = \frac{120 f}{p} = \frac{(120)(400)}{6} = 8000 \text{ rpm}$$

$$n_m = (1-s)\,n_s = (1-0.03)(8000) = 7760 \text{ rpm}$$

(*b*)

$$f_r = s\,f = (0.03)(400) = 12 \text{ Hz}$$

(*c*)

$$3P_d = P_s + P_{FW} = (10)(746) + 300 = 7760 \text{ W}$$

$$3P_g = \frac{3P_d}{(1-s)} = \frac{7760}{1-0.03} = 8000 \text{ W}$$

(*d*) The reflected secondary current is found by

$$I'_2 = \left[\frac{sP_g}{R'_2}\right]^{1/2} = \sqrt{\frac{(0.03)(8000/3)}{0.05}} = 40 \text{ A}$$

$$\text{Losses} = 3(I'_2)^2(R_1 + R'_2) + 3P_c + P_{FW}$$

$$= 3(40)^2(0.05 + 0.05) + 350 + 300 = 1130 \text{ W}$$

$$\eta = \frac{P_s(100)}{P_s + \text{losses}} = \frac{(10)(746)(100)}{(10)(746) + 1130} = 88.94\%$$

(*e*)

$$V = I'_2\left|R_1 + \frac{R'_2}{s} + jX_{eq}\right| = 40\left|0.05 + \frac{0.05}{0.03} + j0.3\right| = 69.71 \text{ V}$$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