LECTURE NOTES

On
Electrical Machine
(Chapter- 5, 6, 7)

<u>Name of the Department- Electrical Engineering</u>

SUBJECT CODE- TH 1

NAME OF THE SUBJECT- ELECTRICAL MACHINE

SEMESTER- 4TH

BRANCH- ETC

COURSE CONTENT:

1. *TRANSFORMER*

State construction & working principle of transformer & define connection of Ideal transformer.
Derive of EMF equation of transformer, voltage transformation ratio.
Discuss Flux, Current, EMF components of transformer and their phasor diagram under no load condition.
Discuss Phasor representation of transformer flux, current EMF primary and secondary voltages under loaded condition.
Explain types of losses in Single Phase (1-ø) Transformer.
Explain open circuit & short-circuit test (simple problems)
Explain Parallel operation of Transformer.

2. *INDUCTION MOTOR*

Explain construction feature, types of three-phase induction motor.
State principle of development of rotating magnetic field in the stator.
Establish relationship between synchronous speed, actual speed and slip of induction motor.
Establish relation between torque, rotor current and power factor.
Explain starting of an induction motor by using DOL and Star-Delta stator. State industrial use of induction motor.

3. *SINGLE PHASE INDUCTION MOTOR*

Explain construction features and principle of operation of capacitor type and shaded pole type of single-phase induction motor.
Explain construction & operation of AC series motor.
Concept of alternator & its application.

MODULE 5 -TRANSFORMERS

Introduction

The transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency. Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electrical power system and distribution systems. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency as high as 99%.

Single Phase Transformer

A transformer is a static device of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig 1. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V_1 whose magnitude is to be changed is applied to the primary.

Depending upon the number of turns of the primary (N_1) and secondary (N_2), an alternating e.m.f. E_2 is induced in the secondary. This induced e.m.f. E_2 in the secondary causes a secondary current I_2. Consequently, terminal voltage V_2 will appear across the load.

If $V_2 > V_1$, it is called a step up-transformer.

If $V_2 < V_1$, it is called a step-down transformer.

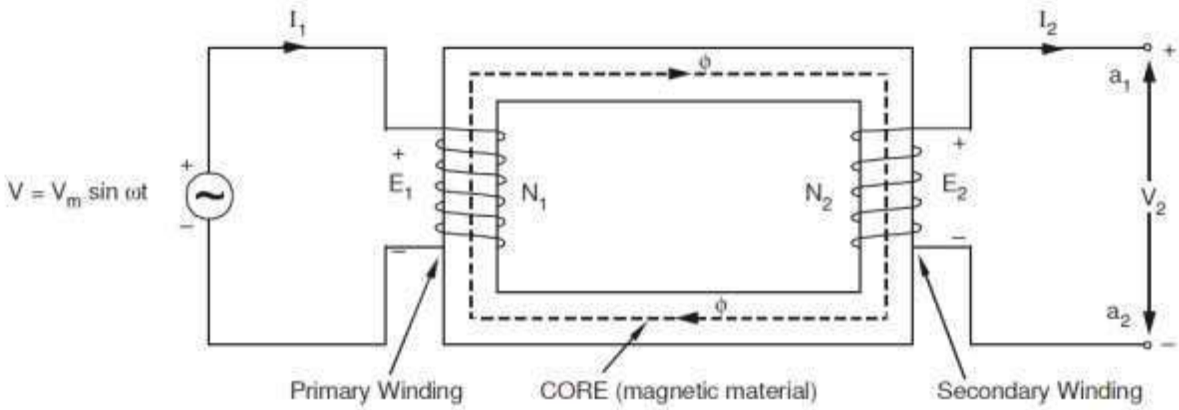


Fig. 1 Schematic diagram of single phase transformer

Constructional Details

Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called (a) core type, and (b) shell type.

Core-type and Shell-type Construction

In core type transformers, the windings are placed in the form of concentric cylindrical coils placed around the vertical limbs of the core. The low-voltage (LV) as well as the high-voltage (HV) winding are made in two halves, and placed on the two limbs of core. The LV winding is placed next to the core for economy in insulation cost. Figure 2(a) shows the cross-section of the arrangement.

In the shell type transformer, the primary and secondary windings are wound over the central limb of a three-limb core as shown in Figure 2(b). The HV and LV windings are split into a number of sections, and the sections are interleaved or sandwiched i.e. the sections of the HV and LV windings are placed alternately.

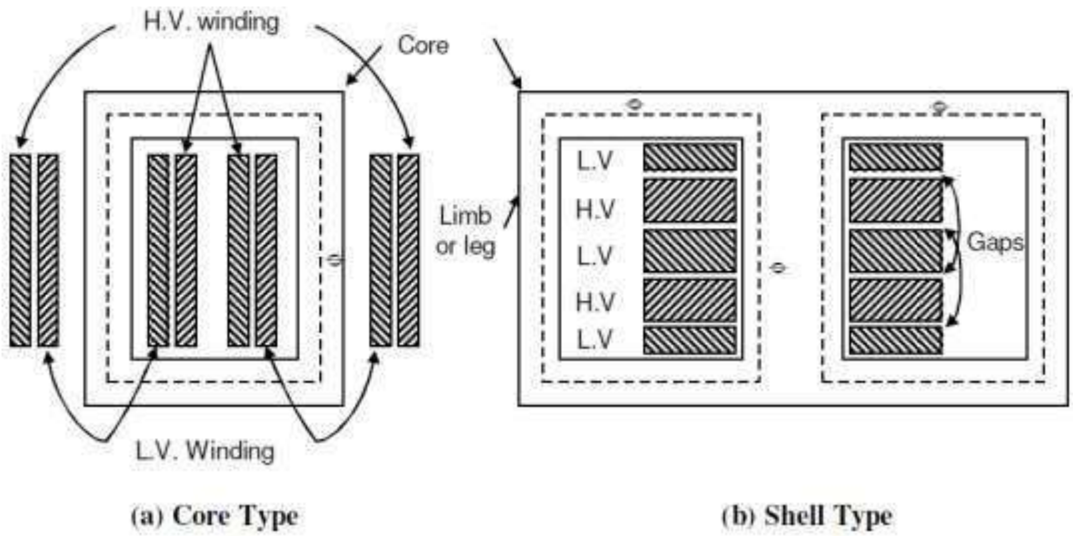


Fig: 2 Core type & shell type transformer

Core

The core is built-up of thin steel laminations insulated from each other. This helps in reducing the eddy current losses in the core, and also helps in construction of the transformer. The steel used for core is of high silicon content, sometimes heat treated to produce a high permeability and low hysteresis loss. The material commonly used for core is CRGO (Cold Rolled Grain Oriented) steel. Conductor material used for windings is mostly copper. However, for small distribution transformer aluminium is also sometimes used. The conductors, core and whole windings are insulated using various insulating materials depending upon the voltage.

Principle of Operation

When an alternating voltage V1 is applied to the primary, an alternating flux ϕ is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to Faraday's laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and e.m.f. E2 is termed as secondary e.m.f.

Clearly, $$E_1 = -N_1 \frac{d\phi}{dt}$$

and $$E_2 = -N_2 \frac{d\phi}{dt}$$

$$\therefore \quad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively.

If $N_2 > N_1$, then $E_2 > E_1$ (or $V_2 > V_1$) and we get a step-up transformer. If $N_2 < N_1$, then $E_2 < E_1$ (or $V_2 < V_1$) and we get a step-down transformer.

If load is connected across the secondary winding, the secondary e.m.f. E_2 will cause a current I_2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level.

The following points may be noted carefully:

(a) The transformer action is based on the laws of electromagnetic induction.

(b) There is no electrical connection between the primary and secondary.

(c) The a.c. power is transferred from primary to secondary through magnetic flux.

(d) There is no change in frequency i.e., output power has the same frequency as the input power.

(e) The losses that occur in a transformer are:

(a) ***core losses***—eddy current and hysteresis losses

(b) ***copper losses***—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

E.M.F. Equation of a Transformer

When the primary winding is excited by an alternating voltage V_1, it is circulating alternating current, producing an alternating flux ϕ.

Let ϕ_m - maximum value of flux
f - Frequency of the supply voltage

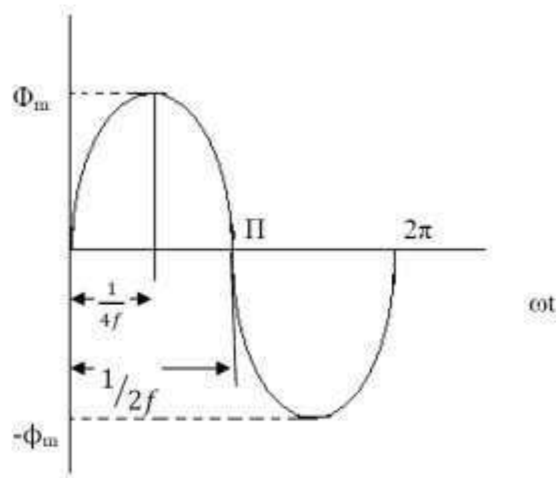


Fig. 3

The flux increases from zero value to maximum value ϕ_m in one fourth of a cycle i.e in 1/4f seconds.

So average rate of change of flux: $\frac{d\emptyset}{dt} = \frac{\emptyset_{max}}{1/4f} = 4f\emptyset_{max}$

Since average emf induced per turn in volt is equal to the average rate of change of flux (according to Faraday's law of electromagnetic induction)

Average emf induced per turn= $4f\emptyset_{max}$ volts

Since flux varies sinusoidally, emf induced will be sinusoidal and form factor for sinusoidal wave is 1.11 i.e the rms value is 1.11 times the average value.

∴ RMS value of emf induced per turn = 1.11× $4f\emptyset_{max}$ volts
If N_1, N_2 - Number of primary turn and secondary turns, then
RMS value of emf induced in primary, E_1 = emf induced per turn× Number of primary turn

$= 4.44 f\phi_{max} \times N_1 = 4.44 f N_1 \phi_{max}$ volt

Similarly , R.M.S. value of the secondary induced e.m.f, $E_2 = 4.44 f N_2 \phi_{max}$ volt

Alternatively

The sinusoidal flux ϕ produced by the primary can be represented as:

$\phi = \phi_m \sin\omega t$

∴Instantaneous value of emf induced per turn

$$= \frac{-d\phi}{dt} \text{ volt} = -\omega \Phi_{max}\cos\omega t = \omega\phi_{max}\sin\left(\omega t - \frac{\pi}{2}\right) \text{ volts}$$

It is clear from the above equation that the maximum value of emf induced per turn

$$= \omega\phi_{max} = 2\pi f\phi_{max} \text{ volts}$$

And rms value of emf induced per turn $= \frac{1}{\sqrt{2}} 2\pi f\phi_{max} = 4.44\, f\phi_{max}$ volts

Hence rms value of emf induced in primary = $E_1 = 4.44 f N_1 \phi_{max}$ volts

And rms value of emf induced in secondary = $E_2 = 4.44 f N_2 \phi_{max}$ volts

In an ideal transformer the voltage drops in primary and secondary windings are negligible, so

EMF induced in primary winding E_1= Applied voltage to primary V_1

And terminal voltage V_2 = EMF induced in primary winding E_2

Voltage Ratio

Voltage transformation ratio is the ratio of e.m.f induced in the secondary winding to the e.m.f induced in the primary winding.

$$\frac{E2}{E1} = \frac{4.44\phi mf\, N2}{4.44\phi mf\, N1}$$

$$\boxed{\frac{E2}{E1} = \frac{N2}{N1} = K}$$

This ratio of secondary induced e.m.f to primary induced e.m.f is known as voltage transformation ratio

$$E_2 = KE_1 \qquad \text{where } K = \frac{N2}{N1}$$

1. If $N_2 > N_1$ i.e. $K>1$ we get $E_2 > E_1$ then the transformer is called step up transformer.

2. If $N_2 < N_1$ i.e. $K<1$ we get $E_2 < E_1$ then the transformer is called step down transformer.

3. If $N_2 = N_1$ i.e. $K=1$ we get $E_2 = E_2$ then the transformer is called isolation transformer or 1:1

transformer.

Current Ratio

Current ratio is the ratio of current flow through the primary winding (I_1) to the current flowing through the secondary winding (I_2). In an ideal transformer -

Apparent input power = Apparent output power.

$$V_1 I_1 = V_2 I_2$$

$$\text{OR} \quad \frac{I_1}{I_2} = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

i) The transformer rating is specified as the products of voltage and current (VA rating).

ii) On both sides, primary and secondary VA rating remains same. This rating is generally expressed in KVA (Kilo Volts Amperes rating).

KVA Rating of transformer = $\frac{V_1 I_1}{1000} = \frac{V_2 I_2}{1000}$ (1000 is to convert KVA to VA)

$I_1 = (\boldsymbol{KAV\ Rating} \times \mathbf{1000})/\mathbf{V_1}$

$I_2 = (\boldsymbol{KAV\ Rating} \times \mathbf{1000})/\mathbf{V_2}$

Example 1: It is desired to have a 4.13 mWb maximum core flux in a transformer at 110V and 50 Hz. Determine the required number of turns in the primary.

Solution: EMF induced in primary, E_1 = 110V

Supply frequency, f = 50Hz

Maximum core flux, ϕ_{max} = 4.13 mWb

= 4.13×10^{-3} Wb

Required number of turns on primary,

$$N_1 = \frac{E_1}{4.44 f \phi_{max}}$$

$$= \frac{110}{4.44 \times 50 \times 4.13 \times 10^{-3}} = 120$$

Example 2: The emf per turn of a single phase 10 kVA, 2200/220V, 50 Hz transformer is 10V. Calculate (i) the number of primary and secondary turns, (ii) the net cross-sectional area of core for a maximum flux density of 1.5T.

