CHAPTER DC

CIRCUITS

DEFINATIONS

Linearelements:

In an electric circuit, a linear element is an electrical element with a linear relationship betweencurrent and voltage. Resistors are the most common example of a linear element; other examplesinclude capacitors,inductors,andtransformers.

NonlinearElements:

A nonlinear element is one which does not have a linear input/output relation. In a diode, forexample, the current is a non-linear function of the voltage. Most semiconductor devices have non-linearcharacteristics.

ActiveElements:

Theelementswhich generates or produces electrical energy arecalledactiveelements.Someoftheexamplesarebatteries,generators,transistors,operationalamplifiers, vacuumtubesetc.

PassiveElements:

Allelementswhichconsumeratherthanproduceenergyarecalledpassiveelements,likeresistors,inductorsandcapacitors.

In unilateral element, voltage – currentrelation is notsame for both the direction.

Example:Diode,Transistors.

Inbilateralelement,voltage–currentrelationissameforboththedirection.Example:Resistor

Thevoltagegeneratedbythesourcedoesnotvarywithany circuitquantity.Itisonlyafunctionoftime.SuchasourceiscalledanidealvoltageSource.

Thecurrentgeneratedbythesourcedoesnotvary withanycircuitquantity.Itisonlyafunctionoftime.Suchasourceis calledas anidealcurrentsource.

Resistance: Itisthepropertyofasubstancewhichopposestheflowofcurrentthroughit.Theresistanceofelementisdenotedbythesymbol “R”.ItismeasuredinOhms.

R=PL /AΩ

INTRODUCTIONTOELECTRICALCIRCUITS

Network theory is the study of solving the problems of electric circuits or electric networks. In thisintroductory chapter, let us first discuss the basic terminology of electric circuits and the types ofnetworkelements.

BasicTerminology

InNetworkTheory,wewillfrequentlycomeacrossthefollowingterms−ElectricCircuit

- Electric
- NetworkCurrent
- Voltage
- Power

So, it is imperative that we gather some basic knowledge on these terms before proceeding further.Let'sstartwithElectricCircuit.

ElectricCircuit

An electric circuit contains a closed path for providing a flow of electrons from a voltage source orcurrent source. The elements present in an electric circuit will be in series connection, parallelconnection,orinanycombinationofseries andparallelconnections.

ElectricNetwork

An electric network need not contain a closed path for providing a flow of electrons from a voltagesource or current source. Hence, we can conclude that "all electric circuits are electric networks" butthe converseneednotbetrue.

Current

Thecurrent"I"flowingthroughaconductorisnothingbutthetimerateofflowofcharge.Mathematically,itcanbewri

ttenas

I=d(Q)/dt

Where,

- QisthechargeanditsunitisColoumb.
- tisthetimeanditsunitissecond.

As an analogy, electric current can be thought of as the flow of water through a pipe. Current ismeasured in terms of Ampere. In general, Electron current flows from negative terminal of source topositive terminal, whereas, Conventional current flows from positive terminal of source to negativeterminal.

Electron current is obtained due to the movement of free electrons, whereas, Conventional current isobtained duetothemovementoffreepositivecharges.Bothofthesearecalledaselectriccurrent.

Voltage

Voltage"V"isnothingbutan electromotiveforce thatcausesthecharge(electrons)toflow.Mathematically,itcanbewrittenas

V =

d(W)/dQWh

ere,

- Wisthepotentialenergyand its unitis Joule.

- QisthechargeanditsunitisColoumb.

Asananalogy,Voltagecanbethoughtofasthepressureofwaterthatcausesthewatertoflowthroughapipe.Itismeasuredintermsof Volt.

Power

Thepower"P"isnothingbutthetimerateofflowofelectricalenergy.Mathematically,itcanbewrittenas

$P=d(W)/dt$

Where,

Wistheelectricalenergyanditismeasuredintermsof Joule.

Itisthetimeanditismeasuredinseconds.Wecanre-

writetheaboveequationas $P=d(W)/dt=d(W)/dQ*d(Q)/dt=VI$

Therefore,powerisnothingbut theproduct ofvoltageVandcurrentI.ItsunitisWatt.

TypesofNetworkElements

WecanclassifytheNetworkelementsintovarioustypesbasedonsomeparameters.Followingarethetypesof

Networkelements–

- ActiveElementsandPassiveElements
- Linear ElementsandNon-linearElements
- BilateralElementsandUnilateralElements
- LumpedElementsandDistributedElements

ActiveElementsandPassiveElements

WecanclassifytheNetworkelementsintoeitheractiveorpassivebasedontheabilityofdeliveringpower.

Active Elements deliverpower to otherelements, which are presentin an electric circuit.Sometimes, they may absorb the power like passive elements. That means active elements have thecapabilityofbothdeliveringandabsorbingpower.Examples:Voltagesourcesandcurrentsources.

Passive Elements can’t deliver power (energy) to other elements, however they can absorbpower. That means these elements either dissipate power in the form of heat or store energy in theformofeithermagneticfieldor electricfield.Examples:Resistors,Inductors,andcapacitors.

LinearElementsandNon-LinearElements

Wecanclassifythenetworkelementsaslinearornon-linearbasedontheircharacteristictoobeythepropertyoflinearity.

LinearElementsaretheelementsthatshowalinearrelationshipbetweenvoltageandcurrent.Examples:Resistors,Inductors,andcapacitors.

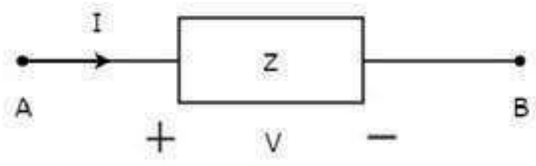
Non-LinearElementsare those thatdonotshowalinearrelationbetweenvoltage andcurrent.Examples:Voltagesources andcurrentsources.

BilateralElements andUnilateralElements

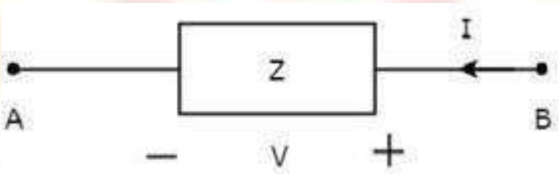
Network elements can also be classified as either bilateral or unilateral based on the directionofcurrentflows throughthenetworkelements.

Bilateral Elements are the elements that allow the current in both directions and offer thesameimpedanceineitherdirectionofcurrentflow.Examples:Resistors,Inductorsandcapacitors.

Theconceptofbilateralelementsisillustratedinthefollowingfigures.



In the above figure, the current (I) is flowing from terminals A to B through a passiveelementhavingimpedance of *Z*Ω. Itis the ratio of voltage (V)across thatelementbetweenterminalsA&B andcurrent(I).



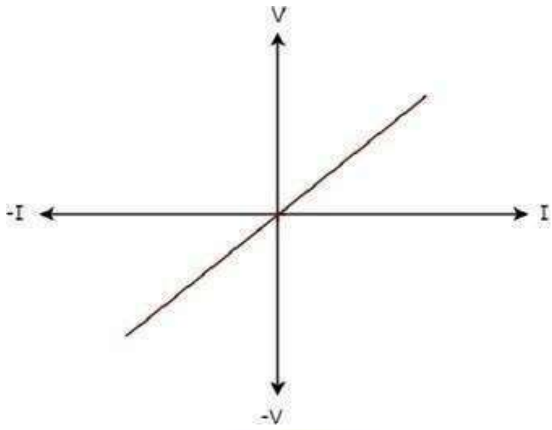
In the above figure, the current (I)is flowing from terminals B to A through a passive elementhaving impedance of *Z* Ω. That means the current (–I) is flowing from terminals A to B. In this casetoo, we will get the same impedance value, since both the current and voltage having negative signs withrespecttoterminalsA&B.

Unilateral Elements are those that allow the current in only one direction. Hence, they offer differentimpedancesinbothdirections.

Wediscussedthetypesofnetworkelementsinthepreviouschapter.Now,letusidentifythenatureofnetworkel ementsfromtheV-Icharacteristicsgiveninthefollowingexamples.

Example1

TheV-Icharacteristicsofanetwork elementisshownbelow.



Step1−Verifyingthenetworkelementaslinearornon-linear.

Fromtheabovefigure,theV-Icharacteristicsofanetworkelementisastraightlinepassingthroughtheorigin.Hence,itislinearelement.

Step2−Verifyingthenetworkelementasactiveorpassive.

ThegivenV-Icharacteristicsofanetworkelementliesinthefirstandthirdquadrants.

Inthefirstquadrant,thevaluesofbothvoltage(V)andcurrent(I) arepositive.So,theratiosofvoltage (V)andcurrent(I)givespositiveimpedancevalues.

Similarly,inthethirdquadrant,thevaluesofbothvoltage(V)andcurrent(I)havenegativevalues.So,theratios ofvoltage(V)andcurrent(I)producepositiveimpedancevalues.

Since,thegivenV-Icharacteristicsofferpositiveimpedancevalues,thenetworkelementisaPassiveelement.

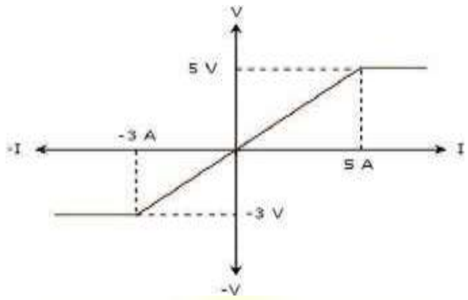
Step3−Verifyingthenetworkelementasbilateralorunilateral.

Foreverypoint(I,V)onthecharacteristics,thereexistsacorrespondingpoint(-I,-V)onthegivencharacteristics.Hence,thenetworkelementis aBilateralelement.

Therefore,thegivenV-IcharacteristicsshowthatthenetworkelementisaLinear,Passive,andBilateralelement.

Example2

TheV-Icharacteristicsofanetwork elementisshownbelow.



Step1−Verifyingthenetworkelementaslinearornon-linear.

Fromtheabovefigure,theV-Icharacteristicsofanetwork elementisastraightlineonlybetweenthepoints (-3A, -3V) and (5A, 5V). Beyond these points, the V-I characteristics are not following thelinearrelation.Hence,itisaNon-linearelement.

Step2−Verifyingthenetworkelementasactiveorpassive.

The given V-I characteristics of a network element lies in the first and third quadrants. In these twoquadrants, the ratios of voltage (V) and current (I) produce positive impedance values. Hence, thenetworkelementis aPassiveelement.

Step3−Verifyingthenetworkelementasbilateralorunilateral.

Consider the point (5A, 5V) on the characteristics. The corresponding point (-5A, -3V) exists on thegiven characteristicsinsteadof(-5A,-5V).Hence,thenetworkelementisaUnilateralelement.

Therefore, the given V-I characteristics show that the network element is a Non-linear, Passive, andUnilateralelement.Thecircuitscontainingthemarecalledunilateralcircuits.

LumpedandDistributedElements

Lumped elements are those elements which are very small in size & in which simultaneous actionstakes place.Typicallumpedelements are capacitors,resistors,inductors.

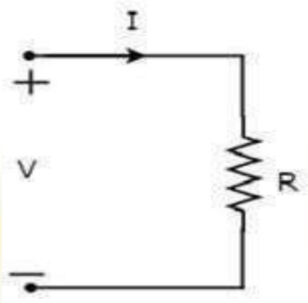
Distributedelementsarethosewhicharenotelectricallyseparableforanalyticalpurposes.

For example, a transmission line has distributed parameters along its length and may extend forhundredsofmiles.

R-L-C ParametersResistor

ThemainfunctionalityofResistoriseitheropposesorrestrictstheflowofelectriccurrent.

Hence, the resistors are used in order to limit the amount of current flow and / or dividing (sharing)voltage. Let the current flowing through the resistor is I amperes and the voltage across it is V volts.Thesymbolofresistoralongwithcurrent,Iandvoltage,Vareshowninthefollowingfigure.



According to Ohm's law, the voltage across resistor is the product of current flowing through it andtheresistanceofthatresistor.Mathematically,itcanberepresentedas

$$V = IR \qquad \text{Equation 1}$$

$$\Rightarrow I = \frac{V}{R} \qquad \text{Equation 2}$$

Where,**R**istheresistanceofaresistor.

FromEquation2,wecanconcludethatthecurrentflowingthroughtheresistorisdirectlyproportional to the applied voltage across resistor and inversely proportional to the resistance ofresistor.

Powerinanelectriccircuitelementcanberepresentedas

$$P = VI \qquad \text{Equation 3}$$

Substitute,Equation1inEquation3.

$$P = (IR)I$$

$$\Rightarrow P = I^2R \qquad \text{Equation 4}$$

Substitute,Equation2inEquation3.

$$P = V(\frac{V}{R})$$

$$\Rightarrow P = \frac{V^2}{R} \qquad \text{Equation 5}$$

So,wecancalculatetheamountofpowerdissipatedintheresistorbyusingoneoftheformulaementionedinEquations 3to5.

Inductor

In general, inductors will have number of turns. Hence, they produce magnetic flux when currentflows through it. So, the amount of total magnetic flux produced by an inductor depends on thecurrent,Iflowingthroughitandtheyhavelinearrelationship.

Mathematically,itcanbewrittenas

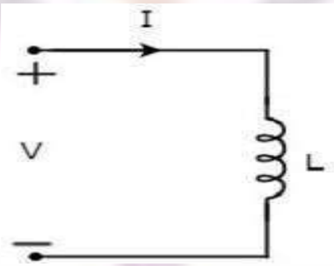
$$\Psi \alpha I$$

$$\Rightarrow \Psi = LI$$

Where,

- ***Ψ***isthetotalmagneticflux
- ***L***istheinductanceofaninductor

LetthecurrentflowingthroughtheinductorisIamperesandthevoltageacrossitisVvolts.TheSymbolofinductoralongwithcurrentIandvoltageV areshowninthefollowingfigure.



AccordingtoFaraday's law,thevoltageacrosstheinductorcanbewrittenas

$$V = \frac{d\Psi}{dt}$$

Substitute*Ψ*=*LI*intheaboveequation.

$$V = \frac{d(LI)}{dt}$$

$$\Rightarrow V = L\frac{dI}{dt}$$

$$\Rightarrow I = \frac{1}{L}\int V dt$$

Fromtheaboveequations,wecanconcludethatthereexistsalinearrelationshipbetweenvoltageacrossinductorandcurrentflowingthroughit.

Weknowthatpowerinanelectric circuitelementcanberepresentedas

$$P = VI$$

Substitute $V = L\frac{dI}{dt}$ in the above equation.

$$P = (L\frac{dI}{dt})I$$

$$\Rightarrow P = LI\frac{dI}{dt}$$

Byintegratingtheaboveequation,wewillgettheenergystoredinaninductoras

$$W = \frac{1}{2}LI^2$$

So,theinductorstorestheenergyintheformofmagneticfield.

Capacitor

In general, a capacitor has two conducting plates, separated by a dielectric medium. Ifpositive voltage is applied across the capacitor, then it stores positive charge. Similarly, if negativevoltageisappliedacrossthecapacitor,thenitstores negativecharge.

So,theamountofchargestoredin thecapacitordependson theappliedvoltage**V**acrossitandthey

$$Q \, \alpha \, V$$

$$\Rightarrow Q = CV$$

have linear relationship. Mathematically,it can be written asWhere,

- ***Q***isthechargestored inthecapacitor.
- ***C***isthecapacitanceofacapacitor.

Letthecurrentflowingthroughthecapacitoris*I*amperesandthevoltageacrossitis*V*volts.Thesymbolofcapacitoralongwithcurrent*I*andvoltage*V*areshowninthefollowingfigure.

Weknowthatthe**current**isnothingbutthe**timerateofflowofcharge**.Mathematically,itcanberepresentedas

I

$$I = \frac{dQ}{dt}$$

Substitute $Q = CV$ in the above equation.

$$I = \frac{d(CV)}{dt}$$

$$\Rightarrow I = C\frac{dV}{dt}$$

$$\Rightarrow V = \frac{1}{C}\int Idt$$

Fromtheaboveequations,wecanconcludethatthereexistsalinearrelationshipbetweenvoltageacrosscapacitorandcurrentflowingthroughit.

Weknowthatpowerinanelectric circuitelementcanberepresentedas

$$P = VI$$

Substitute $I = C\frac{dV}{dt}$ in the above equation.

$$P = V(C\frac{dV}{dt})$$

$$\Rightarrow P = CV\frac{dV}{dt}$$

Byintegratingtheaboveequation,wewillgetthe**energy**storedinthecapacitoras

$$W = \frac{1}{2}CV^2$$

So,thecapacitor storestheenergyintheformofelectricfield.

TypesofSources

Active Elements are the network elements that deliver power to other elements present in an electriccircuit.So,activeelementsarealsocalled assourcesofvoltageorcurrenttype.Wecanclassifythesesourcesintothefollowingtwocategories−

- IndependentSources

- DependentSources

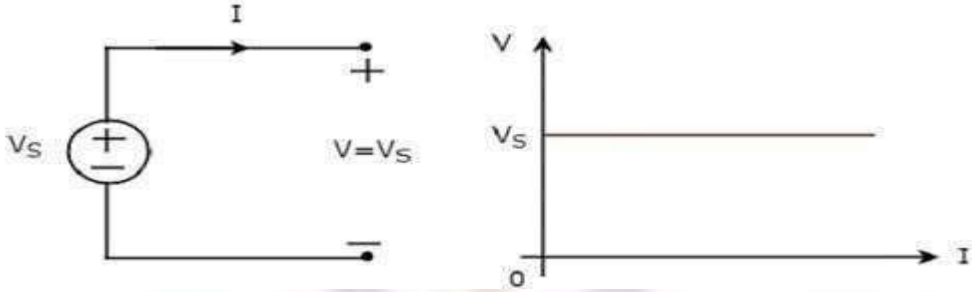
IndependentSources

As the name suggests, independent sources produce fixed values of voltage or current and theseare not dependent on any other parameter. Independentsources can be further dividedinto thefollowingtwocategories−

- IndependentVoltageSources
- IndependentCurrentSources

IndependentVoltageSources

An independent voltage source produces a constant voltage across its two terminals. This voltage isindependentofthe amount ofcurrent thatisflowingthroughthetwoterminalsofvoltagesource.

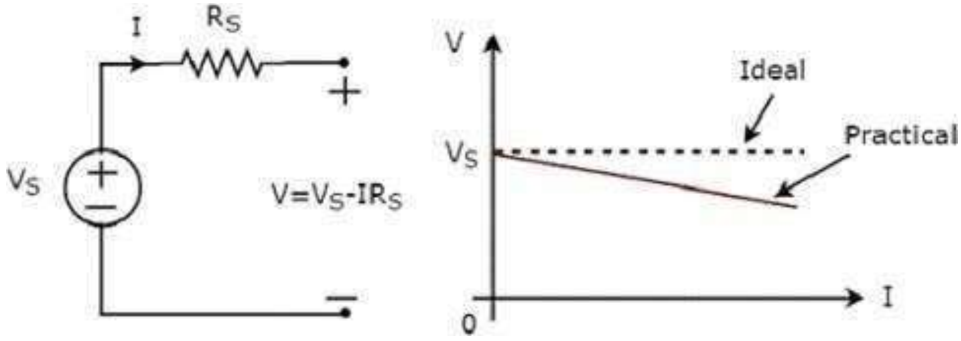


IndependentidealvoltagesourceanditsV-Icharacteristicsareshowninthefollowingfigure.

The V-I characteristics of an independent ideal voltage source is a constant line, which is alwaysequal to the source voltage (VS) irrespective of the current value (I). So, the internal resistance of anindependentidealvoltagesourceis zeroOhms.

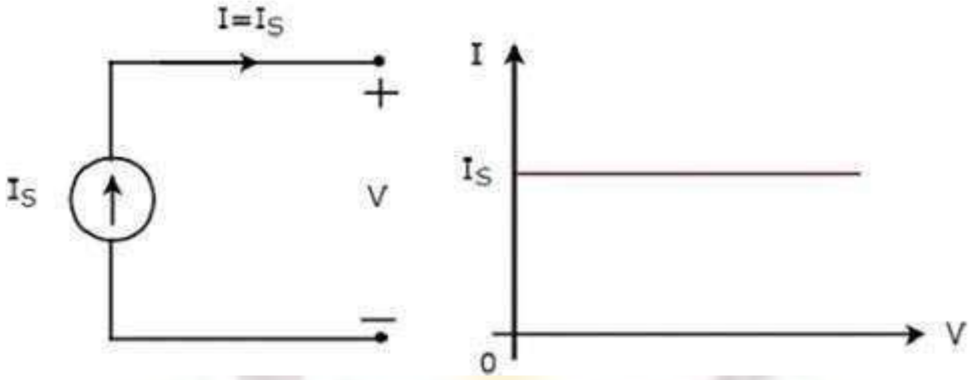
Hence, the independent ideal voltage sources do not exist practically, because there will be someinternalresistance.

Independentpractical voltage source and its V-I characteristics are shown in the following figure. Thereisadeviationin theV-Icharacteristicsof anindependentpracticalvoltagesourcefromtheV-Icharacteristicsofanindependentidealvoltagesource.Thisisdueto thevoltagedropacrosstheinternal resistance(RS)ofanindependentpracticalvoltagesource.



IndependentCurrentSources

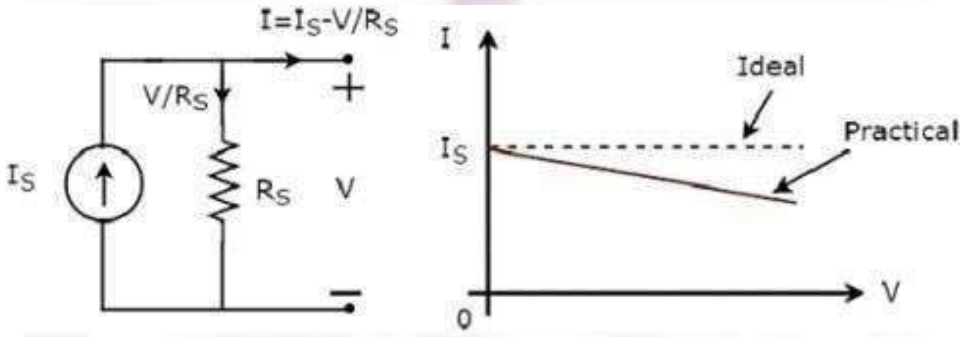
An independent current source produces a constant current. This current is independent of the voltage across its two terminals. Independent ideal current source and its V-I characteristics are shown in thefollowingfigure.



The V-I characteristics of an independent ideal current source is a constant line, which is alwaysequal to the source current (IS) irrespective of the voltage value (V). So, the internal resistance of anindependentidealcurrentsourceisinfiniteohms.

Hence, the independent ideal current sources do not exist practically, because there will be someinternalresistance.

IndependentpracticalcurrentsourceanditsV-Icharacteristicsareshowninthefollowingfigure.



There is a deviation in the V-I characteristics of an independent practical current source from the V-Icharacteristics of an independent ideal current source. This is due to the amount of current flowsthroughtheinternalshuntresistance(RS)ofanindependentpracticalcurrentsource.

DependentSources

As the name suggests, dependent sources produce the amount of voltage or current that is dependentonsomeothervoltageorcurrent.Dependentsourcesarealsocalledascontrolledsources.Dependentsources canbefurtherdividedinto thefollowingtwocategories−

- DependentVoltageSources
- DependentCurrentSources

Dependent VoltageSources

A dependent voltage source produces a voltage across its two terminals. The amount of this voltageis dependent on some other voltage or current. Hence, dependent voltage sources can be furtherclassifiedintothe followingtwocategories−

- VoltageDependentVoltageSource(VDVS)
- CurrentDependentVoltageSource(CDVS)

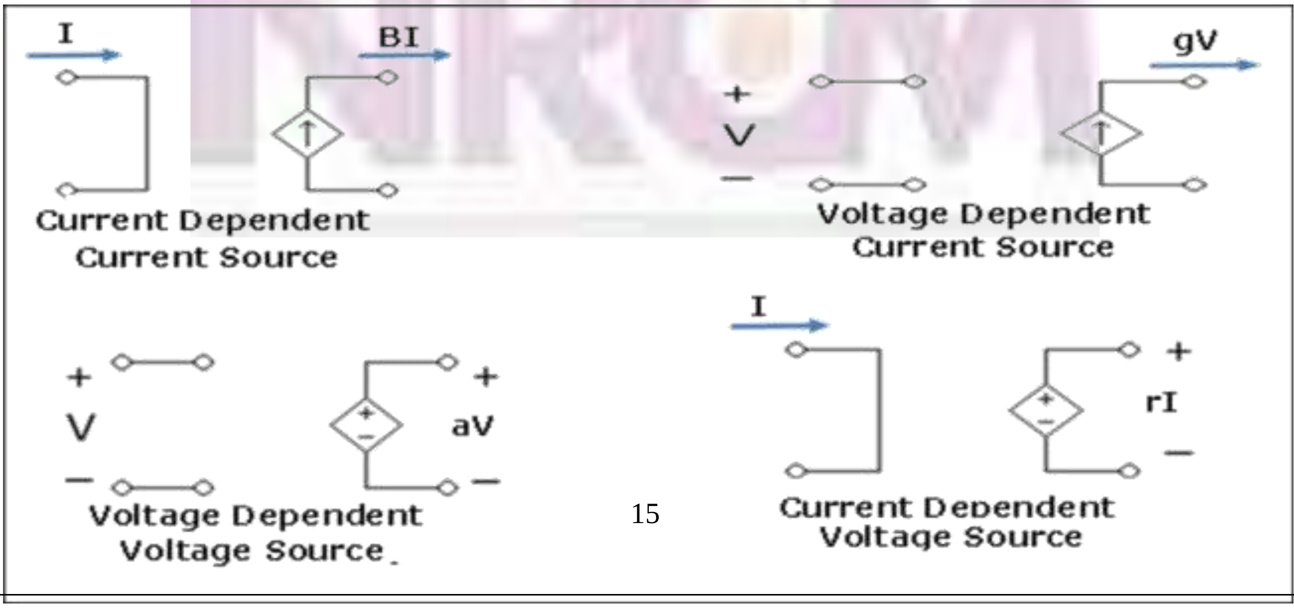
Dependent voltage sources are represented with the signs '+' and '-' inside a diamond shape. Themagnitudeofthevoltagesourcecanberepresentedoutsidethediamondshape.

` **DependentCurrentSources**

A dependent current source produces a current. The amount of this current is dependent on someothervoltageorcurrent.Hence,dependentcurrentsourcescanbefurtherclassifiedintothefollowingtwocategories

- VoltageDependentCurrentSource(VDCS)
- CurrentDependentCurrentSource(CDCS)

Dependent current sources are represented with an arrow inside a diamond shape. The magnitude ofthecurrentsourcecanberepresentedoutsidethediamondshape.Wecanobservethesedependent orcontrolledsources inequivalentmodels oftransistors.



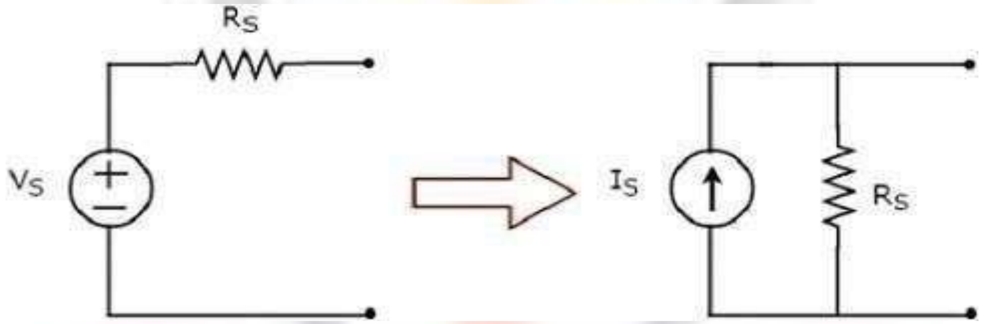
SourceTransformationTechnique

We know that there are two practical sources, namely, voltage source and currentsource. We can transform (convert) one source into the other based on the requirement, while solvingnetwork problems. The technique of transforming one source into the otheris called as sourcetransformationtechnique.Followingarethe twopossiblesource transformations−

- Practicalvoltagesourceintoapracticalcurrentsource
- Practicalcurrentsourceintoapracticalvoltagesource

Practicalvoltagesourceintoapracticalcurrentsource

Thetransformation of practical voltagesourceintoapractical currentsourceis shownin thefollowingfigure



Practical voltage source consists of a voltage source (V_S) in series with a resistor (R_S). This can beconverted into a practical currentsource as shown in the figure. It consists of acurrentsource (I_S)inparallelwitharesistor (R_S).

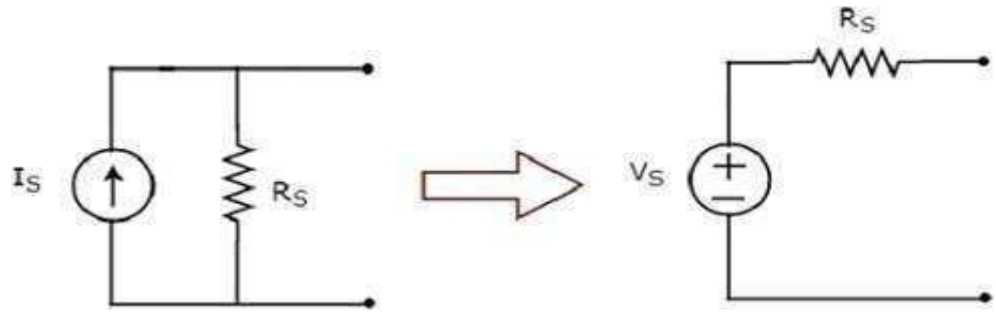
ThevalueofISwillbeequaltotheratioofV$_S$andR$_S$.Mathematically,itcanberepresentedas

$$I_S = \frac{V_S}{R_S}$$

Practicalcurrentsourceintoapracticalvoltagesource

Thetransformation of practical currentsourceintoapractical voltagesourceisshownin thefollowingfigure.

Practical current source consists of a current source (I_S) in parallel with a resistor (R_S). This can beconverted into a practical voltage source as shown in the figure. It consists of a voltage source (V_S) inserieswitharesistor(R_S).



ThevalueofVSwillbeequaltotheproductofISandRS.Mathematically,itcanberepresentedas

$$V_S = I_S R_S$$

Inthischapter,wewilldiscussindetailaboutthepassiveelementssuchasResistor,Inductor,andCapacitor. Letus startwithResistors.

Kirchhoff'sLaws

Networkelementscanbeeitherofactiveorpassivetype.Anyelectricalcircuitornetworkcontainsoneofthese twotypes ofnetworkelementsoracombinationofboth.

Now,letusdiscussaboutthefollowingtwolaws,whicharepopularlyknownasKirchhoff'slaws.

- Kirchhoff'sCurrentLaw
- Kirchhoff'sVoltageLaw

Kirchhoff'sCurrentLaw

Kirchhoff's Current Law (KCL) states that the algebraic sum of currents leaving (or entering) a nodeis equaltozero.

A Node is a pointwhere two or more circuitelements are connected toit. If only twocircuitelements are connected to a node, then it is said to be simple node. If three or more circuit elementsare connectedtoanode,thenitissaidtobe PrincipalNode.

Mathematically,KCLcanberepresentedas

$$\sum_{m=1}^{M} I_m = 0$$

Where,

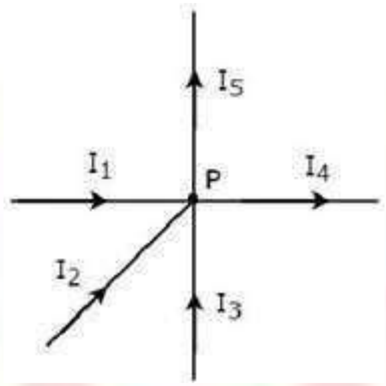
- I_m isthemthbranchcurrentleavingthenode.

- ***M*** isthenumberofbranchesthatareconnectedtoanode.

The above statement of KCL can also be expressed as "the algebraic sum of currents entering a nodeis equal to the algebraic sum of currents leaving a node". Let us verify this statement through thefollowingexample.

Example

WriteKCLequationatnodePofthefollowingfigure.



In theabovefigure,thebranch currentsI_1,I_2andI_3areenteringatnodeP.So,considernegativesignsforthesethreecurrents.

Intheabovefigure,thebranchcurrentsI_4andI_5areleavingfromnodeP.So,considerpositivesignsforthesetwocurrents.

TheKCLequationatnodePwillbe

$$-I_1 - I_2 - I_3 + I_4 + I_5 = 0$$

$$\Rightarrow I_1 + I_2 + I_3 = I_4 + I_5$$

In the above equation, the left-hand side represents the sum of entering currents,whereas theright- handsiderepresents thesumofleavingcurrents.

Inthistutorial,wewillconsiderpositivesignwhenthecurrentleavesanodeandnegativesignwhenitenters a node. Similarly, you can consider negative sign when the current leaves a node and positivesignwhenitentersanode.Inbothcases,theresultwillbesame.

Note−KCLisindependentofthenatureofnetworkelementsthatareconnectedtoanode.

Kirchhoff'sVoltageLaw

Kirchhoff's Voltage Law (KVL) states that the algebraic sum of voltages around a loop ormesh isequaltozero.

A Loop isapath thatterminates atthesamenodewhereitstarted from.In contrast,a Mesh isaloopthatdoesn’tcontainanyotherloops insideit.

Mathematically,KVLcanberepresentedas

$$\sum_{n=1}^{N} V_n = 0$$

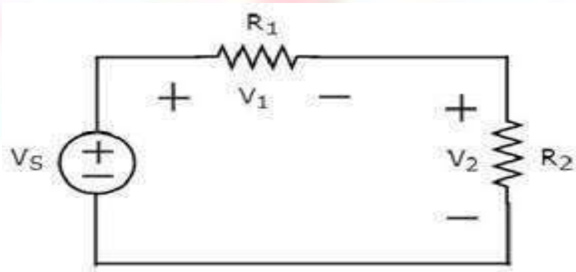
Where,

- **V_n**isthen[th]element’svoltageinaloop(mesh).
- **N**isthenumberofnetwork elementsintheloop(mesh).

The above statement of KVL can also be expressed as "the algebraic sum of voltage sources is equalto the algebraic sum of voltage drops that are present in a loop." Let us verify this statement with thehelpofthefollowingexample.

Example

WriteKVLequationaroundtheloopofthefollowingcircuit.



The above circuit diagram consists of a voltage source, V_S in series with two resistors R_1 and R_2.Thevoltagedropsacrossthe resistors$R_1$and$R_2$are V_1andV_2respectively.

ApplyKVLaroundtheloop.

$$V_S - V_1 - V_2 = 0$$

$$\Rightarrow V_S = V_1 + V_2$$

In the above equation, the left-hand side term represents single voltage source VS. Whereas, theright-hand side represents the sum of voltage drops. In this example, we considered only one voltagesource.That’swhytheleft-handsidecontainsonlyoneterm.Ifweconsidermultiplevoltagesources,thentheleftsidecontainssumofvolt agesources.

In this tutorial, we consider the sign of each element’s voltage as the polarity of the second terminalthat is present while travelling around the loop. Similarly, you can consider the sign of each voltageas the polarity of the first terminal that is present while travelling around the loop. In both cases, the resultwillbesame.

Note−KVLisindependentofthenatureofnetworkelementsthatarepresentinaloop.

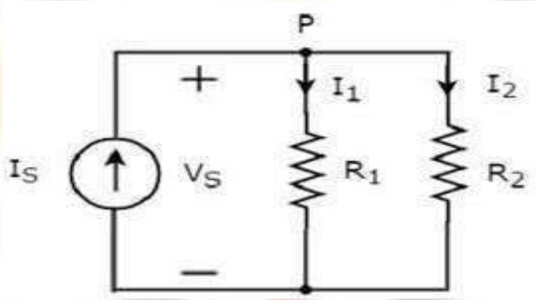
Inthischapter,letusdiscussaboutthefollowingtwodivisionprinciplesofelectricalquantities.

- CurrentDivisionPrinciple
- VoltageDivisionPrinciple

CurrentDivisionPrinciple

Whentwoormorepassiveelementsareconnectedinparallel,theamountofcurrentthatflowsthrougheachelementgetsdivided(shared)amongthemselvesfromthecurrentthatisenteringthenode.

Considerthefollowingcircuitdiagram.



Theabovecircuitdiagramconsistsofaninputcurrentsource**I_S**inparallelwithtworesistors**R_1**and**R_2**. The voltageacrosseachelementis **V_S**.Thecurrentsflowingthroughthe resistors **R_1**and**R_2**are**I_1**and**I_2**respectively.

TheKCLequationatnodePwillbe

$$I_S = I_1 + I_2$$

- Substitute $I_1 = \frac{V_S}{R_1}$ and $I_2 = \frac{V_S}{R_2}$ in the above equation.

$$I_S = \frac{V_S}{R_1} + \frac{V_S}{R_2} = V_S\left(\frac{R_2 + R_1}{R_1 R_2}\right)$$

$$\Rightarrow V_S = I_S\left(\frac{R_1 R_2}{R_1 + R_2}\right)$$

- Substitute the value of V_S in $I_1 = \frac{V_S}{R_1}$.

$$I_1 = \frac{I_S}{R_1}\left(\frac{R_1 R_2}{R_1 + R_2}\right)$$

$$\Rightarrow I_1 = I_S\left(\frac{R_2}{R_1 + R_2}\right)$$

- Substitute the value of V_S in $I_2 = \frac{V_S}{R_2}$.

$$I_2 = \frac{I_S}{R_2}\left(\frac{R_1 R_2}{R_1 + R_2}\right)$$

$$\Rightarrow I_2 = I_S\left(\frac{R_1}{R_1 + R_2}\right)$$

FromequationsofI_1andI_2,wecangeneralizethatthecurrentflowingthroughanypassiveelementcanbefoundbyusingthefollowingformula.

$$I_N = I_S\left(\frac{Z_1||Z_2||\ldots||Z_{N-1}}{Z_1 + Z_2 + \ldots + Z_N}\right)$$

Thisisknownascurrentdivisionprincipleanditisapplicable,whentwoormorepassiveelementsareconnectedinparallelandonlyonecurrententersthenode.

Where,

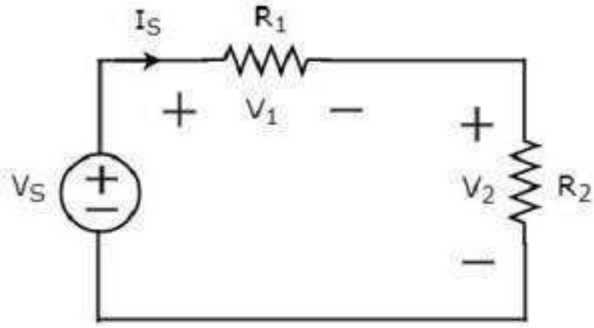
- $I_N$isthecurrentflowingthroughthepassiveelementofNthbranch.
- $I_S$istheinputcurrent,whichentersthenode.

$Z_1,Z_2,\ldots,Z_N$aretheimpedancesof1stbranch,2ndbranch,…,Nthbranchrespectively.

VoltageDivisionPrinciple

When two or more passive elements are connected in series, the amount of voltage present acrosseach element gets divided (shared) among themselves from the voltage that is available across thatentire combination.

Considerthefollowingcircuitdiagram.



The above circuit diagram consists of a voltage source, V_S in series with two resistors R_1 and R_2.The current flowing through these elements is I_S. The voltage drops across the resistors $R_1$and $R_2$are V_1andV_2respectively.

TheKVLequationaroundtheloopwillbe

$$V_S = V_1 + V_2$$

Substitute$V_1=I_SR_1$and$V_2=I_SR_2$intheaboveequation

$$V_S = I_SR_1 + I_SR_2 = I_S(R_1 + R_2)$$

$$I_S = \frac{V_S}{R_1 + R_2}$$

Substitutethevalueof$I_S$in$V_1=I_SR_1$.

$$V_1 = (\frac{V_S}{R_1 + R_2})R_1$$

$$\Rightarrow V_1 = V_S(\frac{R_1}{R_1 + R_2})$$

- Substitute the value of I_S in $V_2 = I_S R_2$.

$$V_2 = (\frac{V_S}{R_1 + R_2})R_2$$

$$\Rightarrow V_2 = V_S(\frac{R_2}{R_1 + R_2})$$

From equations of V_1 and V_2, we can generalize that the voltage across any passive element can befoundbyusingthefollowingformula.

$$V_N = V_S\left(\frac{Z_N}{Z_1 + Z_2 + \ldots + Z_N}\right)$$

Thisisknownasvoltagedivisionprincipleanditisapplicable,whentwoormorepassiveelementsareconnectedinseriesandonlyonevoltageavailableacrosstheentirecombination.

Where,

- $V_N$isthevoltageacrossNthpassiveelement.
- $V_S$istheinputvoltage,whichispresentacrosstheentirecombinationofseriespassiveelements.
- Z_1,Z_2, …,Z_3 are theimpedances of 1stpassiveelement,2nd passiveelement,…,Nth passiveelementrespectively.

NetworkReductionTechniques:

There are two basic methods that are used for solving any electrical network: Nodal analysis andMeshanalysis.Inthischapter,letusdiscussabouttheMeshanalysismethod.

Seriesandparallelconnectionsofresistivenetworks:

If a circuit consists of two or more similar passive elements and are connected in exclusively ofseries type or parallel type, then we can replace them with a single equivalent passive element.Hence,thiscircuitiscalledasanequivalentcircuit.

Inthischapter,letusdiscussaboutthefollowingtwoequivalentcircuits.

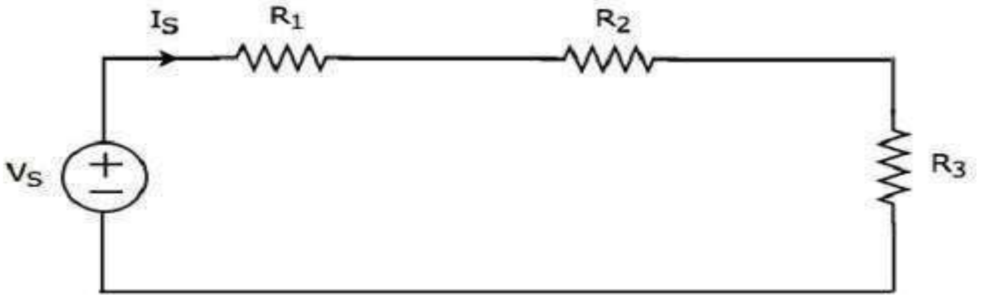
- SeriesEquivalentCircuit
- ParallelEquivalentCircuit

SeriesEquivalentCircuit

Ifsimilarpassiveelementsareconnected in series,thenthesamecurrentwillflowthroughalltheseelements.But,thevoltagegets dividedacrosseachelement.

Considerthefollowingcircuitdiagram.

Ithasasinglevoltagesource(V_S) and threeresistorshavingresistancesofR_1,R_2andR_3.Allthese



elementsareconnectedinseries.ThecurrentISflowsthroughalltheseelements.Theabo

vecircuithasonlyonemesh.TheKVLequationaroundthismeshis

$$V_S = V_1 + V_2 + V_3$$

Substitute $V_1 = I_S R_1$, $V_2 = I_S R_2$ and $V_3 = I_S R_3$ in the above equation.

$$V_S = I_S R_1 + I_S R_2 + I_S R_3$$

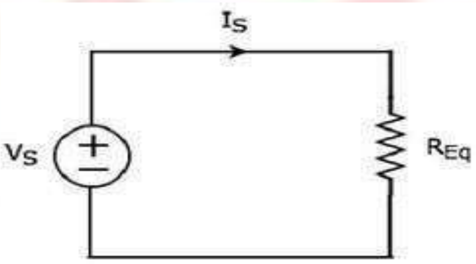
$$\Rightarrow V_S = I_S (R_1 + R_2 + R_3)$$

The above equation is in the form of $V_S = I_S R_{Eq}$ where,

$$R_{Eq} = R_1 + R_2 + R_3$$

Theequivalentcircuitdiagramofthegivencircuitisshowninthefollowingfigure.

Thatmeans,ifmultipleresistorsareconnectedinseries,thenwecanreplacethemwithanequivalentresistor.



The resistance of this equivalent resistor is equal to sum of the resistances of all those multipleresistors. **Note 1** − If 'N' inductors havinginductances of L_1, L_2, ..., L_N are connected in series,thentheequivalentinductancewillbe

$$L_{Eq} = L_1 + L_2 + \ldots + L_N$$

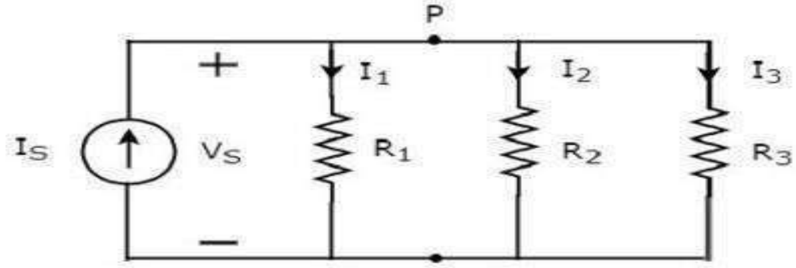
Note 2 − If 'N' capacitors having capacitances of C_1, C_2, ..., $C_N$are connected in series, then theequivalentcapacitancewillbe

$$\frac{1}{C_{Eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_N}$$

ParallelEquivalentCircuit

If similarpassiveelementsareconnectedinparallel,then thesamevoltagewillbe maintainedacrosseachelement.But,thecurrentflowingthrougheachelementgetsdivided.

Considerthefollowingcircuitdiagram.

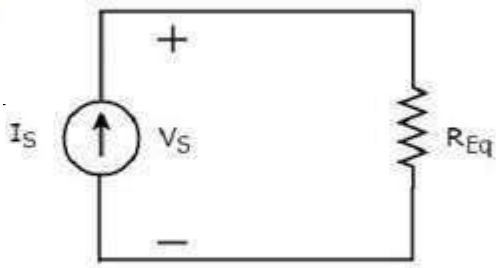


It has a single current source (IS) and three resistors having resistances of R1, R2, and R3. All theseelementsareconnectedinparallel.Thevoltage(VS)isavailableacrossalltheseelements.

The above circuit has only one principal node (P) except the Ground node. The KCL equation at thisprincipalnode (P)is

Theequivalentcircuitdiagramofthegivencircuitisshowninthefollowingfigure.

Substitute $I_1 =$ · above equation.



$$\Rightarrow I_S = V_S(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3})$$

$$\Rightarrow V_S = I_S \left[\frac{1}{(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3})} \right]$$

The above equation is in the form of $V_S = I_S R_{Eq}$ where,

$$R_{Eq} = \frac{1}{(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3})}$$

$$\frac{1}{R_{Eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Thatmeans,ifmultiple resistors are connectedin parallel,then we can replace them with anequivalent resistor. The resistance of this equivalent resistor is equal to the reciprocal of sum ofreciprocalofeach resistanceofallthosemultipleresistors.

Note1−If‘N’inductorshavinginductancesofL1,L2,...,LNareconnectedinparallel,thenthe

$$\frac{1}{L_{Eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_N}$$

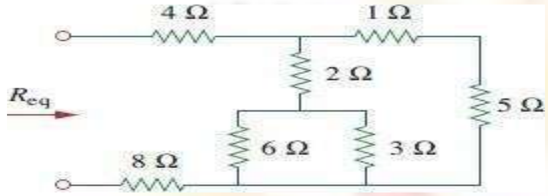
equivalentinductancewillbe

Note2−If'N'capacitorshavingcapacitancesofC1,C2,...,CNareconnectedinparallel,thentheequivalentcapacitancewillbe

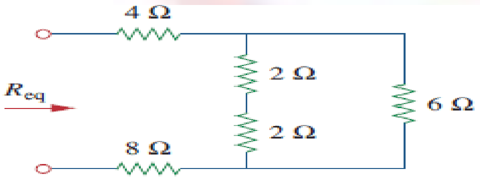
$$C_{Eq} = C_1 + C_2 + \ldots + C_N$$

ExampleProblems:

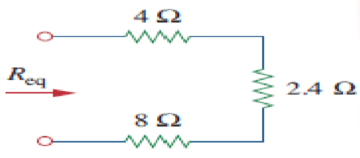
FindtheReqforthecircuitshowninbelowfigure.



