ENERGY CONVERSION-II
LECTURE NOTES

For

Electrical Engineering

Prepared By: Sri. Arabinda Pradhan (Sr.Lecturer)

Three Phase Induction Motor

Construction:

Theinduction motor mainly dividedin to two parts.

(1)Stator (2)Rotor

In caseofD. C.Motorbasicallyitisdividedinto twomainparts(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 insidethe stator. It is cylindrical in shape.

Rotor is divided into twotypes.

(i) Squirrelcage Rotor

(ii) Phasewound Rotor orSlip ringRotor,

Figureshowsthe disassembled viewof aninduction motorwith squirrel cagerotor.

(a)Stator(b)Rotor(c)bearingshields (d)Fan(e) Ventilationgrill (f)terminalbox.

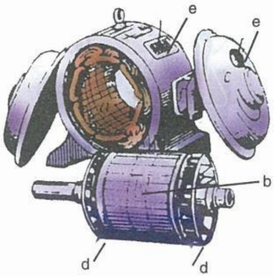


Fig 1.1

Similarlyfigureshows thedisassembled viewof a slip ringmotor(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 placed120^0 spacedegreeapartas showninfig – 1.2.Thefluxdueto threephasewindings isshownin fig 1.3.

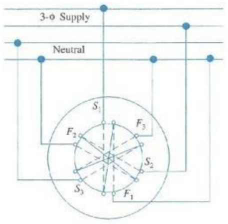


Fig1.2

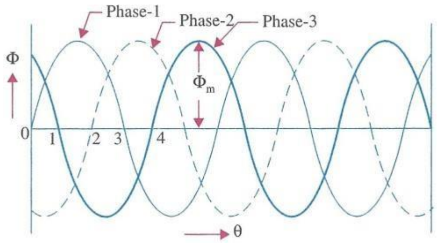


Fig1.3

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, $\phi_2$and $\phi_3$due to three phases. Considering values of $\phi_r$at four instants i.e. 1/6th time period apart corresponding to points marked 0, 1, 2 & 3.

Proof:

Case– 1: Resultant fluxat origin i.e.when$\theta=0^0$At thattime $\phi_1=0$,

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

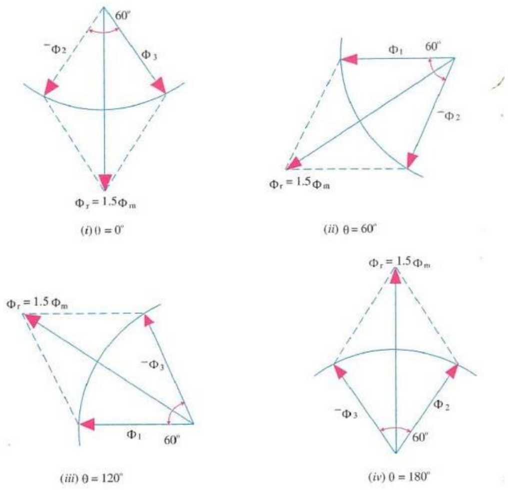


Fig 1.4

Resultantfluxϕ_r:

Asperlawof parallerogram

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

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

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

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

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

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

Case–II: When $\theta=60^0$

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

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

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

III When $\theta = 120^0$

$\phi_1 = \phi_m \mathrm{Sin} < 120^0 = \frac{\sqrt{3}}{2}\phi_m$

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

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

$\phi_r$canbecalculatedasearlier Similarly

$\phi_r = 1.5\phi_m$

Case–IV When$\theta = 180^0$

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

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

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

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

Hencefromtheabovefourcaseswecandrawaconclusionthattheresultantflux(ϕ_r) insidethestatorwindingatanytime=1.5$\phi_m$andtheresultantflux(ϕ_r)rotatesaroundthe stator at syncronous speed.

Howtherotorrotates:

Therotorliesinsidethestator.Thereis anairgap inbetweenthestatorand rotor.The stator slots are provided with three Phase winding.

Whenthreephasestatorwindingsarefedbya3-phasesupplythenarotatingmagnetic flux of constant magnitude will produce.

Thisrotating fluxpasses through airgap andcuts thestationary conductorsontherotor .Thereisalsoa 3-phaserotorwindingontherotor.Thestatorandrotor windingsactas 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 thefluxintheairgap. Thefluxin therotorwindinginteracts withthefluxinthestatorwinding 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 therewould 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.

Slipspeed=$N_s - N_r$.

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

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

$\Rightarrow N_s - N_r = SN_s$

$\Rightarrow N_s - SN_S = N_r$

$\Rightarrow N_s(1-S) = N_r$

ThereforeRotorspeed$N_r = N_s(1-S)$

FrequencyofRotorCurrent :

When therotoris stationary, thefrequency of rotorcurrent is thesameas thesupply frequency. Butwhentherotorstarts revolving,thenthefrequencydependsupontherelativespeed. Letthe frequency of the rotor current be f'

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

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

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

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

Therefore $f' = Sf$

HenceRotorfrequency = slip xsupply frequency

TorqueofanInductionMotor:

Thetorqueofaninductionmotoristhetorqueproducedatthe rotor.Hence$T=T_r$where $T_r$is the rotor torque.

IncaseofD.C.motortorque=ArmatureTorque=T_aT=

$$0.159\phi Z I_a \left(\frac{P}{A}\right) \text{N} \times \text{m}$$

Therefore$T_a = K\phi I_a$

[Where0.159,Z,P andAareall constants)

Whereϕisthefluxproduced bythe filedwindingwhichis pulsatingin nature.

Similarlyincaseofaninductionmotorthetorqueisalsoproportionaltotheproductof flux produced in stator and rotor current.

Howeverthereis anotherfactorwhichistobetakenispowerfactor.Becauseinthis case both flux and current are alternating in nature.

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

WhereI_2–Rotor Current

ϕ-flux produced in thestator.

ϕ_2–Thephaseanglebetweenrotoremfandrotorcurrent(E_2andI_2) As $\phi \alpha$

E_2

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

$$T=KE_2I_2\cos\phi_2$$

StartingTorque:

Thetorquedevelopedbythemotorattheinstantofstartingiscalledstarting torque. Let

E_2= Rotor emf per phase at stand still

R_2=Rotorresistance/ phase

X_2=Rotorreactance/phaseatstand still

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

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

Standstillorstartingtorque$T_{st}=KE_2I_2\cos\phi_2$

Or$T_{st}=KE_2\times\frac{E_2}{\sqrt{R_2^2+R_2}}\times\frac{R_2}{\sqrt{R_2^2+R_2}}=\frac{KE_2^2R_2}{R_2^2+R_2^2}$

Ifsupply voltageVremains constant, then thefluxϕandhenceE_2remainconstant.

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

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

StartingTorqueofaSquirrel –cageInductionMotor:

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 verylarge 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.

StartingTorqueof aslip-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.

Conditionformaximum startingTorque:

AsstartingtorqueT$_{st}$= $\frac{K_2 R_2}{R_2^2+X_2^2}$

Frommathematicsweknowthatdifferentiationofamaximumquantity=0 D (T$_{st}$)

= 0, when T$_{st}$= Maximum starting Torque

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

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

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

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

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

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

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

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

$$\Rightarrow R_2=X_2$$

Hencethestarting torquewillbemaximumwhenRotor resistance=RotorReactance.

RotorEMFandRotor reactanceunderrunningcondition:

RotorEMF: LetE_2=Stand still rotorEMF/phase

X_2=Standstillrotorreactance/phase

Whenrotorstartsrotating,therelativespeedbetweenrotorandrotatingfluxinthe stator starts decreasing.

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

Therotorinducedemfisdirectlyproportionaltothisrelativespeed

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

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

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

Therefore$E_r = SE_2$

RotorReactance:

Thefrequencyoftherotorcurrent $f_r=$

sf

Therefore $X_r = 2\pi s f_r L$

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

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

Therefore $X_r = S\ X_2$

Torqueunderrunningconditions:

AsweknowthatstartingtorqueT$_{st}$=$KE_2I_2\cos\ \phi_2$

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

Sothe torqueunder runningcondition $T_r \alpha E_r I_r \cos\ \phi_r$

WhereE_r= Rotor EMF/Phase under running condition

I_r=RotorCurrent/Phase underrunningcondition

A$_s$$E_r \alpha \phi$

Therefore$T_r \alpha \phi I_r \times \cos\phi_r$

$I_r = \frac{E_r}{Z_r}$ 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 $I_r = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$

Thereforerunningtorque $T_r \alpha E_r I_r$ as ϕ_r

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

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

⇒ As $E_2 \alpha \phi$

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

Therefore $T_r = \frac{K_1 S E_2^2 R_2}{R_2^2 + (S \times X_2)^2}$

Torqueunderstandstillcondition:

Nr=0 atstand still condition

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

Thereforetorqueunderstand still condition

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

Conditionformaximum Torqueunderrunningcondition:

Thetorqueofarotorunder running condition

$T_r = \frac{K_1 S E_2^2 R_2}{R_2^2 + (S \times X_2)^2}$

Theconditionsformaximumtorquemaybeobtainedbydifferentiatingtheabove 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 $\frac{dY}{dS} = 0$

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

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

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

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

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

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

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

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

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 thevalue $R_2=SX_2$

Therefore$T_r=T_r(max)=\frac{KSE_2^2\times SX_2}{(SX_2)^2+(SX_2)^2}$

$$\Rightarrow T_r(max) = \frac{KS^2E_2^2X_2}{2S^2X_2^2} = \frac{KE_2^2}{2X_2}$$

Hence $\boxed{T_r(max)=\frac{KE_2^2}{2X_2}}$

RelationbetweenfullloadTorqueandMaximumTorque:

AsTorque(T) = $\frac{KSE_2^2R_2}{R_2^2+(SX_2)^2}$

E_2ispracticallyconstant

HenceT = $\frac{K_2SR_2}{R_2^2+(SX_2)^2}$

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

Takingfull load slip as $S_f$at full load torqueT_f

Therefore$T_f\alpha$ $\frac{S_fR_2}{R_2^2+(SX_2)^2}$ .... (I)

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

$T_{max}\ \alpha\ \frac{1}{2X_2}$ .... (II)

$$\frac{(i)}{(ii)} = \frac{T_f}{T_{max}} = \frac{S_fR_2}{R_2^2+(S_fX_2)^2}\times\frac{2X_2}{1}$$

$$\frac{T_f}{T_{max}} = \frac{2S_fR_2X_2}{R_2^2+(S_fX_2)^2}$$

DividingX_2^2onboth 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 $\frac{R_2}{X_2} = a$

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

Ingeneral $\frac{\text{operatingTorque}}{\text{MaximumTorque}} = \frac{2as}{s^2+a^2}$

s–operatingslip

RelationbetweenstartingTorqueandMaximumTorque:

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

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

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

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

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

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

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

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

RelationbetweenTorqueandslip:

$$\text{AsTorque}(T) = \frac{KSE_2^2R_2}{R_2^2+(SX_2)^2}$$

TakingTorqueinY axisand slipin X axis

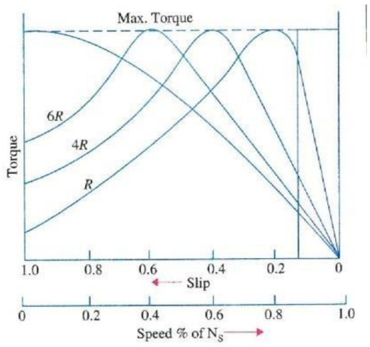


Fig. 1.5

Atorigin i.e. S =0, torqueT =0

Thereforethecurvestartsfromorigin.Atnormalspeed,closedtosynoronismthatis 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 voltageconstant so $E_2$is also constant)

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

ForaparticularinductionmotorR_2isconstant.

Hence $T \alpha S$

Thereforelowvalveofslip,torqueisdirectlyproportionaltoslip.Hencethecurveis straight line for low valve of slip.

Asslip increasesthe torquealsoincreases and becomesmaximum when = $R_2=SX_2$

$$\text{i.e.}S=\frac{R_2}{X_2}$$

Astheslipfurtherincreases(SX_2)becomeshighercomparetoR$_2$. Hence

R_2can be neglected in compare to (SX_2)

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

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

TakingX$_2$isconstantforaparticularinductionmotor

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

Sobeyondthepointofmaximumtorqueanyfurtherincreaseinslip,resultsindecreaseof torque.

Methodofstanding ofInduction Motor

The operation of the squirrel cage induction motor is similar to transformer havingshort 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 oftheir 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 squirrelcage 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.

MethodofStartingof SquirrelCageMotor:

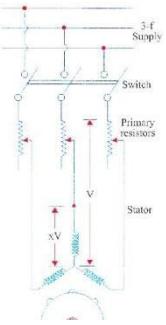
(1) Resistors Method

(2) Star–DeltaMethod

(3) AutotransformerMethod

Intheabovemethods,thesupplyvoltagetothesquirrelcagemotoris reduced during starting.

1) ResistorMethod:



Inthismethodtheresistorsareconnectedinserieswiththestatorphases,togive reduced voltage to the stator winding.

Whenresistorsareconnectedinserieswiththestatorphases,thecurrentinthestator phases will reduce. If the voltage applied across the motor terminals is reduced by 50%, startingcurrentisreducedby 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–DeltaStarter:

This method is used in the case of motors which are built to run normallywithadeltaconnectedstatorwinding.Itconsistsofatwoway switch which connects the motor in star for starting and then in deltafor normal running.

Atstarting,whenstarconnected,the appliedvoltageover each motorphasesisreducedbyafactor $\frac{1}{\sqrt{3}}$.Henceduringstarting, when motor is star connected it takes $\frac{1}{\sqrt{3}}$ timesasmuchasstartingcurrent.

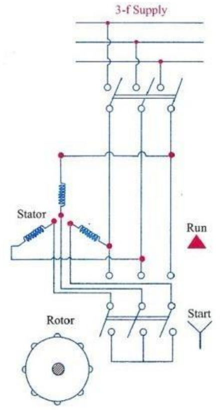


Fig 1.7

Whenthemotorcatchesthespeed80%ofitsnormalspeedswitchischangedtodelta positions at that time $V_L = V_{ph}$.

AutoTransformerMethod :

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 changedtorunningposition, thenfullsupplyvoltageis appliedacrossthemotor.

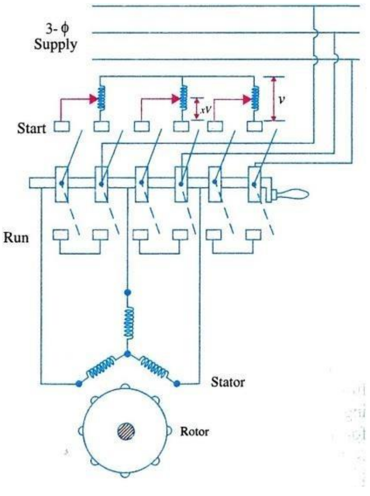


Fig 1.8

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.

Slipring Motor:

RotorRheostatMethod:

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

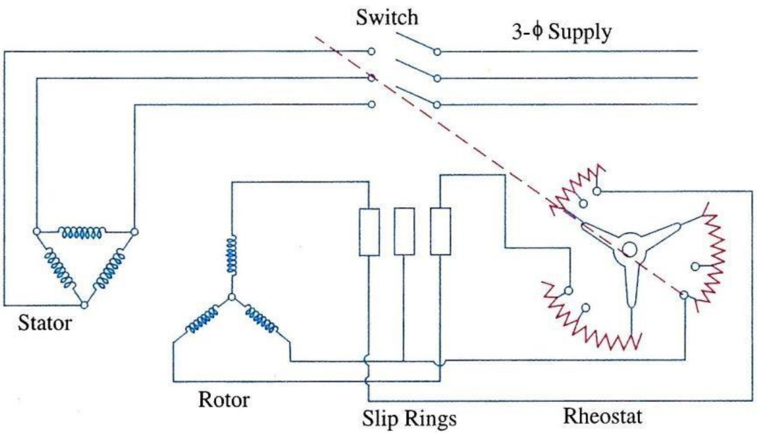


Fig 1.9

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

SpeedControlofInductionMotor:

Thespeed of an inductionmotor can bechangedundertwo main headings.

(i) Controlfromstatorside

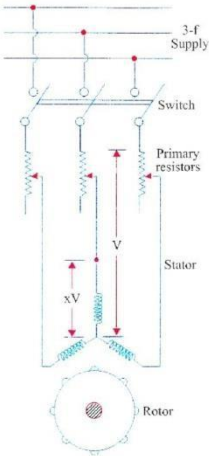
(ii) ControlfromRotor side

(i) Controlfrom statorside:

(a) Bychangingtheappliedvoltage

(b) Bychangingtheapplied frequency

(c) Bychanging theno ofstatorpoles.



(ii) Controlfrom Rotorside:

(a) Rotor RheostaticControl

(b) Cascadeoperation

Fig 1.10

(c) Byinjectingemf intherotorcircuit

Bychangingappliedvoltage :

Thismethodistheeasiestwayforcontrollingspeedofan inductionmotor.Butthis method is rarely used for the following reasons.

(i) Alargechangein voltageis requiredforasmall changeinspeed.

(ii) Duetotheconnectionofresistancesinthestatorphases,largepowerlossoccursat the resistors.

Whentheresistancesareaddedinthestatorcircuit,voltageacrossthestatorphase decreases.

Astorque(T)= $$\frac{KV^2R_2}{R_2^2+X_2^2}$$

$\Rightarrow$TorqueT $=K_1V^2$

$\Rightarrow T \alpha V^2$

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

ByChargingthe numberof statorpoles :

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.

RotorRheostaticControl :

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

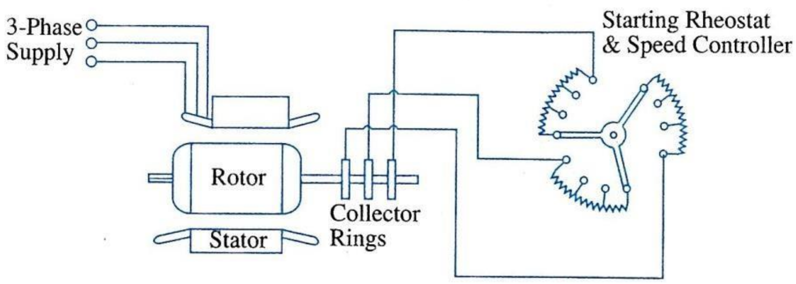


Fig 1.11

Forthispurposetherotorstartermaybeused. As

torque (T) $\alpha \frac{S}{R_2}$

Byincreasingthemotorresistancetorquewilldecrease.Hencespeedwilldecrease.

MotorEnclosures :

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

(i) Totallyenclosed,Nonventilatedtype.
(ii) Splash – Proof type
(iii) Totallyenclosed,Fancooledtype.
(iv) Cowlcovered motor
(v) ProtectedType
(vi) Drip –ProofMotors
(vii) Self(Pipe)VentilatedType
(viii) Separately(Forced)VentilatedType.

InductionGenerator:

Whentherotorofaninductionmotorrunsfasterthanitssynchronousspeedatthattime 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.

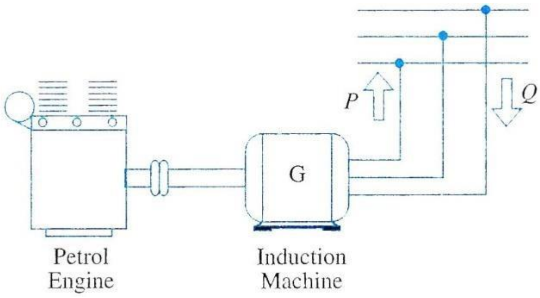


Fig 12

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.

-0-

(Alternators)

INTRODUCTION

An alternating voltage is generated in a single conductor/coil **rotating** in a uniform magnetic field with **stationary** field poles .Similarly, an alternating voltage will also be generated in a **stationary** conductor/coil when the field poles **rotate** past the conductor/coil , as it is the **relative motion**between the field and the conductor/coil that mattersso far asemf induction in a conductor/coil is concerned. The wave shapes of voltage in both the cases are sinusoidal as the wave shape of magnetic flux issinusoidal.

In D.C. generators , the field poles are **stationary** and the armature conductors **rotate**.The voltage generated in the armature conductors is of alternating nature. Thisgenerated alternating voltage is converted to a direct voltage at the brushes with the help of the commutator.

A.C. generators are usually called **Alternators.** They are also called Synchronous generators. Rotating machines that rotate at a speed fixed by the supply frequency and the number of poles are called synchronous machines.

A synchronous generator is a machine for converting mechanical power from a prime mover to ac electric power at a specific voltage and frequency .A synchronous machine rotates at a constant speed called the **synchronous speed**.Synchronous machines are usually of 3-phase type because of various advantages of 3-phase Generation,Transmission and Distribution.Large synchronous generators of several MVA ratings are used to generate bulk power at thermal ,hydro and nuclear power stations.

ADVANTAGESOF ROTATINGFIELD ALTERNATOR

Mostalternatorshavetherotatingfieldandthestationaryarmature.Therotating-field type alternator has several advantages over the rotationg-armature type alternator.

(1) Astationaryarmatureis moreeasilyinsulatedforthehighyoltageforwhichthe alternator is designed. This generated voltage may be as high as 33KV.
(2) Thearmaturewindingscanbebracedbettermechanicallyagainsthighelectro-magnetic forces due to large short-circuit currents when the armature windings are in thestator.
(3) Thearmaturewindings,beingstationary,arenotsubjectedto vibrationandcentrifugal forces.

(4) Theoutputcurrentcanbetakendirectlyfromfixedterminalsonthestationaryarmature without using slip rings, brushes, etc.

(5) The rotating field is supplied with direct current. Usually the field voltage is between 100 to 500 volts. Only two slip rings are required to provide direct current for the rotating field while at least three slip rings would be required for a rotating armature. The insulation of the two relatively low voltage slip rings form the shaft can beprovided easily.

(6) The bulk and weight of the armature windings are substantially greater than the windings of the field poles. The size of the machine is, therefore, reduced.

(7) Rotating field is comparatively light and can be constructed for high speed rotation.The armatures of large alternators are forced cooled with circulating gas or liquids.

(8) The stationary armature may be cooled more easily because the armature can be made large to provide a number of cooling ducts.

SPEEDANDFREQUENCY

The frequency of the generated voltage depends upon the number of field poles and on the speed at which the field poles are rotated. One compete cycle of voltage is generated in an armature coil when a pair of field poles (one north and one south pole) passes over the coil.

LetP=totalnumberoffieldpoles P=

pair of field poles

N=speedofthefieldpolesinr.p.m. n=speed

of the field poles in r.p.s.

f=frequency of thegenerated voltagein Hz

Obviously $\frac{N}{60} = n$ 1.1

and $\frac{P}{2} = p$ 1.2

Inonerevolutionof the rotor, anarmaturecoil iscutby $\frac{\square}{2}$ northpolesand $\frac{\square}{2}$ southpoles.Since

one cycle is generated in an armature coil when a pair of field poles passes over the coil, the number of cycles generated in one revolution of the rotor will be equal to the number of pairsof poles. That is, Number of cycles per revolution =

pAlso,numberofrevolutionspersecond=n

Nowfrequency=numberofcyclespersecond

$$=\frac{number}{revolutons}\text{X}\frac{revolutons}{seconds}$$

f=pxn...1.3

Sincen =N/60and p=p/2

f=$\frac{}{120}$..1.4

Equation(1.2) and (1.4) give the relationship between the number of poles, speed and frequency.

SYNCHRONOUSSPEED

From Eq.(1.4)

Ns=$\frac{}{p}$...(1.5)

Equation (1.5) shows that the rotor speed N bears a constant relationship with the field poles and the frequency of the generated voltage in the armature winding. The speed given by Eq.(1.5)uscalledsynchronousspeedN_s.Amachinewhichrunsatsynchronousspeedis

called synchronous machine. Thus, a synchronous machine is an a.c. machine in which therotor moves at a speed which bears a constant relationship to the frequency of the generated voltage in the armature winding and the number of poles of the machine .Table 1.1 gives the number of poles and synchronous speeds for a power frequency of 50H_z.

Table 1.1

Numberofpoles	Synchronousspeed$N_s$inr.p.m.
2	3000
4	1500
6	1000
8	750
10	600
12	500

EXMPLE1.1

Calculate the highest speed at which (a) 50H_z(b)$60H_z$ alternator can be operated.

Solution

Sinceitisnotpossibletohavefewerthan2poles,theminimumvalueofp=2. f =

$N_s = \frac{}{P}$

ForaminimumvalueofPthespeedNwillbeamaximum.

(a) f=50 Hz,p=2

$N_s = \frac{}{2}$ =3000r.p.m.(Ans.)

(b) f=60Hz,p=2

$N_s = \frac{}{2}$=3600r.p.m.(Ans.)

CONSTRUCTIONOFTHREE-PHASESYNCHRONOUS MACHINES

Similar to other rotating machines, an alternator consists of two main parts namely, the stator and the rotor. The stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated. The output of the machine is taken from the stator. The rotor is the rotating part of the machine. The rotor produces the main field flux.

STATORCONSTRUCTION

The various parts of the stator include the frame, stator core, stator windings andcooling arrangement. The frame may be of cast iron for small-size machines and of welded steel type for large size machines. In order to reduce hysteresis and Eddy-current losses, the stator core is assembled with high grade silicon content steel laminations. A 3-phase windingisputintheshortcutontheinner peripheryofthestatorasshowninFig.1.The windingis star connected. The winding of each phase is distributed over slots . When current flows in a distributed winding it produces an essentially sinusoidal space distribution ofemf.

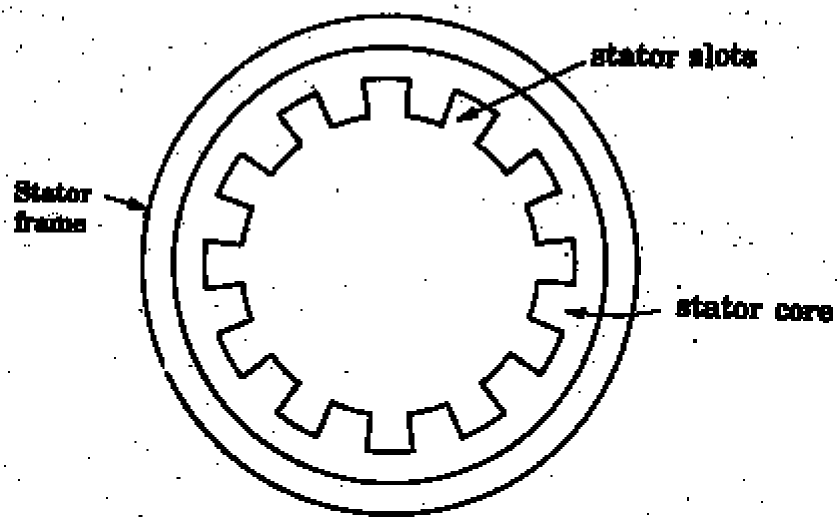


Figure1.1Alternator stator

ROTORCONSTRUCTION

Therearetwotypesofrotorconstructionsnamely,thesalient-poletypeandthe cylindrical rotor type.

Salient-PoleRotor

The term salient means ‘**protruding** ’or ‘**projecting**’. Thus, a salient-pole rotorconsistsofpolesprojectingoutfromthesurfaceoftherotorcor.Figure1.2 showstheend view of a typical 6-pole salient-pole rotor. Salient-pole rotors are normally used for rotors with four or more poles.

Since the rotor is subjected to changing magnetic fields, it is made of this steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled by stacking laminations to the required length and then riveted together. After placing the fieldcoil around each pole body, these poles are fitted by a dove-tail joint to a steel spider keyed to the shaft. Salient-pole rotors have concentrated winding on the poles. Damper bars are usually inserted in the pole faces to damp out the rotor oscillations during sudden change in load conditions. A salient-pole synchronous machine has a non-uniform air gap. The air gap is minimumunderthepole centresanditismaximuminbetweenthepoles.Thepolefacesare so shaped that theradialairgap length increases fromthepolecentreto thepoletips sothat the flux distribution in the air gap is sinusoidal. This will help the machine to generate sinusoidal emf.

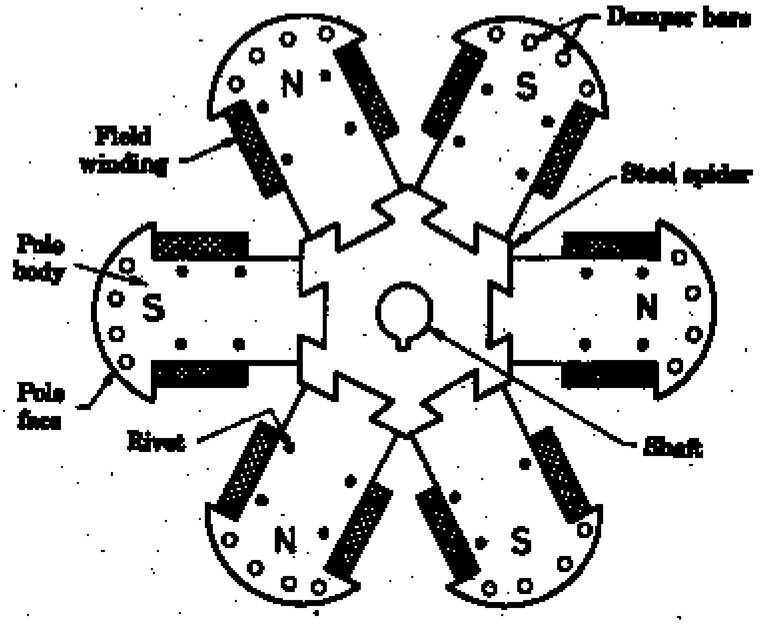


Figure1.2Six-polesalient-polerotor

The individual field-pole windings are connected in series to give alternate north and south polarities. Theends of the field windings areconnected to a dc source(adc generator or a rectifier)through the brushes on the slip rings. The slip rings are metal rings mounted on the shaft and insulated from it. They are used to carry current to or from the rotating part of the machine (usually ac machine) via carbon brushes.

Salient-pole generators have a large number of poles at lower speeds. A salient-pole generator has comparatively a large diameter and a short axial length. The large diameter accommodates a large number of poles.

Salient-pole alternators driven by water turbines are called **hydro-alternators** or**hydro-generators**. Hydro-generators with relatively higher speeds are used with impulse turbines and horizontal configuration. Hydro-generators with lower speeds are used with reaction and Kaplan turbines and have vertical configuration.

CylindricalRotor

A cylindrical-rotor machine is also called a **non-salient pole rotor machine**. It hasrotor so constructed that it forms a smooth cylinder. The construction is such that there are no physical poles to be seen as in the salient-pole construction. Cylindrical rotors are made from solid forgings of high grade nickel-chrome-molybdenum steel. In about two-third of the rotor periphery, slots are cut at regular intervals and parallel to the shaft. The dc field windings are accommodated in these slots. The winding is of distributed type. The un slotted portion of the rotorformstwo(orfour)polefaces.Acylindricalrotormachinehasacomparativelysmall diameter and long axial length. Such a construction limits the centrifugal forces. Thus, cylindrical rotors are particularly useful in high-speed machines. The cylindrical rotor type alternator has two or four poles on the rotor. Such a construction provides a greater mechanical strength and permits more accurate dynamic balancing. The smooth rotor of the machinemakes less windage losses and the operation is less noisy because of **uniform airgap**.

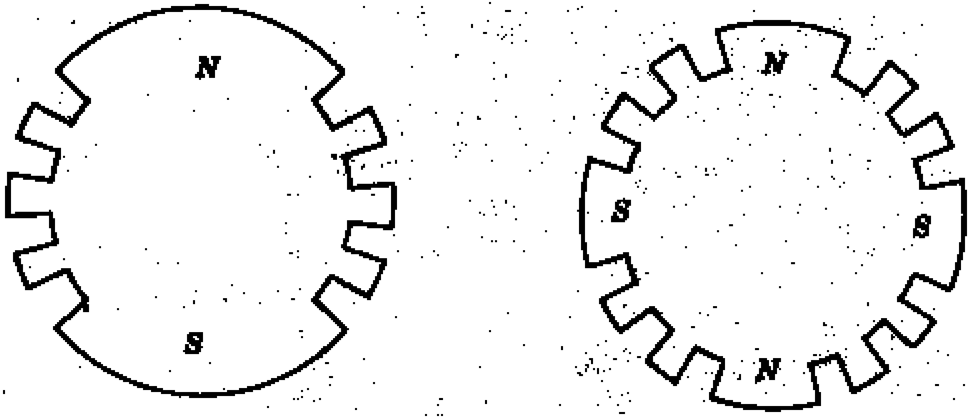


Figure1.3 Endviews oftwo-pole and four polecylindrical rotors

Figure 1.3 shows end views of 2-pole and 4-pole cylindrical rotors. Cylindrical rotor machines are driven by seam are gas turbines. Cylindrical rotor synchronous generators are called turbo-alternators or turbo-generators. Such machines have always horizontal configuration installation. The machines are built in a number of ratings from 10 MVAinstalled in super thermal power plants.

EXCITATIONSYSTEMSFORSYNCHRONOUSMACHINES

Excitationmeansproductionoffluxbypassingcurrentinthefield winding.

Direct current is required to excite the field winding on the rotor of the synchronous machines. For small machines, dc is supplied to the rotor field by a dc generator called exciter. This exciter may be supplied current by a smaller dc generator called **pilot exciter**. The main and pilot exciters are mounted on the main shaft of the synchronous machine(generator or motor).The dc output of the main exciter is giber to the field winding of the synchronous machine through brushes and slip rings. In smaller machines, the pilot exciter may be omitted, but this arrangement is not very sensitive or quick acting when changes of the field current are required by the synchronous machine.

For medium size machines a .c. exciters are used in place of d. c .exciters. A.C. excitersarethree-phasea.c.generators.Theoutputofa.c.exciterisrectifiedandsupplied through brushes and slip-rings to the rotor winding of the main synchronous machine.