Solution: EMF per turn = 10V

Primary induced emf, $E_1 = V_1 = 2{,}200$ V

Secondary induced emf, $E_2 = V_2 = 220$V

Supply frequency, f = 50 Hz

Maximum flux density, $B_{max} = 1.5$ T

For (i)

Number of primary turns,

$$N_1 = \frac{E_1}{EMF\ per\ turn} = \frac{2,200}{10} = 220$$

Number of secondary turns,

$$N_2 = \frac{E_2}{EMF\ per\ turn} = \frac{220}{10} = 22$$

Maximum value of flux,

$$\phi_{max} = \frac{EMF\ per\ turn}{4.44 \times f} = \frac{10}{4.44 \times 50} = 0.045Wb$$

For (ii)

Net cross-sectional area of core,

$$a = \frac{\phi_{max}}{B_{max}} = \frac{0.045}{1.5} = 0.03m^2$$

Example 3: A single phase transformer has 350 primary and 1,050 secondary turns. The net cross-sectional area of the core is 55 cm^2. If the primary winding be connected to a 400 V, 50 Hz single phase supply, calculate (i) maximum value of the flux density in the core and (ii) the voltage induced in the secondary winding.

Solution: Net cross-section area of core,

$$a = 55^2 = 0.0055m^2$$

Maximum value of flux,

$$\phi_{max} = \frac{E_1}{4.44 \times f \times N_1} = \frac{400}{4.44 \times 50 \times 350} = 5.148 \times 10^{-3}Wb$$

For (i)

peak value of flux density in the core,

$$B_{max} = \frac{\phi_{max}}{a} = \frac{5.148 \times 10^{-3}}{0.0055} = 0.936T$$

For (ii)

Voltage induced in the secondary winding,

$$E_2 = E_1 \times \frac{N_2}{N_1} = 400 \times \frac{1050}{350} = 1200V$$

Example 4: A 25 kVA, single phase transformer has 250 turns on the primary and 40 turns on the secondary winding. The primary is connected to 1500 V, 50 Hz mains calculate (i) secondary emf (ii) primary and secondary current on full load (iii) maximum flux in the core.

Solution:

Supply voltage V_i = 1500 V

Primary induced emf, $E_1 = V_i$ = 1500 V

For (i)

Secondary emf,

$$E_2 = \frac{E_1 \times N_2}{N_1} = \frac{1500 \times 40}{250} = 240V$$

For (ii)

Appropriate value of primary current on full load,

$$I_1 = \frac{Rated\ kVA\ 1000}{V_i} = \frac{24 \times 1000}{1500} = 16,667A$$

Appropriate value of secondary current on full load,

$$I_2 = \frac{Rated\ kVA\ \times 1000}{E_2\ or\ V_2} = \frac{25 \times 1000}{240} = 104.167A$$

For (iii)

Maximum value of flux in the core,

$$\phi_{max} = \frac{E_1}{4.44fN_1} = \frac{1500}{4.44 \times 50 \times 250} = 0.027Wbor27mWb$$

Transformer on No-load

a) Ideal transformer

b) Practical transformer

a) Ideal Transformer

An ideal transformer is one that has

(i) No winding resistance

(ii) No leakage flux i.e., the same flux links both the windings

(iii) No iron losses (i.e., eddy current and hysteresis losses) in the core

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer. In fact, practical transformers have properties that approach very close to an ideal transformer.

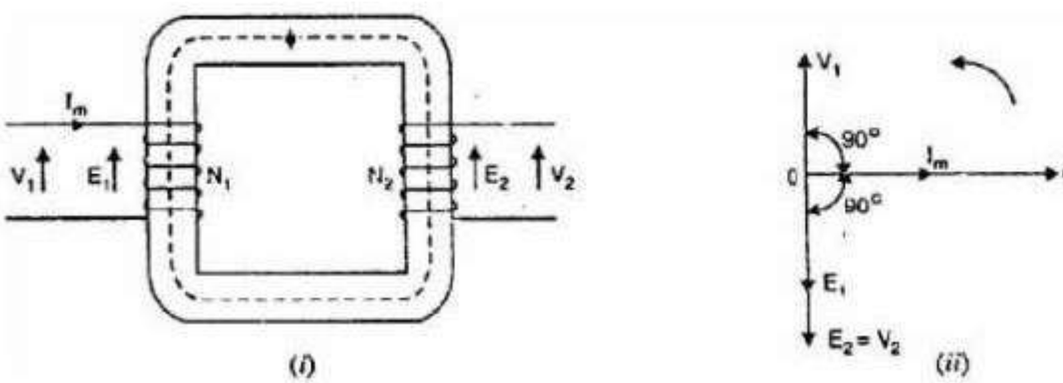


Fig: 4

Consider an ideal transformer on no load i.e., secondary is open-circuited as shown in *Fig.4 (i)* under such conditions, the primary is simply a coil of pure inductance. When an alternating voltage V1 is applied to the primary, it draws a small magnetizing current Im which lags behind the applied voltage by 90°. This alternating current Im produces an alternating flux ϕ which is proportional to and in phase with it. The alternating flux ϕ links both the windings and induces e.m.f. E1 in the primary and e.m.f. E2 in the secondary. The primary e.m.f. E1 is, at every instant, equal to and in opposition to V1 (Lenz's law). Both e.m.f.s E1 and E2 lag behind flux ϕ by 90°.However, their magnitudes depend upon the number of primary and secondary turns. *Fig. 2.4 (ii)* shows the phasor diagram of an ideal transformer on no load. Since flux ϕ is common to both the windings, it has been taken as the reference

$$\boxed{\frac{E2}{E1} = \frac{V2}{V1} = K}$$

phasor. The primary e.m.f. E1 and secondary e.m.f. E2 lag behind the flux ϕ by 90°. Note that E1 and E2 are in phase. But E1 is equal to V1 and 180° out of phase with it.

Phasor Diagram

1. Φ (flux) is reference
2. Im produce ϕ and it is in phase with ϕ, V_1 Leads Im by 90˚
3. E1 and E2 are in phase and both opposing supply voltage V1, winding is purely inductive. So current has to lag voltage by 90˚.
4. The power input to the transformer

$$P = V_1.I_1.\cos(90^\circ)............................ \quad (\cos 90^\circ = 0)$$

$$P = 0 \text{ (ideal transformer)}$$

b. (i) Practical Transformer on no load

No load Transformer means a transformer which has no load connection at secondary winding only normal voltage is applied at the primary winding. Let V_1 is applied at the primary winding. After applying A.C voltage V_1, it is seen that small amount of current I_0 flows through the primary winding. In case of Ideal Transformer, no load primary current (I_0) will be equal to magnetizing current (I_m) of the transformer. We assumed there is no core losses and copper loss, So $I_0 = I_m$. But, in case of actual transformer, there is two losses, i.e i) Iron Losses in the core i.e hysteresis loss and eddy current loss , ii) and a very small amount copper loss in the primary winding.

Consider a practical transformer on no load i.e., secondary on open-circuit as Shown in Fig 5.

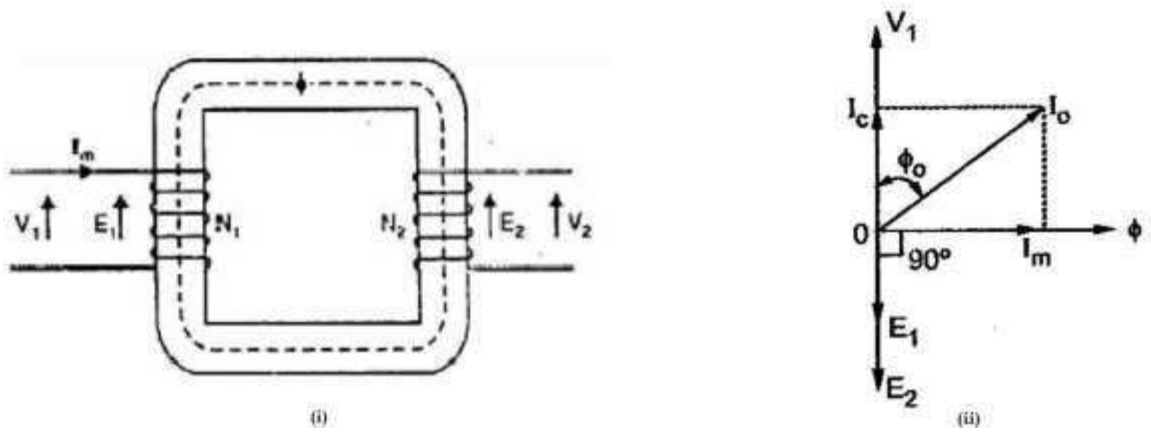


Figure 5.No-load phasor diagram of a single phase transformer

So, the primary current I_0 has two components:

1. I_C = Iron loss component which is same ph of applied voltage $V_1 = I_0 \cos \phi_0$
2. I_m = magnetizing component which is 90⁰ behind $V_1 = I_0 \sin \phi_0$

Hence, the primary current I_0 is vector summation of I_m & I_c , So, we can write that

$$\mathbf{I_0} = \sqrt{\mathbf{I}_m{}^2 + \mathbf{I}_c{}^2}$$

No-load PF, $\cos \emptyset_0 = \frac{I_c}{I_0}$

and is not a 90⁰ behind V_1, but lags it by an angle $\varphi < 90^0$ Which is shown in figure 5. And no load input power, $\mathbf{W_0 = V_1 I_0 Cose\, \varphi_0}$. The magnitude of no load primary current is very small as compared to the full-load primary current. It is 1 percent of the full-load current. As I_0 is very small, the no load primary Cu loss $\mathbf{I_0^2R_1}$ is negligible which means that no load primary input is practically equal to the iron loss in the transformer.

b) ii)Practical Transformer on Load

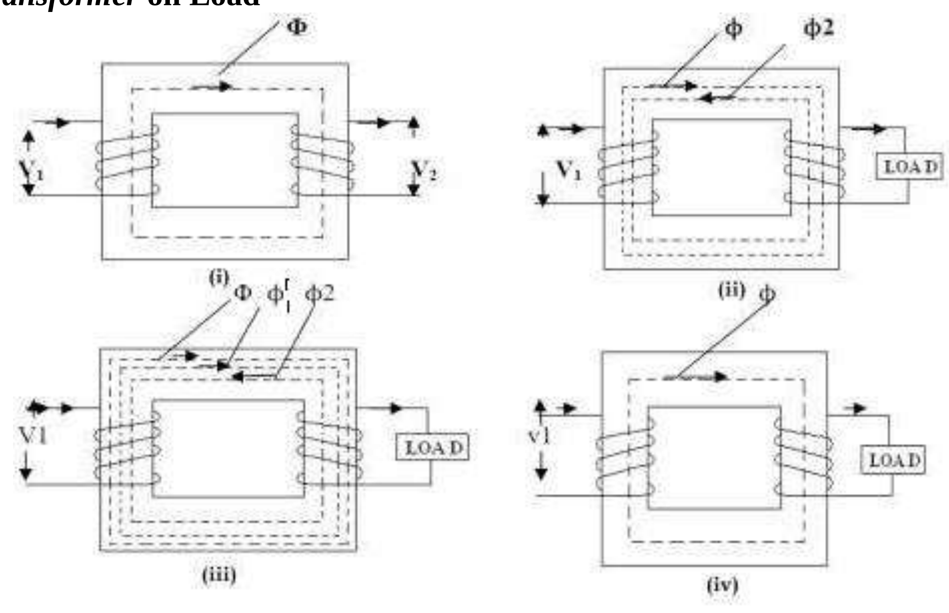


Figure 6. An Ideal transformer at loaded condition

At no load, there is no current in the secondary so that $V_2 = E_2$. On the primary side, the drops in R_1 and X_1, due to I_0 are also very small because of the smallness of I_0. Hence, we can say that at no load, $V_1 = E_1$.

i) When transformer is loaded, the secondary current I_2 is flows through the secondary winding.

ii) Already I_m magnetizing current flow in the primary winding .

iii) The magnitude and phase of I_2 with respect to V_2 is determined by the characteristics of the load.

a) I_2 in phase with V_2 (resistive load)

b) I_2 lags with V_2 (Inductive load)

c) I_2 leads with V_2 (capacitive load)

iv) Flow of secondary current I_2 produce new Flux ϕ_2 fig.6 (ii)

v) Φ is main flux which is produced by the primary to maintain the transformer as constant magnetizing component.

vi) Φ_2 opposes the main flux ϕ, the total flux in the core reduced. It is called demagnetizing Ampere-turns due to this E_1 reduced.

vii) To maintain the ϕ constant primary winding draws more current (I_1') from the supply (load component of primary) and produce ϕ_1' flux which is oppose ϕ_2 (but in same direction as ϕ), to maintain flux constant in the core shown in fig.6 (iii).

viii) The load component current I_1' always neutralizes the changes in the load.

ix) Whatever the load conditions, the net flux passing through the core is approximately the same as at no-load. An important deduction is that due to the constancy of core flux at all loads, the core loss is also practically the same under all load conditions fig.6 (iv).

$$\boxed{\Phi_2 = \phi_1' \quad N_2I_2 = N_1I_1' \quad I_1' = \frac{N2}{N1} X I_2 = KI_2}$$

Phasor Diagram

i) Take (ϕ) flux as reference for all load

ii) The no-load current I_0 lags by an angle Φ_0. $\mathbf{I_0} = \sqrt{\mathbf{I}_m{}^2 + \mathbf{I}_c{}^2}$

iii) The load component I_1', which is in anti-phase with I_2 and phase of I_2 is decided by the load.

iv) Primary current I_1 is vector sum of I_o and I_1'i.e

$$I_1 = \sqrt{I_0^2 + I_1'^2}$$

a) If load is Inductive, I_2 lags E_2 by ϕ_2, shown in phasor diagram fig 7 (a).

b) If load is resistive, I_2 in phase with E_2 shown in phasor diagram fig. 7 (b).

c) If load is capacitive load, I_2 leads E_2 by ϕ_2 shown in phasor diagram fig. 7 (c).

For easy understanding at this stage here we assumed E_2 is equal to V_2 neglecting various drops.

