GOVERNMENT POLYTECHNIC, SONEPUR

LECTURE NOTE

ENERGY CONVERSION- II

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CHAPTER-I

Induction Motor

Construction :

The induction motor mainly divided in to two parts.

(1) Stator (2) Rotor

In case of D. C. Motor basically it is divided into two main parts (i) Yoke (ii) Armature. Yoke is outer & stationary part, similarly the outer portion of the induction motor is known as stator. It is also stationary part of the induction motor. The stator of the induction motor is cylindrical in shape.

The inner part of D. C. Motor i.e., armature is rotating in nature. Similarly the rotating part of the induction motor is known as rotor. The rotor lies inside the stator. It is cylindrical in shape.

Rotor is divided into two types.

(i) Squirrel cage Rotor

(ii) Phase wound Rotor or Slip ring Rotor,

Figure shows the disassembled view of an induction motor with squirrel cage rotor.

(a) Stator (b) Rotor (c) bearing shields (d) Fan (e) Ventilation grill (f) terminal box.

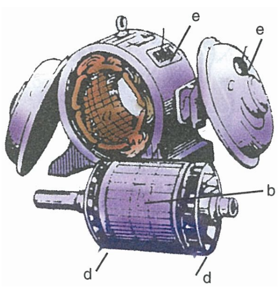


Fig 1.1

Similarly figure shows the disassembled view of a slip ring motor (a) stator (b) rotor (c) bearing shields (d) Fan (e) Ventilation grill (f) Terminal box (g) Slip ring (h) brushes & brush holder.

Production of Rotating Magnetic Field :

When 3 – phase stationary coils are fed with 3 – phase supply, a uniformly rotating magnetic flux of constant magnitude will produce.

It will now be shown that when three – phase winding displaced in space by 120^0, are fed by three phase currents, displaced in time by 120^0, they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

The principle of a 3 – phase, two pole stator having three identical windings placed 120^0 space degree apart as shown in fig – 1.2. The flux due to three phase windings is shown in fig 1.3.

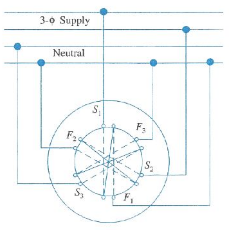


Fig 1.2

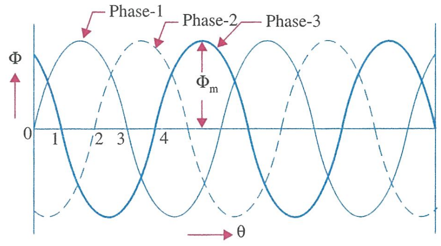


Fig 1.3

Let the maximum value of flux due to any one of the three phases be ϕ_m. The resultant flux ϕ_r, at any instant is given by the vector sum of the individual fluxes ϕ_1, ϕ_2 and ϕ_3 due to three phases. Considering values of ϕ_r at four instants i.e. $1/6^{th}$ time period apart corresponding to points marked 0, 1, 2 & 3.

Proof :

Case – 1 : Resultant flux at origin i.e. when $\theta = 0^0$ At that time $\phi_1 = 0$,

$\phi_2 = \phi m \text{ Sin} < -120^0 = -\frac{\sqrt{3}}{2}\ \phi m$ $\phi_3 = \phi m \text{ Sin} < -240^0 = -\frac{\sqrt{3}}{2}\ \phi m.$

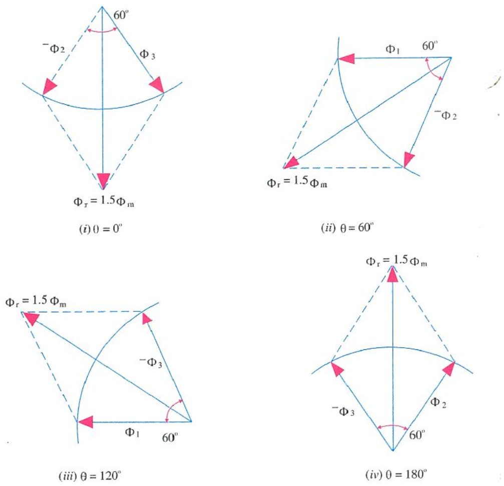


Fig 1.4

Resultant flux ϕ_r :

As per law of parallerogram

$$\phi_r^2 = \phi_2^2 + \phi_3^2 + 2\,\phi_2 \cdot \phi_3 \cdot \cos 60^0$$

$$\Rightarrow \phi_r^2 = \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2.\ \frac{\sqrt{3}}{2}\ \phi_m \cdot \frac{\sqrt{3}}{2}\ \phi_m\ \frac{1}{2}$$

$$\Rightarrow \phi_r^2 = \frac{3}{4}\phi_m^2 + \frac{3}{4}\phi_m^2 + \frac{3}{4}\phi_m^2$$

$$\Rightarrow \phi_r^2 = \frac{9}{4}\phi_m^2$$

$$\Rightarrow \phi_r = \frac{3}{2}\phi_m$$

$$\Rightarrow \phi_r = 1.5\ \phi_m$$

Case – II : When $\theta = 60^0$

Therefore $\phi_1 = \phi_m \text{ Sin} < 60^0 = \frac{\sqrt{3}}{2}\ \phi_m$

$\phi_2 = \phi_m \text{ Sin} < -120^0 + 60^0 = \phi_m \text{ Sin} < -60^0 = \dfrac{-\sqrt{3}}{2}\ \phi_m$

and $\phi_3 = \phi_m \text{ Sin} < -240^0 + 60^0 = \phi_m \text{ Sin} < -180 = 0$

case – III When $\theta = 120^0$

$\phi_1 = \phi_m \text{ Sin} < 120^0 = \dfrac{\sqrt{3}}{2}\ \phi_m$

$\phi_2 = \phi_m \text{ Sin} < -120^0 + 120^0 = \phi_m \text{ Sin} < 0^0 = 0$

$\phi_3 = \phi_m \text{ Sin} < -240^0 + 120^0 = \phi_m \text{ Sin} < -120^0 = \dfrac{-\sqrt{3}}{2}\ \phi_m$

ϕ_r can be calculated as earlier

Similarly $\phi_r = 1.5\phi_m$

Case – IV When $\theta = 180^0$

$\phi_1 = \phi_m \text{ Sin} < 180^0 = 0$

$\phi_2 = \phi_m \text{ Sin} < -120^0 + 180^0 = \phi_m \text{ Sin} < 60^0 = \dfrac{\sqrt{3}}{2}\ \phi_m$

$\phi_3 = \phi_m \text{ Sin} < -240^0 + 180^0 = \phi_m \text{ Sin} < -60^0 = \dfrac{-\sqrt{3}}{2}\ \phi_m$

Similarly ϕ_r can be calculated as earlier $\phi_r = 1.5\ \phi_m$

Hence from the above four cases we can draw a conclusion that the resultant flux (ϕ_r) inside the stator winding at any time = 1.5 ϕm and the resultant flux (ϕ_r) rotates around the stator at syncronous speed.

How the rotor rotates :

The rotor lies inside the stator. There is an air gap in between the stator and rotor. The stator slots are provided with three Phase winding.

When three phase stator windings are fed by a 3-phase supply then a rotating magnetic flux of constant magnitude will produce.

This rotating flux passes through air gap and cuts the stationary conductors on the rotor . There is also a 3-phase rotor winding on the rotor. The stator and rotor windings act as primary and secondary windings of a 3-phase transformer. The air gap acts as core of the transformer. The fluxes passes from stator to rotor winding through induction principle.

The rotating flux produces an emf in the rotor winding. The rotor winding is closed circuit. Hence current will flow in the rotor conductors. When current will flow it will produce the flux in the air gap. The flux in the rotor winding interacts with the flux in the stator winding there by producing a torque, which is responsible for the rotation of the rotor.

Slip(s) :

The rotor never succeeds in catching up with the stator field. It is really did so, then there would be no relative speed between the two, hence no rotor emf, no rotor current and so no torque to maintain rotation. That in why the rotor runs at a speed which is always less than the speed of the stator field.

The difference between synchronous speed N_s to the actual speed of the totor N_r is known as slip speed.

Slip speed = $N_s - N_r$.

Slip (s) or % of Slip (s) = $\frac{N_s - N_r}{N_s} \times 100$

$$\Rightarrow S = \frac{N_s - N_r}{N_s}$$

$\Rightarrow N_s - N_r = SN_s$

$\Rightarrow N_s - SN_S = N_r$

$\Rightarrow N_s(1\text{-}S) = N_r$

Therefore Rotor speed $N_r = N_s\ (1\text{-}S)$

Frequency of Rotor Current :

When the rotor is stationary, the frequency of rotor current is the same as the supply frequency. But when the rotor starts revolving, then the frequency depends upon the relative speed. Let the frequency of the rotor current be f'.

Hence N_s - N_r $= = \frac{120 f'}{P}$

As Ns = $= \frac{120f}{P}$

$$\Rightarrow \frac{N_s - N_r}{N_s} = \frac{120f'}{P} \times \frac{P}{120f}$$

$$\Rightarrow S = \frac{f'}{f}$$

Therefore $f' = Sf$

Hence Rotor frequency = slip x supply frequency

Torque of an Induction Motor :

The torque of an induction motor is the torque produced at the rotor. Hence $T=T_r$ where T_r is the rotor torque.

In case of D.C. motor torque = Armature Torque = T_a

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

There fore $T_a = K\phi I_a$

[Where 0.159, Z, P and A are all constants)

Where ϕ is the flux produced by the filed winding which is pulsating in nature.

Similarly in case of an induction motor the torque is also proportional to the product of flux produced in stator and rotor current.

However there is another factor which is to be taken is power factor. Because in this case both flux and current are alternating in nature.

Therefore $T_r \alpha \phi I_2 \cos \phi_2$

Where I_2 – Rotor Current

ϕ - flux produced in the stator.

ϕ_2 – The phase angle between rotor emf and rotor current (E_2 and I_2)

As $\phi \alpha E_2$

Therefore $T_r = T \alpha E_2 I_2 \cos \phi_2$

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

Starting Torque :

The torque developed by the motor at the instant of starting is called starting torque.

Let E_2 = Rotor emf per phase at stand still

R_2 = Rotor resistance / phase

X_2 = Rotor reactance / phase at stand still

$Z_2 = \sqrt{R_2^2 + X_2^2}$ = Rotor impedance / phase at stand still

Then $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$, $\cos \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$

Stand still or starting torque $T_{st} = K\, E_2\, I_2 \cos \phi_2$

Or $T_{st} = K\, E_2 \cdot \frac{E_2}{\sqrt{R_2^2 + R_2}} \cdot \frac{R_2}{\sqrt{R_2^2 + R_2}} = \frac{K\, E_2^2\, R_2}{R_2^2 + R_2}$

If supply voltage V remains constant, then the flux ϕ and hence E_2 remain constant.

Therefore $T_{st} = K_1 \frac{R_2}{R_2^2 + X_2^2}$

$\Rightarrow Tst = K_1 \frac{R_2}{Z_2^2}$

Starting Torque of a Squirrel – cage Induction Motor :

The resistance of a squirrel cage motor is fixed and small as compared to its reactance which is very large especially at the start because at stand still, the frequency of the rotor currents equal the supply frequency. Hence the starting current I_2 of the rotor, though very large in magnitude, laggs by a very large angle E_2, with the result that the starting torque per ampere is very poor. Hence, such motors are not useful where the motor has to start against heavy loads.

Starting Torque of a slip-ring motor :

The starting torque of such motor is increased by improving its power factor by adding external resistance in the rotor circuit from the star connected rheostat, the rheostat resistance being progressively cut out as the motor gathers speed. Addition of external resistance, however increases the rotor impedance and so reduces the rotor current. At first, the effect of improved power factor predominates the current–decrearing effect of impedance. Hence, starting torque is increased. But after a certain point, the effect of increased impedance predominates the effect of improved power factor and so the torque starts decreasing.

Condition for maximum starting Torque :

As starting torque $T_{st} = \dfrac{K_2 R_2}{R_2^2 + X_2^2}$

From mathematics we know that differentiation of a maximum quantity = 0

D (T_{st}) = 0, when T_{st} = Maximum starting Torque

Therefore $\dfrac{d(T_{st})}{dR_2} = 0$

$$\Rightarrow \frac{d}{dR_2}\left(\frac{K_2 R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow K_2 \frac{d}{dR_2}\left(\frac{R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow \frac{d}{dR_2}\left(\frac{R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow \frac{\left(R_2^2 + X_2^2\right)\cdot \frac{d}{dR_2}\cdot R_2 \;-\; R_2 \frac{d}{dR_2}\left(R_2^2 + X_2^2\right)}{\left(R_2^2 + X_2^2\right)^2} = 0$$

$$\Rightarrow R_2^2 + X_2^2 \cdot 1 - R_2\left(2R_2 + 0\right) = 0$$

$$\Rightarrow R_2^2 + X_2^2 - 2R_2^2 = 0$$

$$\Rightarrow X_2^2 = R_2^2$$

$$\Rightarrow R_2 = X_2$$

Hence the starting torque will be maximum when Rotor resistance = Rotor Reactance.

Rotor EMF and Rotor reactance under running condition :

Rotor EMF : Let E_2 = Stand still rotor EMF / phase

X_2 = Stand still rotor reactance / phase

When rotor starts rotating, the relative speed between rotor and rotating flux in the stator starts decreasing.

$$\text{Slip (s)} = \frac{N_s - N_r}{N_s}$$

The rotor induced emf is directly proportional to this relative speed

i.e. $E_r \propto (N_s - N_r) E_2$

$$\Rightarrow E_r = K (N_s - N_r) E_2$$

$$\Rightarrow E_r = \frac{N_s - N_r}{N_s} \cdot E_2$$

Therefore $E_r = SE_2$

Rotor Reactance :

The frequency of the rotor current

$f_r = sf$

Therefore $X_r = 2\pi s f_r L$

$$\Rightarrow X_r = 2\pi sfL$$

$$\Rightarrow X_r = S(2\pi fL)$$

Therefore $X_r = S X_2$

Torque under running conditions :

As we know that starting torque $T_{st} = KE_2I_2 \cos\phi_2$

Therefore $T_{st} \propto E_2 I_2 \cos\phi_2$

So the torque under running condition $T_r \propto E_r I_r \cos\phi_r$

Where E_r = Rotor EMF/Phase under running condition

I_r = Rotor Current/Phase under running condition

A_s $E_r \propto \phi$

Therefore $T_r \propto \phi I_r \cdot \cos\phi_r$

$I_r = \frac{E_r}{Z_r}$ But $Z_r = R_2 + j X_r = R_2 + j SX_2$

$\text{Cos } \phi_r = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$ and $I_r = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$

Therefore running torque $T_r \alpha E_r I_r$ as ϕ_r

Therefore $T_r \alpha \phi \frac{SE_2}{\sqrt{R_2^2 + (S \cdot X_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (S \cdot X_2)^2}}$

$\Rightarrow$ $T_r \alpha \phi \frac{SE_2 R_2}{R_2^2 + (S \cdot X_2)^2}$

$\Rightarrow$ As $E_2 \alpha \phi$

Otenu $T_r \alpha \frac{SE_2^2 R_2}{R_2^2 + (S \cdot X_2)^2}$

Therefore $T_r = \frac{K_1 SE_2^2 R_2}{R_2^2 + (S \cdot X_2)^2}$

Torque under stand still condition :

Nr = 0 at stand still condition

$S = \frac{N_S - 0}{N_S} = 1$

Therefore torque under stand still condition

$Tr = \frac{K_1 E_2^2 R_2}{R_2^2 + X_2^2}$

Condition for maximum Torque under running condition :

The torque of a rotor under running condition

$T_r = \frac{K_1 SE_2^2 R_2}{R_2^2 + (S \cdot X_2)^2}$

The conditions for maximum torque may be obtained by differentiating the above equation w.r.t slip (s) and then putting it equal to zero.

Let $Y = \frac{1}{T_r}$ (For to make the differentiation easy)

Therefore $Y = \frac{R_2^2 + (SX_2)^2}{K_1 S E_2^2 R_2}$

$$\Rightarrow Y = \frac{R_2}{K_1 S E_2^2} + \frac{S X_2^2}{K_1 E_2^2 R_2}$$

For maximum torque under running condition $\frac{dY}{dS} = 0$

$$\Rightarrow \frac{d}{dS}\left(\frac{R_2}{K_1 S E_2^2}\right) + \frac{d}{dS}\left(\frac{S X_2^2}{K_1 E_2^2 R_2}\right) = 0$$

$$\Rightarrow \frac{d}{dS}\left(\frac{R_2}{S E_2^2}\right) + \frac{d}{dS}\left(\frac{S X_2^2}{E_2^2 R_2}\right) = 0$$

$$\Rightarrow \frac{\frac{dR_2}{dS} \cdot SE_2^2 - R_2 \frac{d}{dS}(SE_2^2)}{(S E_2^2)^2} + \frac{\frac{d}{dS}(SE_2^2) \cdot E_2^2 R_2 - \frac{d}{dS} E_2^2 R_2 \cdot (SX_2^2)}{(E_2^2 R_2)^2} = 0$$

$$\Rightarrow \frac{0 - \cdot E_2^2 R_2}{S^2 E_2^4} + \frac{X_2^2 E_2^2 R_2 - 0}{E_2^4 R_2^2} = 0$$

$$\Rightarrow \frac{-R_2 E_2^2}{S^2 E_2^4} + \frac{X_2^2}{E_2^2 R_2} = 0$$

$$\Rightarrow \frac{R_2}{S^2 E_2^2} = \frac{X_2^2}{E_2^2 R_2}$$

$$\Rightarrow \frac{R_2}{S^2} = \frac{X_2^2}{R_2}$$

$$\Rightarrow R_2^2 = S^2 X_2^2$$

Therefore $\boxed{R_2 = SX_2}$

Hence the torque under running condition will be maximum when $R_2 = SX_2$

As the torque under running condition

$$T_r = \frac{K_1 S E_2^2 R_2}{R_2^2 + (SX_2)^2}$$

Putting the value $R_2 = SX_2$

Therefore $T_r = T_r$ (max) = $\frac{K\,SE_2^2 \cdot SX_2}{(SX_2)^2 + (SX_2)^2}$

$\Rightarrow T_r$ (max) = $\frac{KS^2E_2^2X_2}{2S^2X_2^2} = \frac{K\,E_2^2}{2X_2}$

Hence $\boxed{T_r\ (\text{max}) = \frac{K\,E_2^2}{2X_2}}$

Relation between full load Torque and Maximum Torque :

As Torque (T) = $\frac{K_1\,SE_2^2\,R_2}{R_2^2 + (SX_2)^2}$

E_2 is practically constant

Hence T = $\frac{K_2\,SR_2}{R_2^2 + (SX_2)^2}$

Therefore T α $\frac{SR_2}{R_2^2 + (SX_2)^2}$

Taking full load slip as S_f at full load torque T_f

Therefore T_f α $\frac{S_f R_2}{R_2^2 + (SX_2)^2}$ ………. (I)

As $T_{max} = \frac{K\,E_2^2}{2X_2}$

T_{max} α $\frac{1}{2X_2}$ ……….. (II)

$$\frac{(i)}{(ii)} = \frac{T_f}{T_{max}} = \frac{S_f\,R_2}{R_2^2 + (S_f X_2)^2} \times \frac{2X_2}{1}$$

$$\frac{T_f}{T_{max}} = \frac{2S_f R_2 X_2}{R_2^2 + (S_f X_2)^2}$$

Dividing X_2^2 on both side

$$\Rightarrow \frac{T_f}{T_{max}} = \frac{2S_f \frac{R_2}{X_2}}{\frac{R_2^2}{X_2^2} + S_f^2}$$

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

$$\Rightarrow \frac{T_f}{T_{max}} = \frac{2aS_f}{a^2 + S_f^2}$$

In general $\frac{\text{operating Torque}}{\text{Maximum Torque}} = \frac{2as}{s^2 + a^2}$

s – operating slip

Relation between starting Torque and Maximum Torque :

As $T_{st} = K \frac{R_2}{R_2^2 + X_2^2}$

$$\Rightarrow T_{st} \;\alpha\; \frac{R_2}{R_2^2 + X_2^2} \qquad \text{......................} \text{(i)}$$

But $T_{max} \;\alpha\; \frac{1}{2X_2}$ .... (ii)

$$\frac{(i)}{(ii)} = \frac{T_{st}}{T_{max}} = \frac{R_2}{R_2^2 + X_2^2} \times \frac{2X_2}{1}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{2R_2X_2}{R_2^2 + X_2^2}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{\frac{2R_2X_2}{X_2^2}}{\frac{R_2^2}{X_2^2} + \frac{X_2^2}{X_2^2}}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{\frac{2R_2}{X_2}}{\left(\frac{R_2}{X_2}\right)^2 + 1}$$

$$\Rightarrow \boxed{\frac{T_{st}}{T_{max}} = \frac{2a}{a^2+1}}$$

Relation between Torque and slip :

As Torque (T) = $\dfrac{KSE_2^2R_2}{R_2^2+(SX_2)^2}$

Taking Torque in Y axis and slip in X axis

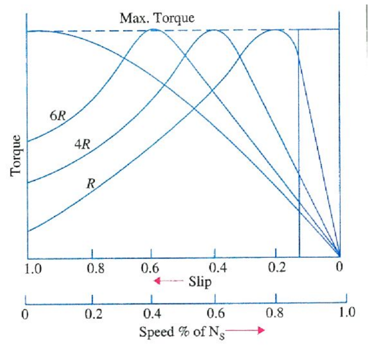


Fig. 1.5

At origin i.e. S = 0, torque T = 0

Therefore the curve starts from origin. At normal speed, closed to synoronism that is when N_r is very near to N_s, then slip is very nearly equal to zero.

