Unit 1

2.3 Construction

There are two basic parts of a transformer i) Magnetic core ii) Winding or coils.

The core of the transformer is either square or rectangular in size. It is further divided into two parts. The vertical portion on which coils are wound is called **limb** while the top and bottom horizontal portion is called **yoke** of the core. These parts are shown in the Fig. 2.4 (a).

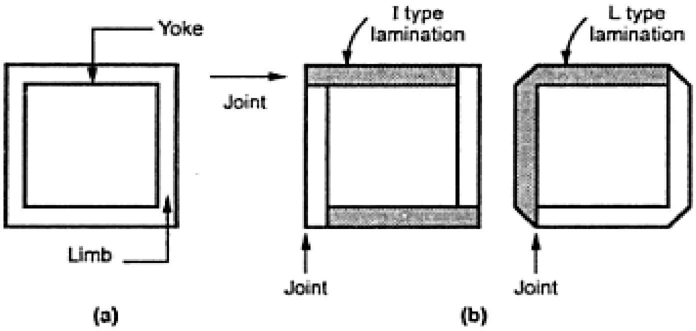


Fig. 2.4 Construction of transformer

Core is made up of laminations. Because of laminated type of construction, eddy current losses get minimised. Generally high grade silicon steel laminations [0.3 to 0.5 mm thick] are used. These laminations are insulated from each other by using insulation like varnish. All laminations are varnished. Laminations are overlapped so that to avoid the air gap at the joints. For this generally 'L' shaped or 'I' shaped laminations are used which are shown in the Fig. 2.4 (b).

The cross-section of the limb depends on the type of coil to be used either circular o ctangular. The different cross-sections of limbs, practically used are shown in th g. 2.5.

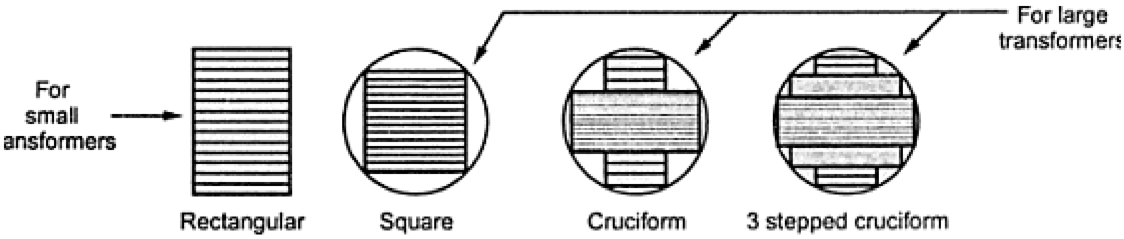
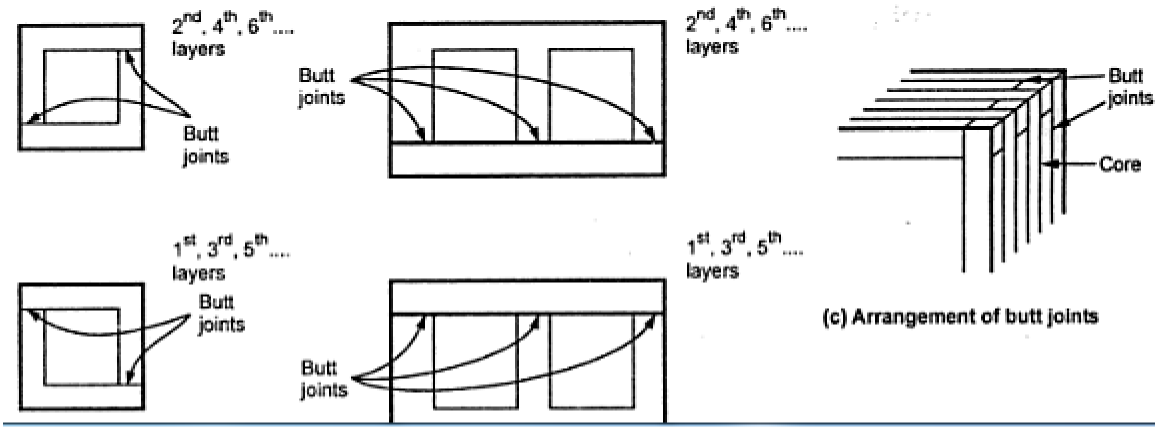


Fig. 2.5 Different cross-sections

To avoid the high reluctance at the joint, the alternate layers are stacked differently tc eliminate the joints. This is called **staggering**. The butt joints are staggered in alternatc layers. It is shown in the Fig. 2.6.



(c) Arrangement of butt joints

The advantages of staggering in transformer are,

1. It avoids continuous air gap.
2. The reluctance of magnetic circuit gets reduced.
3. The continuous air gap reduces the mechanical strength of the core. The staggering helps to increase the mechanical strength of the core.

2.3.1 Types of Windings

The coils used are wound on the limbs and are insulated from each other. In the basic transformer shown in the Fig. 2.2, the two windings wound are shown on two different limbs i.e. primary on one limb while secondary on other limb. But due to this leakage flux increases which affects the transformer performance badly. Similarly it is necessary that the windings should be very close to each other to have high mutual inductance. To achieve this, the two windings are split into number of coils and are wound adjacent to each other on the same limb. A very common arrangement is cylindrical concentric coils as shown in the Fig. 2.7 (a). (See Fig. 2.7. (a) on next page.)

Such cylindrical coils are used in the core type transformer. These coils are mechanically strong. These are wound in the helical layers. The different layers are insulated from each other by paper, cloth or mica. The low voltage winding is placed near the core from ease of insulating it from the core. The high voltage is placed after it.

The other type of coils which is very commonly used for the shell type of transformer is **sandwich coils**. Each high voltage portion lies between the two low voltage portion

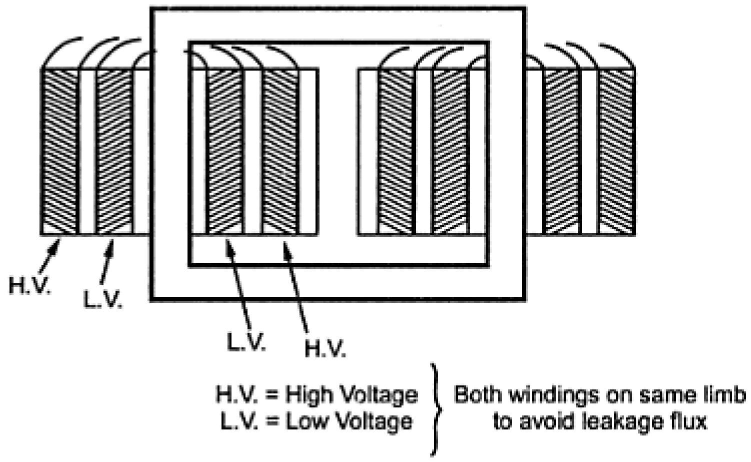


Fig. 2.7 (a) Cylindrical concentric coils

ndwiching the high voltage portion. Such subdivision of windings into small portions duces the leakage flux. Higher the degree of subdivision, smaller is the reactance. The **ndwich coil** is shown in the Fig. 2.7 (b). The top and bottom coils are low voltage coils. l the portions are insulated from each other by paper.

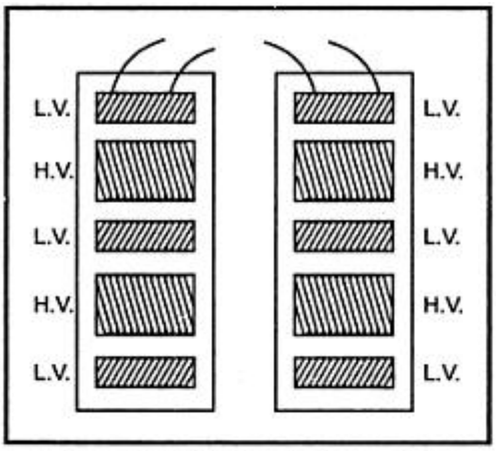


Fig. 2.7 (b) Sandwich coils

2.4 Construction of Single Phase Transformers

The various constructions used for the single phase transformers are,

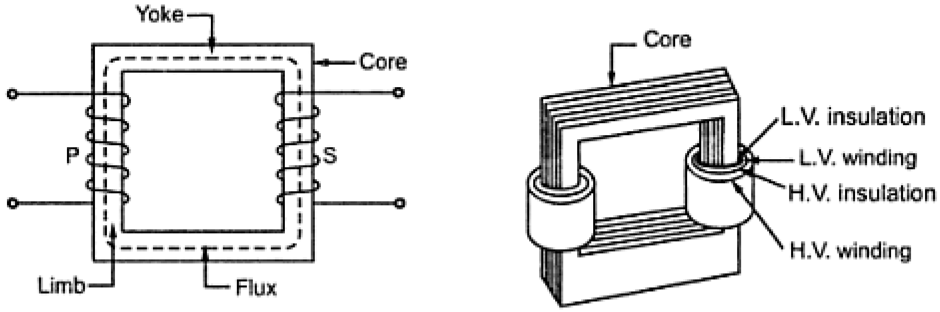
1. Core type 2. Shell type and 3. Berry type

2.4.1 Core Type Transformer

It has a single magnetic circuit. The core is rectangular having two limbs. The winding encircles the core. The coils used are of cylindrical type. As mentioned earlier, the coils are wound in helical layers with different layers insulated from each other by paper or mica. Both the coils are placed on both the limbs. The low voltage coil is placed inside near the core while high voltage coil surrounds the low voltage coil. Core is made up of large number of thin laminations.

As the windings are uniformly distributed over the two limbs, the natural cooling i more effective. The coils can be easily removed by removing the laminations of the to| yoke, for maintenance.

The Fig. 2.8 (a) shows the schematic representation of the core type transformer whil the Fig. 2.8 (b) shows the view of actual construction of the core type transformer.



(a) Representation (b) Construction

2.4.2 Shell Type Transformer

It has a double magnetic circuit. The core has three limbs. Both the windings are placed on the central limb. The core encircles most part of the windings. The coils used are generally multilayer disc type or sandwich coils. As mentioned earlier, each high voltage coil is in between two low voltage coils and low voltage coils are nearest to top and bottom of the yokes.

The core is laminated. While arranging the laminations of the core, the care is taken that all the joints at alternate layers are staggered. This is done to avoid narrow air gap at the joint, right through the cross-section of the core. Such joints are called over lapped or imbricated joints. Generally for very high voltage transformers, the shell type construction is preferred. As the windings are surrounded by the core, the natural cooling does not exist. For removing any winding for maintenance, large number of laminations are required to be removed.

The Fig. 2.9 (a) shows the schematic representation while the Fig. 2.9 (b) shows the outaway view of the construction of the shell type transformer.

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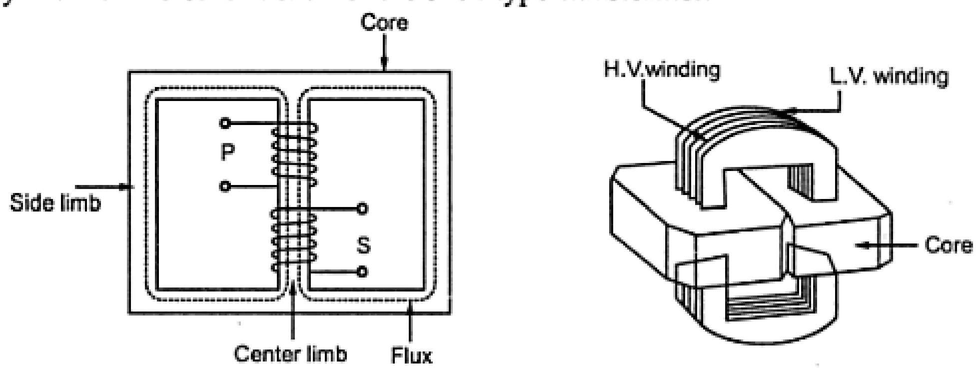


(a) Representation (b) Construction

Fig. 2.9 Shell type transformer

2.4.3 Berry Type Transformer

This has distributed magnetic circuit. The number of independent magnetic circuits are more than 2. Its core construction is like spokes of a wheel. Otherwise it is symmetrical to that of shell type.

Diagramatically it can be shown as in the Fig. 2.10.

The transformers are generally kept in tightly fitted sheet metal tanks. The tanks are constructed of specified high quality steel plate cut, formed and welded into the rigid structures. All the joints are painted with a solution of light blue chalk which turns dark in the presence of oil, disclosing even the minutest leaks. The tanks are filled with the special insulating oil. The entire transformer assembly is immersed in the oil. The oil serves two functions : i) Keeps the coils cool by circulation and ii) Provides the transformers an additional insulation.

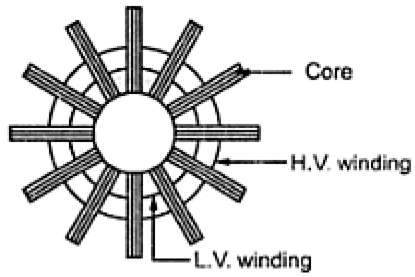


Fig. 2.10 Berry type transformer

The oil should be absolutely free from alkalies, sulphur and specially from moisture. Presence of very small moisture lowers the dielectric strength of oil, affecting its performance badly. Hence the tanks are sealed air tight to avoid the contact of oil with atmospheric air and moisture. In large transformers, the chambers called **breathers** are provided. The breathers prevent the atmospheric moisture to pass on to the oil. The breathers contain the silica gel crystals which immediately absorb the atmospheric moisture. Due to long and continuous use, the sludge is formed in the oil which can contaminate the oil. Hence to keep such sludge separate from the oil in main tank, an air tight metal drum is provided, which is placed on the top of tank. This is called **conservator**.

EMF Equation of a Transformer:

Let a transformer have,

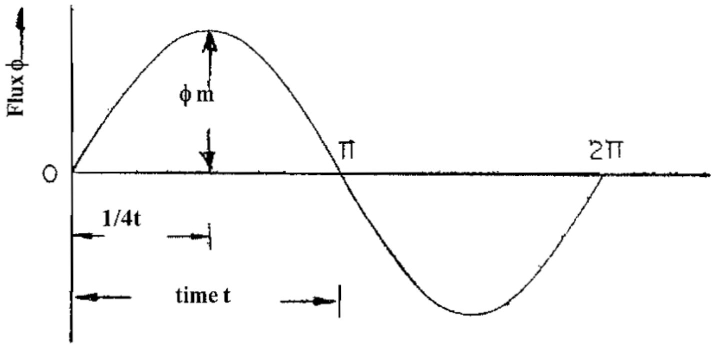
Primary turns = N1

Secondary turns = N2

Maximum value of flux in the core linking both the windings = ? m in webers

Frequency of a.c input in H.Z = f.

The flux in the core will very sinusoidally as shows in figure 8.7.



The flux in the core increases from zero to a maximum value ? m in one quarter cycle (¼ second)

There fore, Average rate of change of flux = $\dfrac{\phi_m}{\frac{1}{4f}} = 4f\,\phi_m$

Therefore, Average e.m.f. induced

Per turn = Average rate of change of flux x 1.

= $4f\,\phi_m$ volts.

The flux varies sinusoidally. Hence the r.m.s. value of induced voltage is obtained by multiplying the average value by form factor, which is equal to 1.11 for a sine wave.

Therefore, Average e.m.f. induced

Per turn = Average rate of change of flux x 1.

= 4f ϕ_m volts.

The flux varies sinusoidally. Hence the r.m.s. value of induced voltage is obtained by multiplying the average value by form factor, which is equal to 1.11 for a sine wave.

There fore R.M.S. value of induced e.m.f.

Per turn = 1.11 x 4 ϕ_m m volts.

= 4.44 f ϕ_m volts.

The primary and secondary windings have N_1 and N_2 turns respectively.

R.M.S. value of induced R.M.F. in primary. E1=4.44 f $\phi_m N_1$

R.M.S. value of induced e.m.f. in secondary, E2 = 4.44 f $\phi_m N_2$

In an ideal transformer on no load,

Applied voltage $V_1 = E_1$

Secondary terminal voltage $V_2 = E_2$

Voltage Ratio

The ratio of secondary voltage to primary voltage is called voltage transformation ratio. It is represented K.

$$\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = K$$

Current Ratio

Neglecting the losses, Input volt ampere = output-volt ampere. $V_1 I_1 = V_2 I_2$

$$\frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{1}{K}$$

Thus the primary current under no load condition has to supply the iron losses i.e. hysteresis loss and eddy current loss and a small amount of primary copper loss. This current is denoted as I_0.

Now the no load input current I_0 has two components :

1. A purely reactive component I_m called magnetising component of no load current required to produce the flux. This is also called **wattless component.**
2. An active component I_c which supplies total losses under no load condition called **power component** of no load current. This is also called **wattful component** or **core loss component** of I_0.

The total no load current I_0 is the vector addition of I_m and I_c.

$$\boxed{\bar{I}_0 = \bar{I}_m + \bar{I}_c} \quad \dots (1)$$

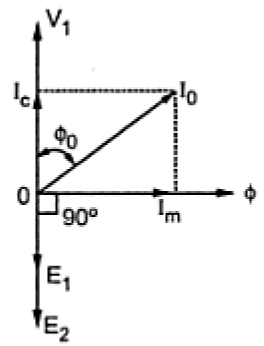


Fig. 2.15 Practical transformer on no load

In practical transformer, due to winding resistance, no load current I_0 is no longer at 90° with respect to V_1. But it lags V_1 by angle ϕ_0 which is less than 90°. Thus cos ϕ_0 is called **no load power factor** of practical transformer.

The phasor diagram is shown in the Fig. 2.15. It can be seen that the two components of I_0 are,

$$\boxed{I_m = I_0 \sin \phi_0} \quad \dots (2)$$

This is magnetising component lagging V_1 exactly by 90°.

$$\boxed{I_c = I_0 \cos \phi_0} \quad \dots (3)$$

This is core loss component which is in phase with V_1.

The magnitude of the no load current is given by,

$$\boxed{I_0 = \sqrt{I_m^2 + I_c^2}} \quad \dots (4)$$

while ϕ_0 = no load primary power factor angle

The total power input on no load is denoted as W_0 and is given by,

$$\boxed{W_0 = V_1 I_0 \cos \phi_0 = V_1 I_c} \quad \dots (5)$$

It may be noted that the current I_0 is very small, about 3 to 5% of the full load rated urrent. Hence the primary copper loss is negligibly small hence I_c is called core loss or on loss component. Hence power input W_0 on no load always represents the iron losses,

as copper loss is negligibly small. The iron losses are denoted as P_i and are constant for all load conditions.

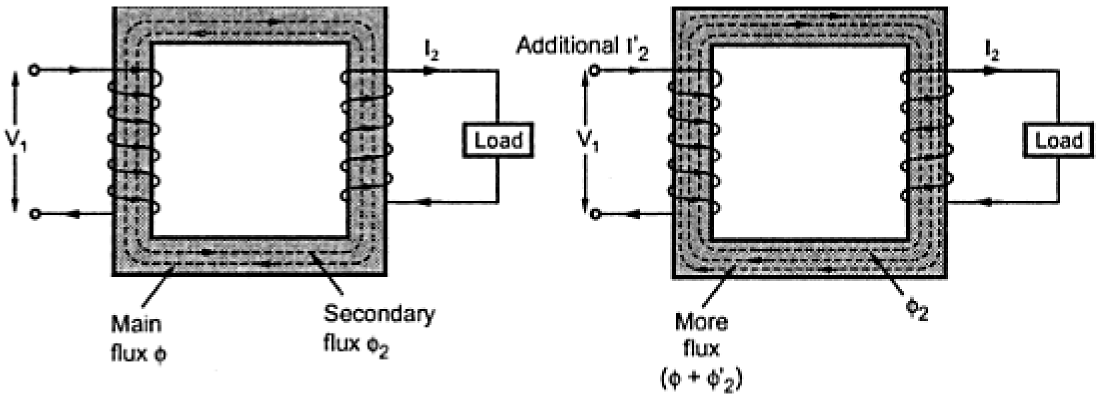
$$\therefore \quad \boxed{W_0 = V_1 I_0 \cos \phi_0 = P_i = \text{iron loss}} \quad \dots (6)$$

2.10 Transformer on Load (M.M.F. Balancing on Load)

When the transformer is loaded, the current I_2 flows through the secondary winding. The magnitude and phase of I_2 is determined by the load. If load is inductive, I_2 lags V_2. If load is capacitive, I_2 leads V_2 while for resistive load, I_2 is in phase with V_2.

There exists a secondary m.m.f. $N_2 I_2$ due to which secondary current sets up its own flux ϕ_2. This flux opposes the main flux ϕ which is produced in the core due to magnetising component of no load current. Hence the m.m.f. $N_2 I_2$ is called **demagnetising ampere-turns**. This is shown in the Fig. 2.16 (a).

The flux ϕ_2 momentarily reduces the main flux ϕ, due to which the primary induced e.m.f. E_1 also reduces. Hence the vector difference $\overline{V}_1 - \overline{E}_1$ increases due to which **primary draws more current from the supply.** This additional current drawn by primary is due to the load hence called load component of primary current denoted as I_2' as shown in the Fig. 2.16 (b).



(a) ϕ_2 opposes ϕ (b) Primary draws more current

Fig. 2.16 Transformer on load

This current I_2' is in antiphase with I_2. The current I_2' sets up its own flux ϕ_2' which opposes the flux ϕ_2 and helps the main flux ϕ. This flux ϕ_2' neutralises the flux ϕ_2 produced by I_2. The m.m.f. i.e. ampere turns $N_1 I_2'$ balances the ampere turns $N_2 I_2$. Hence the net flux in the core is again maintained at constant level.

The load component current I_2' always neutralises the changes in the load. As practically flux in core is constant, the core loss is also constant for all the loads. Hence the transformer is called **constant flux machine.**

As the ampere turns are balanced we can write,

$$N_2 I_2 = N_1 I_2'$$

$$\therefore \quad \boxed{I_2' = \frac{N_2}{N_1} I_2 = K I_2} \quad \dots (1)$$

Thus when transformer is loaded, the primary current I_1 has two components :

1. The no load current I_0 which lags V_1 by angle ϕ_0. It has two components I_m and I_c.
2. The load component I_2' which is in antiphase with I_2. And phase of I_2 is decided by the load.

Hence primary current I_1 is vector sum of I_0 and I_2'.

$$\therefore \qquad \boxed{\bar{I}_1 = \bar{I}_0 + \bar{I}_2'} \qquad \text{... (2)}$$

Assume inductive load, I_2 lags E_2 by ϕ_2, the phasor diagram is shown in the Fig. 2.17 (a).

Assume purely resistive load, I_2 in phase with E_2, the phasor diagram is shown in the Fig. 2.17 (b).

Assume capacitive load, I_2 leads E_2 by ϕ_2, the phasor diagram is shown in the Fig. 2.17 (c).

Note that I_2' is always in antiphase with I_2.

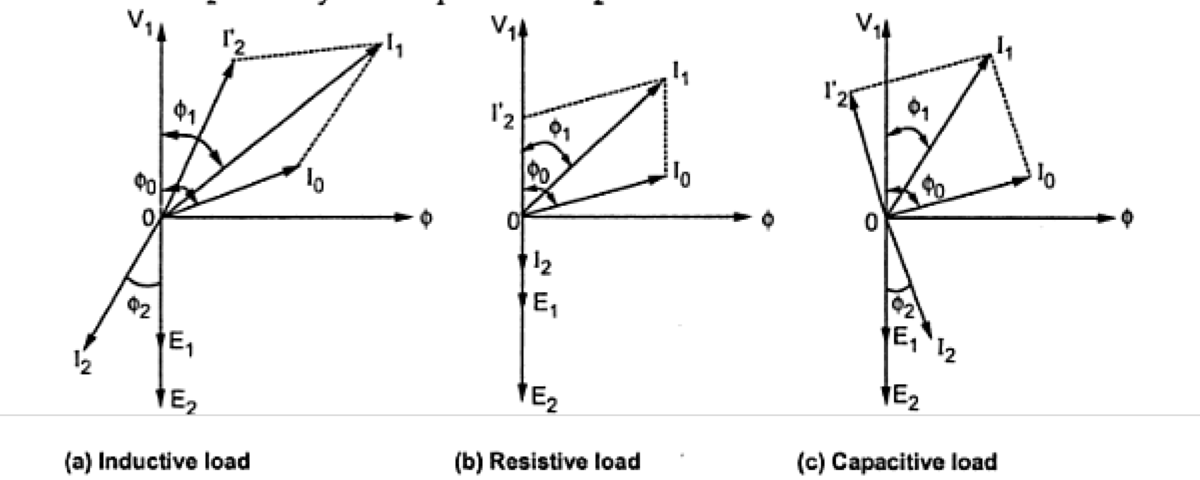


Fig. 2.17

Actually the phase of I_2 is with respect to V_2 i.e. angle ϕ_2 is angle between I_2 and V_2. For the ideal case, E_2 is assumed equal to V_2 neglecting various drops.

The current ratio can be verified from this discussion. As the no load current I_0 is very small, neglecting I_0 we can write,

$$I_1 \cong I_2'$$

Balancing the ampere-turns,

$$N_1 I_2' = N_1 I_1 = N_2 I_2$$

$$\therefore \qquad \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

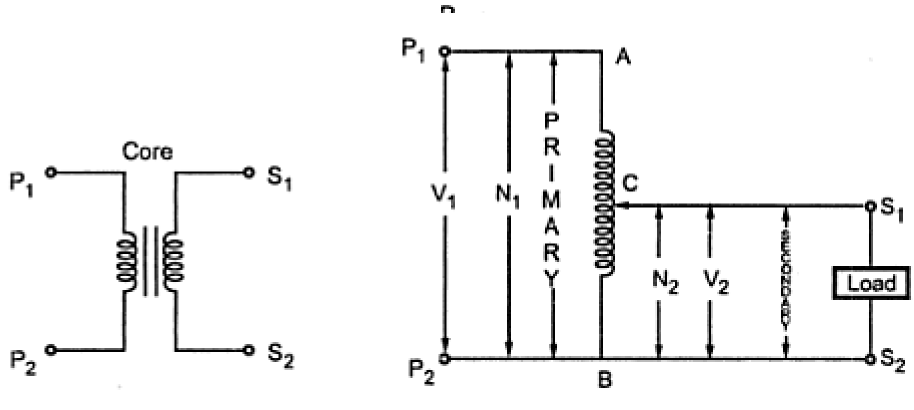
Under full load conditions when I_0 is very small compared to full load currents, the ratio of primary and secondary current is constant.

Uptill now the two winding transformers are discussed in which the windings are electrically isolated and the e.m.f. in secondary gets induced due to induction. In practice, it is possible to use only one winding for the transformer so that part of this winding is common to the primary and secondary. Such a special type of transformer having only one winding such that part of the winding is common to the primary and secondary is called **autotransformer.** Obviously the two windings are electrically connected and it works on the principle of conduction as well as induction. Such an autotransformer is very much economical where the voltage ratio is less than 2 and the electrical isolation of the two windings is not necessary. The power transfer in 2 winding transformer is fully inductively while in autotransformer the power is transferred from primary to secondary by both inductively as well as conductively.

In an autotransformer only one winding is wound on a laminated magnetic core while in 2 winding transformer, two windings are wound. The single winding of the autotransformer is used as primary and secondary. The part of the winding is common to both primary and secondary. The voltage can be stepped down or stepped up using an autotransformer. Accordingly the autotransformers are classified as step up autotransformer and step down autotransformer.

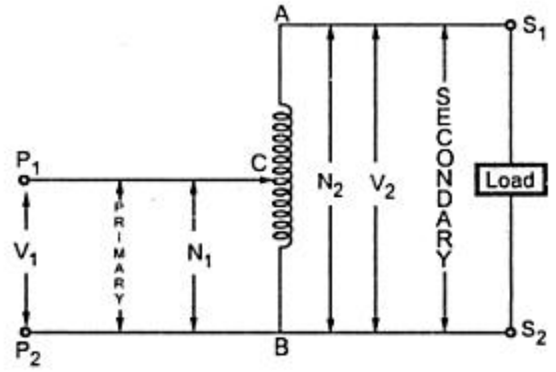
The Fig. 2.56 (a) shows the conventional two winding transformer while the Fig. 2.56 (b) and (c) show the step down and step up autotransformers respectively.

In step down autotransformer shown in the Fig. 2.56 (b), the entire winding acts as a primary while the part of the winding is used common to both primary and secondary. Thus AB forms the primary having N_1 turns while BC forms the secondary with N_2 turns. As $N_2 < N_1$, the output voltage $V_2 < V_1$ and it acts as a step down autotransformer. In step up autotransformer shown in the Fig. 2.56 (c), the entire winding acts as secondary while the part of the winding is used common to both primary and secondary. Thus AB forms the secondary having N_2 turns while BC forms the primary with N_1 turns. As $N_2 > N_1$, the output voltage $V_2 > V_1$ and it acts as a step up autotransformer.



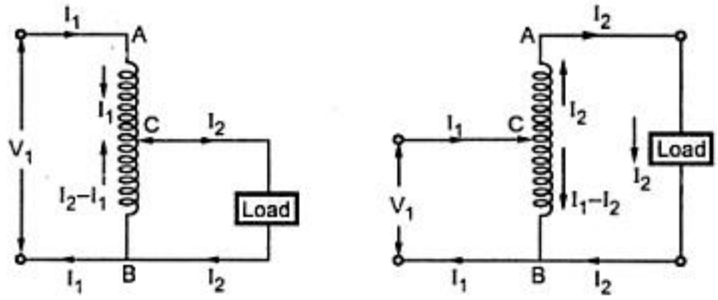
(a) 2 winding transformer

(b) Step down autotransformer



(c) Step up autotransformer

The current distribution in the step down and step up autotransformers is shown in the Fig. 2.57 (a) and (b) respectively.



(a) Step down autotransformer (b) Step up autotransformer

Fig. 2.57 Current distribution in autotransformer

2.31 Transformation Ratio of an Autotransformer

Neglecting the losses, the leakage reactance and the magnetising current, the transformation ratio of an autotransformer can be obtained as,

$$K = \frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

K is greater than unity for step up autotransformer while K is less than unity for step down autotransformer.

Due to the use of single winding, compared to the normal two winding transformer, for the same capacity and voltage ratio, there is substantial saving in copper in case of autotransformers.

For any winding, the cross-section of winding is proportional to the current I. While the total length of the winding is proportional to the number of turns N. Hence the weight of copper is proportional to the product of N and I.

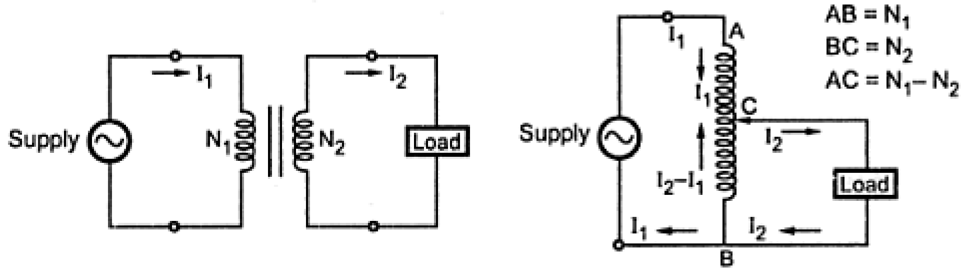
$\therefore$ Weight of copper $\propto$ NI

where $\quad I$ = Current in the winding

and $\quad N$ = Number of turns of the winding

Consider a two winding transformer and step down autotransformer as shown in the Fig. 2.58 (a) and (b).

Consider a two winding transformer and step down autotransformer as shown in the Fig. 2.58 (a) and (b).