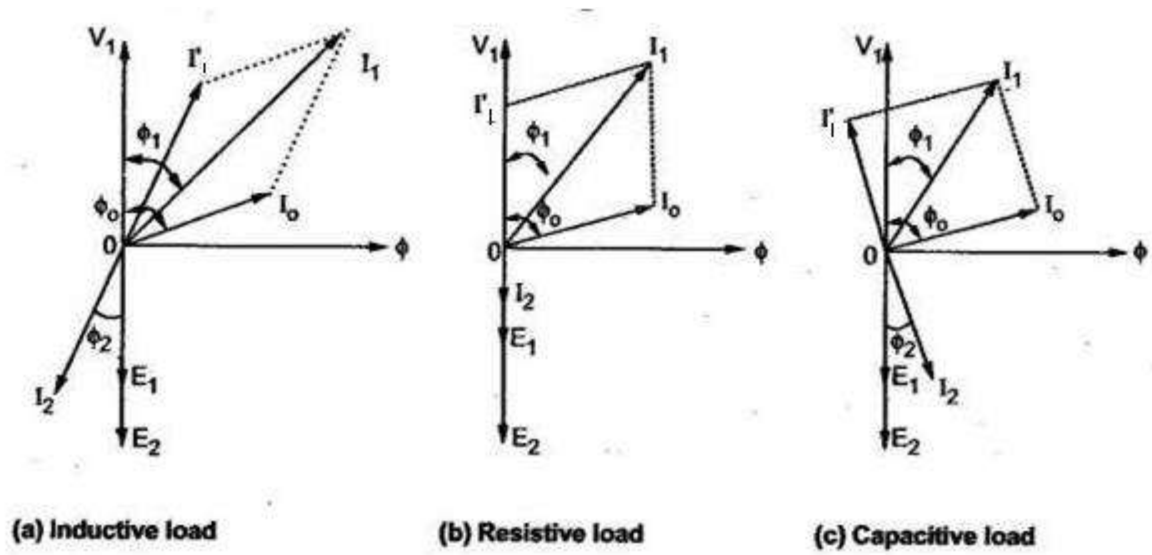


Fig: 7Phasor diagram for an ideal transformer on load

Now, $N_1I_1' = N_2I_2$
Therefore,

$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

Losses in a Transformer

The power losses in a transformer are of two types, namely

1. Core or Iron losses

2. Copper losses

These losses appear in the form of heat and produce (i) an increase in Temperature and (ii) a drop in efficiency.

2.7.1 Core or Iron losses (Pi)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

Hysteresis loss = $k_h f B_m^{1.6}$ watts /m^3

K_h – hysteresis constant depend on material

f - Frequency

B_m – maximum flux density

Eddy current loss = $K_e f^2 B_m^2 t^2$ watts /m^3

Ke – eddy current constant

t - Thickness of the core

Both hysteresis and eddy current losses depend upon

(i) Maximum flux density B_m in the core

(ii) Supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all loads.

Iron or Core losses, Pi = Hysteresis loss + Eddy current loss = Constant losses (Pi)

The hysteresis loss can be minimized by using steel of high silicon content .Whereas eddy current loss can be reduced by using core of thin laminations.

Copper losses (P_{cu})

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test. The copper loss depends on the magnitude of the current flowing through the windings.

$$\text{Total copper loss} = I_1^2R_1 + I_2^2R_2 = I_1^2(R_1 + R_2') = I_2^2(R_2 + R_1')$$

$$\boxed{\text{Total loss} = \text{iron loss} + \text{copper loss} = Pi + Pcu}$$

Efficiency of a Transformer

Like any other electrical machine, the efficiency of a transformer is defined as the ratio of output power (in watts or kW) to input power (watts or kW) i.e.

Power output = power input – Total losses

Power input = power output + Total losses

= power output + P_i + P_{cu}

$$\text{Efficiency} = \frac{power\ output}{power\ input}$$

$$\text{Efficiency} = \frac{power\ output}{power\ input + Pi + Pcu}$$

Power output = $V_2 I_2 \cos\phi$, $\cos\phi$ = load power factor

Transformer supplies full load of current I_2 and with terminal voltage V_2

Pcu = copper losses on full load = $I_2^2 R_{2e}$

$$\text{Efficiency} = \frac{\text{V2I2}\cos\phi}{\text{V2I2}\cos\phi + Pi + I2^2 R2e}$$

$V_2 I_2$ = VA rating of a transformer

$$\text{Efficiency} = \frac{\text{(VA rating)X}\cos\phi}{\text{(VA rating)X}\cos\phi + Pi + I2^2 R2e}$$

$$\boxed{\%\ \text{Efficiency} = \frac{\text{(VA rating)X}\cos\phi}{\text{(VA rating)X}\cos\phi + Pi + I2^2 R2e}\ \text{X 100}}$$

This is full load efficiency and I_2 = full load current.

We can now find the full-load efficiency of the transformer at any p.f. without actually loading the transformer.

$$\text{Full load Efficiency} = \frac{\text{(Full load VA rating)X}\cos\phi}{\text{(Full load VA rating)X}\cos\phi + Pi + I2^2 R2e}$$

Also for any load equal to n x full-load,

Corresponding total losses = $P_i + n^2 P_{cu}$

$$\text{n = fractional by which load is less than full load} = \frac{actual\ load}{full\ load}$$

$$n = \frac{half\ load}{fullload} = \frac{(\frac{1}{2})}{1} = 0.5$$

$$\boxed{\text{Corresponding (n) \% Efficiency} = \frac{n\text{(VA rating)X}\cos\phi}{n\text{(VA rating)X}\cos\phi + Pi + n^2 Pcu}\ \text{X 100}}$$

Condition for Maximum Efficiency

Voltage and frequency supply to the transformer is constant the efficiency varies with the load. As load increases, the efficiency increases. At a certain load current, it loaded further the efficiency start decreases as shown in fig. 2.21.

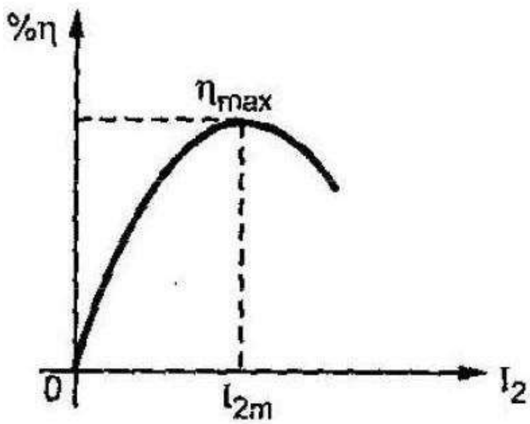


Fig: 8

The load current at which the efficiency attains maximum value is denoted as I_{2m} and maximum efficiency is denoted as ηmax, now we find -

(a) condition for maximum efficiency

(b) load current at which ηmax occurs

(c) KVA supplied at maximum efficiency

Considering primary side,

Load output = $V_1 I_1 \cos\phi 1$

Copper loss = $I_1^2 R_{1e}$ or $I2^2 R2e$

Iron loss = hysteresis + eddy current loss = P_i

$$\text{Efficiency} = \frac{V1I1\cos\phi 1 - \text{losses}}{V1I1\cos\phi 1} = \frac{V1I1\cos\phi 1 - I1^2 R1e + Pi}{V1I1\cos\phi 1}$$

$$= 1 - \frac{I1R1e}{V1I21\cos\phi 1} = \frac{Pi}{V1I1\cos\phi 1}$$

Differentiating both sides with respect to I2, we get

$$\frac{d\eta}{dI2} = 0 - \frac{R1e}{V1\cos\phi 1} = \frac{Pi}{V1I1^2\cos\phi 1}$$

For η to be maximum, $\frac{d\eta}{dI2} = 0$. Hence, the above equation becomes

$$\frac{R1e}{V1\cos\phi 1} = \frac{Pi}{V1I1^2\cos\phi 1} \text{ or } Pi = I_1^2 R_{1e}$$

P_{cu} loss = P_i iron loss

The output current which will make P_{cu} loss equal to the iron loss. By proper design, it is possible to make the maximum efficiency occur at any desired load.

Testing of Transformer

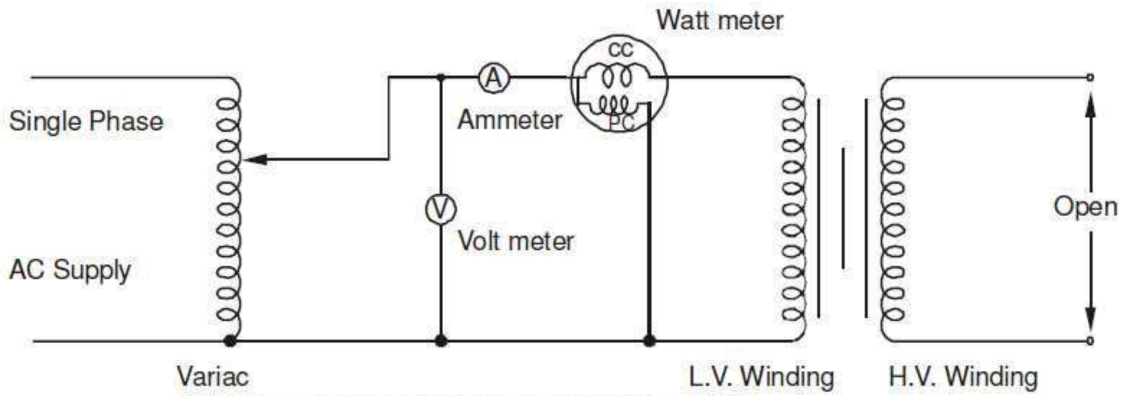
Open circuit test

Short circuit test

Open-Circuit or No-Load Test

This test is conducted to determine the iron losses (or core losses) and parameters R_0 and X_0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left open circuited. The applied primary voltage V_1 is measured by the voltmeter, the no load current I_0 by ammeter and no-load input power W_0 by wattmeter as shown in Fig.2.24.a. As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I_0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses. Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads.

This is the load current at η_{max} in terms of full load current



Iron losses, P_i = Wattmeter reading = W_0
No load current = Ammeter reading = I_0
Applied voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

No - load p.f., $\cos\phi = \dfrac{Wo}{Vo\, Io}$ = no load power factor

$I_m = I_o \sin \phi_o$ = magnetizing component
$I_c = I_o \cos \phi_o$ = Active component

$$R_o = \frac{Vo}{Ic}\ \Omega, \quad X_o = \frac{Vo}{Im}\ \Omega$$

Under no load conditions the PF is very low (near to 0) in lagging region. By using the above data we can draw the equivalent parameter shown in Figure 8.

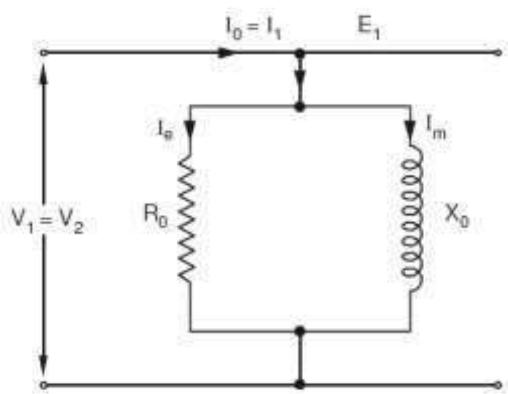


Fig:8

Thus open-circuit test enables us to determine iron losses and parameters R_0 and X_0 of the transformer.

Short-Circuit or Impedance Test

This test is conducted to determine R1e (or R2e), X1e (or X2e) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig.2.25. The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary. Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full load copper losses in the transformer windings.

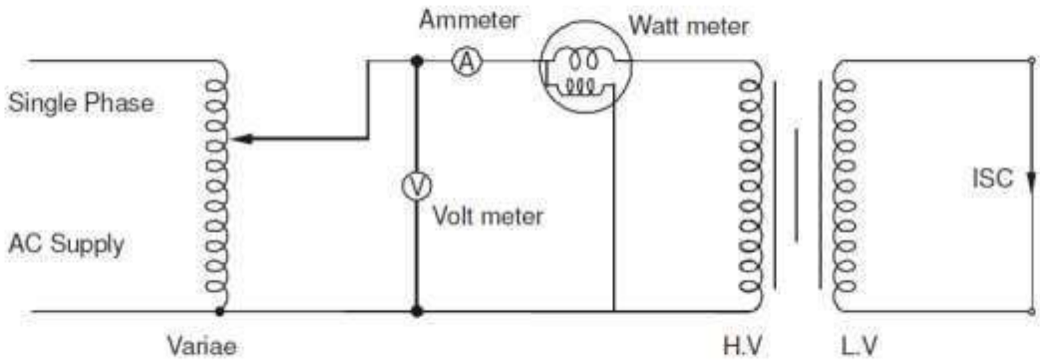


Fig: 9a

Full load Cu loss, PC = Wattmeter reading = W_{sc}
Applied voltage = Voltmeter reading = V_{SC}
F.L. primary current = Ammeter reading = I_1

$Pcu = I_1^2 R_1 + I_1^2 R_2' = I_1^2 R_{1e}$, $R_{1e} = \frac{Pcu}{I1^2}$

Where R_{1e} is the total resistance of transformer referred to primary.

Total impedance referred to primary, $Z1e = \sqrt{Z1e^2 - R1e^2}$,

short – circuit P.F. $\cos\Phi = \frac{Pcu}{Vsc\, I1}$ Thus short-circuit lest gives full-load Cu loss, R1e and X1e.