Solution:



fig(b)



fig(c)

TogetReqwecombine
resistorsinseries andin parallel.The6ohms and3ohms resistorsareinparallel,sotheirequivalentresistanceis

$$6\ \Omega \parallel 3\Omega = \frac{6 \times 3}{6 + 3} = 2\ \Omega$$

Also,the1ohmand5ohmsresistorsareinseries;hencetheirequivalentresistanceis

$$1\ \Omega + 5\ \Omega = 6\ \Omega$$

Thusthecircuit inFig.(b)isreducedtothatinFig.(c).InFig.(b),wenoticethatthetwo2ohmsresistorsare inseries,sothe equivalentresistanceis

$$2\ \Omega + 2\ \Omega = 4\ \Omega$$

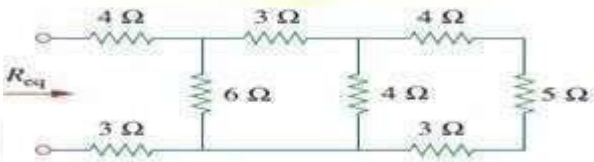
This 4 ohms resistor is now in parallel with the 6 ohms resistor in Fig.(b); their equivalentresistanceis

$$4\ \Omega \parallel 6\ \Omega = \frac{4 \times 6}{4 + 6} = 2.4\ \Omega$$

The circuitin Fig.(b) is now replaced with that in Fig.(c). In Fig.(c), the three resistors arein series.Hence,the equivalentresistanceforthecircuitis

$$R_{eq} = 4\ \Omega + 2.4\ \Omega + 8\ \Omega = 14.4\ \Omega$$

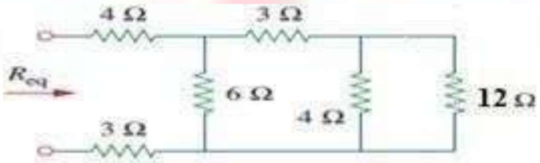
FindtheReqforthecircuitshowninbelowfigure.



fig(a)

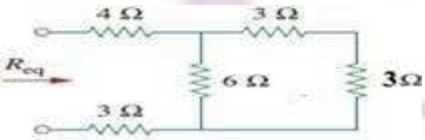
Solution:

Inthegivennetwork4ohms,5ohmsand3ohmscomesinseriesthenequivalentresistanceis4+5+3=12ohms



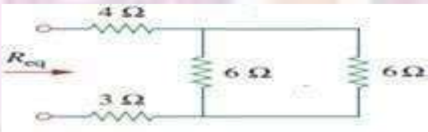
fig(b)

Fromfig(b),4ohmsand12ohmsareinparallel,equivalentis3ohms

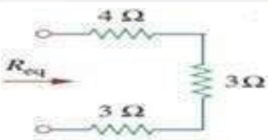


fig(c)

Fromfig(c),3ohmsand3ohmsareinseries,equivalentresistanceis6ohms



fig(d)



fig(e)

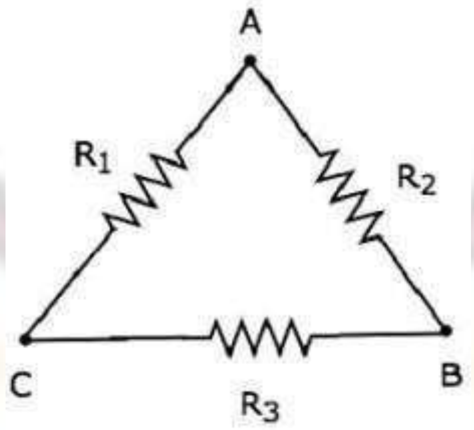
Fromfig(d),6ohmsand6ohmsareinparallel,equivalentresistanceis3ohms

Fromfig(e),4ohms,3ohmsand3ohmsareinseries.HenceReq=4+3+3=10ohms.

Star–to-DeltaandDelta-to-StarTransformationsforResistiveNetworks:DeltatoStarTransformation

DeltaNetwork

Considerthefollowingdeltanetwork asshowninthefollowingfigure.

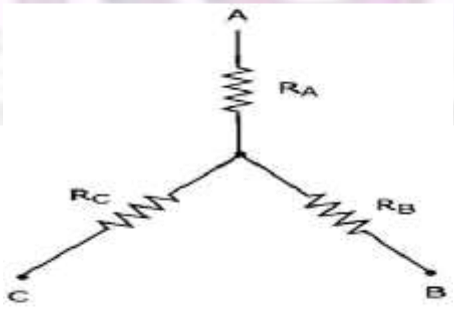


Thefollowingequationsrepresenttheequivalentresistancebetweentwoterminalsofdeltanetwork,whenthe thirdterminalis keptopen.

$$R_{AB} = \frac{(R_1 + R_3)R_2}{R_1 + R_2 + R_3}$$

$$R_{BC} = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3}$$

$$R_{CA} = \frac{(R_2 + R_3)R_1}{R_1 + R_2 + R_3}$$



Thefollowingfigureshowstheequivalentstarnetworkcorrespondingtotheabovedelta

Thefollowingequationsrepresenttheequivalentresistancebetweentwoterminalsofstarnetwork,whenthet hirdterminalis keptopen.

$$R_{AB} = R_A + R_B$$

$$R_{BC} = R_B + R_C$$

$$R_{CA} = R_C + R_A$$

StarNetworkResistancesintermsofDeltaNetworkResistances

Wewillgetthefollowingequationsbyequatingtheright-handsidetermsoftheaboveequationsforwhichtheleft-handsideterms aresame.

$$R_A + R_B = \frac{(R_1+R_3)R_2}{R_1+R_2+R_3} \qquad \text{Equation 1}$$

$$R_B + R_C = \frac{(R_1+R_2)R_3}{R_1+R_2+R_3} \qquad \text{Equation 2}$$

$$R_C + R_A = \frac{(R_2+R_3)R_1}{R_1+R_2+R_3} \qquad \text{Equation 3}$$

By adding the above three equations, we will get

$$2(R_A + R_B + R_C) = \frac{2(R_1R_2 + R_2R_3 + R_3R_1)}{R_1 + R_2 + R_3}$$

$$\Rightarrow R_A + R_B + R_C = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3} \qquad \text{Equation 4}$$

Subtract Equation 2 from Equation 4.

$$R_A + R_B + R_C - (R_B + R_C) = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3} - \frac{(R_1+R_2)R_3}{R_1+R_2+R_3}$$

$$R_A = \frac{R_1R_2}{R_1 + R_2 + R_3}$$

By subtracting Equation 3 from Equation 4, we will get

$$R_B = \frac{R_2R_3}{R_1 + R_2 + R_3}$$

By subtracting Equation 1 from Equation 4, we will get

$$R_C = \frac{R_3R_1}{R_1 + R_2 + R_3}$$

By using the above relations, we can find the resistances of star network from the resistances of deltanetwork.Inthisway,wecanconvertadeltanetworkintoastarnetwork.

StartoDeltaTransformation

In the previous chapter, we discussed about the conversion of delta network into an equivalent starnetwork. Now, let us discuss about the conversion of star network into an equivalent delta network.Thisconversionis calledasStartoDelta Conversion.

Inthepreviouschapter,wegottheresistancesofstarnetworkfromdeltanetworkas

$$R_A = \frac{R_1R_2}{R_1+R_2+R_3} \quad \text{Equation 1}$$

$$R_B = \frac{R_2R_3}{R_1+R_2+R_3} \quad \text{Equation 2}$$

$$R_C = \frac{R_3R_1}{R_1+R_2+R_3} \quad \text{Equation 3}$$

Delta NetworkResistancesintermsofStarNetworkResistances

Letusmanipulatetheaboveequationsinordertogettheresistancesofdeltanetworkintermsofresistancesofstarnetwork.

- Multiplyeachsetoftwoequationsandthenadd.

Byusingtheaboverelations,wecanfindtheresistancesofdeltanetworkfromtheresistancesofstarnetwork. Inthisway,we canconvertstarnetworkintodeltanetwork.

$$R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2^2R_3 + R_2R_3^2R_1 + R_3R_1^2R_2}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2R_3(R_1 + R_2 + R_3)}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2R_3}{R_1+R_2+R_3}$$

Equation 4

- By dividing Equation 4 with Equation 2, we will get

$$\frac{R_AR_B + R_BR_C + R_CR_A}{R_B} = R_1$$

$$\Rightarrow R_1 = R_C + R_A + \frac{R_CR_A}{R_B}$$

- By dividing Equation 4 with Equation 3, we will get

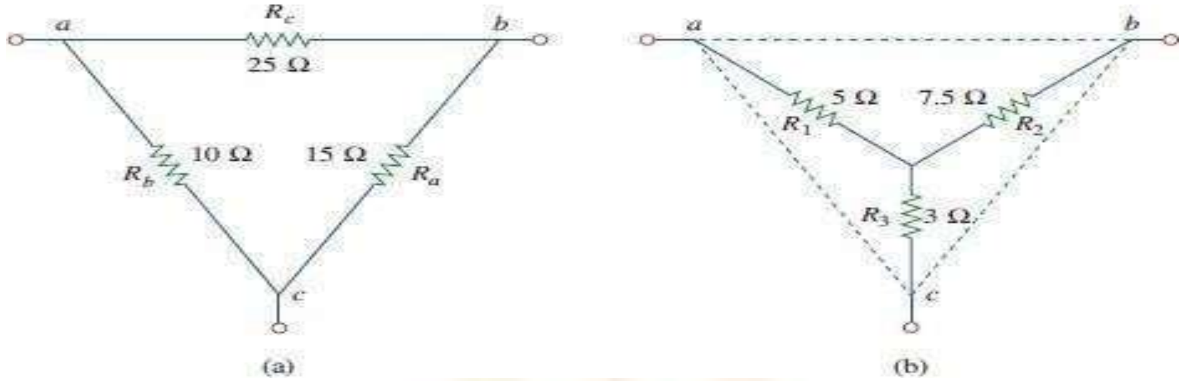
$$R_2 = R_A + R_B + \frac{R_AR_B}{R_C}$$

- By dividing Equation 4 with Equation 1, we will get

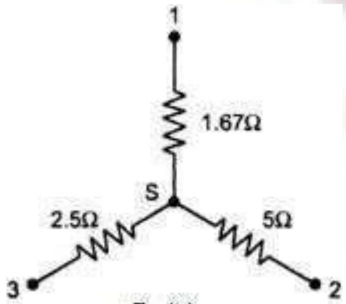
$$R_3 = R_B + R_C + \frac{R_BR_C}{R_A}$$

Exampleproblems:

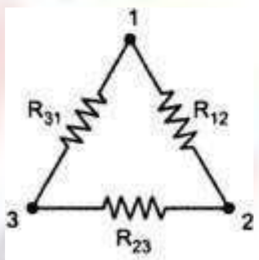
1)ConverttheDeltanetworkinFig.(a)to anequivalentstarnetworkSolution:



1) Convertthestarnetworkinfig(a)todeltanetwork



fig(a)



fig(b)

Solution: Theequivalentdeltaforthegivenstarisshowninfig(b),where

$$R_{12} = 1.67 + 5 + \frac{1.67 \times 5}{2.5} = 1.67 + 5 + 3.33 = \mathbf{10\ \Omega}$$

$$R_{23} = 5 + 2.5 + \frac{5 \times 2.5}{1.67} = 5 + 2.5 + 7.5 = \mathbf{15\ \Omega}$$

$$R_{31} = 2.5 + 1.67 + \frac{2.5 \times 1.67}{5} = 2.5 + 1.67 + 0.833$$

$$= \mathbf{5\ \Omega}$$

MeshAnalysis*:*

Mesh analysis provides general procedure for analyzing circuits using mesh currents as the circuitvariables. Mesh Analysis is applicable only for planar networks. It is preferably useful for the circuitsthathavemanyloops.ThisanalysisisdonebyusingKVLandOhm'slaw.

In Mesh analysis, we will consider the currents flowing through each mesh. Hence, Mesh analysis isalsocalledas Mesh-currentmethod.

A branch is a path that joins two nodes and it contains a circuit element. If a branch belongs to onlyonemesh,thenthebranchcurrentwillbeequaltomeshcurrent.

Ifabranchiscommontotwomeshes,thenthebranch currentwillbeequaltothesum(ordifference)oftwomeshcurrents,whentheyareinsame(oropposite)direction.

ProcedureofMeshAnalysis

Follow thesestepswhilesolvinganyelectricalnetworkorcircuitusingMeshanalysis.

- **Step1**−Identifythemeshesandlabelthemeshcurrentsineitherclockwiseoranti-clockwisedirection.
- **Step2**−Observetheamountofcurrentthatflowsthrougheachelement intermsofmeshcurrents.
- **Step3**−Writemeshequationstoall

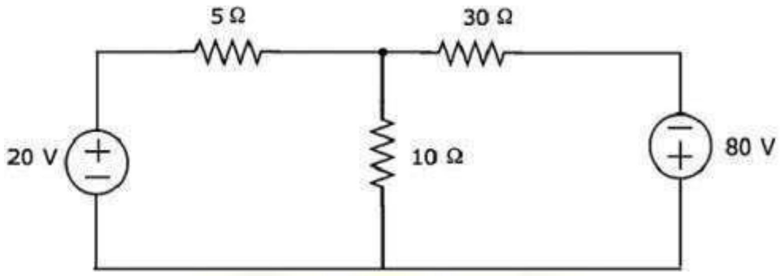
meshes.MeshequationisobtainedbyapplyingKVLfirstandthenOhm’slaw.

- **Step4**−SolvethemeshequationsobtainedinStep3inordertogetthemeshcurrents.

Now,wecanfindthecurrentflowingthroughanyelementandthevoltageacrossanyelementthatispresentinthegivennetworkbyusingmeshcurrents.

Example

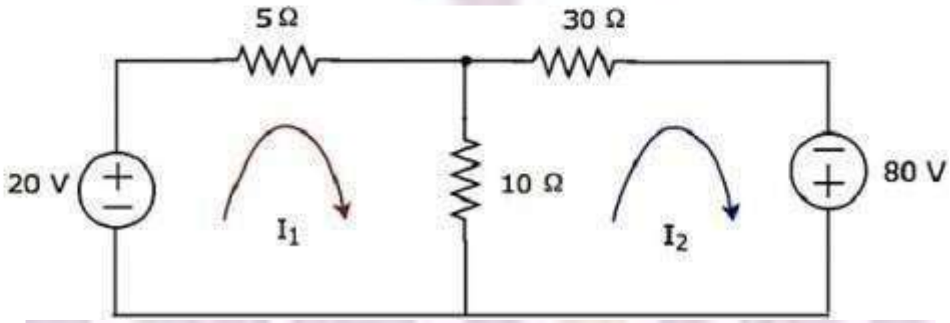
Findthevoltageacross30Ωresistorusing Meshanalysis.



Step1−Therearetwomeshesintheabovecircuit.ThemeshcurrentsI1andI2areconsideredinclockwisedirection.Thesemeshcurrentsareshowninthefollowingfigure.

Step 2−ThemeshcurrentI1flowsthrough20Vvoltagesourceand5Ωresistor.Similarly,themeshcurrent I2 flows through 30 Ω resistor and -80 V voltage source. But, the difference of two meshcurrents,I1andI2,flowsthrough10Ωresistor,sinceitisthecommonbranchoftwomeshes.

Step 3 − In this case, we will get two mesh equations since there are two meshes in the given circuit.When we write the mesh equations, assume the mesh current of that particular mesh as greater thanallothermeshcurrentsofthecircuit.Themeshequationoffirstmeshis



$$20 - 5I_1 - 10(I_1 - I_2) = 0$$

$$\Rightarrow 20 - 15I_1 + 10I_2 = 0$$

$$\Rightarrow 10I_2 = 15I_1 - 20$$

Divide the above equation with 5.

$$2I_2 = 3I_1 - 4$$

Multiply the above equation with 2.

$$4I_2 = 6I_1 - 8 \quad \textbf{Equation 1}$$

The **mesh equation** of second mesh is

$$-10(I_2 - I_1) - 30I_2 + 80 = 0$$

Divide the above equation with 10.

$$-(I_2 - I_1) - 3I_2 + 8 = 0$$

$$\Rightarrow -4I_2 + I_1 + 8 = 0$$

$$4I_2 = I_1 + 8 \quad \textbf{Equation 2}$$

Step 4−Findingmeshcurrents*I1*and*I2*bysolvingEquation1andEquation2.

Theleft-handsidetermsofEquation1andEquation2arethesame.Hence,equatetheright-handsidetermsofEquation1andEquation2inorderfindthevalueof*I1*.

Therefore,thevoltageacross30 Ωresistorofthegivencircuitis84V.

$$6I_1 - 8 = I_1 + 8$$

$$\Rightarrow 5I_1 = 16$$

$$\Rightarrow I_1 = \frac{16}{5} A$$

Substitute I_1 value in Equation 2.

$$4I_2 = \frac{16}{5} + 8$$

$$\Rightarrow 4I_2 = \frac{56}{5}$$

$$\Rightarrow I_2 = \frac{14}{5} A$$

Note 1 − From the above example, we can conclude that we have to solve 'm' mesh equations, if theelectric circuit is having 'm' meshes. That's why we can choose Mesh analysis when the number ofmesheislessthanthenumberofprincipalnodes(exceptthereferencenode) ofanyelectricalcircuit.

Note2 − We can choose either Nodal analysis or Mesh analysis, when the number of meshes isequaltothenumberofprincipal nodes(exceptthereferencenode)inanyelectriccircuit.

So, we got the mesh currents I_1 and I_2 as $\frac{16}{5}$ **A** and $\frac{14}{5}$ **A** respectively.

Step 5 – The current flowing through 30 Ω resistor is nothing but the mesh current I_2 and it is equal to $\frac{14}{5}$ A. Now, we can find the voltage across 30 Ω resistor by using Ohm's law.

$$V_{30\Omega} = I_2 R$$

Substitute the values of I_2 and R in the above equation.

$$V_{30\Omega} = (\frac{14}{5})30$$

$$\Rightarrow V_{30\Omega} = 84V$$

NODALANALYSIS

Nodalanalysisisusedforsolvinganyelectrical network,anditisdefinedas

Themathematicalmethodforcalculating thevoltagedistributionbetweenthecircuitnodes.

Thismethod is alsoknown as the node-voltage method since the node voltages are with respect tothe ground. The following are the three laws that define the equation related to the voltage that ismeasuredbetweeneachcircuitnode:

- Ohm'slaw
- Kirchhoff'svoltagelaw
- Kirchhoff'scurrentlaw

ProcedureofNodalAnalysis

Thefollowingstepsaretobefollowedwhilesolvinganyelectricalcircuitusingnodalanalysis:

Step1:

Toidentifytheprincipalnodesandselectoneofthemasareferencenode.Thisreferencenodewillbetreatedast heground.

Step2:

Allthenodevoltageswithrespecttothegroundfromalltheprincipalnodesshouldbelabelledexcepttherefere ncenode.

Step3:

Thenodalequationsatalltheprincipalnodesexceptthereferencenodeshouldhaveanodalequation.Thenodalequat ionisobtainedfromKirchhoff'scurrentlawandthenfromOhm'slaw.

Step4:

Toobtainthenodevoltages,the nodalequationscanbedeterminedbyfollowingStep3.

Hence,foragivenelectricalcircuit,thecurrentflowingthrough anyelementandthevoltageacrossanyelementcanbedeterminedusingthenodevoltages.

Example1:UsingNodalmethod,findthecurrentthroughresistorr2 (Figure 1).

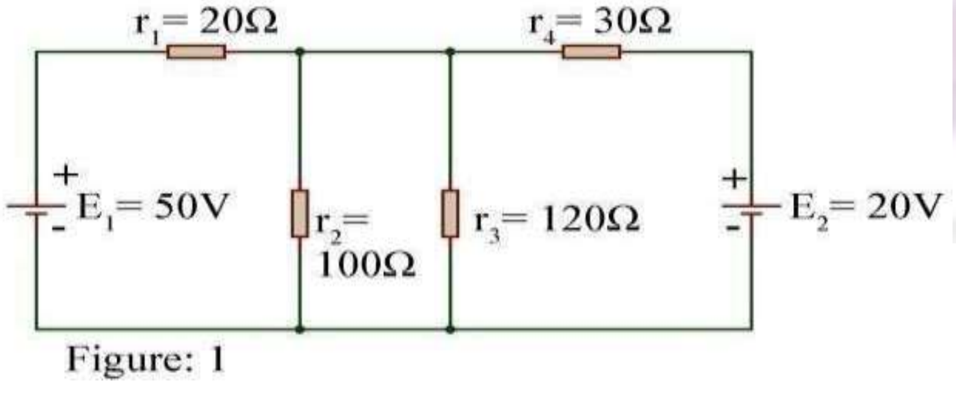


Figure: 1

Solution:Letusredrawthecircuitwithnamingofthenodesandbranchcurrentasshownin figure2.

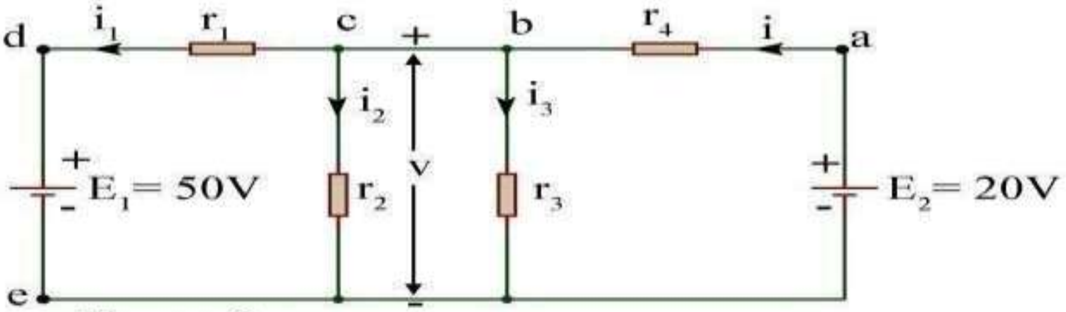


Figure: 2

Atnode“b”, $i = i_1 + i_2 + i_3$

(electricallynodesbandcaresame)Assumingthepolarityofthevoltagev athodecorb,wethusget

$$\frac{20 - v}{r_4} = \frac{v - 50}{r_1} + \frac{v}{r_2} + \frac{v}{r_3}$$

$$\frac{v - 20}{30} + \frac{v - 50}{20} + \frac{v}{100} + \frac{v}{120} = 0$$

or,

$$\therefore v = 31.18V$$

$$\therefore i_2 = \frac{v}{r_2} = \frac{31.18}{100}A = 0.3118A$$

i.e.currentthroughr2=311.8mA.

Example2:UsingNodalmethodfindthecurrentthroughtheresistorsinthecircuitconfigurationoffigure.

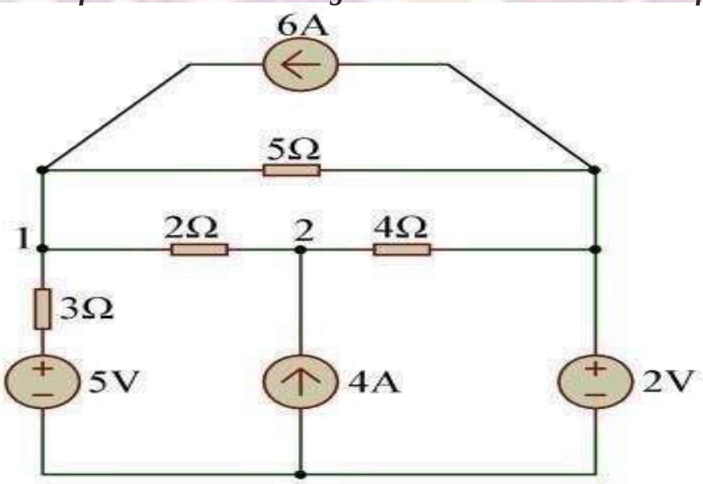


Figure: 3

Solution:

Namingtherespectivenodesofthecircuitas(1)and(2)andassumingthevoltagestobev1(+ve)andv2(+ve)respectivelyatthesenodes,nodalequationatnodes(1) and(2)areasfollows:

Fornode(1),

$$\frac{v_1-5}{3}+\frac{v_1-v_2}{2}+\frac{v_1-2}{5}=6$$

$$v_1(\frac{1}{3}+\frac{1}{2}+\frac{1}{5})-\frac{v_2}{2}-\frac{2}{5}-\frac{5}{3}-6=0$$

or, $\frac{31}{30}v_1-\frac{v_2}{2}-\frac{121}{15}=0$

Fornode(2),

$$\frac{v_2-v_1}{2}+\frac{v_2-2}{4}=4$$

or, $v_2(\frac{1}{2}+\frac{1}{4})-\frac{v_1}{2}-\frac{1}{2}=4$

or, $\frac{3}{4}v_2-\frac{v_1}{2}-\frac{9}{2}=0$ …..(b)

Solving (a) and

(b),v1=15.76Vwhilev2=16.51

V

$$=\frac{v_1-5}{3}=\frac{15.76-5}{3}\approx 3.6A$$

Currentthrough2Ωresistor

$$=\frac{v_1-v_2}{2}=\frac{15.76-16.51}{2}=-0.375A$$

[i.e.,followingfromnode(2)tonode(1)].

Currentthrough5Ωresistor

$$=\frac{v_1-2}{5}=\frac{15.76-2}{5}=2.76A$$

Currentthrough4Ωresistor

$$=\frac{v_2-2}{4}=\frac{16.51-2}{4}=3.63A$$

Figure4confirmstheKCLbothatnodes(1)andnodes(2)

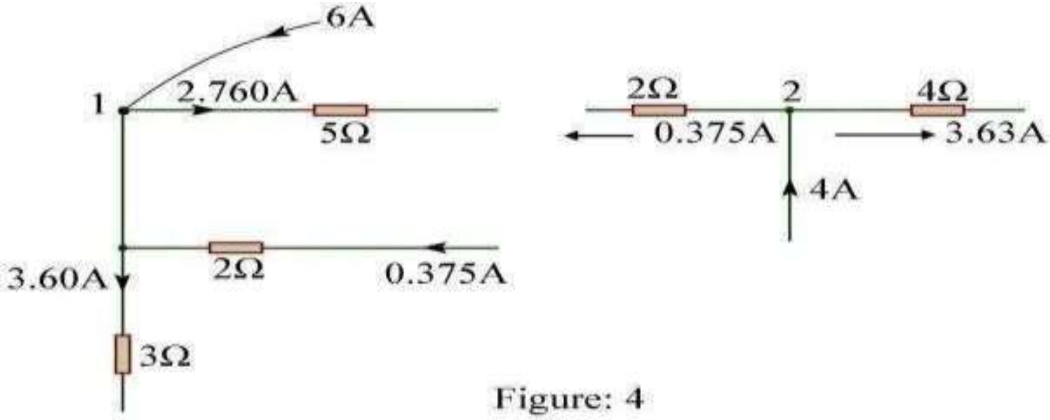


Figure: 4

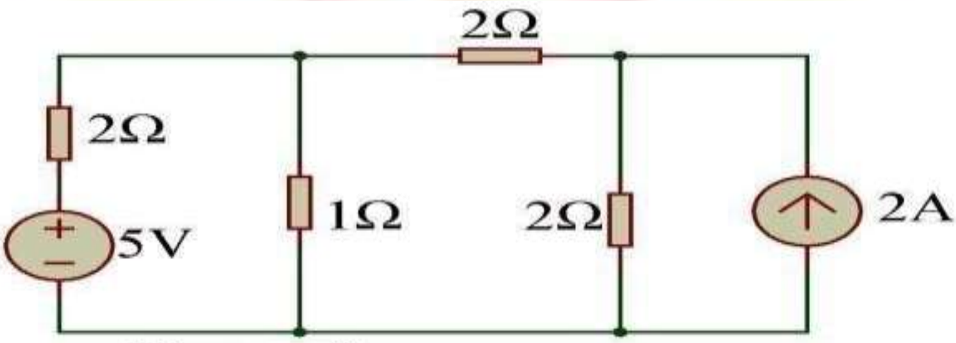


Figure: 7

Solution:

Letusfirstconvertthecurrentsourceoffigure7tovoltagesourceanddrawtheequivalentnetwork(figure8).Letthe+vevoltageatnode(1)bev1V.

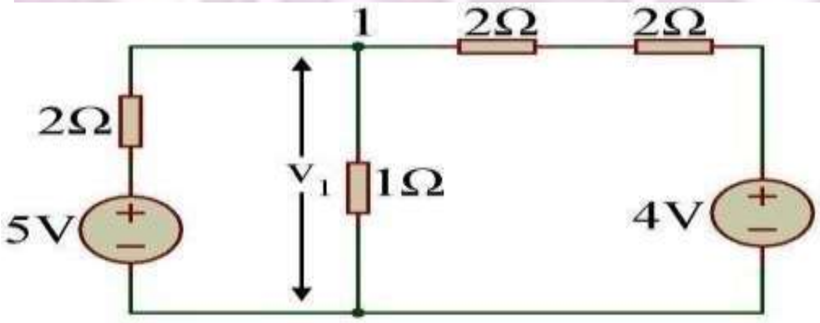


Figure: 8

∴Usingnodalanalysis,

$$\frac{v_1}{1}+\frac{v_1-5}{2}+\frac{v_1-4}{4}=0$$

or, $v_1 = 2V$

Hence,thecurrentthrough1Ωresistoris

$$\frac{v_1}{1} = 2A$$

Example5:FindV1 andV2 infigure9.

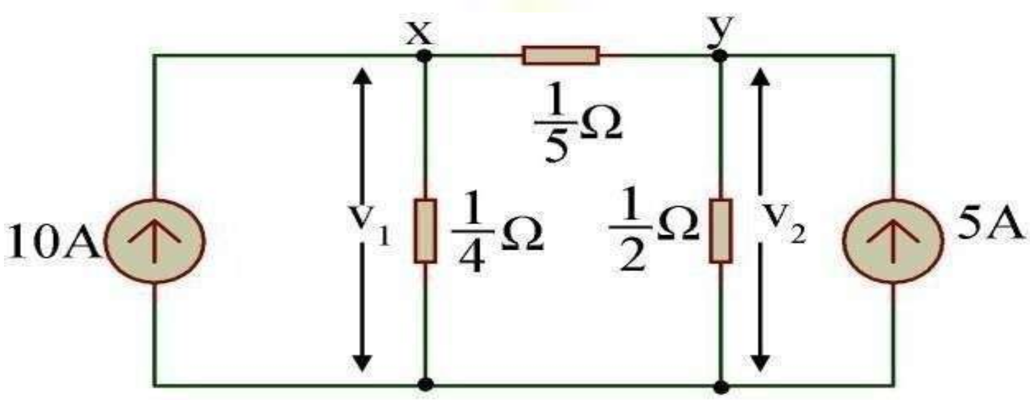


Figure: 9

Solution:

Atnode“x”,

$$10 = \frac{V_1}{1/4} + \frac{V_1 - V_2}{1/5} = 4V_1 + 5V_1 - 5V_2$$

or, $9V_1 - 5V_2 = 10$ …..(1)

Atnode“y”,

$$5 = \frac{V_2}{1/2} + \frac{V_2 - V_1}{1/5} = 2V_2 + 5V_2 - 5V_1$$

or, $-5V_1 + 7V_2 = 5$ …..(2)

Solving(1)and(2),

$$V_2 = 2.5V; V_1 = 2.5V$$

Time-domain analysisoffirst-orderRLandRCcircuits.

Thesolutionofthedifferentialequationrepresentstheresponseofthecircuit.Nowwewillfindouttherespons eofthebasicRLandRCcircuitswithDCExcitation.

RLCIRCUITwithexternalDCexcitation:

Let us take a simple RL network subjected to external DC excitation as shown in the figure. Thecircuitconsists of a battery whose voltage is V in series with a switch, a resistor R, and an inductorL.

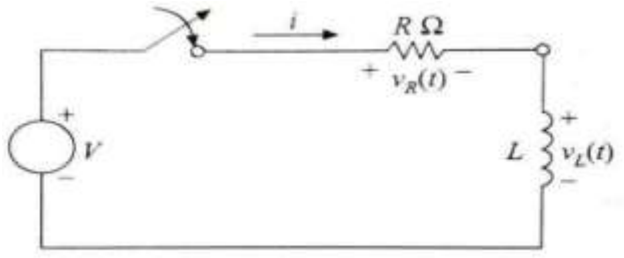


Fig: RL Circuit with external DC excitation

The switch is closed at t = 0. Fig: RL Circuit with external DC excitation When the switch is closedcurrent tries to change in the inductor and hence a voltage VL(t) is induced across the terminals of theInductor in opposition to the applied voltage. The rate of change of current decreases with time whichallows currenttobuilduptoit’smaximumvalue.

It is evident that the current i(t) is zero before t = 0.and we have to find out current i(t)for time t >0.We will find i(t)for time t>0 by writing the appropriate circuitequation and then solving itbyseparation of the variables and integration. Applying Kirchhoff’s voltage law to the above circuit weget:

V=vR(t)+vL(t)i(t)=0fort=0

Onedirectmethodofsolvingsuchadifferentialequationconsistsofwritingtheequationinsuchawaythat the variables are separated, and then integrating each side of the equation. The variables in theabove equation are iand t. This equation is multiplied by dt and arranged with the variables separatedasshownbelow:

Ri.dt+Ldi=V.dt

.eLdi= (V– Ri)dt

i.eLdi/(V– Ri)=dt

Nexteachsideisintegrateddirectlytoget:−(L/R)ln(V−Ri)=t+k

Where kis theintegration constant. In order to evaluate k, an initial condition mustbeinvoked.Prior to t = 0, i (t)is zero, and thus i (0−) = 0. Since the current in an inductorcannot change by afinite amount in zero time without being associated withan infinite voltage, we have i (0+) = 0.Settingi=0att=0,intheaboveequationweobtain

$-(L/R)\ln(V)=k$and,hence,

$-L/R[\ln(V-Ri)-\ln V]=t$Rearranging

wegetln$[(V-Ri)/V]=-(R/L)t$

Takingantilogarithmonbothsidesweget$(V-$

$Ri)/V=e^{-Rt/L}$Fromwhichwecanseethat

$i(t)=(V/R)-(V/R)e^{-Rt/L}fort>0$

Thus,anexpressionfortheresponse valid foralltimetwouldbe$i(t)= V/R[1- e^{-Rt/L}]$Thisis

normallywrittenas:

$i(t)=V/R[1- e^{-t/\tau}]$

where'τ'iscalledthetimeconstantofthecircuitandit'sunitisseconds.ThevoltageacrosstheresistanceandtheInductorfor$t>0$canbewrittenas:$v_R(t)=i(t).R=V[1-e^{-t/\tau}]$

$v_L(t)=V-v_R(t) =V-V[1-e^{-t/\tau}]=V(e^{-t/\tau})$

Aplotofthecurrent$i(t)$andthevoltages$v_R(t)$ &$v_L(t)$isshowninthefigurebelow.

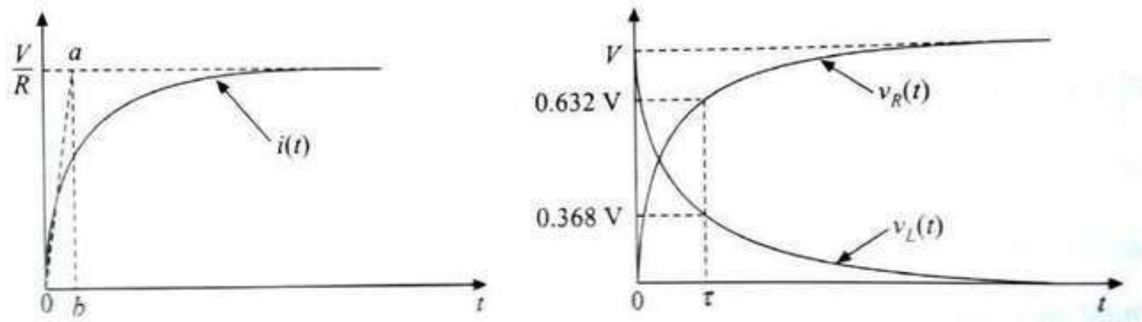


Fig: Transient current and voltages in the Series RL circuit.

At$t=$ 'τ'the voltage acrosstheinductorwillbe$v_L(\tau)=V(e^{-\tau/\tau})= V/e=$

0.36788Vandthevoltageacross theResistorwillbe$v_R(\tau)=V[1-e^{-\tau/\tau}]=0.63212V$

The plots of current i(t) and the voltage across the Resistor vR(t) are called exponential growthcurvesandthe voltageacrosstheinductorvL(t)iscalledexponentialdecaycurve.

RCCIRCUITwithexternalDCexcitation:

A series RC circuit with external DC excitationV volts connected through a switch is shown in thefigure below. If the capacitor is not charged initially i.e. it's voltage is zero ,thenafter the switch S isclosed at time t=0, the capacitor voltage builds up gradually and reaches it's steady state value of Vvolts after a finite time. The charging current will be maximum initially (since initially capacitorvoltageiszeroandvoltageacrossacapacitorcannotchangeinstantaneously)andthenitwillgradually comedown as the capacitor voltagestarts building up. The current and the voltage duringsuchcharging periodsare calledTransientCurrentandTransientVoltage.

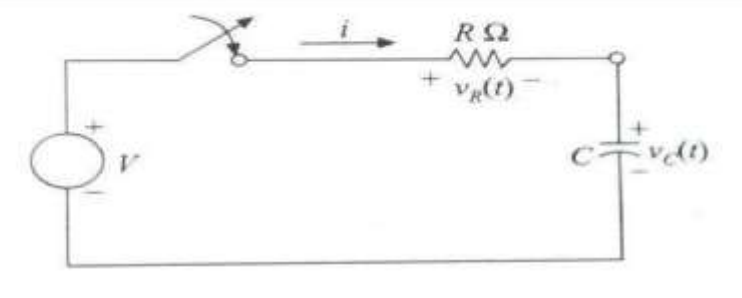


Fig: RC Circuit with external DC excitation

ApplyingKVLaroundtheloopintheabovecircuitwecanwriteV= vR(t)+vC(t)

Usingthestandardrelationshipsofvoltageandcurrentforan IdealCapacitorwegetvC(t)=(1/C)∫

$\boldsymbol{i(t)dt}$ori(t)= C.[dvC(t)/dt]

andusingthisrelation,vR(t)canbewrittenasvR(t)=Ri(t)=R.C.[dvC(t)/dt]

Using theabovetwoexpressionsforvR(t)andvC(t)theaboveexpressionforVcan

berewrittenas:V=R.C.[dvC(t)/dt]+vC(t)

OrfinallydvC(t)/dt+(1/RC). vC(t)=V/RC

The inverse coefficient of vC(t) is known as the time constant of the circuit τand is given by τ = RCandit'sunitsareseconds.

The above equation is a first order differential equation and can be solved by using the same methodofseparationofvariablesas weadoptedfortheLCcircuit.

Multiplying the above equation dvC(t)/dt + (1/RC). vC(t) = V/RC both sides by 'dt' and rearrangingthetermssoastoseparatethevariablesvC(t)andtweget:dvC(t)+(1/RC).vC(t).dt=(V/RC).dt

dvC(t)=[(V/RC)−(1/RC).vC(t)].Dt

dvC(t)/[(V/RC)−(1/RC).vC(t)]=dt

R.C.dvC(t)/[(V−vC(t)]=dt

Nowintegratingbothsidesw.r.ttheirvariablesi.e.'vC(t)'ontheLHSand't'ontheRHSweget

−RCln[V−vC(t)]=t+k

where 'k'is the constant of integration .In order to evaluate k, an initial condition must be invoked.Prior to t = 0, vC(t)is zero, and thus vC(t)(0−) = 0. Since the voltage across a capacitor cannot change byafiniteamountinzerotime,wehavevC(t)(0+)=

0. Setting vC(t)= 0 att = 0, in the above equation we obtain: −RC ln [V] = k and substituting thisvalueofk= −RCln[V]intheabovesimplifiedequation

−RCln[V−vC(t)]=t+kweget:

−RCln[V− vC(t)]=t−RCln[V]

i.e.−RCln[V−vC(t)] +RCln[V]=ti.e.−RC[ln{V −vC(t)}−ln(V)]=t

i.e.ln[{V−vC(t)}/(V)]=−t/RC

Takingantilogarithmweget[{V− vC(t)}/(V)]= e−t/RC

i.evC(t)= V(1−e−t/RC)[V]

whichisthe voltageacrossthecapacitorasa functionoftime.

ThevoltageacrosstheResistorisgivenby:vR(t)=V−vC(t)= V−V(1− e−t/RC)=V.e−t/RC

Andthecurrentthroughthecircuitisgivenby:i(t)=C.[dvC(t)/dt]=(CV/CR)e−t/RC=(V/R)e

−t/RCOrtheotherway:i(t)=vR(t)/R=(V.e−t/RC)/R=(V/R)e−t/RC

Intermsofthetimeconstantτtheexpressionsfor vC(t),vR(t)andi(t)aregivenby:vC(t)=V(1−e

−t/RC)

vR(t)= V.e−t/RC i(t)=(V/R)e−t/RC

Theplotsofcurrenti(t)and thevoltagesacrosstheresistorvR(t)and capacitorvC(t)areshowninthefigurebelow.

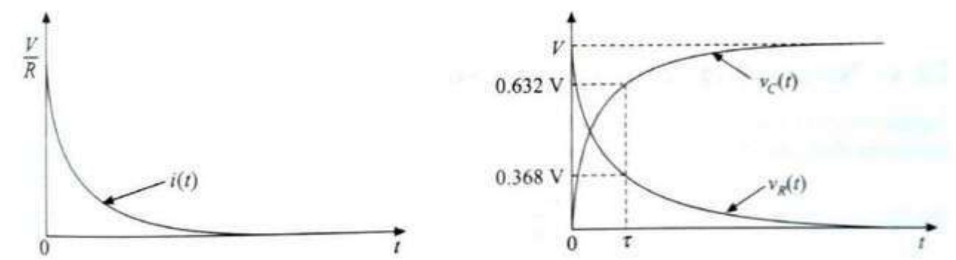


Fig : Transient current and voltages in RC circuit with DC excitation.

At t=‘τ’thevoltageacrossthecapacitorwillbe:

vC(τ)=V[1−e−τ/τ]=0.63212V

thevoltageacrosstheResistorwillbe: vR(τ)=V(e−τ/τ)=V/e= 0.36788V

andthecurrentthroughthecircuitwillbe:i(τ)=(V/R)(e−τ/τ)=V/R.e=0.36788(V/R)

Thusitcanbeseenthatafteronetimeconstantthechargingcurrenthasdecayedtoapproximately36.8%ofit’svalueatt=0.

Att=5τchargingcurrentwillbe

i(5τ)= (V/R)(e−5τ/τ)=V/R.e5 =0.0067(V/R)

Thisvalueisverysmallcomparedtothemaximumvalueof(V/R)att=0.Thusitcanbeassumedthatthecapacitorisfullychargedafter5timeconstants.

Thefollowingsimilaritiesmaybenotedbetweentheequationsforthetransientsinthe LCandRCcircuits:

- ThetransientvoltageacrosstheInductorinaLCcircuitandthetransientcurrentintheRCcircuithavethesame formk.(e−t/τ)
- ThetransientcurrentinaLCcircuitandthetransientvoltageacrossthecapacitorintheRCcircuithavethesame formk.(1−e−t/τ)
- Butthemain differencebetweentheRCandRLcircuitsistheeffectofresistanceonthedurationofthetransients.
- InaRLcircuitalargeresistanceshortens thetransientsincethetimeconstantτ=L/Rbecomessmall.
- WhereasinaRCcircuitalargeresistanceprolongsthetransientsincethetimeconstantτ=RCbecomeslarge.

Example1:FindthecurrentinaseriesRLcircuithavingR=2ΩandL=10HwhenaDCvoltageVof100Visapplied.Findthevalueofthecurrent5secs.aftertheapplicationoftheDCvoltage.

Solution:Thisisastraightforwardproblemwhichcanbesolvedbyapplyingtheformula.

Firstletusfind outtheTimeconstantτoftheseriesLRcircuitwhichisgivenbyτ=L/Rsecs.

∴τ = 10/2=5secs

The current in a series LR circuit after the sudden application of a DC voltage is given by :i(t) = V/R(

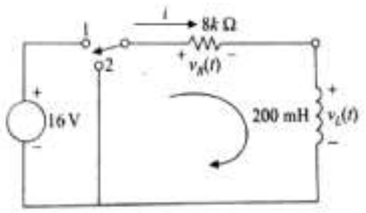
1 – e–t/τ)

∴i(t)at5secs=100/2(1–e–5/5)=5(1–e–1)=50(1–1/e)=31.48

∴i(t)at5secs=31.48Amps

Example : In the circuit shown below the switch is kept in position 1 upto 250 µsecs and then movedto position 2. Find (a) The current and voltage across the resistor at t = 100 µsecs (b) The current andvoltageacross theresistoratt=350µsecs

Solution:Thetimeconstantτofthecircuitisgivenbyτ=L/R=200mH/8KΩ=25µsecandissameinboththeswitchpositions.



a)Thecurrentinthecircuitupto250 μsec(tillswitchisinposition1)isgivenby:

i(t)growing= V/R(1–e–t/τ)=(16/8)X10--3(1–e–t/25x10--6)=2x(1–e–t/25x10–6)mA

Thecurrentinthecircuit@100μsecisgivenby

i(t)@100μsec=2x(1–e–100μsec/25μsec)mA=2x(1–e–4)mA=1.9633mAi(t)@100μsec

=1.9633m

Voltageacrosstheresistorisgivenbyv R@100 μsec= Rx

i(t)@100μsecvR@100μsec= 8KΩx1.9633mA= 15.707V

vR@100μsec = 15.707V

(a) Thecurrentinthecircuit@350μsecisthedecayingcurrentand isgivenby:

i(t)Decaying=I(0).e–t/τwhereI(0)istheinitialcurrentandinthiscaseitisthegrowingcurrent@250μsec.(Sincetheswitchischanged@250μsec)Thetimetistobereckonedfromthistimeof 250μsec.Hencet=(350—250)= 100μsec.Sowehavetocalculatefirsti(t)growing(@250μsec)whichisgivenby:

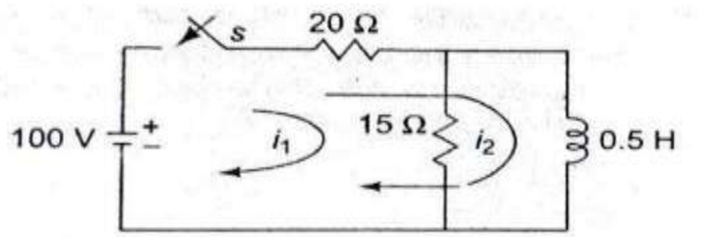
i(t)growing(@250μsec)= V/R(1–e –t/τ)= (16/8)X10--3(1 –e–t/25 μsec)= 2x(1–e–250/ 25μsec)mA=2x(1–e–10)mA= 1.999mA

i(t)growing(@250μsec)=1.999mA=I(0)

Hencei(t)@350μsec=I(0).e–t/τ=1.99xe–100μsec/25μsecmA=1.99xe–4mA=0.03663mAi(t)@350μsec=0.03663mA

ThevoltageacrosstheresistorvR@350μsec=Rxi(t@350μsec)=8KΩx0.03663mAvR@350μsec=0.293V

Example:Inthecircuitshownbelowfindouttheexpressionsforthecurrenti1andi2whentheswitchis closedattimet=0



Solution:Itistobenotedthatinthiscircuittherearetwocurrentloops1 and2.

Currenti1aloneflowsthroughtheresistor15Ωandthecurrenti2aloneflowsthroughtheinductance0.5Hwhereasbothcurrentsi1andi2flowthroughtheresistor20Ω.

ApplyingKVLto thetwoloopstakingcareofthispointweget$20(i_1+i_2)+15i_1=100$i.e$35i_1+20i_2=100$.(1)

and$20(i_1+i_2) +0.5di_2/dt=100$;$20i_1+20i_2 +0.5di_2/dt=100$(2)

Substitutingthevalueof$i_1=[100/35–(20/35)i_2]=2.86–0.57i_2$obtainedfromtheaboveequation(1)intoequation(2)weget:

$20[2.86–0.57i_2]+20i_2+0.5(di_2/dt)=100$

$57.14–11.4i_2+20i_2+ 0.5(di_2/dt)=100$

$(di_2/dt)i_2+17.14\ i_2=85.72$

The solution for this equation is given by $i_2(t) = K.\ e^{– 17.14t} + 85.72/17.14$ and the constant K canbeevaluatedbyinvokingtheinitial condition.Theinitialcurrentthroughtheinductor=0attimet=0. HenceK=--85.72/17.14=--5

Therefore$i_2(t)= 5(1--e^{–17.14t})$Amps

Andcurrent$i_1(t)=2.86–0.57i_2 = 2.86–0.57[5(1--e^{–17.14t})]=0.01+2.85e^{–17.14t}$Amps

Andcurrent$i_1(t)= 0.01+2.85e^{– 17.14t}$Amps

AC CIRCUITS

The alternating quantity is one whose value varies with time. This alternating quantity may be periodic and non-periodic. Periodic quantity is one whose value will be repeated for every specified interval. Generally to represent alternating voltage or current we prefer sinusoidal wave form, because below listed properties

1. Derivative of sine is an sine function only.
2. Integral of sine is an sine function only.
1. It is easy to generate sine function using generators.
2. Most of the 2nd order system response is always sinusoidal.