Therefore $SX_2 << R_2$

$$\Rightarrow T \; \alpha \; \frac{SE_2^2R_2}{R_2^2} \qquad \{\text{Neglecting } (SX_2)^2\}$$

(Taking supply voltage constant so E_2 is also constant)

$$\Rightarrow T \; \alpha \; \frac{S}{R_2}$$

For a particular induction motor R_2 is constant.

Hence T α S

Therefore low valve of slip, torque is directly proportional to slip. Hence the curve is straight line for low valve of slip.

As slip increases the torque also increases and becomes maximum when = $R_2 = SX_2$

i.e. $S = \dfrac{R_2}{X_2}$

As the slip further increases (SX_2) becomes higher compare to R_2.

Hence R_2 can be neglected in compare to (SX_2)

$$\Rightarrow T\alpha \ \frac{S}{(SX_2)^2}$$

$$\Rightarrow T\alpha \ \frac{1}{SX_2^2}$$

Taking X_2 is constant for a particular induction motor

Therefore $T \ \alpha \ \frac{1}{S}$

So beyond the point of maximum torque any further increase in slip, results in decrease of torque.

Method of standing of Induction Motor

The operation of the squirrel cage induction motor is similar to transformer having short circuited on the secondary side.

Due to short circuited on the rotor circuit it will take heavy current when it is directly switched on. Generally when direct switched, take five to seven times of their full load current. This initial excessive current is objectionable, because it will produce large line voltage drop.

Hence it is not advisable to start directly motors of rating above 5 KW. But the starting torque of an induction motor can be improved by increasing the resistance of the rotor circuit. This is easily feasible in the case of slip ring induction motor but not in the case of squirrel cage motors. However, in their case, the initial in rush of current is controlled by applying a reduced voltage to the stator during the starting period, full normal voltage being applied when the motor has run up to speed.

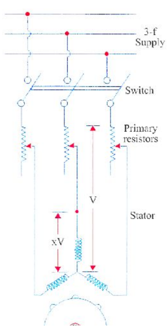
Method of Starting of Squirrel Cage Motor :

(1) Resistors Method

(2) Star – Delta Method

(3) Auto transformer Method

In the above methods, the supply voltage to the squirrel cage motor is reduced during starting.



1) Resistor Method :

In this method the resistors are connected in series with the stator phases, to give reduced voltage to the stator winding.

When resistors are connected in series with the stator phases, the current in the stator phases will reduce. If the voltage applied across the motor terminals is reduced by 50%, starting current is reduced by 50%.

Fig 1.6

When the motor starts running the resistances in the circuit is gradually cut out and full voltage is applied to the stator circuit. This method is useful for the smooth starting of small machines only.

2) Star – Delta Starter :

This method is used in the case of motors which are built to run normally with a delta connected stator winding. It consists of a two way switch which connects the motor in star for starting and then in delta for normal running.

At starting, when star connected, the applied voltage over each motor phases is reduced by afactor $1/\sqrt{3}$. Hence during starting, when motor is star connected it takes $1/\sqrt{3}$ times as much as starting current.

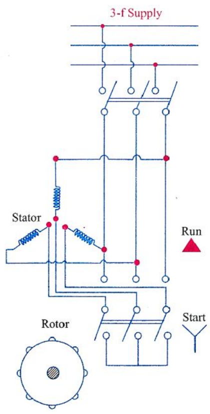


Fig 1.7

When the motor catches the speed 80% of its normal speed switch is changed to delta positions at that time $V_L = V_{ph}$.

Auto Transformer Method :

This starter is popularly known as auto starter in auto transformer the secondary side gets less voltage in compare to primary side.

As shown in the figure, at starting condition, a reduced voltage is applied across the mo terminals. When the motor catches the speed 80% of its normal speed, connections are changed to running position, then full supply voltage is applied across the motor.

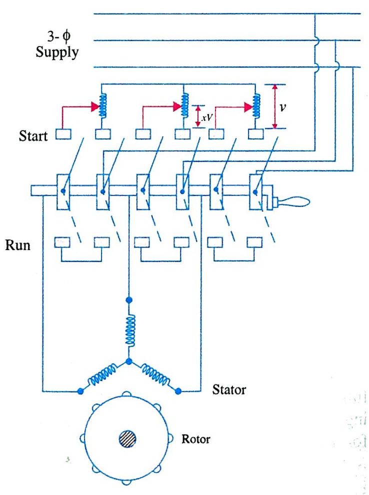


Fig 1.8

Most of the auto starters are provided with 3 – sets of taps so as to reduced the voltage to 80, 65 or 50 percent of line voltage.

Slip ring Motor :

Rotor Rheostat Method :

These motors are practically always started with full line voltage applied across the stator terminals. The value of starting current is adjusted by introducing a variable resistance in the rotor circuit.

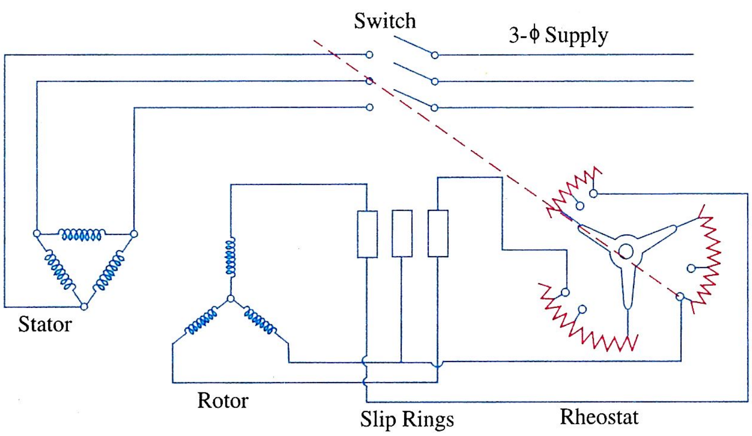


Fig 1.9

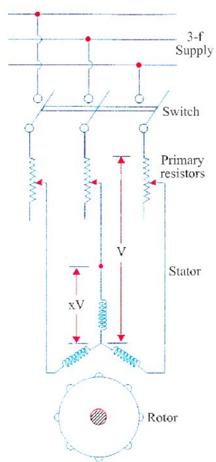
The controlling resistance is in the form of a rheostat, connected in star, the resistance being gradually cut – out of the rotor circuit, as the motor gathers speed

Speed Control of Induction Motor :

The speed of an induction motor can be changed under two main headings.

(i) Control from stator side

(ii) Control from Rotor side



(i) **Control from stator side :**

(a) By changing the applied voltage

(b) By changing the applied frequency

(c) By changing the no of stator poles.

(ii) **Control from Rotor side :**

(a) Rotor Rheostatic Control

(b) Cascade operation **Fig 1.10**

(c) By injecting emf in the rotor circuit

By changing applied voltage :

This method is the easiest way for controlling speed of an induction motor. But this method is rarely used for the following reasons.

(i) A large change in voltage is required for a small change in speed.

(ii) Due to the connection of resistances in the stator phases, large power loss occurs at the resistors.

When the resistances are added in the stator circuit, voltage across the stator phase decreases.

As torque (T) = $\dfrac{KV^2R_2}{R_2^2 + X_2^2}$

$\Rightarrow$ Torque $T = K_1 V^2$

$\Rightarrow T \alpha V^2$

The torque depends on the supply voltage on the stator terminals, when V will decrease T will decrease hence speed will decrease.

By Charging the number of stator poles :

This method is easily applicable to squirrel cage motors because the squirrel cage rotor adopts it self to any reasonable number of stator poles.

The change in number of stator poles is achieved by having two more entirely independent stator windings in the same slots. Each winding gives a different number of poles and hence different synchronous speed.

Rotor Rheostatic Control :

This method is applicable to slip ring motors alone. The motor speed is reduced by introducing an external resistance in the rotor circuit.

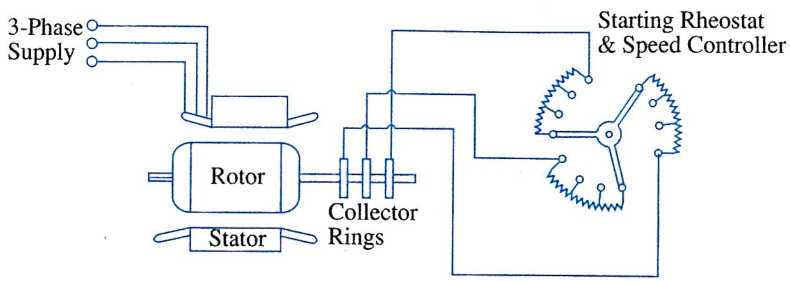


Fig 1.11

For this purpose the rotor starter may be used.

As torque (T) $\alpha \dfrac{S}{R_2}$

By increasing the motor resistance torque will decrease. Hence speed will decrease.

Motor Enclosures :

Enclosed and semi-enclosed motors are practically identical with open motors in mechanical construction and in their operating characterstics. Many different types of frames or enclosures are available to suit particular requirements. Some of the common type of enclosures are given below.

(i) Totally enclosed, Non ventilated type.

(ii) Splash – Proof type

(iii) Totally enclosed, Fan cooled type.

(iv) Cowl covered motor

(v) Protected Type

(vi) Drip – Proof Motors

(vii) Self (Pipe) Ventilated Type

(viii) Separately (Forced) Ventilated Type.

Induction Generator :

When the rotor of an induction motor runs faster than its synchronous speed at that time the induction motor runs as a generator called Induction generator. It converts the mechanical energy it receives into electrical energy is released by the stator.

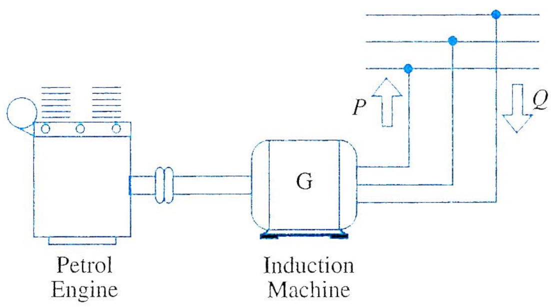


Fig 12

Figure shows a ordinary squirrel cage induction motor which is driven by a petrol engine and is connected to a 3 – phase line. As soon as motor speed exceeds its synchronous speed, it starts delivering active power P to the 3 – phase line. However, for creating its own magnetic field, it absorbs reactive power Q from the line to which it connected.

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CHAPTER-IV

Single Phase induction Motor

A single phase Induction Motor (I.M.) is very similar to 3 Phase squirrel cage I.M. It has a squirrel cage rotor and a single phase winding on stator like 3 phase I.M., single phase I.M. is not self starting. The stator winding produces a magnetic field which polarity reversed after each half cycle. So the field don't produce rotating field. If a single phase I.M. having squirrel cage rotor and 1-phase distributed stator winding, it doesn't develop any resulting starting torque as the torque developed in both the cycle neutralize each other. To make the I.M. starting, we have to add an another winding in the stator circuit is known as auxiliary winding (starting)

Making Single Phase I.M. Self starting :

To make a 1-phase I.M. self starting we should some how produce a revolving stator magnetic field, this may be achieved by converting a 1-phase supply in to two phase supply by using an additional winding. Hence the rotor of the single phase motor starts rotating like 3 phase motor. When it achieves sufficient speed, the additional winding may be removed. But the rotor continue running.

Different types of single phase I.M.-

1. Induction Motors like split-phase, capacitor and shaded pole type.
2. Repulsion type motors
3. A.C. series motors (Commutator motors) etc.

Split Phase Motor:

The Stator circuit of a split phase I.M. is added with an auxiliary winding with the main winding and it is located 90^0 electrically apart from the main winding. The two windings are so designed that the auxiliary winding has high resistance and small reactance while the main winding has low resistance and large reactance.

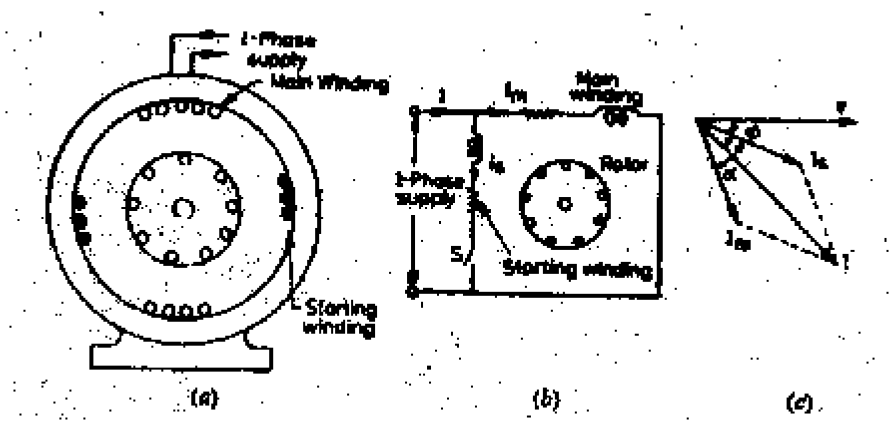


Figure 1 split phase I M motor

Operation-

When supply is given to the starter windings both the windings are energized. Since main winding is made by highly inductive while the auxiliary winding is resistive that produce a weak revolving field for which it produces revolving flux and rotor starts revolving hence the motor started.

The Torque produced is,

$$Ts = K\, I_m\, I_s \,\text{Sin}\, \alpha$$

When α is the phase angle between I_m & I_s. When the motor achieves about 75 % of synchronous speed, the centrifugal switch S will open and the auxiliary winding is cut off from the circuit. Then the motor operates as a 1 – Φ I.M. and it continues to accelerate till it reaches it's normal speed which is below the synchronous speed. The starting torque is proportional to the Current

If the starting period delay exceeds 5 Seconds, the winding may burn out because the winding made of fine wire.

Uses

Fan, Washing machine, small machine tools etc.

Capacitor Start I.M. :

A Capacitor start motor is identical to a split phase motor except that the starting winding has same number of turns as main winding and a capacitor is connected in series with the starting winding.

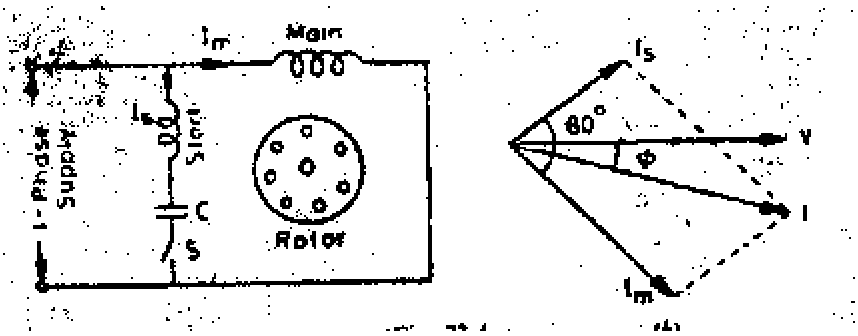


Figure 2 Capacitor Start I.M.

Operation

The value of the capacitor is such that “I_s” leads “I_m” by The starting torque which is more than the split phase I.M. When torque is produced, the rotor starts rotating. When the rotor achieves 75 % of the N_s, the centrifugal switch will be open. Then auxiliary winding is cut off from the circuit. The motor then operate as a 1-phase I.M. and continue to accelerate till it reaches it’s normal speed.

Advantages

It’s starting characteristics are better than the split phase I.M. For the same starting torque, the current of starting winding is only about half that in split phase I.M. so, it is heated less quickly.

Uses :

It is used where low starting torque is required.

Capacitor start and run

It is similar to capacitor start motor except that the starting winding is not opened after starting. So, when the motor runs both windings are connected in the circuit . It has two capacitors with the starting winding. The capacitor C_1 has smaller capacity than C_2 and is connected in the circuit in series with the starting winding permanently during starting as well as running. The large capacitor C_2 is connected in parallel in C_1 for starting purpose only. When the motor approaches about 75 % of N_s then Centrifugal switch is opened and the capacitor C_2 is disconnected from circuit.

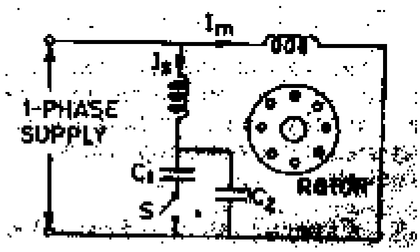


Figure 3 capacitor start induction motor

The important kind of capacitor motor is permanent capacitor motor. In such type the capacitor is permanently connected to the circuit and one in number only.

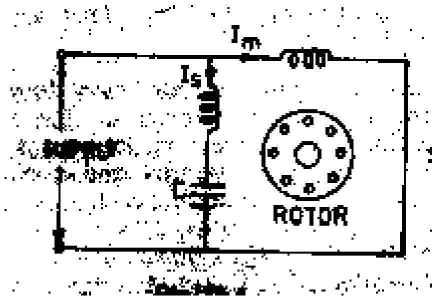


Figure 4 permanent capacitor motor

Characteristics

This type of motor is designed for perfect 2–phase operation at any load and it produces continuous torque as compared to induction motor.

Uses

Due to it's continuous torque and vibration free, it is used in hospitals, studio, refrigerators, compressors, stokers, ceiling fan, blowers etc.

Shaded Pole Motor

The shaded pole motor is very popular for rating up to 0.05 HP. A small portion of pole core of about 30% is slot cut and surrounded by a short circuited ring of Cu strip called shading coil.

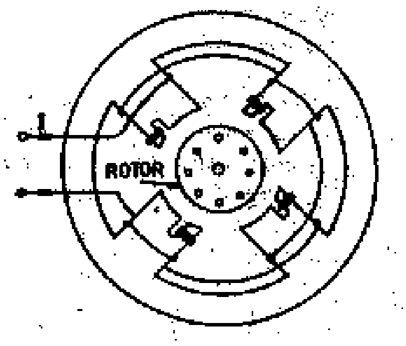


Figure 5 shaded pole motor

Operation

From the total of core, the flux produced and emf is induced in the shading coil. The resulting current in shading coil is in such a direction, so as to oppose I and so the charge in flux according to Lens's law. So this flux in the shaded portion of the pole is weakened while in the unshaded portion is strengthened. The magnetic axis lies along the middle of this part.

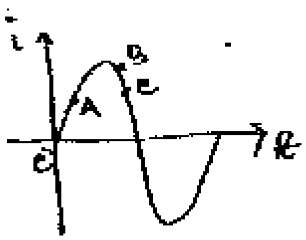


Figure 6 torque in shaded pole motor

During the portion in AB as shown in figure (6), the flux is reached almost maximum value, the flux distribution across the pole is uniform. Since no current is flowing in shading coil, the magnetic axis shift to the centre of the pole.

As the flux decreases as shown in figure (6), from B to C, This again set a induced current in the shading coil. This current flows in such a direction that to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while the unshaded portion is weakened. So the magnetic axis shift to the middle part of the shaded pole.

This shifting of flux is like a rotating weak field moving in the direction from unshaded portion to shaded portion of the pole. Under the influence of the moving field a small staring torque is developed which torque starts to rotate the rotor, additional torque is produced by single phase motor action. Such motors are built in very small sizes of 5-50w but are simple in construction and are extremely rugged, reliable and cheap.they do not need any commutator, switch, brush, collector rings etc. However they suffer from disadvantages of (i) low starting torque, (ii) very little over load capacity and (iii) very low efficiency ranging from 5% to 35% from lower to higher ratings respectively.