Forlargesynchronous generators with ratings offewhundred megawatts, theexcitation requirements become very large. The problem of conveying such amounts of power through high-speed sliding contacts becomes formidable. At present , large synchronous generators and synchronous motors are using brushless excitation systems. A brushless exciter is a small direct-coupled a . c. generator with its field circuit on the stator and the armature circuit on the rotor. The three-phase output of the ac exciter generator is rectified by solid-state rectifiers.The rectified output is connected directly to the field winding, thus eliminating the use of brushes and slip rings.

Abrushless excitation system requiresless maintenance due to absence of brushesand slip rings. The power loss is also reduced.

The d. c. required for the field of the exciter itself is sometimes provided by a small pilot exciter. A pilot exciter is a small a. c. generator with permanent magnets mounted on the rotor shaft and a three-phase winding on the stator. The permanent magnets of the pilot exciter produce the field current of the exciter. The exciter supplies the field current of the main machine. The use of a pilot exciter makes the excitation of the main generator completely independent of external supplies.

VOLTAGEGENERATION

The rotor of the alternator is run at its proper speed by its *prime mover*. The prime mover is a machine which supplies the mechanical energy input to the alternator. The prime movers used for a low and medium speed alternators are water wheels or hydraulic turbines. Steam and gas turbines are used as prime movers in large alternators and run at high speeds. The steam-turbine driven alternators are called *turboalternators* or *turbogenerators* . As the poles of the rotor move under the armature conductors on the stator, the field flux cutsarmature conductors. Therefore voltage is generated in these conductors. This voltage is of alternating nature, since poles of alternate poles of alternate polarity successively pass by a given stator conductor. A 3-phase alternator has a stator with three sets of windings arrangedso that there is a mutual phase displacement of120^0. These windings are connected in starto

providea3-phaseoutput.

E.M.F.EQUATION OFAN ALTERNATOR

Φ=usefulfluxperpoleinwebers(Wb) P=

total number of poles

Z_p =total number ofconductors orcoil sidesinsries per phase

T_p=total numberofcoilsorturnsper phase

n=speedofrotationofrotorinrevolutionspersecond(r.p.s) f=

frequency of generated voltage(H_z)

SincethefluxperpoleisΦ,eachstatorconductorcutsafluxPΦ. The

average value of generated voltage per conductor

$$=\frac{\quad revolution\ in\ Wb}{time\ taken\ for\ one\ revolution\ in\ seconds}$$

Sincen revolutions aremadein one second,onerevolution will be madein 1/n second.

Thereforethetimeforonerevolutionofthearmatureis1/nsecond.Theaverage voltage generated per conductor

$$E_{av}\text{/conductor}=\frac{P\Phi}{\quad}=np\Phi\text{volts}\ldots\ldots 1.6$$

Weknow that $f=\frac{\quad}{120}=\frac{Pn}{2}\ldots\ldots 1.7$

Pn= 2f

SubstitutingthevalueofPninEq.(1.6),weget

$$E_{av}\text{/conductor}=2f\Phi\ldots\ldots 1.8$$

Sincethereare $Z_p$conductorsinseriesperphase,theaveragevoltagegeneratedper phase is given by

$$E_{av}\text{/ phase}=2f\Phi..Z_p\ldots\ldots 1.9$$

Sinceoneturnorcoilhastwosides, $Z_p=2T_p$,andtheexpressionfortheaveragegenerated voltage per phase can be written as

$$E_{av}\text{/ phase}=4f\Phi\ T_p\ldots\ldots 1.10$$

Forthevoltagewave,theformfactorisgivenby

$$k_f=\frac{r.m.s.value}{average\ value}$$

For a sinusoidal voltage, k_f=1.11. Therefore, the r.m.s. value of the generated voltage per phase can be written as

$E_{r.m.s}$/phase= k_f x E_{av}/phase=1.11x4fΦT_p

=4.44 fΦT_p

The suffix r.m.s. is usually deleted, The r.m.s. value of the generated voltage per phase is given by

E_p= 4.44fΦ ..T_p... 1.11

Equation(1.11) has been derived with the following assumptions:

(a) Coils have got full pitch.
(b) All the conductors are concentrated in one stator slot.

ARMATUREWINDINGS

The winding through which a current is passed to produce the main flux is called the *field winding*. The winding in which voltage is induced is called *armature winding*. For synchronous machines the field windings are on the rotor.Therefore,the terms **rotor windings** and **field windings** are used interchangeably. Also,the armature windings are on the stator. Therefore, the term stator windings and armature windings are used interchangeably.

Some basic terms related to the armature winding are defined as follows: A

TURN consists of two conductors connected to one end by an end connector. A

coil is formed by connecting several turns in series .

The turn ,Coil and windings are shown schematically in figure1.4.

The beginning of the turn, or coil, is identified by the symbol S(Start) and the end of the turn or coil by the symbol F(Finish).

The concept of electrical degrees is very useful in the study of machine. If θ_{mech}

=mechanical degrees or angular measure in space

θ_{elect}= electrical degrees or angularmeasure in cycles

For a P-pole machine electrical degree is defined as follows:

$\theta_{elec}= \frac{\square}{2}\theta_{mech}$

Theadvantageofthisnotationisthatexpressionswrittenintermsofelectrical angles apply to machines having any number of poles.

Theangulardistancebetweenthecentresoftwoadjacentpolesonamachineis known as pole pitch or pole span.

Onepolepitch=$180^0_{ed}=\frac{\square}{P}$

Regardlessofthenumberofpolesinthemachine,apolepitchisalways180electrical degrees.

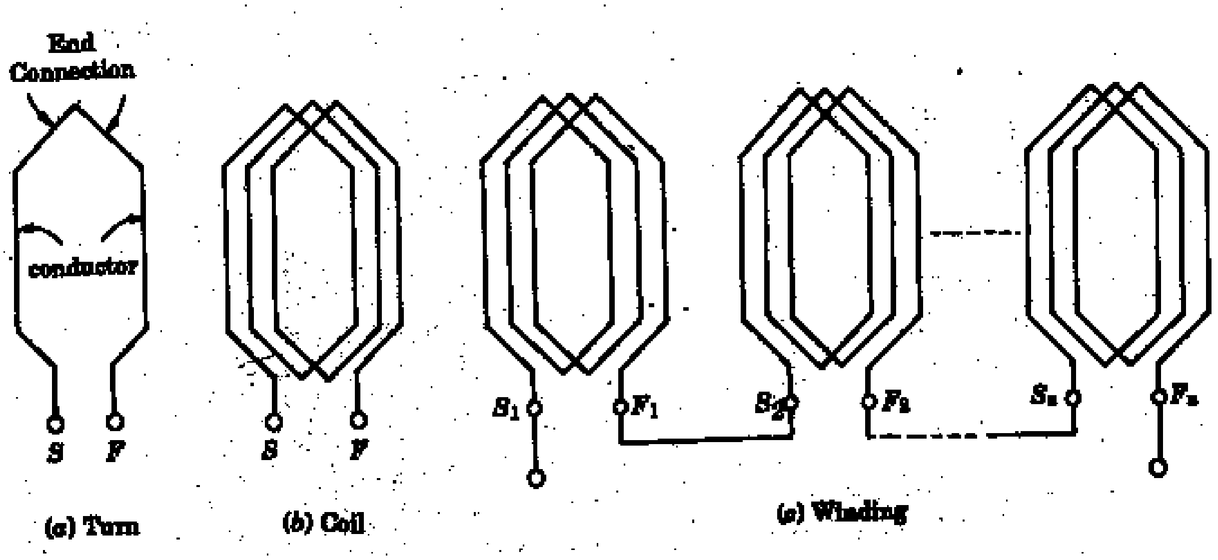


Figure1.4 Turn, coilandwinding

COIL-SPANFACTOR ORPITCHFACTOR

The distance between the two sides of a coil is called the *coil span* or coil pitch.The angular distance between the central line of one pole to the central line of the next pole iscalled *pole pitch*.a pole pitch is always 180 electrical degrees regardless of the number of poles on the machine.A coil having a span equal to 180 degree electrical is called a *full-pitch* coil as shown in figure 1.5(a).

A coil having a span less than 180 electrical degrees is called a short-pitch coil or fractional pitch coil.It is also called a chorded coil.A stator winding using fractional-pitch coils is called a *chorded* winding.If the span of the coil is reduced by an angle of elctrical α degrees, the coil span will be (180-α) electrical degrees as shown in figure 1.6(a).

In case of full-pitch coil two coil sides span a distance exactly equal to the pole pitch of 180 electrical degrees .As a result, the voltage generated in a full-pitch coil is such that the coil side voltages are in phase as shown in figure 1.5(b).Let E_{C1} & E_{C2} be the voltages generated in the coil sides and E_C the resultant coil voltage.Then

$$E_C = E_{C1} + E_{C2}$$

Let **|Ec1|=|Ec2|=E1**

Since E_{C1} & E_{C2} are in phase, the resultant coil voltage E_C is equal to their arithmetic sum.

$$E_C = E_{C1} + E_{C2} = 2\,E_1$$

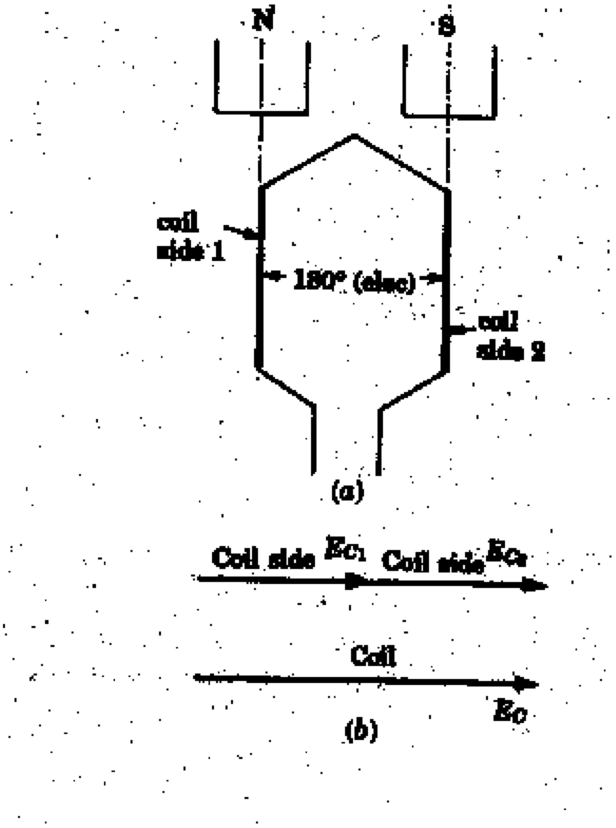


Fig.1.5

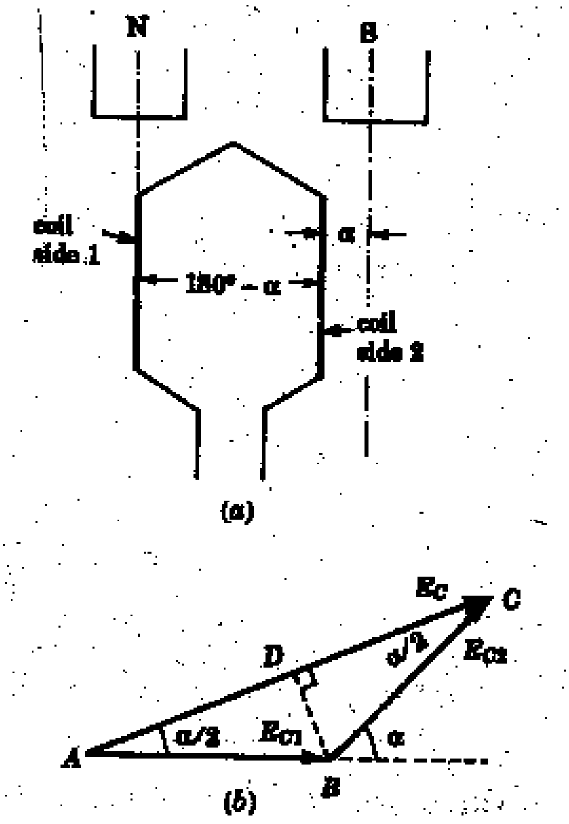


Fig.1.6

If the coil span ofa single coil is less than the pole pitch of180^0(elec.), the voltage generated in each coil sideare *not* in phase.Theresultant coil voltage$E_C$is equal to the *phasor sum* ofE_{C1}& E_{C2}.

If the coil span is reduced byan angle $\propto$elctrical degrees,the coil span is be (180-)$\propto$ electricaldegrees.ThevoltagegeneratedE_{C1}& E_{C2}intwocoilsideswillbeoutofphasew.r.t each other by an angle $\propto electrical$ $degree\ as\ shown\ in\ figure 1.6(b)$ .the phasorsum of
E_{C1}& E_{C2}isE_C(=AC).

Thecoilspanfactororpitchfactor$k_c$isdefinedastheratioofvoltagegeneratedin theshort-pitchcoiltothevoltagegeneratedinthefull-pitchcoil.Thecoilspanfactorisalso called the *chording factor*.

$$k_C = \frac{}{voltage\ generated\ in\ the\ coil\ of\ span}$$

$$= \frac{AC}{2AB} = \frac{2AD}{2AB} = \cos\frac{\propto}{2}$$

k_C=cos $\frac{\propto}{2}$..1.12

Forfull-pitchcoil,$\propto$=0,so,$\cos\frac{\propto}{2}$=1andk_C=1.Forashort-pitchcoilk_C<1.

Advantagesofshort pitchingorchording

1. Shortenstheendsofthewindingandthereforethereisaasavingintheconductor material.
2. Reducestheeffectsofdistortingharmonics,andthusthewaveformof the generated voltage is improved and making it approach a sine wave.

DISTRIBUTIONFACTORORBREADTHFACTOR k_d

In a concentrated winding ,the coil sides of a given phase are concentrated in a singleslotunderagivenpole.Theindividualcoilvoltagesinducedareinphasewitheach other. These voltages may be added arithmetically. In order to determine the induced voltages induced per phase, a given coil voltage is multiplied by the number of series –connected coils per phase. In actual practice, in each phase, coils are not concentrated in a single slot, but are distributed in a number of slots in space to form a polar group under each pole. The voltages induced in coil-sides constituting a polar group are not in phase but differ by an angle equal to the angular displacement β of the slots. The total voltage induced in any phase will be the phasor sum of the individual coil voltages.

The distribution factor or breadth factor is defined as the ratio of the actual voltage obtained to the possible voltage if all the coils of a polar group were concentrated in a single slot.

$$k_d = \frac{\text{Phasor}}{\text{arithmetic sum of coil voltages per phase}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 1.13$$

Let m = the slots per pole per phase, that is slots per phase belt

$$m = \frac{\text{slots}}{\text{Poles x Phases}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.14$$

β = Angular displacement between adjacent slots in electrical degrees

$$\beta = \frac{}{\text{slots/pole}} = \frac{}{\text{slots}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.15$$

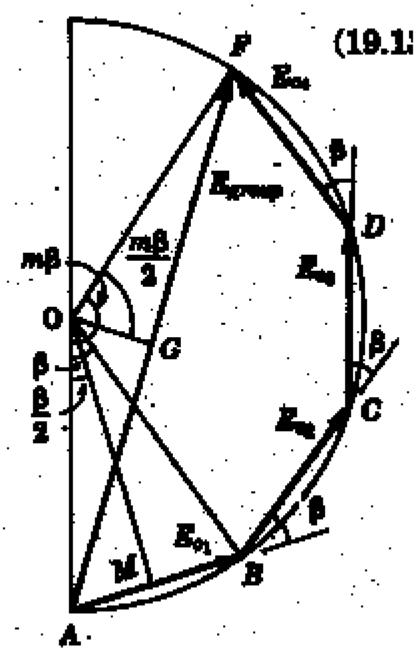


Fig.`1.7

Thus,onephaseofthewindingconsistsofcoilsarrangedinmconsecutiveslots. Voltage E_{c1}, E_{c2}&E_{c3},…….. are the individual coil voltages .Each coil voltage E_c willbe outofphasewiththenextcoilvoltagebytheslotpitch β.Figure1.7showsthevoltage polygon of the induced voltages in the four coilsof a group(m=4).The voltages E_{c1}, E_{c2}, E_{c3}, and E_{c4} are represented by phasors AB,BC,CD and DF respectively in figure 1.7.Each of these phasorsis a chord of a circle with center o and subtends an angle β at O.The phasor sum AF, representing the resultant winding voltage ,subtends an angle m β at thecenter.

Arithmaticsumofindividualcoilvoltages

$=mE_c$=m AB=m(2AM)

=2m sin Aom = 2m OA sin

$$k_d = \frac{}{arithmetic\ sum\ of\ coil\ voltages\ per\ phase} =$$

k_d= ……………………………………..1.16

Itistobenotedthatthedistributionfactor k_d foragivennumberofphasesisdependentonly on the number of distributed slots under agiven pole.It isindependent of the typeof the winding,Lap or wave,or the number of coil,etc. As the number of slots per pole increases the distribution factor decreases.

ACTUALVOLTAGEGENERATED

Takingtheoilspanfactorandthedistributionfactorintoacount,theactualgeneratedvoltage per phase is given by Ep =4.44 $K_c K_d f\Phi T_p$ ……………………………………………………………..1.17

Equation(1.17)iscalledthecompleteemfequationofan alternator.

Thequantity $(K_c K_d T_p)$ issometimescalledeffectiveturnsperphase T_{ep}.

$T_{ep} = K_c K_d T_p$ ……………………………………..1.18

It iasmallerthantheactualnumberofturnsperphaseduetofractionalpitchcoilsanddueto distribution of winding over several slots under each pole.

Thecoil spanfactoranddistributionfactorofawindingaresometimescombinedintoa single winding factorK_w,which is the product ofK_c andK_d. That is

$$K_w = K_c K_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.19$$

Forastarconnectedalternator,thelinevoltageis $\sqrt{3}$timesthephasevoltage.

$$E_L = \sqrt{3}\, E_{ph}$$

AlternativetermsforthevoltageEare

Open circuit voltage per phase

No-Load voltage per phase

Excitationvoltageperphase

Internal voltage per phase

Voltagebehind synchronousreactanceper phase

TheanglebetweentheterminalvoltageVandtheinternalvoltageEisthemachine angleor rotor angleδ.

Example1.2

A 3-phase ,50Hz,8-pole alternator hasastar-connectedwindingwith120slotsand 8 conductors per slot.The flux per pole is 0.05 Wb, sinusoidally distributed.Determine thephase and line voltages.

Solution :

Letustakethefull-pitchcoil,

So, $\propto = 0^0$, $K_c =$ = $\cos 0^0 = 1$ m =

$$\frac{slots}{Poles\ x\ Phase} = \frac{}{8\times 3} = 50\ \text{Hz}$$

$\beta = \frac{\quad}{\text{slots}} = \frac{\quad \times 8}{\quad} = 12$

$Kd = \frac{\quad}{\quad} = \frac{\quad}{\quad} = 0.9567$

Totalnumberofconductors=conductorsperslotXnumberofslots=8x120=960

Conductors per phase = , $Z_p = \frac{960}{3} = 320$

Generatedvoltage per phase= $E_p = 2.22\, K_c K_d f \Phi Z_p$

$= 2.22 \times 1 \times 0.9567 \times 50 \times 0.05 \times 320 = 1699$ volts

GeneratedLinevoltage= $E_L = \sqrt{3}\, E_{ph} = \sqrt{3} \times 1699 = 2942.8$ volts.

ARMATURELEAKAGEREACTANCE

In a n ac machine ,any flux set up by the load current which does not contribute to the usuful flux of the machine is a leakage flux. The effect of this leakage flux is to set up a self-induced emf in the armature windings.

Theleakagefluxesmaybeclassifiedasfollows :

1. **Slot leakage**
2. **Toothheadleakage**
3. **Coil-endorover-hangleakage**

The voltages induced in the armature windings by the air-gap flux is called the air-gap voltages.

The leakage fluxes also induce voltages in the armature windings .These are taken into account by introduction of leakage reactance drops. Most of the reluctances of the magnetic circuits for armature leakage fluxes are due to air paths. The fluxes are therefore nearly proportional to the armature currents producing them and are in phase with these currents. For this reason, the voltages they induce in the armature windings can be taken into account by the use of constant leakage reactances forthe phases, which multiplied by the phase currents ,give the component voltages induced in the phases of the leakage flux. These voltages are the leakage reactance drops and lead the currents producing them by 90^0.

ARMATUREREACTION

When load current flows through the armature windings of an alternator, the resulting mmf produces flux. This armature flux reacts with the main-pole flux, causing the resultantflux to become either less than or more than the original main flux. The effect of the armature(stator)flux onthe flux produced bythe rotorfieldpolesiscalled**armature reaction**. The armature reaction flux is constant in magnitude and rotates at synchronousspeed. The armature reaction depends upon the power factor of the load. If the armature reaction fluxis assumed to act independently ofthemain field flux,it induces avoltagein each phasewhichlagtherespectivephasecurrentsby90^0.Itistobenotedthatarmaturereaction effectsareseen tobe anessentialpartofthetorqueproducingmechanism.

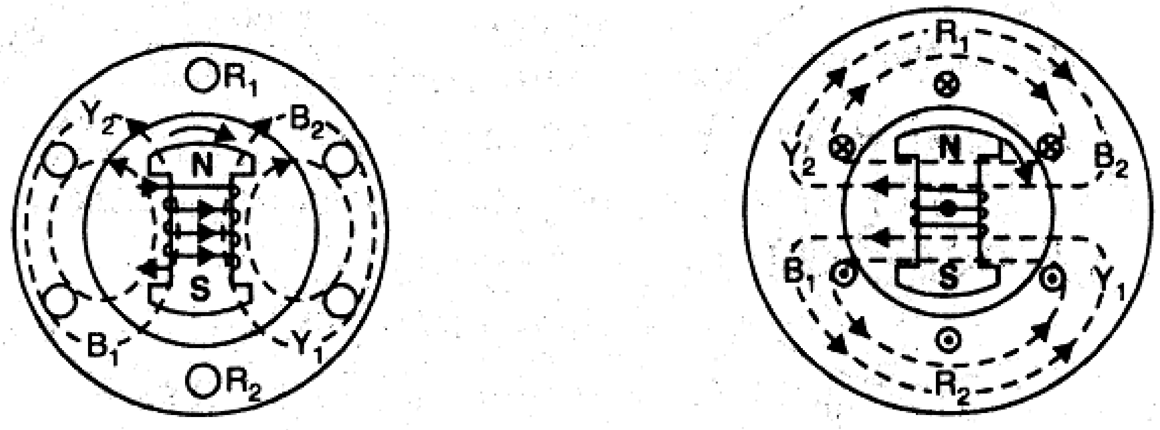
Two things are worth noting about the armature reaction in an alternator. First,the armature flux and the flux produced by rotor ampere-turns rotate at the same speed (synchronous speed) in the same direction and,therefore,the two fluxex are fixed in space relative to each other.Secondly,the modification of flux in the air-gap due to armature flux depends on the magnitude of stator current and on the power factor of the load.It is the load power factor which determines whether the armature flux distorts,opposes or helps the flux produced by rotor ampere-turns.Toillustrate this important point,thefollowing three cases may be considered :

(i) Whenloadp.f.isunity

(ii) Whenloadp.f.iszerolagging

(iii) Whenloadp.f.iszeroleading

When load p.f. is unity : Figure 1.7.1(i) shows an elementary alternator on no-load.since the armature is on open-circuit, there is no stator current in the flux due to rotor currentisdistributedsymmetricallyin theair-gapasshownin fig.1.7.1(i).Sincethedirectionof therotorisassumedclockwise,thegeneratede.m.finphaseR_1 R_2isatitsmaximumandis towards the paper in the conductor$R_1$and outwards in conductorR_2. No armature flux is produced since no current flows in the armature winding.



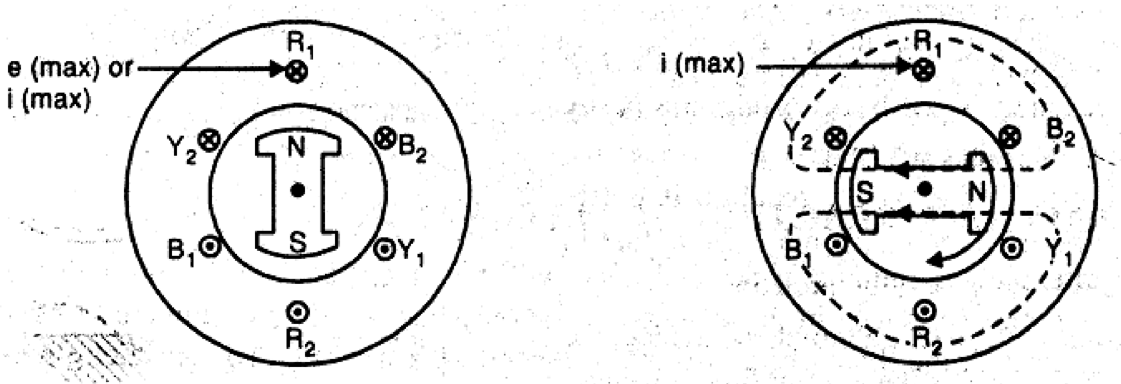
(i) (ii)

Fig.1.7.1

Fig.1.7.1(ii)shows theeffect when aresistiveload(unity p.f.)is connectedacrosstheterminals of the alternator. According to right-hand rule, the current is inwards in the conductors underN-pole and outwards in the conductors under S-pole. Therefore ,the armature flux is clockwise duetocurrentsinthetopconductorsandanticlockwiseduetocurrentinthebottom conductors.Notethatarmaturefluxisat90^0tothemainflux(duetorotorcurrent)andis behind the main flux. In this case, the flux in the air-gap is distorted but not weakened. Therefore,at unity p.f. , the effect of armature reaction is merely to distort the main field;thereis no weakening of the main field and the average flux practically remains the same. Since the magneticfluxdueto statorcurrents(i.e.armature flux)rotatessynchronously with therotor, the flux distortion remains the same for all positions of the rotor.

Whenloadp.f. iszero lagging :

whenapureinductive load(zerop.f. lagging)isconnected acrossthe terminalsof the alternator ,currentlagsbehindthevoltageby90^0.Thismeansthatcurrentwillbemaximumatzero e..m.f. and vice-versa.



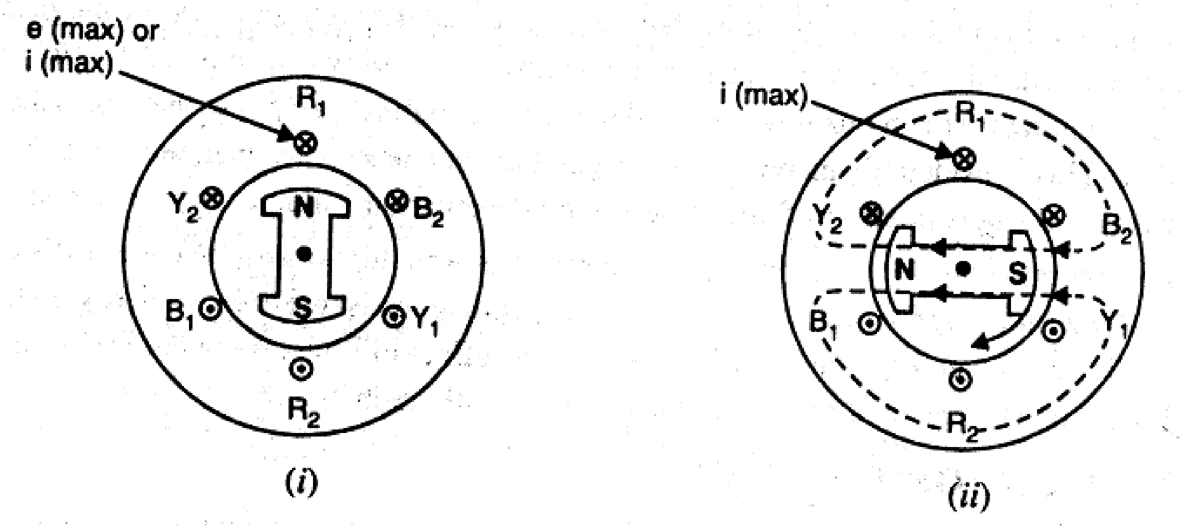
(i) (ii)

Fig.1.7.2

Fig.1.7.2(i)showstheconditionwhenthealternatorissupplyingresistiveload.Notethate.m.f. aswellascurrentinphase$R_1 R_2$ismaximumin thepositionshown.When thealternatoris supplying apureinductiveload,thecurrentinphase$R_1 R_2$willnotreachitsmaximumvalue untilN-pole advanced 90^0electrical as shown in fig.1.7.2(ii). Now the armature flux is from right to left and field flux is from left to right. All the flux produced by armature current (i.e.,armature flux) opposes the field flux and , therefore, weakens it .In other words, armature reaction is directly de-magnetising. Hence, at zero p.f. lagging ,the armature reaction weakens the main flux. This causes a reduction in the generated e.m.f..

Whenloadp.f. iszero leading :

when a pure capacitive load(zero p.f. leading) is connected across the terminals of the alternator,thecurrentinarmaturewindingswillleadtheinducede.m.f.by90^0.Obviously, the effect of armature reaction will be the reverse that for pure inductive load. Thus, armature flux now aids the main flux and the generated e.m.f. is increased.



(i) (ii)

Fig.1.7.3

Fig.1.7.3(i)showstheconditionwhenthealternatorissupplyingresistiveload.Notethate.m.f. aswellascurrent inphase$R_1 R_2$ismaximum inthepositonshown. Whenthealternatoris supplyingapurecapacitiveload,maximumcurrentinphase$R_1 R_2$willoccur

90^0 *electrical* before the occurrence of maximum induced e.m.f. Therefore, maximum current in phase R_1R_2 will occur if the position of the rotor remains 90^0 behind as compared to its position under resistive load. This is illustrated in fig.1.7.3(ii). It is clear that armature flux is now in the same direction as the field flux and therefore, strengthens it. This causes an increase in the generated voltage. Hence at zero p.f. leading, the armature reaction strengthens the main flux.

For intermediate values of p.f., the effect of armature reaction is partly distorting and partly weakening for inductive loads. For capacitive loads, the effect of armature reaction is partly distorting and partly strengthening. Note that in practice, loads are generally inductive.

Summary:

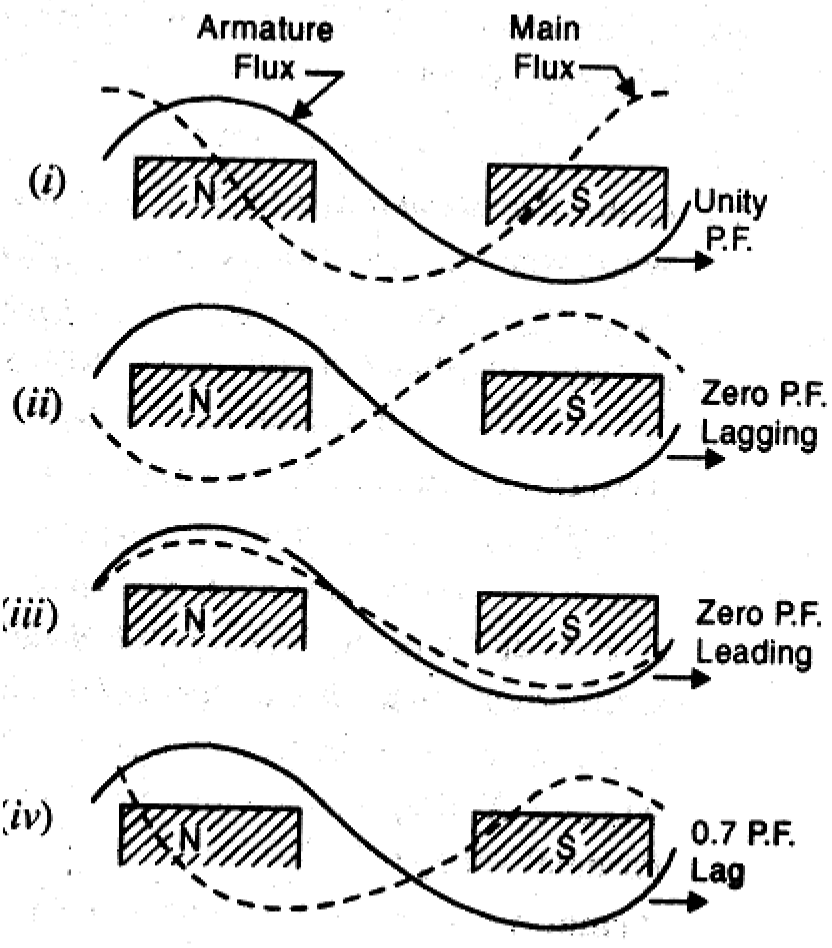


Fig.1.7.4

When the alternator is loaded, the armature flux modifies the air-gap flux .Its angle(electrical) with respect to main flux depends on the load p.f..This is illustrated in Fig.1.7.4.

(a) **When the load p.f. is unity** : the effect of armature reaction is wholly distorting. In other words, the flux in the air-gap is distorted but not weakened. As shown in Fig.1.7.4(i),thearmaturefluxis 90^0electricalbehind themainflux.Theresult isthat flux is strengthened at the trailing pole tips and weakened at the leading pole tips. However,theaverageflux intheair-gappractically remains unaltered.

(b) **When the load p.f. is zero lagging** : the effect of armature reaction is wholly demagnetising.Inotherwords,thefluxintheair-gapisweakened.Asshownin Fig.1.7.4(ii),thewave representing the main flux is moved backwards through 90^0 electrical so that it is in direct opposition to the armature flux. This considerablyreduces the air-gap flux and hence the generated e.m.f..To keep the value of the generated e.m.f. the same,the field excitation will have to be increased to compensate for the weakening of the air-gap flux.

