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Department of Electrical Engineering

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Salient Pole type Three Phase SynchronousGenerators

Introduction:

Thesimplecylindricaltheoryofasynchronousgeneratorignorestheeffectofthereluctance torque on the generator. Fig.3.1 shows a salient-pole rotor with no windings inside athree-phase stator. The stator magnetic field produced in the air gap of the generator induces amagnetic field in the rotor. The flux induced in the rotor will act along the axis of the rotor. Sincethere is an angle between the stator magnetic field and the rotor magnetic field, a torque will beinduced in the rotor which will tend to line up the rotor with the stator field. The magnitude ofthis torque is proportional to 'sin (2δ)' where δis the angle between the two magnetic fields.Thistorqueis known asthe '*reluctancetorque*'.

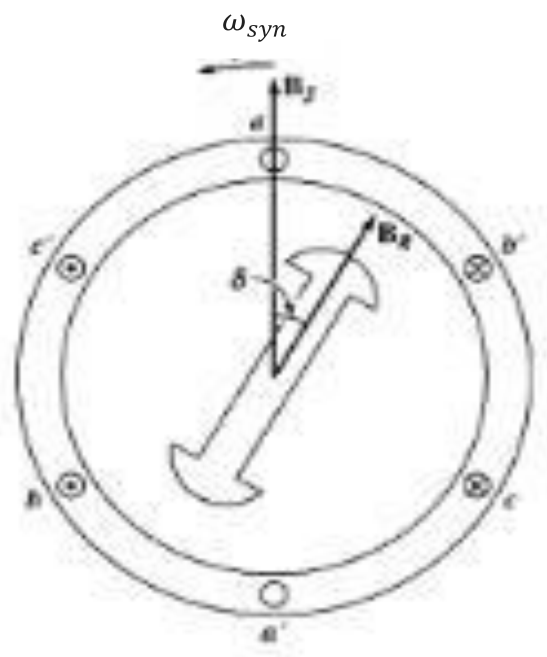


Fig.3.1:Asalient-polerotor,illustratingtheideaof reluctancetorque.

:DevelopmentoftheEquivalentCircuitofaSalient-

PoleSynchronousGeneratorTherearefourelements intheequivalentcircuit

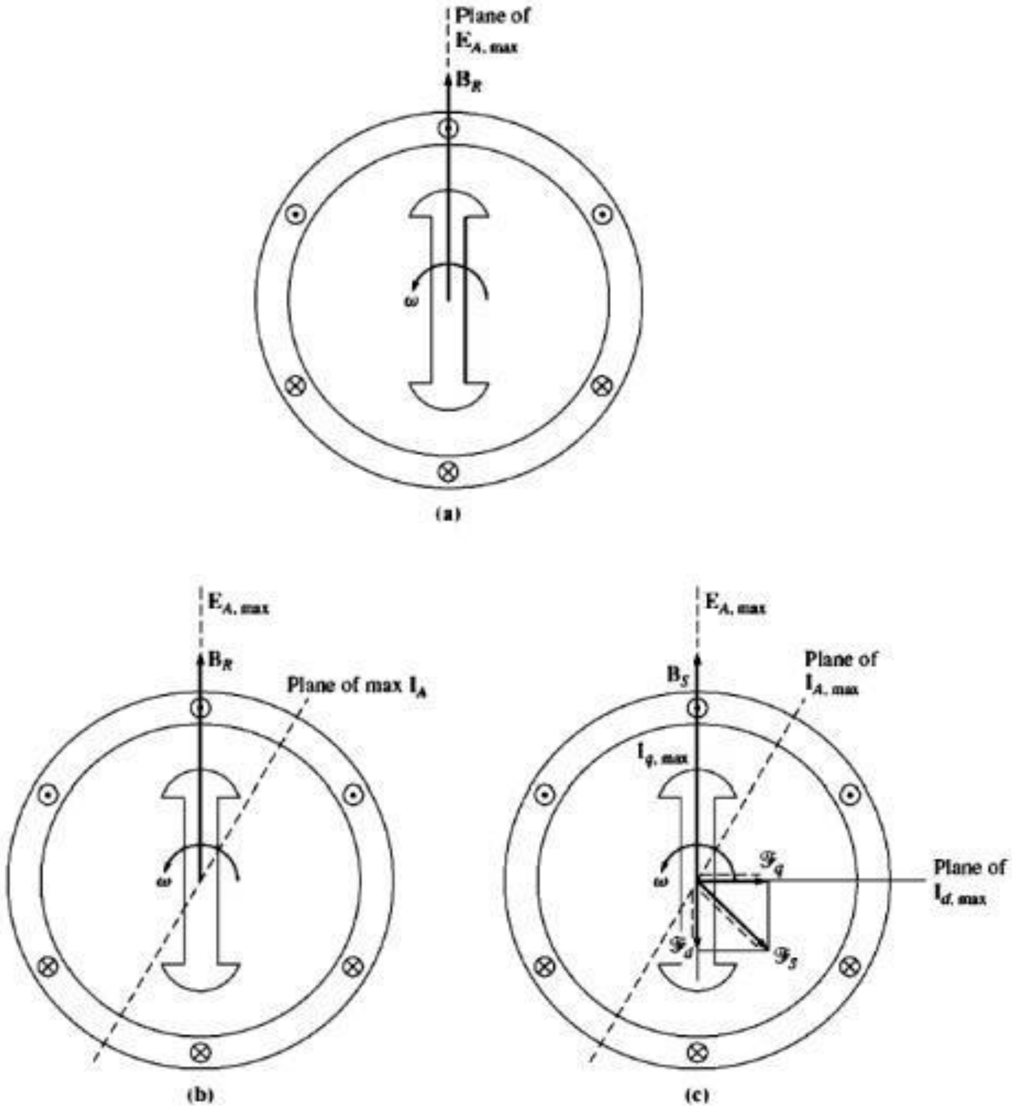
ofasynchronousgenerator:

1. Theresistanceofthestator winding
2. Theself-inductanceofthe statorwinding
3. Theinternal generatedvoltageofthegenerator E
4. Thearmaturereaction ofthesynchronous generator

The first three elements as above remain same as in the case of cylindrical rotor theory ofsynchronousgenerators,butthe4thtermrepresentingthearmature-reactioneffectmustbemodified to explain the salient-pole rotor theory. Fig.3.2 shows a two-pole salient-pole rotorrotating anti• clockwise within a two-pole stator. The rotor flux density B_R points upward. Theequationfor theinducedvoltageonamovingconductor inthepresenceof amagneticfieldis

$$e_{ind}=(v\times B).l \qquad 3.1$$

The voltage in the conductors in the upper part of the stator will be positive out of thepage, and the voltage in the conductors in the lower part of the stator will be into the page. Theplaneof maximum induced voltagewill liedirectlyunder therotor poleatanygiven time.


Plane of $\mathbf{E}_{A,\max}$
$\mathbf{B}_R$
ω
(a)
$\mathbf{E}_{A,\max}$
$\mathbf{B}_R$
Plane of max $\mathbf{I}_A$
ω
(b)
$\mathbf{E}_{A,\max}$
$\mathbf{B}_S$
Plane of $\mathbf{I}_{A,\max}$
$\mathbf{I}_{q,\max}$
$\mathscr{F}_q$
Plane of $\mathbf{I}_{d,\max}$
$\mathscr{F}_d$
$\mathscr{F}_S$
ω
(c)

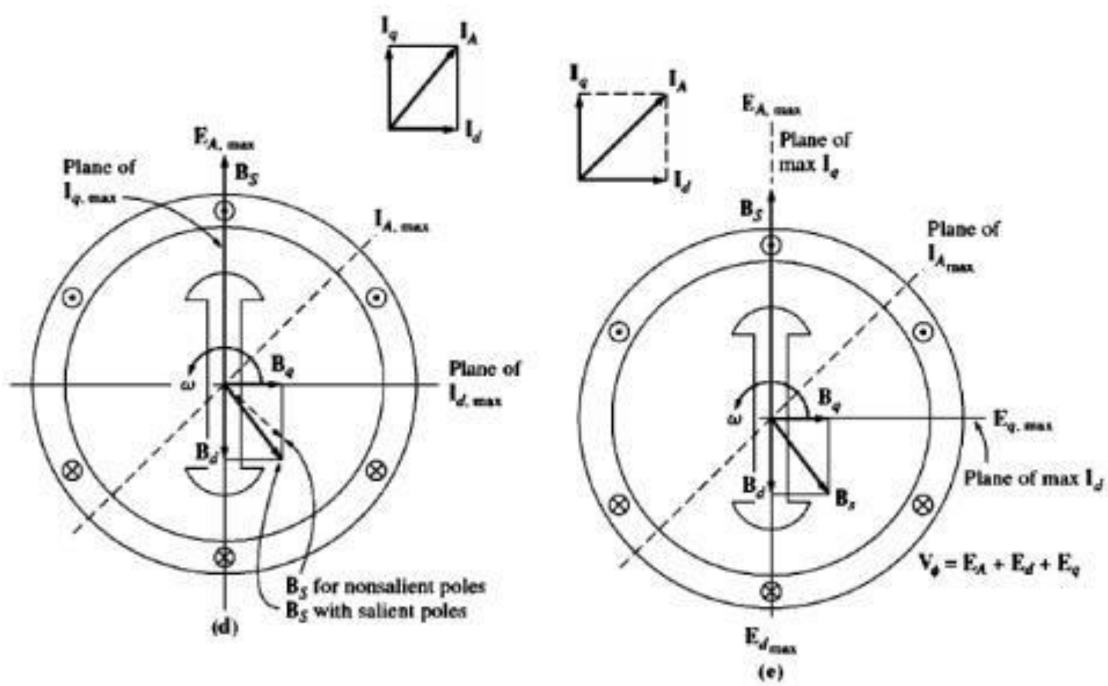


Fig.3.2:Theeffectsofarmaturereactioninasalient-polesynchronous generator.

The rotor magnetic field induces a voltage in the stator which becomes maximum in theconductors directly under the pole faces (Fig.3.2.a). When a lagging load is connected to thegenerator, a stator current will flow that becomes maximum at an angle behind E_A (Fig.3.2.b).This stator current I_A produces a stator magneto-motive force (mmf) in the machine (Fig.3.2.c).The stator mmf produces a stator flux density B_S (Fig.3.2.d). The reluctance of the direct-axisflux path is lower than the reluctance of the quadrature-axis flux path; as a result, the direct-axiscomponent of mmf produces more fluxper ampere-turnthan the quadrature-axis component.The direct- and quadrature-axis stator fluxes produce armature reaction voltages in the stator ofthemachine(Fig.3.2.e).

If a lagging load is now connected to the terminals of this generator, then a current willflow whose peak is delayed behind the peak voltage. This current is shown in Fig. 3.2b. Thestator current flow produces a magneto motive force that lags 90^0 behind the plane of peak statorcurrent, as shown in Fig. 3.2c. In the cylindrical theory, this mmf then produces a stator magneticflux density B_S that lines up with the stator mmf. However, it is actually easier to produce amagnetic flux density in the direction of the rotor than it is to produce one in the directionperpendicular to the rotor. Therefore, the stator mmf can be resolved into components parallel toand perpendicular to the axis of the rotor. Each one of these mmf components produces amagnetic field with more flux per ampere-turn being produced along the direct axis as comparedto that alongthe quadratureaxis.

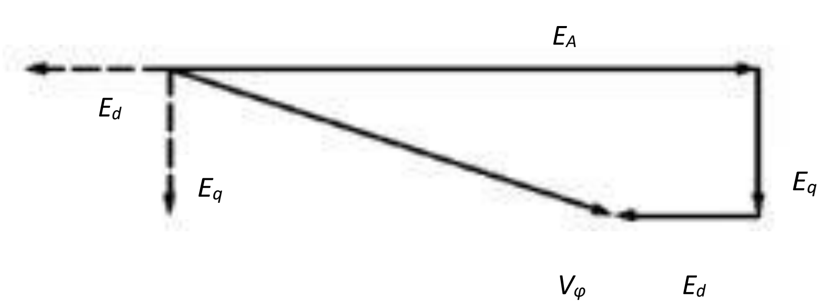


Fig. 3.3: The phase voltage of the generator is just the sum of its internal generated voltage anditsarmaturereaction voltages.

The resulting stator magnetic field is shown in Fig. 3.2d, compared to the field predictedby the cylindrical rotor theory. Now, each component of the stator magnetic field produces avoltage of its own in the stator winding by armature reaction. These armature-reaction voltagesareshown inFig. 3.2e. Thetotal voltagein thestator is thus

$$V_{\emptyset}=E_A+E_d+E_Q \qquad 3.2$$

Here $E_d$is the direct-axis component of the armature-reaction voltage and $E_q$is thequadrature-axiscomponentofarmaturereactionvoltage(Fig.3.3).Eacharmature-reactionvoltage is directly proportional to its stator current and delayed 90° behind the stator current.Therefore, each armature-reaction voltage can be modeled as shown in equations 3.3 and 3.4below.

$$E_d=\mathrm{j}I_d x_d \qquad 3.3$$

$$E_q=\mathrm{j}I_q x_q \qquad 3.4$$

Thestatorterminalvoltagebecomes

$$V_{\emptyset}=E_A-\mathrm{j}I_d x_d-\mathrm{j}I_q x_q \qquad 3.5$$

The armature resistance andself-reactance mustnow be included. The armature self-reactance$X_A$is independent of the rotor angle and is normally added to the direct and quadrature armature-reaction reactancesto produce the direct axis synchronous reactance and the quadrature axissynchronousreactanceofthe generator (equations 3.6and 3.7).

$$X_d=x_d+X_A \qquad 3.6$$

$$X_q=x_q+X_A \qquad 3.7$$

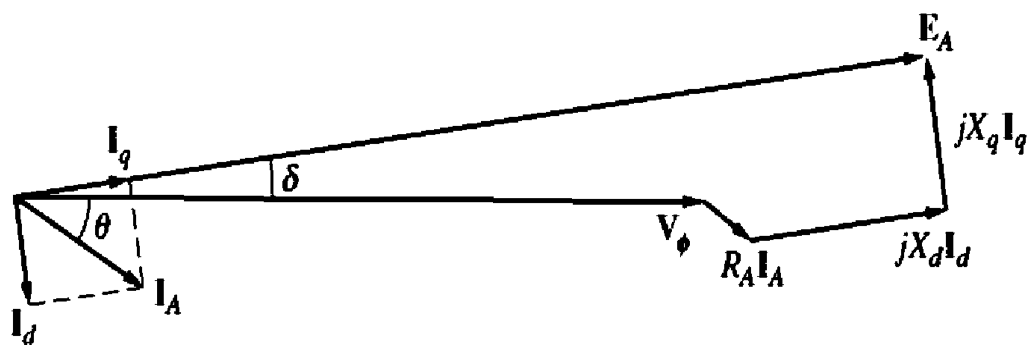


Fig.3.4:Thephasordiagramofasalient-polesynchronousgenerator.

The final expression for the phase voltage of a salient-pole synchronous generator is asmentionedin Eq.3.8 below.

$$E_A=V_{\emptyset}+R_A I_A+\mathrm{j}I_d X_d+\mathrm{j}I_q X_q \qquad 3.8$$

The resulting phasor diagram is shown in Fig. 3.4. In this phasor diagram, the armature currentneedstoberesolvedintotwocomponents-oneinparallelwith$E_A$andtheotherinquadrature withE_A. However, the angle ($\delta + \theta$) between $E_A$and $I_A$is not known before the diagram isconstructed. Normally, the power-factor angle θ is known in advance. But it is possible toconstruct the phasor diagram without having the advance knowledge of the angle δ, as shown inFig.3.5.

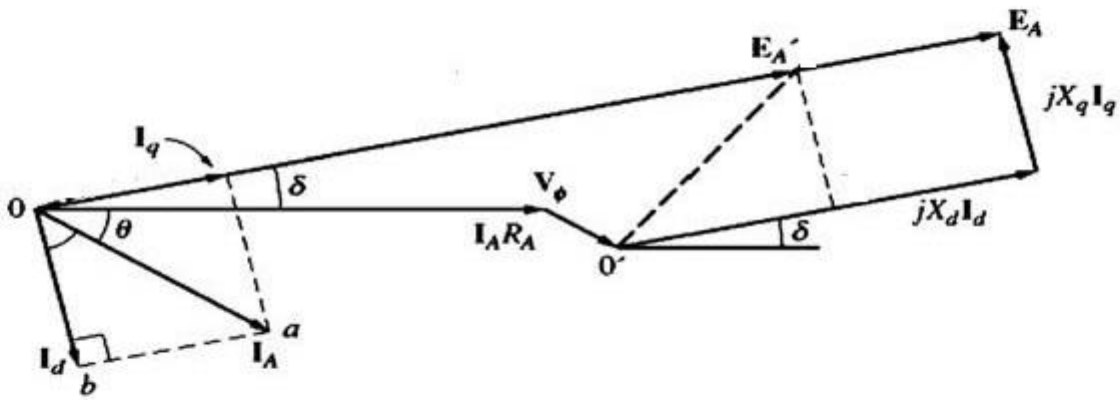


Fig.3.5:Constructingthephasor diagram withno advanceknowledgeofδ.

ThephasorE$'_A$liesatthesameangleas$E_A$andmaybedeterminedasgivenbyequation (3.9)below.

$$E_A' = V_\varnothing + R_A I_A + jI_A X_q \qquad 3.9$$

The power factor angle θ between $V_\phi$and $I_A$can be found by using information known atthe terminals of the generator. Thus the angle δ can be determined with knowledge of thearmature current I_A, power factor angle θ, armature resistance $R_A$and armature quadrature axisreactanceX_q.Oncetheangle$(\delta+\theta)$isknown,thearmaturecurrentcanbebrokendownintodirectand quadraturecomponents andthe internalgenerated voltagecan bedetermined.

TORQUEANDPOWEREQUATIONSOFSALIENT-POLEMACHINE

Thepoweroutputofacylindricalrotorsynchronousgeneratorwithnegligiblestator(armature)resistanc e as afunction oftheloadangleisgivenbyequation(3.10).

$$\frac{3E_A V_\varnothing}{X_s}\sin\delta \qquad 3.10$$

Making the same assumption of negligible stator (armature) resistance the output power of asalient-pole synchronous generator has to be found out as a function of load (torque) angle (Fig.3.6). The power output of a synchronous generator P is the sum of the power due to the direct-axis current $P_d$and the power due to the quadrature-axis current P_q. Both $I_d$and $I_q$contribute totheoutput poweras shown in Fig. 3.6.

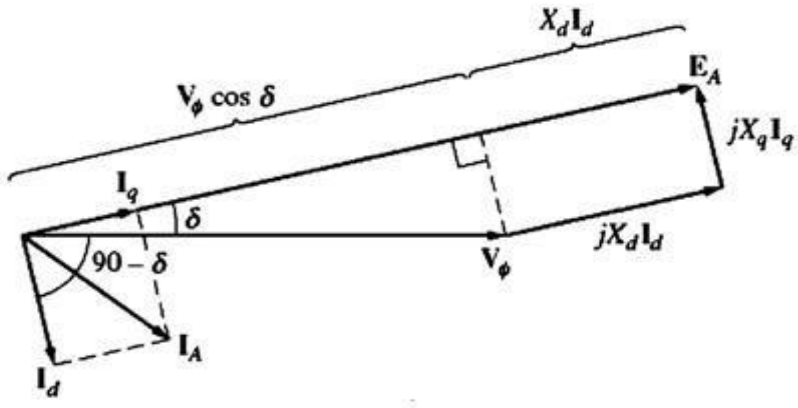


Fig.3.6:Determiningthepoweroutputofasalient-polesynchronousgenerator.

$$P = P_d + P_q = 3V_{\emptyset} I_d \cos(90^0 - \delta) + 3V_{\emptyset} I_q \cos\delta$$

$$= 3V_{\emptyset} I_d \sin\delta + 3V_{\emptyset} I_q \cos\delta \qquad 3.11$$

FromFig. 3.6, thedirect-axis current is givenby

$$I_d = \frac{E_A - V_{\emptyset}\cos\delta}{X_d} \qquad 3.12$$

andthequadrature-axis current isgivenby

$$I_q = \frac{V_{\emptyset}\sin\delta}{X_d} \qquad 3.13$$

SubstitutingEquations(3.12)and(3.13)intoEquation(3.11) yields

$$P = 3V_{\emptyset}\frac{E_A - V_{\emptyset}\cos\delta}{X_d}\sin\delta + 3V_{\emptyset}\frac{V_{\emptyset}\sin\delta}{X_d}\cos\delta$$

$$= \frac{3V_{\emptyset}E_A}{X_d}\sin\delta + 3V_{\emptyset}^2\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin\delta\cos\delta \qquad 3.14$$

$$= \frac{3V_{\emptyset}E_A}{X_d}\sin\delta + \frac{3V_{\emptyset}^2}{2}\left(\frac{X_d - X_q}{X_q X_d}\right)\sin 2\delta \qquad 3.15$$

Thefirsttermofthisexpressionisthesameasthepowerinacylindricalrotormachine,andthesecondtermisthe additionalpowerduetothereluctancetorqueinthemachine.Sincethe inducedtorqueinthegeneratorisgivenby$T_{ind} = \frac{P_{conv}}{\omega_m}$,theinducedtorqueinthemotorcanbe expressedas

$$T_{ind} = \frac{3V_{\emptyset}E_A}{\omega_m X_d}\sin\delta + \frac{3V_{\emptyset}^2}{2\omega_m}\left(\frac{X_d - X_q}{X_d}\right)\sin 2\delta \qquad 3.16$$

The induced torque out of a salient-pole generator as a function of the torque angle δ is plotted inFig.3.7.

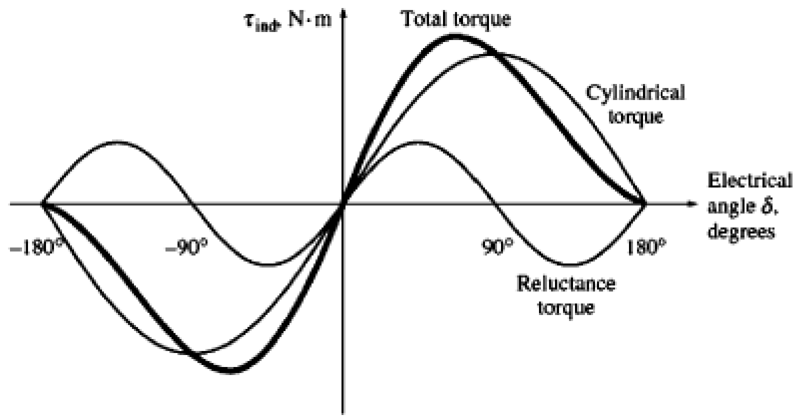


Fig.:3.7: The developed torque versus torque angle for a salient-pole synchronous

generator.Example:A450volt,50Hz,Δconnected,4pole,3-phasesynchronousgeneratorhasdirectaxis reactanceof0.15Ωandquadratureaxisreactanceof0.07Ω.Itsarmatureresistancemaybe neglected.Atfullload thegeneratorsupplies150A atapower factorof0.8lagging.

(a) Findtheinternalgeneratedvoltage$E_A$ofthisgeneratoratfullload,assumingthatithascylindricalr otor reactanceisX_d.
(b) Findthegeneratedinternalvoltage$E_A$ofthisgeneratoratfullloadassumingthatithasasalientpole rotor.

Solution

Sincethegeneratorisdeltaconnectedthearmature current$I_A = \frac{150}{\sqrt{3}} = 86.60$A
Since the power factor is 0.8 the power factor angle is $\cos^{-1} 0.8 = 36.87^o$
Thereforeinternalgenerated voltage

$E_A = V_\phi + jX_d I_A = 415 < 0^o + j(0.15)(86.60 < -36.87^o) = 428.30 < 9.27^o$

Forsalientpolewehavetoconsider thequadratureaxisreactance.

$$E_A' = V_ø + I_A R_A + I_A jX_q$$

$$I_A = 415 < 0^0 + 0 + j(0.07)(86.60 < -36.87^0 = 418.632 + j4.83 = 418.65 < 0.66^0$$

Findingthe magnitudeofI_d,
$I_d = I_A \sin(\theta+\delta) = 86.6 \sin(36.86+0.66) = 52.74$
Similarily$I_q = I_A \cos(36.86+4.83) = 86.60 \cos(36.60+0.66) = 68.92$
Finally$I_d = 52.74 < -89.34^0$
$I_q = 68.92 < 0.66^0$
Theresultinggeneratedvoltageis
$E_A = V_\phi + I_A R_A + jI_d X_d + jX_q I_q$

$= 415 < 0^0 + 0 + (j52.74 < -89.34^0)(0.15) + (j\ 68.92 < 0.66^0)(0.07)$
$= 415 < 0^0 + j7.911 < -89.34 + j4.82 < 0.66 = 415 + 7.91 + j\ 0.115 + j\ 4.81 - 0.05552$
$= 422.85 + j4.925 = 422.87 < 0.66^0$
Itcanbeseenthattherethemagnitudeof$E_A$isnotmuchaffectedinsalientpolebuttheangleof$E_A$is much affected insalientpolethan thenonsalient polemachine.

SLIPTEST

Slip Test is performed in a salient pole synchronous machine to measure the (1) directaxissynchronousreactanceand(2)thequadratureaxissynchronousreactanceofthesynchronousmachine.

THEORY:-
Directaxissynchronousreactanceandquadratureaxissynchronousreactancearethesteadystatereactancesofthesynchronousmachine.Thesereactancescanbemeasured by performing open circuit, short circuit tests and the slip test on synchronousmachine.
(A) Direct-axis synchronous reactances (X_d):- The direct axis synchronous reactance ofsynchronous machine in per unit is equal to the ratio of field current $I_{fSC}$for rated armaturecurrentfrom the short circuit test, to the field current,$I_{fOC}$for rated voltage on the airgapline. Thus, directaxissynchronousreactance(X_d) $= I_{fsc}/I_{foc}$per unit. This direct-axis reactance can befoundout byperformingopen circuit andshortcircuitteston alternator.
(B) Quadrature-axis synchronousreactanceXqbysliptest:-
Forthesliptest,thealternatorshouldbedrivenataspeed,slightlylessthanthesynchronous speed, with its field circuit open. 3 phase balanced reduced voltage of ratedfrequency is applied to armature (stator) terminals of the synchronous machine. Appliedvoltage is to be adjusted, so that the current drawn by the stator winding is full load ratedcurrent.Thestatorcurrentandstatorvoltageundergochangesbetweenminimumandmaximum values. When the crest of the stator mmf wave coincides with the direct axis of therotating field, the induced emf in the open field is zero, the voltage across the stator terminalswill be the maximum and the current drawn by the stator winding is the minimum. Thusapproximate valueofdirectaxis synchronousreactance$X_{ds}$is givenby

$$X_{ds}=E_{max}/I_{min} \qquad 3.17$$

When the crestof statormmf wavecoincideswith the quadrature axisof the rotatingfield, the induced emf in the open circuit field is maximum, the voltage across the statorterminals will be minimum and the current drawn by the stator winding is maximum. Hence,approximate valueofthequadrature-axis synchronousreactance;X_{qs}isgiven by,

$$X_{qs} = \frac{E_{min}}{I_{max}} \qquad 3.18$$

For best result, these values are not taken as the final values. The most accurate method ofdetermining the direct axis synchronous reactances, $X_d$is the one, that has already beendescribedin(A)above,Themostaccuratevalueofquadratureaxissynchronousreactance,$X_q$canbefoundoutbyusingtheaboveinformationi.e$X_{ds}$and X_d.Quadratureaxissynchronousreactance,$X_q=(X_{qs}/X_{ds})\times X_d=(E_{min}/I_{max})(I_{min}/E_{max})X_d$perunitHencetheaccurate value of $X_q$can be found out by recording minimum and maximum values of theabove quantities. Accurate results can be obtained, if the oscillogramsare taken duringexperimentation for stator current, stator voltage and injected voltage across the field. It maybenoted clearly, thatforsynchronous machineX_d*is greater than*X_q, *i.e.* $X_d>X_q$.
Importantcaution for conductingsliptest:-
1) Slip should be extremely low during experimentation. In case of high slip (more thanabout5%)followingeffectsmaybeobserved:-(a)Currentinducedinthedamperwinding

ofalternatorwillproduceanappreciableerror.(b)Inducedvoltageintheopencircuitfieldmayreachd angerous values.

2) Itshouldbeassuredthattheinducedvoltageintheopencircuitislessthantheratingofthevoltmeter connected in the circuit.

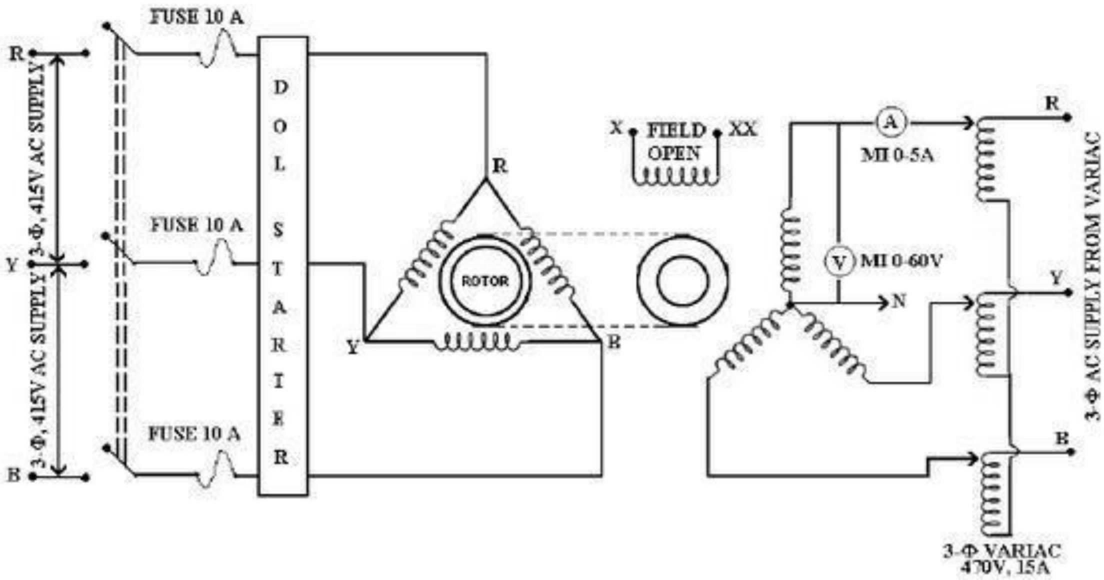


Fig.3.8:SlipTestfordeterminationofdirectaxissynchronousreactanceandquadratureaxissynchro nousreactanceofasalient polesynchronousmachine.

MODULE-II

CHAPTER-4

Parallel Operation of Three Phase AC SynchronousGenerators

PARALLELOPERATIONOFACGENERATOR

SWhyaresynchronousgenerators

operatedinparallel?

Thereareseveralmajoradvantagesofparalleloperationof ACgenerators:
a. SeveralACgeneratorscan supplyabiggerloadthanonemachinebyitself.
b. Having many synchronous generators increases the reliability of the power system, since thefailureofanyoneofthem doesnot causeatotal powerloss to theload.
c. Having many synchronous generators operating in parallel allows one or more of them to beremovedforshutdownand preventive maintenance.
d. If only one ACgenerator is used and the generator is not operating at near full load, then itwill be relatively inefficient. With several smaller machines operating in parallel, it is possible tooperateonlyafractionofthem. Themachinesthoseoperatenearfull loadaremoreefficiently.

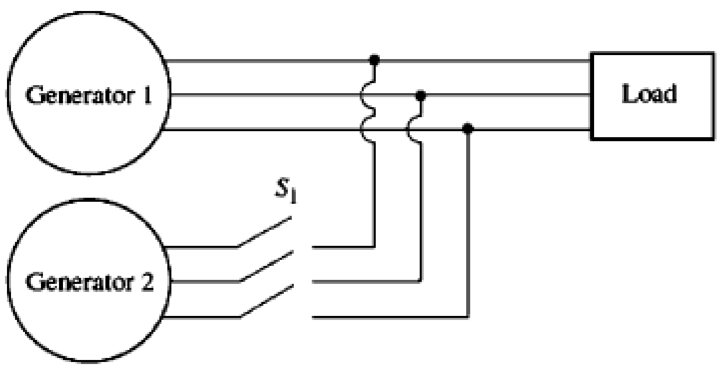


Fig.4.1:A generator beingparalleled witharunningpowersystem.

TheConditionsRequiredforParalleling

Fig.4.1 represents a synchronous generator G_1supplying power to a load, with another generatorG_1abouttobeparalleledwithG_1byclosingtheswitchS_1.Theremustbesomedefiniteconditions met before the switch can be closed and the two generators connected. If the switch isclosed arbitrarily at any moment, the generators will be severely damaged, and the load may losepower. If the voltages are not exactly the same in each of the conductors tied together, there willbe a very large amount of current flow occurs, when the switch is closed. In order to avoid thisproblem, each of the three phases must have exactly the same voltage magnitude and phase angleas the conductor to which it is connected. To maintain this match, the following parallelingconditionsmust befollowing:

I. Thermslinevoltagesof thetwogeneratorsmustbeequal.
II. Thetwogeneratorsmusthavethesamephasesequence.
III. Thephaseanglesofthe twoaphases mustbeequal.
IV. Thefrequencyofthenewgenerator,calledtheincominggenerator,mustbeslightlyhigherthan that ofthe frequencyof the runningsystem.

The condition-I is required for two sets of voltages to be identical, they must of course have thesame rmsmagnitude of voltage. The voltage in phases a and a' will be completely identical at alltimes if both their magnitudes and their angles are the same, which explains condition -III.Condition-

IIensuresthatthesequenceinwhichthepeakvoltagesperphaseinthetwogeneratorsisthesame.Ifthephas esequenceisdifferent(asshowninFig.4.2),theneventhough one pair of voltages (the ‘a’ phases) are in phase, the other two pairs of voltages are 1200 out ofphase. If the generators were connected in thismanner, there would be no problem with phase‘a’, but huge currents would likely to flow in phases ‘b’ and ‘c’, damaging both machines. Tocorrectaphasesequenceproblem,simplyswaptheconnectionsonanytwoofthethreephaseson one of the machines. If the frequencies of both the generators are not extremely nearly equalalthough they are connected together, a large power transientswill occur until the generatorsstabilizeatacommonfrequency.Thefrequenciesofthetwomachinesmustbeverynearlyequal, but they cannot be exactly equal. They must differ by a small amount so that the phaseangles of the oncoming machine will change slowly with respect to the phase angles of therunning system. In that way, the angles between the voltages can be observed and switch S_1canbeclosed when thesystems areexactlyin phase.

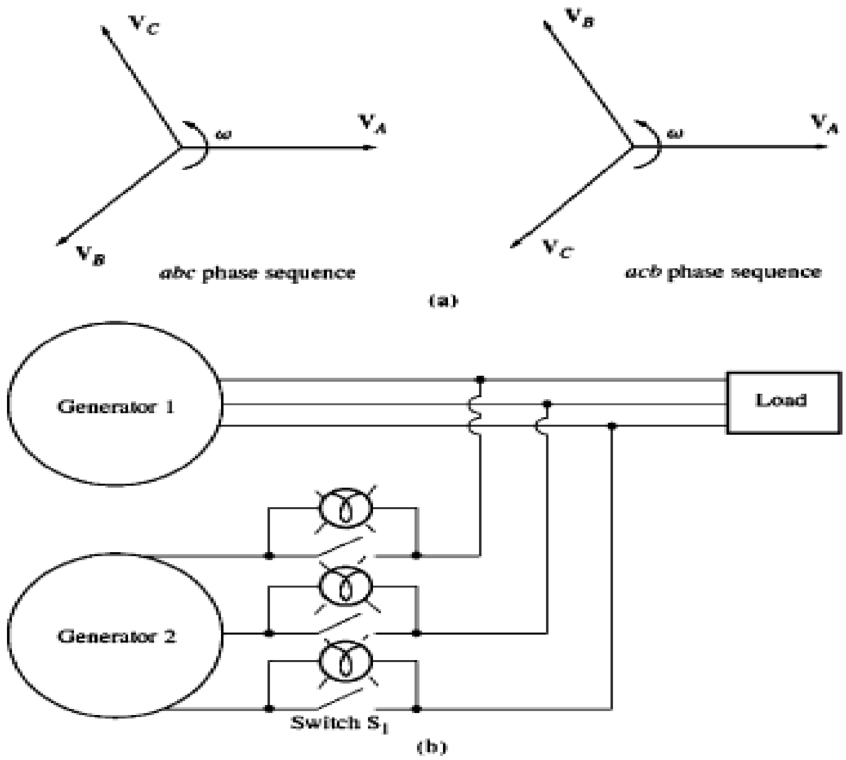


Fig. 4.2: (a) The two possible phase sequences of a three-phase system. (b) The three-light-bulbmethodforcheckingphasesequence.