Uses

It is used in small fans, toys, hair drier of power up to 50 W.

AC Series Motor / Universal Motor

The construction of AC series motor is as like as DC series motors. If a DC Series motor is connected to an AC supply, it will rotate and produce unidirectional torque because the current flowing in both the armature and field reverses at the same time. When a DC series motor operates on a single phase supply, then it is called a AC series motor. The performances of this type of motor will not be satisfactory due to the following reasons.

1. The alternating flux would cause excessive eddy current loss in the yoke and the field core will become extremely heated.
2. Sparking will occur at brushes because of huge voltage and current induced in the short circuited armature coil during commutation period.
3. Power factor is very low.

   Due to the above drawbacks DC series motor required some changes by which AC supply input disadvantages solved.. The changes made are

a) The entire magnetic circuit is laminated in order to reduce the eddy current losses.
b) A high field flux is obtained by using a low reluctance magnetic circuit.
c) Excessive sparking eliminated by using high resistance leads to connect the coil to the commutator segment.

Though this type of motor can be operated either on AC or DC supply, the resulting torque speed curve is same. It is also known as Universal motor.

Operation

When it is connected to an AC supply the same alternating current flows through the field and armature winding. The field winding produces an alternating flux that react with an armature current to produce a torque and the direction of the torque is always same because they (current and flux) reverses simultaneously.

Characteristics

a) Speed increases to a high value with a decreasing load.
b) It has very high starting torque.
c) At Full load, the power factor is 90 %.

   Uses.

   a. Sewing machine b. vacuum cleaners, c. mixer grinders and blenders

d) High speed vacuum cleaners. e. hair driers f. power saw

f. Drills g. Electric Shaver.

Single Phase Repulsion Motor

A repulsion motor is similar to an Ac Series motor except some modification. The brushes are not connected to supply but are short circuited by themselves. The current induced in the armature conductor by mutual induction method.

Construction **Single Phase Repulsion Motor**

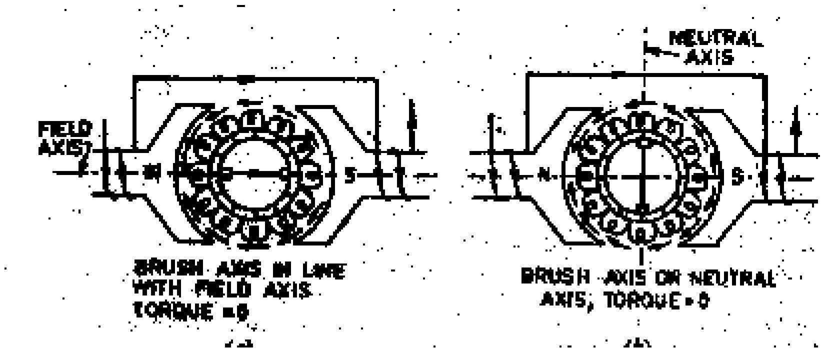


Figure 7 Single Phase Repulsion Motor

The field of the stator winding is connected directly to the AC single phase source. The rotor is similar to a DC motor armature winding connected to the commutator. The brushes are short circuited which make the rotor squirrel cage type. It has very high starting torque and also better power factor as compared to other single phase motor.

Operation

The figure shows, two pole repulsion motor with short circuited brushes. The brush axis is parallel to stator field. The emf is induced in the armature Conductor by induction method and current flows through the rotor conductors. The current flows from N to S brush in two paths. during this brush position half of the rotor conductors under N pole carry current inward and half carry current outward. The same thing occurs under S pole. Therefore, same torque is produced in opposite direction in both the half coils. So the net torque is zero.

If the brush axis is in some angle other than 0^0 or $90^{0,}$ then a torque is developed in the rotor and accelerate the rotor to final speed. The brush axis is shifted in clockwise direction through some angle from stator field axis. The emf is induced in same direction, the current flows in two paths of the rotor winding between N & S. Now the more conductors under North pole carrying current in one direction while more conductors under south pole carrying current in opposite direction, so that the torque is developed in clockwise direction and the rotor rotates to it's final speed.

The direction of rotation of the rotor depends upon the direction in which the brushes are shifted. If the brushes are shifted in clockwise direction from the stator field axis then the net torque in clockwise direction. It has high starting torque.

Use

Commercial refrigerators, compressors and pumps.

CHAPTER -V

COMMUTATOR MOTORS

A.C. Series Motor or Universal Motor

A dc series motor will rotate in the same direction regardless of the polarity of the supply.

When a dc series motor operates on a single phase ac supply it is called an AC series motor. However some changes are required in a DC motor so that it can satisfactorily operates on A.C. supply.

The changes are as follows:

i) The field core is constructed of a material having low hysteresis loss. It is laminated in order to reduce eddy current loss. Hence A.C. series motor requires a more expensive construction than a D.C. series motor.

ii) The series field winding uses as few turns as possible to reduce the reactance of the field winding to minimum. This reduces the voltage drop across the field winding.

iii) A high field flux is obtained by using low reluctance magnetic circuit.

iv) There is considerable sparking between the brushes and the commutator when the motor is used on A.C. supply. It is because the alternating flux establishes high currents in the coils short circuited by the brushes. When the short circuited coils break contact from the commutator, excessive sparking is produced. This can be eliminated by using high resistance leads to connect the coils to the commutator segments.

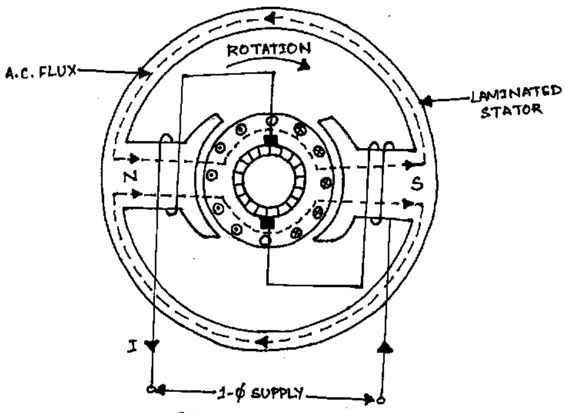
v) In order to reduce the effect of armature reaction thereby improving commutation and reducing armature reactance a compensating winding is used. This winding is put in the stator slot.

The drawback when A.C. supply is given to D.C. series motor (without modification) –

i) The efficiency is low due to hysteresis and eddy current loss.

ii) The power factor is low due to large reactance of the field and armature winding.

iii) The sparking at the brush is excessive.



COMMUTATOR MOTOR

Construction

The construction of an A.C. series motor is very similar to D.C. series motor except that above modification are incorporated.

This type of motor can be operated either on A.C. or D.C. supply and the resulting torque-speed curve is about the same in each case. For this reason it is sometime called universal motor.

Motors that can be used with a 1-phase A.C. source as well as a D.C. source of supply voltage are called universal motors.

Principle of Operation of A.C. series motor

When the motor is connected to an A.C. supply the same alternating current flows through the field and armature windings.

The field winding produces an alternating flux Φ that reacts with the current flowing in the armature to produce a torque.

Since both armature current and flux reverse simultaneously, the torque always acts in the same direction.

Characteristics of A.C. Series Motor

The operating characteristics are similar to those of D.C. series motor –

i) The speed increases to a high value with decrease in load.

ii) The motor torque is high for large armature current, thus giving high starting torque.

iii) At full load, the power factor is about 90 %, however at starting or when carrying overload power factor is low.

Application

The fractional horsepower A.C. series motor have high speed and large starting torque. Therefore be used to drive –

a) High speed vacuum cleaners.

b) Sewing Machine

c) Electric Shavers

d) Drills

e) Mechanical tools etc.

Repulsion Motor

A repulsion motor is similar to an A.C. series Motor except –

i) The brushes are not connected to supply but are short circuited. Hence current are induced in the armature conductor by transformer action.

ii) The field structure has non-silent pole construction

By adjusting the position of short circuited brushes on the commutator, the starting torque can be developed in the motor.

Construction

The field of the stator winding is connected to the 1 – Φ A.C. supply.

The armature or rotor with drum type winding like D.C. motor is connected to a commutator.

Here the brushes are not connected to the supply but are connected to each other or short circuited. Hence it is possible to vary the starting torque by changing the brush axis. So Commutator motor has better power factor than conventional 1-phase motor.

Principle of Operation

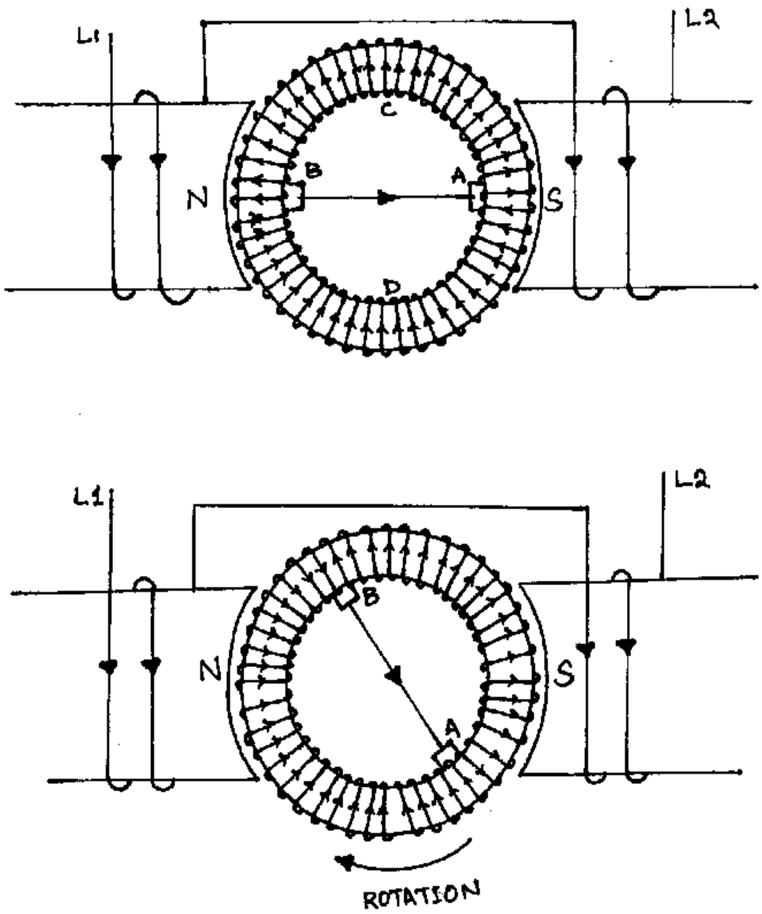
Fig. 1 shows two pole repulsion motor with its two short-circuited brushes

When field current is increasing in the direction shown the left hand pole is north pole and right hand pole is south pole.

i) Here the brush axis is parallel to the stator field.

When the stator winding is energized from 1 – Φ supply emf is induced in the armature conductor by induction. This emf will cause a current to flow in the armature conductor. By lens's law the direction of the emf is such that magnetic field of the resulting armature current will oppose the increase in flux.

The current direction in armature conductor is shown in the Fig.



REPULSION MOTOR

With brushes set in this position, half of the armature conductors under the N-pole carry current inward and half carry current outward. The same is true under south pole.

So as much torque is developed in one direction as in the other and the armature remains stationary.

The armature will also remain stationary if the brush axis is perpendicular to the stator field axis as even then net torque is zero.

If the brush axis is at some angle other than 0^0 or 90^0 to the axis of stator field a net torque is developed on the rotor and rotor accelerate to it’s final speed.

Here in figure 2 because of the new brush position, the greater part of the conductor under the N-pole carry current in one direction. While the greater part of conductor under S-pole carry current in opposite direction.

With brushes in position 2 torque in developed in the clockwise direction and the rotor quickly attains the final speed.

The direction of rotation of the rotor depends upon the direction in which the brushes are shifted. If the brushes are shifted in clockwise direction from the stator field axis, the net torque acts in the clockwise direction and rotor accelerates in the clockwise direction and vice versa.

The total armature torque in a repulsion motor is

T_a = Sin 2α where α is the angle between brush axis and stator field axis.

For maximum torque, $2\alpha = 90^0$ or $\alpha = 45^0$. Thus adjusting α to 45^0 at starting, maximum torque can be obtained during starting period.

Characteristics

a) The repulsion motor has characteristics very similar to those of an A.C. series motor i.e. it has a high starting torque and a high speed at no load.

b) The speed which the repulsion motor develops for any given load will depend upon the position of the brushes.

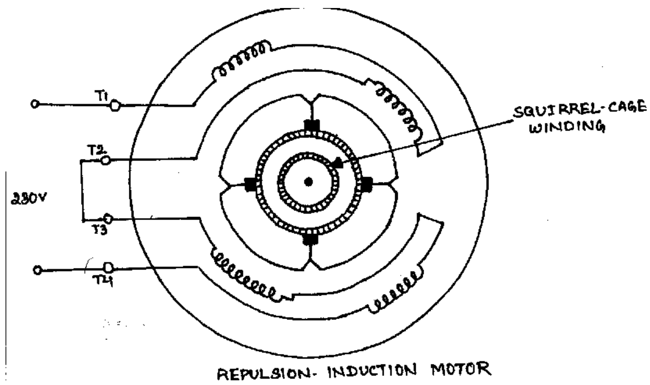
c) In comparison to other single phase motor, the repulsion motor has high starting torque and relatively low starting current.

Repulsion Induction Motor

The repulsion – Induction motor produces a high starting torque entirely due to repulsion motor action and when running, it function through a combination of Induction motor and repulsion motor action.

Construction

The Fig. shows the connection of a 4-pole repulsion Induction motor for 230 V operation. It consist of a stator and a Rotor.



REPULSION- INDUCTION MOTOR

i) The stator carries a single distributed winding fed from single-phase supply.

ii) The rotor is provided with two independent windings placed one side the other. The inner winding is a squirrel-cage winding with rotor bars permanently short circuited. The outer winding is a repulsion commutator armature winding placed over the squirrel cage winding.

The repulsion winding is connected to a commutator on which ride short circuited brushes.

Operation

When single phase stator winding is driven by an A.C. supply the repulsion winding is active. Consequently the motor starts as a repulsion motor with a corresponding high starting torque.

As the motor speed increases, the current shifts from the outer to inner winding due to the decreasing impedance of the inner winding with increasing speed. Consequently at running speed, the squirrel cage winding carries the greater part of rotor current. This shifting of repulsion motor action to induction motor action is thus achieved without any switching arrangement.

It may be seen that the motor starts as a repulsion motor. When running, it function through a combination of principle of induction and repulsion.

Characteristics

The no-load speed of a repulsion – Induction Motor is somewhat above the synchronous speed because of the effect of repulsion winding, however the speed at full load is slightly less than the synchronous speed in an induction motor.

The speed regulation of the motor is about 6 %.

The starting torque is 2.25 to 3 times the full load torque. The starting current is 3 to 4 times the full load current.

Application

This type of motor is used for applications requiring a high starting torque with essentially constant running speed.

Repulsion – Start Induction – Run motor

The action of repulsion motor is combined with that of a 1 – Φ induction motor to produce repulsion – start induction – run motor (also called Repulsion Start Motor)

This motor starts as an ordinary repulsion motor, but after it reaches about 75 % of its full speed, Centrifugal short – circuiting device / switch short circuits its commutator.

From then on it runs as an Induction Motor with a short – circuited squirrel – Cage Rotor.

After the commutator is short circuited, brushes do not carry any current, hence they may also be lifted from the commutator in order to avoid unnecessary wear and tear and friction losses.

Characteristics

The starting torque is 2.5 to 4.5 times the full load torque and the starting current is 3.75 times the full load value.

Due to their high starting torque, repulsion motors were used to operate devices such as refrigerators, pumps, compressor etc.

CHAPTER- VI

SPECIAL PURPOSE ELECTRIC MACHINES

INTRODUCTION

Special purpose electric machines have some features that distinguishes them from conventional machines.Stepper motor belongs to that type machine which rotates by a specific number of degrees in response to an input electrical signal and is widely used in digital control systems.

STEPPER MOTOR

Stepper motors are also known as stepping motors or step motors. A stepper motor is an electro-magnetic motor that rotates by a specific number of degrees in response to an input electrical signal. Typical step sizes are 2^0 ,2.5^0, 7.5^0, 15^0 for each electrical pulse. Note that there is no continuous energy conversion so that the rotor does not rotate continuously as in a conventional electric motor.The stepper motor converts electrical pulses into proportionate mechanical movement. Each revolution of stepper motor is made up of a series of definite individual steps. a step is defined as the angular rotation in degrees of the motor each time it receives the electrical pulse. such a step control is required in many applications. Figure 1.1 illustrates a simple application for a stepper motor. Each time the controller receives an input electrical signal, the paper is driven to a certain incremental distance. Stepper motors are relatively cheap and simple in construction and can be made to rotate in steps in either direction. These motors are excellent candidates for such applications as type-writers, control of floppy disc drives, numerical control of machine tools etc. The two most popular types of stepper motors are :

(i) Permanent-magnet (PM) Stepper Motor

(ii) Variable –reluctance(VR) Stepper Motor

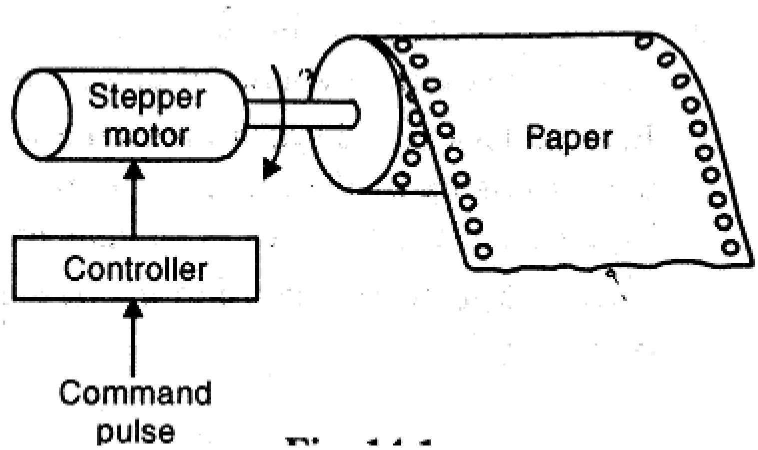


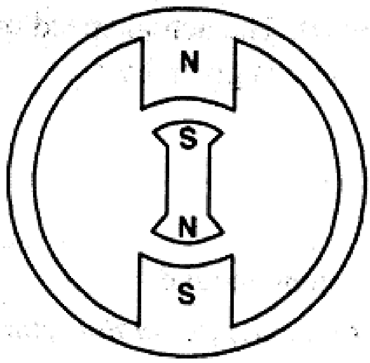
Fig. 1.1

The stator of a stepper motor of either type above carries stator windings which are energized from a dc source to create two or more stator poles. The stator poles are also called stator teeth. The rotor of a stepper motor may be a permanent magnet as in a Permanent Magnet stepper motor or a soft-iron material as in case of a variable reluctance motor. The rotor may also have two or more poles. The rotor poles are also called rotor teeth.

The stator coils are energized in groups referred to as phases. The stator windings may be 2-phase,3-phase or 4-phase windings. The phase windings are brought out to terminals for DC excitation .

PM Stepper Motor

The figure1.2 shows a two-pole 1-phase permanent magnet stepper motor. When the stator is energized, the excitation torque acts on the rotor. The rotor will move to a position where the excitation torque is zero i.e. the rotor will be aligned in parallel to the stator field.



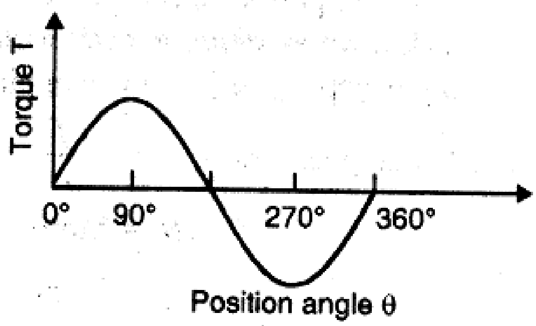
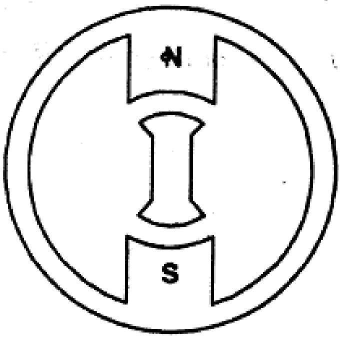


Fig.1.2 Fig.1.3

Fig 1.3 shows how excitation torque varies with thee rotor position for a PM rotor. Note that maximum torque is developed when the rotor is displaced from the stator field by either 90^0 or 270^0 . However , the torque is zero and the rotor is aligned (parallel) with the stator field.