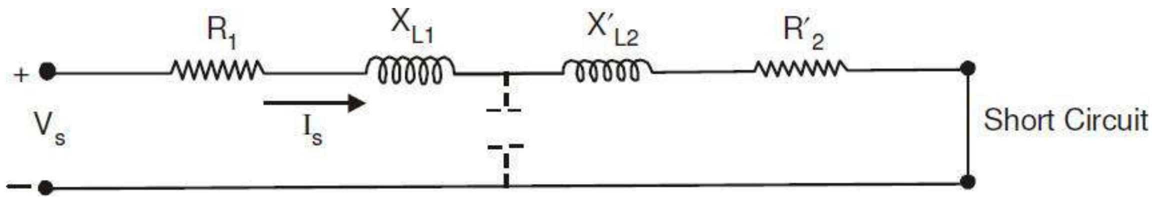


Fig: 9b

From fig: 9b we can calculate,

$$\text{equivalent resistance } R_{eq} = \frac{W_s}{I_s^2} = R_1 + R_2'$$

$$\text{and equivalent impedance } Z_{eq} = \frac{V_s}{I_s}$$

So we calculate equivalent reactance

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} = X_{L1} + X'_{L2}$$

These R_{eq} and X_{eq} are equivalent resistance and reactance of both windings referred in HV side. These are know as equivalent circuit resistance and reactance.

Auto-transformers

The transformers we have considered so far are two-winding transformers in which the electrical circuit connected to the primary is electrically isolated from that connected to the secondary. An auto-transformer does not provide such isolation, but has economy of cost combined with increased efficiency. Fig.2.26 illustrates the auto-transformer which consists of a coil of N_A turns between terminals 1 and 2, with a third terminal 3 provided after N_B turns. If we neglect coil resistances and leakage fluxes, the flux linkages of the coil between 1 and 2 equals N_A ϕm while the portion of coil between 3 and 2 has a flux linkage N_B ϕm. If the induced voltages are designated as E_A and E_B, just as in a two winding transformer,

$$\frac{\bar{E}_A}{\bar{E}_B} = \frac{N_A}{N_B}$$

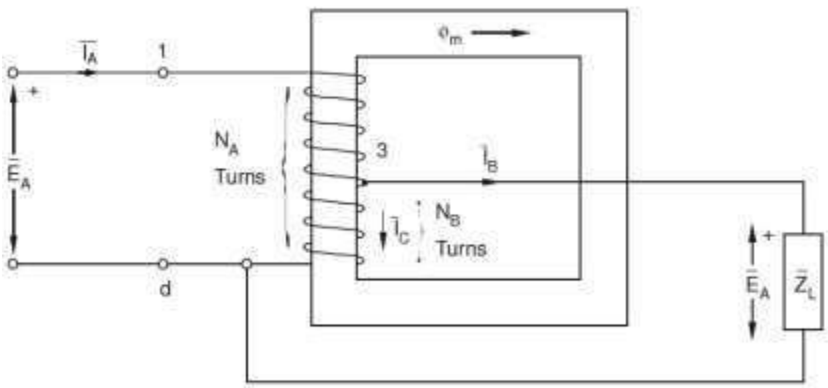


Fig: 10

Neglecting the magnetizing ampere-turns needed by the core for producing flux, as in an ideal transformer, the current I_A flows through only ($N_A – N_B$) turns. If the load current is I_B, as shown by Kirchhoff's current law, the current I_C flowing from terminal 3 to terminal 2 is (I_A - I_B). This current flows through N_B turns. So, the requirement of a net value of zero ampere-turns across the core demands that

Consequently, as far as voltage, current converting properties are concerned, the autotransformer of

$$(N_A - N_B)\,\bar{I}_A + (\bar{I}_A - \bar{I}_B)\,N_B = 0$$

or $$N_A\,\bar{I}_A - N_B\,\bar{I}_B = 0$$

Hence, just as in a two-winding transformer,

$$\frac{\bar{I}_A}{\bar{I}_B} = \frac{N_B}{N_A}$$

Figure: 10 behaves just like a two-winding transformer. However, in the autotransformer we don't need two separate coils, each designed to carry full load values of current.

Parallel Operation of Transformers

It is economical to install numbers of smaller rated transformers in parallel than installing a bigger rated electrical power transformers. This has mainly the following advantages,

To maximize electrical power system efficiency: Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfil the total demand. In this way we can run the system with maximum efficiency.

To maximize electrical power system availability: If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

To maximize power system reliability: if any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfil the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

Conditions for Parallel Operation of Transformers

When two or more transformers run in parallel, they must satisfy the following conditions for satisfactory performance. These are the conditions for parallel operation of transformers.

- ***Same voltage ratio of transformer.***
- ***Same percentage impedance.***
- ***Same polarity.***
- ***Same phase sequence.***
- ***Same Voltage Ratio***

Same voltage ratio of transformer.

If two transformers of different voltage ratio are connected in parallel with same primary supply voltage, there will be a difference in secondary voltages. Now say the secondary of these transformers are connected to same bus, there will be a circulating current between secondaries and therefore between primaries also. As the internal impedance of transformer is small, a small voltage difference may cause sufficiently high circulating current causing unnecessary extra I2R loss.

Same Percentage Impedance

The current shared by two transformers running in parallel should be proportional to their MVA ratings. Again, current carried by these transformers are inversely proportional to their internal impedance. From these two statements it can be said that, impedance of transformers running in parallel are inversely proportional to their MVA ratings. In other words, percentage impedance or per unit values of impedance should be identical for all the transformers that run in parallel.

Same Polarity

Polarity of all transformers that run in parallel, should be the same otherwise huge circulating current that flows in the transformer but no load will be fed from these transformers. Polarity of transformer means the instantaneous direction of induced emf in secondary. If the instantaneous directions of induced secondaryemf in two transformers are opposite to each other when same input power is fed to both of the transformers, the transformers are said to be in opposite polarity. If the instantaneous directions of induced secondary e.m.f in two transformers are same when same input power is fed to the both of the transformers, the transformers are said to be in same polarity.

Same Phase Sequence

The phase sequence or the order in which the phases reach their maximum positive voltage, must be identical for two parallel transformers. Otherwise, during the cycle, each pair of phases will be short circuited.

The above said conditions must be strictly followed for parallel operation of transformers but totally identical percentage impedance of two different transformers is difficult to achieve practically, that is why the transformers run in parallel may not have exactly same percentage impedance but the values would be as nearer as possible.

Why Transformer Rating in kVA?

An important factor in the design and operation of electrical machines is the relation between the life of the insulation and operating temperature of the machine. Therefore, temperature rise resulting from the losses is a determining factor in the rating of a machine. We know that copper loss in a transformer depends on current and iron loss depends on voltage. Therefore, the total loss in a transformer depends on the volt-ampere product only and not on the phase angle between voltage and current i.e., it is independent of load power factor. For this reason, the rating of a transformer is in kVA and not kW.

MODULE- 6
THREE PHASE INDUCTION MOTORS

Three Phase Induction Motor

An electrical motor is an electromechanical device which converts electrical energy into mechanical energy. In the case of three phase AC (Alternating Current) operation, the most widely used motor is a **3 phase induction motor**, as this type of motor does not require an additional starting device. These types of motors are known as self-starting induction motors.

Types and Construction of Three Phase Induction Motor

A 3 phase induction motor consists of two major parts:

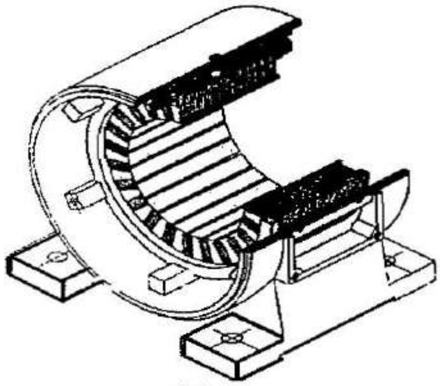
- A stator
- A rotor

According to the rotor construction three phase induction motors are constructed into two major types:

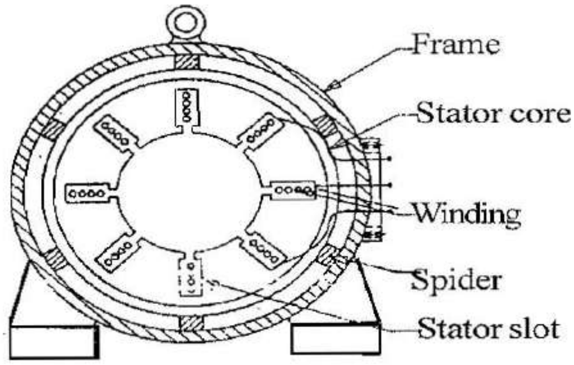
1. Squirrel cage Induction Motors
2. Slip ring Induction Motors

Stator Construction

The **stator** of three phase induction motor is made up of numbers of slots to construct a 3 phase winding circuit which we connect with 3 phase AC source. We arrange the three-phase winding in such a manner in the slots that they produce rotating magnetic field when we switch on the three-phase AC supply source which is of constant magnitude but which revolves at synchronous speed ($N_s = 120f/P$). This revolving magnetic field induces an EMF in the rotor by mutual induction. It is wound with a definite number of poles as per the requirement of the speed. Greater the number of pole lesser the speed and vice versa.
The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in below.



(a)



(b)

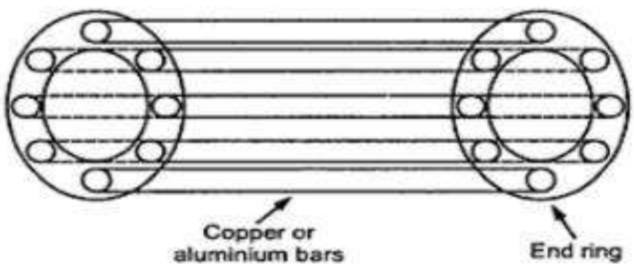
Squirrel cage Rotor Construction

The rotor of the squirrel cage motor shown in Fig as given below contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core.

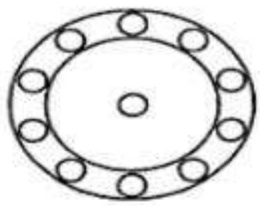
These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings .In small machines the conductor bars and end rings are sometimes made of aluminium with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived.

The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used.

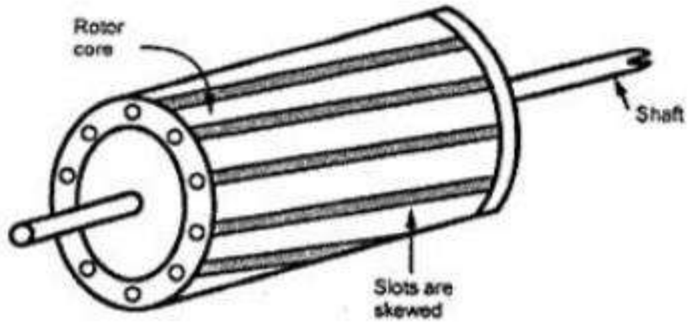
The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.



Cage type structure of rotor



Symbolic representation



Squirrel Cage Rotor

(a) End Shields

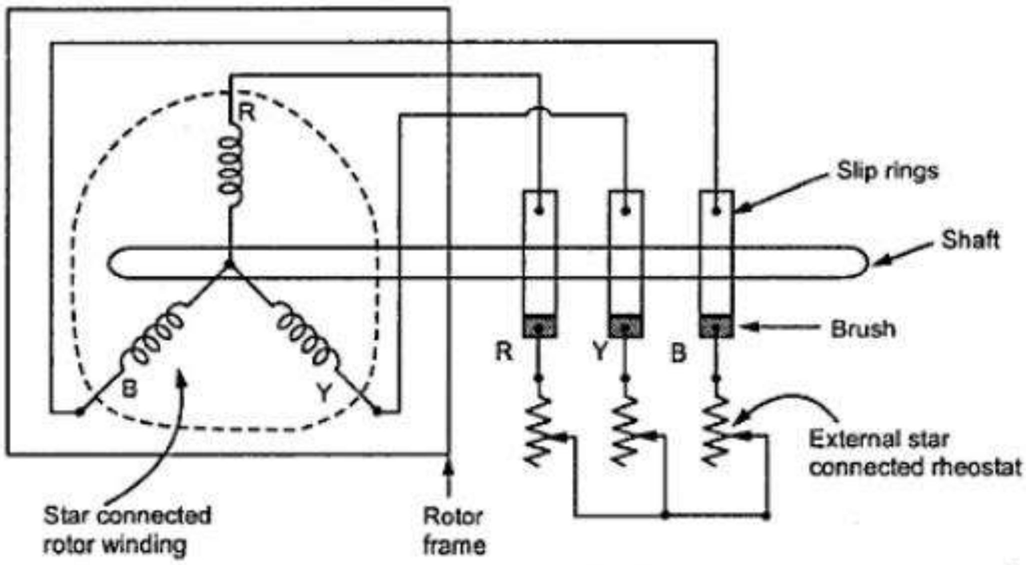
The function of the two end shields is to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts attention.

Slip ring or Phase wound Rotor Construction

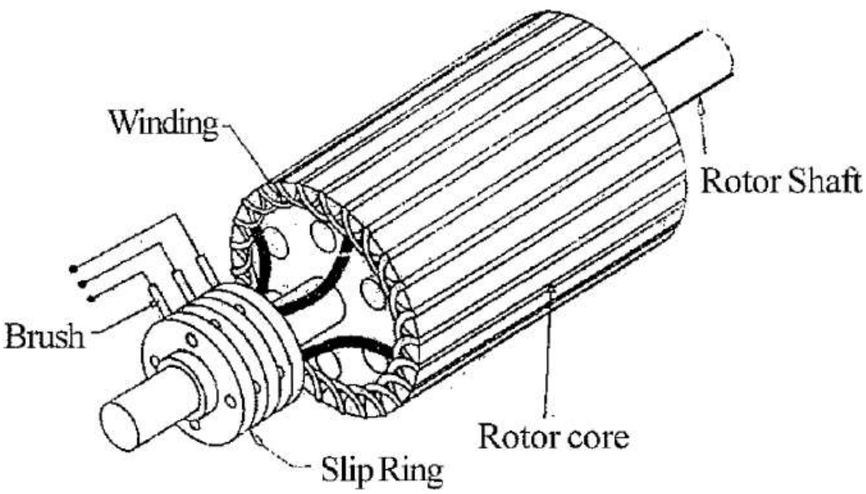
The rotor of the slip ring induction motor is also cylindrical or constructed of lamination.

Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star.

The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig:



Slip ring Rotor



Comparison of Squirrel Cage and Slip Ring Motor

Sl.No.	Property	*Squirrel cage motor*	*Slip ring motor*
1.	**Rotor Construction**	*Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes*	*Winding wire is to be used.* *Wound rotor required attention.* *Slip ring and brushes are needed* also need *frequent maintenance.*
2.	**Starting**	*Can be started by D.O.L., star-delta, auto transformer starters*	*Rotor resistance starter is required.*
3.	**Starting torque**	*Low*	*Very high*
4.	**Starting Current**	*High*	*Low*
5.	**Speed variation**	*Not easy, but could be varied in large steps by pole changing or through smaller incremental steps through thyristors or by frequency variation.*	*Easy to vary speed.* *Speed change is possible by inserting rotor resistance using thyristors or by using frequency variation injecting emf in the rotor circuit cascading.*
6.	**Maintenance**	*Almost ZERO maintenance*	*Requires frequent maintenance*
7.	**Cost**	*Low*	*High*

Principle of Operation

Induction motor works on the principle of electromagnetic induction. When three phase supply is given to the stator winding, a rotating magnetic field of constant magnetic field is produced.
The speed of rotating magnetic field(R.M.F.) is synchronous speed, NS r.p.m.

- $N_S = \dfrac{120f}{P}$ = speed of rotating magnetic field
- f = supply frequency

This rotating field produces an effect of rotating poles around a rotor. Let direction of this magnetic field is clockwise as shown.

Now at this instant rotor is stationary and stator flux R.M.F. is rotating. So its obvious that there exists a relative motion between the R.M.F. and rotor conductors. Now the R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors. Whenever a conductor cuts the flux, emf. gets induced in it. So e.m.f.gets induced in the rotor conductors called rotor induced emf. this is electro – magnetic induction.As rotor forms closed circuit, induced emf. circulates current through rotor called rotor current. Any current carrying conductor produces its own flux. So rotor produces its flux called rotor flux. For assumed direction of rotor current, the direction of rotor flux is clockwise as shown. This direction can be easily determined using right hand thumb rule. Now there are two fluxes, one R.M.F. and another rotor flux. Both the fluxes interact with each. On left of rotor conductor, two fluxes are in same direction hence added up to get high flux area. On right side of rotor conductor, two fluxes are in opposite direction hence they cancel each other to produce low flux area. So rotor conductor experiences a force from left to right, due to interaction of the two fluxes. As all rotor conductor experiences a force, overall rotor experiences a torque and starts rotating. So interaction of the two fluxes is very essential for a motoring action.

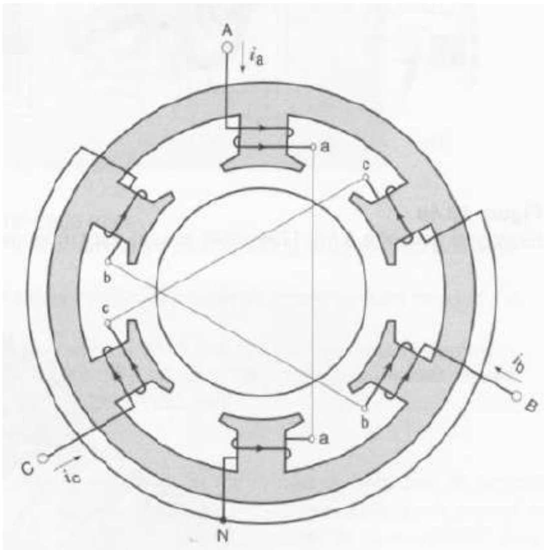
Rotating Magnetic Field and Induced Voltages

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns Coils that are diametrically opposite are connected in series by means of three jumpers that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

The three sets of windings are connected in wye, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line to neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

For a two-pole machine, rotating in the air gap, the magnetic field (i.e., flux density) being sinusoidally distributed with the peak along the centre of the magnetic poles. The result is illustrated in Fig.3.5. The rotating field will induce voltages in the phase coils aa', bb', and cc'. Expressions for the induced voltages can be obtained by using Faraday laws of induction.

Fig: Elementary stator having terminals A, B, C connected to a 3-phase source (not shown).
Currents flowing from line to neutral are considered tobe positive.



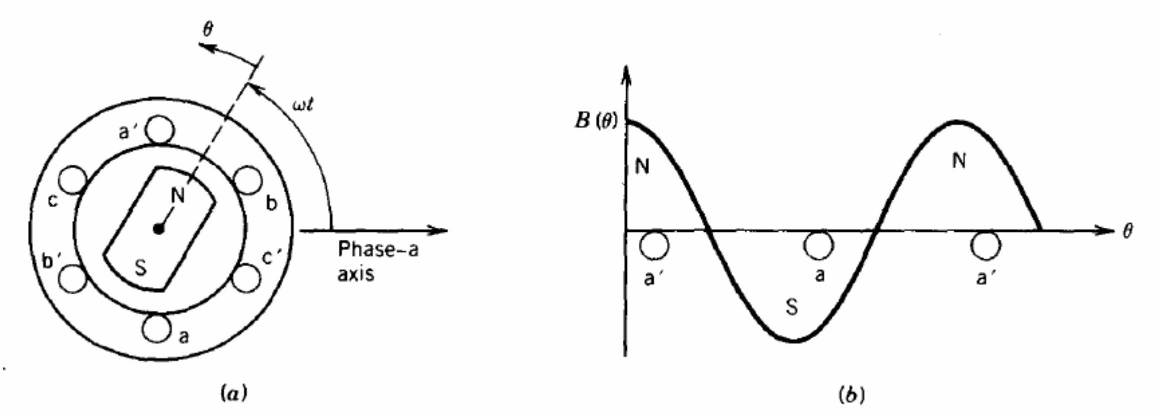


Fig: Air gap flux density distribution.

The flux density distribution in the air gap can be expressed as:

$$B(\theta) = B_{\max} \cos \theta$$

The air gap flux per pole, ϕ_P, is:

$$\phi_p = \int_{-\pi/2}^{\pi/2} B(\theta) lr d\theta = 2B_{\max} lr$$

Where,

l is the axial length of the stator.

r is the radius of the stator at the air gap.

Let us consider that the phase coils are full-pitch coils of N turns (the coil sides of each phase are 180 electrical degrees apart as shown in Fig.3.5). It is obvious that as the rotating field moves (or the magnetic poles rotate) the flux linkage of a coil will vary. The flux linkage for coil aa' will be maximum.

($= N\phi_P \ at \ \omega t = 0^o$) (Fig.3.5a) and zero at $\omega t = 90^o$. The flux linkage $\lambda_a(\omega t)$ will vary as the cosine of the angle ωt.

Hence,

$$\lambda_a(\omega t) = N\phi_p \cos \omega t$$

Therefore, the voltage induced in phase coil **aa'** is obtained from *Faraday law* as:

$$e_a = -\frac{d\lambda_a(\omega t)}{dt} = \omega N\phi_p \sin \omega t = E_{\max} \sin \omega t$$

The voltages induced in the other phase coils are also sinusoidal, but phase-shifted from each other by 120 electrical degrees. Thus,

$$e_b = E_{\max} \sin(\omega t - 120)$$

$$e_c = E_{\max} \sin(\omega t + 120).$$

the *rms* value of the induced voltage is:

$$E_{rms} = \frac{\omega N \phi_p}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} N\phi_p = 4.44 fN\phi_p$$

Where f is the frequency in hertz. Above equation has the same form as that for the induced voltage in transformers. However, $Ø_P$ represents the flux per pole of the machine.

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full-pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor K_W, called the winding factor, must therefore be applied. For most three-phase machine windings K_W is about 0.85 to 0.95.

Therefore, for a distributed phase winding, the rms voltage per phase is

$$Erms = 4.44 f N_{ph} \varphi_p K_W$$

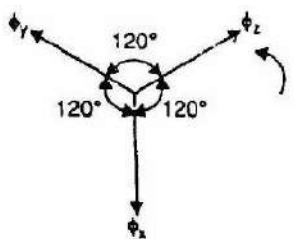
Where N_{ph} is the number of turns in series per phase.

Alternate Analysis for Rotating Magnetic Field

When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating Held. It can be shown that magnitude of this rotating field is constant and is equal to 1.5 m where m is the maximum flux due to any phase.

To see how rotating field is produced, consider a 2-pole, 3-phase winding as shown in Fig. 3.6 (i). The three phases X, Y and Z are energized from a 3-phase source and currents in these phases are indicated as Ix, Iy and Iz. Referring to Fig. as given below, the fluxes produced by these currents are given by:

$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin(\omega t - 120^\circ)$$
$$\phi_z = \phi_m \sin(\omega t - 240^\circ)$$



Here ϕ_m is the maximum flux due to any phase. Above figure shows the phasor diagram of the three fluxes. We shall now prove that this 3-phase supply produces a rotating field of constant magnitude equal to 1.5 ϕ_m. At instant 1, the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 ϕ_m as proved under:

At instant 1, $\omega t = 0°$. Therefore, the three fluxes are given by;

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

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

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

So,

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

At instant 2 [Fig: 3.7 (ii)], the current is maximum (negative) in ϕ_y phase Y and 0.5 maximum (positive) in phases X and Y. The magnitude of resultant flux is 1.5 ϕ_m as proved under:

At instant 2, $\omega t = 30°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 30° = \frac{\phi_m}{2}$$

$$\phi_y = \phi_m \sin(-90°) = -\phi_m$$

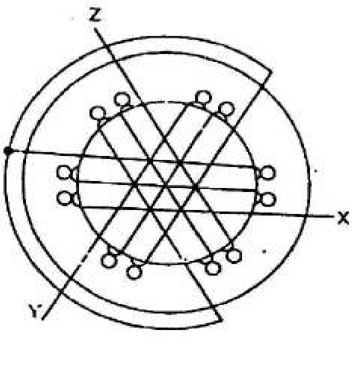
$$\phi_z = \phi_m \sin(-210°) = \frac{\phi_m}{2}$$

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

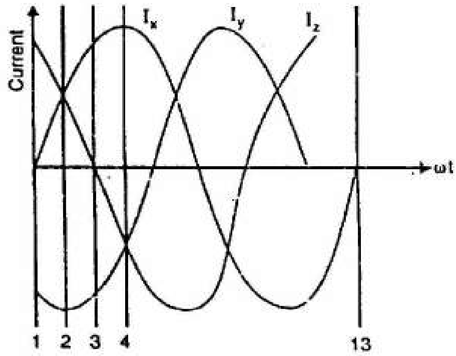
Phasor sum of ϕ_x and ϕ_z, $\phi'_r = 2 \times \frac{\phi_m}{2}\cos\frac{120°}{2} = \frac{\phi_m}{2}$

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

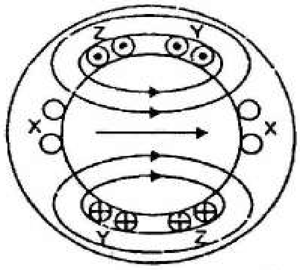
Note that resultant flux is displaced 30° clockwise from position 1.



(i)

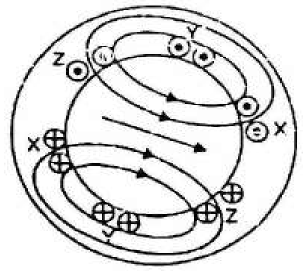


(ii)

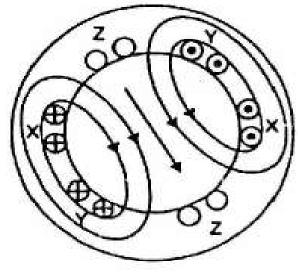


(1)

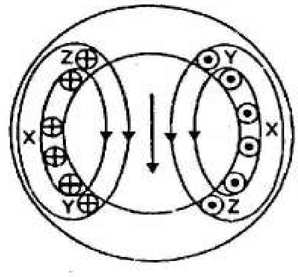
(iii)



(2)



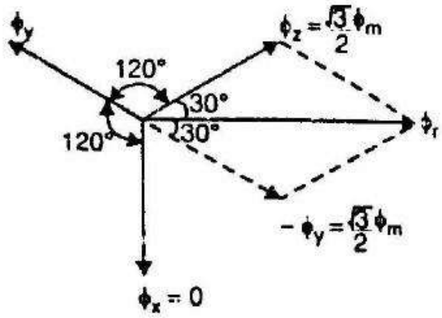
(3)



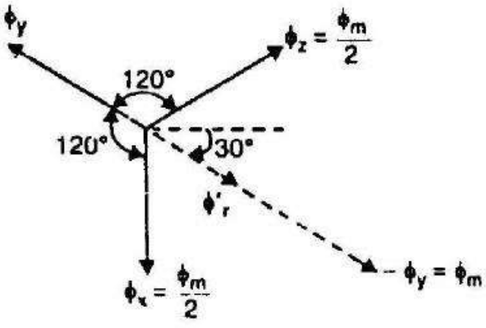
(4)

(iii)

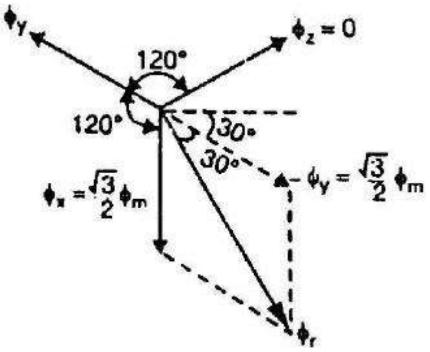
At instant 3, current in phase Z is zero and the currents in phases X and Y are equal and opposite (currents in phases X and Y arc 0.866 × max. value). The magnitude of resultant flux is 1.5 ϕ_m as proved under:



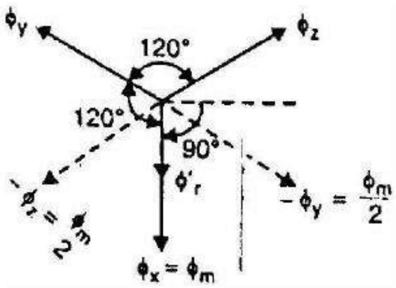
(i)



(ii)



(iii)



(iv)

At instant 3, $\omega t = 60°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-180°) = 0$$

The resultant flux ϕ_r is the phasor sum of ϕ_x and $-\phi_y$ $(\because\ \phi_z = 0)$.