TheGeneralProcedure forParallelingGenerators

SupposethatgeneratorG$_1$istobeconnectedtotherunningsystemasshowninFig.4.2. Thefollowingstepsshould betakentocompletetheparallelconnectionof thegenerators.

First of all, the field current of the oncoming generator should be adjusted until itsterminal voltage is equal to the line voltage of the running system. The voltages are measuredusing voltmeters. Secondly, the phase sequence of the oncoming generator must be comparedwith the phase sequence of the running system. The phase sequence can be checked in a numberof different ways. One way is to alternately connect a small induction motor to the terminals ofeach of the two generators. If the motor rotates in the same direction each time, and then thephase sequence is the same for both generators. If the motor rotates in opposite directions, thenthephasesequencesdiffer,andtwooftheconductorsonthe incominggeneratormustbereversed.Anotherwaytocheckthephasesequenceisthethree-light-bulbmethod.Inthisapproach, three light bulbs are connected across the open terminals of the switch connecting thegenerator to the system as shown in Fig. 5.2(b). As the phase changes between the two systems,thelightbulbsfirstgetbright(largephasedifference)andthengetdim(smallphasedifference).

If all three bulbs get bright and dark together, then the systems have the same phase sequence. Ifthe bulbs brighten in succession, then the systems have the opposite phase sequence, and one ofthesequences must bereversed.

Next, the frequency of the oncoming generator is adjusted to be slightly higher than thefrequency of the running system. This is done first by watching a frequency meter until thefrequencies are close andthen by observing changes in phase between the generators. Theoncoming generator is adjusted to a slightly higher frequency so that when it is connected, it willcome on the line supplying power as a generator, instead of consuming it as a motor. When thefrequencies are very nearly equal, the voltages in the two systems will change phase with respectto each other very slowly. The phase changes are observed, and when the phase angles are equal,theswitch connectingthetwo systems togetherisshut.

Howcanonetellwhenthetwosystemsarefinallyinphase?Asimplewayistowatchthe three light bulbs described above in connection with the discussion of phase sequence. Whenthe three light bulbs all go out, the voltage difference across them is zero and the systems are inphase. This simple scheme works, but it is not very accurate. A better approach is to employ asynchroscope.A synchroscopeis a meter thatmeasures the differencein phase angle betweenthe phases of the two systems. The face of a synchroscopeis shown in Fig. 4.3. The dial showsthe phase difference between the two a phases, with 0 (meaning in phase) at the top and 1800 atthe bottom. Since the frequencies of the two systems are slightly different, the phase angle on themeterchanges slowly.Iftheoncoming

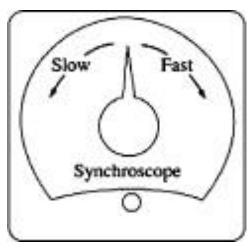


Fig.4.3Synchroscope.

generatoror system is faster than the running system, then the phase angle advances and thesynchroscope needle rotates clockwise. If the oncoming machine is slower, the needle rotatescounterclockwise.Whenthesynchroscopeneedleisintheverticalposition,thevoltagesareinphase, and theswitchcan beshutto connect thesystems.

Notice, though, that a synchroscope checks the relationships on only one phase. It gives noinformation about phase sequence. In large generators belonging to power systems, this wholeprocess of paralleling a new generator to the line is automated, and a computer does this job. Forsmallergenerators, though, theoperatormanuallygoes through theparalleling stepsjustdescribed.

Frequencies-PowerandVoltage-ReactivePowerCharacteristicsofaSynchronousGenerator

All generators are driven by a prime mover, which is the generator's source of mechanical power.The most common type of prime mover is a steam turbine, but other types include diesel engines,gas turbines, water turbines, and even wind turbines. Regardless of the original power source, allprime movers tend to behave in a similar fashion as the power drawn from them increases, i.e.,the speed at which they run tends to decrease. The decrease in speed is generally nonlinear.Therefore, different forms of governor mechanism are usually included to make the decrease inspeedlinearwith theincreasein power demand.

Whatever governor mechanism is present on a prime mover, it will always be adjusted to providea slight drooping characteristic with increasing load. The speed droop (SD) of a prime mover isdefined bytheequation

$$SD=\frac{n_n-n_f}{n_{fl}}\times 100----------4.1$$

Wheren_{nl}istheno-loadprime-moverspeedandn_{fl}isthefull-loadprime-moverspeed.Most generator prime movers have a speed droop of2 to 4 percent. It has to be noted that, mostgovernors have some type of set point adjustment to allow the no-load speed of the turbine to bevaried. A typical speed-vs-power plot is shown in Fig.5.3. Since the shaft speed is related to theresultingelectrical frequencybyEquation (4.2)given below.

$$f_e=\frac{n_{nl}120}{P}-------------4.2$$

The electrical power output of a synchronous generator is related to its frequency. A typical plotof frequency versus power is shown in Fig. 4.4 (b). Frequency-power characteristics of this plotplayanessentialroleintheparalleloperationofsynchronousgenerator.Therelationshipbetween frequencyand power can bedescribed quantitativelybytheequation

$$P=(f_{nl}-f_{syn})---------4.3$$

Where$P$=poweroutput ofthegeneratorinkWf_{nl}=
no- load frequency of the generator in Hzf_{fl}=
full- load frequency of the generator in
Hzf_{syn}=operatingfrequencyofsystem in Hz
s_p=slopeofcurve, inkW/Hz

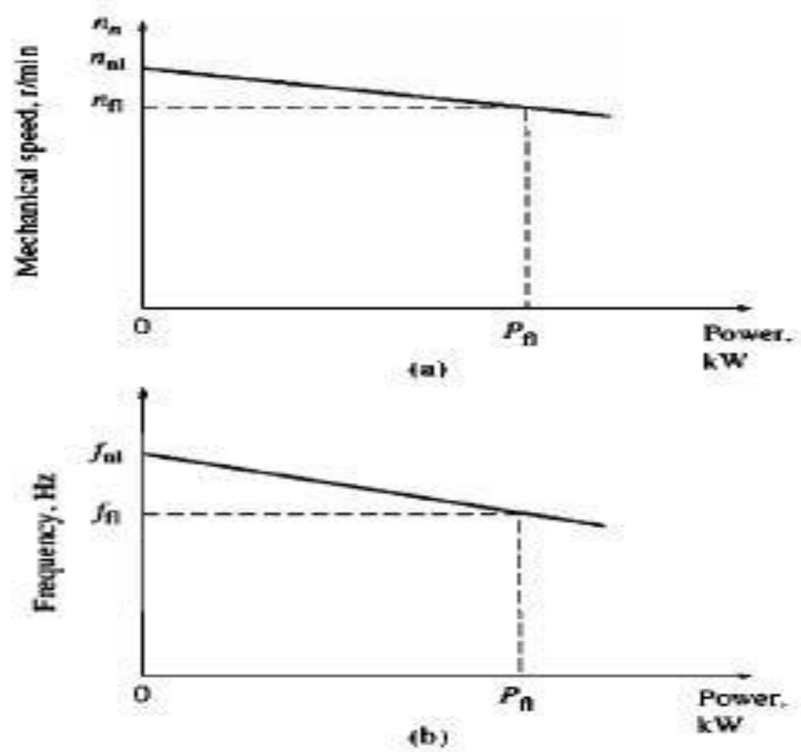


Fig. 4.4(a) The speed-versus-power curve for a typical prime mover. (b) The resulting frequency-versus-powercurveforthegenerator.

A similar relationship can be derived for the reactive power *Q* and terminal voltage *VT*. Aspreviously seen, when a lagging load is added to a synchronous generator, its terminal voltagedrops. Similarly, when a leading load is added to asynchronous generator, its terminal voltageincreases. Therefore, it is possible to make a plot of terminal voltage versus reactive power, suchtype of plot has a drooping characteristic like the one shown in Fig. 4.4. This characteristic is notintrinsically linear, but voltage regulators of many generators include a feature to make it so. TheQ-V characteristic curve can be moved up and down by changing the no-load terminalvoltageset point on the voltage regulator. As like as the frequency-power characteristic, this curve playsanimportant rolein the paralleloperationofsynchronous generators.

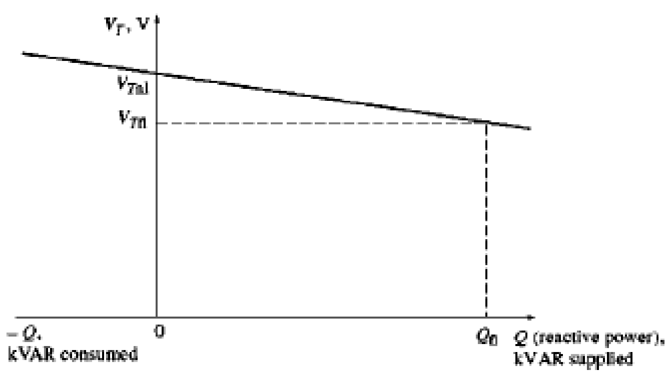


Fig.4.5:Thecurveofterminalvoltage*(V_T)*versusreactivepower*(Q)*forasynchronousgenerator

.

Therelationshipbetweentheterminalvoltageandreactivepowerofageneratorcanbeexpressed by an equation similar to the frequency-power relationship [Equation(4.3)], if thevoltage regulator produces an output that is linear with changes in reactive power. It is importantto realize that, when a single generator is operating individually, the real power *P* and reactivepower *Q* supplied by the generator will be the amount demanded by the load attached to thegenerator. The *P* and *Q* supplied cannot be controlled by the generator's controls. Therefore, forany given real power, the governor set point controls the generator's operating frequency $f_e$andforanygiven reactivepower, thefield currentcontrols thegenerator'sterminal voltage *VT*.

Insummary,fora generator isoperatingbyitselfsupplyingthesystem loads,then;

I. Therealandreactivepowersuppliedbythegeneratorwillbetheamountdemandedbytheattachedload.
II. Thegovernorsetpointsofthegeneratorwillcontroltheoperatingfrequencyofthepowersystem.
III. Thefieldcurrent(orthefieldregulatorsetpoints)controlstheterminalvoltageofthepowersystem.

OperationofGeneratorsinParallelwith LargePowerSystems

When a synchronous generator is connected to a power system, the power system is oftenso large that *nothing* the operator of the generator does will have much of an effect on the powersystem. An example of this situation is the connection of a single generator to the U.S. powergrid. The U.S.powergrid is so large that no reasonable action on the part of the one generatorcancausean observablechangein overallgrid frequency.

This idea is idealized in the concept of an infinite bus. An *infinite bus* is a power systemso large that its voltage and frequency do not vary regardless of how much real and reactivepower is drawn from or supplied to it. The power frequency characteristic of such a system isshowninFig.4.5(a),andthereactivepower-voltagecharacteristicis showninFig.4.5(b).

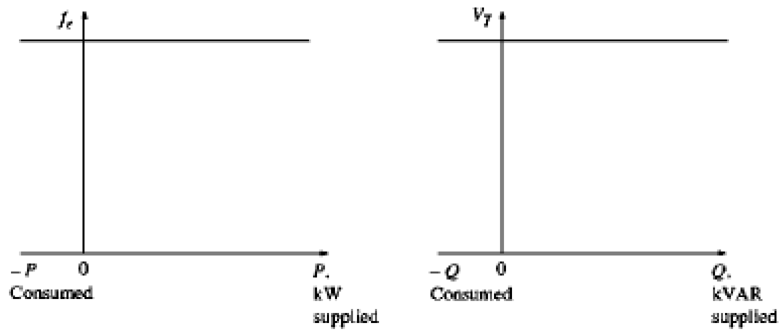


Fig.4.5(a)power frequencycharacteristic (b)thereactivepower-voltagecharacteristic

To understand the behavior of a generator connected to such a large system, examine asystem consisting of a generator and an infinite bus in parallel supplying a load. Assume that thegenerator's prime mover has a governor mechanism, but the field is controlled manually by aresistor. It is easier to explain synchronous generator operation without considering an automaticfield current regulator, so this discussion will ignore the differences caused by the field regulatorwhenoneis present. Such asystem is shownin Fig.4.6(a).

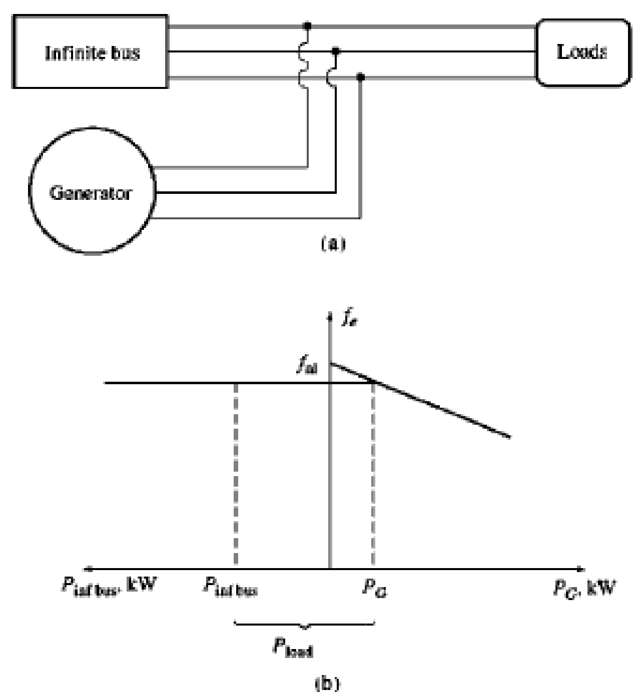


Fig.4.6 (a) Asynchronousgeneratoroperatinginparallelwithaninfinitebus.
(b)Thefrequency-versus-powerdiagram(orhousediagram)forasynchronousgeneratorin parallel withan infinite bus.

When a generator is connected in parallel with another generator or a large system, thefrequencyandterminalvoltageofallthemachinesmustbethesame,sincetheiroutputconductors are tied together. Therefore, their real power frequency and reactive power-voltagecharacteristicscanbeplottedbacktoback,withacommonverticalaxis.Suchasketch, sometimesinformallycalledahousediagram,isshowninFig.4.6(b).Considerthatthegenerator has just been paralleled with the infinite bus according to the previously describedprocedure. Then the generator will be essentially “floating” on the line and supplying a smallamountofrealpower andlittle orno reactivepower.Suchasituationis shownin Fig.4.7.

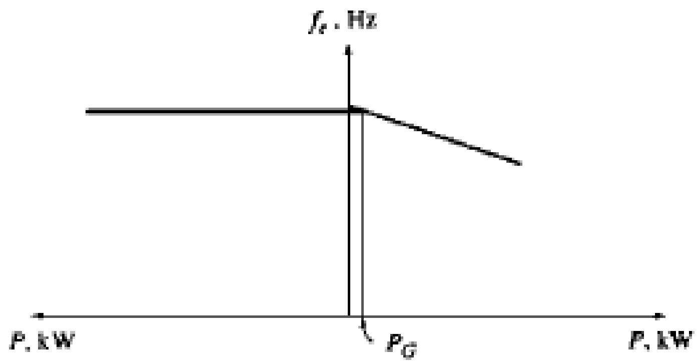


Fig.4.7:Thefrequency-versus-powerdiagram at themomentjustafterparalleling.

Suppose the generator had been paralleledwith the line but, instead of being at a slightly higherfrequency than that of the running system, it was at a slightly lower frequency. In this case,when the process of parallel connectionis completed, the resulting situation can be describedasshown in Fig. 4.8. This characteristic shows that the no-load frequency of the generator is lessthan the system's operating frequency. The power supplied by the generator at this frequency isactually negative. In the other way we can say, when the generator's no-load frequency is lessthan the system's operating frequency, the generator actually consumes electric power instead ofconsumingit that theoncomingmachine'sfrequencyis adjusted

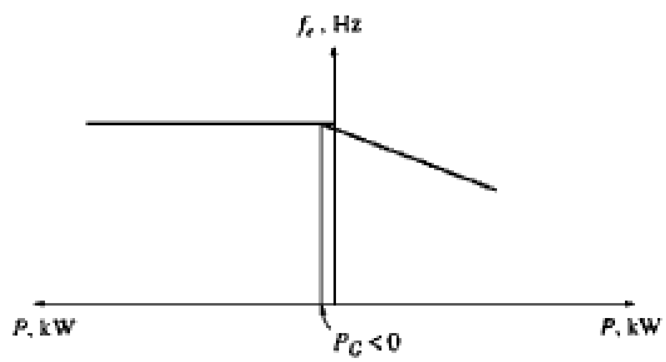


Fig. 4.8:The frequency-versus-power diagram if the no-load frequency of the generator wereslightlyless than systemfrequencybeforeparalleling.

higher than the running system 's frequency. Many of the real generators have a provision forreverse-powertrip,whichisconnectedtothem,soitisimperativethattheycanbeparalleledwith their frequency higher than that of the running system. If such a generator ever starts toconsumepower,it will beautomaticallydisconnected from the line.

What happens when its governor set points are increased and the generator has beenconnected? The effect of this increase is to increase the no-load frequency of the generator. Sincethe frequency of the system is unchanged, the power supplied by the generator increases. This isshown by the house diagram in Fig. 4.9 (a) and phasor diagram in Fig. 4.9 (b). Note that, in thephasor diagram$E$ sin (which is proportional to the power supplied as long as V_T is constant)has increased, while the magnitude of E_A.$(= k\varphi\omega)$remains constant, since both the field current$I_F$and the speed ofrotation ω areunchanged.Asthegovernorsetpoints arefurther increased,the no-loadfrequency increases and the power supplied by the generator increases. Similarly, as thepower outputincreases,$E_A$remains at constant magnitudewhile$E\sin\delta$isfurtherincreased.

What happens in this system if the power output of the generator is increased until itexceeds the power consumed by the load? If this occurs, the extra power generated flows backinto the infinite bus. The infinite bus ideally can supply or consumeany amountof powerwithoutachangeinfrequency,sotheextrapowerwillbeconsumed.Assoonastherealpowerof the generator has been adjusted to the desired value, the phasor diagram of the generator lookslike Fig.4.9 (b).It canbe observed that, at this time the generator is actually operating at aslightly leading power factor, supplying negative reactive power. In other words, the generatorcanbesaid to beconsumingreactivepower.

How can the generator be adjusted so that it will supply some reactive power Q to thesystem?Thiscanbedonebyadjustingthefieldcurrentofthemachine.Tounderstandwhythisis true, it becomes necessary to consider the constraints on the generator's operation under thesecircumstances. The first constraint on the generator is that the power must remain constant when$I_F$is changed. The power into a generator is given by the equation $P_{in}=T_{ind}\omega_m$. Now, the primemover of an alternator has a fixed torque- speed characteristic for any given governor setting.This curve changes only when the governor set points are changed. Since the generator is tied toaninfinitebus,its speedcannotchange.Ifthegenerator'sspeeddoesnotchangeandthegovernor set points have not been changed, the power supplied by the generator must remainconstant.

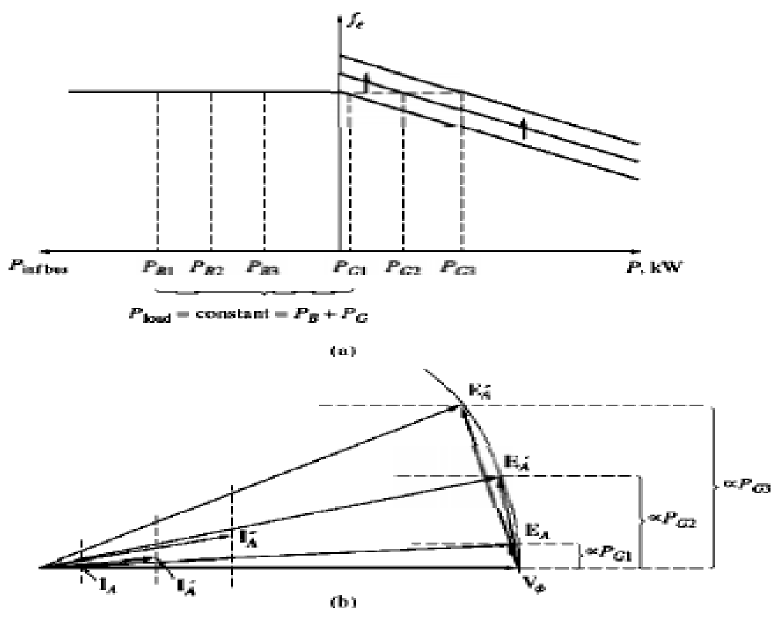


Fig.4.9 Effect of increasing the governor's set points on (a) the house diagram (b) the phasordiagram

Ifthepowersuppliedisconstantasthefieldcurrentischanged,thenthedistancesproportionalto the power in the phasor diagram $(I_A\cos(\theta)$ and E_A. $\sin\delta$)cannot change. When the field currentis increased, the flux Φ increases, and therefore E_A. $(= K\Phi\omega)$ increases. If E_A. increases, but $E_A.\sin\delta$ must remain constant, then the phasorE_A. must "slide" along the line of constant power, asshown in Fig. 4.10. Since V_T is constant, the angle of jX_sI_A. changesas shown, and therefore theangleandmagnitudeof$I_A$changes.Noticethatasaresultthedistanceproportionalto$Q(I_A$sin (θ))increases.Inotherwords,increasingthefieldcurrentinasynchronousgeneratoroperatinginparallel with aninfinitebus increasesthereactivepoweroutput of the generator.

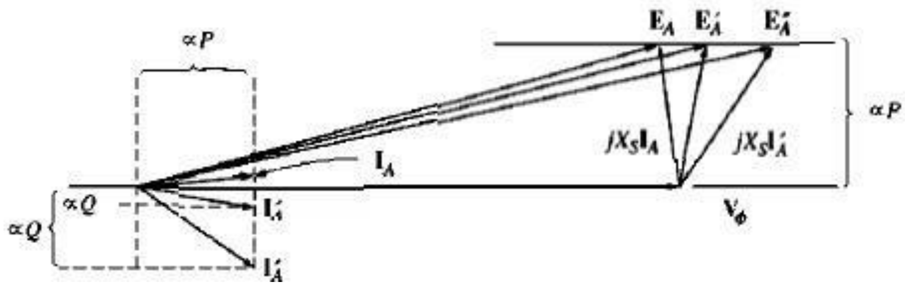


Fig.4.10:Theeffectofincreasingthe generator'sfieldcurrentonthephasor diagramofthemachine.

Tosummarize,when a generatoris operatingin parallelwithaninfinitebus:

1. Thefrequencyandterminalvoltageofthesynchronousgeneratorarecontrolledby thesystemtowhich it is connected.
2. Thegovernorsetpointsofthesynchronousgeneratorcontroltherealpowersuppliedbythegeneratorto thesystem.
3. Thefieldcurrentinthesynchronousgeneratorcontrolsthereactivepowersuppliedbythegeneratorto thesystem.

OperationofGeneratorsinParallelwithOther GeneratorsoftheSame Size

When a single synchronous generator operated individually, the real and reactive powers*(P*and*Q)* suppliedby thegenerator were fixed andconstrainedto be equal to the powerdemanded by the load. Also the frequency and terminal voltage were varied by the governor setpoints and the field current. When a synchronous generator operated in parallel with an infinitebus, the frequency and terminal voltage were necessarily be constant by the infinite bus, and therealandreactivepowers werevaried bythegovernorsetpoints andthefield current.

What will happen when a synchronous generator is connected in parallel not with aninfinite bus, but with another generator of the same size? What will be the effect of changinggovernorset points andfield currents?

If a generator is connected in parallel with another one of the same size, the resultingsystem is as shown in Fig. 4.11(a). In this system, the basic constraint is that the sum of the realand reactive powers supplied by both the two generators must equal the$P$ and Q demanded bythe load. The system frequency is not constrained to be constant, and neither is the power of agivengenerator constrainedtobe constant.The power-frequency diagramforsuchtype ofsystem immediately after G2has been paralleled to the line is shown in Fig. 4.11(b). Here, thetotalpower
$P_{TOT}$is equalto P_{LOAD}isgiven by

$$P_{T0T}=P_{G1}+P_{G2}---------4.4$$

AndthetotalreactivepowerQ_{T0T}isgivenby

$$Q_{T0T}=Q_{G1}+Q_{G2}-----------4.5$$

What happens if the governor set points of *G2* are increased? When the governor set points ofG2are increased, the power-frequency curve of *G2* shifts upward, as shown in Fig. 4.11(c). Thetotal power supplied to the load must not change. At the original frequency f_1, the power suppliedby *G1* and *G2* will now be larger than the load demand, so the system cannot continue to operatewith the same frequency as earlier. There is only one frequency at which the sum of the powersout of the two generators is equal to *PLOAD*. That frequency $f_2$is higher than the original systemoperating frequency. At this frequency, *G2* supplies more power and *G1* supplies less powerthanbefore.

Therefore, when two synchronous generators are operating together, an increase in governor setpointson oneof them will

1. Increasesthesystemfrequency.
2. Increases the power supplied by that generator. while reducing the power supplied by the otherone.

What happens if the field current of *G2* is increased?The resulting behavior is analogous to thereal-power situation and is shown in Fig. 4.11(d). When two generators are operating togetherandthefield current of*G2* is increased,

1. Thesystemterminalvoltageisincreased.
2. The reactive power*Q*supplied by thatgeneratorisincreased,whilethe reactive powersuppliedbythe othergeneratoris decreased.

When two generators of similar size are operating in parallel, a change in the governor setpoints of one of them changes both the system frequency and the power sharing between them. Itwould normally be desired to adjust only one of these quantities at a time. How can the powersharingofthepowersystembeadjustedindependentlyofthesystemfrequency,and viceversa?

The answer is very simple. An increase in governor set points on one generator increasesthat machine's power and increases system frequency. A decrease in governor set points on theothergeneratordecreasesthatmachine'spoweranddecreasesthesystemfrequency.Therefore,to adjust power sharing without changing the system frequency, increase the governor set pointsof one generator and simultaneously decrease the governor set points of the other generator (seeFig. 4.12(a)). Similarly, to adjust the system frequency without changing the power sharing,simultaneouslyincreaseordecreasebothgovernor setpoints(seeFig.4.12(b)).

When two generators of almost similar size are operating in parallel, a change in thegovernor set points of one of them changes both the system frequency and the power sharingbetweenthem.It would bedesiredto adjustonlyoneof thesequantities atatime.

How the power sharing of the power system can be adjusted independently from thesystem frequency, and vice versa? An increase in governor set points of one generator increasesthat machine's power and increases system frequency. A decrease in governor set points on theothergeneratordecreasesthatmachine'spoweranddecreasesthesystemfrequency.Therefore,to adjust power sharing without changing the system frequency, increase the governor set pointsof one generator and simultaneously decrease the governor set points of the other generator (seeFig. 4.12(a)). Similarly, to adjust the system frequency without changing the power sharing,simultaneouslyincreaseordecreasebothgovernor setpoints(seeFig.4.12(b)).

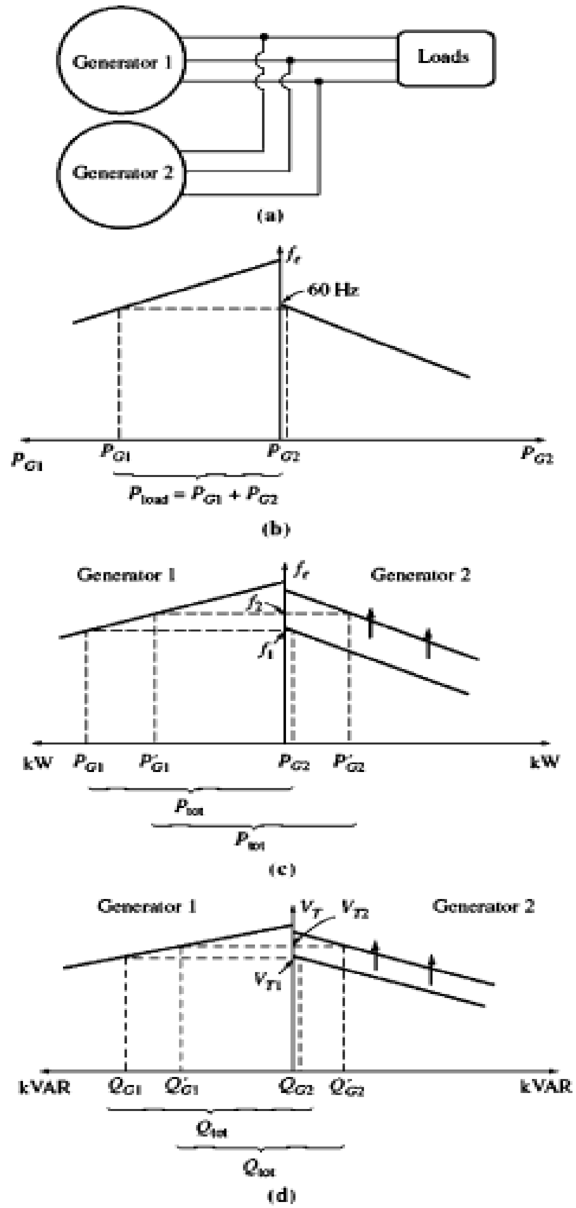


Fig.4.11 (a) A generator Connected in parallel with another machine of the same size. (b) Thecorresponding house diagram at the moment generator 2 is paralleled with the system. (e) Theeffect of increasing generator 2'sgovernor set points on the operation of the system.(d) The effectofincreasing generator 2's field current ontheoperation ofthe system.

The answer is very simple. An increase in governor set points on one generator increasesthat machine's power and increases system frequency. A decrease in governor set points on theothergeneratordecreasesthatmachine'spowleranddecreasesthesystemfrequency.Therefore,to adjust power sharing without changing the system frequency, increase the governor set pointsof one generator and simultaneously decrease the governor set points of the other generator (seeFig. 4.12(a)). Similarly, to adjust the system frequency without changing the power sharing,simultaneouslyincreaseordecreasebothgovernor setpoints(seeFig.4.12(b)).

Reactive power and terminal voltage adjustments work in an analogous fashion. To shiftthe reactive power sharing without changing $V_T$simultaneously increase the field current on onegeneratoranddecreasethefieldcurrentontheother(seeFig.4.12(c)).Tochangetheterminal voltage without affecting the reactive power sharing, simultaneously increase or decrease bothfieldcurrents (seeFig. 4.12(d)).

Tosummarize,inthecaseoftwogeneratorsoperatingtogether:

1. The system is constrained in that the total power supplied by the two generators together mustequaltheamount consumed bytheload. Neitherf_{syn}nor$V_T$is constrained to beconstant.
2. To adjust the real powers sharing between generators without changingf_{syn}simultaneouslyincrease the governor set points on one generator while decreasing the governor set points on theother.Themachinewhosegovernorset pointwasincreased willassumemoreoftheload.
3. To adjust f_{syn}without changing the real power sharing, simultaneously increase or decreasebothgenerators'governor set points.
4. To adjust the reactive power sharing between generators without changing VT, simultaneouslyincrease the field current on one generator while decreasing the field current on the other. Themachinewhosefield current was increasedwill assumemoreofthereactiveload.
5. To adjust V_T without changing the reactive power sharing, simultaneously increase or decreasebothgenerators' field currents.

It is very important that any synchronous generator intended to operate in parallel withother machines have a drooping frequency-power characteristic. If two generators have flat ornearly flat characteristics, then the power sharing between them can vary widely with only thetiniest changes in no-load speed. This problem is illustrated by Fig. 4.13. Notice that even verytiny changes in f_{nl}in one of the generators would cause wild shifts in power sharing. To ensuregood control of power sharing between generators, they should have speed droops in the range of2to 5 percent.

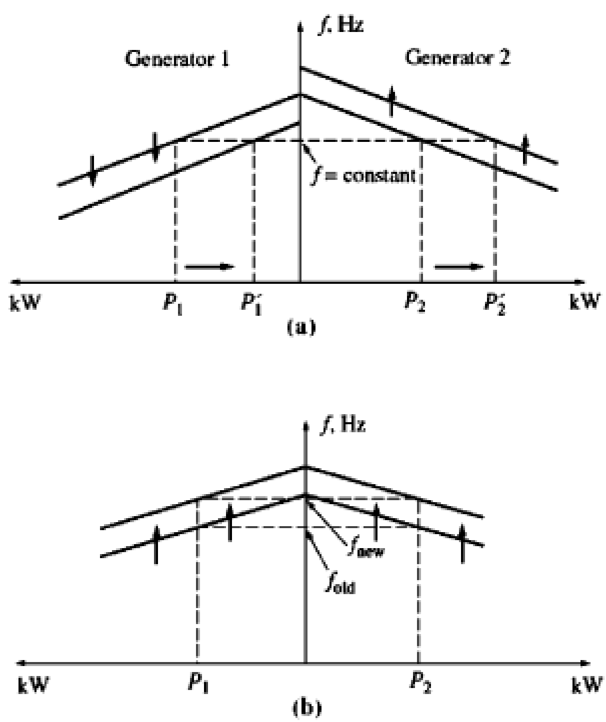
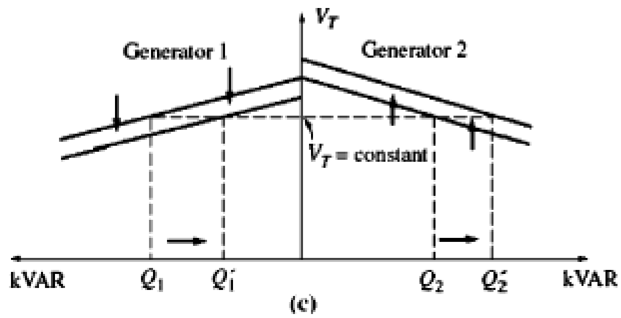


Fig. 4.12 (a) Shifting power sharing without affecting system frequency. (b) Shiftingsystemfrequencywithout affectingpower sharing.



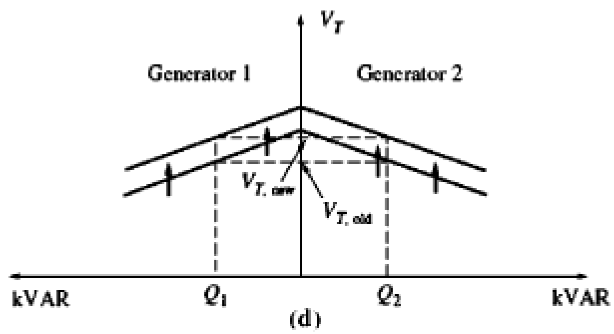


Fig.4.12(c)Shiftingreactivepowersharingwithoutaffectingterminalvoltage.(d)Shiftingterminal voltage without affectingreactivepower sharing.