1.2 Alternating quantity:

defined with degree or radians as reference.

At, 0 degrees --- 0

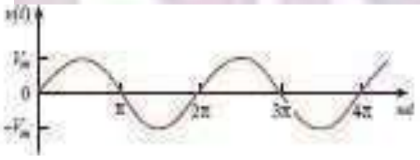
90 degrees --- maximum

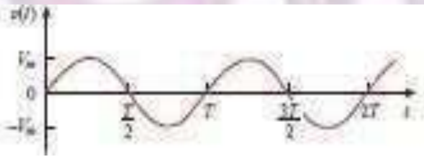
180 degrees --- 0

270 degrees --- maximum

360 degrees --- 0

i.e value of sine function varies with time, firstly increases from zero and reaches maximum and again falls to zero, there after tends to increase in opposite direction and reaches maximum value and falls to zero. This the variation of sine in 1st cycle is called as positive half cycle and other negative half cycle.(i.e during direction is required one and during 2nd half cycle direction actual required direction.). Therefore one positive and negative cycle combinely forms one complete cycle





Sine equation , voltage , V(t) = Vm sin wt.

Where, Vm = peak value or maximum value W – angular frequency.

Definitions:

Peak to peak value: It is total value from positive peak to the negative peak.(2Vm)

Instantaneous value: It is the magnitude of wave form at any specified time. V(t)

Average value : It is ratio of area covered by wave form to its length.(Vd)

$$Vd = (1/T) \int V(t)\, dwt.$$

$$Vd = (1 / 2\Pi) \int Vm \sin wt.dwt$$

$$= - Vm / 2\Pi .\cos wt \text{---with limits of } 2\Pi \text{ and } 0$$

= 0. (i.e. average value of sine wave over a full cycle is zero)

Hence it is defined for half cycle.

$$Vd = (1 / \Pi) \int Vm \sin wt.dwt$$

$$- Vm / \Pi .\cos wt \text{ with limits of } \Pi \text{ and } 0$$

Peak factor:

RMS value:

It is the root mean square value of the function, which given as

$$Vrms = \sqrt{[(1/T) \int V(t)]2\, dwt}.$$

$$= \sqrt{[(1/2\Pi) \int Vm2[(1- \cos 2wt)/2]\, dwt}.$$

$$= \sqrt{[(1/2\Pi) .Vm2[(wt- \sin 2wt / 2wt)/2]}$$

$$= Vm / \sqrt{2} = \text{effective value.}$$

It is the ratio of peak value to the rms value.

$$Pp = Vp / Vrms = \sqrt{2}$$

Form factor:

It is the ratio of average value to the rms value.

$$Fp = Vd / Vrms = 2\sqrt{2} / \Pi = 1.11$$

Eg: Find the peak, peak to peak, average, rms, peak factor and form factor of given current function ,

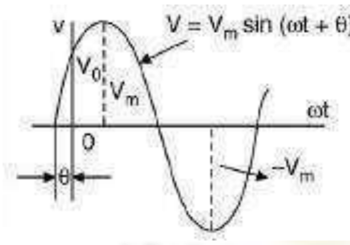
$i(t) = 5 \sin wt.$

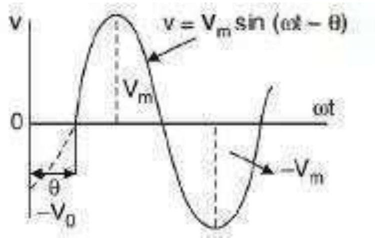
1.4 Phase and phase difference:

Phase of the sine indicates staring phase of the sine wave. i.e

Let , V(t) = Vm sin wt, here we can say that phase is zero as function starts from origin.

V(t)= Vm sin(wt-θ), here we can say that phase of function is θ degrees to right shift.
V(t)= Vm sin(wt+θ), here we can say that phase of function is θ degrees to left shift.





Phase difference is the difference of phase between two wave forms taking one as reference.

Eg: If wave form A is Vm sin (wt+15), B is Vm sin (wt – 30) and C is Vm sin (wt + 45).

Determine the phase difference between every pair if wave forms.

When A and B are compared , phase difference is 45 degrees.

When C and B are compared , phase difference is 75 degrees.

When A and C are compared , phase difference is 30 degrees.

1.5 Phasor diagram:

Phasor diagram is the pictorial representation of sine wave. Here magnitude and phase of the wave function are represented in four quadrant axis. We assume positive phases in anti-clock wise direction and negative phases in clock wise direction. From the phasor diagram we can esily identify the phase difference between different wave forms. We can also identify whether function is right shift or left shift.

1.6 Phase relations of network parameters:

Resistor:

Let us consider resistor allowing alternating current i(t). Then the voltage drop across resistor is given as,

If, V(t) = Vm sin wt

V(t) = i(t).R

= Vm / Im

i(t) = Im sin wt.

$$i(t) = V(t) / R$$

$Z = Vm \sin wt / Im \sin wt.$

$= Vm \sin wt / R$

Hence we can say that V(t) and i(t) in resistor element are in phase

The ratio of V(t) / i(t) = Z = impedance offered by resistor.(ohms).

Inductor:

Let us consider an coil of N turns allowing current i(t).(Im sin wt)

Hence emf induced in the coil is ,

$V(t) = L\, di(t) / dt$

$= L\, d(Im \sin wt) / dt$

$= L\, w\, Im \cos wt$

$= Vm \cos wt = Vm \sin(wt + 90).$

Where, $Vm = L\, w\, Im = Im .XL$

XL = reactance offered by coil.

Impedance offered by coil is , $Z = V(t) / i(t)$

$= Vm \sin(wt + 90) / Im \sin wt$

The function $Vm \sin wt = Vm \angle 0$.

$Z = Vm \angle 90 / Im \angle 0$

$Z = Vm \angle 90 / Im$

$= j\, wL = j\, XL.\ (j = 1\angle 90)$

As there is left shift in V (t), we can say that i(t) lags V(t) by 90 degrees.

Capacitor:

Let us consider an capacitor allowing current i(t).(Im sin wt)

Hence voltage across it is , Where, Vm = $= Vm \sin(wt - 90).$

$V(t) = 1 / C \int i(t)\, dt$

$= 1 / C \int Im \sin wt\, dt$

$= - \cos wt .Im / wC$

Im/ wC = Im .XC

= Vm sin(wt -90) / Im sin wt

XC = reactance offered by capacitor

Impedance offered by capacitor is , Z = V(t) / i(t)

1.7 Power in Ac circuits Z = Vm ∟ – 90 / Im ∟0

The function Vm sinwt = Vm ∟0.

In the case of DC circuits power is given as product of voltage and current in that element.

P = V.I (W)

Let V(t) = Vm sin wt

i(t) = Im sin(wt +90)

Instantaneous power, P (t) = V (t).i (t)

= Vm sin wt. Im sin(wt + Φ)

= Vm.Im sin wt sin (wt + Φ).

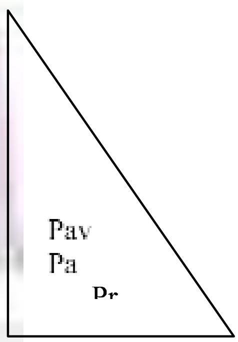
$$\frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}} 2 \sin(w t + \Phi)$$

$$\frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}} [\cos \varphi - \cos (2w t + \Phi)$$

Average power, Pav = 1/ 2π ∫ p(t) dwt.
√2 . √2

= Vrms Irms cos Φ[wt] ----------- with limits 2π and 2π

Pav = Vrms. Irms cos Φ.(W) = true power= active power.



Cos Φ = Pav / Vrms. Irms.= defined as power factor of the circuit.

Cos Φ = Pav / Pa

$$=1/2\pi \int Vm.Im[\cos\Phi - \cos(2wt + \Phi)]dwt$$

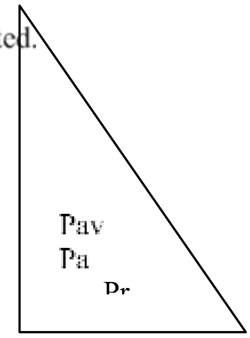
$$\sqrt{2} \;.\; \sqrt{2}$$

Pav = Pa cos Φ = Vrms.Irms cos Φ = active power= W

As average value over full cycle is equal to zero, hence second term can be neglected.

Pr = Pa sin Φ = Vrms.Irms sin Φ= reactive power = VAR

$$Pav = 1/2\pi \int Vm.Im\,[\cos\Phi]\,dwt$$



Let us consider commercial capacitor,

= true power / apparent power

Z = R - jXC

= actual power utilized by load / total generated power.

Where, Z = impedance of the capacitor

Pa = apparent power = Vrms. Irms = V-A

Let us consider commercial inductor   Z = R + jXL

Where, Z = impedance of the coil

XL = reactance offered by the coil.   R = internal resistance of the coil

I(t) Z = I(t) R + I(t) jXL

$I^2 Z = I^2R + j\, I^2XL$

Pa = Pav + j Pr   power triangle with phase Φ

R = internal resistance of the capacitor

XC = reactance offered by the capacitor.

I(t) Z = I(t) R - I(t) jXC

$I^2 Z = I^2R - j\, I^2XC$

Pa = Pav - j Pr   power triangle with phase Φ

Pav = Pa cos Φ = Vrms.Irms cos Φ = active power= W

Pr = Pa sin Φ = Vrms.Irms sin Φ= reactive power = VAR

1.8Complex power:

Complex power is represented with S.

S = V(t).i(t)*

= P+jQ or P-jQ

Where, P = active power

Q = reactive power

Here only useful power is true power where as net reactive power over an cycle will be zero.

Complex numbers:

Complex numbers can be represented in two ways, either rectangle form or polar form

Rectangular form = a + j b

Polar form = $\sqrt{a2 + b2}$ ∠tan-1 (b/a)

Here j operator plays major role in complex number, which is define MODULE vector rotating in anti-clock wise direction with phase 90.

j = 1∟90 = $\sqrt{-1}$

j2 = - 1

j3 = -$\sqrt{-1}$

RMSVALUE:

The **RMS** (**Root Mean Square**) value (also known as **effective** or **virtual** value) of of an alternatingcurrent (AC) is the value of direct current (DC) when flowing through a circuit or resistorfor thespecific time period and produces same amount of heat which produced by the alternating current(AC)whenflowingthroughthesamecircuitorresistorforaspecifictime.

The value of an AC which will produce the same amount of heat while passing through in a heatingelement(suchasresistor)asDCproducesthroughtheelementiscalledR.M.SValue.

- Inshort,
- The RMS Value of an Alternating Current is that when it compares to the Direct Current, then bothAC and DC current produce the same amount of heat when flowing through the same circuit for aspecifictimeperiod.

$$I_{RMS} = \frac{I_M}{\sqrt{2}}, \quad V_{RMS} = \frac{V_M}{\sqrt{2}}$$

Forasinusoidalwave $I = 0.707 \times I_M, V = 0.707 \times V_M$,

or

$I_{RMS}=0.707 x I_M, E_{RMS}= 0.707 E_M$

Actually, the RMS value of a sine wave is the measurement of heating effect of sine wave. Forexample,whenaresistorisconnectedtoacrossanACvoltagesource,itproducesspecificamountofheat(Fig2

– a). When the same resistor is connected across the DC voltage source as shown in (fig 2 – b). Byadjusting the value of DC voltage to get the same amount of heat generated before in AC voltagesource in fig a. It means the RMS value of a sine wave is equal to the DC Voltage source producingthe sameamountofheatgeneratedbyACVoltagesource.

- In more clear words, the domestic voltage level in US is 110V, while 220V AC in UK. This voltagelevel shows the effective value of (110V or 220V R.M.S) and it shows that the home wall socket iscapabletoprovidethesameamountofaveragepositivepoweras110Vor 220VDCVoltage.

- *KeepinmindthattheamperemetersandvoltmetersconnectedinACcircuitsalwaysshowing* **theRMSvalues(ofcurrentandvoltage).**

- ForACsinewave,RMSvaluesofcurrentandvoltageare:

  $I_{RMS}=0.707 x I_M, V_{RMS}= 0.707 V_M$

- Let'sseehowtofindtheR.M.Svaluesofasinewave.
- Weknowthat thevalueofsinusoidalalternatingcurrent(AC)=

  $I_m Sin\omega\theta = I_m Sin\theta$

- Whilethemeanofsquareofinstantaneousvaluesofcurrentininhalforcompletecycleis:The

  Squarerootofthisvalueis:

$$= \int_0^{2\pi} \frac{i^2 \, d\theta}{(2\pi - 0)}$$

$$= \sqrt{\left(\int_0^{2\pi} \frac{i^2 \, d\theta}{2\pi}\right)}$$

Hence,theRMSvalueofthecurrentis(whileputtingI=I_mSinθ):

$$I = \sqrt{\left(\int_0^{2\pi} \frac{i^2 d\theta}{2\pi}\right)} = \sqrt{\left(\frac{I_m^2}{2\pi}\int_0^{2\pi} \sin^2\theta \, d\theta\right)}$$

$$\cos 2\theta = 1 - 2\sin^2\theta \quad \therefore \; \sin^2\theta = \frac{1-\cos 2\theta}{2}$$

$$I = \sqrt{\left(\frac{I_m^2}{4\pi}\int_0^{2\pi}(1-\cos 2\theta)\, d\theta\right)} = \sqrt{\left(\frac{I_m^2}{4\pi}\left|\, \theta - \frac{\sin 2\theta}{2}\right|_0^{2\pi}\right)}$$

$$= \sqrt{\frac{I_m^2}{4} \quad 2} \qquad \sqrt{\frac{I_m^2}{2}} \qquad \therefore \; I = \frac{I_m}{\sqrt{2}} = 707 \, I_m$$

Now,

Therefore,Wemayfindthatforasymmetricalsinusoidalcurrent:

IRMS=MaxValueof Currentx0.707AverageValue:

If we convert the alternating current (AC) sine wave into direct current (DC) sine wave throughrectifiers, then the converted value to the DC is known as the average value of that alternating currentsine wave.

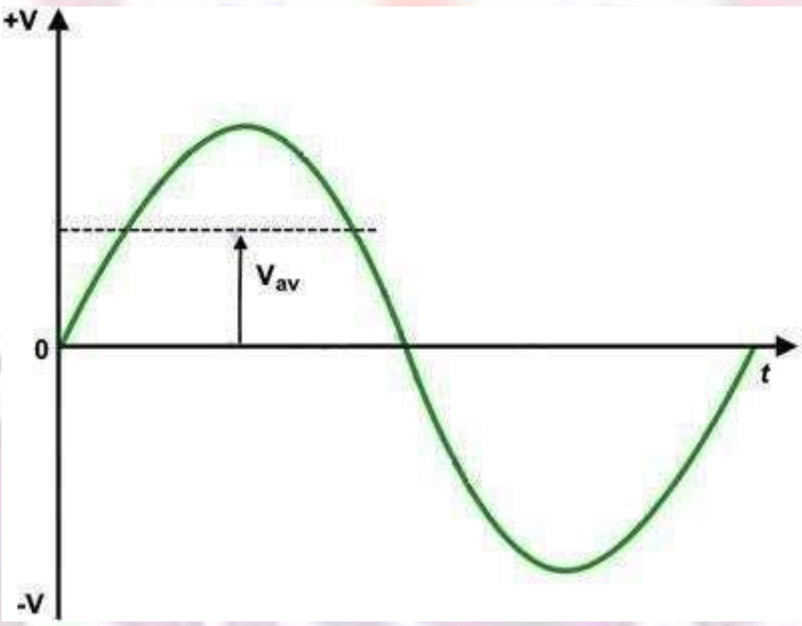


Fig4–AverageValueofVoltage

If the maximum value of alternating current is "I_{MAX}", then the value of converted DC currentthroughrectifierwouldbe"$0.637I_M$"whichisknownasaveragevalueoftheACSinewave(I_{AV}).

AverageValueofCurrent$=I_{AV}=0.637I_M$*AverageValueofVoltage*$=E_{AV}=0.637E_M$

The Average Value (alsoknown as Mean Value) of an Alternating Current (AC)is expressedbythatDirect

Current (DC) which transfers across any circuit the same amount of charge as is transferred by thatAlternatingCurrent(AC)duringthe sametime.

Keep in mind that the average or mean value of a full sinusoidal wave is "Zero" the value of currentin first half (Positive) is equal to the the next half cycle (Negative) in the opposite direction. In otherwords, There are same amount of current in the positive and negative half cycles which flows in theopposite direction, so the average value for a complete sine wave would be "0". That's the reasonthat's why we don't use average value for plating and battery charging. If an AC wave is convertedintoDCthrougharectifier,Itcanbeusedforelectrochemicalworks.

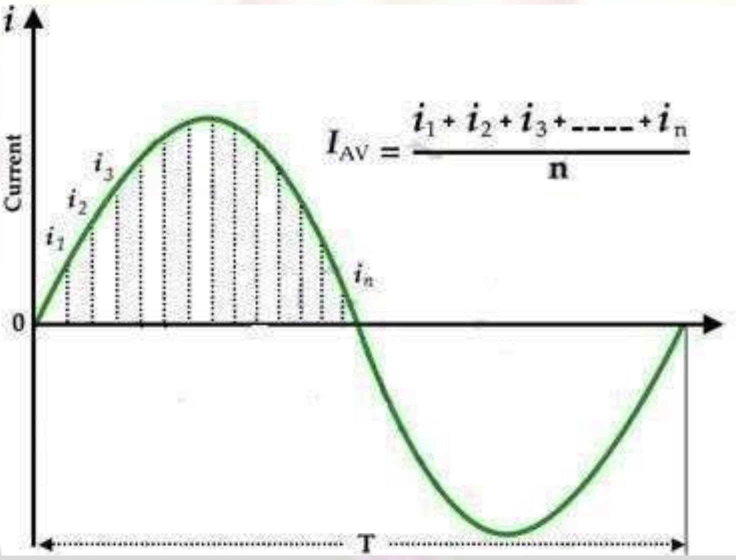


Fig5-AverageValueofCurrent

In short, theaveragevalueof asinewavetaken overacompletecycleis always zero,becausethe positive values (above the zero crossing) offset or neutralize the negative values (below the zerocrossing.)

Weknowthatthe standardequationofalternatingcurrentis

$i=Sin\omega\theta=I_mSin\theta$

- Maximumvalueofcurrentonsinewave=I_m
- Averagevalueofcurrentonsinewave=I_{AV}
- Instantaneousvalueofcurrentonsinewave=i
- Theanglespecifiedfir"i"afterzeropositionofcurrent=θ
- Angleofhalfcycle=πradians
- Angleoffullcycle=2πradians

(a) Averagevalueofcompletecycle:

$$I_{AV} = \frac{1}{2\pi}\int_0^{2\pi} i\, d\theta = \frac{1}{2\pi}\int_0^{2\pi} i_m \, Sin\theta \, d\theta$$

$$= \frac{I_m}{2\pi}\left[-Cos\,\theta\right]_0^{2\pi} = \frac{I_m}{2\pi}(Cos\,2\pi - Cos\,0)$$

$$= \frac{I_m}{2\pi}(1-1) = 0 \;;\quad I_{AV} = 0$$

Leti=Sinωθ=I_mSinθ

Thus,theaveragevalueofasinusoidalwaveoveracompletecycleiszero.

(b) Averagevalueofcurrentoverahalfcycle

$$I_{AV} = \frac{1}{\pi}\int_0^{\pi} i\, d\theta$$

$$= \frac{1}{\pi}\int_0^{\pi} I_m \, Sin\,\theta . d\theta \quad [\because i = I_m \, Sin\,\theta]$$

$$= \frac{I_m}{\pi}\left[-Cos\,\theta\right]_0^{\pi} = \frac{I_m}{\pi}\left[-Cos\,\pi - (-Cos\,0)\right]$$

$$= \frac{I_m}{\pi}[(+1) - (-1)] = \frac{I_m}{\pi}(+2)$$

$$I_{AV} = \frac{2}{\pi} I_m = 0.637\ A$$

AverageValueofCurrent(HalfCycle)

I_{AV}=0.637 V_M

Similarly,theaveragevalueofvoltage overahalfcycle

V_{AV}= 0.637V_M

★ **Average Voltage Value**

$$V_{AV} = \frac{2V_P}{\pi} = 0.637 \times V_P$$

$$V_{AV} = \frac{2V_M}{\pi} = 0.637 \times V_M$$

★ **Average Current Value**

$$I_{AV} = \frac{2I_M}{\pi} = 0.637 \times I_M$$

WhatisPeakVoltageorMaximumVoltageValue?

Peak value is also known as **Maximum Value**, **Crest Value** or **Amplitude**. It is the maximum valueof alternating current or voltage from the "0" position no matter positive or negative half cycle in asinusoidal waveasshowninfig8.Itsexpressedas**I_M**and**E_M**or**V_P**and**I_M.**

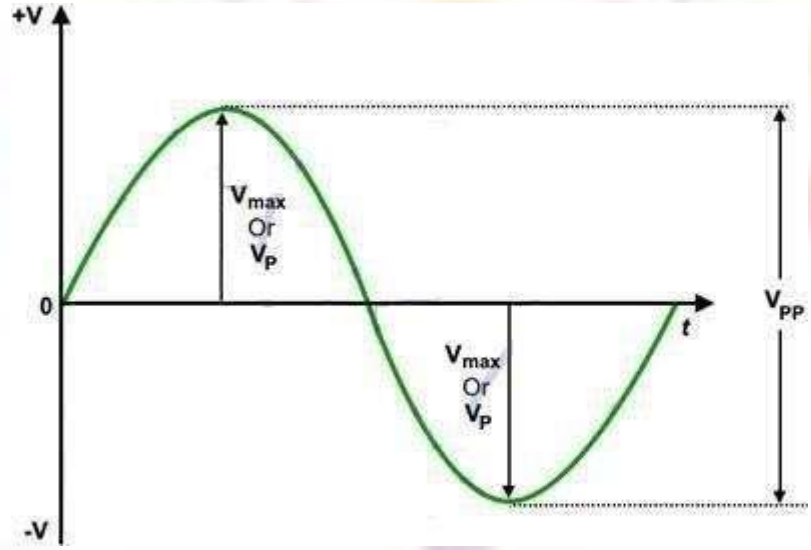
EquationsofPeakVoltageValueis:

$V_P = \sqrt{2} x V_{RMS} = 1.414 V_{RMS}$

$V_P = V_{P-P}/2 = 0.5 V_{P-P}$

$V_P = \pi/2 x V_{AV} = 1.571 x V_{AV}$

Inotherwords,Itisthevalueofvoltageorcurrentatthepositiveorthenegativemaximum



(peaks) withrespect to zero. In simple words, it is the instantaneous value with maximum intensity.Fig8–PeakorMaximumValues ofVoltages

PeaktoPeakValue:

Thesumofpositiveandnegativepeakvaluesisknownaspeaktopeakvalue.Itsexpressedas**I_{PP}** or**V_{PP}.EquationsandformulasforPeak toPeak Voltage**areasfollow:

$V_{P-P} = 2\sqrt{2} x V_{RMS} = 2.828$ x V_{RMS} $V_{P-P} = 2$xV_P $V_{P-P} = \pi x V_{AV} = 3.141xV_{AV}$

Inotherwords,thepeaktopeakvalueofasinewave,isthevoltageorcurrentfrompositive peak to the negative peak and its value is double as compared to peak value or maximum value asshowninfig8above.

PeakFactor:

PeakFactor isalsoknownasCrestFactororAmplitudeFactor.

$$\textbf{Peak Factor} = \frac{\text{Maximum Value}}{\text{R.M.S Value}}$$

It is the ratiobetween maximum value and RMS value of an alternating

wave.Forasinusoidalalternatingvoltage:

$$\frac{E_M}{0.707\,E_M} = 1.414$$

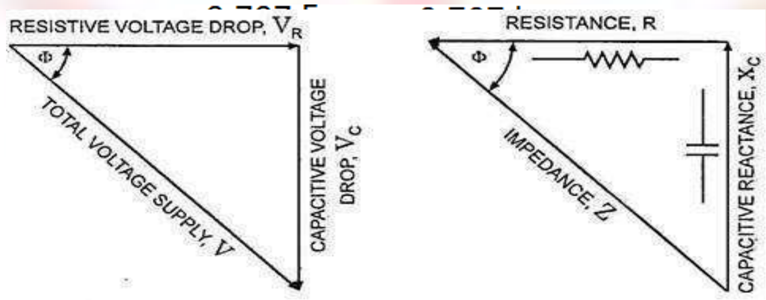
$$\frac{I_M}{0.707\,I_M} = 1.414$$

Forasinusoidalalternatingcurrent:

FormFactor:TheratiobetweenRMSvalueandAveragevalueofanalternatingquantity(CurrentorVoltage)is knownasFormFactor.

$$\textbf{Form Factor} = \frac{\text{RMS Value}}{\text{Average Value}}$$

ApparentPower,TruePower,ReactivePowerandPowerFactor:



(a) Voltage Triangle (b) Impedance Triangle

Fig. 4.19

The product of rms values of current and voltage, VI is called the apparent power and is measured involt-amperes orkilo-voltamperes(kVA).

The true power in an ac circuit is obtained by multiplying the apparent power by the power factor andisexpressedinwattsorkilo-watts(kW).

The product of apparent power, VI and the sine of the angle between voltage and current, sin ϕ iscalled the reactive power. This is also known as wattless power and is expressed in reactive volt-amperesorkilo-voltamperes reactive(kVAR).

$$i.e.\ \text{Apparent power, } S = VI \text{ volt-amperes or } \frac{VI}{1{,}000} \text{ kVA}$$

$$\text{True power, } P = VI\cos\Phi \text{ watts or } \frac{VI\cos\Phi}{1{,}000} \text{ kW}$$

$$\text{Reactive power, } Q = VI\sin\Phi \text{ VAR or } \frac{VI\sin\Phi}{1{,}000} \text{ kVAR}$$

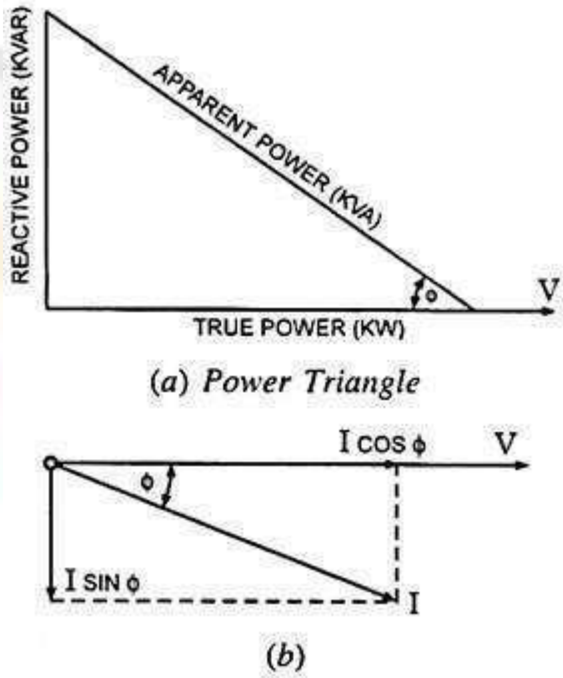
$$\text{and kVA} = \sqrt{(\text{kW})^2 + (\text{kVAR})^2}$$

Theaboverelationscaneasilybefollowedbyreferringtothepowerdiagramshownin Fig.4.7(a).

Powerfactormaybedefinedas:

(i) Cosineofthephaseanglebetweenvoltageandcurrent,

(ii) Theratiooftheresistancetoimpedance,or



(a) Power Triangle

(b)

Fig. 4.7

(iii) Theratiooftruepowertoapparentpower.

The power factor can never be greater than unity.The power factor is expressed either as fraction oras a percentage. It is usual practice to attach the word 'lagging' or 'leading' with the numerical valueofpowerfactortosignifywhetherthecurrentlagsbehindorleads thevoltage.

CONCEPTOFREACTANCE,IMPEDANCE,SUSCEPTANCEANDADMITTANCE:

Reactance is essentially inertia against the motion of electrons. It is present anywhere electric ormagnetic fields are developed in proportion to applied voltage or current, respectively; but mostnotablyincapacitorsandinductors.Whenalternatingcurrentgoesthroughapurereactance,avoltagedrop is produced that is 90^{o} out of phase with the current. Reactance is mathematically symbolizedbytheletter"X" andismeasuredinthe unitofohms(Ω).

Impedance is a comprehensive expression of any and all forms of opposition to electron flow,including both resistance and reactance. It is present in all circuits, and in all components. Whenalternatingcurrentgoes through an impedance,a voltagedrop isproduced thatissomewherebetween 0^{o} and 90^{o} out of phase with the current. Impedance is mathematically symbolized by theletter "Z"andismeasuredintheunitof ohms(Ω),incomplexform

Admittanceisalsoacomplexnumberasimpedancewhichishavingarealpart,Conductance(G)

andimaginary part, Susceptance (B). (itis negative for capacitive susceptance and positive forinductivesusceptance

$$Y = G + jB$$
$$Y \rightarrow Admittance\ in\ Siemens$$
$$G \rightarrow Conductance\ in\ Siemens = \frac{R}{R^2 + X^2}$$
$$B \rightarrow Susceptance\ in\ Siemens = -\frac{X}{R^2 + X^2}$$

$$j^2 = -1$$
$$|Y| = \sqrt{G^2 + B^2} = \frac{1}{\sqrt{R^2 + X^2}}$$
$$\angle Y = arctan\left(\frac{B}{G}\right) = arctan\left(-\frac{X}{R}\right)$$

Susceptance(symbolized *B***)** is an expression of the ease with which alternating current (**AC**) passesthroughacapacitanceorinductance

OtherTermsRelatedToACCircuitsWaveform

- Thepathtracedbyaquantity(suchasvoltageorcurrent)plottedasafunctionofsomevariable(suchastime,degree,radians,temperatureetc.)iscalledwaveform.

Cycle

1. Onecompletesetofpositiveandnegativevaluesofalternatingquality(suchasvoltageandcurrent)isknownas cycle.
2. Theportionofawaveformcontainedinoneperiodoftimeiscalledcycle.
3. Adistancebetweentwosamepointsrelatedtovalueanddirectionisknownascycle.
4. Acycleisacompletealternation.

Period

- Thetimetakenbyaalternatingquantity(suchascurrentorvoltage)tocompleteonecycleiscalleditstimeperiod"T".
- ItisinverselyproportionaltotheFrequency"*f*"anddenotedby"T"wheretheunitoftimeperiodissecond.
- Mathematically;

T=1/f

Frequency

- Frequencyisthenumberifcyclespassedthroughpersecond.Itisdenotedby“f”andhastheunitcyclepersecondi.e.Hz (Herts).
- Thenumberofcompletedcyclesin1secondiscalledfrequency.
- Itisthenumberofcyclesofalternatingquantitypersecondinhertz.
- Frequencyis thenumberofcyclesthatasinewavecompletedinonesecondorthenumberofcyclesthatoccurs inonesecond.

$$f = 1/T$$

Amplitude

- Themaximumvalue,positiveornegative,ofanalternatingquantitysuchasvoltageorcurrentisknownasitsamplitude.ItsdenotedbyVP,IPorEMAXandIMAX.
- Alternation
- Onehalfcycleofasinewave(NegativeorPositive)isknownasalternationwhichspanis180°degree.

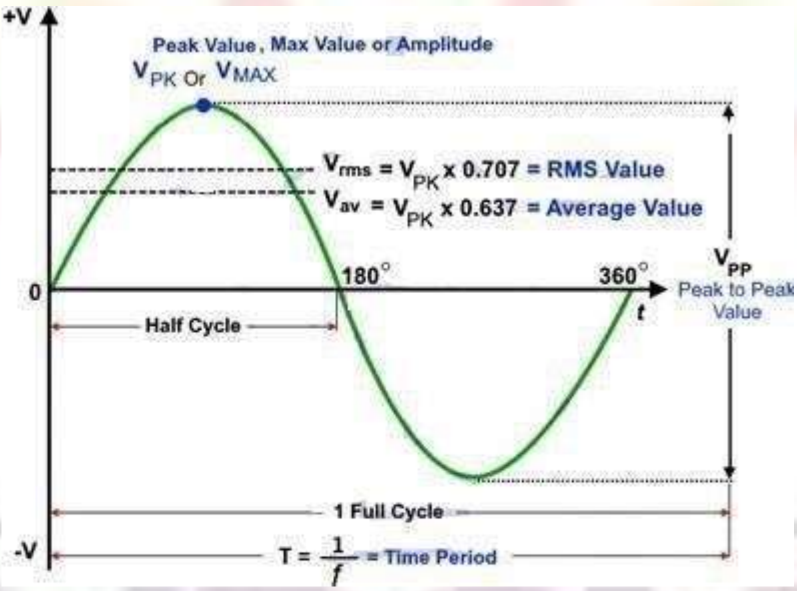


Fig9–DifferentTermsusedinACCircuitsandSineWave

IntroductiontoSinglePhaseACCircuit:

- In a dc circuit the relationship between the applied voltage V and currentflowing through the circuitI is a simple one and is given by the expression I = V/R but in an a c circuit this simple relationshipdoes not hold good. Variations in current and applied voltage setup magnetic and electrostaticeffects respectively and these must be taken into account with the resistance of the circuit whiledeterminingthequantitativerelationsbetweencurrentandappliedvoltage.
- With comparatively low-voltage, heavy- current circuits magnetic effects may be very large, butelectrostatic effects are usually negligible. On the other hand with high-voltage circuits electrostaticeffectsmaybeofappreciablemagnitude,andmagneticeffectsarealsopresent.

- Here it has been discussed how the magnetic effects due to variations in current do and electrostaticeffects due to variations in the applied voltage affect the relationship between the applied voltageandcurrent.

PurelyResistiveCircuit:

- A purely resistive or a non-inductive circuit is a circuit which has inductance so small that at normalfrequency its reactance is negligible as compared to its resistance. Ordinary filament lamps, waterresistances etc., are the examples of non-inductive resistances. If the circuit is purely non-inductive,noreactanceemf(i.e.,self-inducedorbackemf)issetup andwholeoftheappliedvoltageisutilizedinovercomingtheohmic resistanceofthecircuit.
- Consider an ac circuit containing a non-inductive resistance of R ohms connected across a sinusoidalvoltage representedbyv= Vsinwt,asshowninFig.

Asalreadysaid,whenthecurrentflowingthroughapureresistancechanges,nobackemfissetup,

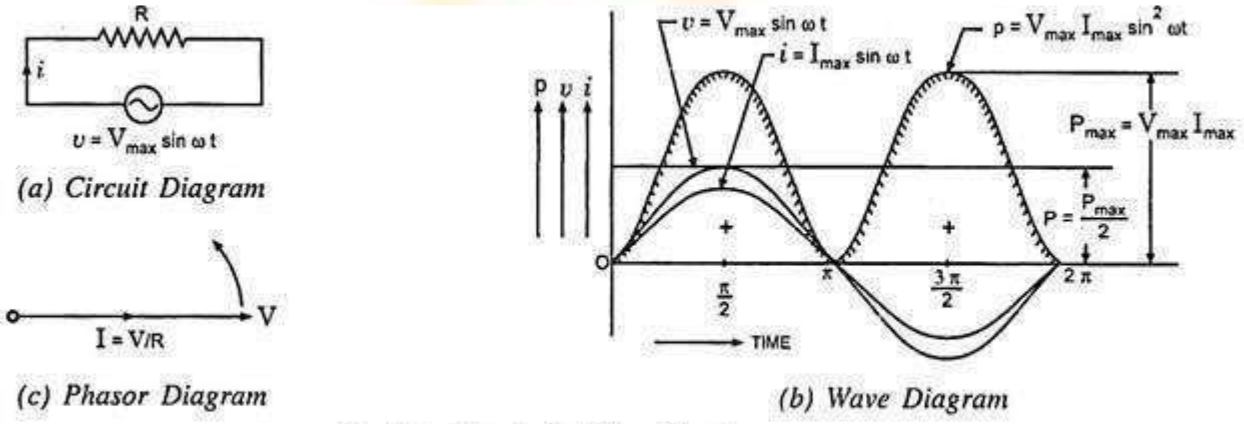


Fig. 4.1 *Purely Resistive Circuit*

$$i.e. \quad iR = v$$

$$\text{or} \quad i = \frac{v}{R} = \frac{V_{max}}{R} \sin \omega t$$

Current will be maximum when $\omega t = \frac{\pi}{2}$ or $\sin \omega t = 1$

$$\therefore \quad I_{max} = \frac{V_{max}}{R}$$

therefore,appliedvoltagehastoovercometheohmicdropofiRonly:

Andinstantaneouscurrentmaybeexpressedas:

$i = I_{max} \sin \omega t$

From the expressions of instantaneous applied voltage and instantaneous current, it is evident that ina pure resistive circuit, the applied voltage and current are in phase with each other, as shown bywave andphasordiagramsinFigs.4.1(b)and(c)respectively.

PowerinPurelyResistiveCircuit:

The instantaneous power delivered to the circuitin question is the product of the instantaneousvaluesofappliedvoltageandcurrent.

$$i.e.\quad p = v\,i = V_{max} \sin \omega t \; I_{max} \sin \omega t = V_{max}\; I_{max} \sin^2 \omega t$$

$$\text{or}\quad p = \frac{V_{max}\; I_{max}}{2}(1 - \cos 2\,\omega\,t) \qquad \text{Since } \sin^2 \omega\,t = \frac{1-\cos 2\,\omega t}{2}$$

$$= \frac{V_{max}\; I_{max}}{2} - \frac{V_{max}\; I_{max}}{2} \cos 2\,\omega\,t$$

$$\text{Average power, } P = \text{Average of } \frac{V_{max}\; I_{max}}{2} - \textit{average of } \frac{V_{max}\; I_{max}}{2} \cos 2\,\omega\,t$$

Since average of $\frac{V_{max}\; I_{max}}{2} \cos 2\,\omega\,t$ over a complete cycle is zero,

$$P = \frac{V_{max}\; I_{max}}{2} = \frac{V_{max}}{\sqrt{2}} \cdot \frac{I_{max}}{\sqrt{2}} = V\,I \text{ watts}$$

WhereVandIarethermsvaluesofappliedvoltageandcurrentrespectively.

Thus for purely resistive circuits, the expression for power is the same as for dc circuits. From thepower curve for a purely resistive circuit shown in Fig. 4.1 (b) it is evident that power consumed in a pure resistivecircuitisnotconstant,itisfluctuating.

However, it is always positive. This is so because the instantaneous values of voltage and current arealwayseither positive or negative and, therefore, the product is always positive. This means that thevoltagesource constantlydeliverspowertothe circuitand the circuitconsumesit.

PurelyInductiveCircuit:

An inductive circuit is a coil with or without an iron core having negligible resistance. Practicallypure inductance can never be had as the inductive coil has always small resistance. However, a coilof thick copper wire wound on a laminated iron core has negligible resistance arid is known as achokecoil.

When an alternatingvoltageis appliedtoapurely inductivecoil,an emf,known as self-inducedemf, is induced in the coil which opposes the applied voltage. Since coil has no resistance, at everyinstantappliedvoltagehastoovercomethisself-inducedemfonly.

Let the applied voltage $v = V_{max} \sin \omega t$

and self inductance of coil = L henry

Self induced emf in the coil, $e_L = -L \frac{di}{dt}$

Since applied voltage at every instant is equal and opposite to the self induced emf *i.e.* $v = -e_L$

$$\therefore \quad V_{max} \sin \omega t = -\left(-L\frac{di}{dt}\right)$$

$$\text{or} \quad di = \frac{V_{max}}{L} \sin \omega t \, dt$$

Integrating both sides we get

$$i = \frac{V_{max}}{L} \int \sin \omega t \, dt = \frac{V_{max}}{\omega L} (-\cos \omega t) + A$$

where A is a constant of integration, which is found to be zero from initial conditions

$$i.e. \quad i = \frac{-V_{max}}{\omega L} \cos \omega t = \frac{V_{max}}{\omega L} \sin\left(\omega t - \frac{\pi}{2}\right)$$

Current will be maximum when $\sin\left(\omega t - \frac{\pi}{2}\right) = 1$, hence, maximum value of current,

$$I_{max} = \frac{V_{max}}{\omega L}$$

and instantaneous current may be expressed as $i = I_{max} \sin\left(\omega t - \frac{\pi}{2}\right)$

From the expressions of instantaneous applied voltage and instantaneous current flowing through apurelyinductive coil it is observed that the current lags behind the applied voltage by π/2 as shown inFig.4.2(b)bywavediagramandinFig4.2(c)byphasordiagram.

InductiveReactance:
ωL intheexpressionImax=V_{max}/ωLisknownasinductivereactanceandisdenotedbyX_Li.e., X_L=ω

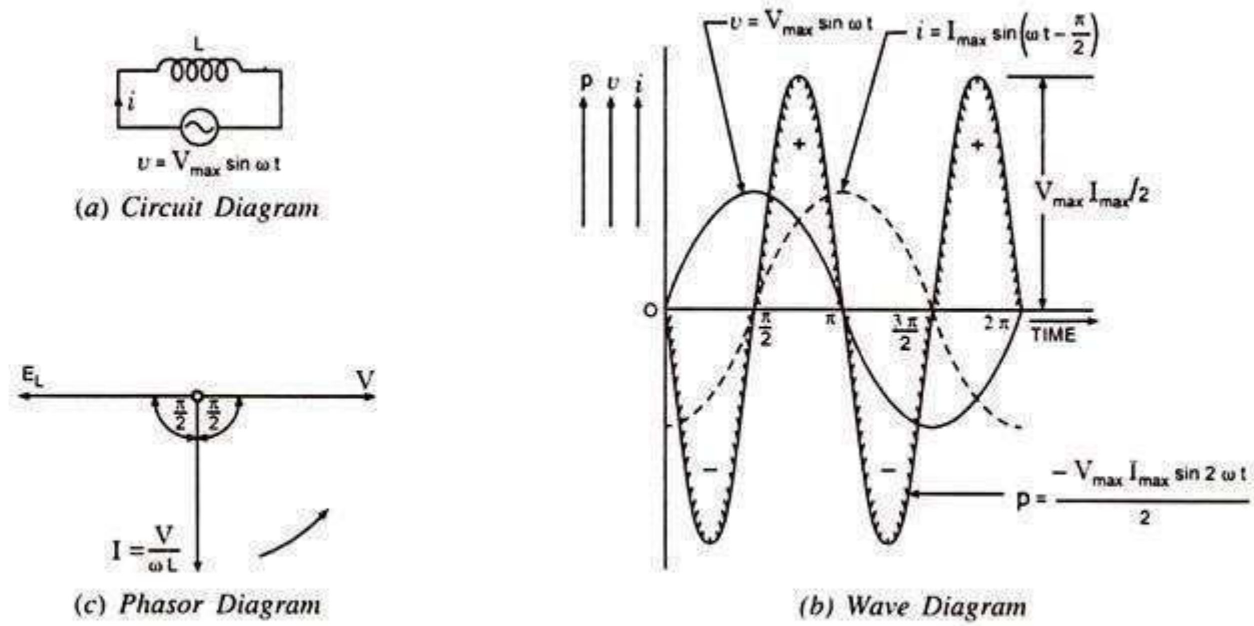


Fig. 4.2 *Purely Inductive Circuit*

LIfLisinhenryandcoisinradianspersecondthen$X_L$willbeinohms.

PowerinPurelyInductiveCircuit:
Instantaneous power, p = v × i = V_{max} sin ω tI_{max} sin (ωt– π/2)Or p = – V_{max} I_{max} sin ω t cos ω t =$V_{max}I_{max}$/2sin2ωt

Thepowermeasuredbywattmeteristheaveragevalueofpwhichiszerosinceaverageof asinusoidalquantity of double frequency over a complete cycle is zero. Hence in a purely inductive circuitpowerabsorbedis zero.

Physicallytheabovefactcanbeexplainedasbelow:
During the second quarter of a cycle the current and the magnetic flux of the coil increases and the coildraws power from the supply source to build up the magnetic field (the power drawn is positive and theenergy drawn by the coil from the supply source is represented by the area between the curve p and thetimeaxis).Theenergystoredinthemagneticfieldduring buildupisgivenasW_{max}=1/2LI^2_{max}.

Inthenextquarterthecurrentdecreases.Theemfofself-inductionwill,however,tendstoopposeits

decrease. The coil acts as a generator of electrical energy, returning the stored energy in the magneticfield to the supply source (now the power drawn by the coil is negative and the curve p lies below thetime axis).The chain of events repeats itself during the next half cycles. Thus, a proportion of power iscontinually exchanged between the field and the inductive circuit and the power consumed by a purelyinductivecoiliszero.

PurelyCapacitiveCircuit:

When a dc voltage is impressed across the plates of a perfect condenser, it will become charged to fullvoltage almost instantaneously. The charging current will flow only during the period of “build up” andwillcease to flow as soon as the capacitor has attained the steady voltage of the source. This implies thatforadirectcurrent,acapacitorisabreakinthecircuitoraninfinitelyhighresistance.

In Fig. 4.4 a sinusoidal voltage is applied to a capacitor. During the first quarter-cycle, the appliedvoltageincreasesto the peak value, and the capacitor is charged to that value. The current is maximum in the beginning of the cycle and becomes zero at the maximum value of the applied voltage, so there is aphase difference of 90° between the applied voltage and current. During the first quarter-cycle thecurrent flowsinthe normaldirectionthroughthe circuit;hence the currentispositive.

In the second quarter-cycle, the voltage applied across the capacitor falls, the capacitor loses its charge,and current flows through it against the applied voltage because the capacitor discharges into the circuit.Thus, the current is negative during the second quarter-cycle and attains a maximum value when theappliedvoltageis zero.

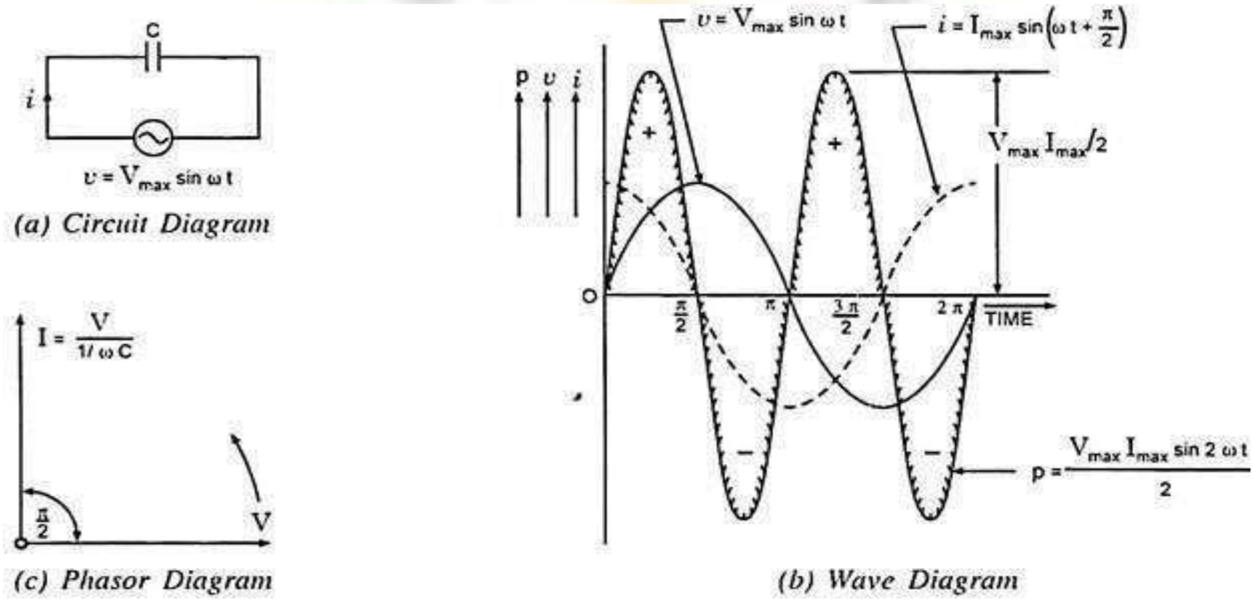


Fig. 4.4 *Purely Capacitive Circuit*

The third and fourth quarter-cycles repeat the events of the first and second, respectively, with thedifference that the polarity of the applied voltage is reversed, and there arecorrespondingcurrentchanges.

In other words, an alternating current flow in the circuit because of the charging and discharging of thecapacitor. As illustrated in Figs. 4.4 (b) and (c) the current begins its cycle 90 degrees ahead of thevoltage, so the current in a capacitor leads the applied voltage by 90 degrees – the opposite of theinductancecurrent-voltagerelationship.

Let an alternating voltage represented by $v = V_{max} \sin \omega t$ be applied across a capacitor of capacitanceCfarads.