(iii) VR Stepper Motor

Fig. 1.4 shows a 2-pole , single phase variable-reluctance(VR) stepper motor.When the stator is energized ,*reluctance torque* acts on the rotor (soft-iron material). The rotor will move a position where reluctance is minimum and air-gap flux is maximum. This means that rotor teeth will align with the energized stator poles.



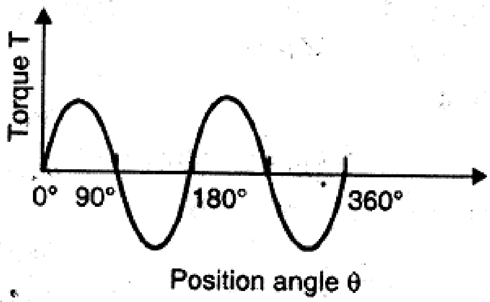


Fig.1.4

Fig.1.5

Fig.1.5 shows how reluctance torque varies with the rotor position for a VR soft-iron rotor.With the rotor at 0^0 or 90^0 , no torque is developed. Maximum torque is developed at 45^0 and 135^0 Which is the position where reluctance torque forces the rotor or move to position of minimum reluctance.

step angle :the angle through which the motor shaft rotates for each command pulse is called step angle. It can be shown that for any PM or VR stepper motor,the step angle can be found from the following two relation:

i) In terms of stator poles (N_s) and rotor poles (N_r), the step angle (α) is given by:

$$\text{Step angle, } \alpha=\frac{N_s-N_r}{N_s \times N_r} \times 360^0$$

where α= Step angle in degrees

(N_s)=Number of stator poles(or teeth)

(N_r)=Number of rotor poles (or teeth)

ii) In terms of stator phases (m) and rotor poles (N_r), the step angle is given by:

step angle,α= $\alpha=\frac{360^0}{m\,N_r}$

α= step angle in degrees

m=Number of stator phases

N_r=Number of rotor poles (or teeth)

stepping rate. An important specification of a stepper motor is the stepping rate. The number of steps per second is known as stepping frequency(f).The actual speed of a stepper motor depends on the step angle (α) and stepping frequency(f) and is given by :

Speed of stepper motor, N $=\frac{\alpha f}{6}$

N = motor speed in r.p.m.

f = stepping frequency i.e. steps/second

Example 1.1

Determine the step angle of a variable-reluctance stepper motor with 12 teeth in the stator and 8 rotor teeth.

Solution :

Number of stator teeth, N_s = 12

Number of rotor teeth, N_r = 8

Step angle, $\alpha=\frac{N_s-N_r}{N_s\times N_r}$ x $360^0=\frac{(12-8)}{(12\times 8)}$ x 360^0 = 15^0/step

Example 1.2

A stepper motor has a step angle of 10^0 and is required to rotate at 200 r.p.m. Determine the pulse rate(steps/second) for this motor.

Solution :

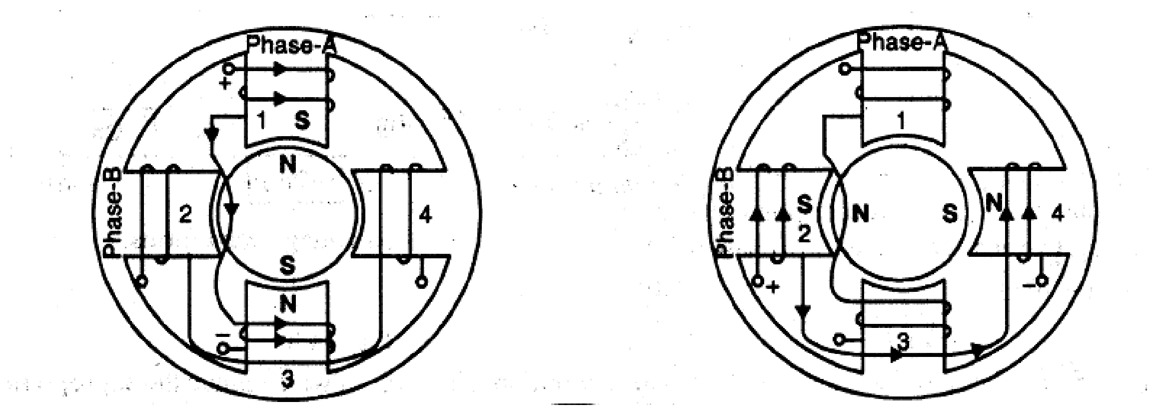
motor speed, N $=\frac{\alpha f}{6}$

Hence , Pulse rate(steps per second) for this motor = $\frac{6 \times N}{\alpha}$ $=\frac{6 \times 200}{10}$ = 120 steps/second

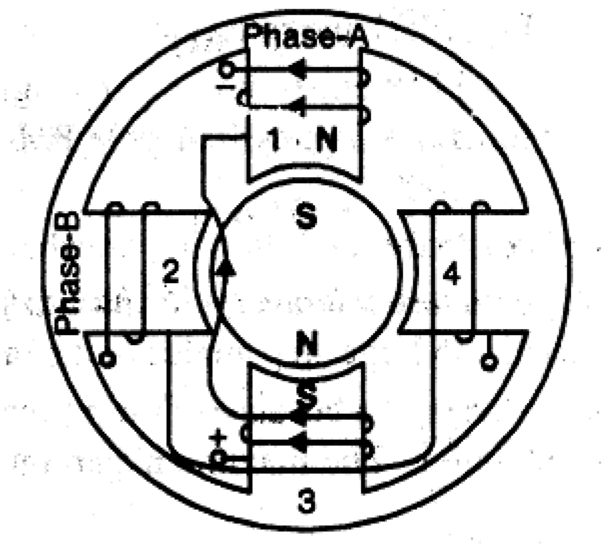
PERMANENT –MAGNET (PM) STEPPER MOTOR

A permanent-magnet(PM) stepper motor is a popular type of stepper motor.It operates on the principle of interaction between permanent-magnet and electromagnetic field.

CONSTRUCTION : The stator construction of a PM stepper motor is composed of steel laminations and carries stator windings. The stator phase windings are energized from a d.c. source to create two or more stator poles. The rotor of the motor is a permanent-magnet made up of high retentivity steel alloy.The rotor has even number of poles. Fig.1.6 shows a two-phase,2-pole PM stepper motor. The motor has two rotor poles.The stator coils are grouped to form 2-phase winding i.e.phase-A winding and phase-B winding.The phase winding terminals are brought out for d.c. excitation.



(i) (ii)



(iii)

Fig.1.6

OPERATION : for this PM stepper motor,the number of rotor poles,N_r = 2 and number of phases, m=2.

Step angle,α =mN_r=360^0/(2x2)= 90^0/step

(i) When only phase-A winding is energized by a constant current as shown in Fig.1.6(i) stator tooth 1 becomes the south pole. This makes the north pole of the PM rotor to align parallel with the south pole(stator tooth 1) of the stator. The rotor will remain locked in this position as long as phase-A winding remains energized. The first row of truth table in Fig. shows that only phase-A winding is excited while phase-B winding is unexcited. Under this condition, step angle α =0^0.The applied voltage waveforms in Fig also tally with the facts shown in the truth table.

(ii) If phase A winding is de-energized and phase-B winding is energised as shown in Fig.1.6(ii), stator tooth 2 becomes south pole. As a result, the north pole of the PM rotor aligns parallel with the south pole(stator tooth2) of the stator. Thus the rotor has displaced 90^0 in the anticlockwise direction.

(iii) If phase B winding is de-energized and phase-A winding is excited by a reverse current the rotor will further rotate 90^0 in anticlockwise direction as shown in Fig1.6(iii). Now the north pole of PM motor aligns with the stator tooth 3.

Truth Table

Cycle	Phase A	Phase B	Position δ°
+	1	0	0
	0	1	90
–	– 1	0	180
	0	– 1	270
+	1	0	360

Fig.1.7

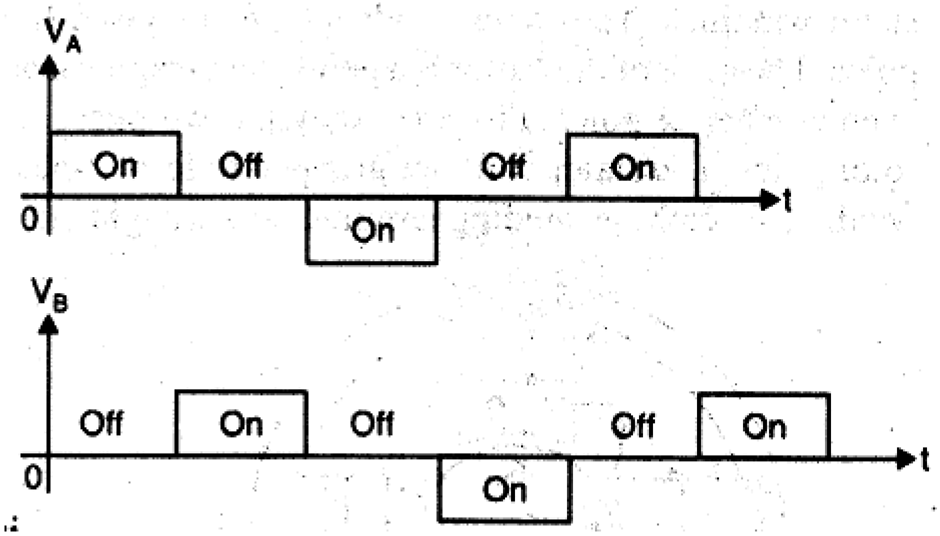


Fig.1.8

(iv) So far the rotor has completed one-half revolution. However, if we continue the appropriate switching the rotor will complete one revolution in 90^0 steps.

We can change the step angle α of a PM stepper motor by changing the number of rotor poles N_r and the number of phases(m).Thus for a 3-phase,24-pole PM stepper motor, the step angle $\alpha = 360^0/mNr = 360^0/3x24 = 5^0$/step.

Limitations : The PM stepper motor has the following draw\backs :

i) It is difficult to make a small permanent magnet rotor with a large number of poles. Therefore ,PM stepper motors are restricted to large step angles in the range of 30^0 to 90^0.

ii) The PM stepper motors have high inertia because of the permanent-magnet rotor. Therefore, these motors have slow acceleration. the maximum step rate (Stepping frequency) is 300 steps/second.

iii) The PM stepper motors have high rotational speed because of large stepping angle. Therefore, motor torque for a given output power is low.

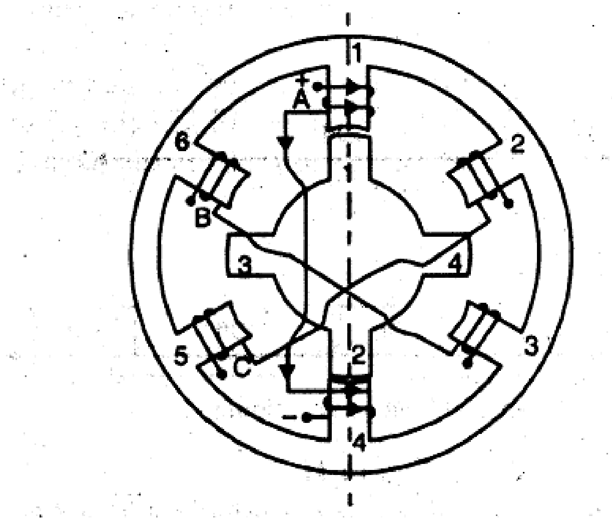
VARIABLE RELUCTANCE(VR) STEPPER MOTOR

The variable Reluctance stepper motor(VR) stepper motor operates on the same principle as the reluctance motor. that is, when a piece of ferro-magnetic material is free to rotate and is placed in a magnetic field the torque acts on the material to bring it to the position of minimum reluctance to the path of magnetic flux.

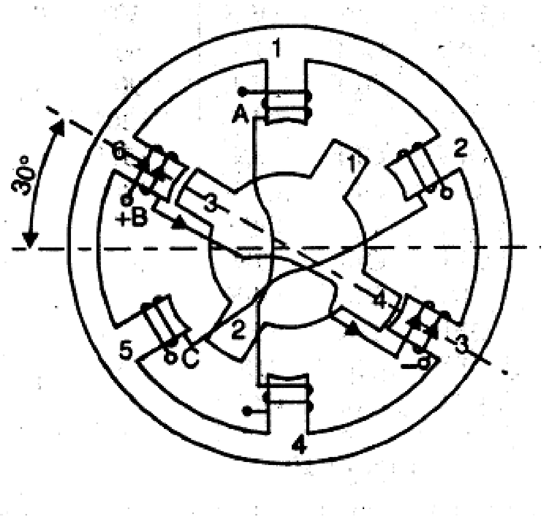
CONSTRUCTION : The stator construction of a VR stepper motor is the same as that of a PM stepper motor. The stator phase windings are wound on each stator tooth. The rotor is made of soft steel with teeth and slots .Figure shows the basic Variable-Reluctance stepper motor. In this circuit, the rotor is shown with fewer teeth than stator. This ensures that only one set of stator and rotor teeth will align at any given instant. In Fig. the stator has six teeth and the rotor has four teeth. The stator has three phases – A,B and C with teeth 1 and 4, 3 and 6 and 2 and 5 respectfully .For this VR stepper motor,

step angle,α $= \frac{N_s - N_r}{N_s \times N_r} \times 360^0 = \frac{6-4}{6 \times 4} \times 360^0 = 30^0$/step

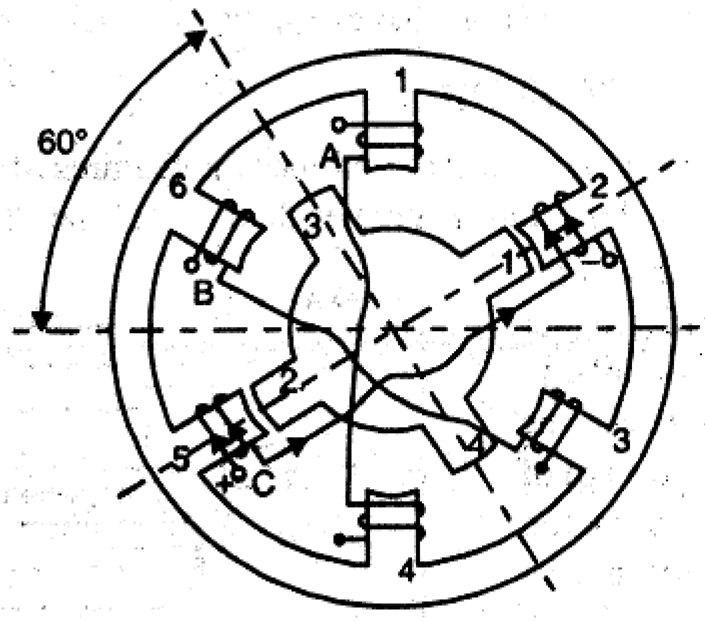
Therefore, the rotor will turn 30^0 each time a pulse is applied.



(i)



(ii)



(iii)

Fig.1.9

OPERATION : When the phase winding is energized,the rotor teeth will align with the energized stator poles.

i) Fig.1.9(i) shows the position of the rotor when phase A is energized with a constant current.As long as phase A is energized,the rotor will be held stationary.Note that in this condition,the rotor teeth 1 and 2 are aligned with the energized stator teeth 1 and 4.the step angle $\alpha=0^0$.Also refer to truth table and applied voltage waveform.

ii) when phase A is switched off and phase B is energized,the rotor will turn 30^0 clockwise so that the rotor teeth 3 and 4 align with the energized stator teeth 6 and 3.

iii) The effect of de-energising phase B and energizing phase C is shown in Fig.1.9(iii).In this circuit,the rotor has further moved 30^0 clockwise so that rotor teeth 1 and 2 align with energized stator teeth 2 and 5.

iv) after the rotor has displaced 60^0 clockwise from iots starting point,the step sequence has completed one cycle. The truth table in fig. shows the switching sequence to complete a full 360^0 rotation for the motor with six stator poles and four rotor poles.

Truth Table

Cycle	Phase A	Phase B	Phase C	Position
1	ON	OFF	OFF	0°
	OFF	ON	OFF	30°
	OFF	OFF	ON	60°
2	ON	OFF	OFF	90°
	OFF	ON	OFF	120°
	OFF	OFF	ON	150°
3	ON	OFF	OFF	180°
	OFF	ON	OFF	210°
	OFF	OFF	ON	240°
4	ON	OFF	OFF	270°
	OFF	ON	OFF	300°
	OFF	OFF	ON	330°
5	ON	OFF	OFF	360°

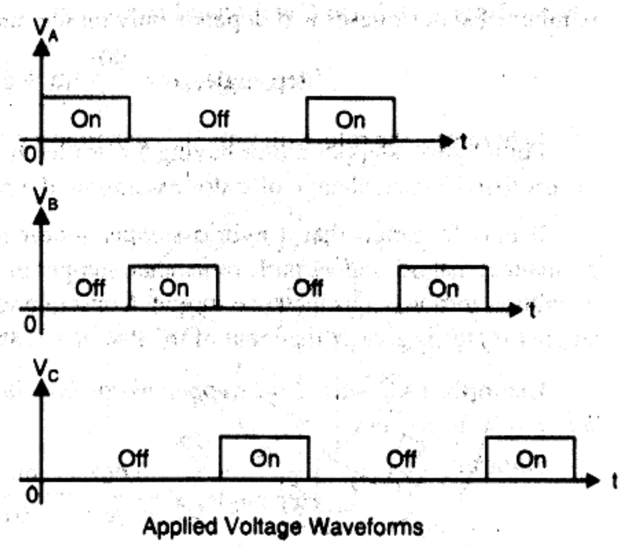


Fig.1.10 Fig.1.11

The direction of rotation will be reversed if the switching sequence is in the order of A,C and B.For this particular motor,applied voltage must have at least five cycle for one revolution.

HYBRID STEPPER MOTOR

The hybrid stepper motor combines the features of the PM and the VR stepper motors.The torque developed by this motor is greater than that of the PM or VR stepper motor.

Construction : Fig1.12 shows the basic construction of a hybrid stepper motor.The stator construction is similar to that of a VR or PM stepper motor. However, the rotor construction combines the design of the rotors of a VR and a PM stepper motor. The rotor of a hybrid stepper motor consists of two identical stacks of soft iron as well as an axially magnetized round permanent magnet. Soft iron stacks are attached to the north and south poles of the permanent magnet as shown in Fig.1.12

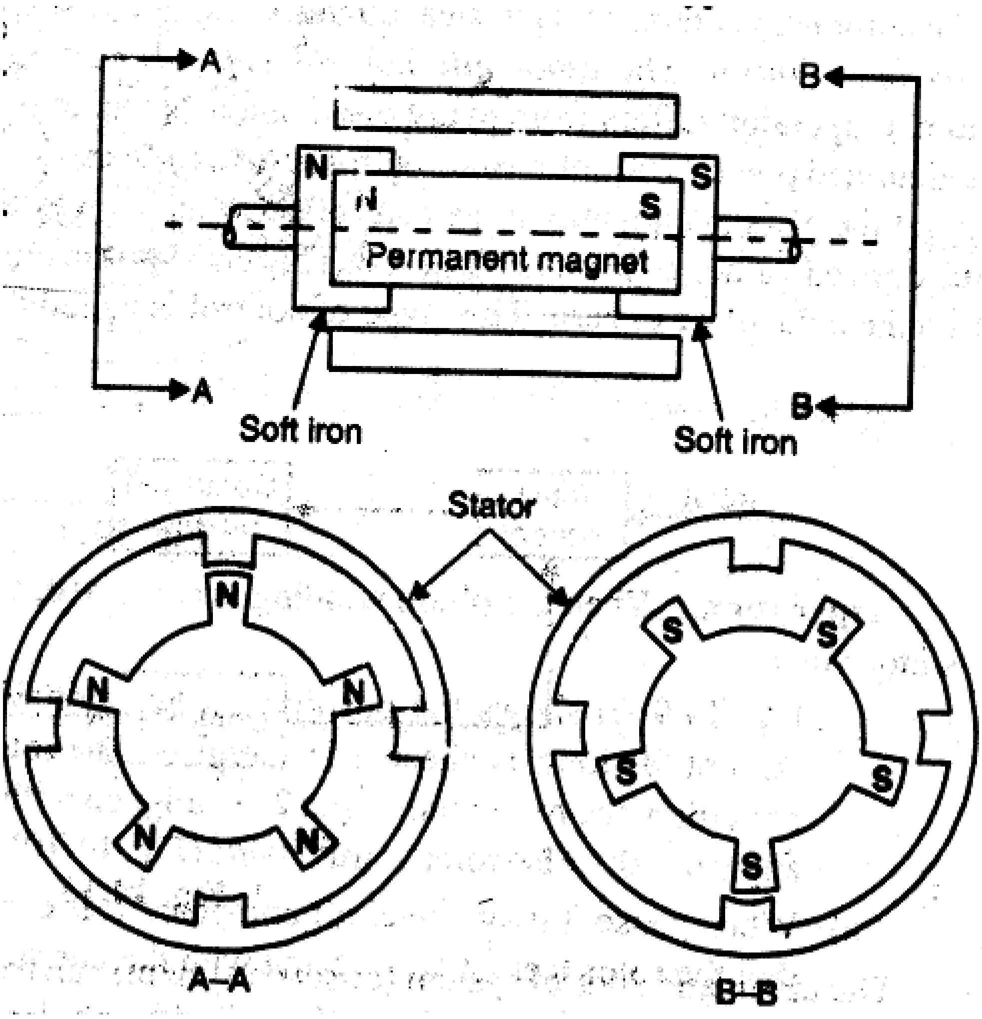


Fig 1.12

The rotor teeth are machined on the sot iron stacks. Thus the rotor teeth on one end become the north pole and those at the other end become the south pole.