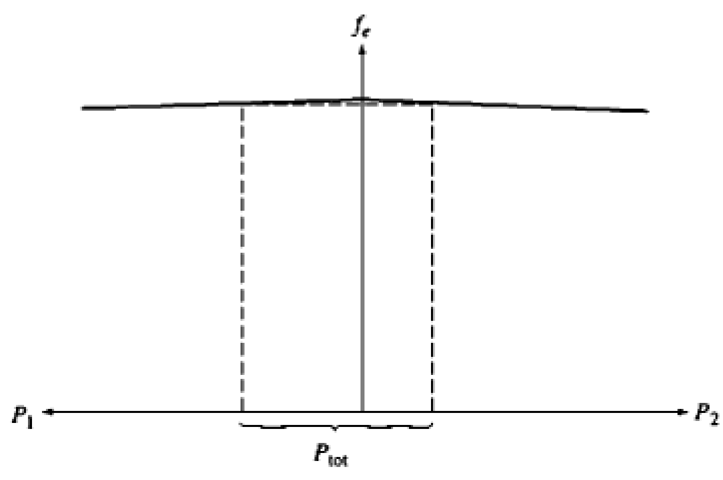


Fig. 4.13: Two synchronous generators with flat frequency-power characteristics. A verytiny change in the no load frequency of either of these machines could cause huge shifts in thepowersharing.

MODULE-II

CHAPTER-5

Three PhaseSynchronousMotor

Introduction:

In order to understand the principle of operation of a synchronous motor, let us examinewhathappensifweconnectthearmaturewinding(laidoutinthestator)ofa3-phasesynchronous machine to a suitable balanced 3-phase source and the field winding to a D.C sourceof appropriate voltage. The current flowing through the field coils will set up stationary magneticpoles of alternate North and South. (for convenience let us assume a salient pole rotor, as shownin Fig. 50). On the other hand, the 3-phase currents flowing in the armature winding produce arotating magnetic field rotating at synchronous speed. In other words there will be moving Northand South poles established in the stator due to the 3-phase currents i.e at any location in thestator there will be a North pole at some instant of time and it will become a South pole after atimeperiodcorrespondingtohalfacycle.(Afteratime= $\frac{1}{2f}$,wheref=frequencyofthe

supply).LetusassumethatthestationarySouthPoleintherotorisalignedwiththeNorthPolein the stator moving in clockwise direction at a particular instant of time, as shown in Fig. 5.1.Thesetwo polesget attracted andtryto maintain this alignment(as

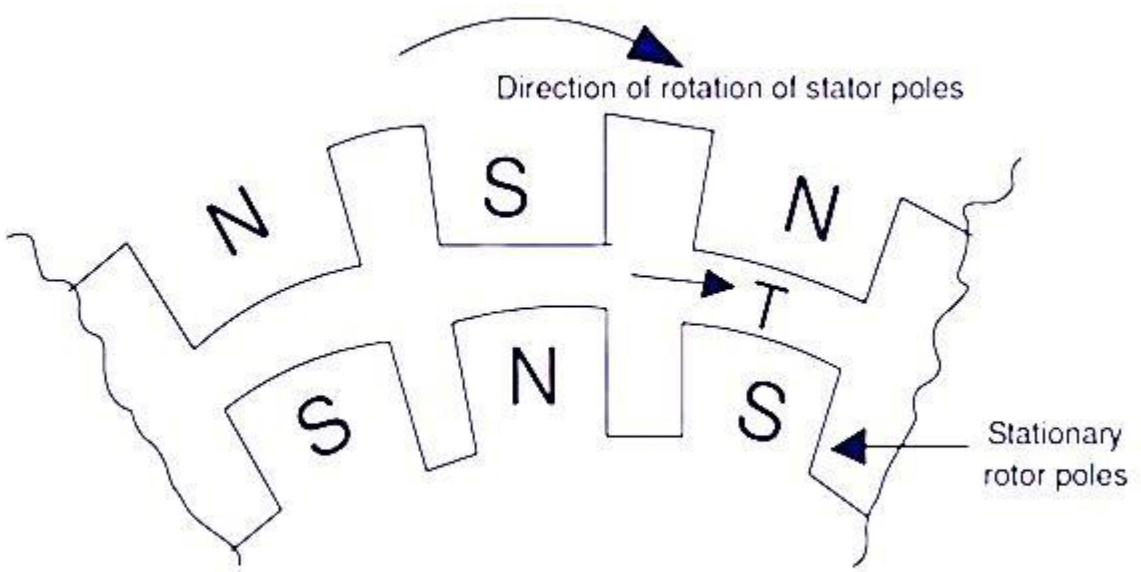


Fig.5.1:Forceofattractionbetween statorpoles androtor poles-resultingin productionoftorqueinclockwisedirection

Per lenz's law) and hence the rotor pole tries to follow the stator pole as the conditions aresuitable for the production of torque in the clockwise direction. However the rotor can not moveinstantaneouslyduetoitsmechanicalinertia,andsoitneedssometimetomove.Inthemeantime,the statorpolewouldquickly(atimedurationcorrespondingtohalfacycle)changeits polarity and becomes a South Pole. So the force of attraction will no longer be present andinstead the like poles experience a force of repulsion as shown in Fig. 5.2. In other words, theconditions are now suitable for the production of torque in the anticlockwise direction. Even thisconditionwillnotlastlongerasthestatorpolewouldagainchangetoNorthPoleafteratimeof $\frac{1}{2f}$.Thustherotorwillexperienceanalternatingforcewhichtriestomoveitclockwiseand

anticlockwiseattwicethefrequencyofthesupply,i.e.atintervalscorrespondingto= $\frac{1}{2f}$seconds.Asthisdurationisquite smallcomparedtothemechanicaltimeconstantof therotor,

therotor cannotrespondand movein anydirection.Therotorcontinues tobestationaryonly.

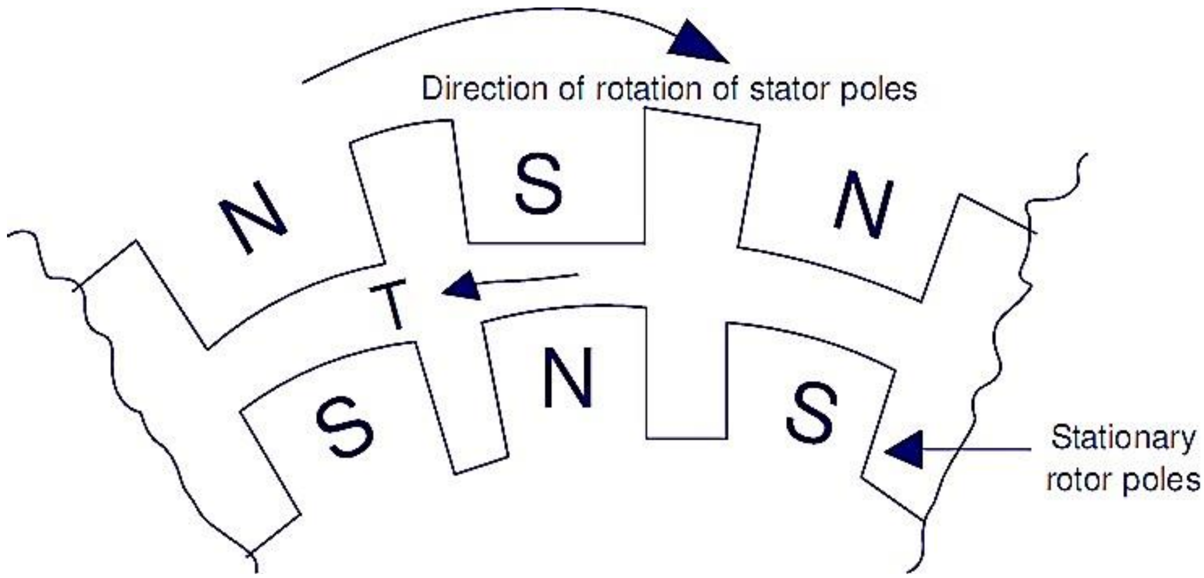


Fig. 5.2: Force of repulsion between stator poles and rotor poles - resulting inproductionoftorquein anticlockwise direction.

On the contrary if the rotor is brought to near synchronous speed by some external meanssay a small motor (known as pony motor-which could be a D.C or AC induction rotor) mountedon the same shaft as that of the rotor, the rotor poles get locked to the unlike poles in the statorand the rotor continues to run at the synchronous speed even if the supply to the pony motor isdisconnected.

Thus the synchronous rotor cannot start rotating on its own or usually we say that thesynchronous rotor has no starting torque. So, some special provision has to be made either insidethe machine or outside of the machine so that the rotor is brought to near about its synchronousspeed. At that time, if the armature is supplied with electrical power, the rotor can pull into stepand continue to operate at its synchronous speed. Some of the commonly used methods forstartingsynchronous rotor aredescribed in thefollowingsection.

:Methodsofstartingsynchronousmotor:

Basicallytherearethreemethods that areusedtostart asynchronous motor:

• To reduce the speed of the rotating magnetic field of the stator to a low enough value that therotor can easily accelerate and lock in with it during one half-cycle of the rotating magneticfield'srotation.Thisisdone by reducing thefrequency of theappliedelectric power. Thismethodisusuallyfollowedinthecaseofinverter-fedsynchronousmotoroperatingundervariablespeed drive applications.

• To use an external prime mover to accelerate the rotor of synchronous motor near to itssynchronous speed and then supply the rotor as well as stator. Of course care should be taken toensure that the directions of rotation of the rotor as well as that of the rotating magnetic field ofthe stator are the same. This method is usually followed in the laboratory- the synchronousmachineisstartedasageneratorandisthenconnectedtothesupplymainsbyfollowingthe synchronizationorparallelingprocedure.Thenthepowersupplytotheprimemoverisdisconnectedso that thesynchronous machine will continueto operate as a motor.

• To use damper windings or amortisseur windings if these are provided in the machine. Thedamper windings or amortisseur windings are provided in most of the large synchronous motorsin order to nullify the oscillations of the rotor whenever the synchronous machine is subjected toaperiodicallyvaryingload.

Eachofthesemethodsofstartingasynchronousmotoraredescribedbelow indetail.

MotorStartingbyreducingthesupplyFrequency

If the rotating magnetic field of the stator in a synchronous motor rotates at a low enoughspeed, there will be no problem for the rotor to accelerate and to lock in with the stator'smagnetic field. The speed of the stator magnetic field can then be increased to its rated operatingspeedbygraduallyincreasingthe supplyfrequency'f' up to itsnormal 50-or60-Hz value.

This approach to starting of synchronous motors makes a lot of sense, but there is a bigproblem:Wherefromcanwegetthevariablefrequencysupply?Theusualpowersupplysystems generally regulate the frequency to be 50 or 60 Hz as the case may be. However,variable-frequency voltage source can be obtained from a dedicated generator only in the oldendays and such a situation was obviously impractical except for very unusual or special driveapplications. But the present day solid state power converters offer an easy solution to this. Wenow have the rectifier- inverter and cycloconverters, which can be used to convert a constantfrequency AC supply to a variable frequency AC supply. With the development of such modernsolid-state variable-frequency drive packages, it is thus possible to continuously control thefrequency of the supply connected to the synchronous motor all the way from a fractionof ahertz up to and even above the normal rated frequency. If such a variable-frequency drive unit isincluded in a motor-control circuit to achieve speed control, then starting the synchronous motoris very easy-simply adjust the frequency to a very low value for starting, and then raises it up tothe desired operating frequency for normal running. When a synchronous motor is operated at aspeed lower than the rated speed, its internal generated voltage (usually called the counter EMF)$E= K f \omega$ will be smaller than normal. As such the terminal voltage applied to the motor must bereduced proportionally with the frequency in order to keep the stator current within the ratedvalue. Generally, the voltage inany variable-frequency power supply variesroughly linearlywiththeoutput frequency.

MotorStartingwithanExternalMotor:

The second method of starting a synchronous motor is to attach an external starting motor(pony motor) to it and bring the synchronous machine to near about its rated speed (but notexactly equal to it, as the synchronization process may fail to indicate the point of closure of themain switch connecting the synchronous machine to the supply system) with the pony motor.Then the output of the synchronous machine can be synchronised or paralleled with its powersupply system as a generator, and the pony motor can be detached from the shaft of the machineor the supply to the pony motor can be disconnected. Once the pony motor is turned OFF, theshaft of the machine slows down, the speed of the rotor magnetic field B_R falls behind B_{net},momentarily and the synchronous machine continues to operate as a motor. As soon as it beginsto operate as a motor the synchronous motor can be loaded in the usual manner just like anymotor.

This whole procedure is not as cumbersome as it sounds, since many synchronous motorsarepartsofmotor-generatorsets,andthesynchronousmachineinthemotor-generatorsetmaybe started with the other machine serving as the starting motor. Moreover, the starting motor isrequiredtoovercome only the mechanicalinertia of the synchronousmachine withoutanymechanical load (load is attached only after the synchronous machine is paralleled to the powersupply system). Since only the motor's inertia must be overcome, the starting motor can have amuch smaller rating than the synchronous motor it is going to start. Generally most of the largesynchronous motors have brushless excitation systems mounted on their shafts. It is then possibleto use these exciters as the starting motors. For many medium-size to large synchronous motors,an external starting motor or starting by using the exciter may be the only possible solution,because the power systems they are tied to may not be able to handle the starting currents neededtouse thedamper(amortisseur) windingapproachdescribed next.

MotorStartingbyUsingdamper (Amortisseur)Winding:

As already mentioned earlier most of the large synchronous motors are provided with damperwindings, in order to nullify the oscillations of the rotor whenever the synchronous machine issubjected to a periodically varying load. Damper windings are special bars laid into slots cut inthepolefaceofasynchronousmachineandthenshortedoutoneachendbyalargeshortingring,similarto thesquirrelcagerotorbars.Apolefacewithasetofdamperwindingsisshownin Fig.. When the stator of such a synchronous machine is connected to the 3-Phase AC supply,the machine starts as a 3-Phase induction machine due to the presence of the damper bars, justlike a squirrel cage induction motor. Just as in the case of a 3-Phase squirrel cage inductionmotor, the applied voltage must be suitably reduced so as to limit the starting current to the saferated value. Once the motor picks up to a speed near about its synchronous speed, the DC supplyto its field winding is connected and the synchronous motor pulls into step i.e. it continues tooperate as a Synchronousmotorrunningat its synchronous speed.

:Behaviour ofasynchronousmotor

The behaviour of a synchronous motor can be predicted by considering its equivalentcircuiton similarlinesto that of asynchronousgeneratorasdescribed below.

Equivalentcircuitmodeland phasordiagramof asynchronousmotor:

The equivalent-circuit model for one armature phase of a cylindrical rotor three phasesynchronous motor is shown in Fig. 5.3 exactly similar to that of a synchronous generator exceptthat the currentflows in to the armature from the supply. All valuesare given per phase.ApplyingKirchhoff's voltagelawto Fig. 5.3.

$$V = I_a R_a + \mathbf{j} I (X_l + X_{as}) + E_f \qquad 5.1$$

Combiningreactances,wehave,

$$X_s = X_l + X_{as} \qquad 5.2$$

SubstitutingEqn. 5.2 inEqn. 5.1

$$V = I (R_a + \mathbf{j} X_s) + E_f \qquad 5.3$$

$$V = I_a Z_s + E_f \qquad 5.4$$

Where:

R_a=armatureresistance(Ω/phase)

X_l=armatureleakagereactance(Ω/phase)X

s=synchronousreactance(Ω/phase)

Zs=synchronousimpedance(Ω/phase)
VT=appliedvoltage/phase(V)I
a=armaturecurrent/phase(A)

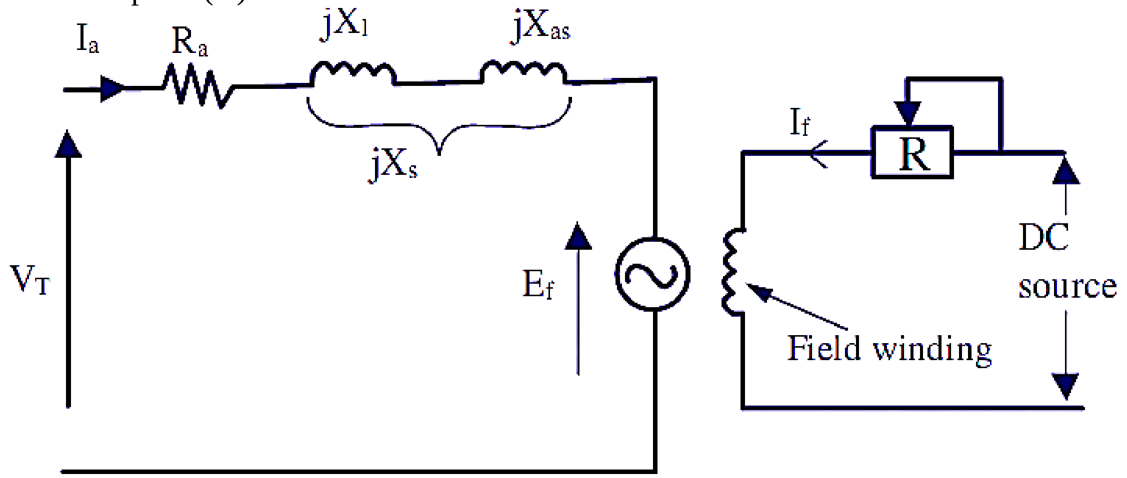


Fig.5.3:Equivalent-circuitmodel foronephaseofasynchronous motorarmature

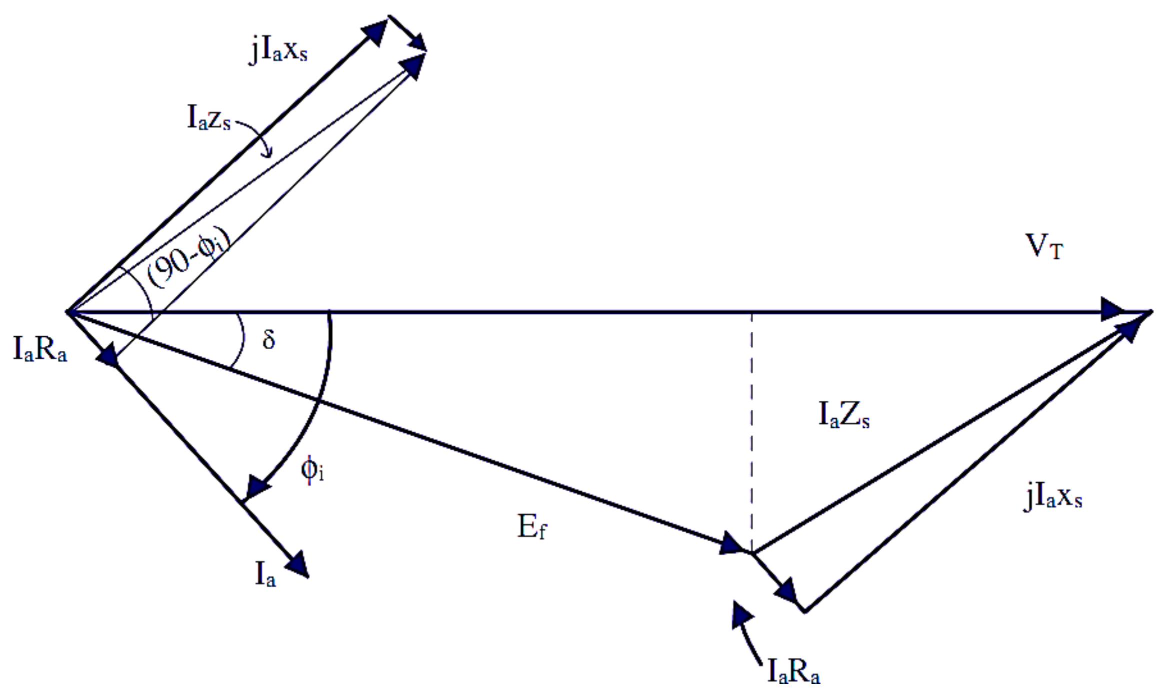


Fig.5.4:Phasordiagramcorrespondingtotheequivalent-circuit model.

ThephasordiagramshowninFig.5.4,illustratesthemethodofdeterminingthecounterEMFwhichis obtained from thephasor equation;

$$E_f = V_T - I_a Z_s \qquad 5.5$$

Thephaseangleδbetweentheterminalvoltage VTandtheexcitationvoltageEinFig.5.4is usuallytermedthe torque angle. Thetorqueangleis alsocalled theloadangle orpowerangle.

Synchronous-motorpowerequation:

Exceptforvery smallmachines,thearmatureresistanceofasynchronousmotorisrelativelyinsignificantcomparedtoits synchronousreactance,sothatEqn.5.4tobeapproximated to

$V = I_a jX_s + E_f$ 5.6

The equivalent-circuit and phasor diagram corresponding to this relation are shown in Fig. 5.5(a)and Fig. 5.5(b). These are normally usedforanalysing the behaviour ofa synchronous motor,duetochangesinloadand/or changesinfield excitation.Fromthis phasor diagram,wehave,

$I_a X_s \cos\theta_i = -E_f \sin\delta$ 5.7

MultiplyingthroughbyVTand rearrangingtermswehave,

$I_a \cos\theta_i = \frac{-V_T E_F}{X_s} \sin\delta$ 5.8

Since the left side of Eqn. 5.8 is an expression for active power input and as the windingresistance is assumed to be negligible this power input will also represent the electromagneticpowerdeveloped, per phase, bythe synchronous motor. Thus,

$P_{in/ph} = V_T I_a \cos\theta_i$ 5.9

Or,

$P_{in,h} = \frac{-V_T E_F}{X_s} \sin\delta$ 5.10

$P_{in,h} = 3 * \frac{-V_T E_F}{X_s} \sin\delta$ 5.11

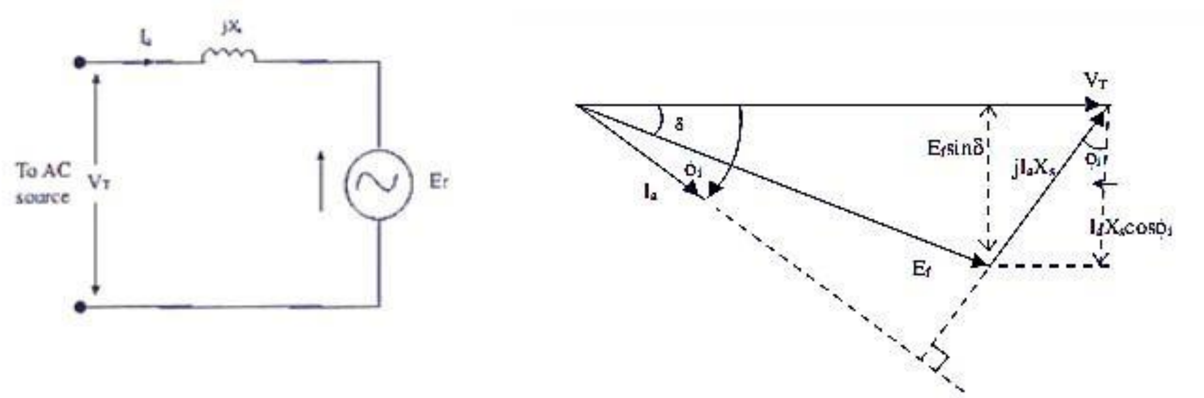
Thus,forathree-phasesynchronousmotor,

$P_{in} = 3 V_T I_a \cos\theta_i$ 5.12

Eqn.5.10,calledthesynchronous-machinepowerequation,expressestheelectromagneticpower developed per phase by a cylindrical-rotor motor, in terms of its excitation voltage andpower angle. Assuming a constant source voltage and constant supply frequency, Eqn. 5.9 andEqn. 5.10 may be expressed as proportionalities that are very useful for analyzing the behaviourofasynchronous-motor:

$P \alpha I_a \cos\theta_i$ 5.13

$P \alpha E_f \sin\delta$ 5.14



(a) (b)

Fig.5.5:(a)Equivalent-circuitofasynchronous-motor,assumingarmatureresistanceisnegligible. (b) Phasor diagram model for a synchronous-motor, assuming armature resistance isnegligible

Effectofchangesinloadonarmaturecurrent,powerangle,andpowerfactorofsynchronousmotor

The effects of changes in mechanical or shaft load on armature current, power angle, and powerfactorcan be seen from the phasor diagramshown inFig. 56;Asalready stated, theappliedstator voltage, frequency, and field excitation are assumed, constant. The initial load conditionsare represented by the thick lines. The effect of increasing the shaft load to twice its initial valueare represented by the light lines indicating the new steady state conditions. These are drawn inaccordance with Eqn. 69 and Eqn. 70, when the shaft load is doubled both $Ia\ \ cos\ ø$iand$Ef\ \ sin\ \ \delta$are doubled. While redrawing the phasor diagrams to show new steady-state conditions, the lineof action of the new jIaX$_s$phasor must be perpendicular to the new I$_a$phasor. Furthermore, asshown in Fig. 5.66, if the excitation is not changed, increasing the shaft load causes the locus ofthe E$_f$phasor to follow a circular arc, thereby increasing its phase angle with increasing shaftload. Note also that an increase in shaft load is also accompanied by a decrease in $ø_i$ resulting inan increase in power factor. As additional load is placed on the machine, the rotor continues toincrease its angle of lag relative to the rotating magnetic field, thereby increasing both the angleof lag of the counter EMF phasor and the magnitude of the stator current. It is interesting to notethatduringallthisloadvariation,however,exceptforthedurationoftransientconditionswhereby the rotor assumes a new position in relation to the rotating magnetic field, the averagespeed of the machine does not change. As the load is being increased, a final point is reached atwhich a further increasein δ fails to cause a corresponding increase inmotor torque, and therotor pulls out of synchronism. In fact as stated earlier, the rotor poles at this point, will fallbehind the stator poles such that they now come under the influence of like poles and the force ofattraction no longer exists. Thus, the point of maximum torque occurs at a power angle ofapproximately 90^{0}for a cylindrical-rotor machine, as is indicated by Eqn. 5.12. This maximumvalue of torque that causes a synchronous motor to pull out of synchronism is called the pull-outtorque. In actual practice, the motor will never be operated at power angles close to 90^{0}asarmaturecurrent will bemanytimes its rated value at thisload.

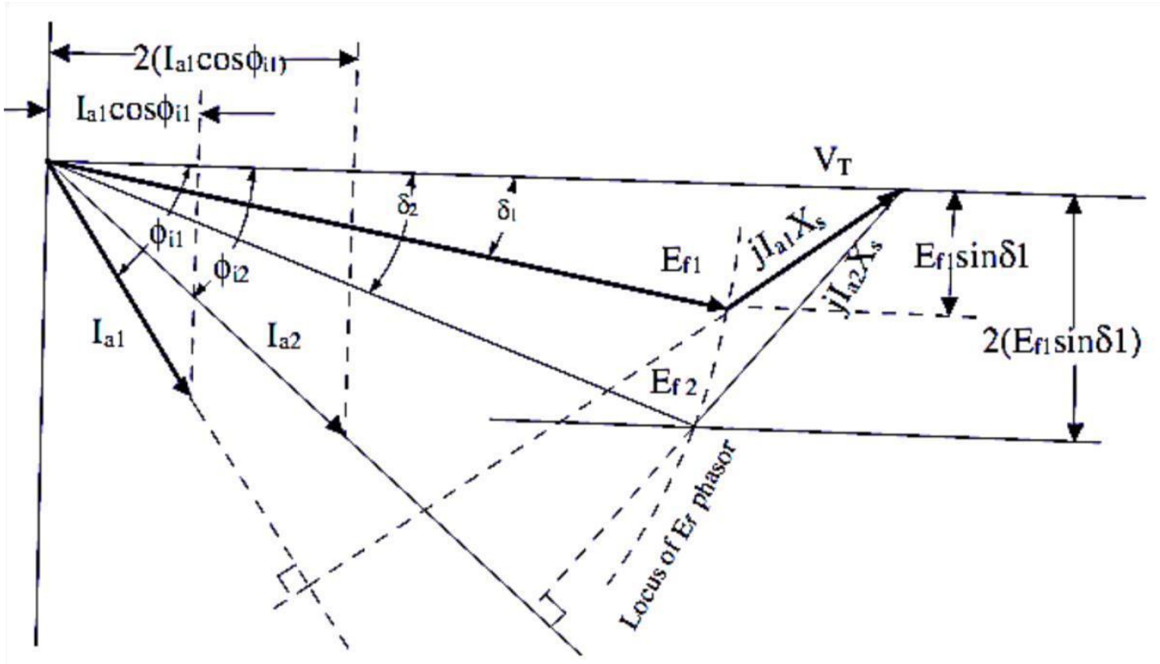


Fig. 5.6: Phasor diagram showing effect of changes in shaft load on armature current, powerangleand power factor of asynchronous motor.

Effectofchangesinfieldexcitationonsynchronousmotorperformance:

Intuitively we can expect that increasing the strength of the magnets will increase the magneticattraction, and thereby cause the rotor magnets to have a closer alignment with the correspondingopposite poles of the rotating magnetic poles of the stator. This will obviously result in a smallerpower angle. This fact can also be seen in Eqn. 5.11 When the shaft load is assumed to beconstant, the steady-state value of $Ef \ \ sin\delta$must also be constant. An increase in Efwill cause atransient increase in$Ef \ \ sin$, and the rotor will accelerate. As the rotor changes its angularposition, δ decreases until $Ef \ \ sin\delta$has the same steady-statevalue as before, at which time therotor is again operating at synchronous speed, as it should run only at the synchronous speed.This change in angular position of the rotor magnets relative to the poles of rotating magneticfield of the stator occurs in a fraction of a second. The effect of changes in field excitation onarmaturecurrent,powerangle,andpowerfactorofasynchronousmotoroperating withaconstant shaft load, from a constant voltage, constant frequency supply, is illustrated in Fig. 5.7.FromEqn. 5.13, wehaveforaconstant shaft load,

$Ef1sin\delta = f2sin\delta = Ef3sin\delta = Efsin\delta$ 5.15

This is shown in Fig. 5.7, where the locus of the tip of the Efphasor is a straight line parallel totheVT phasor. Similarly,fromEqn. 5.13 foraconstantshaft load,

$Ia1cos\text{Ø}i1 = Ia2\ cos\text{Ø}i2 = Ia3\ cos\text{Ø}i3 = Iacos\text{Ø}i$ 5.16

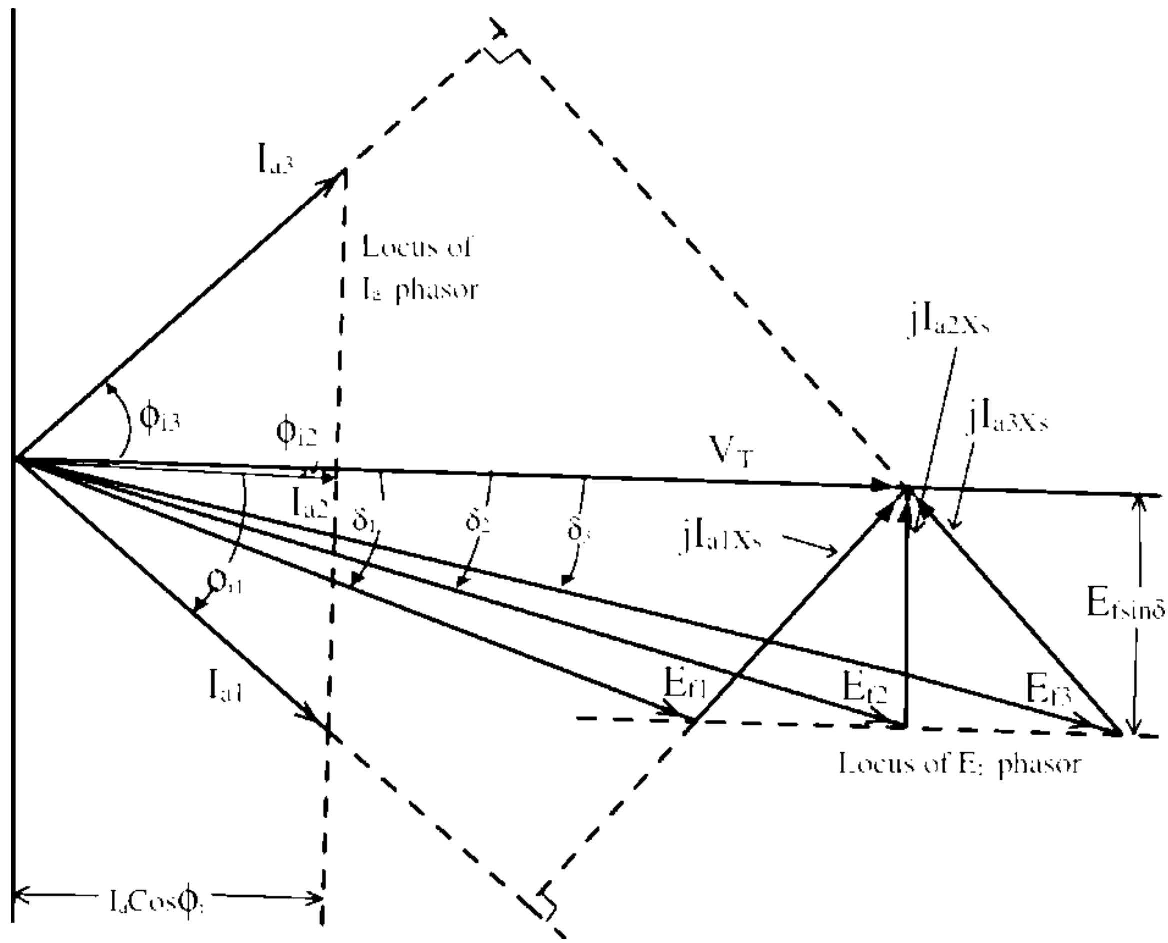


Fig.5.7:Phasordiagramshowingeffectofchangesinfieldexcitationonarmaturecurrent,poweranglean d power factor ofasynchronous motor
ThisisalsoshowninFig.5.7,where thelocusofthetipoftheIaphasorisalineperpendiculartotheVT phasor.

Note that increasing the excitation from Ef1 to Ef3 in Fig. 5.7 caused the phase angle ofthe current phasor with respect to the terminal voltage V (and hence the power factor) to go fromlagging to leading. The value of field excitation that results in unity power factor is called normalexcitation. Excitation greater than normal is called over excitation, and excitation less thannormal is called under excitation. Furthermore, as indicated in Fig. 5.7, when operating in theoverexcited mode, $|Ef| > |VT|$. In fact a synchronous motor operating under over excitationconditionis sometimes called asynchronouscondenser.

Vcurves

Curves of armature current vs. field current (or excitation voltage to a different scale) arecalled V curves, and are shown in Fig. 58 for typical values of synchronous motor loads. Thecurves are related to the phasor diagram in Fig. 5.7, and illustrate the effect of the variation offield excitation on armature current and power factor for typical shaft loads. Itcan be easilynoted from these curves that an increase in shaft loads require an increase in field excitation inorderto maintain thepower factor at unity.

The locus of the left most point of the V curves in Fig. 5.8 represents the stability limit (δ=-90).Any reduction in excitation below the stability limit for a particular load will cause the rotor topulloutof synchronism.

The V curves shown in Fig. 5.8 can be determined experimentally in the laboratory byvarying I_f at constant shaft load and noting Iaas I_f is varied. Alternatively the V curves shown inFig. 5.8 can be determined graphically by plotting |Ia|vs.|Ef| from a family of phasor diagrams asshownin Fig. 5.7,or from thefollowingmathematical expressionfor the Vcurves

$$(I_a X_S)^2 = V_T^2 + E_f^2 - 2V_T E_f \cos\delta \qquad 5.16$$

$$= V_T^2 + E_f^2 - 2V_T E_f \sqrt{1 - Sin^2\delta}$$

$$= V_T^2 + E_f^2 - 2\sqrt{V_T^2 E_f^2 - V_T^2 E_f^2 Sin^2\delta}$$

$$I_a = \frac{1}{X_S}\sqrt{V_T^2 + E_f^2 - 2\sqrt{V_T^2 E_f^2 - X_S^2 P_{in.ph}^2}} \qquad 5.17$$

Eqn. 5.17 is based on the phasor diagram and the assumption that Rais negligible. It is tobenoted that instability will occur, if the developed torque is less than the shaft load plus frictionandwindagelosses,and the expressionunder thesquareroot sign willbenegative.