Theexpressionforinstantaneouschargeisgivenas:

$q = CV_{max} \sin\omega t$

Sincethecapacitorcurrentisequaltotherateofchangeofcharge, thecapacitorcurrentmaybeobtainedbydifferentiatingtheaboveequation:

Fromtheequationsofinstantaneousappliedvoltageandinstantaneouscurrentflowingthroughcapacitance,

itis observed that the currentleads the appliedvoltage by π/2, as shown in Figs. 4.4 (b) and (c) bywaveandphasordiagramsrespectively.

$$i = \frac{dq}{dt} = [C\,V_{max} \sin \omega t] = \omega C\,V_{max} \cos \omega t = \frac{V_{max}}{1/\omega C} \sin\left(\omega t + \frac{\pi}{2}\right)$$

Current is maximum when $t = 0$

$$\therefore \quad I_{max} = \frac{V_{max}}{1/\omega C}$$

Substituting $\frac{V_{max}}{1/\omega C} = I_{max}$ in the above equation for instantaneous current, we get

$$i = I_{max} \sin\left(\omega t + \frac{\pi}{2}\right)$$

CapacitiveReactance:

$1/\omega C$ in the expression $I_{max} = V_{max}/1/\omega C$ is known as capacitive reactance and is denoted by X_Ci.e.,$X_C = 1/\omega C$IfCisin faradsandωisinradians/s,then$X_C$willbeinohms.

PowerinPurelyCapacitiveCircuit:

$$p = v\,i = V_{max} \sin \omega t.\, I_{max} \sin\left(\omega t + \frac{\pi}{2}\right) = V_{max}\, I_{max} \sin \omega t \cos \omega t$$

$$= \frac{V_{max}\, I_{max}}{2} \sin 2\omega t$$

Average power, $P = \frac{V_{max}\, I_{max}}{2} \times$ average of $\sin 2\omega t$ over a complete cycle = 0.

Hence power absorbed in a purely capacitive circuit is zero. The same is shown graphically in Fig. 4.4(b). The energy taken from the supply circuit is stored in the capacitor during the first quarter- cycle andreturnedduringthenext.

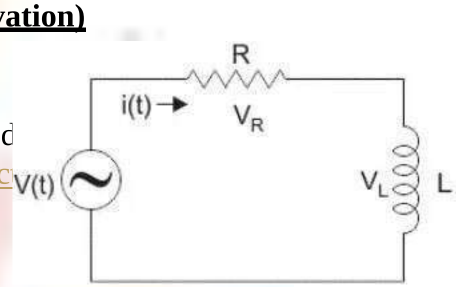
Theenergystoredbyacapacitoratmaximumvoltageacrossitsplatesisgivenbytheexpression:

$$W_C = \frac{1}{2} C V^2_{max}$$

This can be realized when it is recalled that no heat is produced and no work is done while current isflowing through a capacitor. As a matter of fact, in commercial capacitors, there is a slight energy loss inthe dielectric in addition to a minute I^2 R loss due to flow of current over the plates having definite ohmicresistance.

The power curve is a sine wave of double the supply frequency. Although it raises thepower factorfrom zero to 0.002 or even a little more, but for ordinary purposes the power factor is taken to be zero.Obviouslythe phase angle due todielectric andohmiclossesdecreasesslightly.

RLSeriesCircuitAnalysis(PhasorDiagram,Examples&Derivation)

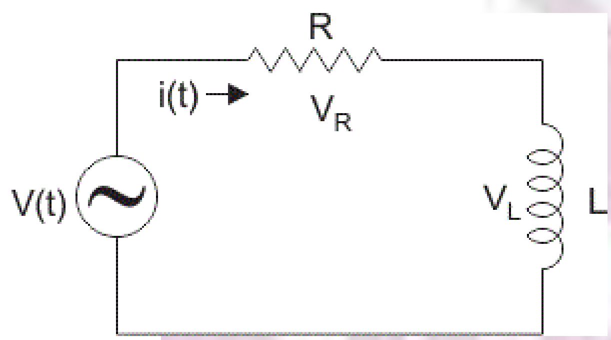


An RL circuit (also known as an RL filter or RL network) is d ... isting ofthe passive circuit elementsof a resistor (R) and an induc... by a voltagesourceorcurrentsource.

Duetothepresenceofaresistorintheidealformofthe

circuit,anRLcircuitwillconsumeenergy,akintoanRCcircuitorRLCcircuit.

This is unlike the ideal form of an LC circuit, which will consume no energy due to the absence of aresistor. Although this is only in the ideal form of the circuit, and in practice, even an LC circuit willconsumesomeenergybecauseofthenon-zeroresistanceofthe componentsandconnectingwires.



Consider a simple RL circuit in which resistor, R and inductor, L are connected in series with a voltagesupply of V volts. Let us think the currentflowing in the circuit is I (amp) and current through resistorand inductoris I_R and I_L respectively. Since both resistanceand inductor are connected in series, so thecurrent in both the elements and the circuit remains the same. i.e $I_R = I_L = I$. Let V_R and V_l be thevoltagedropacross resistor andinductor.

ApplyingKirchhoffvoltagelaw(i.esumofvoltagedropmustbeequaltoapplyvoltage)tothiscircuit

$$V = V_R + V_L$$

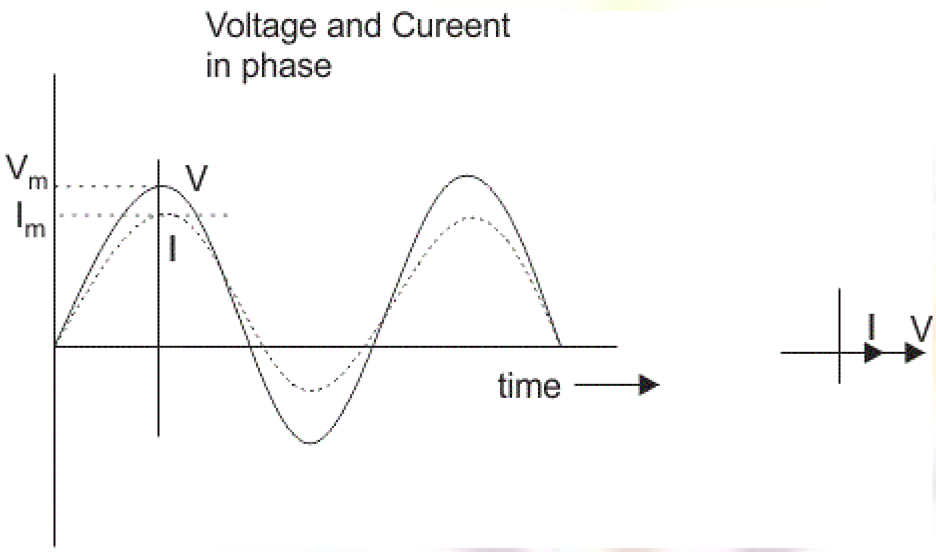
weget,

PhasorDiagramforRLCircuit

Beforedrawingthe**phasordiagramofseriesRLcircuit**,oneshouldknowtherelationship betweenvoltageandcurrentincaseofresistorandinductor.

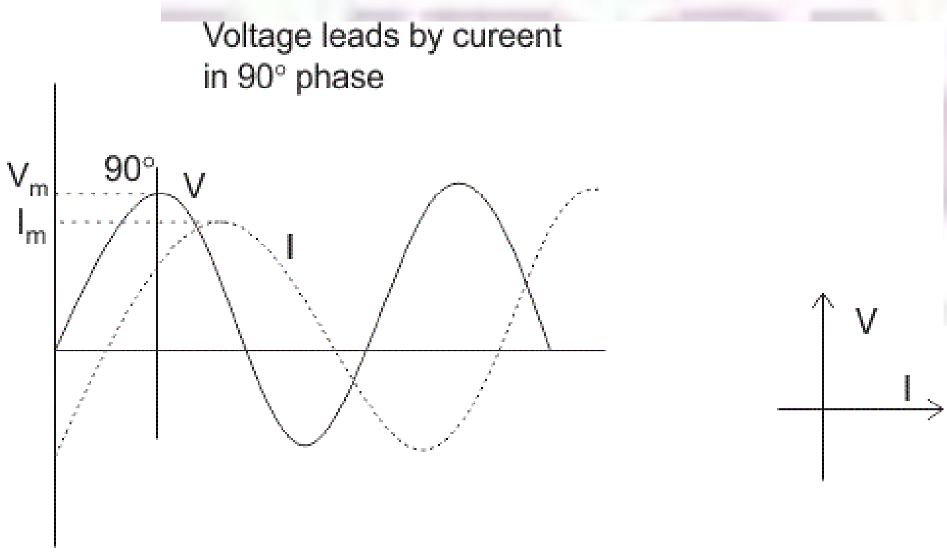
Resistor

Incaseofresistor,thevoltageandthecurrentareinsamephaseorwecansaythatthephaseangledifferencebetweenvoltage andcurrentiszero.



Inductor

Ininductor,thevoltageandthecurrentarenotinphase.Thevoltageleadsthatofcurrentby90^oorinotherwords,volt ageattainsitsmaximumandzerovalue90^obeforethecurrentattainsit.



RLCircuit

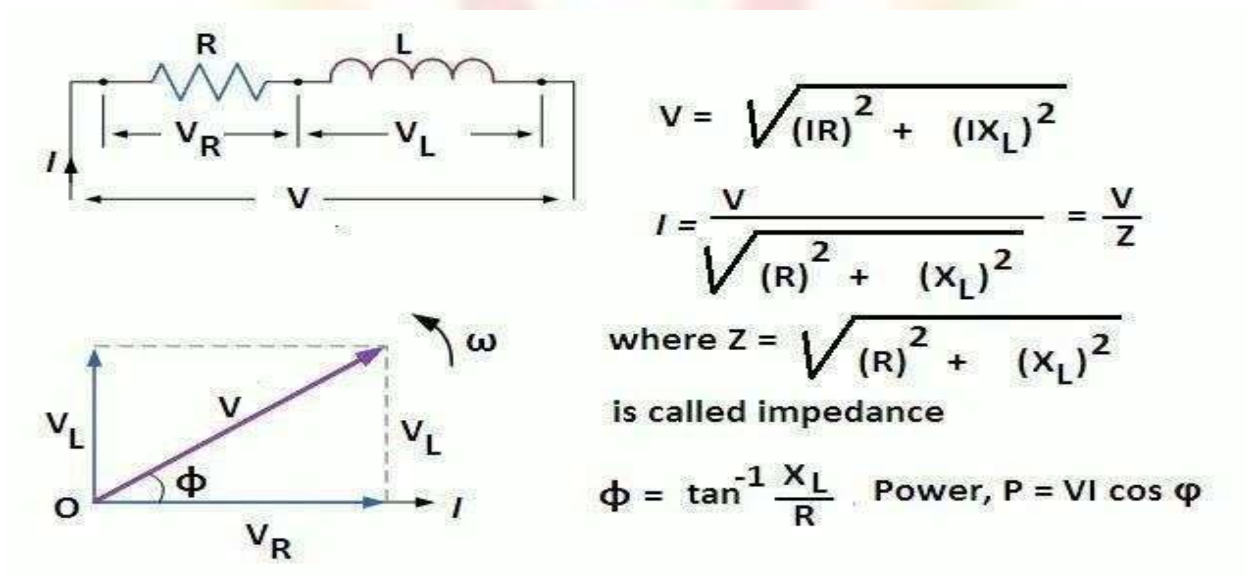
FordrawingthephasordiagramofseriesRLcircuit;followthefollowingsteps:

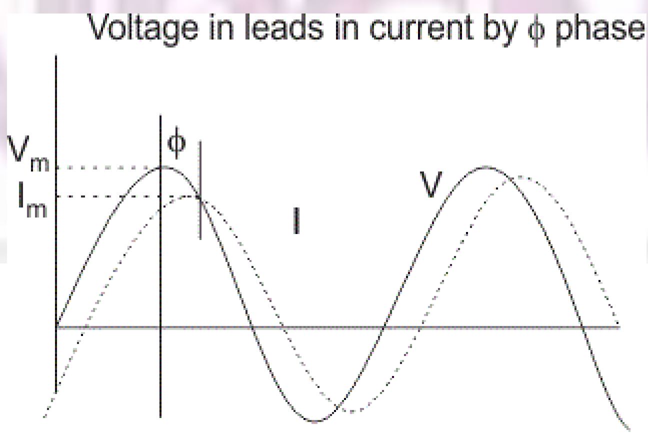
Step- I. In case of series RL circuit, resistor and inductor are connected in series, so current flowing inboth the elements are same i.e I_R = I_L = I. So, take current phasor as reference and draw it on horizontalaxisas shownindiagram.

Step- II. In case of resistor, both voltage and current are in same phase. So draw the voltage phasor, $V_R$along same axis or direction as that of current phasor. i.e V_R is in phase with I. **Step- III.** We know thatin inductor, voltage leads current by 90°, so draw V_L (voltage drop across inductor) perpendicular tocurrentphasor.

Step- IV. Now we have two voltages V_R and V_L. Draw the resultant vector(V_G) of these two voltages.Suchas,

an$V_R^2 + V_L^2 = V_G^2$ingleweget,phaseangle $\theta = \tan^{-1}(V_L^1/V_R^2)$

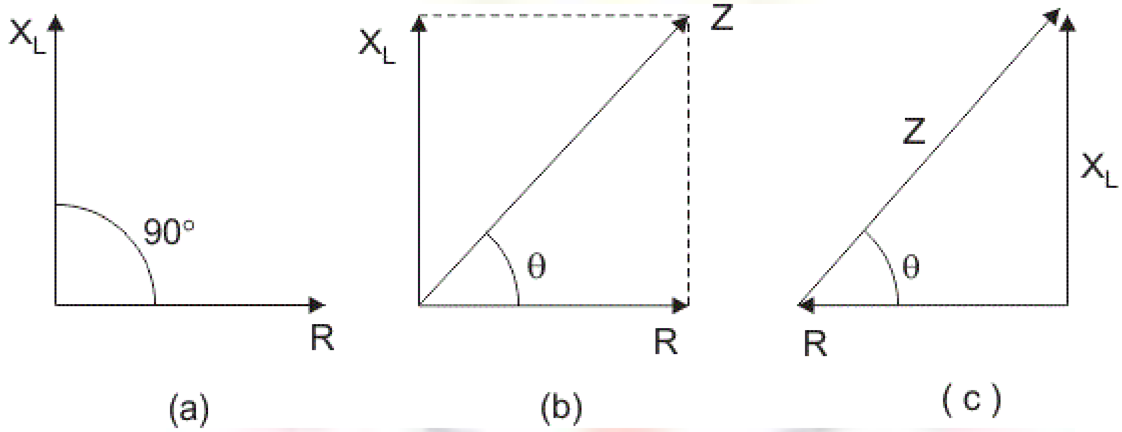




CONCLUSION: In case of pure resistive circuit, the phase angle between voltage and current is zero and in case of pure inductive circuit, phase angle is 90° but when we combine both resistance and inductor, the phase angleofaseriesRLcircuitis between0° to90°.

ImpedanceofSeriesRLCircuit
Theimpedanceofseries RL circuitopposestheflowofalternatingcurrent.
TheimpedanceofseriesRLCircuitisnothingbutthecombineeffectofresistance(R)andinductivereactance(X_L) ofthecircuitasawhole.TheimpedanceZinohmsis givenby,

$Z=(R^2+X_L^2)^{0.5}$ andfromrightangletriangle,phaseangle$\theta=\tan^{-1}(X_L/R)$.



SeriesRLCircuitAnalysis
In series RL circuit, the values of frequency f, voltage V, resistance R and inductanceL are known andthere is no instrument for directly measuring the value of inductive reactance and impedance; so, forcompleteanalysisofseriesRLcircuit,followthesesimplesteps:

Step 1. Since the value of frequency and inductor are known, so firstly calculate the value of inductivereactanceX_L:$X_L=2\pi fL$ ohms.

Step2. Fromthevalueof$X_L$andR,calculatethetotalimpedanceofthecircuitwhichisgivenby
$$Z=\sqrt{(R^2+X_L^2)}$$

Step3. Calculatethetotalphaseanglefor thecircuit$\theta=\tan^{-1}(X_L/R)$.

Step4. UseOhm'sLawandfindthevalueofthetotalcurrent:I=V/Zamp.

Step5. CalculatethevoltagesacrossresistorRandinductor LbyusingOhm'sLaw.Sincethe

$V_R = RI \ Volts \ and \ V_L = X_L I \ Volts$
resistorandtheinductorareconnectedinseries,socurrentinthemremainsthesame.

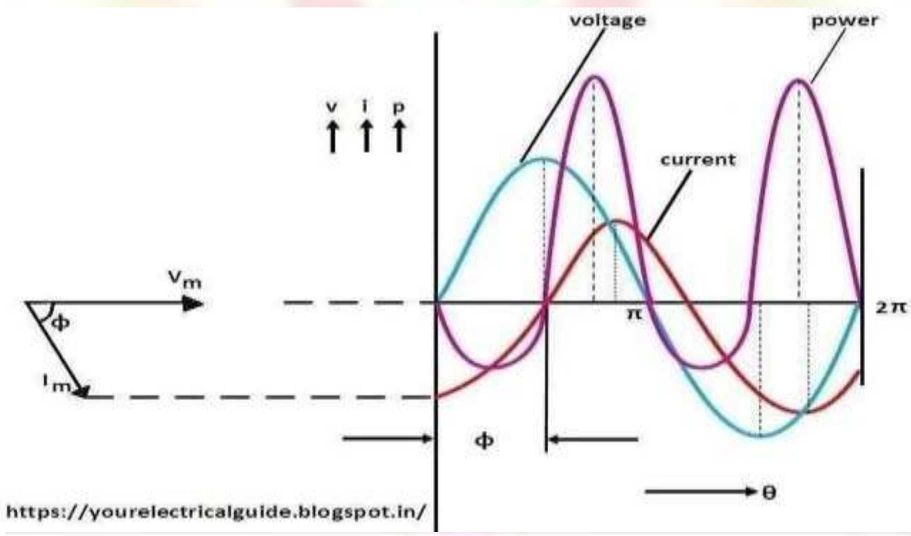
PowerinanRLCircuit
InseriesRLcircuit,someenergyisdissipatedbytheresistorandsomeenergyisalternatelystoredandreturnedbytheinductor-

1. Theinstantaneouspowerdeliverbyvoltagesource VisP =VI(watts).
2. Power dissipatedbytheresistorintheformofheat,P=I^2R(watts).
3. Therateatwhichenergyisstoredin inductor,

$$P = V_L I = LI\frac{dI}{dt} \ (watts)$$

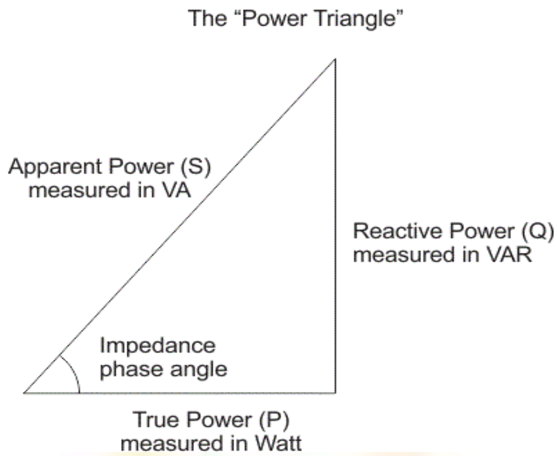
PowerinseriesRLcircuitisgivenbyaddingthepowerdissipatedbytheresistorandthepowerbytheinductor.

$$P = I^2R + LI\frac{dI}{dt}$$



The power waveform for RL series circuitis shown in the figure. In thisfigure, voltage wave isconsidered as a reference. The points for the power waveform are obtained from the product of thecorrespondinginstantaneous values ofvoltageandcurrent.

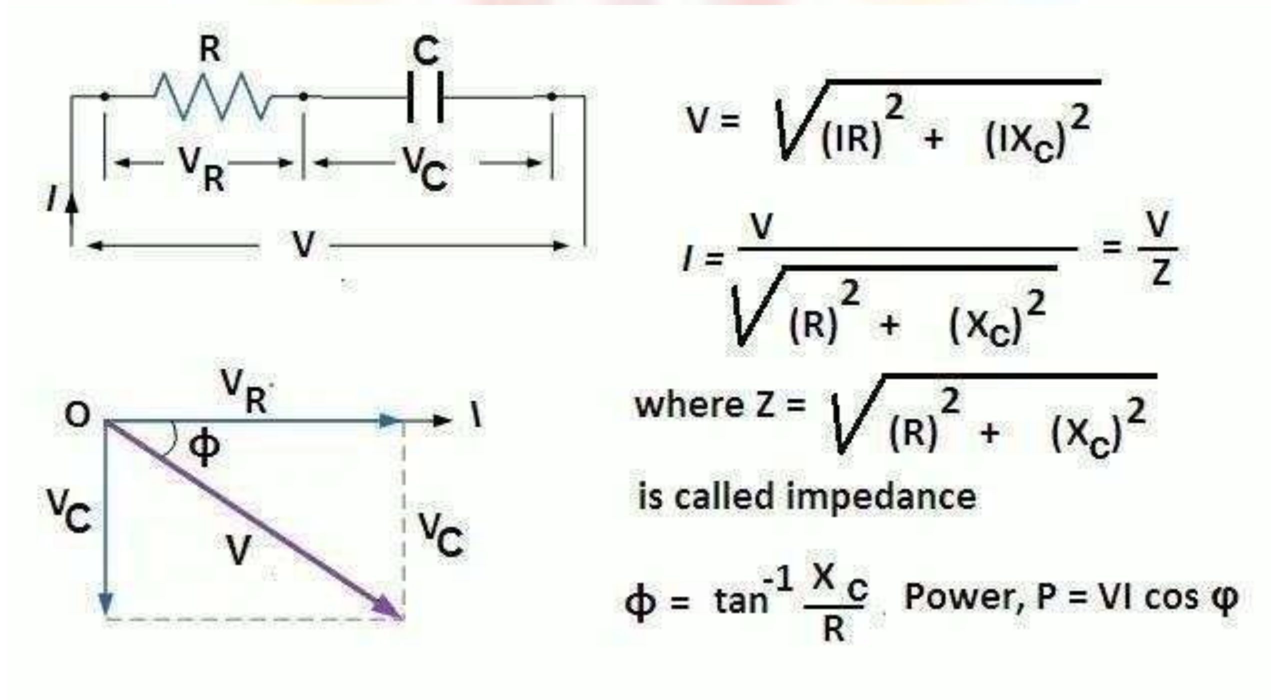
Itisclearfromthepowerwaveformthatpowerisnegativebetween0andφandbetween$180^o$and(180^o +φ).Thepowerispositiveduringrestofthecycle.



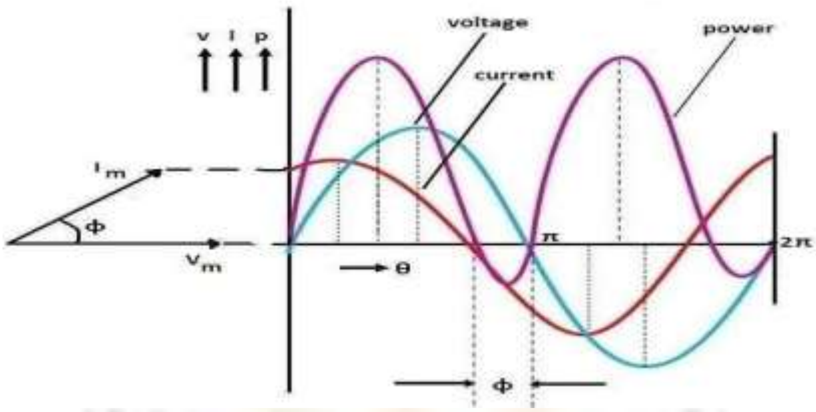
PowertriangleforseriesRLcircuitisshownbelow,

Theelectricalpowerfactorcosθisdefined asratioofthetruepowertoapparentpower.

RCSeriesCircuit



In an RC series circuit, a pure resistance (R) is connected in series with a pure capacitor (C). To draw thephasor diagram of RC series circuit, the current*I*(RMS value) is taken asreferencevector.VoltagedropV$_R$isinphasewithcurrentvector,whereas,the voltagedropin capacitivereactanceV$_C$lagsbehindthecurrentvectorby90^o,since current leads the voltage by 90^{o}in the pure capacitive circuit. The vector sum of these two voltagedropsis equaltotheappliedvoltageV(RMSvalue).



The power waveform for RC series circuitis shown in the figure. In this figure, voltage wave isconsidered as a reference. The points for the power waveform are obtained from the product of thecorresponding instantaneous values of voltage and current. It is clear from the power waveform thatpower is negative between (180^{o}– φ) and 180^{o}and between (360^{o}– φ) and 360^{o}. The power ispositiveduringrestofthecycle.

Since the area under the positive loops is greater than that under the negative loops, the net power over acomplete cycle is positive. Hence a definite quantity of power is consumed by the RC series circuit. Butpowerisconsumedinresistanceonly;capacitordoesnotconsumeanypower.

RLCCIRCUIT:

In an **RLC circuit**, the most fundamental elements of a resistor, inductor, and capacitorare connectedacross a voltagesupply. All of these elements are linear and passive in nature. Passive componentsareones that consume energy rather than producing it; linear elements are those which have a linearrelationshipbetweenvoltageandcurrent.

There are number of ways of connecting these elements across voltage supply, but the most commonmethod is toconnect these elements eitherin series or in parallel. The**RLC circuit**exhibits theproperty of resonance in same way as LC circuit exhibits, but in this circuit the oscillation dies outquicklyascomparedtoLC circuitdue tothepresence ofresistorinthe circuit.

SeriesRLCCircuit

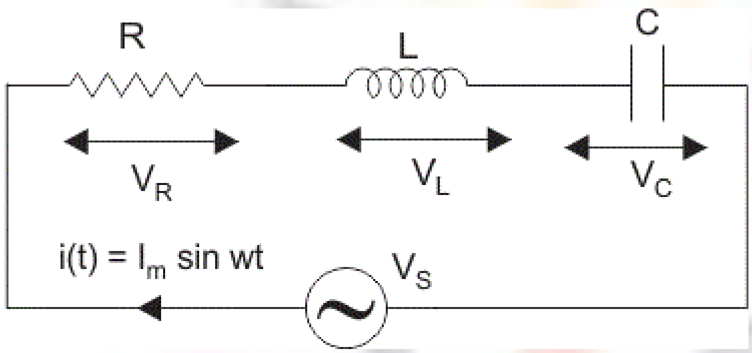
Whenaresistor,inductorandcapacitorareconnectedinserieswiththevoltagesupply,thecircuitsoformedis calledseriesRLCcircuit.

Sinceallthesecomponentsareconnectedinseries,thecurrentineachelementremainsthesame,

$$I_R = I_L = I_C = I(t) \ where \ I(t) = I_M \sin \omega t$$

Let$V_R$bethevoltageacrossresistor,R.$V_L$bethevoltageacrossinductor,L.$V_C$bethevolta

geacrosscapacitor,C.$X_L$betheinductivereactance.



$X_C$bethecapacitivereactance.

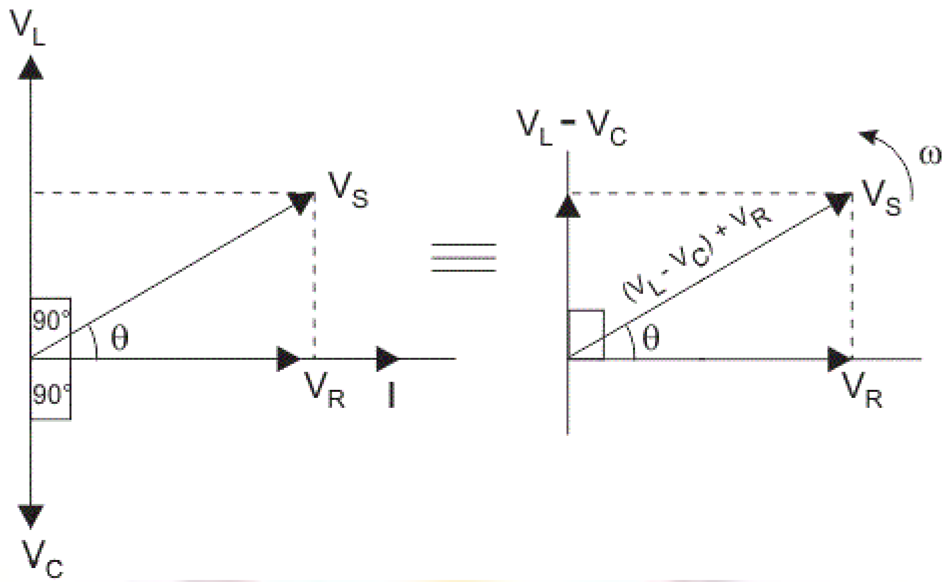
The total voltage in the RLC circuit is not equal to the algebraic sum of voltages across the resistor, theinductor, and the capacitor; but it is a vector sum because, in the case of the resistor the voltage is in-phasewith the current, for inductor the voltage leadsthecurrentby 90^oandforcapacitor, thevoltagelagsbehindthecurrentby90^o.

So,voltagesineachcomponentarenotinphasewitheachother;sotheycannotbeaddedarithmetically. The figure below shows the phasor diagram of the series RLC circuit. For drawing thephasor diagram for RLC series circuit, the current is taken as reference because, in series circuit thecurrent in each element remains the same and the corresponding voltage vectors for each component aredrawn inreferencetocommoncurrentvector.

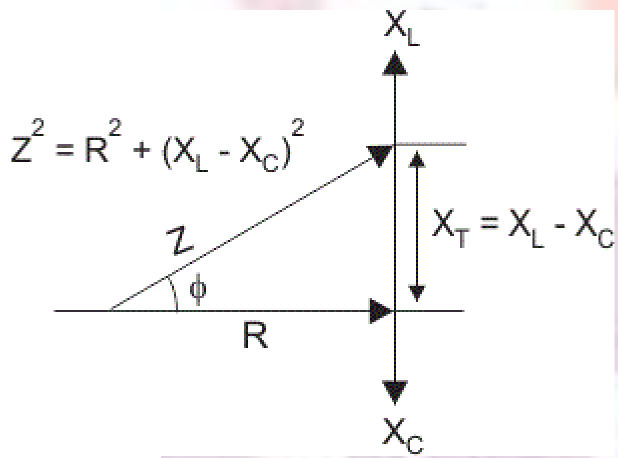
$$V_S^2 = V_R^2 + (V_L - V_C)^2 (if V_L > V_C)$$

$$V_S^2 = V_R^2 + (V_L - V_C)^2 (if V_L < V_C)$$

$$Where \ V_R = IR, V_L = IX_L, V_C = IX_C$$



TheImpedance fora SeriesRLC Circuit



The impedance Z of a series RLC circuit is defined as opposition to the flow of current duecircuitresistanceR,inductivereactance,$X_L$andcapacitivereactance,X_C.Ifthe inductive reactance isgreaterthanthecapacitivereactancei.e$X_L>X_C$,thentheRLCcircuithaslaggingphaseangleandif the capacitive reactance is greater than the inductive reactance i.e $X_C> X_L$then, the RLC circuithaveleadingphaseangleandifbothinductiveandcapacitivearesamei.e$X_L=X_C$thencircuitwillbehavea spurelyresistivecircuit.

Weknowthat

$$V_S^2 = V_R^2 + (V_L - V_C)^2$$

Where,

$$V_R = IR, V_L = I\ X_L, V_C = I\ X_C$$

Substitutingthevalues

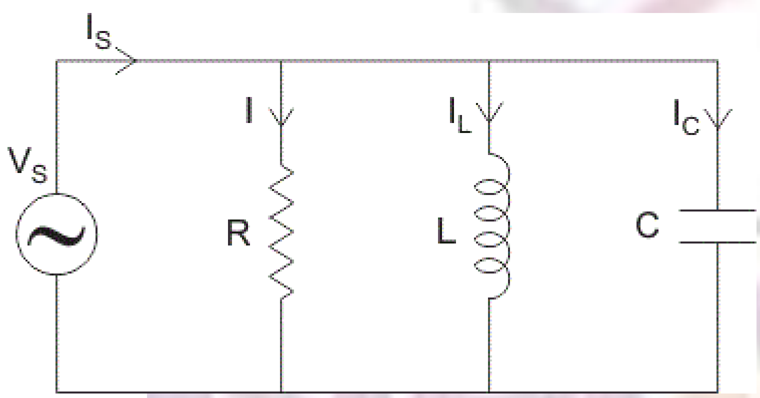
$$V_S^2 = IR^2 + (I\ X_L - I\ X_C)^2$$

$$V_S = I\sqrt{R^2 + (X_L - X_C)^2}\ or\ impedance\ Z = \sqrt{R^2 + (X_L - X_C)^2}$$

ParallelRLCCircuit

In parallel RLC Circuitthe resistor, inductor and capacitor are connected in parallel across a voltagesupply. The parallel RLC circuit is exactly opposite to the series RLC circuit. The applied voltageremainsthe sameacrossallcomponents andthe supplycurrentgetsdivided.

The total current drawn from the supply is not equal to mathematical sum of the current flowing in theindividual component, but it is equal to its vector sum of all the currents, as the current flowing inresistor, inductor and capacitor are not in the same phase with each other; so they cannot be addedarithmetically.

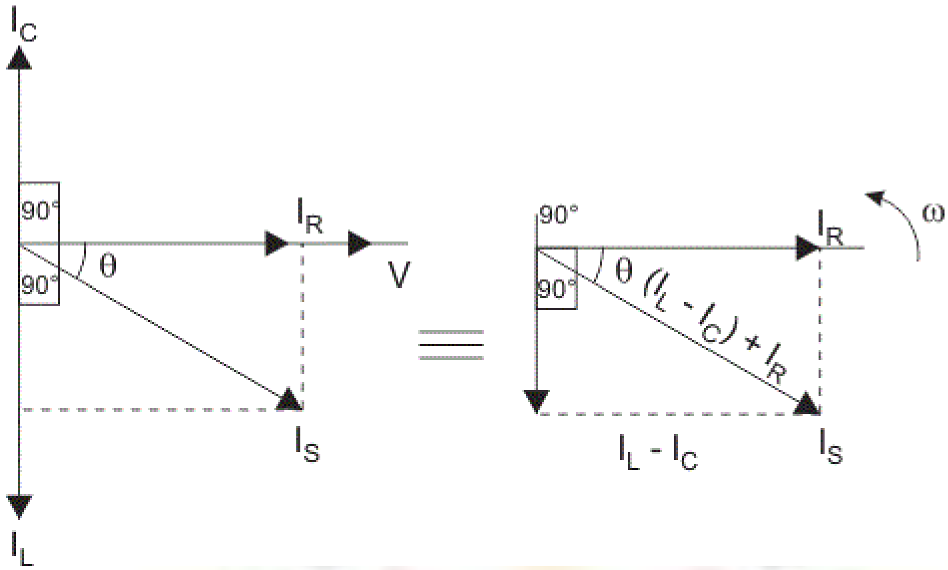


PhasordiagramofparallelRLCcircuit,$I_R$isthecurrentflowingintheresistor,Rinamps.$I_C$isthe

currentflowinginthe capacitor,Cin amps.

$I_L$isthecurrentflowinginthe inductor,Linamps.

$I_S$isthesupplycurrentinamps.IntheparallelRLCcircuit,allthecomponentsareconnectedinparallel;so the voltageacross each element is same. Therefore, for drawing phasor diagram, take voltage asreferencevectorandall theothercurrents i.eI_R, I_C,$I_L$aredrawnrelativeto this voltage vector. Thecurrent througheachelementcanbefoundusingKirchhoff'sCurrentLaw, which states that the sum of currents entering a junction or node is equal to the sum ofcurrentleavingthatnode.



$$I_S^2 = I_R^2 + (I_L - I_C)^2$$

$$Now,\ I_R = \frac{V}{R}, I_C = \frac{V}{X_C}\ and\ I_L = \frac{V}{X_L}$$

$$I_S = \sqrt{\frac{V^2}{R^2} + \left(\frac{V}{X_L} - \frac{V}{X_C}\right)^2}$$

$$So,\ admitance,\ \frac{1}{Z} = \frac{I_S}{V} = Y = \sqrt{\frac{1}{R^2} + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}$$

As shown above in the equation of impedance, Z of a parallel RLC circuit; each element has reciprocalof impedance (1 / Z) i.e. admittance, Y. So in parallel RLC circuit, it is convenient to use admittanceinsteadofimpedance.

ResonanceinRLCCircuit

Inacircuitcontaininginductor andcapacitor,theenergy isstoredintwo differentways.

1. Whenacurrentflowsininductor,energyisstoredinmagneticfield.

Whenacapacitorischarged,energyisstoredinstaticelectricfield.Themagneticfieldintheinductorisbuilt by the current, which gets provided by thedischarging capacitor. Similarly, the capacitor is chargedby the current produced by collapsing magnetic field of inductor and this process continues on and on,causingelectricalenergytooscillatebetweenthemagneticfieldandtheelectricfield.

In some cases at certain a certain frequency known as the resonant frequency, the inductive reactance ofthe circuit becomes equal to capacitive reactance which causes the electrical energy to oscillate betweenthe electric field of the capacitor and magnetic field of the inductor. This forms a harmonic oscillatorforcurrent. In **RLC circuit**, the presence of resistor causes these oscillation s to die out over period of timeanditis calledas the dampingeffectofresistor.

FORMULAFORRESONANTFREQUENCY

$$X_L = X_C$$

$$We\ know\ that,\ X_L = 2\pi f L\ and\ X_C = \frac{1}{2\pi f C}$$

$$Therefore\ at\ resonant\ frequency,\ f_r :, 2\pi f_r L = \frac{1}{2\pi f_r C}$$

$$or\ f = \frac{1}{2\pi\sqrt{LC}}$$

Duringresonance,atcertainfrequencycalledresonantfrequency,f_r.

When resonance occurs, the inductive reactance of the circuit becomes equal to capacitive reactance,which causes the circuit impedance to be minimum in case of series RLC circuit; but when resistor,inductor and capacitor are connected in parallel, the circuitimpedance becomes maximum, so theparallelRLC circuitis sometimescalledasanti-resonator.Note

thatthelowestresonantfrequencyofavibratingobjectisknownas itsfundamentalfrequency

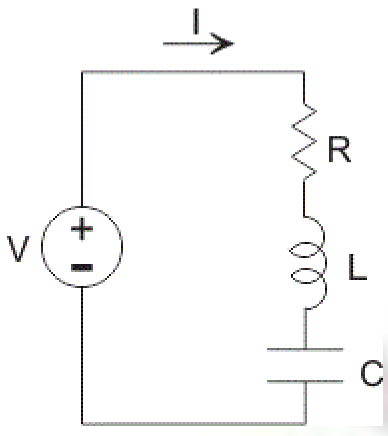
DIFFERENCEBETWEENSERIESRLCCIRCUITANDPARALLELRLCCIRCUIT

.	RLCSERIESCIRCUIT	RLCPARALLELCIRCUIT
1	Resistor,inductorandcapacitorareconnectedinseries	Resistor,inductorandcapacitor areconnectedinparallel
2	Currentissameineachelement	Currentisdifferentinallelements and thetotal currentisequal tovector sum o each branch ofcurrenti.e $I^2 = I^2 + (I–$ sR $I_L)^2$

3	Voltageacrossalltheelementsisdifferentandthetotalvoltageisequaltothevectorsum of voltagesacrosseachcomponenti.eV_S =V_R + 2 (V_L–V_C)^2	Voltageacrosseachelementremainsthsame
4	Fordrawingphasordiagram,currentistakenasreferencevector	For drawing phasor diagram,voltage is taken as referencevector
5	Voltageacrosseachelementisgivenby :V_R=IR,V_L=IX_L,V_C=IX_C	Currentineachelementisgivenby :I_R=V/R,I_C=V /X_C,I_L=V/X_L
6	Its moreconvenienttouse impedanceforcalculations	Itsmoreconvenienttouseadmittancefor calculations
7	Atresonance,whenX_L =X_C,thecircuithasminimumimpedance	Atresonance,whenX_L=X_C, the circuit has maximumimpedance

EquationofRLCCircuit

Considera**RLCcircuit**havingresistor R,inductor L, andcapacitor C connectedinseries andaredrivenbyavoltagesourceV.LetQbethechargeonthecapacitorandthecurrentflowinginthecircuit



$$L.I'(t) + Q.I(t) + \frac{1}{C}Q(t) = V(t)$$

isI.ApplyKirchhoff'svoltagelaw

In this equation; resistance, inductance, capacitanceand voltage are known quantities but current andcharge are unknown quantities. We know that an current is a rate of electric charge flowing, so it isgivenby

DifferentiatingagainI'(t)=Q''(t)

$$L.Q''(t) + R.Q'(t) + \frac{1}{C} = V(t)$$

Differentiatingtheaboveequationwithrespectto't'weget,

$$L.I''(t) + Q.I'(t) + \frac{1}{C}I(t) = V'(t)$$

Now at time t = 0, V(0) = 0 and at time t = t, V(t) = $E_O$sinωt Differentiating with respect to 't' we getV'(t)=ω$E_O$cosωtSubstitutethe valueofV'(t)inabove equation

$$L.I''(t) + R.I'(t) + \frac{1}{C}I(t) = \omega E_o \cos \omega t$$

LetussaythatthesolutionofthisequationisI_P(t)=Asin(ωt–ǿ)andifI_P(t)isasolutionofaboveequationthenitmustsatisfythis equation,

$$L.I_P(t) + R.I_P(t) + \frac{1}{C}I_P(t) = \omega E_o \cos \omega t$$

NowsubstitutethevalueofI_P(t)anddifferentiateitweget,

$$\frac{dQ}{dt}(t) = I(t) \ or \ I(t) = Q(t)$$

$$-L\omega 2A\sin(\omega t-\phi)+R\omega A\cos(\omega t-\phi)+\frac{1}{C}A\sin(\omega t-\phi)=\omega E_o\cos\omega t$$

$$-L\omega 2A\sin(\omega t-\phi)+R\omega A\cos(\omega t-\phi)\frac{1}{C}A\sin(\omega t-\phi)=\omega E_o\cos(\omega t-\phi+\phi)$$

Applytheformulaofcos(A+B)andcombinesimilartermsweget,

$$\left(\frac{1}{C}-L\omega^2\right)A\sin(\omega t-\phi)+R\omega A\cos(\omega t-\phi)$$

$$=\omega E_o\cos\phi\cos(\omega t-\phi)-\omega E_o\sin\phi\cos(\omega t-\phi)$$

Matchthecoefficientofsin(ωt–φ)andcos(ωt–φ)onbothsidesweget,

$$\left(-\frac{1}{C}+2L\omega\right)A=\omega E_o\sin\phi\ and\ R\omega A=\omega E_o\cos\phi$$

Now we have two equations and two unknowns i.e φ and A, and by dividing theabove two equations weget,

$$\tan\phi=\frac{-\frac{1}{C}+2L\omega}{R\omega}$$

Squaringandaddingaboveequation,weget

$$A\sqrt{\left(-\frac{1}{C}+2L\omega\right)^2+(R\omega)^2}=\omega\ E_o$$

$$or\ A=\frac{\omega\ E_o}{\sqrt{\left(-\frac{1}{C}+2L\omega\right)^2+(R\omega)^2}}$$

AnalysisofRLCCircuitUsing

LaplaceTransformationStep1: Drawaphasordiagramforgi

vencircuit.

Step2: UseKirchhoff'svoltagelawinRLCseriescircuitandcurrentlawinRLCparallelcircuittoformdifferentia lequationsinthetime-domain.

Step 3 : Use Laplace transformationto convert these differential equations from time- domain into the s-domain.

Step4: Forfindingunknownvariables,solvetheseequations.

Step5: ApplyinverseLaplacetransformationtoconvertbackequationsfroms-domainintotimedomain.

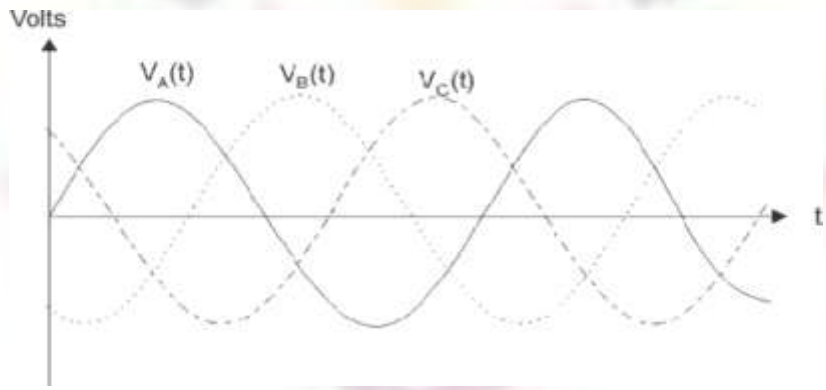
ApplicationsofRLCCircuit

Itisusedaslowpassfilter,highpassfilter,band-passfilter,band-stopfilter,voltagemultiplierandoscillatorcircuit.Itis usedfortuningradiooraudioreceiver.

BALANCEDTHREEPHASECIRCUITS:

There are two types of systems available in electrical circuits, single phase and three phase. Insingle phase circuits, there will be only one phase, i.e the current will flow through only one wire andthere will be one return path called neutral line to complete the circuit. So in single phase minimumamount of power can be transported. Here the generating station and load station will also be singlephase.

Threephasecircuitisthepolyphasesystemwherethreephasesaresendtogetherfromgeneratortothe load. Each phase are having a phase difference of 1200 ,i.e 1200 angle electrically. So from thetotal of 3600 , three phase are equally divided into 1200 each. The power in three phase system iscontinuous as all the three phases are involved in generating the total power. The sinusoidal waves for 3phasesystemis shownbelow.



The three phase can be used as single phase each. So if the load is single phase, then one phase can betakenfromthethree phasecircuitand the neutralcanbeusedasgroundtocompletethe circuit.

Whythreephaseispreferredoversinglephase?

There are various reasons for this question because there are numbers of advantages over single phasecircuit. The three phase system can be used as three single phase line so it can act as three single phasesystem. The three phase generation and single phase generation is same in the generator except thearrangement of coil in the generator to get 1200 phase difference. The conductor needed in three phasecircuitis75%thatofconductorneededinsinglephasecircuit.

And also the instantaneous power in single phase system falls down to zero as in single phase we can seefrom the sinusoidal curve but in three phase system the net power from all the phases gives a continuouspowertotheload.

Till now we can say that there are three voltage sources connected together to form a three phasecircuit and actually it is inside generator. The generator is having three voltage sources which are actingtogetherin1200phasedifference.Ifwecanarrangethreesinglephasecircuitwith120Dphasedifference,then it will become a three phase circuit. So 120D phase difference is must otherwise the circuit will notwork,thethreephaseloadwillnotbeabletogetactiveandit mayalsocausedamagetothesystem.

The size or metal quantity of three phase devices is not having much difference. Now of weconsider the transformer, it will be almost same size from both single phase and three phase becausetransformer will make only the linkage of flux. So the three phase system will have higher efficiencycomparedtosinglephaseforthesameorlittledifferenceinmassoftransformer,threephaselinewillbe out whereas in single phase will be only one. And losses will be minimum in three phase circuit. Sooverall in conclusion the three phase system will have better and higher efficiency compared to thesingle phasesystem.

A balanced polyphase system is one in which there are two or more equal voltages of the samefrequency displaced equally in time phase, which supply power to loads connected to the lines. Ingeneral, in a n-phase balanced polyphase system, there are n-equal voltages displaced in time phase by360degree

n or 2π n (except in the case of a 2-phase system, in which there are two equal voltages differing inphase by 90D). Systems of six or more phases are used in polyphase rectifiers to obtain rectified voltagewith low ripple. But three phase system is most commonly used polyphase system for generation andtransmission of power. Hence we study in detail the 3-phase voltage generation and analysis of 3-phasecircuitinthis unit.

A 3-phase system has the following advantages over single phase system. For a given frame sizeof a machine a 3-phase machine will have large capacity than a single phase machine. The torqueproducedina3-phasemotorwillbemoreuniformwhereasina1-phasemotoritispulsating.Theamountof copper required in a certain amount of power over a particular distance, is less compared to a singlephase system.

Phasesequence:

It is the order in which the phase voltages will attain their maximum values. From the fig it isseen that the voltage in A phase will attain maximum value first and followed by B and C phases. Hencethree phasesequenceisABC.Thisisalsoevidentfromphasordiagraminwhichthe phasorswithits+vedirection of anti-clockwise rotation passes a fixed point is the order ABC, ABC and so on. The phasesequence depends on the direction of rotation of the coils in the magnetic field. If the coils rotate in theopposite

directionthenthephasevoltagesattainsmaximumvalueintheorderACB.Thephasesequencegetsreversedwithdirectionofrotation.Thenthe voltageforthissequencecanbe representedas

$$e_a = E_m \sin \omega t$$
$$e_c = E_m \sin(\omega t - 120^0)$$
$$e_b = E_m \sin(\omega t - 240^0)$$

TheRMS valuesofvoltagecanbeexpressedas

$$E_A = E\angle 0^0$$
$$E_C = E\angle -120^0$$
$$E_B = E\angle -240^0$$

Starand Deltaconnection:

The three phase windings have six terminals i.e., A,B,C are starting end of the windings andA',B'andC'arefinishingendsofwindings.For3phasesystemstwotypesofcommoninterconnectionsareemployed.