(c) **When the load p.f. is zero leading**: the effect of armature reaction is wholly magnetising.Inotherwords,thefluxintheair-gapisincreased.Asshownin Fig.1.7.4(iii),the wave representing the main flux is now moved forwardthrough90^0 electrical so that it aids the armature flux. This considerably increases the air-gap flux and hence the generated e.m.f.. To keep the value of the generated e.m.f. the same,the field excitation will have to be reduced .

(d) **Forintermediatevalues ofload p.f**.: theeffect ofarmaturereaction is partly distorting and partly weakening for inductive loads. For capacitive loads, the effect is partly distorting and partly strengthening .Fig.1.7.4(iv) shows the effect of armature reaction for an inductive load. In practice, load on the alternator is generally inductive.

For the intermediate values of p.f. , the effect of armature reaction is partly distorting andpartly weakening for inductive loads.For capacitive loads the effect of armature reaction is partly distorting and partly strengthening. Note that in practice, the loads are generally inductive.

SYNCHRONOUSIMPEDANCE

The actual generated voltage consists of the summation of two component voltages. One of these component voltages is the voltage that would be generated if there were no armature reaction. It is the voltage that would be generated because of only the field excitation. This component of the generated voltage is called the excitation voltage, E_{exc}.

The other component of the generated voltage is called thearmature reaction voltage,E_{AR}. This is the voltage that must be added to the excitation voltage to take care of the effect of armature reaction upon the generated voltage

$$E_a = E_{exc} + E_{AR} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.20$$

Since armature reaction results, in a voltage effect in a circuit caused by change in flux by current inthe same circuit ,its effect is of the nature of an inductive reactance .Therefore,$E_{AR}$is equivalent to a voltage of inductive reactance and

$$E_{AR} = -j..X_{AR}I_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.21$$

The inductive reactance $X_{AR}$is a ficticitous reactance which will result in a voltage in the armature circuit to account for the effect of armature reaction upon the voltage relations of the armature circuit. Therefore, armature reaction voltage can be modeled as an inductor in series with the internal generated voltage.

In addition to the effects of armature reaction, the stator winding also has a self-inductance and a resistance.

LetL_a=Self-inductanceofstatorwinding

X_a= Self-inductive reactance of stator winding

R_a=Armature (stator) resistance

TheterminalvoltageVisgivenby

$$V = E_a - jI_aX_{AR} - jI_aX_a - I_aR_a$$

WhereI_aR_a=armatureresistancedrop

I_aX_a=armatureleakagereactancedrop I_aX_{AR} =

armature reaction voltage

The armature reaction effects and the leakage flux effects in the machine are both represented by inductive reactances . Therefore, it is customary to combine them in to a single reactance, called the synchronous reactance of the machine, X_s.

$X_s = X_{AR} + X_a$ ……………………………………..1.22

∴ $V = E_a - jX_sI_a - R_aI_a$

Or $V = E_a - (R_a + jX_s)I_a$……………………………………..1.23

$V = E_a - Z_sI_a$..1.24

Where $Z_s = R_a + jX_s$..1.25

The impedance Z_s is called the *synchronous impedance*.

The synchronous reactance X_s is the ficticious reactance employed to account for the voltage effects in the armature circuit produced by the actual armature leakage reactance and by the change in air-gap flux caused by the armature reaction.

Similarly, the synchronous impedance Z_s is a ficticious impedance employed to account for the voltage effects in the armature circuit produced by the actual armature resistance, the actual armature leakage reactance and the change in air-gap flux caused by the armature reaction.

EQUIVALENT CIRCUIT AND PHASOR DIAGRAMS OF A SYNCHRONOUS GENERATOR

The equivalent reactance of a synchronous generator is shown in figure 1.8(a). It is redrawn in Fig.1.8(b) by taking $X_s = X_{AR} + X_a$

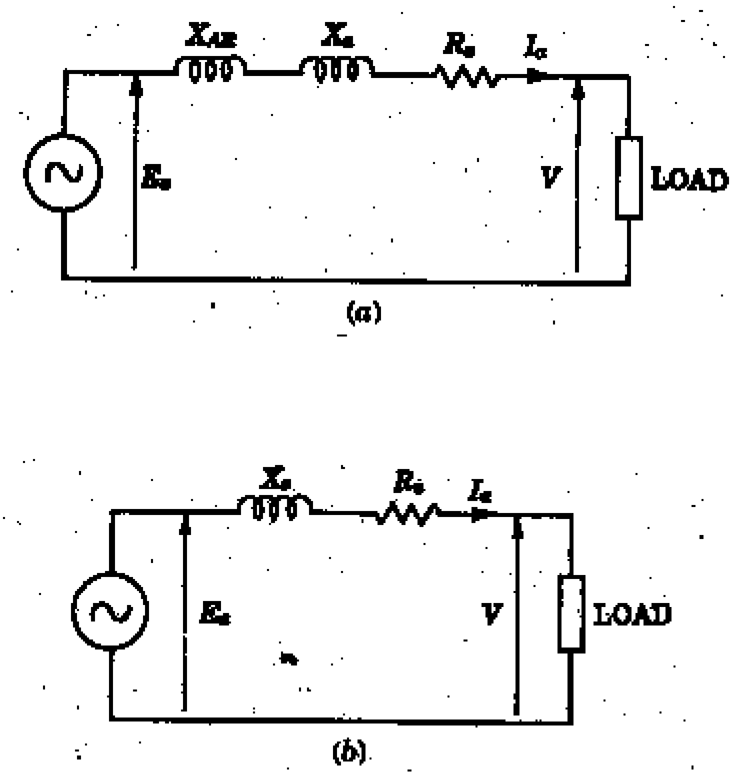


Fig.1.8 Equivalentcircuitof asynchronous generator

a) LaggingpowerfactorCosΦ

Figure 1.9(a) shows the phasor diagram for lagging p.f. load. The power factor is CosΦ lagging.In this diagram the terminal voltage V is taken as reference phasor along OA such that OA =V. For lagging power factor Cos Φ, the direction of armature current$\mathbf{I_a}$lags behind thevoltage**V**byanangleΦalongOB,whereOB=$\mathbf{I_a}$.Thevoltagedropinthearmature resistanceisI_aR_a.It is represented by phasor AC.The voltage drop in the synchronous reactanceis$\mathbf{I_aX_s}$.It is represented by CD .It leads the current$\mathbf{I_a}$by$90^0$and, therefore,CDis drawn in a direction perpendicular to OB. The total voltage drop in the synchronousimpedanceisthephasorsumof$\mathbf{I_aR_a}$ & $\mathbf{I_aX_s}$.ItisrepresentedbyAD.ThephasorOD represents$\mathbf{E_a}$.

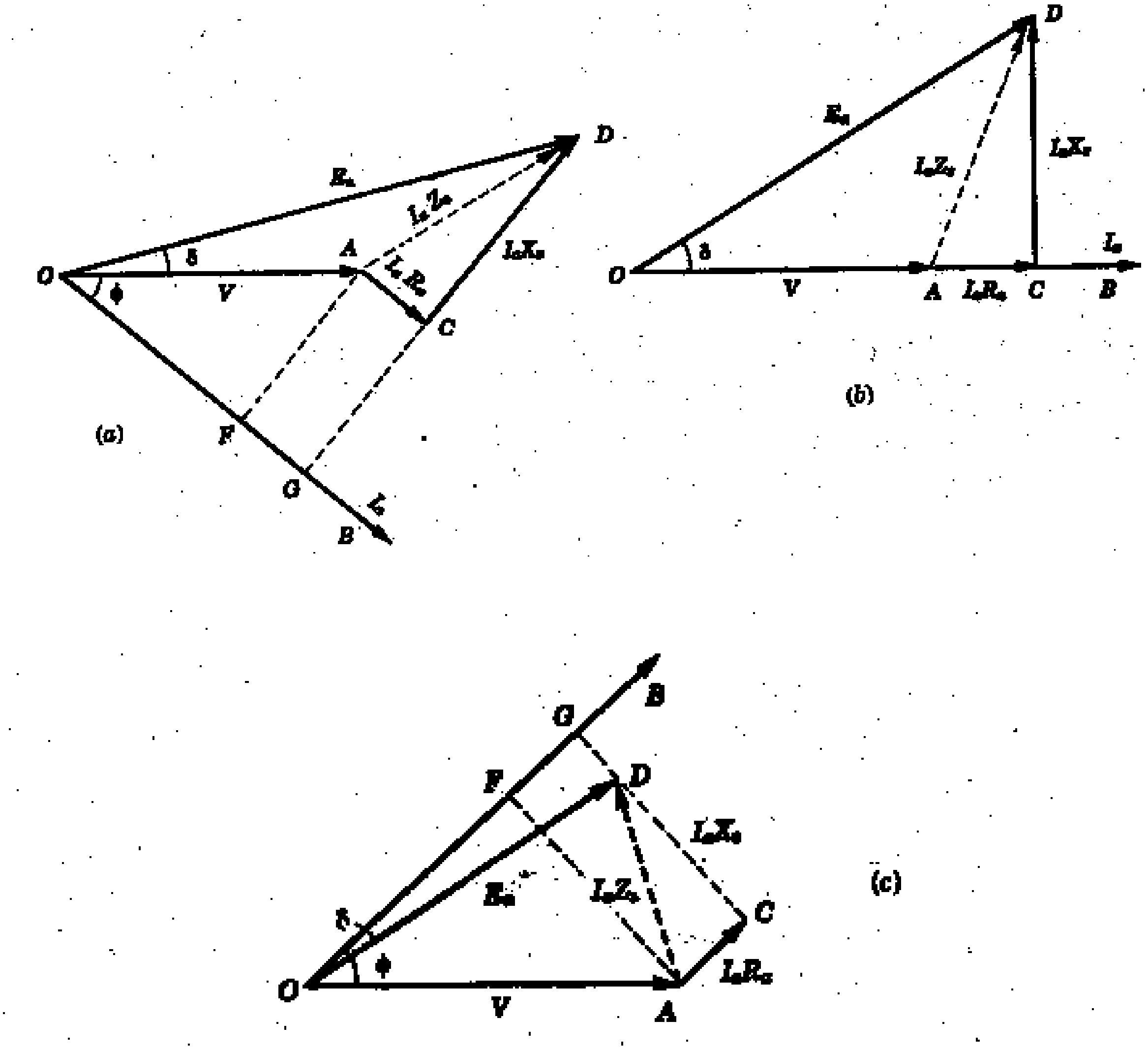
ThemagnitudE$\mathbf{E_a}$canbefoundfromtheright-angledtriangleOGD $OD^2 =$

$$OG^2 + GD^2 = (OF + FG)^2 + (GC + CD)^2$$

$$E_a^2 = (V\,cos\Phi + I_aR_a\,)^2 + (V\,sin\Phi + I_aX_s\,)^2$$

$$E_a = \sqrt{(V\,cos\Phi + I_aR_a\,)^2 + (V\,sin\Phi + I_aX_s\,)^2}$$

……………………………………..1.26



a) Phasor diagram for lagging power factor cos ϕ (b) Phasor diagram for unity power factor
(c) Phasor diagram for leading power factor cos ϕ

Fig.1.9

b) UnitypowerfactorCos Φ

Figure1.9(b)showsthe phasor diagramforunitypowerfactor load.

Fromtheright-angledtriangleOCD OD^2

$= OC^2 + CD^2 = \qquad (OA + AC)^2 + (CD)^2$

$E_a^2 = (V + I_aR_a)^2 + (I_aX_s)^2$

$E_a = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$……………………………………..1.27

c) LeadingpowerfactorCosΦ

Figure1.9(c)showsthephasordiagram forleadingpowerfactorload.

Fromtheright-angledtriangleOGD OD^2

$= OG^2 + GD^2 = (OF + \quad FG)^2 + (GC - CD)^2$

$$E_a^2 = (V\cos\Phi + I_a R_a)^2 + (V\sin\Phi - I_a X_s)^2$$

$$E_a = \sqrt{(V\cos\Phi + I_a R_a)^2 + (V\sin\Phi - I_a X_s)^2}$$

…………………………………..1.28

The angle δbetweenE_a& V is called the **power angle** or **Torque angle** of the machine. It varies with load and is a measure of air-gap power developed in themachine.

VOLTAGEREGULATION

The voltage regulation of as synchronous generator is defined as the change in terminal voltage from no-load to full-load divided by the full-load voltage when the speed and field current remaining constant.

It isexpressedasa fractionor a percentage of full-loadterminalvoltage.It canbewritten as

Per unitvoltage regulation= $\frac{\text{[illegible]}}{V}$

Percentagevoltageregulation=== $\frac{\text{[illegible]}}{V}$ x100

WhereE_0=magnitudeofgeneratedvoltageperphase V =

magnitude of rated terminal voltage per phase

Thevoltageregulation dependsupon thepowerfactor oftheload. For unity and lagging power factors, there isalwaysa voltage drop withthe increase of load, butfora certain leading p.f. the full-load regulation is zero. In this case the terminal voltage is same for both full-loadand no-load conditions. At lowerleading powerfactors thevoltagerises with the increase of load,and the regulation is negative.

DETERMINATIONOFVOLTAGEREGULATION

The KVA ratings of commercial alternators are very high(.Example 500MVA). It is neither convenient nor practicable to determine the voltage regulation by direct loading. There are several indirect methods of determining the voltage regulation of an alternator. These methods require only a small amount of power as compared to the power required for a direct loading method.

Threesuchmethods are

(i) Synchronousimpedancemethod

(ii) Ampere-Turnmethod

(iii) ZeropowerfactororPotiermethod

Forthesynchronousimpedancemethodthe followingtests areconducted.

MEASUREMENTOFSYNCHRONOUSIMPEDANCE

Thefollowingtestsareperformedonanalternatortoknowitsbperformance.

a) DCresistance test
b) Open-circuittest
c) Short-circuitTest

DCRESISTANCE TEST

Assume that the alternator is star connected with d.c. field winding open(Fig. 1.10) , measure the d.c. resistance between each pair of terminals either by using ammeter-voltmeter method or by using Wheat stone's bridge. The average of three sets of resistancevalues $R_t$is taken. This value of$R_t$is divided by 2 to get the d.c. resistance(ohmic resistance) per phase.The alternator should be at rest. Since the effective a.c. resistance is larger than d.c. resistance due to skin effect, therefore, effective a.c. resistance per phase is obtained by multiplying the d.c. resistance by a factor of 1.2 to 1.75 depending on the size of themachine.

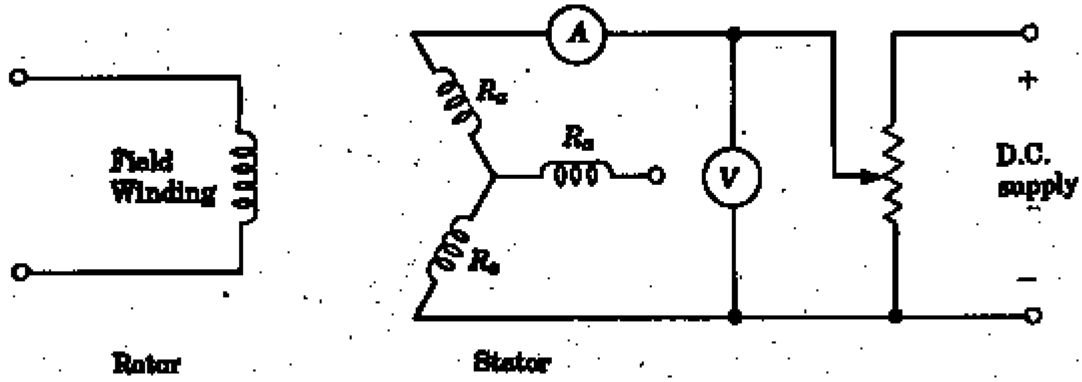


Fig.1.10D.C.resistancetestonanalternator.

Open–circuitTest

Thealternatorisrunatratedsynchronousspeedandtheloadterminalsarekeptopen Fig.1.11. That is, all the loads are disconnected .The field current is set to zero.

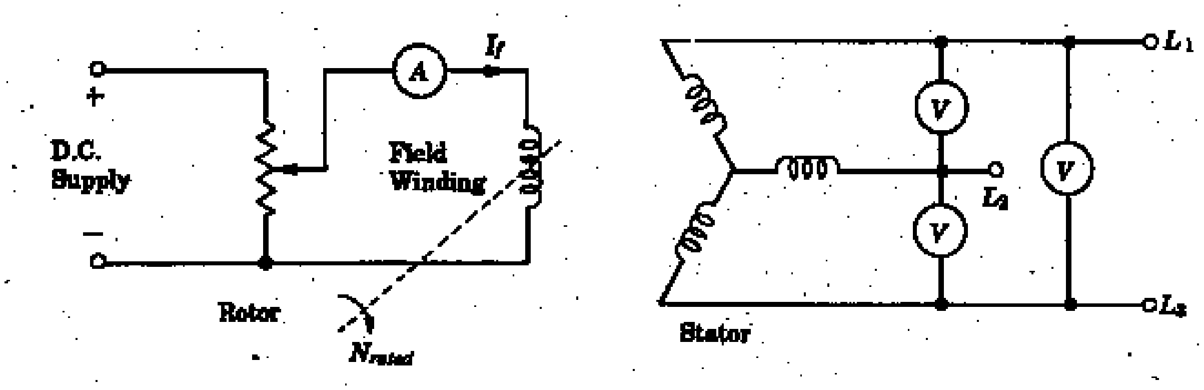


Fig.1.11**Open-circuittestonanalternator.**

Then the field current is gradually increasedin steps, and the terminal voltage$E_t$is measured at each step.The excitation current may be increased to get 25% more than rated voltage of the alternator.A graph is plotted between the open-circuit. phase voltage E_p (= $E_t/\sqrt{3}$) and field currentI_f.The characteristics curve so obtained is called open-circuit characteristics(O.C.C.).It takes the shape of a normal magnetization curve.The extension of the linear portion of an O.C.C is called the air-gap line of the characteristics. The O.C.C. and the air-gap line are shown in figure 1.12.

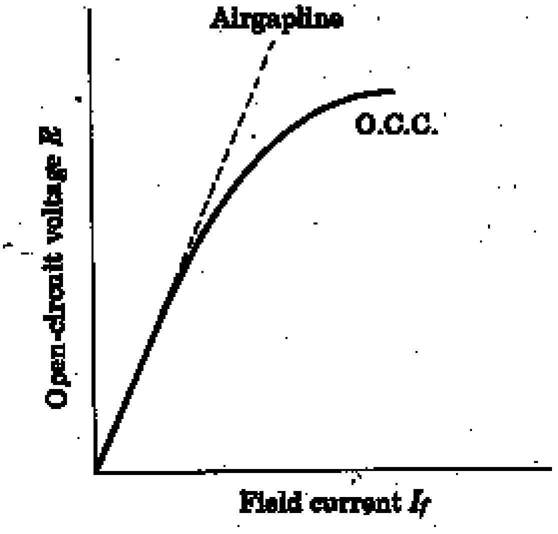


Fig.1.12TheO.C.C.ofanalternator

Short-CircuitTest

The armature terminals are shorted through three ammeters (Fig. 1.13) . Care should be taken in performing this test, and the field current should first be decreased to zero before starting the alternator. Each ammeter should have a range greater than the rated full-load value. Thealternatoris then run at synchronous speed. Then thefield current is gradually increased in steps , and the armature current is measured at each step. The field current may be increased to getarmaturecurrentsupto150%oftheratedvalue.Thefieldcurrent$I_f$andtheaverageof threeammeterreadings at each stepis taken.Agraph is plottedbetween thearmaturecurrent$I_a$and the field currentI_f.The characteristics so obtained is called *short-circuit characteristics* (SCC).This characteristic is a straight line as shown in figure1.14.

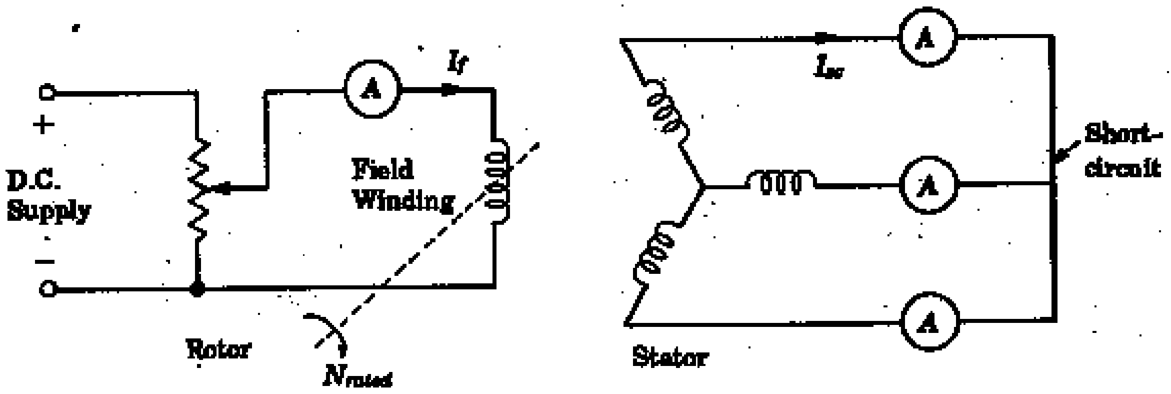


Fig.1.13

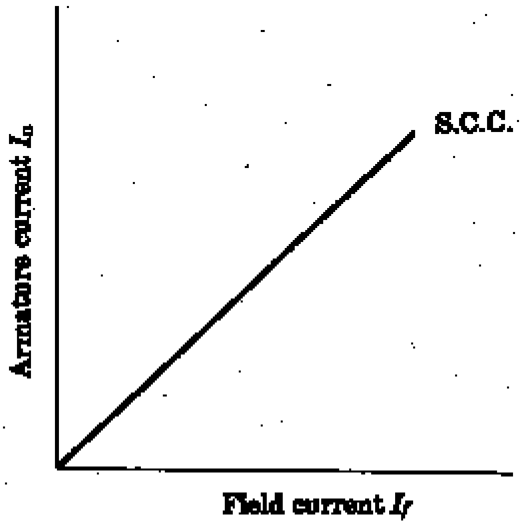


Fig.1.14.TheS.C.Cofanalternator

Calulationof Zs

The open-circuit characteristic (O.C.C.) and short-circuit characteristic(S.C.C) are drawn onthe same curve sheet.Determine the value ofI_{sc}at the field current that gives the ratedalternatorvoltageperphase.Thesynchronousimpedance$Z_s$willthenbeequaltothe Open-Circuit voltage divided by the short circuit current at that field current which gives the rated e.m.f. per phase.

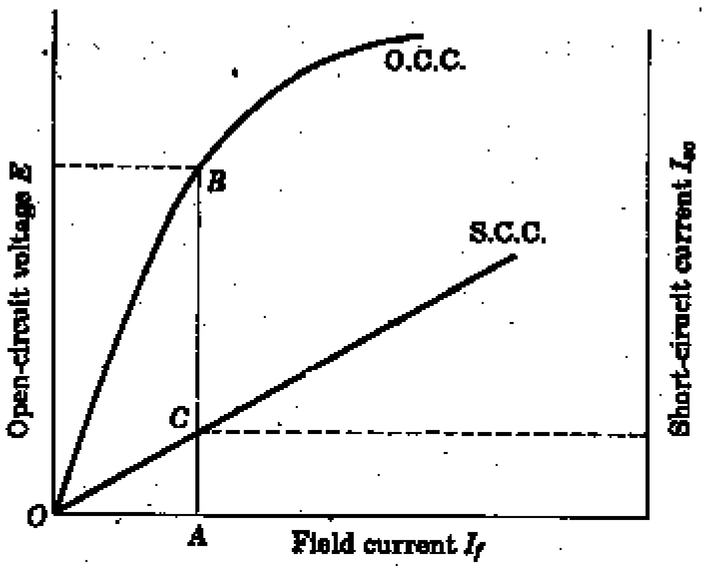


Fig.1.15

$$Zs=\frac{\quad}{short-circuit\ armature\ current}$$ forthesamevalueoffieldcurrent.

Now,knowingtheSynchronousimpedanceandArmatureresistancewecanfindoutthe Synchronous reactance

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

Once we know $R_a$andX_s,thephasordiagram can bedrawnforanyloadand any P.F.. Fig 1.16. shows the phasor diagram for the usual case of inductive load ; theloadpowerfactorbeing $\cos\emptyset$lagging. Note that in drawing the phasor diagram,current$I_a$has been taken as the reference phasor. The I_aR_a dropisin phase with $I_a$while$I_aX_s$drop leads $I_a$by 90^0.The phasor sum of V,$I_aR_a$and I_aX_s givestheno-load e.m.f. E_0

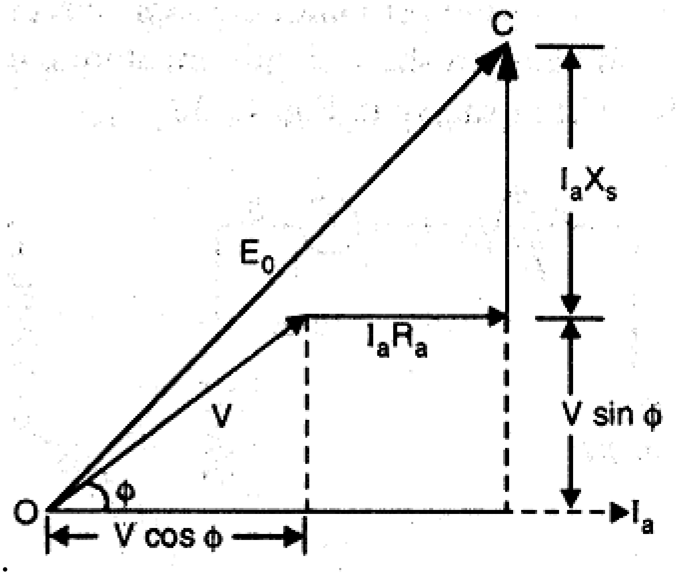


Fig.1.16

Now,

$E_0 = \sqrt{(OB)^2 + (BC)^2}$

$OB = V\cos\phi + I_aR_a$ and $BC = V\sin\phi + I_aX_s$

$\therefore E_0 = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$

$\therefore \%$ voltage regulation $= \frac{[illegible]}{V} \times 100$

Drawback : This method is easy but it gives approximate results .The reason issimple. The combined effect of X_L(armature leakage reactance) and X_{AR}(reactance of armature reaction) is measured on short-circuit.Since the current in this condition is almost lagging 90^0 ,the armature reaction will provide its worst demagnetizing effect. It follows that under any normal operation at,say 0.8 or 0.9 lagging power factors will produce error in calculations.This method gives a value higher than the value obtained from an actual load test.For this reason, it is called *pessimistic method*.

Example1.3

A500v,50kVAsingle-phasealternatorhasaneffectivearmature resistanceof0.2Ω .Anexcitationcurrentof10Aproduces200Aarmaturecurrentonshort-circuitandane.m.f. of 450 volt on open circuit.Calculate the synchronous reactance.

Solution :

Zs= $\frac{}{short-circuit\ armature\ current} = \frac{450}{200} = 2.25\ \Omega$

Xs=$\sqrt{Z_s^2 - R_a^2} = \sqrt{2.25^2 - 0.2^2}$ =2.241Ω

Example1.4

A 3-phase 2300V ,50Hz,1500 kVA star-connected alternator has a resistancebetween each pair of nterminals as measured by direct current is 0.16 Ω. Assume that the effective resistance is 1.5 times the ohmic resistance.A field current of 70A produces a short- circuit current equal to full-load current of 376 A in each line.The same field current produces an e.m.f. of 700 volt on open circuit.Calculate the synchronous reactance of the machine andits full-load regulation at 0.8 power factor Lagging

Solution :

Zs= $\frac{}{short-circuit\ armature\ current} = \frac{}{376}$ =1.075Ω

Ohmicresistanceperphase==0.08Ω $\frac{}{2}$

Effective resistance per phase =R_a= 1.5 x 0.08 = 0.12 Ω

Synchronousreactance= $X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{1.075^2 - 0.12^2}$ = 1.068Ω

$S_{3\emptyset} = \sqrt{3}$; =>1500 x $10^3 = \sqrt{3}$ $\times$2300I_L; =376A

Ratedvoltageperphase = $V_p = 2300/\sqrt{3}$=1328V

Phase current $I_{ap} = I_L$=376 A

$E_p = V_p + I_{ap} Z_s$

Let V_p betaken asreferencephasor:

V_p=V_pL0^0= 1328 L0^0volts =1328 + j 0 volts

I_{ap}=I_{ap}L$\cos^{-1}0.8$=376L-36.87^0A

Z_s=R_s+jX_s=0.12+j1.068=1.075L83.59^0Ω

E_p=1328+ j0+(376L-36.87^0)(1.075L83.59^0) =1328+404.2L46.72^0

=1328+277.1+j294.26= 1605.1+j294.26=1631L10.39^0volt

PercentageRegulation =$\frac{}{V_P}$x 100 = 22.8%

AMPERE-TURNMETHOD

This method of finding voltage regulation considers the opposite view to the synchronous impedance method. It assumes the *armature leakage reactance to be additional armature reaction.* Neglecting armature resistance(always small),this method assumes that change in terminal p.d. on load is due entirely to armature reaction. The same two tests(Open and short circuit test)are required as for synchronous reactance determination ; the interpretation of the results only is different. Under short-circuit, the current lags by90^0($R_a$considered zero)and the power factor is zero.Hence,the armature reaction is entirely demagnetizing. Since,the terminal p.d. is zero,all the field AT(ampere-turns)areneutralized by armature AT produced by the short circuit armature current.

(i) Suppose the alternator is supplying full-load current at normal voltage V(i.e.,operating loadvoltage)and zerop.f.lagging.Thend.c.field ATrequired willbethoseneeded toproducenormalvoltageV(orif $R_a$istobetakenintoaccount,thenV+$I_aR_a\cos Ø$)onno-load plusthoseto overcomethe armaturereaction.

LetAO=fieldATrequiredtoproducethenormal voltageV(orV+$I_aR_a\cos Ø$)at no-load.

OB_1=fieldATrequiredtoneutralizethearmaturereaction

Thentotalfield ATrequired arethephasor sum ofAO+OB_1(Fig.1.17(i))

totalfieldAT, A B_1 =AO+O B_1 ………phasorsum

The AO can be found from O.C.C. andO B_1can be determined from S.C.C.. Note that the use of a d.c. quantity(field AT)as a phasor is perfectly valid in this case because the d.c. field is rotating at the same speed as the a.c. phasors i.e. $\omega = 2\pi f$.

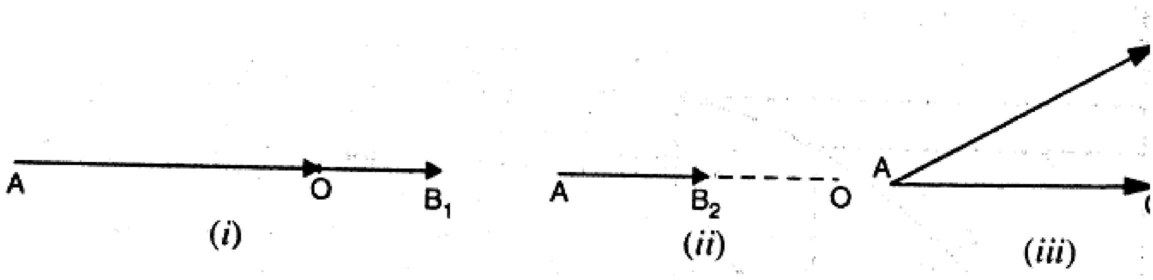


Fig1.17

(ii) For a full-load current of zero p.f. leading, the armature AT are unchanged. Since they aid the main field, less field AT are required to produce the given e.m.f.

So,the total field AT, AB_2= AO-B_2O................................phasor difference

Where B_2O=field AT required to neutralize armature reaction

ThisisillustratedinFig1.17(ii).Notethatagain AOisdeterminedfromO.C.C.and B_2O from S.C.C.

(iii) Between zero lagging and zero leading power factors,the armature m.m.f. rotates through180^0. At unity p.f. ,armature reaction is cross-magnetising only.Therefore, O $B_3$is drawn perpendicular to AO(Fig.1.17(iii)).Now A B_3shows the required AT in magnitude and direction.

GeneralCase.

Itmaynowbediscussedthecasewhenthepfhasanyvaluebetweenzero(lagging or leading) and inity.If thepower-factor is $\cos\emptyset$lagging,then$\emptyset$is laid off to the rightofthevertical lineOB_3as showninFig.1.18(i).Thetotal fieldATrequired are AB_4 i.e.,phasorsumofAO andOB_4.Ifthepowerfactoris $\cos\emptyset$leading,then $\emptyset$is laid offto the left of the vertical line O B_3as shown in Fig.1.18(ii).The total field AT required are AB_5i.e.,phasor sum of AO and OB_5.

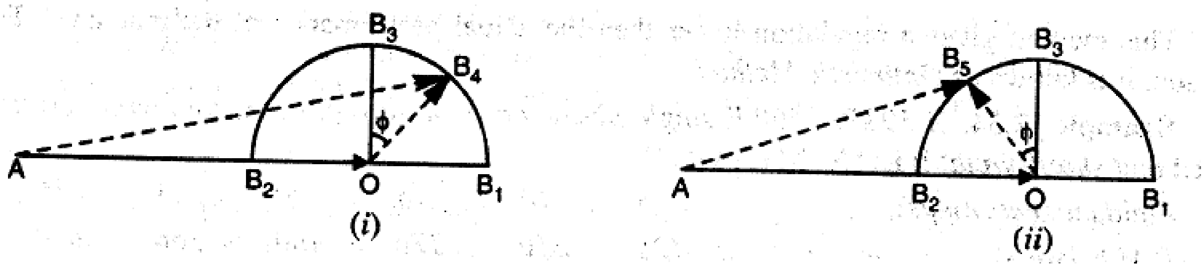


Fig1.18

Since current $\propto$ AT , it is more convenient to work in termsof field current.Fig. 1.19 showsthe current diagram for the usual case fo lagging power factor.Here AO represents the field currentrequiredto producenormalvoltage V (or$V+I_aR_a cos\Phi$) on no-load. The phasor OB represents the field current required for producing full-load current on short –circuit.The resultant field current is AB and the phasor sum of AO and OB.Note thatphasor AB represents the field current required for demagnetizing an dto produce voltage V and $I_aR_a cos\Phi$drop.(if $R_a$is taken into account).