(a) Two winding transformer (b) Step down autotransformer

Fig. 2.58

Let $\quad W_{TW}$ = Total weight of copper in two winding transformer

W_{AT} = Weight of copper in autotransformer

Weight of copper of primary $\propto N_1 I_1$

Weight of copper of secondary $\propto N_2 I_2$

$\therefore \quad W_{TW} \propto N_1 I_1 + N_2 I_2$ ... Total weight of Cu

In case of step down autotransformer.

Weight of copper of section AC $\propto (N_1 - N_2) I_1$

Weight of copper of section BC $\propto N_2 (I_2 - I_1)$

$\therefore \quad W_{AT} \propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$ ... Total weight of Cu

Taking ratio of the two weights,

$$\frac{W_{TW}}{W_{AT}} = \frac{N_1 I_1 + N_2 I_2}{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}$$

$$= \frac{N_1 I_1 + N_2 I_2}{N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1}$$

$$= \frac{N_1 I_1 + N_2 I_2}{N_1 I_1 + N_2 I_2 - 2 N_2 I_1}$$

But $K = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

$$\therefore \quad \frac{W_{TW}}{W_{AT}} = \frac{N_1 I_1 + KN_1 \cdot (I_1 / K)}{N_1 I_1 + KN_1 \cdot (I_1 / K) - 2(KN_1) I_1}$$

$$= \frac{2N_1 I_1}{2N_1 I_1 - 2KN_1 I_1} = \frac{1}{1-K}$$

$$\therefore \quad W_{AT} = (1 - K)\, W_{TW}$$

$\therefore$ Saving of copper $= W_{TW} - W_{AT} = W_{2T} - (1 - K)\, W_{TW}$

$$\boxed{\text{Saving of copper} = K\, W_{TW}}$$ ... For **step down autotransformer**

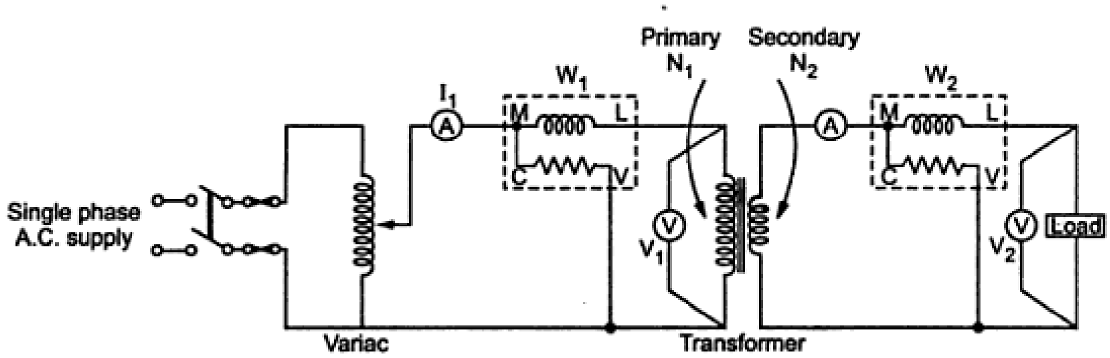
Thus saving in copper is K times the total weight of copper in two winding transformer.

Thus saving in copper is K times the total weight of copper in two winding transformer.

And $$\boxed{\text{Saving of copper} = \frac{1}{K} W_{TW}}$$ ... For **step up autotransformer**

In this method the required load is directly connected to the secondary of the transformer. Hence this method is also called **direct loading test** on transformer. The various meters are connected on primary and secondary side of the transformer. Then the load is varied from no load to full load and the readings on the various meters are recorded.

The Fig. 7.1 shows the experiment set up for the load test on transformer. An ammeter, voltmeter and a wattmeter is connected on primary as well as secondary side of the transformer. The primary is connected to the supply through variac which is used to adjust primary voltage to its rated value at each load condition.



The load is to be varied from no load to full load in desired steps. All the time, keep primary voltage V_1 constant at its rated value with the help of variac. The following observation table is prepared.

No.	Primary side			Secondary side		
	V_1 V	I_1 A	W_1 W	V_2 V	I_2 A	W_2 W
1	Rated			E_2	0	0
2 ⋮						

The first reading is to be noted on no load for which $I_2 = 0$ A and $W_2 = 0$ W.

From the observation table,

$$W_1 = \text{Input power to the transformer}$$

$$W_2 = \text{Output power delivered to the load}$$

$$\therefore \quad \boxed{\%\eta = \frac{W_2}{W_1} \times 100}$$

The first reading is on no load for which,

$$V_2 = E_2$$

Thus at any other load, regulation can be obtained as,

$$\boxed{\%R = \frac{E_2 - V_2}{V_2} \times 100}$$

where V_2 is secondary terminal voltage at corresponding load. The graph of $\%\eta$ and $\%R$ on each load against load current I_L is plotted as shown in the Fig. 7.2.

where V_2 is secondary terminal voltage at corresponding load. The graph of $\%\eta$ and $\%R$ on each load against load current I_L is plotted as shown in the Fig. 7.2.

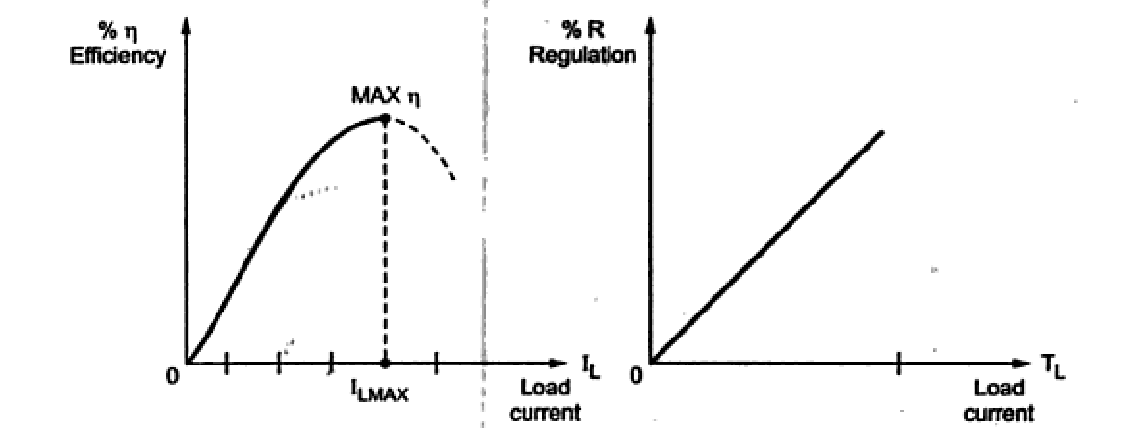


Fig. 7.2 Efficiency and regulation characteristics

The efficiency increases as load increases upto particular load. After that load, efficiency decreases as load increases. The regulation increases as the load increases as V_2 keeps on decreasing as the load increases.

The important **advantage** of this method is that the results are accurate as load is directly used,

The **disadvantages** of this method are,

1. For large rating transformers, suitable load is difficult to obtain in the laboratory. It can not be loaded upto its full load capacity in the laboratory.
2. There are large power losses during the test.

Open Circuit Test (O.C. Test)

The experimental circuit to conduct O.C. test is shown in the Fig. 3.25.

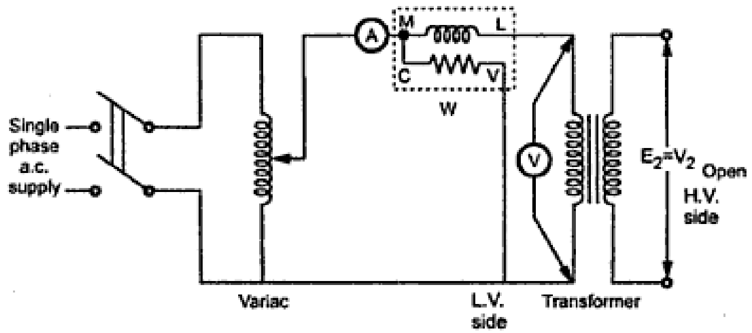


Fig. 3.25 Experimental circuit for O.C. test

The transformer primary is connected to a.c. supply through ammeter, wattmeter and variac. The secondary of transformer is kept open. Usually low voltage side is used as primary and high voltage side as secondary to conduct O.C. test.

The primary is excited by rated voltage, which is adjusted precisely with the help of a variac. The wattmeter measures input power. The ammeter measures input current. The voltmeter gives the value of rated primary voltage applied at rated frequency.

Sometimes a voltmeter may be connected across secondary to measure secondary voltage which is $V_2 = E_2$ when primary is supplied with rated voltage. As voltmeter resistance is very high, though voltmeter is connected, secondary is treated to be open circuit as voltmeter current is always negligibly small.

When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeter and wattmeter are to be recorded.

The observation table is as follows.

V_0 volts	I_0 amperes	W_0 watts
Rated		

$$V_o = \text{Rated voltage}$$

$$W_o = \text{Input power}$$

$$I_o = \text{Input current} = \text{No load current}$$

As transformer secondary is open, it is on no load. So current drawn by the primary is no load current I_o. The two components of this no load current are,

$$I_m = I_o \sin \phi_o$$
$$I_c = I_o \cos \phi_o$$

where $\cos \phi_o$ = No load power factor

And hence power input can be written as,

$$W_o = V_o I_o \cos \phi_o$$

The phasor diagram is shown in the Fig. 3.26.

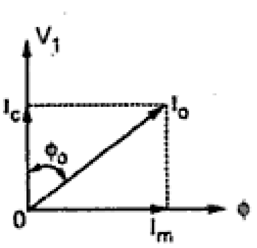


Fig. 3.26

As secondary is open, $I_2 = 0$. Thus its reflected current on primary I_2' is also zero. So we have primary current $I_1 = I_o$. The transformer no load current is always very small, hardly 2 to 4 % of its full load value. As $I_2 = 0$, secondary copper losses are zero. And $I_1 = I_o$ is very low hence copper losses on primary are also very very low. Thus the total copper losses in O.C. test are negligibly small. As against this the input voltage is rated at rated frequency hence flux density in the core is at its maximum value. Hence iron losses are at rated voltage. As output power is zero and copper losses are very low, the total input power is used to supply iron losses.

This power is measured by the wattmeter i.e. W_o. Hence the wattmeter in O.C. test gives iron losses which remain constant for all the loads.

$$\therefore \quad W_o = P_i = \text{Iron losses}$$

Calculations : We know that,

$$W_o = V_o I_o \cos\phi$$

$$\therefore \quad \cos\phi_o = \frac{W_o}{V_o I_o} = \text{No load power factor}$$

Once $\cos\phi_o$ is known we can obtain,

$$I_c = I_o \cos\phi_o$$

and

$$I_m = I_o \sin\phi_o$$

Once I_c and I_m are known we can determine exciting circuit parameters as,

$$R_o = \frac{V_o}{I_c} \quad \Omega$$

and

$$X_o = \frac{V_o}{I_m} \quad \Omega$$

Key Point : *The no load power factor $\cos\phi_o$ is very low hence wattmeter used must be low power factor type otherwise there might be error in the results. If the meters are connected on secondary and primary is kept open then from O.C. test we get R_o' and X_o' with which we can obtain R_o and X_o knowing the transformation ratio K.*

3.17.2 Short Circuit Test (S.C. Test)

In this test, primary is connected to a.c. supply through variac, ammeter and voltmeter as shown in the Fig. 3.27.

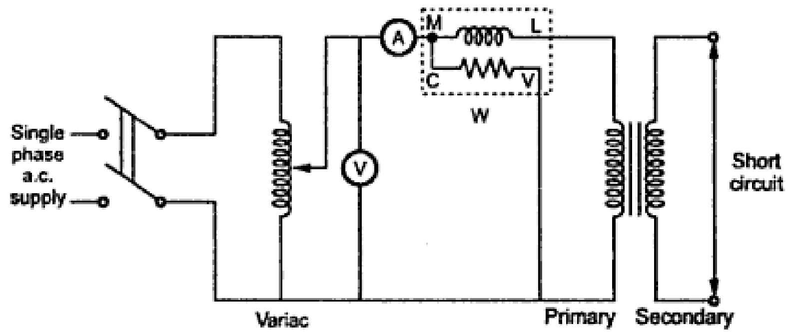


Fig. 3.27 Experimental circuit for S.C. test

The secondary is short circuited with the help of thick copper wire or solid link. As high voltage side is always low current side, it is convenient to connect high voltage side to supply and shorting the low voltage side.

As secondary is shorted, its resistance is very very small and on rated voltage it may draw very large current. Such large current can cause overheating and burning of the transformer. To limit this short circuit current, primary is supplied with low voltage which is just enough to cause rated current to flow through primary which can be observed on an ammeter. The low voltage can be adjusted with the help of variac. Hence this test is also called **low voltage test** or **reduced voltage test**. The wattmeter reading as well as voltmeter, ammeter readings are recorded. The observation table is as follows.

V_{sc} volts	I_{sc} amperes	W_{sc} watts
	Rated	

Now the currents flowing through the windings are rated currents hence the total copper loss is full load copper loss. Now the voltage applied is low which is a small fraction of the rated voltage. The iron losses are function of applied voltage. So the iron losses in reduced voltage test are very small. Hence the wattmeter reading is the power loss which is equal to full load copper losses as iron losses are very low.

$$\therefore \quad W_{sc} = (P_{cu})\text{ F.L.} = \text{Full load copper loss}$$

Calculations : From S.C. test readings we can write,

$$W_{sc} = V_{sc} I_{sc} \cos\phi_{sc}$$

$$\therefore \quad \cos\phi_{sc} = \frac{V_{sc} I_{sc}}{W_{sc}} = \text{Short circuit power factor}$$

$$W_{sc} = I_{sc}^2 R_{1e} = \text{Copper loss}$$

$$\therefore \quad \boxed{R_{1e} = \frac{W_{sc}}{I_{sc}^2}}$$

While

$$\boxed{Z_{1e} = \frac{V_{sc}}{I_{sc}} = \sqrt{R_{1e}^2 + X_{1e}^2}}$$

$$\therefore \quad \boxed{X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}}$$

Thus we get the equivalent circuit parameters R_{1e}, X_{1e} and Z_{1e}. Knowing the transformation ratio K, the equivalent circuit parameters referred to secondary also can be obtained.

Important Note : If the transformer is step up transformer, its primary is L.V. while secondary is H.V. winding. In S.C. test, supply is given to H.V. winding and L.V. is shorted. In such case we connect meters on H.V. side which is transformer secondary though for S.C. test purpose H.V. side acts as primary. In such case the parameters calculated from S.C. test readings are referred to secondary which are R_{2e}, Z_{2e} and X_{2e}. So before doing calculations it is necessary to find out where the readings are recorded on transformer primary or secondary and accordingly the parameters are to be determined. In step down transformer, primary is high voltage itself to which supply is given in S.C. test. So in such case test results give us parameters referred to primary i.e. R_{1e}, Z_{1e} and X_{1e}.

Key Point: *In short, if meters are connected to primary of transformer in S.C. test, calculations give us R_{1e} and Z_{1e}. If meters are connected to secondary of transformer in S.C. test calculations give us R_{2e} and Z_{2e}.*

3.17.3 Calculation of Efficiency from O.C. and S.C. Tests

We know that,

From O.C. test, $W_o = P_i$

From S.C. test, $W_{sc} = (P_{cu})$ F.L.

$$\therefore \quad \% \eta \text{ on full load} = \frac{V_2 (I_2) \text{ F.L.} \cos\phi}{V_2 (I_2) \text{ F.L.} \cos + W_o + W_{sc}} \times 100$$

Thus for any p.f. $\cos\phi_2$ the efficiency can be predetermined. Similarly at any load which is fraction of full load then also efficiency can be predetermined as,

$$\% \eta \text{ at any load} = \frac{n \times (\text{VA rating}) \times \cos\phi}{n \times (\text{VA rating}) \times \cos\phi + W_o + n^2 W_{sc}} \times 100$$

where n = Fraction of full load

or
$$\% \eta = \frac{n V_2 I_2 \cos\phi}{n V_2 I_2 \cos\phi + W_o + n^2 W_{sc}} \times 100$$

where $I_2 = n (I_2)$ F.L.

3.17.4 Calculation of Regulation

From S.C. test we get the equivalent circuit parameters referred to primary or secondary.

The rated voltages V_1, V_2 and rated currents (I_1) F.L. and (I_2) F.L. are known for the given transformer. Hence the regulation can be determined as,

$$\% R = \frac{I_2 R_{2e} \cos\phi \pm I_2 X_{2e} \sin\phi}{V_2} \times 100$$

$$= \frac{I_1 R_{1e} \cos\phi \pm I_1 X_{1e} \sin\phi}{V_1} \times 100$$

where I_1, I_2 are rated currents for full load regulation.

A 20 KVA, 2500/250V, 50 Hz, single phase transformer gave the following test result .O.C. test (On L.V. side): 250 V, 1.4 A, 105 Watts S.C. test (On L.V. side): 104 V, 8 A, 320 W Compute the parameters of the approximate equivalent circuit referred to HV and LV sides. Also draw the exact equivalent circuit referred to the LV side and also calculate the efficiency at half the full load at UPF.

Sol. : 20 kVA, $V_1 = 2500$ V, $V_2 = 250$ V

$$V_0 = 250\text{ V},\quad I_0 = 1.4\text{ A},\quad W_0 = 105\text{ W}$$

The O.C. test is conducted on l.v. side which is secondary of the transformer. Thus O.C. test will give us R'_0 and X'_0.

$$\cos\phi_0 = \frac{W_0}{V_0 I_0} = \frac{105}{250\times 1.4} = 0.3 \text{ lagging}$$

$$I_c = I_0 \cos\phi_0 = 1.4\times 0.3 = 0.42\text{ A}$$

$$I_m = I_0 \sin\phi_0 = 1.4\times 0.9539 = 1.33551\text{ A}$$

$\therefore$

$$R'_0 = \frac{V_0}{I_c} = \frac{250}{0.42} = \mathbf{595.238\ \Omega}$$

and

$$X'_0 = \frac{V_0}{I_m} = \frac{250}{1.33551} = \mathbf{187.193\ \Omega}$$

$$K = \frac{250}{2500} = 0.1$$

$\therefore$

$$R_0 = \frac{R'_0}{K^2} = \frac{595.238}{(0.1)^2} = \mathbf{59.5238\ k\Omega}$$

and

$$X_0 = \frac{X'_0}{K^2} = \frac{187.193}{(0.1)^2} = \mathbf{18.7193\ k\Omega}$$

$$(I_1)\text{F.L.} = \frac{\text{kVA}\times 10^3}{V_1} = \frac{20\times 10^3}{2500} = 8\text{A}$$

Now

$$I_{sc} = 8\text{A},\ V_{sc} = 104\text{ V},\ W_{sc} = 320\text{ W}$$

The meters are on h.v.side i.e. on primary side hence short circuit test gives parameters referred to primary.

$$R_{1e} = \frac{W_{sc}}{(I_{sc})^2} = \frac{320}{(8)^2} = \mathbf{5\ \Omega}$$

$$Z_{1e} = \frac{V_{sc}}{I_{sc}} = \frac{104}{8} = \mathbf{13\ \Omega}$$

$\therefore$

$$X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2} = \mathbf{12\ \Omega}$$

As $I_{sc} = (I_1)$F.L., W_{sc} gives copper losses on full load.

$\therefore$

$$(P_{cu})\text{F.L.} = 320\text{ W}$$

$$P_i = W_0 = 105\text{ W} = \text{iron losses}$$

$\therefore$

$$R_{2e} = K^2 R_{1e} = (0.1)^2\times 5 = \mathbf{0.05\ \Omega}$$

$$X_{2e} = K^2 X_{1e} = (0.1)^2\times 12 = \mathbf{0.12\ \Omega}$$

$$Z_{2e} = K^2 Z_{1e} = (0.1)^2\times 13 = \mathbf{0.13\ \Omega}$$

The exact equivalent circuit referred to the low voltage side is as shown in the Fig. 6.80.

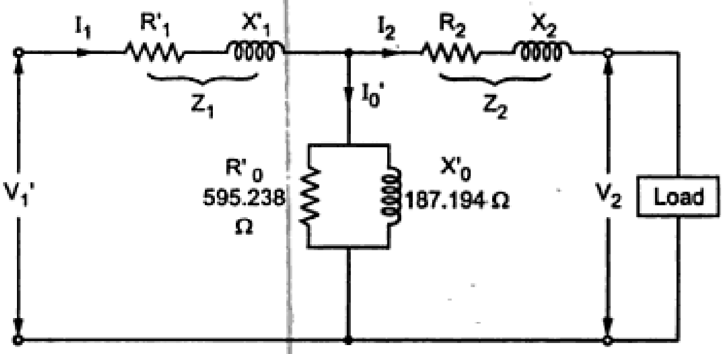


Fig. 7.12

To find % η at half load and cosϕ = 1.

$$n = \text{half load} = 0.5$$

$$\%\eta = \frac{n \times kVA \times 10^3 \times \cos\phi}{n \times kVA \times 10^3 \times \cos\phi + n^2 (P_{cu})\, F.L. + P_i} \times 100$$

To find % η at half load and cosϕ = 1.

$$n = \text{half load} = 0.5$$

$$\%\eta = \frac{n \times kVA \times 10^3 \times \cos\phi}{n \times kVA \times 10^3 \times \cos\phi + n^2 (P_{cu})\, F.L. + P_i} \times 100$$

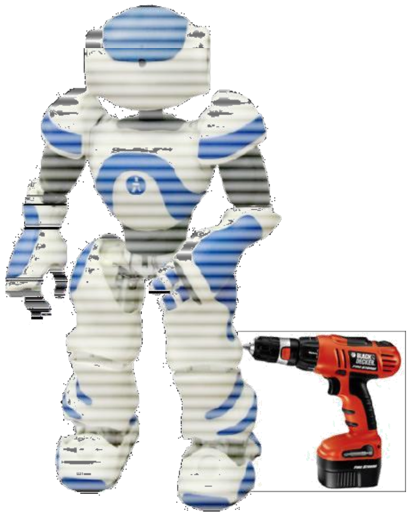
$$= \frac{0.5 \times 20 \times 10^3 \times 1}{0.5 \times 20 \times 10^3 \times 1 + 0.25 \times 320 + 105} \times 100$$

$$= \mathbf{98.1836\ \%}$$

Unit 2 DC MOTOR

DC Motors

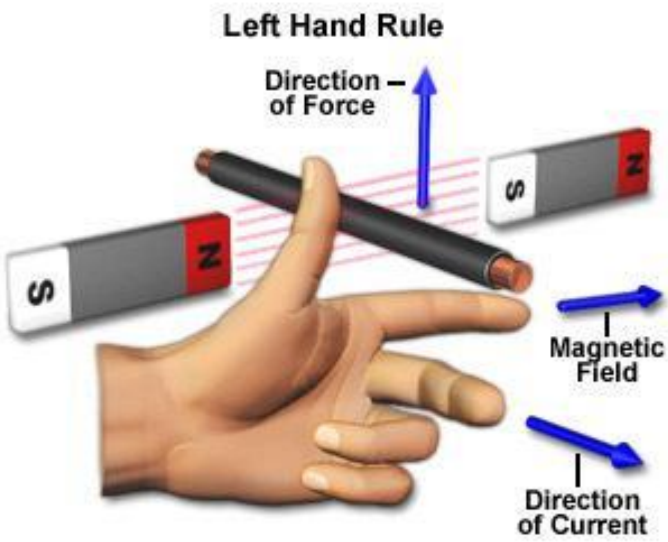
Although ac motors are used in most of the cases, DC motors have many applications and used for multi-purpose applications.

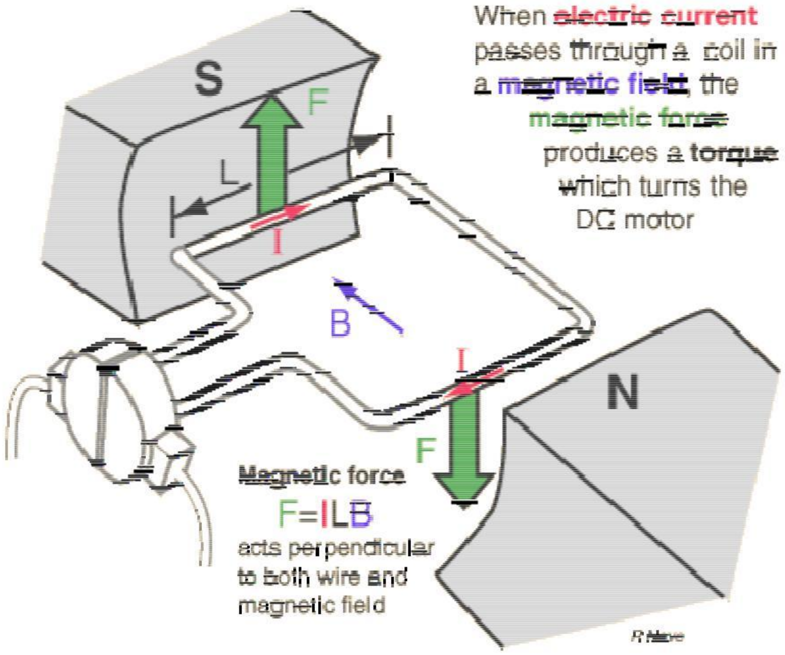


DC Motor Principle

A machine that converts dc power into mechanical energy is known as dc motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of the force is given by Fleming's left hand rule.

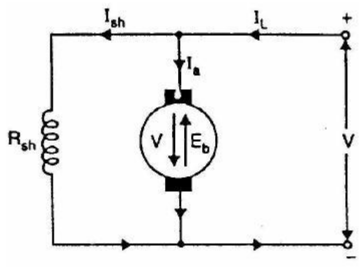
Fleming Left Hand Rule





Back or Counter EMF

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence an e.m.f. is induced in them.



The induced e.m.f. acts in opposite direction to the applied voltage V(Lenz's law) and is known as back or counter e.m.f. E_b.

Significance of Back E.M.F

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load.

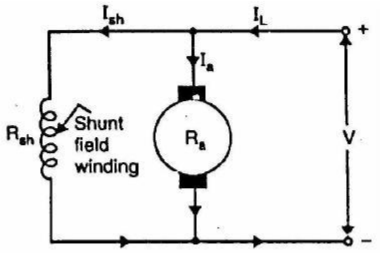
Back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

DC Motor Types

- Shunt Wound
- Series Wound
- Compound wound

Shunt Wound Motor

In shunt wound motor the field winding is connected in parallel with armature.

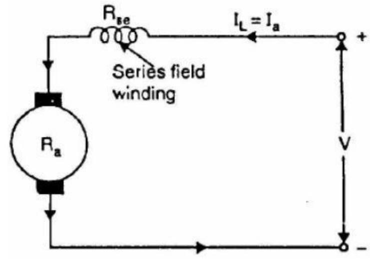


The current through the shunt field winding is not the same as the armature current.

Shunt field windings are designed to produce the necessary m.m.f. by means of a relatively large number of turns of wire having high resistance. Therefore, shunt field current is relatively small compared with the armature current

Series Wound Motor

- In series wound motor the field winding is connected in series with the armature. Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed with much fewer turns than shunt field windings for the same mmf.

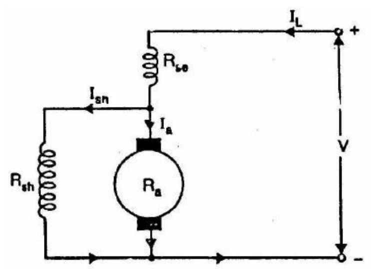


Therefore, a series field winding has a relatively small number of turns of thick wire and, therefore, will possess a low resistance.

Compound Wound Motor

Compound wound motor has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections

1) Short-shunt connection
2) Long shunt connection

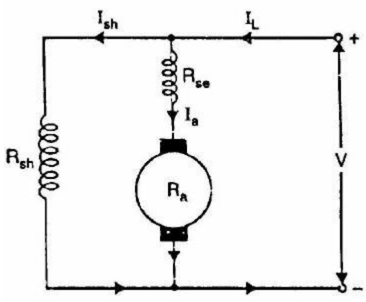


Short-shunt connection

When the shunt field winding is directly connected across the armature terminals it is called short-shunt connection.

Compound Wound Motor

When the shunt winding is so connected that it shunts the series combination of armature and series field it is called long-shunt connection.



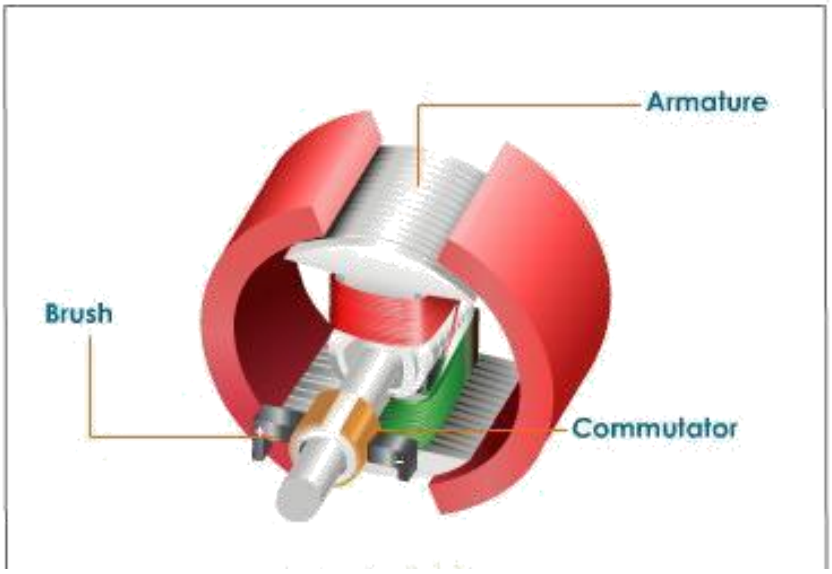
Long-shunt connection

Parts of a DC Motor

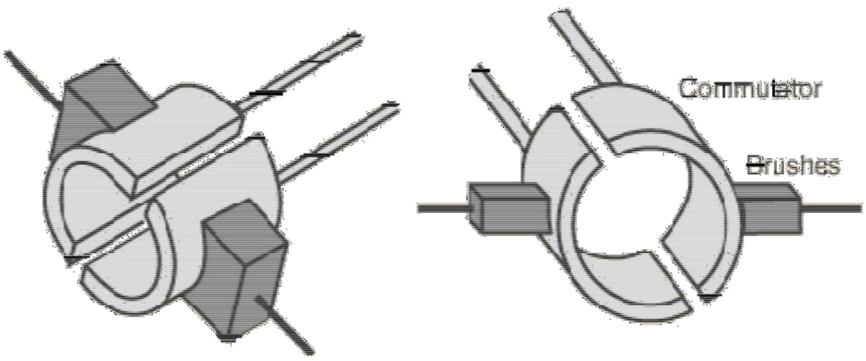
A simple motor has six parts

- Armature/ Rotor
- Commutator
- Brushes
- Axle
- Permanent Magnet
- DC Power supply

Parts of a DC Motor



Commutator and Brushes



Commutation in DC Motor

In order to produce unidirectional force (or torque) on the armature conductors of a motor, the conductors under any pole must carry the current in the same direction at all times.

The function of commutator and brush gear in a dc motor is to cause the reversal of current in a conductor as it moves from one side of a brush to the other.

Voltage Equation of Motors

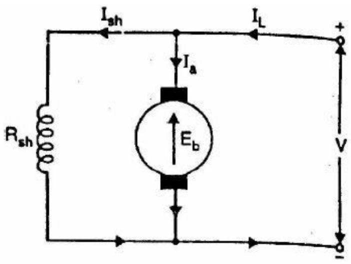
Let in a d.c. motor

V = applied voltage

E_b = back e.m.f.