Starconnection:

The finishing ends or starting ends of the three phase windings are connected to a commonpoint as shown in. A', B', C' are connected to a common point called neutral point. The other endsA, B, C are called line terminals and the common terminal neutral are brought outside. Then it iscalled a 3 phase 4 wire star connected systems. If neutral point is not available, then it is called 3phase,3wirestarconnection.

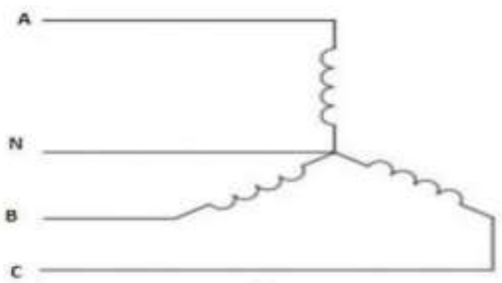
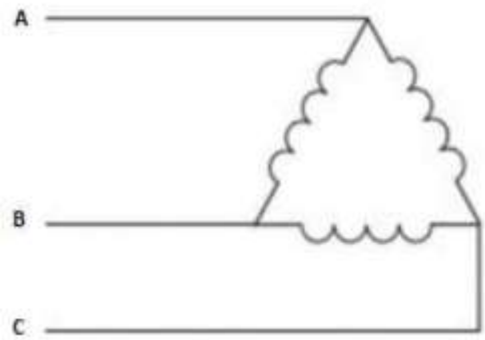


Fig.1.2

Deltaconnection:

In this form of interconnection the dissimilar ends of the three coils i.e A and B’, B and C’,and C and A’ are connected to form a closed Δ circuit (starting end of one phase is connected tofinishing end of the next phase). The three junction are brought outside as line terminal A, B, C. thethree phase windings are connected in series and form a closed path. The sum of the voltages in theclosedpathforbalancedsystemofvoltages atanyinstantwillbezerofig.



The main advantage of star connection is that we can have two different 3- phase voltages.The voltage that was the line terminalsbetween A & B,B&C,and C & A are calledlinevoltagesand form a balanced three phase voltage. Another voltage is between the terminals A & N, B& N,and C &N are called phase voltage and form another balanced three phase voltage (line to neutralvoltageorwyevoltage).

Relationbetweenlineandphasevoltageandcurrentsinbalancedsystems:

Inthissectionwewillderivetherelationbetweenlineandphasevaluesofvoltagesandcurrentsof3-phasestarconnectedanddeltaconnectedsystems.

1Starconnection:

Wewillemploydoublesubscriptnotationtorepresentvoltagesandcurrents.Theterminalcorresponding to first subscript is assumed to be at a higher potential with respect to the terminalcorrespondingtosecondsubscript.

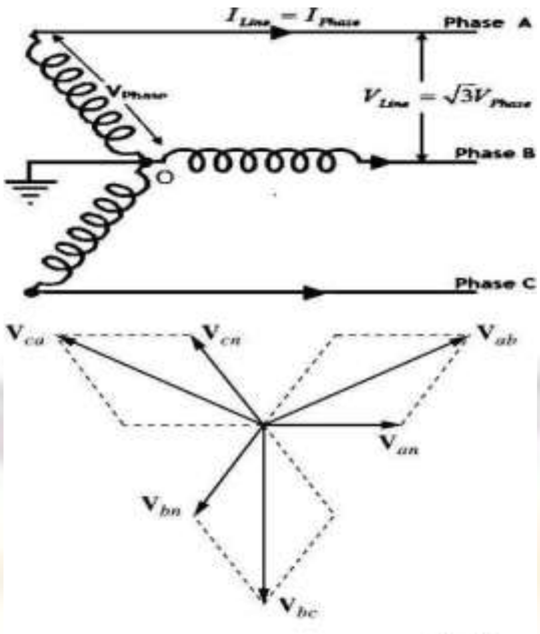


Fig.1.4

The voltage across each coil, i.e., the voltage between A & A',B& B', and C & C' are called phasevoltages(acting from finishing end to starting end). VAA, VBB, VCC, or VAN, VBN, VCN represent phasevoltages.

The voltages across line terminals A & B, B & C, C & D are called line voltages. Theconnection diagram and the corresponding phasor diagram of voltages is shown in fig. From the starconnected3 phasesystem,itisclearlyobservedthat whatever currentsflowthroughthelinesA,B,Calso flow through the respective phase windings. Hence in star connected system, the phase currentsandlinecurrentsareidentical .

Phasecurrent(Iph)=Linecurrents(IL)Iph=ILine

ThevoltageVABbetweenlinesAandBisobtainedbyaddingVANandVNBrespectively.

VAB=VAN+VNB=VAN-VBN

Similarly

VBC= VBN+VNC= VBN–VCNVCA=VCN+VNA=VCN –VAN

ThelinevoltageVABisobtainedbyaddingVANwithreversedvectorofVBN.VABbisectstheanglebetweenV ANandVBN.

$$V_{AB}=\sqrt{3}V_{ph}$$

Linevoltage=√3phasevoltage

The line voltages V_{AB}, V_{BC}, V_{CA} are equal inmagnitude and differ in phase by 120^0.Hence they form a balanced 3-phase voltage of magnitude $\sqrt{3}\ V_{ph}$. The two voltages differ in phaseby 30^0.Whenthesystemisbalanced,thethreephasecurrentsI_A,I_B,I_C arebalanced.Themagnitudeandphaseangleofcurrentisdeterminedbycircuitparameters.

I_A, I_B, I_C are line or phase currents. The current in the neutral wire is I_N and is by applyingkirchoff's currentlawatstarpoint,weget

$I_N=-(I_A+I_B+I_C)$

Ifthecurrentsarebalanced,thentheneutralcurrentis zero.

1.1.1 Delta connectionorMESH connection:

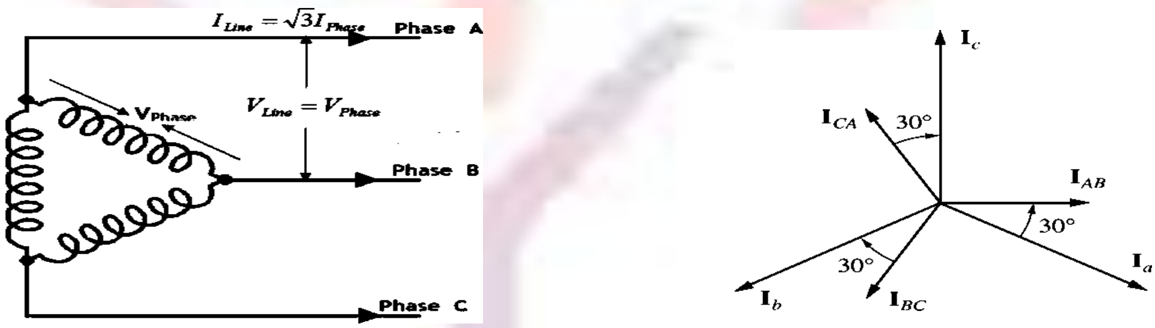


Fig.1.5.

The currents flowingthrough the phase windings$I_{AA'}$,$I_{BB'}$,and$I_{CC'}$ or I_{AB},I_{BC}, and$I_{CA}$are calledphase currentsandare balancedasshowninphasediagramFig.1.5.

ByapplyingKCLatnodeA

$$I_A+I_{CA}= I_{AB}, I_A= I_{AB}-I_{CA}$$

SimilarlybyapplyingKCLatnodesBandC

$$I_B=I_{BC}-I_{AB} \quad I_C=I_{CA}-I_{BC}$$

Thelinecurrent$I_A$isobtainedbyadding$I_{AB}$and$-I_{CA}$vectorially.$I_A$bisectstheanglebetween$I_{AB}$and$-I_{CA}$

$I_L = \sqrt{3} I_{ph}$ Line current(I_L)=√3phasevoltage(I_{ph})

The line current I_A, I_B, I_C and also equal and differ in phase by 120^0. They form a balanced systemofcurrents.Theline andphasecurrents differinphaseby30^0.

Analysisofbalancedthreephasecircuits

A set of three impedances interconnectedin the form of a star or delta form a 3-phase star ordelta connected load. If the three impedances are identical and equal then it is a balanced 3-phaseload,otherwiseitis anunbalanced3-phaseload.

Theanalysisofbalanced3-phasecircuitsisillustratedasfollows

Balanceddeltaconnectedload:

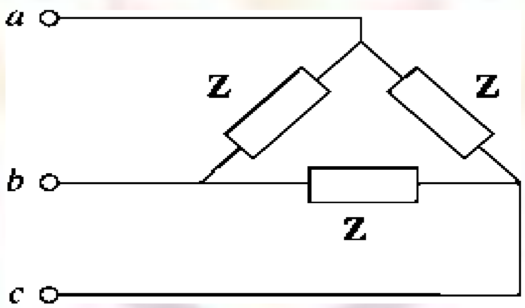


Fig.1.6

Letusconsiderabalanced3-phasedeltaconnectedloadDeterminationofphasevoltages:

$$V_{AB} = V\angle 0^0, V_{BC} = V\angle -120^0, V_{CA} = V\angle -240^0 = V\angle 120^0$$

Determinationofphasecurrents:

Phasecurrent=Phasevoltage/Loadimpedance

$$I_{AB} = \frac{V_{AB}}{Z};\ I_{BC} = \frac{V_{BC}}{Z};\ I_{CA} = \frac{V_{CA}}{Z}$$

Determinationoflinecurrents:

LinecurrentsarecalculatedbyapplyingKCLatnodesA,B,C

$$I_A = I_{AB} - I_{CA};\ I_B = I_{BC} - I_{AB};\ I_C = I_{CA} - I_{BC}$$

Note:Linecurrentsarealsobalancedandequalto√3phasecurrent.

Balancedstarconnectedload:

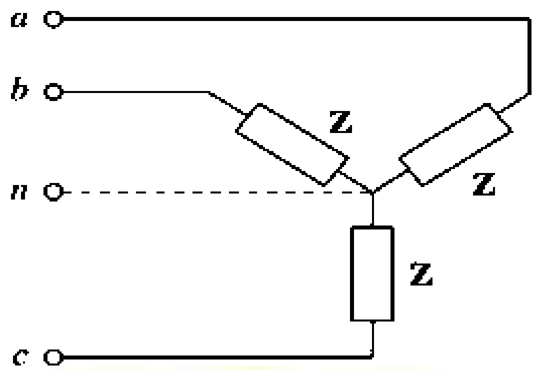


Fig.1.7

Letusconsiderabalanced3-phasestarconnectedload.Forstarconnection,phasevoltage=Linevoltage/(√3)

ForABC sequence,thephasevoltageispolarformaretakenas

$$V_{AN}= V_{ph}\angle -90^0;V_{CN}=V_{ph}\angle 150^0;V_{BN}=V_{ph}\angle 30^0$$

For starconnection linecurrentsandphasecurrentsareequal

$$I_A= \frac{V_{AN}}{Z};I_B=\frac{V_{BN}}{Z};I_C= \frac{V_{CN}}{Z};$$

TodeterminethecurrentintheneutralwireapplyKVLatstarpoint

$$I_N+I_A+I_B+I_C=0$$

$$I_N=-(I_A+I_B+I_C)\text{(sincetheyarebalanced)}$$

In a balanced system the neutral currentis zero. Hence if the load is balanced, the currentand voltage will be same whether neutral wire is connected or not. Hence for a balanced 3-phase starconnected load, whether the supply is 3- phase 3 wire or 3-phase 4 wire, it is immaterial. In case ofunbalancedload,therewillbeneutralcurrent.

UNITII

ELECTRICALINSTALLATIONS

SWITCHGEAR:

Theapparatususedforswitching,controllingandprotectingtheelectricalcircuitsandequipmentis knownas switchgear.

COMPONENTSOFSWITCHGEAR

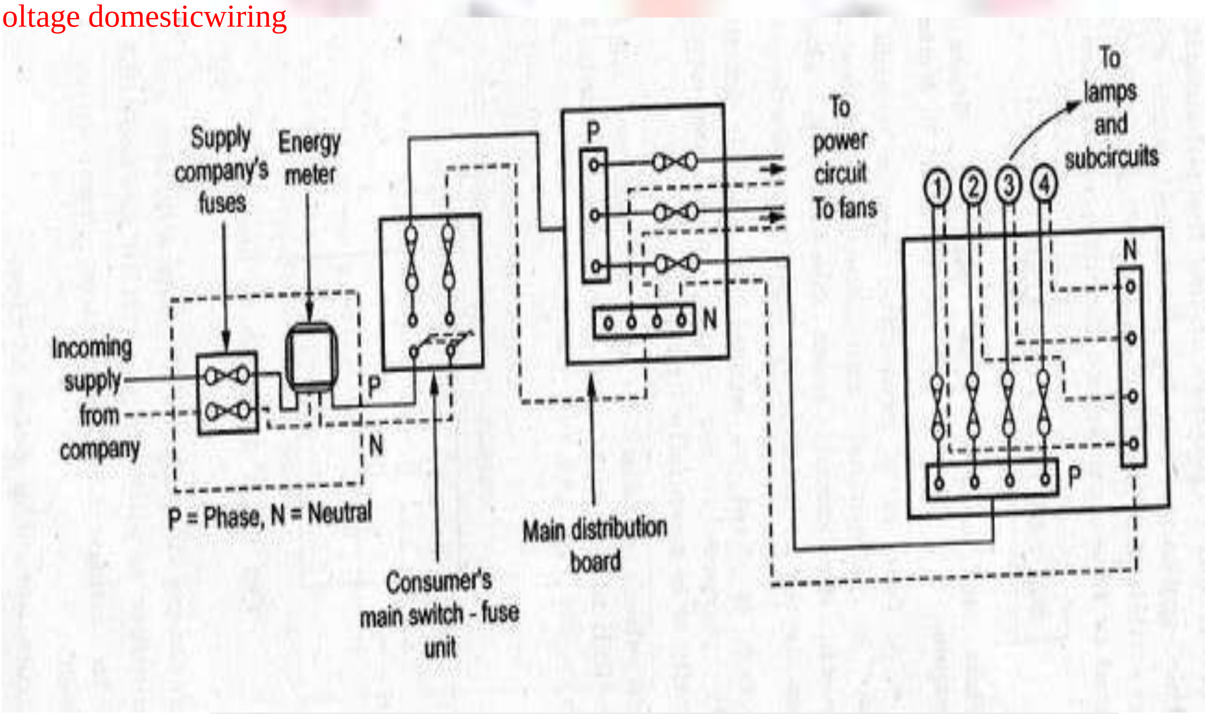
Alow-tensionlineisalowvoltagelineandahigh-tensionlineisahighvoltageline.InIndia**LT**supplyisof400Voltsforthree-phaseconnectionand230Voltsforsingle-phaseconnection.

CLASSIFICATIONOFSWITCHGEAR:

Switchgearcanbeclassified onthebasisofvoltagelevelintothefollowing:

1. Lowvoltage(LV)Switchgear:upto1KV
2. Mediumvoltage(MV)Switchgear:3KVto33KV
3. Highvoltage(HV)Switchgear:Above33KVTherea refourtypesofcomponents ofLTswitchgear

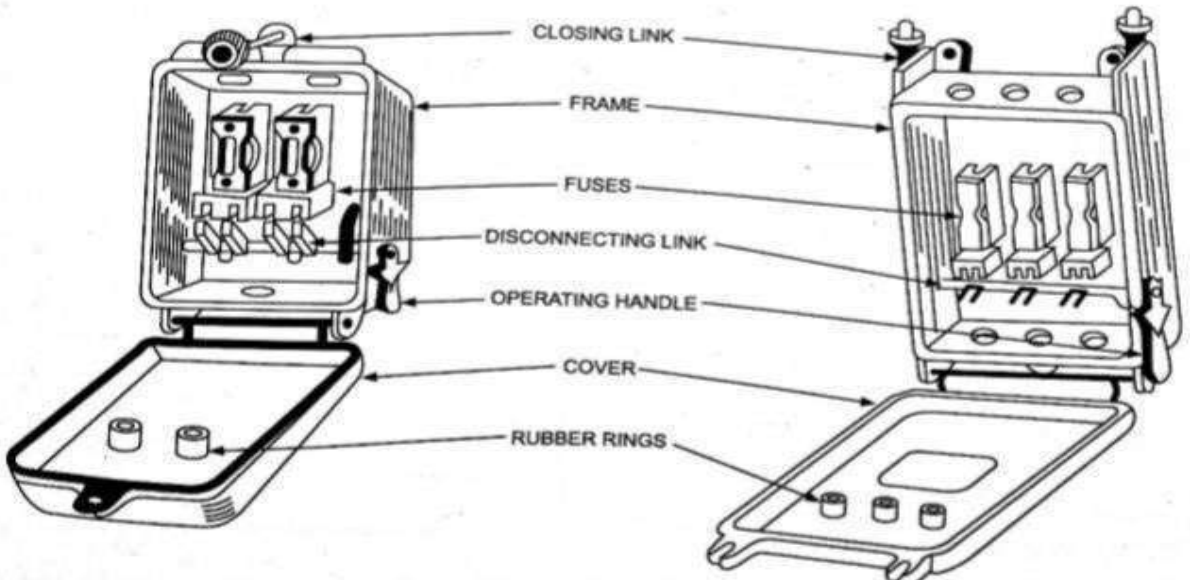
1. SwitchFuseUnit(SFU)
2. MiniatureCircuitBreaker(MCB)
3. EarthLeakageCircuitBreaker(ELCB)
4. MoldedCaseCircuitBreaker(MCCB)Lowv oltage domesticwiring



SWITCHFUSEUNIT(SFU):

Switch fuse is a combined unit and is known as an iron clad switch, being made of iron. It maybe double pole for controlling single phase two-wire circuits or triple pole for controlling three-phase,3-wire circuits or triple pole with neutral link for controlling 3-phase, 4-wire circuits. The respectiveswitches are known as double pole iron clad (DPIC), triple pole iron clad (TPIC), and triple pole withneutrallinkironclad(TPNIC)switches.

MiniatureCircuitBreaker(MCB):



(a) DPIC Switch　　*(b) TPIC Switch*

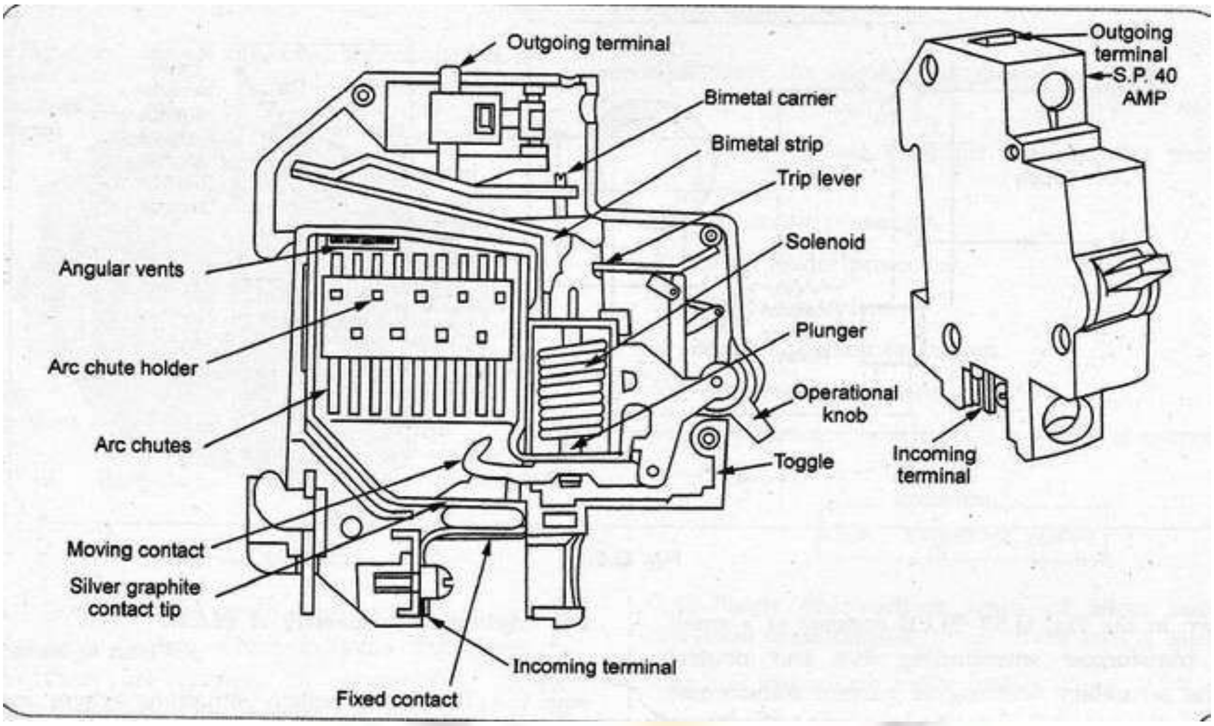
Adevicewhichprovidesdefiniteprotectiontothewiringinstallationsandsophisticatedequipmentagainstover-currentsandshort-circuitfaults

Thermal operation (overload protection) is achieved with a bimetallic strip, whichdeflects when heated by any over-currents flowing through it. In doing so, releases the latchmechanismandcauses thecontactstoopen.

MCBsareavailablewithdifferentcurrentratingsof0.5,1.2,2.5,3,4,5,6,7.5,10,16,20,

25,32,35,40,63,100,125,160A andvoltageratingof240/415VACandupto220VDC.Operatingtimeisveryshort(lessthan5ms).

Theyaresuitablefortheprotectionofimportantandsophisticatedequipment,suchasair-conditioners,refrigerators,computersetc.



WorkingPrincipleofMCB

The primary function of a miniature circuit-breaker is to protect an installation or applianceagainstsustainedoverloadingandshort-circuitfaults,

When the current overflow occurs through MCB – Miniature Circuit Breaker, the bimetallicstrip gets heated and deflects by bending. The deflection of the bi-metallic strip releases a latch. Thelatchcauses theMCB toturnoffbystoppingthecurrentflowinthecircuit.

MOLDEDCASECIRCUITBREAKER(MCCB):

It is a type of electrical protection device that can be**used for a wide range of voltages, andfrequenciesofboth50Hzand60Hz,**themaindistinctionsbetweenmoldedcaseandminiaturecircuitbreaker are that MCCB can have current rating up to 2500 amperes, and its trip setting arenormallyadjustable.MCCBsare **muchlargerthanMCBs**.AnMCCB hasthree mainfunctions:

- **PROTECTIONAGAINSTOVERLOAD.**
- **Protectionagainstelectricalfaults.**
- **Switching a circuit ON and OFF.** This is a less common function of circuitbreakers, but they can be used for that purpose if there is not an adequate manualswitch.

OperatingMechanism: Atitscore, theprotectionmechanismemployedbyMCCBsis basedonthesamephysicalprinciples usedbyalltypesofthermal-magneticcircuitbreakers.

- **Overload protection** is accomplished by means of a **thermal mechanism**. MCCBs have **abimetallic contact what expands and contracts in response to changes in temperature.**Undernormaloperatingconditions,thecontactallowselectriccurrentthroughtheMCCB.

However, as soon as the current exceeds the adjusted trip value, the contact will start to heatandexpanduntilthecircuitisinterrupted.

- **Thethermalprotection**againstoverloadisdesignedwithatimedelaytoallowshortdurationovercurrent, which is a normal part of operation for many devices. However any over currentconditions,thatlastsmorethanwhatisnormallyexpectedrepresentanoverload,andtheMCCB is tripped to protect the equipment and personnel. On the other hand,faultprotection isaccomplishedwithelectromagneticinduction,andtheresponseisinstant.Faultcurrentsshouldbeinterruptedimmediately, nomatteriftheirdurationisshortorlong.Wheneverafault occurs,**the extremely high current induces a magnetic field in a solenoid coil located inside thebreaker-thismagneticinductiontripsacontactandcurrentisinterrupted**.Asacomplement to the magnetic protection mechanism, MCCBshave internal arc dissipationmeasures tofacilitateinterruption.

EARTHLEAKAGECIRCUITBREAKER(ELCB):

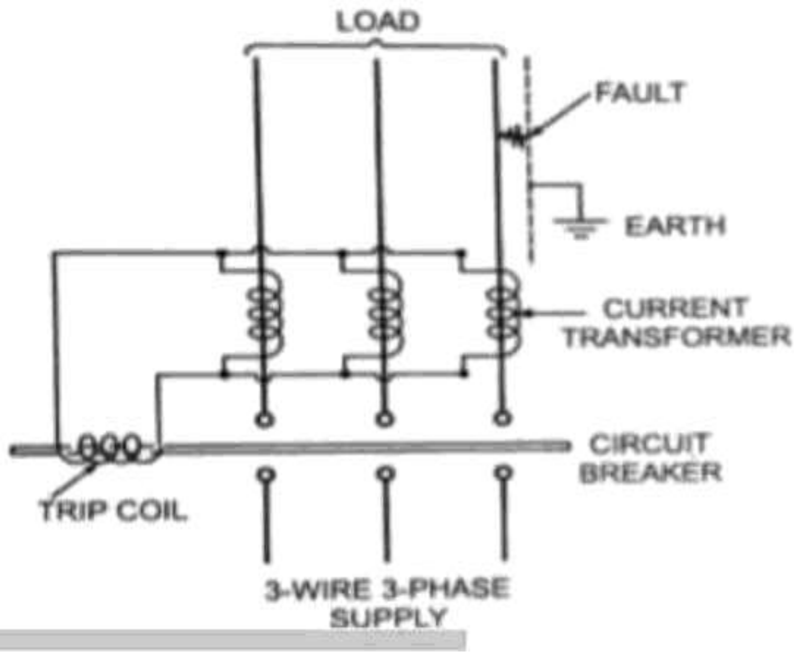
Itisadevicethatprovides**protectionagainstearthleakage**.Theseareoftwotypes.

1. **CURRENTOPERATEDEARTHLEAKAGECIRCUITBREAKER:**
2. **Voltageoperatedearthleakagecircuitbreaker.**

1.Currentoperatedearthleakagecircuitbreaker:

It is used when the **product of the operating current in amperes and the earth-loopimpedance in ohms does not exceed 40**. such circuit breakers is used where consumer's earthingterminal is connected to a suitable earth electrode. A current-operated earth leakage circuit breaker is**appliedtoa3-phase,3-wire circuit**.

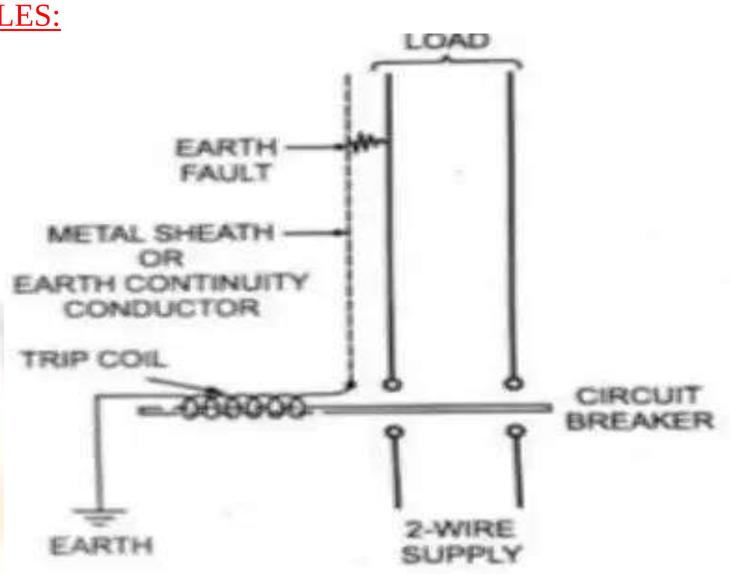
In normal condition when there is no earth leakage, the algebraic sum of the currents in thethreecoilsofthecurrenttransformersiszero,andnocurrentflowsthroughthetripcoil.Incaseofanyearth leakage, the currents are unbalanced and the trip coil is energized and thus the circuit breaker istripped.



VOLTAGEOPERATEDEARTHLEAKAGECIRCUITBREAKER:

It is suitable for use when **the earth–loop impedance exceeds the values applicable to fusesor excess-current circuit breaker or to current operated earth leakage circuit breaker.** When the**voltage between the earth continuity conductor (ECC) and earth electrode rises to sufficientvalue, the trip coil will carry the required current to trip the circuit breaker**. With such a circuitbreakertheearthingleadbetweenthetripcoilandtheearthelectrodemustbeinsulated.

TYPES OFWIRES ANDCABLES:



Wire:

A**wire**isdefinedasoneelectricalconductor,whileacableisdefinedasagroupofindividuallyinsulatedwires (conductors)encased togetherinsheathing.

- Sheathingisanon-conductingmaterialwithprotectivepropertiestoshieldtheconductingpartofthewire/cable.
- Wiresandcablescanbemadefromvarious materials,suchascopper,gold, andaluminum.
- Thetwocategoriesofsingle-conductorwiresaresolidandstranded(alsocalledbraided).
- Solid wire is rigid and conducts electricity better. Stranded wire consists of smaller wiresbraided together. Stranded wires are less prone to breakage when flexed repeatedly, which iswhythis typeofwireiscommoninphonechargers.
- **Jumper wires**are pre-cut flexible stranded wires of different lengths that have stiff ends toallowthewiretobeeasilyinsertedinabreadboard.
- **Hook-up wire**is typically single conductor insulated wire used in low current, low voltage(<600Volts)applicationsformakinginternalconnections.
- **Magnetwire**isacopperor aluminumwirecoatedwithaverythinlayer ofinsulation.Magnetwire allows multiple layers of wire to be wound together without short circuiting. When thewireiswoundintoacoilandenergized,itcreatesanelectromagneticfield.Magnetwireisoftenusedintransformers,inductors,motors,electromagnets.

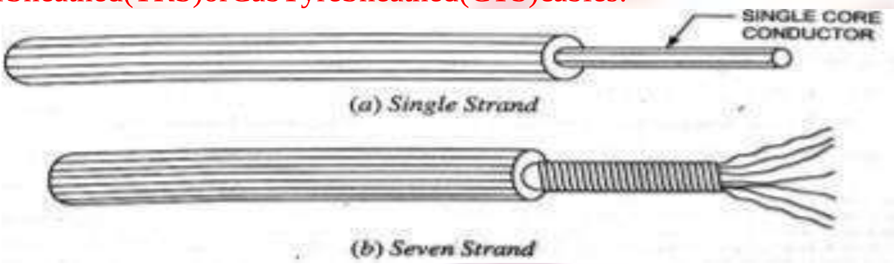
For internalwiring ofanybuilding,wiresandcablesmaybecategorizedintofollowinggroups:

1. **ConductorUsed:**Accordingtoconductormaterialusedin thecables,thesemay bedividedintotwo classesknownas**copperconductor**cablesand**aluminiumconductor**cables.
2. **NumberofCoresUsed:**Itmaybedividedintodifferentclassesknownas:singlecorecables,twincorecables,threecorecables,twocorewithECC(EarthContinuityConductor)cablesetc.
3. **VoltageGrading:**Accordingtovoltagegradingthecablesmaybedividedintotwoclasses (i) 250/440Voltcablesand(ii)650/1100voltcables
4. **TypesofInsulationUsed:**Accordingtotypeofinsulationthecablesareoffollowingtypes:
    - VulcanizedIndianRubber(VIR)insulatedcables
    - ToughRubber Sheathed(TRS)or CabTyreSheathed(CTS)cables.
    - LeadSheathedCables.
    - PolyvinylChloride(PVC)Cables.
    - Weatherproofcables.
    - Flexiblecordsandcables.
    - XLPEcables.
    - Multi-strandcables.

VULCANIZEDINDIANRUBBER(VIR)INSULATEDCABLES:

VIRcablesareavailablein240/415voltsaswellasin650/1100voltgrades.VIRcablesconsistsof either Tinned copper conductor Covered with a layer of VIR insulation. Over the rubber InsulationcottontapesheathedCoveringisprovidedwithMoistureresistantcompoundbitumenwaxorsomeotherinsulatingmaterialformakingthecablesmoistureproof.

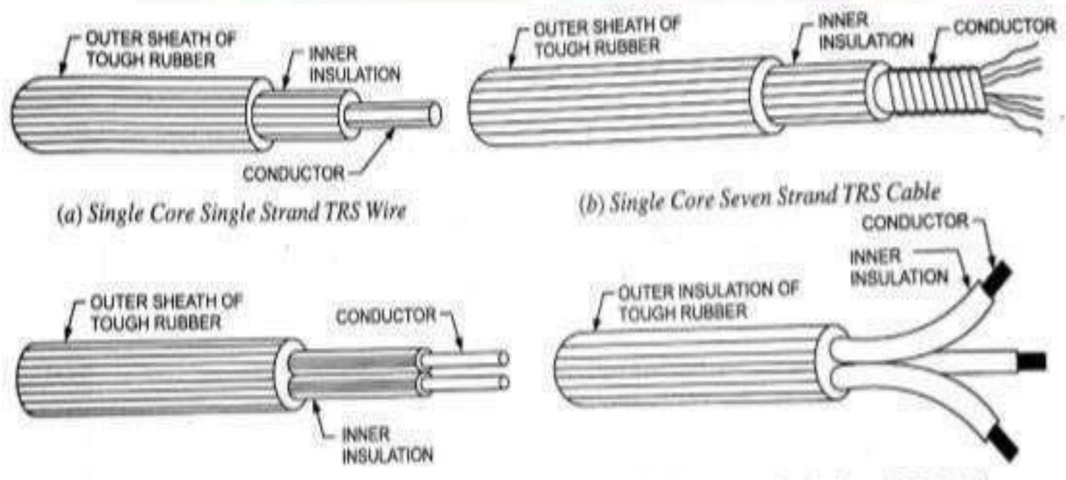
ToughRubberSheathed(TRS)orCabTyreSheathed(CTS)cables:



(a) Single Strand

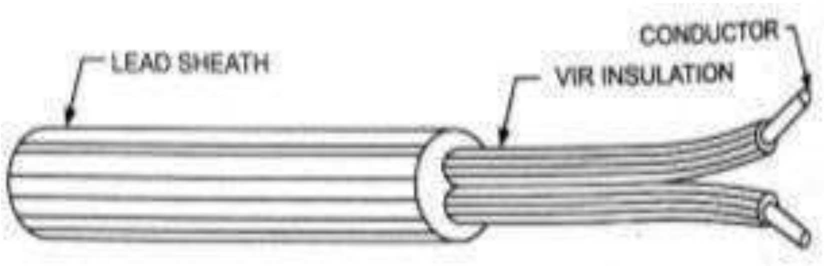
(b) Seven Strand

Thesecablesareavailablein250/440voltand650/1100voltgradesandusedinCTS(orTRS)wiring. TRS cable is nothing but a VIR conductor with an outer protective covering of toughrubber,whichprovidesadditionalinsulationandprotectionagainstwearandtea



LEADSHEATHEDCABLES:

These cables are available in 240/415 volt grade. The lead sheathed cable is a vulcanized rubberinsulated conductor covered with a continuous sheath of lead. The lead sheath provides very goodprotection against the absorption of moisture and sufficient protection against mechanical injury andsocanbeusedwithoutcasingorconduitsystem.



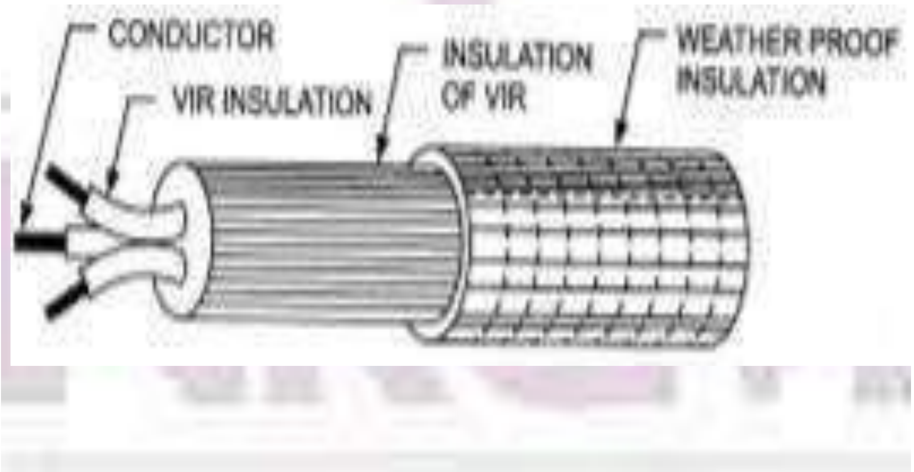
POLYVINYLCHLORIDEINSULATEDCABLES:

Thesecablesareavailablein250/440voltand650/1100voltgrades

- PVCinsulationhasbetterinsulatingqualities.
- PVCinsulationprovidesbetterflexibility.
- PVCinsulationhasnochemicaleffectonmetalofthewire.
- ThinlayerofPVC insulationwillprovidethedesiredinsulationlevel.
- PVCcoatedwiregivessmallerdiameterofcableand,therefore,moreno.ofwirescanbeacc ommodatedintheconduitofagivensizeincomparisonto VIRorCTSwires.

WEATHERPROOFCABLES:

i. Thesecablesareusedfor outdoorwiringandfor powersupplyorindustrialsupply
ii. ThesecablesareeitherPVCinsulatedorvulcanizedrubberinsulatedconductorsbeingsuitably tapedbraidedandthencompoundedwithweatherresistingmaterial.
iii. Thesecablesareavailablein240/415voltand650/1100voltgrades

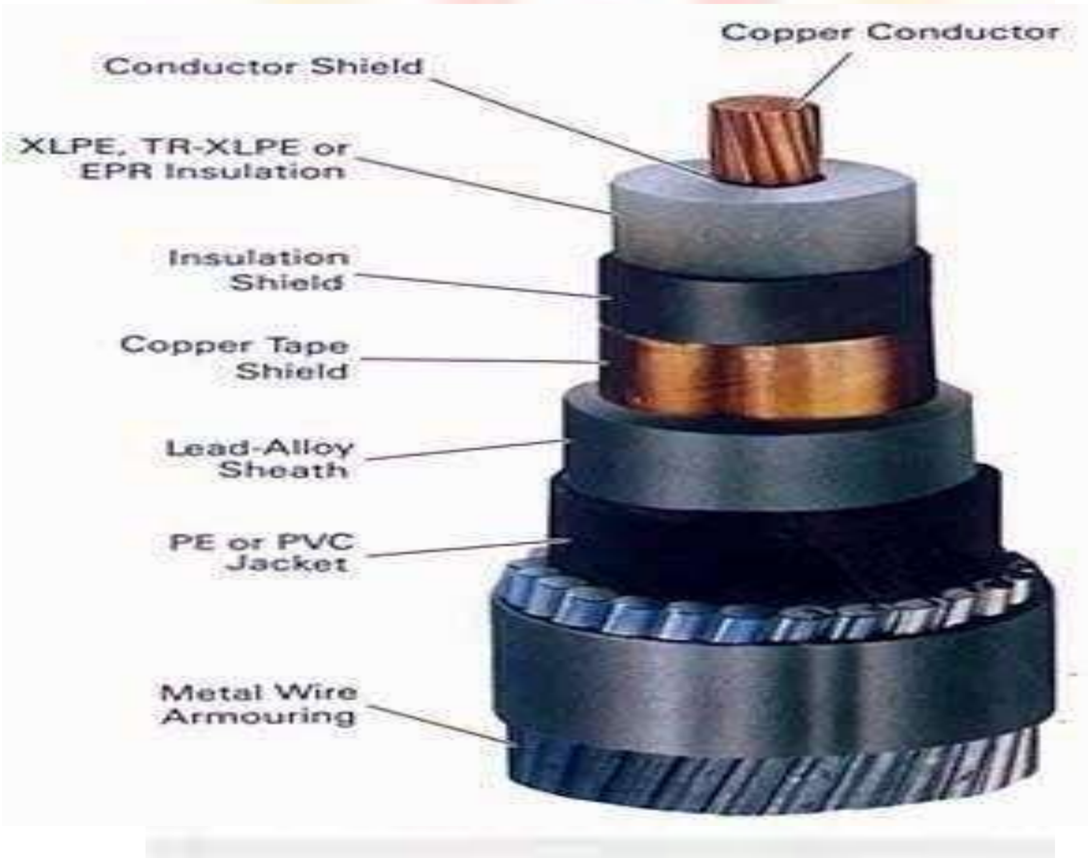


FLEXIBLECORDSANDCABLES:

Flexible cords and cables are used to connect electrical equipment to a power source. Flexiblecords may have an electrical plug that connects to a power source or they may be permanently wiredintoapowersource.Extensioncords(cordsets),cables,andelectricalcordsaretypesofflexiblecords.

XLPECABLE:

XLPEcable (Cross-linked polyethylene)is a type of electrical cable commonly usedforpowertransmission and distribution. XLPE cable is made of a thermoset material, which means it is highlyresistanttoheat,moisture,andchemicals.



MULTI-STRANDCABLES:

A stranded wire is one that is made of multiple thin strands – often made of copper. They arethentwistedandbundledtogetherwithinaPVCcable,therebycreatingamulti-strandconductor.

Versatileinnature,theyareavailableindifferenttypes.

EARTHING:

Earthing is defined as "the process in which the instantaneous discharge of the electrical energytakes place by transferring charges directly to the earth through low resistance wire." Low resistanceearthingwire ischosento providetheleastresistancepathforleakage offaultcurrent.

1. Themainobjectiveofearthingistoprovidesafetyofoperation.
2. Anotherobjectiveof theearthing,thoughnotwidelyusednowadays,istosaveconductingmaterial.

METHODSOFEARTHING:

Earthing should be done in a way so that on a short circuit, the earth loop impedance is lowenough to pass 3 times the current if fuses are used, and 1.5 times the current if MCBs are used. Themetalworkshouldbesolidlyearthedwithoutusinganyswitchorfuseinthecircuit.

Therearedifferenttypesofearthingmethodsareused:

1. StriporWireEarthing.
2. RodEarthing.
3. PipeEarthing.
4. PlateEarthing.

PipeandPlateEarthingsarecommonlyused.

STRIP OR WIRE EARTHING: In this system of earthing, strip electrodes of cross section not lessthan 25 mm X 1.6 MM if of copper and 25 mm X 4 mm if of galvanized iron or steel are buried inhorizontaltrenches ofminimumdepth0.5metre.Ifroundconductorsareused

RODEARTHING: Inthis typeofearthing,12.5mmdiameterssolidrodsofcopperor16mmdiametersolidrodsofgalvanizedironorsteelor hollowsection25mmGI pipesoflengthnotlessthan2.5metresaredrivenverticallyintothe eartheithermanuallyorbypneumatichammer.

PIPEEARTHING:

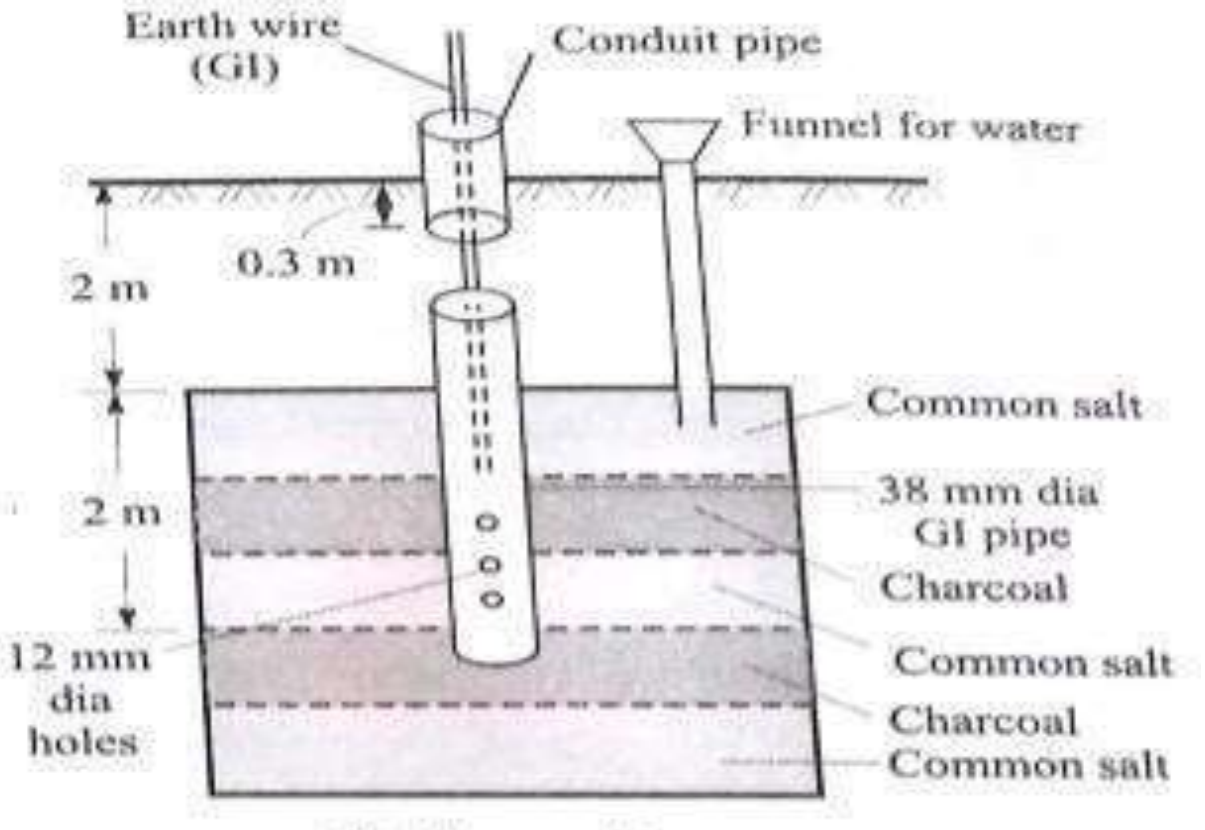
Earthing, is the process of connecting an electrical system to the earth. This is done to protectagainstelectricalshocks,reduceelectromagneticinterference,andprovideastablereferencevoltageforthesystem.Pipeearthingisatypeofearthingsystemthatusesapipemadeofgalvanizedironorcopperburiedinthe groundtoconnecttheelectricalsystemtothe earth.

The pipe used for earthing is typically around 2-3 meters in length and 40-50 mm in diameter.The top end of the pipe is connected to the electrical system, while the bottom end is buried in a pitfilledwithcharcoalandsalt.Thepipeisthenconnectedtoagroundingplateorrod,whichisalsoburiedintheground.

WORKINGPRINCIPLEOFPIPEEARTHING:

The principle behind pipe earthing is that the earth acts as a large conductor, which can absorband dissipate electrical charges. When an electrical fault occurs in the system, such as a short circuit orlightning strike, the current flows through the pipe and into the ground. The charcoal and salt in the pithelp toimprovetheconductivityofthesoil,makingiteasierforthecurrenttoflow.

The grounding plate or rod also helps to improve the conductivity of the earth, as it provides alarger surface area for the current to flow through. The size and depth of the pit, as well as the type ofsoil,areimportantfactorsthatcanaffecttheeffectiveness ofthepipeearthingsystem.



(b) Pipe earthing.

PLATEEARTHING:

PlateEarthingisamethodwhereaplatemadeofgalvanizedcopperorironisburiedverticallyatleast 3 meters below ground level. This plate connects all conductors to the earth, providing a path forelectrical discharge. The Diagram of Plate Earthing typically illustrates this setup, showing the plate'spositioninrelationtothegroundlevelandtheconductors itconnects.