The family of V curves shown in Fig. 5.8 represent computer plots of Eqn. 5.17, by taking thedatapertainingtoa three-phase10 hp synchronousmotori.eVph=230Vand Xs=1.2Ω/phase.

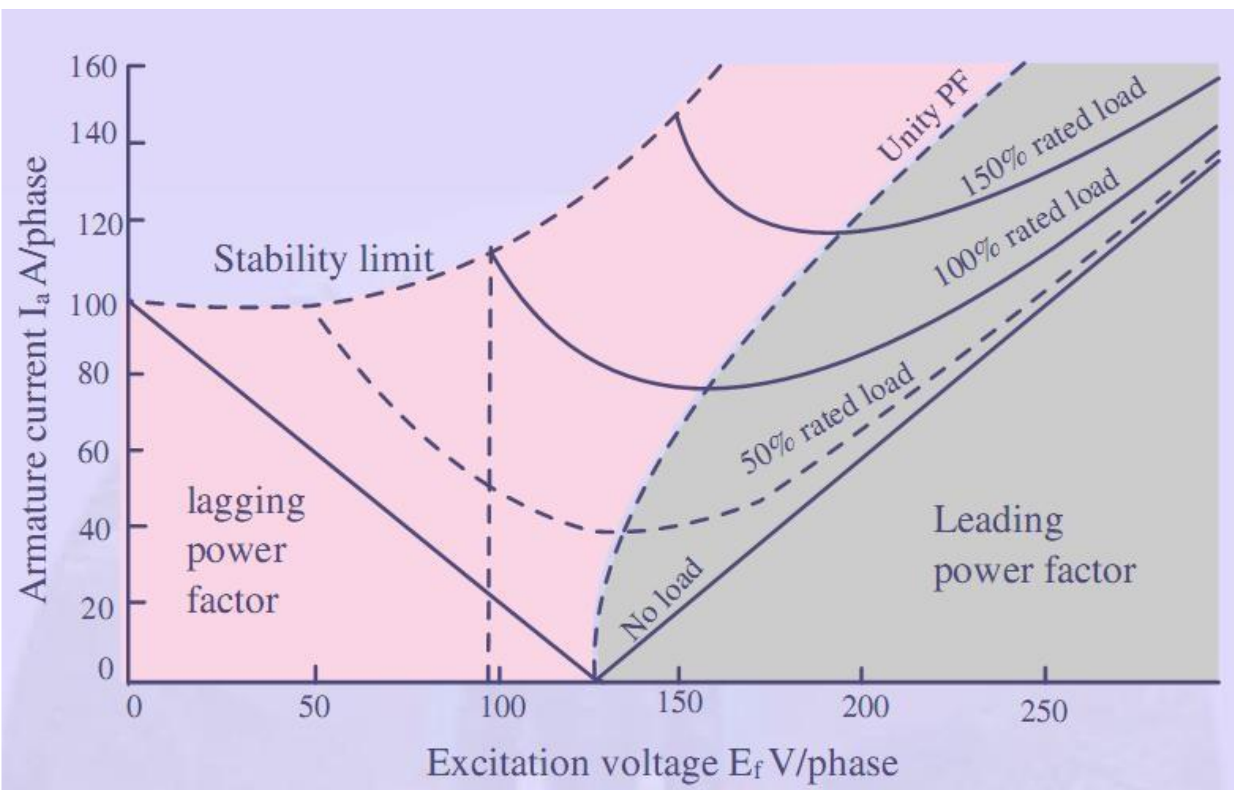


Fig.5.8:Familyofrepresentative Vcurves for asynchronous motor

Synchronous-motorlossesandefficiency:

The flow of power through a synchronous motor, from stator to rotor and then to shaft output, isshown in Fig. 5.9. As indicated in the power-flow diagram, the total power loss for the motor isgiven by

$$P_{loss}=P_{scl}+P_{cor}+P_{fcl}+P_{f,w}+P_{stray}\ \mathrm{W} \qquad 5.18$$

where:
Pscl= stator-copper lossPfcl = field-copper.lossP_{core}=coreloss
Pf,w=frictionandwindagelossPs tray=strayload loss

Except for the transient conditions that occur when the field current is increased or decreased(magnetic energy storedor released), the total energy supplied to thefield coils is constant andall of it is consumed as I^2R losses in the field winding. Just as in the case of the synchronousgenerator,theoverall efficiencyofasynchronousmotoris given by

$$5=\frac{P_{shaft}}{P_{in}+P_{field}}=\frac{P_{shaft}}{P_{shaft}+P_{loss}} \qquad 5.19$$

Generally,thenameplatesofsynchronousmotorsandmanufacturers'specificationsheetscustomarily provide the overall efficiency for rated load and few load conditions only. Hence,onlythetotallossesattheseloadscanbedetermined.Theseparationoflossesintothecomponentslisted inEqn.5.18needsaveryinvolvedtestprocedureinthelaboratory.However,a closer approximation of the mechanical power developed can be calculated by subtracting thecopper losses of the armature and field winding if these losses can be calculated. The shaft powercanthenbecalculatedsubtractingthemechanicallossesfromthemechanical powerdeveloped.

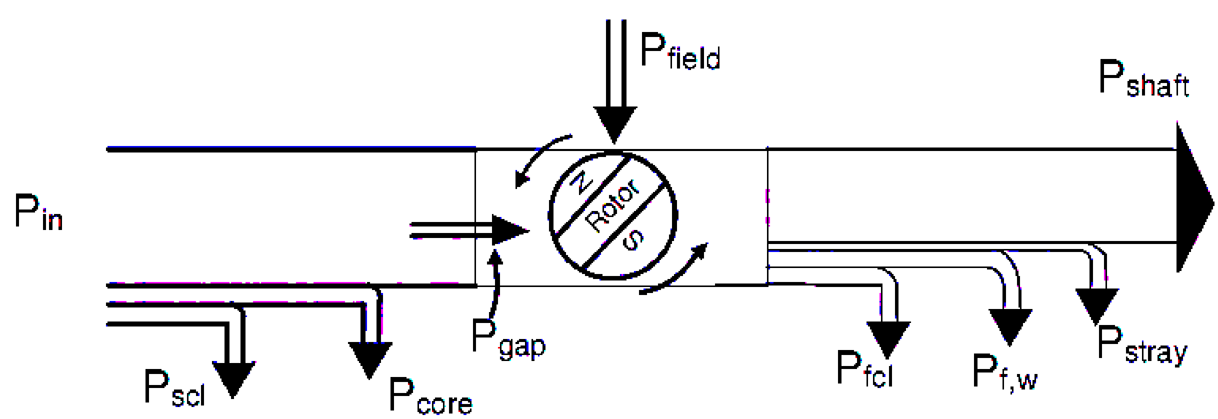


Fig.5.9:Power flowdiagramforasynchronousmotor

v =velocityofthebar*relative tothemagneticfield*

B=magneticfluxdensityvector
I=length ofconductor in themagneticfield

MODULE-III

CHAPTER-6

Three PhaseTransformer

Objective:

Afterstudyingthis unit, thestudents will be able to

- Identifythecommontypes oftransformersfrom theirschematicdiagrams.
- choosethecorrecttransformerkVAfortheapplication,giventhevoltage,current,andphaserequirement ofaload
- Pointouttheadvantagesanddisadvantageofconnectingabankof3-phase transformer.
- Connecttwotransformersinparallelproperly.
- Convertabalance3-phasetobalance2-phaseandviceversawithsuitabletransformationconnections.

Introduction:

Modern electrical systems are almost exclusively three-phase systems, which has beenadopted world over to generate, transmit and distribute electrical power. Therefore to change thelevelof voltages in thesystem threephasetransformers should be used.

When two poly phase systems have different voltages and/or phase angles, these systemscan be interconnected using transformers having various possible types of connections. Any oneof these connections can be accomplished either with a bank of single-phase transformers or by asingle polyphasetransformer.

Apoly-phasetwo-windingtransformercontainsanumberofsetsofprimaryandsecondary windings. Each set wound around a separate magnetic core leg. A three-phase two-winding transformer has three sets of primary and secondary windings, and a two-phase two-windingtransformerhastwo sets of primaryand secondarywindings.

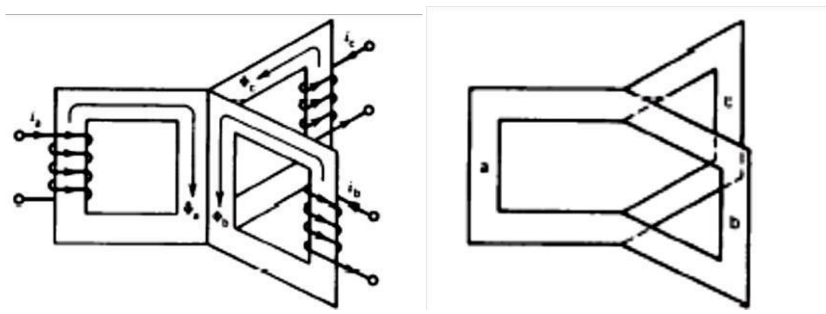
InElectricalMachine-Ithebasictheoryofoperationofatwo-windingtransformerandthe transformer laws were discussed. This chapter focuses, the principles of the two-windingtransformerareapplied to polyphasesystems.

Construction:

Athree-phasetransformercanbeconstructedbyhavingthreeprimaryandthreesecondary windings on a common magnetic circuit as shown in Fig. 6.1(i). The primaries as wellas secondarymaybeconnected in star ordelta.

Here three, single phase transformersare so placed that they share a common centrallimb. The primary and the secondary windings of each phase are placed on their outer limbs. Iftheprimarywindingsareconnectedtoabalanced3-phasesupply,thefluxes$\phi_A(t)$,$\phi_B(t)$and

$\phi_C(t)$ will be produced in the cores differing in time phase mutually by 120°. The return paths ofthese fluxes are through the central limb of the core structure. In other words the central limbcarries sum of these three fluxes. Since instantaneous sum of the fluxes, $\phi_A(t) + \phi_B(t) + \phi_C(t)$ =0 ,no flux lines will exist in the central limb at any time. As such the central limb can be removedwithout affecting the working of the transformer; this modification gives a three leg core type 3-phasetransformeras shown in fig6.1(ii).



(i) (ii)

Fig.6.1 Threephase core typetransformer

Inthiscase,anytwolegswillactasareturnpathforthefluxinthethirdleg.Forexample,ifflux is ϕ in one leg at some instant, then flux are ϕ /2 in the opposite direction through the othertwolegsat thesameinstant.

A further simplification of the structure can be obtained by bringing the limbs in the sameplane as shown in the figure 6.2. In core structure of figure 6.1, we note that the reluctance seenby the three fluxes are same, Hence magnetizing current will be equal in all the three phases. Inthe simplified core structure of figure 6.2, reluctance encountered by the flux $\phi_B(t)$ is differentfromthereluctanceencounteredbyfluxes$\phi_A(t)$and$\phi_C(t)$,hencethemagnetizingcurrentsortheno load currents drawn will remain slightly unbalanced. This degree of unbalanced for no loadcurrent has practically no influence on the performance of the loaded transformer. Transformerhavingthis typeofcorestructureiscalled thecoretype transformer.

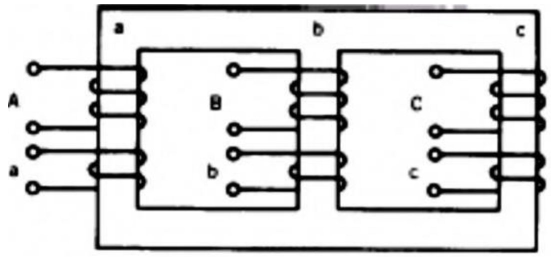
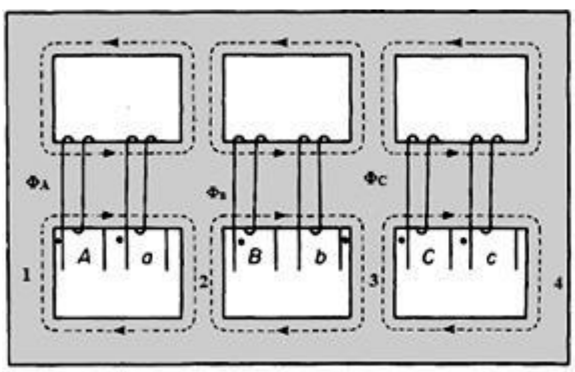


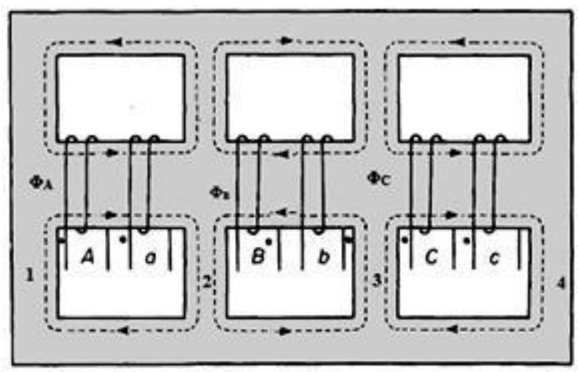
Fig.6.2Simplifiedthree phasethreelimbcoretypetransformer

A 3-phase shell type transformer can be obtain by placing three single phase transformers side bysideasshowninfig.6.3.Inthemagneticcircuits2and3thenetfluxisfoundtobetheresultant ofhalfofthefluxproducebytwophasesatanyinstant,whichis86.6%ofthefluxproducebyonephase.Inthe centralareathefluxis$\phi=\phi_A=\phi_B=\phi_C$.Thefluxcarriedbythemagnetic circuits1and4is$\frac{\phi}{2}$,therefore theareasare50% ofthe centrallimb,whereasthecross-sectional areaof thecircuit2 and 3are86.6%of thecentrallimb.

IfthewindingofphaseBiswoundinthereverseddirectionwhichisshownbythedotmarkasshown infig.6.3(ii),thedirectionofphaseBfluxinthelimb2and3 reverses,for whichtheresultantfluxintheselimbsbecomes $\frac{\phi}{2}$,thustheareaofcross-sectionoftheportions marked 1, 2, 3 and 4 is equal to one half of the central limb area. By this area the weight of thecorematerial can bereduced considerably.



(i)



(ii)

Fig.6.3Threephaseshell typetransformer(i)with 3windingswoundin samedirection,(ii)withcentralwindingwound in the reversedirection.

For the same capacity, a 3-phase transformer weighs less, occupies less space and the cost ismuch less compared to a bank of single phase transformers. For these advantages of a single unitof 3-phase transformer, In fact all large capacity transformers are a single unit of three phasetransformer.

A disadvantage of the three-phase transformer is when one phase becomes defective; theentire three-phase unit must be removed from service. Where as in other type case the other twotransformers may be reconnected to supply service on an emergency basis until repairs can bemade.

Differencebetweenasingleunit3 phase transformerandbankof3 singlephasetransformers

Thechoiceoftransformerbetweenthetwocanbedoneonthebasisoftheadvantagesanddisadvantages listedbelow it the tabularform

	Bankof3singlephasetransformers	Singleunit3phasetransformer
1	Morecostlyduetomoreiron,threeseparatetanks, more oil and more auxiliary equipments.	Lesscostlyaslessvolumeofiron,onetanksoless oil and lessauxiliaryequipments.
2	Asthreeseparatetransformersitrequires sixh.v.bushingswhichincreasethecost.	Itrequiresonlythreebushingswhichreduces thecost.
3	More floor space is required which increasesthecapital.	Lessfloorspaceisrequiredwhichdecreases thecapital.
4	Ifonephase/transformerdamaged,thenit canbeeasilyreplacedbyasinglephaseunit.	Ifonephaseisdamaged,wholetransformerhasto bereplaced,whichincreasesthe cost.
5	Only one single phase transformer is requiredas standbyunit.	Onecompletethreephasetransformeris requiredas standbyunit.
6	Becauseofmoreironpart,moreironloss hencelessefficient.	Comparatively less iron part so more efficient.
7	Easyfortransportation aseachunit issmall.	Comparativelytothefirstcasemoredifficult fortransportation.

Three-PhaseTransformerconnections

Athree-phasetransformercanbebuiltbysuitablyconnectingabankofthreesinglephase transformers or by one three-phase transformer. The primary or secondary windings maybeconnectedineitherstar(Y)ordelta(Δ)arrangement.Thefourmostcommonconnectionsare (i) Y-Y (ii) Δ - Δ (iii) Y- Δ and (iv) Δ -Y. These four connections are described below. In thefigure,the windingsat theleft arethe primariesand thoseattherightarethesecondaries.

The primary and secondary voltages and currents are also shown. The notations used are givenby;

V_1,V_2Ratedprimaryandsecondaryphasevoltages,I_1, I_2:

Rated primary and secondary phase currents,N_1, N_2:

Primaryandsecondarynumberof turns,

$S=V_1I_1=V_2I_2=$RatedkVA

Star-Star(Y-Y)Connection

To apply arated voltageto theprimary terminalsa lineto line voltage of $\sqrt{3}V_1$issupplied, so that the primary rated voltage V_1 is impressed across each of the primary coils of theindividualtransformer.ThisensuresV$_2$tobeinducedacrosseachofthesecondarycoilandthe line to line voltage in the secondary will be$\sqrt{3}V_2$. Now we have to calculate how much loadcurrentorkVAcanbesuppliedbythisbankofthreephasetransformerswithoutoverloadingany of the single phase transformers. From the individual rating of each transformer, we knowmaximumallowablecurrentsofprimaryandsecondarywindingsareI_1andI_2respectively.Since secondarysideisconnectedinstar,linecurrentandthewindingcurrents(phasecurrent)aresame.

Therefore total kVA that can be supplied to a balanced 3-phase load is $\sqrt{3}(V_L)(I_L)=\sqrt{3}(\sqrt{3}V_2)I_2=3V_2I_2=3s$ i.e.threetimestheKvaratingofeachsinglephase transformer.

Phasevoltagetransformationratio= $\frac{V_2}{V_1}=\frac{N_2}{N_1}=k$

Linevoltagetransformationratio= $\frac{\sqrt{3}V_2}{\sqrt{3}V_1}=\frac{N_2}{N_1}=k$

Note *:*

1. *Unlessanduntilmentionsimplyturnsratiointhesensephaseturnsratioandtransformationratio sensephasetransformation ratio.*
2. *The3-phasetransformersare always specifiedwith line voltages*.

This type of connection requires less insulation as the phase voltage is less than the line voltage.For which it require less number of turns/phase but more cross sectional area of conductor. It iseconomical for high voltage low current rating transformers. As the cross sectional areas ofconductorsaremoreit ismoremechanicallystrong.

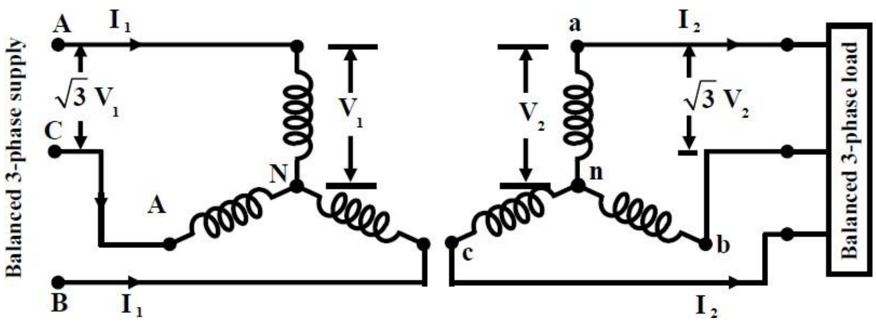


Fig.6.3Star-Starconnections

With both primary and secondary connected in star no closed path exists among thewindings. As the triplen harmonics are always in phase, by virtue of the Y connection they getcanceled in the line voltages. Non-triplen harmonics like fundamental become 3 times phasevalue and appear in the line voltages. Line currents remain sinusoidal except for non-triplenharmoniccurrents.

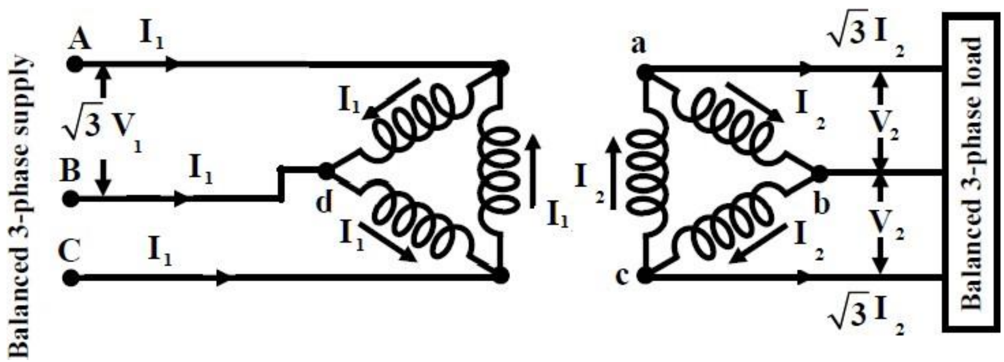
Delta- Delta (□-)□Connection

As discussed above, toapply a rated voltage to the primary terminalsa line to linevoltage of $V_1$is supplied, so that the primary rated voltage V_1 is impressed across each of theprimarycoilsoftheindividualtransformer,asfordeltaconnectionbothlineandphasevoltages are same. This ensures V_2 to be induced across each of the secondary coil and the line to linevoltage in the secondary will also be V_2. Now we have to calculate how much load current orkVA can be supplied by this bank of three phase transformers without over loading any of thesingle phase transformers. Since secondary side is connected in delta, we can connect a load insuchawaythatthewindingcurrents(phasecurrent)shouldnotexceedI_2,forwhichtheline currentbecomes $\sqrt{3}I_2$.WhenthecurrentinsecondarywindingbecomesI_2,thecorresponding reflectedphasecurrentintheprimarybecomesI_1andthelinecurrentbecomes $\sqrt{3}I_1$.Therefore totalkVAthatcanbesuppliedtoabalanced3-phaseloadanddrawnfromthesupplyisgivenby $\sqrt{3}(V_L)(I_L)= \sqrt{3}V_2(\sqrt{3}I_2)=3V_2I_2=3s$ i.e.threetimestheKvaratingofeachsinglephase transformer.

Phase voltage transformationratio=Linevoltage transformationratio= $\frac{V_2}{V_1}=\frac{N_2}{N_1}=k$

Asthephaseandlinevoltagesaresameitrequiresmoreinsulationbutmorenumberofturns/phase,whereasthecrosssectionalareasofconductorsarelesscomparetoY-Yconnection. For which it is more economical for low voltage and high current applications. Duetothelesscrosssectionalareasofconductorsitismechanicallyweakcompare toY-Ytransformers.

Fig.6.4 Delta-Deltaconnections



With mesh connection on both primary side and secondary side a closed path is available for thetriplen harmonics to circulate currents. Thus the supply current is nearly sinusoidal (but for thenon-triplen harmonic currents). The triplen harmonic currents inside the closed mesh windingcorrect the flux density wave to be nearly sinusoidal. The secondary voltages will be nearlysinusoidal. Third harmonics currents flow both in the primary and the secondary and hence themagnitudesof thesecurrents, so also thedrops dueto them will be lower.

Star-Delta(Y-)Connection

Forthisconnectionalinetolinevoltageof$\sqrt{3}V_1$issupplied,sothattheprimaryrated voltage V_1 is impressed across each of the primary coils of the individual transformer. Thisensures V_2 to be induced across each of the secondary coil and the line to line voltage in thesecondary will also be V_2as it is connected in delta. Now we have to calculate how much loadcurrentorkVAcanbesuppliedbythisbankofthreephasetransformerswithoutoverloadinganyofthe singlephasetransformers.Sincesecondarysideisconnectedindelta,wecanconnecta loadinsuchawaythatthe winding currents(phasecurrent)shouldnotexceedI_2,for whichthe linecurrentbecomes $\sqrt{3}I_2$ .WhenthecurrentinsecondarywindingbecomesI_2,the correspondingreflectedphasecurrentintheprimarybecomesI_1andthelinecurrentsarealsoI_1asitisstarconnected.ThereforetotalkVAthatcanbesuppliedtoabalanced3-phaseloadand drawnfromthesupplyisgivenby $\sqrt{3}(V_L)(I_L)=\sqrt{3}V_2(\sqrt{3}I_2)=3V_2I_2=3S$i.e.threetimestheKva ratingofeachsinglephasetransformer.

Phasevoltagetransformationratio= $\frac{V_2}{V_1}=\frac{N_2}{N_1}=k$

Linevoltagetransformationratio= $\frac{V_2}{\sqrt{3}V_1}=\frac{N_2}{\sqrt{3}N_1}=\frac{k}{\sqrt{3}}$

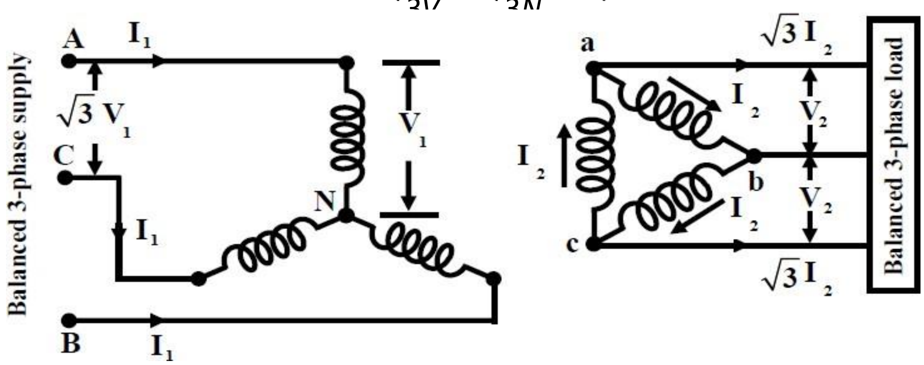


Fig.6.5Star-Deltaconnections

Thistransformerconnectiongivesleastsecondary terminalvoltageamongthealltypesofconnection. Commonly used in a step-down transformer. This transformer is generally usedattheendofatransmissionline.wyeconnectionontheHVsidereducesinsulationcosts,theneutralpoint on theHVside canbegrounded, stablewith respect tounbalanced loads.

Delta- Star (Δ-Y)Connection

Inthisconnectiontoapplyaratedvoltagetotheprimaryterminalsalinetolinevoltageof $V_1$is supplied, so that the primary rated voltage V_1 is impressed across each of the primarycoils of the individual transformer, as for delta connection both line and phase voltages are same.This ensures V_2 to be induced across each of the secondary coil and the line to line voltage in thesecondarywillalsobe$\sqrt{3}V_2$.NowwehavetocalculatehowmuchloadcurrentorkVAcanbe supplied by this bank of three phase transformers without over loading any of the single phasetransformers. From the individual rating of each transformer, we know maximum allowablecurrents of primary and secondary windings are I_1 and I_2respectively. Since secondary side isconnected in star, line current and the winding currents (phase current) are same. When thecurrentinsecondarywindingbecomesI_2,thecorrespondingreflectedphasecurrentinthe primarybecomesI_1andthelinecurrentbecomes $\sqrt{3}I_1$.ThereforetotalkVAthatcanbesupplied to a balanced 3-phase load and drawn from the supply is given by $\sqrt{3}(V_L)(I_L)=\sqrt{3}(\sqrt{3}V_2)I_2=3V_2I_2=3s$ i.e.threetimesthekVAratingofeachsinglephase transformer.

Phasevoltagetransformationratio$=\dfrac{V_2}{V_1}=\dfrac{N_2}{N_1}=k$

Linevoltagetransformationratio$=\dfrac{\sqrt{3}V_2}{V_1}=\dfrac{\sqrt{3}N_2}{N_1}=\sqrt{3}k$

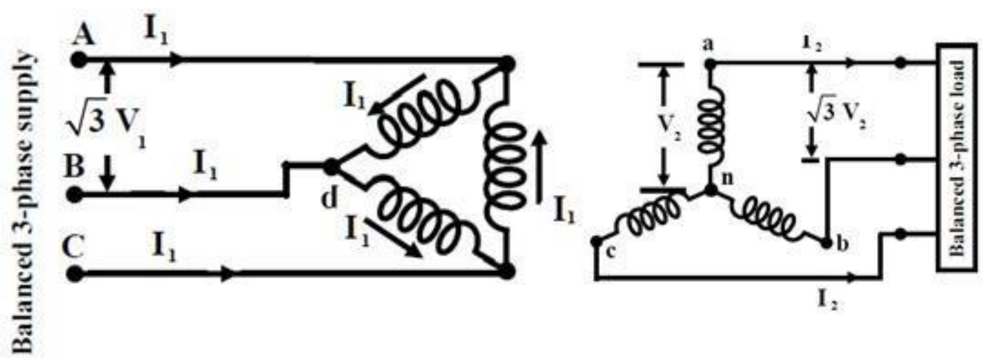


Fig.6.6 Delta-Starconnections

Forthesameturnsratioandappliedvoltagethistransformerconnectionprovideshighestsecondaryterminalvoltageforwhichitiscommonlyusedasastep-uptransformer.Thistransformerisgenerallyusedat thebeginningendof atransmission line.

Dy and Yd connection (without neutral connection) Behavior of the bank with meshconnection on one side is similar to the one discussed under Dd connection. The harmoniccurrents and drops and the departure of the flux density from sinusoidal are larger in the presentcasecomparedto Dd banks.

Basicsofthreephaseconnection

In a single phase transformer there are only two windings namely primary and secondary.However, in a 3-phase transformer there will be separately 3 primary and 3 secondary coils. Sothese3primaryandsecondarycoilsaretobeproperlyconnectedsothatthevoltagelevelofa balanced3-phasesupplymaybechangedtoanother3-phasebalancedsystemofdifferentvoltagelevel.

Fortransformer-A,primaryterminalsaremarkedas A_1A_2 andthesecondaryterminalsare markedas a_1a_2.Themarkingsaredoneinsuchawaythat A_1 and a_1 representthedot(•) terminals.Similarlyterminals forB andCtransformers aremarkedandshownin figure6.7.

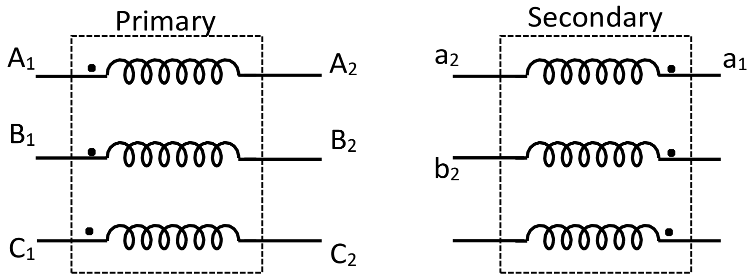


Fig.6.7Terminalmarkingwithdots

Itmaybenotedthatindividuallyeachtransformerwillworkfollowingtherulesofsinglephasetransformeri.e,inducedvoltagein a_1a_2 willbeinphasewithappliedvoltageacross A_1A_2 andthe ratioofmagnitudeofvoltagesandcurrentswillbeasusualdecidedby a where $a=N_1/N_2$,the turnsratio.Thiswillbetruefortransformer-Bandtransformer-Caswelli.e.,inducedvoltagein b_1b_2 willbeinphasewithappliedvoltageacross B_1B_2 andinducedvoltagein c_1c_2 willbeinphase with applied voltageacross C_1C_2.

ProperStarConnection

Now joining the terminals A_2, B_2 and C_2 of the 3 primary coils of the transformers and noconnections are made between the secondary coils of the transformers. Now to the free terminals A_1, B_1 and C_1 a balanced 3-phase supply with phase sequence A-B-C is connected as shown infigure6.8. Primaryis said to be connected in star.

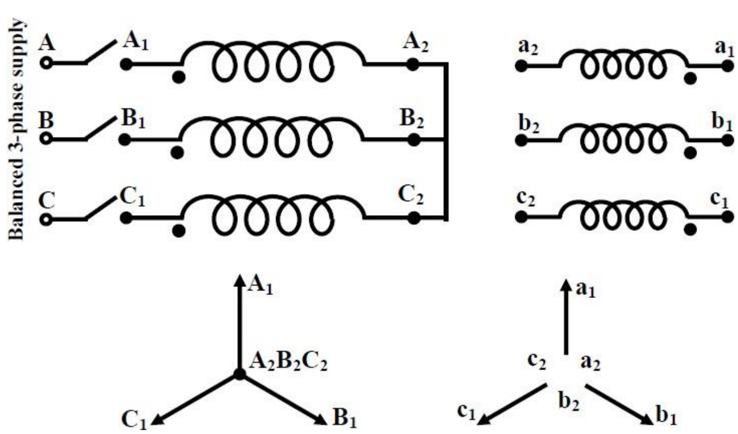


Fig.6.8Starconnectedprimarywith secondarycoilsleftunconnected

ToimpressaphasevoltageofV_1acrosseachofprimarycoilthesupplylinevoltagehasto be$\sqrt{3}V_1$.However,thephasors$\bar{V}_{A_1A_2}$,$\bar{V}_{B_1B_2}$and$\bar{V}_{C_1C_2}$willhaveamutualphasedifferenceof120^0 as shown in figure 6.8. Then from the fundamental principle of single phase transformer weknow, secondarycoilvoltage$\bar{V}_{a_1a_2}$willbeparallelto$\bar{V}_{A_1A_2}$,$\bar{V}_{b_1b_2}$willbeparallelto$\bar{V}_{B_1B_2}$and$\bar{V}_{c_1c_2}$ will be parallel to$\bar{V}_{C_1C_2}$. Thus the secondary induced voltage phasors will have same magnitudeV_2 butaredisplacedby120^0mutually.Sincethesecondarycoilsarenotconnected,thesecondaryvoltagephasors areshownindependentwithout anyconnectionsbetween them.

Nowifthesecondarycoilterminalsa_2,$b_2$and$c_2$arejoinedtogetherphysicallyasshown infigure6.9.Sothesecondarycoilphasorsshouldnotbeshownisolatedasa_2,$b_2$andc_2 become equipotential due to shorting of these terminals. Thus, the secondary coil voltage phasors shouldnotonlybeparalleltotherespectiveprimarycoilvoltagesbutalsoa_2,$b_2$and$c_2$shouldbe equipotential. Therefore, shift and place the phasors$\bar{V}_{a_1a_2}$,$\bar{V}_{b_1b_2}$and $\bar{V}_{c_1c_2}$in such a way that theyremainparallelto therespectiveprimarycoil voltagesandthepointsa_2,$b_2$and $c_2$aresuperposed.

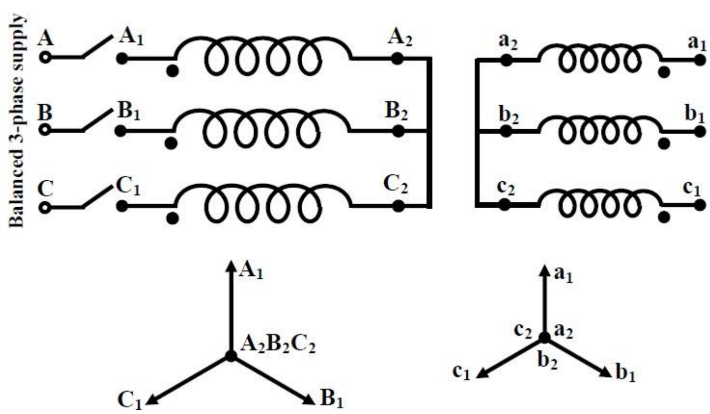
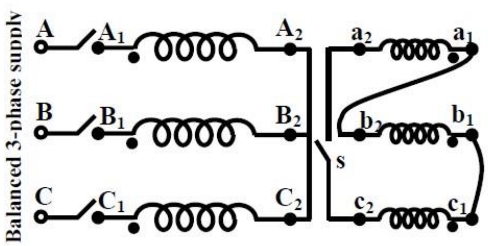


Fig.6.9Both primaryand secondaryarestarconnected

An examination shows that either by connecting the secondary coil terminals a_2, b_2 and $c_2$togetherora_1,$b_1$and$c_1$togetherthesecondaryterminalvoltageshasamutualphasedisplacement of 120^0. Any other type attempt to connect in star will leads to an improper starconnection.