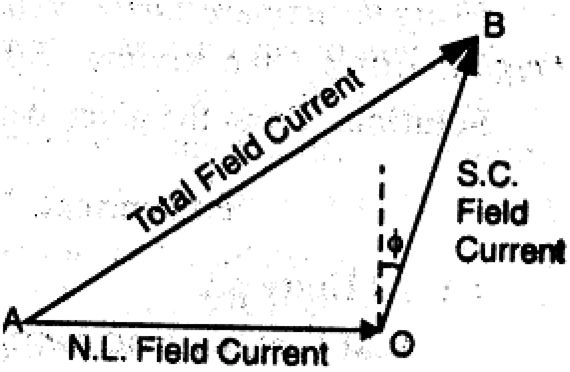
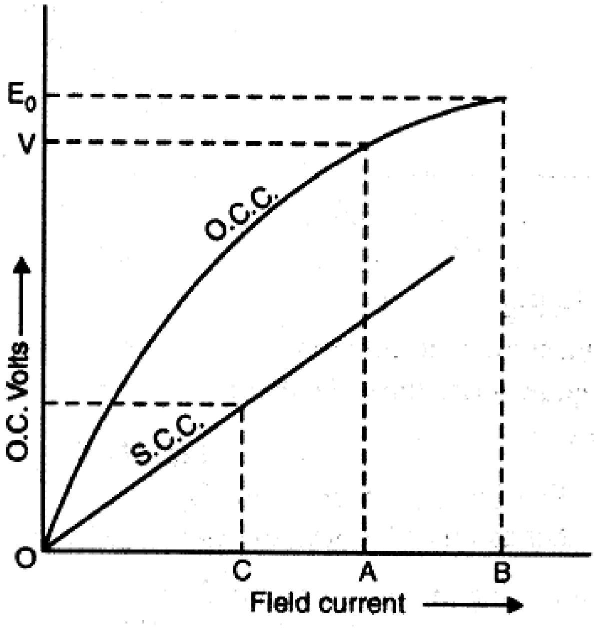


Fig.1.19

PROCEDUREFORATMETHOD

Suppose the alternator is supplying full-load current$I_a$at operating voltage Vand p.f. $cos\Phi$ lagging.The procedure for finding voltage regulation for AT method is as under :

(i) FromtheO.C.C.,fieldcurrentOArequiredtoproducetheoperatingloadvoltageV(or $cos\Phi$) $V + I_aR_a$ is determined as shown in Fig.1.20.The field current OA isalid offhorizontally asshownin Fig.1.21.



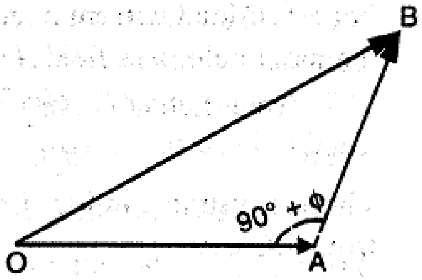


Fig.1.20 Fig.1.21

(ii) FromS.C.C.,thefieldcurrentOCrequiredforproducingfull-loadcurrent$I_a$onshort- circuit is determined.The phasor AB(=OC) is drawn at an angleof $(90^0 + \emptyset)$ i.e.,Arg(OAB)=($90^0 + \emptyset$)as shown in Fig. 1.21.

(iii) ThephasorsumofOAandABgivesthetotalfieldcurrentOBrequired.TheO.C. voltage E_0corresponding to field current OB on O.C.C. is the no-load e.m.f.

voltageregulation = $\frac{\quad}{V}\times 100$

Thismethodgivesaregulationlowerthantheactualperformanceofthe machine.For this reason,it is known as *Optimistic method*.

ZEROPOWERFACTORMETHODORPOTIERMETHOD

In this method, we separately determine the voltage drop duetoarmatureleakagereactance(= I_aX_l) and voltage drop due to armature reaction(= I_aX_{AR}).Therefore, it gives more accurate results. The Potier method consists of the following steps:

(i) PlottingO.C.C.:

The open-circuit characteristics (O.C.C.) of the alternator is plotted by conducting no-load test on the alternator as explained earlier .The lower part of O.C.C. is practically a straight line and when extended becomes the air-gap line. Therefore, air-gap line represents O.C.C. of the alternator if the reluctance of the iron portion of the magnetic circuit of the machine is neglected as compared to the reluctance of the air-gap.

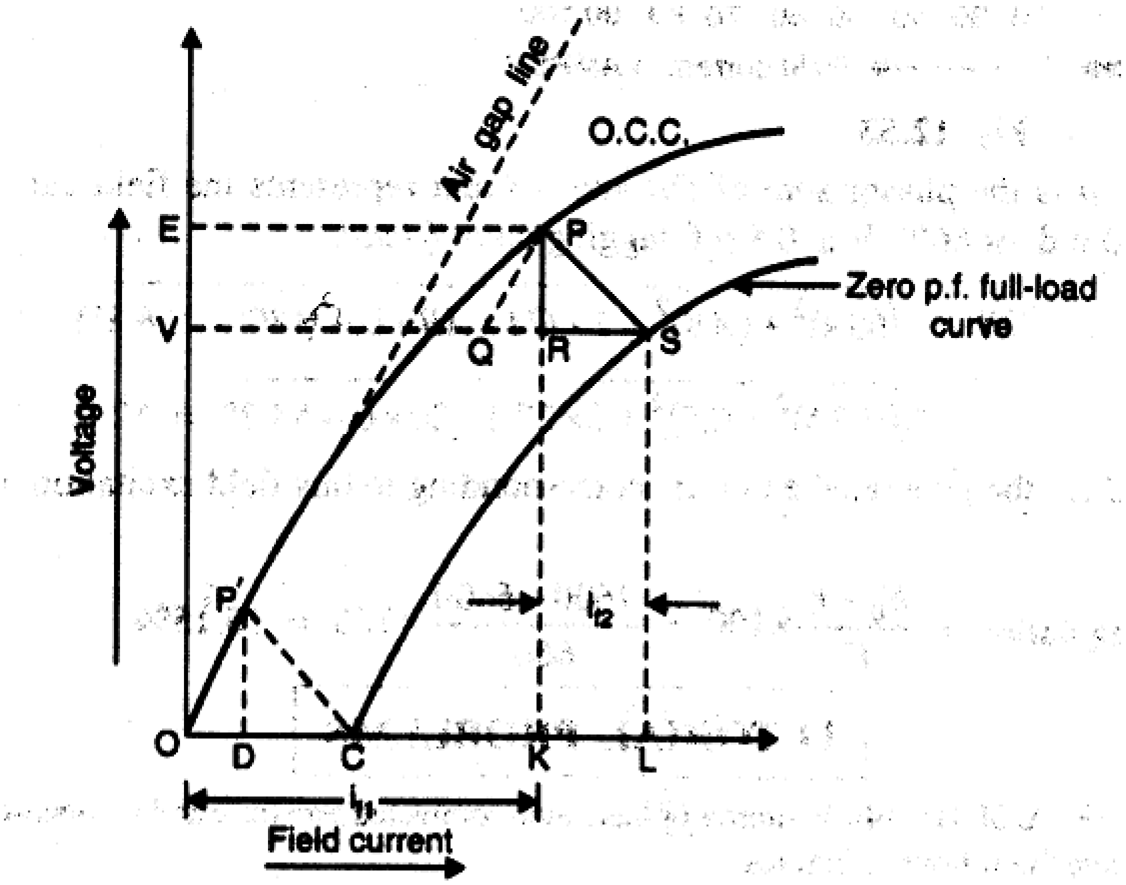


Fig.1.22

(ii) **Plottingzerop.f.(lagging)full-load curve**:

This is the curve between the terminal voltage and field current when the alternator is delivering its full rated current to a zero power factor(lagging) load. The test is carried out by running the alternator at synchronous speed and connecting a purely inductive 3-phase load to its terminals. The load is varied in steps and at each step, the field current is adjusted so thatthe armature current is equal to its rated value. Thereis no need to plot the full curve. Only two points S &C (see fig.1.22) are sufficient. The point S corresponds to a field current whichgives the rated terminal voltage while the zero p.f. load is adjusted to draw the rated armature current. The point C corresponds to the short-circuit conditions on the alternator(i.e. terminal voltage =0) with the field current adjusted to give rated armature current. Since the armature resistance isnegligible,theshort-circuitcurrentlagsbehindtheresultantinducede.m.f.by90^0 .Therefore,pointCconstitutesapointonthezerop.f.curve.

(iii) **Costructingpotiertriangle**:

Referring to Fig. 1.22 OC is field current producing full-load armature current on short-circuit(thecurrentlagsby 90^0).Therefore,thefieldcurrentOCmustbesufficientto counter the demagnetising effect of armature reaction and armature leakage reactance to drop at full-load. From S, draw SQ equal to and parallel to OC. From point Q, draw a line QP paralleltoair-gapline.ThislinemeetsO.C.CatpointP.FrompointP,drawPRperpendicular to QS and meeting it at point R. The triangle PRS is known as POTIER TRIANGLE. The following information is conveyed by the potier triangle :

a) ThelengthPRrepresentsthearmatureleakagereactancedrop(I_aX_l).

b) ThelengthRS(=KL= i_{f2}) represents the field current to overcome the demagnetising effect of armature reaction at full-load.The length RQ represents the field current necessary to balance the armature leakage reactance drop(I_aX_l).

c) The Potier triangle is the same for a given armature current and hence can be transferredanywheretofitbetweenthetwocharacteristics.Thepotiertriangle PRS is transferred to the baseline as triangle P’DC and is identical to Potier triangle PRS.

PHASOR DIAGRAM : Suppose the full-load terminal voltage of the alternatorisV.Lettheloadp.f.be $\cos\phi$lagging.Thephasordiagram forthis condition is shown in Fig.1.23

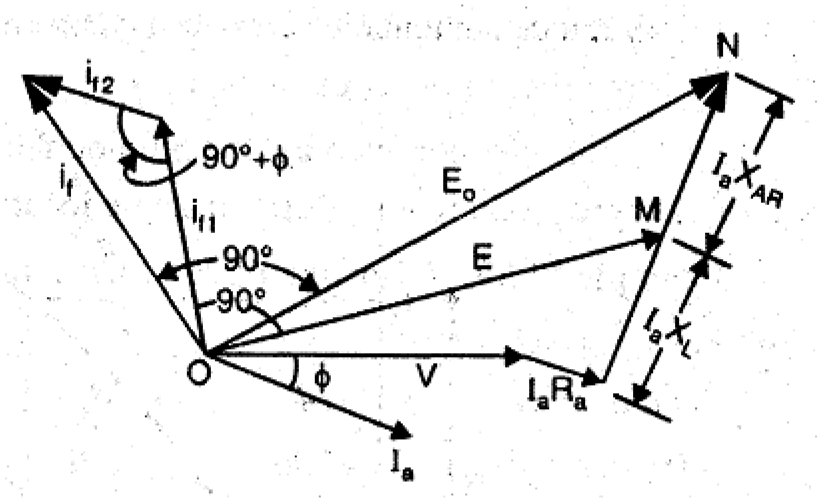


Fig.1.23

Here the voltage V is taken as the reference phasor and current $I_a$lags behind V byϕ. The $I_aR_a$drop is drawn parallel to the current phasor and$I_aX_L$drop is drawn perpendicular to it.The phasor OM represents the induced e.m.f E(=phasorsumofV,$I_aR_a$andI_aX_L).FromO.C.C.inFig.1.22,thefieldcurrent corresponding to induced e.m.f.Eisi_{f1}(=OK).The field current$i_{f1}$is drawn 90^0 aheadofE.Thecurrentphasor(=RS=DCini_{f2}Fig.1.22)representsthe fieldcurrentnecessarytoovercomethedemagnetisingeffectofarmature reaction at full-load andis drawn parallel to thecurrent phasorI_a.The phasor sumof i_{f1}&i_{f2} gives the total field currenti_f requiredtoproduceE_0.The phasorE_0(=ON) lagsbehind$i_f$by90^0.Note that phasor MN representsthe voltage drop I_aX_{AR}due to armature reaction.

Percentagevoltageregulation=$\frac{}{V}$x 100

PROCEDUREFORPOTIERMETHOD

ForsolvingproblemsrelatingtoPotier method,thefollowingprocedureisadopted:

(i) Supposethe terminalvoltageper phaseisV.

(ii) Findthearmatureleakagereactancedrop($= I_aX_L$)fromthepotier triangle.

(iii) AddI_aX_L)(and$I_aR_a$ifgiven)vectoriallytoV togetE.

(iv) From the O.C.C, find the field current required toproduceE. Let itbei_{f1} .

(v) Fromthepotiertriangle,findthefieldcurrentnecessaryforbalancing armature reaction. Let it be i_{f2}.

(vi) Findthephasor sumofi_{f1}& i_{f2}togetthe resultantfieldcurrenti_f.

(vii) FromtheO.C.C.,findthee.m.f.correspondingtofieldcurrenti_f.This gives us E_0 .Therefore, we can find the voltage regulation.

LIMITATIONSOFPOTIERMETHOD

ThePotiermethodhasthefollowingdrawbacks:

(a) The Potier triangle is based on the assumption that the armature leakage reactanceisconstantandtheO.C.C.ofthealternatoristhesameunderloadasit is under open-circuit conditions. However ,this is not correct. Therefore, the value of armature leakage reactance determined by the potier triangle method is not absolutely accurate. In order to distinguish the value of leakage reactance thus determined from the absolutely correct value, the value of leakage reactance determined by the potier triangle method is sometimes called potier leakage reactance.

(b) In the potier triangle method, some error is also introduced due to the fact that it is not possibleto obtain exactly zero P.F. for the zero power factor load test.

(c) A greater amount of error is exhibited by machines of salient pole constructionthanthenon-salientpoleconstruction.Bestresultsareobtainedby determiningthevalueofarmatureleakagereactanceandthem.m.f.ofarmature reaction from a potier triangle located as high as possible on the test curves.

PARALLELOPERATIONOFALTERNATORS

It is rare to find a 3-phase alternator supplying its own load independently except under test conditions. In practice, a very large number of 3-phase alternators operate in parallel because the various power stations are interconnected through the national grid. Therefore, the output of any single alternator is small compared with the total inter- connected capacity. For example, the total capacity of the interconnected system may be over 40,000MW while the capacity of the biggest single alternator may be 500MW.For this reason, the performance of a single alternator is unlikely to affect appreciably the voltage and frequency of the wholesystem .An alternator connected to such a system is said to be connected to *infinite bus-bars*. The outstanding electrical characteristics of such bus-bars are that they are constant – voltage ,constant-frequencybus-bars.

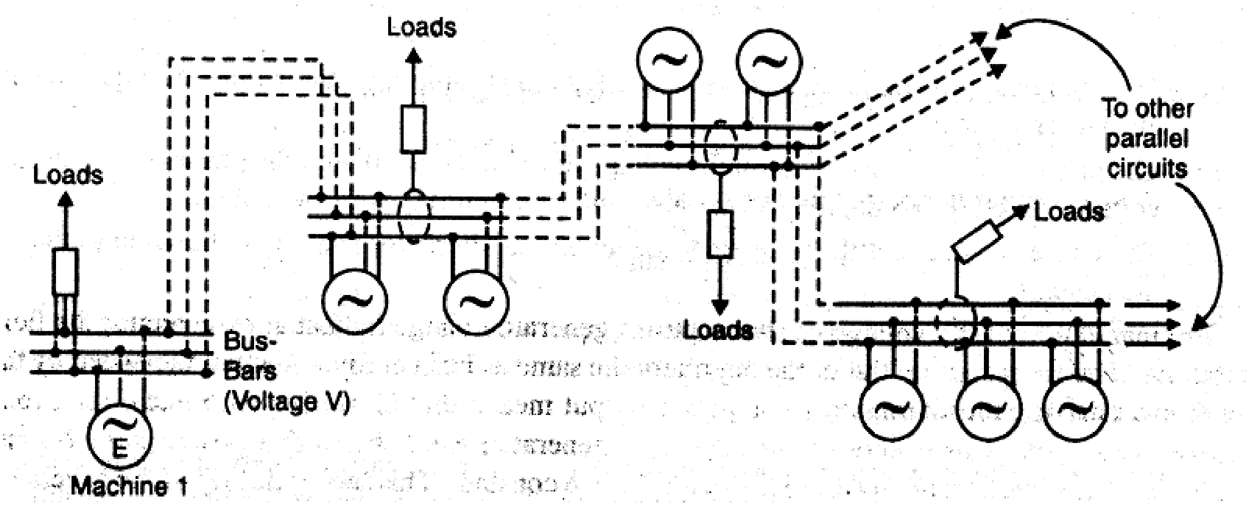


Fig.1.24

Fig. 1.24 Shows a typical infinite bus system .Loads are tapped fromthe infinite busatvarious load centers. The alternators may be connected to or disconnected from the infinitebus, depending on the power demand on the system. If an alternator is connected to infinitebus-bars, no matter what power is delivered by the in-coming alternator, the voltage and the frequency of the system remain the same. The operation of connecting an alternator to the infinite bus-bars is known as parallel with the infinite bus-bars. It may be noted that before an alternator is connected to an infinite bus-bars, certain conditions must be satisfied.

ADVANTAGESofPARALLELOPERTIONSOFALTERNATORS

Thefollowing aretheadvantagesof operatingalternators in parallel.

(i) Continuity of service : The continuity of service is one of the important requirements of any electrical apparatus. If one alternator fails, the continuity of supply can be maintained through the other healthy units. This will ensure un-interrupted supply to theconsumers.

(ii) Efficiency :The load on the power system varies during the whole day ; being minimum during the late night hours. Since, alternators operate most efficiently when delivering full-load ,units can be added or put-off depending upon the load requirement. This permits the efficient operation of power system.

(iii) Maintainance and Repair : It is often desirable to carry out routine maintenance andrepair of one or more units. For this purpose , the desired unit /units can be shut down and the continuity of supply is maintained through the other units.

(iv) Load growth: The load demand is increasing due to the increase in use of electricalenergy. The load growth can be met by adding more units without disturbing the original installation .

CONDITIONSFORPARALLELINGALTERNATORWITHINFINITEBUSBARS

The proper method of connecting an alternator to the infinite bus-bars is called synchronising. A stationary alternator must not be connected to live bus-bars. It is because the induced e.m.f. iszeroatstand-stillandashort-circuitwillresult.Inordertoconnectanalternatorsafelytothe infinite bus-bars , the following conditions are met.

(i) Theterminalvoltage(r.m.s.value)oftheincomingalternator must be the same as bus-barsvoltage.

(ii) Thefrequencyofthegeneratedvoltageoftheincoming alternator must be equal to the bus-bars frequency.

(iii) The phase of the incoming alternator voltage must be identical with the phase of the bus-bars voltage. In other words, the two voltages must be in-phase with each other.

(iv) The phase sequence of the voltage of the incoming alternator should be same as that of the bus-bars.

The magnitude of the voltage of the incoming alternator can be adjusted by changing its field excitation.Thefrequencyoftheincomingalternatorcanbechangedby adjustingthespeedof the prime-mover driving the alternator.

Condition(i)isindicatedbyavoltmeter,condition(ii)&(ii)areindicatedbysynchronizing lamps or a synchroscope. The condition (iv) is indicated by a phase sequence indicator.

METHODSOF SYNCHRONISATION

The method of connecting an incoming alternator safely to the live busbars is called synchronising. The quality of voltage between the incoming alternators and the busbars can be easily checked by a voltmeter. The phase sequence of the alternator and the busbars can be checked by a phase sequence indicator. Differences in frequency and phase of the voltages of the incoming alternators and busbars can be checked by one of the following two methods.

1. **Bythreelamps(onedark,two bright)method**.

2. **By synchroscope**

Three-Lamp method : In this method of synchronising ,three lampsL_1, L_2 *and*$L_3$are connected as shown inFig1.25.The lamp$L_1$is straight connected between the corresponding phases(R_1&R_2)andtheother twoarecross-connectedbetweentheothertwophases.Thus, lamp$L_2$is connected betweenY_1&$B_2$and lamp L_3betweenB_1&Y_2.When thefrequency & phase of the voltage of the incoming alternator is the same as that of the busbars, the straight connected lampL_1will be dark while cross-connected lampL_2& L_3will be equally bright. At this instant ,the synchronisation is perfectand the switch of the incoming alternator can be closedtoconnectittothebusbars.InFig.1.25PhasorsR_1, Y_1& B_1 representthebusbar voltages and phasorsR_2, Y_2&B_2 represent the voltages of the incoming alternator. At the instant when $R_1$is inphasewithR_2,voltage across lamp$L_1$is zero and voltages across lamps

L_2&$L_3$are equal. Therefore ,lamp$L_1$is darkwhile lamps L_2&L_3will be equally bright .At this instant, the switch of the incoming alternator can be closed.Thus,incoming alternator gets connected in parallel with the busbars.

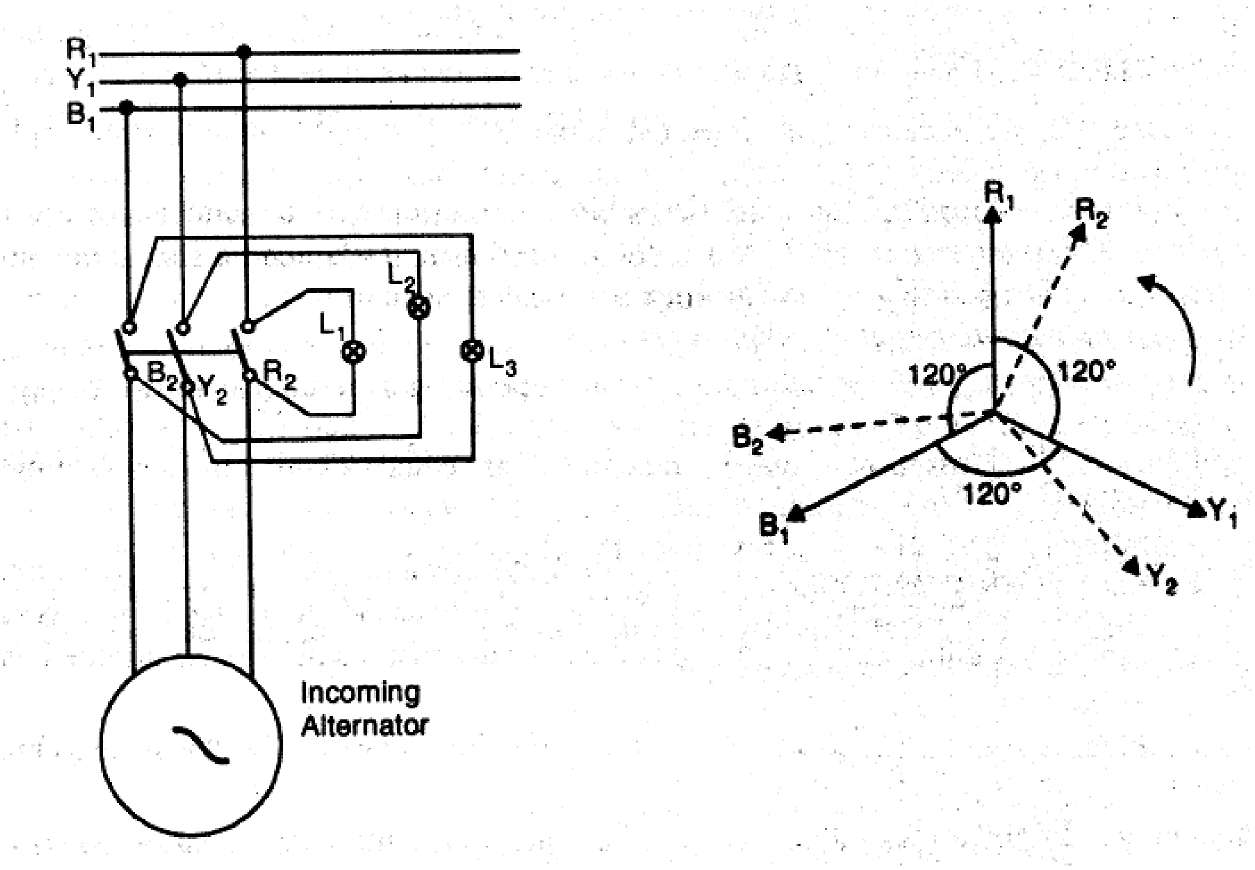


Fig.1.25

Synchroscope : A synchroscope is an instrument that indicates by means of arevolving pointerthephasedifferenceandthefrequencydifferencebetweenthevoltagesofthe incoming alternator and the busbars(Fig. 1.26). It is essentially a small motor ,the field being supplied from the busbars through a potential transformer and the rotor from the incoming alternator.Pointerisattachedtotherotor.Whentheincomingalternatorisrunningfast ,(i.e.the frequency of the incoming alternator is higher than that of the busbars),the rotor and hence pointer moves in the clock-wise direction. When the incoming alternator is running slow that is ,(frequency of the incoming alternator is lower than that of the busbars),the pointer moves in anti-clockwise direction.When the frequency of the incoming alternator is equal to that of the busbars , no torque acts on the rotor and the pointer points vertically upwards ("12 O' Clock").It indicates the correct instant for connecting the incoming alternator tothe busbars. The synchroscope method is superior to the Lamp method because it not only gives a positiveindication ofthe timeto closethe switch but also indicates theadjustments to bemade should there be a difference between the frequencies of the incoming alternator and thebusbars.

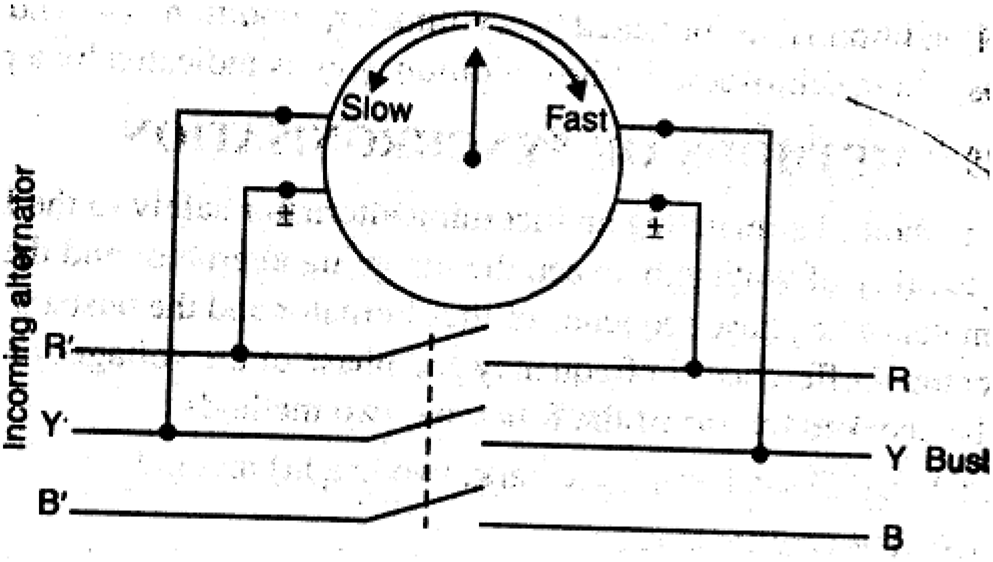


Fig.1.26

Synchronisingaction :

When two or more alternators have been connected in parallel ,they will remain in stable operation under all normal conditions i.e., voltage ,frequency, speed and phase equality will continue .In other words, once synchronised properly, the alternators will continue to run in synchronism under all normal conditions. Ifone alternator tries to fall out of synchronism ,it is immediately counteractedby the production of a synchronisingtorque whichbrings it back to synchronism. This automatic action is called the synchronising action of thealternators.

Consider two similar single-phase alternators 1 &2 operating in parallel as shown inFig. 1.27 (i).For simplicity, let us assume that the alternators are at no-load. When in exact synchronism , magnitudes of the small e.m.f. s E_1(Machine 1) &E_2(machine 2) are equal. These e.m.f.s are acting in the same direction with respect to the external circuit as shown in Fig.1.27(ii).But in relation to each other, these e.m.f.s are in phase opposition i.e. ,if we trace the closed circuit formed by the two alternators we find that the e.m.f.s oppose each other as shown in Fig 1.27(iii).When the alternators arein exact synchronism,E_1&$E_2$are in exact phase opposition.Since, $E_1 = E_2$inmagnitude, no current flowsin the closed circuitformed bythe two alternators.

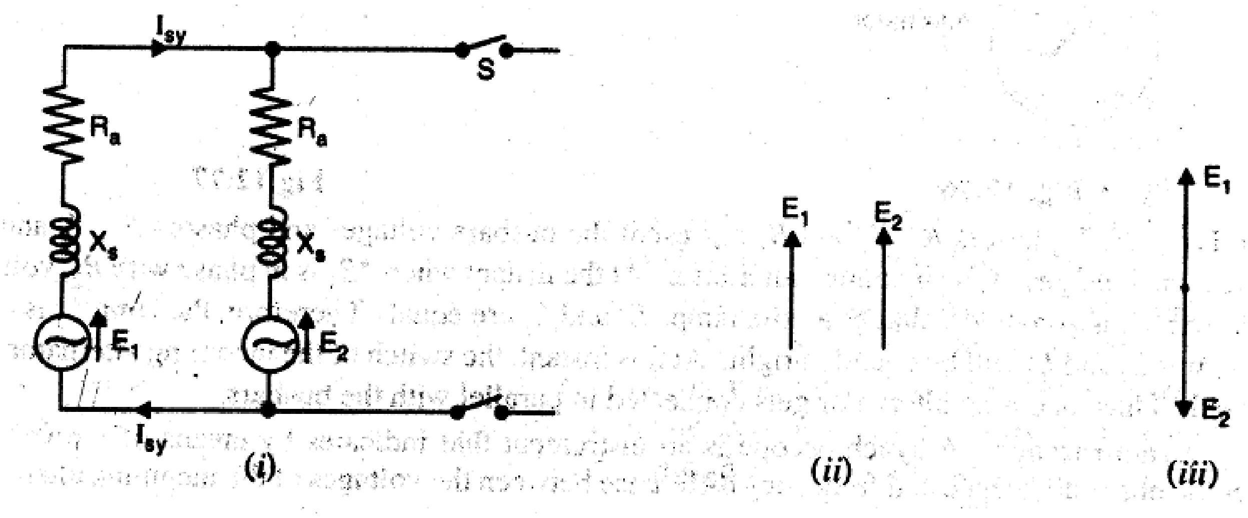


Fig.1.27

Ifonealternatordropsoutofsynchronism,thereis anautomaticactiontore-establish synchronism.

Letus discussthis point.

(i) **Effectofspeedchange**: Suppose,duetoanyreason,thespeedofmachine2falls.Then emfE_2 will fall back a phase angle of α electrical degrees as shown in Fig 1.28.(thoughstill $E_1 = E_2$).Therewillberesultante.m.f.$E_r$intheclosedcircuit

formed by the two alternators.The emf$E_r$will circulate current (known as synchronising currentI_{sy}) in this closedcircuit.

SynchronisingcurrentI_{sy}=

ThecurrentI_{sy}lags behind$E_r$by anangle givenby θ:

$$\tan \theta = \frac{}{2R_a} = \frac{}{R_a} R_a =$$

armatureresistanceofeachalternator

X_s= synchronous reactance of each alternator Z_s

=synchronousimpedanceofeachalternator

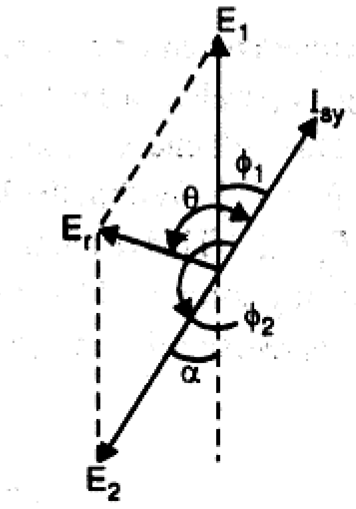


Fig.1.28

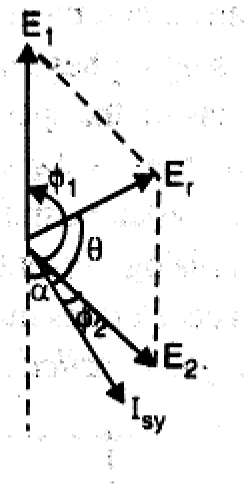


Fig.1.29

Since,$R_a$is very small as compared toX_s, θ is nearly90^0so that the current$I_{sy}$is almost in phase withE_1& in phase opposition to E_2.This means that machine 1 is generating and machine 2 is motoring . consequently, the machine 1tends to slow down andmachine 2, by acceptingpower,tendstoaccelerate.Thisrestoresthestatusquoi.e.,synchronismisre established.

Conversely,if E2 tends to advance in phase,as shown in Fig.1.29 The directions of $E_r$andI_{sy}arechangedsuchthatnowmachine2isgeneratingandmachine2ismotoring .Onceagain thesynchronism is restored.