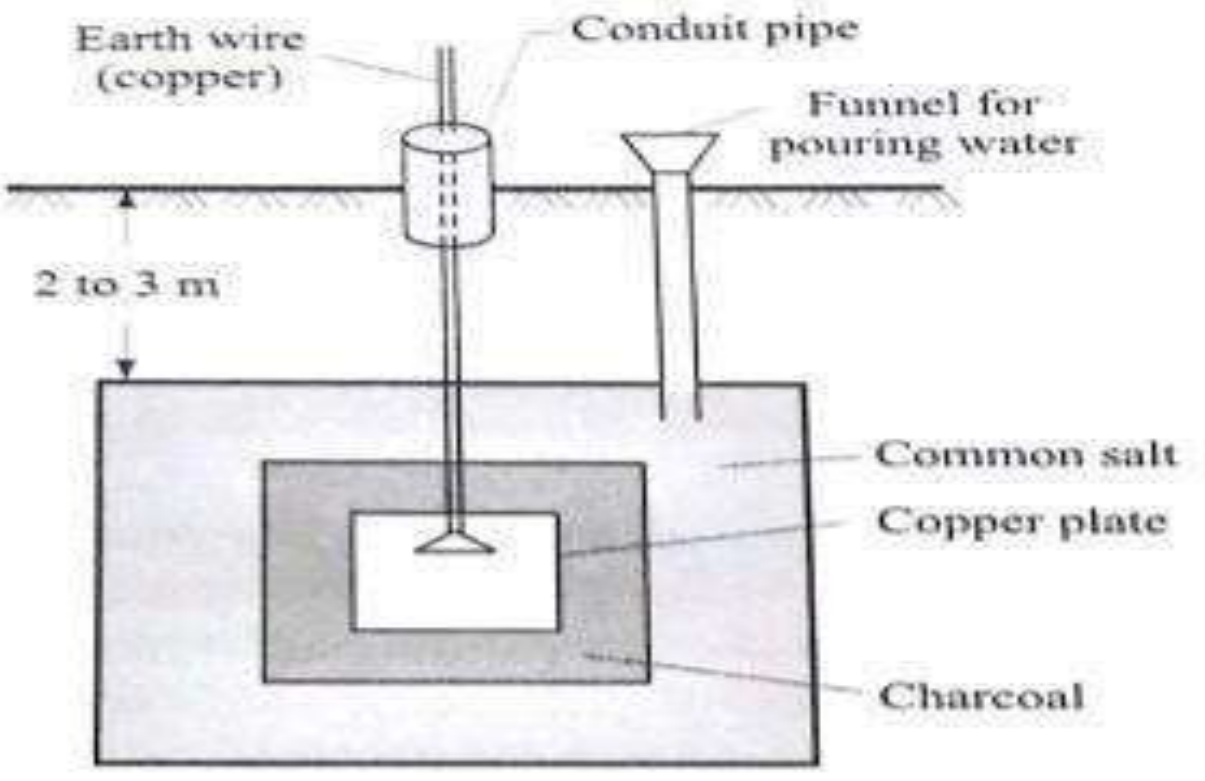
The Plate Earthing Diagram also often includes the dimensions of the plate. For instance, a copper plate used inthis method typically measures 600mm x 600mm x6.35mm. The plate's size and material can vary based onspecificrequirements,buttheprincipleremainsthesame,toprovideasafepathforfaultcurrenttotheearth.

The diagram of plate earthing shows a plate electrode, which is either made of galvanizediron or steel (with a minimum thickness of 6.3 mm) or copper (with a minimum thickness of 3.15mm).Theplateshouldbeatleast60cmby60cminsize.

Theplateisburiedin theearth,surroundedbyalternatinglayersofcharcoalandsalt.Thecharcoallayerisusedtoretainmoisture,whichhelpstomaintainalow earthresistance.

Agalvanizedironstripisconnectedtotheplateandextendsabovetheground.Thisstripisusedtoconnecttheplatetothe electricalsystemthatisbeingearthed.

Apipeisalsoshowninthediagram,whichisusedforwateringtheeartharoundtheplate.Thishelpstomaintainthemoisturelevelsaroundtheplate,ensuringeffectiveearthing.



(*a*) Plate earthing.

Finally,aninspectionchamberisbuiltaroundtheearthpit.Thischamberallowsforregularinspectionandmaintenanceoftheearthingsystem.

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Finally,aninspectionchamberisbuiltaroundtheearthpit.Thischamberallowsforregularinspectionandmaintenanceoftheearthingsystem.

PLATEEARTHINGPROCEDURE

TheprocedureforPlateEarthinginvolvesseveralsteps,oftenillustratedinaDiagramofPlateEarthing:

1. **Earth Pit**: An earth pit is excavated at a suitable location in the substation, with a minimumsize of900mmx900mmandadepthof3mbelowthesurface.
2. **Plate Electrode**: A GI plate of minimum size 600mm x600mm and thickness of 6.3 mm isused. If a copper plate is used, a minimum thickness of 3.15mm is required. The plate issurroundedbyalternatinglayers ofcharcoalandsalt.
3. **Earthing Connection**: Galvanized Iron strips are fixed and welded to the plate at twodifferent locations. Loose earthing can adversely affect the electrode system resistivity, sotheseconnectionsaremadestrong.
4. **Water Connection**: A pipe is fixed at the top to maintain moist conditions around the earthplate.Thepipeiscoveredwithawiremesh, andwaterispouredthroughit.Theexcavatedpitisthenfilledwithstone-freesoil.
5. **Inspection Chamber:** A brick chamber is built over the earth pit on a P.C.C layer. The top coverisplacedwithcastironhinges toaCIframe.

THEIMPORTANT DIFFERENCEBETWEENEARTHINGANDGROUNDING

Parameter	**Earthing**	**Grounding**
Definition	It protects humanlifefromelectrocuted.	It protectstheentirepowersystemfrommalfunctioning.

Potential	Itcontain szeropote ntial.	Itdoesnotposs essanyzeropo tential.
Location	It isplacedb etween theequip mentbody andeartha ndkeptunder theearth’s surface.	It is placedbe tweenthe neutralof the equipme nt and ground.
Types	Itisoffivetyp es such asPipe, Plate, Rodearthing, tap earthing,an d strip earthing.	Itisofthreety pessuchasS olid,Resista nce,and React anceg round ing.
Color of wire	Theearthwire isofgreencolo r.	Thegrounde dwireisblacki ncolor.
Example	Itisinusein transformer, generator, andmotorfor connecting to the	It isinuseasa neutralge nerator andpower transformer and connected to the

	earth.	ground.
Application	Earthingdischarges theelectrical energy to theearth. Itismainlyinuse to avoid shocking thehumans.	Groundingprovidesthereturnpathtothe current.Itismainlyin use forunbalancingwhen theelectricsystemoverloads.

Somemorefacts:

1. Theearthingisfortheconnectionofthenon-currentcarryingparttotheearth.Whereas,ingroundingthecurrent-carryingpartdirectlyconnectedtotheground.
2. Thegroundingis responsibleforloadbalancingandearthingisresponsibleforprotectionfromelectricalshock.
3. Theearthingelectrodemustnotbeplacednearthebuildingwhoseinstallationsystemisearthed morethan1.5maway.
4. Theresistanceoftheearthwireshouldbelessthan1ohm.
5. Itmustbetakencarethat thematerialofwireusedfortheelectrodeandcircuitshouldbethesame.
6. Theelectrodeshavetobeinaverticalpositionsothatitcantouchthelayersoftheearth.
7. Thesizeofthe conductormustbemore than2.6squaremmandonlyhalfofthe wireshouldbeusedforelectricalwiring.

BATTERIES

TypesofBatteries:Therearetwotypesofbatterieswhicharegivenbelow:

1) PrimaryBattery
2) SecondaryBattery

- Primarybatteriesare“singleuse”andcannotberecharged.Dry cellsand(most)alkalinebatteries areexamplesofprimarybatteries.
- Thesecondtypeisrechargeableandiscalledasecondarybattery.EX:Nickel-cadmium(NiCd),leadacid,andlithium ionbatteries.

IMPORTANTCHARACTERISTICSFORBATTERIES:

ElectricalCharacteristics:

Therearethreeimportant characteristicsofanaccumulator(orstoragebattery)namely,

- Voltage
- Capacityand
- Efficiency

Voltage: Average emf of cell is approximately 2.0 volts. The value of emf of a cell does not remainconstantbutvarieswiththechangeinspecificgravityofelectrolyte,temperatureandthelengthoftimesince itwaslastcharged.

Capacity: The quantity of electricity which a battery can deliver during single discharge until itsterminalvoltagefallsto1.8V/celliscalledthecapacityofabattery.

$$\text{Capacity of Battery or Cell} = I_d T_d$$

Efficiency: Theefficiencyofthecellcanbegivenintwoways:

1. ***The Quantity or Ampere – Hour (A-H) Efficiency:*** The ratio of output ampere-hour duringdischarging to the input ampere-hour during charging of the battery is called ***quantity orampere-hour*** efficiencyofthebattery.

$$\eta_{AH} = \frac{I_d T_d}{I_c T_c}$$

WhereI_d=DischargingCurrentinAmpere

I_c=ChargingCurrentinAmpere

T_d=DischargingTimeofcellorbatteryinhours

T_c=ChargingTime ofcellorbatteryinhours

2. ***EnergyorWatt –Hour(W-H)Efficiency:***Theratioofoutputwatt-hourduringdischargingto theinput watt-hour during charging of the battery is called ***energy or watt-hour*** efficiency of

thebattery.

$$\eta_{WH} = \frac{V_d I_d T_d}{V_c I_c T_c}$$

Where V_d=AverageTerminalVoltageduringDischarging

V_c=AverageTerminalVoltage during Charging

I_d=DischargingCurrentinAmpere

I_c=ChargingCurrentinAmpere

T_d=DischargingTimeofcellorbatteryinhours

T_c=ChargingTimeofcellorbatteryinhours

TWOWATTMETERMETHOD

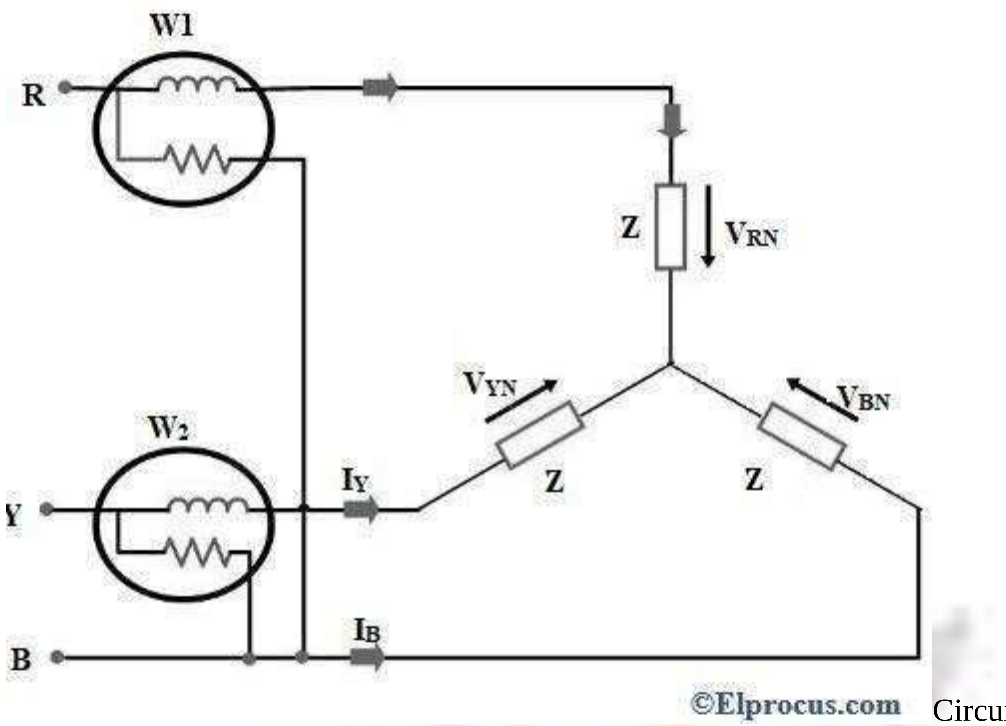
Athree-phasetwo-watt metermeasuresthecurrentandvoltagefromanyofthe2supplylinesof3phasecorrespondingtothe3rdsupplylineof3phase.The3phase2wattmeterissaidtobeata balancedloadconditionifthecurrentineveryphaselagatanangle“φ” withphasevoltage.

CONSTRUCTIONOFTWOWATTMETERMETHOD

The3-phasepowerofa3-phasecircuitcanbemeasuredusing3waystheyare,

- 3WattmeterMethod
- 2WattmeterMethod
- 1Wattmeter Method.

The main concept of 2 Wattmeter with 3 phase voltage is to balance the 3 phase load by satisfying thecondition of current lagging at an angle ‘φ’ with the voltage phase. The schematic diagram of 3 phase2wattmeterisshownbelow



Circuit Diagram

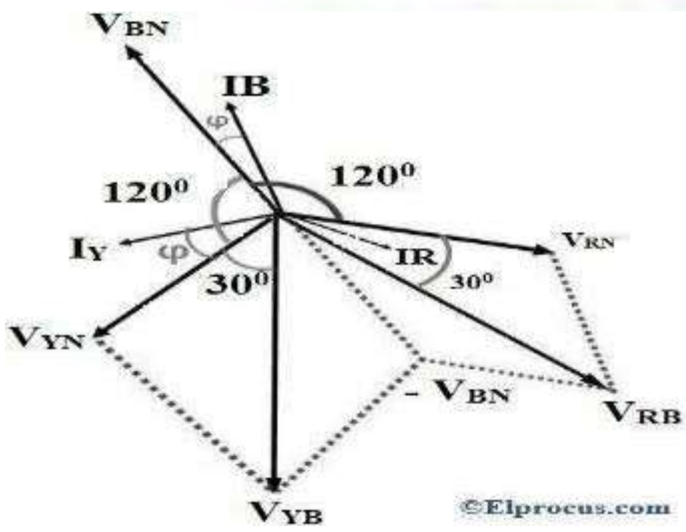
Itconsistsof2wattmeterslikeW1andW2,whereeachwattmeterhasacurrentcoil'CC'andapressurecoil'PC'.Here,oneendofwattmeter'W1'isconnectedto'R'terminalwhereasone endofwattmeter'W2′isconnectedto'Y'terminal.Thecircuitalso consistsof3 inductors'Z'whichareconstructedinastar topology. The 2 ends of inductors are connected to 2 terminals of a wattmeter whereas the thirdterminaloftheinductoris connectedtoB.

DERIVATIONOFTWOWATTMETERMETHOD

TwoWattmeterisusedtodeterminetwo mainparameterstheyare,

- Powerfactor
- Reactivepower.

Considertheloadusedasaninductiveloadwhichisrepresentedbyfollowingthephasordiagramasshownbelow.



ThevoltagesVRN,VYN,andVBNareelectrically120^0inphasewithoneother,wecanobservethatthecurrentp hase lags atthe"φ^0"angle withvoltagephase.

ThecurrentinwattmeterW1isrepresentedas

$$W_1=I_R(1)$$

where$I_R$iscurrent

ThepotentialdifferenceacrossthewattmeterW1coilisgivenas

$$W_1= \sim V_{RB}=[\sim V_{RN}-\sim V_{BN}]\ldots\ldots\ldots(2)$$

Where**V_{RN}andV_{BN}**arevoltages

Thephasedifferencebetweenthevoltage‘V_{YB}‘andcurrent‘I_Y‘isgivenas$(30^0+\varphi)$Hencethepower measuredbywattmeterisgivenas

$W_2=V_{YB}I_Y\cos(30^0+\varphi)$.(3)

Atbalancedloadcondition

$I_R=I_Y=I_B=I_L$and..(4)

$V_{RY}=V_{YB}=V_{BR}=V_L$ (5)

Thereforeweobtainwattmeterreadingsas

$W_1=V_LI_L\cos(30^0-\Phi)$AND
.. (6)$W_2=V_LI_L\cos(30^0+\varphi)$ .... (7)

TOTALPOWERDERIVATION

Thetotalwattmeterreading isgivenas

$$W_1+W_2=V_LI_L\cos(30^0-\varphi)+V_LI_L\cos(30^0+\varphi) \quad (8)$$

$$=V_LI_L[\cos(30^0-\Phi)+\cos(30^0+\Phi)]$$

$$=V_LI_L[\cos30^0\cos\varphi+\sin30^0\sin\varphi+\cos30^0\cos\varphi-\sin30^0\sin\varphi]$$

$$=V_LI_L[2\cos30^0\cos\Phi]$$

$$=V_LI_L[(2\sqrt{3}/2)\cos30^0\cos\varphi]$$

$$=\sqrt{3}[V_LI_L\cos\Phi]$$

(9)$W_1+W_2=P$
(10)

Where‘P’isthetotalobservedpowerina 3-phasebalancedloadcondition.

POWERFACTORDERIVATION

Definition:Itistheratiobetweenactualpowerobservedbytheloadtoapparentpowerflowinginthecircuit.

Thepowerfactorofthreephasebalancedloadconditioncanbedeterminedandderivedfromwattmeterreadings asfollows

Fromequation9

$$W1+W2=\sqrt{3}V_LI_LCOS\Phi$$

Now $W1-W2=V_LI_L[\cos(30^0-\varphi)-\cos(30^0+\varphi)]$

$$=V_LI_L[COS30^0COS\Phi+SIN30^0SIN\Phi-COS30^0COS\Phi+SIN\ 30^0SIN\Phi]$$

$$=2V_LI_L\sin30^0\sin\varphi$$

$$W1-W2=V_LI_LSIN\Phi \quad (11)$$

Dividingequations11and9

$[W1 - W2 \backslash W1 + W2] = V_LI_LSIN\ \Phi / \sqrt{3}\ V_LI_LCOS\ \Phi$ $TAN\Phi=\sqrt{3}[W1-W2\backslash W1+W2]$

Thepowerfactoroftheloadisgivenas

$$COS\Phi=COSTAN^{-1}[\sqrt{3}][W1-W2\backslash W1+W2] \qquad (12)$$

ReactivePowerDerivation

Definition:Itistheratiobetweencomplexpowercorrespondingtostorageandrevivalofenergyratherthanconsumption.

Toobtainreactivepower,wemultiplyequation11with

$$\sqrt{3}[W1-W2]=\sqrt{3}[V_LI_LSIN\ \Phi]=P_RP_R=\sqrt{3}[W1-W2]...(13)$$

Where$P_r$isthereactivepower obtainedfrom2wattmeters.

ELEMENTARYCALCULATIONSFORENERGYCONSUMPTIONANDSAVINGS:

Electrical energy is supplied to a consumer by the supplier. To charge the electrical energyconsumedbyaconsumer,anenergymeterisinstalledtoitsquantity.Thereadingoftheenergymeteristaken every month. The difference between the fresh reading and the previous reading tell about theconsumptionofelectricalenergyinthatmonth. Thisquantityofenergyismultipliedbytherate(tariff)fixed by the supplier to prepare an electricity bill. However, some other charges such as meter rent,GST,othertaxesapplicableetc.arealsoaddedinthebill.

BATTERYBACK-UP:Thetime(inhrs)forwhichabatterycandeliverthedesiredcurrentiscalledbatteryback-upofthebank.

EX:Aconsumerusesa10kWgeezer,a6kWelectricfurnaceandfive100Wbulbsfor15hours.How manyunits (kWh)ofelectricalenergyhavebeenused?

Explanation : Given thatLoad – 1=10kWgeezer

Load– 2 =6kWelectricfurnace

Load–3=500watt(five100wattbulbs) Totalload =10kW+6kW+0.5kW=16.5kWTimetaken=155hours

Energyconsumed=PowerinkW×Timeinhours

= 16.5×15= 247.5kWh

So, thetotalenergyconsumption=247.5units

Ifthecostper unitis2.5,thenthetotalcostofenergyconsumption247.5×2.5=618.75/-

PowerFactorImprovement

Thecosineofanglebetweenvoltageandcurrentinana.c.circuitisknownaspowerfactor.

Most of the loads (*e.g.* induction motors, arc lamps) are inductive in nature and hence have lowlaggingpowerfactor.Thelowpowerfactorishighlyundesirableasitcausesanincreaseincurrent,resultinginadditionallossesofactivepowerinalltheelementsofpowersystemfrompowerstationgeneratordowntotheutilizationdevices.Inordertoensuremostfavorableconditionsforasupplysystemfromengineeringandeconomicstandpoint,itisimportanttohavepowerfactorasclosetounityaspossible.

PowerTriangle:

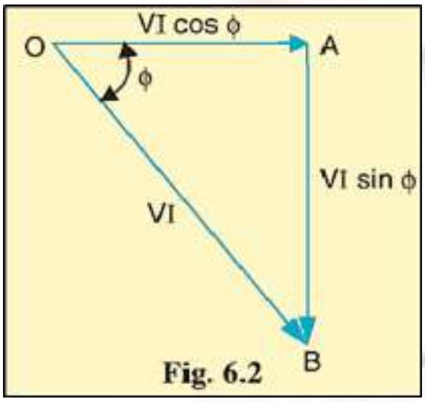
OA=*VI*cosφandrepresentsthe***active power***,*(P)*inwattsorkW.

AB=*VI*sinφandrepresentsthe***reactivepower***,*(Q)*inVARorkVAR.

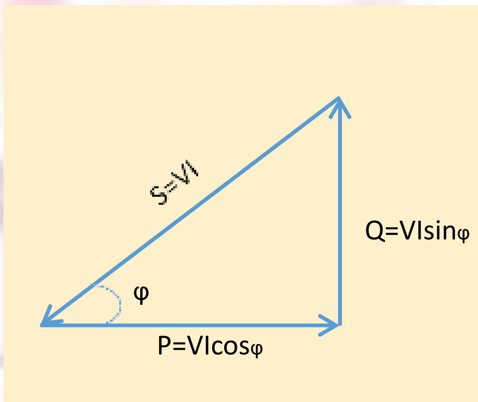
OB=*VI*andrepresentsthe***apparentpower***,*(S)*inVAorkVA.

(i) Theapparentpower**(S)**inana.c.circuithastwocomponentsviz.,active**(P)** andreactivepower**(Q)**atrightanglestoeachother. $OB^2 = OA^2 + AB^2$ or $S^2 = P^2 + Q^2$

(ii) Powerfactor, $\cos\varphi = \frac{OA}{OB} = \frac{P}{S} = \frac{kW}{kVA}$



laggingpower factor



Leadingpowerfactor

(iii) The lagging reactive power is responsible for the low power factor. It is clearfrom the power triangle that smaller the reactive power component, the higher is the powerfactorofthecircuit.

$kVAR = kVA\sin\varphi = \frac{kW}{\cos\varphi}\sin\varphi$

kVAR=kWtanφ

(iv) Forleadingpowerfactor,thepowertrianglebecomesreversed.Thisfactprovides a key to the power factor improvement. If a device taking leading reactive power (e.g.capacitor) is connected in parallel with the load, then the lagging reactive power of the load willbe partlyneutralised,thusimprovingthepowerfactoroftheload.

(v) Thepower factorofacircuitcanbedefinedinoneofthefollowingthree ways:

(a) Powerfactor=cosφ=cosineofanglebetweenVandI.

(b) Powerfactor= $\frac{R}{Z} = \frac{Resistor}{Impedance}$.

(c) Powerfactor= $\frac{VI\cos\varphi}{VI} = \frac{Activepower}{Apparentpower}$

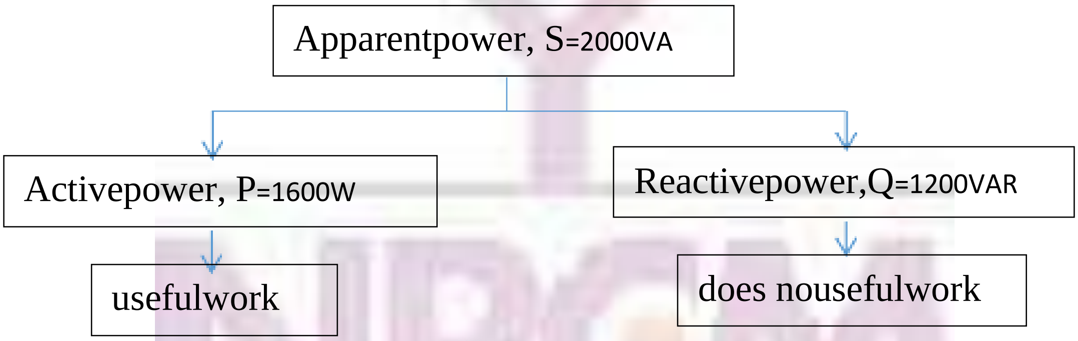
(vi) The reactive power is neither consumed in the circuit nor does it do any usefulwork. It merely flows back and forth in both directions in the circuit. A wattmeter does notmeasurereactivepower.

Example:

Supposeacircuitdrawsacurrentof10Aatavoltageof200Vanditsp.f.is0·8lagging.Apparentpower,

S=VI=200×10=2000VA.

Activepower,P=VIcosφ=200×10 ×0·8=1600W.ReactivepowerQ =VIsinφ=200× 10×0·6=1200VAR.



The circuit receives an apparent power of 2000 VA and is able to convert only 1600 watts intoactive power. The reactive power is 1200 VAR and does no useful work. It merely flows intoand out of the circuit periodically. In fact, reactive power is a liability on the source because thesource has tosupplytheadditionalcurrent(i.e.,Isinφ).

- **DisadvantagesofLowPowerFactor:**

Thepowerfactorplaysanimportanceroleina.c.circuitssincepowerconsumeddependsuponthisfactor.

$P = V_L I_L \cos\varphi$ (Forsinglephasesupply)

$\therefore I_L = \frac{P}{V_L \cos\varphi}$ ……………………………….(i)

$P = \sqrt{3} V_L I_L \cos\varphi$ (For3phasesupply)

$\therefore I_L = \frac{P}{\sqrt{3} V_L \cos\varphi}$ …………………………...(ii)

It is clear from above that for fixed power and voltage, the load current is inversely proportionalto the power factor. Lower the power factor, higher is the load current and vice-versa. A powerfactorless thanunityresultsinthefollowingdisadvantages:

(i) LargekVAratingofequipment.Theelectricalmachinery(e.g.,alternators,transformers,switchgear)isalwaysratedin*kVA.

$$kVA = \frac{kW}{\cos\varphi}$$

It is clear that kVA rating of the equipment is inversely proportional topower factor. Thesmaller the power factor, the larger is the kVA rating. Therefore, at low power factor, the kVAratingoftheequipmenthastobemademore,makingtheequipmentlargerandexpensive.

i.e $\cos\varphi \propto \frac{1}{kVA}$

(ii) Greater conductor size. To transmit or distribute a fixed amount of power at constantvoltage, the conductor will have to carry more current at low power factor. This necessitateslargeconductor size.

For example, take the case of a single phase a.c. motor having an input of 10 kWon full load,theterminalvoltagebeing250V.Atunityp.f.,theinputfullloadcurrentwouldbe10,000/250 =40A.At0·8 p.f;thekVAinputwouldbe10/0·8 =12·5andthecurrentinput12,500/250=50 A. If the motor is worked at a low power factor of 0·8, the cross-sectional area of the supplycables and motor conductors would have to be based upon a current of 50 A instead of 40 Awhichwouldberequiredatunitypowerfactor.

Large copper losses. The large current at low power factor causes more I^2R losses in all theelements ofthesupplysystem.Thisresultsinpoorefficiency.

Poor voltage regulation. The large current at low lagging powerfactor causes greater voltagedropsinalternators,transformers,transmissionlinesanddistributors.Thisresultsinthedecreased voltage available at the supply end, thus impairing the performance of utilisationdevices. In order to keep the receiving end voltage within permissible limits, extra equipment(i.e.,voltageregulators)isrequired.

The above discussion leads to the conclusion that low power factor is anobjectionable feature inthesupplysystem

CausesofLowPowerFactor

Low power factor is undesirable from economic point of view. Normally, thepower factor ofthe whole load on the supply system in lower than 0·8. The following are the causes of lowpowerfactor:

(*i*) Most of the a.c. motors are of induction type(1φ and 3φ induction motors)which havelowlagging power factor. Thesemotors work at a power factor which is extremely small onlightload(0·2to0·3)andrisesto0·8or0·9atfullload.

(iii) Arc lamps, electric discharge lamps and industrial heating furnaces operateat low laggingpowerfactor.

(iv) The load on the power system is varying; being high during morning andevening andlow at other times. During low load period, supply voltage is increased which increases themagnetizationcurrent.Thisresultsinthe decreasedpowerfactor.

PowerFactorImprovement:

The low power factor is mainly due to the fact that most of the power loadsare inductive and,therefore, take lagging currents. In order to **improve** the power factor, some device takingleading power should be connected in parallel with the load. One of such devices can be acapacitor. The capacitor draws a leadingcurrent and partly or completely neutralises the laggingreactive componentofloadcurrent.Thisraises thepowerfactoroftheload.

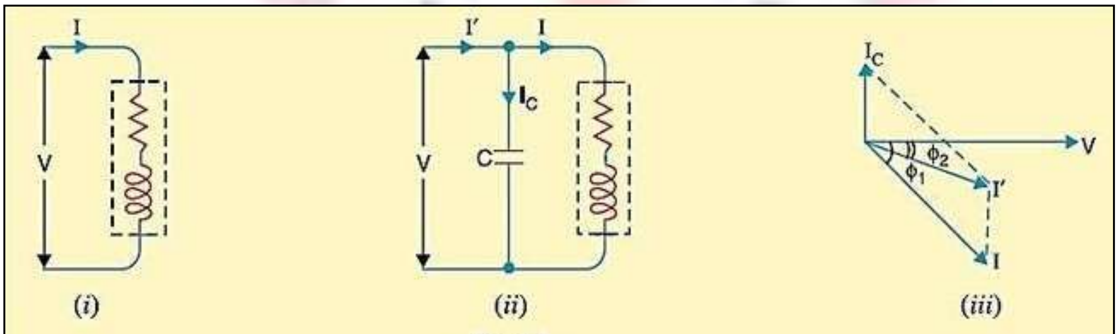


Fig. 6.3

Illustration. To illustrate the power factor improvement by a capacitor, considera single *phaseloadtakinglaggingcurrentIata powerfactorcos$φ_1$as shown inFig.6.3.

The capacitor C is connected in parallel with the load. The capacitor draws current $I_C$whichleads the supply voltage by 90º.The resultingline currentI′ isthe phasor sum of I and $I_C$andits angle of lag is $φ_2$as shown in the phasor diagram of Fig. 6.3. (iii). It is clear that $φ_2$is lessthan $φ_1$, so that cos $φ_2$is greater than cos $φ_1$. Hence, the power factor of the load is improved.Thefollowingpointsareworthnoting:

(i) ThecircuitcurrentI′afterp.f. correctionislessthantheoriginalcircuitcurrentI.

(ii) Theactiveorwattfulcomponentremainsthesamebeforeandafterp.f.correctionbecauseonlythelagging reactivecomponentisreducedbythe capacitor.

∴Icos $φ_1$=I′cos $φ_2$

(iii) The lagging reactive component is reduced after p.f. improvement and is equal tothe difference between lagging reactive component of load (I sin $φ_1$) and capacitor current

(I_C)i.e.,
$I' \sin\varphi_2 = I \sin\varphi_1 - I_C$

(iv) As $I\cos\varphi_1 = I'\cos\varphi_2$

$\therefore VI\cos\varphi_1 = VI'\cos\varphi_2$ [Multiplying by V]

Therefore, active power (kW) remains unchanged due to power factor improvement.

(v) $I'\sin\varphi_2 = I\sin\varphi_1 - I_C$

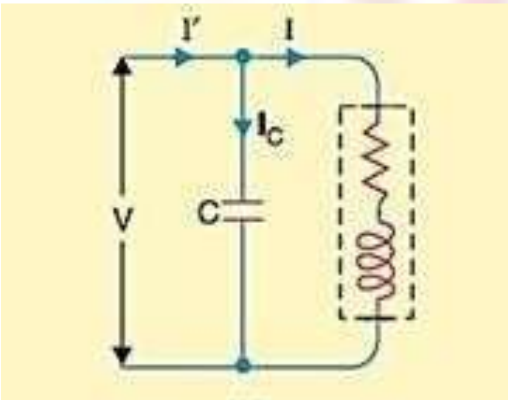
$\therefore VI'\sin\varphi_2 = VI\sin\varphi_1 - VI_C$ [Multiplying by V] i.e., Net kVAR after p.f. correction = [Lagging kVAR before p.f. correction − leading kVAR of equipment].

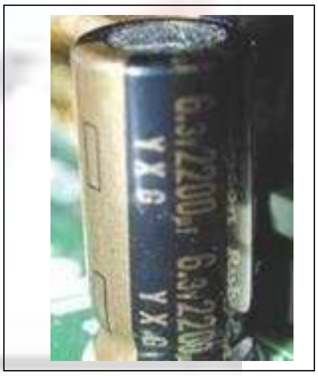
Power Factor Improvement Equipment*

Normally, the power factor of the whole load on a large generating station is in the region of 0·8 to 0·9. However, sometimes it is lower and in such cases it is generally desirable to take special steps to improve the power factor. This can be achieved by the following equipment:

1. **Static capacitors.**
2. **Synchronous condenser.**
3. **Phase advancers.**

1. Static capacitor. The power factor can be improved by connecting capacitors in parallel with the equipment operating at lagging power factor. The capacitor (generally known as static capacitor) draws a leading current and partly or completely neutralises the lagging reactive component of load current. This raises the power factor of the load.





For three-phase loads, the capacitors can be connected in delta or star as shown in Fig. 6.4. Static capacitors are invariably used for power factor improvement in factories.

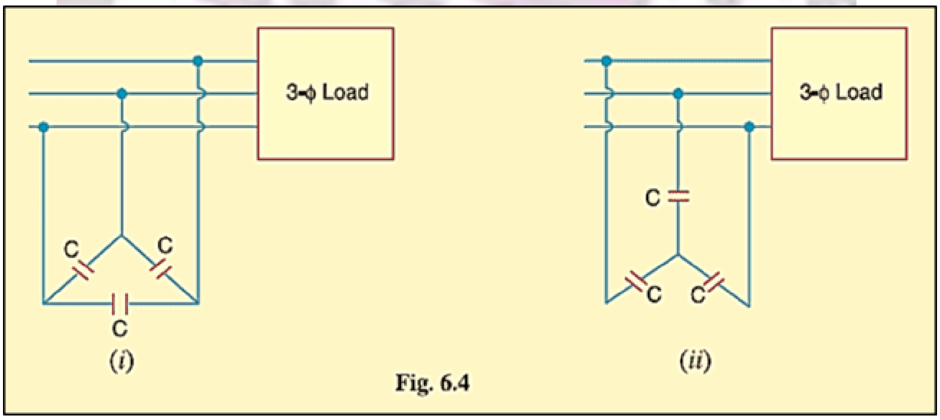


Fig. 6.4

Synchronous condenser. A synchronous motor takes a leading current when over-excited and,therefore, behaves as a capacitor. An over-excited synchronous motor running on no load isknown as *synchronouscondenser.* When such a machine is connected in parallel with thesupply, it takes a leading current which partly neutralises the lagging reactive component of theload.Thusthepowerfactorisimproved.
Fig 6.5 shows the power factor improvement by synchronous condenser method. The 3φ loadtakes current *IL* atlow lagging power factor cos φ*L*. The synchronous condenser takes acurrent *Im*which leads the voltage by an angle φ*m**. The resultant current *I* is the phasor sum of*Im*and*IL*andlagsbehindthevoltageby an angleφ.Itisclearthatφislessthan φ*L*sothatcosφisgreaterthan cos φ*L*.
Thus the power factor is increased from cos φ*L*to cos φ. Synchronous condensersare generallyusedatmajorbulksupplysubstationsforpowerfactorimprovement.

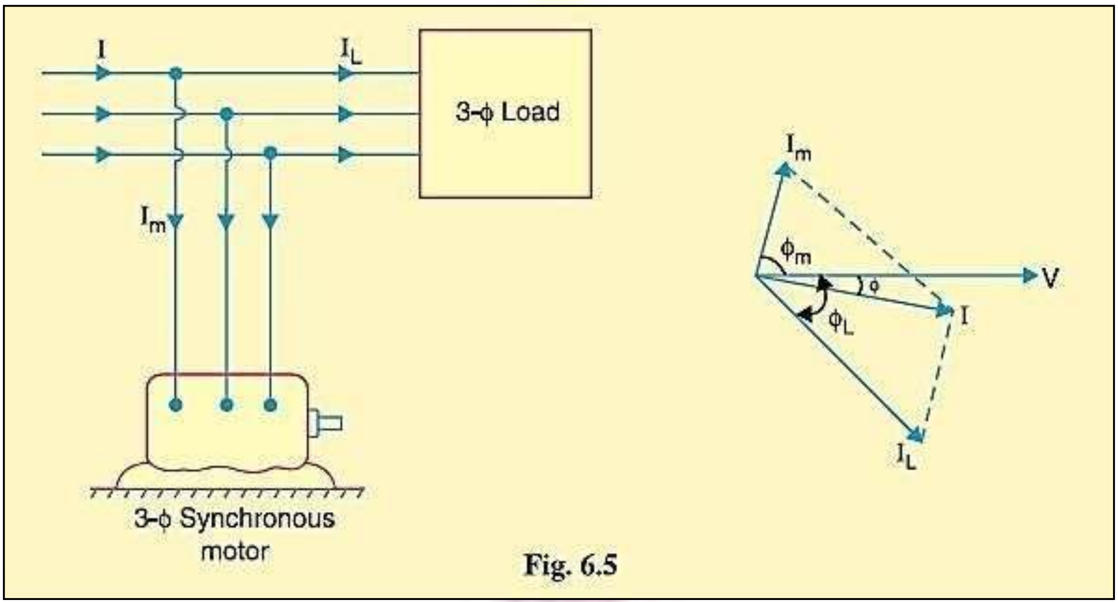


Fig. 6.5

Q. Compare between the mechanism of improving power factor withstatic capacitor andSynchronousmotor

staticcapacitor	Synchronousmotor
The p.f. improvement by switchingonthecapacitorsinvariousgroupings	Thep.f.improvementbyvaryingthefieldexcitation

Q.Whatarethesimilaritystatesbetweenasynchronousmotorandcapacitor?

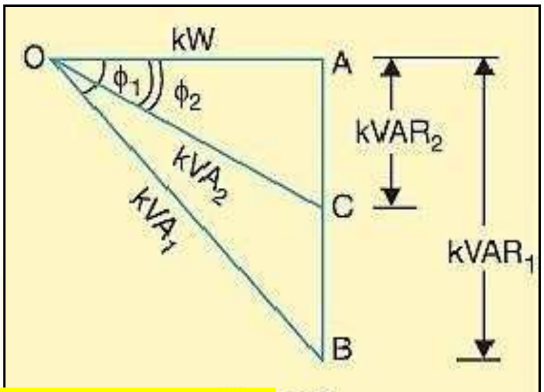
synchronousmotortakesaleadingcurrentwhenover-excitedand,therefore,behavesasacapacitor

Q.Atwhatconditionsansynchronousmotorisknown assynchronouscondenser?

1. whenanSynchronousmotor isanover-excitedand takesaleadingcurrent .
2. whensynchronousmotorrunningonnoload.

CalculationsofPowerFactorCorrection

The power factor correction can also be illustrated from power triangle. Thus referring to Fig.6.7, the power triangle OAB is for the power factor cos φ1, whereas power triangle OAC is forthe improved power factor cos φ2. It may be seen that active power (OA) does not change withpowerfactorimprovement.
However, the lagging kVAR of the loadis reduced by the p.f. correction equipment, thusimprovingthep.f.tocosφ_2.



6.7

BC =AB−AC
$kVAR_{final}=kVAR_1-kVAR_2$ $kVAR_{final}=OA(\tan\varphi_1-\tan\varphi_2)$ $kVAR_{final}=kW(\tan\varphi_1-\tan\varphi_2)$

Knowing
*thelaggingkVAR1supplied bytheload
*theleadingkVAR2 suppliedbythep.f.correctionequipment(**staticcapacitor** or**Synchronousmotor**),thedesiredresultscanbeobtained.

Example
6.3Asinglephasea.c. generatorsuppliesthefollowingloads:
(i) Lightingloadof20kWatunitypowerfactor.
(ii) Inductionmotor load of100kWatp.f.0·707lagging.
(iii) Synchronousmotorloadof50kWatp.f.0·9leading.
CalculatethetotalkWandkVAdeliveredbythegeneratorandthepowerfactoratwhichitworks.

Solution:Usingthesuffixes1,2and3toindicatethedifferentloads,wehave,

$$kVA_1 = \frac{kW_1}{\cos\phi_1} = \frac{20}{1} = 20\ kVA$$

$$kVA_2 = \frac{kW_2}{\cos\phi_2} = \frac{100}{0\cdot 707} = 141\cdot 4\ kVA$$

$$kVA_3 = \frac{kW_3}{\cos\phi_3} = \frac{50}{0\cdot 9} = 55\cdot 6\ kVA$$

These loads are represented in Fig. 6.10. The three kVAs' are not in phase. In orderto find thetotal kVA, we resolve each kVA into rectangular components – kW andkVAR as shown in Fig.6.10.
The totalkWandkVARmaythenbecombinedtoobtaintotalkVA.

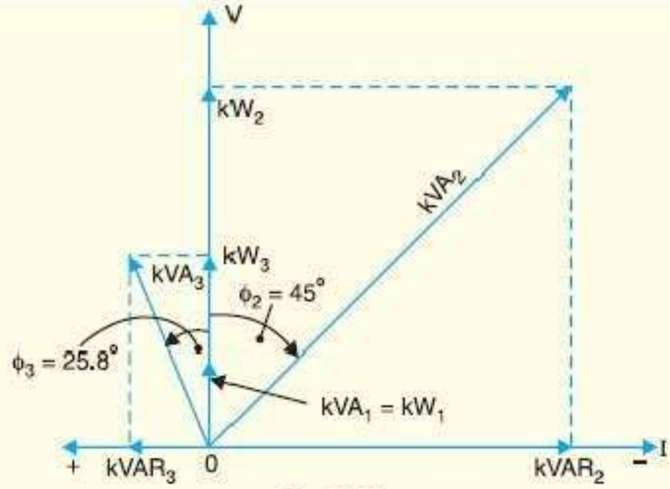


Fig. 6.10

$$kVAR_1 = kVA_1 \sin\phi_1 = 20 \times 0 = 0$$
$$kVAR_2 = kVA_2 \sin\phi_2 = -141{\cdot}4 \times 0{\cdot}707 = -100 \text{ kVAR}$$
$$kVAR_3 = kVA_3 \sin\phi_3 = +55{\cdot}6 \times 0{\cdot}436 = +24{\cdot}3 \text{ kVAR}$$

Note that $kVAR_2$ and $kVAR_3$ are in opposite directions ; $kVAR_2$ being a lagging while $kVAR_3$ being a leading kVAR.

$$\text{Total kW} = 20 + 100 + 50 = \mathbf{170\ kW}$$
$$\text{Total kVAR} = 0 - 100 + 24{\cdot}3 = -75{\cdot}7 \text{ kVAR}$$
$$\text{Total kVA} = \sqrt{(\text{kW})^2 + (\text{kVAR})^2} = \sqrt{(170)^2 + (75{\cdot}7)^2} = \mathbf{186\ kVA}$$
$$\text{Power factor} = \frac{\text{Total kW}}{\text{Total kVA}} = \frac{170}{186} = \mathbf{0{\cdot}914\ lagging}$$

The power factor must be lagging since the resultant kVAR is lagging.

UNIT-III

ELECTRICALMACHINES

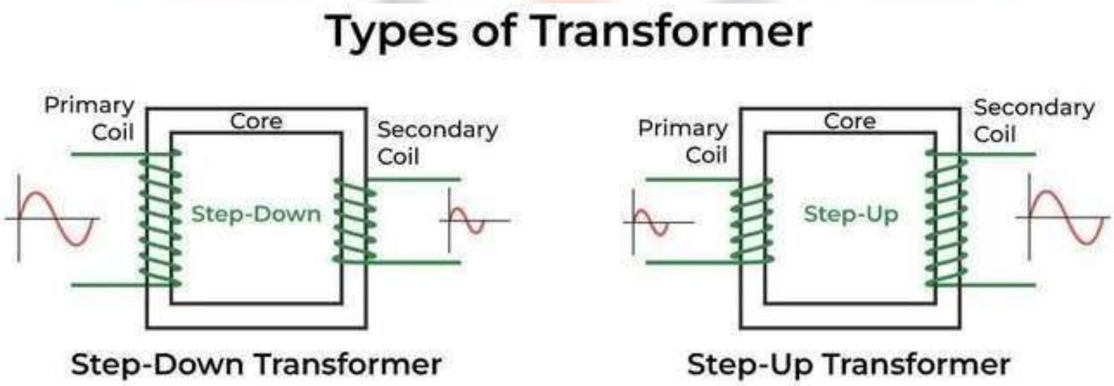
A transformerisastaticelectricaldevice thattransmitsACpowerfrom one circuitto another ataconstant frequency, but the voltage levelmay be changed,implying the voltage can be increasedordecreaseddependingontherequirement

Transformeristhesimplestdevicethatisusedtotransferelectricalenergyfromonealternating-currentcircuittoanothercircuitormultiplecircuits,throughtheprocessofelectromagneticinduction. A transformer works on the principle of **electromagnetic induction** to step up or stepdown voltage. Transformer eitherincreases AC voltage (Step-up transformer) or decreases ACvoltage (Step- down transformer). Transformer which is normally utilized in the transmission anddistribution of alternating current power is fundamentally a voltage control device. Transformer areused for a wide range of purposes, including increasing the voltage from electric generators toenable long-distance transmission of electricity and decreasing the voltage of conventional powercircuitstorunlow-voltagedeviceslikedoorbellsandtoyelectrictrains.

TypesofTransformer

TransformertypesbasedonVoltageLevel

There are primarily two types of Transformer based on the operating voltage. The following aresomeofthem:



- **Step-downTransformer:**Theprimaryvoltageisconvertedtoalowervoltageacrossthe

secondary output using a step-down transformer. The number of windings on the primary side of astep-down transformer is more than on the secondary side. As a result, the overall secondary-to-primary winding ratio will always be less than one. Step-down transformer are used in electricalsystems that distribute electricity over long distances and operate at extremely high voltages toensure minimum loss and economical solutions. Step-down transformer are used to change high-voltageintolow-voltagesupplylines.

- **Step-up Transformer:** The secondary voltage of a step-up transformeris raised from thelowprimary voltage. Because the primary windinghas fewer turns than the secondary winding inthis sort of transformer, the ratio of the primary to secondary winding will be greater than one.Step-up transformer are frequently used in electronics stabilizers, inverters, and other devices thatconvertlowvoltagetoasignificantlyhighervoltage.Astep-uptransformerisalsousedinthe distributionofelectricalpower.Forapplicationsconnectedtopowerdistribution,highvoltageisnecessary.I nthegrid,astep-uptransformerisusedtoraisethevoltagelevelpriortodistribution.

TransformerTypesbasedonCoreMaterial

DifferenttypesofTransformerareusedinthepowerandelectronicsindustries,dependingonthecorematerial s,whichare:

- **Iron Core Transformer:** Multiple soft iron plates are used as the core of an iron coretransformer.The iron's strongmagnetic properties of the iron core transformerhave extremelyhigh flux linkage.As a result,the iron core transformerhashigh efficiency. The soft iron coreplatescomeinavarietyofsizesand shapes.A fewtypicalshapesincludeE,I,U,andL.
- **FerriteCoreTransformer:**Duetoitshighmagneticpermeability,aferritecoretransformeruseso ne.Inthehigh-frequencyapplication,thiskindoftransformerprovidesincredibly low losses. In high-frequency applications like switch mode power supplies (SMPS),RF-relatedapplications,etc.,ferritecoretransformerare usedasaresult.
- **Toroidal Core Transformer:** Iron core or ferrite core are two examples of toroid-shapedcore materials used in transformer. For their excellent electrical performance, toroids, which have aring- or donut-shaped core material, are frequently used. The ring form results in very low leakageinductanceandextremelyhighinductanceandQfactors.
- **Air Core transformer:** The core material of an air core transformer is not a real magneticcore. The air is used solely in the air-core transformer flux linkage. The primary coil of an air-coretransformergeneratesanalternating current,producinganelectromagneticfieldallaroundit.

TransformerTypesbasedonWindingArrangement

- **AutoWindingtransformer:**Theprimary andsecondary windingshavealwaysbeenfixed, but with an auto-winding transformer, they can be connected in series, and the center-tappednode can be moved. The secondaryvoltage canbe alteredbychanging the location of the centraltap. The auto is used to alert the self or a single coil and is not the abbreviation for Automatic. Thiscoil createsaratiousingmainandsecondarycomponents.Themainandsecondary ratioisdeterminedbythelocationofthecentertapnode,whichchangestheoutputvoltage.TheVARIAC,ade vicethatgeneratesvariableACfromasteadyACinput,isused themostfrequently.