ProperDeltaConnection

To connect windings in delta, one should be careful enough to avoid dead short circuit.Suppose we want to carry out star / delta connection. The primary windings are connected byshortingA_2,B_2andC_2togetherasshowninthefigure6.10.Asweknow,indeltaconnection, coils are basically connected in series and from the junction points, connection is made to supplyload. Suppose we connect quite arbitrarily (without paying much attention to terminal markingsand polarity), a_1 with b_2 and b_1 with c_1. As shown in the phasor diagram in figure 6.11, if avoltmeterisconnectedacrossS(i.e.,between$a$2and$c$2),itisgoingtoreadthelengthofthe phasor$\bar{V}_{a_2c_2}$(V_2 +2V_2 cos60^0 =2V_2). So if the switch‘s’ is closed it is equivalent to put a shortcircuit across a voltage source which results in very large circulating current. So this type ofconnectionshould beavoided.



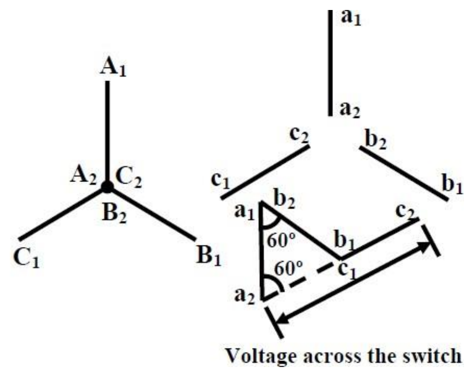
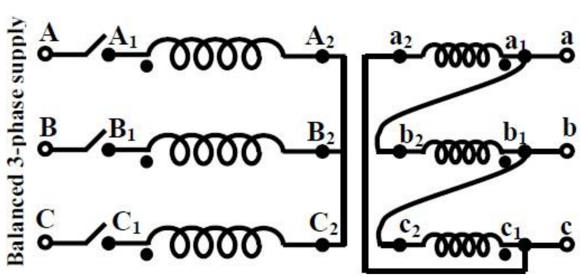


Fig.6.10ImproperDelta Fig. 6.11 Phasor diagram

Anotheralternativewaytoattemptdeltaconnectioninthesecondarycouldbe:joina$_1$withb$_2$andb$_1$withc$_2$.Beforejoininga$_2$withc$_1$tocompletedeltaconnection,examinetheopencircuit voltage$\bar{V}_{a_2c_1}$. Following the methods described before it can easily be shown that $\bar{V}_{a_2c_1}$=0, whichallows to join a_2 with c_1 without any circulating current. So this is a correct delta connection andis shown in figure 6.12. Although voltage exists in each winding, the resultant sum becomes zeroas they are 120° mutually apart. The output terminals are taken from the junctions as a, b and $c$forsupplying3-phaseload. Thecorrespondingphasor diagram is shown in figure6.13.



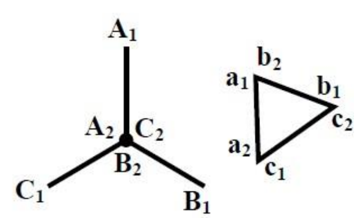


Fig.6.12Star-Delta connection Fig. 6.13 Phasor diagram

Anothervalid deltaconnection on theLV sideis also possible byjoining$a_2$with b_1, $b_2$with c_1 and$c_2$with a_1.

TheperunitsystemforThreePhaseTransformer

The process of solving circuits containing transformers using the referring method whereall the different voltage levels on different sides of the transformers are referred to a commonlevel,can bequitetedious.

The Per-unit System of measurements eliminates this problem. The required conversionsarehandled automaticallybythe method.

Inper-unitsystem,eachelectricalquantityismeasuredasadecimalfractionofsome baselevel.Anyquantitycanbeexpressed onaper-unit basisbytheequation

$$Quantity\,per\,unit = \frac{actual\,value}{base\,value\,of\,quantity}$$

Two basequantitiesareselected todefineagivenper-unitsystem.Theonesusuallyselectedarevoltage and power.In a single phasesystem,therelationships are:

$$P_{base}, Q_{base}\,or\,S_{base} = V_{base} * I_{base}$$

$$R_{base}, X_{base}, Z_{base} = \frac{V_{base}}{I_{base}}$$

$$Y_{base}, B_{base}, G_{base} = \frac{I_{base}}{V_{base}}$$

and $$Z_{base} = \frac{(V_{base})^2}{S_{base}}$$

Allother valuescan becomputed oncethebasevaluesofS(orP) andV havebeen selected.

$$V_{p.u.} = \frac{V(volt)}{V_{base}}$$

$$I_{p.u.} = \frac{I(Amps)}{I_{base}(Amps)} = \frac{I(Amps)}{\frac{S_{base}}{V_{base}}}$$

$$Z_{p.u.} = \frac{Z(ohm)}{Z_{base}(ohm)} = Z(ohm) * \frac{I_{base}}{V_{base}} = Z(ohm) * \frac{S_{base}}{(V_{base})^2}$$

In a power system, a base apparent power and voltage are selected at a specified point in thesystem. A transformer has no effect on the base apparent power of the system, since the apparentpowerequals theapparent power out.

Voltage changes as it goes through a transformer, so V_{base} changes at every transformer inthe system according to its turns ratio.Thus, the process of referring quantities to a commonlevel is automaticallytaken careof.

Many times, when more transformers are involved in a circuit one is required to choose acommonbasevalueforallofthem.Parametersofallthe machinesareexpressedonthiscommon base. This is a common problem encountered in the case of parallel operation of two ormore transformers. The conversion of the base values naturally lead to change in the per unitvalues of their parameters. An impedance $Z_{p.u.old}$ on the old base of $S_{baseold}$ and $V_{baseold}$ shall getmodifiedon new base$S_{basenew}$,$V_{basenew}$as

$$Z_{p.u.} = \left(Z_{p.u.old} \frac{V^2_{baseold}}{S_{baseold}} \right) \frac{S_{basenew}}{V^2_{basenew}}$$

The term inside the bracket is nothing but the ohmic value of the impedance and this getsconverted into the new per unit valuebythe new$S_{base}$and V_{base}.

If all the equivalent circuit parameters are referred to the secondary side and per unitvalues of the new equivalent circuit parameters are computed with secondary voltage and currentasthe basevalues, thereis no changeintheper unit values. This can beeasilyseenby,

$$Z'_{p.u.} = Z'_{ohm} \frac{S'_{base}}{V'^2_{base}} \quad but \quad Z'_{ohm} = \frac{1}{a^2} Z_{ohm}$$

Where

a - is the turns ratio of primary to secondaryZ-impedanceas seen byprimary,

Z'-impedanceasseenbysecondary.

S'_{base} =S_{base}-asthe transformerratingisunaltered.

$$V'_{base} = \frac{V_{base}}{a}$$

Fromtheaboverelationshipsitcanbeseenthat $Z'_{p.u.} = Z_{p.u.}$

Thus the per unit values help in dispensing away the scaling constants. The veracity of theparameters can be readily checked. Comparison of the parameters of the machines with those ofsimilar ones throw in useful information about the machines. Comparing the efficiencies of twotransformers at any load one can say that the transformer with a higher p.u. resistance has highercopperlosses without actuallycomputingthe same.

Application of per unitvalues for the calculation of voltage regulation, efficiency andloadsharingofparallelconnected transformerswillbediscussed lateratappropriateplaces.

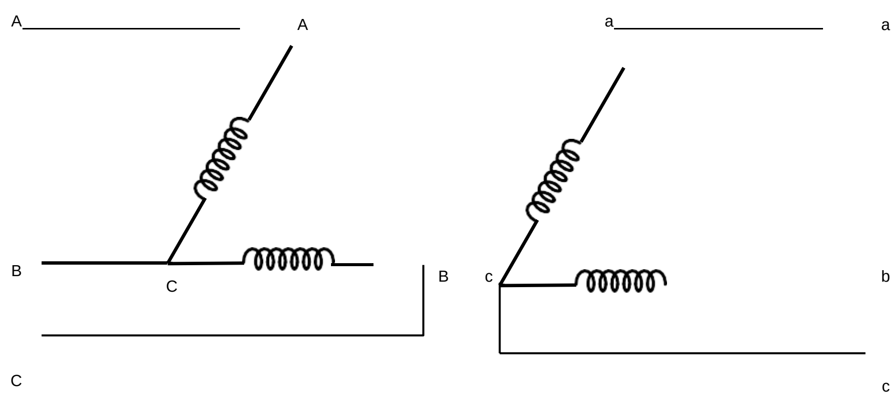
Open-DeltaorV-V Connection

When a three phase transformer bank connected in delta-delta supplies a balance 3-phaseload, share the load equally. If one transformer is removed from the bank still it is possible tosupply 3-phase power though at a reduced level, the resulting connection becomes open delta orVconnection.

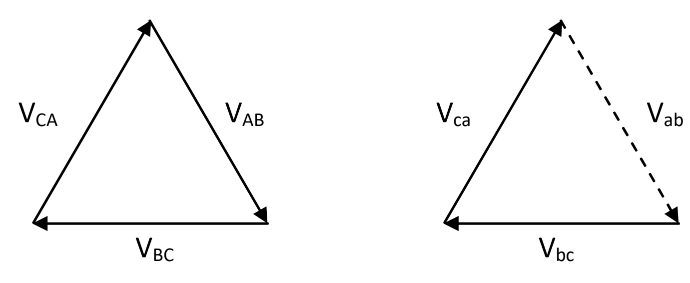
Fig. 6.14(i) shows open delta or V connection; one transformer is removed. As the threeterminalsaredirectlyconnectedacrossabalancedsupplyvoltagethevectorsumofalltheline voltageswill bezero, i.e.$V_{AB}+V_{BC}+V_{CA}=0$

Fig. 6.14(ii) shows the phasor diagram for voltages. Here V_{AB}, V_{BC} and V_{CA} represent theline-to-linevoltagesoftheprimary;V_{ab},V_{bc}andV_{ca}representline-to-linevoltagesofthesecondary. The secondary line voltages V_{bc} and V_{ca} are directly available which are representedbysolid line. Thevoltageacrossthe opendeltaterminals '*ab*'isindicated bydotted lineV_{ab}.

AsthesecondaryterminalvoltageV_{ab}formstheclosingsideofthesecondaryvoltage triangle, it is similar to primary voltage triangle for which we can write $V_{ab}+V_{bc}+V_{ca}=0$ .Hencetwo transformers in open deltacan deliver3-phasepower.



(i)



(ii)

Fig.6.14(i)Opendeltaconnection (ii)Phasordiagramforopendelta

If$|V_{bc}|=|V_{ca}|=V$andwithV_{ca}asthereference $V_{ca}=V\angle 0^0$and$V_{bc}=V\angle 120^0$, V_{ab} canbe calculatedas

$V_{ab} = -(V_{bc} + V_{ca})$

$$V_{ab}=-(V\angle 120^0+V\angle 0^0)$$

$$V_{ab}=-[V(\cos 120^0+j\sin 120^0)+V]$$

$$\vec{V}_{ab}=-[V(-\frac{1}{2}+j0.866)+V]$$

$$\vec{V}_{ab}=V(-\frac{1}{2}-j0.866)=V\angle -120^0$$

Itshowsundernoloadcondition,thesecondarylinevoltageformabalance3-phasesystemofvoltages.

kVAdeliveredbyopendelta:

LetV$_{ph}$andI$_{ph}$betheratedphasevoltageandcurrentrespectivelyofeachofthetransforme r.

Case-Iinclosedelta

LinevoltageV$_l$=V$_{ph}$

and Linecurrent $I_l=\sqrt{3}I_{ph}$

VAdeliveredbythebank of transformers indelta$=\sqrt{3}V_l I_l=\sqrt{3}V_{ph}(\sqrt{3}I_{ph})=3V_{ph}I_{ph}$

Case-IIinopendelta

Line voltage

$V_L=V_{ph}$andLinecurrent

$I_L=I_{ph}$

VAdeliveredbythebank of transformersin delta$=\sqrt{3}V_L I_L=\sqrt{3}V_{ph}I_{ph}$Itisthus seen that theVA ratingofopen-deltais$\sqrt{3}V_{ph}I_{ph}$andnot $2V_{ph}I_{ph}$.

$$\frac{kVA in open delta}{kVA in close delta}=\frac{\sqrt{3}V_{ph}I_{ph}}{3V_{ph}I_{ph}}=0.577=57.7\%$$

1.kVAsuppliedbyeachtransformer$=\frac{\sqrt{3}V_{ph}I_{ph}}{2}=0.866V_{ph}I_{ph}$,thisimplieseachtransformeris underloaded byafactorof13.4%.

2.$utilisation factor or rating factor=\frac{Actual available kVA}{Actual installed kVA in open delta}=\frac{\sqrt{3}V_{ph}I_{ph}}{2V_{ph}I_{ph}}=86.6\%$

Forexample,threeidenticalsingle-phasetransformers,eachofcapacity10kVA,areconnectedin close delta. The total rating of the three transformers is 30 kVA. When one transformer isremoved, the system reverts to V-V circuit and can deliver 3-phase power to a 3-phase load.However, the kVA capacity of the V-V circuit is reduced to 30 x 0.577 = 17.3 kVA and not 20kVAasmightbeexpected.Thisreducedcapacitycanbedeterminedinanalternateway.The availablecapacityofthetwotransformersis20kVA.WhenoperatinginV-Vcircuit,only86.6%of therated capacityis available i.e. 20 x0.866 =17.3 kVA.

PowerFactorofTransformersinV-VCircuit

WhenV-Vcircuitisdelivering3-phasepower,thepowerfactorofthetwotransformersis not the same (except at unity p.f.). Therefore, the voltage regulation of the two transformerswillnot be thesame.If theload power factor angleisϕ, then,

p.f.of transformer 1=cos(30^0-ϕ)

p.f.of transformer 2=cos(30^0+ϕ)

i. When p.fis unityi.e.ϕ=0^0, each transformer operatesat thesamep.f. of0.866.
ii. Whenloadp.f=0.866,i.e.ϕ=30^0,oneofthetransformeroperatesatunityp.f.whereastheother at a p.f. of0.5.

Applicationsof OpenDeltaorV-V Connection

TheV-Vcircuithasanumberoffeaturesthatarcadvantageous.Afewapplicationsaregiven below bywayof illustration:

i. Thecircuitcanbe employedinanemergencysituationwhenonetransformerina complete □-□□circuit must be removed for repair and continuity of service is required.
ii. ii. Upon failure of the primary or secondary of one transformer of a complete □-□□circuit, thesystemcanbeoperatedasV-Vcircuitandcandeliver3-phasepower(withreducedcapacity)toa3-phaseload.
iii. AcircuitissometimesinstalledasV-Vcircuitwiththeunderstandingthatitscapacitymaybeincreasedbyaddingonemoretransforme complete □-□□circuit. As rtofor discussedearlier.

ScottConnectionorThree-phasetotwo-phaseconversion

Scott connection is a type of circuit used to derive two-phase current from a three-phasesource or vice-versa. The Scott three-phase transformer was invented by an engineer Charles F.Scott.In1980stobypassThomasEdison'srotary converterandthereby permittwo-phasegeneratorplants to drive NikolaTesla'sthree-phasemotors.

At present though three phase power is mostly used, but for certain applications two-phasesupplies areessential, such as

(i) Single-phasearcfurnaces.

(ii) Lowvoltagesingle-phaserural application.

(iii) Electrictraction

(iv) Two-phasecontrolmotors.

Atwophasesystemofvoltagesconsistoftwoequalvoltagesdisplacedfromeachotherbyatimephaseangle of90^0,so itcannot be takenfrom two separatesingle phasesupplies.

The Scott connection uses two single-phase transformers of a special design to transformthree-phasevoltagesandcurrentsinto two-phasevoltagesand currents.

1. Thefirsttransformer,calledthe‘‘maintransformer,’’hasacenter-tappedprimarywinding connected to the three-phase circuit with the secondary winding connected to thetwo-phase circuit. It is vital that the two halves of the center-tapped primary winding arewound around the same core leg so that the ampere-turns of the two halves cancel outeach other. The ends of the center-tapped main primary winding are connected to two ofthephases of thethree-phasecircuit.

2. Thesecondtransformer,calledthe‘teasertransformer,’hasoneendofitsprimarywindingconnectedtothethirdphaseofthethree-phasecircuitandtheotherendconnected to the center tap of the primary winding of the main. If the main transformerhas a turns ratio of 1: 1, then the teaser transformer requires a turns ratio of 0.866:1 forbalancedoperation.

The Scott connection requires no primary neutral connection, so zero-sequence currents areblocked. The secondary windings of both the main and teaser transformers are connected tothe two-phase circuit. The Scott connection is shown in figure.6.15 for a two-phase, five-wirecircuit. The principle of operation of the Scott connection can be most easily seen by firstapplying a current to the teaser secondary windings, and then applying a current to the mainsecondarywinding,calculatingtheprimarycurrentsseparatelyandsuperimposingtheresults.

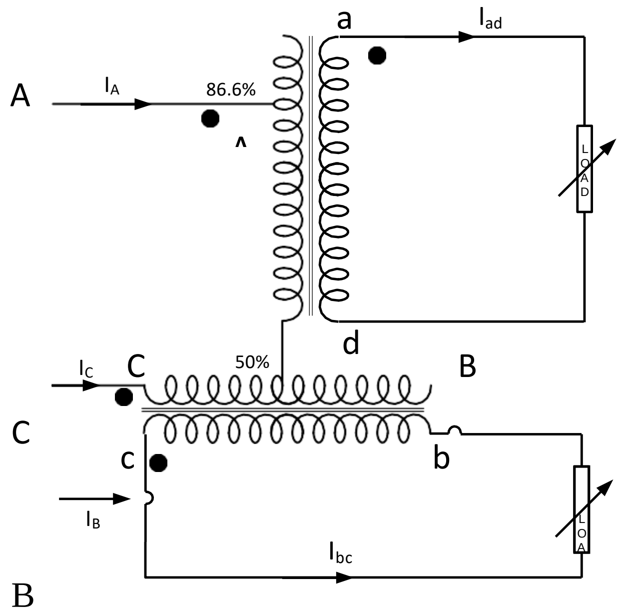


Fig.6.15Scottconnectionoftwosinglephasetransformers

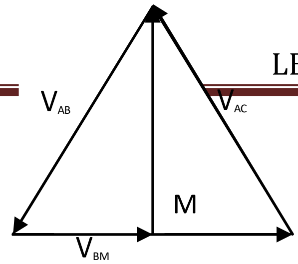
Principleofoperation

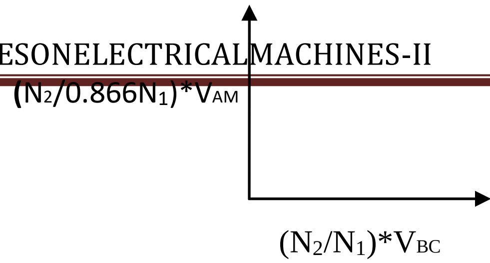
The ScottConnectedTransformercanconvertabalancedthreephasesupply totwophase supply if the load on the two phase supply is balanced then the line current drawn from thethreephasewill bebalanced. Wewill seehow it is possible.

In the above diagram we have taken two single phase transformers. Let us say we haveN_1,N_2bethenumberofturnsofthetransformers.Thefirsttransformeristappedby50%sothe numberofturnsofcoilbecomes$\frac{N1}{2}$onbothsidesoftapping.Forthesecondtransformerthe supply voltage is applied to 86.6% of the primary no of turns i.e. $0.866N_1$.Then we suppliedbalanced three phase supply to V_A, V_B and V_C respectively. Let V_1 and V_2 be the inducedvoltages.

Now drawing the phasor V_{BC}, V_{AB}& V_{CA}. Now the voltage phasor V_{MC} will be half ofV_{BC} and voltage phasor V_{MA} will be V_{MC}+V_{CA}. It shows that the voltage phasor V_{AM} is rightangleto thevoltagephasorV_{BC}, hence, induced voltageV_2 will bein phasewith thevoltageV_{AM} anditsmagnitudewillbe$(\frac{N_2}{0.866N_1})$*V_{MA}.VoltagephasorV_1willbeinphasewiththevoltage V_{BC} anditsmagnitudewillbe $(\frac{N_2}{N_1})$ *V_{BC}.

A V1


V_{AB}
V_{AC}
M
V_{BM}


$(N_2/0.866N_1)*V_{AM}$
$(N_2/N_1)*V_{BC}$

B M C V2

M

(i) (ii)

Fig.6.15Phasor diagramofscott connectedtransformers(i) primaryside(ii) Secondaryside

Fromthephasortriangle

$$\vec{V}_{MA} = \vec{V}_{MC} + \vec{V}_{CA}$$

If $V_{AB} = V_{BC} = V_{CA} = V_L$ (*Linevoltage*) ,then $\vec{V}_{BC}$ asthe reference phasor $\vec{V}_{BC} = V_L\angle 0^0$, $\vec{V}_{CA} = V_L\angle 120^0$, $\vec{V}_{AB} = V_L\angle -120^0$, $\vec{V}_{BM} = \vec{V}_{MC} = \frac{1}{2}V_L\angle 0^0$.

$\vec{V}_{MA}$ can be rewritten as

$$\vec{V}_{MA} = \frac{1}{2}V_L\angle 0^0 + V_L\angle 120^0 = \frac{1}{2}V_L + V_L(\cos 120^0 + j\sin 120^0) = j0.866V_L = 0.866V_L\angle 90^0$$

HenceV_{MA},thevoltageacrosstheteaseris0.866ofthatacrossthemainandleadsitby90^{0}as showninthephasordiagraminfigure6.15.As$\vec{V}_{MA} = 0.866\left|\vec{V}_L\right|$,sothemagnitudeofboththe secondaryvoltageswillbesamei.e.be $\left(\frac{N_2}{N_1}\right)$ *V_L,andtheyaredisplacedintimephasebyan angle of 90^{0}forwhich thesecondaryvoltagesare balanced two phase.

CalculationofNeutral

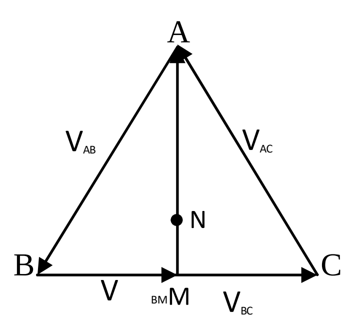


Fig.6.16Phasordiagramofscottconnectedtransformersinprimarysidewithneutral

Thevoltagebetweenthelinesandneutralpointonthethreephasesideis $\frac{V_L}{\sqrt{3}} = 0.578V_L$,which lessthantheteaserprimaryvoltageisasitis0.866V_L.Hencetheneutralmustbeontheteaser primary. Theneutral pointis,therefore,0.866V_L − 0.578V_L = 0.288V_L fromM.In otherwordsfromthephasor diagram

$$\left|\vec{V}_{MA}\right| = 0.866V_L, \left|\vec{V}_{MN}\right| = 0.288V_L \text{ and } \left|\vec{V}_{NA}\right| = 0.578V$$

And the neutral divides the teaser primary MA in the ratio of V_{AN}: V_{MN}=0.578:0.288=2:1. Hence $\frac{Number of turns in AN}{Number of turns in MN}=2$

Loadoperation

Forsimplicityletusconsiderabalancetwophaseloadconnectedatthesecondaries.As theloadisbalance $I_{ad}=I_{bc}=I_2$ With I_{bc} asthereference, $\vec{I}_{bc}=I_2$ $\vec{I}_{ad}=jI_2$

Thecurrent in thesecondarycan becalculated bymmf balance.Consideringthe teaser transformer,

$$N_2 I_2=\frac{\sqrt{3}}{2}N_1 I_A$$

$$\Rightarrow \boxed{\vec{I}_A=\frac{2}{\sqrt{3}}\frac{N_2}{N_1}\vec{I}_2}$$

Consideringthemaintransformer,

$$N_2\vec{I}_2=\frac{N_1}{2}\vec{I}_B-\frac{N_1}{2}\vec{I}_C$$

$$N_2\vec{I}_2=\frac{N_1}{2}\left(\vec{I}_B-\vec{I}_C\right)$$

$$\vec{I}_B-\vec{I}_C=2\frac{N_2}{N_1}\vec{I}_2 \text{...}(i)$$

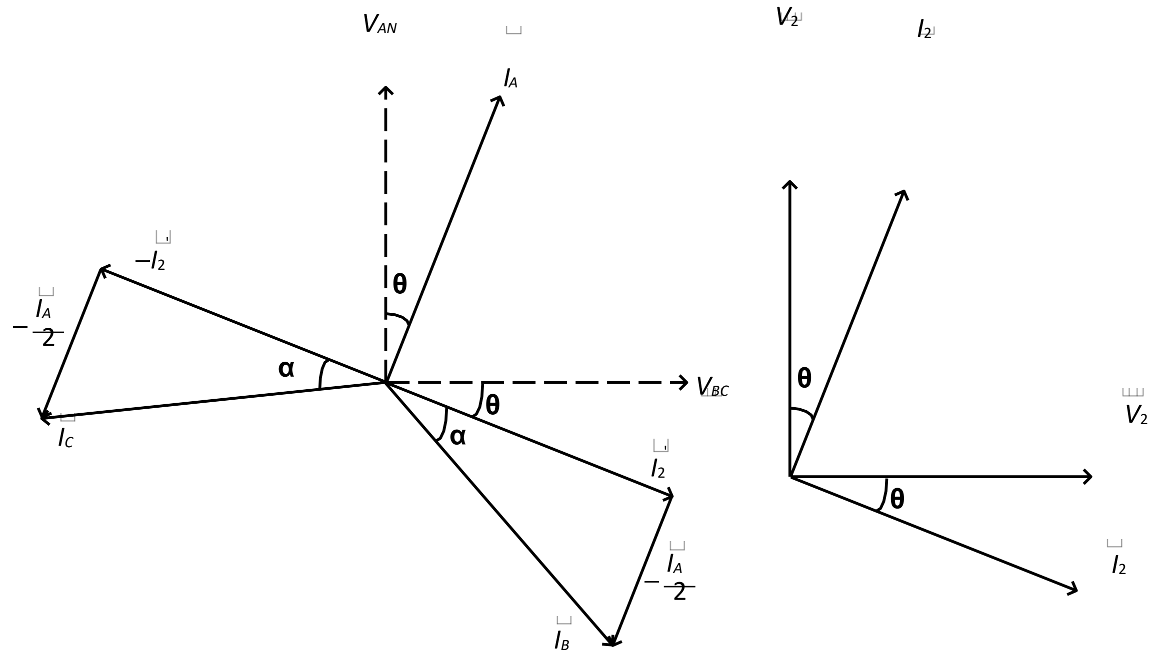
Weknow that

$$\vec{I}_A+\vec{I}_B+\vec{I}_C=0$$

$$\Rightarrow \vec{I}_B+\vec{I}_C=-\vec{I}_A \text{...}(ii)$$

Solvingequation i andii, wehave

$$\Rightarrow \boxed{\vec{I}_B=\frac{N_2}{N_1}\vec{I}_2-\frac{1}{\sqrt{3}}\frac{N_2}{N_1}\vec{I}_2=\vec{I}_2-\frac{\vec{I}_A}{2}} \text{ and } \boxed{\vec{I}_C=-\frac{N_2}{N_1}\vec{I}_2-\frac{1}{\sqrt{3}}\frac{N_2}{N_1}\vec{I}_2=-\vec{I}_2-\frac{\vec{I}_A}{2}}$$



Themagnitudeofall the threephasecurrents aregiven by

$$|I_A| = \frac{2}{\sqrt{3}}\frac{N_2}{N_1}|I_2|$$

$$|I_B|=|I_C|=\sqrt{\left(\frac{N_2}{N_1}I_2\right)^2+\left(\frac{1}{\sqrt{3}}\frac{N_2}{N_1}I_2\right)^2}=\frac{2N_2}{\sqrt{3}\,N_1}|I_2|$$

Hencethemagnitudesofallthethreephasesaresame.But theinputcurrentto bebalance‘α’has to be 30^0.

$$\alpha=\tan^{-1}\left(\frac{\frac{1}{\sqrt{3}}\frac{N_2}{N_1}I_2}{\frac{N_2}{N_1}I_2}\right)=\tan^{-1}\left(\frac{1}{\sqrt{3}}\right)=30^0$$

TheAdvantagesoftheScottTconfiguration

1. If desired,athreephase,two phase, orsingle phaseload maybesupplied simultaneously
2. Theneutralpointscan be availablefor groundingorloadingpurposes

TheDisadvantageswhenusedfor3Phase Loading

1. Thistypeofasymmetricalconnection(3phases,2coils),reconstructsthreephasesfrom2 windings. This can cause unequal voltage drops in the windings, resulting in potentiallyunbalancedvoltages to beapplied to theload.

2. The transformation ratio of the coils and the voltage obtained may be slightly unbalanceddueto manufacturingvariances of theinterconnected coils.
3. Thisdesign’sneutralhastobe solidlygrounded.If itisnotgroundedsolidly,the secondaryvoltagescouldbecomeunstable.

4. The inherent single phase construction and characteristics of this connection produces acomparatively bulky and heavier transformer when compared with a normal three phasetransformerof thesame rating.

VectorGroupof3-phasetransformerconnection

Three balanced 3-phase voltages can be connected in star or mesh fashion to yield abalanced 3-phase 3-wire system. The transformers that work on the 3-phase supply have star,mesh or zigzag connected windings on either primary secondary or both. In addition to givingdifferentvoltageratios,theyintroducephaseshiftsbetweeninputandoutputsides.Theseconnectionsarebroadlyclassified into 4 popular vectorgroups.

1. Group I:zerophasedisplacementbetweentheprimaryandthesecondary.
2. Group II:180^0phasedisplacement.
3. GroupIII:30^0 lagphase displacementofthesecondarywithrespecttothe primary.
4. Group IV:30^0 leadphase displacementofthesecondarywithrespecttothe primary.

The secondary voltages of a 3-phase transformer may undergo a *phase shift* of 30° leading or 30°lagging or 0° i.e, no phase shift or 180° reversal with respective line or phase to neutral voltages.Onthenameplateofathreephasetransformer,thevectorgroupismentioned.Typicalrepresentation of the vector group could be Yd_1 or Dy_{11} etc. The first capital latter Y indicatesthat the primary is connected in star and the second lower case latter d indicates delta connectionof the secondary side. The third numerical figure conveys the angle of phase shift based on *clockconvention*. The minute hand is used to represent the primary phase to neutral voltage and alwaysshown tooccupy the position12. The hour hand representsthe secondary phase toneutralvoltage and may, depending upon phase shift, occupy position other than 12 as shown in thefigure6.17.

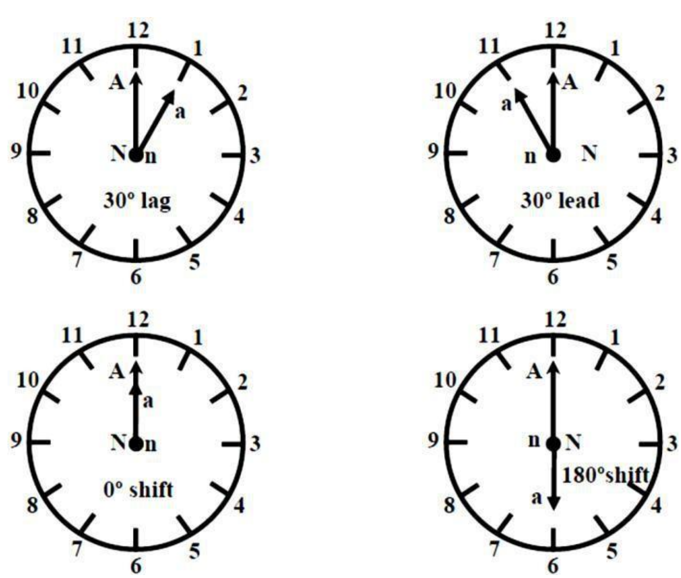


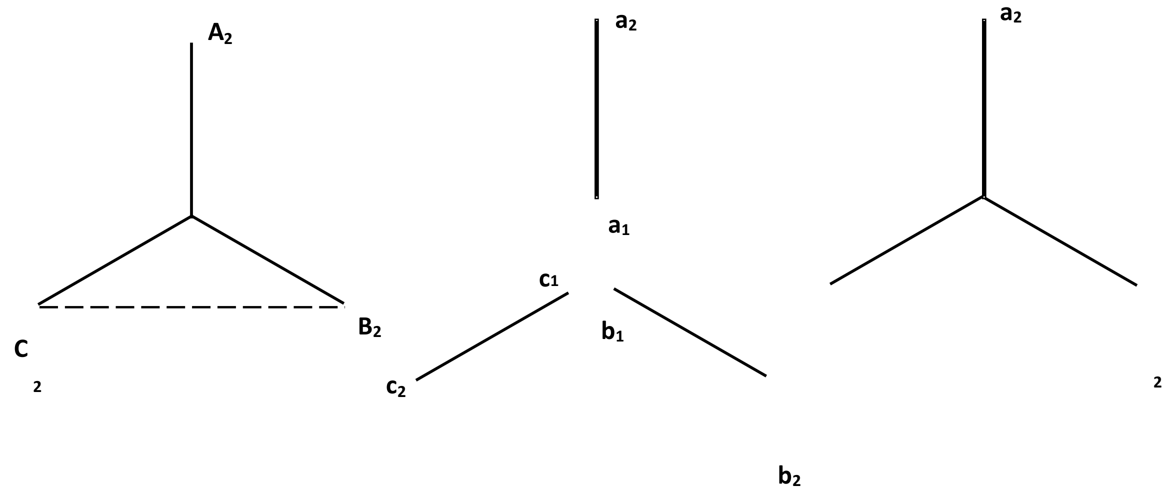
Fig.6.17: Clockconventionrepresentingvectorgroups.

6.10.1GroupI:zerophasedisplacementbetweentheprimaryandthesecondary.

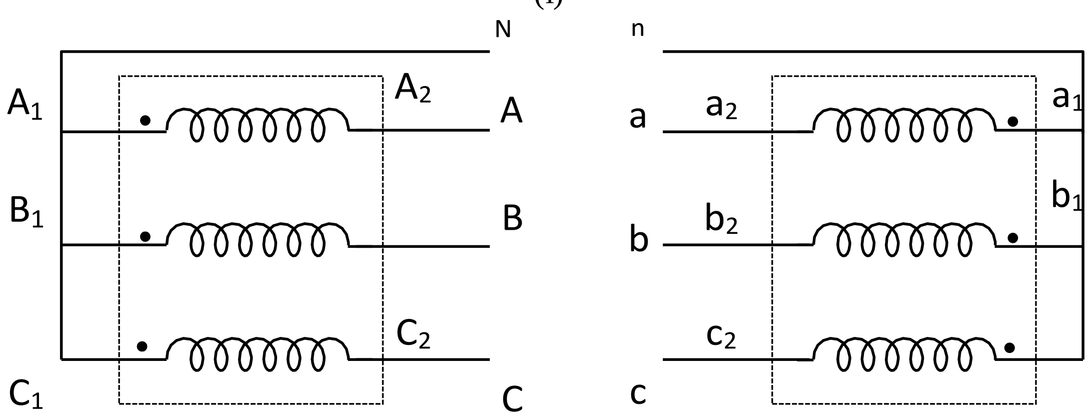
The phase displacement between the primary and secondary respective line or phase toneutralvoltages is zero forthis groupconnections.

6.10.1.1 Yy0Connection

For Yy arrangement first the primary is connected in star with $A_1B_1C_1$ connected togetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshowninfigure6.18(i),here $a_1a_2$isparalleltoA_1A_2.Similarly$b_1b_2$and$c_1c_2$areparalleltoB_1B_2andC_1C_2respectively.In the secondary side if $a_1b_1c_1$ connected together then the line voltages C_2B_2 and c_2b_2 in primaryandsecondary siderespectively coincide witheachother andthusthere isnophase anglebetweenprimaryand secondary.