(ii) **Effect of inequality ofe.m.f.s**: The automatic re-establishment of synchronism oftwo alternators operating in parallel also extends to any changes tending to alter the individual e.m.f. s . When in exact synchronism ,then$E_1=E_2$(magnitude) and they are inexactphase oppositionasshown in Fig.1.30(i).Suppose due toany reason, e.m.f.E_1increases.Then resultant e.m.f.$E_r$exists in the closed circuit formed by thetwoalternators.Then$E_r=E_1 - E_2$andisin-phasewithE_1.Theresultant e.m.f. $E_r$sends synchronising currentI_{sy}in the closed circuit.Here again the currentI_{sy} almost lags behind$E_r$by90^0(as Zs=Xs) as shown in Fig.1.30(ii). AlsoI_{sy}lags almost 90^0behind$E_1$and leads E_2almost by90^0.Thepower produced is practically zero ; just enough to overcome copper losses. The currentI_{sy} lagsbehind$E_1$and produces a demagnetising armature reaction effect on machine1.AtthesametimeI_{sy}leadsE_2 andproducesmagnetising armature reactioneffectonthemachine2.Thus,E_1tendstofallandE_2tendstorise.The resultisthatsynchronismisre-established.Theconverseistruefor$E_2 > E_1$as shown in Fig.1’30(iii)

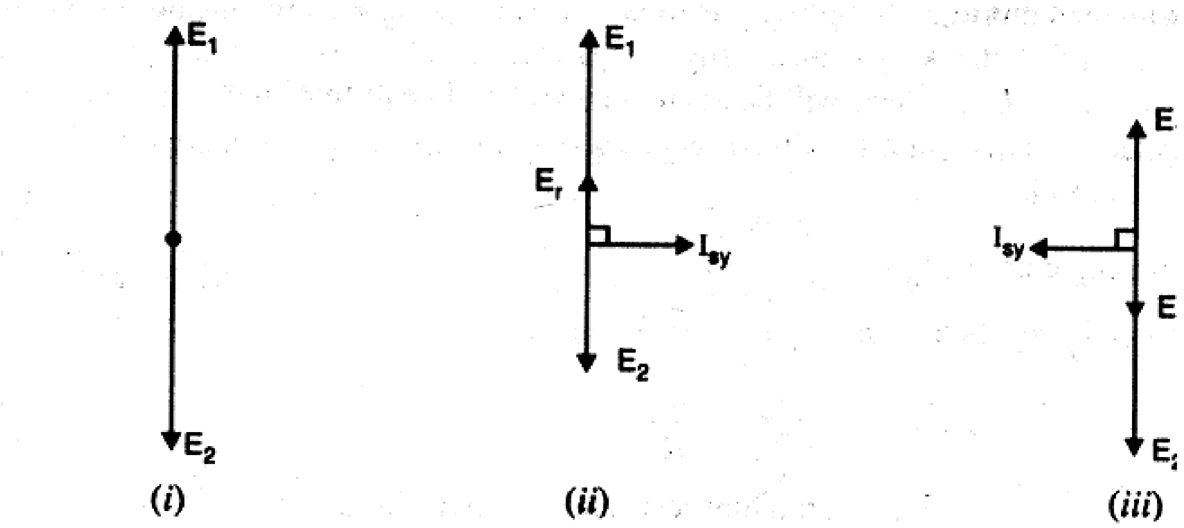
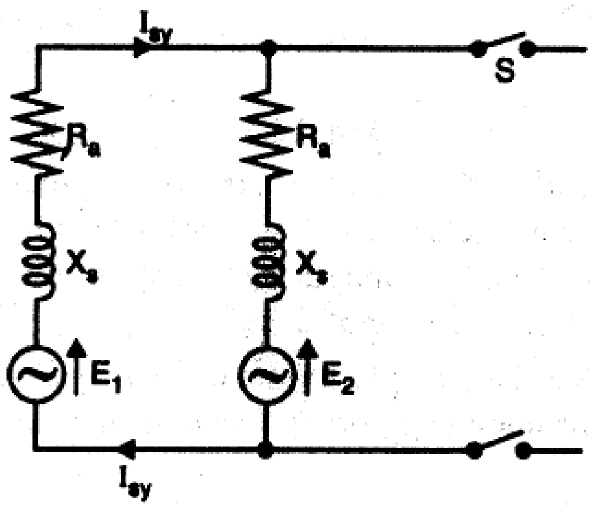


Fig.1.30

SYNCHRONISINGPOWER:

When two alternators are operating in parallel, each machine has an inherent tendency to remain synchronised . Consider two similar single-phase alternators 1&2operatinginparallelatno-loadasshowninFig.suppose ,due toanyreason ,thespeed of machine 2 decreases. This will cause$E_2$to fall back by a phase angle ofαelectrical degrees asshown in Fig.1.31(though still$E_1 = E_2$).Within the local circuit formed by two alternators,the resultant e.m..f$E_r$is the phasor difference $E_1 - E_2$.This resultant e.m.f. results in the production of synchronising currentI_{sy} which sets up synchronising torque. The synchronising torque retards machine 1and accelerates machine 2 so that synchronism is re-established.The power associated with synchroniosing torque is called synchronizingpower.

InFig.1.32,machine1isgeneratingandmachine2ismotoring.Thepowersupplied by machine 1 is called **synchronising power**.



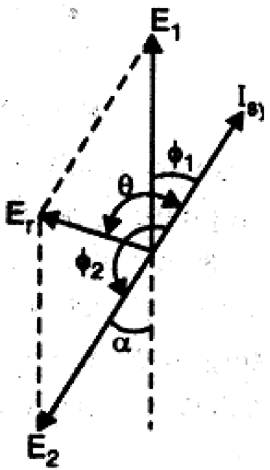


Fig.1.31

Fig.1.32

Referringto Fig.1.32wehave,

Synchronising power , $P_{sy} = E_1 I_{sy} \cos \Phi_1 = E_1 I_{sy} \cos(90^0 - \theta) = E_1 I_{sy} \sin \theta$

$= E_1 I_{sy}$ (As $\theta = 90^0$so that $\sin \theta = 1$)

The synchronizing power goes to supply power input to machine 2 and the Cu losses in the local circuit of two machines.

∴ $E_1 I_{sy} = E_2 I_{sy}$+Culosses

Resultante.m.f.,E_r=2E [As $E_1 = E_2 = E$ (say)]

$=2E \cos(90^0 -$) =2 E = 2 EX (Asαis small)

=αE

Notethatinthisexpression, αisinelectrical radians.

synchronising current I_{sy}= = ...$R_a$ofbothmachinesis negligible

HereX_s=synchronizing reactanceof eachmachine

∴synchronizing power supplied by machine1 is$P_{sy} = E_1 I_{sy}$= E = $2X_s$

$$P_{sy} = \frac{\alpha E^2}{2X_s}$$

Total synchronizing power for threephases =3P_{sy}= $2X_s$

Notethatthisisthevalueofsynchronizingpowerwhentwoalternatorsoperatein parallel at no-load.

……………………………..xxxxxxxxxxxxxxxxxxxxxxxxx……………………………

SYNCHRONOUSMOTOR

Defination:

AsynchronousMotoriselectricallyidenticalwithanalternation.

CharacteristicFeature :→

(1) Itrunseitheratsynchronousspeedornotatall.Theonlywaytochangeitsspeedisto verythesupplyfrequency $\left(\because N_S = \frac{120\,f}{P}\right)$

(2) Itisnotinherentlyselfstarting.Ithasberunuptosynchronous(orrearlysynchronous) speed by means before it can be synchronorised to the supply

(3) Itiscapableofbeingoperatedunderawiderangeofpowerfactorbothlaggingand leadig.

Construction:→

Likean alternator, asynchronous motor has thefollowing main parts :

(i) Astatorwhichhouses3-phasedistributedarmaturewindingintheslotsofthestator core and receives powers from a 3ϕ -supply.

(ii) Arotorthathasasetofsalientpolesexcitedbydirectcurrenttoform alternatorNand S poles.

Theexcitingcoilareconnectedinseriestothe slipringsanddirectcurrent isfedinto the winding from an external excite on mounted on the rotor shaft.

Thestator iswound for thesame numberof polesasthe rotor poles

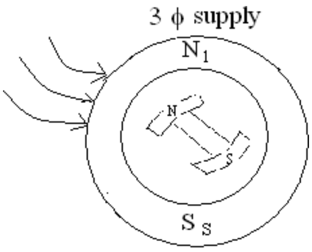


Fig (a)

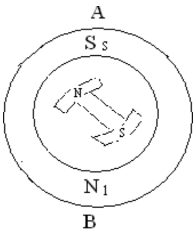


Fig - (b)

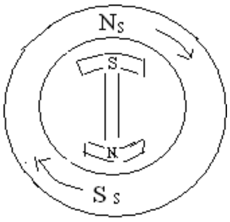


Fig - (c)

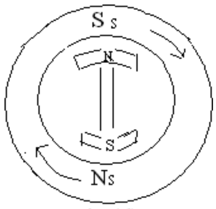


Fig-(d)

PrincipleofOperation :→

When a 3ϕ winding is fed by a 3ϕ supply then a magnetic field of constant magnitude but rotating synchronous speed is produced in the stator. Consider a two pole stator which are shown two stator pole Ns and Ss rotating at synchronous speed in clockwise direction.

With the rotor position as shown in fig. suppose the stator pole are at that instant situated at point B. The two similar poles N and Ns as well as S and Ss will repel each other with the result that the rotor tends to rotate on the anticlockwise direction.

But half a period later stator poles having rotate around interchange their position i.e.NsisatpointBandSsisatpointA.Underthese conditionNsatleastSandSsattractN. Hence rotor tends to rotate clockwise (which is just the reverse direction).

It is seen that due to continuous and rapid rotation the stator pole, te rotor is subjected a torque which is rapidly revenging owing to this large inertial, the rotor cannot instantaneously respond to such likely revenging torque with the result that it remains stationary.

Considering the condition in fig(b) the stator and rotor are alternating each other. Suppose that the rotor is not stationary but is rotating clockwise with such a speed that itrotates through one pole pitch by the times the stator poles interchanged their positions. As shown in fig(c). Hence again stator and rotor poles attract each other. It means that if the rotor pole also shift their position along with the stator poles, then they will produce atorque.

Methodofstarting :

Thefollowing stepsare adopted forstarting ofasynchronous motor.

(1) Thefed windingis shorted thatmeans D.C.excitation isnot given tothe fieldwinding.

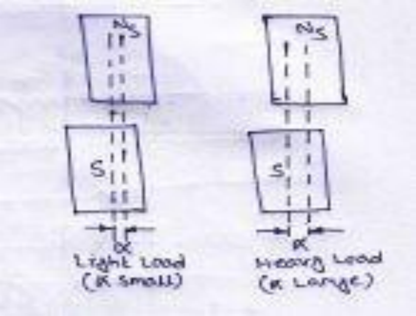
(2) Reducedvoltagewiththehelpofauto-transtransformerisappliedacrossthestator terminal.

(3) Whenthemotorsatfarnearly9%ofthesynchronousspeed,ad.c. excitationasappliedto the field winding. At that time the motor is synchronized.

(4) fullsupplyvoltageis appliedacross statorterminals by cuttingout the autotransformer.

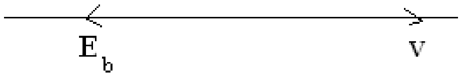
(5) themotor thencan beoperatedatany powerfactor bythed.c.excitation.

(6) **At** light load or heavy load condition the rotor advances and backs to the stator flux respectively with an angle α. It is called the load angle.

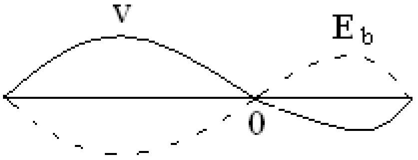


Motoronno-load:

When a 3ϕ supply is feed to a synchronous motor, the motor starts rotating. As a result back emf (E_s) is set up in the alternator (stator) by the rotor flux which oppose the applied voltage 'V' his back emf of (Es) depends on rotor excitation only (and not on peed) as in D.C. motor. The net voltage of armature (stator in the voter difference of V & E_bArmature current is obtained by dividing this vector difference of voltage by the armature impendance



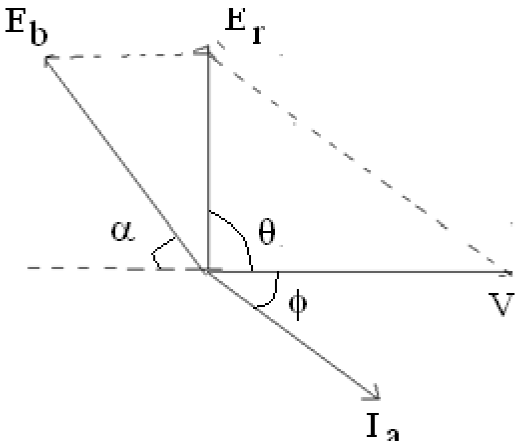
i.e. $I_a = \dfrac{\vec{V}-\vec{E}_b}{S}$



The Fig, show condition when the moor is running on no- direction on no-load & is having loss. As field excitation is given such that Eb = V

Thevector differenceof E_b& Vis f hencehencethearmaturecurrent is also zero)

If the motor is on no load but it has losses then θ vector for Eb faces back by a certain angle 'α' . So that a resultant voltage E_R& hence current '$I_a$is brought into existence which supplies the losses.

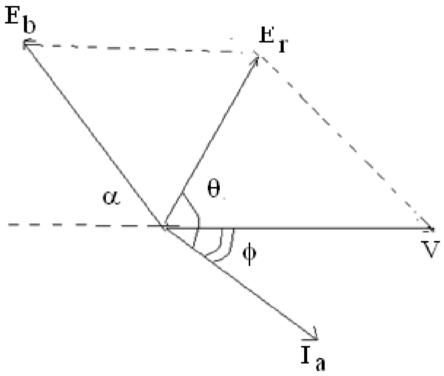


Motoron Load:

(Effect ofvarying load with constant excitation)

Iftheloadmotorislandedthentheback emf(E_b)placesbackbyacertain valuecalledthe “load angle” or coupling angle.

Thenet voltagecurrent thearmature $\vec{E_R}=V-E_b$

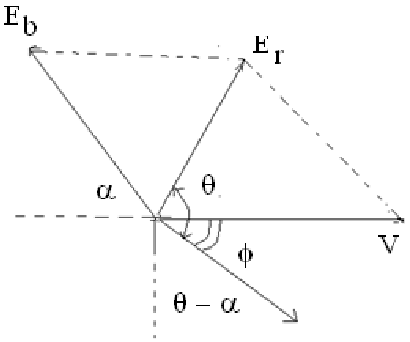


If the motor is further loaded, its rotor further back by a greater value of load angle ‘α’ the resultant voltage ‘E_R’ is increased and the motor draws an increased armature current but at a devised power factor.

$$I_a=\frac{\vec{V}-\vec{E_b}}{Z_S}=\frac{\vec{V}-\vec{E_b}}{R_a+jX_s}$$

$$\Rightarrow V=E_b+I_aZ_s$$

$$=E_b+I_a(R+jX_S$$



Where Z_S = Synchronousimpedance/phase

R_a = Armature resistance / phase

X_S= Synchronousreactance/phase

Theangle‘θ’ isknown as“initialangle”by which‘I_a’ lagsbehind E_R.

$$\theta = \tan^{-1}\frac{X_s}{R_a}$$

φisthephaseanglebywhich‘I_a’lagsbehind‘V’. If

$R_a$is negligible , then θ = 90°

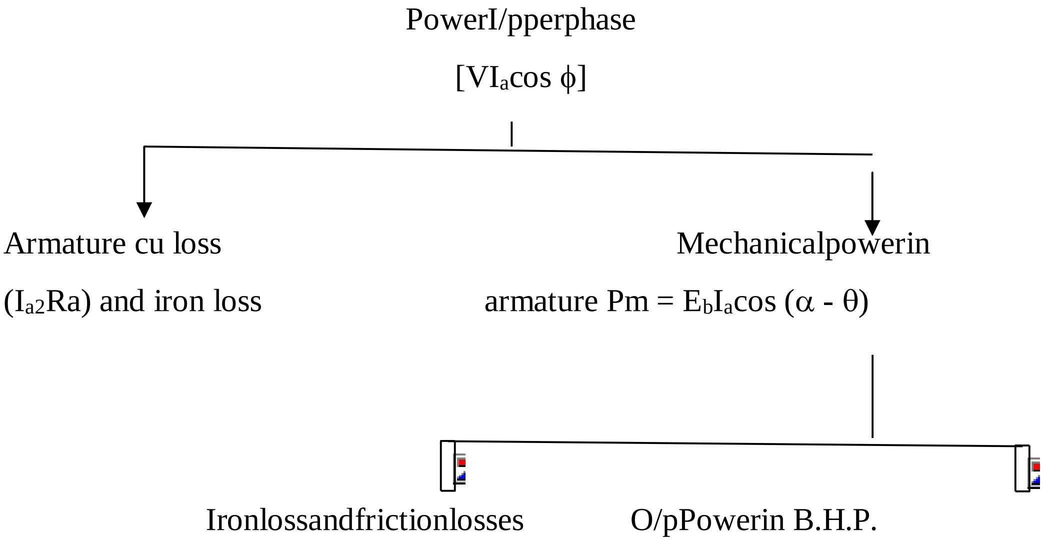
MotorI/p perphase=$VI_a\cos\phi$

Total I/p to the motor = $\sqrt{3}V_L$

$I_L\cos\phi$Mechanicalpowerdevelopedintherotorperp

hase $P_m = E_b I_a \cos(\alpha - \phi)$

DifferentPowerstagesinaSynchronousMotor



PowerI/pperphase

[$VI_a\cos\phi$]

Armature cu loss

($I_a^2R_a$) and iron loss

Mechanicalpowerin

armature $P_m = E_bI_a\cos(\alpha - \theta)$

Ironlossandfrictionlosses

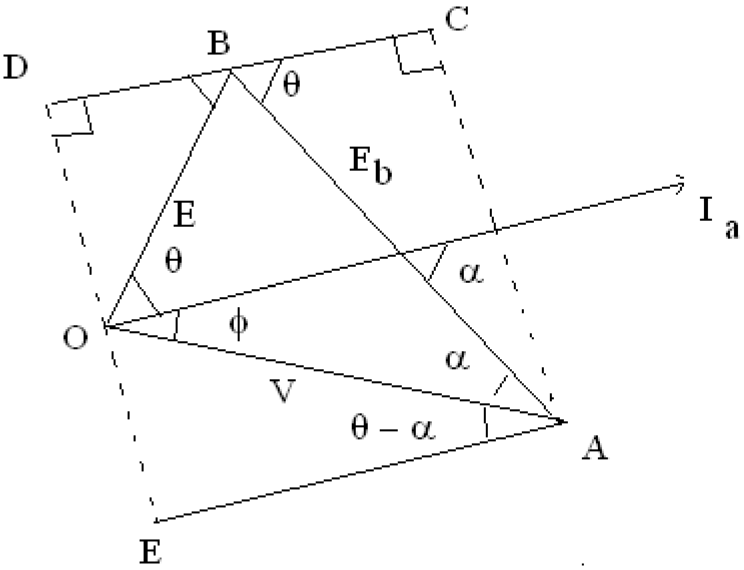
O/pPowerin B.H.P.

PowerorTorqueDeveloped bytheMotor:

OA represents supply voltage/phase. The armature current per phase $=I_a$AB is theback emf ata load angle of α OBgivestheresultantvoltage$E_R = IZ_s$. ‘I’leads‘V’by angle ‘ϕ’ and lags behind ‘E_R’ by a angle ‘θ’.

$$\theta = \tan \frac{X_3}{R_a}$$

Line CD is drawn at an angle θ to AB, AC and ED are perpendicular to CD (and hence to AE also)



Mechanicalpowerperphasedevelopedintherotoris

$$P_m = E_b I \cos\Psi \text{ ------------------(i)}$$

Fn ΔOBD, $BD = IZ_s \cos\Psi$

$BD = CD - BC = AE - BC$

$IZ_s \cos\Psi = V\cos(\theta - \alpha) - E_b \cos$

$$\Rightarrow I\cos\psi = \frac{V}{Z_s}\cos(\theta - \alpha) - \frac{E_b}{Z_s}\cos\theta$$

Substitutingthisvalueinequation(1), weget Pmper phase.

$$P_m = E_b\left[\frac{V}{Z_s}\cos(\theta - \alpha) - \frac{E_b}{Z_s}\cos\theta\right]$$

i.e.

$$\boxed{P_m = \frac{E_b V}{Z_s}\cos(\theta - \alpha) - \frac{E_b^2}{Z_s}\cos\theta}$$

Maximumpowerdevelopeddependsontheloadangle‘α’.Soconditionformaximumpower developed can be found by differential long $P_m$wants α and then equating it to zero

$$\frac{dP_m}{d\alpha} = 0$$

$$\Rightarrow \frac{d}{d\alpha}\left[\frac{E_b V}{Z_s}\cos(\theta-\alpha) - \frac{E_b^2}{Z_s}\cos\theta\right] = 0$$

$$\Rightarrow \frac{E_b V}{Z_s}\left[-\sin(\theta-\alpha)\right] - 0 = 0$$

$$\Rightarrow -\frac{E_b V}{Z_s}\sin(\theta-\alpha) = 0$$

$$\Rightarrow \sin(\theta-\alpha) = 0$$

$$\Rightarrow \sin(\theta-\alpha) = \sin 0$$

$$\Rightarrow \theta-\alpha = 0$$

$$\Rightarrow \theta = \alpha$$

Value of maximum power

$$(P)_{m\max} = \frac{V E_b}{Z_s}\cos(\theta-\alpha) - \frac{E_b^2}{Z_s}\cos\alpha$$

$$= \frac{V E_b}{Z_s} - \frac{E_b^2}{Z_s}\cos\alpha$$

$$= \frac{V E_b}{Z_s} - \frac{E_b^2}{Z_s}\cos\theta$$

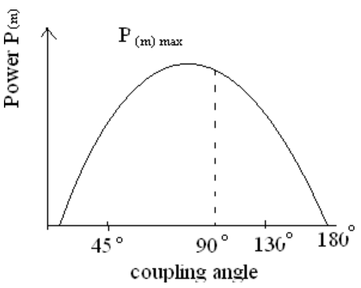
Now, maximum power developed in the rotor depends on the value of internal angle 'θ'.

→When $\theta = \alpha = 90°$

The power will be maximum.

$$(P_m)_{\max} = \frac{V E_b}{Z_s}$$

If 'T_g' is the grass rotor torque developed by the motor, then



$$\left.\begin{aligned} T_g \times 2\pi N_s &= P_m \\ \Rightarrow T_g &= \frac{P_m}{2\pi N_s} \end{aligned}\right\} N_s \text{ in rps}$$

$$\Rightarrow T_g = \frac{P_m}{2\pi N_s/60} \quad [N_s \text{ in rpm}]$$

$$\Rightarrow T_g = \frac{60}{2\pi} \times \frac{P_m}{N_s} = \boxed{9.55 \frac{P_m}{N_s} N-m}$$

Shafttorqueisgiven as

$$\boxed{T_{sh} = 9.55 \frac{P_{oul}}{N_s}} \text{ N-M}$$

SynchronousMotorwithdifferentexcitations

(i) WhenE_b=V,is knownas normalexcitation

(ii) WhenE_b<V, isknown asunder excitation,lagging pf.

(iii) WhenE_b>V, isknownasoverexcitation. leadingpf.

Thediagram shows theinduced back emfin various pf.

i) Laggingpf:

$$AC^2=AB^2+BC^2=[V-E_R\cos(\theta-.)]^2+[E_R\sin(\theta-.)]^2$$

$$E_b=\sqrt{[V-IaZs\cos(\theta-\varphi)]^2+[IaZs\sin(\theta-\varphi)]2}$$

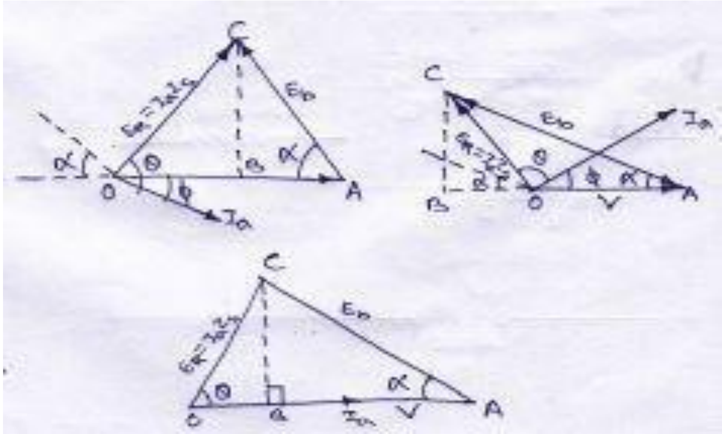
ii) Leadingpf:

$$\boldsymbol{E_b}=\boldsymbol{V}+\boldsymbol{I_a Z_s}\cos[180^0-(\theta+\varphi)]+jI_a Z_s\sin[180^0-(\theta+\varphi)]$$

iii) Unity pf:

$OB=I_aR_a$, $BC=I_aX_s$

$E_b=(V-I_aR_a)+jI_aX_s$



Motoron Load

⇒Effect ofvarying excitation with constant load.

Suppose a synchronous motor is operating with normal excitation ($E_b=V$) at unity power factor with a given load. The armature is drowning a power of Via per phase which is enough to meet themechanical loadon themotor.Theeffect of changing excitation with loadremains constant is discussed below.

Fig -(a)

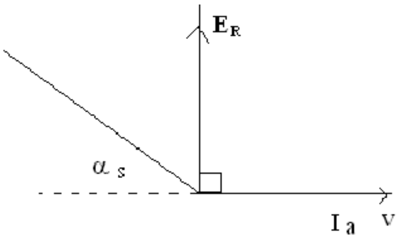
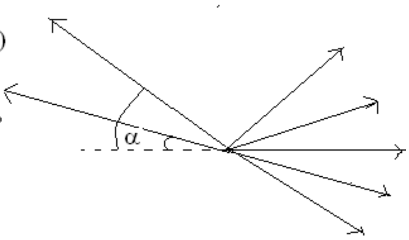
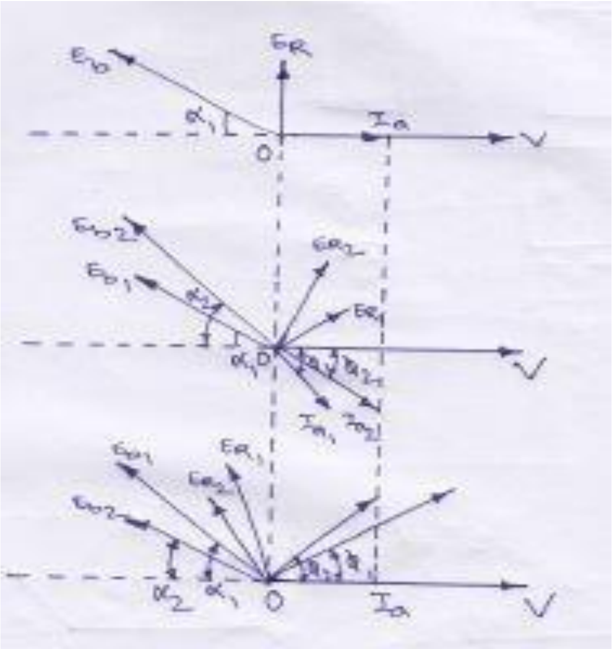


Fig (b)





ExcitationDecreases:

As shown in fig (1) suppose due to decrease in excitation, back emf is reduced to $E_{n,1}$ at the same load angle 'α'. The resultant voltage $E_{R,1}$ causes a lagging armature current I_{a_1},toflow.Eventhough I_{a_1} islargerthan I_{a_2} inmagnitude.Itiscapableof producing necessaryVI$_a$forcarryingtheconstantloadbecause $I_{a_1}\cos\phi$.Componentislessthan I$_a$so that $VI_a \cos\phi_1 < VI_a$.

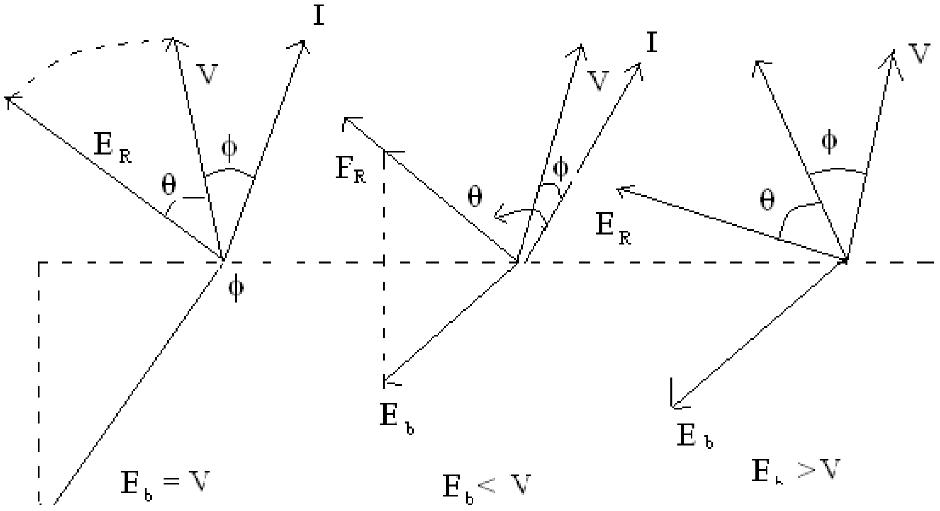
Hence,itbecomesnecessaryforloadangletoincreasefrom$\alpha_1$toα_2,itincreaseback emffromE_{b_1}toE_{b_2},whichincreasesresultantvoltagefromE_{R_1} to E_{R_2} consequently,the armaturecurrentincreasesto I_{a_2}whoseinphagecomponent.

(b)Excitation Increased

The effect of increasing field excitation is shown in fig (c), where increased $E_n$is shown at the original load angle α_1The resultant voltage causes loading current I_{a_1} whose in phase component is larger thanI_a. Hence armature develops more power than the load in the motor. Accordingly, load angle decreases from $\alpha_1$to $\alpha_2$which develops resultant voltage from E_{R_1} toE_{R_2} consequentlyarmaturecurrentdecreasesfrom I_{a_1} toI_{a_2}whosein phase component.$I_{a_2}\cos\phi_2 = I_a$. In the casearmaturecurrent develops power sufficient to carry the constant load on the motor.

Hence,itisseenthatvariationsintheexcitationofthesynchronousmotorrunningwith given load. Produces variation in its load angle only.

EffectofExcitationonArmatureCurrentandPowerFactor.



Considerasynchronousmotorinwhichmechanicalloadisconstant. Fig

(a) shows the case for 100% excitation i.e. when$E_b=V$

TheamaturecurrentIlagsbehind ‘V’byan smallangleϕwith $E_R$is fixed bystator constantsi.e.$\tan\theta=\frac{X_s}{R_a}$.Infig(b),theexcitationislossthen100%$E_b<V$.Here$E_R$is advancedin clockwisedirection& alsoarmature current. Themagnitudeof‘I’isincreasedbut its power factor is decreased. The component of Icosϕ remains the same as before but wattless component I sin ϕ is increased.

AsexcitationisdecreasedIwillincreasedbutp.f.will decreased.

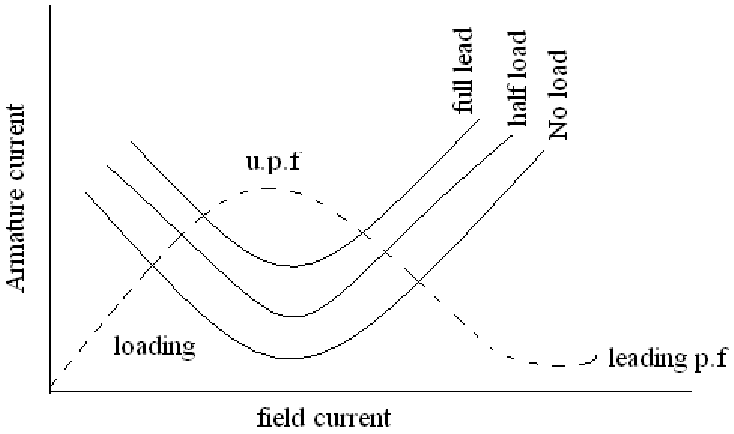
Fig. (c) represents the conduction for over excited motor i.e. $E_b>V$. Here the resultant voltage$E_R$ispulledinanticlockwisedirection&also‘I’.Nowthemotorisdrawinga loading current.

forsamevoltageofexcitation,‘I’willbeinphasewith‘v’i.e.p.f.isunity AC that the current drawn by the motor would be maximum.

V-Curve.

Magnitudeofarmaturecurrentvarieswithexcitation.Thecurrenthaslargevaluefor low & high value of excitation. In between them, at any certain excitation. The current is minimum. The variation of current ‘I’ with excitation is shown in fig below which is known as V-curve. Since it looks like ‘V’.

Motor runs with loading p.f. when over-excited and with lagging p.f. when under excited. In between, the powerfactor will beunity. Thevariation ofp.f.with excitation (shown in dotted line) which is known as inverted v-curve, since is looks like inverted ‘V’. It is seen that the armature current will be minimum when the p.f. will be unity.



SynchronousCondenser/Capacitor

Bothtransformer&inductionmotordrawslaggingcurrentsfromthelienonlight loads, the power drawn by them has a large reactive component and power factor is verylow.

Itisseenthatanover-excitedsynchronousmotorwillrunwithleadingp.f.byusing synchronousmotorandtransformers.Thepowerfactorcanbeincreasedandthereactive components of power can be decreased when synchronous motors are used for this purpose (p.f.improvement),isknownassynchronouscondenserorsynchronouscapacitorbecauseit draws a leading current from the line like a capacitors because it draws a leading current from the line like a capacitor.

HuntingorPhase Swinging.

Whensynchronousmotorisusedfordrivingavaryingload.Thenaconditionknownas hunting is produced. Hunting may also be caused if supply frequency is pulsating.