This rotor teeth of both north and south poles are displaced in angle for the proper alignment of the rotor pole with that of the stator as shown in Fig.1.12

OPERATION : The operating mode of the hybrid stepper motor is very similar to that of a PM or VR stepper motor.The phase windings are energized in proper sequence and the rotor rotaes in steps.Unlike the VR or PM stepper motors,the step angle of a hybrid stepper motor is independent of the number of stator phases and depends only on the number of rotor teeth(N_r).It is given by :

Step angle, α = $90^0/N_r$ in deg

For a hybrid stepper motor having 5 rotor teeth,the step angle alpha =$90^0/N_r$ =90^0/5 =18^0/step. It means that for each change of stator excitation,the rotor will turn by a step of 18^0.

It may be noted that a hybrid stepper motor operates under the combined principles of the PM and VR stepper motors.Therefore,the hybrid motor develops both excitation torqe and relucatance torque.Consequently the resultant torque developed by the hybrid stepper motor is greater than that of the PM or VR stepper motor.

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CHAPTER VII

THREE PHASE TRANSFORMER

All alternating current electrical energy is nearly generated by three phase alternating current generators. Similarly three phase systems are used for transmission and distribution of electrical energy. There are several reasons why a three phase system is preferred over a single phase system. Some of the important reasons are

- Smaller size - KVA ratings of three phase generators and horse power ratings of three phase motors for a given physical size are higher than those of similar single phase units.
- Superior operating characteristics - operating characteristics of three phase motors and other appliances are superior to those of similar single phase units.
- Better efficiency - the efficiency of transmission and distribution of power in three phase system are better than in a single phase system.

Alternating current generated through a three phase generator has to be transmitted at higher voltage level for economic reason. Again at the receiving end of transmission line it is necessary to transform the energy through a suitable lower voltage level for distribution. It is therefore often necessary to transform the three phase voltage system to a higher or lower value.

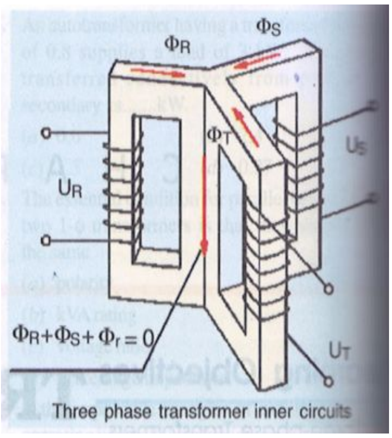
Electric energy may be transferred from one three phase current to another three phase current with a change in voltage by means of a three phase transformer. Voltage transmission on a three phase system may also be performed by using three separate single phase transformer with the winding of the transformer connected in star or delta.

Advantages of single three phase transformer over a bank of three single phase transformers

Recently, three phase transformer are increasingly being used for both step up and step down applications for the following reasons-

- The cost of one three phase transformer is less than the cost of three single phase transformer required to supply the same KVA output.
- The3 phase transformer weights less and occupies less space than 3 single phase transformer.
- The bus bar structure, switchgear and other wiring for a three phase transformer installation
  are simpler than those for three single phase transformer.

But there is one major advantage in using a bank of three single phase transformers than a
Single three phase transformer. If one single phase transformer among the bank becomes defective, it can be disconnected and power can be supplied by the other two single phase transformers unless replacement/repair is possible. However in a three phase transformer, If one of the phase winding becomes defective, the entire transformer must be taken out of a Service for repair work, thereby completely disturbing the power supply.



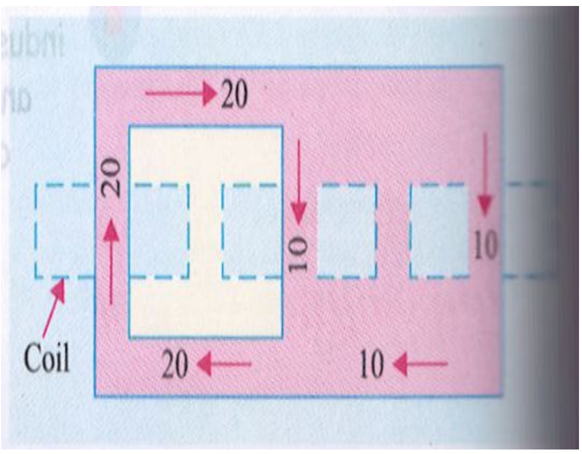


Fig.1.1 Fig.1.2

1.2. Construction

The three phase transformers are also core type and shell type. The basic principle of a three phase transformer is shown in figure.1.1, in which only primary windings have been shown interconnected in star and put across three phase supply. Three cores are 120° apart and their empty legs are shown contact with each other. The centre leg formed by these three carriers the flux produced by the three phase currents I_R, I_Y and I_B. As at any instant $\mathbf{I_R + I_Y + I_B = 0}$, hence the sum of three fluxes is also zero. Therefore it will make no difference if the common leg is removed. In that case any two legs will act as their return path for the third Just as in a three phase system any two conductors act as the return for the current in the third conductor.

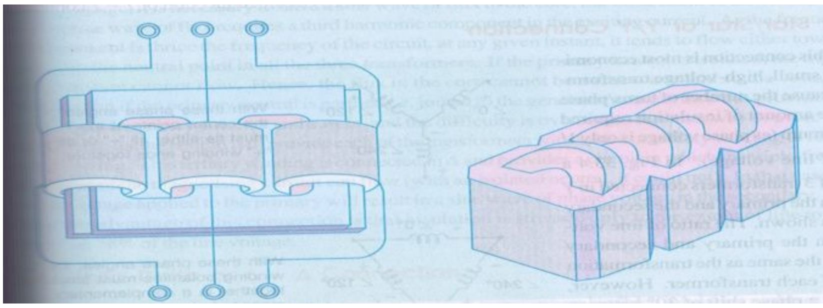


Fig.1.3

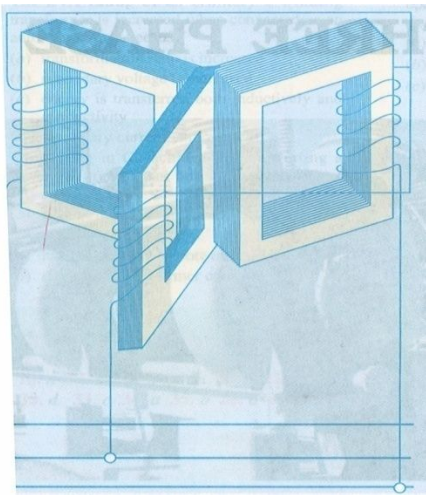


Fig.1.4

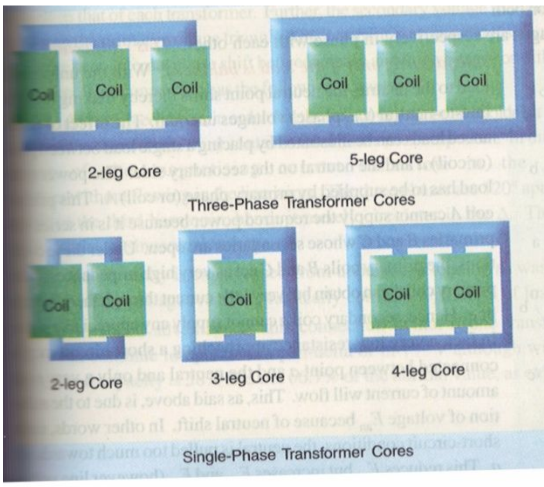


Fig.1.5

1.3. Grouping of the three phase transformer

Three phase transformers are divided into four groups according to their phase displacement between the line voltage on the hv and lv side.

Group1- 0 degree displacement (star-star or delta-delta)

Group2 - 180 degree displacement (star-star or delta-delta but the secondary is reversed)

Group3- +30 degree displacement (sta-delta)

Group4- -30 degree displacement (delta-star)

Thus a connection Yd11 gives the following information

Y indicates that hv is connected in star

d indicates that lv is connected in delta

11 indicate that lv line voltage lags hv line voltage by +30 degree. (Measured from hv phasor in anticlockwise direction).

The phase difference between the hv & lv windings for different types of connection can be represented by comparing it with the hour hand of the clock. When the hour hand of the clock is at 12 O'clock position, the phase displacement is zero. Similarly

Position of hour hand of clock	Phase displacement
0	0°
11	+30°
1	-30°
6	180°

Depending on the phase displacement of the voltages of hv (high voltage) & lv (low voltage) sides, transformers are classified into groups called "Vector group". Transformer having the same phase displacement between the hv & lv sides are classified into one same group. For successful parallel operation of transformers, they should belong to the same vector group. For example, a star-star connected three phase transformer can be paralleled with another three phase transformer whose windings are either star-star connected or delta-delta connected. A star-star connected transformer cannot be paralleled with another star-delta connected transformer as this may result in short-circuiting of the secondary side.

1.4. Three phase transformer connection

There are various methods available for transforming three phase voltages to higher or lower 3 phase voltages i.e. For handling a considerable amount of power. Usually star connection is used for high voltage transformation and delta connection is used for high current transformation. The most common connection are

1. Y-Y
2. Δ-Δ
3. Y-Δ
4. Δ-Y
5. Open Δ or V-V
6. Scott connection or T-T connection

1.5. Star/Star or Y-Y connection:-

This connection is most economical for small, high voltage transformer because the no of turns per phase and the amount of insulation required is minimum (as phase voltage is only 1/√3 of line

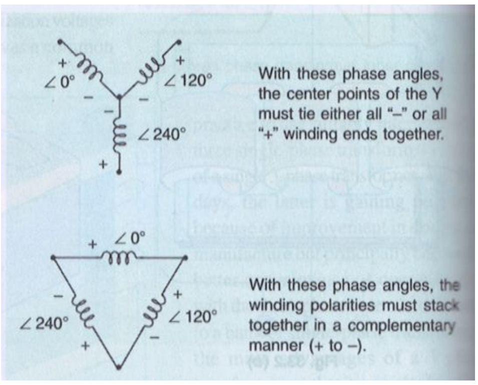


Fig.1.6

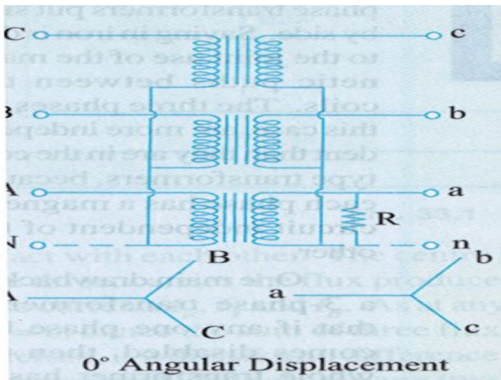


Fig.1.7

Voltage). In figure1.7 a bank of three transformers connected in star on both the primary and secondary sides are shown. The ratio of line voltage on the primary and secondary sides is the same as the transformation ratio of each transformer. However there is a phase sift of 30° between the phase voltages and line voltages both on the primary and secondary sides. Of course line voltages on both sides as well as primary voltages are respectively in phase with each other. This connections works satisfactorily only if the load is balanced. With the unbalanced load to the neutral, the neutral point shifts there by making the 3 line- to-neutral

(I.e. phase) voltages unequal. The effect of unbalanced loads can be illustrated by placing a single load between phase (or coil) a and the neutral on secondary side. The power in the load has to be supplied by primary phase (or coil) A. This primary coil A cannot supply the required power because it is in series with primaries B and C whose secondaries are opened. Under these condition the primary coils B and C act as very high impedances so that primary coil A can obtain but very little current through them from the line. Hence secondary coil a cannot supply appreciable power. In fact, a very low resistance approaching a short circuit may be connected between point A and the neutral and only a very small amount of current will flow. This, as said above, is due to the reduction of voltage E_{an} because of neutral shift. In other words, under short-circuit condition, the neutral is pulled too much towards coil a. This reduces Ean but increases Ebn & Ecn (however line voltage E_{AB}, E_{BC},E_{CA} are unaffected). On the primary side, Ean will be practically reduced to zero whereas E_{BN} & E_{CN} will rise to nearly full primary line voltage. This difficulty of shifting (or floating) neutral can be obviated by connecting the primary neutral (shown dotted in the figure) back to the generator so that primary coil A can take its required power from between its line and the neutral. It should be noted that if a single phase load is connected between the lines a and b, there will be a similar but less pronounced neutral sheet which results in an over voltage on one or more transformers.

Another advantage of stabilizing the primary neutral by connecting it to neutral of the generator is that it eliminates distortion in the secondary phase voltages. This is explained as follows. For delivering a sine wave of voltage, it is necessary to have a sine wave of flux in the core, but on account of the characteristics of iron, a sine wave flux requires a third harmonic component in the exciting current. As the frequency of this component is thrice the frequency of three circuit, at any given instant of time, it needs it tends to flow either towards or away from the neutral point in all the three transformers. If the primary neutral is isolated the triple frequency current cannot flow. Hence, the flux in the core cannot be a sine wave and so the voltages are distorted. But if the primary neutral is earthed i.e. joined to the generator neutral, then this provides a path for the triple frequency currents and e.m.fs and the difficulty is overcome. Another way of avoiding this trouble of oscillating neutral is to provide each of the transformers with a third or tertiary winding of relatively low KVA rating. This tertiary winding connected in delta and provides a circuit in which the triple frequency component of the magnetising current can flow (with an isolated neutral, it could not). In this case a sine wave of voltage applied to the primary will result in a sine wave of phase voltage in the secondary. As said above, the advantage of this connection is that insulation is stressed only to the extent of line to neutral voltage i.e. 58% of the line voltage.

1.6. Delta-Delta or Δ-Δ connection:-

This connection is economical for large, low voltage transformers in which insulation problem is not so urgent, because it increases the number of turns/phase. The transformers connection and voltage triangles are shown in fig 1.8 The ratio of transformation between primary and secondary line voltage is exactly the same as that of each transformers. Further, the secondary voltage triangle abc occupy the same relative position as the primary voltage triangle ABC i.e. there is no angular displacement between the two. Moreover, there is no internal phase shift between phase and line voltages on either side as was the case in Y-Y connection. This connection has the following advantages:

-4-

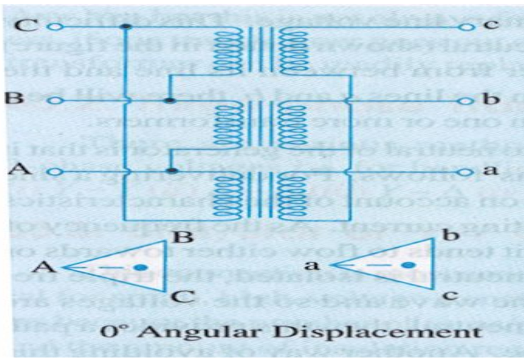


Fig.1.8

1. As explained above, in order that the output voltage be sinusoidal, it is necessary that the magnetising current of the transformer must contained a third harmonic component. In this case third harmonic component of the magnetising current can flow in the Δ connected transformer primaries without flowing in the line wires. The three phases are 120° apart which is 3X120°=360° with respect to the third harmonic, hence it merely circulates in the Δ. Therefore the flux is sinusoidal which results in sinusoidal voltages.

2. No difficulty is experienced from unbalanced loading as was the case in Y-Y connection. The three phase voltages remain practically constant regardless of load imbalance.

3. An added advantage of this connection is that if one transformer becomes disable, the system can continue to operate in open delta or in V-V although with reduced available capacity. The reduced capacity is 58% and not 66.7% of the normal value as explained in Art.1.9.

1.7. Wye/Delta or Y-Δ connection:-

The main use of this connection is at the substation end of the transmission line where the voltage is to be stepped down. The primary winding is Y connected with grounded neutral as shown in fig1.9 the ratio between the secondary and primary line voltage is 1/√3 times the transformation ratio of each transformer. There is a 30° shift between the primary and secondary line voltages which means that a Y-Δ transformer bank cannot be paralleled with either a Y-Y and Δ-Δ bank. Also, a third harmonic current flows in the Δ to provide a sinusoidal flux.

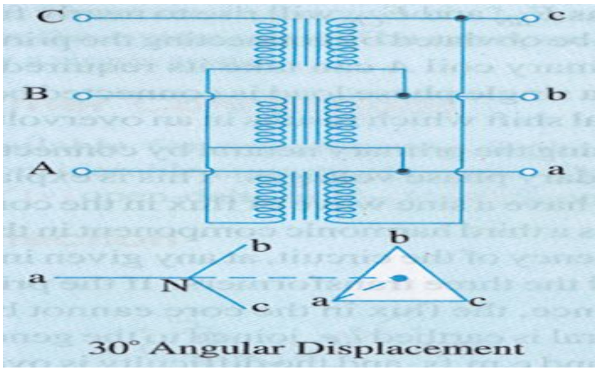


Fig.1.9

1.8. Delta/Wye or Δ-Y connection:-

This connection is generally employed where it is necessary to step up the voltage as for example at the beginning of high tension transmission system. The connection is show in fig1.10 the neutral of the secondary is grounded for providing three phase four wire service. In recent years, these connections has gained considerable popularity because it can be used to serve both the three phase power equipment and single phase lighting circuit.

This connection is not open to the objection of a floating neutral and voltage distortion because the existence of a Δ connection allows a path for the third harmonic currents. It would be observed that the primary and secondary line voltages and line currents are out of phase with each other by 30°. Because of this 30° shift it is impossible to parallel such a bank with a Δ-Δ and **Y-Y** bank of transformers even though the voltage ratios are correctly adjusted. The ratio of secondary to primary voltage is √3 times the transformation ratio of each transformer.

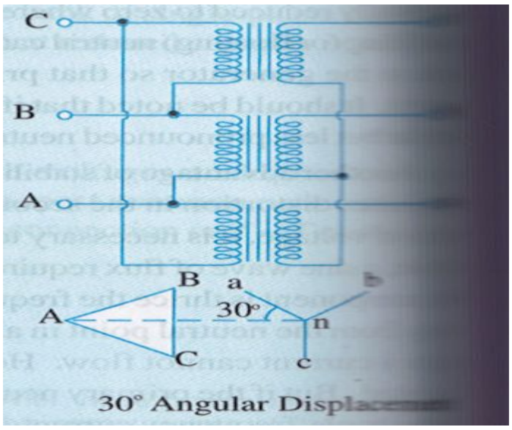


Fig.1.10

Example 1.1. A 3 phase, 50 Hz transformer has a delta-connected primary and star connected secondary, the line voltage being 22000 V and 400V respectively. The secondary has a star connected balanced load at 0.8 power factor lagging. The line current on the primary side is 5A.Determine the current in each coil of the primary and in each secondary line. What is the output of the transformer in KW ?

Solution : It sould be noted that in 3 phase tranformer, the phase tranformation ratio is equal to the turn ratio but the terminal or line voltages depend upon the method of connection employed. The delta/star connection is shown in figure 1.11 .