(i)

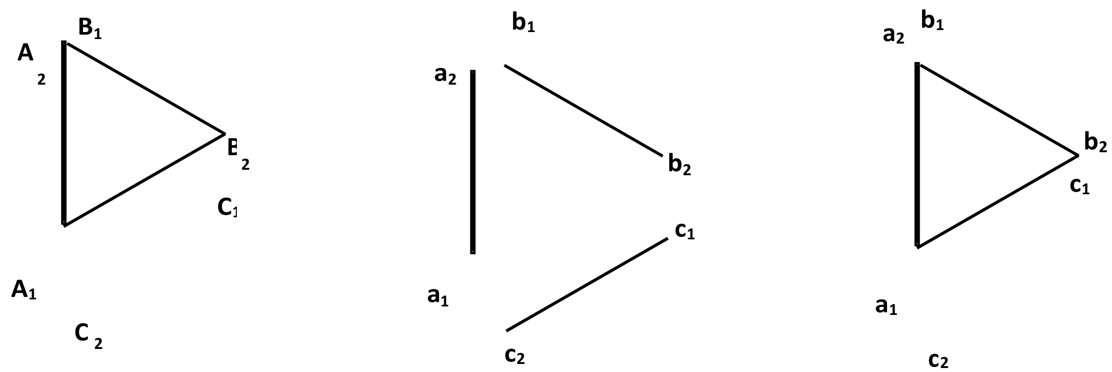


(ii)

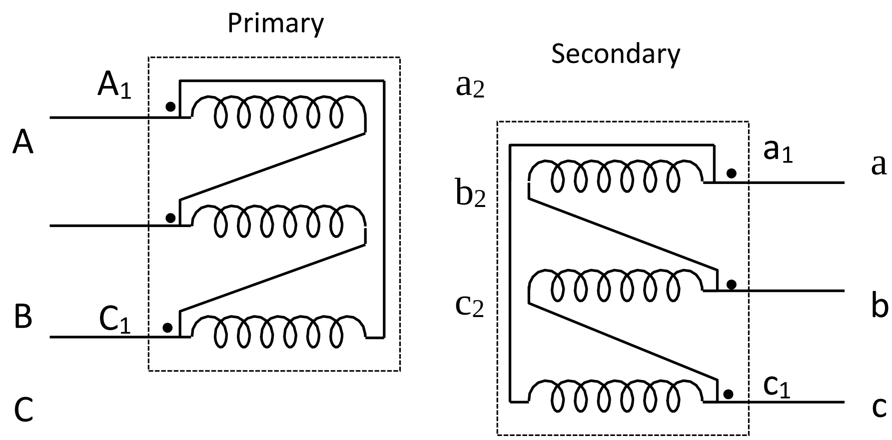
Fig.6.18(i)Phasordiagram ofYy0arrangement(ii) Connectiondiagramforit

6.10.1.2 Dd0Connection

ForDdarrangementfirsttheprimaryisconnectedindeltawithA_2B_1,B_2C_1andC_2A_1connectedtogetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshown in figure 6.19(i), here a_1a_2 is parallel to A_1A_2. Similarly b_1b_2 and c_1c_2 are parallel to B_1B_2 and C_1C_2 respectively. In the secondary side to have a phase displacement of 0^0, a_2b_1, b_2c_1 and c_2a_1 connectedtogether.



(i)

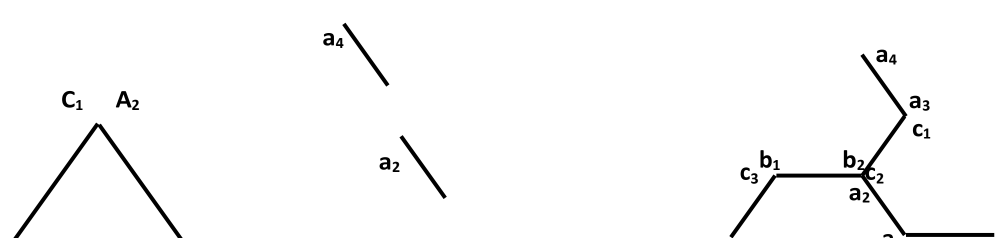


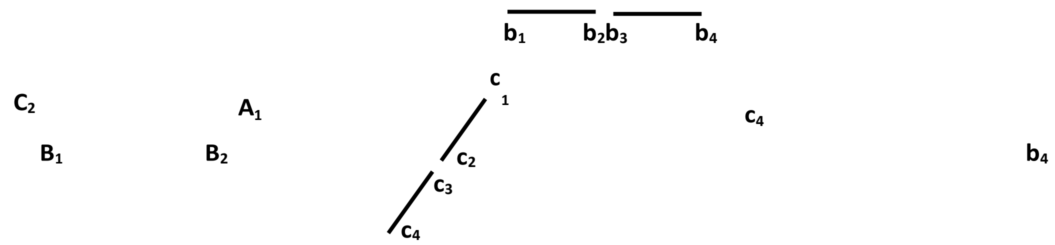
(ii)

Fig.6.19(i)Phasordiagram ofDd0 arrangement(ii) Connectiondiagram forit

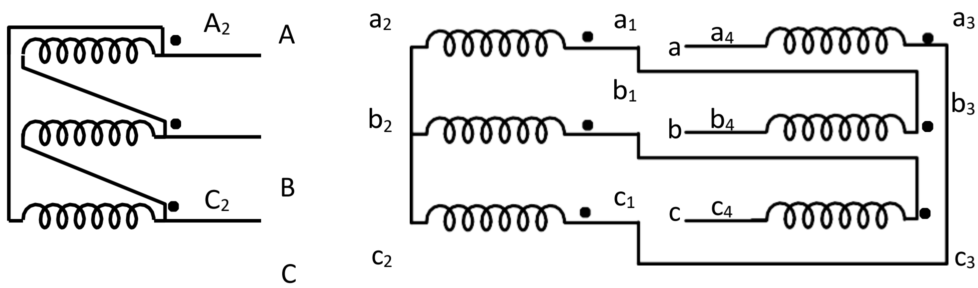
6.10.1.3 Dz0Connection

A zigzag transformer is a special purpose transformerwith a zigzagor 'interconnectedstar' winding connection, such that each output is the vector sum of two phases offset by 120°.For such a transformer it requires two secondaries corresponds to each primary of exactly equalnumbers of turns. The primary is connected in delta and the corresponding two set of secondaryphasors are shown in the figure below. The phase voltage formed by the phasors b_1b_2 and c_3c_4 isparallel to C_1C_2,makingaphasedisplacement of0^0between the primaryand secondary.





(i)



(ii)

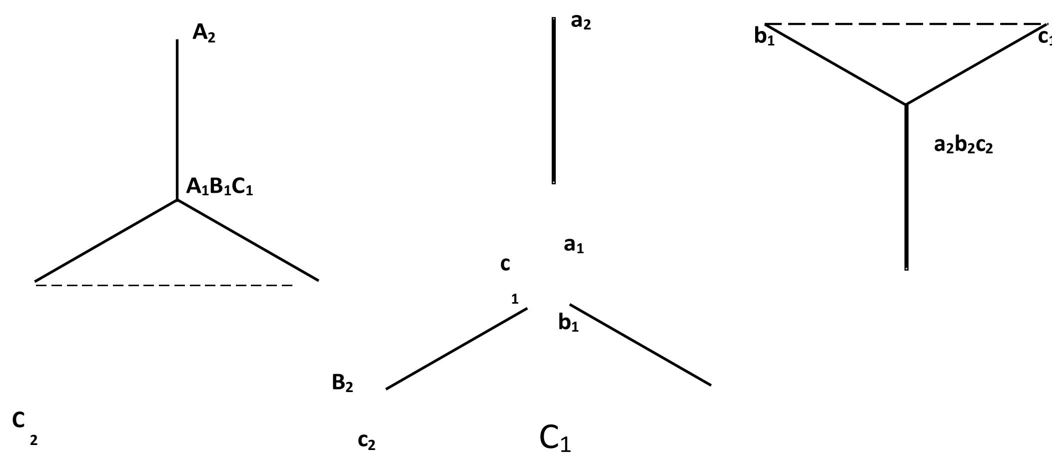
Fig.6.20(i)Phasordiagram ofDz0arrangement(ii) Connectiondiagramforit

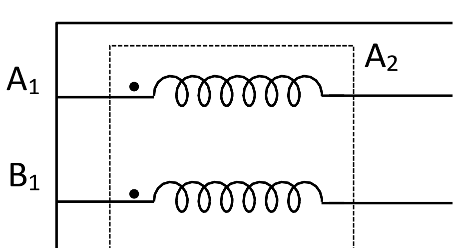
6.10.2GroupII:180^0 phasedisplacement.

The phase displacement between the primary and secondary respective line or phase toneutralvoltages is 1800forthis groupconnections.

6.10.2.1 Yy6Connection

Forthisarrangementfirsttheprimaryisconnectedinstarwith$A_1B_1C_1$connectedtogether and the secondary kept open. The corresponding phasor diagram are shown in figure6.21(i), here a_1a_2 is parallel to A_1A_2. Similarly b_1b_2 and c_1c_2 are parallel to B_1B_2 and C_1C_2respectively. In the secondary side all the phasors are reversed with respect to the primaryconnections,soastogetaphasedisplacementof180^0.Forwhichinthesecondary side,terminals$a_2b_2c_2$areconnected together toform theneutral as shownin figure6.21.





a

1

a

b_2

b

(i)

N

n

c

(ii)

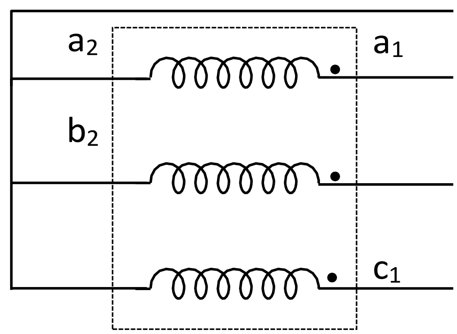
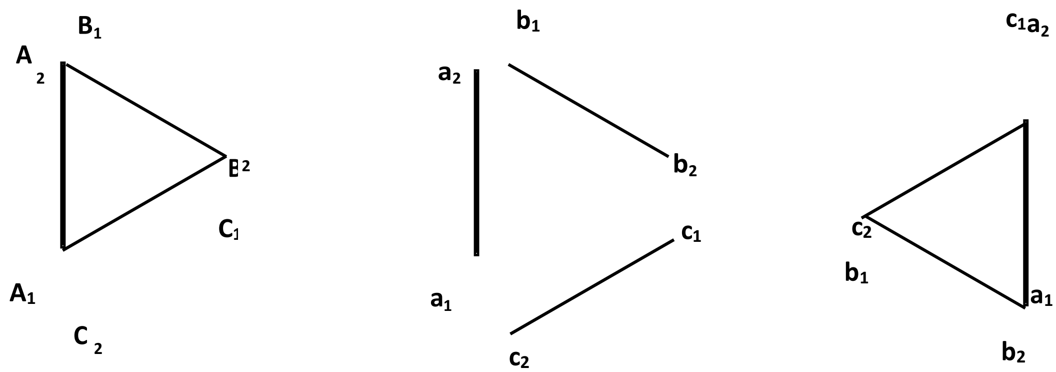


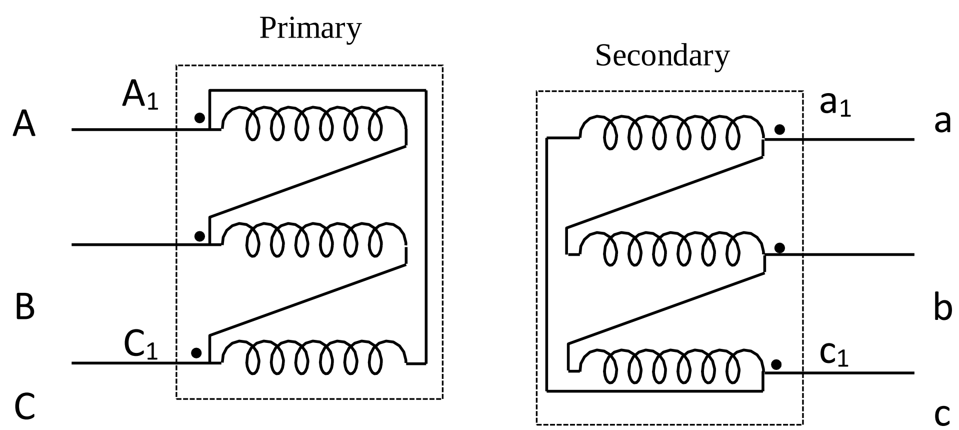
Fig.6.21(i)Phasordiagram ofYy0arrangement(ii) Connectiondiagramforit

6.10.2.2 Dd6Connection

For this arrangement first the primary is connected in delta with A_2B_1, B_2C_1 and C_2A_1connectedtogetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshownin figure 6.22(i), here a_1a_2 is parallel to A_1A_2. Similarly b_1b_2 and c_1c_2 are parallel to B_1B_2 andC_1C_2 respectively. In the secondary side to have a phase displacement of 180^0, a_2c_1, b_2a_1 and $c_2b_1$areconnected together.



(i)

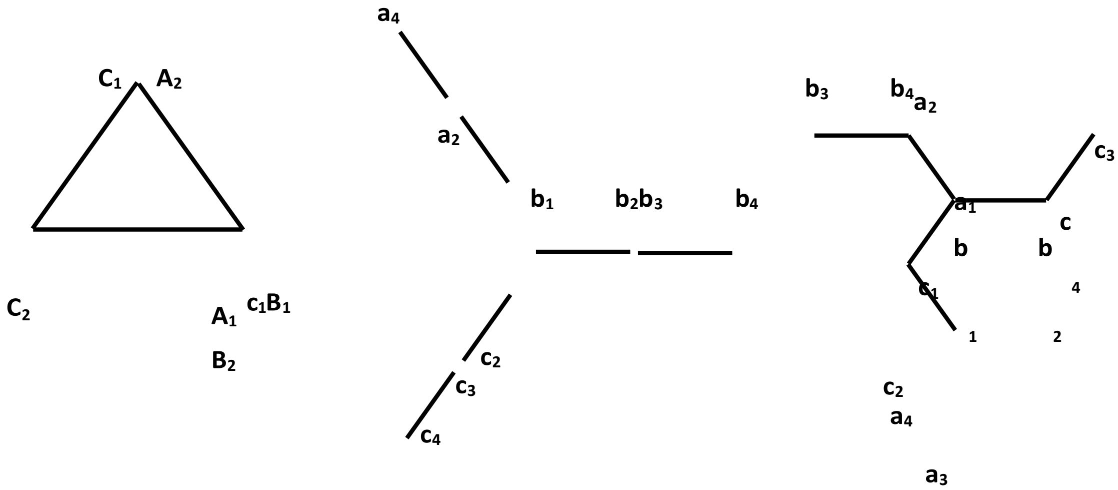


(ii)

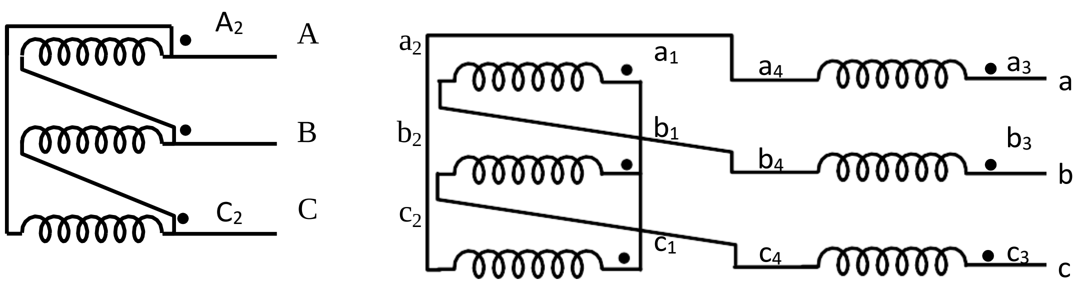
Fig.6.22PhasordiagramofDd6arrangement(ii)Connectiondiagramforit

6. 10.2.3Dz6Connection

The primary is connected in delta and the corresponding two set of secondary phasors areshown in the figure below. The phase voltage formed by the phasors b_1b_2 and c_4c_3 is anti paralleltoC$_2$C$_1$, makingaphasedisplacement of180^0betweenthe primaryand secondary.



(i)



(ii)

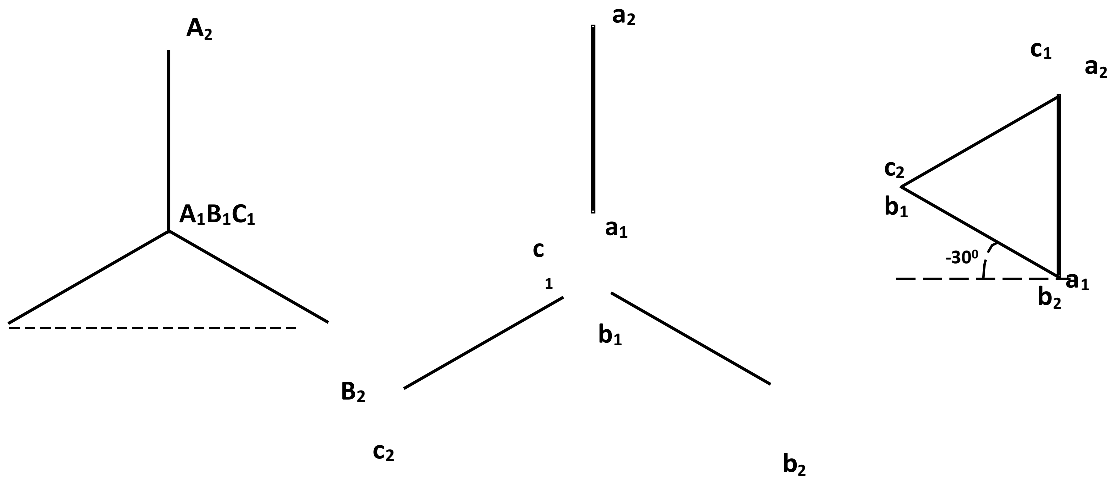
Fig.6.23PhasordiagramofDz6arrangement(ii) Connectiondiagramforit

GroupIII:30^0lagphasedisplacementofthesecondarywithrespecttotheprimary.

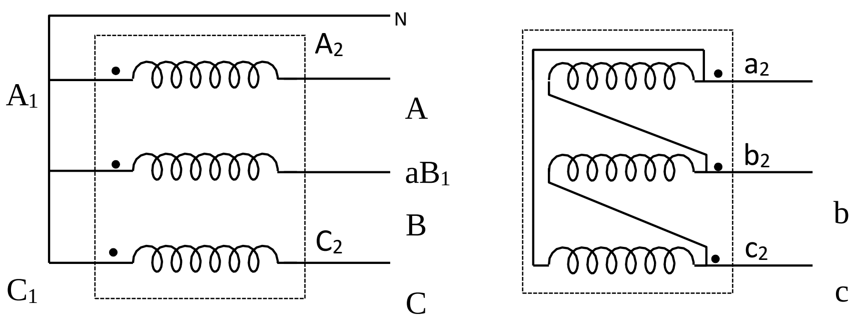
A phase displacement of -30^0 means that the secondary line phase lags the correspondingprimaryphasor by30^0asshown in fig. below.

Yd1Connection

For Yd arrangement first the primary is connected in star with $A_1B_1C_1$ connected togetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshowninfigure6.24(i),here $a_1a_2$isparalleltоA_1A_2.Similarly$b_1b_2$and$c_1c_2$areparalleltoB_1B_2andC_1C_2respectively.In the secondary has to be delta connected its line and phase voltages are same. The line voltageb_1b_2, is lagging by an angle 30^0 to the primary line voltage C_2B_2phasor, c_1c_2, is lagging by anangle30^0toA_2C_2 andsoon.Forwhichthe arrangementshownbelowprovidesaphasedisplacement of30^0laggingbetween thecorrespondinglinevoltages of primaryand secondary.



(i)

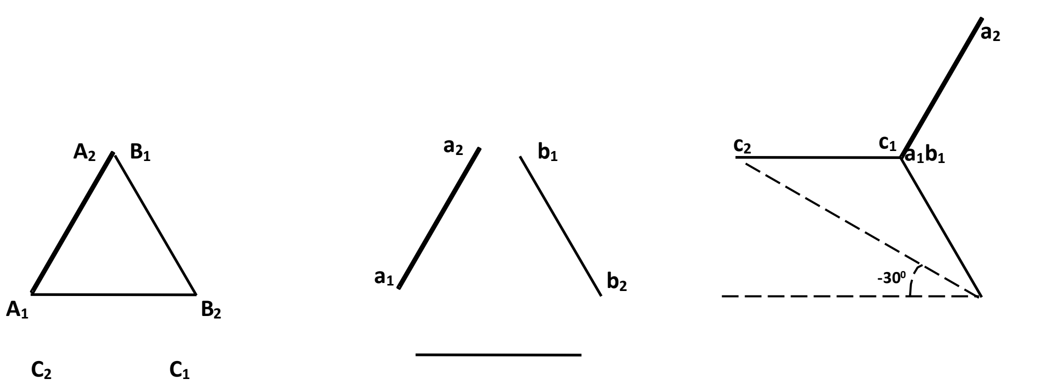


(ii)

Fig.6.24PhasordiagramofYd1arrangement(ii)Connectiondiagramforit

6.10.3.2 Dy1Connection

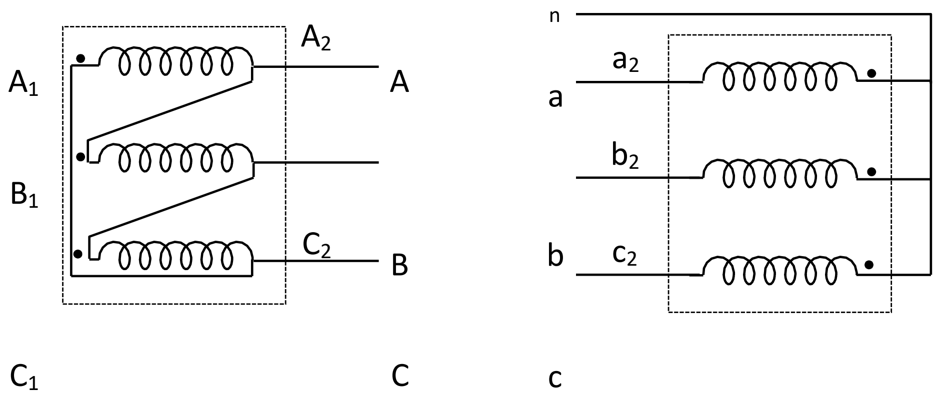
For Dy arrangement first the primary is connected in delta with A_2B_1, B_2C_1 and C_2A_1connectedtogetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshownin figure 6.25(i), here a_1a_2 is parallel to A_1A_2. Similarly b_1b_2 and c_1c_2 are parallel to B_1B_2 andC_1C_2 respectively. The line voltage c_2b_2, is lagging by an angle 30^0 to the primary line voltageC_1C_2phasor, a_2c_2, is lagging by an angle 30^0 to A_1A_2 and so on.For which the arrangementshown below provides a phase displacement of 30^0 lagging between the corresponding linevoltagesof primaryand secondary.



c

2 c_1

(i)

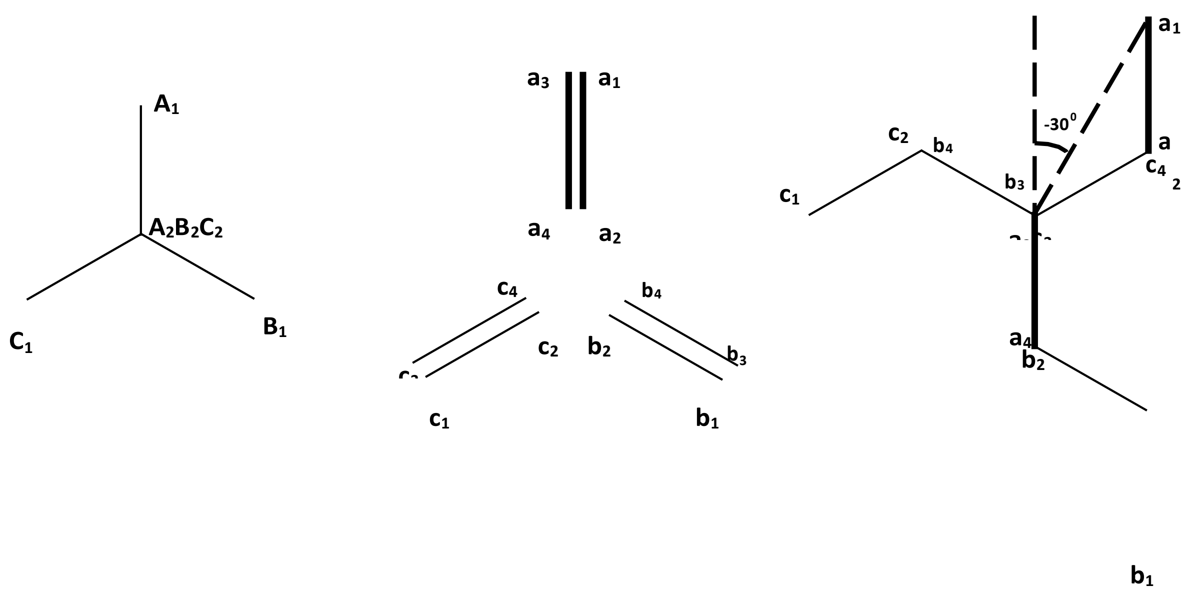


(ii)

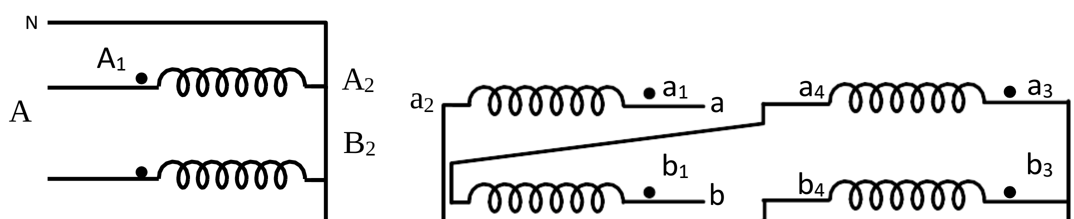
Fig.6.25PhasordiagramofDy1arrangement(ii)Connectiondiagramforit

6. 10.3.3Yz1Connection

Forthisarrangementfirsttheprimaryisconnectedinstarwith$A_2B_2C_2$connectedtogether and the secondary kept open. The corresponding phasor diagram are shown in figure6.26(i), here a_1a_2 and a_3a_4 is parallel to A_1A_2. Similarly $b_1b_{2,}$ b_3b_4 and $c_1c_{2,}$ c_3c_4 are parallel toB_1B_2andC_1C_2respectively.Tohaveaphasedisplacementof30^0laggingbetweenthecorresponding phase voltages phasor c_3c_4 and a_1a_2 are connected in series, which forms theresultantphasevoltage$c_3a_{1.}$



(i)



b_2

B

C_2 c_2

C

(ii)

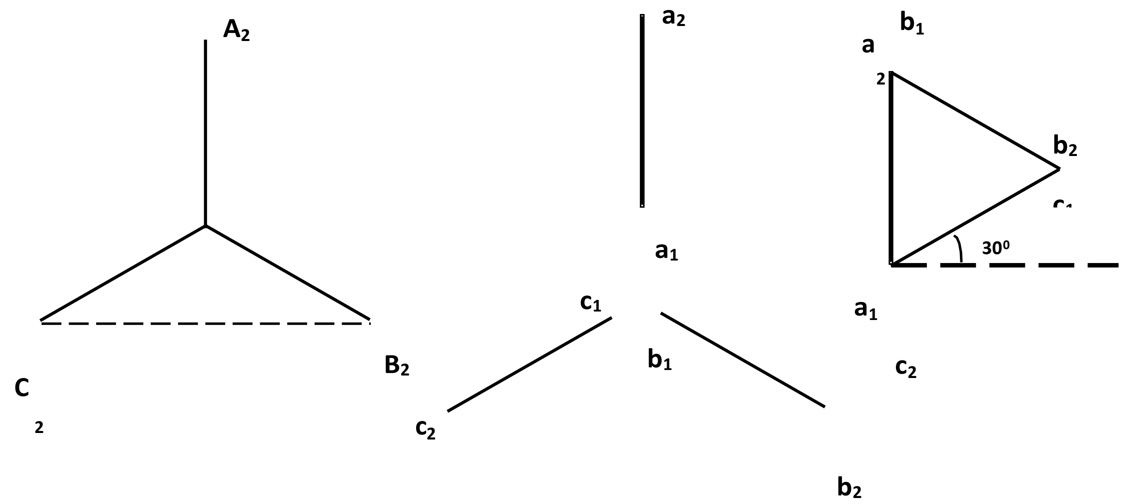
Fig.6.26PhasordiagramofYz1 arrangement(ii) Connectiondiagramforit

6.10.4GroupIV:30^0leadphasedisplacementofthesecondarywithrespecttotheprimary.

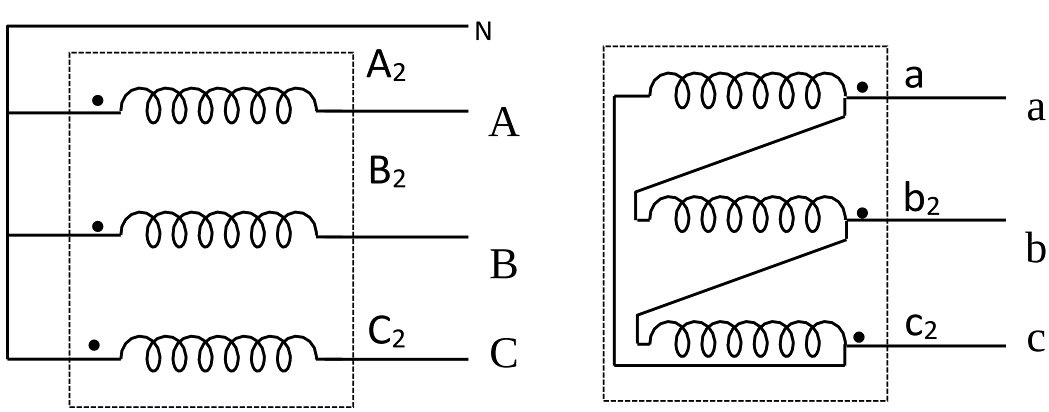
A phase displacement of 30^0 means that the secondary line phase leads the correspondingprimaryphasor by30^0asshown in fig. below.

6. 10.4.1Yd11Connection

For Yd arrangement first the primary is connected in star with $A_1B_1C_1$ connected togetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshowninfigure6.24(i),here $a_1a_2$isparalleltoA$_1$A$_2$.Similarly$b_1b_2$and$c_1c_2$areparalleltoB_1B_2andC_1C_2respectively.In the secondary has to be delta connected its line and phase voltages are same. The line voltagec_1c_2,is leading by an angle 30^0 to the primary line voltage C_2B_2phasor, a_1a_2 leading by an angle30^0 to $A_2C_2$and so on.For which the arrangement shown below provides a phase displacementof 30^0leadingbetween thecorrespondinglinevoltages of primaryand secondary.



(i)

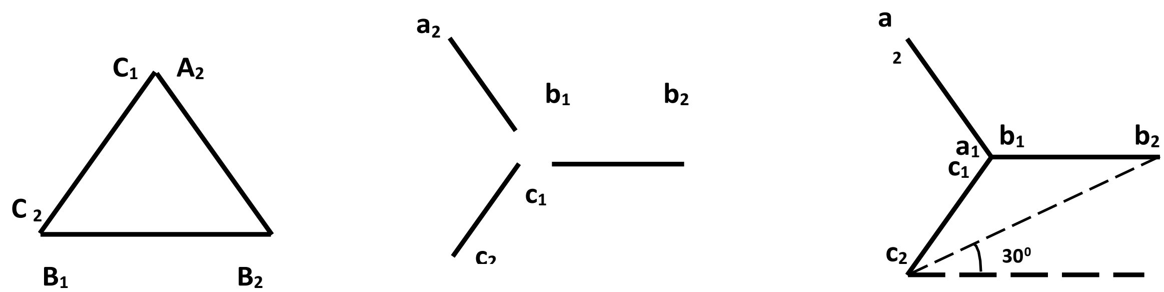


(ii)

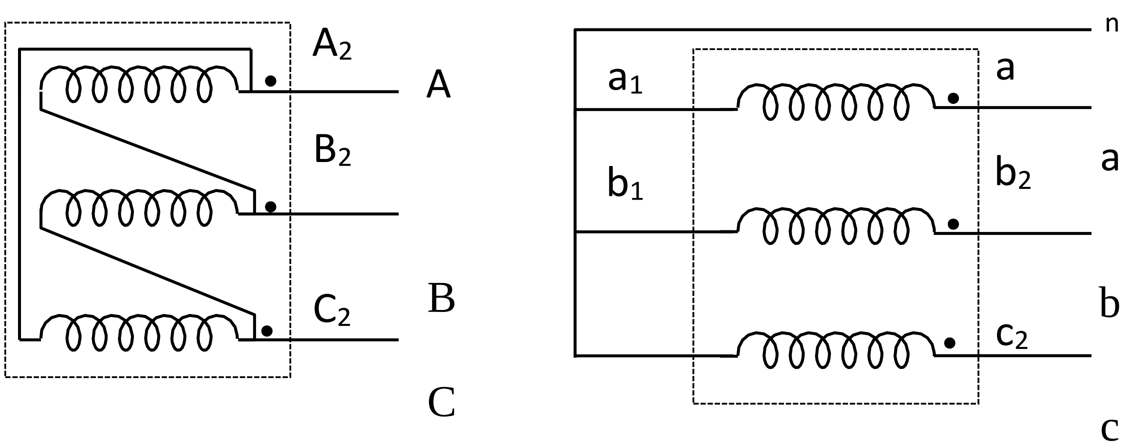
Fig.6.27PhasordiagramofYd11arrangement(ii)Connectiondiagramfor it

6.10.4.2 Dy11Connection

For Dy arrangement first the primary is connected in delta with A_2C_1, B_2A_1 and C_2B_1connectedtogetherandthesecondarykeptopen.Thecorrespondingphasordiagramareshownin figure 6.28(i), here a_1a_2 is parallel to A_1A_2. Similarly b_1b_2 and c_1c_2 are parallel to B_1B_2 andC_1C_2 respectively.The line voltage c_2b_2, is leading by an angle 30^0 to the primary line voltageB_1B_2phasor, a_2b_2 leading by an angle 30^0 to A_1A_2 and so on.For which the arrangement shownbelow provides a phase displacement of 30^0 leading between the corresponding line voltages ofprimaryand secondary.