R_a = armature resistance

I_a = armature current



Since back e.m.f. E_b acts in opposition to the applied voltage V, the net voltage across the armature circuit is $V-E_b$. The armature current I_a is given by

$$I_a = \frac{V - E_b}{R_a}$$

$$V = E_b + I_a R_a$$

This is known as voltage equation of the d.c. motor

Condition For Maximum Power

The mechanical power developed by the motor is $P_m = E_b I_a$

Since, V and Ra are fixed, power developed by the motor depends upon armature current. For maximum power, dP_m/dI_a should be zero.

$$\therefore \quad \frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

$$\text{or} \quad I_a R_a = \frac{V}{2}$$

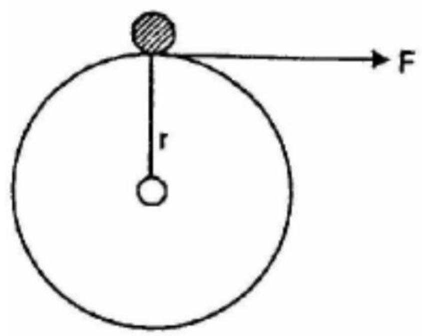
$$\text{Now,} \quad V = E_b + I_a R_a = E_b + \frac{V}{2} \qquad \therefore \quad E_b = \frac{V}{2}$$

Hence mechanical power developed by the motor is maximum when back e.m.f. is equal to half the applied voltage.

Armature Torque of a DC Motor

Torque is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts

$$T = F \times r$$



In dc motor, each conductor is acted upon by circumferential force, F at a distance r.

Let in a d.c. motor

r = average radius of armature in m

ℓ = effective length of each conductor in m

Z = total number of armature conductors

A = number of parallel paths

i = current in each conductor = I_a/A

B = average flux density in Wb/m2

ϕ = flux per pole in Wb

P = number of poles

Force on each conductor, $F = B\, i\, \ell$ newtons

Torque due to one conductor = $F \times r$ newton- metre

Total armature torque, $T_a = Z\,F\,r$ newton-metre

$= Z\,B\,i\,\ell\,r$

$i = I_a/A,\ B = \phi/a \qquad a = 2\pi r\ell/P.$

where a is the x-sectional area of flux path per pole

$$T_a = Z \times \frac{\phi}{2\pi r \ell / P} \times \frac{I_a}{A} \times \ell \times r = \frac{Z\phi I_a P}{2\pi A}\ \text{N - m}$$

$$T_a = 0.159\, Z\phi I_a \left(\frac{P}{A}\right)\ \text{N - m}$$

Since Z, P and A are fixed for a given machine,

$$\therefore \quad \boxed{T_a \propto \phi I_a}$$

Speed of a DC Motor

$$E_b = V - I_a R_a$$

But $$E_b = \frac{P\phi Z N}{60\ A}$$

$$\therefore \quad \frac{P\phi Z N}{60\ A} = V - I_a R_a$$

or $$N = \frac{(V - I_a R_a)}{\phi} \frac{60\ A}{P Z}$$

or $$N = K \frac{(V - I_a R_a)}{\phi}$$ where $$K = \frac{60 A}{PZ}$$

Speed of a DC Motor

But $$V - I_a R_a = E_a$$

$$\therefore \quad N = K \frac{E_b}{\phi}$$

or $$\boxed{N \propto \frac{E_b}{\phi}}$$

Therefore, in a dc motor speed is directly proportional to back emf, E_b and inversely proportional to flux, φ.

Speed Relations

$$N_1 \propto \frac{E_{b1}}{\phi_1} \quad \text{and} \quad N_2 \propto \frac{E_{b2}}{\phi_2}$$

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

(i) For a shunt motor, flux practically remains constant so that $\phi_1 = \phi_2$.

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

(ii) For a series motor, $\phi \propto I_a$ prior to saturation.

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$$

where I_{a1} = initial armature current
I_{a2} = final armature current

Problem

A 220 V dc shunt motor runs at 500 rpm when the armature current is 50 A. Calculate the speed if the torque is doubled. Given that Ra=0.2 Ω

$T_{a2}/T_{a1}=I_{a1}/I_{a2}$; $N_2/N_1=E_{b2}/E_{b1}$

$E_b=V_a-I_aR_a$

Losses and Efficiency of a DC Motor

Losses in DC Motor:

1) Copper Loss
2) Iron Loss
3) Mechanical Loss

The efficiency of a d.c. motor is the ratio of output power to the input power

$$\text{Efficiency, } \eta = \frac{\text{output}}{\text{input}} \times 100 = \frac{\text{output}}{\text{output} + \text{losses}} \times 100$$

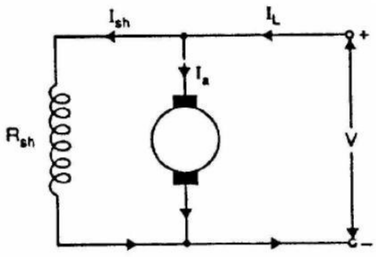
DC Motor Characteristic

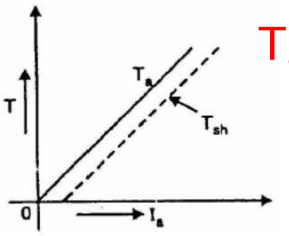
(i) Torque and armature current characteristics (T_a/I_a): It is the curve between armature torque and armature current of a dc motor

(ii) Speed and armature current characteristics (N/I_a): It is the curve between speed and armature current.

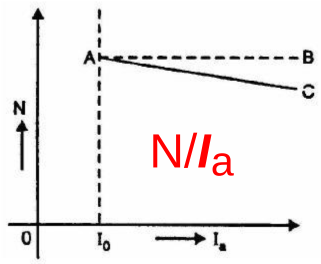
(iii) Speed and torque characteristics (N/T_a): It is the curve between speed and armature torque.

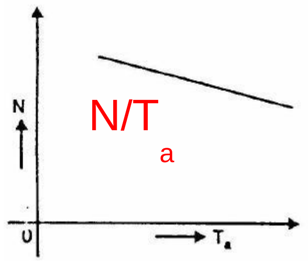
Characteristics of a shunt motor



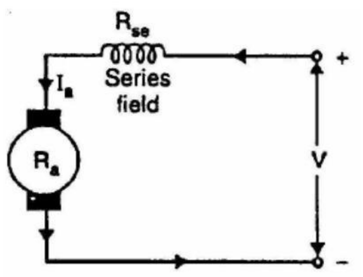


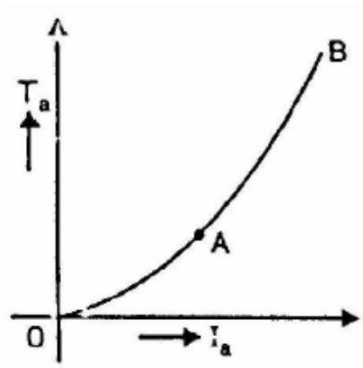
T_a/I_a





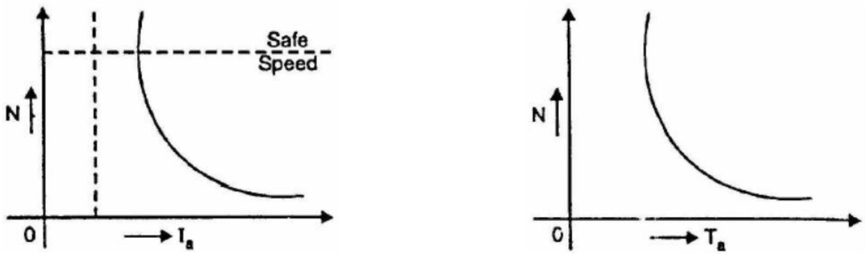
Characteristics of a Series Motor





$$T_a \propto \phi I_a$$

Upto magnetic saturation, $\phi \propto I_a$ so that $T_a \propto I_a^2$

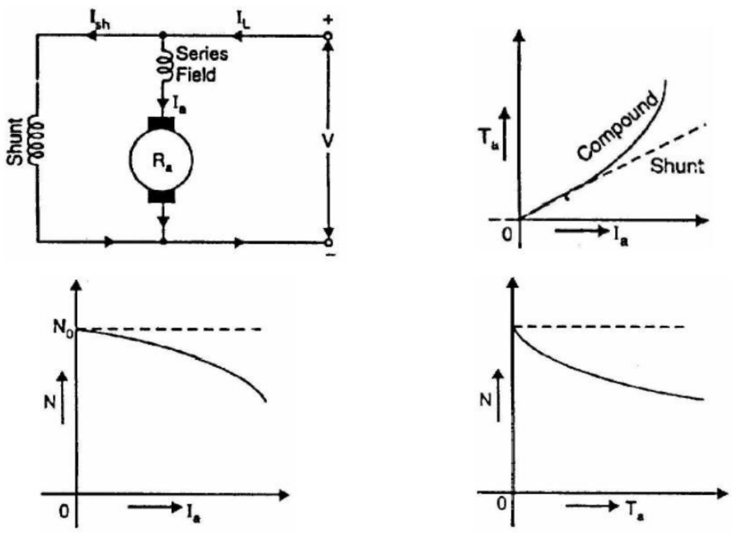


N/I_a Characteristic. The speed N of a series motor is given by;

$$N \propto \frac{E_b}{\phi} \quad \text{where} \quad E_b = V - I_a(R_a + R_{se})$$

$$N \propto \frac{1}{\phi}$$

Characteristics of a compound motor



Applications of DC Motor

Shunt Motor:

The characteristics of a shunt motor reveal that it is an approximately constant speed motor.

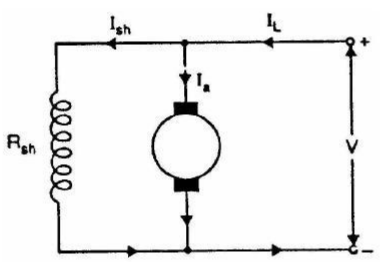
Industrial Use: Lathes, Drills, Boring Mills, Shapers , Spinning, and weaving machines

Series Motor: It is a variable speed motor i.e. speed is low at high torque and vice versa. This motor is used when large starting torque is required.

Industrial Use: Electric Traction Cranes, Elevators, hair drier, Sewing machine

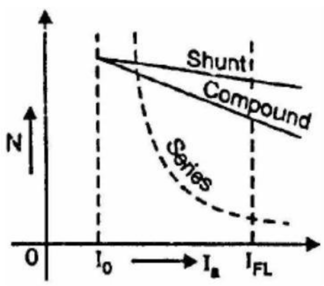
Problem

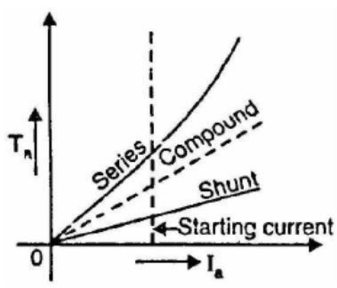
A 440 V shunt Motor has armature resistance of 0.8 Ω and field resistance of 200 Ω. Determine the back emf when giving an output of 7.46 KW at 85% efficiency.



Motor input power=
Motor input current=19.95 A
Shunt current= V/R_{sh}=2.2 A
Armature Current, Ia = 17.75 A
Back emf=V-IaRa=425.8 V

Comparison of three types of Motor





1) The speed regulation in shunt motor is better than series motor
2) The starting torque of a series motor is more than other motor
3) Both shunt and compound motors have definite no load speed, however series motors have dangerously high speed at no load.

DC machine

Motors and generators are dc machines. There are several tests to judge the performance of a DC machine. The efficiency of a dc machine depends upon the losses. The smaller the losses, the greater is the efficiency of the machine.

Armature Reaction

What is meant by armature reaction?

In dc machine, the main field is produced by the field coils. In both the generating and motoring modes, the armature carries current and magnetic field is established, which is called armature flux. The effect of armature flux on main field is called the armature reaction.

What armature reaction does?

It demagnetizes or weakens the magnetic flux/field.

It cross-magnetises or distorts it.

Overcome:

The demagnetizing effect can be overcome by adding extra ampere-turns on the main field. The cross magnetizing effect can be reduced by having common poles.

Advantage of DC Motor

Although a far greater percentage of electric motors in service are a.c. motors,the d.c. motor is of considerable industrial importance. The principal advantage of a d.c. motor is that its speed can be changed over a wide range by a variety of simple methods. Such a fine speed control is generally not possible with a.c. motors. In fact, fine speed control is one of the reasons for the strong competitive position of d.c. motors in the modem industrial applications.

Speed Control of DC Motor

The speed of a dc motor is given by

$$N \propto \frac{E_b}{\phi}$$

or

$$N = K\frac{(V - I_a R)}{\phi} \text{ r.p.m.}$$

where $R = R_a$ for shunt motor

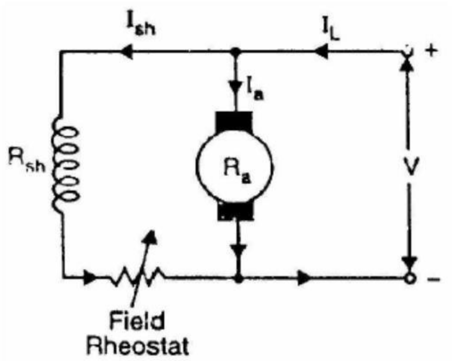
$= R_a + R_{se}$. for series motor

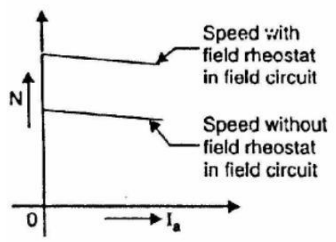
i) **Flux Control**: By varying the flux per pole.

ii) **Armature Control**: By varying the resistance in the armature circuit.

iii) **Voltage Control**: By varying the applied voltage.

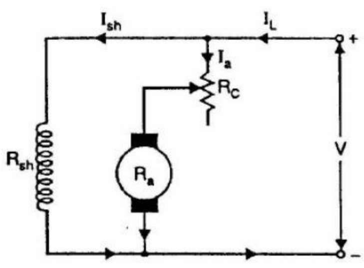
Flux Control Method

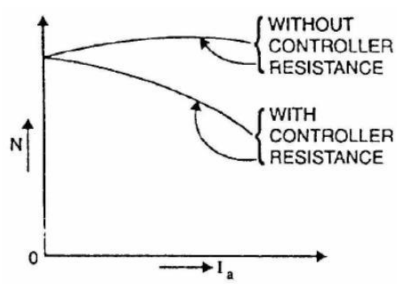




It is based on the fact that by varying the flux f, the motor speed (N) can be changed and hence the name flux control method. In this method, a variable resistance is placed in series with shunt field winding.

Armature Control Method





$$N \propto V - I_a(R_a + R_C)$$

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed.

This is done by inserting a variable resistance in series with the armature.

Voltage Control Method

In this method, the voltage source supplying the field current is different from that which supplies the armature. This method avoids the disadvantages of poor speed regulation and low efficiency as in armature control method. However, it is quite expensive. Therefore, this method of speed control is employed for large size motors where efficiency is of great importance.

Quotation

Learn to enjoy every minute of your life. Be happy now. Don't wait for something outside of yourself to make you happy in the future. Think how really precious is the time you have to spend, whether it's at work or with your family. Every minute should be enjoyed and savored. - Earl Nightingale

UNIT 3. INDUCTION MOTORS

OBJECTIVE

The aim of this chapter is to gather knowledge about the following topics of Induction motors.

1. Construction, types and principle of operation of 3-phase induction motors.
2. Equivalent circuit of 3-phase induction motor.
3. The performance calculation by means of finding torque, slip and efficiency.
4. Different types of starters like auto-transformer starter, star-delta starter.
5. Various methods of speed control 3-phase induction motor.
6. Principle of operation of single phase induction motor.

INTRODUCTION

An **induction motor** (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction.

The induction motor with a wrapped rotor was invented by Nikola Tesla Nikola Tesla in 1882 in France but the initial patent was issued in 1888 after Tesla had moved to the United States. In his scientific work, Tesla laid the foundations for understanding the way the motor operates. The induction motor with a cage was invented by Mikhail Dolivo-Dobrovolsky about a year later in Europe. Technological development in the field has improved to where a 100 hp (74.6 kW) motor from 1976 takes the same volume as a 7.5 hp (5.5 kW) motor did in 1897. Currently, the most common induction motor is the cage rotor motor.

An electric motor converts electrical power to mechanical power in its rotor (rotating part). There are several ways to supply power to the rotor. In a DC motor this power is supplied to the armature directly from a DC source, while in an induction motor this power is induced in the rotating device. An induction motor is sometimes called a *rotating transformer* because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives.

Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes (which are required in most DC motors) and the ability to control the speed of the motor.

CONSTRUCTION

A typical motor consists of two parts namely stator and rotor like other type of motors.

1. An outside stationary stator having coils supplied with AC current to produce a rotating magnetic field,
2. An inside rotor attached to the output shaft that is given a torque by the rotating field.

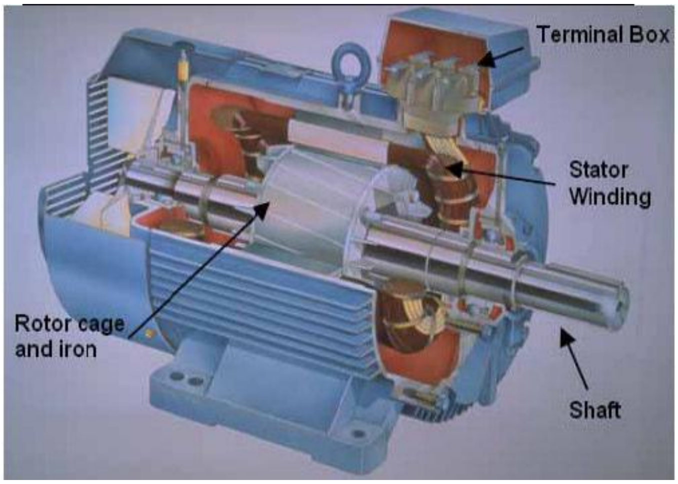


Figure. Induction motor construction

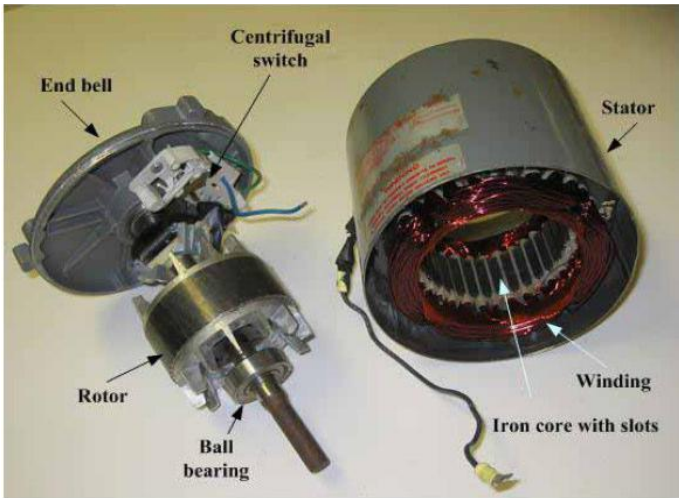


Figure. Induction motor components.

Stator construction

The stator of an induction motor is laminated iron core with slots similar to a stator of a synchronous machine. Coils are placed in the slots to form a three or single phase winding.

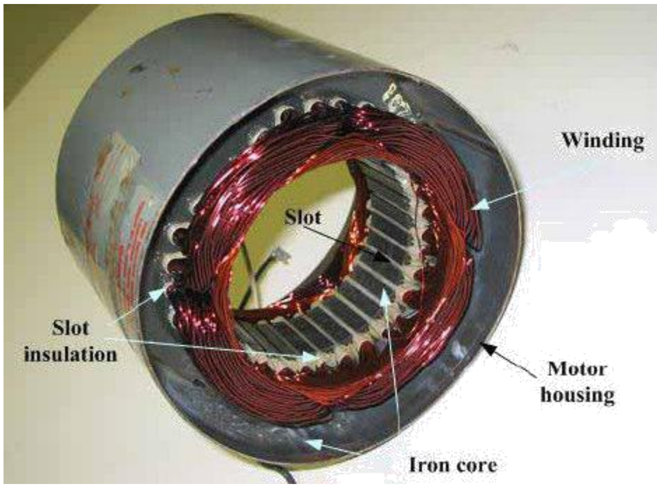


Figure. Single phase stator with windings.

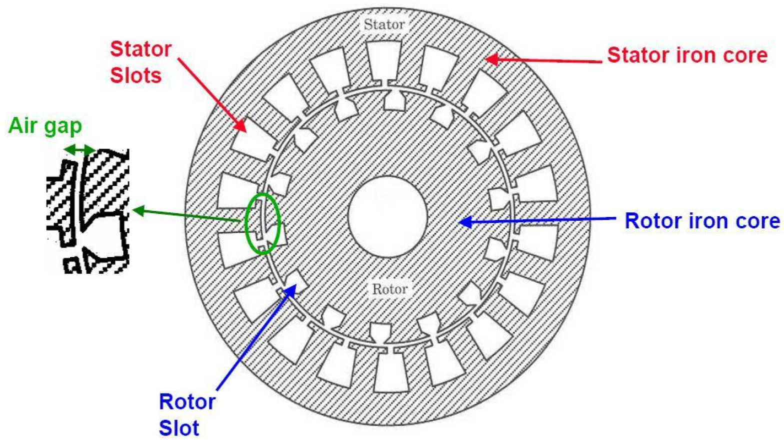


Figure. Induction motor magnetic circuit showing stator and rotor slots

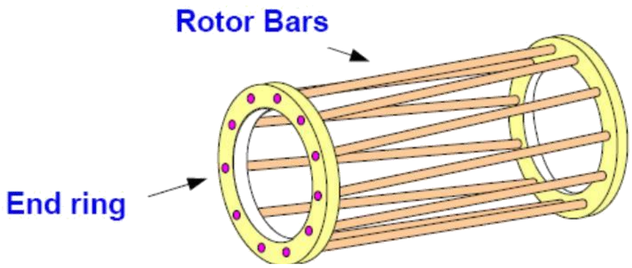
Type of rotors

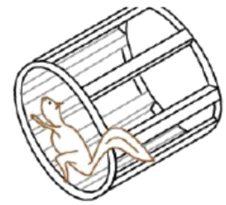
Rotor is of two different types.

1. Squirrel cage rotor
2. Wound rotor

Squirrel-Cage Rotor

In *the squirrel-cage rotor*, the rotor winding consists of single copper or aluminium bars placed in the slots and short-circuited by end-rings on both sides of the rotor. Most of single phase induction motors have Squirrel-Cage rotor. One or 2 fans are attached to the shaft in the sides of rotor to cool the circuit.





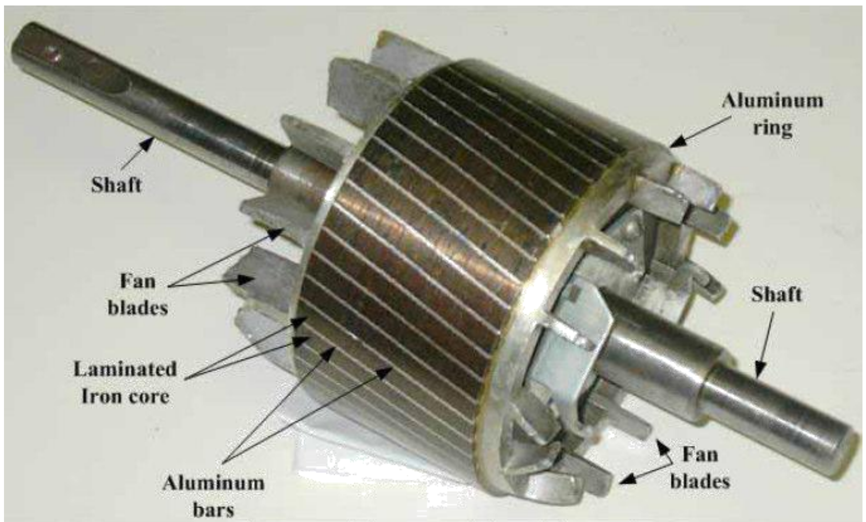


Figure. Squirrel cage rotor

Wound Rotor

In the *wound rotor*, an insulated 3-phase winding similar to the stator winding wound for the same number of poles as stator, is placed in the rotor slots. The ends of the star-connected rotor winding are brought to three slip rings on the shaft so that a connection can be made to it for starting or speed control.

It is usually for large 3 phase induction motors.

Rotor has a winding the same as stator and the end of each phase is connected to a slip ring.

Compared to squirrel cage rotors, wound rotor motors are expensive and require maintenance of the slip rings and brushes, so it is not so common in industry applications.

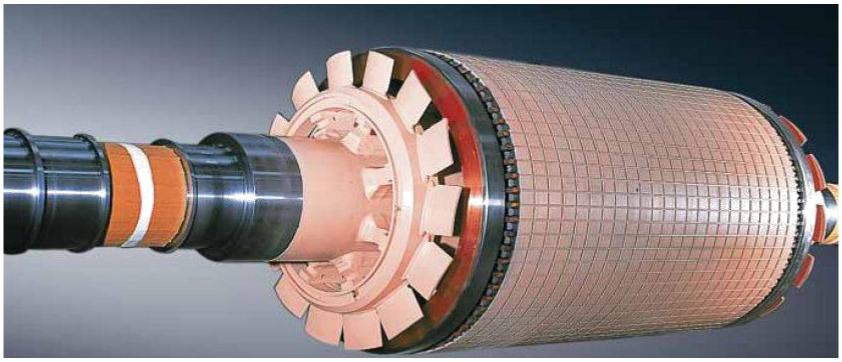


Figure. Wound rotor of a large induction motor. (Courtesy Siemens).

PRINCIPLE OF OPERATION

An AC current is applied in the stator armature which generates a flux in the stator magnetic circuit.

This flux induces an emf in the conducting bars of rotor as they are "cut" by the flux while the magnet is being moved ($E = BV$L (Faraday's Law))

A current flows in the rotor circuit due to the induced emf, which in term produces a force, ($F = BI$L) can be changed to the torque as the output.

In a 3-phase induction motor, the three-phase currents i_a, i_b and $i_{c,}$ each of equal magnitude, but differing in phase by 120°. Each phase current produces a magnetic flux and there is physical 120 °shift between each flux. The total flux in the machine is the sum of the three fluxes. The summation of the three ac fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. Such a magnetic flux produced by balanced three phase currents flowing in thee-phase windings is called a rotating magnetic flux or rotating magnetic field (RMF).RMF rotates with a constant speed (Synchronous Speed). Existence of a RFM is an essential condition for the operation of an induction motor.

If stator is energized by an ac current, RMF is generated due to the applied current to the stator winding. This flux produces magnetic field and the field revolves in the air gap between stator and rotor. So, the magnetic field induces a voltage in the short-circuited bars of the rotor. This voltage drives current through the bars. The interaction of the rotating flux and the rotor current generates a force that drives the motor and a torque is developed consequently. The torque is proportional with the flux density and the rotor bar current (F=BLI). The motor speed is less than the synchronous speed. The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap.

However, for these currents to be induced, the speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and no currents will be induced. If by some chance this happens, the rotor typically slows slightly until a current is re-induced and then the rotor continues as before. This difference between the speed of the rotor and speed of the rotating magnetic field in the stator is called *slip*. It is unitless and is the ratio between the relative speed of the magnetic field as seen by the rotor the (*slip speed*) to the speed of the rotating stator field. Due to this an induction motor is sometimes referred to as an asynchronous machine.

SLIP

The relationship between the supply frequency, f, the number of poles, p, and the synchronous speed (speed of rotating field), n_S is given by

$$n_S = \frac{120 f}{p}$$

The stator magnetic field (rotating magnetic field) rotates at a speed, n_s, the synchronous speed. If, n= speed of the rotor, the slip, s for an induction motor is defined as

$$s = \frac{n_s - n}{n_S}$$

At stand still, rotor does not rotate , n = 0, so s = 1.

At synchronous speed, $n = n_S$, s = 0

The mechanical speed of the rotor, in terms of slip and synchronous speed is given by,

$$n=(1-s)\, n_S$$

Frequency of Rotor Current and Voltage

With the rotor at stand-still, the frequency of the induced voltages and currents is the same as that of the stator (supply) frequency, f_e.

If the rotor rotates at speed of n, then the relative speed is the slip speed:

$$n_{slip}=n_S-n$$

n_{slip} is responsible for induction.

Hence, the frequency of the induced voltages and currents in the rotor is, $f_r = sf_e$.

Example1:

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: $n_r = (1\text{-}s)\, n_s = (1 - 0.05)\,(1200) = 1140$ rpm

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

EQUIVALENT CIRCUIT

The induction motor consists of a two magnetically connected systems namely, stator and rotor. This is similar to a transformer that also has two magnetically connected systems namely primary and secondary windings. Also, the induction motor operates on the same principle as the transformer. Hence, the induction motor is also called as rotating transformer

The stator is supplied by a balanced three-phase voltage that drives a three-phase current through the winding. This current induces a voltage in the rotor. The applied voltage (V_1) across phase A is equal to the sum of the

–induced voltage (E_1).

–voltage drop across the stator resistance (I_1R_1).

–voltage drop across the stator leakage reactance ($I_1\, j\, X_1$).

Let

I_1 = stator current/phase

R_1 = stator winding resistance/phase

X_1 = stator winding reactance/phase

R_R = stator winding resistance/phase

X_R = stator winding reactance/phase

I_R = rotor current

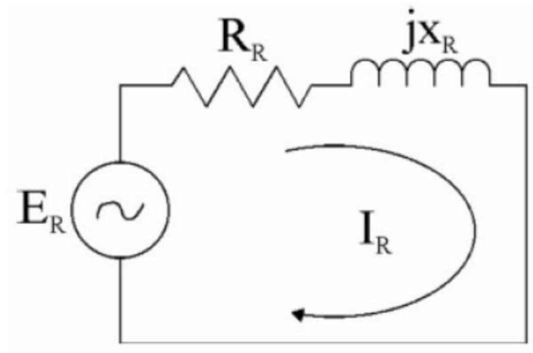
V_1 = applied voltage to the stator/phase

$I_o = I_c + I_m$ (Im-magnetising component, Ic-core loss component)

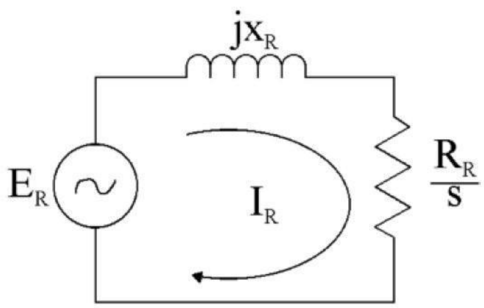
Rotor circuit alone

$$I_R = \frac{E_R}{R_R + jX_R} = \frac{s \cdot E_{R_0}}{R_R + s \cdot jX_{R_0}}$$

$$I_R = \frac{E_{R_0}}{\frac{R_R}{s} + jX_{R_0}}$$



The rotor circuit can be represented as



So, the induction motor can be represented as

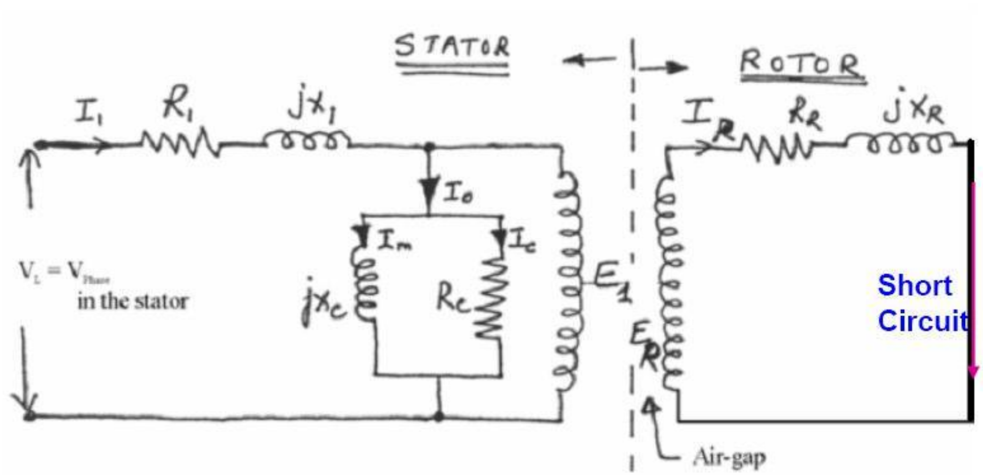


Figure. Equivalent circuit of one phase out of 3 phase of an induction motor

Transformation is done using the effective turns ratio, $a_{eff}$for currents.