Phase voltage on primary side= 22000V

Phase voltage on secondary side= 400/√3

K=400/22000x√3 = 1/55√3

Primary phase current = 5/√3 A

Secondary phase current= (5/√3)/K =(5/√3)/(1/55√3) =**275 A**

Output = $\sqrt{3}V_L I_L \cos\Phi$ =√3x400x275x0.8 =**15.24 KW**

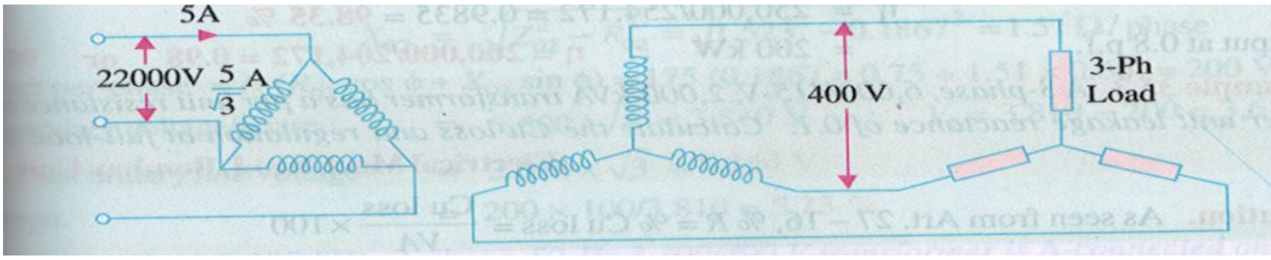


Fig.1.11

Example 1.2. A 500KVA, 3 phase, 50 Hz transformer has a voltage ratio (line voltage) of 33/11 KV and is delta/star connected. The resistances per phase are: high voltage 35 Ω, low voltage 0.876 Ω and the iron loss is 3050 W. calculate the value of efficiency at full load and ½ of full laod respectively A) at unity P.F. and B) 0.8 P.F.

Solution: Transformation ratio (K)= 11000/√3x33000 = 1/3√3

Per phase R_{02}= 0.876+$(1/3\sqrt{3})^2$x35=2.172 Ω

Secondary phase current= 500000/(√3x11000) = 500/11√3 A

Full load condition :

Full load total Cu loss= 3x$(500/11\sqrt{3})^2$x2.172 =4490W

Iron loss=3050 W

Total full load losses=4490+3050 =7540 W:

Outout at unity P.F= 500KW

Full load efficiency=500000/507540=0.9854 or **98.54 %**

Output at 0.8 P.F=0.8x500=400KW

Efficincy=400000/407540= 0.982 or **98.2%**

Half load condition :

Output at unity P.F= 250 KW

Cu losses = $(1/2)^2$x4490 =**1,222 W**

Total losses= 3050+ 1222= 4172 W

Efficiency=250000/254172=0.9835 or **98.35%**

Output at 0.8 P.F=200 KW

Efficiency= 200000/204172= 0.98 or 98%

1.9. Open- Delta or V-V Connection.

If one of the transformers of a Δ-Δ is removed and 3phase supply is connected to the primaries as shown in Fig. 1.12, then three equal 3 phase valtages will be at the secondary terminals on no load. This method of transforming 3-pahse power by means of only two transformers is called the open -Δ or V-V connection.

It is employed:

1. When the three-phase load is too small to warrant the installation of full three phase transformer bank.
2. When one of the transformers in a Δ-Δ bank is disabled, so that service is continued although at reduced capacity, till the faulty transformers is repaired or a new one is substituted.
3. When it is anticipated that in future the load will increase necessitating the closing of open delta.

One important point to note is that the total load that can be carried by a V-V bank is not two-third of the capacity of a Δ-Δ bank but it is only 57.7% of it. That is a reduction of 15% (STRICTLY, 15.5%) from its normal rating. Suppose there is Δ-Δ bank of three 10-kVA transformers. When one transformer removed, then it runs in V-V. The total rating of the transformer kVA rating but only 0.866 of it i.e. 20x0.866=17.32 (or 30x0.57=17.3kVA). The fact that the ratio of V- capacity to Δ-capacity is 1/ $\sqrt{3} = 57.7\%$(or nearly 58%) instead of 66.67 percent can be proved as follows:

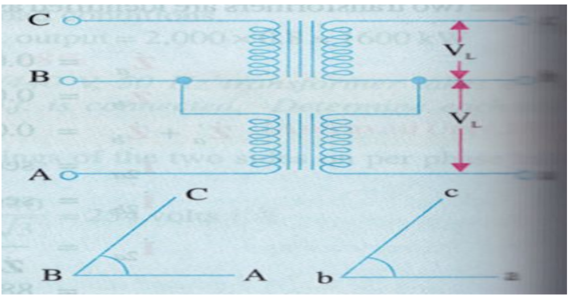


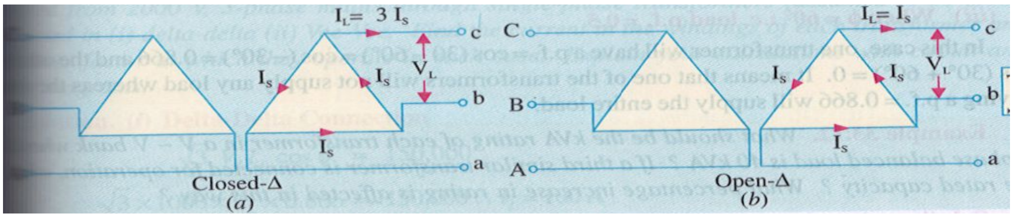
Fig1.12

As seen from fig 1.13(a)

Δ-Δ capacity = $\sqrt{3}.V_L I_L = \sqrt{3}.V_L(\sqrt{3}I_S) = 3\, V_L.I_S$

In Fig1.13 (b) it is obvious that when Δ-Δ bank becomes V-V bank, the secondary line current I_L becomes equal to the secondary phase current I_S.

(V-V- capacity/Δ-Δ capacity) = $\sqrt{3}.V_L I_S / 3\, V_L.I_S = 1/\sqrt{3} = 0.577$ or 58%



(a) Fig1.13 (b)

It means that the 3-phase load which can be carried without exceeding the rating of the transformers is 57.7 per cent of the original load rather than the expected 66.7%.It is obvious from above that when one transformer is removed from a Δ-Δ bank.

1. The bank capacity is reduced from 30 kVA to 30X0.577=17.3KVA and not to 20 kVA as might be tought off hand.
2. Only 86.6% of the rated capacity of the two remaining transformers is avalible (i.e. 20X0.866=17.3kVA). In other words, ratio of operating capacity to avalible capacity on an open -Δ is 0.866. This factor of 0.866 is sometimes called the utility factor.
3. Each transformer will supply 57.7% of load and not 50% when operating in V-V.

However, it is worth noting that if three transformers in a Δ-Δ bank are delivering their rated load and one transformer is removed, the overload on each of the remaining transformers is 73.2% because

(Total load in V-V)/ (VA/transformer) = $\sqrt{3}.V_L I_S / V_L I_S = \sqrt{3} = 1.732$

This over-load may be carried temporarily but some provision must be made to reduce the load if overheating and consequent breakdown of the remaining two transformers is to be avoided.

The disadvantages of this connection are:

1. The average power factor at which the V-bank opeates is less than that of the load, this power factor is actually 86.6% of the balanced load power factor. Another significant point to note is that, except for a balanced unity power factor load, the two transformers in the V-V bank operate at different power factors.
2. Secondary terminal voltages tend to become unbalanced to a great extent when the load is increased, this happens even when the load is perfectly balanced.

   It may, however be noted that if two transformers are operating in V-V and loaded to rated capacity in the above example, to 17.3kVA, the addition of a third transformer increases the total capacity by √3 or 173.2% (i.e to 30kVA). it means that for an increase in cost of 50% for the third transformer. The increase in capacity is 73.2%when converting from a V-V system to a Δ-Δ system.

1.10. Power supplied by V-V connection:

When a V-V bank of two transformer supplies a balanced 3-phae load of power factor cos ϕ, then one transformer operates at a p.f. of $\cos(30^0 - \phi)$ and the other at $\cos(30^0 + \phi)$. Consequently, the two transformers will not have the same voltage regulation.

$P_1 = KVA \times \cos(30^0 - \phi)$ And $P_2 = KVA \times \cos(30^0 + \phi)$

i) When $\phi=0$ i.e. load p.f. =1

Each transformer will have a p.f. = $\cos 30^0 = 0.866$

ii) When $\phi=30^0$ i.e. load p.f. =0.866,

In this case, one transformer has a p.f. of $\cos(30^0 - 30^0) = 1$ and the other of $\cos(30^0 + 30^0) = 0.866$

iii)) when $\phi=60^0$ i.e. load p.f.=0.5, In this case, one transformer has a p.f. of cos (30^0 - 60^0) = cos (-30^0)=0.866 and the other of cos (30^0 +60^0) = cos (90^0)=0. It means that one of the transformers will not supply any load whereas the other having a power factor of 0.866 will supply the entire load.

Example 1.3. What should be the kVA rating of each transformer in a V – V bank when the 3 – phase balanced load is 40 kVA? If a third similar transformer is connected for operation ,what is the rated capacity? What percentage increase in rating is affected in this way?

Solution. As pointed out earlier, the kVA rating of each transformer has to be 15% greater.

kVA / transformer = (40 / 2) x 1.15 = **23**

Δ – Δ bank rating = 23 x 3 = 69; Increase = [(69 – 40) / 40] x 100 = **72.5 %**.

1.11. Scott Connection or T-T connection:

This is a connection by which 3-phase to 3-phase transformation is accomplished with the help of two transformers as shown in Fig. 1.14. Since it was first proposed by Charles F. Scott, it is frequently referred to as Scott connection. This connection can also be used for 3-phase to 2-phase transformation as explained.

One of the transformers has centre taps both on the primary and secondary ending (Fig1.14) and is known as the main transformer. It forms the horizontal member of the connection (Fig.1.15).

The other transformer has a 0.866 tap and is known as teaser transformer. One end of both the primary and secondary of the teaser transformer is joined to the centre taps on both primary and secondary of the main transformer respectively as shown in Fig. 1.15(a) . The other end A of the teaser primary and the two ends B and C of the main transformer primary are connected to the 3-phase supply.

The voltage diagram is shown in Fig 1.15(a) where the 3-pahse supply line voltage is assumed to be 100 V and a transformation ratio of unity. For understanding as to how 3-phase transformation results from this arrangement, it is desirable to think of the primary and secondary vector voltage forming geometrical Ts' (from which this connection gets its name).

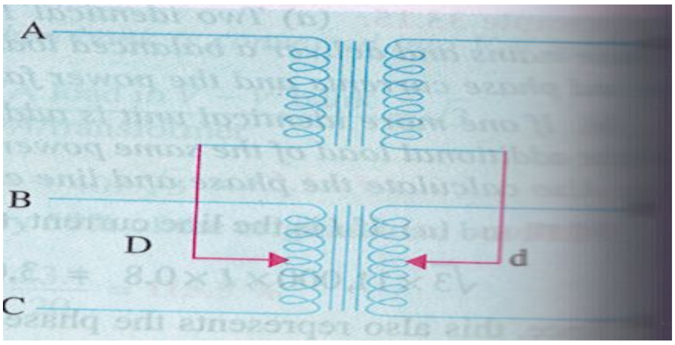


Fig1.14

In the primary voltage T of Fig 1.15(a) E_{DC} and E_{DB} are each 50V and differ in phase by 180^0 because both coils DB and DC are on the same magnetic circuit and are connected in opposition. Each side of the equilateral triangle represents 100 V. The voltage E_{DA} being the altitude of the equilateral triangle is equal to $(\sqrt{3}/2)$ X100=86.6 V and lags behind the voltage across the main by 90^0. The same relation holds good in the secondary winding so that *abc* is a symmetrical 3-phase system.

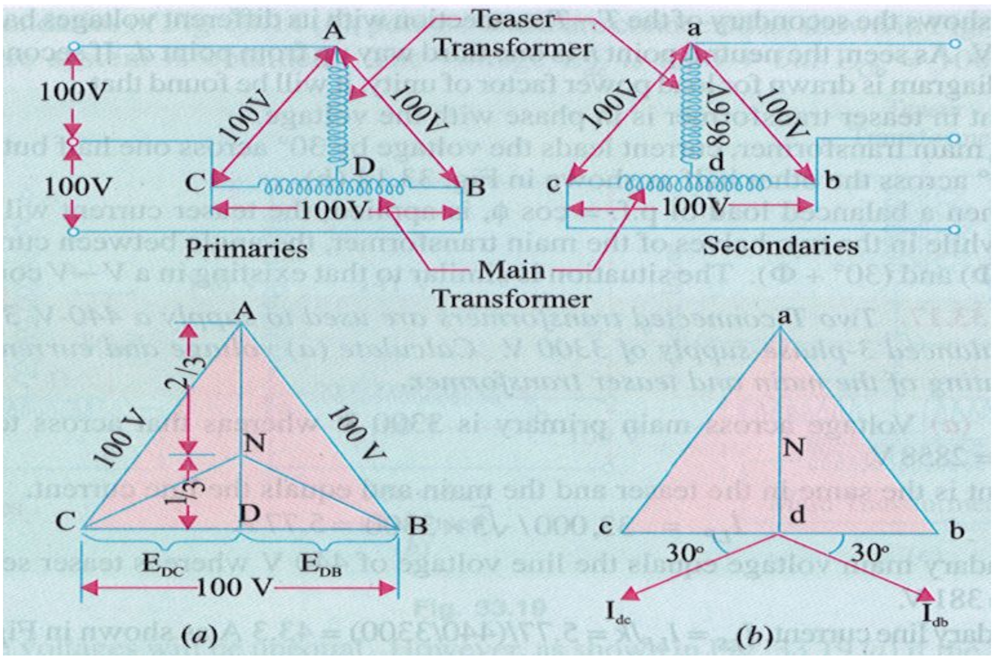


Fig.1.15

With reference to the secondary voltage triangle of Fig. 1.15(b),it is should be noted that for a load of unity power factor, current I_{db} lags behind voltage E_{db} by 30^0 and I_{db} leads

E_{dc} by 30^0 . In other words, the teaser transformer and each half of the main transformer, all operate at different power factors.

Obviously, the full rating of the transformers is not being utilized. The teaser transformer operates at only 0.866 of its rated voltage and the main transformer coils operate at $\cos 30^0 = 0.866$ power factor, which is equivalent to the main transformer's coils working at .86.6 per cent of their kVA rating. Hence the capacity to rating ratio in a T-T. Connection is 86.6%- the same as in V-V connection if two identical units are used, although heating in the two cases is not the same.

If, however, both the teaser primary and secondary windings are designed for 86.6volts only, then they will be operating at full rating, hence the combined rating of the arrangement would become (86.6+86.6)/(100+86.6)=0.928 of its total ratting. In other words, ratio of kVA utilized to that available would be 0.928 which makes this connection more economical than open-Δ with its ratio of 0.866.

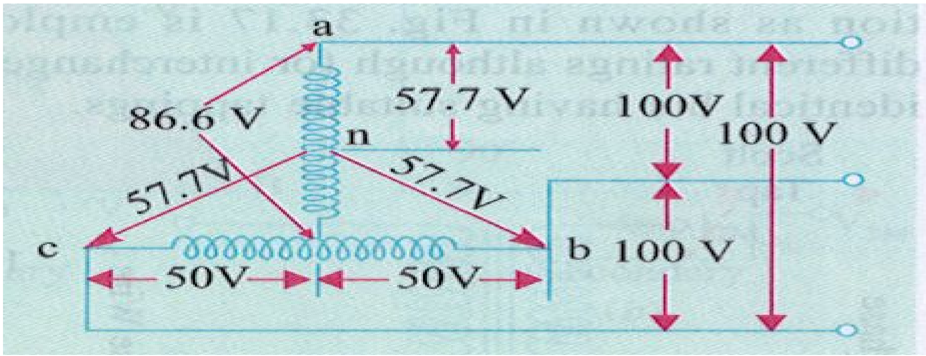


Fig1.16

Fig1.16 shows the secondary of the T-T connection with its different voltages based on a nominal voltage of 100 V. As seen, the neutral point n is one third ways up from point d. If secondary voltage and current vector diagram is drawn for load power factor of unity, it will be found that

1. Current in teaser transformer is in phase with the voltage.
2. In the main transformer, current leads the voltage by 30° across one half but lags the voltage by 30° across the other half as shown in figure 33.15(b)

Hence when a balanced load of power factor =COSΦ, is applied , the teaser current will lag or lead the voltage by Φ while in the two halves of the main transformer, the angle between current voltage will be (30°-Φ) and (30°+Φ). The situation is similar to that existing in a V-V connection.

Example-1.4. Two T- connected transformers are used to supply a 440V, 33KVA balanced load from a balanced three phase supply of 3300V. Calculate (a) Voltage and current rating of each coil (b) KVA rating of the main and teaser transformer.

Solution :- (a) Voltage across main primary is 3300V where as that across teaser primary is =0.866 X 3300 =2858V

The current is the same in the teaser and the main and equals the line current.

ILP=33000/√3X3300=5.77A

The secondary main voltage equals the line voltage of 440V whereas teaser secondary voltage =0.866 X 440=381V

The secondary line current, I**ls**= **ILP**/k=5.77/(440/3300)=43.3A as shown in figure1.17

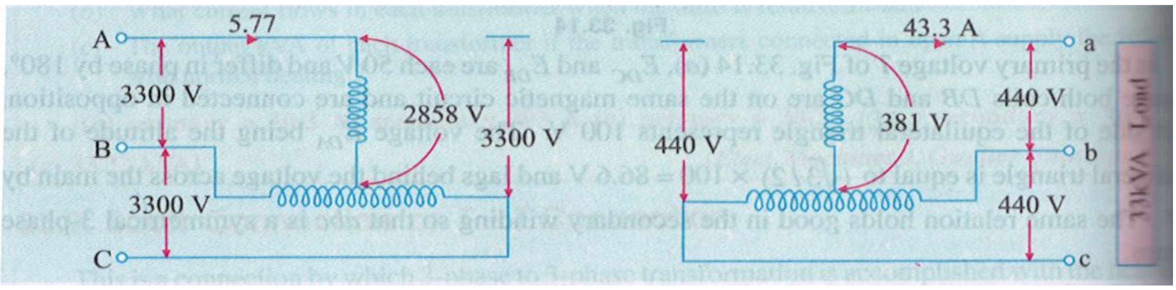


Fig.1.17

(b) Main KVA= 3300 X 5.77 X 10^{-3}=**19KVA**

Teaser KVA = 0.866 X main KVA= 0.866 X 19= **16.4KVA**

1.12. Three-phase to Two-phase Conversion and vice-versa

This conversion is required to supply two-phase furnaces, to link two-phase circuit with 3-phase system and also to supply a 3-phase apparatus from a 2-phase supply source. For this purpose, Scott connection as shown in fig 1.18 is employed. This connection requires two transformers of different ratings although for interchangeability and provision for spares, both transformers may be identical but having suitable tappings.

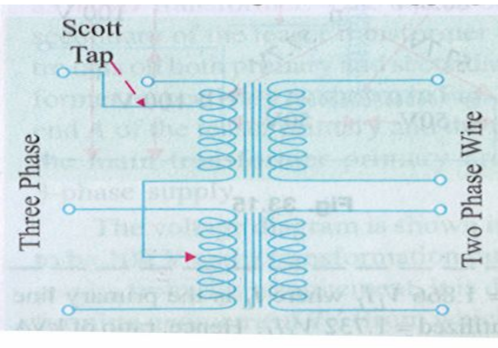


Fig1.18

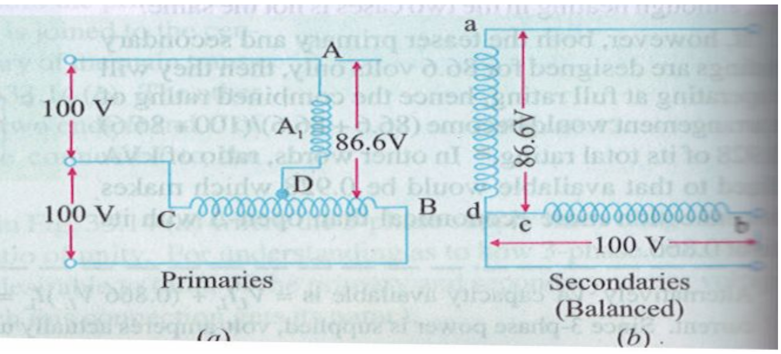


Fig.1.19

If, in the secondaries of Fig.1.15 (b), points c and d are connected as shown in Fig.1.19 (b), then a 2-phase, 3-wire system is obtained. The voltage E_{dc} is 86.6 V but E_{cb} = 100V, hence the resulting 2-phase voltages will be unequal. However, as shown in Fig.1.20 (a) if the3-phase line is connected to point A_1, such that DA_1 represents 86.6%of the teaser primary turns (which are the same as that of main primary), then this will increase the volts/turn in the ratio of 100:86.6, because now 86.6 volts are applied across 86.6 percent of turns and not 100% turns. In other words, this will make volts/turn the same both in primary of the teaser and that of the main transformers. If the secondaries are of both the transformers have the same number of turns, then the secondary voltage will be equal magnitude as shown, thus resulting in a 2-phase, 3-wire system.