(i)

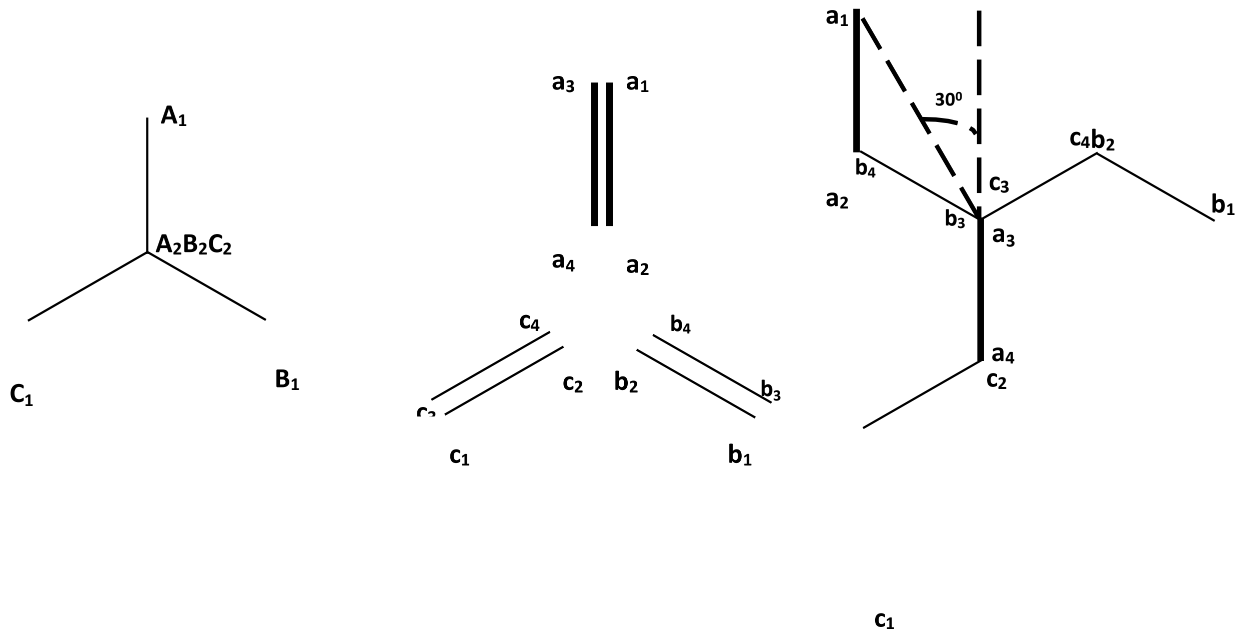


(ii)

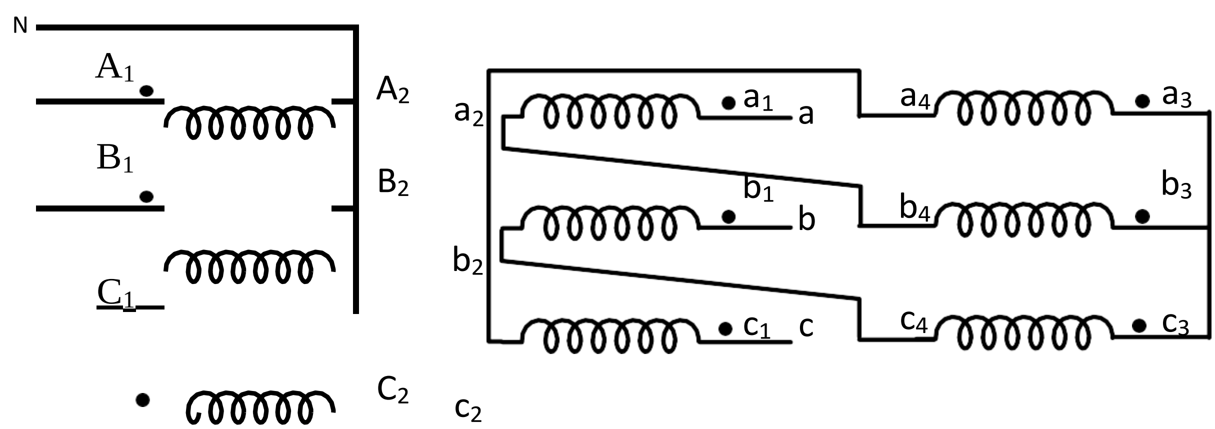
Fig.6.28PhasordiagramofDy11arrangement(ii)Connectiondiagramfor it

6.10.4.3 Yz11Connection

Forthisarrangementfirsttheprimaryisconnectedinstarwith$A_2B_2C_2$connectedtogether and the secondary kept open. The corresponding phasor diagram are shown in figure6.26(i), here a_1a_2 and a_3a_4 is parallel to A_1A_2. Similarly b_1b_2, b_3b_4 and c_1c_2, c_3c_4 are parallel toB_1B_2andC_1C_2respectively.Tohaveaphasedisplacementof30^0leadingbetweenthecorresponding phase voltages phasor c_3c_4 and b_2b_1 are connected in series, which forms theresultant phasevoltagec_3b_1.



(i)



(ii)

Fig.6.29PhasordiagramofY11 arrangement(ii)Connectiondiagramforit

Paralleloperationoftransformers

Parallel operation mean two or more transformers are connected to the same supply bus barson the primary side and to a common bus bar/load on the secondary side. Such requirement isfrequentlyencounteredinpractice.Thereasons thatnecessitateparalleloperationareas follows.

1. Non-availabilityof asingle largetransformerto fulfill theload demand.
2. To fulfill the future demand. The power demand might have increased over a time anumberof transformersconnected in parallelwill thenbepressed intoservice.
3. Toimprovedreliability.Evenifoneofthetransformersgetsintoafaultoristakenoutformaintena

nce/repair thecontinuityof theservicecan bemaintained.

4. To reduce the spare capacity. If many smaller size transformers are used one machine canbe used as spare. If only one large machine is feeding the load, a spare of similar ratinghasto beavailable.

5. Itmaybeeasiertotransportsmalleronestositeandworktheminparallelcomparetoalargeunit.

Conditionstobefulfilledforparalleloperation

Therearesomeessentialconditionswhichshouldbefulfilledbeforeconnectingtransformersin parallel.

1. Thepolaritymustbethesame,sothatthereisnocirculatingcurrentbetweenthetransformers.
2. Theprimaryand secondaryvoltage ratingofthetransformershouldbe same.
3. 3-phasetransformersmust belongto thesamevectorgroup.
4. Thephasesequencemustbethe sameand no phasedifferencemust exist betweenthevoltagesof thetwo transformers.
5. The magnitudes of leakage impedances of the transformers should be inversely proportionalto their KVA ratings for better load sharing. i.e. The per unit impedance of each machine onitsown basemustbethe same.
6. Thequalityoftheimpedancesi.e.$\frac{x}{r}$ratioshouldbesame.

Polaritymust be same: Inside the loop formed by the two secondaries the resulting voltagemust be zero. If it is wrongly connected, the secondary winding voltages will aid each other.Since the windings are already closed by virtue of the parallel connection, a situation like deadshortcircuit prevails resultingin largecurrent.

Same voltage ratio: If the ratio is different, when the primaries are connected to same bus bars,the secondaries do not show the same voltage, paralleling them result in a circulating currentbetween the secondaries. Reflected circulating current will be there on the primary side also.Thus even without connecting a load considerable current can be drawn by the transformers andthey produce copper losses. In such cases the combined full load of the two transformers canneverbemet without one transformer gettingoverloaded.

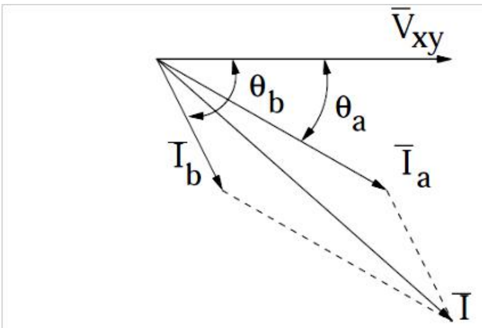
Same vector group: A Y d1 transformer can be paralleled with a Dy1 transformer but not with asay, Y d11 transformer. Here also wrong selection of vector groups will essentially mean deadshortcircuit inthesecondarydueto differenceinphasesbetween the correspondingphases.

Same phase sequence: The phase sequence of operation becomes relevant only in the case ofpoly phase systems. If the phase sequences are not the same then the two transformers cannot beconnected in parallel even if they belong to same vector group. If transformer connected withwrong phasor group due to difference in phases between the corresponding phases it leads to adead shortcircuit. Thephasesequencecan befound out bythe useof aphasesequenceindicator.

Same per unit impedance Transformers of different ratings may be required to operate inparallel.Iftheyhavetosharethetotalloadinproportiontotheirratingsthelargermachinehasto draw more current. The voltage drop across each machine has to be the same by virtue of theirconnection at the input and the output ends. Thus the larger machines have smaller impedanceand smaller machines must have larger ohmic impedance. Thus the impedances must be in theinverse ratios of the ratings. As the voltage drops must be the same the per unit impedance ofeachtransformer on its own base, must be equal.

Same quality of impedance: The fulfillment of this condition means that the sum of the KVAshandled by the transformers will be equal to the load KVA. To understand this, let us look at thephasor diagrams shown in figure 6.30 and 6.31. Let V_{XY} be the voltage phasor across the parallelbranches of Z_{ea} and Z_{eb}. Suppose the qualities of the impedances are different with power factorangles$\theta_A$and$\theta_B$respectively.ThecurrentphasorsI$_a$andI$_b$canbedrawnasshowninfigure 6.31. Since the ratio of impedances are in the inverse proportion of the magnitudes of theimpedances, then if I_a is rated current, I_b too will be rated. But in this case current supplied to theload, I is less than the sum of the magnitudes of the currents I_a and I_b for obvious reason. In otherwords, although the individual transformers will be operating at their rated kVAs, kVA suppliedto the load (S = VI) will be less than sum of kVAs of the transformers. Transformers in this caseoperate at different power factors.

However, if the qualities of the impedances are same, I_a and I_b will be in same phase andscalar sum ofI_a and$I_b$will be equal to load currentI. Thisensures scalar sum of the kVAs,indeed is kVA supplied to the load and the transformers operate at the same power factors. Aslightdifferencein thequalities oftheimpedancesof thetransformers canalways allow.



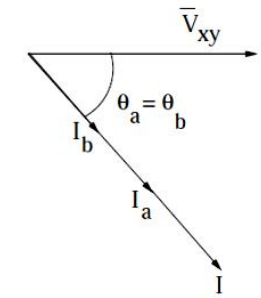


Fig. 6.30: Phasor sum when the x/r ratios are different.Fig. 6.31: Phasor sum when the x/rratiois same.

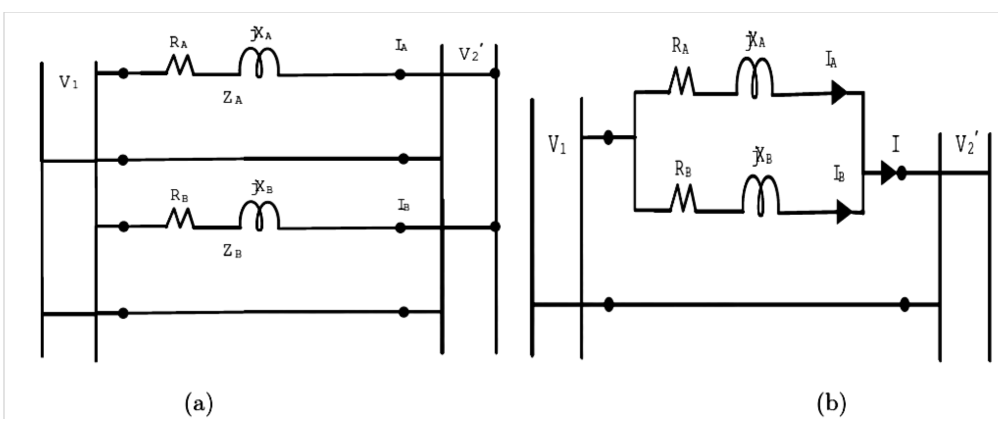
Performanceoftwoormoresinglephasetransformersworkinginparallelcanbecomputedusing their equivalent circuit. In the case of poly phase banks also the approach is identical andthe single phase equivalent circuit of the same can be used. Basically two cases arise in theseproblems.

Case A: when the voltage ratio of the two transformers is the sameandCaseB: whenthevoltageratiosarenot thesame.

Thesearediscussednow insequence.

CaseA:Equalvoltageratios

Always two transformers of equal voltage ratios are selected for working in parallel. Thisway one can avoid a circulating current between the transformers. Load can be switched onsubsequently to these bus bars. Neglecting the parallel branch of the equivalent circuit the aboveconnection can be shown as in Fig. 6.32(a),(b). The equivalent circuit is drawn in terms of thesecondaryparameters. This maybefurthersimplified asshown under Fig.6.32(c).



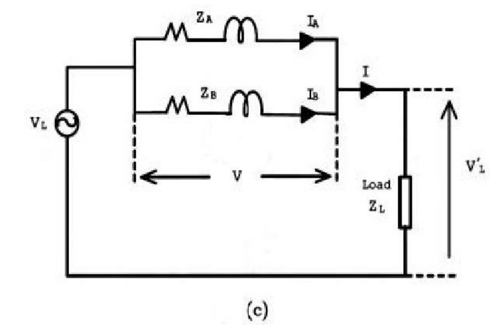


Fig.6.32

Thevoltagedropacrossthetwotransformersmustbethesamebyvirtueofcommonconnectionatinput aswell asoutput ends.Byinspection thevoltageequationfor thedrop canbewrittenas

$$I_A Z_A = I_B Z_B = IZ = v \qquad \text{(say)}$$

Here $I = I_A + I_B$

andZistheequivalentimpedanceof twotransformers givenby,

$$Z = \frac{Z_A Z_B}{Z_A + Z_B}$$

Thus $I_A = \frac{v}{Z_A} = \frac{IZ}{Z_A} = I.\frac{Z_B}{Z_A + Z_B}$ and $I_B = \frac{v}{Z_B} = \frac{IZ}{Z_B} = I.\frac{Z_A}{Z_A + Z_B}$

Iftheterminalvoltageis $V = IZ_L$ thentheactivepowersuppliedbyeachofthetwotransformersis given by

$$P_A = \text{Real}(VI_A^*) \text{ and } Q_A = \text{Imag}(VI_A^*)$$

$$P_B = \text{Real}(VI_B^*) \text{ and } Q_B = \text{Imag}(VI_B^*)$$

From the above it is seen that the transformer with higher impedance supplies lesser load currentand vice versa. If transformers of dissimilar ratings are paralleled the transformer with largerratingshallhavesmallerimpedanceasithastoproducethesamedropastheothertransformer,atalargercurrent.Thustheohmicvaluesoftheimpedancesmustbeintheinverseratioofthe ratingsofthetransformers. $I_A Z_A = I_B Z_B$, therefore $\frac{I_A}{I_B} = \frac{Z_A}{Z_B}$.

Expressing the voltage drops in p.u basis, we aim at the same per unit drops at any load for thetransformers.Theperunitimpedancesmustthereforebethesameontheirrespectivebases.Fig. 6.33 shows the phasor diagram of operation for these conditions. The drops are magnified andshown to improve clarity. It is seen that the total voltage drop inside the transformers is v but thecurrents I_A and I_B are forced to have a different phase angle due to the difference in the internalpowerfactor angles $\phi_A$and ϕ_B.

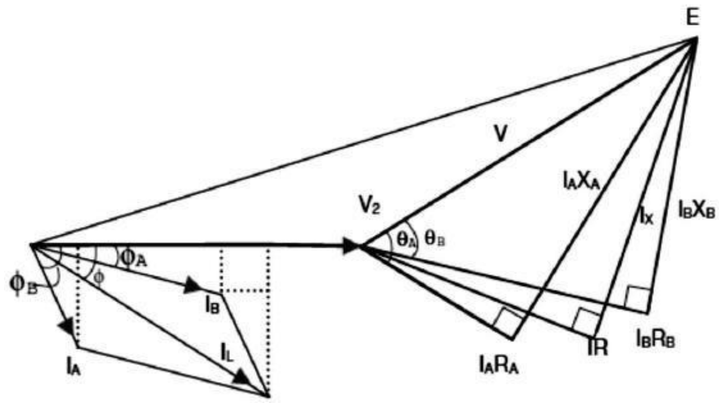


Fig.6.33Phasordiagramofoperationoftwotransformersworkinginparallel

This forces the active and reactive components of the currents drawn by each transformer to bedifferent (even in the case when current in each transformer is the same). If we want them toshare the load current in proportion to their ratings, their percentage (orp.u) impedances must bethe same. In order to avoid any divergence and to share active and reactive powers also properly,$\phi_A = \phi_B$. Thus the condition for satisfactory parallel operation is that the p.u resistances and p.ureactance must be the same on their respective bases for the two transformers. To determine thesharingof currents and powereither p.uparameters orohmicvalues can beused.

CaseB:Unequalvoltageratios

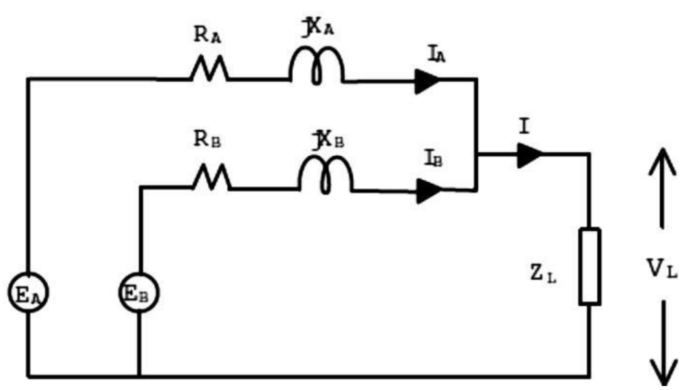


Fig.6.40Equivalentcircuitsforunequalvoltageratio

One may notbe abletogettwotransformersof identicalvoltageratioinspite of onesbestefforts. Due to manufacturing differences, even in transformers built as per the same design, thevoltage ratios may not be the same. In such cases the circuit representation for parallel operationwill be different as shown in Fig. 40. In this case the two input voltages cannot be merged to one,astheyaredifferent.Theloadbringsaboutacommonconnectionattheoutputside.$E_A$andE_B

aretheno-loadsecondaryemf.$Z_L$istheloadimpedanceatthesecondaryterminals.Byinspectionthe voltageequation can bewritten asbelow:

$$E_A = I_A Z_A + (I_A + I_B) Z_L = V + I_A Z_A$$

$$E_B = I_B Z_B + (I_A + I_B) Z_L = V + I_B Z_B$$

SolvingthetwoequationstheexpressionforIAandIBcanbeobtainedas

$$I_A = \frac{E_A Z_B + (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)} \quad \text{and}$$

$$I_B = \frac{E_B Z_A + (E_B - E_A) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

Z_A and Z_B are phasors and hence there can be angular difference also in addition to the differenceinmagnitude.Whenloadisnotconnectedtherewillbeacirculatingcurrentbetweenthetransfo rmers. The currents in that case can be obtained by putting Z_L = inf (after dividing thenumeratorand thedenominator byZ_L). Then,

$$I_A = -I_B = \frac{(E_A - E_B)}{(Z_A + Z_B)}$$

If theload impedancebecomes zeroas inthecase of ashort circuit,wehave,

$$I_A = \frac{E_A}{Z_A} \quad \text{and} \quad I_B = \frac{E_B}{Z_B}$$

Insteadof thevalue ofZLif thevalue ofV is known , thecurrentscan beeasilydetermined(fromEqns. 93)as

$$I_A = \frac{E_A - V}{Z_A}, \quad I_B = \frac{E_B - V}{Z_B}$$

If more than two transformers are connected across a load then the calculation of load currentsfollowing the method suggested above involves considerable amount of computational labor. Asimpler and more elegant method for the case depicted in Fig. 41 is given below. It is known bythename parallelgeneratortheorem.

$$I_L = I_A + I_B$$

But

$$I_A = \frac{E_A - V}{Z_A}, \quad I_B = \frac{E_B - V}{Z_B}$$

$$V = I_L Z_L$$

MODULE-III

CHAPTER-7

Single PhaseandSpecial PurposeMotors

Introductiontosinglephaseinductionmotor

The characteristics of single phase induction motors are identical to 3-phase induction motorsexceptthatsinglephaseinductionmotorhasnoinherentstartingtorqueandsomespecialarrangements have to be made for making itself starting. It follows that during starting period thesingle phase induction motor must be converted to a type which is not a single phase inductionmotor in the sense in which the term is ordinarily used and it becomes a true single phaseinduction motor when it is running and after the speed and torque have been raised to a pointbeyond which the additional device may be dispensed with. For these reasons, it is necessary todistinguish clearly between the starting period when the motor is not a single phase inductionmotor and the normal running condition when it is a single phase induction motor. The startingdevice adds to the cost of the motor and also requires more space. For the same output a 1-phasemotoris about 30% larger than acorresponding3-phasemotor.

The single phase induction motor in its simplest form is structurally the same as a polyphaseinductionmotorhavingasquirrelcagerotor,theonlydifferenceisthatthesinglephaseinduction motor has single winding on the stator which produces mmf stationary in space butalternating in time, a polyphase stator winding carrying balanced currents produces mmf rotatingin space around the air gap and constant in time with respect to an observer moving with themmf. The stator winding of the single phase motor is disposed in slots around the inner peripheryofalaminated ringsimilar to the3-phasemotor.

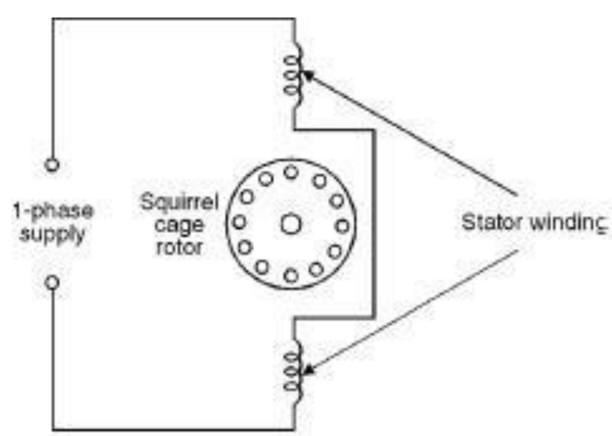


Fig.7.1: Elementarysingle phaseinduction motor

An induction motor with a cage rotor and single phase stator winding is shown schematically inFig. 7.1. The actual stator winding as mentioned earlier is distributed in slots so as to produce anapproximatelysinusoidal spacedistribution ofmmf.

PRINCIPLEOFOPERATION

Suppose the rotor is at rest and 1-phase supply is given to stator winding. The current flowing inthe stator winding givesrise to an mmf whose axis is along the winding and it is a pulsatingmmf,stationaryinspaceandvaryinginmagnitude,asafunctionoftime,varyingfrompositive maximum to zero to negative maximum and this pulsating mmf induces currents in the short-circuited rotor of the motor which gives rise to an mmf. The currents in the rotor are induced dueto transformer action and the direction of the currents is such that the mmf so developed opposesthe stator mmf. The axis of the rotor mmf is same as that of the stator mmf. Since the torquedeveloped is proportional to sine of the angle between the two mmf and since the angle is zero,thenet torqueactingon therotor is zero and hencethe rotor remains stationary.

For analytical purposes a pulsating field can be resolved into two revolving fields of constantmagnitudeandrotatinginoppositedirectionsasshowninFig.1.1andeachfieldhasamagnitude equal to half themaximum lengthof the original pulsatingphasor.

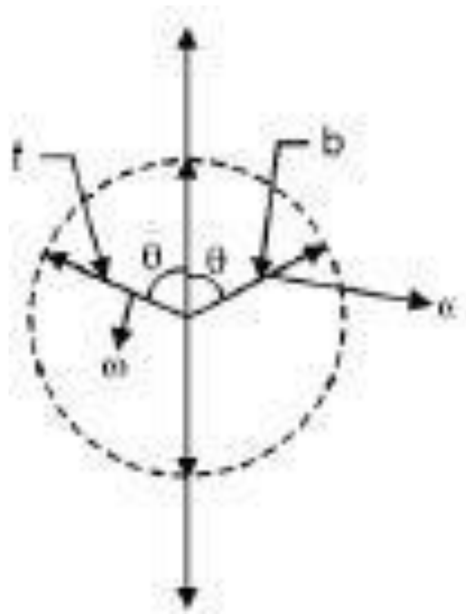


Fig.7.2.Representation of thepulsatingfield byspacephasor.

Thesecomponentwavesrotateinoppositedirectionatsynchronousspeed.Theforward(anticlockwise) and backward-rotating (clockwise) mmf waves' f and b are shown in Fig. 7.2. Incase of 3-phase induction motor there is only one forward rotating magnetic field and hencetorque is developed and the motor is self-starting. However, in single phase induction motor eachofthesecomponentsmmfwaveproducesinductionmotoractionbutthecorrespondingtorquesis in opposite direction. With the rotor at rest the forward and backward field produce equaltorquesbutopposite indirection andhence nonettorque isdevelopedon the motor andthemotor remains stationary. If the forward and backward air gap fields remained equal when therotor is revolving, each of the component fields would produce a torque-speed characteristicsimilar tothat of a polyphase inductionmotor with negligible leakage impedance asshown bythedashedcurves fand bin Fig. 7.3.

The resultant torque-speed characteristic whichisthe algebraic sumof the two componentcurves shows that if the motor were started by auxiliary means it would produce torque in what-everdirection it was started.

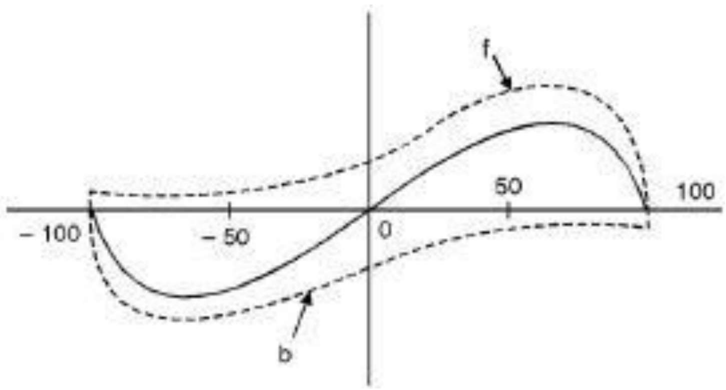


Fig.7.3 Torque-speed characteristic of a 1-phase induction motor based on constant forward andbackwardfluxwaves

In reality the two fields, forward and backward do not remain constant in the air gap and also theeffect of stator leakage impedance can't be ignored. In the above qualitative analysis the effectsofinduced rotorcurrents havenot been properlyaccounted for.

When single phase supply is connected to the stator and the rotor is given a push along theforward rotating field, the relative speed between the rotor and the forward rotating magneticfield goes on decreasing and hence the magnitude of induced currents also decreases and hencethe mmf due to the induced current in the rotor decreases and its opposing effect to the forwardrotating field decreases which means the forward rotating field becomes stronger as the rotorspeeds up. However for the backward rotating field the relative speed between the rotor and thebackward field increases as the rotor rotates and hence the rotor emf increases andhence themmf due to this component of current increases and its opposing effect to the backward rotatingfield increases and the net backward rotating field weakens as the rotor rotates along the forwardrotating field. However, the sum of the two fields remains constant since it must induce the statorcounter emf which is approximately constant if the stator leakage impedance drop is negligible.Hence,withthe rotor inmotionthe torque ofthe forwardfieldisgreaterandthatof thebackwardfield is shownin Fig. 7.4.

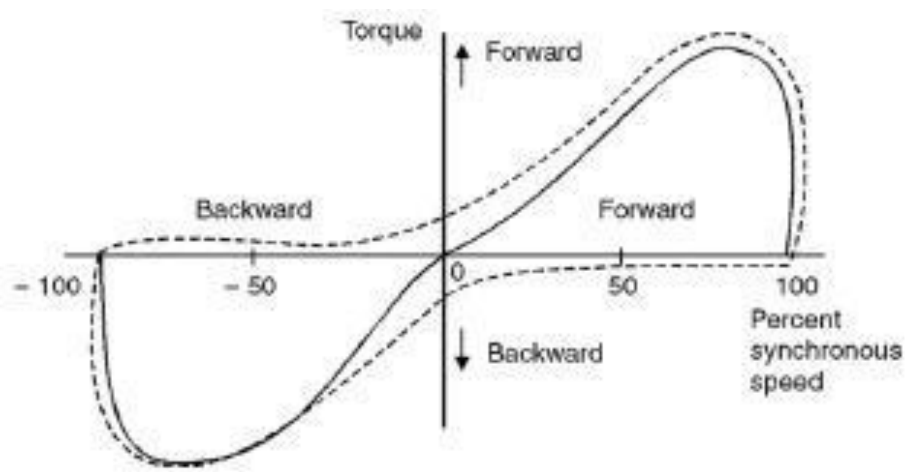


Fig.7.4. Torque-speed characteristic of a 1-phase induction motor taking into account changes inthefluxwaves.

In the normal running region at a few per cent slip the forward field is several times stronger thanthe backward field and the flux wave does not differ materially from the constant amplituderevolving field in the air gap of a balanced polyphase motor. Therefore, in the normal runningrange of the motor, the torque-speed characteristic of a single phase motor is not very muchdifferent from that of a polyphase motor having the same rotor and operating with the samemaximumairgap fluxdensity.

Double-statorfrequencytorquepulsationareproducedbytheinteractionoftheoppositelyrotating flux and mmf waves which move past each other at twice synchronous speed. Thesedouble frequency torques produce noaverage torque as these pulsations aresinusoidal and overthe complete cycle the average torque is zero. However, sometimes these are additive to the maintorque and for another half a cycle these are subtractive and therefore a variable torque acts on theshaft of the motor which makes the motor noisier as compared to a polyphase induction motorwhere the total torque is constant. Such torque pulsations are unavoidable in single phase circuits.Mathematically

$T \alpha I^2$

$I = Im \sin wt \quad T = KI^2 \sin^2 wt$

$= KIm^2(1-\cos wt)/2$

So the expression for torque contains a constant term superimposed over by a pulsating torquewithpulsation frequencytwicethe supplyfrequency.

STARTINGOFSINGLEPHASEINDUCTIONMOTORS

The single phase inductions motors are classified based on the method of starting method and infact are known by the same name descriptive of the method. Appropriate selection of thesemotors depends upon the starting and running torque requirements of the load, the duty cycle andlimitations on starting and running current drawn from the supply by these motors. The cost ofsingle phase induction motor increases with the size of the motor and with the performance suchas starting torque to current ratio (higher ratio is desirable), hence, the user will like to go in for asmaller size (hp) motor with minimum cost, of course, meeting all the operational requirements.However, if a very large no. of fractional horsepower motors are required, a specific design canalways be worked out which might give minimum cost for a given performance requirements.Followingarethe startingmethods.

(a) **Split-phase induction motor**. The stator of a split phase induction motor has two windings,themainwindingandtheauxiliarywinding.Thesewindingsaredisplacedinspaceby90 °electrical as shown in Fig. The auxiliary winding is made of thin wire (super enamel copperwire) so that it has a high R/X ratio as compared to the main winding which has thick superenamel copper wire. Since the two windings are connected across the supply the current Im andIa in the main winding and auxiliary winding lag behind the supply voltage V, Ia is leading thecurrent Im shown in Fig.This means the current through auxiliary winding reaches maximumvaluefirstandthemmforfluxduetoIaliesalongtheaxisoftheauxiliarywindingandafter some time (t = θ/w) the current Im reaches maximum value and the mmf or flux due to Im liesalongthemainwindingaxis.Thusthemotorbecomesa2-phaseunbalancedmotor.Itisunbalancedsincethetwocurrentsarenotexactly90°apart.Becauseofthesetwofieldsastarting torque is developed and the motor becomes a self-starting motor. After the motor starts,the auxiliary winding is disconnected usually by means of centrifugal switch that operates atabout 75 % of synchronous speed. Finally the motor runs because of themain winding. Sincethis being single phase some level of humming noise is always associated with the motor duringrunning. A typical torque speed characteristic is shown in Fig.It is to be noted that the directionof rotation of the motor can be reversed by reversing the connection toeither the main windingorthe auxiliarywindings.

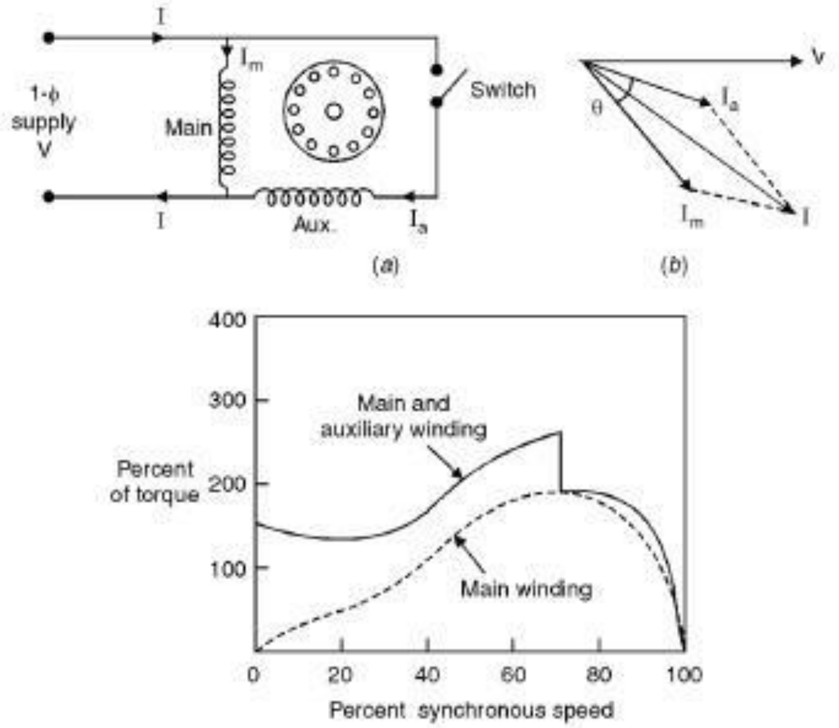


Fig.7.5: Splitphaseinductionmotor (a)Connection(b)Phasordiagramatstarting, (c)typicaltorque-speedcharacteristic.

(b) Capacitorstarts inductionmotor.

Capacitorsareusedtoimprovethestartingandrunningperformanceofthesinglephaseinductionsmotors.

The capacitor start induction motor is also a split phase motor. The capacitor of suitable value isconnected in series with the auxiliary coil through a switch such that Ia the current in theauxiliary coil leads the currentIm in the main coil by 90 ° in time phase so that the startingtorque is maximum for certain values of Ia and Im. This becomes a balanced 2-phase motor if themagnitude of Ia and Im are equal and are displaced in time phase by 90°. Since the two windingsare displaced in space by 90 ° as shown in Fig. 7.6 maximum torque is developed at start.However, the auxiliary winding and capacitor are disconnected after the motor has picked up75% of the synchronous speed. The motor will start without any humming noise. However, afterthe auxiliary windingis disconnected, therewillbesomehummingnoise.

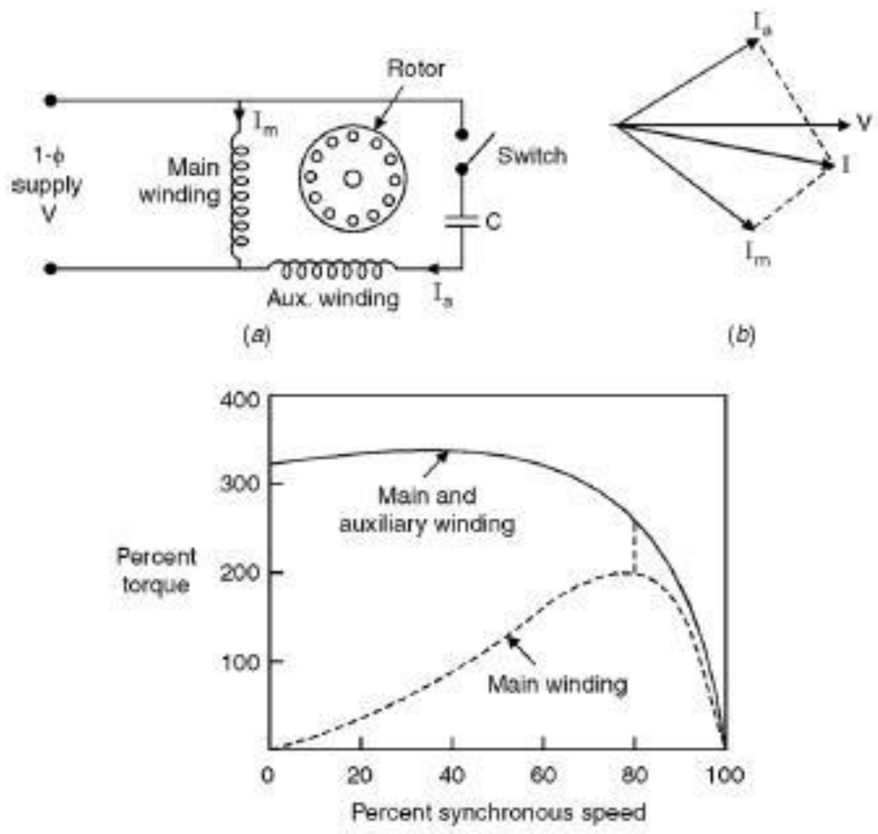


Fig.7.6.Capacitorstartmotor(a)Connection(b)Phasordiagramatstart(c) Speedtorquecurve.