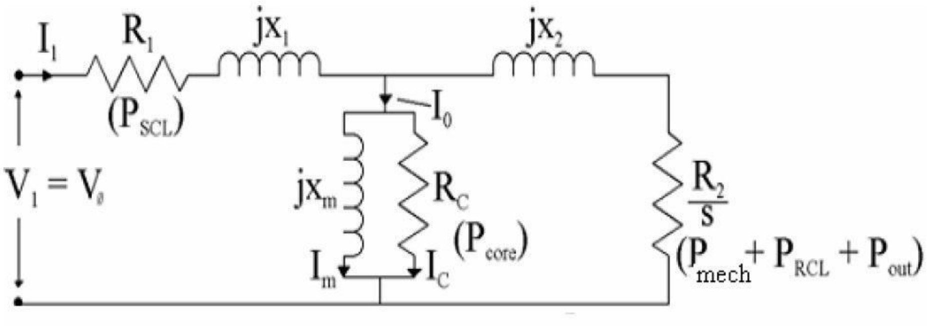
$$I_2 = \frac{I_R}{a_{eff}}$$

Impedance transfer is made using the ratio a_{eff}^2; where R_2 and X_2 are transferred values.

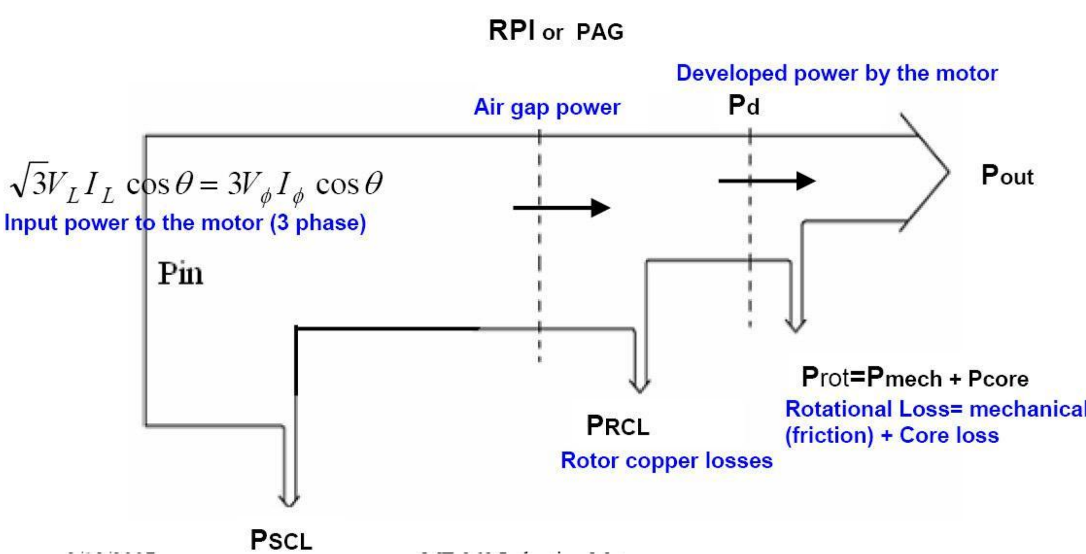
$R_2 = a_{eff}^2 R_R$

$X_2 = a_{eff}^2 X_R$

Equivalent circuit referred to stator is



POWER FLOW



where

P_{SCL} – stator copper losses

P_{RCL} – rotor copper losses

RPI – rotor power input

The concept of the total air gap power can be introduced where:

$$P = P_{ag} = I_2^2.\frac{R_2}{s} = I_2^2.(R_2 + \frac{R_2}{s} - \frac{R_2.s}{s})$$
$$= I_2^2.(R_2 + \frac{R_2}{s}(1-s))$$

The mechanical power however is only developed across the new variable resistance, hence P_{mech} is:

$$P_{mech} = I_2^2.\frac{R_2}{s}(1-s)$$
$$= (1-s).P_{ag}$$
$$= \frac{1-s}{s}.P_2$$

As the rotor copper loss is $P_2 = I_2^2 R_2 = sP_g$ then a ratio of powers can be defined:

$$P_{ag} : P_2 : P_{mech} = 1 : s : (1-s)$$

The motor torque is given by

$$T_{mech} = \frac{P_{mech}}{\omega_{mech}} = \frac{I_2^2.\frac{R_2}{s}.(1-s)}{\omega_{synch}.(1-s)} = \frac{1}{\omega_{synch}}.I_2^2.\frac{R_2}{s}$$

The ideal efficiency can be determined by firstly assuming that the power transferred across the air gap equals the input power.

$$P_{ag} = P_{in}$$
$$P_2 = s.P_{ag}$$
$$P_{out} = P_{mech} = P_{ag}.(1-s)$$

Therefore efficiency is given by

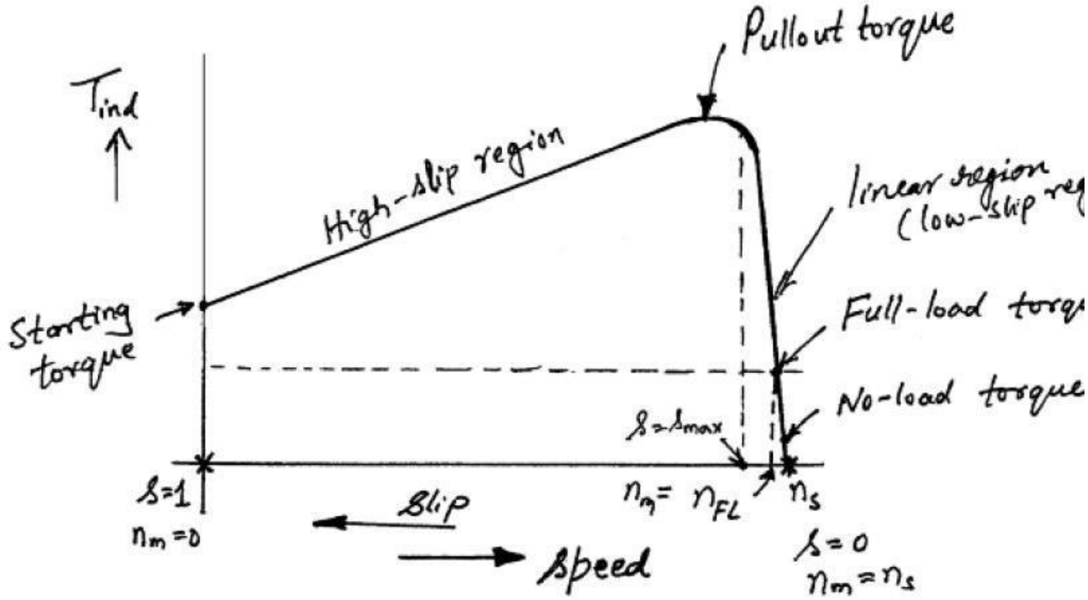
$$Eff_{ideal} = \frac{P_{out}}{P_{in}} = \frac{P_{ag}.(1-s)}{P_{ag}} = (1-s)$$

The efficiency increases as the speed increases, hence an induction machine should always be operated at low values of slip to ensure efficient (and high power factor) operation

TORQUE – SPEED CHARACTERISTICS

For small values of slip s, the torque is directly proportional to s.

For large values of slip s, the torque is inversely proportional to s.



Example 2

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

a) $P_{in} = \sqrt{3} V_T I_L \cos(\theta)$

$P_{in} = \sqrt{3}(480)(60)(0.85) = 42.4 \text{ kW}$

$P_{AG} = P_{in} - P_{SCL} = 42.4 - 2 = 40.4\text{kW}$

b) $P_d = P_{AG} - P_{RCL} = 40.4 - 0.7 = 39.7 \text{ kW}$

c) $P_{out} = P_d - P_{rot} = 39.7 - 2.4 = 37.3 \text{ kW}$

d) $\eta = \dfrac{P_{out}}{P_{in}} = \dfrac{37.3}{42.4} = 88\%$

Example 3

A 460 V, 25 hp, 60 Hz, four pole, Y-connected induction motor has the following impedances:

$R_1 = 0.641\ \Omega$ $R_2 = 0.332\ \Omega$

$X_1 = 1.106\ \Omega$ $X_2 = 0.464\ \Omega$ $X_m = 26.3\ \Omega$

Mechanical loss is 100 W and core loss is 1 kW for a slip = 2.2%, find:

(a) The speed.

(b) The stator current.

(c) Power factor

(d) The developed and output power

(e) The developed and output torque

(f) Efficiency

Solution:

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

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

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

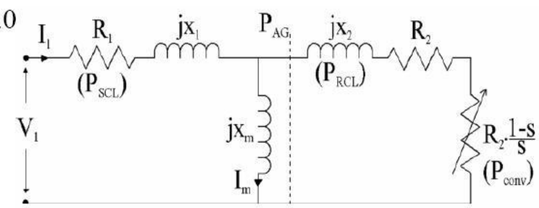
$$I_1 = \frac{V_{phase}}{Z_{total}} = 18.88\angle -33.6$$

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

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

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

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



STARTING OF 3-PHASE INDUCTION MOTORS

There are two important factors to be considered in starting of induction motors:

1. The starting current drawn from the supply, and
2. The starting torque.

The starting current should be kept low to avoid overheating of motor and excessive voltage drops in the supply network. The starting torque must be about 50 to 100% more than the expected load torque to ensure that the motor runs up in a reasonably short time.

At synchronous speed, s = 0, and therefore , $\frac{R_2}{s}$ = □ .so $I_2' = 0$.

The stator current therefore comprises only the magnetising current i.e. $I_1 = I_\varphi$ and is quite therefore quite small.

At low speeds, $\frac{R_2'}{s} + jX_2 = \square$ is small, and therefore I_2' is quite high and consequently I_1 is quite large.

Actually the typical starting currents for an induction machine are ~ 5 to 8 times the normal running current.

Hence the starting currents should be reduced. The most usual methods of starting 3-phase induction motors are:

For slip-ring motors

Rotor resistance starting

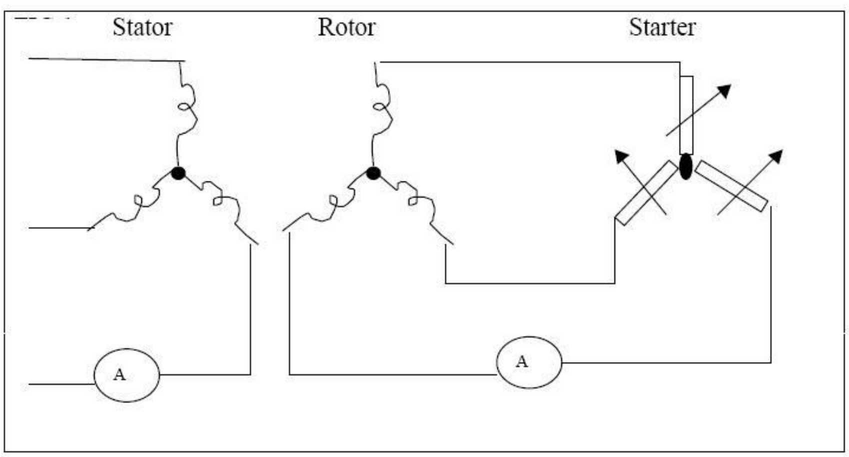
For squirrel-cage motors

Direct-on -line starting
Star-delta starting

Autotransformer starting.

1. Rotor resistance starting

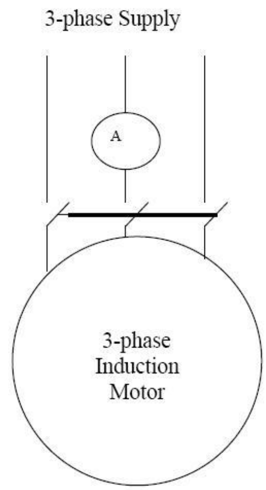
By adding eternal resistance to the rotor circuit any starting torque up to the maximum torque can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period. The added resistance also reduces the starting current, so that a starting torque in the range of 2 to 2.5 times the full load torque can be obtained at a starting current of 1 to 1.5 times the full load current.



2. Direct-on-line starting

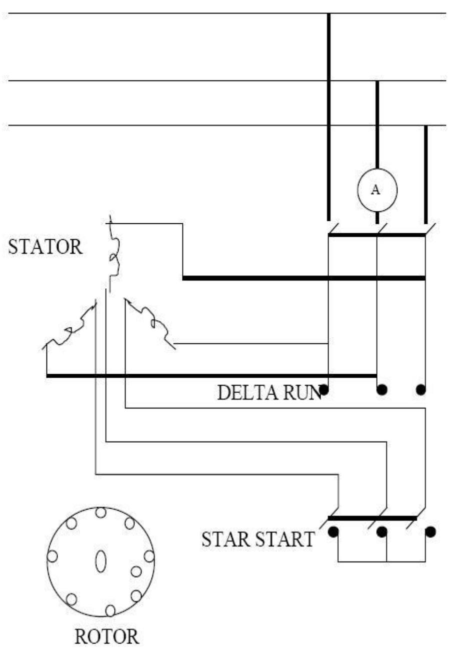
This is the most simple and inexpensive method of starting a squirrel cage induction motor. The motor is switched on directly to full supply voltage. The initial starting current is large, normally about 5 to 7 times the rated current but the starting torque is likely to be 0.75 to 2 times the full load torque. To avoid excessive supply voltage drops because of large starting currents the method is restricted to small motors only.

To decrease the starting current cage motors of medium and larger sizes are started at a reduced supply voltage. The reduced supply voltage starting is applied in the next two methods.



3. Star-Delta starting

This is applicable to motors designed for delta connection in normal running conditions. Both ends of each phase of the stator winding are brought out and connected to a 3-phase change -over switch.

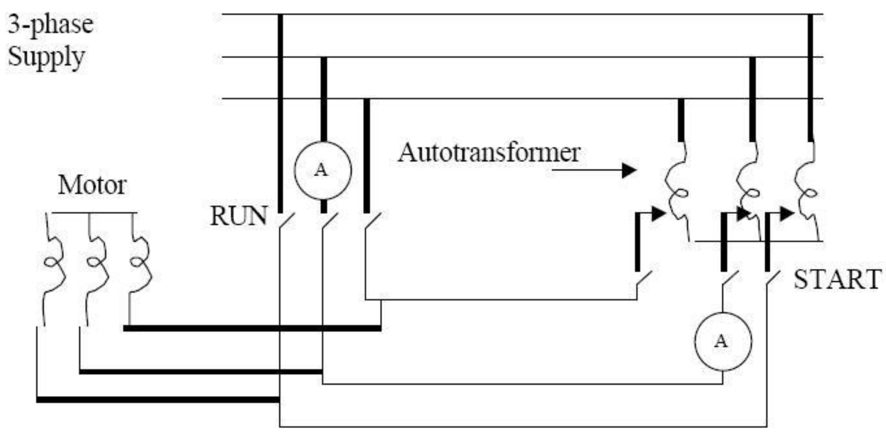


For starting, the stator windings are connected in star and when the machine is running the switch is thrown quickly to the running position, thus connecting the motor in delta for normal operation. The phase voltages & the phase currents of the motor in star connection are reduced to 1/√3 of the direct -on -line values in delta. The line current is 1/3 of the value in delta.

A disadvantage of this method is that the starting torque (which is proportional to the square of the applied voltage) is also reduced to 1/3 of its delta value.

4. Auto-transformer starting

This method also reduces the initial voltage applied to the motor and therefore the starting current and torque. The motor, which can be connected permanently in delta or in star, is switched first on reduced voltage from a 3-phase tapped auto -transformer and when it has accelerated sufficiently, it is switched to the running (full voltage) position. The principle is similar to star/delta starting and has similar limitations. The advantage of the method is that the current and torque can be adjusted to the required value, by taking the correct tapping on the autotransformer. This method is more expensive because of the additional autotransformer.



SPEED CONTROL OF INDUCTION MACHINES

We have seen the speed torque characteristic of the machine. In the stable region of operation in the motoring mode, the curve is rather steep and goes from zero torque at synchronous speed to the stall torque at a value of slip s = ˆs. Normally ˆs may be such that stall torque is about three times that of the rated operating torque of the machine, and hence may be about 0.3 or less. This means that in the entire loading range of the machine, the speed change is quite small. The machine speed is quite stiff with respect to load changes. The entire speed variation is only in the range n_S to $(1 - s)n_S$, n_S being dependent on supply frequency and number of poles.

The foregoing discussion shows that the induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However, the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved.

1.Speed control by changing applied voltage

From the torque equation of the induction machine, we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in figure below. These curves show that the slip at maximum torque remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same.

Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.

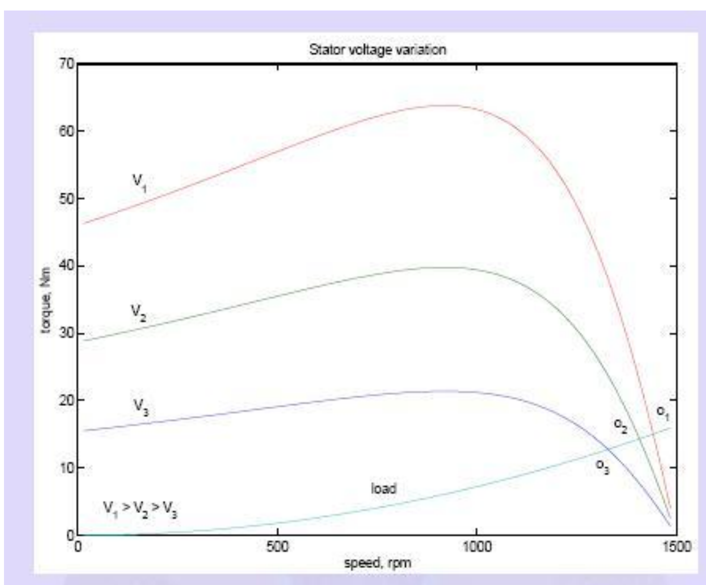


Figure. Speed-torque curves: voltage variation

The figure above also shows a load torque characteristic, one that is typical of a fan type of load. In a fan (blower) type of load, the variation of torque with speed is such that $T \alpha \omega^2$. Here one can see that it may be possible to run the motor to lower speeds within the range n_s to $(1 - s)n_s$. Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads. One may note that if the applied voltage is reduced, the voltage across the magnetizing branch also comes down. This in turn means that the magnetizing current and hence flux level are reduced. Reduction in the flux level in the machine impairs torque production, which is primarily the explanation for figure.

If, however, the machine is running under lightly loaded conditions, then operating under rated flux levels is not required. Under such conditions, reduction in magnetizing current improves the power factor of operation. Some amount of energy saving may also be achieved. Voltage control may be achieved by adding series resistors (a lossy, inefficient proposition), or a series inductor / autotransformer (a bulky solution) or a more modern solution using semiconductor devices. A typical solid state circuit used for this purpose is the AC voltage controller or AC chopper. Another use of voltage control is in the so-called 'soft-start' of the machine. This is discussed in the section on starting methods.

2. Rotor resistance control

From the expression for the torque of the induction machine, torque is dependent on the rotor resistance. The maximum value is independent of the rotor resistance. The slip at maximum torque is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Figure below shows a family of torque-speed characteristic obtained by changing the rotor resistance.

Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque.

For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines, there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation.

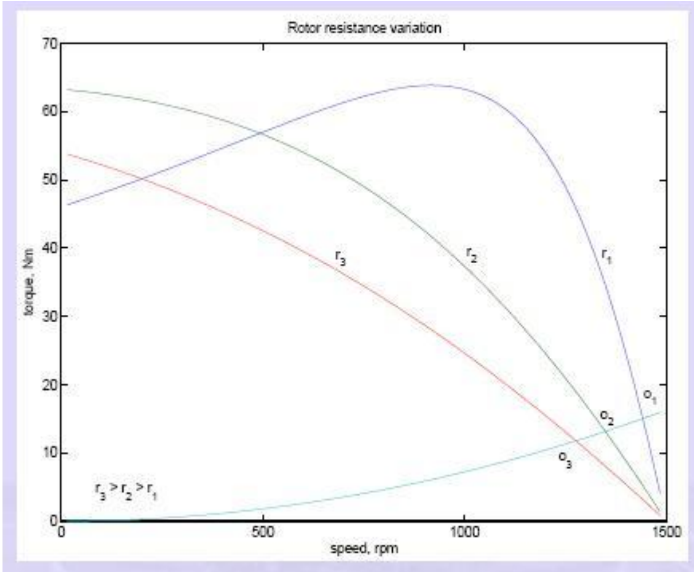


Figure. Speed-torque curves: rotor resistance variation

The resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A 'solid-state' alternative to a rheostat is a chopper controlled resistance where the duty ratio control of of the chopper presents a variable resistance load to the rotor of the induction machine.

3. Pole changing schemes

Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by $n_S = f_S/p$ (in rev./s) where p is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps.

If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type.

The following figure serves to illustrate the basic principle. Consider a magnetic pole structure consisting of four pole faces A, B, C, D as shown in figure below.

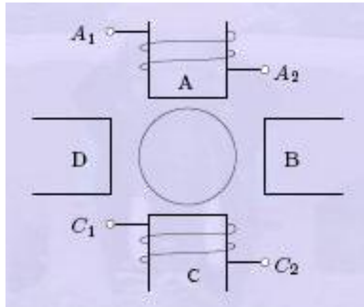
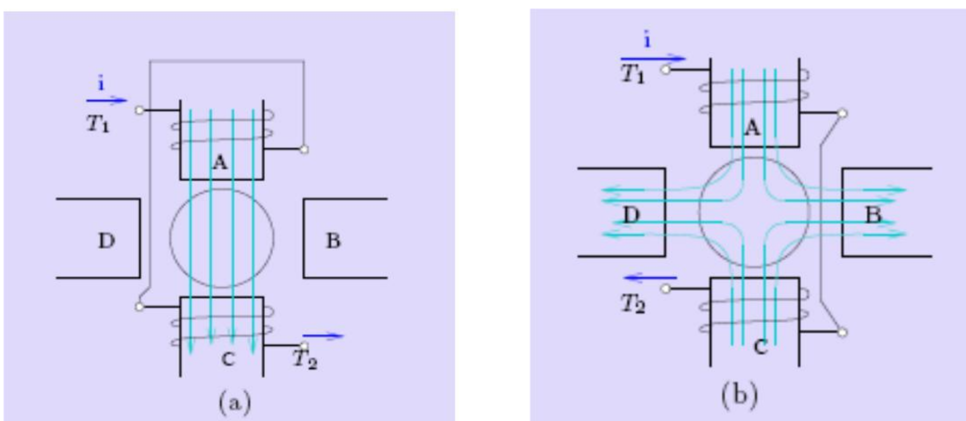


Figure. Pole arrangement

Coils are wound on A & C in the directions shown. The two coils on A & C may be connected in series in two different ways — A_2 may be connected to C_1 or C_2. A1 with the other terminal at C then form the terminals of the overall combination. Thus two connections result as shown in figure (a) & (b) below.



Now, for a given direction of current flow at terminal A_1, say into terminal A_1, the flux directions within the poles are shown in the figures. In case (a), the flux lines are out of the pole A (seen from the rotor) for and into pole C, thus establishing a two-pole structure. In case (b) however, the flux lines are out of the poles in A & C. The flux lines will be then have to complete the circuit by flowing into the pole structures on the sides. If, when seen from the rotor, the pole emanating flux lines is considered as north pole and the pole into which they enter is termed as south, then the pole configurations produced by these connections is a two-pole arrangement in fig. 31(a) and a four-pole arrangement in fig. 31(b). Thus by changing the terminal connections we get either a two pole air-gap field or a four-pole field. In an induction machine this would correspond to a synchronous speed reduction in half from case (a) to case (b).

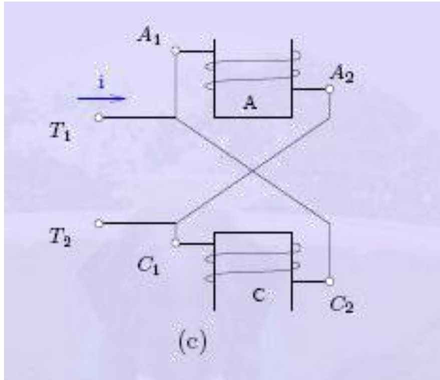


Figure: Pole Changing: Various connections

Further note that irrespective of the connection, the applied voltage is balanced by the series addition of induced emfs in two coils. Therefore the air-gap flux in both cases is the same. Cases (a) and (b) therefore form a pair of constant torque connections.

Consider, on the other hand a connection as shown in the figure(c). The terminals T_1 and T_2 are where the input excitation is given. Note that current direction in the coils now resembles that of case (b), and hence this would result in a four-pole structure. However, in figure(c), there is only one coil induced emf to balance the applied voltage. Therefore flux in case (c) would therefore be halved compared to that of case (b) (or case (a), for that matter). Cases (a) and (c) therefore form a pair of constant horse-power connections. It is important to note that in generating a different pole numbers, the current through one coil (out of two, coil C in this case) is reversed.

4. Stator frequency control

The expression for the synchronous speed indicates that by changing the stator frequency also it can be changed. This can be achieved by using power electronic circuits called inverters which convert dc to ac of desired frequency. Depending on the type of control scheme of the inverter, the ac generated may be variable-frequency-fixed-amplitude or variable-frequency variable-amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the ac output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation for the induced emf in the induction machine.

$$V = 4.44N\O_m f$$

where N is the number of the turns per phase, _m is the peak flux in the air gap and f is the frequency. Note that in order to reduce the speed, frequency has to be reduced. If the frequency is reduced while the voltage is kept constant, thereby requiring the amplitude of induced emf to remain the same, flux has to increase. This is not advisable since the machine likely to enter deep saturation. If this is to be avoided, then flux level must be maintained constant which implies that voltage must be reduced along with frequency. The ratio is held constant in order to maintain the flux level for maximum torque capability.

Actually, it is the voltage across the magnetizing branch of the exact equivalent circuit that must be maintained constant, for it is that which determines the induced emf. Under conditions where the stator voltage drop is negligible compared the applied voltage, the above equation is valid.

In this mode of operation, the voltage across the magnetizing inductance in the ’exact’ equivalent circuit reduces in amplitude with reduction in frequency and so does the inductive reactance. This implies that the current through the inductance and the flux in the machine remains constant. The speed torque characteristics at any frequency may be estimated as before. There is one curve for every excitation frequency considered corresponding to every value of synchronous speed. The curves are shown below. It may be seen that the maximum torque remains constant.

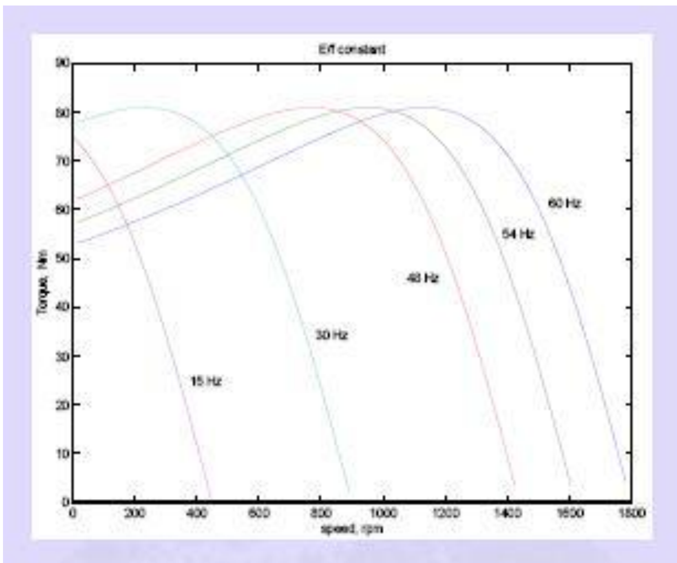


Figure. Torque-speed curves with E/f held constant

With this kind of control, it is possible to get a good starting torque and steady state performance. However, under dynamic conditions, this control is insufficient. Advanced control techniques such as field- oriented control (vector control) or direct torque control (DTC) are necessary.

SINGLE-PHASE INDUCTION MOTORS

There are probably more single-phase ac induction motors in use today than the total of all the other types put together.

It is logical that the least expensive, lowest maintenance type of ac motor should be used most often. The single-phase ac induction motor fits that description.

Unlike polyphase induction motors, the stator field in the single-phase motor does not rotate. Instead it simply alternates polarity between poles as the ac voltage changes polarity.

Voltage is induced in the rotor as a result of magnetic induction, and a magnetic field is produced around the rotor. This field will always be in opposition to the stator field (Lenz's law applies). The interaction between the rotor and stator fields will not produce rotation, however. The interaction is shown by the double-ended arrow in figure below, view A. Because this force is across the rotor and through the pole pieces, there is no rotary motion, just a push and/or pull along this line.

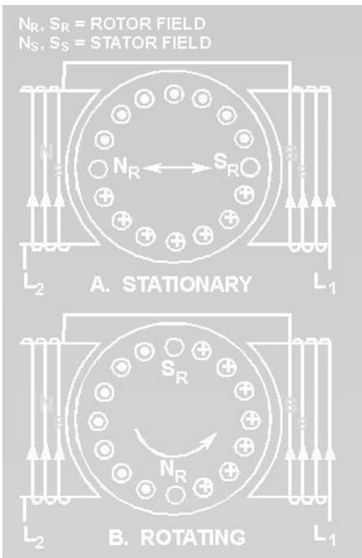


Figure. Rotor currents in a single-phase ac induction motor.

Now, if the rotor is rotated by some outside force (a twist of your hand, or something), the push-pull along the line in figure 4-10, view A, is disturbed. Look at the fields as shown in figure, view B. At this instant the south pole on the rotor is being attracted by the left-hand pole. The north rotor pole is being attracted to the right-hand pole. All of this is a result of the rotor being rotated 90° by the outside force. The pull that now exists between the two fields becomes a rotary force, turning the rotor toward magnetic correspondence with the stator. Because the two fields continuously alternate, they will never actually line up, and the rotor will continue to turn once started. It remains for us to learn practical methods of getting the rotor to start.

There are several types of single-phase induction motors in use today. Basically they are identical except for the means of starting. In this chapter we will discuss the split-phase and shaded-pole motors; so named because of the methods employed to get them started. Once they are up to operating speed, all single-phase induction motors operate the same.

Split-Phase Induction Motors

One type of induction motor, which incorporates a starting device, is called a split-phase induction motor. Split-phase motors are designed to use inductance, capacitance, or resistance to develop a starting torque. The principles are those that you learned in your study of alternating current.