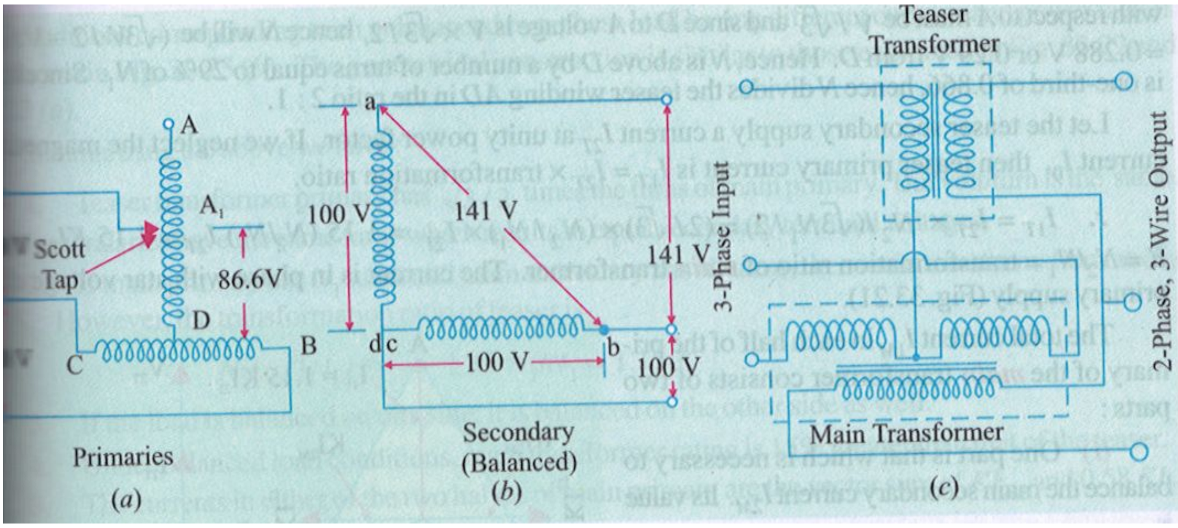


Fig1.20

Consider the same connection drawn slightly differently as in fig.1.21. The primary of the main transformer having N_1 turns is connected between terminals CB of a 3-phse supply. If supply line voltage is V. then obviously $V_{AB}=V_{BC}=V_{CA}$= V but voltage between A and D is V x $\sqrt{3}/2$. As said above, the number of turns between A and D should be $(\sqrt{3}/2)N_1$

for making volt/turn the same in both primaries. If so, then secondaries having equal turns , the secondary terminal voltages will be equal in magnitude although in phase quadrature.

-12-

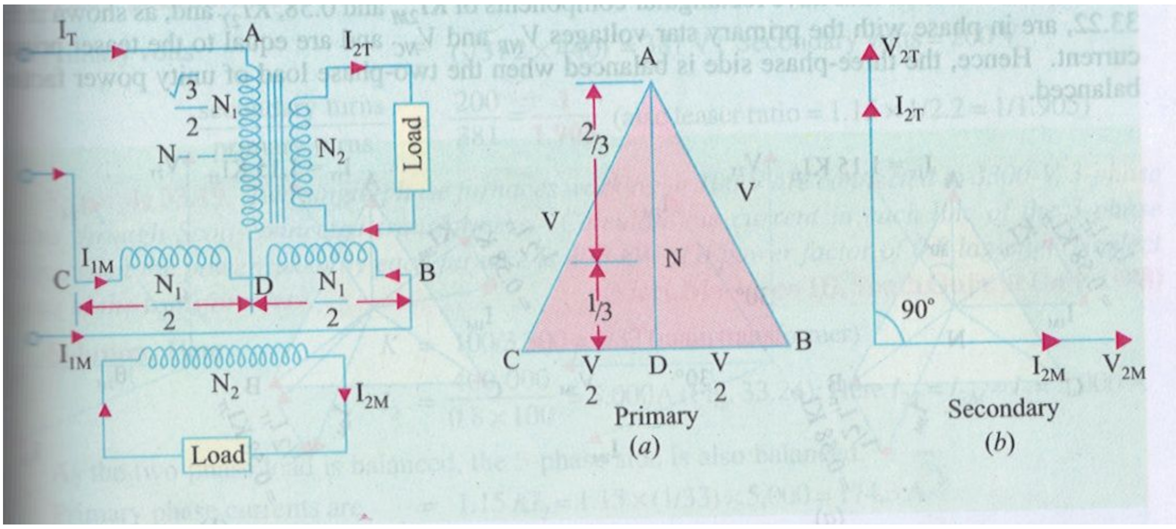


Fig1.21 Fig1.22

It is to be noted that point D is not the neutral point of the primary supply because its voltage with respect to any line is not $V/\sqrt{3}$. Let N be the neutral point. Its position can be determined as follows. Voltage N of with respect to A must be $V/\sqrt{3}$ and since D to A voltage is $V \times \sqrt{3}/2$, hence N will be $\sqrt{3}V/2 - V/\sqrt{3} = 0.288V$ or 0.29V from D. Hence, N is above D by a number of turns equal to 29% of N_1. Since 0.288 is one third of 0.866, hence N divides the teaser winding AD in the ratio 2:1.

Let the teaser secondary supply a current I_{2T} at unity power factor. If we neglect the magnetizing current I_o, then teaser primary current is $I_{1T} = I_{2T} \times$ transformation ratio

$\therefore$ $I_{1T} = I_{2T} \times N_2/(\sqrt{3}N_1/2) = (2/\sqrt{3}) \times (N_2/N_1) \times I_{2T} = 1.15 \times (N_2/N_1) \times I_{2T} = 1.15K\ I_{2T}$ where $= N_2/N_1 =$ transformation ratio of main transformer. The current is in phase with star voltage of the primary supply (figure1.22)

The total current I_{1M} **in each half of the of the primary of the main transformer consists of two parts:**

1. **One part is that which is necessary to balance** the main secondary current I_{2M}, its value is $= I_{2M} \times (N_2/N_1) = K\ I_{2M}$

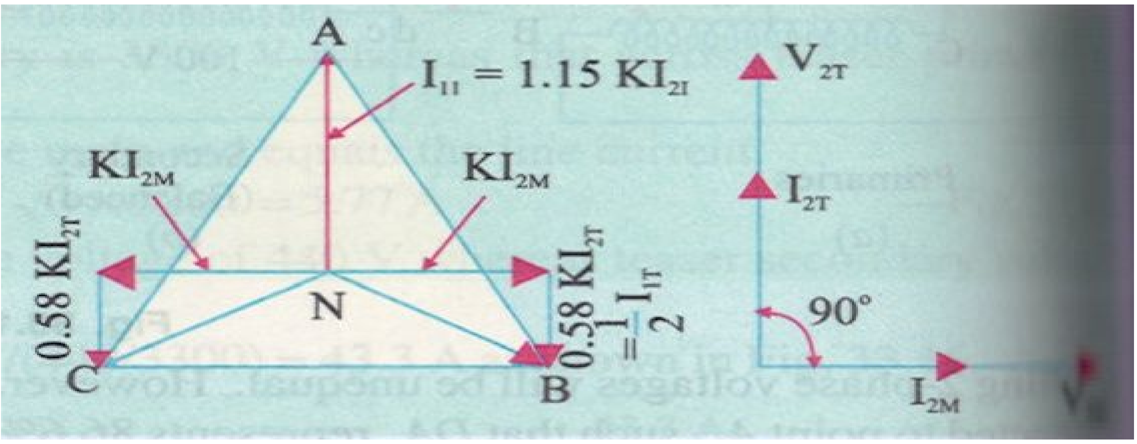


Fig1.23

2. The second part is equal to one half of the teaser primary current i.e. $0.5\ I_{1T}$. This is so because the main transformer primary forms a return path for the teaser primary current which divides itself into two halves at mid point D in either direction. The value of each half is $=0.5\ I_{1T}=1.15K\ I_{2T}/2= 0.58\ K\ I_{2T}$.

Hence the current in the lines B and C are obtained vectorially as shown in fig.1.23. It should be noted that as the two halves of the teaser primary current flow in opposite directions from point D, they have no magnetic effect on the core and play no part at all in balancing the secondary ampere-turns of the main transformer.

The line currents thus have rectangular components of K I_{2M} and 0.58 K I_{2T} and as shown in fig. 1.23, are in phase with primary star voltages V_{NB} and V_{NC} and are equal to the teaser primary current. Hence, the three phase side is balanced when the two phase load of unity power factor is balanced.

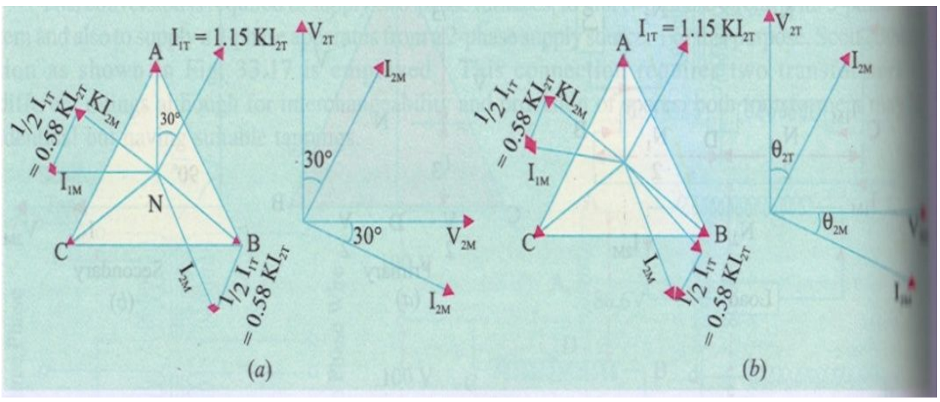


Fig1.24

Figure 1.24(a) illustrates the condition corresponding to a balanced two phase load at a lagging power factor of 0.866. The construction is the same as in figure 1.23. it will be seen that the three- phase side is again balanced. But under these conditions the main transformer rating is 15%greater than that of the teaser, because its voltage is 15% greater although its current is the same.

Hence, ***we conclude that if the load is balanced on one side, it would always be balanced on the other side.***

The conditions corresponding to an unbalanced two-phase load having different currents and power factors are shown in figure 1.24(b). The geometrical construction is similar to those explained in figure 1.23 and 1.24(a).

Summarizing the above we have:

1. Teaser transformer primary has √3/2 times the turns of main primary. But volt/turn is the same. Their secondaries have the same turns which result in equal secondary terminal voltages.

2. If main primary has N_1 turns and main secondary has N_2 turns, then main transformation ratio is N_2/ N_1. However, the transformation ratio of teaser is $N_2/ (\sqrt{3}\ N_1/2) = 1.15\ N_2/ N_1 = 1.15K$.

3. If the load is balanced on one side, it is balanced on the other side as well.

4. Under balanced load conditions, main transformer rating is 15% greater than that of the teaser.

5. The currents in either of the two halves of main primary are the vector sum of $K\ I_{2M}$ and $0.58K\ I_{2T}$(or $0.5\ I_{1T}$)

Example 1.5. Two transformers are required for Scott connection operating from a 440V, three phase supply for supplying two single phase furnaces at 200V on the two phase side. If the total output is 150KVA, calculate the secondary to primary turn ratio and the winding currents of each transformer.

Soln: - **main transformer**

Primary volts= 440V ∴ secondary volts=200V ∴ N_2/ N_1=200/440=1/2.2

Secondary current = 150000/2 X 200=**375 A**

Primary current =375 X 1/2.2=**197A**

Teaser transformer

Primary volts= (√3/2 X 440) =381V: Secondary volts =200V

Secondary turns /primary turns =200/381=**0.52**(also teaser ratio =1.15 X 1/2.2=0.52).

1.13. Parallel operation of three phase transformer

Transformers are said to be connected in parallel when their primary windings are connected to a common voltage supplier and their secondary windings are connected to a common load.

1.14. Reasons for parallel operation

1. Extension of loads - for large loads it may be impracticable or uneconomical to have a single large transformer.

2. Capacity to spare – in substations the total load required may be supplied by an appropriate no of transformers of standard size. This reduces the spare capacity of the substation.

3. Future extension - there scope of future extension of a substation to supply a load beyond the capacity of the transformers already installed.

4. If there is a breakdown of transformer in system of transformers connected in parallel, there is no interruption of power supply for essential service. Similarly when a transformer is taken out of service for its maintenance and inspection the continuity of supply is maintained.

1.15. Condition for parallel operation

All the condition which applied to the parallel operation of single phase transformer also is applied to the parallel running of three phase transformer but with the following addition

1. The voltage ratio must refer to the terminal ***voltage of primary and secondary.*** It is obvious that this ratio may not be equal to the ratio of the number of turns per phase. For example, if V1, V2 are the primary and secondary terminal voltages, then for Y/Δ connection the turn ratio is V2/ (V1/√3) = √3V2/ V1.

2. The phase displacement between primary and secondary voltages must be the same for all transformers which are to be connected for parallel operation.

3. Phase sequence must be the same.

4. All the three transformers in the three phase transformer bank will be of the same construction either core or shell.

Note 1: IN dealing with three phase transformer calculation are made for one phase only. The value of equivalent impedance used is the impedance per phase referred to secondary.

2. In case the impedance of primary and secondary windings are given separately then primary impedance must be referred to secondary by multiplying it with (transformation ratio)^2.

3. For Y/Δ or Δ/ Y transformers should be remembered that the voltage ratio as given in the question is referred to terminal voltages and are quite different from turn ratio.

1.16. Tap changers in transformers

The modern equipments, utilising electrical energy are design to operate satisfactorily at one voltage level. It is therefore of paramount importance to keep the consumers' terminal voltage, within the prescribed limits. The transformer output voltage and hence the consumers' terminal voltage, can be controlled by providing taps either on the primary or on the secondary.

The principle of regulating the secondary output voltage is based on changing the number of turns in the secondary quantities. V_2= (N_2/ N_1) X V_1.

If the tap changer is design to operate, when the transformer is out of circuit, it is then called off-load (or no load) tap changer. A tap changer design to operate with the transformer in the circuit is called on load tap changer.

1.17. No load (or off-load) Tap changer

This tap changer is used for seasonal voltage variation. And elementary form of no load tap changer is illustrated in figure.1.25. It has six studs mark from one to six. The winding is tapped at six points equal to the number of studs. The tapping leads are connected to six correspondingly marks stationary studs arranged in circle. The face plate carrying the six studs, can be mounted anywhere on the transformer, say on the yoke or any other convenient place. The rotatable arm R can be rotated by means of hand wheel, from outside the tank.

If the winding is tapped at 2.5% intervals, than with the rotatable arm R

- At studs 1,2: Full winding is in circuit
- At studs 2,3: 97.5% of the winding is in circuit
- At studs 3,4: 95% of the winding is in circuit
- At studs 4,5: 92.5% of the winding is in circuit
- At studs 5,6: 90% of the winding is in circuit

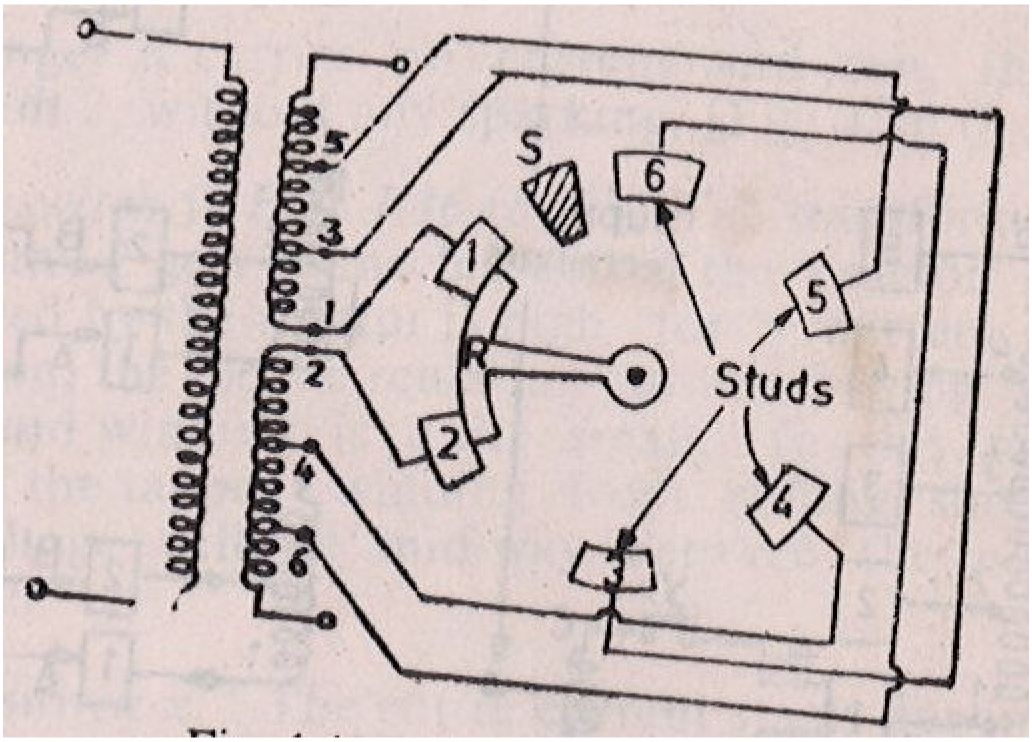


Figure1.25

Stop S fixes the final position and prevents the arm R from being rotated clockwise. In the absence of stop S, the arm R may come in contact with studs 1 and 6. In such a case, only the lower part of the winding is cut out circuit and this is undesirable from mechanical stress considerations.

The tap changing must be carried out only after the transformer is disconnected from the supply. Suppose arm R is at studs 1, 2. For bringing arm R at studs 2and 3, the transformer is first de-energised and then arm R is rotated two bridge studs 2 and 3. After this, transformer is switched on to the supply and now 97.5% of the winding remains in circuit.

1.18. On-load tap changer

The tap changer s used for daily or sort period voltage alteration. The output voltage can be regulated with the changer, without any supply interruptions. During the operation of an on-load tap changer.

- The main circuit should not be opened otherwise dangerous sparking will occur and
- No part of the tap winding should get short circuited

One form of elementary on load tap-changer is illustrated in figure 1.26(a). The centre tap reactor C prevents the tapped from getting short circuited. The transformer tapings are connected to the correspondingly marked segment s 1 to 5. Two moveable fingers, A and B connected to centre-tapped reactor via. Switches x and y, make contact with anyone of the segments under normal operations.

In fig.1.26 (a), both the fingers are in contact with segment 1 and full winding is in circuit switches x, y are closed. One half of the total current flows through x, lower half of the reactor and then to the external circuit. It is seen that currents in the upper and lower halves of the reactor flow in opposite direction. Since the whole reactor is wound in the same direction the m.m.f produced by one half is opposite to the m.m.f produced by the secondary half. These m.m.fs are equal and the net m.m.f is practically zero: therefore the reactor is almost non inductive and the impedance offered by it is very small. Consequently the voltage drop in the centre-tap reactor is negligible.

When a change in voltage is required the finger A and B can be brought to segment to, by adopting the following sequence of operations.

- Open switch y figure 1.26 (b1). The entire current must now flow through the lower half of the reactor. It therefore, becomes highly inductive and there is a large voltage drop. It should be noted that the rector must be designed to handle full load current, momentarily.
- The finger B carries no current and can therefore, be moved to segment 2, without any sparking (figure 1.26(b2)).
- Close switch Y figure1.26 (b3) the transformer winding between taps 1 and 2 gets connected across the reactor. Since the impedance offered by the reactor is high for a current flowing in only one direction, the local circulating current flowing through the reactor and tapped winding is quite small. In this manner, the reactor prevents the tapped winding from getting short circuited. The terminal voltage will be mid-way between the potentials of tappings 1 and 2.
- Open switch x: The entire currents start flowing through the upper half of the reactor, manifested by large voltage drop, fig.1.26 (b4).
- Move the finger A from segment 1 to segment 2 and then close switch x: The winding between taps 1 and 2 is therefore completely out of circuit, fig. 1.26(b5). If further change in voltage is required, the above sequence of operations is repeated.
- For large power transformers the switches x and y may be circuit breakers.