TypesofTransformerbasedonUsage

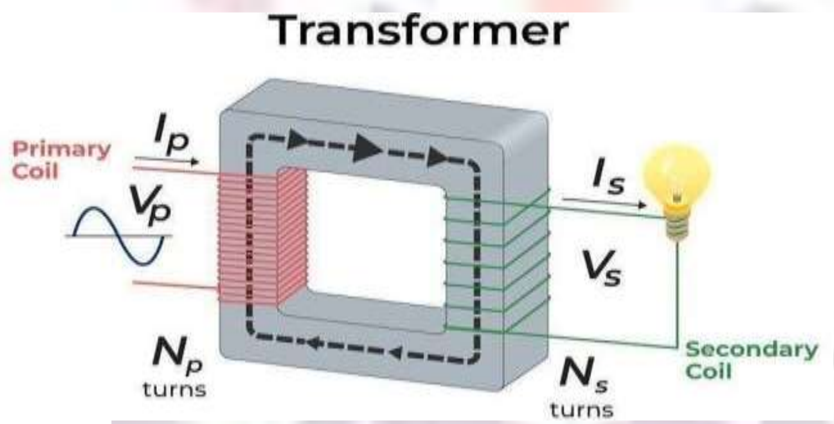
Transformercomeinawiderangeofvariants,eachofwhichoperatesinadistinctfield.Thus,basedontheirpro poseduse,transformercanbe categorizedasfollows:

- **Power Transformer:** The energy is transferred to the substation or the general electricalsupplyusingalargerpowertransformer.Betweenthemajordistributiongrid andthepowergenerator, this transformer serves as a link. Power Transformer can be further divided into threegroupsbasedontheirpowerratingandspecification-
- Smallpowertransformer,
- Mediumpowertransformer,and
- Largepowertransformer

- **Measurement Transformer:** Instrument transformeris another name for measurementtransformer. This is yet another measurement tool that is usually utilized in the power domain. Toseparate the primary power and convert the current and voltage in a smaller ratio to its secondaryoutput,ameasuringtransformerisused.
- **DistributionTransformer:**Thedistributiontransformerfunctionasastep-downtransformer,convertinghigh gridvoltage to the appropriate voltage for the end user, typically110V or 230V. Depending on the conversion capacity or ratings, the distribution transformer mightbelessinsizeorlarger.
- **Pulse Transformer:** One of the most popular PCB-mounted transformer that generateselectrical pulses with a consistent amplitude are pulse transformer. It is utilized in a number ofdigitalcircuitswherethedemandforisolatedpulsecreationexists.
- **Audio Output Transformer:**Another frequent transformer in the electronics industry isthe audiotransformer.Itisspecificallyusedinapplicationsinvolvingaudiowhereimpedancematchingisnecessary.

WORKINGPRINCIPLEOFATRANSFORMER

The fundamental principle of how the transformer functions are mutual induction between the twocoilsorFaraday’sLawofElectromagneticInduction.Belowisadescriptionofhowthetransformer operates. The laminated silicon steel core of the transformer is covered by two distinctwindings. According to the diagram below, the primary winding is the one to which the AC supplyisconnected,andthesecondarywindingistheonetowhichtheloadisconnected.Onlyalternating current can be used because mutual induction between the two windings requires analternatingflux.



The transformer primary winding produces an alternating flux, known as the mutual flux, when analternatingvoltageisapplied,inaccordance withthemutualinductance principle.

AccordingtoFaraday’sruleofelectromagneticinduction,thisalternatingfluxlinksthetransformer primary and secondary windings magnetically and generates EMFs E_1 in the primarywindingandE2inthesecondarywinding.TheEMF(E_1)isreferredtoastheprimaryEMF,

while

theEMF(E_2)isthesecondaryEMF.

$$E_2 = -N_2 \frac{d\phi_m}{dt}$$

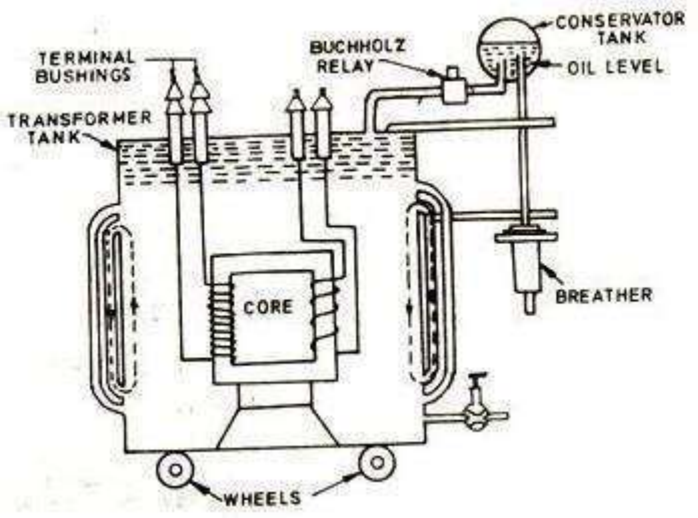
AndDividingaboveequations,toobtaintheratioas:

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

From the expression above,itis clear that the size of EMFs $E_1$and E_2isdependenton thenumberof turnsin the transformerprimary andsecondary windings, respectively.If $N_2 > N_1$,then $E_2 > E_1$, and the transformer will be a step-up transformer; if $N_2 < N_1$, then $E_2 < E_1$, andthetransformerwillbeastep-downtransformer.

If a load is now connected across the secondary winding, the load current I_2 will flow through theload as a result of the EMF E_2. As a result, a transformer makes it possible to transfer electricitywithachangeinvoltagelevelfromoneelectriccircuittoanother.

CONSTRUCTIONOFATRANSFORMER



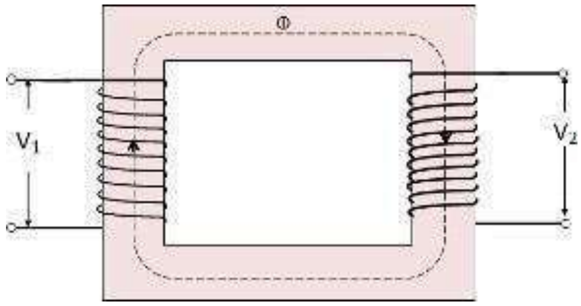
Atransformermajorlyconsistsofthreeparts:

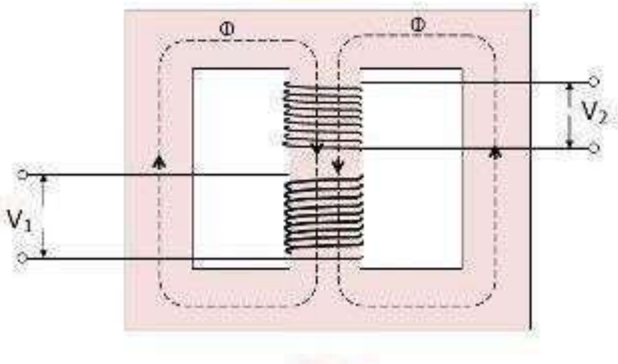
Core

The transformer core serves as a support for the winding. Additionally,it offers a magnetic fluxflow channel with minimal resistance. As seen in the image, the winding is looped around the core.To cut down on losses in a transformer, it has a laminated soft iron core. Core composition isdetermined by variables including operational voltage, current, and power, among others. The corediameterisnegativelycorrelatedwith ironlossesanddirectlycorrelatedwithcopperlosses.

The core lamination joined in the form of a strip which is shown infig.. For avoiding narrow gaps inbetween layer, the laminated layers are staggered in order. And these staggered joints are said'imbrieated'joint.Constructionally,thetransformeraretwotypes.Thetwotypesare—

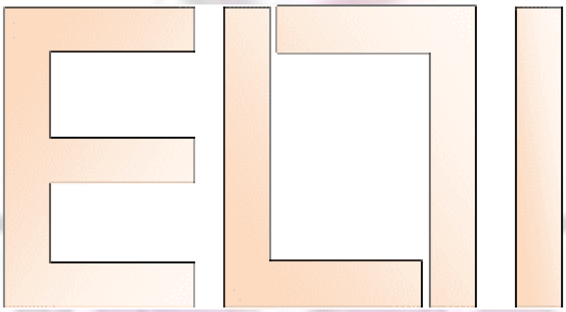
1. Coretype.
2. Shelltype.

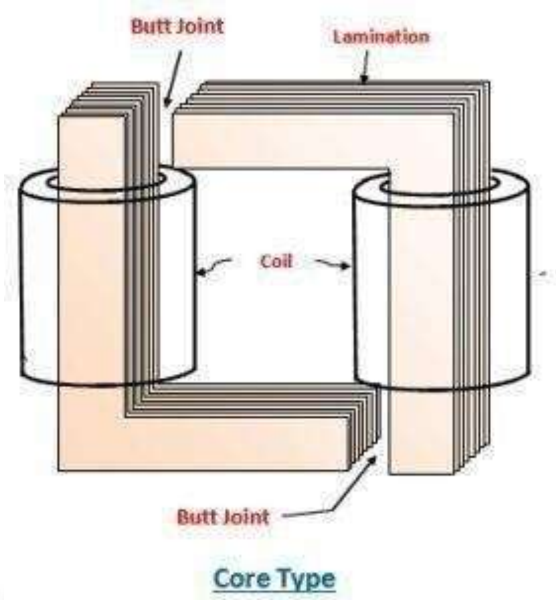




Shell Type

In both core is shell-type transformer, the laminations are in the following types. i.e L, E, &I typeswhich are shown in fig. To avoid high reluctance at joints, the laminations are butted each otherwhichisshowninfig.

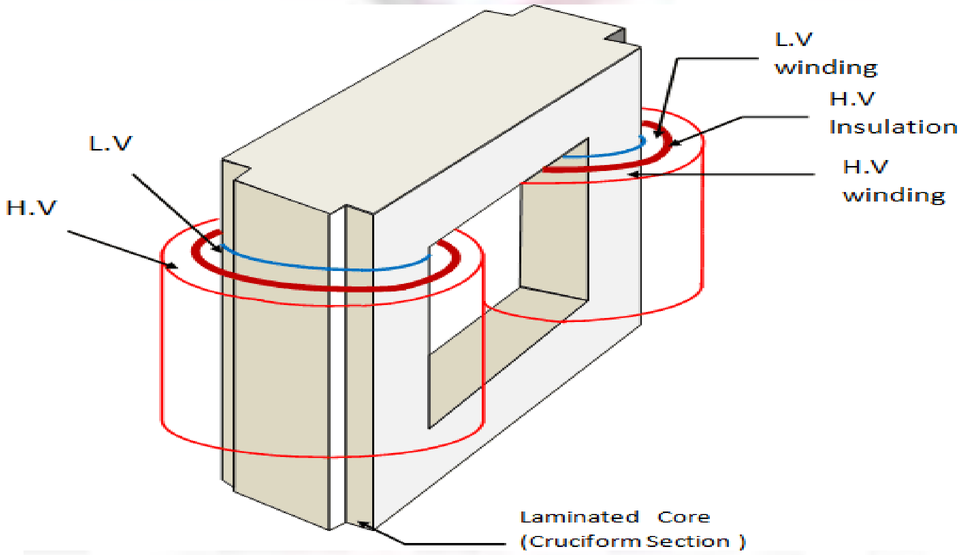




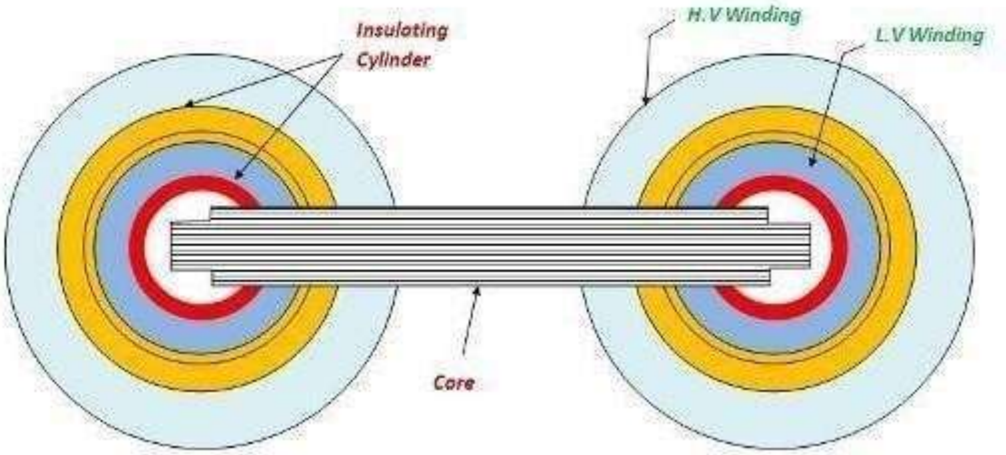
Core-typeTra nsformer

In this Core type transformer, the windings surround a considerable part of the core. Generally, thecore of the core-type transformer is a rectangular shape and the coils are both circular or rectangularinform and the windings are located on the opposite limbs of the core which is shown in fig. In mostof the large-size core –type transformer, round or circular cylindrical coils are used because themechanicalstrengthofcircularcylindricalcoilsishigh.

And these cylindrical coils are wound in a helical layer with different layers insulated from eachotherbypaper,cloth,micartaboardorcoolingducts.Forreducingleakageflux,andH.V&L.V

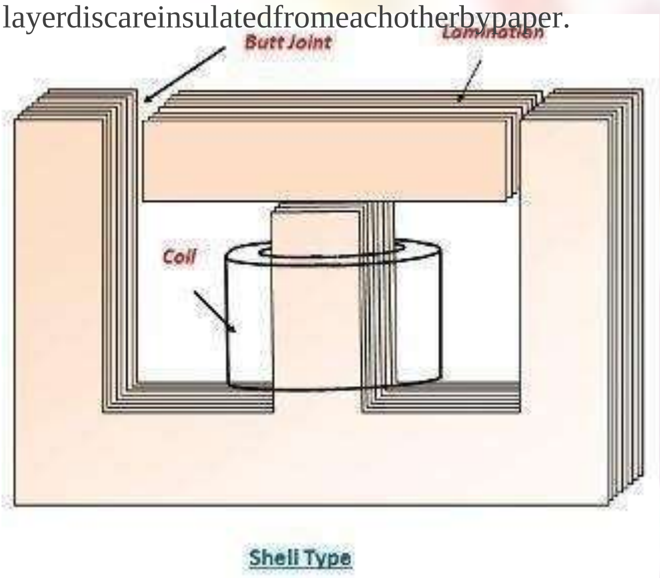


winding are placed one after another separating with high insulation cylinder on fuller board whichisshowninfig.



ShelltypeTransformer

The shell type transformer is a simple rectangular form and the core surrounds the considerableportionofthewindingswhich isshown infig.Boththeprimary&secondarywindingsareplacedinthe one limb. And the coils are wound in from of multi-layer disc type. The different layers of themulti-layerdiscareinsulatedfromeachotherbypaper.



Windings

The copper wires that are wound over the transformer core are known as windings. Copper cablesare used because Copper's high conductivity reduces transformer loss because resistance to currentflowlowers as conductivity rises.And copper's high degree of ductility makesitpossible toproduceincrediblythinwiresoutofit.

The two basic types of windings are. windings for the primary and secondary coils. The primarywinding is the group of winding turns that receive supply current. The numberof winding turnsfrom which output is derived is known as secondary winding. Insulation coating agents are used toinsulatetheprimaryandsecondarywindingsfromoneanother.

InsulationAgents

Transformer require insulation to keep the windings apart and prevent short circuits. This makesmutual induction easier.Transformerstability anddurability are influenced by insulation agents.In a transformer, the following are employed as insulating mediums: Insulating fluid, tape, Paper,andLaminationmadeofwood.

Tank

Atransformermaintankservestwopurposes:

- Thecore and thewindingsare protectedfromtheelements,such asrainanddust.
- It functions as an oil container as well as a support for all other

transformerattachments.

TransformerOil

The majority of the huge transformer are submerged in oil. The transformer oil adds insulationbetweentheconductors,improvesheatdissipationfromthecoils,andhasfault-detectingcapabilities.Transformeroilistypicallymade ofhydrocarbonmineraloil.

OilConservators

The oil conservator is situated above the transformer tank and bushings. Some transformeroilconservators contain a rubberbladder.When a transformerisloaded, the ambient temperaturerises, causing the amount of oil inside the transformer to increase. The transformer conservator tankhas enough room for the increased transformer oil. It also serves as a reservoir for oil that is used toinsulatebuildings.

Breather

All oil-immersed transformer with conservator tank includes it. It aids in the protection of the oilagainstmoisture.

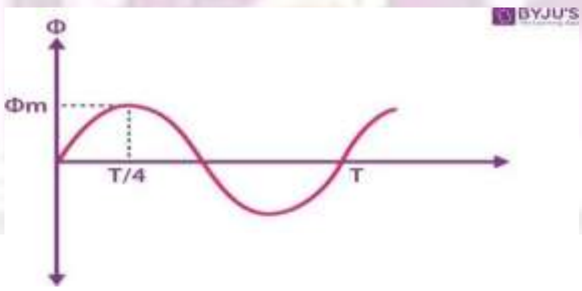
RadiatorsandFans

The majority of the power lost in the transformer is dissipated as heat. Radiators and fans aid in thedissipationofheatgeneratedbythetransformerandprovideprotectionagainstfailure.Themajorityofdry transformerarecooledbynaturalair.

IdealTransformer

The ideal transformer has no losses. There is no magnetic leakage flux, ohmic resistance in itswindingsandnoironlossinthecore.

EMFEQUATIONOFTRANSFORMER



N1– Numberofturnsintheprimary

N_2 – Number of turns in the

secondaryΦ_m–

Maximumfluxintheweber(Wb)

T –Timeperiod.Itisthetimetakenfor 1cycle.

The flux formed is a sinusoidal wave. It rises to a maximum value of Φ_m and decreases to anegative maximum of Φ_m. So, flux reaches a maximum in one-quarter of a cycle. The time taken isequaltoT/4.

Averagerateofchangeofflux=Φ_m/(T/4)=4fΦ_mWhere,f=frequency,T=1/f

Induced EMF per turn = Rate of change of flux per turnForm factor = RMS value / average

valueRMSvalue=1.11(4fΦ_m)=4.44fΦ_m[formfactorofasinewaveis1.11]

RMSvalueofEMFinduced in winding= RMSvalueofEMFperturnxNo.ofturns

PrimaryWinding

RMSvalueof inducedEMF=E_1=4.44fΦm*N_1

SecondaryWinding

RMSvalueof inducedEMF=E_2=4.44fΦm*N_2

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f\,\Phi m$$

This

istheEMFequationofthetransformer.Foranidealtransformeratnoloadcondition,E_1=Supplyvolt

ageontheprimarywinding

E_2=Terminalvoltage(theoreticalorcalculated) onthesecondarywindingVoltageTransformationRatio

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

Kiscalledthevoltagetransformationratio,whichisaconstant.Case1:IfN

2>N_1,K>1,itiscalledastep-uptransformer.

Case2:IfN_2<N_1,K<1,itiscalledastep-downtransformer.

IDEALTRANSFORMER:

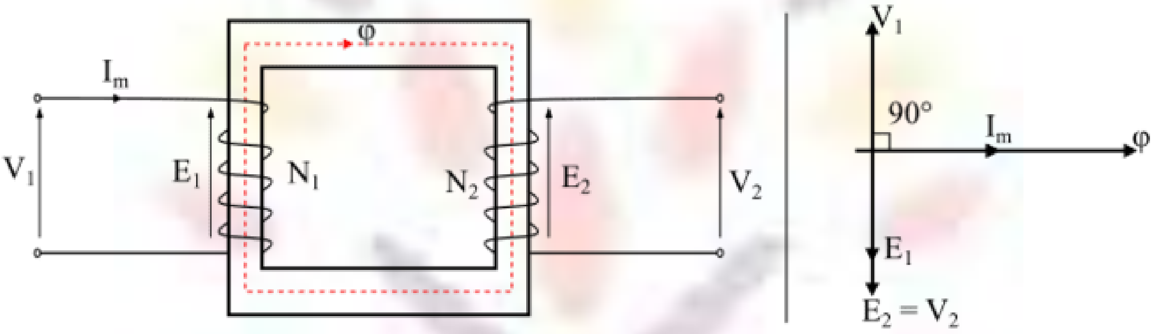
An*idealtransformer*isanimaginarytransformerwhichhas thefollowingcharacteristics−

- Theprimaryandsecondarywindings havenegligible(orzero)resistance.
- Noleakageflux,i.e.,wholeofthefluxisconfinedtothemagneticcircuit.
- Themagnetic core hasinfinite permeability, thus negligiblemmf is require to establishfluxinthecore.
- Therearenolossesduewindingresistances,hysteresisandeddycurrents.Hence,theefficien

cyis 100%.

WokingofIdealTransformerIdealTransformeronNoLoad

Consideranidealtransformeronno-load,i.e.,itssecondarywindingisopencircuited(seethefigure).Thus,theprimarywindingisacoilofpureinductance.

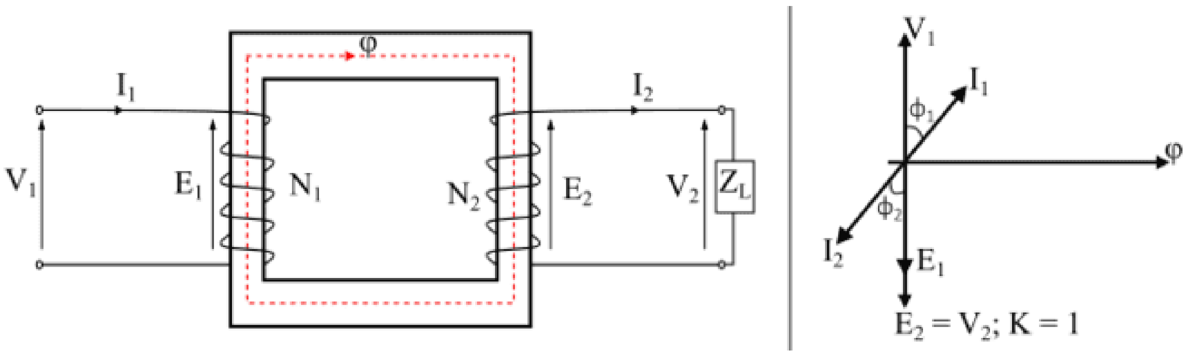


WhenanalternatingvoltageV1isappliedtotheprimarywinding,itdrawsaverysmallmagnetising current Imto establish the flux in the core, which lags behind the applied voltage by90°. The magnetising current Improduces an alternating flux ϕm which is proportional to and inphase with it.This alternatingflux (ϕm)links the primary and secondary windingsmagneticallyandinduces EMFE1intheprimarywindingandEMFE2inthesecondarywinding.

The EMF induced in the primary winding E1 isequal to andin opposition to the applied voltageV1 (according to Lenz's law). The EMFs E1 and E2 lag behind the flux (ϕm) by 90°, although theirmagnitudes depend upon the number of turns in the primary and the secondary windings. From thephasor diagram of the ideal transformer on no-load, it is clear that the flux is common to both thewindings,hence it can be taken as the reference phasor. Also, the EMFs E1 and E2 are in phasewitheachother,butE1isequaltoV1and180°outofphasewithit.

IdealTransformerOn-Load

When load is connected across the terminals of secondary winding of the ideal transformer, thetransformer is said to be loaded and a load current flows through the secondary winding and theload.



Consider an inductive load of impedance ZL is connected across the secondary winding of the idealtransformer (see the figure). Then, the secondary EMF E2 will cause a currentI2 toflow throughthe secondarywindingandtheload,whichisgivenby,

I2=E2/ZL=V2/ZL

Since,foranidealtransformer,theEMFE2isequaltosecondaryterminalvoltageV2.

Here, the load is inductive, therefore, the current I2 will lag behind the E2 or V2 by an angle ϕ2.Also,theno-loadcurrentI0beingneglectedbecausethetransformerisidealone.

The current flowing in the secondary winding (I2) sets up an mmf (N2I2) which produces a flux ϕ2in opposite direction to the main flux (ϕm). As a result, the total flux in the core changes from itsoriginal value, however, the flux in the core should not changes from its original value. Therefore, tomaintain the flux in the core at its original value, the primary current must develop an MMF whichcan counter-balance the demagnetising effectof the secondary mmf N2I2. Hence, the primarycurrentI1mustflowsuchthat,N1I1=N2I2

⇒I1=(N2/N1)×I2=KI2

Therefore, the primary winding must draw enough current to neutralise the demagnetising effect ofthe secondary current so that the main flux in the core remains constant. Hence, when the secondarycurrent (I2) increases, the primary current (I1) also increases in the same manner and keeps themutualflux(ϕm)constant.

It is clearfrom the phasor diagram of the ideal transformer on-load that the secondary current I2lagsbehindthesecondaryterminalvoltageV2byanangleofϕ2.

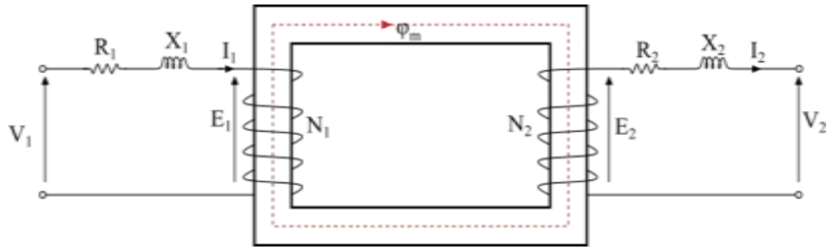
PRACTICALTRANSFORMER

A*practicaltransformer*istheonewhichhasfollowing properties−

- Theprimaryandsecondarywindingshavefiniteresistance.
- Thereisaleakageflux,i.e.,wholeofthefluxisnotconfinedtothemagneticcircuit.
- Themagneticcorehasfinitepermeability,thusaconsiderableamountofmmfisrequiretoestablishfluxinthecore.
- Therearelossesinthetransformerduetowindingresistances,hysteresisandeddycurrents.

Therefore, theefficiencyofa practicaltransformerisless than100%.

Thefigureshowsatypicalpracticaltransformer,whichpossessallthecharacteristicsthataredescribedabove.



TransformeronNoLoadCondition

When the transformer is operating at no load, the secondary winding is open-circuited, which meansthere is noload on the secondary side of the transformer and, therefore, current in the secondarywill be zero. While primary winding carries a small current I_0 called no-load current which is **2 to10%oftheratedcurrent**.

This current is responsible for supplying the iron losses (hysteresis and eddy current losses) in thecore and a very small amount of copper losses in the primary winding. The angle of lag dependsuponthelossesinthetransformer.Thepowerfactorisverylowandvariesfrom**0.1to0.15**.

Theno-loadcurrentconsistsoftwocomponents:

- ReactiveormagnetizingcomponentI$_m$

(It is in quadrature with the applied voltage V_1. It produces flux in the core and does not consumeanypower).

- **ActiveorpowercomponentI$_w$**,alsoknowasaworkingcomponent

(It is in phase with the applied voltage V_1. It supplies the iron losses and a small amount of primarycopperloss).

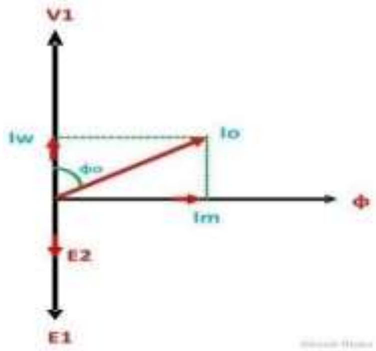
Thefollowingstepsaregivenbelowtodrawthephasordiagram:

1. Thefunctionofthemagnetizingcomponentistoproducethemagnetizingflux,andthus,itwillbeinp hasewiththeflux.
2. Inducedemfintheprimaryandthesecondarywindinglagstheflux ϕby90degrees.
3. Theprimarycopperlossisneglected,andsecondarycurrentlossesarezeroas$I_2=0$.

Therefore, the current I_0 lags behind the voltage vector V_1 by an angle ϕ_0 called the no- load power factorangleandisshowninthephasordiagramabove.

4. TheappliedvoltageV$_1$isdrawnequalandoppositetotheinducedemfE$_1$becausethedifferencebet weenthetwo,atnoload,isnegligible.
5. ActivecomponentI$_w$isdrawninphasewiththeappliedvoltageV$_1$.

6. ThephasorsumofmagnetizingcurrentIm andtheworkingcurrentIw givestheno-load



currentI0.

Fromthephasordiagramdrawnabove,thefollowingconclusionsaremade:

Working component $I_w = I_0 Cos\varphi_0$

No load current $I_0 = \sqrt{I_w^2 + I_m^2}$

Magnetizing component $I_m = I_0 \, Sin\varphi_0$

Power factor $Cos\,\varphi_0 = \frac{I_w}{I_0}$

No load power input $P_0 = V_1 I_0 Cos\varphi_0$

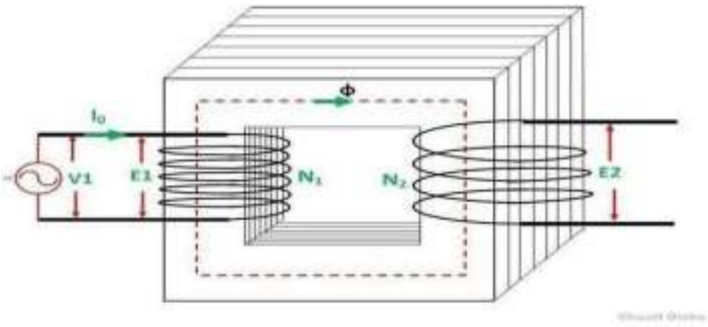
Thisisallabouttransformerinnoloadcondition.TRANSFOR MERONLOAD CONDITION

When the transformer is on the loaded condition, the secondary of the transformer is connected toload. The load can be resistive, inductive or capacitive. The current I2 flows through the secondarywinding ofthetransformer.Themagnitude ofthesecondarycurrentdependsontheterminalvoltageV2 and the load impedance. The phase angle between the secondary current and voltage depends onthenatureoftheload.

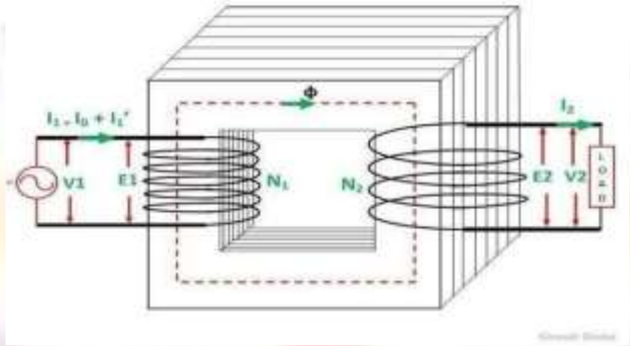
Operationof theTransformeronLoadCondition

TheOperationoftheTransformeronLoadConditionisexplainedbelow:

- When the secondary of the transformer is kept open, it draws the no-load current from themain supply. The no-load current induces the magnetomotive force N0I0 and this force set up theflux Φ in the core of the transformer. The circuit of the transformer at no load condition is shown inthefigurebelow:



When the load is connected to the secondary of the transformer, I_2 current flows through theirsecondary winding. The secondary current induces the magnetomotive force N_2I_2 on the secondarywinding of the transformer. This force set up the flux φ_2 in the transformer core. The flux $\varphi_2$opposesthefluxφ,accordingto**Lenz'slaw**.



- As the flux φ_2 opposes the flux φ, the resultant flux of the transformer decreases and this fluxreduces theinduced EMF E_1. Thus, the strength of the $V_1$is more than E_1 and an additionalprimarycurrentI'_1drawnfromthemainsupply.

Theadditionalcurrentisusedforrestoringtheoriginalvalueof thefluxinthecore of thetransformer so that $V_1 = E_1$. The primary current I'_1 is in phase opposition with the secondarycurrentI_2.Thus,itiscalledthe**primarycounter-balancingcurrent**.

- The additional currentI'_1 induces the magnetomotive force $N_1I'_1$. And this force set up theflux φ'_1. The direction of the flux is the same as that of the φ and it cancels the flux φ_2 whichinducesbecauseoftheMMFN_2I_2

Now,$N_1I_1' = N_2I_2$

$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

Therefore,

- The phase difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primaryside ofthetransformer.

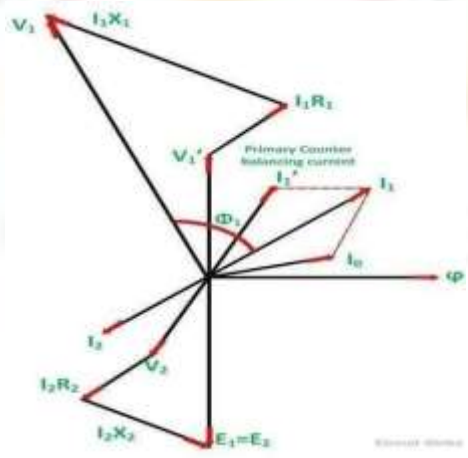
- Thepowerfactorofthesecondarysidedependsuponthetypeofloadconnectedtothetransformer.

If the load is inductive as shown in the above phasor diagram, the power factor will belagging, and if the load is capacitive, the power factor will be leading. The total primarycurrent I_1 isthe vectorsumofthecurrentsI_0andI_1'.i.e

$$\overline{I_1} = \overline{I_0} + \overline{I_1'}$$

PhasorDiagramofTransformeronInductiveLoad

Thephasordiagramoftheactualtransformerwhenitisloadedinductivelyisshownbelow:



PhasorDiagramoftheTransformeronInductiveLoadStepstod

rawthephasordiagram

- Takefluxϕ,areference
- InducesemfE_1andE_2lagsthefluxby90degrees.
- Thecomponentoftheappliedvoltagetotheprimaryequalandoppositetoinducedemfintheprimarywinding.E_1isrepresentedbyV_1'.
- CurrentI_0lagsthevoltageV_1'by90degrees.
- Thepowerfactoroftheloadislagging.ThereforecurrentI_2isdrawnlaggingE_2byanangleϕ_2.
- The resistance and the leakage reactance of the windings result in a voltage drop, and hencesecondaryterminalvoltageV_2isthephasedifferenceofE_2andvoltagedrop.

V_2= E_2–voltagedrops

I_2R_2isinphasewith$I_2$and$I_2X_2$is in quadraturewithI_2.

- ThetotalcurrentflowingintheprimarywindingisthephasorsumofI_1'andI_0.

- PrimaryappliedvoltageV_1isthephasorsumofV_1'andthevoltagedropintheprimarywinding.
- CurrentI_1'isdrawnequalandoppositetothecurrent$I_2$$V_1$=V

1'+voltagedrop

I_1R_1isinphasewithI_1andI_1X_IisinquadraturewithI_1.

ThephasordifferencebetweenV_1andI_1givesthepowerfactorangle$\phi_1$oftheprimarysideofthetransformer.

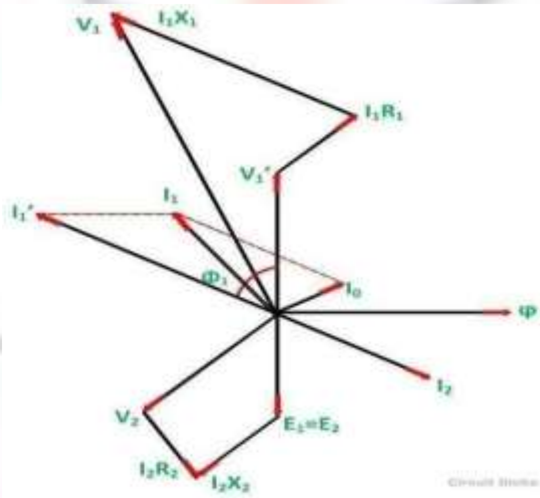
- The power factor of the secondary side depends upon the type of load connected to thetransformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will belagging, andiftheloadiscapacitive,thepowerfactor willbeleading.
 WhereI_1R_1istheresistivedropintheprimarywindings

I_2X_2isthereactivedropinthesecondarywindingSimi

larly

PhasorDiagramofTransformeronCapacitiveLoad

TheTransformerontheCapacitiveload(leadingpowerfactorload)isshownbelowinthephasordiagram.



PhasorDiagramoftheTransformeronCapacitiveLoadStepsto

draw thephasordiagramatcapacitiveload

- Takefluxϕareference
- InducesemfE_1andE_2lagsthefluxby90degrees.
- Thecomponentof theappliedvoltagetotheprimaryequalandoppositetoinducedemfintheprimarywinding.E_1isrepresented byV_1'.
- CurrentI_0lagsthevoltageV_1'by90degrees.
- Thepowerfactoroftheloadisleading. ThereforecurrentI_2isdrawnleadingE_2

- Theresistanceandtheleakagereactanceofthewindingsresultinavoltagedrop,andhencesecondaryterminalvoltageV_2isthephasordifferenceofE_2andvoltagedrop.

$V_2 = E_2$–voltagedrops

I_2R_2isinphasewithI_2andI_2X_2isin quadraturewithI_2.

- CurrentI_1'isdrawnequalandoppositetothecurrentI_2
- ThetotalcurrentI_1flowingintheprimarywindingisthephasorsumofI_1'andI_0.
- PrimaryappliedvoltageV_1isthephasorsumofV_1'andthevoltagedropintheprimarywinding.

$V_1 = V_1' +$voltagedrop

I_1R_1isinphasewithI_1andI_1X_IisinquadraturewithI_1.

- ThephasordifferencebetweenV_1andI_1givesthepowerfactorangle$\phi_1$oftheprimaryside ofthetransformer.
- Thepowerfactorofthesecondarysidedependsuponthetypeofloadconnectedtothetransformer.

Thisisallaboutthephasordiagramonvariousloads.

Thetransformer'sequivalent circuit:

Tomodelarealtransformeraccurately,weneedtoaccountforthefollowinglosses:

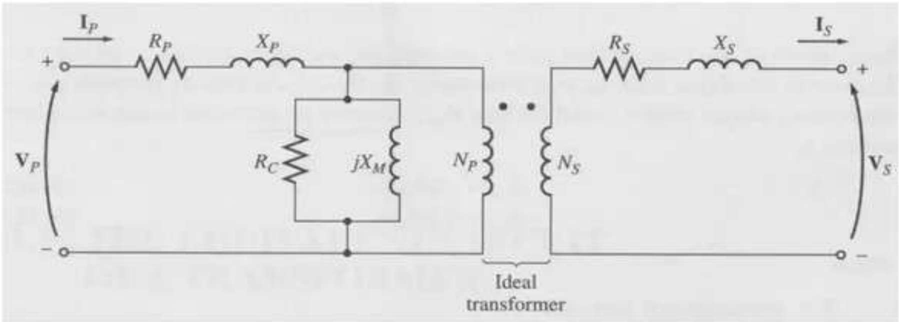
1. COPPERLOSSES–RESISTIVEHEATINGIN THEWINDINGS:I^2R.

2. EDDY CURRENT LOSSES – RESISTIVE HEATING IN THE CORE: PROPORTIONALTOTHESQUAREOFVOLTAGEAPPLIEDTOTHETRANSFORMER.

3. HYSTERESISLOSSES–ENERGYNEEDEDTOREARRANGEMAGNETICDOMAINS IN THE CORE: NONLINEAR FUNCTION OF THE VOLTAGE APPLIED TO THETRANSFORMER.

4. LEAKAGE FLUX – FLUX THAT ESCAPES FROM THE CORE AND FLUX THATPASSESTHROUGHONEWINDINGONLY.

THEEXACTEQUIVALENTCIRCUITOFAREALTRANSFORMER

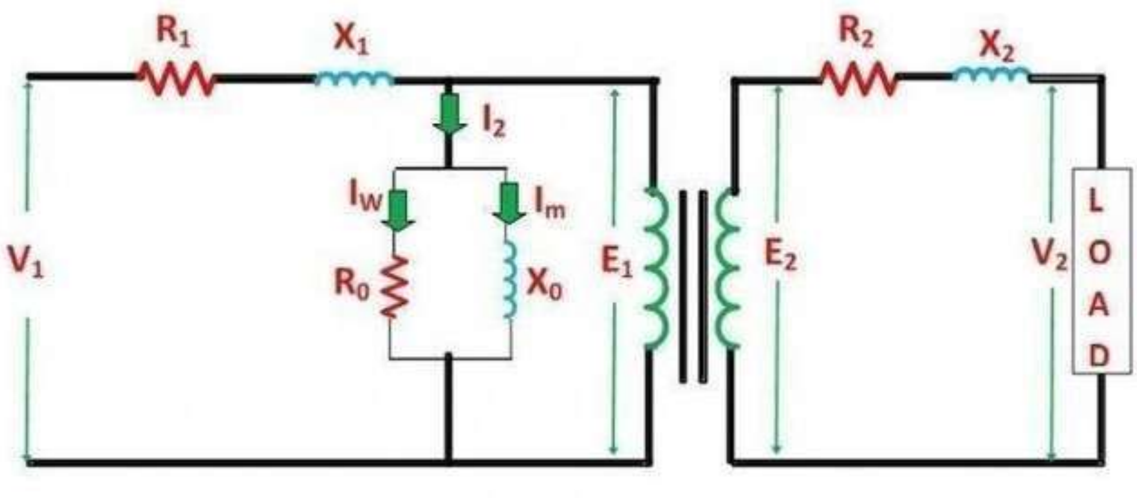


- CooperlossesaremodeledbytheresistorsRpandRs.
- Theleakagefluxcanbemodeledbyprimaryandsecondaryinductors.
- ThemagnetizationcurrentcanbemodeledbyareactanceXMconnectedacrosstheprimaryvoltagesource.

Thecore-losscurrentcanbemodeledby aresistanceRCconnectedacrosstheprimaryvoltagesource.
Bothmagnetizingandcorelosscurrentsarenonlinear;therefore,XMandRCarejustapproximations.

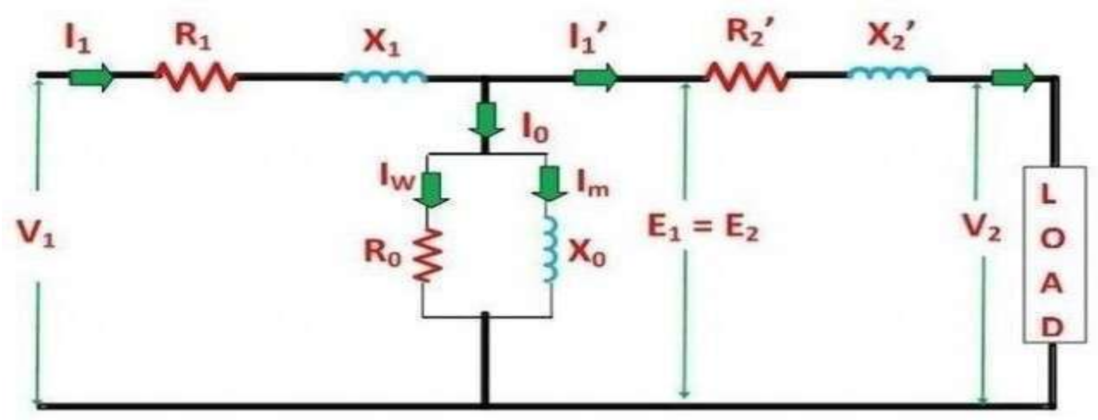
THEEXACTEQUIVALENTCIRCUITOFAREALTRANSFORMER:

Thesimplifiedequivalentcircuitofatransformerispresentedbyconsideringalltheproperties ofthetransformer either on the primary or secondary side. The main equivalent circuit of the transformerisshownbelowinthediagram:



EquivalentCircuitofTransformerwhenallthequantitiesarereferredtoPrimaryside

In this method, to derive the equivalent circuit of transformer, all the features are to be considered asthe primarysectionaspresentedinthefigurebelow:



EquivalentCircuitofTransformerReferredtoPrimarySide(Reference:**circuitglobe.com**)

The following quantities are the values of resistance and reactance that can be calculated by the nextequations.Secondaryresistancebasedontheprimarysideisobtainedas:

$R2' = R2/K^2$

Theequivalentresistanceaccordingtotheprimaryconsiderationisobtainedas:

$Rep = R1 + R2'$

Thesecondreactancebasedontheprimarysideispresentedas:

$X2'' = X2/K^2$

Theequivalentreactancedependsupontheprimarysideisobtainedas:

$Xep = X1 + X2'$

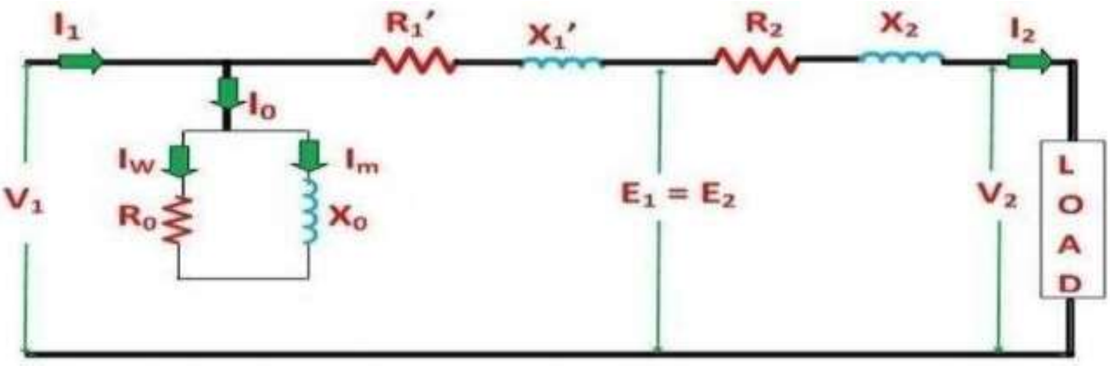
APPROXIMATEEQUIVALENTCIRCUITOFTRANSFORMER

Due to the small value of I0in comparison with I1, it is less than 4 percent of the total load of theprimarycurrentandmodifiesthevoltagereductionnegligibly.Asaresult,itisaperfectapproximation to reduce the excitation effect of the circuit in the approximate equivalent circuit oftransformer method. The resistance and reactance of winding are arranged in a series configurationwhich can now be introduced as the equivalentreactance and resistance of transformer, based onany particular side. But in this method, it is the primary side or side 1 that determines the features ofthe circuitbasedonthenextequation:

$V2'' = KV2$

EQUIVALENTCIRCUITOFTRANSFORMERWHENALLTHEQUANTITIESAREREFERREDTO SECONDARYSIDE

Theequivalentcircuitoftransformerorthebasicdiagramispresentedbelowwhenallthefeaturesare designedbasedonthesecondaryside.



EquivalentCircuitReferredtoSecondarySide

The following properties are the values for resistance and reactance which can be obtained below.Basicresistancebasedonthesecondarysideisformulatedas

$R1''=K^2R1$

Theequivalentvalueofresistanceaccordingtothesecondarytermisobtainedas

$Res=R2+R1'$

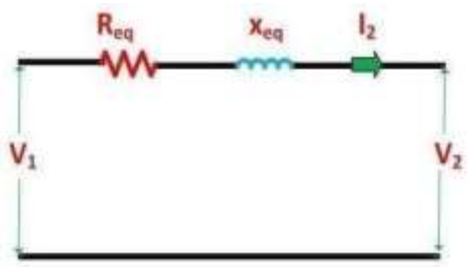
Theprimaryvalueofreactancebasedonthesecondarysideispresentedas

$X1''=K^2X1$

Andtheequivalentvalueofreactanceisobtainedas

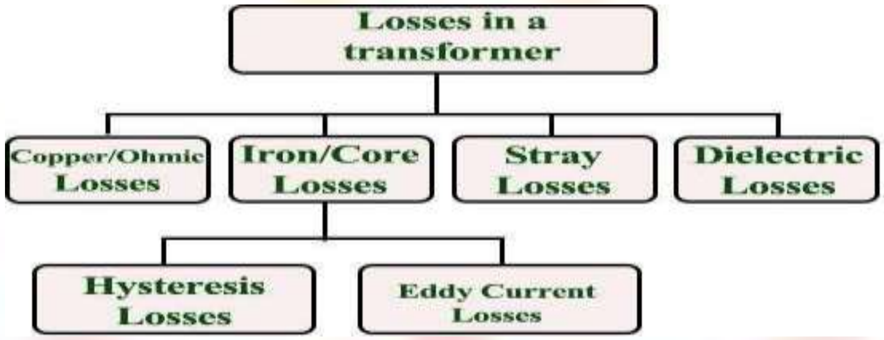
$Xes=X2+X1'$

Because the no-load current or I0is commonly 2 to 4 percent of the full load value of rated current,the parallel configuration includes the R0resistance and X0reactance can be removed from thecircuitwithout introducing any particular error in the performance of the transformer when the loadisapplied.
We can also apply further simplification in the equivalent circuit of transformer by removing theparallel terms in the circuit including R0 and X0. This simplified diagram of the system is presentedbelow:



SIMPLIFIEDEQUIVALENTCIRCUITOFTRANSFORMERT

YPESOFLOSSESINTRANSFORMERS:



An ideal ***transformer*** is very efficient, they don't have energy losses. It means power supplied to thetransformer's input terminal must be equivalent to the power supplied to the transformer's outputone. So the input power and output power in an ideal transformer are equal including zero ***energylosses***.

In reality, both the input and output powers of the transformer will not equal because of electricallosses within the transformer.Because the transformeris a static device,itdoesn'thave anymovable parts, so we cannot observe mechanical losses but electrical losses will occur like copperandiron.This articlediscussesanoverviewofdifferenttypesoflossesinatransformer.

