SYNERGY INSTITUTE OF ENGINEERING & TECHNOLOGY

Department of Electrical Engineering

LECTURE NOTE (Academic Session 2023-24)

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Subject Code : **REL4C002** **Subject Credit** :**3**

UNIT–ELECTROMECHANICALENERGYCONVERSION

1.1 Electromechanical-Energy-ConversionPrinciples:

Theelectromechanical-energy-conversion processtakesplace through the mediumoftheelectricormagneticfieldoftheconversiondeviceofwhichthestructuresdependontheirrespectivefunctions.

- Transducers:microphone,pickup,sensor,loudspeaker
- Forceproducingdevices:solenoid, relay,andelectromagnet
- Continuousenergyconversionequipment:motor,generator

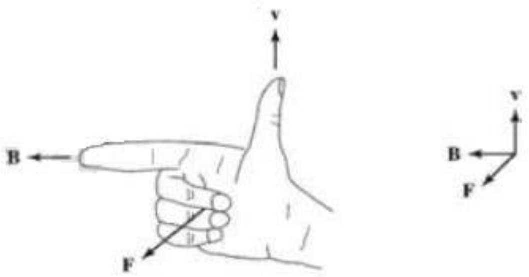
1.2 ForcesandTorques inMagneticFieldSystems:

TheLorentzForceLawgivestheforce$F$onaparticleofcharge$q$inthepresenceofelectricandmagneticfields.

$F=q\left(E+v\times B\right)$

Where,F:newtons,q:coulombs,E:volts/meter,B:telsas, v:meters/second

- Inapureelectric-fieldsystem,
  $F=qE$
- Inpuremagnetic-fieldsystems,
  $F=q\left(v\times B\right)$



Righthandrulefor$F=q(v\times B)$

Forsituationswherelargenumbersofchargedparticlesareinmotion,

$Fv= \rho(E+v\times B)$

$J=\rho vFv$

$=J\times B$

ρ(charge density): coulombs/m3, Fv(force density): newtons/m3, $J = \rho v$(current density):

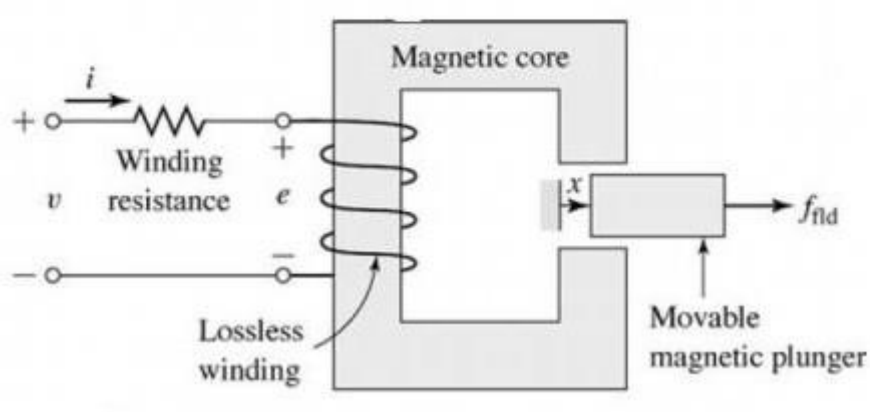
amperes/m2.Mostelectromechanical-energy-conversiondevicescontainmagneticmaterial.

- Forcesactdirectlyonthemagneticmaterialofthesedeviceswhichareconstructedofrigid,non-deformingstructures.
- Theperformanceofthesedevicesistypicallydeterminedbythenetforce,ortorque,actingonthemovingcomponent.It is rarelynecessarytocalculatethedetailsoftheinternalforcedistribution.

- Just as acompassneedle triesto alignwith the earth’smagnetic field,the two setsof fieldsassociatedwiththe rotorandthe statorofrotatingmachineryattempttoalign,andtorque isassociatedwiththeirdisplacementfromalignment.
- In a motor, the stator magnetic field rotates ahead of that of the rotor, pulling on it and performingwork.
- Foragenerator,therotordoestheworkonthestator.

TheEnergyMethod:

- Basedontheprincipleofconservationofenergy:energyisneithercreatednordestroyed;itismerelychangedinform.
- Belowfigureshowsamagnetic-field-basedelectromechanical-energy-conversiondevice.
- Alosslessmagnetic-energy-storagesystemwithtwoterminals
- Theelectricterminalhastwoterminalvariables:*e*(voltage),*i* (current).
- Themechanicalterminalhastwoterminal variables:*f*fld(force),*x*(position)
- Thelossmechanismis separatedfromtheenergy-storagemechanism.
- Electricallosses: ohmiclosses...
- Mechanical losses:friction,windage.
- Fig.1.3:asimple force-producing device with asingle coilforming the electricterminal,and amovableplungerservingasthemechanicalterminal.
- Theinteractionbetweentheelectricandmechanicalterminals,i.e.theelectromechanicalenergyconversion,occursthroughthemediumofthe magneticstoredenergy.



- *W*fld:thestoredenergyinthe magnetic field
- From the above equation force can be solved as a function of the flux λ and the mechanical terminalposition*x*.
- Theaboveequationsformthebasisfortheenergymethod

1.3 EnergyBalance:

Considertheelectromechanicalsystemswhosepredominantenergy-storagemechanismisinmagneticfields.Formotoraction,theenergytransfercanbeaccountedas

$$\begin{pmatrix}\text{Energy input}\\ \text{form electric}\\ \text{sources}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy}\\ \text{output}\end{pmatrix} + \begin{pmatrix}\text{Increase in energy}\\ \text{stored in magnetic}\\ \text{field}\end{pmatrix} + \begin{pmatrix}\text{Energy}\\ \text{converted}\\ \text{into heat}\end{pmatrix}$$

Theabilitytoidentifyalossless-energy-storagesystemistheessenceoftheenergymethod.

- Thisisdonemathematicallyaspartofthemodelingprocess.
- Forthelosslessmagnetic-energy-storagesystemofFig.1.2canberearrangedand gives

$$dW_{elec} = d_{mech} + d_{fld}$$

Here *e*is the voltage induced in the electric terminals by the changing magnetic stored energy. It is throughthis reaction voltage that the external electric circuit supplies powerto the coupling magnetic field andhencetothe mechanicaloutputterminals.

$dW_{elec}=eidt$

- The basic energy-conversion process is one involving the coupling field and its action and reactiononthe electric andmechanicalsystems.
- Combiningabovetwoequation –

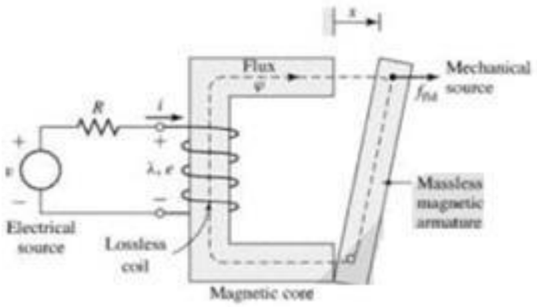
$$dW_{elec} = ei\ dt = dW_{mech} + dW_{fld}$$

1.4 EnergyinSingly-ExcitedMagneticFieldSystems:

Inenergy-conversionsystemsthemagneticcircuitshaveairgapsbetweenthestationaryandmovingmembersinwhichconsiderableenergyisstoredinthemagnetic field.

This field acts as the energy-conversion medium, and its energy is the reservoir between theelectricandmechanicalsystem.

Belowfigureshowsanelectromagneticrelayschematically.Thepredominantenergystorageoccursintheairgap,andthepropertiesofthemagneticcircuitaredeterminedbythedimensionsoftheairgap.



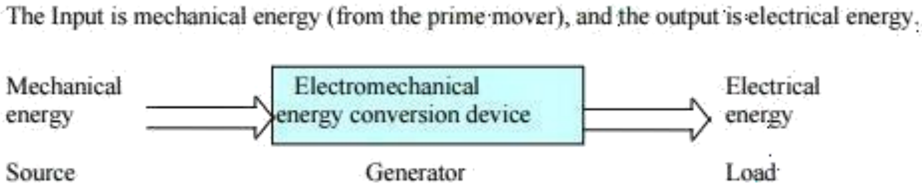
UNIT II
DCGENERATORS

Generators:

There are two types of generators, one is ac generator and other is dc generator. Whatever may be the typesof generators, it always converts mechanical power to electrical power. An ac generator produces alternatingpower.

A DC generator produces direct power. Both of these generators produce electrical power, based on samefundamentalprincipleofFaraday'slaw ofelectromagneticinduction.Accordingtothislaw,whenanconductor moves in a magnetic field it cuts magnetic lines force, due to which an EMF is induced in theconductor. The magnitude of this induced EMF depends upon the rate of change of flux (magnetic line force)linkage with the conductor. This EMF will cause ancurrent to flow if the conductor circuit is closed. Hencethemostbasic twoessentialpartsof ageneratorare

1. Amagneticfield
2. Conductorswhichmoveinsidethatmagneticfield.



ConstructionalFeatures:

ADCgeneratorhasthefollowingparts

1. Yoke
2. Poleofgenerator
3. Fieldwinding
4. ArmatureofDC generator
5. Brushesof generator
6. Bearing

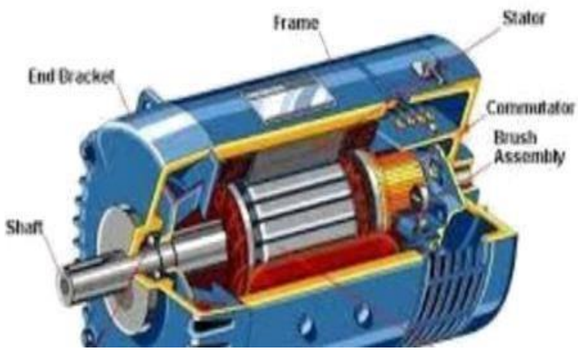


Figure:ACutAwayViewofPracticalDCGenerator

YokeofDCGenerator:

YokeofDCgeneratorservestwopurposes,

1. It holds themagneticpolecoresofthegeneratorandactsas coverofthegenerator.
2. Itcarriesthemagneticfieldflux.

In small generator, yoke are made of cast iron. Cast iron is cheaper in cost but heavier than steel. But forlarge construction of DC generator, where weight of the machine is concerned, lighter cast steel or rolledsteel is preferable for constructing yoke of DC generator. Normally larger yokes are formed by rounding arectangular steel slab and the edges are welded together at the bottom. Then feet, terminal box and hangersareweldedtothe outerperipheryof theyokeframe.

ArmatureCoreofDC Generator:

The purpose of armature core is to hold the armature winding and provide low reluctance path for the fluxthrough the armature from N pole to S pole. Although a DC generator provides direct current but inducedcurrentin the armature isalternatingin nature.That iswhy,cylindrical ordrum shaped armature core isbuild up of circular laminated sheet. In every circular lamination, slots are either die - cut or punched on theouter periphery and the key way is located on the inner periphery as shown. Air ducts are also punched of cutoneachlaminationforcirculationofairthroughthe coreforprovidingbettercooling.

ArmatureWinding ofDCGenerator:

Armature winding are generally formed wound.These are firstwound in the form of flatrectangularcoilsand are then pulled into their proper shape in a coil puller. Various conductors of the coils are insulated fromeach other. The conductors are placed in the armature slots, which are lined with tough insulating material.This slot insulation is folded over above the armature conductors placed in it and secured in place by specialhardwoodenorfiberwedges.

CommutatorofDCGenerator:

Thecommutatorplaysavitalroleindcgenerator.Itcollectscurrentfromarmatureandsendsittotheloadas direct current. It actually takes alternating current from armature and converts it to direct current and thensend it to external load. It is cylindrical structured and is build up of wedge - shaped segments of highconductivity, hard drawn or drop forged copper. Each segment is insulated from the shaft by means ofinsulated commutator segment shown below. Each commutator segment is connected with correspondingarmatureconductorthroughsegmentriserorlug.

BrushesofDCGenerator:

The brushes are made of carbon. These are rectangular block shaped. The only function of these carbonbrushes of DC generator is to collect current from commutator segments. The brushes are housed in therectangularbox shaped brush holder.As shown in figure,the brush face is placed on the commutatorsegmentwithattachedtothebrushholder.

BearingofDCGenerator:

For small machine, ball bearing is used and for heavy duty dc generator, roller bearing is used.The bearing must always be lubricated properly for smooth operation and long life of generator.**EMFequationforDCgenerator:**

ThederivationofEMFequationforDC generatorhastwoparts:

1. InducedEMFofoneconductor

2. InducedEMFofthegenerator

DerivationforInducedEMFofOneArmatureConductor:

For one revolution of the conductor,Let,

Φ=Fluxproducedbyeachpoleinweber(Wb)andP=numberofpolesintheDCgenerator.Therefore,Totalflux producedbyallthepoles=ø*p

And,
Time taken to complete one revolution = 60/NWhere,
N= speed ofthearmatureconductorinrpm.

Now,accordingtoFaraday's lawofinduction,theinducedemfofthearmatureconductorisdenotedby"e"whichisequal torateof cuttingtheflux.

Therefore,

$$e = \frac{d\phi}{dt} \quad and\ e = \frac{total\ flux}{time\ take}$$

InducedEMFofoneconductoris

$$e = \frac{\phi P}{\frac{60}{N}} = \phi P\frac{N}{60}$$

DerivationforInducedEMFforDCGenerator:

LetussupposethereareZtotalnumbersofconductorin agenerator,and arranged in such amannerthatallparallelpathsarealwaysinseries.Here,

Z = total numbers of conductorA = number of parallel pathsThen,
Z/A= numberofconductorsconnectedinseries
Weknowthatinduced EMFineachpathissameacrossthelineTherefore,

InducedEMFofDC generator
E= EMFofoneconductor×numberofconductorconnectedinseries.InducedEMFof DCgeneratoris

$$e = \phi P\frac{N}{60} X \frac{Z}{A}\ volts$$

Simplewavewound generator
Numbers of parallel paths are only 2 = ATherefore,
InducedEMFforwavetypeofwindinggeneratoris

$$\frac{\phi PN}{60} X \frac{Z}{2} = \frac{\phi ZPN}{120}\ volts$$

Simplelap-woundgenerator
Here, number of parallel paths is equal to number of conductors in one path i.e. P = A

Therefore,InducedEMFforlap-woundgeneratoris

$$E_g = \frac{\phi ZN}{60} X \frac{P}{A}\ volt$$

MethodsofExcitation:

An electric generator or electric motor consists of a rotor spinning in a magnetic field. The magnetic fieldmay be produced by permanent magnets or by field coils. In the case of a machine with field coils, a currentmustflow in the coils to generate the field,otherwise no poweris transferred to orfrom the rotor.Theprocessofgeneratingamagneticfieldbymeansofan electriccurrentiscalledexcitation.

For a machine using field coils, which is most large generators, the field current must be supplied, otherwisethe generator will be useless. Thus it is importantto have a reliable supply. Although the output of agenerator can be used once it starts up, it is also critical to be able to start the generators reliably. In any case,itisimportanttobeabletocontrolthefieldsincethiswillmaintainthesystemvoltage.

Typesofexcitation

(1) Separatelyexcitedgenerator.

(2) Self excitedgenerator.

Selfgeneratorisclassifiedinto3types.

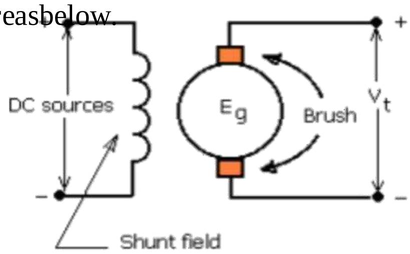
1. Shuntgenerator.
2. Seriesgenerator.
3. Compoundgenerator.

Compoundgeneratorisagainclassifiedinto2types.

1. Shortshuntgenerator.
2. Longshuntgenerator.

Separatelyexcitedgenerators:

These kinds of generators have provided field exciter terminals which are external DC voltage source issuppliestoproduce separatelymagneticfieldwinding(shuntfield)formagnetize ofthe generatorasillustratedinfigureasbelow.



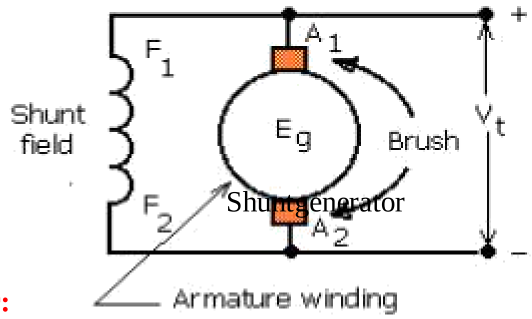
Separately excited generators.

Selfexcitedfieldgenerator:

This type of generator has produced a magnetic field by itself without DC sources from an external. Theelectromotive force that produced by generator at armature winding is supply to a field winding (shunt field)instead of DC source from outside of the generator. Therefore, field winding is necessary connected to thearmaturewinding.Theymaybefurtherclassifiedas

a) Shuntgenerator:

This generator, shunt field winding and armature winding are connected in parallel through commutatorandcarbonbrushasillustratedinthefigurebelow.



Shuntgenerator

b) Seriesgenerator:

The field winding and armature winding is connected in series. There is different from shunt motor due tofieldwindingisdirectlyconnectedtothe electricapplications(load).

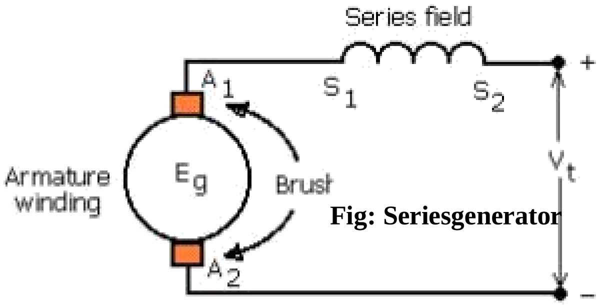


Fig: Seriesgenerator

Therefore, field winding conductor must be sized enough to carry the load current consumption and the basiccircuitasillustratedbelow

C) Compoundgenerator:

Thecompoundgeneratorhasprovidedwithmagneticfieldincombinewithexcitationofshuntandseriesfield winding, the shunt field has many turns of fine wire and caries of a small current, while the seriesfield winding provided with a few turns of heavy wire since it is in series with an armature winding andcariestheloadcurrent.Therearetwokindsofcompoundgeneratorasillustratedinfiguresbelow.

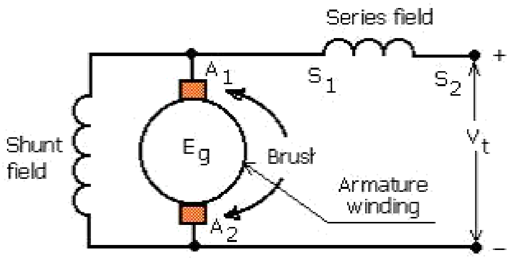
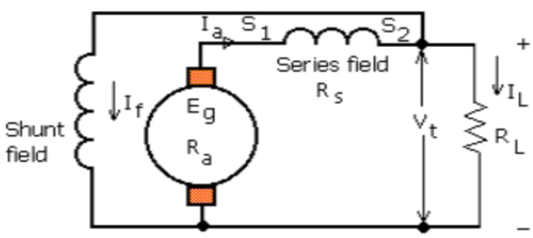


Fig:Ashort-shuntcompoundgenerator



A long-shunt compound generator

Characteristicofseparately excitedgenerator:

Thegeneratedelectromotiveforce(EMF)isproportionaltobothofamagneticdensityoffluxperpoleandthespeedof thearmaturerotatedasexpressionbytherelationasfollowing.

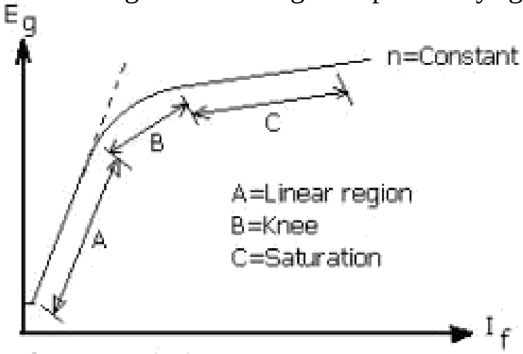
$$Eg = \kappa\varphi n$$

Where

K = Constant for a specific machineφ=Thedensityoffluxperpole

n = Speed of the armature rotationEg=Generatorvoltage

By holding the armature speed (n) at a constant value it can show that generator voltage (Eg) is directlyproportional to the magnetic flux density. Which, flux density is proportionately to the amount of fieldcurrent(If).Therelationof fieldcurrentandgenerate voltageasimpressedbyfigure.



The magnetization curve on open circuit of the separately excited dc machine.

From the figure when the field current (If) is become zero a small generate voltage is produce due to aresidualmagnetism.

As the field current increases cause to increase generated voltage linearly up to the knee of the magnetizationcurve.Beyond this pointby increasing the field currentstill furthercauses saturation of the magneticstructure.

Generator voltage (Eg) is also directly to the armature speed. The formula and a magnetization curve can bebothimpressedaboutthisrelation.

$$E_g' = E_g \times \frac{n'}{n}$$

Where

Eg=GeneratorvoltageorthevalueofEMFatspeednEg'=GeneratorvoltageorthevalueofEMFatspeedn'n=Speedof the generatorarmature(n' $\neq$n)

VoltageRegulation:

Whenweaddloadonthegenerator,theterminalvoltagewilldecreasedueto

(a) Thearmaturewindingresistanceismainlyofarmatureresistance.Itiscauseddirectlydecreaseinterminalvoltageasfollowingrelation.

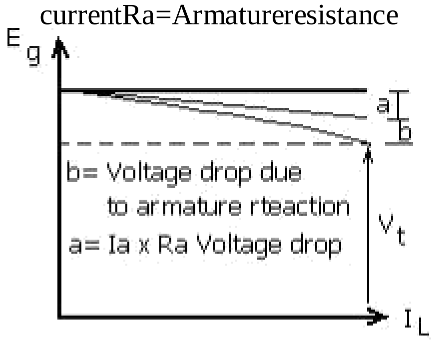
$$Vt=Eg-IaRa$$

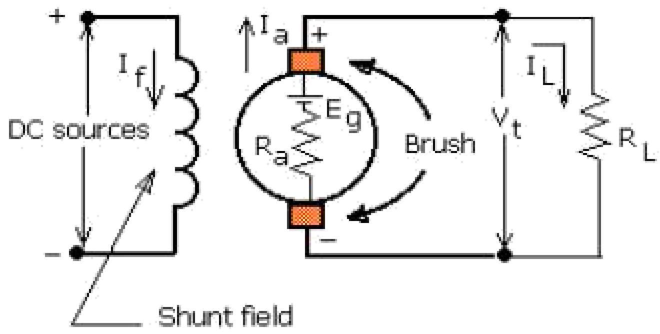
Where,

Vt=Terminaloroutput voltage

Ia = Armature current or load

currentRa=Armatureresistance





(a) Loadcharacteristico **(b)Circuit diagrama separatelyexcitedDCgenerator**

The decrease in magnetic flux due to armature reaction. The armature current establishes a magneto motiveforce (MMF), which it distorts to main flux, and makes result in weakened flux. We can put inter-polebetweenmainfieldpolestoreducethearmaturereaction.

To have some measure by how much the terminal voltage change from no-load condition and on loadcondition,whichiscalled“voltageregulation”.

$$\text{Voltage regulation} = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100 = \%$$

WhereV_{nl}=No-loadterminal voltageV_{fl}= Full-loadterminalvoltage

Remark:

Aseparatelyexcitedgeneratorhasdisadvantageofrequiringanexternal

DCsource.Itisthereforeusedonlywhereawiderange of terminalvoltagerequired.

Example:

The separately excited generator of example 1 is driven at revolving speed 1000 rpm and the field current isadjusted to 0.6 Amp. If the armature circuit resistance is 0.28 ohm, plot the output voltage as the load currentis varied from 0 to 60 Amp. Neglect armature reaction effects. If the full-load current is 60 Amp, what is thevoltageregulation?