Capacitor-Start Single Phase Induction Motor

The first type of split-phase induction motor that will be covered is the capacitor-start type. figure below shows a simplified schematic of a typical capacitor-start motor. The stator consists of the main winding and a starting winding (auxiliary). The starting winding is connected in parallel with the main winding and is placed physically at right angles to it. A 90-degree electrical phase difference between the two windings is obtained by connecting the auxiliary winding in series with a capacitor and starting switch. When the motor is first energized, the starting switch is closed. This places the capacitor in series with the auxiliary winding.

The capacitor is of such value that the auxiliary circuit is effectively a resistive-capacitive circuit (referred to as capacitive reactance and expressed as X_C). In this circuit the current leads the line voltage by about 45° (because X_C about equals R). The main winding has enough resistance-inductance (referred to as inductive reactance and expressed as X_L) to cause the current to lag the line voltage by about 45° (because X_L about equals R). The currents in each winding are therefore 90° out of phase - so are the magnetic fields that are generated. The effect is that the two windings act like a two-phase stator and produce the rotating field required to start the motor.

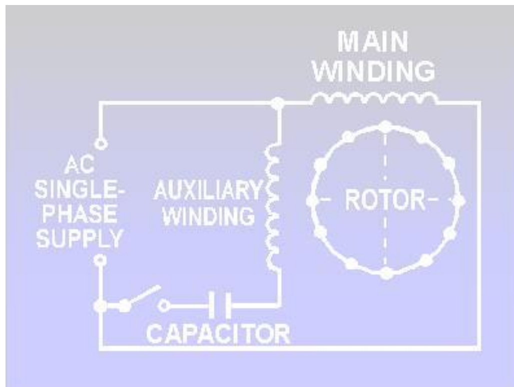


Figure. Capacitor-start, ac induction motor.

When nearly full speed is obtained, a centrifugal device (the starting switch) cuts out the starting winding. The motor then runs as a plain single-phase induction motor. Since the auxiliary winding is only a light winding, the motor does not develop sufficient torque to start heavy loads. Split-phase motors, therefore, come only in small sizes.

Resistance Start Single Phase Induction Motor

Another type of split-phase induction motor is the resistance-start motor. This motor also has a starting winding figure in addition to the main winding. It is switched in and out of the circuit just as it was in the capacitor-start motor. The starting winding is positioned at right angles to the main winding. The electrical phase shift between the currents in the two windings is obtained by making the impedance of the windings unequal.

The main winding has a high inductance and a low resistance. The current, therefore, lags the voltage by a large angle. The starting winding is designed to have a fairly low inductance and a high resistance. Here the current lags the voltage by a smaller angle. For example, suppose the current in the main winding lags the voltage by 70°. The current in the auxiliary winding lags the voltage by 40°. The currents are, therefore, out of phase by 30°. The magnetic fields are out of phase by the same amount. Although the ideal angular phase difference is 90° for maximum starting torque, the 30-degree phase difference still generates a rotating field. This supplies enough torque to start the motor. When the motor comes up to speed, a speed-controlled switch disconnects the starting winding from the line, and the motor continues to run as an induction motor. The starting torque is not as great as it is in the capacitor-start.

Figure. Resistance-start ac induction motor.

Shaded-Pole Induction Motors

The shaded-pole induction motor is another single-phase motor. It uses a unique method to start the rotor turning. The effect of a moving magnetic field is produced by constructing the stator in a special way. This motor has projecting pole pieces just like some dc motors. In addition, portions of the pole piece surfaces are surrounded by a copper strap called a shading coil. A pole piece with the strap in place is shown in figure below.

The strap causes the field to move back and forth across the face of the pole piece. Note the numbered sequence and points on the magnetization curve in the figure. As the alternating stator field starts increasing from zero (1), the lines of force expand across the face of the pole piece and cut through the strap. A voltage is induced in the strap. The current that results generates a field that opposes the cutting action (and decreases the strength) of the main field. This produces the following actions: As the field increases from zero to a maximum at 90°, a large portion of the magnetic lines of force are concentrated in the unshaded portion of the pole (1). At 90° the field reaches its maximum value. Since the lines of force have stopped expanding, no emf is induced in the strap, and no opposing magnetic field is generated. As a result, the main field is uniformly distributed across the pole (2). From 90° to 180°, the main field starts decreasing or collapsing inward. The field generated in the strap opposes the collapsing field. The effect is to concentrate the lines of force in the shaded portion of the pole face (3). You can see that from 0° to 180°, the main field has shifted across the pole face from the unshaded to the shaded portion. From 180° to 360°, the main field goes through the same change as it did from 0° to 180°; however, it is now in the opposite direction (4). The direction of the field does not affect the way the shaded pole works. The motion of the field is the same during the second half-cycle as it was during the first half of the cycle.

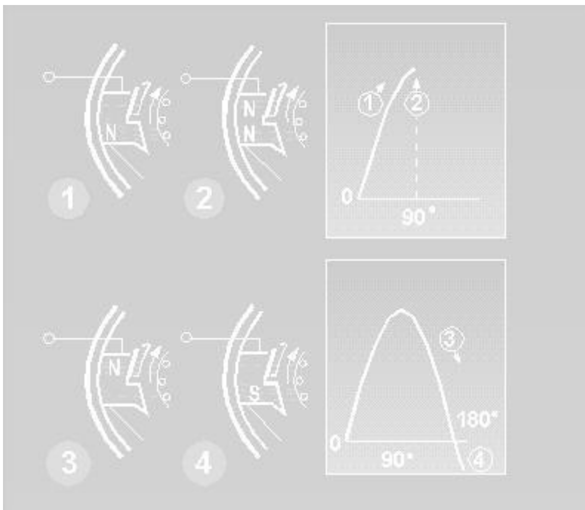


Figure. Shaded poles as used in shaded-pole ac induction motors.

The motion of the field back and forth between shaded and unshaded portions produces a weak torque to start the motor. Because of the weak starting torque, shaded-pole motors are built only in small sizes. They drive such devices as fans, clocks, blowers, and electric razors.

SUMMARY

In this chapter, construction and working of 3-phase induction motor has been discussed. The induction motor rotates at a speed less than the synchronous speed and also called asynchronous motor. The difference between the synchronous speed and the rotor speed is the slip speed. Various configuration of the equivalent circuit have been analysed. A general expression for torque has been derived, which is used to plot the torque-slip characteristics of the motor. Various methods of starting and speed control are also discussed. The working principle and types of single phase induction motors have also been discussed.

Unit IV
SYNCHRONOUS MACHINES

INTRODUCTION

- A synchronous machine is one, in which a perfect constant relationship exists between the speed, frequency and number of poles.
- The field system of these machines is excited by direct current, normally obtained by a special d.c. generator called the exciter and mounted on the extension of the shaft of synchronous machine.
- Synchronous machines are mainly used as alternators for the production of a.c. power.
- The prime-mover commonly used for the alternators are (1) steam turbine (is) Hydraulic turbine (ii Internal combustion engine or diesel engine.
- From the concept of design, synchronous alternators are fundamentally of two types
    - ✓ salient pole type i.e. with projecting poles
    - ✓ Non salient pole type i.e. in which the poles do not project.
- Low speed alternators driven by hydraulic turbines are built as salient pole machines.
- These types of generators are designed for speeds varying from 150 to 600 rpm, the speed being dependent on the water head available.
- Such generators are generally known as water wheel generators, hydro generators or salient pole alternators.
- Salient pole construction is also used for alternators driven by internal-combustion engine or diesel engine.
- High speed alternators are driven by steam turbine, because the efficiency of steam turbine is high at higher speeds.
- These are built as non-salient pole type and commonly termed as turbo generators or non-salient pole alternators.
- Turbo generators are normally designed for 2 poles i.e. for a speed of 3000 rpm with a frequency of 50 Hz.

ADVANTAGES OF ROTATING FIELD OVER ROTATING ARMATURE

- As everywhere a.c. is used, the generation level of a.c. voltage may be higher as 11 kV to 33 kV.
- This gets induced in the armature. For stationary armature large space can be provided to accommodate large number of conductors and the insulation.
- It is always better to protect high voltage winding from the centrifugal forces caused due to the rotation. So high voltage armature is generally kept stationary.
- This avoids the interaction of mechanical and electrical stresses.
- It is easier to collect larger currents at very high voltages from a stationary member than from the slip ring and brush assembly.

- The voltage required to be supplied to the field is very low (110 V to 220 V d.c.) and hence can be easily supplied with the help of slip ring and brush assembly by keeping it rotating.
- The problem of sparking at the slip rings can be avoided by keeping field rotating which is low voltage circuit and high voltage armature as stationary.
- Due to low voltage level on the field side, the insulation required is less and hence field system has very low inertia.
- It is always better to rotate low inertia system than high inertia, as efforts required to rotate low inertia system are always less.
- Rotating field makes the overall construction very simple.
- With simple, robust mechanical construction and low inertia of rotor, it can be driven at high speeds. So greater output can be obtained from an alternator of given size.
- If field is rotating, to excite it by an external d.c. supply two slip rings are enough. One each for positive and negative terminals.
- As against this, in three phase rotating armature, the minimum number of slip rings required is three and can not be easily insulated due to high voltage levels.
- The ventilation arrangement for high voltage side can be improved if it is kept stationary.
- Due to all these reasons the most of the alternators in practice use rotating field type of arrangement.
- For small voltage rating alternators rotating armature arrangement may be used.

CONSTRUCTION

- As mentioned earlier, most of the alternators the winding terminology is slightly different than in case of d.c. generators.
- In alternators the stationary winding is called ' Stator' while the rotating winding is called ' Rotor.
- Key Point Most of the alternators have stator as armature and rotor as field, in practice.
- Constructional details of rotating field type of alternator are discussed below.

STATOR

- The stator is a stationary armature.
- This consists of a core and the slots to hold the armature winding similar to the armature of a d.c. generator.
- The stator core uses a laminated construction.
- It is built up of special steel stampings insulated from each other with varnish or paper.
- The laminated construction is basically to keep down eddy current losses.
- Generally choice of material is steel to keep down hysteresis losses.
- The entire core is fabricated in a frame steel plates.
- The core F slots on its periphery housing the armature conductors.
- Frame does carry any flux and serve the support to the core.

- Ventilation is maintained with the help of holes in the frame. The section of a alternator stator is show the Fig. 6.2

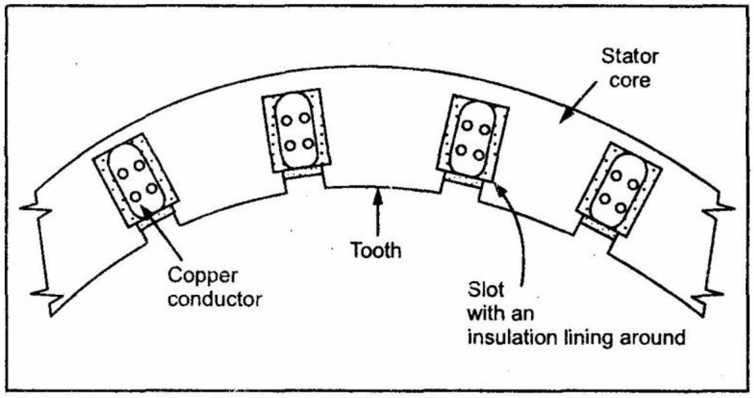


Fig. 6.2 Section of an alternator stator

ROTOR

- There are two types of rotors used in alternators,

  i) Salient pole type ant:

  ii) Smooth cylindrical type.

SALIENT POLE TYPE ROTOR

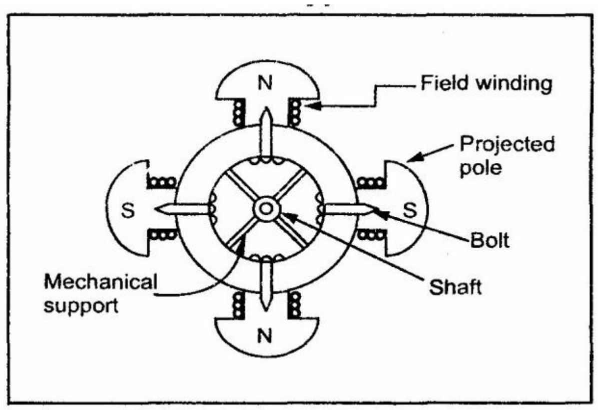


Fig. 6.3 Salient pole type rotor

- This is also called projected pole type as all the poles are projected out from the surface of the rotor.
- The poles are built up of thick steel laminations.
- The poles are bolted to t rotor as shown in the Fig. 6.3.
- The pc face has been given a specific shape discussed earlier in case of d.c.
- The field winding is provided on the pc shoe. These rotors have large diameter and small axial lengths.
- The limiting factor for the size of the rotor is the centrifugal force acting on the member of the machine.

- As mechanical strength of salient pole type is less, this is preferred for low speed alternators ranging from 125 r.p.m. to 500 r.p.m. The prime movers used to drive such rotor are generally water turbines and J.C. engines.

SMOOTH CYLINDRICAL TYPE ROTOR

- This is also called non salient type or non-projected pole type of rotor.
- The rotor consists of smooth solid steel cylinder, having number of slots accommodate the field coil.
- The slots are covered at the top with the help of steel o manganese wedge.
- The un-slotted portions of the cylinder itself act as the poles.
- The poles are not projecting out and the surface of the rotor is smooth which maintains uniform air gap between stator and the rotor.
- These rotors have small diameters and large axial lengths.
- This is to keep peripheral speed within limits.
- The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging between 1500 to 3000 r.p.m.
- Such high speed alternators are called ‘ turbo alternators’ .
- The prime movers used to drive such type of rotors are generally steam turbines, electric motors.
- Let us list down the differences between the two types in tabular form.

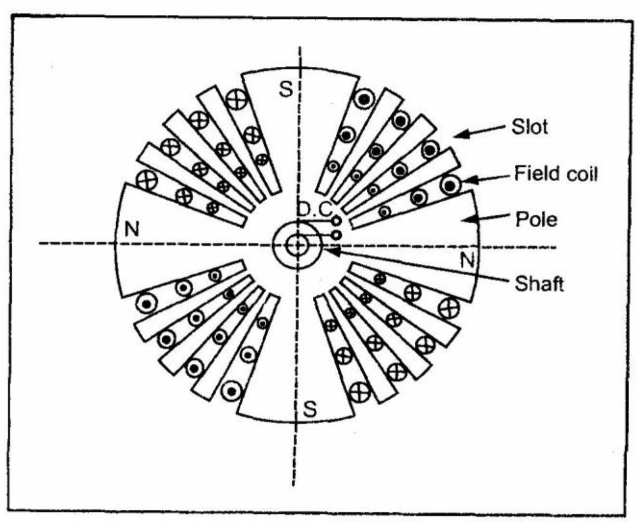


Fig. 6.4 Smooth cylindrical rotor

DIFFERENCE BETWEEN SALIENT AND CYLINDRICAL TYPE OF ROTOR

Salient Pole Type	Smooth Cylindrical Type
1 Poles are projecting out from the surface.	1. Unslotted portion of the cylinder acts as poles hence poles are non projecting.
2 Air gap is non uniform.	2. Air gap is uniform due to smooth cylindrical periphery.
3 Diameter is high and axial length is small.	3. Small diameter and large axial length is the feature.
4. Mechanically weak.	4. Mechanically robust.
5. Preferred for low speed alternators.	5. Preferred for high speed alternators i.e. for turboalternators.
6. Prime mover used are water turbines, I.C. engines.	6. Prime movers used are steam turbines, electric motors.
7. For same size, the rating is smaller than cylindrical type.	7. For same size, rating is higher than salient pole type.
8. Separate damper winding is provided.	8. Separate damper winding is not necessary.

EXCITATION SYSTEM

- The synchronous machines whether alternator or motor are necessarily separately excited machines.
- Such machines always require d.c. excitation for their operation.
- The field systems are provided with direct current which is supplied by a d.c. souite at 125 to 600 V.
- In many cases the exciting current is obtained from a d.c. generator which is mounted on the same shaft of that of alternator.
- Thus excitation systems are of prime importance. Many of the conventional system involves slip rings, brushes and commutators.

BRUSHLESS EXCITATION SYSTEM

- With the increase in rating of an alternator, the supply of necessary magnetic fi becomes difficult as the current values may reach upto 4000 A.
- If we use convention excitation systems such as a d.c generator whose output is supplied to the alternator f through brushes and slip rings; then problems are invariably associated with slip ring commutators and brushes regarding cooling and maintenance.
- Thus modern excitatioi systems are developed which minimizes these problems by avoiding the use of L Such excitation system is called brushless excitation system which is shown in the Fig. 6.5.

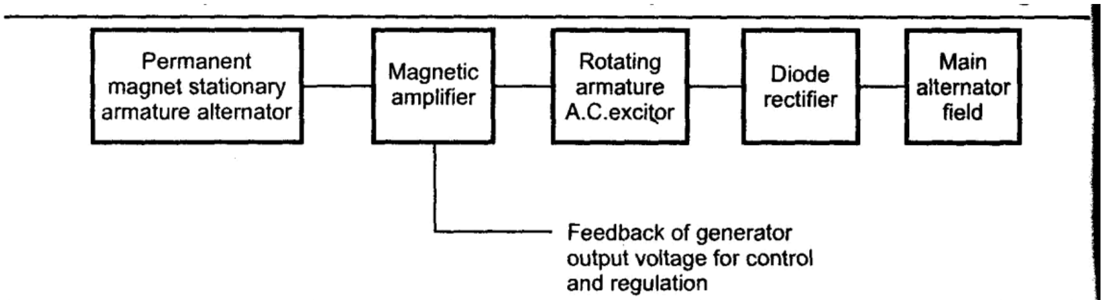


Fig. 6.5 Brushless excitation system

- It consists of silicon diode rectifiers which are mounted on the same shaft of alternator and will directly provide necessary excitation to the field.
- The power required for rectifiers is provided by an a.c. excitor which is having stationary field but rotating armature.
- The field of an excitor is supplied through a magnetic amplifier which will control a regulate the output voltage of the alternator since the feedback of output voltage alternator is taken and given to the magnetic amplifier.
- The system can be made s contained if the excitation power for the magnetic amplifier is obtained from a small permanent magnet alternator having stationary armature which is driven from the main shaft.
- The performance and design of the overall system can be optimized by selecting proper frequency and voltage for a.c. excitor.
- The additional advantage that can be obtained with this system is that it is not necessary to make arrangement for spare excitors, generator-field circuit breakers and field rheostats.

METHODS OF VENTILATION

1. Natural Ventilation:

A fan is attached to either ends of the machine. The ventilating medium is nothing but an atmospheric air which is forced over the machine parts, carrying away the heat. This circulation is possible with or without ventilating ducts. The ventilating ducts if provided may be either axial or radial.

2. Closed Circuit Ventilating System:

An atmospheric air may contain injurious elements like dust, moisture, and acidic fumes etc. which are harmful for the insulation of the winding. Hence for large capacity machines, closed circuit system is preferred for ventilation. The ventilating medium used is generally hydrogen. The hydrogen circulated over the machine parts is cooled with the help of water cooled heat exchangers. Hydrogen provides very effective cooling than air which increases the rating of the machine upto 30 to 40% for the same size. All modern alternators use closed circuit ventilation with the help of hydrogen as a ventilating medium.

WORKING PRINCIPLE

- The alternators work on the principle of electromagnetic induction.
- When there is a relative motion between the conductors and the flux, e.m.f. gets induced in the conductors.
- The d.c. generators also work on the same principle.
- The only difference in practical alternator and a d.c. generator is that in an alternator the conductors are stationary and field is rotating.
- But for understanding purpose we can always consider relative motion of conductors with respect to the flux produced by the field winding.
- Consider a relative motion of a single conductor under the magnetic field produced by two stationary poles.
- The magnetic axis of the two poles produced by field is vertical, shown dotted in the Fig. 6.6.

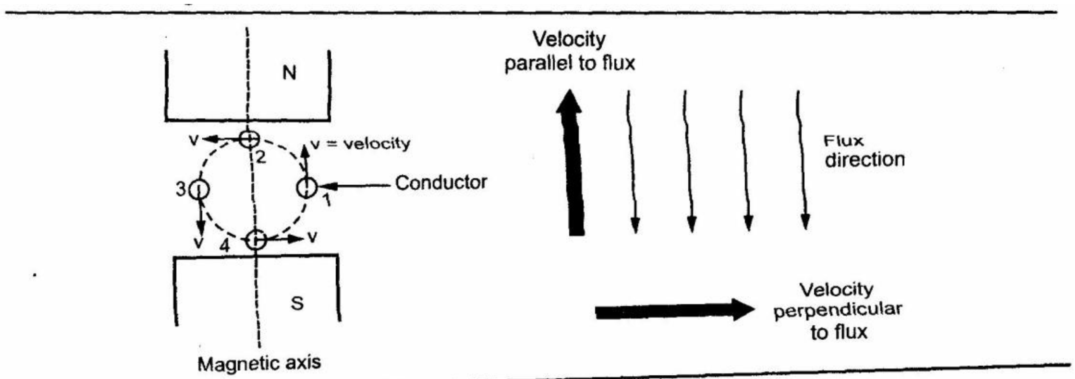


Fig. 6.6 Two pole alternator

- Let conductor starts rotating from position 1.
- At this instant, the entire velocity component is parallel to the flux lines.
- Hence there is no cutting of flux lines by the conductor.
- So at this instant is zero and hence induced e.m.f. in the conductor is also
- As the conductor moves from position I towards position 2, the part of the velocity corn ponent becomes perpendicular to the flux lines and proportional to that, .m.i g induced in the conductor.
- The magnitude of such an induced e.m.f. increases as the conductor moves from position 1 towards 2.
- At position 2, the entire velocity component is perpendicular to the flux lines. Hence there exists maximum cutting of the flux lines.
- And at this instant, the induced e.m.f. in the conductor is at its maximum.
- As the position of conductor changes from 2 towards 3, the velocity component perpendicular to the flux starts decreasing and hence induced e.m.f. magnitude also starts decreasing.
- At position 3, again the entire velocity component is parallel to the flux lines and hence at this instant induced e.m.f. in the conductor is zero.
- As the conductor moves from position 3 towards 4, the velocity component perpendicular to the flux lines again starts increasing.

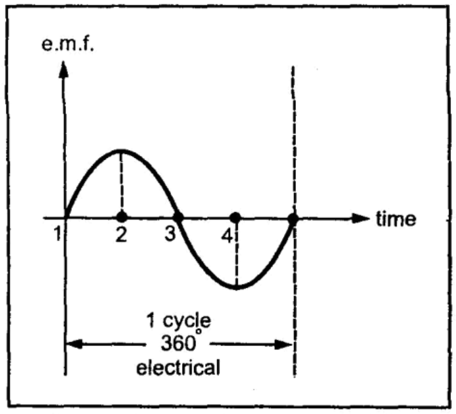


Fig. 6.7 Alternating nature of the induced e.m.f.

- But the direction of velocity component now is opposite to the direction of velocif component exsisting during the movement of - conductor from position 1 to 2.
- Hence an inducei e.m.f. in the conductor increases but in the opposite direction
- At position 4, it achieves maxima in the I direction, as the entire velocity component becoim perpendicular to the flux lines.
- Again from position 4 to 1, induced e.m decreases and finally at position 1, again becom zero.
- This cycle continues as conductor rotates certain speed.
- So if we plot the magnitudes of the induced e.m against the time, we get an alternating nature of the induced e.m.f. as shown in the Fig. 6.7.
- This is the working principle of an alternator.

MECHANICAL AND ELECTRICAL ANGLE

- We have seen that for 2 pole alternator, one mechanical revolution corresponds to electrical cycle of an induced e.m.f.
- Now consider pole alternator i.e. the field winding is designedt produce 4 poles.
- Due to 4 poles, the magnetic a exists diagonally shown dotted in the Fig. 6.8.
- Now in position 1 of the conductor, the ve1oci component is parallel to the flux lines while position 2, there is gathering of flux lines and entire velocity component is perpendicular to the flux L.
- So at position 1, the induced e.m.f. in the conductor i zero while at position 2, it is maximum. Similarly a conductor rotates, the induced e.m.f. will k maximum at positio,ns 4,6 and 8 and will be minimum at positions 3, 5 and 7.
- So during one complete revolution of the conductor, induced e.m.f. will experience four times maxima, twice in either direction and four times zero.
- This is I because of the distribution of flux lines due to existence of four poles.
- So if we plot the nature of the induced e.m.f for one revolution of the conductor, we get the two electrical cycles of the induced e.m.f., as shown in the Fig. 6.9.

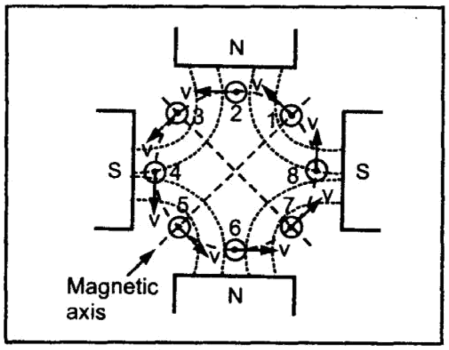


Fig. 6.8 4 Pole alternator

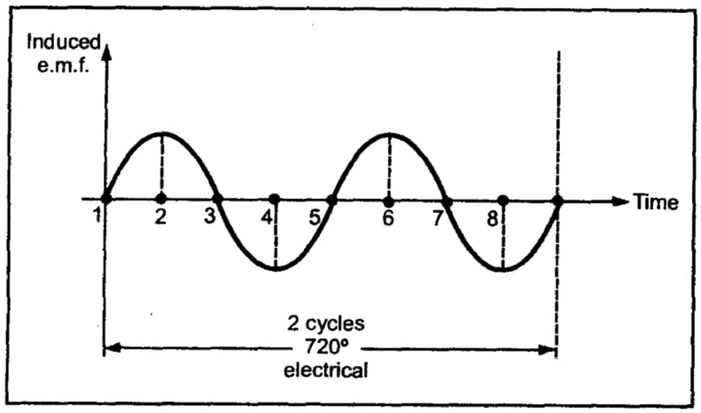


Fig. 6.9 Nature of the induced e.m.f.

key point

- Thus the degrees electrical of the induced e.m.f. i.e. number of cycles of the induced e.mf. depends on the number of poles of an alternator.
- So for a four pole alternator we can write, 360° mechanical = 720° electrical
- From this we can establish the general relation between degrees mechanical and degrees electrical as,

$$360^\circ \text{ mechanical} = 360^\circ \times \frac{P}{2} \text{ electrical}$$

where P = number of poles

$$\boxed{1^\circ \text{mechanical} = \left(\frac{P}{2}\right)^\circ \text{ electrical.}}$$

Frequency of Induced E.M.F.

Let P = Number of poles

N = Speed of the rotor in r.p.m.

and I = Frequency of the induced e.m.f

From the discussion above in article 6.9.1, we can write, One mechanical revolution of rotor = $\frac{P}{2}$ cycles of e.m.f. electrically

Thus there are P/2 cycles per revolution.

As speed is N r.p.m., in one second, rotor will complete $\left(\frac{N}{60}\right)$ revolutions

But cycles/sec = frequency = f

$\therefore$ Frequency f = (No. of Cycles per revolution) × (No. of revolutions per second)

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

$$\therefore \quad \boxed{f = \frac{PN}{120} \quad \text{Hz (cycles per sec).}}$$

So there exists a fixed relationship between three quantities, the number of poles F, the speed of the rotor N in r.p.m. and f the frequency of an induced e.m.f. in Hz.

Key Point

Such a machine bearing a fixed relationship between P, N and f is called synchronous machine and hence alternators are also called synchronous generators.

SYNCHRONOUS SPEED (Ns)

From the above expression, it is clear that for fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated e.m.f. constant at the required value. Such a speed is called synchronous speed of the alternator denoted as Ns

$$\text{So} \quad \boxed{N_s = \frac{120f}{P}}$$

where f = required frequency

GENERALIZED EXPRESSION FOR E.M.F. EQUATION OF AN ALTERNATOR

Considering full pitch, concentrated winding,

$$E_{ph} = 4.44\, f \phi\, T_{ph} \quad \text{volts}$$

But due to short pitch, distributed winding used in practice, this Eph will reduce by factors K and Kd. So generalised expression for e.m.f. equation can be written as,

$$\boxed{E_{ph} = 4.44\, K_c K_d\, f \phi\, T_{ph} \quad \text{volts}}$$

For full pitch coil, K = 1

For concentrated winding, Kd = 1

Key Point: For short pitch and distributed winding K and Kd are always less than unity.

$$n = \frac{\text{slots}}{\text{pole}} = \frac{120}{8} = 15$$

$$m = \text{slots/pole/phase} = \frac{n}{3} = \frac{15}{3} = 5$$

$$\beta = \frac{180°}{n} = \frac{180°}{15} = 12°$$

$$\therefore \quad K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\frac{\beta}{2}\right)} = \frac{\sin\left(\frac{5 \times 12}{2}\right)}{5 \times \sin\left(\frac{12}{2}\right)} = \mathbf{0.957}$$

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

Ex. 6.3:

Sol. :

$$n = \frac{\text{slots}}{\text{pole}} = \frac{36}{4} = 9$$

$$\beta = \frac{180°}{9} = 20°$$

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

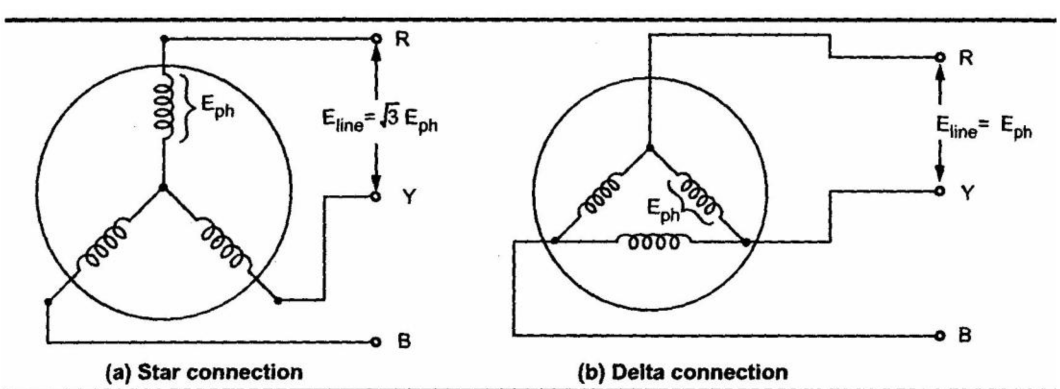
$$\therefore \quad \alpha = \text{angle of short pitch} = 20°$$

$$\therefore \quad K_c = \cos\left(\frac{\alpha}{2}\right) = \cos(10) = \mathbf{0.9848}$$

Line Value of Induced E.M.F.

If the armature winding of three phase alternator is star connected, then the value of induced e.m.f. across the terminals is 3 ,Ephwere Eph is induced e.m.f. per phase. While if it is delta connected, line value of e.m.f. is same as E.

This is shown in the Fig. 6.25 (a) and (b).



(a) Star connection (b) Delta connection

Practically most of the alternators are star connected due to following reasons:

1. Neutral point can be earthed from safety point of view.

2. For the same phase voltage, voltage available across the terminals is more than delta connection. 3. For the same termmal voltage, the phase voltage in star is — $\frac{1}{\sqrt{3}}$ limes line value. This reduces strain on the insulation of the armature winding. Ex. 6.4: An alternator runs at 250 r.p.m. and generates an e.m.f at 50 Hz. There are 216 slots each containing 5 conductors. The winding is distributed and full pitch. All the conductors of each phase are in series and flux per pole is 30 mWb which is sin usoidally distributed. If the winding is star connected, determine the value of induced e.m.f available across the term inals.