Since the auxiliary winding and capacitor are to be used intermittently, these can be designed forminimum cost. However, it is found that the best compromise among the factors of startingtorque, starting current and costs results with a phase angle somewhat less than 90° between Imand Ia. A typical torque-speed characteristic is shown in Fig. high starting torque being anoutstandingfeature.

(c) **Permanent-split capacitor motor.**In this motor the auxiliary winding and capacitor are notdisconnected from the motor after starting, thus the construction is simplified by the omission oftheswitch as shown in Fig.7.7

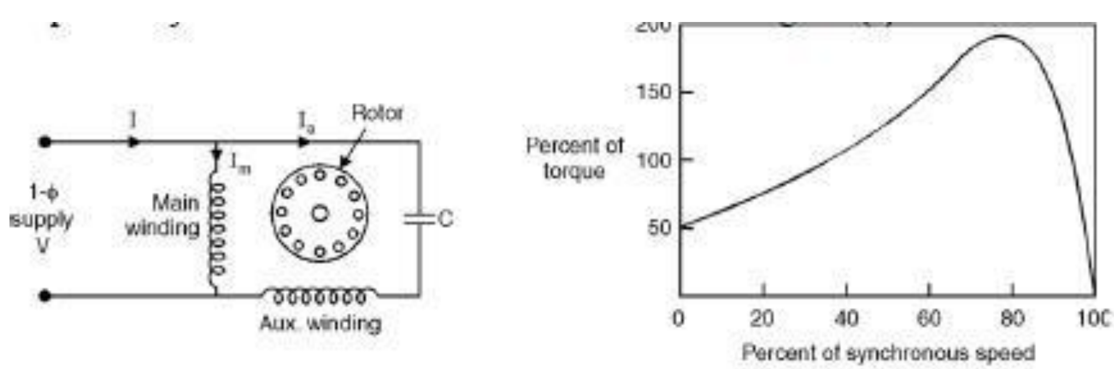


Fig.7.7:Permanent-splitcapacitormotor

Heretheauxiliarywindingandcapacitorcouldbesodesignedthatthemotorworksasaperfect2-phasemotoratanyonedesiredload.Withthisthebackwardrotatingmagneticfieldwouldbe completely eliminated. The double stator frequency torque pulsations would also be eliminated;thereby the motor starts and runs as a noise free motor. With this there is improvement in p.f. andefficiency of the motor. However, the starting torque must be sacrificed as the capacitance isnecessarily a compromise between the best starting and running characteristics. The torque-speedcharacteristicofthe motor is shown in Fig.

(d) **Capacitor start, capacitor run motor**. If two capacitors are used with the auxiliary winding(as shown in Fig.7.8) one for starting and other during the start and run, theoretically optimumstartingandrunningperformancecan both beachieved.

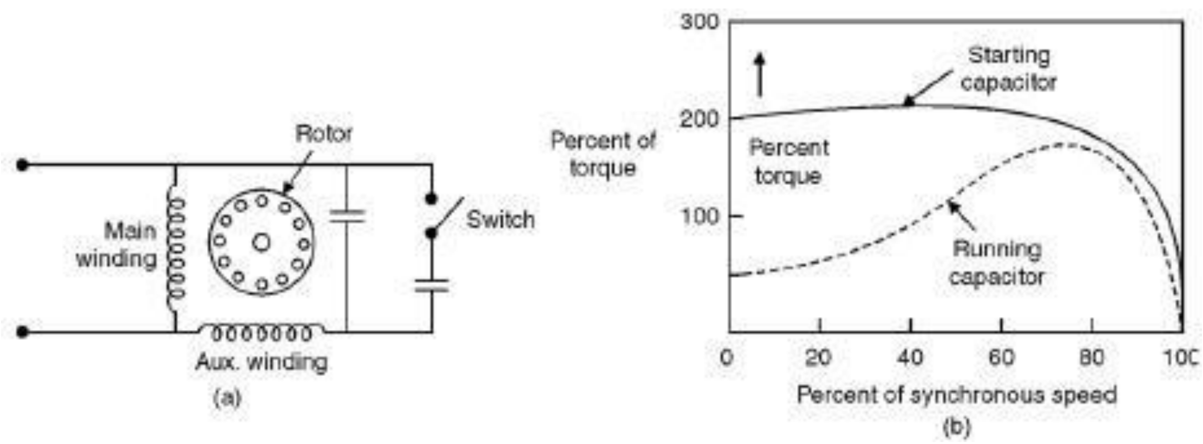


Fig.7.8: (a)Capacitorstartcapacitorrunmotor(b)Torque-speedcharacteristic.

The small value capacitor required for optimum running conditions is permanently connected inseries with the auxiliary winding and the much larger value required for starting is obtained by acapacitor connected in parallel with the running capacitor. The starting capacitor is disconnectedafterthemotorstarts.

(e) **Shaded pole induction motor.**(Fig.7.9 shows schematic diagram of shaded pole inductionmotor.) The stator has salient poles with one portion of each pole surrounded by a short-circuitedturn of copper called a shading coil. Induced currents in the shading coil (acts as an inductor)cause the flux in the shaded portion of the pole to lag the flux in the other portion. Hence the fluxunder the unshaded pole leads the flux under the shaded pole which results in a rotating fieldmoving in the direction from unshaded to the shaded portion of the pole and a low starting torqueis produced which rotates the rotor in the direction from unshaded to the shaded pole (A typicaltorque speed characteristic). The efficiency is low. These motors are the least expensive type offractional horse power motor and are built up to 1/20 hp. since the rotation of the motor is in thedirectionfromunshadedtowardstheshadedpartofthepole,ashadedpolemotorcanbereversed only by providing two sets of shading coils which may be opened and closed or it maybereversed permanentlybyinvertingthecore.

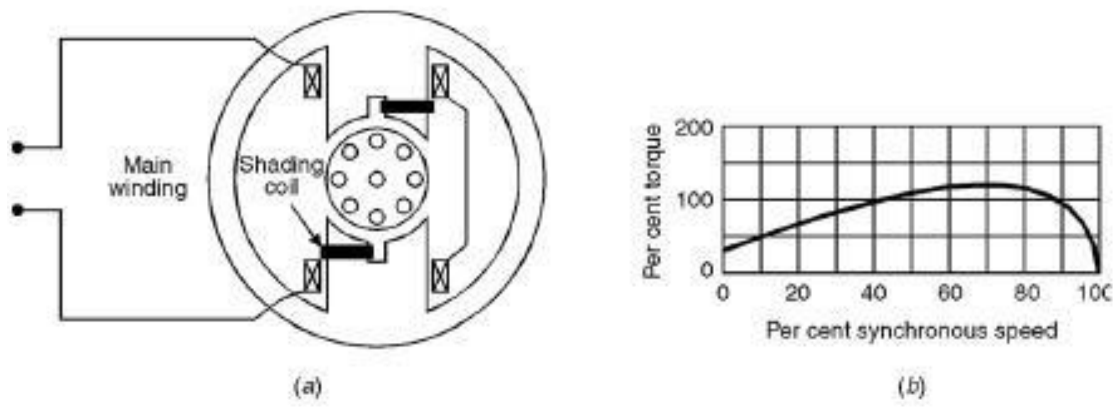


Fig.7.9.Shadedpolemotorandtypicaltorque-speedcharacteristic

Reluctancemotor

The *variable reluctance motor* is based on the principle that an unrestrained piece of iron willmovetocompleteamagneticfluxpathwithminimum *reluctance*,themagneticanalogofelectricalresistance. (Fig.below)

Synchronousreluctance

If the rotating field of a large synchronous motor with salient poles is de-energized, it will stilldevelop 10 or 15% of synchronous torque. This is due to variable reluctance throughout a rotorrevolution. There is no practical application for a large synchronous reluctance motor. However,itis practical in small sizes.

If slots are cut into the conductor less rotor of an induction motor, corresponding to the statorslots, a *synchronous reluctance motor* results. It starts like an induction motor but runs with asmall amount of synchronous torque. The synchronous torque is due to changes in reluctance ofthemagneticpathfromthestatorthroughtherotorastheslotsalign.Thismotorisaninexpensive means of developing a moderate synchronous torque. Low power factor, low pull-outtorque,andlowefficiencyarecharacteristicsofthedirectpowerlinedrivenvariablereluctance motor. Such was the status of the variable reluctance motor for a century before thedevelopmentof semiconductor powercontrol.

Switchedreluctance

Ifanironrotorwithpoles,butwithoutanyconductors,isfittedtoamulti-phasestator,a *switched reluctance motor*, capable of synchronizing with the stator field results. When a statorcoil pole pair is energized, the rotor will move to the lowest magnetic reluctance path. (Fig. 7.10below) A switched reluctance motor is also known as a variable reluctance motor. The reluctanceofthe rotor to stator fluxpath varieswith the position of therotor.

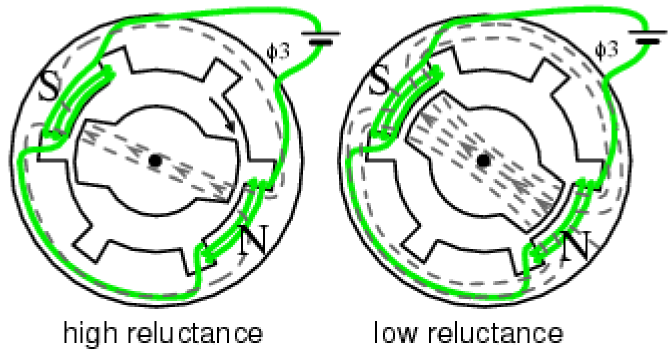


Fig.7.10:Reluctanceisa function ofrotorpositionin avariable reluctance motor.

Sequential switching (Fig. 7.11) of the stator phases moves the rotor from one position to thenext. The magnetic fluxseeks the path of least reluctance, the magnetic analog of electricresistance.This is anover simplifiedrotorand waveforms to illustrateoperation.

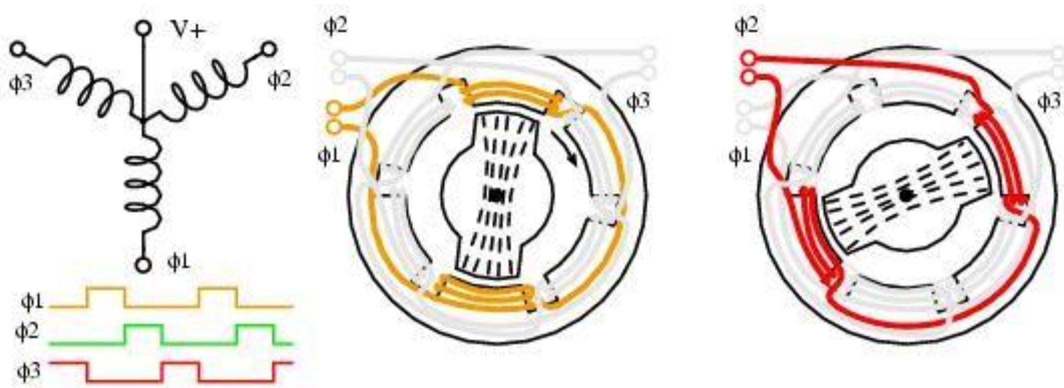


Fig.7.11:Sequentialswitchingofstatorphasesofthereluctancemotor

If one end of each 3-phase winding of the switched reluctance motor is brought out via acommon lead wire, we can explain operation as if it were a stepper motor (Fig. 7.11). The othercoil connections are successively pulled to ground, one at a time, in a *wave drive* pattern. Thisattractstherotor to theclockwise rotatingmagneticfield in 60^{o}increments.

Various waveforms may drive variable reluctance motors. (Fig. 7.12) Wave drive (a) issimple, requiring only a single ended unipolar switch. That is, one which only switches in onedirection. More torque is provided by the bipolar drive (b), but requires a bipolar switch. Thepower driver must pull alternately high and low. Waveforms (a & b) are applicable to the steppermotor version of the variable reluctance motor. For smooth vibration free operation the 6-stepapproximation of a sine wave (c) is desirable and easy to generate. Sine wave drive (d) may begeneratedbyapulse width modulator (PWM), ordrawn from the power line.

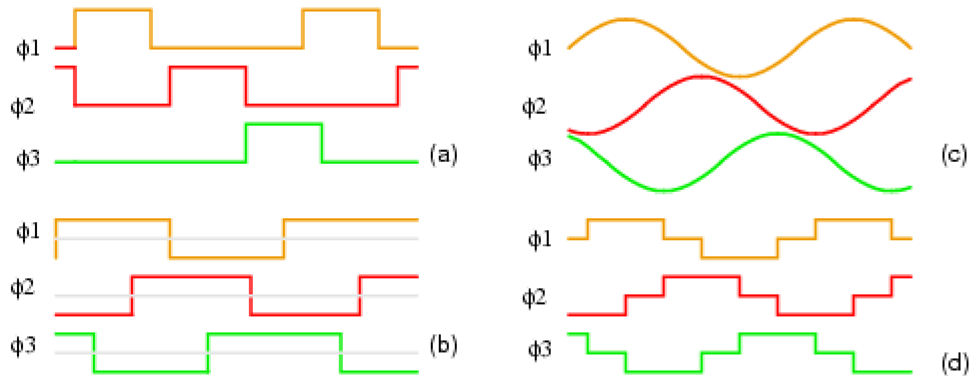


Fig.7.12:Variablereluctancemotordrivewaveforms:(a)unipolarwavedrive,(b)bipolarfullstep (c) sinewave(d)bipolar6-step.

Doubling thenumber ofstator polesdecreases the rotating speedand increases torque. Thismight eliminate a gear reduction drive. A variable reluctance motor intended to move in discretesteps, stop, and start is a *variable reluctance stepper motor*, covered in another section. If smoothrotation is the goal, there is an electronic driven version of the switched reluctance motor.Variable reluctancemotors orsteppersactuallyuserotorslikethose inFig.7.13.

Electronicdrivenvariablereluctancemotor

Variablereluctancemotorsarepoorperformerswhendirectpowerlinedriven.However,microprocessors and solid state power drive makes this motor an economical high performancesolutionin somehigh volumeapplications.

Though difficult to control, this motor is easy to spin. Sequential switching of the field coilscreates a rotating magnetic field which drags the irregularly shaped rotor around with it as itseeks out the lowest magnetic reluctance path. The relationship between torque and stator currentishighlynonlinear– difficult to control.

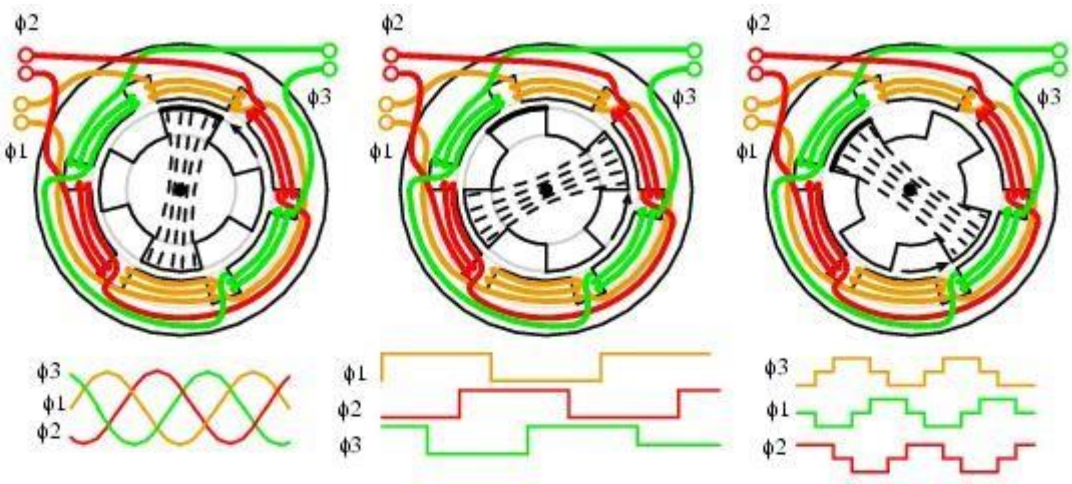


Fig.7.13:Electronicdrivenvariable reluctancemotor

Electronicdrivenvariablereluctancemotor.

An electronic drivenvariable reluctance motor(Fig. 7.14) resemblesabrushlessDCmotorwithout a permanent magnet rotor. This makes the motor simple and inexpensive. However, thisis offset by the cost of the electronic control, which is not nearly as simple as that for a brushlessDC motor. Electronic control makes it practical to drive the motor well above and below thepower line frequency. A variable reluctance motor driven by a *servo*, an electronic feedbacksystem,controls torqueand speed, minimizingrippletorque(Fig. 7.14).

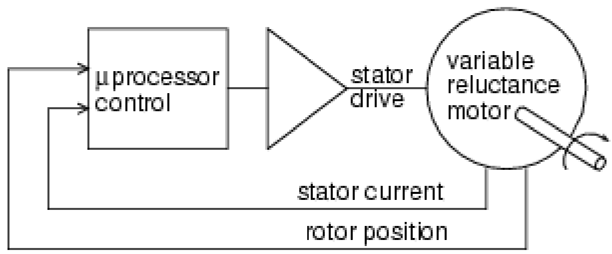


Fig.7.14: Electronicdrivenvariable reluctancemotor.

This is the opposite of the high ripple torque desired in stepper motors. Rather than a stepper, avariable reluctance motor is optimized for continuous high speed rotation with minimum rippletorque.Itisnecessarytomeasuretherotorpositionwitharotarypositionsensorlikeanopticalor magnetic encoder, or derive this from monitoring the stator back EMF. A microprocessorperforms complex calculations for switching the windings at the proper time with solid statedevices. This must be done precisely to minimize audible noise and ripple torque. For lowestripple torque, winding current must be monitored and controlled. The strict drive requirementsmake this motor only practical for high volume applications like energy efficient vacuum cleanermotors, fan motors, or pump motors. One such vacuum cleaner uses a compact high efficiencyelectronic driven 100,000 rpm fan motor. The simplicity of the motor compensates for the driveelectronicscost.Nobrushes,nocommutator,norotorwindings,nopermanentmagnets,simplifies motor manufacture. The efficiency of this electronic driven motor can be high. But, itrequires considerable optimization, using specialized design techniques, which is only justifiedforlargemanufacturingvolumes.

Advantages

- Simpleconstruction-nobrushes,commutator,orpermanentmagnets,noCuorAlintherotor.
- Highefficiencyandreliabilitycompared toconventional AC orDC motors.
- Highstartingtorque.
- Costeffective comparedtobrushlessDCmotorinhighvolumes.
- Adaptabletoveryhighambienttemperature.
- Lowcostaccuratespeed controlpossibleifvolumeishighenough.

Disadvantages

- Currentversustorqueishighlynonlinear
- Phaseswitchingmustbe precise tominimizerippletorque
- Phasecurrentmustbecontrolled tominimizerippletorque
- Acousticandelectricalnoise

- Notapplicable to lowvolumes duetocomplexcontrolissues

StepperMotors

STEPPERMOTOR–anelectromagneticactuator.Itisanincrementaldrive(digital)actuatorandis driven in fixed angularsteps.

Thismeansthatadigitalsignalisusedtodrivethemotorandeverytimeitreceivesadigitalpulseit rotates a specificnumberof degrees in rotation.

- Each step of rotation is the response of the motor to an input pulse (or digitalcommand).
- Step-wise rotation of the rotor can be synchronized with pulses in a command-pulse train, assuming that no steps are missed, thereby making the motor respondfaithfullyto thepulse signal in an open-loop manner.
- Stepper motors have emerged as cost-effective alternatives for DC servomotors inhigh-speed, motion-control applications (except the high torque-speed range) withtheimprovementsinpermanentmagnetsandtheincorporationofsolid-statecircuitryand logicdevices in their drive systems.
- Todaysteppermotorscanbefoundincomputerperipherals,machinetools,medical equipment, automotive devices, and small business machines, to name afewapplications.

Steppermotors areusuallyoperatedin openloopmode.

DCMOTORSVS.STEPPERMOTORS

- Steppermotorsareoperatedopenloop,whilemostDCmotorsareoperatedclosed loop.
- Stepper motors are easily controlled with microprocessors; however logic anddriveelectronics aremorecomplex.
- Stepper motors are brushless and brushes contribute several problems, e.g., wear,sparks,electrical transients.
- DC motors have a continuous displacement and can be accurately positioned,whereas stepper motor motion is incremental and its resolution is limited to thestep size.
- Stepper motors can slip if overloaded and the error can go undetected. (A fewsteppermotors useclosed-loop control.)
- Feedback control with DC motors gives a much faster response time compared tosteppermotors.

ADVANTAGESOFSTEPPERMOTORS

- Position error is noncumulative. A high accuracy of motion is possible, even under open-loopcontrol.
- Largesavingsinsensor(measurementsystem)andcontrollercostsarepossiblewhentheopen-loopmodeis used.
- Becauseoftheincrementalnatureofcommandandmotion,steppermotorsareeasilyadaptableto digital control applications.

- Noserious stabilityproblems exist,even underopen-loop control.
- Torquecapacityandpowerrequirementscanbeoptimizedandtheresponsecanbecontrolledbyelectronicswitching.Brushlessconstruction hasobvious advantages.

DISADVANTAGESOFSTEPPERMOTORS

- Theyhavelow torque capacity(typicallylessthan 2,000 oz-in)comparedtoDC motors.
- Theyhavelimitedspeed(limitedbytorquecapacityandbypulse-missingproblemsduetofaultyswitchingsystems and drive circuits).
- Theyhavehigh vibration levels due to stepwisemotion.
- Large errorsandoscillationscanresultwhenapulseismissedunderopen-loopcontrol.

STEPPERMOTORBASICS

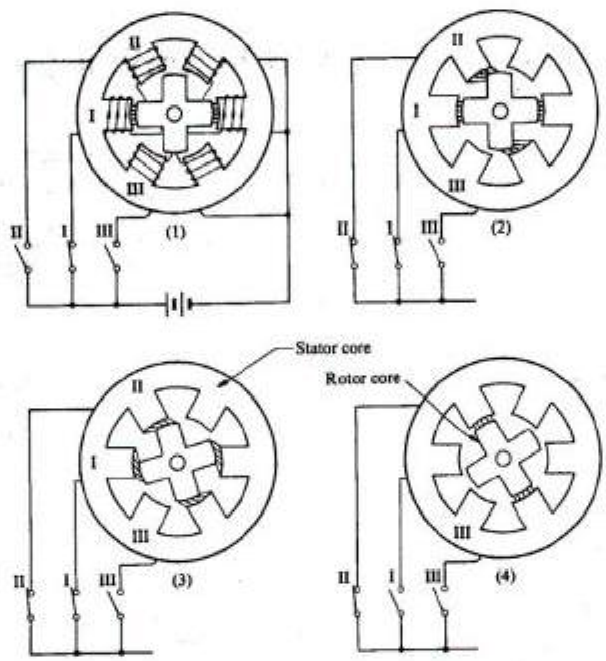


Fig.7.15:Steppermotorstatesformotion

STEPPERMOTORSTATESFORMOTION:-

The above figure (7.15) is the cross-section view of a single-stack variable-reluctance motor. Thestator core is the outer structure and has sixpolesor teeth. The inner device is called the rotorand has four poles. Both the stator and rotor are made of soft steel. The stator has three sets ofwindings as shown in the figure. Each set has two coils connected in series. A set of windings iscalled a “phase”. The motor above, using this designation, is a three-phase motor. Current issuppliedfromthe DCpower sourceto thewindings viatheswitchesI,II,and,III.

Starting with state (1) in the upper left diagram, note that in state (1), the winding of Phase I issupplied with current through switch I. This is called in technical terms, “phase I is excited”.Arrows on the coil windings indicate the magnetic flux, which occurs in the air-gap due to theexcitation. In state I, the two stator poles on phase I being excited are in alignment with two ofthefour rotor teeth. This is an equilibrium state.

Next, switch II is closed to excite phase II in addition to phase I. Magnetic flux is built up at thestator poles of phase II in the manner shown in state (2), the upper right diagram. A counter-clockwisetorqueiscreatedduetothe“tension”intheinclinedmagneticfluxlines.Therotorwill begin to move and achieve state (3), the lower left diagram. In state (3) the rotor has moved15°. When switch I is opened to de-energize phase I, the rotor will travel another 15° and reachstate (4). The angular position of the rotor can thus be controlled in units of the step angle by aswitching process. If the switching is carried out in sequence, the rotor will rotate with a steppedmotion;the switchingprocess canalso control the averagespeed.

STEP ANGLE

The step angle, the number of degrees a rotor will turn per step, is calculated as follows:

$$\textbf{Step Angle}\ (\Theta_S) = \frac{360°}{S}$$

$$S = mN_r$$

$$m = number\ of\ phases$$

$$N_r = number\ of\ rotor\ teeth$$

For this motor:

$$m = 3$$

$$N_r = 4$$

$$S = mN_r = 3 \bullet 4 = 12$$

$$\Theta_S = \frac{360°}{12} = 30°\ per\ step$$

Basicwiringdiagram:

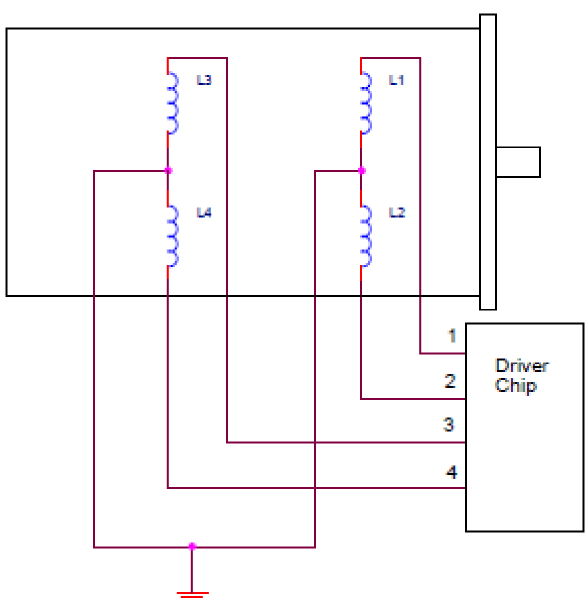


Fig.7.16: twophasestepper motorwiringdiagram.

Thestepangle, thenumber ofdegreesarotorwillturnperstep, iscalculated asfollows:

TWOPHASESTEPPER-MOTORWIRINGDIAGRAM

The above motor is a two-phase motor. This is sometimes called UNIPOLAR. The two-phasecoils are center-tappedand in this case they the center-taps are connected toground. The coilsare wound so that current is reversed when the drive signal is applied to either coil at a time. Thenorth and south poles of the stator phases reverse depending upon whether the drive signal isappliedto coil 1 as opposed to coil 2.

STEPSEQUENCING

Therearethreemodesofoperationwhenusingasteppermotor.Themodeofoperationisdeterminedbythe step sequenceapplied. Thethreestep sequences are:

Wave

FullH=HIGH=+V

HalfSteppingL= LOW=0V

WAVESTEPPING

Thewavesteppingsequenceis shown below.

STEP	L1	L2	L3	L4
1	H	L	L	L
2	L	H	L	L
3	L	L	H	L
4	L	L	L	H

Wavesteppinghaslesstorquethenfullstepping.Itistheleaststableathigherspeedsandhas low power consumption.

FULLSTEPPING

Thefull steppingsequenceis shown below.

STEP	L1	L2	L3	L4
1	H	H	L	L
2	L	H	H	L
3	L	L	H	H
4	H	L	L	H

HALF-STEPPING–ACOMBINATIONOF WAVEANDFULLSTEPPING

Thehalf-stepsequenceisshownbelow.

STEP	L1	L2	L3	L4
1	H	L	L	L
2	H	H	L	L
3	L	H	L	L
4	L	H	H	L
5	L	L	H	L
6	L	L	H	H
7	L	L	L	H
8	H	L	L	H

Thehalf-step sequence hasthe mosttorqueandisthe moststableathigherspeeds.Italsohasthehighestresolutionof themain steppingmethods.Itisa combinationoffulland wavestepping.

Universalmotor

Generally, the electric motorsare operated either in DC Power or AC Power. But for somespecific applications, it is desirable to introduce a motor that operates on either ac or dc supply.Theword'Universal'signifiesthatsomethingwhichiscompatiblewithversatileinputs.Wehave built small series motorsup to ½ KW rating which operates on single phase ac supply aswell as on dc. Such motors are called **universal motors**. An**universal motor** is a specificallydesigned series wound motor, that operates at approximately the same speed and output on eitherac or dc voltage.In case of **universalmotor**, the speed of rotation is slightly lesser whenoperating inAC.Because, the reactance voltagedrop ispresenton ac butnoton dc. So, themotor speed is somewhat lower for same load in ac operation than dc. This takes place especiallyat high loads. Most universal motors are designed to operate at speeds exceeding 3500 rpm. Wewillexplain discuss theconstruction ofthis typeof motor.

ConstructionofUniversalMotor

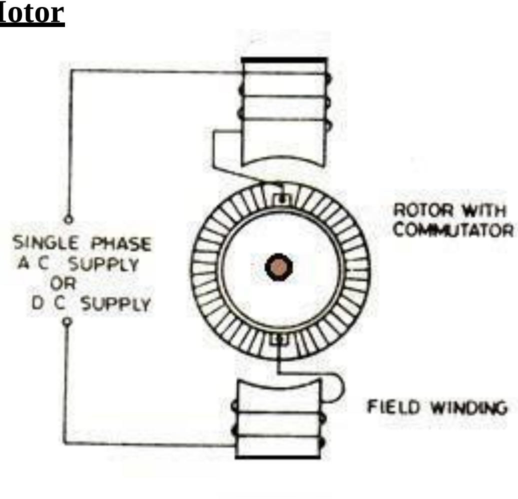


Fig.7.17:Universalmotor

Basically, **an universal motor** is similar to a dc series motor in construction. However it isconstructed with few series field turns, laminated armature and field circuits, low reluctancemagneticpath,increasedarmatureconductorsandcommutatorsegments.Theframesofuniversalmotorareusuallymadeupofaluminum,rolledsteelandcastiron.Thecommutationon ac is much poorer than on dc, due to current induced in the short circuited armature coils .Ifwe use wide brushes then the short circuited current is excessive and motor starting torque isreduced. Brushes used are high resistance carbon ones so as to aid commutation. Compensatingwindings which are used in most large rating motors to improve commutation are not used inuniversalmotors.Inthismotorarmaturecurrentisquitesmallwhichcannotcauseanycommutationproblems.

Typesofuniversalmotors

Universalmotors areoftwo types. Theyare:

- **Compensatedtype(distributed field):**Itisofagaintwotypesnamely:

(i) Singlefieldcompensatedmotor–itresemblesthestatorwindingof2pole,splitphaseacmotor.

(ii) Two-fieldcompensatedmotor–ithasstatorwindingwhichconsistsofmainwindingandacompensatedwindingspaced 90electrical degrees apart.

- **Uncompensatedtype(concentratedfield):** Itisusedforhigherspeedsandsmalleroutput ratings. Concentrated field type is usually a salient pole machine. Laminated corehaving either straight or skewed slots or commutator are also present .The uncompensatedmotorissimplerandlessexpensivethancompensatedmotorbutgivespoorspeedregulation.

Workingprincipleof universalmotor

Now let us discuss the **operation** of this kind of motor in brief. In series circuit, same amount ofcurrent flows through all components. Similarly in a series wound motor, the same current flowsthroughfieldwindingsandarmaturewindingboth.

Inan**universalmotor**,bothwindingsconnected in series with each other. When the motor is supplied from ac or dc supply, magneticfields are developed around the armature winding and field winding. They react on each other toproduce an unidirectional torque forcefully. In some other words, the interaction in betweenseries magnetic field and armature field causes to develop a torque and this torque leads to rotatethe shaft. However a series motor which is specifically designed for dc operation suffers fromfollowingdrawbacks when it is used on single phaseacsupply:-

- Itsefficiencyis lowdueto hysteresisand eddycurrentlosses.
- Thep.fis lowduetolargereactanceofthe fieldand armaturewindings.
- Thesparkingatthebrushesis excessive.

Characteristicsof Universal Motor

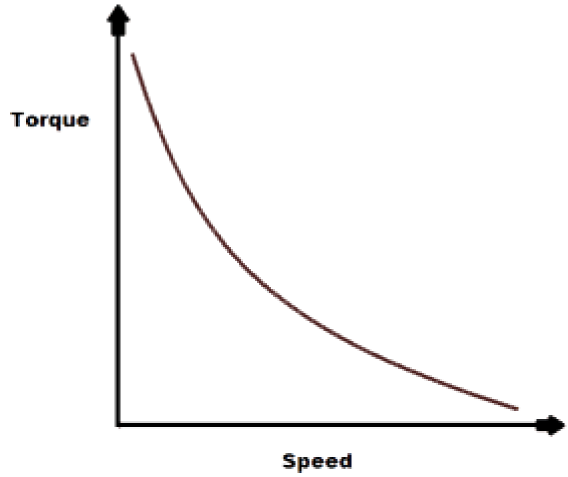


Fig.7.18:Torque-speedcharacteristicsofuniversalmotor

The **torque – speed (τ – N) characteristics of an universal motor** is quite similar to that of aseries wound dc motor. It has high starting torque at low speed and low starting torque at highspeed. In small series motors losses are large at no-load to restrict the speed to a definite value. Acentrifugal switch is placed on the motor shaft. The tension of the springs of the switch isadjusted so that the switch opens at a pre determined speed. An external resistor R is placed inseries with armature to reduce the speed. When speed drops due to increase of load, the switchcontacts close thereby shorting the resistor R thus raising the speed. Universal motors are highspeed, small size motors as compared to other motors of same output. Here the full load powerfactoris high (0.9).

Speedcontrolofuniversalmotor

Speedcontrolofuniversalmotorisbestobtainedbysolid-statedevices.Sincethespeedofthesemotorsisnotlimitedbythesupplyfrequencyandmaybeashighas20,000rpm,theyaremostsuitableforapplicationsrequiringhighspeeds.Thefactorsthatdeterminethespeedforanydcmotorarethesameasthoseforacseriesoruniversalmotorsi.e.fluxandgeneratedvoltage.Generatedvoltagechangeisrarelyemployedinspeedcontrolmethod.Insteadlinevoltageisvaried .This has been accomplished by means of tapped resistor, rheostat in series with the line.Another methodisbyusingatappedfield,therebyreducingthefluxandhenceraisingthespeed.This can beachieved byanyoneof themethods that follow:

- Byusingfieldpoleswoundinvarioussectionswithwiresofdifferentsizeandbringingoutthetaps from each section.
- By using tapped nichrome wirescoilswound over a single fieldpole.In thismethodtorquedecreases with increasein speed.

ApplicationsofUniversalMotor

Universalmotorsfinditsapplicationsinvariousdevices.Theseare:

- Theverysmallpoweroutputratinguniversalmotors,whichusuallydoesnotexceed5to10 watts are employed in equipments such as sewing machines , fans , portable handtools,hairdryers , motion pictureprojectorsand electric shavers.
- The higher rating (5-500 W) universal motor are used in vacuum cleaners, food mixers,blenders,camerasand calculatingmachines.
- This type of machine is used in table fans, polishers, portable drills and other kitchenappliances.