Solution:

Fromexample1,Eg=153voltswhenthefieldcurrentis0.6Amp,whichistheopencircuitterminalvoltage.Whenthegeneratorisloaded,theterminalvoltageisdecreasedbyinternalvoltagedrop,

Namely.

$$Vt=Eg-IaRa$$

Foraloadcurrentof,say40Amp.

$$Vt=153-(40\times0.28)=141.80\text{Volts.}$$

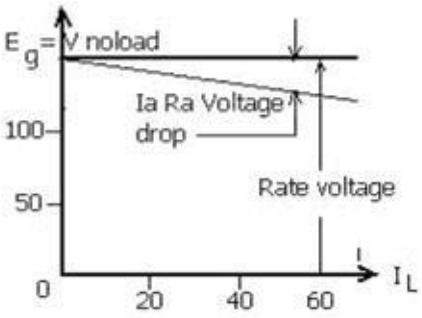
Thiscalculationisforanumberof loadcurrentsandtheexternalcharacteristiccanbeplottedasshowinfig.10atfullloadtheterminalvoltage.

$$V_t=153-(60\times0.28)=136.20\text{Volts.}$$

Therefore the voltage regulation is

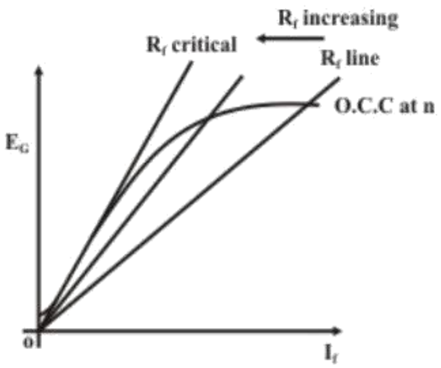
$$\text{Voltage regulation} = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100 = \%$$

$$= \frac{153-136.2}{136.2} \times 100 = 12.3\,\%$$

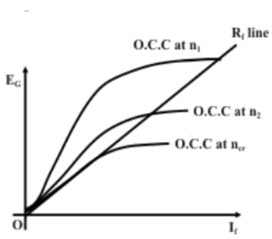


CriticalFieldResistance andCriticalSpeed:

The critical field resistance is the maximum field circuit resistance for a given speed with which the shuntgenerator would excite. The shunt generator will build up voltage only if field circuit resistance is less thancriticalfieldresistance.Itisatangenttotheopencircuitcharacteristicsofthegeneratoratagivenspeed.



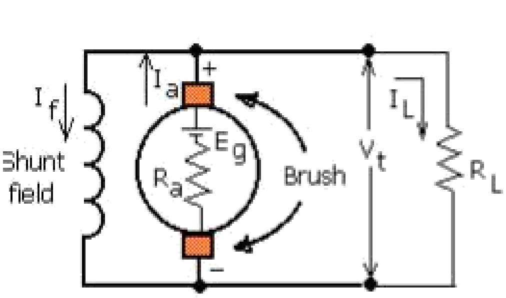
Suppose a shunt generator has built up voltage at a certain speed. Now if the speed of the prime mover isreduced without changing Rf, the developed voltage will be less as because the O.C.C at lower speed willcome down (refer to figure). If speed is further reduced to a certain critical speed (ncr), the present fieldresistance line will become tangential to the O.C.C atncr. For any speed below ncr, no voltage built up ispossibleinashuntgenerator.



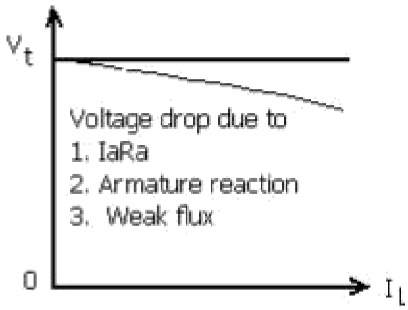
Loadcharacteristics:

SelfexcitedDCshuntgenerator:

A shunt generator has its shunt field winding connected in parallel with the armature so that the machineprovides it own excitation. For voltage to build up, there must be some residual magnetism in the field poles.Therewillbeasmallvoltage(Er) generated.



(a) Shuntgeneratorcircuit



(b)loadcharacteristic ofshuntgenerator

If the connection of the field and armature winding are such that the weak main pole flux aids to the residualflux, the induced voltage will become larger. Thus more voltage applied to the main field pole and cause tothe terminal voltage increase rapidly to a large value. When we add load on the generator, the terminalvoltagewilldecreasedueto.

The armature winding

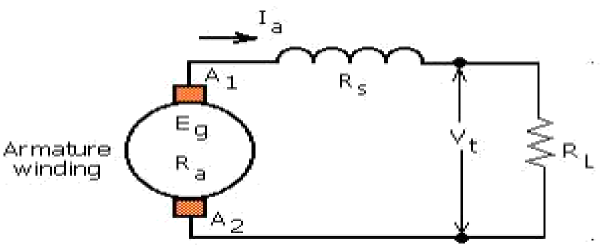
resistancea)Thearmaturereactio

n

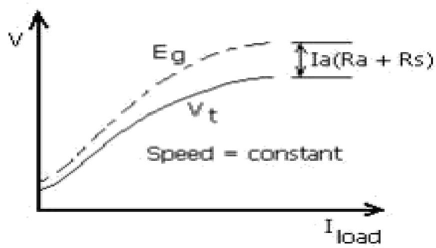
c) Theweakenedfluxduetotheconnectionofthegeneratortoaidsoropposetotheresidual

SeriesGenerator:

The field winding of a series generator is connect in series with the armature winding. Since it carries theload current, the series field winding consists of only a few turns of thick wire. At no-load, the generatorvoltage is small due to residual field flux only. When a load is added, the flux increase, and so does thegeneratedvoltage.



a)Circuit diagramof seriesgenerator



(b)loadcharacteristics

Figure shows the load characteristic of a seriesgenerator driven at a certain speed. The dash line indicatedthe generated EMF of the same machine with the armature opencircuited and the field separated excited. Thedifferentbetweenthetwocurvesis simplythevoltagedrop (IR)intheseriesfieldandarmaturewinding.

$$V_t=E_g-I_aR_a+R_f$$

Where

R_f=Theseriesfieldwindingresistance

R_a=Thearmaturewindingresistance

The series generators are obviously not suited for applications requiring good voltage regulation. Therefore,they have been used very little andonlyin specialapplicationsforexample,asvoltage booster. Thegenerator is placed in series with a supply line. When the current consumption is increase, the generatedvoltageoftheseriesmachinegoesupbecausethemagnetic fieldcurrentisincreases.

Compoundgenerator:

The compound generator has both a shunt and a series winding. The series field winding usually wound onthe top of a shunt field. The two winding are usually connected such that their ampere-turns act in the samedirection.Assuchthe generatorissaidtobecumulativelycompound.

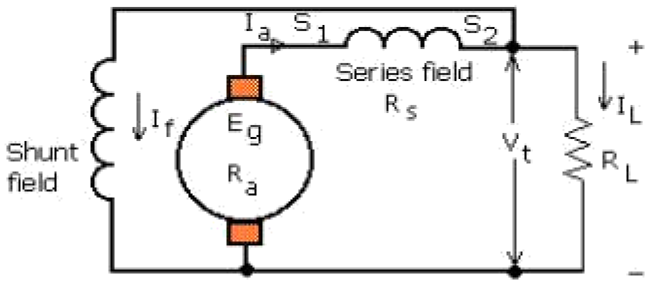
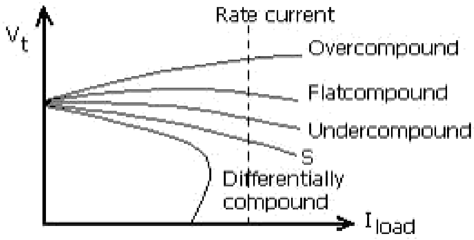


Fig: Simplecircuitforcompound generator



Terminal voltage characteristic of compound generator

(a) Curve s is represent the terminal voltage characteristic of shunt field winding alone. Under-compound,this condition the addition of series field winding too short it is cause the terminal voltage no rise tocertainvalueandreduce while increasinginloadcurrent.

(b) Flat compound by increasing the number of a series field turns. It is cause to rise up in terminal voltageandwhenno-loadandfullloadconditionaterminalvoltage ismadenearlysamevalueorequal.

(c) Over-compound, if the number of series field turns is more than necessary to compensated of the reducevoltage. In this case while a full load condition a terminal voltage is higher than a no-load voltage.Therefore over-compound generator may use where load is at some distance from generator. Voltagedropinthe line hascompensatedbyusedof anover-compoundgenerator.

(d) If a reversing the polarity of the series field occur this cause to the relation between series field and shuntfield, the field will oppose to each other more and more as the load current increase. Therefore terminalvoltagewilldrop,suchgeneratorissaidtobeadifferentiallycompound.

The compound generator are used more extensively than the other type of dc generator because its design tohaveawide varietyofterminalvoltagecharacteristics.

MachineEfficiency:

The efficiency of any machine is the ratio of the ratio of the output power to the input power. The inputpower is provided by the prime mover to drive the generator. Because part of the energy delivered to thegenerator is converted into heat, it represents wasted energy. These losses are generally minimized in thedesignstage;however,someof theselossesareunavoidable.

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100\% \quad \text{or}$$

$$\text{Efficiency} = \frac{\text{Output power} \times 100\%}{\text{Input power} + \text{losses}}$$

Losses ofgenerator:

Thelossesofgenerators maybeclassifiedas

1) Copperlosses

   The copper losses are present because of the resistance of the windings. Currents flowing through thesewindings create ohmic losses. The windings that may be present in addition to the (I2 R) armaturewindingarethefieldwindings,inter-poleandcompensatewindings.

2) Ironlosses

   As the armature rotates in the magnetic field, the iron parts of the armature as well as the conductors cutthe magnetic flux. Since iron is a good conductor of electricity, the EMF s induced in the iron partscourses to flow through these parts. These are the eddy currents. Another loss occurring in the iron is duetotheHysteresislossispresentinthearmaturecore.

3) Other rotationallossesconsistof

   3.1 bearingfrictionloss

   3.2 frictionoftherushes riding onthecommentator

   3.3 windagelosses

Windagelossesarethoseassociatedwithovercomingairfrictioninsettingupcirculationcurrentsofairinsidethe machineforcoolingpurposes.Theselossesareusuallyverysmall.

ApplicationsofDCGenerators:

ApplicationsofSeparatelyExcitedDCGenerators:

These types of DC generators are generally more expensive than self-excited DC generators because of theirrequirement of separate excitation source. Because of that their applications are restricted. They are generallyusedwheretheuse of self-excitedgeneratorsareunsatisfactory.

1. Because of their ability of giving wide range of voltage output, they are generally used for testingpurposeinthe laboratories.
2. Separatelyexcitedgeneratorsoperate inastable conditionwithanyvariationinfieldexcitation.Because ofthisproperty they are used assupply source ofDCmotors,whose speedsare to becontrolledforvariousapplications.Example- WardLeonardSystemsofspeedcontrol.

ApplicationsofShuntWoundDCGenerators:

The application of shunt generators is very much restricted for its dropping voltage characteristic. They areusedtosupplypowertotheapparatussituatedveryclosetoitsposition.ThesetypeofDCgenerators generally give constant terminal voltage for small distance operation with the help of field regulators from noloadtofullload.

1. Theyareusedforgenerallighting.
2. Theyareusedtochargebatterybecausetheycanbemadetogiveconstantoutputvoltage.
3. Theyareusedforgivingthe excitationtothealternators.
4. Theyarealsousedforsmallpowersupply.

ApplicationsofSeries WoundDCGenerators:

These types of generators are restricted for the use of power supply because of their increasing terminalvoltage characteristic with the increase in load current from no load to full load. We can clearly see thischaracteristic from the characteristic curve of series woundgenerator. They give constant current in thedropping portion of the characteristic curve. For this property they can be used as constant current source andemployedforvariousapplications.

1. Theyareusedforsupplyingfieldexcitation currentinDClocomotivesforregenerativebreaking.
2. This types of generators are used as boosters to compensate the voltage drop in the feeder in various typesofdistributionsystemssuchasrailwayservice.
3. Inseriesarclighteningthistypeofgeneratorsaremainlyused.

ApplicationsofCompoundWoundDCGenerators:

Among various types of DC generators, the compound wound DC generators are most widely used becauseof its compensating property. We can get desired terminal voltage by compensating the drop due to armaturereactionandohmicdropintheintheline.Suchgeneratorshavevariousapplications.

1. Cumulative compound wound generators are generally used lighting, power supply purpose and forheavypowerservicesbecauseoftheirconstantvoltageproperty.Theyaremainlymadeovercompounded.
2. Cumulativecompoundwoundgenerators arealsoused fordrivingamotor.
3. For small distance operation,such as powersupply for hotels,offices,homes and lodges,the flatcompoundedgeneratorsaregenerallyused.
4. The differential compound wound generators, because of their large demagnetization armature reaction,areusedforarcweldingwherehugevoltagedropandconstantcurrentisrequired.

AtpresenttimetheapplicationsofDCgeneratorsbecomeverylimitedbecauseoftechnicalandeconomic reasons. Now days the electric powerismainly generated in the form of alternating currentwiththehelpofvariouspowerelectronicsdevices.

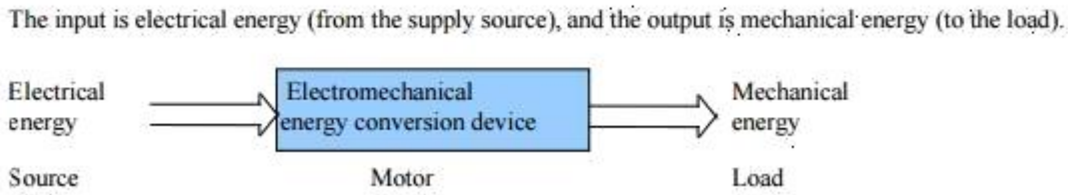
UNIT– III
DCMOTORSANDTESTING

DirectCurrentMotor(DCmotor):

DC motor is similar to dc generator; in fact the same machine can act as motor or generator. The onlydifference is that in a generator the EMF is greater than terminal voltage, whereas in motor the generatedvoltage EMF is less than terminal voltage. Thus the power flow is reversed, that is the motor convertselectricalenergyintomechanicalenergy.Thatisthereverseprocessofgenerator.

DC motors are highly versatile machines. For example, dc motors are better suited fore many processes thatdemand a high degree of flexibility in the control of speed and torque. The dc motor can provided highstartingtorqueaswellashighdeceleratingtorqueforapplicationrequiringquickstoporreversals.

DC motors are suited in speed control with overwide range iseasily to achieve compare with otherselectromechanical.



BasicPrinciples:

(a) EnergyConversion

Ifelectricalenergyissuppliedtoaconductorlyingperpendiculartoamagneticfield,theinteraction of current flowing in the conductor and the magnetic field will produce mechanical force (andtherefore,mechanicalenergy).

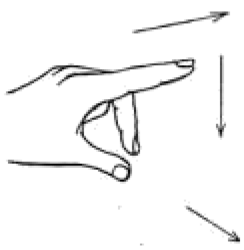
(b) ValueofMechanicalForce

There are two conditions which are necessary to produce a force on the conductor. The conductormust be carrying current, and must be within a magnetic field. When these two conditions exist, a forcewill be applied to the conductor, which will attempt to move the conductorin adirection perpendiculartothemagnetic field.ThisisthebasictheorybywhichallDCmotorsoperate.

Theforceexertedupontheconductorcanbeexpressedasfollows.

$$F = BilNewton \qquad (1)$$

where B is the density of the magnetic field, l is the length of conductor, and i the value of currentflowingintheconductor.ThedirectionofmotioncanbefoundusingFleming'sLeftHandRule.



Fleming'sLeftHandRule

The first finger points in the direction of the magnetic field (first - field), which goes from the North pole tothe South pole. The second finger points in the direction of the current in the wire (second - current). Thethumb then points in the direction the wire is thrust or pushed while in the magnetic field (thumb - torque orthrust).

Principleofoperation:

Consider a coil in a magnetic field of flux density B (figure). When the two ends of the coil are connectedacross a DC voltage source, current I flows through it. A force is exerted on the coil as a result of theinteraction of magnetic field and electric current. The force on the two sides of the coil is such that the coilstartstomoveinthe directionof force.

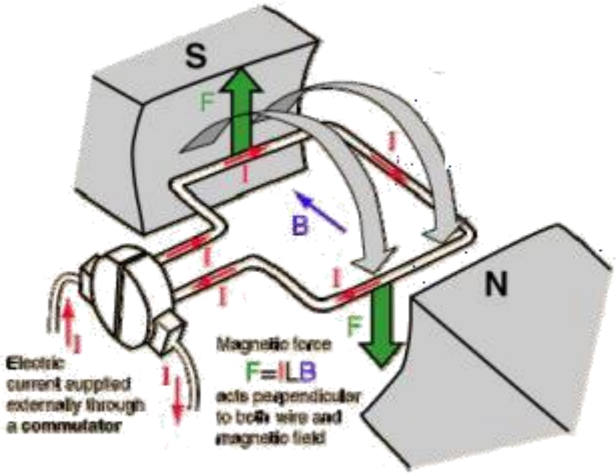


Fig.1.TorqueproductioninaDCmotor

In an actual DC motor, several such coils are wound on the rotor, all of which experience force, resulting inrotation. The greater the current in the wire, or the greater the magnetic field, the faster the wire movesbecauseof thegreaterforcecreated.

At the same time this torque is being produced, the conductors are moving in a magnetic field. At /dt) asshown in different positions, the flux linked with it changes, which causes an emfto be induced (e = dfigure. This voltage is in opposition to the voltage that causes current flow through the conductor and isreferredtoasa counter-voltage orbackemf

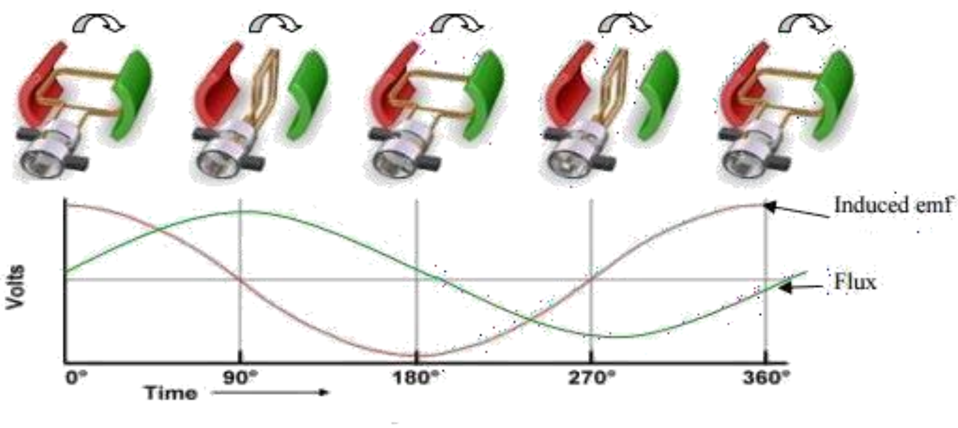


Fig.2.Inducedvoltageinthearmaturewinding ofDCmotor

The value of current flowing through the armature is dependent upon the difference between the appliedvoltage and this counter-voltage. The current due to this counter-voltage tends to oppose the very cause foritsproductionaccordingtoLenz'slaw. Itresultsintherotorslowingdown. Eventually, therotorslowsjustenough so that the force created by the magnetic field (F = Bil) equals the load force applied on the shaft.Thenthesystemmovesatconstantvelocity.

Construction:

DC motors consist of one set of coils, called armature winding, inside another set of coils or a set ofpermanentmagnets,calledthestator.Applyingavoltagetothecoils producesatorqueinthearmature,resultinginmotion.

Stator:

Thestatoris thestationaryoutsidepartofamotor.

- Thestatorofapermanentmagnetdcmotoriscomposedoftwoormorepermanentmagnetpolepieces.
- Themagneticfieldcanalternativelybecreatedbyan electromagnet.Inthis case,aDCcoil(fieldwinding)iswoundaroundamagneticmaterialthatformspartofthestator.

Rotor:

Therotoris theinnerpartwhichrotates.

- The rotor is composed of windings (called armature windings) which are connected to the externalcircuitthrougha mechanicalcommutator.Bothstatorandrotoraremadeofferromagneticmaterials.Thetwoareseparatedby air-gap.

Winding:

Awindingismadeupofseriesorparallel connectionofcoils.

- Armaturewinding-Thewindingthrough whichthevoltageis appliedorinduced.
- Fieldwinding-Thewindingthroughwhichacurrentispassedtoproduceflux(fortheelectromagnet)
- Windings areusuallymadeofcopper.

TorqueDeveloped:

The turning or twisting moment of a force about an axis is called torque. It is measured by the product of theforceandtheradiusatwhichthisforceacts.

Considerapulley ofradiusmeteractedduponbyacircumferentialforceofnewtonwhichcauses it torotateat

rpm.

Then torque $T = F \times r$ newton-metre(N-m

Work done by this force in one revolution

=Force $\times$ distance

$= F \times 2\pi r$ joule

Power developed $= F \times 2\pi r \times N$ joule/second or watt $= (F \times r) \times 2\pi N$ watt

Now, $2\pi N =$ angular velocity ω in radian per second and $F \times r =$ torque T

Hence, power developed $= T \times \omega$ watt or $P = T\omega$ watt

Moreover, if N is in rpm, then

$\omega = 2\pi N / 60$ rad/s

$$\text{Hence, } P = \frac{2\pi N}{60} \times T \text{ or } P = \frac{2\pi}{60} NT = \frac{NT}{9.55}$$

DCMotorEquivalentcircuit:

The schematic diagram for a DC motor is shown below. A DC motor has two distinct circuits: Field circuitand armature circuit. The input is electrical power and the output is mechanical power. In this equivalentcircuit,thefieldwindingissuppliedfromaseparateDCvoltagesourceofvoltageVf.RfandLfrepresentthe resistance and inductance of the field winding. The current If produced in the winding establishes themagnetic field necessary for motor operation. In the armature (rotor) circuit, VT is the voltage applied acrossthe motor terminals, Ia is the current flowing in the armature circuit, Ra is the resistance of the armaturewinding,andEbisthetotalvoltageinducedinthearmature.

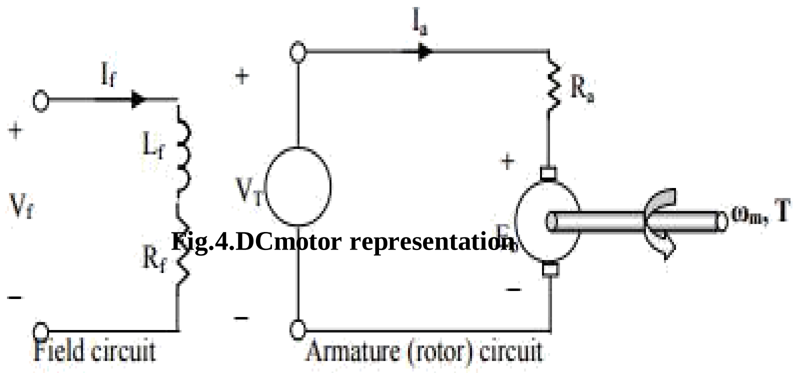


Fig.4.DCmotor representation

CounterEMFinDCmotor:

When voltage is applied to dc motor, current will flow into the positive brush through the commutator intothe armature winding. The motor armature winding is identical to the generator armature winding. Thus theconductors on the north field poles are carry current in one direction, while all conductors on the south fieldpoles carry the current in opposite direction. When the armature carry current it will produce a magnetic fieldaround the conductor of it own which interact with the main field. It is cause to the force developed on allconductorsandtendingtoturnthearmature.

The armature conductors continually cut through this resultant field. So that voltages are generated in thesameconductorsthatexperienceforceaction.Whenoperatingthemotorissimultaneouslyactingasgenerator.Naturallymotoractionisstrongerthangenerator action.

Although the counter EMF is opposite with the supplied voltage, but it cannot exceed to applied voltage. Thecounter EMF is serves to limit the current in an armature winding. The armature current will be limited to thevaluejustsufficienttotakecareofthedevelopedpowerneededtodrivethe load.