Sol. :

$$N_s = 250 \text{ r.p.m., } f = 50 \text{ Hz}$$

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

$$\therefore \quad 250 = \frac{120 \times 50}{P}$$

$$\therefore \quad P = 24$$

$$\therefore \quad n = \frac{\text{slots}}{\text{pole}} = \frac{216}{24} = 9$$

$$\therefore \quad m = \frac{n}{3} = 3$$

$$\therefore \quad \beta = \frac{180^\circ}{9} = 20^\circ$$

$$\therefore \quad K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\frac{\beta}{2}\right)} = \frac{\sin\left(\frac{3 \times 20}{2}\right)}{3 \times \sin\left(\frac{20}{2}\right)}$$

$$= 0.9597$$

$$K_c = 1 \text{ as full pitch coils.}$$

Total no. of conductors $Z = 216 \times 5 = 1080$

$$\therefore \quad Z_{ph} = \frac{Z}{3} = \frac{1080}{3} = 360$$

$$T_{ph} = \frac{Z_{ph}}{2} \quad \text{... (2 conductors constitute 1 turn)}$$

$$= \frac{360}{2} = 180$$

$$\therefore \quad E_{ph} = 4.44 \, K_c \, K_d \, f \, \phi T_{ph}$$

$$= 4.44 \times 1 \times 0.9597 \times 30 \times 10^{-3} \times 50 \times 180$$

$$= 1150.48 \text{ V}$$

$$E_{line} = \sqrt{3} \, E_{ph} \quad \text{... (star connection)}$$

$$= \sqrt{3} \times 1150.48$$

$$= 1992.70 \text{ V.}$$

Ex. 6.5: A 3 phase, 16 pole, star connected alternator has 144 slots on the armature periphery. Each slot contains 10 conductors. it is driven at 375 r.p.m. The line value of e.m.f.available across the terminals is observed to be 2.657 kV. Find the frequency of the induced e.rn.f. and flux per pole.

Sol. :

$$P = 16 \qquad N_s = 375 \text{ r.p.m.}$$
$$\text{slots} = 144 \qquad \text{conductors/slot} = 10$$
$$E_{line} = 2.657 \text{ kV}$$
$$N_s = \frac{120 f}{P}$$
$$\therefore \quad 375 = \frac{120 \times f}{16}$$
$$\therefore \quad f = 50 \text{ Hz}$$

Assuming full pitch winding , $K_c = 1$

$$\therefore \quad n = \frac{\text{slots}}{\textit{pole}} = \frac{144}{16} = 9$$
$$\therefore \quad m = \frac{n}{3} = 3$$
$$\therefore \quad \beta = \frac{180^\circ}{n} = \frac{180^\circ}{9} = 20^\circ$$
$$\therefore \quad K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\frac{\beta}{2}\right)} = \frac{\sin\left(\frac{3 \times 20}{2}\right)}{3 \times \sin\left(\frac{20}{2}\right)} = 0.9597$$
$$\text{Total conductors} = \text{slots} \times \text{conductors/slot}$$
$$\text{i.e.} \quad Z = 144 \times 10 = 1440$$
$$\therefore \quad Z_{ph} = \frac{Z}{3} = \frac{1440}{3} = 480$$
$$T_{ph} = \frac{Z_{ph}}{2} = \frac{480}{2} = 240$$
$$E_{ph} = \frac{E_{line}}{\sqrt{3}} = \frac{2.657}{\sqrt{3}} = 1.534 \text{ kV}$$
$$= 1.534 \text{ kV}$$
$$\text{Now} \quad E_{ph} = 4.44\, K_c\, K_d\, f\, \phi T_{ph}$$
$$\therefore \quad 1.534 \times 10^3 = 4.44 \times 1 \times 0.9597 \times \phi \times 50 \times 240$$
$$\therefore \quad \phi = 0.03 \text{ Wb} = \mathbf{30\ mWb}$$

PARAMETERS OF ARMATURE WINDING

There are three important parameters of an armature winding of an alternator. These are,

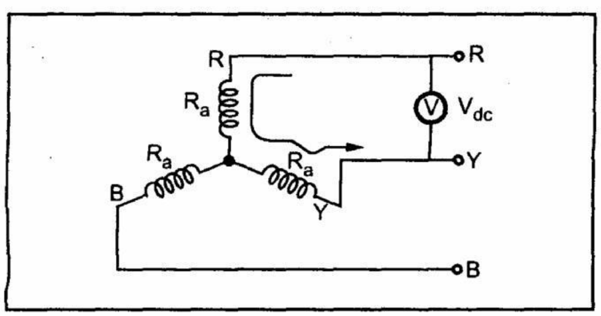
1. Armature resistance Ra
2. Armature leakage reactance XL
3. Reactance corresponding to armature reaction

The equivalent circuit and the concept of synchronous impedance plays an important role in determining the regulation of an alternator.

ARMATURE RESISTANCE

Every armature winding has its own resistance. The effective resistance of an armature winding per phase is denoted as Raph f /ph or Ra Wph.
Generally the armature resistance is measured by applying the known d.c. voltage and measuring the d.c. current through it. The ratio of applied voltage and measured current is the armature resistance. But due to the skin effect, the effective resistance under a.c. conditions is more than the d.c. resistance. Generally the effective armature resistance under a.c. conditions is taken 1.25 to 1.75 times the d.c. resistance.
While measuring the armature resistance, it is necessary to consider how the armature winding is connected whether in star or delta. Consider a star connected armature winding as shown in the Fig. 6.26.
When the voltage is applied across any two terminals of an armature winding, then the equivalent resistance is the series combination of the two resistances of two different phase windings.
RRY = resistance between R-Y terminals Ra + Ra = 2 Ra

Where Ra = armature resistance per phase
Fig. 6.26 Star connected alternator



$$\therefore \quad R_a = \frac{R_{RY}}{2} \ \Omega/ph$$

Thus in star connected alternator, the armature resistance per phase is half of the resistance observed across any two line terminals.
Consider the delta connected alternator as shown in the Fig. 6.27. When voltage is applied across any two terminals, then one phase winding appears in parallel with series combination of other two.

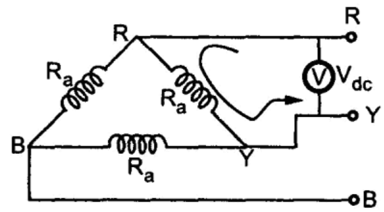


Fig. 6.27 Delta connected alternator

Hence the equivalent resistance across the terminals is parallel combination of resistances Ra and 2

$$R_{RY} = R_a \parallel 2R_a \ \ \Omega/ph = \frac{R_a \times 2R_a}{R_a + 2R_a} = \frac{2}{3} R_a$$

$$\boxed{R_a = \frac{3}{2} R_{RY}}$$

6.15 ARMATURE LEAKAGE REACTANCE

When armature carries a current, produces its own flux. Some part of flux completes its path through the around the conductors itself. Such a I called leakage flux. This is shown in Fig. 6.28.

Key Point : This leakage flux makes the armature winding inductive in nature. So winding possesses a leakage reactance, in addition to the resistance

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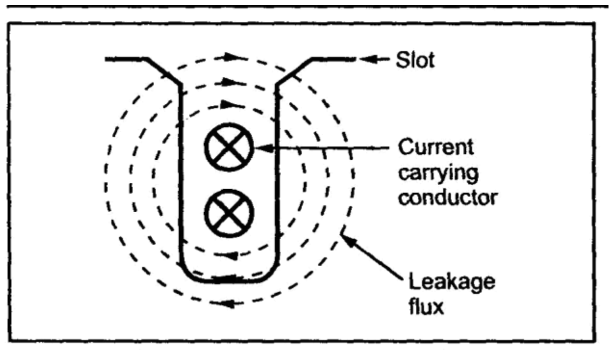
6.15 ARMATURE LEAKAGE REACTANCE

When armature carries a current, produces its own flux. Some part of flux completes its path through the around the conductors itself. Such a I called leakage flux. This is shown in



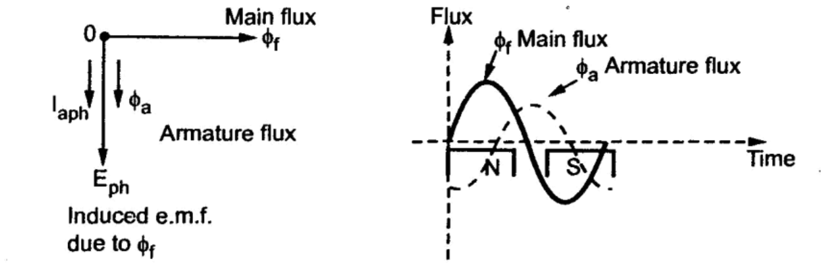
Key Point : This leakage flux makes Harmature winding inductive in nature.
Sowinding possesses a leakage reactance, in addition to the resistance.
So if L' is the leakage inductance of the armature winding per phase, then leakage reactance per phase is given by XL = 2 f L /ph. The value of leakage reactance is much higher than the armature resistance. Similar to the d.c. machines, the value of armature resistance is very very smalL

6.16 ARMATURE REACTION

When the load is connected to the alternator, the armature winding of the alternator carries a current. Every current carrying conductor produces its own flux so armature of the alternator also produces its own flux, when carrying a current. So there are two fluxes. present in the air gap, one due to armature current while second is produced by the field winding called main flux. The flux produced by the armature is called armature flux.
Key Point So effect of the armature flux on the main flux affecting its value and the distribution is called armature reaction.
The effect of the armature flux not only depends on the magnitude of the current flowing through the armature winding but also depends on the nature of the power factor of the load connected to the alternator.
Let us study the effect of nature of the load power factor on the armature reaction.

6.16.1 UNITY POWER FACTOR LOAD

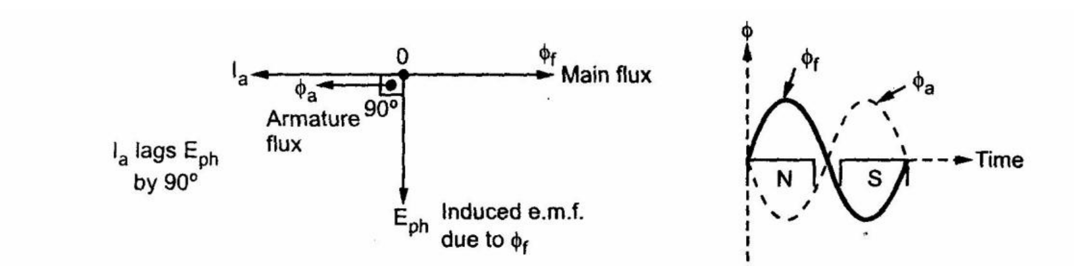
Consider a purely resistive load connected to the alternator, having unity power factor.
As induced e.m.f. E drives a current of ' aph and load power factor is unity, E and ' aph are in phase with each other.
If is the main flux produced by the field winding responsible for producing E then E lags by 90°
Now current through armature ' a' produces the armature flux say4 So flUX 4 and ' a are always in the same direction.
This relationship between 4 4 E and can be shown in the phasor diagram. Refer to the Fig. 6.29



It can be seen from the phasor diagram that there exists a phase difference of 90° between the armature flux and the main flux. The waveforms for the two fluxes are also shown in the Fig. 6.29. From the waveforms it can be seen that the two fluxes oppose each other on the left half of each pole while assist each other on the right half of each pole. Hence average flux in the air gap remains constant but its distribution gets distorted. Key Point Hence such distorting effect of armature reaction under unity p.f.
condition of the load is called cross magnetising effect of armature reaction.
Due to such distortion of the flux, there is small drop in the terminal voltage of the alternator.

6.16.2 ZERO LAGGING POWER FACTOR LOAD

Consider a purely inductive load connected to the alternator having zero lagging power factor. This indicates that ‘ aph driven by E lags EPh by 90° which is the power factor angle 4).
Induced e.m.f. E lags main flux 4) by 90° while 4)a is in the same direction as that of ‘ a the phasor diagram and the waveforms are shown in the Fig. 6.30.



It can be seen from the phasor diagram that the armature flux and the main flux are exactly in opposite direction to each other.

Key Point So armature flux tries to cancel the main flux. Such an effect of armature reaction is called demagnetising effect of the armature reaction.

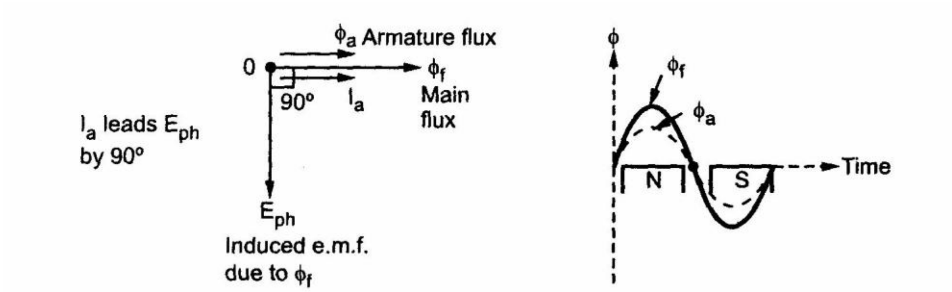
As this effect causes reduction in the main flux, the terminal voltage drops. This drop in the terminal voltage is more than the drop corresponding to the unity p.f. load.

6.16.3 ZERO LEADING POWER FACTOR LOAD

Consider a purely capacitive load connected to the alternator having zero leading power factor. This means that armature current Iaph driven by E leads E by 90°, which is the power factor angle .

Induced e.m.f. E phasor diagram and

h lags f by 90° while Iaph and a are always in the same direction. The the waveforms are shown in the Fig. 6.31.



It can be seen from the phasor diagram and waveforms shown in the Fig. 6.31, the armature flux and the main field flux are in the same direction i.e. they are helping eachother. This results into the addition in main flux.

Key Point Such an effect of armature reaction due to which armature flux assists field flux is called magnetising effect of the armature reaction.

As this effect adds the flux to the main flux, greater e.m.f. gets induced in the armature. Hence there is increase in the terminal voltage for leading power factor loads. For intermediate power factorloads i.e. between zero lagging and zero leading the armature reaction is partly cross magnetising and partly demagnetising for lagging power factor loads or partly magnetising for leading power factor loads.

6.16.4 Armature Reaction Reactance (Xar)

In all the conditions of the load power factors, there is change in the terminal voltage due to the armature reaction. Mainly the practical loads are inductive in nature, due to demagnetising effect of armature reaction, there is reduction in the terminal voltage. Now this drop in the voltage is due to the interaction of armature and main flux. This drop is not across any physical element.

But to quantify the voltage drop due to the armature reaction, armature winding is assumed to have a fictitious reactance. This fictitious reactance of the armature is called armature reaction reactance denoted as Xar Wph. And the drop due to armature reaction can be accounted as the voltage drop across this reactance as ‘ a Xar. Key Point The value of this reactance changes as the load power factor changes, as armature reaction depends on the load power factor.

6.17 CONCEPT OF SYNCHRONOUS REACTANCE AND IMPEDANCE

From the above discussion, it is clear that armature winding has one more parameter which is armature reaction reactance in addition to its resistance and the leakage reactance.

The sum of the fictitious armature reaction reactance accounted for considering armature reaction effect and the leakage reactance of the armature is called synchronous reactance of the alternator denoted as X

So $$X_s = X_L + X_{ar} \quad \Omega/ph$$

As both XL and Xar are ohmic values per phase, synchronous reactance is also specified as ohms per phase.
Now from, this, it is possible to define an impedance of the armature winding. Such an impedance obtained by combining per phase values of synchronous reactance and armature resistance is called synchronous impedance of the alternator denoted as Z

So $$Z_s = R_a + j X_s \quad \Omega/ph$$

and $$|Z_s| = \sqrt{R_a^2 + (X_s)^2} \quad \Omega/ph$$

For getting a standard frequency, alternator is to be driven at synchronous speed. So word synchronous used in specifying the reactance and impedance is referred to the working speed of the alternator. Generally impedance of the winding is constant but in case of alternator, synchronous reactance depends on the load and its power factor condition, hence synchronous impedance also varies with the load and its power factor conditions.

623 METHODS OF DETERMINING THE REGULATION

The regulation of an alternator can be determined by various methods. In case of small capacity alternators it can be determined by direct loading test while for large capacity alternators it can be determined by synchronous impedance method.
The synchronous impedance method has some short comings. Another method which is popularly used is ampere-turns method. But this method also has certain disadvantages. The disadvantages of these two methods are overcome in a method called zero power factor method. Another important theory which gives accurate results is called Blondel' s two reaction theory. Thus there are following methods available to determine the voltage regulation of an alternator,

1. Direct loading method

623 Methods of Determining the Regulation

2. Synchronous impedance method or E.M.F. method
3. Ampere-turns method or M.M.F. method
4. Zero power factor method or Potier triangle method
5. ASA modified form of M.M.F. method
6. Two reaction theory.

But from the syllabus point of view only synchronous impedance and M.M.F. methods are discussed in this chapter.

6.24 SYNCHRONOUS IMPEDANCE METHOD OR E.M.F. METHOD

The method is also called E.M.F. method of determining the regulation. The r requires following data to calculate the regulation.

1. The armature resistance per phase (Ra)
2. Open circuit characteristics which is the graph of open circuit voltage against the field current. This is possible by conducting open circuit test on the alternator.
3. Short circuit characteristics which is the graph of short circuit current against field current. This is possible by conducting short circuit test on the alternator.

Let us see, the circuit diagram to perform open circuit as well as short circuit test on the alternator. The alternator is coupled to a prime mover capable of driving the alternator at its synchronous speed. The armature is connected to the terminals of a switch. The other terminals of the switch are short circuited through an ammeter. The voltmeter is connected across the lines to measure the open circuit voltage of the alternator.

6.24.1 OPEN CIRCUIT TEST

The field winding is connected to a suitable d.c. supply with rheostat connected in series. The field excitation i.e. field current can be varied with the help of this rheostat. The circuit diagram is shown in the Fig. 6.39.
Procedure to conduct this test is as follows

1. Start the prime mover and adjust the speed to the synchronous speed of the alternator.
2. Keeping rheostat in the field circuit maximum, switch on the d.c. supply.
3. The T.P.S.T. switch in the armature circuit is kept open.
4. With the help of rheostat, field current is varied from its minimum value to the rated value. Due to this, flux increases, increasing the induced e.m.f. Hence voltmeter reading,

which is measuring line value of open circuit voltage increases. For various values of field current, voltmeter readings are observed.

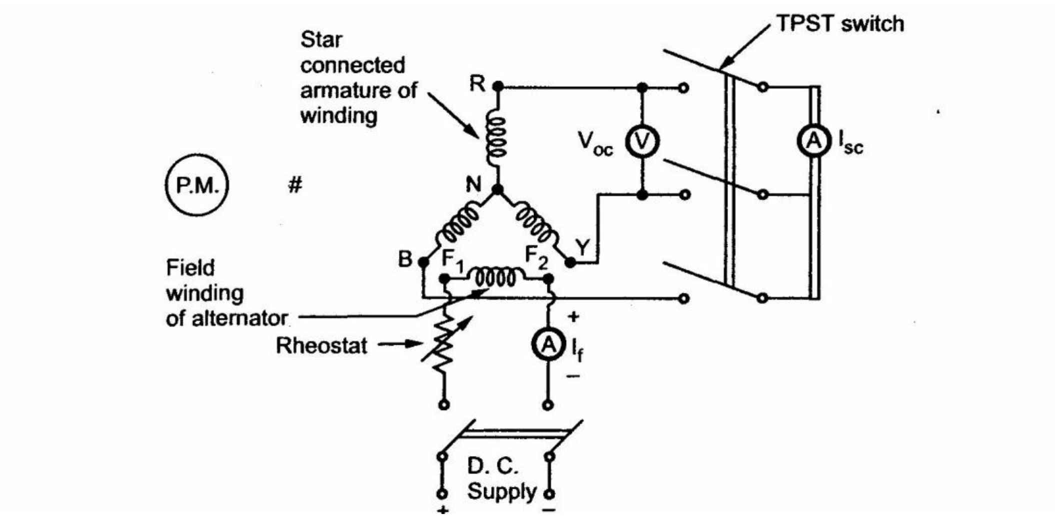


Fig. 6.39 Circuit diagram for open circuit and short circuit test on alternator

The observations for open circuit test are tabulated as below

Sr. No.	I_f A	V_{oc} (line) V	V_{oc} (phase) = V_{oc} (line)/$\sqrt{3}$ V
1			
2			
:			
:			

.From the above table, graph of (Voc) against I is plotted.
Key Point This is called open circuit characteristics of the alternator, called O.C.C. This is shown in the Fig. 6.40.

6.24.2 SHORT CIRCUIT TEST

After completing the open circuit test observations, the field rheostat is brought to maximum position, reducing field current to a minimum value. The T.P.S.T. switch is closed. As ammeter has negligible resistance, the armature gets short circuited. Then the field excitation is gradually increased till full load current is obtained through armature winding. This can be observed on the ammeter connected in the armature circuit. The graph of short circuit armature current against field current is plotted from the observation table of short circuit test. This graph is called short circuit characteristics, S.C.C. This is also shown in the Fig. 6.40

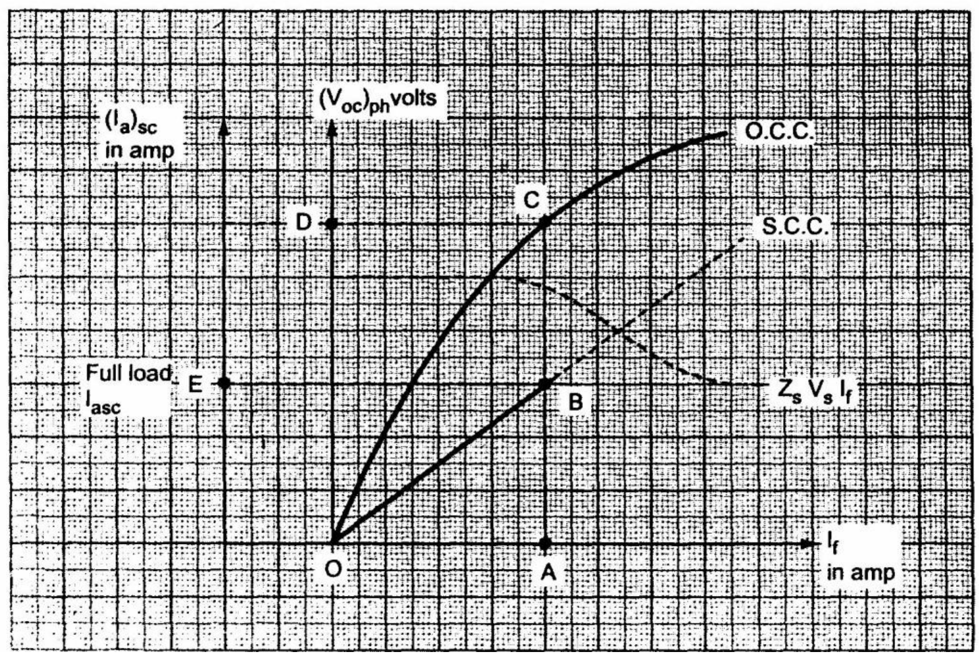


Fig. 6.40 O.C.C. and S.C.C. of an alternator

SPECIAL MACHINES

7.1 Introduction

There are numerous practical applications like recording instruments, clocks, teleprinters, timing devices, computer peripherals which need special motors. The power rating of such motors is very small. Some of them are even fractional horse power motors hence these motors are called fractional kW motors. Some of these special purpose motors are discussed in this chapter.

7.2 Reluctance Motor

The reluctance motor has basically two main parts called stator and rotor.

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

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

The construction of the reluctance motor is shown in the Fig. 7.1(a) while the practical rotor of a reluctance motor is shown in the Fig. 7.1(b) I

I

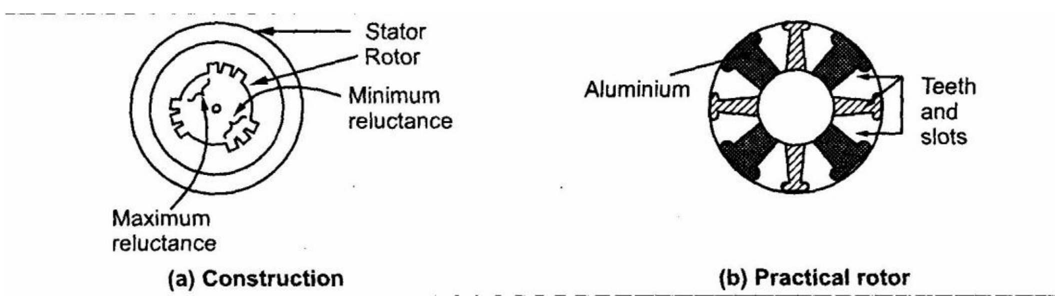


Fig. 7.1 Reluctance motor

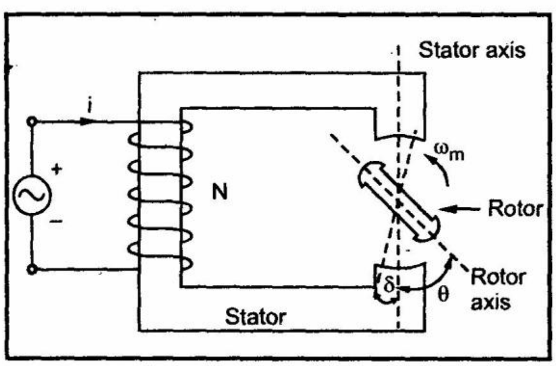
7.2.1 WORKING PRINCIPLE

The stator consists of a single winding called main winding. But single winding can not produce rotating magnetic field. So for production of rotating magnetic field, there must be at least two windings separated by certain phase angle. Hence stator consists of an additional winding called auxiliary winding which consists of capacitor in series with it. Thus there exists a phase difference between the currents carried by the two windings and corresponding fluxes. Such two fluxes react to produce the rotating magnetic field. The technique is called split phase technique of production of rotating magnetic field. The speed of this field is synchronous speed which is decided by the number of poles for which stator winding is wound.

The rotor carries the short circuited copper or aluminium bars and it acts as squirrel cage rotor of an induction motor. If an iron piece is placed in a magnetic field, it aligns itself in a minimum reluctance position and gets locked magnetically. Similarly in the reluctance motor, rotor tries to align itself with the axis of rotating magnetic field in a minimum reluctance position. But due to rotor inertia it is not possible when rotor is standstill. So rotor starts rotating near synchronous speed as a squirrel cage induction motor. When the rotor speed is about synchronous, stator magnetic field pulls rotor into synchronism i.e. minimum reluctance position and keeps it magnetically locked. Then rotor continues to rotate with a speed equal to synchronous speed. Such a torque exerted on the rotor is called the reluctance torque. Thus finally the reluctance motor runs as a synchronous motor. The resistance of the rotor must be very small and the combined inertia of the rotor and the load should be small to run the motor as a synchronous motor

7.2.2 MATHEMATICAL ANALYSIS

Consider an elementary reluctance motor as shown in the Fig. 7.2



N **Fig. 7.2 Elementary reluctance motor**

The variation of the inductance of the windings is sinusoidal with respect to rotor position. The variation of the inductance with respect toO is of double frequency and is given by,

$$L(\theta) = L'' + L' \cos 2\theta$$

The stator winding is exciteal by a.c. supply

hence = Ifl sinwt

The energy stored is a function of inductance and given by,

$$W = \frac{1}{2} L(\theta) i^2$$

The flux linkage is given by,

$$\lambda(\theta) = L(\theta) i$$

Then the torque is given by

$$T = -\frac{\partial W}{\partial \theta} + i \frac{\partial \lambda}{\partial \theta}$$

$$= -\frac{1}{2} i^2 \frac{\partial L}{\partial \theta} + i^2 \frac{\partial L}{\partial \theta}$$

$$= -\frac{1}{2} i^2 \frac{\partial L}{\partial \theta}$$

Substituting the values of i and L,

$$T = -I_m^2 L' \sin 2\theta \sin^2 \omega t$$

If rotor is rotating at an angular velocity corn then finally the torque equation can be expressed interms of and m as,

$$T = -\frac{1}{2} I_m^2 L' \left\{ \sin 2(\omega_m t - \delta) - \frac{1}{2} [\sin 2(\omega_m t + \omega t - \delta) + \sin 2 (\omega_m t - \omega t - \delta)] \right\}$$

where $\theta = \omega_m t - \delta$

and $\delta =$ rotor position at $t = 0$

The above equation gives instantaneous torque produced. The average torque is zero as average of each term in the above equation is zero. The value of torque is not zero when t = m and at this condition the magnitude of the average torque is,

$$\boxed{T_{av} = \frac{1}{4} I_m^2 L' \sin 2\delta}$$

The speed corresponding to the frequency = m is nothing but the synchronous speed. The S is a torque angle. The maximum torque occurs at = 45 º which is termed as pull-out torque.of synchronism.

Key Point: Any load demanding torque more than pull-out torque pulls the motor out

7.2.3 TORQUE-SPEED CHARACTERISTICS

The torque-speed characteristic is shown in the Fig. 7.3 The startng torque is highly dependent on the position of the rotor.

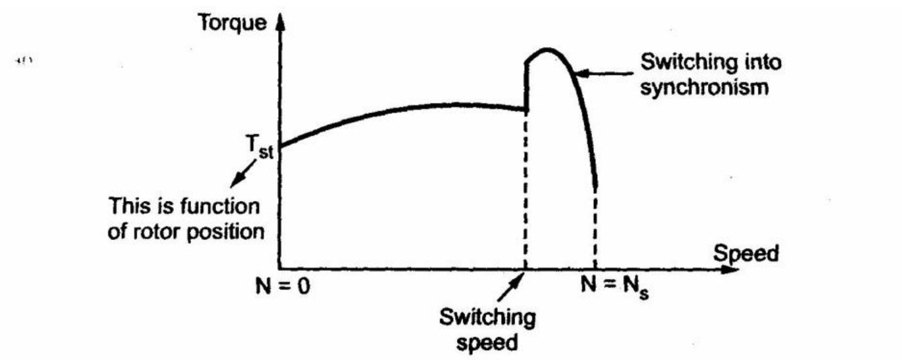


Fig. 7.3 Torque-speed characteristics of reluctance motor

7.2.4 ADVANTAGES

The reluctance motor has following advantages,

1) No d.c. supply is necessary for rotor.
2) Constant speed characteristics.
3) Robust construction.
4) Less maintenance.

7.2.5 LIMITATIONS

The reluctance motor has following limitations,

1. Less efficiency
2. Poor power factor
3. Need of very low inertia rotor.
4. Less capacity to drive the loads.

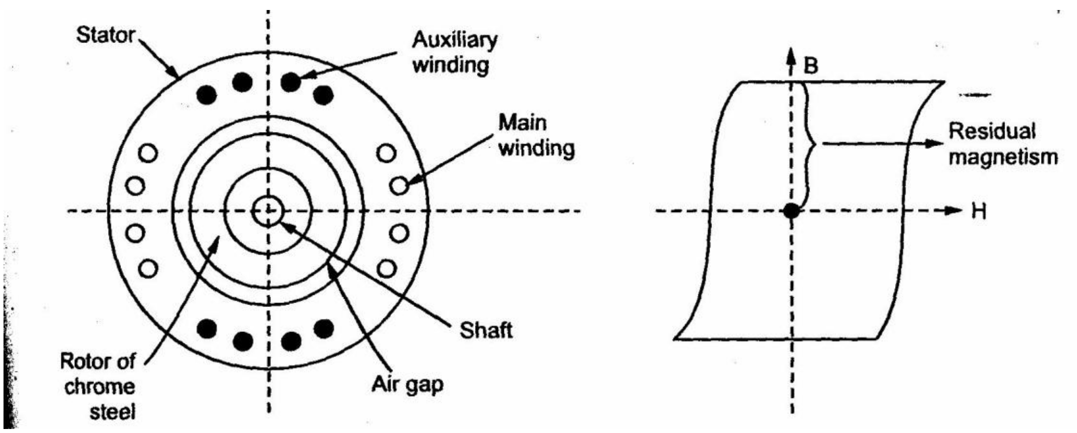
7.2.6 APPLICATIONS

This motor is used in signalling devices, control apparatus, automatic regulators, recording instruments, clocks and all kinds of timing devices, teleprinters, gramophones etc.