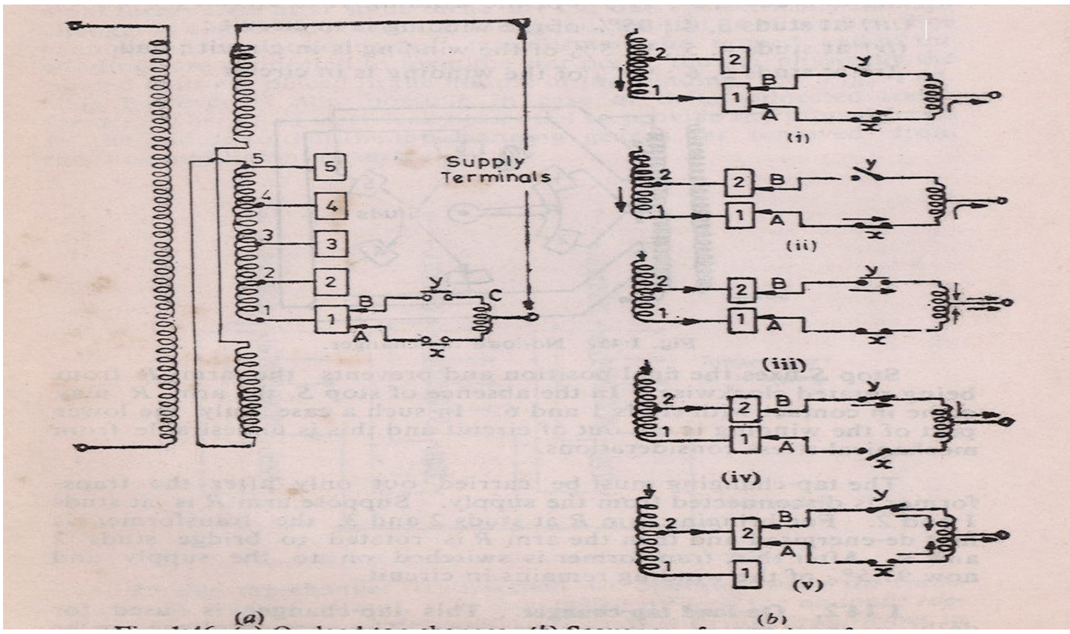


Figure1.26

1.19. Maintenance of Transformer

The normal life of transformer is about 30 years. It could even be longer if operated carefully and maintained regularly. The main object of maintenance of transformers is to maintain its insulation in good condition. Factors affecting the insulation of a transformer are: moisture, presence of oxygen, and solid impurities.

Maintenance of transformers needs (i) external inspection, and (ii) internal inspection periodically.

The external inspection requires inspection of parts and auxiliaries of the transformer that can be done without opening the tank or lowering the oil level but with the transformer taken out of service,e.g. megger tests, ratio tests, water –flow tests, taking out sample of oil and testing it, inspection of bushings,breathers,oil level,tank,gaskets,ground wire for all auxiliary apparatus,etc.In the case of large transformers, the condition of circulating pumps, on load tapping gears, oil gauges, pressure relief devices, oil gauges,etc.,need to be checked.

1.20. Checking and testing of transformer oil

The deterioration of insulation oil is generally due to oxidation, especially when the transformer works under the condition of high temperatures. Oxidation is due to the formation of acids, sludge and water which accompanies the chemical change. Samples of transformer oil are taken out carefully and tested for colour and odour. Cloudiness in oil may be due to suspended moisture or suspended solid matter. Dark brown colour may indicate dissolved asphalt, green colour dissolved copper compounds; and acid smell indicates the presence of volatile acids.

The oil samples may be tested as follows:

(a) The dielectric strength of oil should be tested as per IS: 335 – 1953.The oil should withstand the test voltage of at least 30kV for one minute without breakdown.

(b) Cracle test for free water should be performed as per IS: 335 – 1953.The test is only qualitative.

(c) The acidity of oil should be determined as per IS: 1866 – 1961.

(d) Sludge test: The traces of solid matter in oil samples may be examined as per IS: 1866 – 1961.

1.21. Insulation resistance

The insulation resistance is measured by megger test along with the temperature. This is because the insulation resistance in megohms gets reduced to nearly half for every 10^0c temperature rise. The insulation resistance should not be less than two megohms for each 1000 v of operating voltage.

1.22. Internal inspection of Transformer

Take samples of oil from top and bottom for testing: Lower oil in transformer. Check inside bushings, brackets, HV, LV windings for damage insulation; check connections, ground of core, insulation condition of various parts, and inside condition. An inspection schedule should be drawn for checks monthly, quarterly and yearly inspection.

1.23. Maintenance schedule

Every hour: Check temperature of oil, windings, ambient, load & voltage. Adjust load to keep the temperature rise within a permissible limit.

Daily: (a) Check oil level; if low, fill in dry oil.

(b) Check the colour of the silica gel in the breather. Colour should be blue. If the colour of the silica gel becomes pink replace them.

Quarterly: Check for proper working of cooling fans, circulating pumps, etc.

Half-yearly: Check the dielectric strength of oil, bushes, insulators, cable boxes, filter, and replace oil if necessary.

Yearly: Check oil for acidity, sludge formation, contacts, lightning arrestors, etc.

Check alarms, relays, etc.

Check earth resistance.

Five yearly: Carry out overall inspection of the transformer including lifting of core and coils. Clean the transformer with dry transformer oil.

1.24 Diagnostic tests for power Transformer

The Transformer is the heart of the Grid S/S & it is the most costly equipment in it. Any failure in it will not only damage the equipment nearby & may also create danger to the life of the Operating staff. It takes a lot of time to replace a power Transformer, which will affect the steady power supply. Hence it becomes very essential to ascertain the condition of the Transformer under service. The monitoring of Transformer's condition is not that simple as it sounds. Because no test give a very clear picture about the condition. So to ascertain the real condition of the Transformer diagnostic analysis has to be done from a set of results. This is known as diagnostic analysis of a power Transformer.

Normally every utility make some routine tests at least annualy to the transformer. Any slight deviation in the routine test, diagnostic analysis may refer to. Even this analysis is essential at a new condition for signature impression as well as to detect any design or assembly defect. The total life of the Transformer may be devided in three segmants. The initial period, which is a small period usually 4 to 5 years, is known as **INFANT MORTALITY.** The percentage of failure is quite high in this period. Any failure in this period attributes to design or assemble failure. The 2nd stage which is quite longer period is the **NOMAL PERIOD** & has a very less percentage of failure. In this period attribute to poor maintenance. The 3rd period is the **AGEING PERIOD.** Again the persentage of failure increases in this period bacause of ageing factor of mainly soild insulation used. The Frequency of analysis should be more may be almost in every 2 years. This life cycle characteristic is known as **BATH TUB CHARECTETISTIC** because of shape.

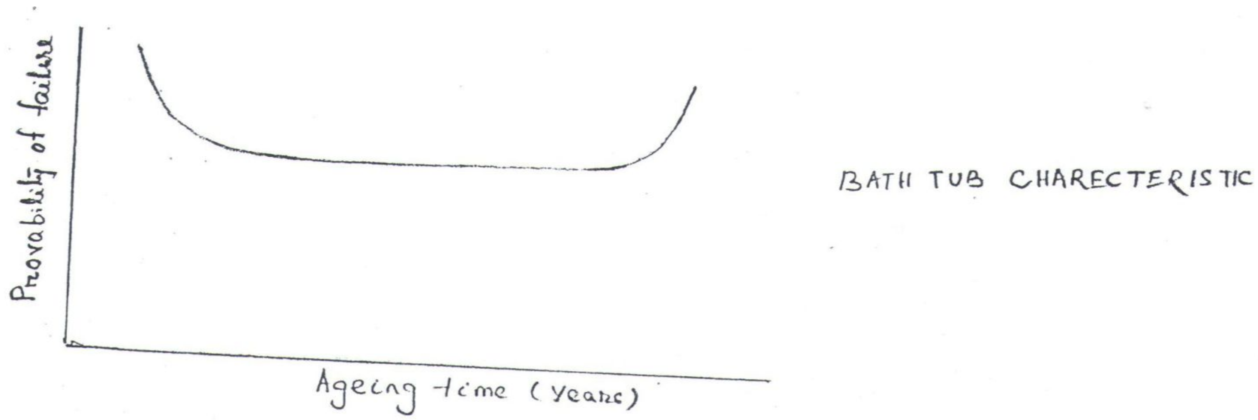


Fig.1.27

The normal routine test that may be conducted atleast every year are;

- IR value.
- PI value.
- Trans value
- BDV Test value.
- However, BDV may be done aditionaly atleast in every 2 months.
- If any abnormalities are found in the above tests, then only we have to go for dissolved gas analysis (DGA Test), otherwise it is not required.

The life of the Transformer is generally the life of the soild insulation, the cellulosic paper. The degree of deterioration of the insulation is mainly due to the diffrent stress that act on the transformwer under service, which reflects on the life of the transformer used, The stree that act.

- **Mechanical stress:** between conductors, leads & windings due to over currents or fault current, mainly due to system short circuits.
- **Thermal Stress:** Due to local heating, over load currents & leakage flux or due to malfunctioning of cooling system.
- **Dialectric Stree:** System over voltage, Transient impluse condition or due to internal resonance within a winding.
- **Environmental Stress:** Moisture ingress, pollution.

Even may new type of insulation has been developed, the cellulosic paper is still widely used.

The rising temperature in presence of moisture & oxygen accelerate the aging process of the soild insulation, For a example, the paper with 2% moisture ages three times taster then 1% moisture & 30 times to 3% moisture content. The degradation product from oil oxidation, such as peroxides & water soluble acid absorbs in paper & makes it brittle & low strength oxycellulose. The oxidation gradully deplets the natural oxidation inhibitors present in naphthalenic oil & products are acid, ketones, peroxides, soap, and aldehyds. This causes colloidal contamination in the oil which form hydrocorbon which again polymerisis to form partly conduting sludge & get deposited on the windings thus it makes heat transfer more diffcult & oxidation become more faster due to rise of temperture, So it is conclusive that presence of moisture & oxygen in oil or paper is the main culprit to reduce life of the transformer. The routine test must be conducted regularly to know the presence of the moisture & weather it is within the limit or not. If the value is low then there is no problem othewise we have to go for further analysis regrading the presence of moisture & other conducting gaese & where it is present (whether in oil or in paper or in both).A accordingly steps will be taken. The oxidations also accelerate due to partial discharge.

By now our stand is more clear that;

- We want to know whether any moisture or any conducting soluble gas or conducting particulars present in the insulation.
- If present not within limit then it is essential to know where it is and in which formand how to separate it out & to increase the life period.
- We should not allow to increase the moisture content in oil and if however it has entered then it is assentail to knwo to what level the damage has been taken place. So that we can decrease the effect to certain level and increase the life of our transformer.

1.25. Routine test

(1) IR value:

It is simlpy the insulation resistance of the insulating materials i.e. paper & oil in combination, A DC petential is applied usally 5 KV between diffrent windings, between winding & tank of the transformer. Earlier, the value was noted after allowing the current for 15 sec. But now a day value is noted after 1 min. As the real values can be known only after allowing the current for certain time. What should be the IR Value? It is a real debate. It depends upon the size & shape of the insulating materials & also affected by different environmental condition. In a thumb rule people consider it as 1.5 MΩ/ KV. If there is any huge variation then it is generally marked, Before taking the IR value all clamps & connectors should be propely tightened & bushing & tanks should be cleaned. This test has least importance unless & untill the value is out right low.

(2) PI Value:

It is known as polarisation index. It is a number having no uint. It is a ratio of insulation resitence value taken for 10 min. to 1 min. Now the question arises what is polarisation & how its value is affected due to the presence of moisture or any conducting soluble gas.

In a conductor there is free electron, which is free to move under application of external field, but in case of insulator there is no free electron. At normal condition the electron moves arround the protons such that CG of both consider with each other, has no net polar effect, when an external field is applied the rotation of the electron arround the proton is no more circular but eccentric as shown in the figure.

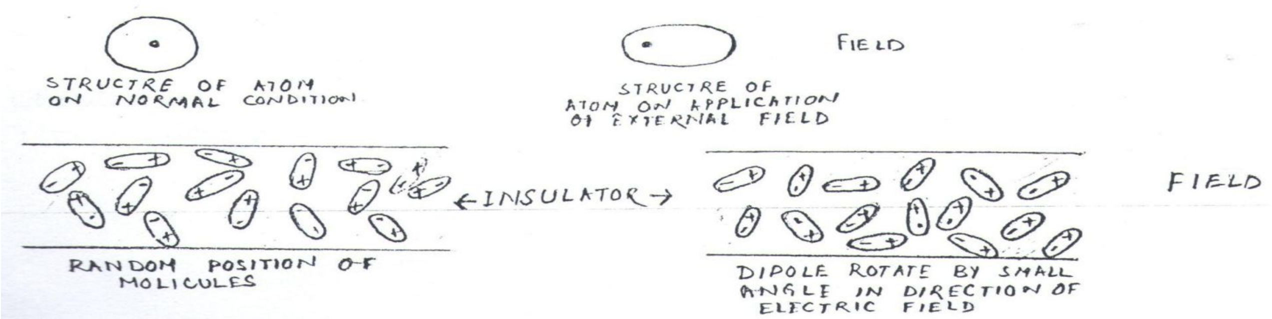


Fig.1.28

This implies when an electrical field is applied the CG of proton & electron are no more same but displaced with a small gap. This result into a electrical dipole or it can be said that polarisation has taken place. This dipoles orient around itself in such a manner that the net electrical field produced by the dipoles, opposes the applied electrical field. The reduction in applied field reduces the current or increase the resistance values. The increasing value is more & more as more & more dipole oriented around itself. After around 10min almost all orientation takes place so 10 min values is taken.T he polarisation index has a other name that is **DRYNESS FACTOR**.

The name suggests that the dryness of the insulation has a certain role over that ratio which is known as polarisation index. If there is some moisture or desolve conducting gases present in a insulator then a conduction sphere appears around the insulator which does not allow to penetrate the external field.This reduces the polarisation effect.So reductuion & PI value indicates the presence of moisture or any desolve conducting gases in the insulator,as per IS the value above 1.5 is consider to be good.

3) Tan δ value:

The PI value is affectec by moisture & desolve gases but there may be many other conducting non soluble substances which allowed more current to flow to the insturator causing more heat & oxidation.Thus causing detoriation of insulating materials.Tan δ test gives more clear-cut picture regarding the presence of any conducting materials presence in the insulator.

When a insulator is in between two conducting substances it is nothing but a capacitor.So when we apply a AC potential between two winding or winding & tank which is earthed acts as a capacitive circuit as both solid & liquid insulator are in between .Idealy the current should lead the voltage by an angle of 90^0 .But practically it will not beacuase of certain resistance present in it.The angle by which it falls to reach 90^0 is known as δ angle.

Fig.1.29

$\tan\delta = V_R / V_C = R / X_C$

Higher is the value of Tanδ, more is the resistive materials present in the insulation in any form as per value upto 0.2 allowed.

To major the Tanδ value the instrument used is nothing but a Sheraing bridge, supported by a software to give the result directly in Tanδ.

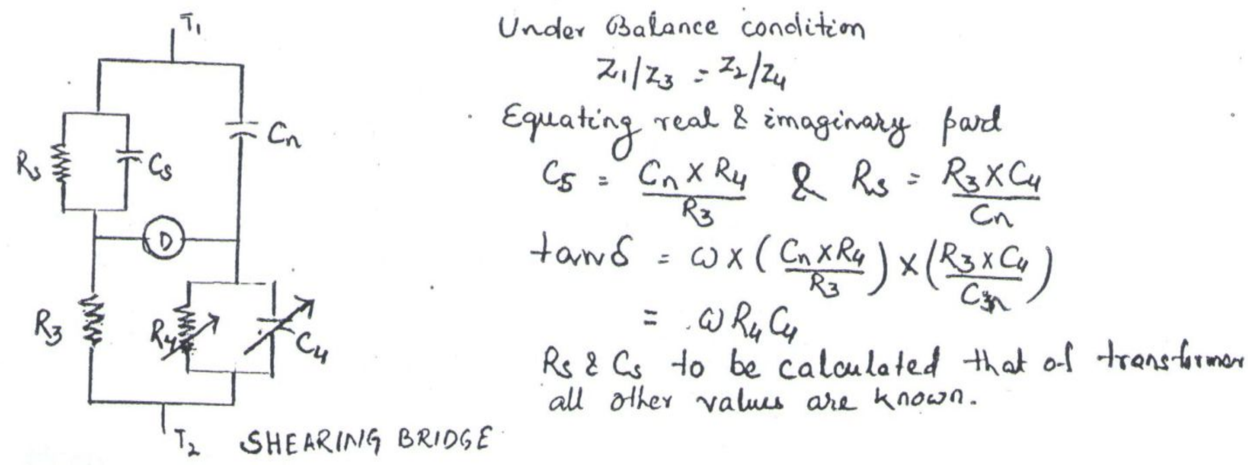


Fig.1.30

4) BDV Test value:

It is a very simple test. The breakdown voltage (BDV) of an insulator is the potential at which it loses its insulating property & become conducting. Oil is taken in a glass or plastic container of usually 300ml to 500ml capacities. The electrode are of copper, brass bronze or stainless steel well polished having spherical shape of dia 12.5mm to 13mm separated by 2.5± 0.1mm.

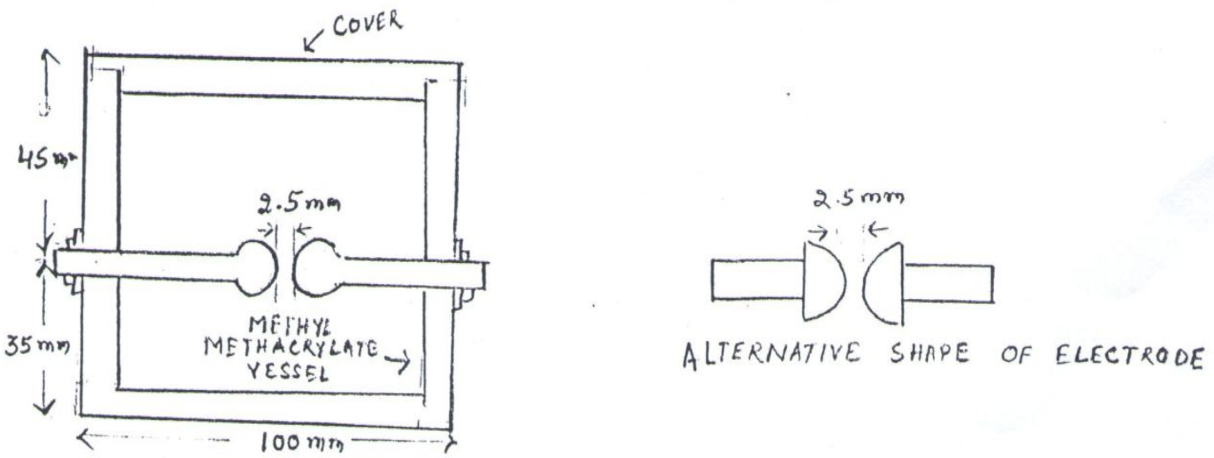


Fig.1.31

The oil under test should be between 15^0C to 35^0C preferably 27^0C.The applied potential at rated frequency should be raised gradually at a rate around 2KV per sec till flash over takes place. The test kits automatically switch OFF within 0.02sec, The average of six tests result is taken. The time interval between two tests should be 5min. if the disappearance of air bubble does not take place. The value recommended by IS is above 50KV.This test may be taken in every month. Proper care should be taken at sampling time; so that no external moisture enters to it.

SUMMARY

BDV	>50KV <50KV	Good. Should be taken again in a better weather condition & if it is still low, then filtration or dehydration may be required & will be decided after other tests.
PI	>1.5 <1.5	Good. Filtration or dehydration may be required & will be decided after other tests.
Tanδ	<0.2 >0.2	Good. Filtration or dehydration may be required & will be decided after other tests.

Other Test:

1) IR, PI & Tanδ.
2) Test on Oil & DGA.
3) Recovery Voltage Measurement.
4) Dielectric Spectroscopy Test.
5) Magnetic Balance Test.
6) Turns Ratio Test.
7) Frequency Response Analysis.
8) Coil Resistance Test.
9) Degree of polymerisation Test. (DP)
10) Partial Discharge Test (PD)
11) Surge Voltage Analysis Test.