In the case of no load is connected to the shaft. The counter EMF will almost equal to the applied voltage.The power develops by the armature in this case is just the power needed to overcome the rotational losses.It'smeanthatthearmaturecurrentIAiscontrolledandlimitedbycounterEMFtherefore

Where:

$$Ia = \frac{VL - Ea}{Ra}$$

V_L=LinevoltageacrossthearmaturewindingR_a=

Resistance ofthearmaturewinding

E_a=InducedEMForgeneratedvoltage

I_a= Armaturecurrent

Since,EAisinducedorgeneratedvoltageitisdependonthefluxperpoleandthespeedofthearmaturerotate(n) inrpm.
Therefore $Ea = K\varphi n$

Where:

K=theconstant valuedependingonarmaturewindingandnumberofpoleofmachine.φ=Rotationof thearmature

And,

$$K = \frac{Z \times P}{a}$$

Where

Z =Totalnumberofconductorinthearmaturewinding

a=Numberofparallelcircuitinthearmaturewindingbetweenpositiveandnegativebrushes.Forwavewoundarmature "a" =2

Lapwoundarmature"a" =P

MechanicalpowerdevelopsinDCmotor(P_d):

Let,

P_d=Mechanicalpowerdevelop

T=Torque exertedonthearmature

$$Pd = \omega T = \left(\frac{2\pi n}{60}\right) T$$

$$\text{Where: } T = P_d / \omega = \frac{Ea \times Ia}{2\pi n / 60} = \frac{K\varphi n \times Ia}{(2\pi n)/60}$$

DCMachineClassification:

DC Machines can be classified according to the electrical connections of the armature winding and the fieldwindings.The differentwaysinwhich these windingsare connected lead to machinesoperatingwithdifferentcharacteristics.The fieldwinding can be eitherself-excitedorseparately-excited,thatis,theterminals of the winding can be connected across the input voltage terminals or fed from a separate voltagesource (as in the previous section). Further, in self-excited motors, the field winding can be connected eitherin series or in parallel with the armature winding. These different types of connections give rise to verydifferenttypesofmachines,aswe willstudyinthissection.

(a) Separatelyexcitedmachines:

- Thearmatureandfieldwindingareelectricallyseparatefromeachother.
- Thefieldwinding isexcitedbyaseparateDCsource.

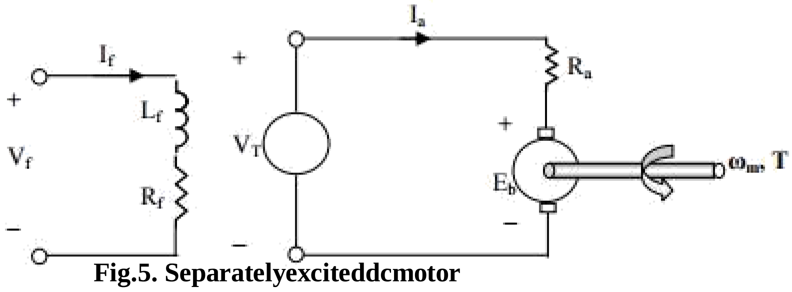


Fig.5. Separatelyexciteddcmotor

Thevoltageandpowerequationsforthismachinearesameasthosederivedintheprevioussection.Notethatthetotalinputpower=Vf If+VTIa

(b) Selfexcitedmachines:

Inthesemachines,insteadofaseparatevoltagesource,thefieldwindingisconnectedacrossthemainvoltageterminals.

1. Shunt machine:
   - Thearmatureandfieldwindingareconnectedinparallel.
   - Thearmaturevoltageandfieldvoltagearethesame.

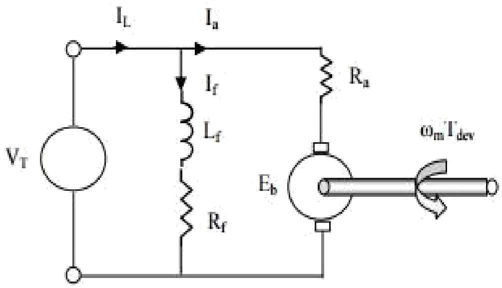


Fig.6.shuntmotor

Totalcurrentdrawnfromthesupply,$I_L=I_f+I_a$Totalin

putpower=V_T*I_L

Voltage, current andpowerequationsaregiveninequations(7),(8)and(9).

2. **SeriesDCmachine:**
   - Thefieldwindingandarmaturewindingareconnectedinseries.
   - Thefieldwindingcarriesthesamecurrentasthearmaturewinding.

Aserieswound motorisalsocalledauniversal motor.Itis universalinthesensethatitwillrunequallywellusingeitheranac oradc voltagesource. Reversing thepolarityofboththestatorandtherotorcancelout.Thusthemotorwillalwaysrotatethesamedirectionregardlessof the voltagepolarity.

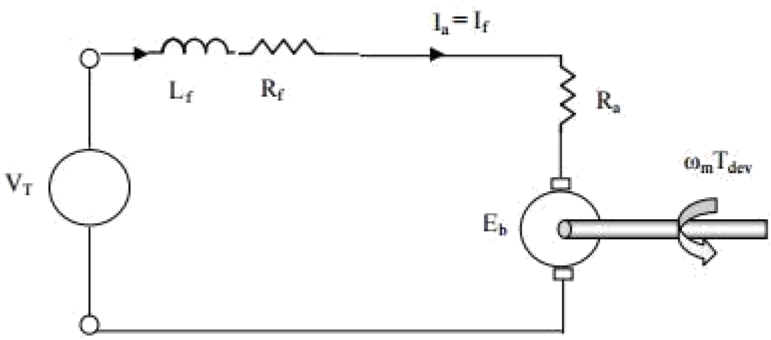


Fig.7.SeriesMotor

3. **CompoundDCmachine:**

If both series and shunt field windings are used, the motor is said to be compounded. In a compoundmachine, the series field winding is connected in series with the armature, and the shunt field winding isconnectedinparallel.Twotypesofarrangementsarepossibleincompoundmotors:

Cumulativecompounding-

Ifthemagneticfluxesproducedbybothseriesandshuntfieldwindingsareinthesamedirection(i.e.,additive),themachineiscalledcumulativecompound.

Differentialcompounding-Ifthetwofluxesareinopposition,themachineis differentialcompound.Inboththesetypes,theconnectioncanbeeithershortshuntorlongshunt.

SpeedcontrolofDCmotor:

Manyapplicationsrequirethespeedofamotortobevariedoverawiderange.Oneofthemostattractivefeatures ofDCmotorsincomparisonwithACmotorsistheeasewithwhichtheirspeedcanbevaried.

Weknowthattheback emfforaseparately excitedDCmotor:

$$E_b = K\phi\omega_m = V_T - I_a R_a$$

Rearranging the terms,

$$\text{Speed } \omega_m = (V_T - I_a R_a)/K\phi$$

Fromtheaboveequation,itisevidentthatthespeedcanbevariedbyusinganyofthefollowingmethods:

- Armaturevoltagecontrol (By varyingV_T)
- FieldControl
- Armatureresistancecontrol(ByvaryingR_a)

Armaturevoltagecontrol

Thismethodisusuallyapplicabletoseparatelyexcited DCmotors.Inthismethodofspeedcontrol,Raandfieldcurrentarekeptconstant.

In normaloperation,thedrop acrossthearmatureresistanceissmallcomparedtoEb

Since,Eb = $K\o\omega_m$

Angularspeedcanbe expressedas:

$$\omega_m = V_T/K\o \qquad (8)$$

Fromthisequation,Ifflux iskept constant,thespeedchangeslinearlywithVT.

- Astheterminalvoltageisincreased,thespeedincreasesandviceversa.
- Therelationshipbetweenspeedandappliedvoltageisshowninfigure8.Thismethodprovidessmoothvariationof speedcontrol.

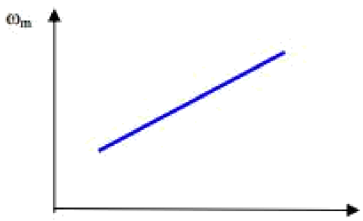


Fig.8.Variationofspeedwithappliedvoltage

Speedcanbecontrolledbyvaryingfieldcurrent If.

- Thefieldcurrentcanbechangedbyvaryinganadjustablerheostatinthefieldcircuit(asshowninfigure9).

- By increasing the value of total field resistance, field current can be reduced, and therefore speed canbeincreased.

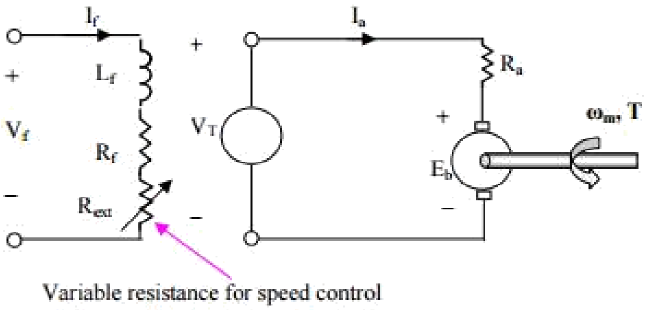


Fig.9:DCmotor speedcontrolcircuit

Therelationshipbetweenthefield windingcurrentandangularspeedisshowninfigure10

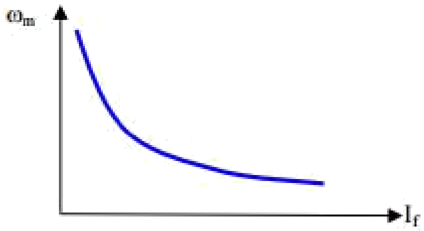


Fig.10:Variationofspeedwithfieldcurrent

ArmatureResistanceControl:

The voltage across the armature can be varied by inserting a variable resistance in series with the armaturecircuit.

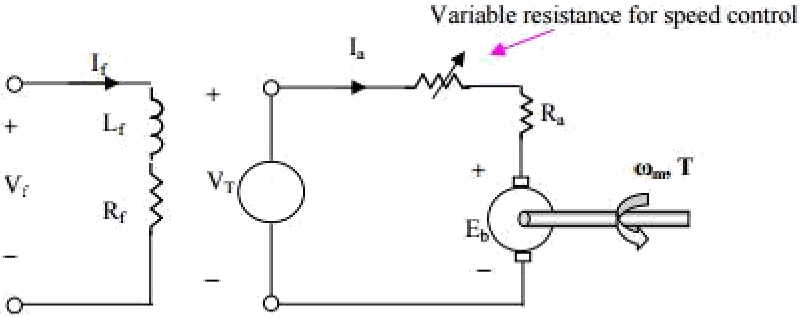


Fig.11. Armature resistancemethodfor speedcontrol

Fromspeed-torquecharacteristics,weknowthat:

$$T_{dev} = \frac{K\phi}{R_a}(V_T - K\phi\omega_m)$$

For a load of constant torque V_T constant, as the armature resistance Ra is increased, speed decreases. As theactual resistance of the armature winding is fixed for a given motor, the overall resistance in the armaturecircuitcanbeincreasedbyinsertinganadditionalvariableresistanceinseries withthearmature.The variationifspeedwithrespecttochangeinthisexternalresistanceisshowninfigure12.Thismethodprovidessmoothcontrolof speed.

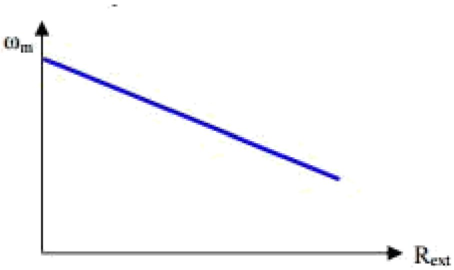


Fig.12: Variationof speedwithexternalarmatureresistance

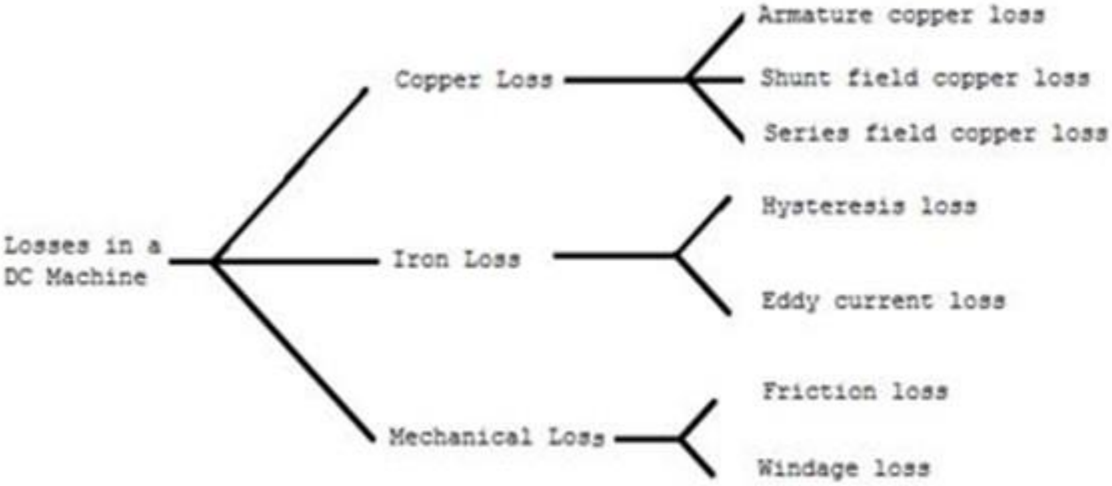
DCShuntMotorspeedcontrol:
AllthreemethodsdescribedabovecanbeusedforcontrollingthespeedofDCShuntMotors.

SeriesMotorspeedcontrol:

Thespeedisusuallycontrolledbychanginganexternalresistanceinserieswiththearmature.The other two methods described above are not applicable to DC series motor speed control.**Applicationsofdcmotors:**

DC Shuntmotor	Lathes,pumps,fans,discandband sawdriverequiringmoderatetorques
DCseriesmotor	Electrictraction,high speedtools
DCcompoundmotor	Rollingmillsandotherloadsrequiringlargemomentarytorques

Types ofLossesinaDC Machines:



Thelossescanbedividedintothreetypesinadcmachine(GeneratororMotor).Theyare

1. Copperlosses
2. Ironorcorelosses and
3. Mechanicallosses.

Alltheselossesseemasheatandthereforeincreasethetemperatureofthemachine.Furthertheefficiencyofthemachine willreduce.

1. CopperLosses:

Thislossgenerallyoccursduetocurrentinthevariouswindingsonofthemachine.Thedifferentwindinglossesare;

Armature copper loss = I^2a
RaShunt field copper loss =
I^2shRshSeriesfieldcopperloss
=I^2seRse
Note:There'sadditionallybrushcontactlossattributabletobrushcontactresistance(i.e.,resistanceinthemiddleofthesurfaceofbrushandcommutator).Thislossismostlyenclosedinarmaturecopperloss.

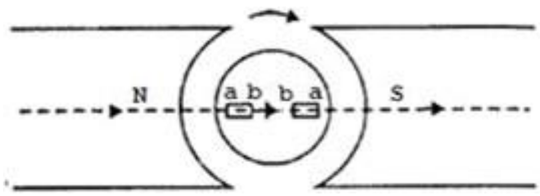
2. IronLosses:

Thislossoccurswithinthearmatureofad.c.machineandareattributabletotherotationofarmaturewithinthemagneticfieldof thepoles.They'reof 2sortsviz.,

(i) Hysteresisloss

(ii) Eddycurrentloss.

Hysteresisloss:



Hysteresis loss happens in the armature winding of the d.c. machine since any given part of the armature isexposed to magnetic field of reverses as it passes underneath sequence poles. The above fig shows the 2 poleDC machine of rotating armature. Consider a tiny low piece ab of the armature winding. Once the piece ab isunderneathN-pole,the magnetic lines pass from a tob. Halfarevolutionwellalong,identicalpieceofironisunderneath S-pole andmagneticlinespassfrom bto ain orderthatmagnetism within the ironisoverturned. So as to reverse constantly the molecularmagnetswithin the armature core, particular quantity of power must be spent that is named hysteresis loss.It'sgivenbySteinmetzformula.

Thesteinmetzformulais

Hysteresis loss $Ph=\eta B^{16}max$ fV

wattsWhere,

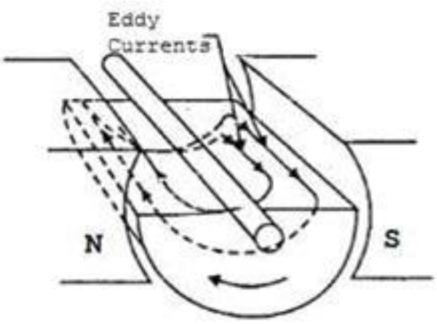
η=Steinmetzhysteresisco-efficient
Bmax = Maximum flux Density in armature
windingF=Frequencyofmagneticreversals
= NP/120(N isinRPM)
V= Volumeofarmatureinm^3

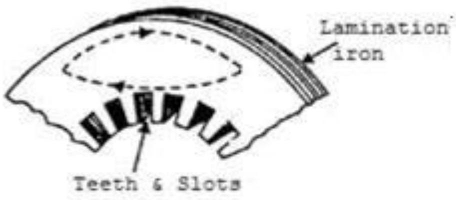
Ifyouwanttocutbackthislossinad.c.machine,armaturecoreiscreatedofsuchmaterialsthathaveanlesservalueofSteinmetzhysteresisco-efficiente.g.,siliconsteel.

Eddycurrentloss:

In additiontothevoltagesevokedwithinthearmatureconductors,someofothervoltagesevokedwithinthearmaturecore. Thesevoltagesturnoutcurrentcurrentswithinthecoilcoreasshownin Fig.Theseare

referred to as eddy currents and power loss attributable to their flow is named eddy current loss. This lossseemsasheatthatincreasesthetemperatureofthemachineandefficiencywilldecrease.





If never-ending cast-iron core is employed, the resistance to eddy current path is tiny attributable to massivecross-sectional space of the core. Consequently, the magnitude of eddy current and therefore eddy currentloss are massive. The magnitudes of eddy current are often decreased by creating core resistance as high assensible. The core resistances are often greatly exaggerated by making the core of skinny, spherical ironsheets referred to as lamination's shown in the fig. The lamination's are insulated from one another with alayerofvarnish.The insulating layerfeatures ahigh resistance,thus only small amountof currentflowsfrom one lamination to the opposite. Also, as a result of every lamination is extremely skinny, the resistanceto current passing over the breadth of a lamination is additionally quite massive. Therefore laminating a corewillincreasethecoreresistancethatdropstheeddycurrentandthereforethe eddycurrentloss.

Eddy Current loss $Pe=KeB^2maxf^2t^2V$ WattsWhere,ke=constant

Bmax = Maximum flux density in wb/m^2T=Thicknessoflaminationinm

V=Volumeofcoreinm^3

Note: Constant(**Ke**)dependupontheresistanceofcoreandsystemofunitused.

It may wellbenotedthat eddycurrentloss besubjecttouponthesq.oflaminationthickness.Forthis reason,laminationthicknessoughttobeunbrokenastinyaspotential.

3.MechanicalLoss:

Theselosses areattributabletofrictionand windage.

- Frictionloss occurs duetothefriction inbearing,brushesetc.
- Windageloss occurs duetotheairfrictionofrotatingcoil.

DC machineisalsofurtherclassifiedinto(i)constantlosses(ii)variablelosses.

Constantlosses:

ThoselossesinaDCgeneratorthatstayconstantatallloads arereferredtoas constant losses.TheconstantlossesinaveryDCgeneratorare:

(a) Ironlosses

(b) Mechanicallosses

(c) Shuntfieldlosses

Variablelosses:

Those losses in a DC generator that differ with load are referred to as variable losses. The variable losses in averyDCgeneratorare:

Copper loss in armature winding

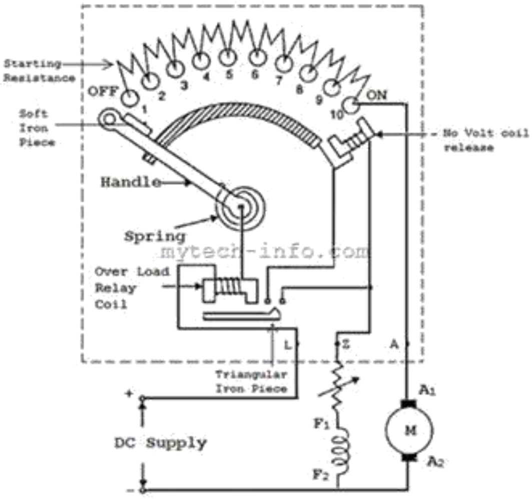
(I^2Ra)Copperlossinseriesfieldwinding(I^2seRs

e)

Totallosses=Constant losses+Variablelosses.

Generallythiscopperlossisconstantforshuntandcompoundgenerators.

Threepointstarter:



The figure above shows that typical representation diagram of a 3 point starter for DC shunt motors with itsprotectivedevices.Itcontains3terminalsnamelyL,Z,&A;hencenamed3pointstarter.Thestarterismade up of of starting resistances divided into many section and which are connected in series within thearmature. The each tapping point on the starting resistances is carried out to a no. of studs. The starter 3terminals L,Z& A are connected to the positive terminal of line, shunt field and armature terminal of motorrespectively. The remaining terminal of the shunt and armature are connected to the negative line terminal.The No volt coil release is connected in series with field winding. The handle one end is connected to the Lterminal by means of over load release coil. Then another end of handle travels against the twisting spring &make touching base with every single stud in the course of starting operation, tripping out the startingresistanceasitmovesabove everystudinclockwise.

Disadvantage:

In point starter, no volt relay coil is connected in series with field circuit; hence it carries shunt current in thefield.When the speed control of DC motorthrough field regulator,it may be weakened the shunt fieldcurrent to such extent the no volt coil release mightnot in a position to hold the starter handle in ONposition.Thismightthemotordisconnectedfrom the sourcewhenitisnotanticipated.Thiscanbeovercomebyusingthepointstarter.

ArmatureReactioninDCMotor

- InitiallytheDCsupplyis turnedon withthehandleis inOFFposition.
- Now the handle is moved towards clockwise direction to the 1st stud. Once it contacts with the 1ststud,immediatelytheshuntfieldcoilisconnectedtothesupply,howevertheentirestartingresistancesisinjectedwitharmaturecircuitinseries.
- As the handle moved gradually towards the final stud, so that the starting resistance is cut out step bystep in armature circuit. And finally the handle is detained magnetically by the No volt coil releasesinceitisenergizedbythefiledwinding.
- In case if the shunt field winding excitation is cut out by accident or else the supply is interruptedthen the no volt coil release gets demagnetized and handle returned back to the original positionundertheinfluence of spring.

Note: If we were not used No volt coil release; then if the supply is cut off the handle would remain in thesameposition,causinganextremecurrentinarmature.

- If any fault occurs on motor or overload, it will draw extreme current from the source. This currentraise the ampere turns of OLR coil (over load relay) and pull the armature Coil, in consequence shortcircuiting the NVR coil (No volt relay coil). The NVR coil gets demagnetized and handle comes tothe rest position under the influence of spring. Therefore the motor disconnected from the supplyautomatically.

CharacteristicofDCShuntMotor:

Generally, three characteristic curves are considered important for DC motors which are, (i) Torque vs.armature current, (ii) Speed vs. armature current and (iii) Speed vs. torque. These are explained below foreach type of DC motor. These characteristics are determined by keeping the following two relations in mind.T_aaϕ.$I_a$and

N aE_b/ϕ

These aboveequations can be studied at-emf and torque equation ofdcmachine. Fora DC motor,magnitude of the back emf is given by the same emf equation of a dc generator i.e. E_b = PϕNZ / 60A. For amachine,P,ZandAareconstant,therefore,N a E_b/ϕ

Characteristics of DC series motorsTorquevs.armaturecurrent(T_a-I_a)

This characteristic is also known as electrical characteristic. We know that torque is directly proportional tothe product of armature current and field flux, T_a a ϕ.I_a. In DC series motors, field winding is connected inseries with the armature, i.e. I_a= I_f. Therefore, before magnetic saturation of the field, flux ϕ is directlyproportional to Ia.Hence, before magnetic saturation Ta α Ia^2. Therefore, the Ta-Ia curve is parabola forsmallervaluesof Ia.

After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, thetorque varies proportionally to Ia only, T a Ia.Therefore, after magnetic saturation, Ta-Ia curve becomes astraight line.