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 1.5\ \phi_m$$

Note that resultant flux is displaced 60° clockwise from position 1.

At instant 4 the current in phase X is maximum (positive) and the currents in phases V and Z are equal and negative (currents in phases V and Z are $0.5 \times$ max. value). This establishes a resultant flux downward as shown under:

At instant 4, $\omega t = 90°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 90° = \phi_m$$

$$\phi_y = \phi_m \sin(-30°) = -\frac{\phi_m}{2}$$

$$\phi_z = \phi_m \sin(-150°) = -\frac{\phi_m}{2}$$

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

Phasor sum of $-\phi_z$ and $-\phi_y$, $\phi'_r = 2 \times \frac{\phi_m}{2} \cos\frac{120°}{2} = \frac{\phi_m}{2}$

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

Note that the resultant flux is downward i.e., it is displaced 90° clockwise from position 1.

It follows from the above discussion that a 3-phase supply produces a rotating field of constant value (= 1.5 ϕ_m, where ϕ_m is the maximum flux due to any phase).

Speed of rotating magnetic field

The speed at which the rotating magnetic field revolves is called the synchronous speed (Ns). The time instant 4 represents the completion of one-quarter cycle of alternating current Ix from the time instant 1. During this one quarter cycle, the field has rotated through 90°. At a time instant represented by 13 or one complete cycle of current Ix from the origin, the field has completed one revolution. Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current. In general, fur P poles, the rotating field makes one revolution in P/2 cycles of current.

$$\therefore \quad \text{Cycles of current} = \frac{P}{2} \times \text{revolutions of field}$$

or $$\text{Cycles of current per second} = \frac{P}{2} \times \text{revolutions of field per second}$$

Since revolutions per second is equal to the revolutions per minute (N_s) divided by 60 and the number of cycles per second is the frequency f,

$$\therefore \quad f = \frac{P}{2} \times \frac{N_s}{60} = \frac{N_s P}{120}$$

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

The speed of the rotating magnetic field is the same as the speed of the alternator that is supplying power to the motor if the two have the same number of poles. Hence the magnetic flux is said to rotate at synchronous speed.

Slip

We have seen above that rotor rapidly accelerates in the direction of rotating field. In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor. The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the suitor field speed (Ns). This difference in speed depends upon load on the motor. The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed i.e.

$$\% \text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

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

Rotor Current Frequency

The frequency of a voltage or current induced due to the relative speed between a vending and a magnetic field is given by the general formula;

$$\text{Frequency} = \frac{NP}{120}$$

where N = Relative speed between magnetic field and the winding
P = Number of poles

For a rotor speed N, the relative speed between the rotating flux and the rotor is $N_s - N$. Consequently, the rotor current frequency f' is given by;

$$f' = \frac{(N_s - N)P}{120}$$

$$= \frac{sN_sP}{120} \qquad \left(\because s = \frac{N_s - N}{N_s}\right)$$

$$= sf \qquad \left(\because f = \frac{N_sP}{120}\right)$$

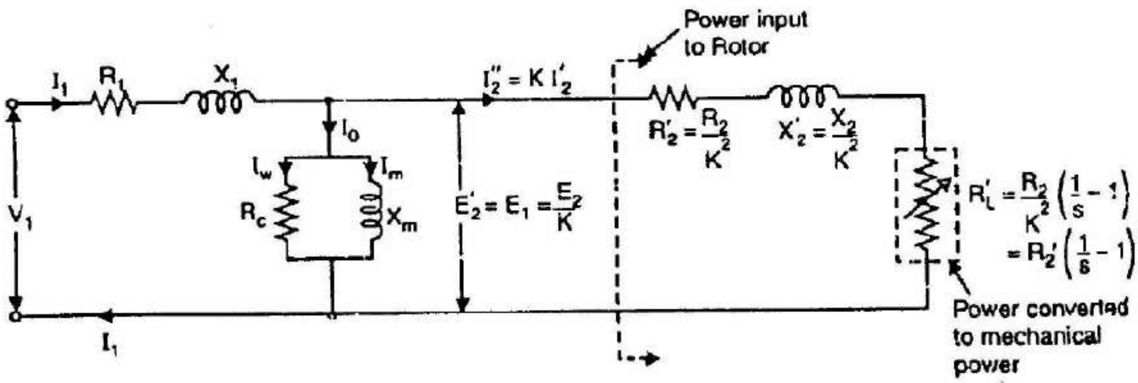
i.e., Rotor current frequency = Fractional slip x Supply frequency

(i) When the rotor is at standstill or stationary (i.e., $s = 1$), the frequency of rotor current is the same as that of supply frequency ($f' = sf = 1 \times f = f$).

(ii) As the rotor picks up speed, the relative speed between the rotating flux and the rotor decreases. Consequently, the slip s and hence rotor current frequency decreases.

Power and Torque Relations of Three Phase Induction Motor

The transformer equivalent circuit of an induction motor is quite helpful in analyzing the various power relations in the motor. Fig. shows below the equivalent circuit per phase of an induction motor where all values have been referred to primary (i.e., stator).



(i) Total electrical load $= R'_2\left(\frac{1}{s}-1\right)+R'_2=\frac{R'_2}{s}$

Power input to stator $= 3V_1 I_1 \cos\phi_1$

There will be stator core loss and stator Cu loss. The remaining power will be the power transferred across the air-gap i.e., input to the rotor.

(ii) Rotor input $= \frac{3(I''_2)^2 R'_2}{s}$

Rotor Cu loss $= 3(I''_2)^2 R'_2$

Total mechanical power developed by the rotor is

$$P_m = \text{Rotor input} - \text{Rotor Cu loss}$$

$$= \frac{3(I''_2)^2 R'_2}{s} 3(I''_2)^2 R'_2 = 3(I''_2)^2 R'_2\left(\frac{1}{s}-1\right)$$

(iii) If T_g is the gross torque developed by the rotor, then,

$$P_m = \frac{2\pi N\ T_g}{60}$$

or $$3(I''_2)^2 R'_2 \left(\frac{1}{s} - 1\right) = \frac{2\pi N\ T_g}{60}$$

or $$3(I''_2)^2 R'_2 \left(\frac{1-s}{s}\right) = \frac{2\pi N\ T_g}{60}$$

or $$3(I''_2)^2 R'_2 \left(\frac{1-s}{s}\right) = \frac{2\pi N_s (1-s)\ T_g}{60} \qquad [\because N = N_s(1-s)]$$

$$\therefore \quad T_g = \frac{3(I''_2)^2 R'_2 / s}{2\pi N_s / 60} \quad \text{N - m}$$

or $$T_g = 9.55 \frac{3(I''_2)^2 R'_2 / s}{N_s} \quad \text{N - m}$$

Note that shaft torque T_{sh} will be less than T_g by the torque required to meet windage and frictional losses.

Induction Motor Torque

The mechanical power P available from any electric motor can be expressed as:

$$P = \frac{2\pi N T}{60} \quad \text{watts}$$

where N = speed of the motor in r.p.m.
T = torque developed in N-m

$$\therefore \quad T = \frac{60}{2\pi}\frac{P}{N} = 9.55\frac{P}{N} \ \text{N - m}$$

If the gross output of the rotor of an induction motor is P_m and its speed is N r.p.m., then gross torque T developed is given by:

$$T_g = 9.55 \frac{P_m}{N} \ \text{N - m}$$

Similarly, $$T_{sh} = 9.55 \frac{P_{out}}{N} \ \text{N - m}$$

Note. Since windage and friction loss is small, $T_g = T_{sh}$,. This assumption hardly leads to any significant error.

Rotor Output

If T_g newton-metre is the gross torque developed and N r.p.m. is the speed of the rotor, then,

$$\text{Gross rotor output} = \frac{2\pi N T_g}{60} \quad \text{watts}$$

If there were no copper losses in the rotor, the output would equal rotor input and the rotor would run at synchronous speed Ns.

$$\therefore \quad \text{Rotor input} = \frac{2\pi N_s T_g}{60} \quad \text{watts}$$

$$\therefore \quad \text{Rotor Cu loss} = \text{Rotor input} - \text{Rotor output}$$

$$= \frac{2\pi T_g}{60}(N_s - N)$$

(i) $$\frac{\text{Rotor Cu loss}}{\text{Rotor input}} = \frac{N_s - N}{N_s} = s$$

$$\therefore \quad \text{Rotor Cu loss} = s \times \text{Rotor input}$$

(ii) $$\text{Gross rotor output, } P_m = \text{Rotor input} - \text{Rotor Cu loss}$$

$$= \text{Rotor input} - s \times \text{Rotor input}$$

$$\therefore \quad P_m = \text{Rotor input } (1 - s)$$

(iii) $$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s = \frac{N}{N_s}$$

(iv) $$\frac{\text{Rotor Cu loss}}{\text{Gross rotor output}} = \frac{s}{1 - s}$$

It is clear that if the input power to rotor is “Pr” then “s.Pr” is lost as rotor Cu loss and the remaining (1 - s) Pr is converted into mechanical power. Consequently, induction motor operating at high slip has poor efficiency.

Note.

$$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s$$

If the stator losses as well as friction and windage losses arc neglected, then,

$$\text{Gross rotor output} = \text{Useful output}$$

$$\text{Rotor input} = \text{Stator input}$$

$$\therefore \quad \frac{\text{Useful output}}{\text{Stator output}} = 1 - s = \text{Efficiency}$$

Hence the approximate efficiency of an induction motor is 1 − s. Thus if the slip of an induction motor is 0.125, then its approximate efficiency is = 1 − 0.125 = 0.875 or 87.5%.

Torque Equations

The gross torque Tg developed by an induction motor is given by;

$$T_g = \frac{\text{Rotor input}}{2\pi\, N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

$$= \frac{60 \times \text{Rotor input}}{2\pi\, N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

Now $\quad$ Rotor input $= \dfrac{\text{Rotor Cu loss}}{s} = \dfrac{3(I'_2)^2 R_2}{s}$ $\qquad$ (i)

As shown in Sec. 8.16, under running conditions,

$$I'_2 = \frac{s\, E_2}{\sqrt{R_2^2 + (s\, X_2)^2}} = \frac{s\, K\, E_1}{\sqrt{R_2^2 + (s\, X_2)^2}}$$

where $\quad K = \text{Transformation ratio} = \dfrac{\text{Rotor turns/phase}}{\text{Stator turns/phase}}$

$$\therefore \quad \text{Rotor input} = 3 \times \frac{s^2\, E_2^2 R_2}{R_2^2 + (s\, X_2)^2} \times \frac{1}{s} = \frac{3\, s\, E_2^2 R_2}{R_2^2 + (s\, X_2)^2}$$

(Putting me value of I'_2 in eq.(i))

Also $\quad$ $\text{Rotor input} = 3 \times \dfrac{s^2\, K^2\, E_1^2 R_2}{R_2^2 + (s\, X_2)^2} \times \dfrac{1}{s} = \dfrac{3\, s\, K^2\, E_1^2 R_2}{R_2^2 + (s\, X_2)^2}$

(Putting me value of I'_2 in eq.(i))

$$\therefore \quad T_g = \frac{\text{Rotor input}}{2\pi\, N_s} = \frac{3}{2\pi\, N_s} \times \frac{s\, E_2^2 R_2}{R_2^2 + (s\, X_2)^2} \qquad \text{...in terms of } E_2$$

$$= \frac{3}{2\pi\, N_s} \times \frac{s\, K^2\, E_1^2 R_2}{R_2^2 + (s\, X_2)^2} \qquad \text{...in terms of } E_1$$

Note that in the above expressions of T_g, the values E_1, E_2, R_2 and X_2 represent the phase values.

Rotor Torque

The torque T developed by the rotor is directly proportional to:

(i) rotor current

(ii) rotor e.m.f.

(iii) power factor of the rotor circuit

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

or $$T = K E_2 I_2 \cos\phi_2$$

where I_2 = rotor current at standstill

E_2 = rotor e.m.f. at standstill

$\cos\phi_2$ = rotor p.f. at standstill

Note. The values of rotor e.m.f., rotor current and rotor power factor are taken for the given conditions.

Starting Torque (Ts)

Let,

E_2 = rotor e.m.f. per phase at standstill

X_2 = rotor reactance per phase at standstill

R_2 = rotor resistance per phase

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$ ...at standstill

Rotor current/phase, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

Rotor p.f., $\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

$$\therefore \quad \text{Starting torque, } T_s = K E_2 I_2 \cos\phi_2$$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$= \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Generally, the stator supply voltage V is constant so that flux per pole ϕ set up by the stator is also fixed. This in turn means that e.m.f. E_2 induced in the rotor will be constant.

$$\therefore \quad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where K_1 is another constant.

It is clear that the magnitude of starting torque would depend upon the relative values of R_2 and X_2 i.e., rotor resistance/phase and standstill rotor reactance/phase.

It can be shown that $K = 3/2 \pi N_s$.

$$\therefore \quad T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Note that here N_s is in r.p.s.

Condition for Maximum Starting Torque

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstill rotor reactance/phase.