When a synchronous motor is loaded its rotor falls back in phase by the coupling angle ‘α’. As the load is progressively increased, thus angle also increases so as to produced motor torque to meet with the increased load. If now there is a sudden decrease in the motor load, the rotor is pull back to new value of ‘α’. In this way rotor starts oscillating about its new position of equilibrium. Corresponding to the new load. If the timeperiod ofthose oscillations equals to the natural time period of the machine, then mechanical resonance is set up. The amplitude of these oscillations may become so large to throw the machine out of synchronous.

To stop the oscillations damper or damping grids are employed. These damper-consists of (short circuited copper were in the faces of the field poles of the motor. The oscillatory motion of the rotor sets up eddy currents in the dampers which flows in such a way as to suppress the oscillations.

Comparisonbetweeninductionmotorandsynchronousmotor.

InductionMotor		**SynchronousMotor**	
1.	Itsspeeddecreasesslightlyastheload increased.	1.	Itrunsateithersynchronousspeedornot at all
2.	Italwaysrunwithlaggingpower factor.	2.	Itcanberununderawiderangofp.f. both lagging & leading.
3.	Itisself –starting.	3.	Itisinherentlynotself-starting.
4.	D.C.excitationisnot required	4.	D.C.excitationisrequired.
5.	Itischeap&simple	5.	Itiscostlier&complicated.

ApplicationofSynchronousMotor:

1. Powerfactorcorrection:

Overexcitedsynchronousmotorhavingleadingp.f.arewidelyuseforimprovingp.f. of power systems.

2. Constantspeed application.

High speed synchronous motor (above 600rpm) are used for centrifugal pumps, belt driven reciprocating, compressor, blowers, line shafts, rubber & paper mills etc.

Low speed synchronous motors (below 600rpm) are used for drives such as centrifugal and screw type pumps, balls and tube mills, vaccum pumps, choppers and metal rolling mills etc.

3. Voltageregulation:

The voltage at the end of a long transmission line varies greatly when large inductive loadsarepresent. By installing asynchronous motorwith afield regulator, this voltagerisecan be controlled.

By varying the excitation, the p.f. can be made lagging on leading which helps to maintain the lien voltage at its normal value.

Example:-1

A 75-kW, 3-ϕ, Y-connected, 50-Hz. 440-V cylindrical rotor synchronous motoroperates at rated condition with 0.8 p.f. leading. The motor efficiency excluding field andstator losses, is 95% and X_5= 2.5Ω. Calculate (i) mechanical power developed (ii) armature current (iii) back e.m.f. (iv) power angle and (v0 maximum or pull-out torque of themotor.

Solution: $N_S=120\times 50/4=1500$rpm=25rps

(i) $P_m=P_{in}=P_{out}/\ \eta=75\times 10^3/0.95 = 78.950W$

(ii) Sincepower inputisknown

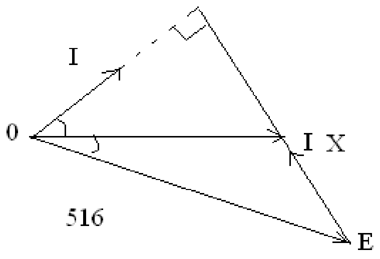
$\therefore \sqrt{3}\times 440\times I_a\times 0.8=78.950; I_a=129A$

(iii) Applied voltage /phase = 440/ $\sqrt{3}$ =254V.LetV=254∠0°asshowninfig Now,

$V = E_b + jIX_S$or $E_b = V - jI_aX_S = 254\ \angle 0° - 129$

$\angle 36.9°\times 2.5\ \angle 90° = 250\ \angle 0° - 322\ \angle 126.9° = 254 - 322$

$(\cos 126.9° + \sin 126.9°) = 254 - 322\ (-0.6+j\ 0.8) = 516\angle -30°$



iv) $\therefore \alpha=-30°$

v) pull–out torqueoccurswhen = $\alpha = 90°$

maximum $P_m = 3\frac{E_b V}{X_S}\sin\delta = 3\frac{256\times516}{2.5}\sin 90^o = 157,275\,W$

$\therefore$ pull-out torque=9.55×157, 275/1500 = 1,000 N-m.

Example:2

A 20-pole, 693-V, 50Hz, 3ϕ, Δ- connected synchronous motor is operating at no-load with normal excitation. It has armature ressistance per phase of zero and synchronousreactance of 10Ω. If rotor is retarded by 0.5°(mechanical) from its synchronous position, compute.

(i) rotordisplacementinelectrical degrees

(ii) armatureemf/ phase

(iii) armaturecurrent/phase

(iv) powerdrawnbythemotor

(v) powerdevelopedbyarmature

Howwillthesequantitieschangewhenmotorisloadedandtherotordisplacementincreasesto 5° (mechanical) ?

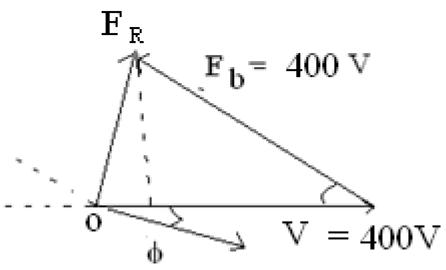
Solution:

(i) $\alpha(elect.) = \frac{P}{2}\times\alpha(mech)$

$\therefore \alpha(elect) = \frac{20}{2}\times 0.5 = 5^o(elect)$

(ii) $V_P = V_L/\sqrt{3} = 693/\sqrt{3}$

$= 400V,$



$\therefore E_R = V_p - E_b\cos\alpha) + jE_b\sin\alpha = (400 - 400\cos 5^o + j400\sin 5^o)$

$= 1.5 + j\,35 = 35\angle 87.5$V / phase

(iii) $Z_S = 0 + j10 = 10\angle 90°$; $I_a = E_R/Z_S = 35\angle 87.5°/10\angle 90°$

$= 3.5\angle -2.5°$ A/ phase

Obviously, I_a lagsbehind V_p by2.5 °

(iv) Powerinput/phase $V_pI_a\cos\phi = 400\times3.5\times\cos 2.5° = 1399$W Total

input power = $3\times1399 = 4197$ W

(v) SinceRaisnegligible,armatureCulossisalsonegligible.Hence4197Walso represent power developed by armature.

Example– 3

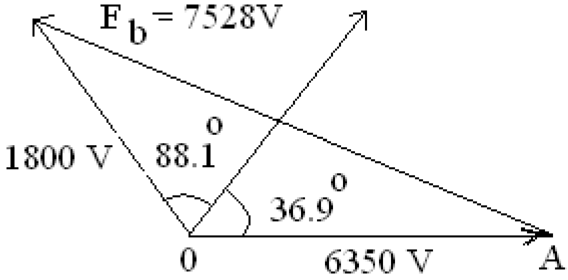
The input to an 11000-V, 3-phase, star-connected synchronous motor is 60 A. The effectiveresistanceandsynchronousreactanceperphasearerespectively1ohmand30 ohm.Find(i)thepowersuppliedtothemotor(ii)mechanicalpowerdevelopedand(iii) induced emf for a power factor of 0.8 leading.

Solution **:**(i)Motorpower input = $\sqrt{3}\times 11000\times 60\times 0.8=915kW$

(i) star Cu loss/phase = $60^2\times 1=3600W$; Cu loss for three phase = $3\times 3600=10.8kW$

$P_m=P_2-$rotorCuloss$=915-10.8=904.2$kW

$V_P=11000\ \sqrt{3}=6350V, \phi=\cos^{-1}0.8=36.9^o$;



$\theta=\tan^{-1}(30/1)=88.1^o$;

$Z_S=30\Omega$;statorimpedancedrop/phase= I_aZ_s

$=60\times 30=1800$ V

Asseenfrom Fig.38.25

$$E_b^2=6350^2+1800^2-2\times 6350\times 1800\times\cos(88.1^o+36.9^o)$$

$=6350^2+1800^2-2\times 6350\times 1800\times -0.572$

$\therefore E_b=7528$V;linevalueof$E_b=7528\times\sqrt{3}=$ 1.3042.

Example-4:A500-V,1-phasesynchronousmotorgives anetoutput mechanicalpower of 7.46 kW and operates at 0.9 p.f.lagging. Its effectiveresistanceis 0.8 Ω. Iftheironand friction losses are 500 W and excitation losses are 800 W, estimate the armaturecurrent. Calculate the commercial efficiency.

Solution **:**Motor input = $VI_a\cos\phi$; Armature Cu loss = $I_aR_a^2$Power developed in armatureis $P_m= VI_a\cos\phi - I_aR_a^2$

$\therefore I_a^2R_a-VI_a\cos\phi+P_m=0$ or $\therefore I_a=\dfrac{V\cos\phi\pm\sqrt{V^2\cos^2\phi-4R_aP_m}}{2R_a}$

Now, $P_{out}=7.46$ kW=7,460W

$P_m = P_{out}$+ironandfrictionlosses+excitation losses

=7460 +500+800=8760W

$$I_a = \frac{500\times0.9\pm\sqrt{(500\times0.9)^2-4\times0.8\times3760}}{2\times0.8} = \frac{450\pm417.7}{1.6} = \frac{32.3}{1.6} = 20.2A$$

Example:-5

The synchronous reactance per phase of a 3-phase star-connected 6.600 V synchronous motor is 10Ω. For a certain load , the input is 900 kW and the induced line emf is 8,900 V.(line value) Evaluate the line current. Neglectresistance.

Solution : Applied voltage / phase = 6.600/ √3 = 3, 810 V

Back e.m.f. / phase = 8,900 / √ 3 = 5, 140 V

Input= $\sqrt{3}V_L.I\cos\phi$=900.000

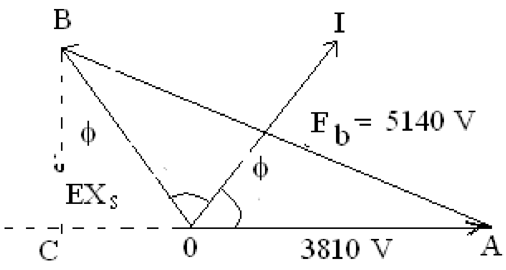
∴ $I\cos\phi$ =9× 105 / √3×6.600 =78.74 A

InΔABCofvectordigraminFigwehave$AB^2=AC^2+BC^2$Now

OB = $I.X_S$= 10 I

BC=OB cosϕ=10 × 78.74 =787.4 V

$\therefore 5,140^2 = 787.4^2 + AC^2$



∴ AC =5,079V

OC =5,079 – 3, 810 =1,269 V

Tan ϕ = 1269/787.4= 1.612 ϕ = 58.2°, cosϕ = 0527Now

Icosϕ=78.74;I=78.74/0.527=149.4A

SinglePhaseinductionMotor

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 fieldwhichpolarity 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)

MakingSinglePhaseI.M.Selfstarting:

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 like3 phase motor. When it achieves sufficient speed, the additional winding may be removed. But the rotor continue running.

DifferenttypesofsinglephaseI.M.-

1. InductionMotorslikesplit-phase,capacitorandshadedpoletype.
2. Repulsiontype motors
3. A.C.seriesmotors(Commutatormotors)etc.

SplitPhaseMotor:

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 twowindings are so designed that the auxiliary winding has high resistance and small reactance while the main winding has low resistance and large reactance.

Figure1splitphaseIM

***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 aweak revolving field for which it produces revolving fluxand rotorstarts revolving hence the motor started.

TheTorqueproducedis,

$$Ts=KI_mI_sSin\alpha$$

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

Ifthestartingperioddelayexceeds5Seconds,thewindingmayburnoutbecausethewinding made of fine wire.

Uses

Fan,Washingmachine,smallmachinetoolsetc.

CapacitorStartI.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.

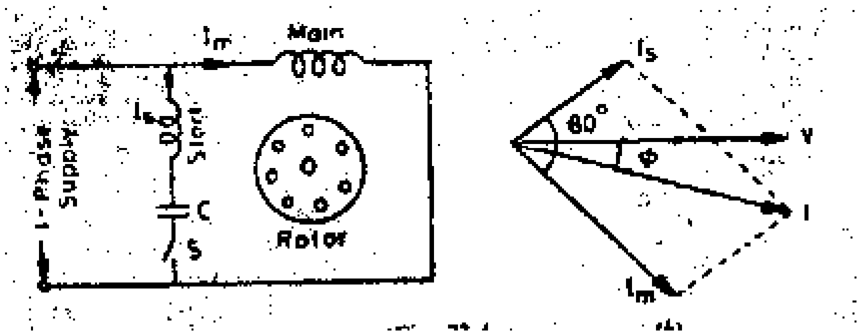


Figure2 CapacitorStartI.M.

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 isheated less quickly.

Uses:

Itisusedwherelowstartingtorqueisrequired.

Capacitorstartandrun

It is similar to capacitor start motor except that the starting winding is not openedafter starting. So, when the motor runs both windings are connected in the circuit . It has two capacitors with the starting winding. The capacitor C_1has smaller capacity than $C_2$and is connectedinthecircuitinseries withthestarting windingpermanentlyduringstartingaswell 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.

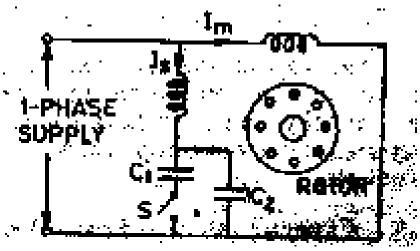


Figure 3 capacitor start induction motor

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.

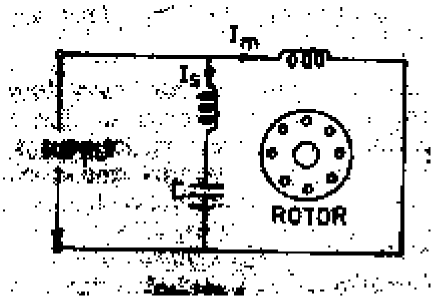


Figure 4 permanent capacitor motor

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.

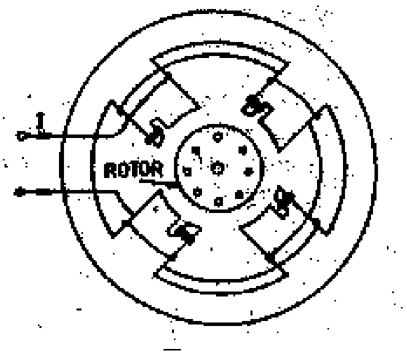


Figure5 shaded pole motor

Operation

From the total of core, the flux produced and emf is induced in the shadingcoil. 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 axislies along the middle of this part.

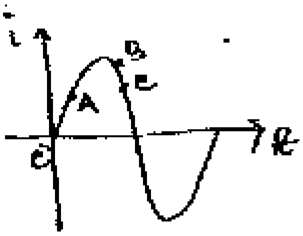


Figure6torqueinshadedpolemotor

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 5-50wbut 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

Itis usedin smallfans, toys, hairdrierofpower upto 50 W.

ACSeriesMotor/Universal Motor

The construction of AC series motor is as like as DC series motors. Ifa DC Series motor isconnectedtoanACsupply,itwillrotateandproduceunidirectionaltorquebecausethe 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. Theperformances of this type of motor will not be satisfactory due to the followingreasons.

1. Thealternatingfluxwouldcauseexcessiveeddycurrentlossintheyokeandthefield core will become extremely heated.
2. Sparkingwilloccuratbrushesbecauseofhugevoltageandcurrentinducedinthe short circuited armature coil during commutation period.
3. Powerfactorisverylow.

   DuetotheabovedrawbacksDCseriesmotorrequiredsomechangesbywhichAC supply input disadvantages solved.. The changes made are

a) Theentiremagneticcircuitislaminated inorder toreducetheeddycurrentlosses.
b) Ahigh fieldflux isobtained by usingalowreluctancemagneticcircuit.
c) Excessivesparkingeliminatedbyusinghighresistanceleadstoconnectthecoiltothe commutator segment.

Thoughthistypeofmotorcanbeoperatedeitheron ACorDCsupply,theresulting 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) Speedincreasesto ahighvaluewith adecreasingload.
b) Ithasveryhighstartingtorque.
c) AtFullload,thepowerfactoris90%.

   Uses.

   a. Sewingmachine b.vacuumcleaners,c.mixergrindersandblenders

d) Highspeedvacuumcleaners.e.hairdriers f.powersaw
f. Drillsg.ElectricShaver.

SinglePhaseRepulsionMotor

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 currentinduced in the armature conductor by mutual induction method.

*Construction*SinglePhaseRepulsionMotor

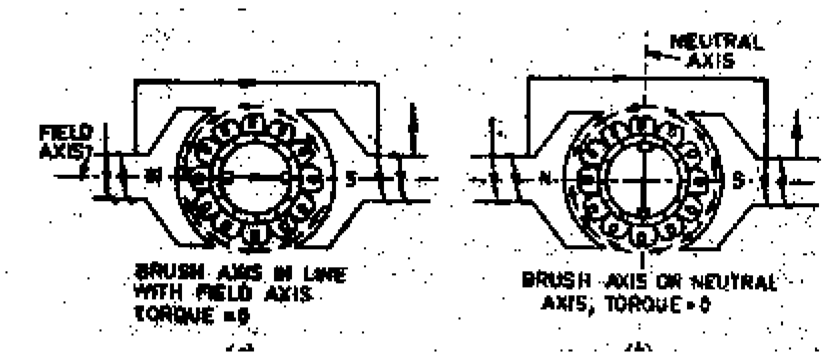


Figure7SinglePhaseRepulsionMotor

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 carrycurrent 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.

Ifthebrushaxisisinsomeangleotherthan0^0or90^0,thenatorqueisdevelopedinthe 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

Commercialrefrigerators,compressorsand pumps.

COMMUTATORMOTORS

A.C.SeriesMotororUniversalMotor

Adcseriesmotorwill rotateinthesamedirectionregardlessofthepolarityof the supply.

Whenadcseriesmotoroperates on asinglephase acsupply itiscalled anAC series motor. However some changes are required in a DC motor so that it can satisfactorilyoperates on A.C. supply.

Thechanges areas follows:

i) The field core is constructed of a material having low hysteresis loss. It is laminatedin 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.

ii)A highfieldfluxisobtainedbyusinglowreluctancemagneticcircuit.

iv) There is considerable sparking between the brushes and the commutator when the motorisusedon A.C.supply. Itisbecausethealternatingfluxestablishes highcurrentsinthe 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.

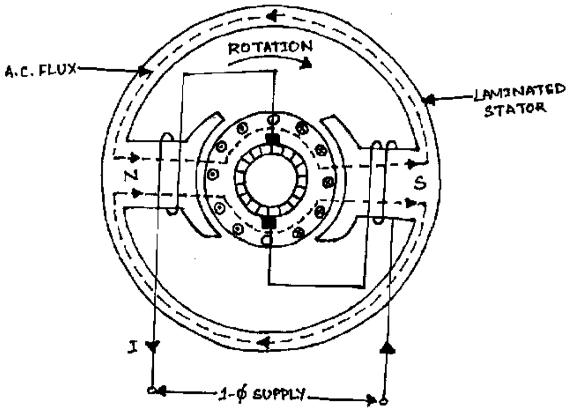
v) In order to reduce the effect of armature reaction thereby improving commutation and reducing armature reactance a compensating winding is used. This winding is put in the stator slot.

ThedrawbackwhenA.C.supplyisgiventoD.C.seriesmotor(withoutmodification) –

i) Theefficiencyislowduetohysteresisandeddycurrentloss.

ii) Thepowerfactoris low dueto largereactanceofthefieldand armaturewinding.

iii) Thesparking at thebrush isexcessive.



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.

PrincipleofOperationof A.C.seriesmotor

WhenthemotorisconnectedtoanA.C.supplythesamealternatingcurrentflows through the field and armature windings.

ThefieldwindingproducesanalternatingfluxΦthatreactswiththecurrentflowing in the armature to produce a torque.

Sinceboth armaturecurrent and fluxreversesimultaneously, thetorquealways acts in the same direction.

CharacteristicsofA.C.Series Motor

TheoperatingcharacteristicsaresimilartothoseofD.C.seriesmotor–

i) Thespeedincreases toahighvaluewith decrease in load.

ii) Themotortorqueishigh forlargearmaturecurrent, thusgivinghighstartingtorque.

iii) Atfullload,thepowerfactorisabout90%,howeveratstartingorwhencarrying overload power factor is low.

Application

ThefractionalhorsepowerA.C.seriesmotorhavehighspeedandlargestartingtorque. Therefore be used to drive –

a) Highspeedvacuumcleaners.

b) SewingMachine

c) ElectricShavers

d) Drills

e) Mechanicaltoolsetc.

Repulsion Motor

ArepulsionmotorissimilartoanA.C.seriesMotorexcept–

i) Thebrushesarenotconnectedtosupplybutareshortcircuited.Hencecurrentareinduced in the armature conductor by transformer action.

ii) Thefield structurehas non-silentpoleconstruction

Byadjustingthepositionofshortcircuitedbrushesonthecommutator,thestartingtorque can be developed in the motor.

Construction

Thefield ofthe stator winding isconnectedto the 1 –Φ A.C. supply.

ThearmatureorrotorwithdrumtypewindinglikeD.C.motorisconnectedtoacommutator. 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.

PrincipleofOperation

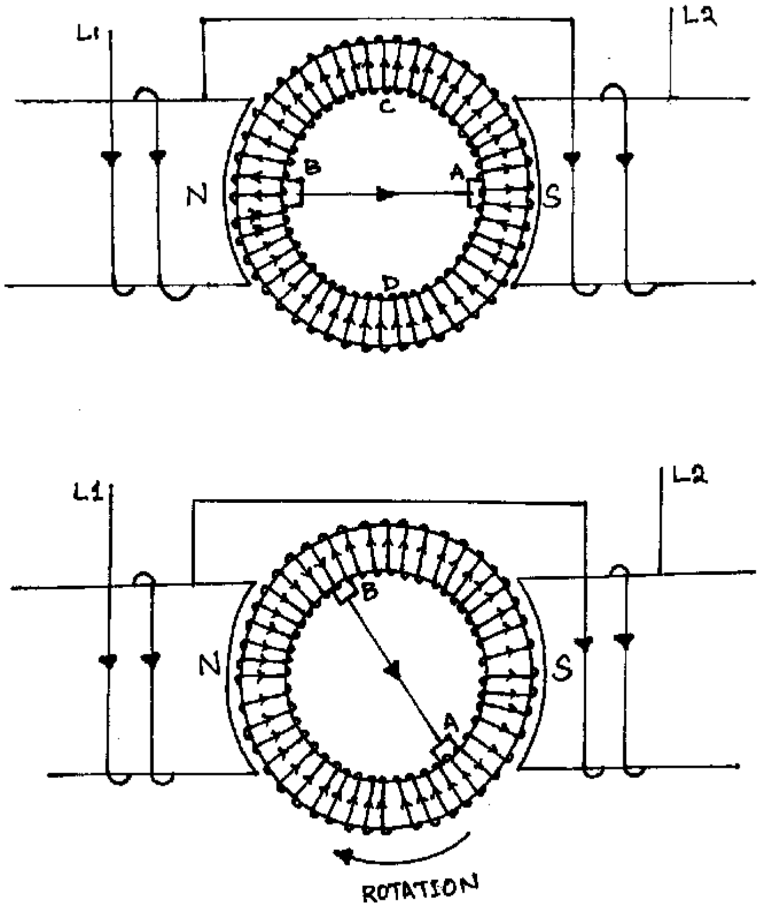
Fig.1showstwo polerepulsionmotorwith itstwoshort-circuited brushes

Whenfieldcurrentisincreasing inthedirectionshownthelefthandpoleisnorthpoleand right hand pole is south pole.

i) Herethebrushaxisisparalleltothestator 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’slawthedirectionofthe emfissuch thatmagneticfieldofthe resultingarmaturecurrent will oppose the increase in flux.

Thecurrent direction inarmatureconductor isshown 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.

Herein figure2 because ofthenewbrushposition, thegreaterpartoftheconductorunderthe 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 torqueactsintheclockwisedirection androtoracceleratesintheclockwisedirectionandvice versa. Thetotalarmaturetorqueina repulsionmotor is

T_a=Sin 2αwhereαistheangle betweenbrushaxisandstatorfield axis.

Formaximumtorque,$2\alpha=90^0$or$\alpha=45^0$.Thusadjustingαto45^0atstarting,maximum torque can be obtained during starting period.

Characteristics

a) Therepulsionmotorhas characteristicsverysimilartothoseofan A.C.seriesmotori.e.it has a high starting torque and a high speed at no load.

b) Thespeedwhichtherepulsionmotordevelopsforanygivenloadwilldependuponthe position of the brushes.

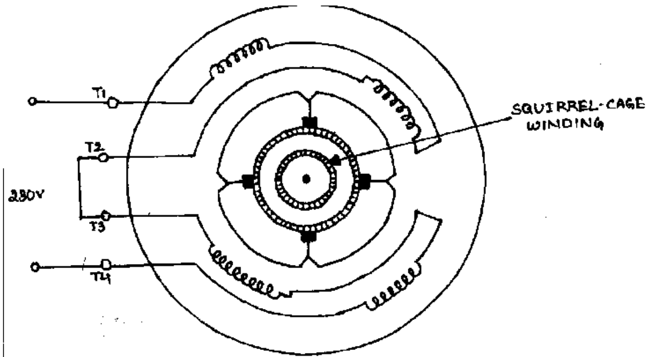
c) In comparisontoothersinglephasemotor,therepulsionmotorhashighstartingtorqueand relatively low starting current.

RepulsionInductionMotor

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

TheFig.showstheconnectionofa4-polerepulsionInductionmotorfor230Voperation. It consist of a stator and a Rotor.



REPULSION- INDUCTION MOTOR

i) Thestatorcarries asingledistributed windingfedfromsingle-phasesupply.

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 cagewinding.

Therepulsionwindingis connectedtoacommutatoronwhichrideshortcircuited brushes.

Operation

Whensinglephasestator windingisdrivenbyanA.C.supplytherepulsionwindingisactive. 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 slightlyless than the synchronous speed in an induction motor.

Thespeed regulation of themotor 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

Thistypeofmotorisusedforapplicationsrequiringahighstartingtorquewithessentially constant running speed.

Repulsion–Start Induction –Run motor

Theactionofrepulsionmotoriscombinedwiththatofa1 –Φinduction motortoproduce repulsion – start induction – run motor (also called Repulsion Start Motor)

Thismotorstartsasanordinaryrepulsionmotor,butafteritreaches about75%ofitsfull 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 alsobeliftedfromthecommutatorinordertoavoidunnecessarywearandtearandfriction losses.

Characteristics

Thestartingtorqueis2.5 to4.5timesthefullloadtorqueandthestartingcurrentis3.75 times the full load value.

Duetotheirhighstartingtorque,repulsionmotorswereusedtooperatedevicessuchas refrigerators, pumps, compressor etc.

SPECIAL ELECTRICAL 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 aspecific 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 electricalsignal.Typical step sizes are2^0,2.5^0, 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)StepperMotor
(ii) Variable–reluctance(VR)StepperMotor

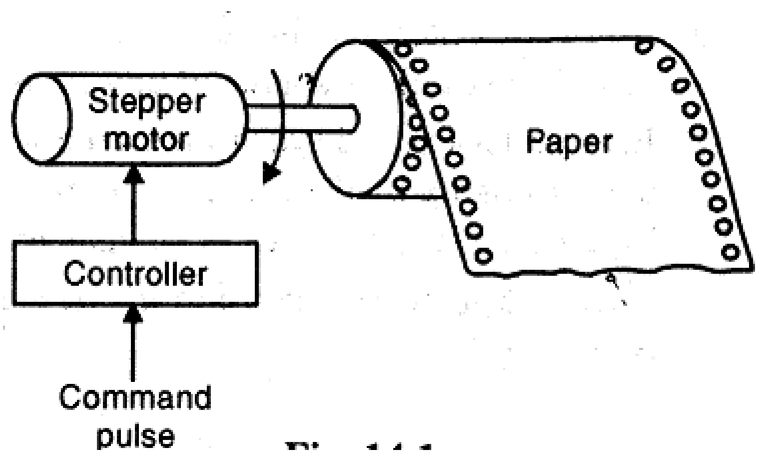


Fig. 1.1

The stator of a stepper motor of either type above carries stator windings which areenergizedfrom adcsourcetocreatetwoormorestatorpoles.Thestatorpoles 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 materialasin case of a variable reluctance motor. The rotor may also have two or morepoles. Therotorpoles arealsocalled rotorteeth.

The stator coils are energized in groups referred to as phases. The stator windingsmaybe2-phase,3-phaseor4-phasewindings.Thephasewindingsare brought out to terminals for DC excitation .

PMStepperMotor

Thefigure1.2showsatwo-pole1-phasepermanentmagnetsteppermotor.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.

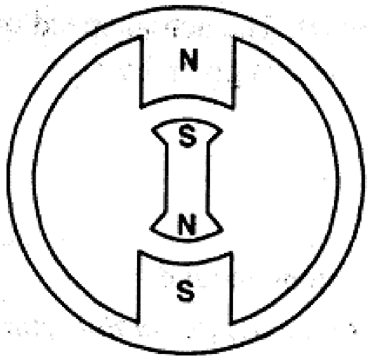


Fig.1.2

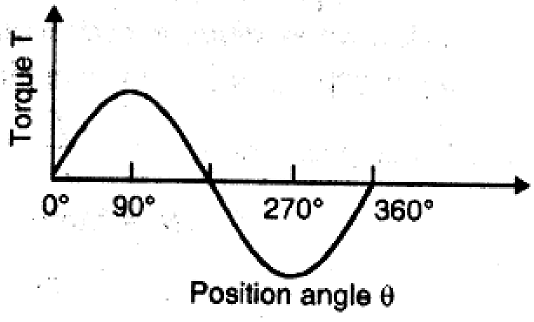


Fig.1.3

Fig 1.3 shows how excitation torque varies with thee rotor position for a PM rotor. Notethat maximum torqueis developed when the rotor is displaced from thestatorfieldbyeither 90^0or270^0.However,thetorqueiszeroandtherotor is aligned (parallel) with the stator field.

(iii) VRStepperMotor

Fig. 1.4 shows a 2-pole , single phase variable-reluctance(VR) stepper motor.Whenthestatorisenergized,*reluctancetorque*actsonthe rotor (soft-ironmaterial).Therotorwillmoveapositionwhere reluctanceisminimum and air-gap flux is maximum. This means that rotor teeth will align with the energized stator poles.

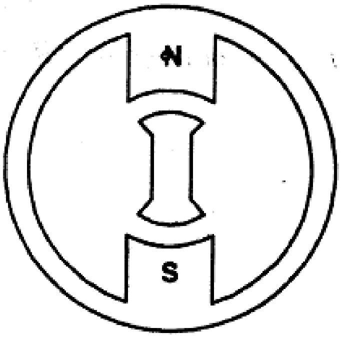


Fig.1.4

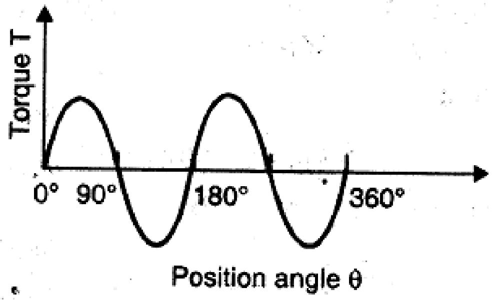


Fig.1.5

Fig.1.5 shows how reluctance torque varies with the rotor position for a VR soft-ironrotor.Withtherotorat 0^0or 90^0,notorqueisdeveloped.Maximumtorqueis developed at$45^0$and 135^0Which is the position where reluctance torque forces the rotor or move to position of minimum reluctance.

stepangle:theanglethroughwhichthemotorshaftrotatesforeachcommand 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) Intermsofstatorpoles(N_s)androtorpoles(N_r),thestepangle(α)is given by:

Stepangle,α= x 360^0

where α=Stepanglein degrees

(N_s)=Numberofstatorpoles(orteeth) (

N_r)=Numberof rotorpoles (orteeth)

ii) Intermsofstatorphases(m)androtorpoles(N_r),thestepangleisgiven by:

stepangle,α=α=$\frac{}{m N_r}$

α= step angle in degrees

m=Numberofstatorphases

N_r =Numberof rotorpoles (orteeth)

steppingrate. Animportantspecificationofasteppermotoristhesteppingrate.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 isgiven by :

Speed of stepper motor, N =

N=motor speedin r.p.m.

f=steppingfrequency i.e. steps/second

Example1.1

Determinethestep angleofavariable-reluctancesteppermotorwith12teeth inthestator and 8 rotor teeth.

Solution :

Numberofstatorteeth,N_s=12

Number of rotor teeth, N_r= 8

Stepangle, α= x360^0= x 360^0=15^0/step

Example1.2

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 :

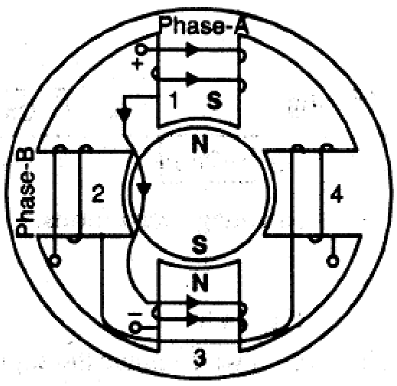
motorspeed,N=$\frac{}{6}$

Hence, Pulserate(stepspersecond)for thismotor=$\frac{}{}=\frac{}{}$=120 steps/second 10

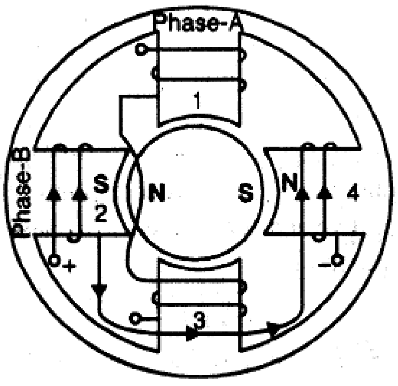
PERMANENT–MAGNET(PM)STEPPERMOTOR

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.