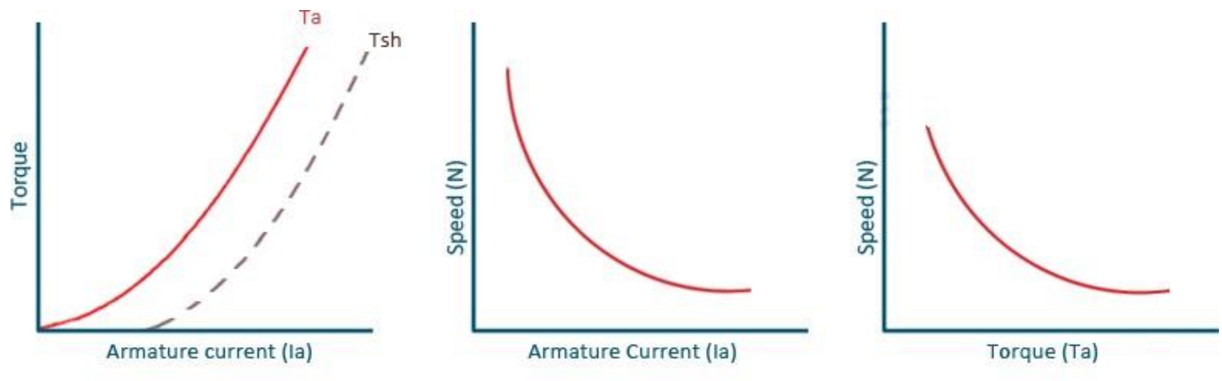
Theshafttorque(Tsh)islessthanarmaturetorque(Ta)duetostraylosses.Hence,thecurveTshvsIaliesslightlylower. InDCseriesmotors,(priortomagneticsaturation)torqueincreasesasthesquareofarmaturecurrent,thesemotorsareuse dwherehighstartingtorqueisrequired.

Speed vs. armature current (N-Ia)Weknowtherelation,NaE$_b$/ϕ

For small load current (and hence for small armature current) change in back emfEb is small and it may beneglected. Hence, for small currents speed is inversely proportional to ϕ. As we know, flux is directlyproportional to Ia, speed is inversely proportional to Ia. Therefore, when armature current is very small thespeedbecomesdangerouslyhigh.Thatiswhyaseriesmotorshouldneverbestartedwithoutsomemechanicalload. But, at heavy loads, armature current Ia is large.And hence, speed is low which results in decreased backemfEb.DuetodecreasedEb,morearmaturecurrentisallowed.

Speedvs.torque(N-Ta)

Thischaracteristic isalso called asmechanical characteristic.From the above two characteristicsof DCseriesmotor,itcanbefoundthatwhenspeedishigh,torqueislowandviceversa.



Characteristics of DC series motor

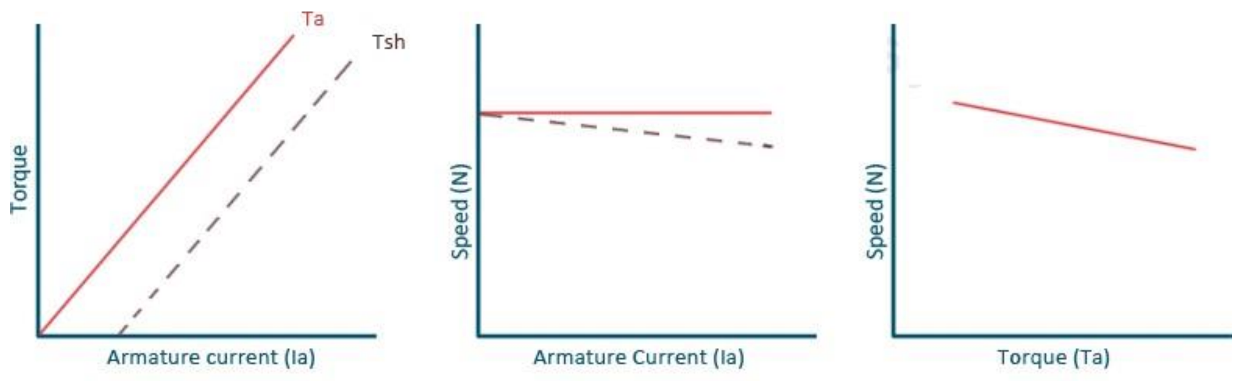
CharacteristicsofDCshuntmotors:

Torquevs.armaturecurrent(Ta-Ia):

In case of DC shunt motors, we can assume the field flux ϕ to be constant. Though at heavy loads, ϕdecreases in a small amount due to increased armature reaction. As we are neglecting the change in the fluxϕ, we can say that torque is proportional to armature current. Hence, the Ta-Ia characteristic for a dc shuntmotor will be a straight line through the origin. Since heavy starting load needs heavy starting current, **shuntmotorshouldnever be startedonaheavyload**.

Speedvs.armaturecurrent(N-Ia):

As flux ϕ is assumed to be constant, we can say N a Eb. But, as back emf is also almost constant, the speedshould remain constant. But practically, ϕ as well as Eb decreases with increase in load. Back emfEbdecreasesslightlymorethanϕ,therefore,thespeeddecreasesslightly.Generally,thespeeddecreasesonly by 5 to 15% of full load speed. Therefore, **a shunt motor can be assumed as a constant speed motor**. Inspeed vs. armature current characteristic in the following figure, the straight horizontal line represents theidealcharacteristic andtheactualcharacteristicisshownbythe dottedline.



Characteristics of DC shunt motor

CharacteristicsofDCcompoundmotor:

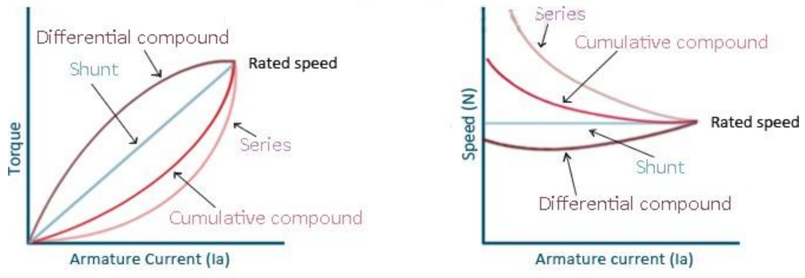
DC compound motors have both series as well as shunt winding. In a compound motor, if series and shuntwindings are connected such that series flux is in direction as that of the shunt flux then the motor is said tobe cumulatively compounded. And if the series flux is opposite to the direction of the shunt flux, then themotor is said to be differentially compounded. Characteristics of both these compound motors are explainedbelow.

(a) Cumulativecompoundmotor:

Cumulative compound motors are used where series characteristics are required but the load is likely to beremoved completely. Series winding takes care of the heavy load, whereas the shunt winding prevents themotor from running at dangerously high speed when the load is suddenly removed. These motors havegenerallyemployedaflywheel,wheresuddenandtemporaryloadsareappliedlikeinrollingmills.

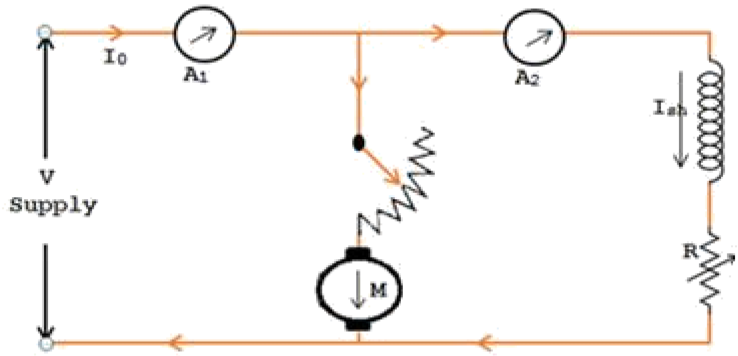
(b) Differentialcompound motor:

Since in differential field motors, series flux opposesshunt flux, the total flux decreases with increase inload.Dueto this,thespeed remainsalmostconstantorevenitmay increaseslightly with increaseinload (N aE_b/ϕ).Differentialcompoundmotorsarenotcommonlyused,buttheyfindlimitedapplicationsinexperimentalandr esearchwork.



Characteristics of DC compound motor

Swinburne'sTestforDCMachines:



In this technique, the DC Generator or DC Motor is run as a motor at no load; with that losses of the DCmachines

are determined. When the losses of DC machine well-known, then we can find the efficiency of a DCmachine in advance at any desired load. In DC machines this test is applicable only throughout the flux isconstant atallload(DCShuntmachineandDCCompoundMachine).This testmaintains oftwosteps;

On no load the DCmachine run as a motorwith the supply voltage isvaried to the normal rated voltage.With the use of the field regulator R the motor speed is varied to run the rated speed which is shown in thefigure.

Let

V=SupplyVoltage

I0 = Noloadcurrentreadby A1

Ish = Shunt Field current ready by

A2No load armature current Iao = I0 –

IshNo load Input power to motor =

VI0NoloadInput powertomotor=VIa0

= V(I0–Ish)

Astheoutputpowerisnil,thenoloadsinputpowertothearmatureprovidesIronloss, armaturecopperloss,frictionlossandwindageloss.

ConstantlossWc=InputpowertoMotor–Armaturecopperloss

$$Wc= VI0– (I0 – Ish^2Ra)$$

Astheconstantlossesareidentified,theefficiencyoftheDCmachineatanyloadscanbedetermined.Supposeitisdesired todeterminetheDCmachine efficiencyatnoloadcurrent.Then,

Armaturecurrent Ia=I-Ish(ForMotoring)

Ia=I+Ish(ForGenerating)

To find the Efficiency when running as a motor:Inputpowertomotor=VI

Armature copper loss =Ia^2Ra = (I-

Ish^2Ra)ConstantLoss=Wc

TotalLoss =(I-Ish2Ra)+Wc

Motor Efficiency η = (Input power – Losses)/

Inputη=**{VI–(I-Ish^2Ra)}/VI**

TofindtheEfficiencywhenrunningasaGenerator:

Output PowerofGenerator=VIArmature

copper loss =Ia^2Ra =

(I+Ish^2Ra)ConstantLoss=Wc

TotalLoss=(I+Ish^2Ra)+Wc

MotorEfficiencyη=Outputpower/(Outputpower

+Losses)η=**VI/{VI+(I+Ish^2Ra) +Wc}**

Merits:

- Sincethistestis noloadtest,powerrequiredis less.Hencethecostis economic.
- Theefficiencyofthemachinecanbefoundveryeasily,becausetheconstantlossesarewellknown.
- Thistestisappropriate.

Demerits:

- WhentheDCmachineis loaded,this test does not deliberatethestrayloadlossthat occurs.
- Usingthismethodwecannot checktheDCmachineperformancesat fullload.

UNIT–IV

SINGLEPHASETRANSFORMERS

TRANSFORMERS:

The transformer is a device that transfers electrical energy from one electrical circuit to another electricalcircuit. The two circuits may be operating at different voltage levels but always work at the same frequency.Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electricalpowersystemanddistributionsystems.

SINGLEPHASETRANSFORMERS:

INTRODUCTION

In its simplest form a single-phase transformer consists of two windings, wound on an iron core one of thewindings is connected to an ac source of supply f. The source supplies a current to this winding (calledprimary winding) which in turn produces a flux in the iron core. This flux is alternating in nature (ReferFigure 4.1). If the supplied voltage has a frequency f, the flux in the core also alternates at a frequency f. thealternating fluxlinkingwith the second winding,inducesavoltage E2in the secondwinding (calledsecondary winding). [Note that this alternating flux linking with primary winding will also induce a voltagein the primary winding,denoted as E1. Applied voltage V1is very nearly equal to E1]. If the numberofturns intheprimaryandsecondarywindings isN1 andN2 respectively,weshallseelaterinthis unitthat

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}.$$

The load is connected across the secondary winding, between the terminals a1, a2. Thus, the load can besuppliedatavoltagehigherorlowerthanthesupplyvoltage,dependingupontheratioN1/N2

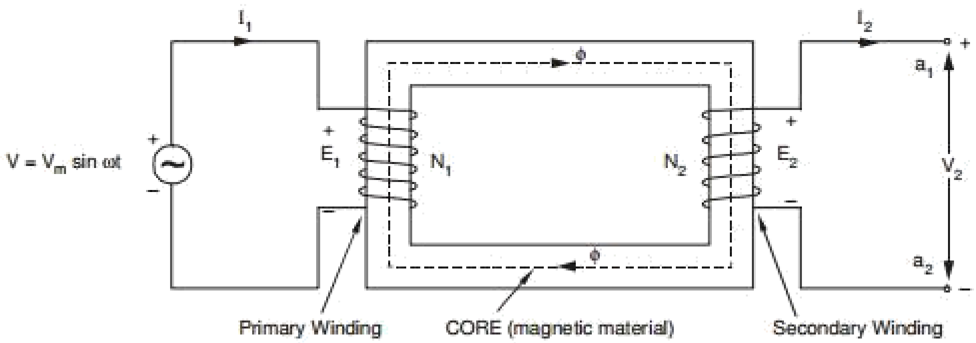


Figure 4.1 : Basic Arrangement of Transformer

When a load is connected across the secondary winding it carries a current I2, called load current. Theprimary current correspondingly increases to provide for the load current, in addition to the small no loadcurrent. The transfer of power from the primary side (or source) to the secondary side (or load) is through themutualfluxandcore.Thereisnodirectelectricalconnectionbetweentheprimaryandsecondarysides.

In an actual transformer, when the iron core carries alternating flux, there is a power loss in the core calledcore loss, iron loss or no load loss. Further, the primary and secondary windings have a resistance, and thecurrentsinprimaryandsecondarywindingsgiverisetoI2Rlossesintransformerwindings,alsocalled copper losses. The losses lead to production of heat in the transformers, and a consequent temperature rise.Therefore,intransformer,coolingmethodsareadoptedtoensurethatthetemperatureremainswithinlimitsothatnodamageisdonetowindings’insulationandmaterial.

IntheFigure4.1ofasingle-phasetransformer,theprimarywindinghasbeenshownconnectedtoasourceof constant sinusoidal voltage of frequency f Hz and the secondary terminals are kept open. The primarywinding of N1 turns draws a small amountof alternating currentof instantaneous value i0,called theexciting current. This current establishes flux φ in the core (+ve direction marked on diagram). The strongcouplingenablesalloftheflux φ tobeconfinedtothecore(i.e.thereisnoleakageofflux).

ConstructionofaTransformer:

Therearetwobasic partsof atransformer:

1. Magneticcore
2. Windingor coils

Magneticcore:

The core of a transformer is either square or rectangular in size. It is further divided in two parts. The verticalportionon which the coilsare bound iscalled limb,whilethe topand bottom horizontal portioniscalledyokeof thecoreasshowninfig.2.

Coreismadeupoflaminations.Becauseoflaminatedtypeofconstruction,eddycurrentlossesgetminimized.

Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminationsare insulated from each other by using insulation like varnish. All laminations are varnished. Laminations areoverlapped so that to avoid the airgap at the joints. For this generally _L‘ shaped or _I‘ shaped laminationsareusedwhichareshowninthefig.3below.

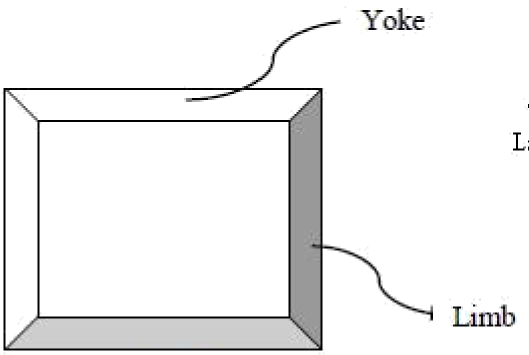


Fig. 2

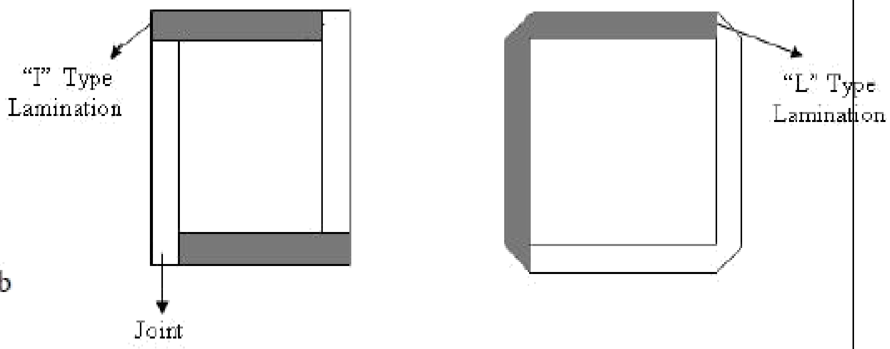


Fig. 3

Winding:

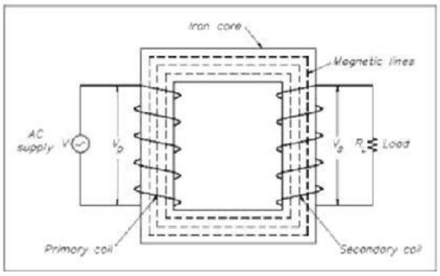
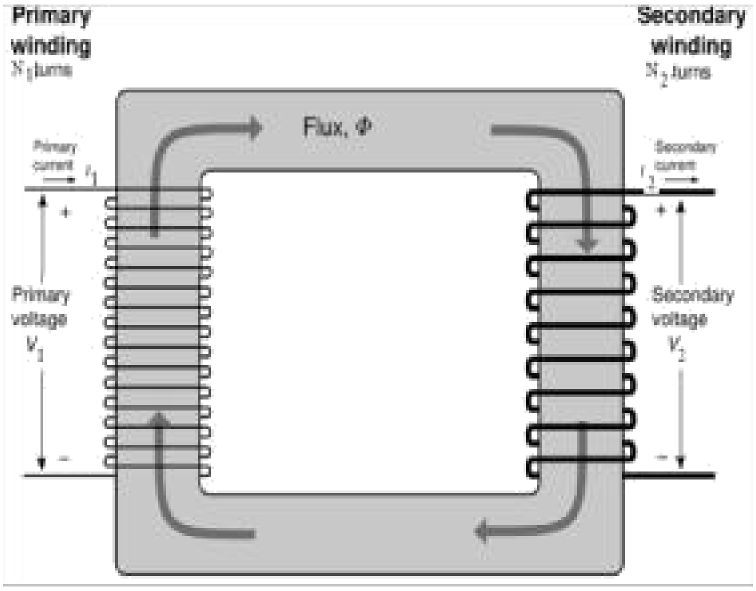


Fig.4SinglePhaseTransformer

There are two windings, which are wound on the two limbs of the core, which are insulated from each otherand from the limbs as shown in fig. 4. The windingsare made up of copper, so that, they possess a verysmall resistance. The winding which is connected to the load is called secondary winding and the windingwhich is connected to the supply is called primary winding. The primary winding has N1number of turnsandthesecondarywindingshaveN2numberof turns.

PrincipleofoperationofaSinglePhaseTransformer:

]



A single phase transformer works on the principle of mutual induction between two magnetically coupledcoils.Whentheprimarywindingisconnectedtoanalternatingvoltageofr.m.svalue,V1volts,analternating currentflows through the primary windingand setup an alternating flux in the material of thecore. This alternating flux ϕ, links not only the primary windings but also the secondary windings. Therefore,an e.m.f e1 is induced in the primary winding and an e.m.f e2 is induced in the secondary winding, e_1 and $e_2$aregiven:

$$e1 = -N1 \frac{d\varphi}{dt} \text{ --------- (a)}$$

Iftheinduced e.m.fise1 and e2 arerepresentedbytheirrms values E1andE2 respectively,then

$$e2 = -N2 \frac{d\varphi}{dt} \text{ ----------(b)}$$

$$E1 = -N1 \frac{d\varphi}{dt} \text{ --------- (1)}$$

$$E2 = -N2 \frac{d\varphi}{dt} \text{ ---------- (2)}$$

$$\text{Therefore, } \frac{E2}{E1} = \frac{N2}{N1} = k \text{ --------------- (3)}$$

K is known as the transformation ratio of the transformer. When a load is connected to the secondarywinding,acurrentI2flowsthroughtheload,V2istheterminalvoltageacrosstheload.Asthepower transferredfromthe primarywindingtothe secondarywindingissame,Powerinputtothe primarywinding =Poweroutputfromthesecondarywinding.

Thedirectionsofemf‘sE_1andE_2inducedinthe primaryandsecondarywindingsare suchthat,theyalwaysopposetheprimaryappliedvoltage V_1.

$E_1I_1 = E_2I_2$

(Assuming that the power factor of the primary is equal to the secondary).

Or, $\frac{E2}{E1} = \frac{I1}{I2} = k$ ------- (4)

From eqn (3) and (4), we have

$\frac{E2}{E1} = \frac{N2}{N1} = \frac{I1}{I2} = k$ -------------- (5)

EMFEquationofa Transformer:

Consider a transformer

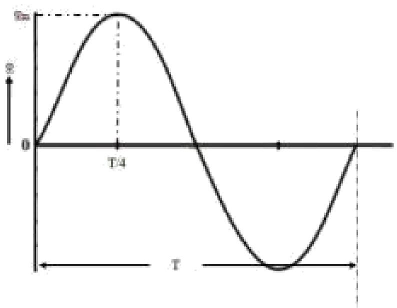
having,N1=Primaryturns

N2=Secondaryturns

Φm = Maximum flux in the

coreΦm=Bm×Awebers

f=frequencyofacinput in hertz(Hz)



Thefluxin thecorewillvary sinusoidalasshownin figure,sothatitincreasesfromzero tomaximum“ϕm”inone quarterof thecyclei.e,1/4f second.

Therefore, average rate of change of flux = ${\phi m}/_{1/4f}$

$= 4f\varphi_m$

We know that, the rate of change of flux per turn means that the induced emf in volts.

Therefore, average emf induced per turn $= 4f\varphi_m$ volts.

Since the flux is varying sinusoidally, the rms value of induced emf is obtained by multiplying the average value by the form factor .

Therefore, rms value of emf induced per turns = $1.11\times4f\times\varphi_m$

$= 4.44f\varphi_m$ volts

The rms value of induced emfin the entire primary winding = (induced emf per turn) × number of primary turns

i.e, $E_1 = 4.44 f \varphi_m \times N_1 = 4.44 f B_m \times A \times N_1$
Similarly;
$E_2 = 4.44 f \varphi_m \times N_2 = 4.44 f B_m \times A \times N_2$

TransformationRatio:

(1) VoltageTransformationRatio

(2) CurrentTransformationRatio

VoltageTransformationRatio:

VoltagetransformationratiocanbedefinedastheratioofthesecondaryvoltagetotheprimaryvoltagedenotedbyK.

Mathematically given as $K = \frac{Secondary\ Voltage}{PrimarPrimar\ Voltage} = \frac{V_2}{V_1}$

$$K = \frac{E_2}{E_1} = \frac{4.44\ f\ \varphi_m N_2}{4.44\ f\ \varphi_m N_1} = \frac{N_2}{N_1}$$

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

CurrentTransformationRatio:

ConsideranidealtransformerandwehavetheinputvoltampereisequaltooutputvoltAmpere.Mathematically,InputVoltampere=OutputVoltampere

$$V_1 I_1 = V_2 I_2$$

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

$$\therefore,\ K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

Transformeronno-Load:

Theory of Transformer On No-load, and Having No Winding Resistance and No Leakage Reactance ofTransformer

Let us consider one electrical transformer with only core losses, which means, it has only core lossesbut no copper loss and no leakage reactance of transformer. When an alternating source is applied in theprimary,thesourcewillsupplythecurrentformagnetizingthecoreoftransformer.