7.3 HYSTERESIS MOTOR

This is the synchronous motor which does not require any d.c. excitation to the rotor and it uses non projected poles.

It consists of a stator which carries main and auxiliary windings so as to produce rotating magnetic field. The stator can also be shaded pole type. The rotor is smooth cylindrical type made up of hard magnetic material like chrome steel or alrüco for high retentivity. This requires to select a material with high hysteresis loop area. The rotor does not carry any winding. The construction is shown in the Fig. 7.4 (a) while nature of hysteresis ioop required for rotor material .



(a) Cross-sectional view of hysteresis motor   (b) Hysteresis loop for rotor material

When stator is energised, it produces rotating magnetic field. The main and both the windir must be supplied continuously at start as well as in running cor as to maintain the rotating magnetic field. This field induces poles in the rot hysteresis phenomenon is dominant for the rotor material chosen and due to whk pole axis lag behind the axis of rotating magnetic field. Due to this, rotor poles get a towards the moving stator field poles. Thus rotor gets subjected to torque called hysi torque. This torque is constant at all speeds. When the stator field axis moves forwar to high retentivity the rotor pole strength remains maintained. So higher the r higher is the hysteresis torque.

Initially rotor starts rotating due to combined effect of hysteresis torque as well a due to eddy currents induced in the rotor. Once the speed is near about the synchronow stator pulls rotor into synchronism. In such case, as relative motion between stator field rotor vanishes, so the torque due to eddy currents vanishes. Only hysteresis t present which keeps rotor running at synchronous speed. The high retentivity, ensures continuous magnetic locking between stator and rotor. Due to principle of magnetic I the motor either rotates at synchronous speed or not at all.

7.3.1 MATHEMATICAL ANALYSIS

The eddy current loss in the machines is given by,

$$P_e = K_e f_2^2 B^2$$

where K_e = eddy current constant

f_2 = frequency of eddy currents

B = flux density

We know the relation between rotor frequency f and supply frequency f,

$$f_2 = sf_1$$

where s = slip

$$\therefore \quad P_e = K_e s^2 f_1^2 B^2$$

The torque due to eddy currents is given by

$$T_e = \frac{P_e}{s\omega_s} = \frac{K_e s^2 f_1^2 B^2}{s\omega_s}$$

So $\boxed{T_e \propto s}$

So when rotor rotates at synchronous speed, the slip becomes zero and torque eddy current component vanishes. It only helps at start. The hysteresis loss is given by,

$$P_h = K_h f_2 B^{1.6}$$

$$= K_h s f_2 B^{1.6}$$

The corresponding torque is given by,

$$\boxed{T_h = \frac{P_h}{s\,\omega_s} = K = \text{constant}}$$

where $K = \dfrac{K_h\, f_1\, B^{1.6}}{\omega_s} = \text{constant}$

Key Point: Thus the hysteresis torque component is constant at all the rotor speeds.

7.3.2 TORQUE-SPEED CHARACTERISTICS

The starting torque and running torque is almost equal in this type of motor. As stator carries mainly the two windings its direction can be reversed by interchanging the terminals of either main winding or auxiliary winding. The torque-speed characteristics is as shown in the Fig. 7.5.

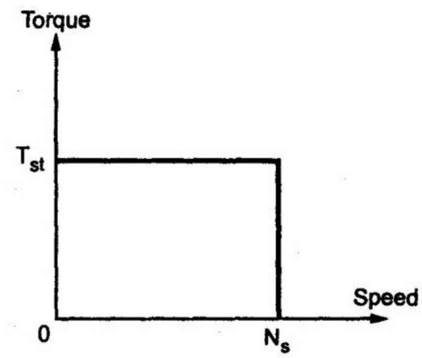


Fig. 7.5 Torque characteristics of hysteresis motor

As seen from the characteristics torque at start is almost same throughout the operation of the motor.

7.3.3 Advantages

The advantages of this motor are:

1) As rotor has no teeth, no winding, there are no mechanical vibrations.
2) Due to absence of vibrations, the operation is quiet and noiseless.
3) Suitability to accelerate high inertia loads
4) Possibility of multispeed operation by employing gear train.

7.3.4 Applications

Due to noiseless operation it is used in sound recording instruments, sound producing equipments, high quality record players, tape recorders, electric clocks, teleprinters, timing devices etc.

7.6 VARIABLE RELUCTANCE MOTORS

It is the most basic type of stepper motor. This helps to explain the principle of operation of the stepper motors.
The motor has a stator which is usually wound for three phases. The stator has six salient poles with concentrated exciting windings around each one of them. The stator construction is laminated and assembled in a single stack. The number of poles on the stator and rotor are different. This gives the motor ability,
1. of bid jrection rotation and
2. self starting capability.

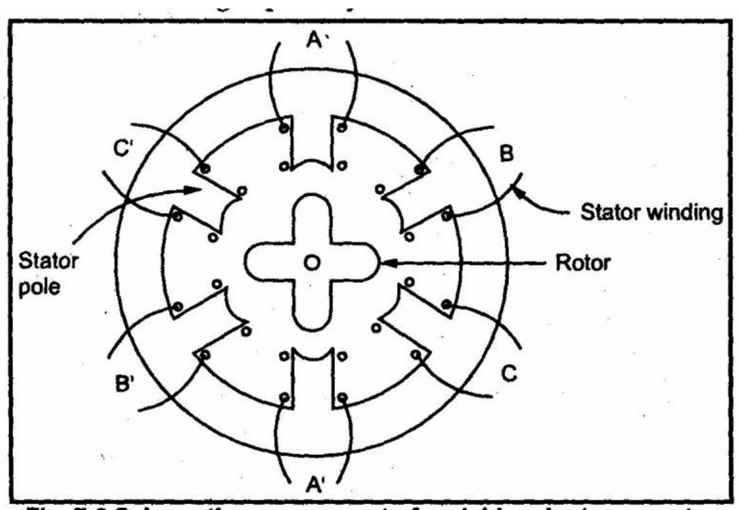


Fig. 7.6 Schematic arrangement of variable reluctance motor

The rotor is made out of slotted steel laminations. If the number of stator poles are N and the number of rotor poles
are Nr then for a. three phase
motor, the rotor poles in terms
N q are given by,

$$N_r = N_s \pm \left(\frac{N_s}{q}\right)$$

where q = Number of phases For example for N =6
and q = 3, the rotor poles are,

$$N_r = 6 \pm \left(\frac{6}{3}\right) = 8, 4$$

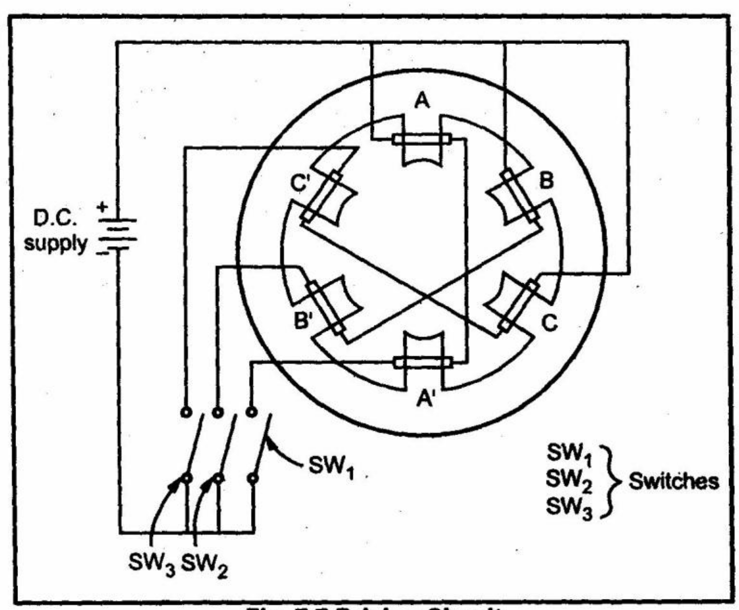


Fig. 7.7 Driving Circuit

For our discussion, 4 pole rotor constructi6n is elected. So rotor has 4 salient poles without any exciting winding as shown in the Fig. 7.6.
The coils wound around diametrically opposite poles are connected in series and the three phases are energised from a d.c. source with the help of switches. The basics driving circuit is shown in the Fig. 7.7.

7.6.1 OPERATION

The operation is based on various reluctance positions of rotor with respect to t When any one phase of the stator is excited, it produces its magnetic field whose axis I along the poles, the phase around which is excited. Then rotor moves in such a direction as to achieve minimum reluctance position. Such a position means a position where axis magnetic field of stator matches with the axis passing through any two poles of the rotor. I. us see the operation when phases A, B and C are energised in sequence one after the other, with the help of switches SW SW and SW
1. When the phase AA' is excited with the switch SW closed, then stator magnetic ax exists along the poles formed due to AA 1 e vertical Then rotor adjusts itself in a

mmimun reluctance position i.e. matching its own axis passing through the two poles exactly wit stator magnetic axis. This position is shown in the Fig. 7.8 (a)

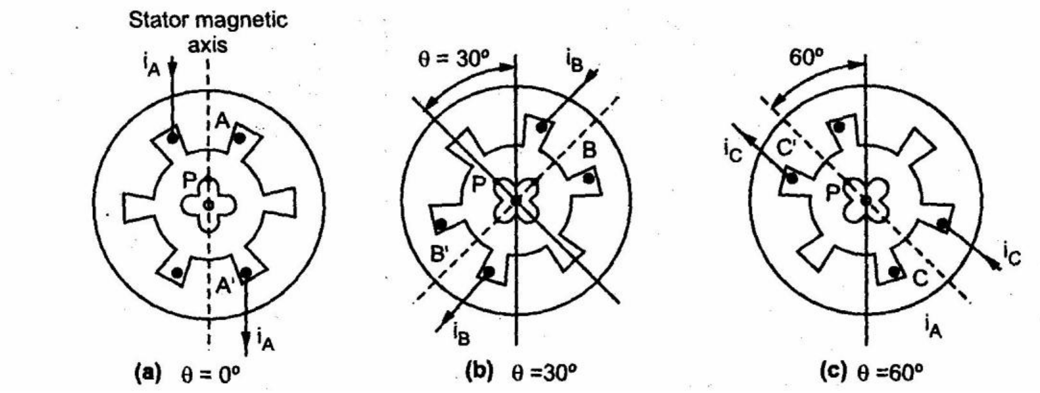


Fig.

2. When the phase BB’ is excited with the switch SW closed and phase AA’ de energised with the switch SW open, then stator magnetic axis shifts along the pales formed due to BB’ , shown dotted in the Fig. 7.8 (b). Then rotor tries to align in the minimum reluctance position and turns through 3Ø in anticlockwise direction. So axis passing through two diagonally opposite poles of rotor matches with the stator magnetic axis. This is the new minimum reluctance position. The point? shown on the rotor has rotated through 30° in anticlockwise direction as shown in the Fig. 7.8 (b)

3. When the phase CC’ is excited with the switch SW closed and the phases AA’ and B are de energised, then the stator magnetic axis shifts along the poles formed due to CC’ , shown dotted in the Fig. 7.8 (c). Then to achieve minimum reluctance position, rotor gets subjected to further anticlockwise torque. So it turns through further 30° in anticlockwise direction.

Hence point P is now at 6G° from its starting position, in anticlockwise direction as shown in the Fig. 7.8 (c). By successively exciting the three phases in the specific sequence, the motor takes twelve steps to complete one resolution.

Now if i is the current passing through the phase which is excited then the torque developed by the motor, which acts on the rotor is expressed as,

$$T_m = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

where L is the inductance of the relevant phase at an angle 0.

Since the torque is proportional to the square of the phase current (T x i) , it is independent of the direction of i. The direction of rotation is totally decided from the sequence in which the phases are excited.

7.6.2 IMPORTANT OBSERVATIONS

From the above discussion, the following important observations can be made:
i) The rotor can be moved in a specific direction, by exciting the stator phases in a specific sequence.
ii) When the phases are excited in the sequence A-B-C-A ..., the rotor moves in the anticlockwise direction, as explained earlier.
iii) When the phases are excited in the sequence C-B-A-C ..., the rotor moves in the clockwise direction, which can be easily verified.
iv) The distance through which the rotor moves when all three phases are excited once is called one rotor tooth pitch.

$$\text{rotor tooth pitch} = \frac{360°}{N_r}$$

v) The step angle is denoted as α_s and given by,

$$\alpha_s = \frac{360°}{q N_r}$$

So for three phases and four rotor poles the step angle is,

$$\alpha_s = \frac{360°}{3 \times 4} = 30°$$

This is shown in the previous section. If the number of phases are increased to eight and the number of rotor poles to six then the step angle becomes,

$$\alpha_s = \frac{360°}{8 \times 6} = 7.5°$$

7.6.3 MICROSTEPPING

In the above discussion we have assumed that the windings are excited one at a time. if the two phases are excited simultaneously i.e. keeping AA' excited, the BB' is also excited with switch SWI and SW2 closed, then the stator magnetic axis shifts to a mid position rather than along BB' . Hence rotor gets aligned along this moves through a half step i.e. 15°.
A logical extension of this technique is to control the currents in the phase windings so that several stable equilibrium positions are created. Normally the step angle is reduced by factor of $\frac{1}{2}, \frac{1}{5}, \frac{1}{10}, \frac{1}{16}$ or $\frac{1}{32}$. This technique is called microstepping.

A further reduction in step angle can be achieved by increasing the number of poles of I the stator and rotor or by adopting different constructions such as,

i) Using reductiongear mechanism

ii) Using multistack arrangement

7.6.4 REDUCTION GEAR STEPPER MOTOR

Fig. 7.9 shows a reduction gear stepper motor. The stator has 8 salient poles and four phases for use as exciting winding. The rotor has 18 teeth and 18 slots uniformly distributed around. Each salient pole of the stator consists of two teeth, forming an interleaving slot of the same angular periphery as the rotor teeth or slots. When the coil A-A' is excited, the resulting electromechanical torque brings the rotor to the position as shown in the Fig. 7.9.

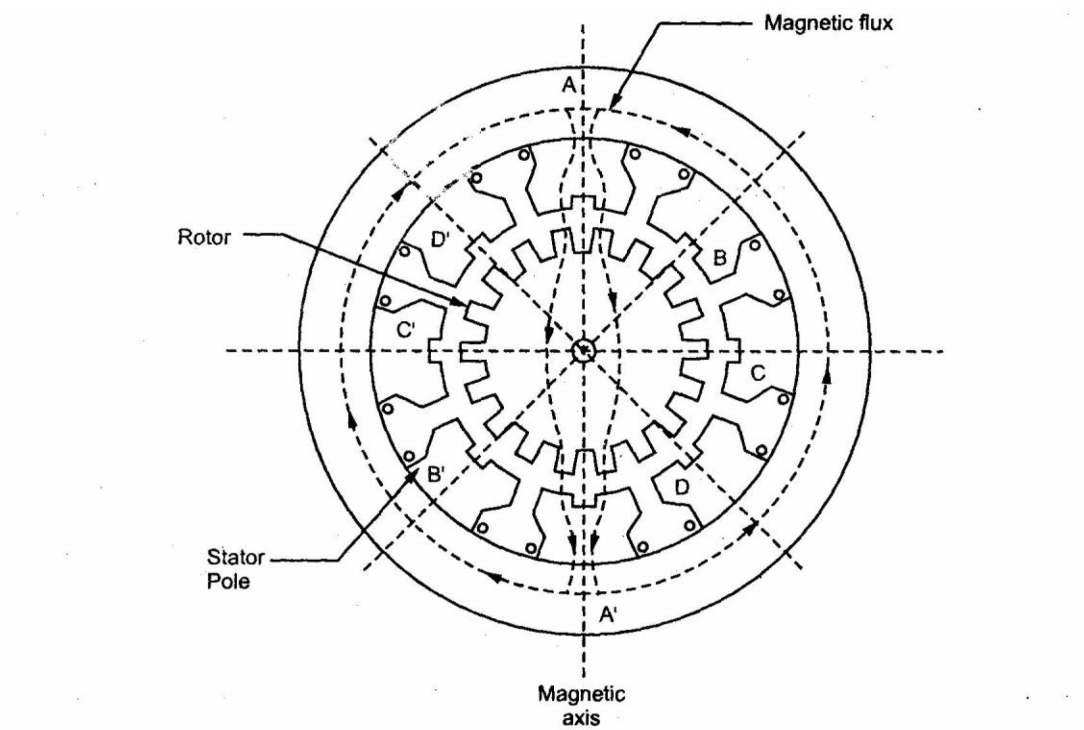


Fig. 7.9 Reduction gear stepper motor

With this arrangement, the step angle reduces to 5°. By successive excitation of coils A-A' , B —B' , C —C' and D —D' , the rotor makes 72 steps to complete one revolution. The general relationship between step angle a , number of stator phases q and rotor poles or teeth N remains satne as,

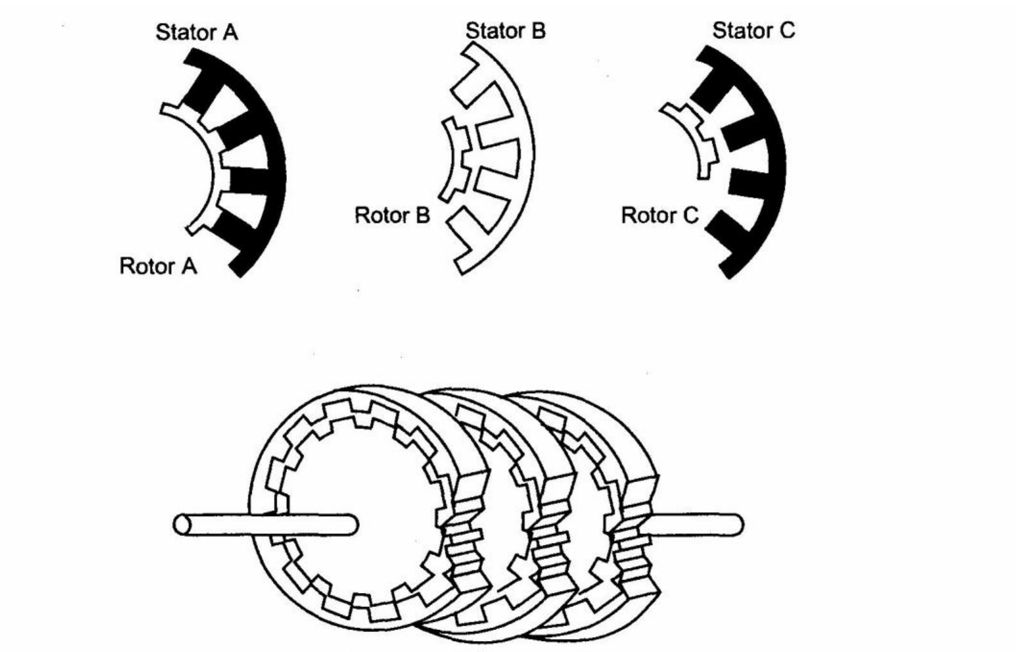
$$\alpha_s = \frac{360°}{q N_r}$$

By choosing different combinations of number of rotor teeth and stator phases, any desired step angle can be achieved.

7.6.5 MULTISTACK STEPPER MOTOR

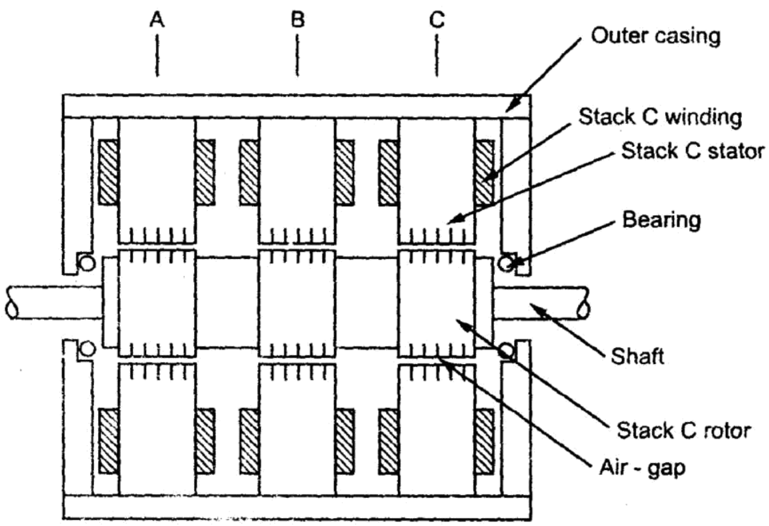
As mentioned earlier, these are used to obtain small step size, typically ranging between 2 to 15°.

In a m stack motor, the motor is divided into a m number of magnetically isolated sections called stacks, along its axial length. The m stacks of stator have a common frame while the rotors are mounted on a common shaft. The stators and rotors have the same number of poles (teeth). The stator poles in m stacks are aligned while the rotor poles are shifted by (1/rn) of the pole pitch from one another. All the stator windings in a stator stack are excited simultaneously hence each stator stack forms a phase. So number of stator phases is equal to number of stator stacks. Generally three stack stepper motors are used. The Fig. 7.10 shows the arrangement in three stack stepper motor alongwith shifting of the rotor poles by (1/3) of the pole pitch from one another.



The Fig. 7.11 shows the cross sectional view of a three stack, three phase variable reluctance motor. In each stack, the stator and rotor laminations have 12 poles. The poles of the stator are in one line while the rotor poles are offset from each other by one third of the pole pitch.

The various windings in one stack are energized simultaneously. When phase A of stator is excited then rotor poles of stack A get aligned with the stator poles. But due to offset, rotor poles of stack B and C do not align. Now if phase A is de-energized and phase B is energized, rotor poles of stack B get aligned with the stator poles. Thus, rotor moves by one third of pole pitch. When B is de-energized and C is excited, rotor further moves by one third of pole pitch so that rotor poles of stack C get aligned with the stator poles.



If m is the number of stac± phases and Nr ‘ be the rotor poles then the step angle is givenby,

$$\alpha_s = \frac{360^\circ}{m\,N_r}$$

In the case discussed above, m = 3 and N = 12 hence the step angle is,

$$\alpha_s = \frac{360^\circ}{3 \times 12} = 10^\circ$$

An alternative design where the rotor stacks are aligned and stator stacks are offset also is used in practice.

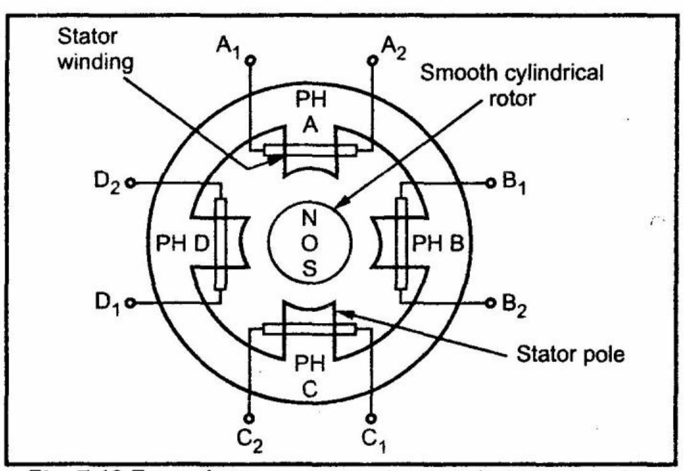
7.6.6 Advantages of Variable Reluctance Motor

The ‘ variable reluctance stepper motor has following advantages

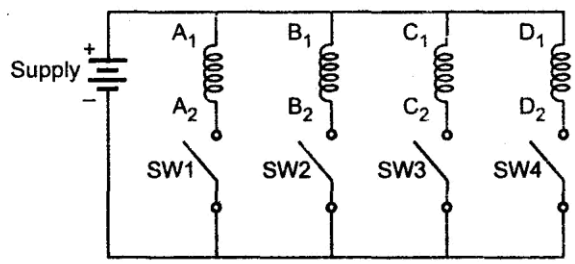
1. High torque to inertia ratio.
2. High rates of acceleration.
3. Fast dynamic response
4. Simple and low cost machine.
5. Efficient cooling arrangement as all the windings are on stator and there is no winding on rotor.
6. Rotor construction is robust due to absence of brushes.

7.7 PERMANENT MAGNET STEPPER MOTOR

The stator of tWs type is multipolar. As shown in the Fig. 7.12, the stator has four poles. Around the poles the exciting coils are wound. The number of slots per pole per phase is usually chosen as one in such multipolar machines.



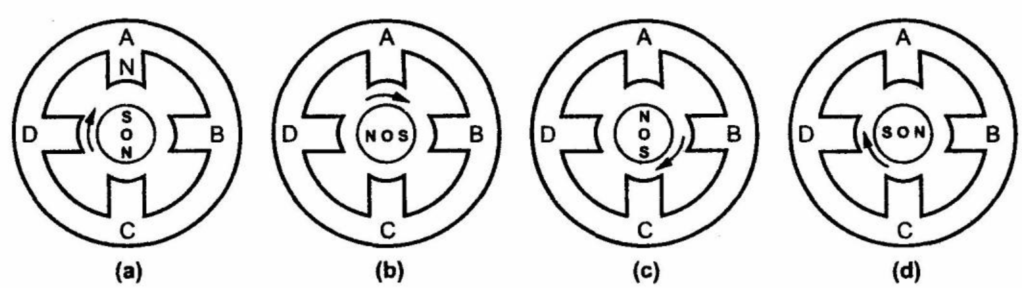
The rotor may be salient or smooth cylindrical. But generally it is smooth cylindrical type as shown in the Fig. 7.12. It is made
out of ferrite material which permanently magnetised. Due to this the motor is
called permanent magnet stepper motor.
The voltage pulses to the stator winding can be obtained by using a driving circuit. The basic driving circuit for four phase permanent magnet stepper motor is shown in the Fig. 7.13.



7.7.1 OPERATION

As soon as the voltage pulses are applied to various phases with the help of driving circuit, a rotor starts rotating through a step for each input voltage pulse.

1. At first, switch SWI is closed exciting the phase A. Due to its excitation we have N pole in phase A as shown in the Fig. 7.14 (a). Due to the electromechanical torque developed, rotor rotates such that magnetic axis of permanent magnet rotor adjusts with the magnetic axis of the stator, as shown in the Fig. 7.14 (a).



2. Next phase B is excited with switch SW2, disconnecting phase A. Due to this, rotor further adjusts its own magnetic axis with N pole of phase B. Hence it rotates through 9Ø0 further in clockwise direction as shown in the Fig. 7.14 (b).

Similarly when phase C and phase D are sequentially excited, the rotor tends to rotate through 90° in clockwise direction, every time when phase is excited. When such sequence is repeated, it results into a step motion of a permanent magnet stepper motor. The stepper motors with permanent magnet rotors with large number of poles can not be manufactured in small size. Hence small steps are not possible. This is the biggest disadvantage of permanent magnet stepper motor. This is overcome by the use of variable reluctance type stepper motor.

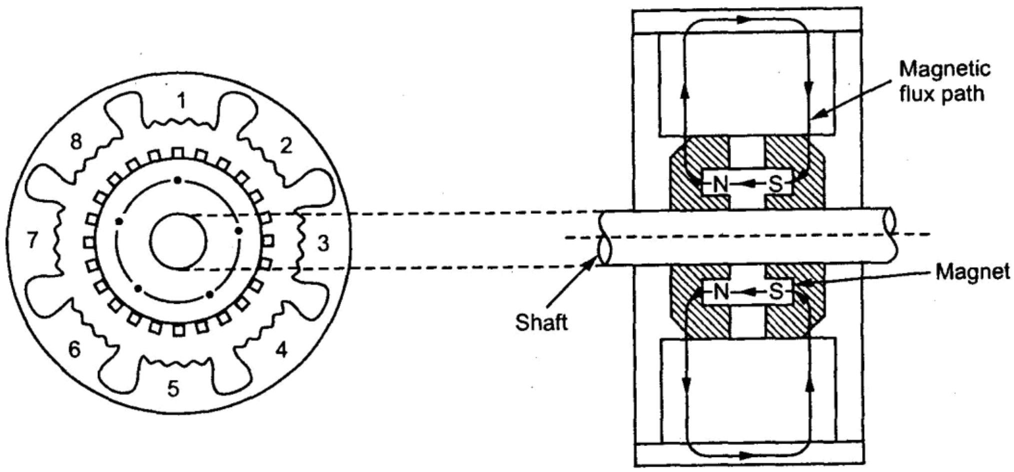
7.8 Comparison Between Variable Reluctance and Permanent Magnet Stepper Motor

	Variable reluctance stepper motor	Permanent magnet stepper motor
1.	The rotor is not magnetised.	The rotor is magnetised.
2.	High torque to inertia ratio.	Low torque to inertia ratio.
3.	High rates of acceleration.	Acceleration is slow
4.	The dynamic response is fast.	Very slow dynamic response
5.	Maximum stepping rate can be as high as 1200 pulses per second.	Maximum stepping rate can be around 300 pulses per second
6.	It can be manufactured for large number of poles	It can not be manufactured for large number of poles due to difficulties in construction.
7.	Very small step angle is possible.	The step angles are high in the range of 30° to 90°
8.	It does not have a detent torque.	Its main advantage is the presence of a detent torque.
9.	The rotor has salient pole construction.	The rotor has mostly smooth cylindrical type of construction.

However, now a days a disk type of permanent magnet stepper motors are designed which have the low inertia and smaller step angles.

7.9 HYBRID STEPPER MOTOR

The hybrid stepper motor uses the principles of the permanent magnet and variable reluctance stepper motors. In the hybrid motors, the rotor flux is produced by the permanent magnet and is directed by the rotor teeth to the appropriate parts of the airgap. The permanent magnet is placed in the middle of the rotor. It is magnetized in the axial direction. Each pole of the magnet is surrounded with soft-toothed laminations.
The main flux path is from the north pole of the magnet, into the end stack, across the airgap through the stator pole, axially along the stator, through the stator pole, across the air
gap and back to the magnet south pole via the other end stack.
There are usually 8 poles on the stator. Each pole has between 2 to 6 teeth. There is two phase winding. The coils on poles 1,3,5 and 7 are connected in series to form phase A while the coils on poles 2,4,6 and 8 are connected in series to form phase B. The windings A and B are energised alternately
When phase A carries positive current, stator poles 1 and 5 become south and 3 and 7 become north. The rotor teeth with north and south polarity align with the teeth of stator



poles I and 5 and 3 and 7 respectively. When phase A is de energised and phase B is excited, rotor will move by one quarter of tooth pitch.

The torque in a hybrid motor is produced by the interaction of the rotor and the stator produced fluxes. The rotor field remains constant as it is produced by the permanent magnet. The motor torque Tm is proportional to the phase current.

Following are the main advantages of the hybrid stepper motor

1. Very small step angles upto 1.8°
2. Higher torque per unit volume which is more than in case of variable reluctance motor
3. Due to permanent magnet, the motor has some detent torque which is absent in variable reluctance motor

These are the various types of the stepper motors. After discussing the various types and the operating principle, let us discuss the important parameters related to a stepper motor. The stepper motor characteristics are mainly the indication of its important parameters.

7.10 IMPORTANT DEFINITIONS

1. HOLDING TORQUE

It is defined as the maximum static torque that can be applied to the shaft of an excitea motor without causing a continuous rotation.