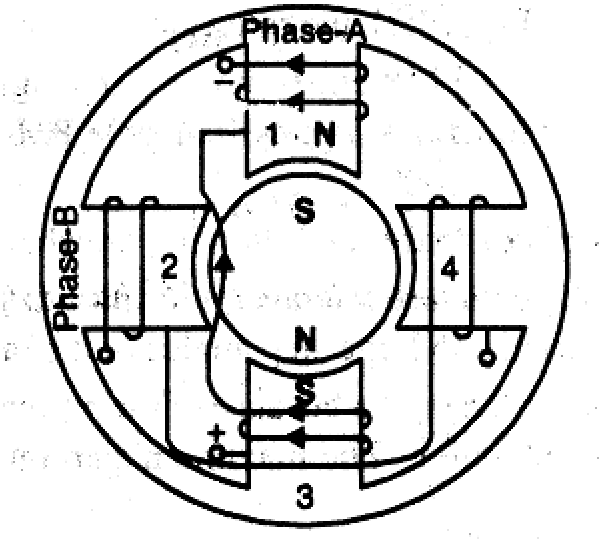
CONSTRUCTION : The stator construction of a PM stepper motoris composed ofsteel laminations and carries stator windings. The stator phase windings are energized from a d.c. source to create two or more stator poles. The rotor of the motor is a permanent-magnet made up of high retentivity steel alloy.The 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

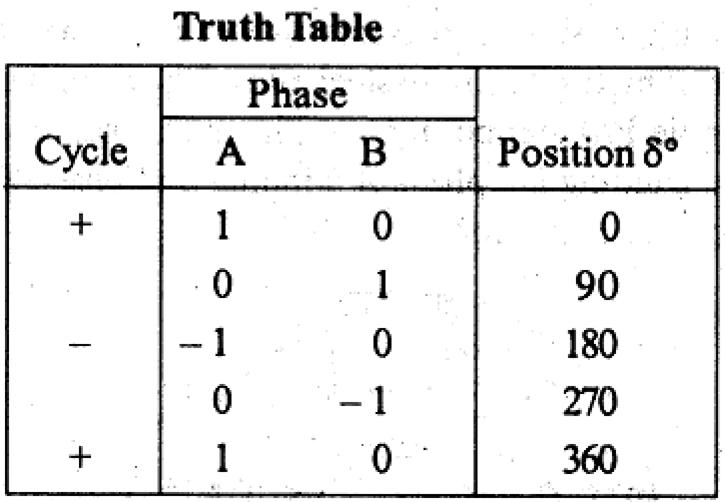
OPERATION:forthisPMsteppermotor,thenumberofrotorpoles, N_r=2 andnumber of phases, m=2.

Stepangle,$=\alpha mN_r=360^0/(2x2)=90^0$/step

(i) When only phase-A winding is energized by a constant current asshowninFig.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. Therotor 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 excitedwhilephase-Bwindingisunexcited.Underthiscondition,stepangleα $=0^0$The applied voltage waveforms in Fig also tally with the facts shown in thetruth table.

(ii) IfphaseAwindingisde-energizedandphase-Bwindingisenergisedasshownin Fig.1.6(ii),statortooth 2becomessouth pole.Asaresult, thenorthpoleofthePM rotor aligns parallel with the south pole(stator tooth2) of the stator. Thus the rotor has displaced 90^0in the anticlockwise direction.

(i)If phase B winding is de-energized and phase-A winding is excited by a reverse current the rotor will further rotate90^0in anticlockwise direction as shown in Fig1.6(iii). Now the north pole of PM motor aligns with the stator tooth3.



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

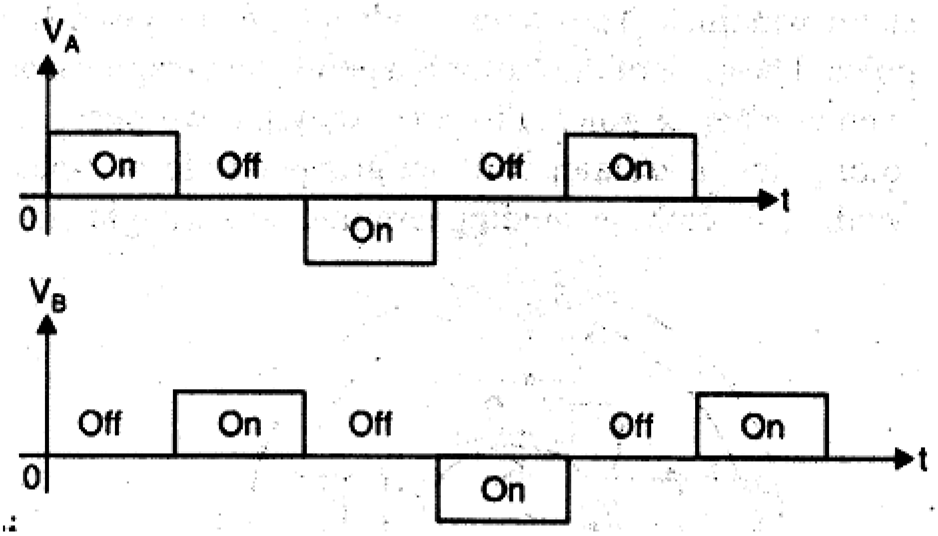


Fig.1.8

(iv)Sofartherotorhascompletedone-halfrevolution.However,ifwecontinuethe appropriate switching the rotor will complete one revolution in 90^0 steps.

We can change the step angle$\alpha$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 = 360^0/mNr= 360^0/3x24= 5^0/step.

Limitations:ThePMstepper motorhasthefollowingdraw\backs :

i) Itisdifficulttomakeasmallpermanentmagnetrotorwithalargenumberofpoles. Therefore,PM stepper motors are restricted to large step angles in therange of30^0 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.

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

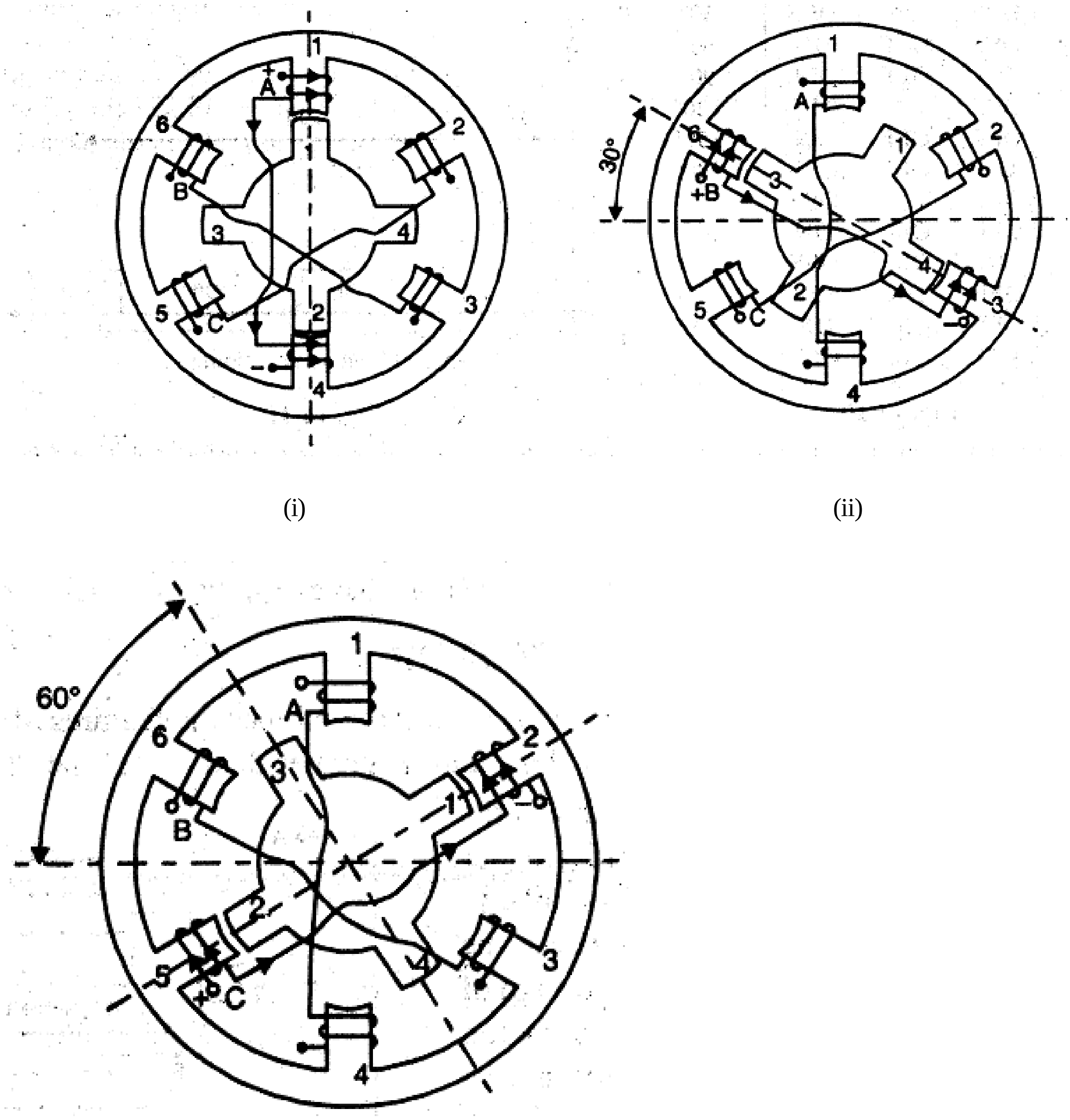
VARIABLERELUCTANCE(VR)STEPPERMOTOR

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 statorconstructionofaVRsteppermotoristhesameasthatof 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,

stepangle,$\alpha = \times 360^0 = = 30^0$/step

Therefore,the rotorwillturneach 30^0 time apulseis applied.



(i)

(ii)

(iii)

Fig.1.9

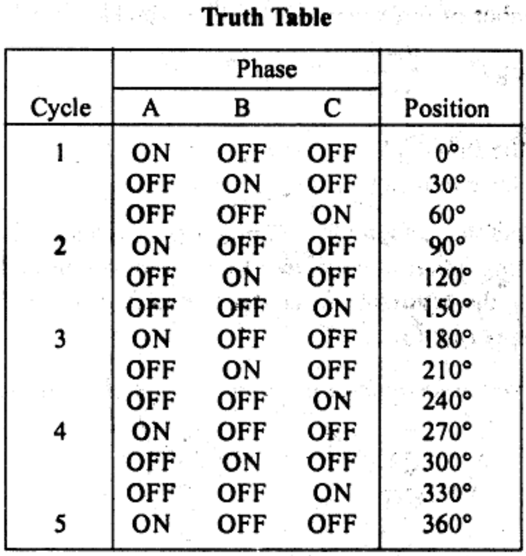
OPERATION :Whenthephasewindingisenergized,therotorteethwillalignwiththe energized stator poles.

i) Fig.1.9(i) shows the position of the rotor when phase A is energized with a constant current.AslongasphaseAisenergized,therotorwillbeheldstationary.Notethat inthiscondition,therotorteeth1and2arealigned withthe energizedstator 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 Bisenergized,therotorwillturn 30^0 clockwise so that the rotor teeth 3 and 4 align with the energized stator teeth 6 and 3.

iii) Theeffectofde-energisingphaseBandenergizingphaseCisshowninFig.1.9(iii).In this circuit,the rotor has further moved30^0clockwise so that rotor teeth 1 and 2 align with energized stator teeth 2 and 5.

iv) aftertherotorhasdisplacedclockwise60^0fromiotsstartingpoint,thestepsequence has completed one cycle. The truth table in fig. shows the switching sequence to complete a full 360^0rotation 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°

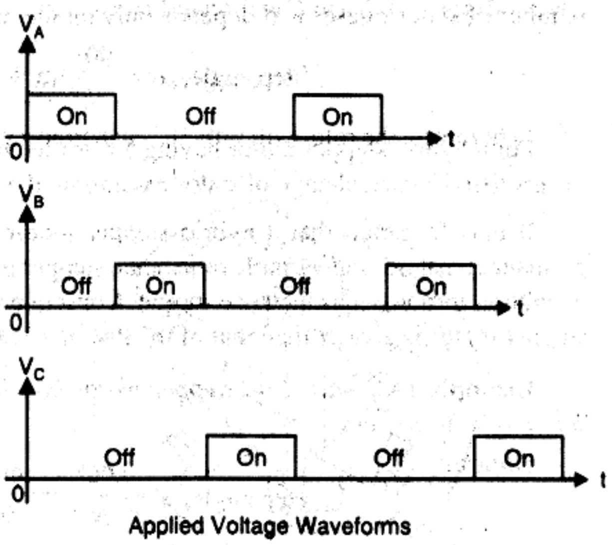


Fig.1.10 Fig.1.11

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 fivecycle for one revolution.

HYBRIDSTEPPERMOTOR

The hybrid stepper motor combines the features of the PM and the VR steppermotors.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 thedesign oftherotors of aVR and aPM stepper motor.Therotor 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

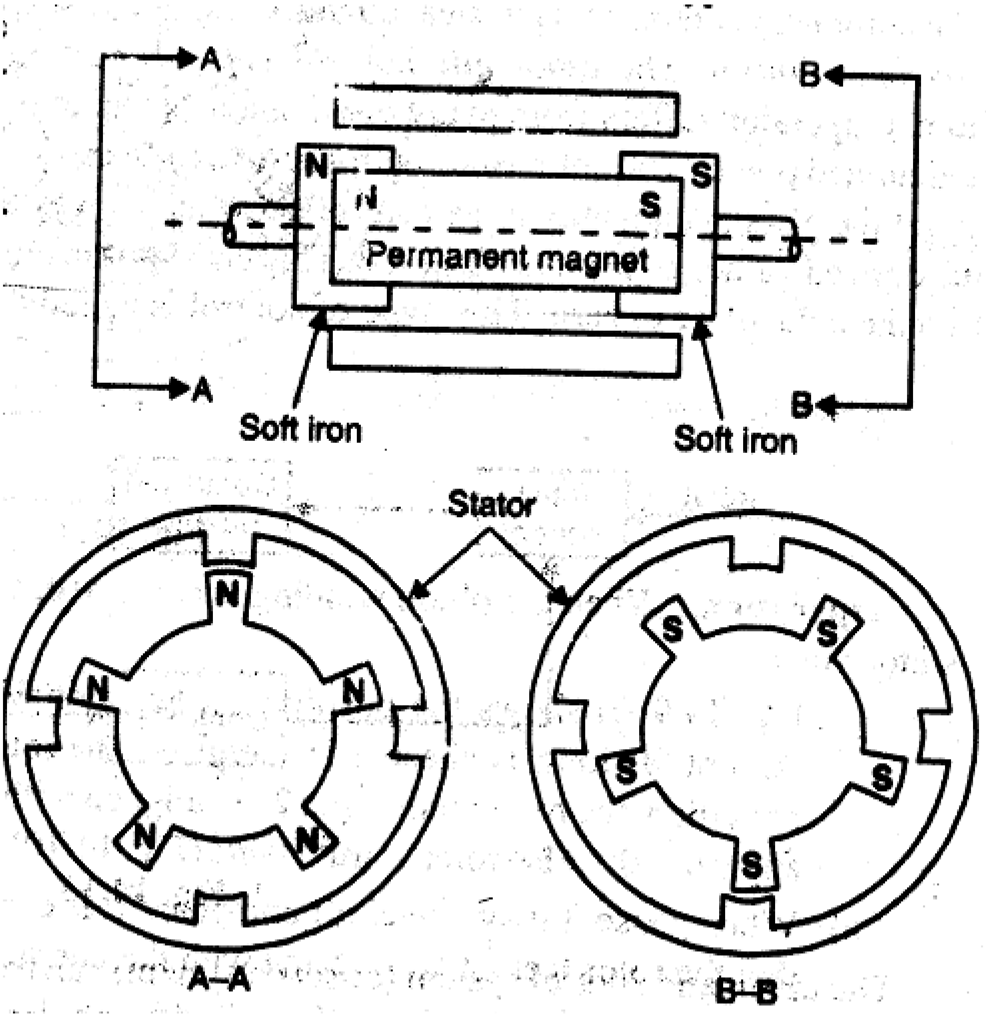


Fig1.12

Therotorteeth aremachinedonthesotironstacks.Thustherotorteethon oneend become the north pole and those at the other end become the south pole.

This rotorteethofbothnorth andsouthpolesaredisplacedinanglefortheproper 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 ofa 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 :

Stepangle,α=$90^0/N_r$indeg

Forahybridsteppermotorhaving5rotorteeth,thestepanglealpha=$90^0/N_r=90^0/5$ =18^0/step.Itmeansthatforeachchangeofstatorexcitation,therotorwillturnbyastepof 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 torqeand relucatance torque.Consequently the resultant torque developed by the hybrid stepper motor is greater than that of the PM or VR stepper motor.

………………………………………..xxxxxxxxxxxxxxx………………………………………

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-

- Thecostofonethreephasetransformerislessthanthecostofthreesinglephase transformer required to supply the same KVA output.
- The3phasetransformerweightslessandoccupieslessspacethan3singlephase transformer.
- Thebusbarstructure,switchgearandotherwiringforathreephasetransformer installation
  aresimplerthanthoseforthreesinglephasetransformer.

Butthereisonemajoradvantageinusingabankofthreesingle 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.

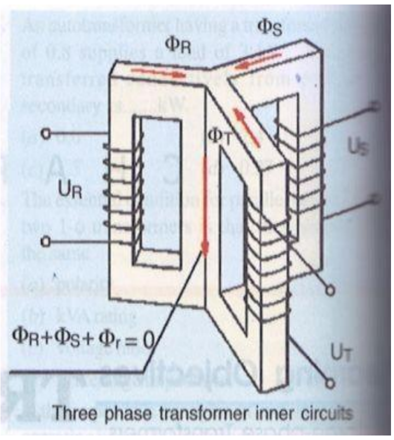


Fig.1.1

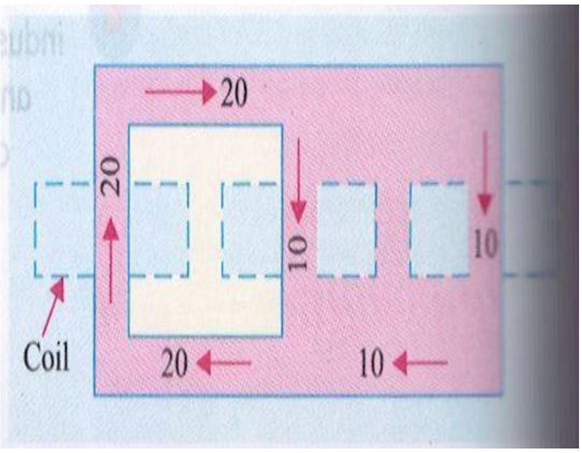


Fig.1.2

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 **$I_R+ I_Y+ I_B= 0$**, 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 returnpath for the third Just as in a three phase system any two conductors act as the return for the current in the third conductor.

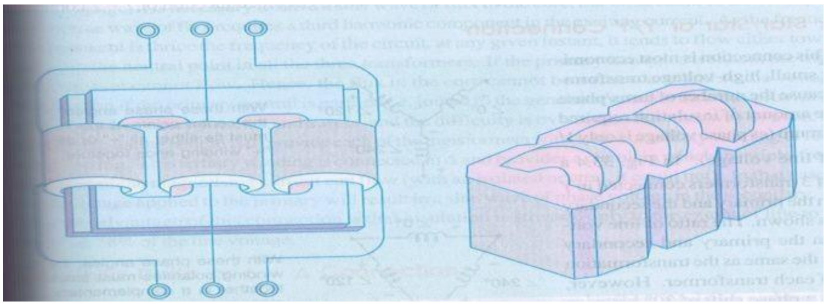


Fig.1.3

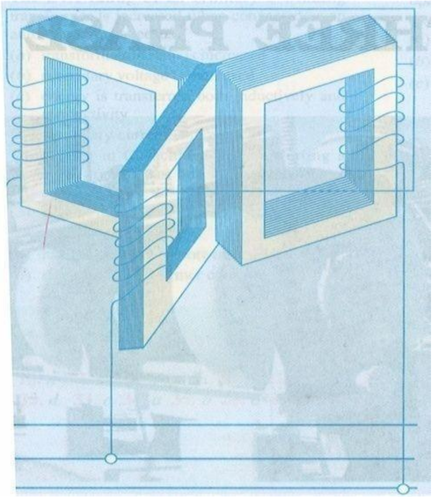


Fig.1.4

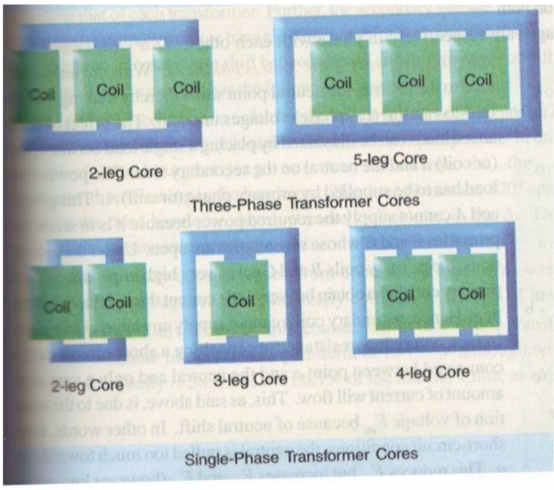


Fig.1.5

Groupingofthethreephasetransformer

Threephasetransformersaredividedintofourgroupsaccordingtotheirphase displacement between the line voltage on the hv and lv side.

Group1- 0degreedisplacement(star-starordelta-delta)

Group2-180degreedisplacement(star-starordelta-deltabutthesecondaryis reversed)

Group3- +30degreedisplacement(sta-delta)

Group4- -30degreedisplacement(delta-star)

ThusaconnectionYd11givesthefollowinginformation Y

indicates that hv is connected in star

dindicatesthat lvis connectedindelta

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

Positionof hourhand ofclock	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.

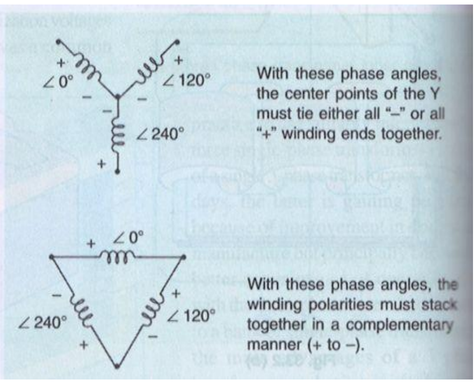
Threephasetransformerconnection

There are various methods available for transforming three phase voltages tohigher 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. OpenΔ orV-V
6. ScottconnectionorT-T connection

Star/StarorY-Yconnection:-

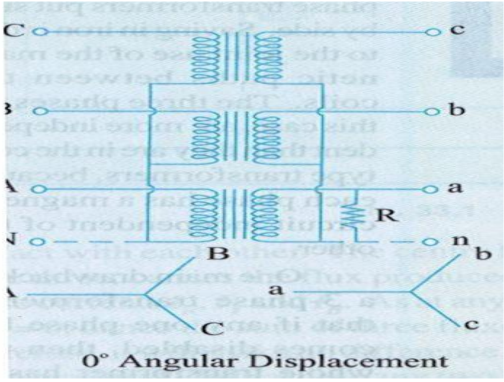
This connection is most economical for small, high voltage transformer because the no of turns per phase and the amount of insulation required is minimum (as phase voltage is only 1/√3 of line



With these phase angles, the center points of the Y must tie either all “–” or all “+” winding ends together.

With these phase angles, the winding polarities must stack together in a complementary manner (+ to –).

Fig.1.6



0° Angular Displacement

Fig.1.7

Voltage). In figure1.7 a bank of three transformers connected in star on both the primary and secondarysides areshown.Theratio oflinevoltageon theprimaryand secondarysides 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 singleloadbetween phase(orcoil)aand theneutral on secondaryside.The powerin theload 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 waveand so the voltages are distorted. But if the primary neutral is earthed i.e. joined to the generatorneutral,then thisprovidesapath forthetriplefrequency currents ande.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 KVArating. 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).Inthiscaseasinewaveofvoltageappliedtotheprimarywillresultinasinewaveof 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.

Delta-DeltaorΔ-Δconnection:-

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:

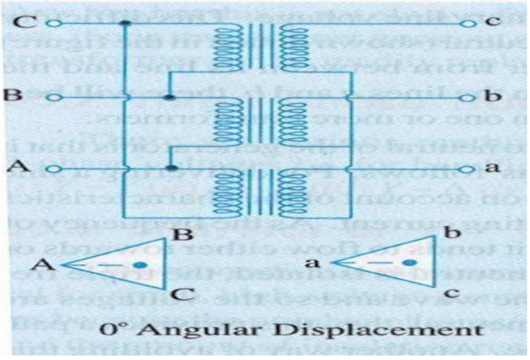


Fig.1.8

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 casethirdharmoniccomponent ofthemagnetising current can flow in theΔconnected transformer primaries without flowing in the line wires. The three phases are 120° apartwhich 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 loadimbalance.

3. Anaddedadvantageofthisconnectionisthatifonetransformerbecomes 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.

Wye/DeltaorY-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 $1/\sqrt{3}$ 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.

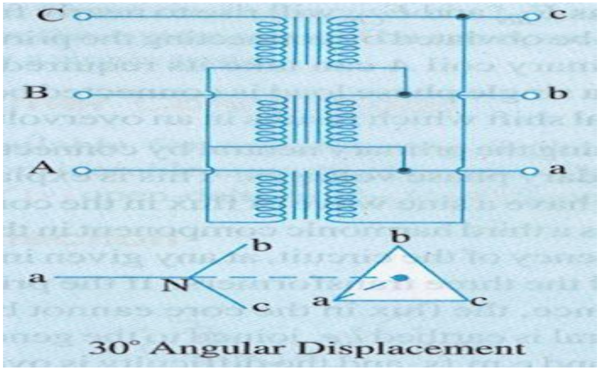


Fig.1.9

Delta/WyeorΔ-Yconnection:-

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 isgrounded 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 voltagedistortion 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.

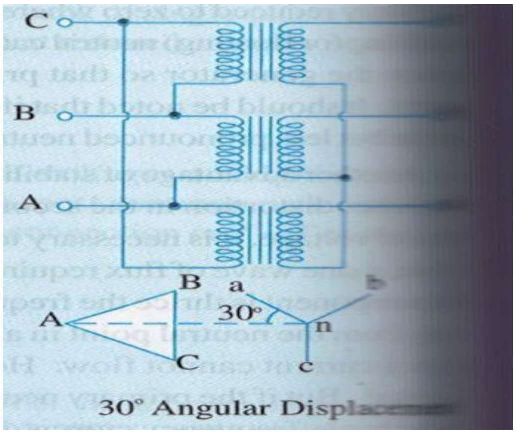


Fig.1.10

Example1.1. A3phase,50Hztransformerhasadelta-connectedprimary andstarconnected 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

Phasevoltageonsecondaryside=400/√3

K=400/22000x√3 = 1/55√3

Primaryphasecurrent= 5/√3A

Secondaryphasecurrent=(5/√3)/K=(5/√3)/(1/55√3)=**275A**

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

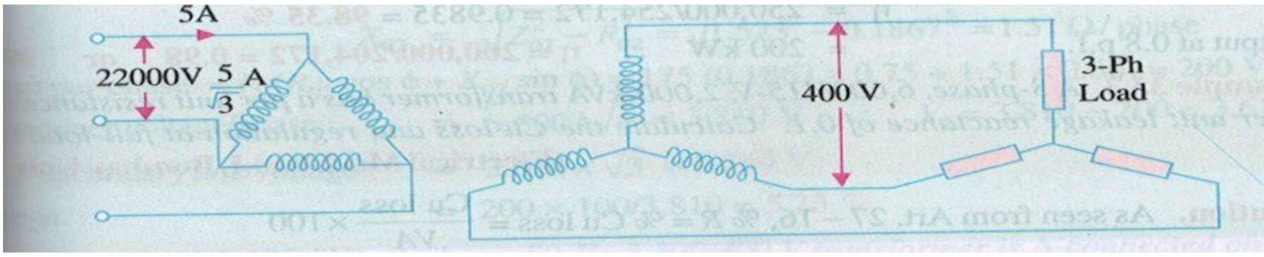


Fig.1.11

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:Transformationratio(K)=11000/$\sqrt{3}$x33000=1/3$\sqrt{3}$ Per

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

Secondaryphasecurrent=500000/($\sqrt{3}$x11000)= 500/11$\sqrt{3}$ A

Fullload condition:

FullloadtotalCuloss=3x$(500/11\sqrt{3})^2$x2.172=4490W Iron

loss=3050 W

Totalfullloadlosses=4490+3050=7540W: Outout

at unity P.F= 500KW

Fullload efficiency=500000/507540=0.9854or**98.54 %**

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

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

Half load condition :

Outputat unityP.F=250 KW

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

Totallosses=3050+1222=4172W

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

Outputat0.8P.F=200 KW

Efficiency=200000/204172=0.98or98%

Open- Delta or V-V Connection.

If one of the transformers of a Δ-Δ is removed and 3phase supply is connected to theprimaries 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.

Itis 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 inV-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 is1/$\sqrt{3} = 57.7\%$(or nearly 58%) instead of 66.67 percent can be proved as follows:

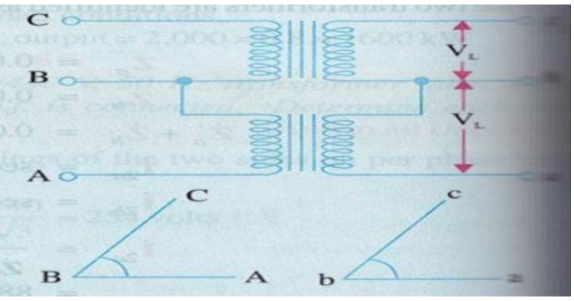


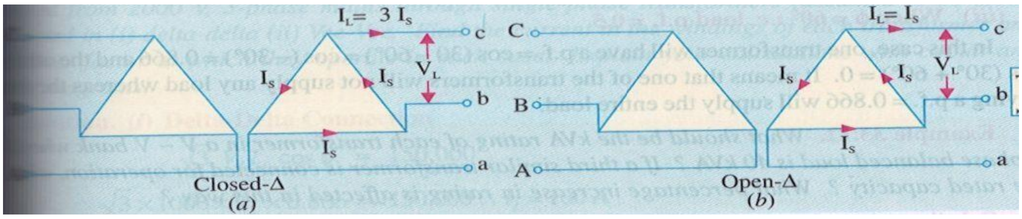
Fig1.12

Asseenfromfig1.13(a)

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

InFig1.13(b)itisobviousthatwhenΔ-ΔbankbecomesV-Vbank,thesecondary line current $I_L$becomes equal to the secondary phase current I_S.

(V-V-capacity/Δ-Δcapacity)$=\sqrt{3}.V_L I_S/3V_L.I_S=1/\sqrt{3}=0.577$or58%



(a) Fig1.13 (b)

It means that the3-phase loadwhich can becarried without exceeding therating 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 andnot 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 avaliblecapacity on an open -Δis 0.866. This factorof0.866 is sometimes called the utility factor.
3. Each transformer will supply 57.7% of load and not 50% when operatingin 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

(TotalloadinV-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.

Thedisadvantagesofthisconnectionare:

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-Vbank 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.

PowersuppliedbyV-Vconnection:

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

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

Eachtransformerwill haveap.f.= $\cos30^0=0.866$

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

Inthiscase,onetransformerhasap.f.ofcos$(30^0-30^0)=1$andtheotherofcos$(30^0+30^0)= 0.866$

iii))when$\phi=60^0$ i.e.loadp.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 ofeach transformer in a V– V bank when the3 – phase balanced loadis 40 kVA?If a third similar transformer is connectedfor operation ,whatistheratedcapacity?Whatpercentageincreaseinratingisaffectedinthis way?

Solution.Aspointedoutearlier,thekVAratingofeachtransformerhastobe15%greater. kVA /

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

Δ– Δbank rating=23x3=69;Increase =[(69–40)/ 40]x 100=**72.5 %**.

ScottConnection orT-T connection:

This is aconnection by which 3-phaseto 3-phase transformation is accomplishedwith 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 onboth 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 getsits name).

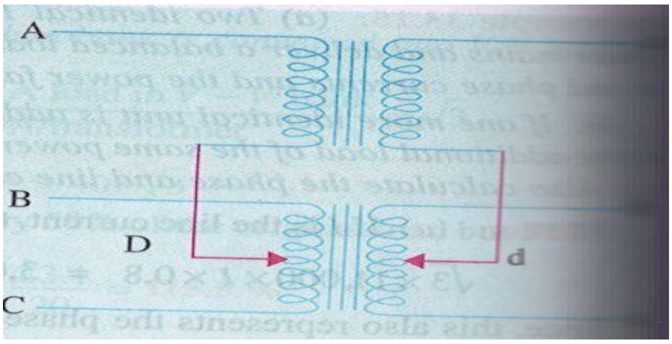


Fig1.14

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 (√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.