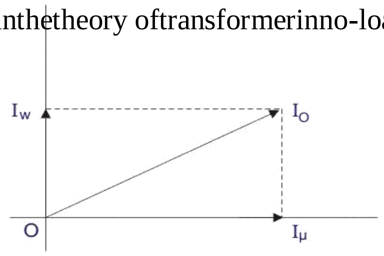
But this current is not the actual magnetizing current, it is little bit greater than actual magnetizing current.Actually, total current supplied from the source has two components, one is magnetizing current which ismerelyutilizedformagnetizingthe core andothercomponentofthe sourcecurrentisconsumedforcompensating the core losses in transformer. Because of this core loss component, the source current in**transformer on no-load** condition supplied from the source as source current is not exactly at 90° lags ofsupply voltage, but it lags behind an angle θ is less than 90°. If total current supplied from source is Io, it willhave one component in phase with supply voltage V1 and this component of the currentIw is core losscomponent.Thiscomponentistakeninphasewithsourcevoltage,becauseitisassociatedwithactiveor workinglossesin transformer.Othercomponentofthe source currentisdenoted asIμ. Thiscomponentproducesthealternatingmagneticfluxinthecore,soitiswatt-less;meansitisreactivepartofthetransformer source current. Hence Iμ will be in quadrature with V1 and in phase with alternating flux Φ.Hence,totalprimarycurrentin**transformeronno-load**conditioncanberepresentedas $I_0 = I_\mu + I_w$

$$|I_\mu| = |I_0|\cos\theta$$

$$|I_w| = |I_0|\sin\theta$$

$$|I_w| = \sqrt{|I_\mu|^2 + |I_w|^2}$$

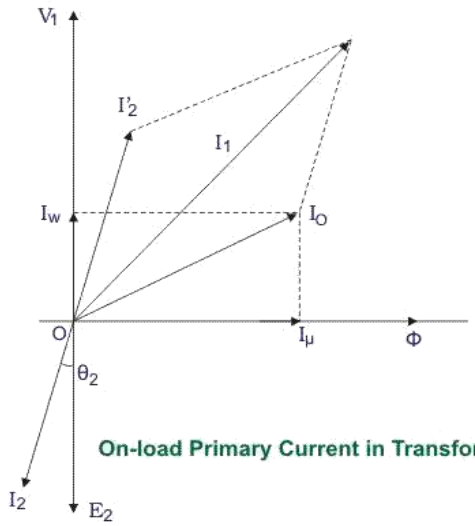
Nowyouhaveseen howsimpleis toexplainthetheory oftransformerinno-load.



Excitation Current of Transformer

TransformerOnLoad:

Theory ofTransformerOn Load ButHaving No Winding Resistance andLeakage ReactanceNow wewillexaminethebehaviorofabovesaid**transformeronload**thatmeansloadis connected to the secondary terminals. Consider, transformer having core loss but no copper loss and leakagereactance. Whenever load is connected to the secondary winding, load current will start to flow through theload as well as secondary winding. This load current solely depends upon the characteristics of the load andalso upon secondary voltage of the transformer. This current is called secondary current or load current, hereitis denoted as I2. As I2 is flowing through the secondary, a self mmf in secondary winding will beproduced.Hereitis N2I2,where,N2 is thenumberofturns ofthesecondarywindingoftransformer.



On-load Primary Current in Transformer

This mmf or magneto motive force in the secondary winding produces flux φ2. This φ2 will oppose the mainmagnetizing flux and momentarily weakens the main flux and tries to reduce primary self inducedemf E1. IfE1 falls down below the primary source voltage V1, there will be an extra current flowing from source toprimary winding. This extra primary current I2′ produces extra flux φ′ in the core which will neutralize thesecondary counter flux φ2. Hence the main magnetizing flux of core, Φ remains unchanged irrespective ofload.

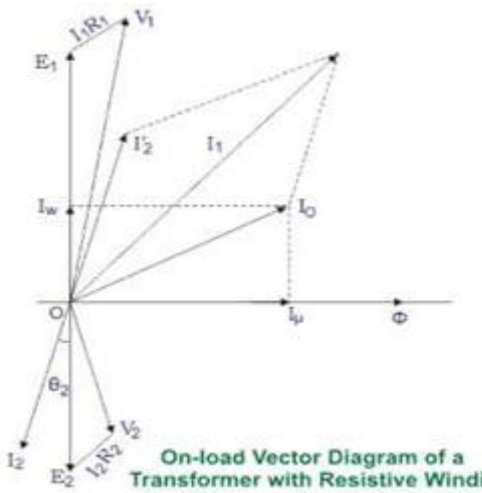
So total current, this transformer draws from source can be divided into two components, first one is utilizedfor magnetizing the core and compensating the core loss i.e. Io. It is no-load component of the primarycurrent. Second one is utilized for compensating the counter flux of the secondary winding. It is known asload componentofthe primary current.Hence total no load primarycurrentI1ofaelectrical powertransformerhavingnowindingresistanceandleakagereactancecanberepresentedasfollows

$$I_1 = I_0 + I_2'$$

Where θ2 is the angle between Secondary Voltage and Secondary Current of transformer. Now we willproceedonefurtherstepktowardmorepracticalaspectofa transformer.

TransformerOnLoad,WithResistiveWinding,ButNoLeakageReactance

Now, consider the winding resistance of transformer but no leakage reactance. So far we have discussedabout the transformerwhich has ideal windings,means winding with no resistance and leakage reactance,but now we will consider one transformer which has internal resistance in the winding but no leakagereactance.Asthewindingsareresistive,therewouldbeavoltagedropinthe windings.



On-load Vector Diagram of a Transformer with Resistive Winding

We have proved earlier that, total primary current from the source on load is I_1. The voltage drop in theprimary winding with resistance, $R_1$is R_1I_1. Obviously, induced emf across primary winding E_1, is notexactlyequaltosourcevoltage V_1.E_1islessthanV_1byvoltagedropI_1R_1.

$$V_1 = E_1 + I_1R_1$$

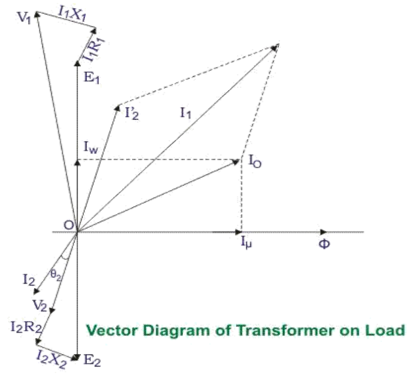
Again in the case of secondary, the voltage induced across the secondary winding, E2 does not totally appearacrosstheloadsinceitalsodropsbyanamountI2R2,whereR2isthesecondarywindingresistanceandI2issecon darycurrentorloadcurrent.

Similarly,voltageequationofthesecondarysideofthetransformerwillbe

$$V_2 = E_2 - I_2R_2$$

TheoryofTransformeronLoad,WithResistanceAsWellAsLeakageReactanceinTransformerWindings:

Nowwewillconsiderthecondition,whenthereisleakagereactanceoftransformeraswellaswindingresistanceoftransformer.



Let leakage reactances of primary and secondary windings of the transformer are X1 and X2 respectively.HencetotalimpedanceofprimaryandsecondarywindingoftransformerwithresistanceR1andR2respectively,canberepresentedas,

$$Z_1 = R_1 + jX_1 \ (impedance\ of\ primary\ winding)$$

$$Z_2 = R_2 + jX_2 \ (impedance\ of\ secondary\ winding)$$

We have already established the voltage equation of a **transformer on load**, with only resistances in thewindings, where voltage drops in the windings occur only due to resistive voltage drop. But when weconsider leakage reactances of transformer windings, voltage drop occurs in the winding not only because ofresistance,itisbecauseofimpedanceoftransformerwindings.Hence,actualvoltageequationofatransformer can easily be determined by just replacing resistances R1 & R2 in the previously establishedvoltage equationsbyZ1andZ2.

Therefore,thevoltageequationsare,

$$V_1 = E_1 + I_1Z_1 \ \& \ V_2 = E_2 - I_2Z_2$$

$$V_1 = E_1 + I_1(R_1 + jX_1)$$

$$\Rightarrow V_1 = E_1 + I_1R_1 + jI_1X_1$$

$$V_2 = E_2 - I_2(R_2 + jX_2)$$

$$\Rightarrow V_2 = E_2 - I_2R_2 - jI_2X_2$$

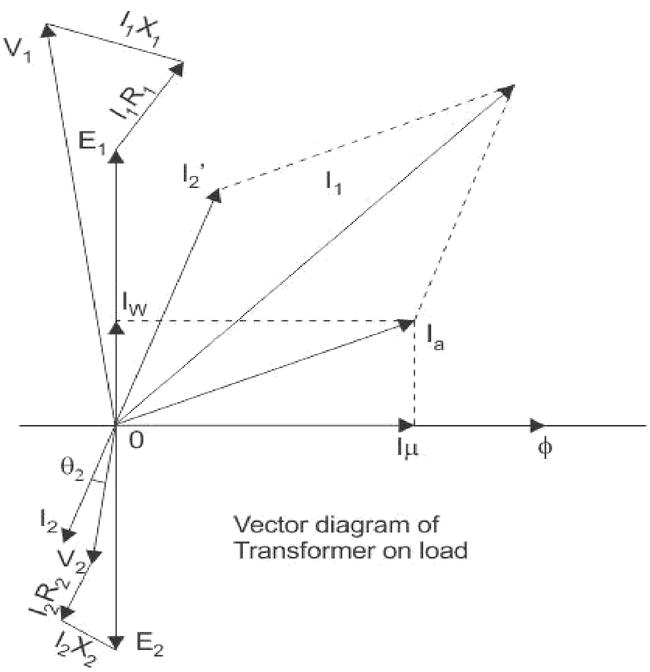
Resistance drops are in the direction of current vector but, reactive drop will be perpendicular to the currentvectorasshownintheabovevectordiagram oftransformer.

EquivalentCircuitofTransformer:

Equivalent impedance of transformer is essential to be calculated because the electrical power transformer isan electrical power system equipment for estimating different parameters of electrical power system whichmay be required to calculate total internal impedance of an electrical power transformer, viewing fromprimary side or secondary side as per requirement. This calculation requires equivalent circuit of transformerreferred to primary **or** equivalent circuit of transformer referred to secondary sides respectively. Percentageimpedance is also very essential parameter of transformer. Special attention is to be given to this parameterduring installing a transformer in an existing electrical power system. Percentage impedance of differentpowertransformersshouldbe properlymatchedduringparalleloperationofpowertransformers.Thepercentage impedance can be derived from equivalent impedance of transformer so, it can be said thatequivalentcircuitoftransformerisalsorequiredduringcalculationof%impedance.

EquivalentCircuitofTransformerReferredto Primary:

Fordrawingequivalentcircuitoftransformerreferredtoprimary,firstwehavetoestablishgeneralequivalent circuit of transformer then, we will modify it for referring from primary side. For doing this, firstweneedtorecallthecompletevectordiagramof atransformerwhichisshowninthefigurebelow



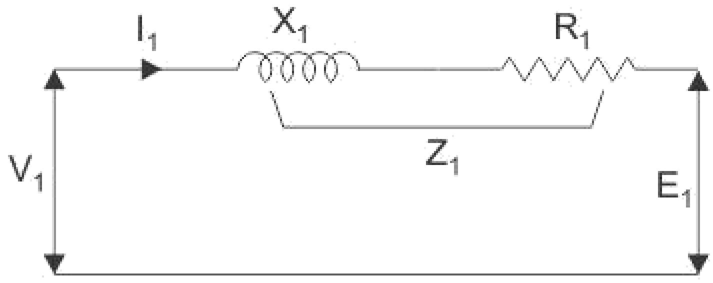
Letusconsiderthetransformationratiobe,

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

In the figure above, the applied voltage to the primary is V1 and voltage across the primary winding is E1.Total current supplied to primary is I1. So the voltage V1 applied to the primary is partly dropped by I1Z1 orI1R1 + j.I1X1 before it appears across primary winding. Thevoltage appeared across winding is counteredbyprimaryinducedemf E1.So voltageequationofthisportionofthetransformercanbewrittenas,

Theequivalent circuitforthat equationcanbedrawnasbelow,

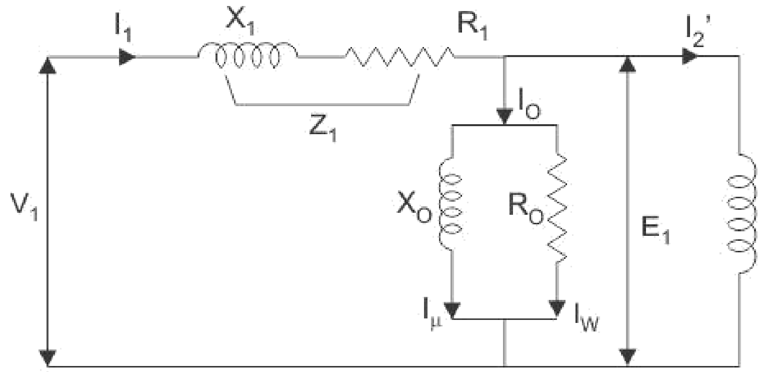
$$V_1 - (I_1R_1 + jI_1X_1) = E_1$$



Equivalent Circuit

From the vector diagram above, it is found that the total primary current I1 has two components, one is no - load component Io and the other is load component I2′. As this primary current have two components orbranches, so there must be a parallel path with primary winding of transformer. This parallel path ofcurrentis known as excitation branch of equivalent circuit of transformer. The resistive and reactive branches of theexcitationcircuitcanberepresentedas

$$R_0 = \frac{E_1}{I_w} \; and \; X_0 = \frac{E_1}{I_\mu}$$

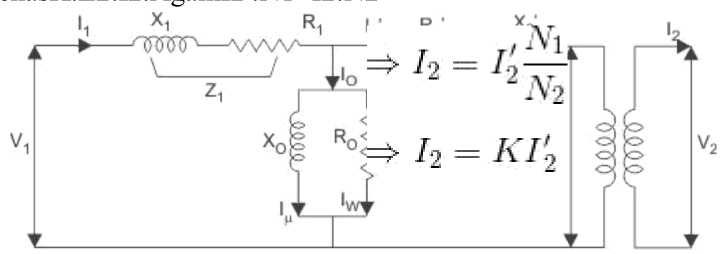


Equivalent Circuit of Primary Side of Transformer

The load component I2′ flows through the primary winding of transformer and induced voltage across thewinding is E1 as shown in the figure right. This induced voltage E1 transforms to secondary and it is E2 andload component of primary current I2′ is transformed to secondary as secondary current I2. Current ofsecondary is I2. So the voltage E2 across secondary winding is partly dropped by I2Z2 or I2R2 + j.I2X2beforeitappearsacrossload.TheloadvoltageisV2.

Thecompleteequivalentcircuitoftransformerisshownbelow.

Now if we see the voltage drop in secondary from primary side, then it would be ′K′ times greater and wouldbewrittenasK.Z2.I2.AgainI2′.N1=I2.N2



$$\Rightarrow I_2 = I_2' \frac{N_1}{N_2}$$

$$\Rightarrow I_2 = K I_2'$$

Equivalent Circuit of Transformer referred to Primary

Therefore,

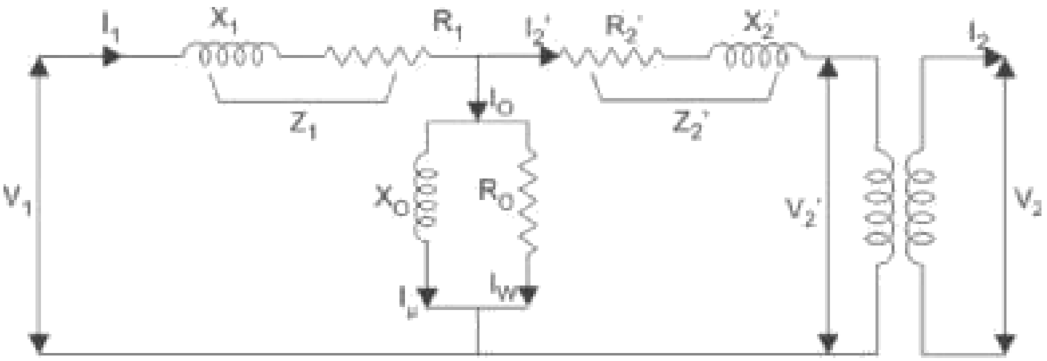
$$KZ_2I_2 = KZ_2KI_2' = K^2Z_2I_2'$$

Fromaboveequation,secondaryimpedanceoftransformerreferredtoprimaryis,

$$Z_2' = K^2Z_2$$

So,thecompleteequivalent circuit oftransformerreferredtoprimaryisshowninthefigurebelow,

$$Hence,\ R_2' = K^2R_2\ and\ X_2 = K^2X_2$$

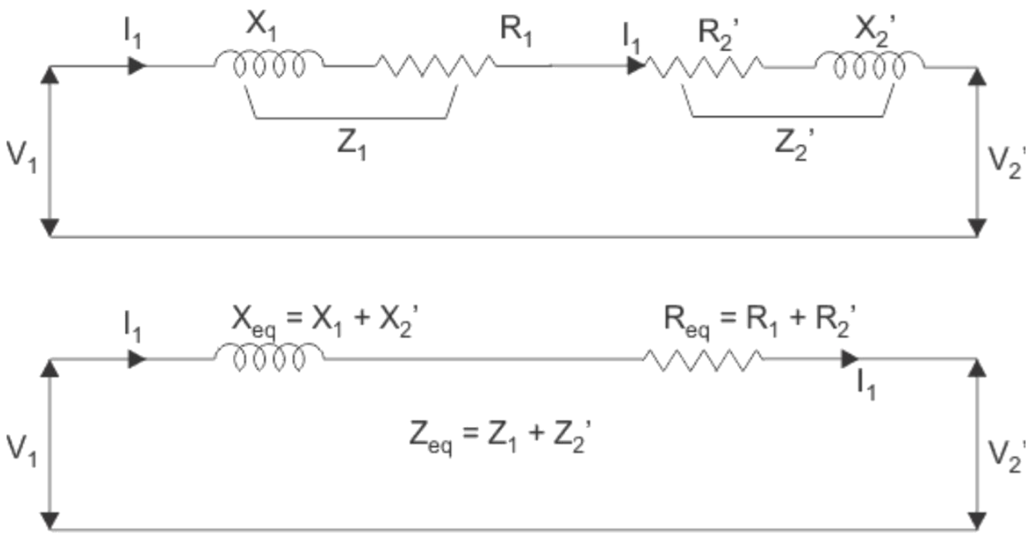


Equivalent Circuit of Transformer referred to Primary

ApproximateEquivalentCircuitofTransformer:

Since Io is very small compared to I1, it is less than 5% of full load primary current, Io changes the voltagedropinsignificantly.Hence,itisgoodapproximationtoignoretheexcitationcircuitinapproximateequivalent circuit of transformer. The winding resistance and reactance being in series can now be combinedinto equivalent resistance and reactance of transformer, referred to any particular side. In this case it is side 1orprimaryside.

$$Here,\ V_2' = KV_2$$



Approximate Equivalent Circuit of Transformer referred to Primary

EquivalentCircuitofTransformerReferredtoSecondary

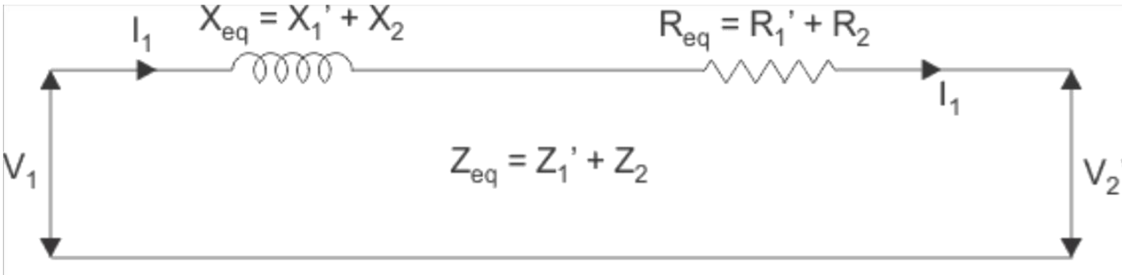
In similar way, approximate equivalent circuit of transformer referred to secondary can be drawn.Whereequivalentimpedanceoftransformerreferredto secondary,canbederivedas

$$Z_1 = \frac{Z_1}{K^2}$$

$$Therefore,\ R_1' = \frac{R_1}{K^2}$$

$$X_1' = \frac{X_1}{K^2}$$

$$Here,\ V_1' = \frac{V_1}{K}$$



Approximate Equivalent Circuit of Transformer referred to Secondary

LossesinTransformer:

Lossesoftransformeraredivided mainlyintotwotypes:

1. IronLoss
2. CopperLosses

IronLoss:

Thisisthepowerlossthatoccursintheironpart.Thislossisduetothealternatingfrequencyoftheemf.Ironlossinfurtherclassifiedintotwootherlosses.

a) Eddycurrentloss

b) Hysterisisloss

a) Eddy CurrentLoss:

This powerloss is due to the alternating flux linking the core, which will induced an emfin the corecalled the eddy emf, due to which acurrent called the eddy current is being circulated in the core. Asthere is some resistance in the core with this eddy current circulation converts into heat called the eddycurrentpowerloss.Eddycurrentlossisproportionaltothesquareofthesupplyfrequency.

b) HysterisisLoss:

This is the loss in the iron core, due to the magnetic reversal of the flux in the core, which results in theformof heatinthecore.Thislossisdirectlyproportionaltothesupplyfrequency.

Eddy current loss can be minimized by using the core made of thin sheets of silicon steel material, andeach lamination is coated with varnish insulation to suppress the path of the eddy currents. Hysterisis losscanbe minimizedbyusingthecore materialhavinghighpermeability.

CopperLoss:

This is the power loss that occurs in the primary and secondary coils when the transformer is on load. Thispoweriswastedintheformofheatduetotheresistanceofthecoils.Thislossisproportionaltothe sequenceoftheloadhenceitiscalledtheVariablelosswhereastheIronlossiscalledastheConstantlossasthesupplyvoltageandfrequencyareconstants

Efficiency:

Itistheratiooftheoutput powertotheinput

powerofatransformerInput=Output+Totallosses

=Output+Ironloss +Copperloss

Efficiency =

$$\eta = \frac{outputpower}{outputpower + Ironloss + copperloss}$$

$$= \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + W_{eron} + W_{copper}}$$

Where, V_2 is the secondary (output) voltage, I_2 is the secondary (output) current and $\cos\Phi$ is the power factor of the load.

The transformers are normally specified with their ratings as KVA,

Therefore,

$$Efficiency; \eta = \frac{(KVA) \times 10^3 \times cos\varphi}{(KVA) \times 10^3 \times cos\varphi \times W_{iron} + W_{copper}}$$

Since the copper loss varies as the square of the load the efficiency of the transformer at any desired load n is given by

$$Efficiency; \eta = \frac{n \times (KVA) \times 10^3 \times cos\varphi}{n \times (KVA) \times 10^3 \times cos\varphi \times W_{iron} + n^2 \times W_{copper}}$$

where,

Wcopper is the copper loss at full loadWcopper=I^2Rwatts

ConditionforMaximumEfficiency:

In general for the efficiency to be maximum for any device the losses must be minimum. Between the ironand copperlossesthe iron lossisthe fixed lossand the copperlossisthe variable loss.When these twolossesareequalandalsominimumtheefficiencywillbe maximum.

ThereforetheconditionformaximumefficiencyinatransformerisCopperloss =Ironloss

O.C.andS.C.Tests onSinglePhaseTransformer:

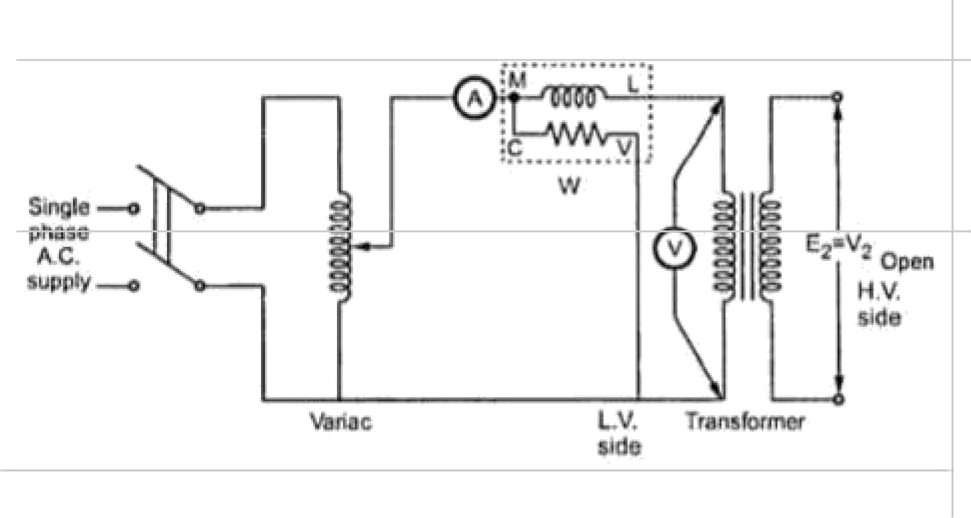
Theefficiencyandregulationofatransformeronanyloadconditionandatanypowerfactorconditioncanbe predetermined by indirect loading method. In this method, the actual load is not used on transformer. Butthe equivalent circuit parameters of a transformer are determined by conducting two tests on a transformerwhichare,

1. Opencircuit test(O.CTest)
2. Shortcircuittest(S.C.Test)

The parameters calculated from these test results are effective in determining the regulation and efficiency ofatransformeratanyloadandpowerfactorcondition,withoutactuallyloadingthetransformer.Theadvantage of this method is that without much power loss the tests can be performed and results can beobtained. Let us discuss in detail how to perform these tests and how to use the results to calculate equivalentcircuitparameters.