Now $$T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} \qquad \text{(i)}$$

Differentiating eq. (i) w.r.t. R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = K_1 \left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2} \right] = 0$$

or $$R_2^2 + X_2^2 = 2R_2^2$$

or $$R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

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

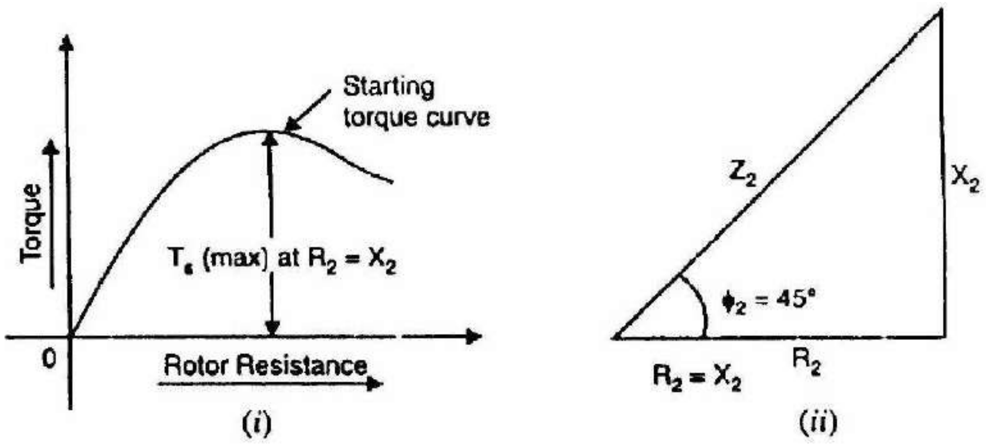


Fig: 3.14

Fig. 3.14 shows the variation of starting torque with rotor resistance. As the rotor resistance is increased from a relatively low value, the starting torque increases until it becomes maximum when $R_2 = X_2$. If the rotor resistance is increased beyond this optimum value, the starting torque will decrease.

Effect of Change of Supply Voltage

$$T_s = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Since $E_2 \propto$ Supply voltage V

$$\therefore \quad T_s = \frac{K_2 V^2 R_2}{R_2^2 + X_2^2}$$

where K_2 is another constant.

$$\therefore \quad T_s \propto V^2$$

Therefore, the starting torque is very sensitive to changes in the value of supply voltage. For example, a drop of 10% in supply voltage will decrease the starting torque by about 20%. This could mean the motor failing to start if it cannot produce a torque greater than the load torque plus friction torque.

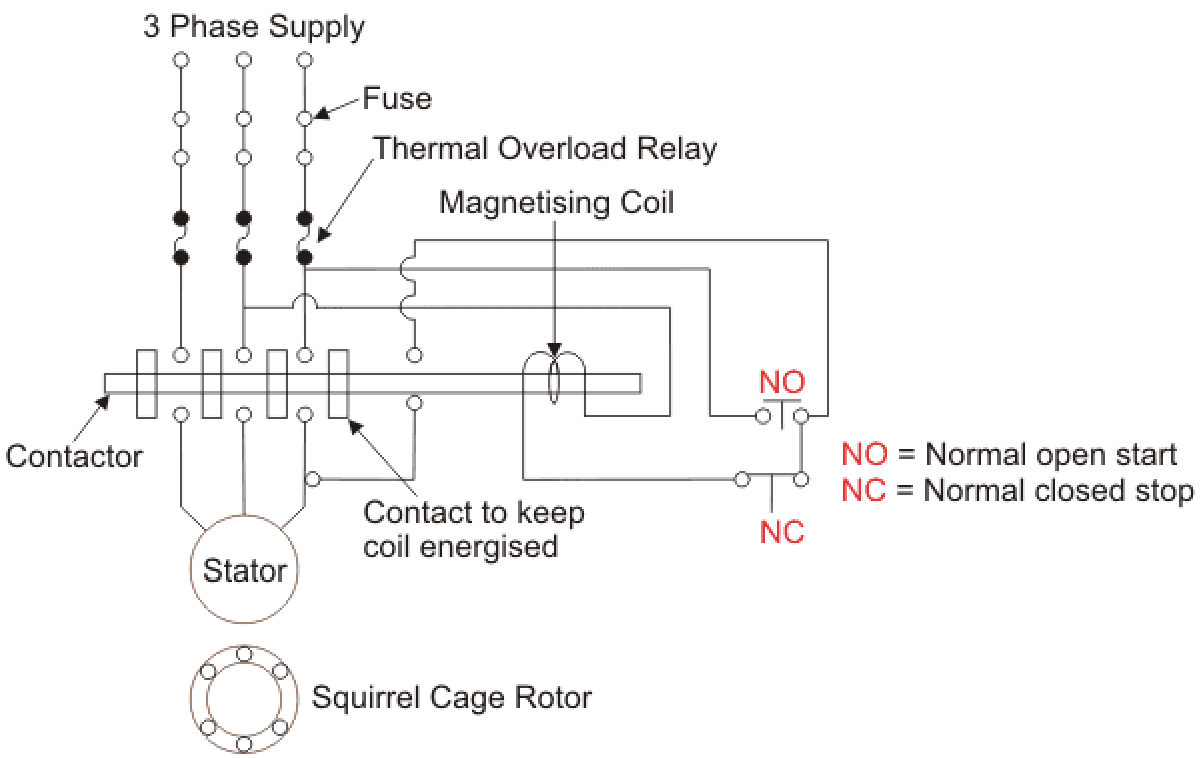
Methods of Starting Three Phase Induction Motors

The method to be employed in starting a given induction motor depends upon the size of the motor and the type of the motor. The common methods used to start induction motors are:

(i) Direct-on-line starting
(ii) Star-delta starting

(i) DIRECT-ON-LINE STARTING

A **DOL starter** (or **Direct On Line starter** or **across the line starter**) is a method of starting of a 3 phase induction motor. In DOL Starter an induction motor is connected directly across its 3-phase supply, and the DOL starter applies the full line voltage to the motor terminals. Despite this direct connection, no harm is done to the motor. A DOL motor starter contains protection devices, and in some cases, condition monitoring. A wiring diagram of a DOL starter is shown below:



Since the DOL starter connects the motor directly to the main supply line, the motor draws a very high inrush current compared to the full load current of the motor (up to 5-8 times higher). The value of this large current decreases as the motor reaches its rated speed. A direct on line starter can only be used if the high inrush current of the motor does not cause an excessive voltage drop in the supply circuit. If a high voltage drop needs to be avoided, a star delta starter should be used instead. Direct on line starters are commonly used to start small motors, especially 3 phase squirrel cage induction motors.

$$I_a = \frac{(V - E)}{R_a}$$

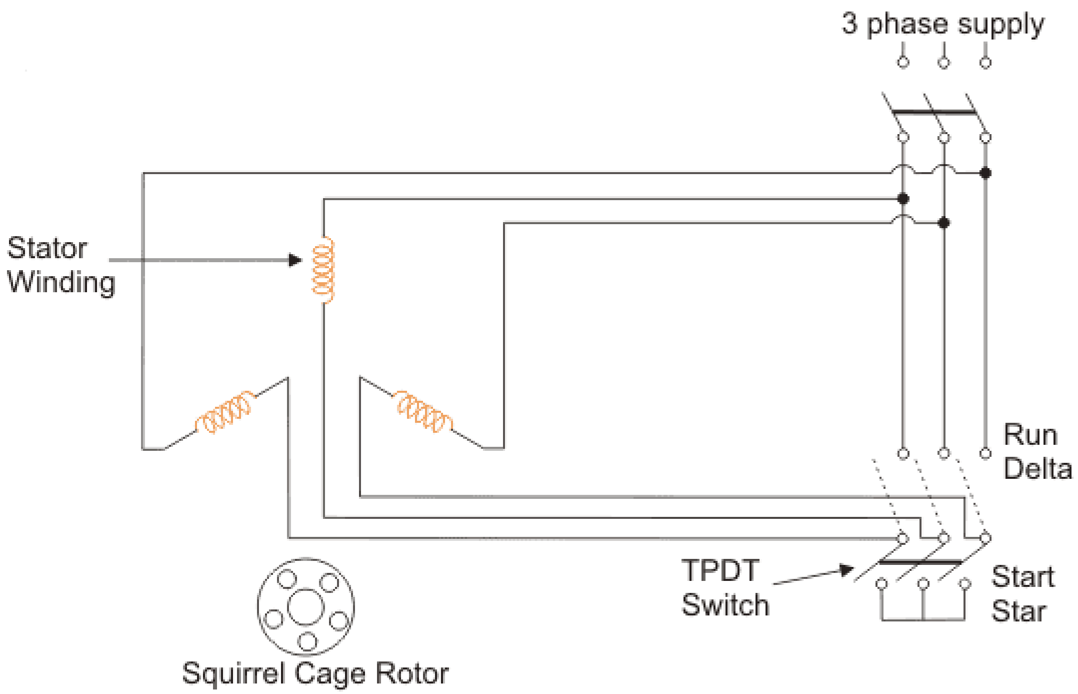
As we know, the equation for armature current in the motor. The value of back emf (E) depends upon speed (N), i.e. E is directly proportional to N.

At starting, the value of E is zero. So starting current is very high. In a small rating motor, the rotor has more considerable axial length and small diameter. So it gets accelerated fastly. Hence, speed increases and thus the value of armature current decreases rapidly. Therefore, small rating motors smoothly run when it is connected directly to a 3-phase supply. If we connect a large motor directly across 3-phase line, it would not run smoothly and will be damaged, because it does not get accelerated as fast as a smaller motor since it has short axial length and larger diameter more massive rotor. However, for large rated motors, we can use an oil immersed DOL starter.

Working of DOL starter:

A direct online starter consists of two buttons, a GREEN button for starting and a RED for stopping purpose of the motor. The **DOL starter** comprises of an MCCB or circuit breaker, contactor and an overload relay for protection. These two buttons, i.e. Green and Red or start and stop buttons control the contacts. To start the motor, we close the contact by pushing Green Button, and the full line voltage appears to the motor. A contactor can be of 3 poles or 4-poles. Below given contactor is of 4-pole type. It contains three NO (normally open) contacts that connect the motor to supply lines, and the fourth contact is “hold on contact” (auxiliary contact) which energizes the contactor coil after the start button is released. If any fault occurs, the auxiliary coil gets de-energized, and hence the starter disconnects the motor from supply mains.

(ii)STAR-DELTA STARTING



A star delta starter will start a motor with a star connected stator winding. When motor reaches about 80% of its full load speed, it will begin to run in a delta connected stator winding. **A s**tar delta starter is a type of reduced voltage starter. We use it to reduce the starting current of the motor without using any external device or apparatus. This is a big advantage of a star delta starter, as it typically has around 1/3 of the inrush current compared to a DOL starter. The starter mainly consists of a TPDP switch which stands for Tripple Pole Double Throw switch. This switch changes stator winding from star to delta. During starting condition stator winding is connected in the form of a star.

CHAPTER 7- SINGLE PHASE INDUCTION MOTORS

Single Phase Induction Motors

Single phase Induction motors perform a great variety of useful services at home, office, farm, factory and in business establishments. Single phase motors are generally manufactured in fractional HP ratings below 1 HP for economic reasons. Hence, those motors are generally referred to as fractional horsepower motors with a rating of less than 1 HP. Most single phase motors fall into this category. Single phase Induction motors are also manufactured in the range of 1.5, 2, 3 and up to 10 HP as a special requirement.

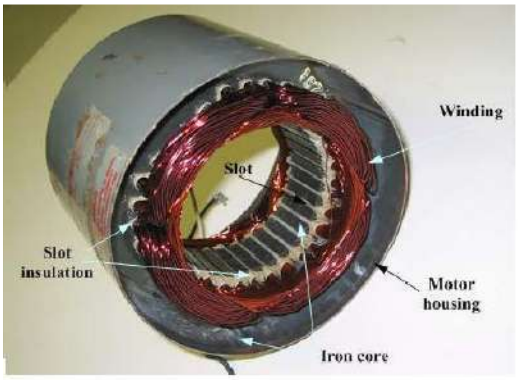


Fig: 1(a) Stator

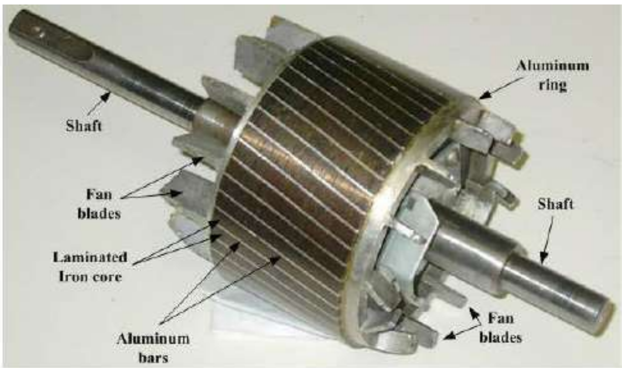


Fig: 1(b) Squirrel cage rotor

CAPACITOR-START, INDUCTION-RUN MOTOR

A drive which requires a large starting torque may be fitted with a capacitor-start, induction-run motor as it has excellence starting torque as compared to the resistance-start, induction-run motor.

CONSTRUCTION AND WORKING

Fig: 2(a) shows the schematic diagram of a capacitor-start, induction-run motor. As shown, the main winding is directly connected across the main supply whereas the starting winding is connected across the main supply through a capacitor and centrifugal switch.

Both these windings are placed in a stator slot at 90 degree electrical apart, and a squirrel cage type rotor is used.

As shown in Fig: 2(b), at the time of starting the current in the main winding lags the supply voltages by 90 degrees, depending upon its inductance and resistance. On the other hand, the current in the starting winding due to its capacitor will lead the applied voltage, by say 20 degrees.

Hence, the phase difference between the main and starting winding becomes near to 90 degrees. This in turn makes the line current to be more or less in phase with its applied voltage, making the power factor to be high, thereby creating an excellent starting torque.

However, after attaining 75% of the rated speed, the centrifugal switch operates opening the starting winding and the motor then operates as an induction motor, with only the main winding connected to the supply.