2. Detent Torque

It is defined as the maximum static torque that can be applied to the shaft of an unexcited motor without causing a continuous rotation.

Under this torque the rotor comes back to the normal rest position even if excitation ceases. Such positions of the rotor are referred as the detent positions.

3. Step Angle:

It is defined as the angular displacement of the rotor in response to each input pulse.

4. Critical Torque:

It is defined as the maximum load torque at which rotor does not move when an exciting winding is ener This is also called pullout torque.

5. Limiting Torque:

It is defined for a given pulsing rate or stepping rate measured in pulses per second, as the maximum load torque at which motor follows the control pulses without missing any step. This is also called pull in torque.

6. Synchronous stepping rate:

It is defined as the maximum rate at which the motor can step without missing steps. The motor can start, stop or reverse at this rate.

7. Slewing rate:

It is defined as the maximum rate at which the motor can step unidirectionally. The slewing rate is much higher than the synchronous stepping rate. Motor will not be able to stop or reverse without missing steps at this rate.

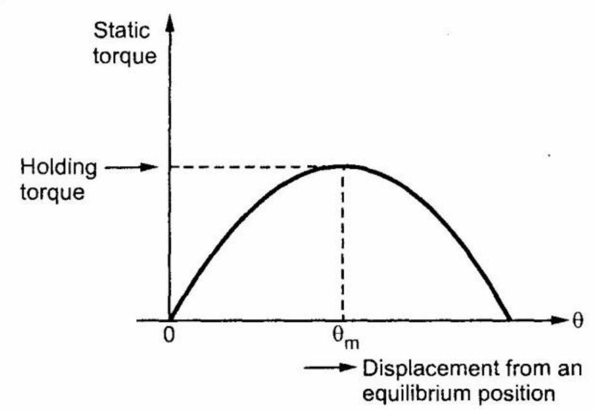
7.11 Stepper Motor Characteristics

The Stepper motor characteristics are classified as
1. Static characteristics and
2. Dynamic characteristics
The static are at the stationary position of the motor while the dynamic are under running conditions of the motor.

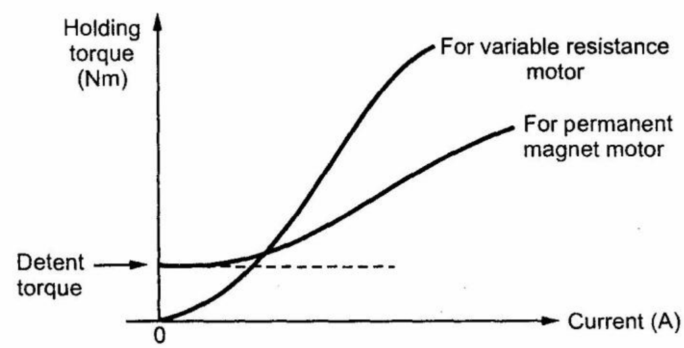
7.11.1 Static Characteristics

These characteristics include
1. Torque displacement characteristics
2. Torque current characteristics

Torque-displacement characteristics: This gives the relationship between electromagnetic torque developed and displacement angle 0 from steady state position. These characteristics are shown in the Fig. 7.16



Torque-current characteristics : The holding torque of the stepper motor increases with the exciting current. The relationship between the holding torque and the current is called as torque-current characteristics. These characteristics are shown in the Fig.7.17



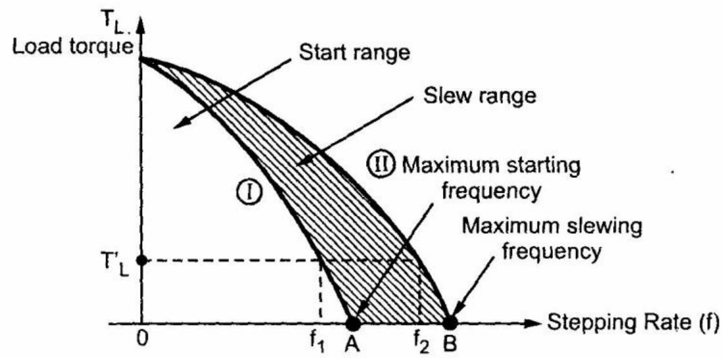
7.11.2 DYNAMIC CHARACTERISTICS

The stepping rate selection is very important in proper controlling of the stepper motor. The dynamic characteristics gives the information regarding torque stepping rate. These are also called torque stepping rate curves of the stepper motor. These curves are shown in the Fig. 7.18.

When stepping rate increases, rotor gets less time to drive the load from one position to other. If stepping rate is increased beyond certain limit, rotor can not follow the command and starts missing the pulses.

Now if the values of load torque and stepping rate are such that point of operation lies to

the left of curve I, then motor can start and synchronise without missing a pulse.



For example, for a load torque of TL, the stepping rate selection should be less than f so that motor can start and synchronize, without missing a step.

But the interesting thing is that once motor has started and synchronized, then stepping rate can be increased e.g. upto f for the above example. Such an increase in stepping rate from f to f is without missing a step and without missing the synchronism. But beyond f if stepping rate is increased, motor will loose its synchronism.

So point A as shown in the Fig.7.18 indicates the maximum starting stepping rate or maximum starting frequency. It is defined as the maximum stepping rate with which unloaded motor can start or stop without loosing a single step.

While point B as shown in the Fig. 7.18 indicates the maximum slewing frequence. It is defined as the maximum stepping rate which unloaded motor continues to run without missing a step.

Thus area between the curves I and II shown hatched indicates, for various torque values, the range of stepping rate which the motor can follow without missing a step, provided that the motor is started and synchronized. This area of operation of the stepper motor is called slew range. The motor is said to be operating in slewing mode.

It is important to remember that in a slew range the stepper motor can not be started, stopped or reversed without losing steps.

Thus slew range is important for speed control applications. In position control, to get the exact position the motor may be required to be stopped or reversed. But it is not possible in a slew range. Hence slew range is not useful for position control applications.

To achieve the operation of the motor in the slew range motor must be accelerated carefully using lower pulse rate. Similarly to stop or reverse the motor without loosing acceleration and deceleration of the stepper motor, without losing any step is called Ramping

7.12 APPLICATIONS OF STEPPER MOTORS

Due to the digital circuit compatibility of the stepper motors, they are widely used in computer peripherals such as serial printers, linear stepper motors to printers, tape drives, floppy disc drives, memory access mechanisms etc. The stepper motors are also used in serial printers in typewriters or word processor systems, numerical control of machine tools, robotic control systems, number of process control systems, actuators, spacecrafts, watches etc. X-Y recorders and plotters is another field in which stepper motors are preferred.

Review Questions

1. Write a note on reluctance motor and its applications.
2. Write a note on hystersis motor and its applications.
3. Show that in hysteresis motor, the eddy current torque component vanishes.
4. What is a stepper motor ? Explain the basic concept of a stepper motor.
5. Which are the various types of stepper motors ?
6. Explain the operation of a variable reluctance motor.
7. What is a step angle ? State the expression for the same.
8. How rotor tooth pitch is defined ?
9. What is microstepping ?
10. Explain in brief the following types of stepper motors

i) Reduction gear stepper motor
ii) Multi stack stepper motor
iii) Permanent magnet stepper motor
iv) Hybrid stepper motor

11. Compare variable reluctance motor with permanent magnet stepper motor.
12. State the advantages and disadvantages of variable reluctance motor.
13. Explain the important characteristics of permanent magnet stepper motor.
14. State the advantages of the hybrid stepper motors.
15. Define the following terms related to a stepper motor

i) Holding torque ii) Detent torque iii) Step angle iv) Critical torque v) Limiting torque vi) Slew rate vu) Synchronous stepping rate

University Questions

October-2002

1.
What are the applications of stepper motors
?
(2 Marks)

2.
Write brief note on
the following
i) Hysteresis motor
(8 Marks) May-
2003

1. Give the advantages of reluctance machines. (2 Marks)
2. Explain the principle of operation of hysteresis motor. (8 Marks)

November-2003

1. Give the applications of stepper motor.
2. Explain the principle of operation of reluctance
machines. April-2004

1.

State the
applications of stepper motor.
2.
Describe
the construction and principle of operation of reluctance
machine.
3.
Explain t
he construction and bperation of stepper motor.
November-2004
1. What are different types of stepper motor?
2. Explain the principle of operation of hysteresis motor.
3. Explain the principle of operation of permanent magnet stepper motor.

Unit 5

Structure Of Power Systems

For economical and technological reasons (which will be discussed in detail in later chapters), individual power systems are organized in the form of electrically connected areas or regional grids (also called power pools). Each area or regional grid operates technically and economically independently, but these are eventually interconnected to form a national grid (which may even form an international grid) so that each area is contractually tied to other areas in respect to certain generation and scheduling features. India is now heading for a national grid.

The siting of hydro stations is determined by the natural water power sources. The choice of site for coal fired thermal stations is more flexible. The following two alternatives are possible.

1. Power stations may be built close to coal mines (called pit head stations) and electric energy is evacuated over transmission lines to the load centers.

2. Power stations may be built close to the load centers and coal is transported to them from the mines by rail road.

In practice, however, power station siting will depend upon many factors technical, economical and environmental. As it is considerably cheaper to transport bulk electric energy over extra high voltage (EHV) transmission lines than to transport equivalent quantities of coal over rail road, the recent trends in India (as well as abroad) is to build super (large) thermal power stations near coal mines. Bulk power can be transmitted to fairly long distances over transmission lines of 400 kV and above. However, the country's coal resources are located mainly in the eastern belt and some coal fired stations will continue to be sited in distant western and southern regions.

As nuclear stations are not constrained by the problems of fuel transport and air pollution, a greater flexibility exists in their siting, so that these stations are located close to load centers while avoiding high density pollution areas to reduce the risks, however remote, of radioactivity leakage.

In India, as of now, about 75% of electric power used is generated in thermal plants (including nuclear). 23% from mostly hydro stations and 2%. come from renewables and others. Coal is the fuel for most of the steam plants, the rest depends upon oil/natural gas and nuclear fuels.

Electric power is generated at a voltage of 11 to 25 kV which then is stepped up to the transmission levels in the range of 66 to 400 kV (or higher). As the transmission capability of a line is proportional to the square of its voltage, research is continuously being carried out to raise transmission voltages. Some of the countries are already employing 765 kV. The voltages are expected to rise to 800 kV in the near future. In India, several 400 kV lines are already in operation. One 800 kV line has just been built.

For very long distances (over 600 km), it is economical to transmit bulk power by DC transmission. It also obviates some of the technical problems associated with very long distance AC transmission. The DC voltages used are 400 kV and above, and the line is connected to the AC systems at the two ends through a transformer and converting/inverting equipment (silicon controlled rectifiers are employed for this purpose). Several DC transmission lines have been constructed in Europe and the USA. In India two HVDC transmission line (bipolar) have already been commissioned and several others are being planned. Three back to back HVDC systems are in operation.

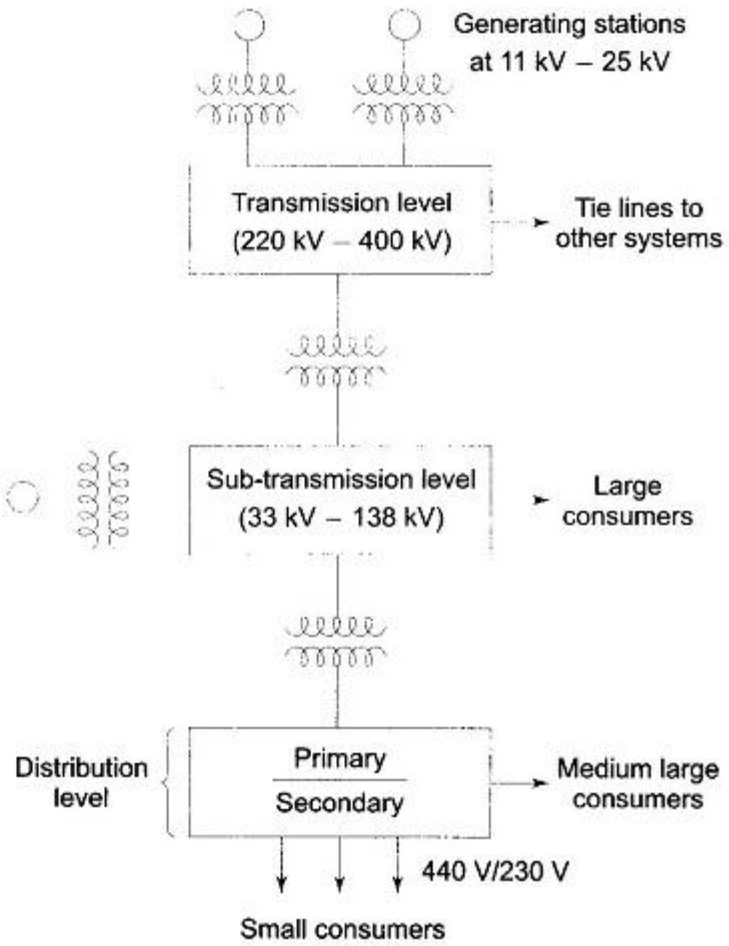


Fig. 1.3 Schematic diagram depicting power system structure

The first stepdown of voltage from transmission level is at the bulk power substation, where the reduction is to a range of 33 to 132 kV, depending on the transmission line voltage. Some industries may require power at these voltage levels. This stepdown is from the transmission and grid level to subtransmission level.

The next stepdown in voltage is at the distribution substation. Normally, two distribution voltage levels are employed:

1. The primary or feeder voltage (11 kV)

2. The secondary or consumer voltage (415 V three phase/230 V single phase).

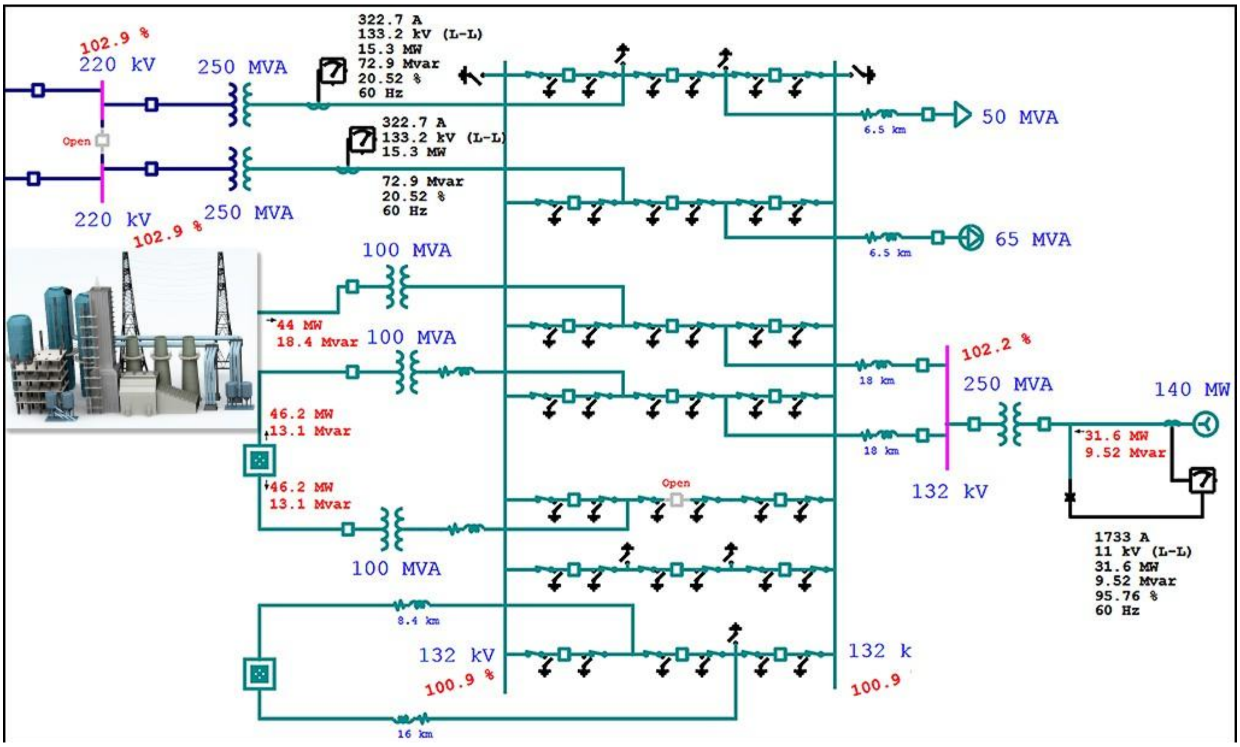
The distribution system, fed from the distribution transformer stations, supplies power to the domestic or industrial and commercial consumers.

Thus, the power system operates at various voltage levels separated by transformer. Figure 1.3 depicts schematically the structure of a power system. Though the distribution system design, planning and operation are subjects of great importance, we are compelled, for reasons of space, to exclude them from the scope of this book.

Single line diagram

Electrical Single-Line Diagram

The ETAP One-Line Diagram is a user-friendly interface for creating and managing the network database used for schematic network visualization.



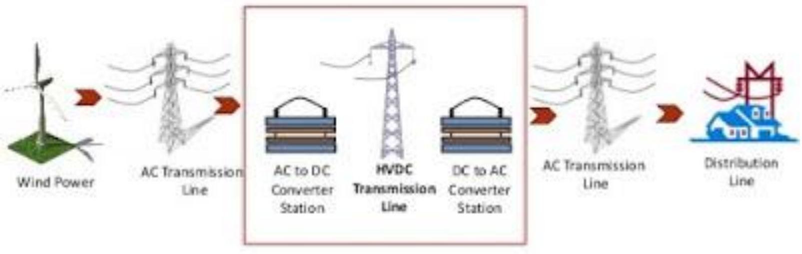
ETAP one-line diagram provides complete bus-breaker connectivity, allowing you to visualize network topology with complete confidence. Applying ground-breaking technologies never before used for power systems software, you can interactively model, monitor, and manage the electrical network as well as execute simulation scenarios and analyze their results in a simple and intuitive manner.

Key Features

- Built-in intelligent graphics
- Autobuild one-line diagram
- Built-in and user-defined templates for substations, protection, etc.
- Datablock templates for visualizing user-defined properties and results
- Bus - Breaker and Bus - Branch representation of electrical networks
- Network nesting
- Integrated 1-phase, 3-phase, & DC systems
- Integrated AC, DC, & grounding systems
- Automatic display of energized & de-energized elements using dynamic continuity check
- Theme manager with standard, phase, layers, voltage, area, & grounding / earthing colors

HVDC – Advantage & Disadvantage

A scheme diagram of HVDC Transmission is shown below for ease in understanding the advantages and disadvantages.



There is a list of advantages of High Voltage DC Power Transmission, HVDC when compared with High Voltage AC Power Transmission, HVAC. They are listed below with detail while comparing with HVAC.

Line Circuit:

The line construction for HVDC is simpler as compared to HVAC. A single conductor line with ground as return in HVDC can be compared with the 3-phase single circuit HVAC line (**Why? Can't we supply power with two phases in HVAC?)**. As because when Line to Earth Fault or Line-Line Fault 3-phase system cannot operate. This is why we compared the a single conductor line with ground as return can be compared with the 3-phase single circuit HVAC line. Thus ***HVDC line conductor is comparatively cheaper while having the same reliability as 3-phase HVAC system.***

Power Per Conductor:

Power Per conductor in HVDC $P_d = V_d I_d$

Power Per Conductor in HVAC $P_a = V_a I_a Cos Ø$

Where I_d and $I_a$are the line current in HVAC and HVDC circuit respectively & $V_d$and V_a are the voltage of line w.r.t ground in HVDC and HVAC respectively.

As crest voltage is same for Insulators of Line, therefore line to ground voltage in HVDC will be root two (1.414) times that of rms value of line to ground voltage in HVAC.

$V_d = 1.414V_a$and $I_d = I_a$ (assumed for comparison purpose)

Therefore,

$P_d / P_a = V_d I_d / V_a I_a Cos Ø$

$= V_d I_d / (V_d/1.414) I_d Cos Ø$

$= 1.414/Cos Ø$

As Cos$\varnothing$ <= 1,

$P_d / P_a > 1$

$P_d > P_a$

Therefore, we see that power per conductor in HVDC is more as compared to HVAC.

Power Per Circuit:

Now, we will compare the power transmission capabilities of 3-phase single circuit line with**Bipolar HVDC Line. (Bipolar HVDC Line have two conductors one with +ive polarity and another with –ive polarity.)**

Therefore, for Bipolar HVDC Line,

$P_d = 2 \times V_d I_d$

While for HVAC Line,

$P_{ac} = 3 \times V_a I_a \text{Cos}\varnothing$

Hence,

$P_d / P_{ac} = 2V_d I_d / 3V_a I_a \text{Cos}\varnothing$

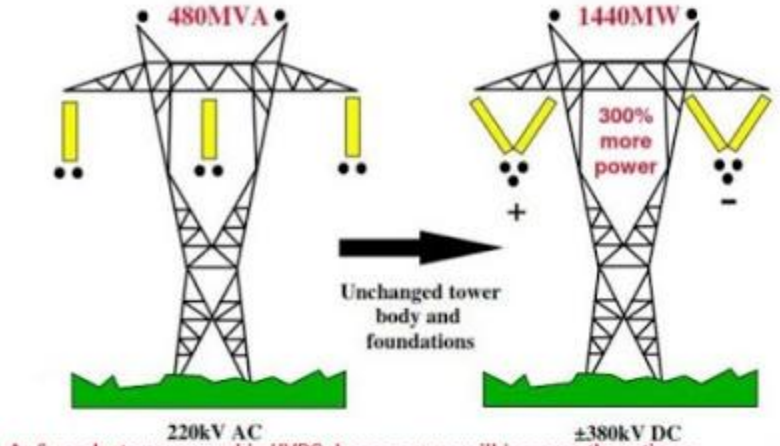
But $V_d = 1.414V_a$ and $I_d = I_a$

$P_d / P_{ac} = (2 \times 1.414) / 3\text{Cos}\varnothing$

$= 2.828 / 3\text{Cos}\varnothing \approx 0.9$ (as Cos$\varnothing$ <1)

Thus we see that power Transmission Capability of Bipolar HVDC Line is same as 3-phase single circuit HVAC Line. But in case of HVDC, we only need two conductors while in 3-phase HVAC we need three conductors, therefore number of Insulators for supporting conductors on tower will also reduce by 1/3. Hence, HVDC tower is cheaper as compared to HVAC.

Observe the figure below carefully, you will get to know three important points about HVDC
.



As 6 conductors are used in HVDC, hence power will increase three times.

No Charging Current:

Unlike HVAC, there is no charging current involved in HVDC which in turn reduces many accessories.

No Skin Effect:

In HVDC Line, the phenomenon of Skin Effect is absent. Therefore current flows through the whole cross section of the conductor in HVDC while in HVAC current only flows on the surface of conductor due to Skin Effect.

No Compensation Required:

Long distance AC power transmission is only feasible with the use of Series and Shunt Compensation applied at intervals along the Transmission Line. For such HVAC line, Shunt Compensation i.e. Shunt Reactor is required to absorb KVARs produced due to the line charging current (because the capacitance of line will dominate during low load / light load condition which is famously known as **Farranty Effect**.) during light load condition and series compensation for stability purpose.

As HVDC operates at unity power factor and there is no charging current, therefore no compensation is required.

Less Corona Loss and Radio Interference:

As we know that, Corona Loss is directly proportional to (f+25) where f is frequency of supply. Therefore for HVDC Corona Loss will be less as f=0. As Corona Loss is less in HVDC therefore Radio Interference will also be less compared to HVAC.
The interesting thing in HVDC is that, Corona and Radio Interference decreases slightly by foul whether condition like snow, rain or fog whereas they increases Corona and hence Radio Interference in HVAC.

Higher Operating Voltage:

High Voltage Transmission Lines are designed on the basis of Switching Surges rather than Lightening Surges as Switching Surges is more dangerous compared to Lightening Surges.
As the level of Switching Surges for HVDC is lower as compared with HVAC, therefore the same size of conductors and Insulators can be used for higher voltage for HVDC when compared with HVAC.

No Stability Problem:

As we know that for two Machine system, power transmitted,
$P = (E1E1Sin\delta)/X$
Where X is inductive reactance of the line, E1 & E2 are the sending and receiving end voltage respectively.

As the length of line increases the value of X increases and hence lower will be the capability of Machine to transmit power from one end to another. Thus, reducing the Steady State Stability Limit. As the Transient Stability Limit is lower than Steady State Stability Limit, thus for longer line Transient Stability Limit becomes very poor.

EHVAC

The first 735 kV system was commissioned in Canada in 1965. Since then, voltage levels up to 765 kV have been introduced in Russia with neighboring countries, U.S.A, South Africa, Brazil, Venezuela and South Korea. The general trend of 800 kV investments is indicated in the diagram, which shows the total capacity of power transformers and generator step-up transformers for 800 kV delivered by ABB. Since the 90's, the investments in 800 kV systems have been much lower compared to the 70's and 80's. However, plans are under way for future introduction of 800 kV in India and China. The planned introductions of voltages in the UHV range, i.e. 1000 kV and above, have been cancelled or postponed in several countries. e.g. Russia, Italy and U.S.A. Future 1000 kV lines are only considered in Japan.

HVDC

The first HVDC system for ± 500 kV and above was the Cabora Bassa project, commissioned in 1979. The Brasilian Itaipu project is the only HVDC system operating at ±600 kV so far. The major HVDC investments at these voltage levels were made in the late 80's and early 90's. However, an increasing interest in high-capacity HVDC links have been noted in recent years, as seen from the diagram, which shows all HVDC projects for ±500 kV and above. The need for higher voltage levels can be anticipated for HVDC projects in the near future, especially when the transmission line is more than 1000 km long. From a technical point of view, there are no special obstacles against higher DC voltages. Present solutions are extendable to e.g. ±800 kV when the need arises. The need for higher voltage levels can be anticipated for HVDC projects in the near future, especially when the transmission line is more than 1000 km long. From a technical point of view, there are no special obstacles against higher DC voltages. Present solutions are extendable to e.g. ±800 kV when the need arises.

Design aspects for AC DC transmission lines

The general design criteria for AC and DC transmission lines can be divided into electrical and mechanical aspects, both having considerable effects on the investment and operation costs. The power transmission capacity determines the voltage level and the number of parallel circuits, which has a great influence on the investment costs. Other aspects are emergency loading capability and reactive power compensation of AC lines. The power losses affects mainly the operating costs and should therefore be optimized with regard to investment cost of the line conductors at the given voltage level. The insulation performance is determined by the overvoltage levels, the air clearances, the environmental conditions and the selection of insulators. The requirements on the insulation performance affect mainly the investment costs for the towers. The corona performance influences heavily on the design of the conductor bundles and, subsequently, on the mechanical forces on the towers from wind and ice loading of the conductors. Any constraints on the electromagnetic fields at the ground level will, however, primarily influence the costs for the right-of-way. The mechanical loading, and hence the investment cost of towers, insulators and conductors, depends mainly on the design of the conductor bundles and the climatic conditions.

1. MERITS & DEMERITS OF HVDC

Merits of HVDC

Undersea cables, where high capacitance causes additional AC losses. (e.g., 250 km Baltic Cable between Sweden and Germany),

Endpoint-to-endpoint long-haul bulk power transmission without intermediate.

Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install

Power transmission and stabilization between unsynchronized AC distribution systems.

Connecting a remote generating plant to the distribution grid, for example Nelson River Bipoler.

Stabilizing a predominantly AC power-grid, without increasing prospective short circuit current.

Reducing line cost. HVDC needs fewer conductors as there is no need to support multiple phases. Also, thinner conductors can be used since HVDC does not suffer from the skin effect.

Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies.

Synchronize AC produced by renewable energy sources.

Demerits

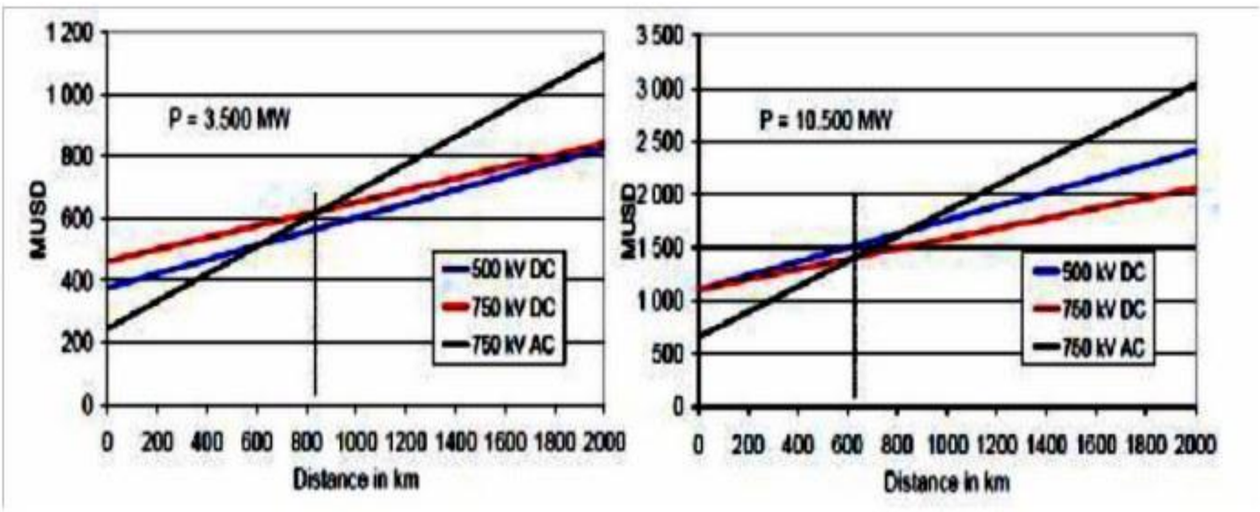
Circuit breaking Is difficult in D.C circuits, therefore the coast of dc circuit is high.

D.C system does not have step up or step down transformers to change the voltage level.

The coast of converter station is very high. Both ac and dc harmonics are generated. System control stability is quite difficult.

2. ECONOMICAL COMPARISION EHVAC and HVDC

The trend of power electronic components, for use in the main circuit of an HVDC transmission, being developed means that the relative cost of HVDC transmissions is reduced as the components become cheaper as a result of continuing innovative technological developments. Thus a large converter station with a cost of 50 USD/kW is today cheaper in current dollars compared with the situation 20 years ago. The dc line is less costly compared with an 800 kV ac line. On the other hand, the converter station cost offsets the gain in reduced cost of the transmission line. Thus a short line is cheaper with ac transmission, while a longer line is cheaper with dc.



In a general comparison of HVDC vs. EHVAC power transmission, the design of the transmission lines and the related investment costs are of great importance. The aim of this paper has been to focus on the differences in the design of line insulation and conductor configuration, and its influence on the mechanical loads. For the line insulation, air clearance requirements are more critical with EHVAC due to the nonlinear behavior of the switching overvoltage withstand. The corona effects are more pronounced at AC voltage, therefore, larger conductor bundles are needed at higher system voltages. The altitude effects are more important to HVDC lines, since the lightning overvoltage withstand is the most sensitive insulation parameter with regard to air density. The mechanical load on the tower is considerably lower with HVDC due to less number of sub conductors required to fulfill the corona noise limits. The high transmission capacity of the HVDC lines, combined with lower requirements on conductor bundles and air clearances at the higher voltage levels, makes the HVDC lines very cost efficient compared to EHVAC lines. The cost advantage is even more pronounced at the highest voltage levels.

MERITS & DEMERITS OF HVDC

Merits of HVDC

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Endpoint-to-endpoint long-haul bulk power transmission without intermediate.

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