OpenCircuitTest (O.C.Test)

Theexperimentalcircuit toconductO.Ctest is shownintheFig.



The transformer primary is connected to a.c. supply through ammeter, wattmeter and variac. The secondaryoftransformeriskeptopen.Usuallylowvoltagesideisusedasprimaryandhighvoltagesideassecondarytoc onductO.Ctest.

The primary is excited by rated voltage, which is adjusted precisely with the help of a variac. Thewattmeter measures input power. The ammeter measures input current. The voltemeter gives the value ofratedprimaryvoltageappliedatratedfrequency.

SometimesavoltmetermaybeconnectedacrosssecondarytomeasuresecondaryvoltagewhichisV_2 = E_2 when primary is supplied with rated voltage. As voltmeter resistance is very high, though voltmeter isconnected,secondaryis treatedtobeopencircuitasvoltmetercurrentisalwaysnegligiblysmall.

When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeterandwattmeteraretoberecorded.

Let,

Vo = Rated voltageWo=Input power

Io=Input current = noloadcurrent

Astransformersecondaryisopen,itisonnoload.SocurrentdrawnbytheprimaryisnoloadcurrentIo.Thetwocomp onentsof thisnoloadcurrentare,

$$I_m = I_o \sin \Phi_o \quad I_c = I_o \cos \Phi_o$$

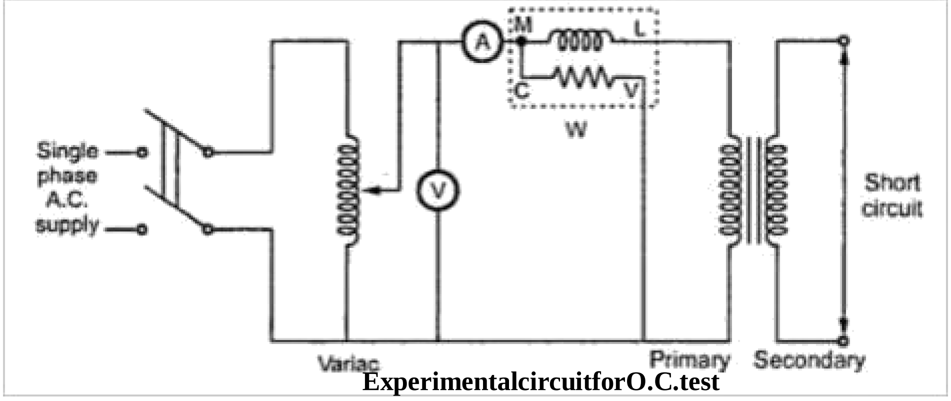
where$\cos\Phi_o$ = No load power factorAnd hence power input can be written as,$W_o=V_oI_o\cos\Phi_o$

ThephasordiagramisshownintheFig.
Assecondaryisopen,I_2=0.Thusitsreflectedcurrentonprimaryisalsozero.SowehaveprimarycurrentI_1 =Io. The transformer no load current is always very small, hardly 2 to 4 % of its full load value. As I_2 = 0,secondary copper losses are zero. And I_1 = Io is very low hence copper losses on primary are also very verylow. Thus the total copper losses in O.C. test are negligibly small. As against this the input voltage is rated atrated frequency hence flux density in the core isat itsmaximum value.Hence iron lossesare at ratedvoltage. As output power is zero and copper losses are very low, the total input power is used to supply ironlosses.Thispowerismeasuredbythewattmeteri.e.Wo.HencethewattmeterinO.C.test givesironlosses

which remain constant for all the loadsWo=Pi=Ironlosses

ShortCircuitTest (S.C.Test):

Inthis test,primaryis connectedtoa.c.supplythroughvariac,ammeterandvoltmeteras shownintheFig.



ExperimentalcircuitforO.C.test

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

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

Now the current flowing through the windings are rated current hence the total copperloss is full loadcopper loss. Now the voltage supplied is low which is a small fraction of the rated voltage. The iron lossesare functionofapplied voltage.So theironlossesin reducedvoltage testare very small.Hence thewattmeterreadingis thepowerlosswhichisequaltofullloadcopperlosses as ironlossesareverylow.

∴ Wsc=(Pcu)F.L.=Fullloadcopperloss

Calculations:FromS.C.testreadingswecanwrite,

Wsc= VscIsccosΦsc

$\therefore$ $\cos\Phi_{sc} = V_{sc} I_{sc} / W_{sc}$ = short circuitpowerfactor

$W_{sc} = I_{sc}^2 R_{1e}$ = copperloss

$\therefore$ $R_{1e} = W_{sc} / I_{sc}^2$

while $Z_{1e} = V_{sc}/I_{sc} = \sqrt{(R_{1e}^2 + X_{1e}^2)}$

$\therefore$ $X_{1e} = \sqrt{(Z_{1e}^2 - R_{1e}^2)}$

Thuswegettheequivalent circuit parameters R1e,X1eandZ1e.KnowingthetransformationratioK,theequivalentcircuitparametersreferredtosecondaryalsocanbeobtained.

Important Note : If the transformer is step up transformer, its primary is L.V. while secondary is H.V.winding.In S.C.test,supplyisgiventoH.V.windingandL.Visshorted.In suchcaseweconnectmeterson H.V.side which is transformersecondary through forS.C. testpurpose H.V side acts as primary.In suchcase the parameters calculated from S.C. test readings are referred to secondary which are R2e, Z2e and X2e.So before doing calculations it is necessary to find out where the readings are recorded on transformerprimary orsecondary and accordingly the parameters are to be determined.In stepdown transformer,primary is high voltage itself to which supply is given in S.C. test. So in such case test results give usparametersreferredtoprimaryi.e.R1e,Z1eandX1e.

Key point : In short, if meters are connected to primary of transformer in S.C. test, calculations give us R1eandZ1eifmetersareconnectedtosecondaryoftransformerinS.C.testcalculations giveusR2eandZ2e.

CalculationofEfficiencyfromO.C.andS.C.Tests:

Weknowthat,

FromO.C.test,Wo=Pi

FromS.C.test,Wsc=(Pcu)F.L.

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

Thus foranyp.f.cosΦ2theefficiencycanbepredetermined.Similarlyatanyloadwhichisfractionoffullloadthenalsoefficiencycanbepredeterminedas,

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

where n= fraction offullload

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

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

CalculationofRegulation

FromS.C.testweget theequivalentcircuit parametersreferredtoprimaryorsecondary.

TheratedvoltagesV1,V2andratedcurrents(I1)F.L.and(I2)F.L.areknownforthegiventransformer.Hencetheregulationcanbe determinedas,

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

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

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

For any other load the currents I_1, I_2 must be changed by fraction n.

$\therefore$ I_1, I_2 at any other load $= n(I_1)$F.L., $n(I_2)$F.L.

Key Point : Thus regulation at any load and any power factor can be predetermined, without actually loading the transformer.

Sumpner's Test Or Back-To-Back Test On Transformer:

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they cannot help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test give more accurate results of regulation and efficiency than O.C. and S.C. tests.

Sumpner's Test:

Sumpner's test or back to back test can be employed only when two identical transformers are available. Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical transformers are connected in parallel across a supply. Secondaries are connected in series such that emf's of them are opposite to each other. Another low voltage supply is connected in series with secondaries to get the readings, as shown in the circuit diagram shown below.

In above diagram, T1 and T2 are identical transformers. Secondaries of them are connected in voltage opposition, i.e. EEF and EGH. Both the emf's cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated. The current drawn from V1 is 2I0, where I0 is equal to no load current of each transformer. Thus input power measured by wattmeter W_1 is equal to iron losses of both transformers.

i.e. iron loss per transformer Pi=W1/2.

Now, a small voltage V2 is injected into secondary with the help of a low voltage transformer. The voltage V2 is adjusted so that, the rated current I2 flows through the secondary. In this case, both primaries and secondaries carry rated current. Thus short circuit test is simulated and wattmeter W2 shows total full load copper losses of both transformers.

i.e. copper loss per transformer PCu=W2/2.

From above test results, the **full load efficiency of each transformer** can be given as–

$$\%\text{ full load efficiency of each transformer} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

Predetermination of Voltage Regulation:

Modern power systems operate at some standard voltages. The equipments working on these systems are therefore given input voltages at these standard values, within certain agreed tolerance limits. In many applications this voltage itself may not be good enough for obtaining the best operating condition for the loads. A transformer is interposed in between the load and the supply terminals in such cases. There are additional drops inside the transformer due to the load currents. While input voltage is the responsibility ofthesupplyprovider,thevoltageattheloadisthe onewhichtheuserhastoworryabout.

If undue voltage drop is permitted to occur inside the transformer the load voltage becomes too low andaffects its performance. It is therefore necessary to quantify the drop that takes place inside a transformerwhen certain load current, at any power factor, is drawn from its output leads. This drop is termed as thevoltage regulation and is expressed as a ratio of the terminal voltage (the absolute value per se is not tooimportant).

The voltage regulation can be defined in two ways- Regulation Down and Regulation up. These twodefinitionsdifferonly in the reference voltage as can be seen below.Regulation down: This is defined as ‖the change in terminal voltage when a load current at any power factor is applied, expressed as a fraction oftheno-loadterminalvoltage.

Expressedinsymbolicformwehave,

$$Regulation = \frac{|V_{nl}| - |V_l|}{|V_l|}$$

Where,
V_{nl}istheno-loadterminalvoltage. $V_l$isloadvoltage
.

Normallyfullloadregulation is ofinterestasthepartloadregulation isgoingtobelower.
Thisdefinitionismorecommonlyusedinthecaseofalternatorsandpowersystemsastheuser-endvoltageis guaranteed by the power supply provider. He has to generate proper no-load voltage at the generatingstation to provide the user the voltage he has asked for. In the expressions for the regulation, only thenumericaldifferencesofthe voltagesaretakenandnotvectordifferences.

In the case of transformers both definitions result in more or less the same value for the regulation as thetransformer impedance is very low and the power factor of operation is quite high. The power factor of theload is defined with respect to the terminal voltage on load. Hence a convenient starting point is the loadvoltage. Also the full load output voltage is taken from the name plate. Hence regulation up has someadvantage when it comes to its application. Fig. 23 shows the phasor diagram of operation of the transformerunderloadedcondition.Theno-loadcurrentI0isneglectedinviewofthelargemagnitudeofI‘2.

PredeterminationofEfficiency:

Transformerswhich are connected to the powersuppliesand loadsand are in operation are required tohandle load current and power as per the requirements of the load. An unloaded transformer draws only themagnetization current on the primary side, the secondary current being zero. As the load is increased theprimary and secondary currents increase as per the load requirements. The volt amperes and wattage handledby the transformeralso increases.Due to the presence ofno load losses and I2R losses in the windingscertain amount of electrical energy gets dissipated as heat inside the transformer. This gives rise to theconceptofefficiency.

Efficiencyofpowerequipmentisdefinedatanyloadastheratioofthepoweroutputtothepowerinput.Puttinginthe formof anexpression,

While the efficiency tells us the fraction of the input power delivered to the load, the deficiency focuses ourattention on losses taking place inside transformer. As a matter of fact the losses heat up machine. Thetemperaturerise decidestheratingof theequipment.

The temperature rise of the machine is a function of heat generated the structural configuration, method ofcooling and type of loading (or duty cycle of load). The peak temperature attained directly affects the life oftheinsulationsof themachineforanyclassofinsulation.

A typical curve for the variation of efficiency as a function of output is given in Fig. The losses that takeplaceinsidethemachineexpressedasafractionoftheinputissometimestermedasdeficiency.Exceptinthe case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handlingthe power. Thus the value for the efficiency is always less than one. In the case of a.c. machines the rating isexpressed in terms of apparent power. It is nothing but the product of the applied voltage and the currentdrawn. The actual power delivered is a function of the power factor at which this current is drawn. As thereactive power shuttles between the source and the load and has a zero average value over a cycle of thesupply wave it does not have any direct effect on the efficiency. The reactive power however increases thecurrent handled by the machine and the losses resulting from it. Therefore the losses that take place inside atransformer at any given load play a vital role in determining the efficiency. The losses taking place inside atransformercanbeenumeratedasbelow:

1. Primarycopperloss
2. Secondarycopperloss
3. Ironloss
4. Dielectricloss
5. Strayloadloss

Theseareexplained insequencebelow.

Primary and secondary copper losses take place in the respective winding resistances due to the flow of thecurrentinthem

The primary and secondary resistances differfrom theird.c.values due to skin effect and the temperaturerise of the windings. While the average temperature rise can be approximately used, the skin effect is hardertogetanalytically.TheshortcircuittestgivesthevalueofRetakingintoaccounttheskin effect.

The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is afunctionof the materialusedforthecore.

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

Forconstantvoltageandconstantfrequencyoperationthiscanbetakentobeconstant.Theeddycurrentloss inthecorearisesbecauseoftheinducedemfinthesteellaminationsheetsandtheeddiesofcurrentformedduetoit.ThisagainproducesapowerlossPeinthe lamination.

$$P_e = K_e B^2 f^2 t^2$$

wheret is the thickness of the steel lamination used. As the lamination thickness is much smaller than thedepth of penetration of the field, the eddy current loss can be reduced by reducing the thickness of thelamination. Present day laminations are of 0.25 mm thickness and are capable of operation at 2 Tesla. Thesereduce the eddy current losses in the core. This loss also remains constant due to constant voltage andfrequency of operation. The sum of hysteresis and eddy current losses can be obtained by the open circuittest.

The dielectric losses take place in the insulation of the transformerdue to the large electric stress. Inthe case of low voltage transformers this can be neglected. For constantvoltage operation this can beassumedtobeaconstant.

The stray load losses arise out of the leakage fluxes of the transformer. These leakage fluxes link themetallic structural parts, tank etc. and produce eddy current losses in them. Thus they take place 'all round'the transformerinstead of adefinite place ,hence the name 'stray'.Also the leakage fluxisdirectlyproportional to the load current unlike the mutual fluxwhich is proportional to the applied voltage. Hencethis loss is called 'stray load' loss. This can also be estimated experimentally. It can be modeled by anotherresistance in the series branch in the equivalent circuit. The stray load losses are very low in air-coredtransformersduetotheabsence of the metallic tank

Thus, the different losses fall in to two categories Constant losses (mainly voltage dependant) and Variablelosses (current dependant). The expression for the efficiency of the transformer operating at a fractional loadxof itsrating,ataloadpowerfactorof Θ2,canbewrittenas

Here S in the volt ampere rating of the transformer (V'2 I'2 at full load), Pconst being constant losses andPvarthe variable lossesatfullload.

UNIT-V
THREEPHASETRANSFORMERS

Introduction:

Electric power is generated in generating stations, using three phase alternators at 11 KV. This voltage isfurther stepped up to 66 KV, 110 KV, 230 KV or 400 KV using 3 phase power transformers and power istransmitted at this high voltage through transmission lines. At the receiving substations, these high voltagesare stepped down by 3 phase transformers to 11 KV. This is further stepped down to 400 volts at load centersby means of distribution transformers. For generation, transmission and distribution, 3 phase system iseconomical. Therefore 3 phase transformers are very essential for the above purpose. The sectional view of a3phasepowertransformerisshowninFig.5.1.

Fig.5.1100KVAoilimmersed powertransformer

1. Tap-changerswitchhandle
2. Porcelain-bushinginsulator(Forhighvoltage)
3. Bushinginsulators(Forlowvoltages)
4. Oilgauge
5. Oiltank
6. Breatherplug
7. Coolingpipes
8. Tankfrontwall
9. Core,
10. Highvoltagewinding
11. Lowvoltagewinding
12. Wheels orrollers.

ConstructionofThreephasesTransformer:

Three phase transformers comprise of three primary and three secondary windings. They are wound over thelaminated core as we have seen in single phase transformers. Three phase transformers are also of core typeor shell type as in single phase transformers. The basic principle of a three phase transformer is illustrated infig 5.2 in which the primary windings and secondary windings of three phases are shown. The primarywindingscanbeinterconnectedinstarordeltaandputacrossthreephasesupply.

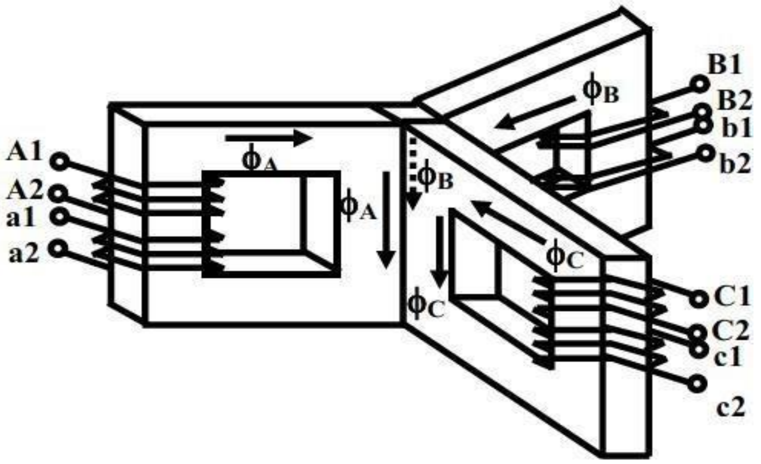


Fig.5.23-phasecore-typeTransformer

The three coresare 120° apart and theirunwound limbs are shown in contactwith each other. The centercore formed by these three limbs, carries the flux produced by the three phase currents IR, IY and IB. As atanyinstantIR+Iy+IB=0,thesumofthreefluxes(fluxinthecenterlimb)isalsozero.

Therefore it will make no difference if the common limb is removed. All the three limbs are placed in oneplaneincaseof apracticaltransformerasshowninfig5.3.

The core type transformers are usually wound with circular cylindrical coils. The construction and assemblyoflaminationsandyokeofathreephasecoretypetransformerisshowninfig5.4onemethodofarrangementof windingsinathreephasetransformerisshown.

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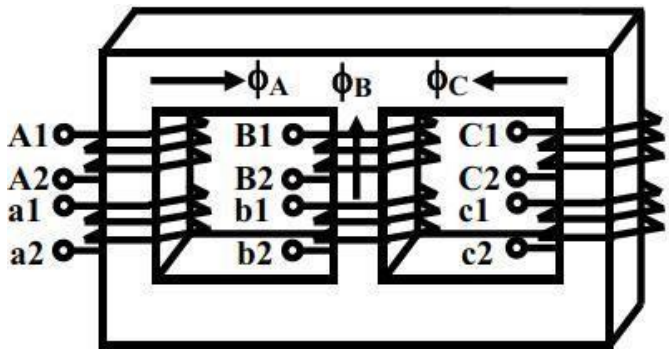


Fig.5.3Apracticalcoretypethreephasetransformer

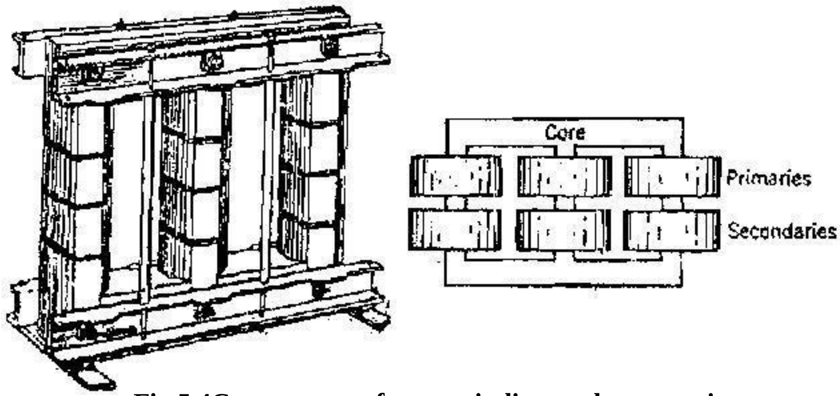


Fig.5.4Coretypetransformerwindingsandconstruction

In the other method the primary and secondary windings are wound one over the other in each limb. Thelow-tension windings are wound directly over the core but are, of course, insulated for it. The high tensionwindings are wound over the low— tension windings and adequate insulation is provided between the twowindings.

The primary and secondary windings of the three phase transformer can also be interconnected as star ordelta.

ThreePhaseTransformerconnections:

The identical single phase transformers can be suitably inter-connected and used instead of a single unit 3—phase transformer. The single unit 3 phase transformer is housed in a single tank. But the transformer bank ismade up of three separate single phase transformers each with its own, tanks and bushings. This method ispreferred in mines and high altitude power stations because transportation becomes easier. Bank method isadopted also when the voltage involved is high because it is easier to provide proper insulation in each singlephasetransformer.

Ascomparedtoabankofsinglephasetransformers,themainadvantagesofasingleunit3-phasetransformer are that it occupies less floor space for equal rating, less weight costs about 20% less and furtherthatonlyoneunitistobehandledandconnected.

There are various methods available for transforming 3 phase voltages to higher or lower 3 phase voltages.Themostcommonconnectionsare(i)star—star(ii)Delta—Delta(iii)Star—Delta(iv)Delta—Star.

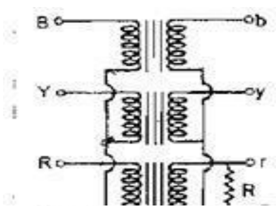


Fig4.5Star-starconnection

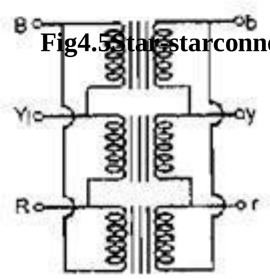


Fig.5.6Delta-deltaconnection

The star-star connection is most economical for small, high voltage transformers because the number ofturns per phase and the amount of insulation required is minimum (as phase voltage is only 1/3 of linevoltage.Infig.5.5abankofthreetransformersconnectedinstaronboththeprimaryandthesecondary sidesisshown.Theratiooflinevoltagesontheprimarytothesecondarysidesisthesameasatransformationratioof singlephasetransformer.

The delta— delta connection is economical for large capacity, low voltage transformers in which insulationproblemisnotaseriousone.Thetransformerconnectionareasshowninfig.5.6.

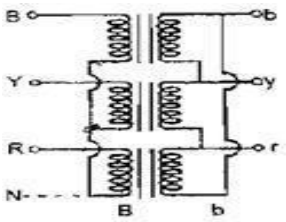


Fig.5.7Star-deltaconnection

The main use of star-delta connection is at the substation end of the transmission line where the voltage isto be stepped down. The primary winding is star connected with grounded neutral as shown in Fig.5.7.The ratio between the secondary and primary line voltage is 1/3 times the transformation ratio of eachsingle phase transformer. There is a 30° shift between the primary and secondary line voltageswhichmeansthat astar-deltatransformerbankcannot beparalleledwitheitherastar-staroradelta-deltabank.

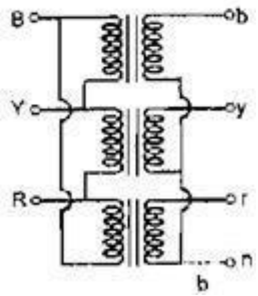


Fig.5.8Delta-starconnection

Delta-Star connection is generally employed where it is necessary to step up the voltage. The connection isshown in fig. 5.8. The neutral of the secondary is grounded for providing 3-phase, 4-wire service. Theconnection is very popular because it can be used to serve both the 3-phase power equipment and singlephaselightingcircuits.