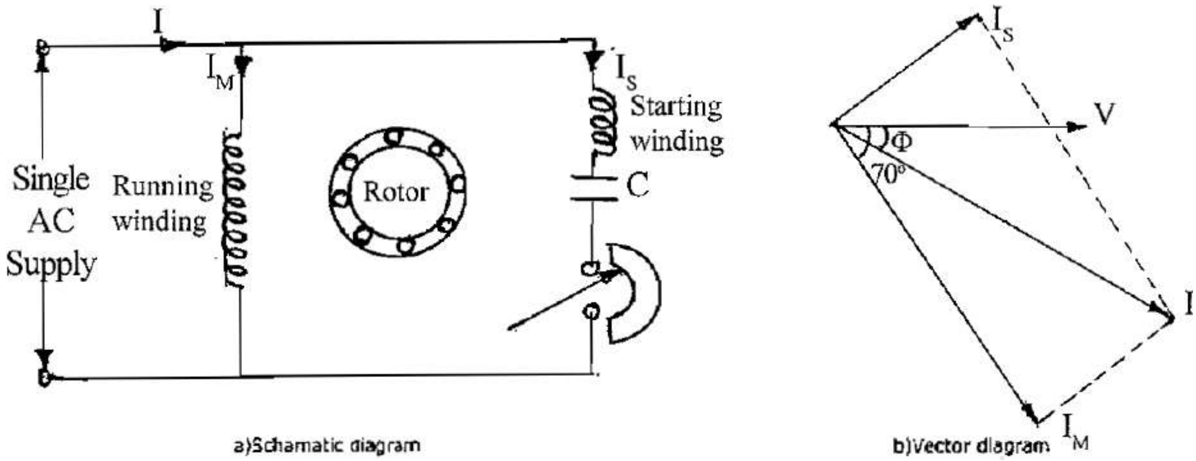


Fig: 2

As shown in Fig: 4.9(b), the displacement of current in the main and starting winding is about 80/90 degrees, and the power factor angle between the applied voltage and line current is very small. This results in producing a high power factor and an excellent starting torque, several times higher than the normal running torque.

APPLICATIONS

Due to the excellent starting torque and easy direction-reversal characteristics,

- Used in belted fans,
- Used in blowers dryers,
- Used in washing machines,

Used in pumps and compressors

2. <u>CAPACITOR-START, CAPACITOR-RUN MOTORS</u>

As discussed earlier, one capacitor-start, induction-run motors have excellent starting torque, say about 300% of the full load torque and their power factor during starting in high.

However, their running torque is not good, and their power factor, while running is low. They also have lesser efficiency and cannot take overloads.

CONSTRUCTION AND WORKING

The aforementioned problems are eliminated by the use of a two valve capacitor motor in which one large capacitor of electrolytic (short duty) type is used for starting whereas a smaller capacitor of oil filled (continuous duty) type is used for running, by connecting them with the starting winding as shown in Fig:3. A general view of such a two valve capacitor motor is shown in Fig: 3.

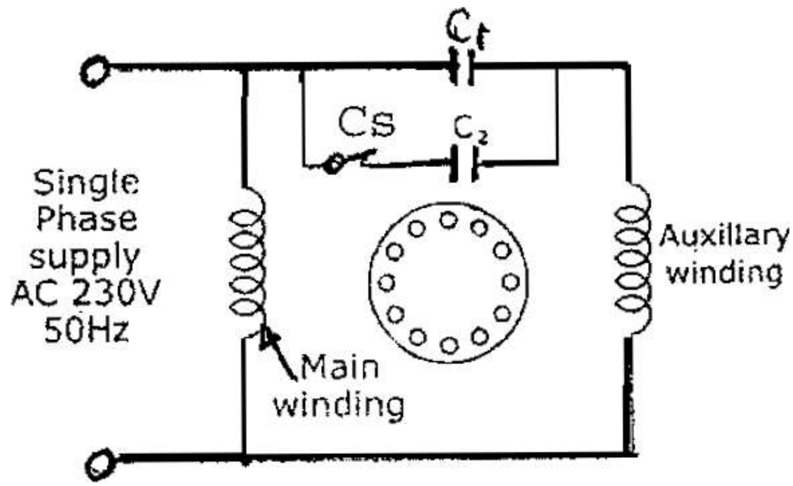


Fig: 3

This motor also works in the same way as a capacitor-start, induction-run motor, with exception, that the capacitor C1 is always in the circuit, altering the running performance to a great extent.

The starting capacitor which is of short duty rating will be disconnected from the starting winding with the help of a centrifugal switch, when the starting speed attains about 75% of the rated speed.

This motor has the following advantages:

- The starting torque is 300% of the full load torque
- The starting current is low, say 2 to 3 times of the running current.
- Starting and running power factor are good.
- Highly efficient running.
- Extremely noiseless operation.
- Can be loaded upto 125% of the full load capacity.

APPLICATIONS

- Used for compressors, refrigerators, air-conditioners, etc.
- Higher starting torque.
- High efficiency, higher power factor and overloading.

- Costlier than the capacitor-start — Induction run motors of the same capacity.

SHAPED POLE STARTING

The motor consists of a yoke to which salient poles are fitted as shown in Fig: 4(a) and it has a squirrel cage type rotor.

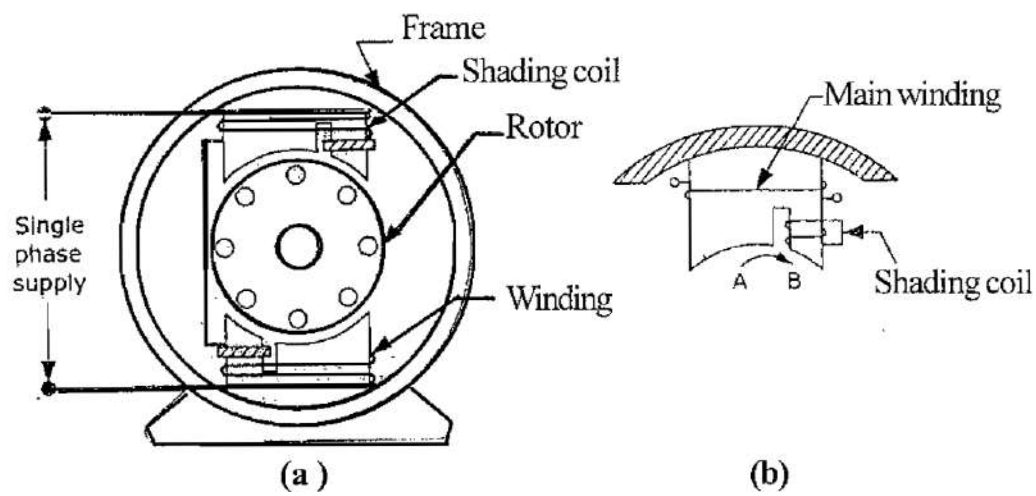


Fig: 4

A shaded pole made of laminated sheets has a slot cut across the lamination at about one third the distance from the edge of the pole.Around the smaller portion of the pole, a short-circuited copper ring is placed which is called the shading coil, and this part of the pole is known as the shaded part of the pole. The remaining part of the pole is called the unshaded part which is clearly shown in Fig: 4.(b).

Around the poles, exciting coils are placed to which an AC supply is connected. When AC supply is effected to the exciting coil, the magnetic axis shifts from the unshaded part of the pole to the shaded part as will be explained in details in the next paragraph. This shifting of axis is equivalent to the physical movement of the pole.

This magnetic axis, which is moving, cuts the rotor conductors and hence, a rotational torque is developed in the rotor.By this torque the rotor starts rotating in the direction of the shifting of the magnetic axis that is from the unshaded part to the shaded part.

Single Phase Series Motor

The single-phase series motor is a commutator-type motor. If the polarity of the line terminals of a dc series motor is reversed, the motor will continue to run in the same direction. Thus, it might be expected that a dc series motor would operate on alternating current also. The direction of the torque developed in a dc series motor is determined by both filed polarity and the direction of current through the armature [$T \propto \phi I_a$].

Operation

Let a dc series motor be connected across a single-phase ac supply. Since the same current flows through the field winding and the armature, it follows that ac reversals from positive to negative, or from negative to positive, will simultaneously affect both the field flux polarity and the current direction through the armature. This means that the direction of the developed torque will remain positive, and rotation will continue in the same direction. Thus, a series motor can run both on dc and ac.

However, a series motor which is specifically designed for dc operation suffers from the following drawbacks when it is used on single-phase ac supply:

1. Its efficiency is low due to hysteresis and eddy-current losses.
2. The power factor is low due to the large reactance of the field and the armature winding.
3. The sparking at the brushes is excessive.

In order to overcome these difficulties, the following modifications are made in a D.C. series motor that is to operate satisfactorily on alternating current:

1. The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.
2. The field winding is provided with small number of turns. The field-pole areas is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage drop.
3. The number of armature conductors is increased in order to get the required torque with the low flux.
4. In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a compensating winding is used.

The compensating winding is put in the stator slots. The axis of the compensating winding is 90 (electrical) with the main field axis. It may be connected in series with both the armature and field as shown in Fig: 5. In such a case the motor is conductively compensated.

The compensating winding may be short circuited on itself, in which case the motor is said to be inductively compensated shown in Fig: 6.

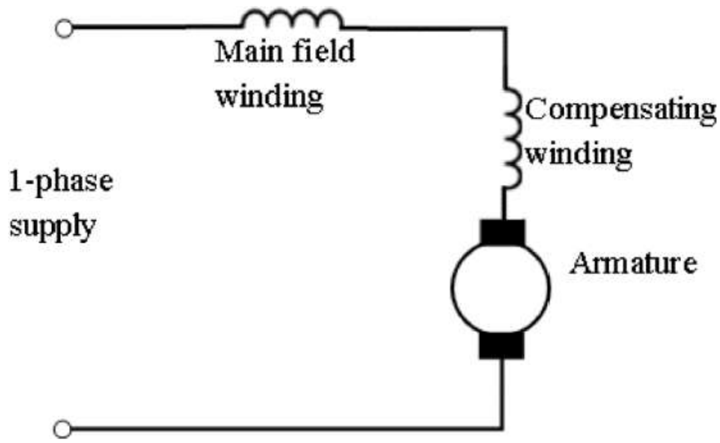


Fig: 5

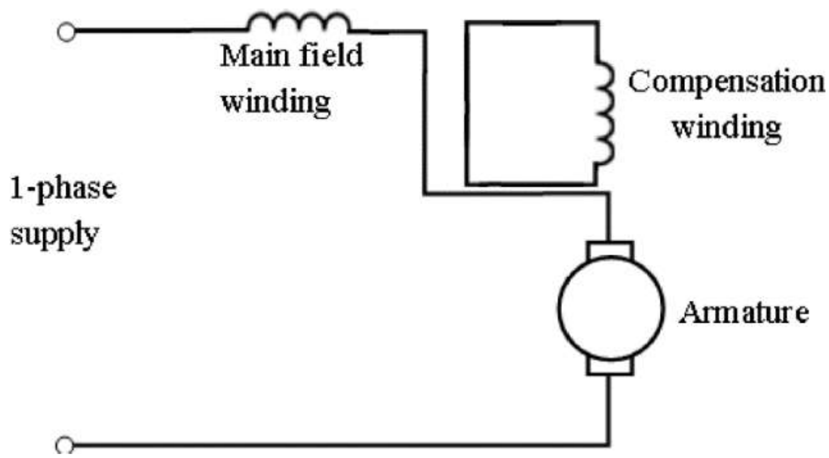


Fig: 6

The characteristics of single-phase series motor are very much similar to those of D.C. series motors, but the series motor develops less torque when operating from an a.c. supply than when working from an equivalent D.C. supply [Fig: 7]. The direction of rotation can be changed by interchanging connections to the field with respect to the armature as in D.C. series motor.

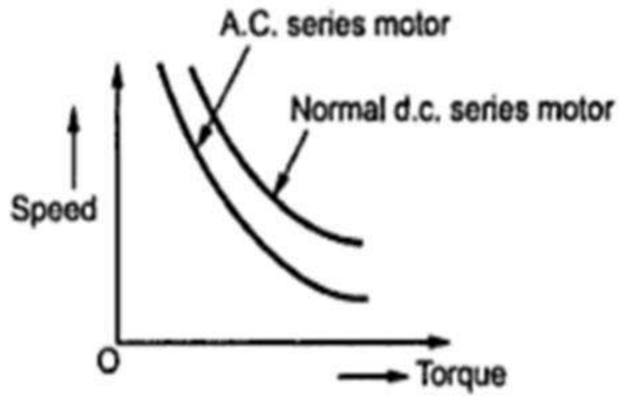


Fig: 7

Speed control of universal motors is best obtained by solid-state devices. Since the speed of these is not limited by the supply frequency and may be as high as 20,000 r.p.m. (greater than the maximum synchronous speed of 3000 r.p.m. at 50 Hz), they are most suitable for applications requiring high speeds.

ALTERNATOR:

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

Application:

Electric generator: Most power generation stations use synchronous machines as their generators. Connection of these generators to the utility grid requires synchronization conditions to be met.

Automotive alternators: Alternators are used in modern automobiles to charge the battery and to power the electrical system when its engine is running.

Diesel electric locomotive alternators: The traction alternator usually incorporates integral silicon diode rectifiers to provide the traction motors with up to 1200 volts DC (DC traction, which is used directly) or the common inverter bus (AC traction, which is first inverted from dc to three-phase ac).

The first diesel electric locomotives, and many of those still in service, use DC generators as, before silicon power electronics, it was easier to control the speed of DC traction motors. Most of these had two generators: one to generate the excitation current for a larger main generator.

Marine alternators: Marine alternators used in yachts are similar to automotive alternators, with appropriate adaptations to the salt-water environment. Marine alternators are designed to be explosion proof so that brush sparking will not ignite explosive gas mixtures in an engine room environment. They may be 12 or 24 volt depending on the type of system installed.

Radio alternators

High frequency alternators of the variable-reluctance type were applied commercially to radio transmission in the low-frequency radio bands.