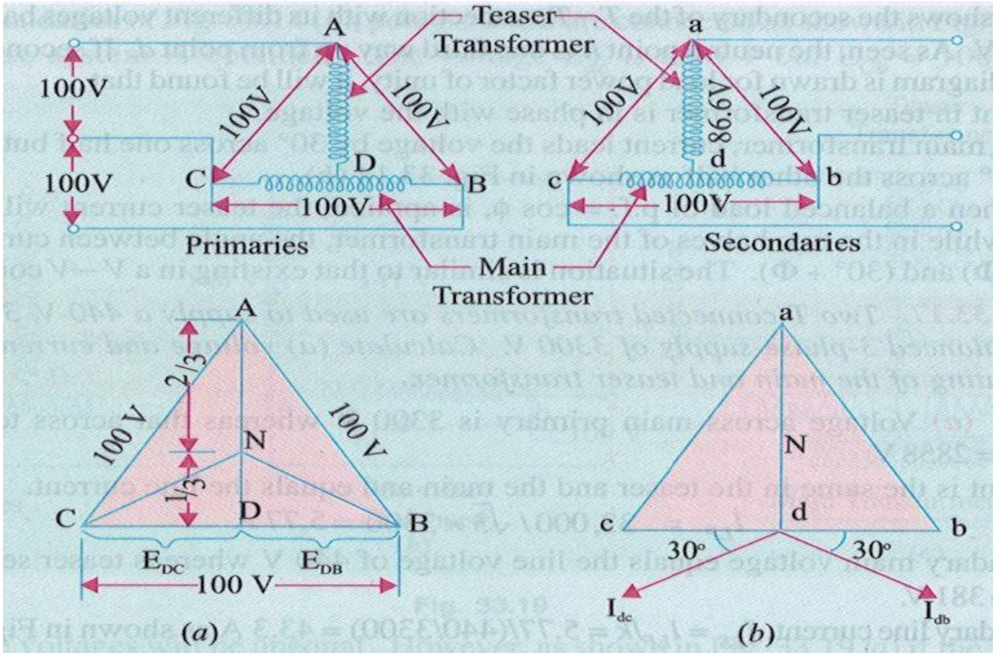


Fig.1.15

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 cos30^0= 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,bothteteaserprimaryandsecondarywindingsaredesignedfor 86.6volts only, then they will be operating at full rating, hence the combined rating of the arrangementwouldbecome(86.6+86.6)/(100+86.6)=0.928ofitstotalratting.Inother 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.

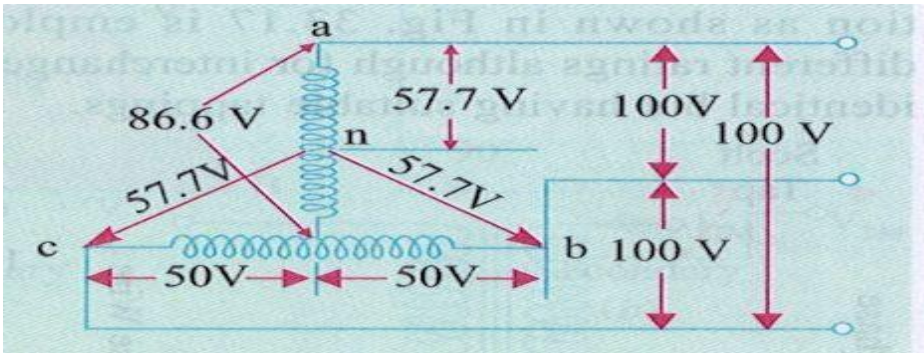


Fig1.16

Fig1.16 shows the secondary of the T-T connection with its different voltages basedon 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, itwill be found that

1. Currentinteasertransformerisinphasewiththevoltage.
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 figure33.15(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,theanglebetweencurrentvoltagewillbe(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) Voltageand current rating of each coil (b) KVA rating of the main and teasertransformer.

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

Thecurrentis thesame intheteaserandthe mainandequals thelinecurrent.

ILP=33000/√3X3300=5.77A

Thesecondarymainvoltageequalsthelinevoltageof440Vwhereasteasersecondary voltage =0.866 X 440=381V

Thesecondary linecurrent, I**ls**=**ILP**/k=5.77/(440/3300)=43.3A asshown in figure1.17

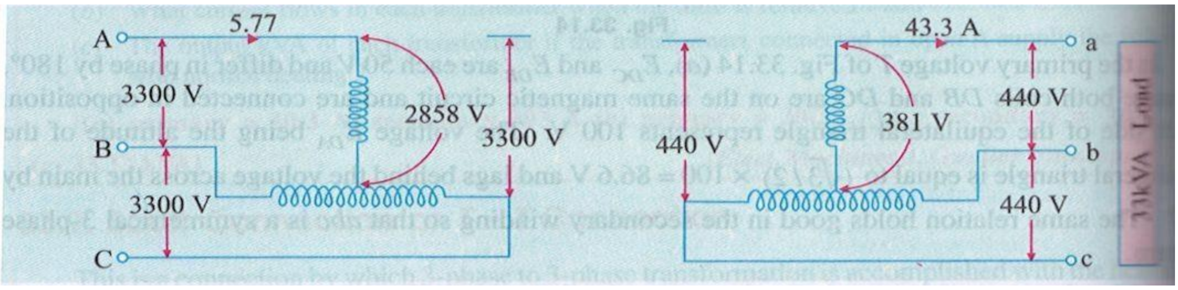


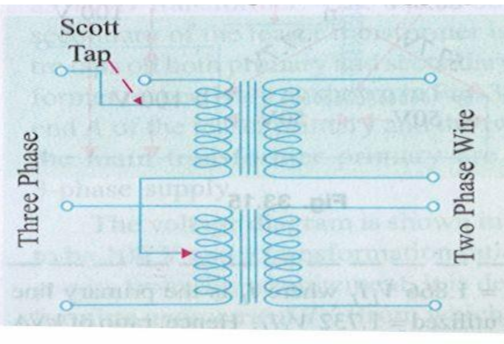
Fig.1.17

(b)MainKVA=3300X5.77X 10^{-3}=**19KVA**

TeaserKVA=0.866XmainKVA=0.866X19=**16.4KVA**

Three-phasetoTwo-phaseConversionandvice-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.Forthis purpose, Scott connection as shownin fig1.18 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.



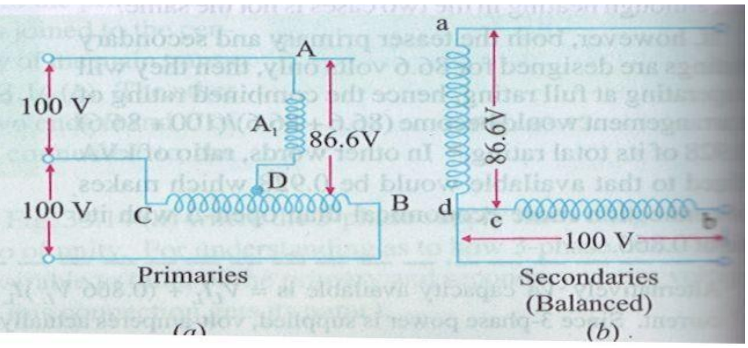


Fig1.18

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_1represents 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 boththetransformers 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.

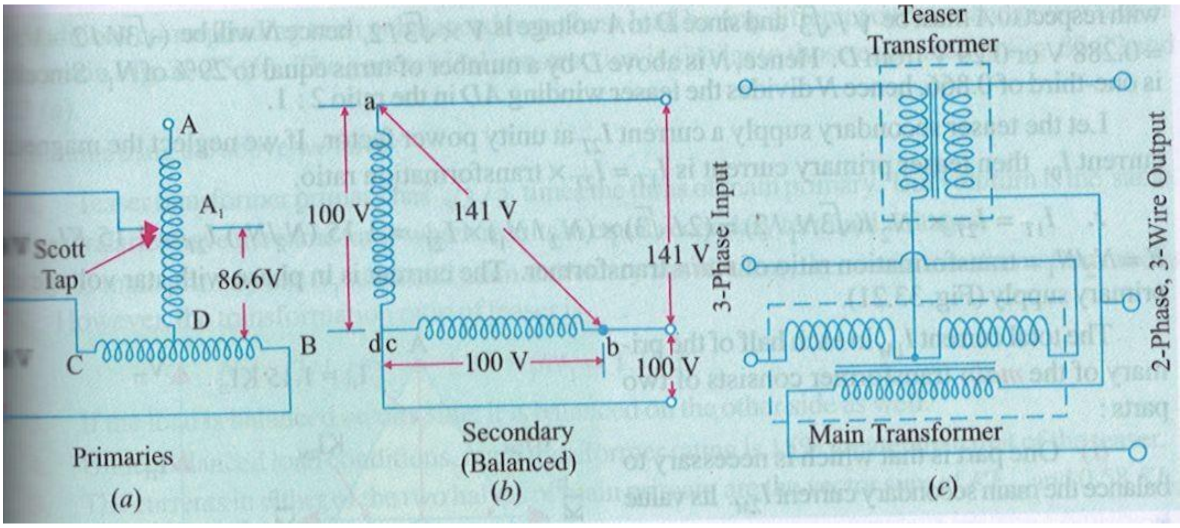
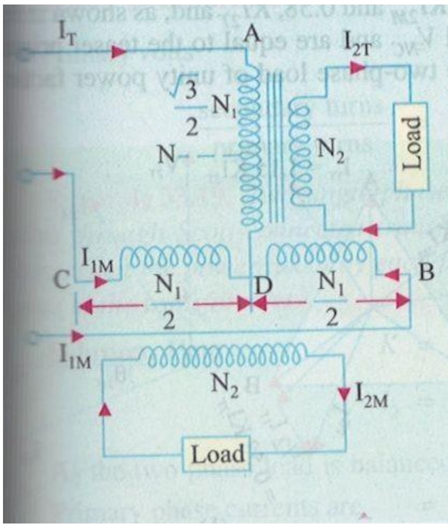


Fig1.20

Consider the same connection drawn slightly differently as in fig.1.21. The primary of the main transformer having N_1turns 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 √3/2. As said above, the number of turns between A and D should be (√3/2)N_1

formakingvolt/turnthesameinbothprimaries.Ifso,thensecondarieshavingequalturns, the secondary terminal voltages will be equal in magnitude although in phase quadrature.



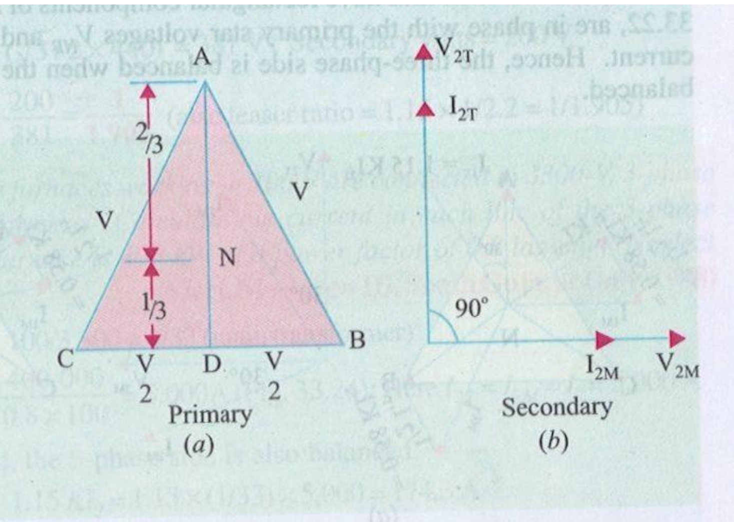


Fig1.21 Fig1.22

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/√3. Let N be the neutral point. Its position can be determined as follows. VoltageNofwith respect to Amust beV/√3 and sinceDto Avoltage is V X √3/2, hence N will be √3V/2 – V/√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 $I_{1T}=I_{2T}X$ transformation ratio

∴$I_{1T}=I_{2T}X\ N_2/(\sqrt{3}N_1/2) = (2/\sqrt{3})\ x\ (N_2/N_1)\ X\ I_{2T}=1.15\ x\ (N_2/N_1)\ X\ I_{2T}=1.15K\ I_{2T}$where $=N_2/N_1$=transformationratioofmaintransformer.Thecurrentisinphasewithstarvoltageof the primary supply (figure1.22)

Thetotalcurrent I_{1M}**ineachhalfoftheoftheprimaryofthemaintransformerconsistsof two parts:**

1. **Onepartisthatwhichisnecessarytobalance**themainsecondarycurrentI_{2M},its value is $= I_{2M}X\ (N_2/N_1)= K\ I_{2M}$

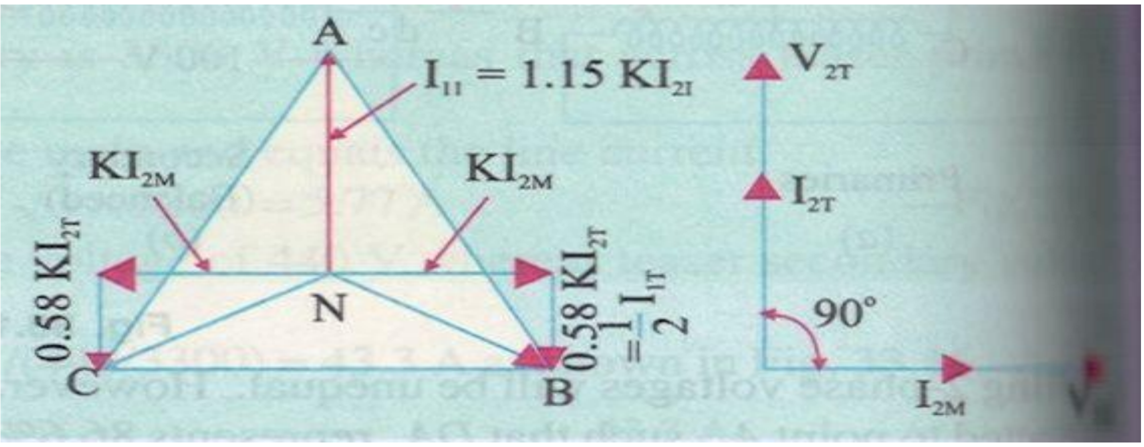


Fig1.23

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 currentwhich 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 infig.1.23. It should be noted that as the two halves of the teaser primary current flow in oppositedirections from point D,theyhaveno magneticeffect on thecore and playno partat 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}andas 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 sideis balanced when the two phase loadof unity power factor is balanced.

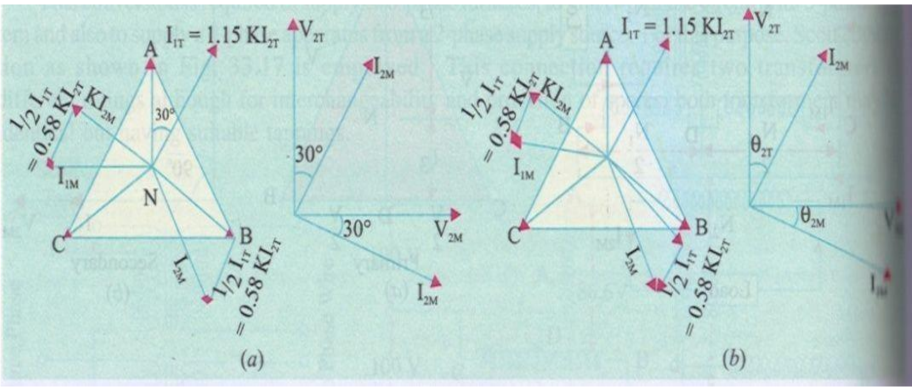


Fig1.24

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).

Summarizingtheabovewehave:

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_1turns and main secondary has N_2turns, then main transformationratioisN_2/N_1.However,thetransformationratioofteaseris$N_2/(\sqrt{3}N_1/2)$ $=1.15N_2/N_1=1.15K$.

3. Ifthe loadis balanced onone side,it is balancedon the othersideaswell.

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

5. Thecurrents ineitherof thetwohalvesofmain primaryarethevectorsum of$KI_{2M}$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:- **maintransformer**

Primaryvolts= 440V ∴secondaryvolts=200V ∴N_2/N_1=200/440=1/2.2

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

Primarycurrent=375X 1/2.2=**197A**

Teasertransformer

Primaryvolts=(√3/2X440)=381V:Secondary volts=200V

Secondary turns /primary turns =200/381=**0.52**(also teaser ratio =1.15 X1/2.2=0.52).

Paralleloperationofthreephasetransformer

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.

Reasonsforparallel 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.

Conditionforparalleloperation

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 $V2/ (V1/\sqrt{3}) = \sqrt{3}V2/ V1$.

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. Phasesequencemustbethe same.

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

Note1: INdealing with threephasetransformercalculation aremadeforonephaseonly. 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 $(\text{transformationratio})^2$.

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.

Tapchangersintransformers

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.

Theprincipleofregulatingthesecondaryoutputvoltageisbasedonchangingthe 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.

No load (oroff-load) Tapchanger

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.

Ifthewinding istapped at2.5% intervals,than withtherotatablearm R

- Atstuds 1,2: Fullwinding isin circuit
- Atstuds 2,3: 97.5%of thewinding is incircuit
- Atstuds 3,4: 95%of thewinding is incircuit
- Atstuds 4,5: 92.5%of thewinding is incircuit
- Atstuds 5,6: 90%of thewinding is incircuit

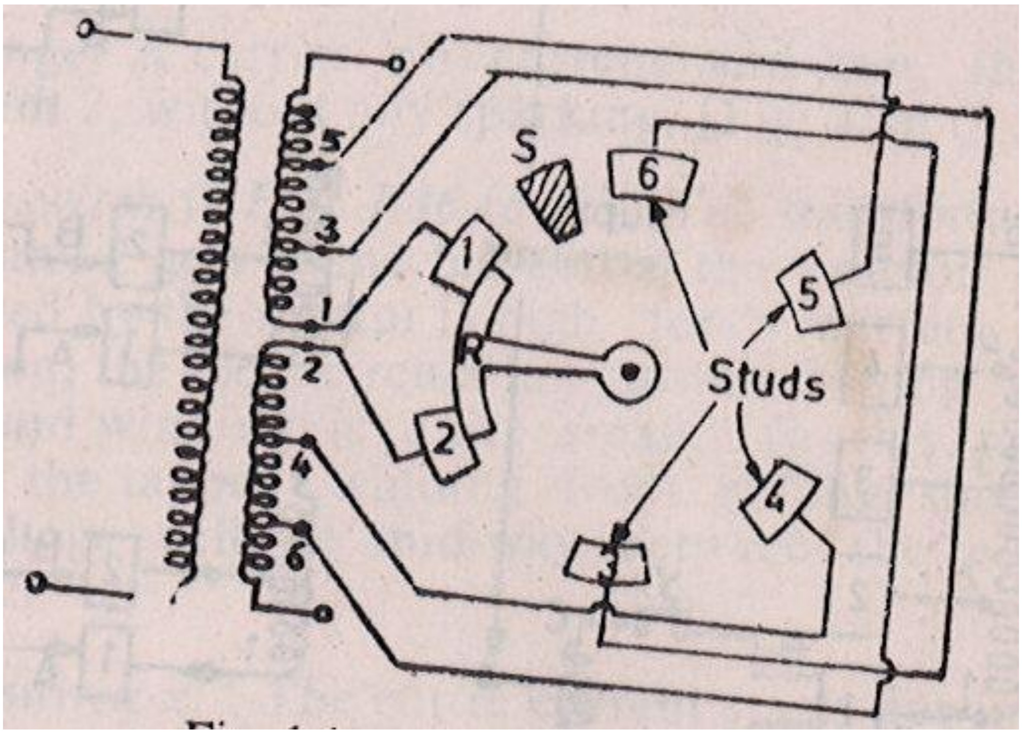


Figure1.25

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, thetransformer is first de-energised and then arm R is rotated two bridge studs 2 and 3. Afterthis, transformer is switched on to the supply and now 97.5% of the winding remains in circuit.

On-loadtapchanger

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.

- Themaincircuitshouldnotbeopenedotherwise dangeroussparkingwilloccurand
- Nopart ofthetapwinding shouldget shortcircuited

Oneform of elementary on load tap-changer is illustrated in figure 1.26(a). Thecentretap 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 halfof the reactor and then to the external circuit. It is seen that currents in the upper andlowerhalvesofthereactorflowin oppositedirection. Sincethewholereactoris woundin 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 practicallyzero:therefore the reactor is almost non inductive and the impedance offered by it is verysmall. 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 segmentto, 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 alarge 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 highfor 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 voltagewill 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.
- Forlargepowertransformerstheswitchesxandymaybecircuitbreakers.

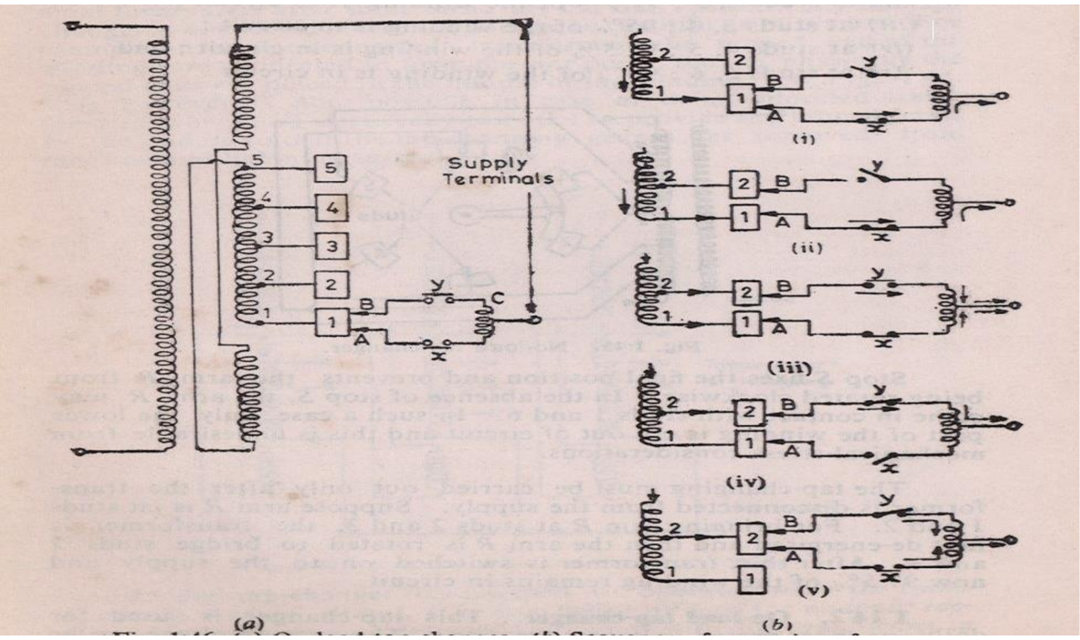


Figure1.26

MaintenanceofTransformer

The normal life of transformer is about 30 years. It could even be longer if operated carefully and maintained regularly. The main object of maintenanceoftransformers is to maintain itsinsulationin 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,groundwire 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.

Checkingandtestingoftransformeroil

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.

Theoil samplesmay betested as follows:

(a) ThedielectricstrengthofoilshouldbetestedasperIS:335 –1953.Theoilshould withstand the test voltage of at least 30kV for one minute without breakdown.

(b) CracletestforfreewatershouldbeperformedasperIS:335 –1953.Thetestisonly qualitative.

(c) Theacidityofoilshouldbedetermined asper IS:1866–1961.

(d) Sludgetest:Thetracesofsolidmatterinoilsamplesmaybe examinedasperIS:1866 – 1961.

Insulationresistance

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.

InternalinspectionofTransformer

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.

Maintenanceschedule

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

Daily:(a) Check oillevel; if low,fill in dryoil.

(b)Checkthecolourofthesilicagelinthebreather.Colourshouldbeblue.Ifthe colour of the silica gel becomes pink replace them.

Quarterly:Checkforproper workingof cooling fans,circulatingpumps, etc.

Half-yearly:Checkthedielectricstrengthofoil,bushes,insulators,cableboxes, filter,and replace oil if necessary.

Yearly: Checkoilforacidity,sludgeformation,contacts,lightningarrestors,etc.

Check alarms, relays, etc.

Checkearthresistance.

Fiveyearly:Carryoutoverallinspectionofthetransformerincludingliftingofcoreand coils. Clean the transformer with dry transformer oil.

1.24DiagnostictestsforpowerTransformer

TheTransformer 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 dangerto 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 thecondition 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 setof 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 averyless percentageoffailure. In this periodattributeto 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.

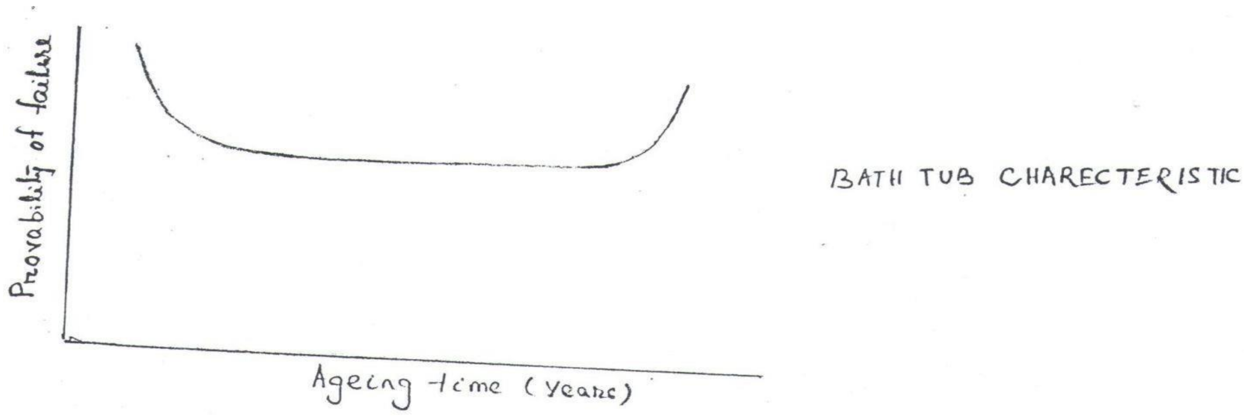


Fig.1.27

Thenormal routinetest that maybeconducted atleastevery year are;

- IRvalue.
- PIvalue.
- Trans value
- BDVTestvalue.
- However,BDVmaybedoneaditionalyatleast in every 2months.
- If any abnormalities are found in the above tests, then only we have to go fordissolved 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.

- **Mechanicalstress:**betweenconductors,leads&windingsduetoovercurrentsor fault current, mainly due to system short circuits.
- **ThermalStress:**Duetolocalheating,overloadcurrents&leakagefluxordueto malfunctioning of cooling system.
- **DialectricStree:**Systemovervoltage,Transientimpluseconditionorduetointernal resonance within a winding.
- **EnvironmentalStress:**Moistureingress, pollution.

Evenmaynewtypeofinsulationhasbeendeveloped,thecellulosicpaperisstillwidely 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 fasterdue 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.

Bynow ourstand is moreclearthat;

- 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 thenit is assentail to knwoto what level thedamagehas been taken place. So that we can decrease the effect to certain level and increase the life of our transformer.

1.25.Routinetest

(1) IRvalue:

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) PIValue:

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 polareffect, when an external field is applied therotation oftheelectronarroundtheprotonis no more circular but eccentric as shown in the figure.

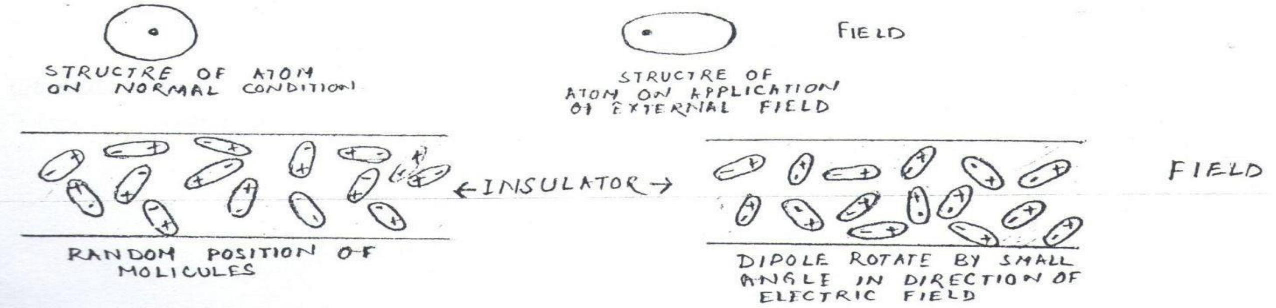


Fig.1.28

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 orientationtakes placeso 10 minvaluesis taken.Thepolarisation indexhas aother 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) Tanδ 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 aAC 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.

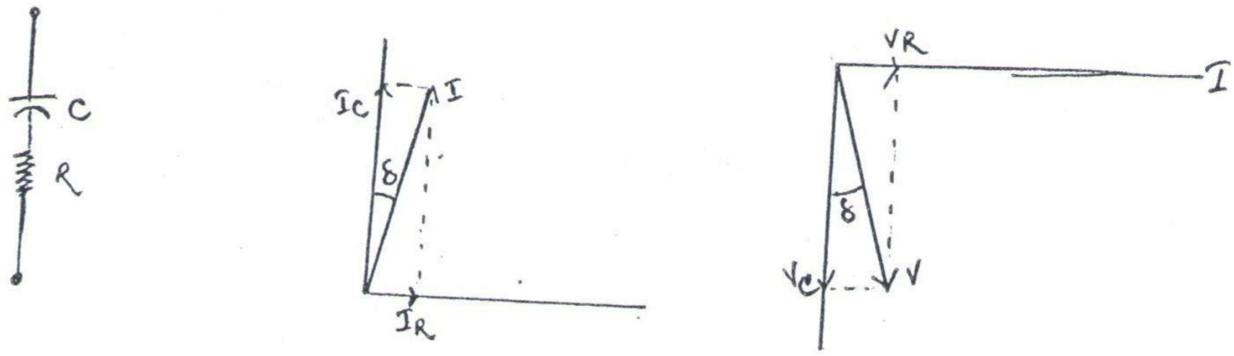
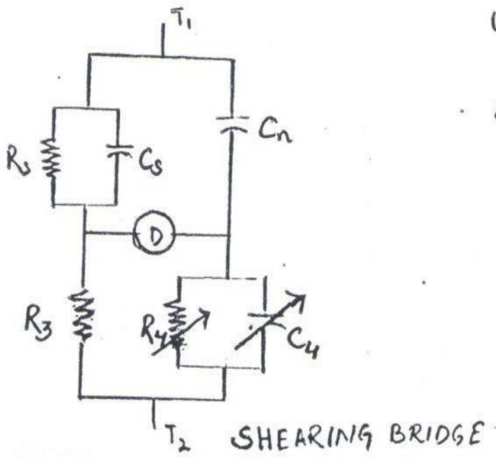


Fig.1.29

Tanδ=V_R/ V_C=R/ X_C

HigheristhevalueofTanδ,moreistheresistivematerialspresentintheinsulationinany form as per value upto 0.2 allowed.

TomajortheTanδvaluetheinstrumentusedisnothingbutaSheraingbridge, supported by a software to give the result directly in Tanδ.



Under Balance condition

$Z_1/Z_3 = Z_2/Z_4$

Equating real & imaginary part

$C_S = \frac{C_n \times R_4}{R_3}$ & $R_S = \frac{R_3 \times C_4}{C_n}$

$\tan\delta = \omega \times \left(\frac{C_n \times R_4}{R_3}\right) \times \left(\frac{R_3 \times C_4}{C_n}\right)$

$= \omega R_4 C_4$

Rs & Cs to be calculated that of transformer all other values are known.

Fig.1.30

4) BDVTest value:

It is a very simple test. The breakdown voltage (BDV) of an insulator is the potential at which it loses itsinsulatingproperty & become conducting. Oil istaken 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.

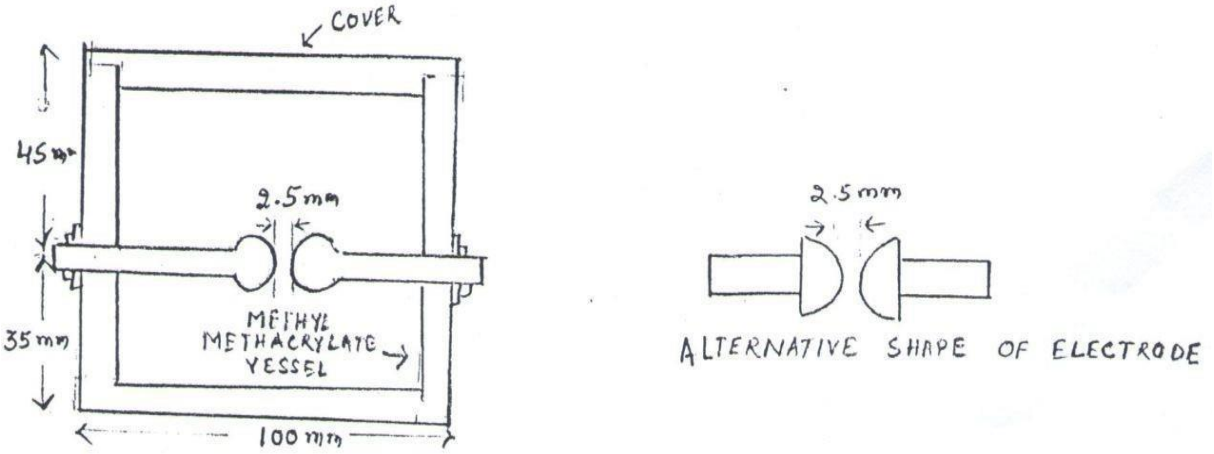


Fig.1.31

The oil under test should be between 15^{0}C to 35^{0}C preferably 27^{0}C.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 maybetakenineverymonth.Propercareshould betakenatsamplingtime;sothatno external moisture enters to it.

SUMMARY

BDV	>50KV <50KV	Good. Shouldbe takenagain inabetterweathercondition &if itis still low, then filtrationor dehydrationmaybe required&willbedecidedafter other tests.
PI	>1.5 <1.5	Good. Filtrationordehydrationmayberequired&willbedecided after other tests.
Tanδ	<0.2 >0.2	Good. Filtrationordehydrationmayberequired&willbedecided after other tests.

OtherTest:

1) IR,PI&Tanδ.
2) Teston Oil&DGA.
3) RecoveryVoltageMeasurement.
4) DielectricSpectroscopyTest.
5) MagneticBalanceTest.
6) TurnsRatio Test.
7) FrequencyResponseAnalysis.
8) CoilResistanceTest.
9) Degreeofpolymerisation Test.(DP)
10) PartialDischargeTest(PD)
11) SurgeVoltageAnalysisTest.