VectorGroupof3-phasetransformer:

The secondary voltages of a 3-phase transformer may undergo a phase shift of either +30° leading or -30°lagging or0° i.e,no phase shiftor180° reversal with respective line orphase to neutral voltages.On thename plate of a three phase transformer, the vector group is mentioned. Typical representation of the vectorgroup could be Ydl or Dy 11 etc. The first capital latter Y indicates that the primary is connected in star andthe second lower case latter d indicates delta connection of the secondary side. The third numerical figureconveysthe angle of phase shiftbasedonclock convention.The minute handisused to representtheprimaryphasetoneutralvoltageandalwaysshowntooccupytheposition12.Thehourhandrepresentsthe

secondary phase to neutral voltage and may, depending upon phase shift, occupy position other than 12 asshowninthefigure4.9.Theanglebetweentwoconsecutive numbersontheclockis30°

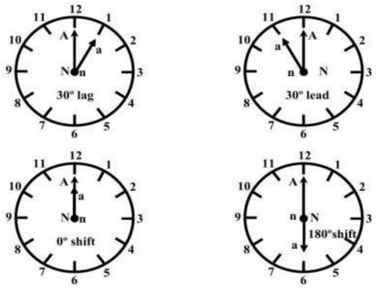


Fig.4.9Clockconventionrepresentingvectorgroups

Delta/delta(Dd0, Dd6)connection:

The connection of Dd0 is shown in fig. 4.10 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideiszerodegree(0°).

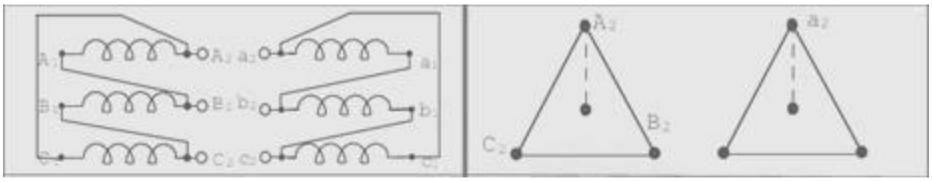


Fig 5.10 Dd0connectionandphasordiagram

The connection of Dd6 is shown in fig. 5.11 and the voltages on primary and secondary sides are also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideis180°.

Fig5.11 Dd6connectionandphasordiagram

This connection proves to be economical for large low voltage transformers as it increases number of turnsper phase. Primary side line voltage is equal to secondary side line voltage. Primary side phase voltage isequal to secondary side phase voltage. There is no phase shift between primary and secondary voltages forDd0 connection.Thereis180°phaseshiftbetweenprimaryandsecondaryvoltages forDd6 connection.

Advantages:

- **Sinusoidal Voltage at Secondary:** In order to get secondary voltage as sinusoidal, the magnetizingcurrent of transformer must contain a third harmonic component. The delta connection provides aclosed path for circulation of third harmonic component of current. The flux remains sinusoidalwhichresultsinsinusoidalvoltages.

- **Suitable for Unbalanced Load:** Even if the load is unbalanced the three phase voltages remainsconstant.Thusitsuitableforunbalancedloadingalso.
- **Carry 58% Load if One Transfer is Faulty in Transformer Bank:** If there is bank of singlephase transformers connected in delta-delta fashion and if one of the transformers is disabled thenthesupplycanbecontinuedwithremainingtowtransformersofcoursewithreducedefficiency.
- **No Distortion in Secondary Voltage:** there is no any phase displacement between primary andsecondary voltages. There is no distortion of flux as the third harmonic component of magnetizingcurrent can flow in the delta connected primary windings without flowing in the line wires .there isnodistortioninthesecondaryvoltages.

- **Economicalfor Low Voltage:**Due to deltaconnection,phase voltage issame asline voltagehence winding have more number of turns. But phase current is (1/√3) times the line current. Hencethe cross-section of the windings is very less. This makes the connection economical for lowvoltagestransformers.
- **Reduce Cross section of Conductor:** The conductor is required of smaller Cross section as thephase current is 1/√3 times of the line current. It increases numberof turns per phase and reducesthenecessarycrosssectionalareaofconductors thusinsulationproblemisnotpresent.
- **AbsentofThirdHarmonicVoltage:**Duetocloseddelta,thirdharmonicvoltages areabsent.
- Theabsenceofstarorneutralpointprovestobeadvantageousinsomecases.

Disadvantages:

- Duetotheabsenceofneutralpointitis notsuitableforthreephasefourwiresystem.
- Moreinsulationisrequiredandthevoltageappearingbetweenwindingsandcorewillbeequaltofullline voltageincaseofearthfaultononephase.

Application:

- Suitableforlarge,lowvoltagetransformers.
- This Type of Connection is normally uncommon but used in some industrial facilities to reduceimpactof SLG faultsontheprimarysystem
- Itisgenerally used in systemswhere itneed to be carry large currentson low voltagesandespecially when continuity of service is to be maintained even though one of the phases developsfault.

Star/star(YyO,Yy6)connection:

This is the most economical one for small high voltage transformers. Insulation cost is highly reduced.Neutral wire can permit mixed loading. Triplen harmonics are absent in the lines. These triplen harmoniccurrents cannot flow, unless there is a neutral wire. This connection produces oscillating neutral. Threephaseshelltypeunitshavelargetriplenharmonicphasevoltage.Howeverthreephasecoretypetransformersw ork satisfactorily.A tertiarymesh connectedwindingmay be required to stabilize theoscillatingneutralduetothirdharmonicsinthreephase banks.

The connection of Yy0 is shown in fig. 5.12 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideiszerodegree(0°).

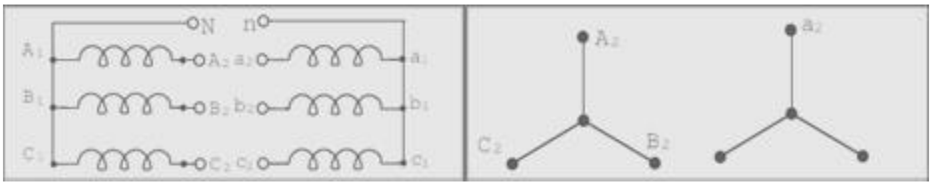


Fig.5.12Yy0connection and phasordiagram

The connection of Yy6 is shown in fig. 4.13 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideis180°.

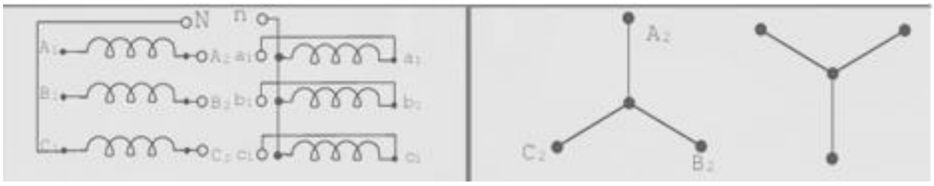


Fig 4.13.Yy6connection and phasordiagram

- InPrimaryWindingEachPhaseis120°electricaldegrees out ofphasewiththeothertwophases.
- InSecondaryWindingEachPhaseis120°electricaldegrees outofphasewiththeothertwophases.
- Eachprimarywindingismagneticallylinkedtoonesecondarywindingthroughacommoncoreleg.Sets of windings that are magnetically linked are drawn parallel to each other in the vector diagram.IntheY-Yconnection,eachprimaryandsecondarywindingisconnectedtoaneutralpoint.
- The neutral point may or may not be brought out to an external physical connection and the neutralmayormaynotbegrounded.

Advantages ofY-y connection:

- **No Phase Displacement:** The primary and secondary circuits are in phase; i.e., there are no phaseangle displacementsintroduced by the Y-Y connection. Thisisan importantadvantage whentransformers are used to interconnect systems of different voltages in a cascading manner. Forexample, suppose there are four systems operating at 800, 440, 220, and 66 kV that need to beinterconnected. Substations can be constructed using Y-Y transformer connections to interconnectany two of these voltages. The 800 kV systems can be tied with the 66 kV systems through a single800to66kVtransformationorthroughaseriesofcascadingtransformationsat 440,220and66kV.
- **Required Few Turns for winding:** Due to star connection, phase voltages is (1/√3) times the linevoltage. Hence less number of turns is required. Also the stress on insulation is less. This makes theconnectioneconomicalforsmallhighvoltagepurposes.

- **Required Less Insulation Level**: If the neutral end of a Y-connected winding is grounded, thenthere is an opportunity to use reduced levels of insulation at the neutral end of the winding. Awindingthatisconnectedacrossthephasesrequiresfullinsulationthroughoutthewinding.
- **HandleHeavyLoad:**Duetostarconnection,phasecurrentissameaslinecurrent.Hencewindings have to carry high currents. This makes cross section of the windings high. Thus thewindings aremechanicallystrongandwindingscanbearheavyloads andshortcircuitcurrent.
- **Use for Three phases Four Wires System:**As neutral is available, suitable for three phases fourwiresystem.
- **Eliminate Distortion in Secondary Phase Voltage:** The connection of primary neutral to the neutral ofgenerator eliminates distortion in the secondary phase voltages by giving path to triple frequencycurrentstowardtogenerator.
- **Sinusoidal voltage on secondary side:** Neutral give path to flow Triple frequency current to flowGeneratorsidethussinusoidalvoltageonprimarywillgivesinusoidalvoltageonsecondaryside.
- **Used as Auto Transformer:** A Y-Y transformermay be constructed as an autotransformer, withthepossibility ofgreatcostsavingscomparedtothetwo-windingtransformerconstruction.
- **Better Protective Relaying:** The protective relay settings will be protecting better on the line togroundfaults whentheY-Ytransformerconnectionswithsolidlygrounded neutralsareapplied.

Disadvantages:

- **The Third harmonic issue:** The voltages in any phase of a Y-Y transformer are 1200 apart fromthe voltages in any other phase. However, the third-harmonic components of each phase will be inphase with each other. Nonlinearities in the transformer core always lead to generation of thirdharmonic.Thesecomponentswilladdupresultinginlarge(canbeevenlargerthanthefundamentalcom ponent) thirdharmoniccomponent.
- **Overvoltage at Lighting Load:** The presence of third (and other zero-sequence) harmonics at anungroundedneutralcan causeovervoltage conditionsatlightload.When constructing aY-Ytransformerusing single-phase transformersconnectedin abank,themeasuredline-to-neutralvoltages are not 57.7% of the system phase-to-phase voltage at no load but are about 68% anddiminish very rapidly as the bank is loaded. The effective values of voltages at different frequenciescombine by taking the square root of the sum of the voltages squared. With sinusoidal phase-to-phasevoltage,thethird-harmoniccomponentofthephase-to-neutralvoltageisabout60%.
- **Voltage drop at Unbalance Load:** There can be a large voltage drop for unbalanced phase-to-neutral loads. This is caused by the fact that phase-to-phase loads cause a voltage drop through theleakage reactance of the transformer whereas phase-to-neutral loads cause a voltage drop throughthemagnetizingreactance,whichis100to1000timeslargerthantheleakagereactance.
- **Overheated Transformer Tank:** Under certain circumstances, a Y-Y connected three-phase trans-can produce severe tank overheating that can quickly destroy the transformer. This usually occurswithanopenphaseontheprimarycircuitandloadonthesecondary.

- **Over Excitation of Core in Fault Condition:** If a phase-to-ground fault occurs on the primarycircuit with the primary neutral grounded, then the phase-to-neutral voltage on the un faulted phasesincreases to 173% of the normal voltage. This would almost certainly result in over excitation of thecore,withgreatlyincreasedmagnetizingcurrentsandcorelosses
- If the neutrals of the primary and secondary are both brought out, then a phase-to-ground fault onthe secondary circuit causes neutral fault current to flow in the primary circuit. Ground protectionre-layingintheneutraloftheprimarycircuitmaythenoperateforfaults onthesecondarycircuit
- **Neutral Shifting:**Ifthe load on the secondary side unbalanced then the performance ofthisconnection isnotsatisfactory then the shifting of neutral pointispossible.To preventthis,starpointof theprimaryisrequiredtobeconnectedtothestarpointof thegenerator.
- **Distortion of Secondary voltage:** Even though the star or neutral point of the primary is earthed,the third harmonic present in the alternator voltage may appear on the secondary side. This causesdistortioninthesecondaryphase voltages.
- **Over Voltage at Light Load:** The presence of third (and other zero-sequence) harmonics at anungroundedneutralcancauseovervoltageconditionsatlightload.
- **Difficulty in coordination of Ground Protection:** In Y-Y Transformer, a low-side ground faultcausesprimarygroundfaultcurrent,makingcoordinationmore difficult.
- **Increase Healthy Phase Voltage under Phase to ground Fault:** If a phase-to-ground fault occurson the primary circuit with the primary neutral grounded, then the phase-to-neutral voltage on theUN faulted phase's increases to 173% of the normal voltage. If the neutrals of the primary andsecondary are both brought out, then a phase-to-ground fault on the secondary circuit causes neutralfaultcurrenttoflowintheprimarycircuit.
- **Trip the T/C in Line-Ground Fault:** All harmonics will propagate through the transformer, zero-sequence current path is continuous through the transformer, one line-to-ground fault will trip thetransformer.
- **Suitable for Core Type Transformer:** The third harmonic voltage and current is absent in suchtype ofconnectionwith three phasewire system orshell type ofthree phase units,the thirdharmonic phase voltage may be high. Thistype ofconnection ismore suitable forcore typetransformers.

Application:

- This TypeofTransformerisrarely usedduetoproblems withunbalancedloads.
- Itiseconomicalforsmallhighvoltagetransformersasthenumberofturnsperphaseandtheamountof insulationrequiredisless.

Star/Deltaconnection(Yd1/Yd11):

Thereisa+30Degreeor-30DegreePhaseShiftbetweenSecondaryPhaseVoltagetoPrimaryPhaseVoltage.TheconnectionofYd1isshowninfig.4.14andthevoltagesonprimaryandsecondarysidesare

also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltagesideandlowvoltagesideis-30°.

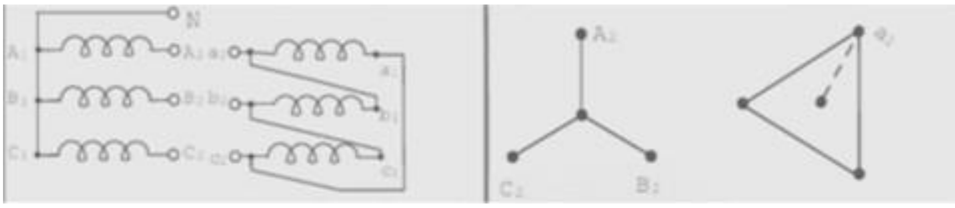


Fig 5.14.Yd1connection and phasordiagram

The connection ofYd11 is shown in fig.4.15 and the voltageson primary and secondary sidesis alsoshown on the phasor diagram. The phase angle difference between the phase voltage of high voltage sideandlowvoltagesideis30°.

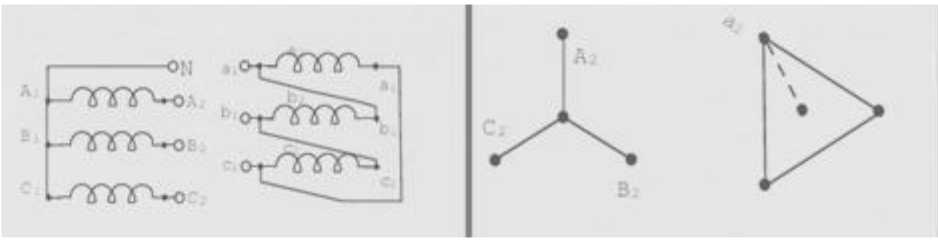


Fig5.15.Yd11connection and phasordiagram

Advantages:

- Theprimarysideisstarconnected.Hencefewernumbersofturnsarerequired.Thismakestheconnectioneconomicalforlargehighvoltagestepdownpowertransformers.
- Theneutralavailableontheprimarycanbe earthedtoavoiddistortion.
- Theneutralpointallows bothtypes ofloads(singlephaseorthreephases)tobemet.
- Largeunbalancedloadscanbehandledsatisfactory.
- The Y-D connection has no problem with third harmonic components due to circulating currentsinD. It is also more stable to unbalanced loads since the D partially redistributes any imbalance thatoccurs.
- Thedeltaconnectedwindingcarriesthirdharmoniccurrentduetowhichpotentialofneutralpointis stabilized. Some saving in cost of insulation is achieved if HV side is star connected. But inpractice the HV side is normally connected in delta so that the three phase loads like motors andsingle phase loads like lighting loads can be supplied by LV side using three phase fourwiresystem.
- **As Grounding Transformer:** In Power System Mostly grounded Y- Δ transformer is used for nootherpurposethantoprovideagoodgroundsourceinungroundedDeltasystem.

Disadvantages:

- In this type of connection, the secondary voltage is not in phase with the primary. Hence it is notpossibletooperatethisconnectioninparallelwithstar-starordelta-deltaconnectedtransformer.
- One problem associatedwith this connection isthat the secondary voltage isshifted by 30^0 withrespect to the primary voltage. This can cause problemswhen paralleling 3-phase transformerssince transformers secondary voltages must be in-phase to be paralleled. Therefore, we must payattentiontotheseshifts.
- If secondary of this transformer should be paralleled with secondary of another transformer withoutphaseshift,therewouldbeaproblem

Application:

- Itiscommonlyemployedforpowersupplytransformers.
- This type of connection is commonly employed at the substation end of the transmission line. Themain use with this connection is to step down the voltage. The neutral available on the primary sideis grounded. It can be seen that there is phase difference of 30° between primary and secondary linevoltages.
- Commonly used in a step-down transformer, Y connection on the HV side reduces insulation coststhe neutral point on the HV side can be grounded, stable with respect to unbalanced loads. As forexample, at the end of a transmission line. The neutral of the primary winding is earthed. In thissystem, line voltage ratio is 1/√3 Times of transformer turn-ratio and secondary voltage lags behindprimaryvoltageby30°.Alsothirdharmonic currentsflowsin

Delta-starconnection(Dy1/Dy11):

In this type of connection, the primary connected in delta fashion while the secondary current is connectedin star. There is s +30 Degree or-30 Degree Phase Shift between Secondary Phase Voltage to PrimaryPhaseVoltage.

The connection of Dy1 is shown in fig. 4.16 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideis-30°.

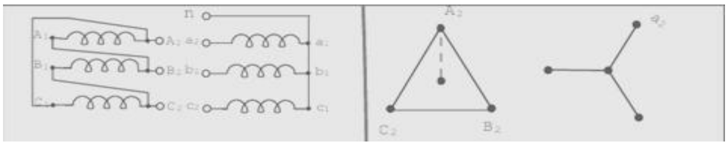


Fig 5.16.Dy1connectionand phasordiagram

The connection of Dy11 is shown in fig. 5.17 and thevoltageson primary and secondary sidesis alsoshown on the phasor diagram. The phase angle difference between the phase voltage of high voltage sideandlowvoltagesideis30°.

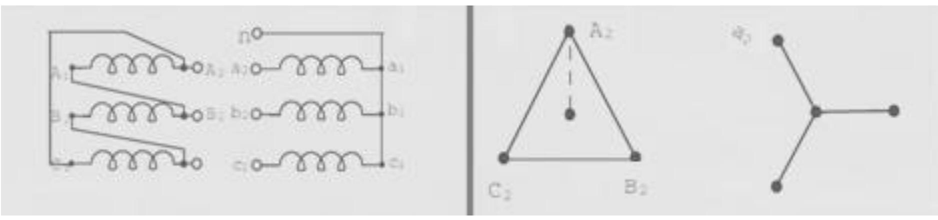


Fig5.17.Dy11connection andphasordiagram

Advantages:

- **CrosssectionareaofwindingislessatPrimaryside:**Onprimarysideduetodeltaconnectionwindingcross -sectionrequiredisless.
- **UsedatThreephasefourwireSystem:**Onsecondaryside,neutralisavailable,duetowhichitcanbeusedfor 3-phase,4wiresupplysystem.
- **No distortionofSecondary Voltage:**Nodistortion duetothird harmoniccomponents.
- **HandledlargeunbalancedLoad:**Largeunbalancedloadscanbehandledwithout anydifficulty.
- **Grounding Isolation between Primary and Secondary:** Assuming that the neutral of the Y-connected secondary circuit is grounded, a load connected phase-to-neutral or a phase-to-groundfault produces two equal and opposite currents in two phases in the primary circuit without anyneutral ground current in the primary circuit. Therefore, in contrast with the Y-Y connection, phase-to-ground faults or current unbalance in the secondary circuit will not affect ground protectiverelaying applied to the primary circuit. Thisfeature enablespropercoordination of protectivedevicesandisaveryimportantdesignconsideration.
- The neutral of the Y grounded is sometimes referred to as a grounding bank, because it provides alocalsourceof groundcurrentatthesecondarythatisisolatedfromtheprimarycircuit.

- **Harmonic Suppression:** The magnetizing current must contain odd harmonics for the inducedvoltages to be sinusoidal and the third harmonic is the dominant harmonic component. In a three-phase system the third harmonic currents of all three phases are in phase with each other becausethey are zero-sequence currents. In the Y-Y connection, the only path for third harmonic current isthrough the neutral. In the Δ -Y connection, however, the third harmonic currents, being equal inamplitude and in phase with each other, are able to circulate around the path formed by the Δconnectedwinding.Thesamethingistruefortheotherzero-sequenceharmonics.
- **Grounding Bank:**Itprovidesalocal source of ground currentat the secondary thatisisolatedfrom the primary circuit. For suppose an ungrounded generator supplies a simple radial systemthrough Δ-Y transformer with grounded Neutral at secondary as shown Figure. The generator cansupplyasingle-phase-to-neutralloadthroughthe-groundedYtransformer.

Disadvantages:

- In this type of connection, the secondary voltage is not in phase with the primary. Hence it is notpossibletooperatethisconnectioninparallelwithstar-starordelta-deltaconnectedtransformer.
- One problem associatedwith this connection isthat the secondary voltage isshifted by 30^0 withrespect to the primary voltage. This can cause problemswhen paralleling 3-phase transformerssince transformers secondary voltages must be in-phase to be paralleled.Therefore, we must payattentiontotheseshifts.
- If secondary of this transformer should be paralleled with secondary of another transformer withoutphaseshift,therewouldbeaproblem.

Application:

- **Commonly used in a step-up transformer:** As for example, at the beginning of a HT transmissionline. In this case neutral point is stable and will not float in case of unbalanced loading. There is nodistortionoffluxbecauseexistenceofa-connectionallowsapathforthethird-harmoniccomponents. The line voltage ratio is √3 times of transformer turn-ratio and the secondary voltageleads the primary one by 30°. In recentyears, this arrangement has become very popular fordistributionsystemasitprovides3-Ø,4-wiresystem.
- **Commonly used in commercial, industrial, and high-density residential locations:** To supplythree- phase distribution systems. An example would be a distribution transformer with a deltaprimary, running on three 11kV phases with no neutral or earth required, and a star (or wye)secondary providing a 3-phase supply at 400 V, with the domestic voltage of 230 available betweeneachphaseandanearthedneutralpoint.
- **UsedasGeneratorTransformer:**TheΔ-Ytransformerconnectionisuseduniversallyforconnectinggeneratorstotransmissionsystems.

Delta-zigzagandStarzigzag connections(Dz0/Dz6&Yz1/Yz6):

The connection of Dz0 is shown in fig. 4.18 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideis0°.

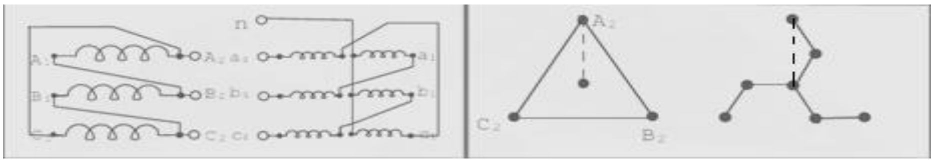


Fig5.18.Dz0connection andphasordiagram

The connection of Dz6 is shown in fig. 4.19 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideis180°.

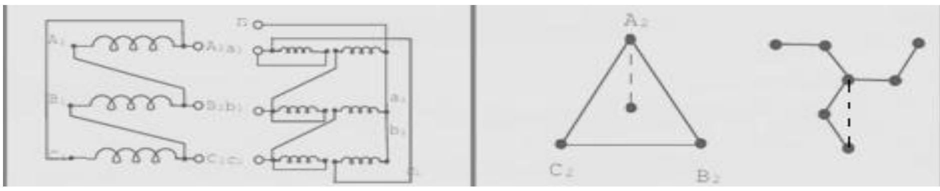


Fig5.19.Dz6connection andphasordiagram

The connection of Yz1 is shown in fig. 4.20 and the voltages on primary and secondary sides is also shownon the phasor diagram. The phase angle difference between the phase voltage of high voltage side and lowvoltagesideis-30°.

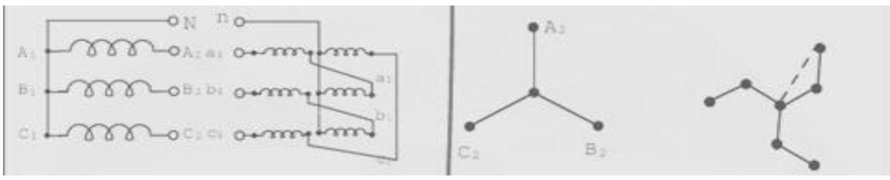


Fig5.20.Yz1connection andphasordiagram

The connection of Yz11 is shown in fig. 5.21 and the voltages on primary and secondary sidesis alsoshownonthephasordiagram.Thephaseangle differencebetweenthephasevoltageof high voltagesideandlowvoltageside is30°.

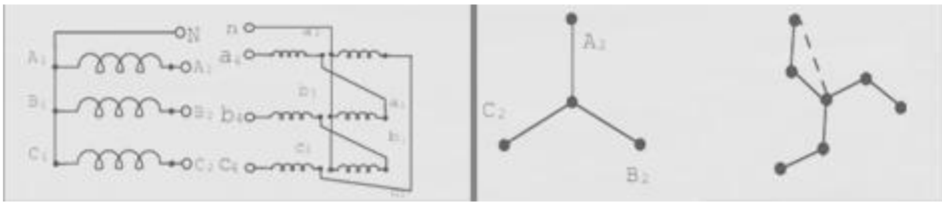


Fig 4.22Yz11connectionand phasordiagram

- These connections are employed where delta connections are weak. Interconnection of phases inzigzagwindingeffectsareductionofthirdharmonicvoltagesandatthesametimepermitsunbalancedloading.
- This connection may be used with either delta connected or star connected winding either for step-uporstep-downtransformers.Ineithercase,the zigzagwindingproducesthe same angulardisplacement asadeltawinding,andatthesametimeprovides aneutralforearthingpurposes.
- The amount of copper required from a zigzag winding in 15% more than a corresponding star ordeltawinding.Thisisextensivelyusedforearthingtransformer.
- Due to **zigzag** connection (interconnection between phases), third harmonic voltages are reduced. Italso allows unbalanced loading. The zigzag connection is employed for LV winding. For a giventotal voltage per phase, the zigzag side requires 15% more turns as compared to normal phaseconnection. In cases where delta connections are weak due to large number of turns and small crosssections,thenzigzagstarconnectionispreferred.Itisalsousedinrectifiers.

Scottconnection:

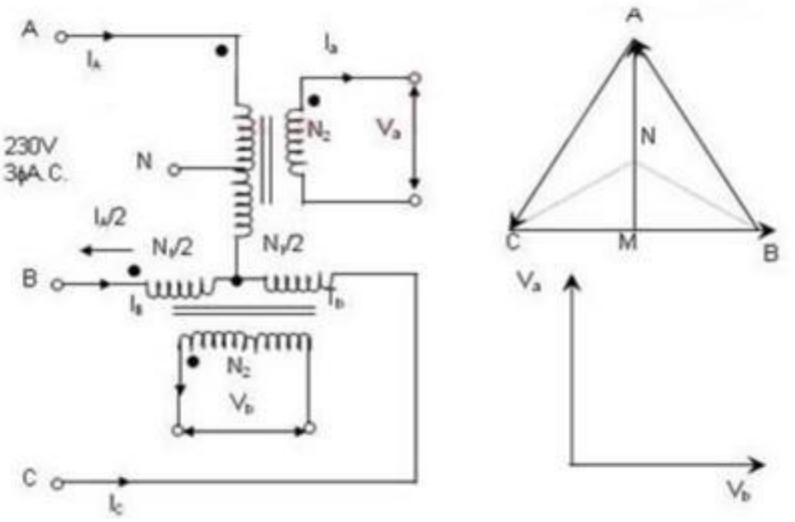
Therearetwomainreasonsfortheneedtotransformfromthreephasestotwophases,

1. Togiveasupplytoanexistingtwophasesystemfromathreephasesupply.
2. Tosupplytwophasefurnacetransformersfromathreephasesource.

Two-phase systems can have 3-wire, 4-wire, or 5-wire circuits. It is needed to be considering that a two-phase system is not 2/3 of a three-phase system. Balanced three-wire, two-phase circuits have two phasewires, both carrying approximately the same amount of current, with a neutral wire carrying 1.414 times thecurrentsinthephasewires.Thephase-to-neutralvoltagesare90°outof phasewitheachother.

Two phase 4-wire circuits are essentially just two ungrounded single-phase circuits that are electrically 90°out of phase with each other. Two phase 5-wire circuits have four phase wires plus a neutral; the four phasewiresare90° outof phasewitheachother.

A Scott-T transformer (also called a Scott connection) is a type of circuit used to derive two-phase powerfrom athree-phase source orvice-versa. The Scottconnection evenly distributesa balanced load betweenthe phases of the source. Scott T Transformers require a three phase power input and provide two equalsingle phase outputs called Main and Teaser. The MAIN and Teaser outputs are 90 degrees out of phase.TheMAINandtheTeaseroutputs mustnotbeconnected inparallel orinseries as itcreatesavectorcurrent imbalance on the primary side. MAIN and Teaser outputs are on separate cores. An external jumper is alsorequired to connect the primary side of the MAIN and Teaser sections. The schematic of a typical Scott TTransformerisshownbelow:



5.23Connectiondiagramof Scott-connectedtransformerandvectorrelationofinput andoutput

From the phasor diagram it is clear that the secondary voltages are of two phases with equal magnitude and90°phasedisplacement.

Scott T Transformeris built with two single phase transformers of equal power rating.Assuming thedesired voltage is the same on the two and three phase sides, the Scott-T transformer connection consists ofa center-tapped 1:1 ratio main transformer, T1, and an 86.6% (0.5√3) ratio teaser transformer, T2. Thecenter-tapped side of T1 is connected between two of the phases on the three-phase side. Its center tap thenconnects to one end of the lower turn count side of T2, the other end connects to the remaining phase. Theothersideofthetransformersthenconnectsdirectlytothetwopairsofatwo-phasefour-wiresystem.

If the main transformer has a turn's ratio of 1: 1, then the teaser transformer requires a turn's ratio of 0.866:1 for balanced operation. 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 main secondarywinding,calculatingtheprimarycurrentsseparatelyandsuperimposingtheresults.

The primary three-phase currents are balanced; i.e., the phase currents have the same magnitude and theirphase angles are 120° apart. The apparent power supplied by the main transformer is greater than theapparent power supplied by the teaser transformer. This is easily verified by observing that the primarycurrentsinbothtransformershavethesamemagnitude;however,theprimaryvoltageoftheteasertransformer is only 86.6% as great as the primary voltage of the main transformer. Therefore, the teasertransformsonly86.6%of theapparentpowertransformedbythemain.

- The total real power delivered to the two phase load is equal to the total real power supplied fromthethree-phasesystem,thetotalapparentpowertransformedbybothtransformersisgreaterthanthetotalapparentpowerdeliveredtothetwo-phase load.

- The apparentpowertransformedbythe teaseris0.866XIH1=1.0andthe apparentpowertransformedbythemainis 1.0XIH2=1.1547 foratotalof2.1547 ofapparent powertransformed.
- The additional 0.1547 per unit of apparent power is due to parasitic reactive power owing betweenthetwohalvesoftheprimarywindinginthe maintransformer.
- Single-phasetransformersusedintheScottconnectionarespecialtyitemsthatarevirtuallyimpossible to buy ‘‘off the shelf ’’ nowadays. In an emergency, standard distribution transformerscanbeused.

If desired, a three phase, two phase, or single phase load may be supplied simultaneously using scott-connection. The neutral points can be available for grounding or loading purposes. The Scott T connectionin theory would be suitable for supplying a three, two and single phase load simultaneously, but such loadsarenotfoundtogetherinmodernpractice.

The Scott T would not be recommended as a connection for 3 phase to 3 phase applications for thefollowingreasons:

The loads of modern buildings and office buildings are inherently unbalanced and contain equipment thatcan be sensitive to potential voltage fluctuations that may be caused by the Scott T design. A properly sizedScott T transformer will have to be a minimum of 7.75% larger than the equivalent Delta-Wye transformer.Properly sized, it would be a bulkier and heavier option and should not be considered a less expensivesolution.

OpenDeltaorV-Connection:

As seen previously in connection of three single phase transformers that if one of the transformers is unableto operate then the supply to the load can be continued with the remaining two transformers at the cost ofreduced efficiency.Theconnectionthatobtained iscalled V-Vconnectionoropendeltaconnection.

Consider the Fig. 5.24 in which 3 phase supply is connected to the primaries. At the secondary side threeequalthreephasevoltageswillbeavailableonnoload.

The voltages are shown on phasor diagram. The connection is used when the three phase load is very verysmalltowarranttheinstallationof fullthreephasetransformer.

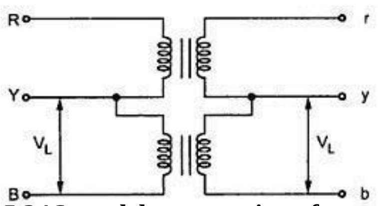
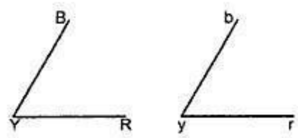


Fig.5.24Opendeltaconnection oftransformeratnoload



If one of the transformers fails in Δ - Δ bank and if it is required to continue the supply even though atreduced capacity until the transformer which is removed from the bank is repaired or a new one is installedthenthistypeof connectionismostsuitable.

When it is anticipated that in future the load increase, then it requires closing of open delta. In such casesopen delta connection is preferred. It can be noted here that the removal of one of the transformers will notgivethetotalloadcarriedbyV -Vbankastwothirdofthecapacityof Δ-Δbank.

TheloadthatcanbecarriedbyV-Vbankisonly57.7% of it.

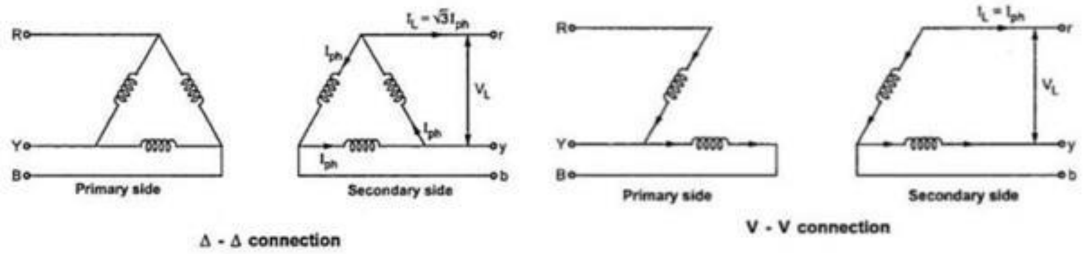


Fig.5.25Delta-deltaandV-Vconnection

ItcanbeseenfromtheFig.4.25ofdeltadeltaconnectionthat

Δ -Δcapacity=√3VL IL =√3 VL(√3 Iph)

Δ -Δ capacity=3 VLIph

It can also be noted from the Fig. 5.25 V-V connection that the secondary line current IL is equal to thephasecurrentIph.

$$\text{V-Vcapacity} = \sqrt{3} V_L I_L = \sqrt{3}\, V_L I_{ph}$$

$$\text{So,}\ \frac{\text{V-Vcapacity}}{\text{Delta-capacity}} = \frac{\sqrt{3} V_L I_{ph}}{3 V_L I_{ph}} = \frac{1}{\sqrt{3}} = 0.577 \simeq 58\%$$

Thus the three phase load that can be carried without exceeding the ratings of the transformers is 57.5percentoftheoriginalload.Henceitisnot66.7% whichwasexpectedotherwise.

Thereductionintheratingcanbecalculatedas{(66.67-57.735)/(57.735)}x100=15.476

Suppose that we consider three transformers connected in Δ - Δ fashion and supplying their rated load. Nowone transformer is removed then each of the remaining two transformers will be overloaded. The overloadoneachtransformerwillbegivenas,

$$\frac{\text{TotalloadinV-V}}{\text{VAratingofeachtransformer}} = \frac{\sqrt{3} V_L I_{ph}}{V_L I_{ph}} = \sqrt{3} = 1.732$$

Thisoverloadcanbecarriedtemporarilyifprovisionismadetoreducetheloadotherwiseoverheatingandbreakdownof theremainingtwotransformerswouldtakeplace.

- ThelimitationwithV-Vconnectionaregivenbelow:
  Theaveragep.f.atwhichV-Vbankisoperatingislessthanthatwiththeload.Thispowerp.fis 86.6%ofthebalancedloadp.f.

- ThetwotransformersinV-Vbankoperateatdifferentpowerfactorexceptforbalancedunityp.f .load.
- The terminals voltages available on the secondary side become unbalanced. This may happen eventhoughloadisperfectlybalanced.
- Thus in summary we can say that if tow transformers are connected in V - V fashion and are loadedto rated capacity and one transformer is added to increase the total capacity by √3 or 173.2 %. Thustheincreaseincapacityis73.2% whenconvertingfromaV-VsystemtoaΔ-Δsystem.
- With a bank of tow single phase transformers connected in V-V fashion supplying a balanced 3phase load with cosΦasp.f., one of the transformer operate at a p.f. of cos (30-Φ) and other at cos(30+Φ).Thepowersof towtransformersaregivenby,

$$P1 = KVA\cos(30-\Phi)$$

$$P_2 = KVA \quad \cos \quad (30+\Phi)$$

OscillatingNeutral:

In addition to the operation of transformers on the sinusoidal supplies, the harmonic behavior becomesimportantasthesizeandratingofthetransformerincreases.Theeffectsoftheharmoniccurrentsare

1. Additionalcopperlosses duetoharmoniccurrents
2. Increasedcorelosses
3. Increasedelectro-

magneticinterferencewithcommunicationcircuits.Ontheotherhandtheharmonicvoltagesof thetransformercause

1. Increaseddielectricstress oninsulation
2. Electrostaticinterferencewithcommunicationcircuits.
3. Resonancebetweenwindingreactanceandfeedercapacitance.

In the present times a greater awareness is generated by the problems of harmonic voltages and currentsproduced by non-linear loads like the power electronic converters. These combine with non-linear nature oftransformer core and produce severe distortions in voltages and currents and increase the power loss. Thusthestudyofharmonicsisofgreatpracticalsignificanceintheoperationoftransformers.

Inthecaseofsinglephasetransformersconnectedtoformthreephasebank,eachtransformerismagnetically decoupled from the other. The flow of harmonic currents are decided by the typeof theelectrical connection used on the primary and secondary sides. Also, there are three fundamental voltages inthepresentcaseeachdisplacedfromtheotherby120electricaldegrees.Becauseofthesymmetryofthe a.c. wave about the time axis only odd harmonics need to be considered. The harmonics which are triplen(multiples of three) behave in a similar manner as they are co-phasal or in phase in the three phases. Thenon-triplen harmonics behave in a similar manner to the fundamental and have ±120° phase displacementbetweenthem.

When the connection of the transformer is Yy without neutral wires both primary and secondary connectedinstarnoclosedpathexists.Asthetriplenharmonicsarealwaysinphase,byvirtueoftheYconnection

they get canceled in the line voltages. Non-triplen harmonics like fundamental, become 0 times phase valueand appear in the line voltages. Line currents remain sinusoidal except for non-triplen harmonic currents.Fluxwaveineachtransformerwillbeflattoppedandthephasevoltagesremainpeaked.Thepotentialofthe neutral is no longer steady. The star point oscillates due to the third harmonic voltages. This is termed as"oscillatingneutral".

Tertiarywinding:

ApartfromthePrimary&Secondarywindings,theresometimesplacedathirdwindinginpowertransformers called "Tertiary Winding". Its purpose is to provide a circulating path for the harmonics(especiallythirdharmonics)producedinthetransformersalongwithpowerfrequency(50Hz.thirdharmonic means 150 Hz oscillations). In delta-delta, delta-star and star-delta transformers all voltages arebalanced and there is no floating of neutral or oscillating neutral. The floating of neutral is developed in thecase star-star connection only. The transformers are sometimes constructed with three windings. The mainwindings are connected to form star-star connection and the third winding known as tertiary winding is usedto make a closed delta connection to stabilize the neutrals of both primary and secondary circuits. Thetertiarywindingcarriesthethird-harmonic currents.

ThreeWindingTransformers:

Thus far we have looked at transformers which have one single primary winding and one single secondarywinding.Butthebeautyoftransformersisthattheyallowustohavemorethanjustonewindingineitherthe primary or secondary side. Transformers which have three winding are known commonly as ThreeWindingTransformers.

Theprincipalofoperationofathreewindingtransformerisnodifferentfromthatofanordinarytransformer.Primaryandsecondaryvoltages,currentsandturnsratiosareallcalculatedthesame,thedifference this time is that we need to pay special attention to the voltage polarities of each coil winding, thedot convention marking the positive (or negative) polarity of the winding, when we connect them together.Threewindingtransformers,alsoknownasathree-coil,orthree-windingtransformer,containoneprimaryandtwosecondarycoilsonacommonlaminatedcore.Theycanbeeitherasingle-phasetransformerorathree-phasetransformer,(three-winding,three-phasetransformer)the operationisthesame.

Three Winding Transformers can also be used to provide either a step-up, a step-down, or a combinationof both between the various windings. In fact a three winding transformers have two secondary windings onthesamecorewitheachoneprovidingadifferentvoltage orcurrentleveloutput.

As transformers operate on the principal of mutual induction, each individual winding of a three windingtransformersupportsthesamenumberofvoltsperturn,thereforethevolt-ampereproductineachwindingis the same, that is NP/NS = VP/VS with any turns ratio between the individual coil windings being relativetotheprimarysupply.

In electronic circuits, one transformer is often used to supply a variety of lower voltage levels for differentcomponents in the electronic circuitry. A typical application of three winding transformers is in powersuppliesandTriacSwitchingConverters.Soatransformerhavetwosecondarywindings,eachofwhichis

electrically isolated from the others, just as it is electrically isolated from the primary. Then each of thesecondarycoilswillproduceavoltagethatisproportionaltoitsnumberof coilturns.

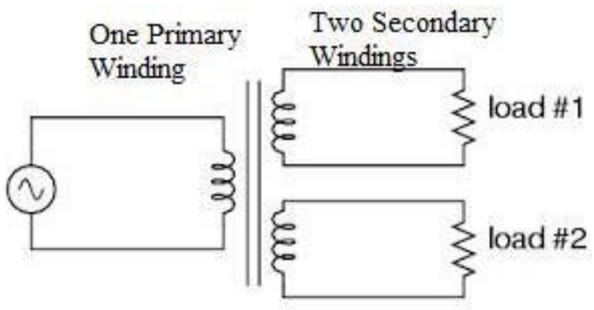


Fig.5.27Athreewindingtransformer

The secondary windings can be connected together in various configurations producing a higher voltage orcurrent supply. It must be noted that connecting together transformer windings is only possible if the twowindings areelectrically identical.Thatistheircurrentandvoltageratingsarethesame.

Paralleloperationofthree phasetransformer:

Advantagesofusingtransformersinparallel:

1. **To maximize electrical power system efficiency:** Generally electrical power transformer gives themaximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on onlythose transformers which will give the total demand by running nearerto its full load rating for thattime. When load increases, we can switch none by one other transformer connected in parallel to fulfillthetotaldemand.Inthiswaywecanrunthesystemwithmaximumefficiency.
2. **To maximize electrical power system availability:** If numbers of transformers run in parallel, we canshut down any one of them for maintenance purpose. Other parallel transformers in system will servetheloadwithouttotalinterruptionof power.
3. **To maximize power system reliability:** If any one of the transformers run in parallel, is tripped due tofault of other parallel transformers is the system will share the load, hence power supply may not beinterruptedifthesharedloadsdonotmakeothertransformersoverloaded.
4. **To maximize electrical power system flexibility:** There is always a chance of increasing or decreasingfuture demand of power system. If it is predicted that power demand will be increased in future, theremust be a provision of connecting transformers in system in parallel to fulfill the extra demand because,itisnoteconomicalfrom businesspointofviewtoinstallabiggerratedsingle transformerbyforecasting the increased future demand as it is unnecessary investment of money. Again if futuredemand isdecreased,transformersrunning in parallel can be removed from system to balance thecapitalinvestmentanditsreturn.

Conditionsforparalleloperation:

Certain conditions have to be met before two or more transformers are connected in parallel and share acommonloadsatisfactorily.Theyare,

1. Thevoltageratio mustbethesame.
2. Theperunitimpedanceofeachmachineonitsownbasemustbethesame.
3. Thepolarity mustbethesame,sothatthereis nocirculatingcurrentbetweenthetransformers.
4. The phase sequence must be the same and no phase difference must exist between the voltages ofthetwotransformers.
5. **Same voltage ratio:**Generally the turns ratio and voltage ratio are taken to be the same.Iftheratio is large there can be considerable error in the voltages even if the turns ratios are the same.When the primariesare connected to same busbars,ifthe secondariesdo notshow the samevoltage, paralleling them would result in a circulating current between the secondaries. Reflectedcirculating current will be there on the primary side also. Thus even without connecting a loadconsiderable current can be drawn by the transformers and they produce copper losses. In twoidentical transformers with percentage impedance of 5 percent, a no-load voltage difference of onepercent will result in a circulating current of 10 percent of full load current. This circulating currentgetsaddedtotheloadcurrentwhentheloadisconnectedresultinginunequalsharingoftheload.In such casesthe combined full load ofthe two transformerscan neverbemetwithoutonetransformergettingoverloaded.
6. **Per unit impedance:** Transformers of different ratings may be required to operate in parallel. Ifthey have to share the total load in proportion to their ratings the larger machine has to draw morecurrent.The voltage drop acrosseach machine hasto be the same by virtue of theirconnection atthe input and the output ends. Thus the larger machines have smaller impedance and smallermachines must have larger ohmic impedance. Thus the impedances must be in the inverse ratios ofthe ratings. As the voltage drops must be the same the per unit impedance of each transformer on itsown base, must be equal. In addition if active and reactive power are required to be shared inproportiontotheratingstheimpedanceanglesalsomustbethesame.Thuswehavetherequirementthatper unitresistance and perunitreactance of both the transformersmustbe thesameforproperloadsharing.
7. **Polarity of connection:** The polarity of connection in the case of single phase transformers can beeither same or opposite. Inside the loop formed by the two secondaries the resulting voltage must bezero. If wrong polarity is chosen the two voltages get added and short circuit results. In the case ofpolyphase banks it is possible to have permanent phase error between the phases with substantialcirculating current. Such transformer banks must not be connected in parallel. The turns ratios insuchgroupscanbeadjustedtogiveveryclosevoltageratiosbutphaseerrorscannotbecompensated. Phase error of 0.6 degree gives rise to one percent difference in voltage. Hence polyphasetransformersbelongingtothesamevectorgroupalonemustbetakenforparalleling.Transformer s having —30° angle can be paralleled to that having +30° angle by reversing the phasesequence of both primary and secondary terminals of one of the transformers. This way one canovercometheproblemof thephaseangle error.

8. **Phase sequence-** The phase sequence of operation becomes relevant only in the case of poly phasesystems. The poly phase banks belonging to same vector group can be connected in parallel. Atransformer with +30° phase angle however can be paralleled with the one with — 30° phase angle,the phase sequence is reversed forone of them both at primary and secondary terminals.If thephase sequences are not the same then the two transformers cannot be connected in parallel even ifthey belong to same vector group. The phase sequence can be found out by the use of a phasesequenceindicator.