Therearedifferentkindsoflossesthatwillbeoccurredinthetransformersuchascopper,hysteresis, eddy, iron, stray & dielectric. The copper loss commonly occurs due to the resistance inthe transformer winding whereas hysteresis losses will be occurred due to the magnetization changewithinthecore.

1. CoreLossesOrIronLosses

Eddy current loss and hysteresis loss depend on the magnetic properties of the material used for theconstructionofthecore.So,theselossesarealsoknownascorelossesorironlosses.

Hysteresis loss in transformer: The reason is the reversal of magnetization in the transformercore. This loss depends on the volume and grade of the iron, frequency of magnetic reversals andvalueoffluxdensity.WehavetheSteinmetzformula:

Wh=ηBmax1.6fV(watts)

Where,η=SteinmetzhysteresisconstantV=volumeofthecorein m3

Eddy current loss in transformer: The AC current is supplied to the primary winding whichsets up alternating magnetizing flux in the transformer. When this flux flow to a secondary winding,it produces induced emf in it. But some part of this flux also gets linked with other conducting partssuch as steel core or iron body or the transformer, which will result in induced emf in those parts,causing small circulating current in them. This current is called as eddy current. Due to the current,some energywillbedissipatedintheformofheat.

We=ηBmax^2f^2t^2V(watts)

Where,η=SteinmetzhysteresisconstantV=volumeofthecoreinm3T=Thick

nessofcore

CopperLoss

The ohmic resistance of the transformer windings creates copper loss. The copper loss for theprimary winding is I12R1 and for the secondary winding is I22R2. Where, I1 and I2 are current inprimaryand secondarywindingrespectively,R1andR2aretheresistancesofprimaryandsecondary winding respectively.We can see thatCuloss is proportional to square of the current,and currentdependsontheload.Sothatcopperlossintransformervarieswiththeload

StrayLoss

The reason for the types of loss is the occurrence of the leakage field. When compared with copperandironlosses,thepercentageofstraylossesareless,sotheselossescanbe neglected.

DielectricLoss

Theoilofthetransformeristhereasonforthis loss.Oilintransformerisaninsulatingmaterial. When theoilinthetransformergetsdeterioratesthenthetransformer’sefficiencywillbeaffected.

VOLTAGE REGULATIONOFTRANSFORMER:

Transformer’svoltageregulationistheratioofthedifferencebetweentransformernoloadandfullloadoutputv oltagetoitsfullloadoutputvoltage expressedasa percentage(%).

Inotherwords,transformervoltageregulationisthemeasureofsupplyingconstantoutputvoltagewithdifferentloadcurrents.

In simple words, the change in magnitude of input and output voltage of the transformer is know asvoltage regulation. i.e. the change in transformer secondary terminal voltage from no load to fullloadrelatedtothenoloadvoltageisknownas“voltageregulation”.

Mathematically,thevoltageregulationisexpressedbythefollowingformula.

$$\text{Voltage Regulation} = \frac{V_{\text{No Load}} - V_{\text{Full Load}}}{V_{\text{Full Load}}}$$

$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

Voltageregulationforprimarywindingofthetransformer

$$\% \text{ Voltage Regulation} = \frac{E_1 - V_1}{E_1} \times 100$$

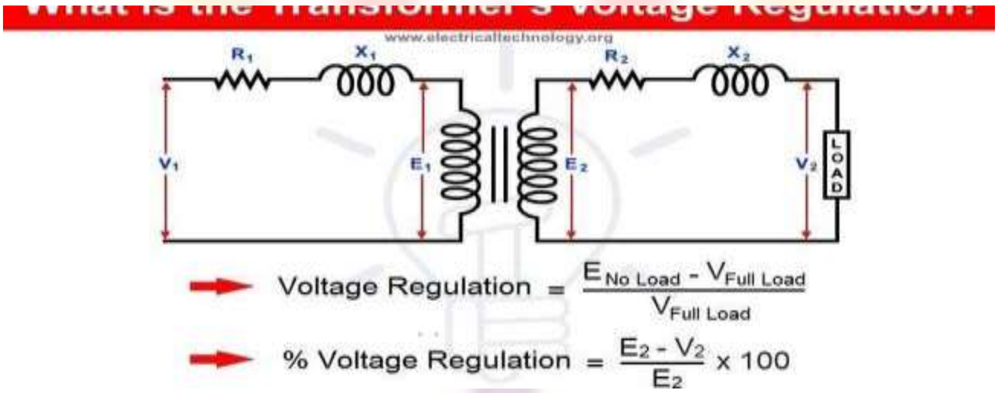
Where:

- E1= No load primary terminal voltageV1
- = Full load primary terminal voltageE2 =
- No load secondary terminal
- voltageV2=Fullloadsecondaryterminalvol tage

ATransformerwillgenerally provideahigheroutputvoltageatnoloadthanwhenthetransformeris fully loaded according to the transformer nameplatedata rating capacity. Stated differently, underload,atransformer'soutputvoltagedrops slightly.

Power transformershould provide a constant output voltage (ideally as it is not possible in real). Soitis the better option to have as much aslittle variation in output voltage with differentloadcurrents. In this scenario, voltage regulation shows that how much a transformer can provide aconstantsecondaryvoltagewithdifferentloadsconnectedtothetransformeroutput.

Thefollowingbasictransformercircuitandsolvedexamplewillcleartheconceptoftransformer'svoltageregulation.



In first scenario, Suppose there is no load connected to the transformer's secondary, In this case ofopencircuit:

- Noloadcurrentisflowingduetoopencircuit.
- Whennoloadcurrentflows,thereisnovoltagedropandreactivedropsacrossresistorandinductorsrespectably.

Voltagedropsacrossprimaryterminalsarenegligible.

Insecondscenario, thetransformerisloadedi.e.thereis a loadconnectedtothesecondaryterminalsofthetransformer.Inthiscaseofloadedcircuit:

Loadcurrentisflowingdue tocompletedcircuitandloadconnectedtothesecondaryterminals.
Loadcurrentflowsthroughtheload,sotheremustbevoltagedropsacrossresistorsandinductors.
Thisway,theaveragevalueofvoltageregulationismorethanthatoftransformerat

noload.TRANSFORMEREFFICIENCY

Comparing systemoutputwithinputwillconfirmtransformerefficiency.Thesystemiscalled betterwhenitsefficiencyishigh.

MeasureEfficiencyofTransformer

Likeanyotherelectricalmachine,theefficiencyofatransformercanbedefinedastheoutputpowerdividedbytheinputpower.Thatisefficiency=output/input.

Inelectricaldevices,transformersarethemosthighlyefficientones.Itisduetothefactthatmostofthetransformershavefullloadefficiencybetween95%to98.5%.

Asatransformerbeinghighlyefficient,theoutputvalueisequivalenttoinputvalue,andhenceitisimpracticaltomeasuretheefficiencyofthetransformerbyusingoutput/input.

Anothermethortofindefficiencyofatransformerisusing,efficiency=(input-losses)/input=1-(losses/input).

ConditionForMaximumEfficiency

Youcanseeinthebelowformular:Wehave,Cop

perloss = I12R1Ironloss =Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

η will be maximum at $\frac{d\eta}{dI_1} = 0$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{V_1I_1^2\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$I_1^2R_1 = W_i$$

Hence, the efficiency of a transformer will be maximum when copper loss and iron losses are equal.Sothat,Copperloss= Ironloss.

ApplicationofTransformer

Thefollowingaresomeofthemostcommonusesfortransformer:

- Thetransformertransmitselectricalenergythroughwiresoverlongdistances.
- TransformerswithmultiplesecondariesareusedinradioandTVreceivers,whichrequireseveraldifferentvoltages.
- Transformersareusedas voltageregulators.

ROTATINGMAGNETICFIELDINTHREE-PHASEINDUCTIONMOTOR:

When3-phasesupplyisfedtothestatorwindingof the3-phaseinductionmotor,a*rotatingmagneticfield(RMF)* isproduced. Thismagneticfieldissuchthatitspoles donotremaininafixed

position on the stator but go on shifting their positions around the stator. For this reason, it is knownas*rotatingmagneticfield(RMF)*orRMF.

Mathematically, it can be shown that the magnitude of this rotating magnetic field is constant and isequalto1.5timesofthemaximumflux(ϕ_m)duetocurrentinanyphase.

Thespeedof therotatingmagneticfieldis known as*synchronousspeed(NS)*.Thevalueofsynchronous speed depends upon the number poles (P) on the stator and the supply frequency (f).Therefore,

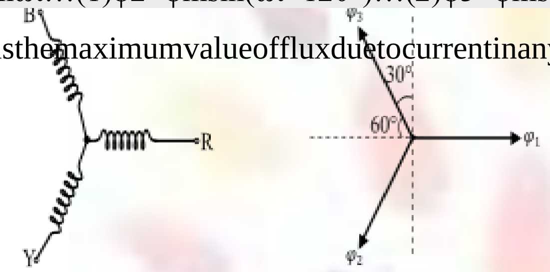
Synchronousspeed,$N_s=120f/P$RPM

MathematicalAnalysisofRotatingMagneticField

Consider three identical coils which are displaced 120° apart from each other in space. Let thesethree coilsareenergisedfromabalanced3-phasesupply.Hence,eachcoilwillproduceanalternatingfluxalongitsownaxis.Now,letthethreeinstantaneousfluxesaregivenby,

$\varphi_1=\varphi_m\sin\omega t \dots(1)\ \varphi_2=\varphi_m\sin(\omega t-120°)\dots(2)\ \varphi_3=\varphi_m\sin(\omega t+120°)\dots(3)$

Here,$\phi_m$isthemaximumvalueoffluxduetocurrentinanyphase.Thephasordiagramshowsthe



threefluxes.

Todeterminethemagnitudeoftheresultantflux,resolveeachfluxintohorizontalandverticalcomponents andthenfindtheirphasorsum.

Thus,theresultanthorizontalcomponentoffluxisgivenby,$\varphi_h=\varphi_1-\varphi_2\cos60°-\varphi_3\cos60°=\varphi_1-(\varphi_2+\varphi_3)\cos60°$

$\Rightarrow\varphi_h=\varphi_1-1/2(\varphi_2+\varphi_3)$

$\Rightarrow\varphi_h=(\varphi_m\sin\omega t)-1/2[\varphi_m\sin(\omega t-120°)+\varphi_m\sin(\omega t+120°)]$

$\Rightarrow\varphi_h=(\varphi_m\sin\omega t)-\varphi_m/2(\sin\omega t\cos120°-\cos\omega t\sin120°+\sin\omega t\cos120°+\cos\omega t\sin120°)$

$\Rightarrow\varphi_h=\varphi_m\sin\omega t-[\varphi_m/2\times(2\sin\omega t)\times(-1/2)]$

$\Rightarrow\varphi_h=3/2\varphi_m\sin\omega t\dots(4)$

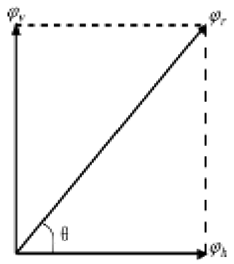
Theresultantverticalcomponentofthefluxisgivenby,$\varphi_v=0-\varphi_2\cos30°+\varphi_3\cos30°=(-\varphi_2+\varphi_3)\cos30°$

$\Rightarrow\varphi_v=[-\varphi_m\sin(\omega t-120°)+\varphi_m\sin(\omega t+120°)]\cos30°$

$\Rightarrow\varphi_v=\sqrt{3}/2\varphi_m[-(\sin\omega t\cos120°-\cos\omega t\sin120°)+(\sin\omega t\cos120°+\cos\omega t\sin120°)]$

$\Rightarrow\varphi_v=\sqrt{3}/2\varphi_m(2\cos\omega t\sin120°)=\sqrt{3}/2\varphi_m\times(2\cos\omega t)\times\sqrt{3}/2$

$\Rightarrow\varphi_v=3/2\varphi_m\cos\omega t\dots(5)$



Therefore,theresultantflux isgivenby,

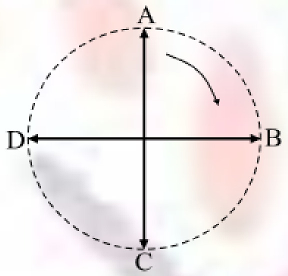
$\varphi r=\sqrt{(\varphi h^2+\varphi v^2)}=(3/2\varphi m\sin\omega t)2+(3/2\varphi m\cos\omega t)2$

$\Rightarrow \varphi r=3/2\varphi m(\sqrt{\sin^2\omega t+\cos^2\omega t})=3/2\varphi m\ldots(6)$

Hence, from the eqn. (6) itis clear that themagnitude of the resultant rotating magnetic field isequal to 1.5 times of maximum value of the flux (ϕm) per phase. Also, the resultant flux (ϕr) isindependentoftime,i.e.,itisconstantflux.

Again,$\tan\theta=\varphi v/\varphi h=(3/2\varphi m\cos\omega t)/(3/2\varphi m\sin\omega t)=\cot\omega t=\tan(90°-\omega t)$

$\therefore\theta=(90°-\omega t)\ldots(7)$



Eqn.(7) showsthattheangleisthefunctionoftime.Hence,

- **Case1**–Atωt=0°;θ=90°.ItiscorrespondingtopositionAintheabovefigure.
- **Case 2** – At ωt = 90°; θ = 0°. It is corresponding to position
- B.**Case 3** – At ωt = 180°; θ = -90°. It is corresponding to position
- C.**Case4**–Atωt=270°;θ=-180°.ItiscorrespondingtopositionD.

Hence,itcanbeseenthattheresultantfluxrotatesinspaceintheclockwisedirectionwithanangularvelocityofωradianspersecond.Therefore,fora machineofPpoles,

$\omega=2\pi f$;and$f=PNs/120$;

Thefollowingconclusionscanbedrawnfromtheabovediscussion−

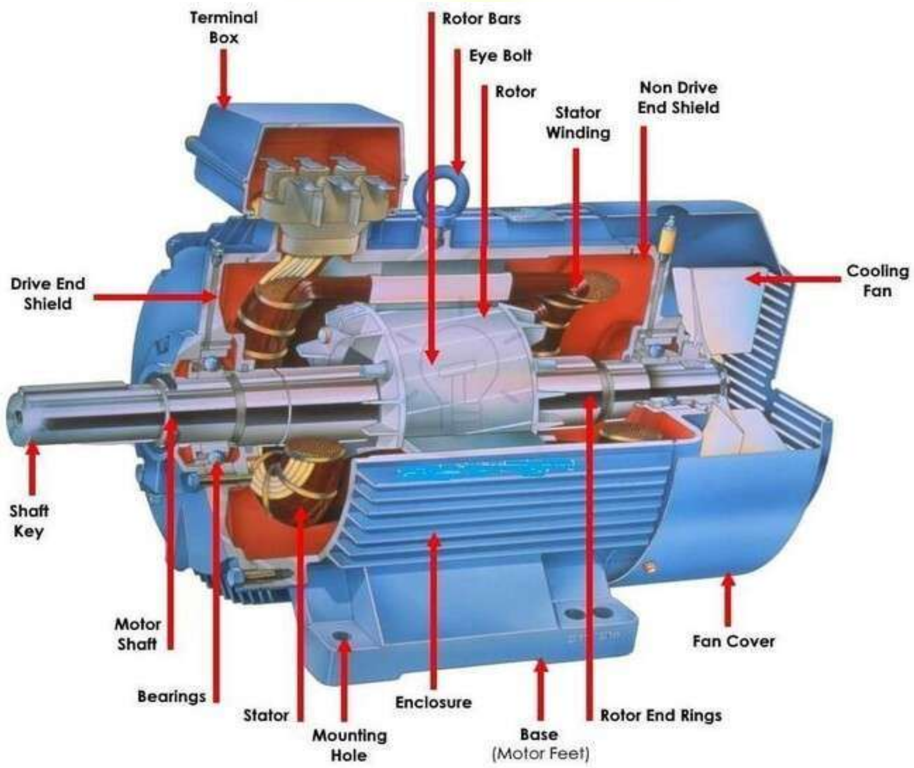
The3-phasecurrentsofabalanced3-phasesupplysystemproducearesultantfluxofconstantmagnitudeinthemotor.Themagnitude ofthefluxateveryinstantis1.5ϕm.
Theresultantfluxisrotatinginnatureanditrotatesatanangularvelocitysameasthatofthesupplycurrents.
Thedirectionofrotationoftheresultantfluxdependsuponthephasesequenceofsupplysystem.

CONSTRUCTIONANDWORKINGOFATHREE-PHASEINDUCTIONMOTOR:

The three-phase induction motor is one of the A.C.motors, which is widely used for variouspurposes in industry. These motors never run at a Synchronous speed but a little less than thesynchronousspeed.Thespeedofthesemotorsdependsuponthesupplyfrequency.

Therefore, these motors are not generally used for speed control. However, we prefer D.C. motorswhere large variations of speed are required. These motors are preferred in industry because theyhave low price, simple & rugged construction, can be manufactured with characteristics to suit theindustrialrequirement.

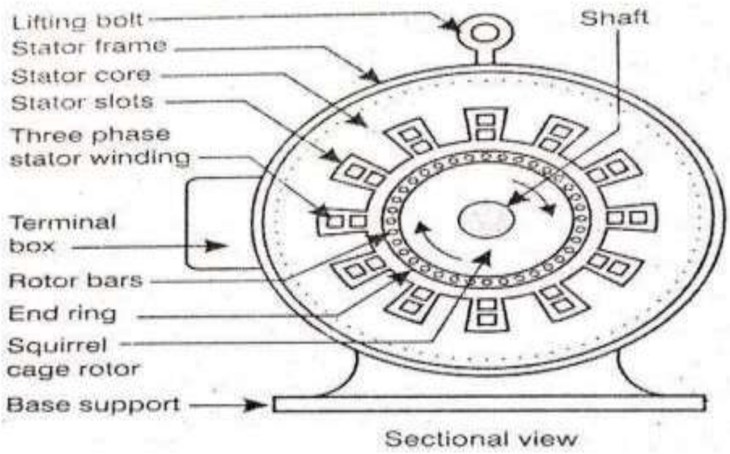
These motors differ from other types of motor, in that there is no electrical connection between therotor& supply.Therequired voltage&currentareinducedbyinductionfromthe**statorwinding**thatiswhy,thenamegivenisinductionmotor.



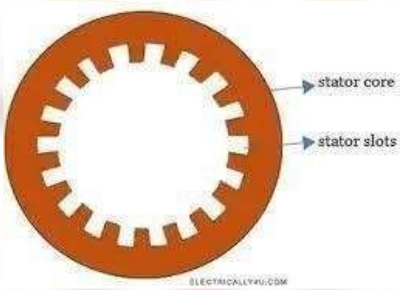
CONSTRUCTIONOFTHREEPHASEINDUCTIONMOTOR:

It can be better understood if we see the construction of three phase induction motor which hastwomajorparts :

1. Stationarypart,knownasStator
2. Rotatingpart,knownasRotor.



Stator:Itisthestationarypartofthemotor.It hasthreemainparts:

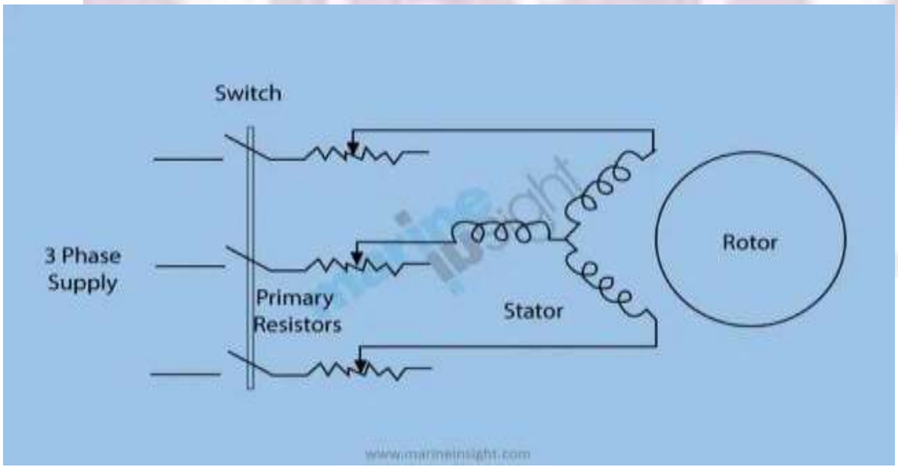


FrameorYoke

It is the outer part of the three phaseinduction motor. Its main function of the frame is to supportthe stator core & stator winding. It acts as a covering, and it provides protection & mechanicalstrengthtoallthe innerpartsofthethreephaseinductionmotor.

Statorcore

The main function of stator core is to carry the alternating flux. In order to reduce the eddy currentloss, the stator core is laminated. The core is made up of thin silicon steel laminations. These areinsulated from each other by varnish, the slots are cut on inner periphery of core stampings. Thestatorwindingsareplacedintheseslots.



Statorwindings

Stator winding is made up of super enamelled copper wire. Three phase windings are placed in thestator core slots & six terminals are brought out. They may be star connected or may be deltaconnected.The windingsareconnectedinstaratstarting.

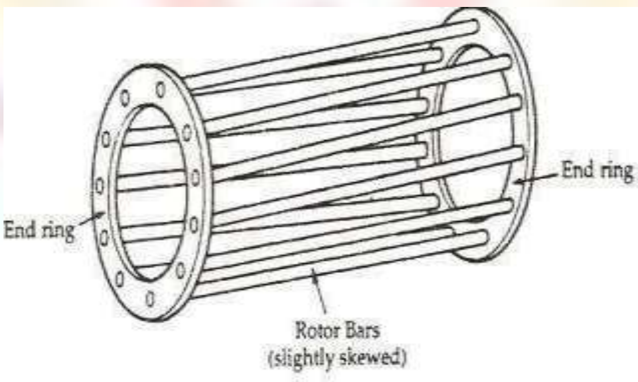
1. Rotor

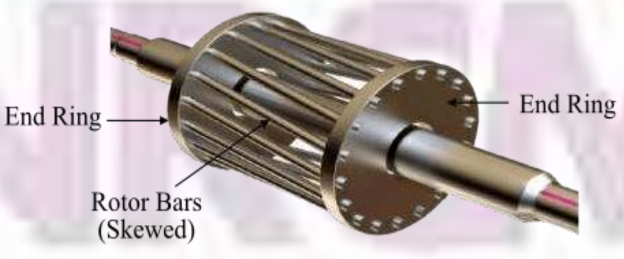
It is a rotating part of the motor. It is mounted on the shaft. It consists of hollow laminated corehaving slots on its outer periphery. The windings placed in these slots (rotor winding) may be one ofthe followingtwotypes:

1. Squirrelcagerotor
2. Slipringrotororwoundrotororphasewoundrotor.

1. Squirrelcagerotor

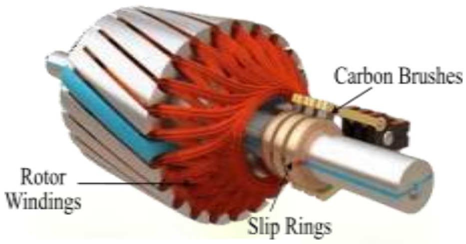
Therotorconsistsofacylindricallaminatedcorewithparallelslotsforcarryingtherotorconductors.The**squirrelcage**rotorconsistsofaaluminium,brassorcopperbars.Thesealuminium,brass or copper bars are called rotor conductors & are placed in the slots on the periphery of therotor.Therotor conductorsarepermanentlyshortedbythecopper,oraluminumringscalledthe **endrings.** To provide mechanical strength, these rotor conductors are braced to the end ring & henceform a complete closed circuitresemblinglike acage &hence gotits name as squirrel cageinductionmotor.

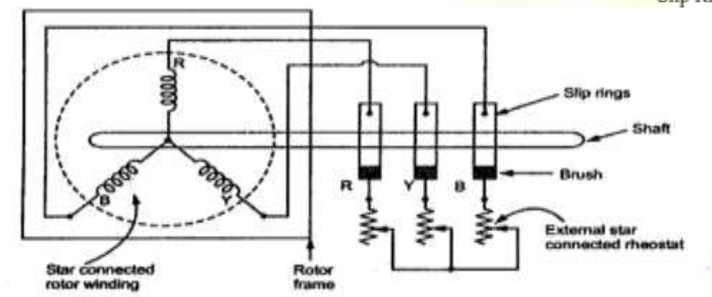




2. Slipringrotororwoundrotororphasewoundrotor

Thewoundrotorconsistsaslottedarmature.Insulatedconductorsareputintheslots&connectedto form a three phase double layer distributed winding similar to the stator winding. The rotorwindings areconnectedinstar.





The open end of the star circuit is brought outside the rotor and connected to the insulated slip rings.The slip rings are mounted on the shaft with brushes placing on them. The brushes are connected tothree phase variable resistors connected in star. The purpose of slip rings & brushes is to provide ameansforconnectingexternalresistorsinthecircuit.

PRINCIPLEANDWORKINGOF3PHASEINDUCTIONMOTOR

Inductionmotorworksontheprincipleof electromagneticinduction.

Whenthreephasesupplyisgiventothestatorwinding,arotatingmagneticfieldofconstantmagneticfieldisproduced.

Thespeedofrotatingmagneticfieldissynchronousspeed,NSr.p.m.

- $N_S = \frac{120f}{P}$ = speed of rotating magnetic field
- f = supply frequency

This rotating field produces an effect of rotating poles around a rotor. Let direction of this magneticfieldisclockwiseasshown.

Now at this instant rotor is stationary and stator flux R.M.F. is rotating. Soitsobvious that there existsa relativemotionbetweentheR.M.F. androtorconductors.

NowtheR.M.F.getscutbyrotorconductorsasR.M.F.sweepsoverrotorconductors.

Whenever a conductor cuts the flux, emf. gets induced in it. So e.m.f.gets induced in the rotorconductorscalledrotorinducedemf.thisiselectro–magneticinduction.

Asrotorformsclosedcircuit,inducedemf.circulatescurrentthroughrotorcalledrotorcurrent.

Any current carrying conductor produces its own flux. So rotor produces its flux called rotor flux. Forassumeddirectionofrotorcurrent,thedirectionofrotorfluxisclockwiseasshown.

Thisdirectioncanbeeasily determinedusingrighthandthumbrule.Nowtherearetwofluxes,one R.M.F.andanotherrotorflux.

Both the fluxes interact with each. On left of rotor conductor, two fluxes are in same directionhenceaddeduptogethighfluxarea.

Onrightsideofrotorconductor,twofluxesarein opposite directionhencetheycanceleachothertoproduce lowfluxarea.

So rotor conductor experiences a force from left to right, due to interaction of the two fluxes. As allrotorconductorexperiencesaforce,overallrotorexperiencesatorqueandstartsrotating.

So interaction of the two fluxes is very essential for a motoring action. As seen from the figure, thedirection of force is same as that of rotating magnetic field. Hence rotor starts rotating in the samedirectionasthatofR.M.F.

ADVANTAGESOFINDUCTIONMOTOR

The motor construction and the way electric power is supplied give the induction motor severalbenefitssuchas:

– Theyarerobustandsimpleinconstructionwithveryfewmovingparts
– Theycanefficientlyoperateinaruggedandharshenvironmentsuchasinseagoingvessels
– Themaintenancecostof3phaseinductionmotorislessandunlikethatofDCorsynchromotor,theydonothavepartslikebrushes,commutersorslipringsetc.

3 Phase induction motor does not need any additional starting mechanism or arrangement as theycangenerateself-startingtorquewhenthree-phaseACsupplyisprovidedtothem,unlikesynchronous motors. However, the single-phase induction motor needs some auxiliary arrangementforthestartingtorque

– The final output of athree-phasemotorisnearly 1.5 timesthe rating (output) of asingle-phase motorofthesamesize.

DISADVANTAGESOF3PHASEINDUCTIONMOTOR:

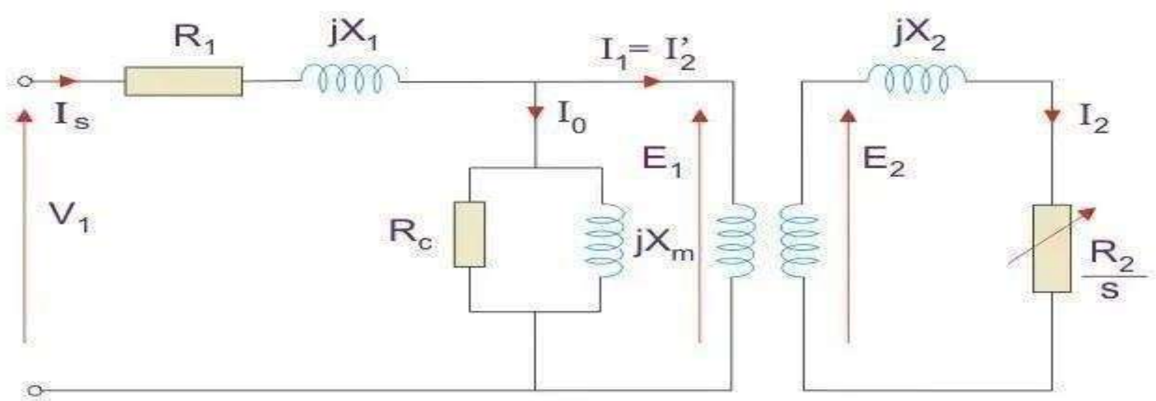
– During starting, it draws high initial starting current when attached to a heavy load. Thiscauses a dip in voltage during the starting period of the machine. Soft starting methods are connectedtothe3phaseelectricmotortoavoidthisproblem.
– Induction motor operates at lagging power factor which results in increased I2R losses andefficiency reduction,especiallyatlowload.Tocorrectandimprovethepowerfactor,staticcapacitorbanks canbeusedwiththistype ofACmotor.
– Speed control of 3 phase induction motor is difficult as compared to DC motors. A variablefrequencydrivecanbeintegratedwiththe inductionmotorforspeedcontrol.

EQUIVALENTCIRCUITOFANINDUCTIONMOTOR:

The equivalent circuit of any machine shows the various parameter of the machine such as itsOhmiclossesandalsootherlosses.

The losses are modeled just by inductorand resistor. The copper losses are occurred in the windingsso the winding resistanceis taken into account. Also, the winding has inductancefor which there is avoltage dropdue to inductive reactanceand also a term called power factorcomes into the picture.Therearetwotypesofequivalentcircuitsincase ofathree-phaseinductionmotor-

ExactEquivalentCircuit

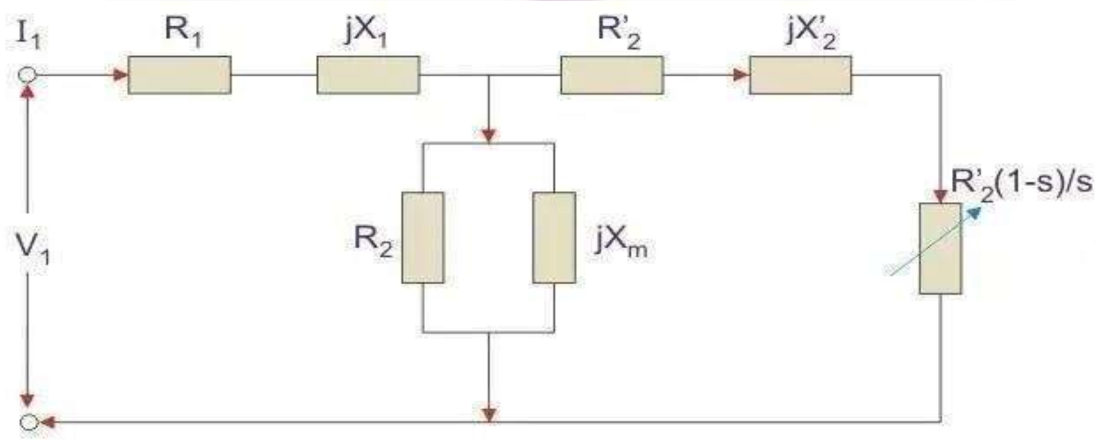


Here,R1isthewindingresistance ofthestator.X1istheinductanceofthestatorwinding.Rcis

thecoreloss component.

XMisthemagnetizingreactanceofthewinding.

R2/s is the power of the rotor, which includes output mechanical power and copper loss of rotor. Ifwedrawthecircuitwithreferredtothestatorthenthecircuitwilllooklike-



Herealltheotherparametersaresameexcept-

R2’istherotorwindingresistancewith referred tostatorwinding.X2’ isthe rotorwindinginductancewithreferredtostatorwinding.

R2(1 – s) / s is the resistance which shows the powerwhich is converted to mechanical poweroutput or useful power. The power dissipated in that resistor is the useful power output or shaftpower.

APPROXIMATEEQUIVALENTCIRCUIT

The approximate equivalent circuit is drawn just to simplify our calculation by deleting one node.The shunt branch is shifted towards the primary side. This has been done as the voltage dropbetween the stator resistance and inductance is less and there is not much difference between thesupplyvoltageandtheinducedvoltage.However,thisisnotappropriateduetofollowingreasons-

1. Themagneticcircuitofinductionmotorhasanairgapsoexcitingcurrentislargercomparedtotransformersoexactequivalentcircuitshouldbeused.
2. Therotorandstatorinductanceislargerininductionmotor.
3. Ininductionmotor,weusedistributedwindings.

This model can be used if approximate analysis has to be done for large motors. For smaller motors,wecannotusethis.

PowerRelationofEquivalentCircuit

1. Input power to stator- 3 V1I1Cos(Ө). Where, V1 is the stator voltage

applied.I1isthecurrentdrawnbythestatorwinding.Cos(Ө)isthestatorpower.

2. Rotorinput==

Powerinput-Statorcopperandironlosses.

3. RotorCopperloss= Slip×powerinputtotherotor.
4. DevelopedPower=(1–s)×Rotor inputpower.

TORQUE-SPEED &TORQUE-SLIPCHARACTERISTICSOFANINDUCTIONMOTOR

Torque-slipCharacteristics

Torque-slip characteristics give the relation between torque and slip. The torque-slip characteristicsshow how the torque changes with a change in slip. The slip is defined as a ratio of synchronousspeed and the actual speed of the rotor. The actual speed of the rotor varies with loading condition.Therefore,theslipchangeswithloadingcondition.

$$T = \frac{ksR_2E_{20}^2}{R_2^2 + (sX_{20})^2}$$

Inthepreviousarticle,wehavederivedthetorqueequationofaninductionmotor.

From the above equation, if R2 and X20 are kept constant, the torque depends on the slip. Thetorque- slip characteristics curve looks like a rectangular hyperbola. And this curve is divided intothreeregions;

- Lowslipregion
- Mediumslipregion
- Highslip region

LowSlipRegion

At synchronous speed, the slip of an induction motor is zero. Hence, the torque developed in therotor is zero. Therefore, an induction motoralways runs slightly less than the synchronous speed.Andinthisconditionslipisverylow.

Whentheslipisverylow,$(sX_{20})^2$isnegligiblecomparedtotheR2.So,forlowslIfwe

$$T = \frac{k_1 s}{R_2}$$

considerrotorresistanceR2as constant;Tas

Hence, at low slip conditions, the torque is directly proportional to the slip. This is the normaloperating region for an induction motor. In the low-slip region, the torque-slip curve is a straightline.

MediumSlipRegion

If the load increases, the speed of an induction motor decreases, and slip increases. As the slipincreases, the term $(sX_{20})^2$ becomes high compared to Rotor resistance R2. And in this condition,wecanneglecttherotorresistanceR2.

$$T = \frac{k_3 R_2}{s X_{20}^2}$$

$$T \propto \frac{1}{s}$$

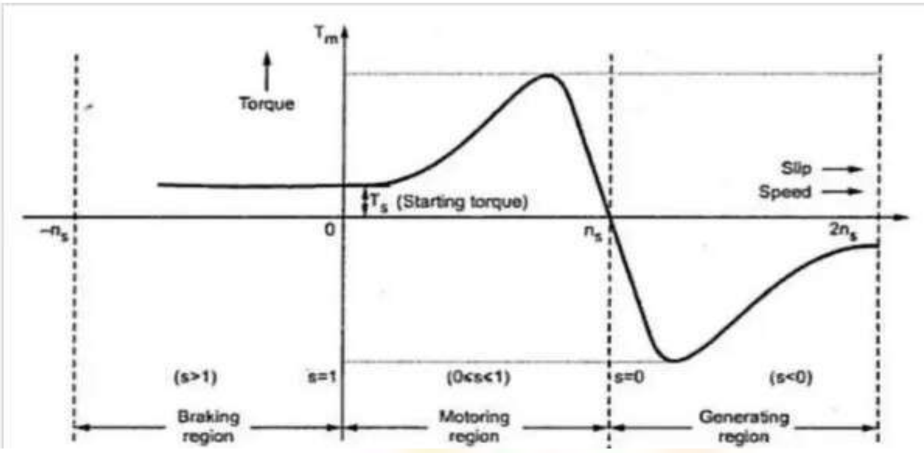
So,thetorqueisinverselyproportionaltotheslip.Duringthisregion,thecurveshapesarectangular hyperbola and passes through the point of maximum torque. The maximum torque isachievedwhenR2

=sX20.This torqueisknownaspull-outtorqueorbreakdowntorque.

HighSlipRegion

If we increase the torque beyond the maximum torque point, the torque starts decreasing. Thiscondition is when the load increases. During this condition, the motor speed decreases, and theoverloadprotection mustbeactivatedtodisconnectamotorfromthesupply.Ifthemotorcontinuously runs in this region, the motor will damage due to overheating. This region in a torque-slipcurveis decreasingregionafterthemaximumtorquepoint.

Generally, the induction motor operates for the value of slip between zero to SM. The slip SM is aslip at the maximum torque point. The pull-out torque for an induction motor is 2 to 3 times of ratedfull-loadtorquefortypicaloperation.Therefore,themotorcanhandleoverloadforshortperiod withoutstalling.Thetorque-slipcurveoftheinductionmotorforconstantrotorresistanceisshowninthefigurebelow.



Similartotheabove description,thiscurveisalsodividedintothreeparts;

- Motoringregion
- Generatingregion
- Breakingregion

MotoringRegion

In this mode of operation, the slip of an induction motor is between zero to one. When the stator issupplied by electric power, the rotor rotates below synchronous speed. And the torque of a motorvariesfromzerotofull-loadtorqueasslipvariesfromzerotoone.

During this condition, the torque is directly proportional to the slip. Generally, the induction motoroperates in this region.The slip is zero at synchronous speed and the slip is one at standstillcondition.

Generating Region

In generating mode of operation, the induction motor runs above the synchronous speed and itbehaves as an induction generator. The speed of a motor increases above synchronous speed withthe helpofexternaldeviceslikeaprimemover.

Duringgeneratingregion,the slipand torque both are negative.Hence,the machinesreceivemechanical energy and deliver electrical energy. During the generating region, the motor requires to supplyreactiveelectricpower.

BrakingRegion

In the braking region, the polarity of supply voltage is changed.Hence, the motor rotates in areversedirection.Thismodeisusedtostopthemotor.Thismethodofelectricalbrakingisknownasplugging .Duringbrakingmode,theslipisgreaterthanone.

By this method, the motor stops within a short time. But the kinetic energy stored in the load isdissipatedasheat.Therefore,duringthebreaking,averyhighamountofheat isgenerated.Andalso,if the stator is connected with the supply, it is also generated as heat. Hence, it is contained todisconnectthesupplyfromthestatorbeforeenteringthebrakingmode.

LossesinInductionMotor

There are two types of losses that occur in induction motors are- fixed and variable loss. The fixedlossesarecorelossandmechanicalloss,andthevariablelossesarecopperlossandstrayloss.

In the energy conversion process, the electrical energy can not be fully converted into mechanicalenergy because some part of the electrical energy gets wasted in the form of heatenergy. Theenergywastedinthemotorintheformofheatenergycontributestopowerloss.

Thefollowing lossesoccurinaninductionmotor.

1. ConstantorFixedloss
2. VariableLoss

ConstantorFixedLossesinInductionMotor

Constantlossesare thelossesthatremainconstantwhen themotoroperatesasperitsratedparameters.Theconstantlossescanbedividedintothefollowingcategories.

1. Ironor corelosses
2. Mechanicallosses
3. BrushfrictionlossesI

ronorCoreLosses

Iron losses in an induction motor are the heat loss that gets dissipated in the core of the motor due tothe alternating magnetic fieldcreated by the stator winding. These losses are also known as corelossesorhysteresislosses.

Twotypesofironlossesoccurinaninductionmotor:Hyst

- eresisloss
- Eddycurrent loss

Themagneticcoreofaninductionmotoropposeschangesinmagneticfielddirectionandbecauseof hysteresis lag the Hysteresis losses occur in the magnetic core. On the other hand, Eddy currentlosses occur because the alternating magnetic field induces a voltage in the core, and the inducedvoltage cause the setting up of circulating current(Eddy current), and this circulating current causesheatloss I^2R inthecore.

The iron loss does not vary with load, therefore these are the fixed losses. The iron losses remainconstant whether the motor is operating at no load or at full load. These losses happen because ofmagnetic flux and we know, the average magnetic flux remains constant, provided the voltage andfrequency are maintained as per the motor's rated voltage & frequency. The iron losses can bereducedbytheuseofahigh-qualitylaminatedironcore.

Other factors like the shape and size of the core, the design of the rotor and stator slots, andoperating temperature also affect the iron losses in the motor. A higher temperature leads to anincrease in the core resistance, and consequently, it contributes to higher losses. Therefore, themotorshouldbeadequatelycooledtoreducetheironlossesaswellasthecopperlosses.

TheironlosscanbemathematicallycalculatedbytheSteinmetzequation.

$$P_i = P_h + P_e$$

$$P_i = \eta B_m^{1.6} f V + K_e B_m^2 f^2 t^2 V^2$$

$Where,$

$P_i = Iron\ or\ Core\ loss(Watt)$

$P_h = Hysteresis\ loss(watt)$

$P_e = Eddy\ current\ loss(Watt)$

$\eta = Steinmetz\ coefficient$

$B_m = Max.flux\ density(W_b/m^2)$

$f = frequency\ of\ magnetic\ reversal(H_z)$

$V = Volume\ of\ material(m^3)$

$t = Thickness\ of\ laminations(m)$

MechanicalLosses

Themechanical lossesinaninductionmotoroccurbecauseoftworeasons.Theyare-

- FrictionLoss
- **WindageLoss**

Friction and windage loss are the two types of mechanical losses that occur in an induction motor.The main reason for these losses is the rotation of the motor. The rotating parts like the rotor shaft,fans, and bearing cause mechanical losses in the rotating machine. All the rotating equipment hasthese types oflosses.

The friction and windage losses depend on the speed of the motor, the quality of the bearings, andthedesignofthemotor.

Thefrictionlossoccursbecauseoftherubbingofmovingpartsofthemotorwitheachother,suchas the friction between the rotor shaft and the bearings, friction between the balls and outer cage ofthe bearing, and friction between the inner and outer cage of the bearing. The motor takes extrapowerfromthemainstoovercomethisfrictionloss.

When the motor rotates, it has to cut the surrounding air for its rotation. The air exerts a force on themotor’s components, like the rotor fans. The resistance offered by surrounding air cause windageloss.Thewindagelossdependsonthespeedofthemotorandthe densityofthesurroundingair.

Mechanical losses are constant losses and they do not vary with load. The mechanical losses can beminimizedbytheproperdesignoftherotorandtheuseofhigh-qualitybearings.

BrushFrictionLoss

Squirrel cage induction motors do not have carbon brushes, it’s rotor is internally short-circuited.Therefore, no brush friction loss occurs in this type of motor. However, the slip ring or wound rotorinduction motors have slip rings and carbon brushes and the power loss on account of brush frictionhappensinthesetypesofmotors.

Carbon brushes collect the current from the slip ring. The slip ring is a rotating part and the carbonbrushes are fixed parts, and there exists friction between the contact surfaces of the carbon brushesandtheslipring.Thus,thebrushfrictionlossoccursinthesliperinginductionmotor.

VariableLossesinInductionMotor

The losses that vary with load are called variable losses. The major variable loss in an inductionmotoris**copperloss.**Thefollowingsarethevariablelossesinaninductionmotor.

CopperLoss

The winding of the induction motor is made of copper that has finite resistance R. When currentflow through the stator and rotor winding, the power loss(I2R loss)in the form of heat occurs in thewindingiscalledcopperloss.

The copper loss occurs in the stator and rotor of an induction motor. The copper loss in the stator iscalled stator copper loss, and copper loss in the rotor is called the rotor copper loss. The copperlosses dependon the magnitude of the currentpassing through the statorand rotor,anditisproportional to the square of the magnitude of the current. The copper loss in the induction motorcanbecalculatedusingthefollowingformula.

$$P_c = P_s + P_r$$

$$P_c = I_s^2 R_s + I_r^2 R_r$$

Where,

P_c = *Total copper loss*

P_s = *Stator copper loss*

P_r = *Rotor copper loss*

I_s = *Stator current*

R_s = *Stator winding Resistance*

I_r = *Rotor Current*

R_r = *Rotor Resistance*

Thetotalcopperlossina3-phaseinductionmotoris;

$$P_c = 3\, I_s^2 R_s + 3\, I_r^2 R_r$$

The currentof the motor increase with an increase in load, therefore these losses are notconstantand vary with load. The copper loss is also called a variable loss. The slip of the induction motorvaries with load and losses also vary accordingly. Therefore, the copper loss in the rotor is alsocalled slip power loss. The copper loss can be minimized by selecting a high-quality copper wire forstatorandrotorwinding.

The resistance of the winding also depends on the temperature. The resistance of the conductorincreaseswith an increase in the temperature. Thus, the operating temperature also contributes tocopper loss because copper loss is proportional to the resistance of the winding. Therefore, adequatecoolingofthemotorisamustforreducingthecopperlossesintheinduction.

StrayLossininductionmotor

It is desired that all the generated flux in the stator must be 100% coupled to the rotor and thereshould be no leakage flux. However, practically the entire flux does not link to the rotor and someparts of the flux leak in the magnetic path. The leakage flux gets linked to other conductive parts ofthe motor such as the motor frame, bearings, and housing, and creates eddy currents that causeenergyloss.Thus,theleakagefluxcontributes tostraylossintheinductionmotor.Thestraylossisa variable loss, and it depends on the factors like design of the motor, core material, and the load onthe motor.

The core of the motor should be of high-quality material in order to minimize the stray loss intheinductionmotor.

PowerStagesInAnInductionMotor

Powerstagesdiagramshowingthepowerlossesinadifferentpartofthemachine.SeeFigure1.

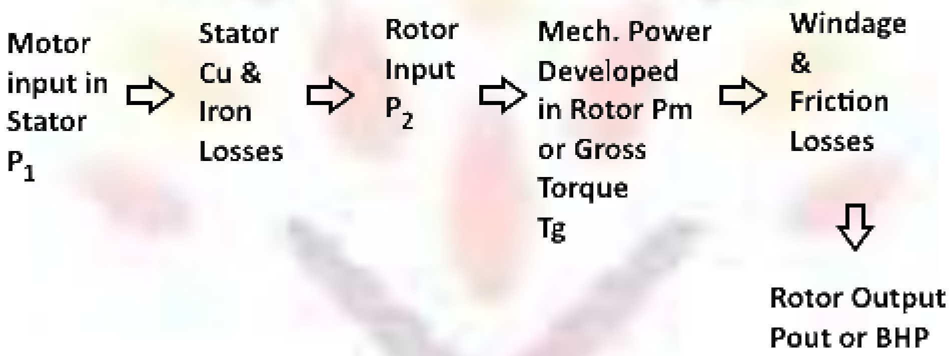


Figure1:PowerStagesandLossesDiagramof3PhaseInductionMotorThedifferen tstagesofthisdiagramarediscussedasfollows:

1. Motorinputor statorinput=statoroutput+statorlosses
2. Rotorinput=statoroutput
3. Rotorgrossoutput

Developedinrotor,Pm=Rotorinput-rotorcu.loss

GrossTorquedeveloped,Tg=Rotorgrossoutput/2πN---(1)

IftherewerenoCu.Lossesintherotor,thenrotoroutputwillbeequaltorotorinputandtherotorwillrunatsynchr onousspeed:

Tg=Rotorinput/ 2πNs---(2)

Fromequation (1) Rotor output=Tg2πN---(3)Fromequation(2)Rotorinput=Tgx2ΔNs---(4)

Ascopperlosses=Rotorinput-Rotoroutput.SoRotorCu.losses=Tg2π(Ns–N)---(5)Fromequation(4)&(5)

RotorCu.Loss/RotorInput= (Ns–N

)/NsOrRotorCu.Loss =SxRotorinput---(6)

AndRotorgrossoutput=Rotorinput-RotorCu.Loss---(7)Rotorgrossoutput=(1-S)Rotorinput

Rotor efficiency=Rotor grossoutput/RotorInput

=(1-S)RotorInput/RotorInput=1-S

Rotorefficiency= 1-S=1-(Ns-N)/Ns=N/Ns

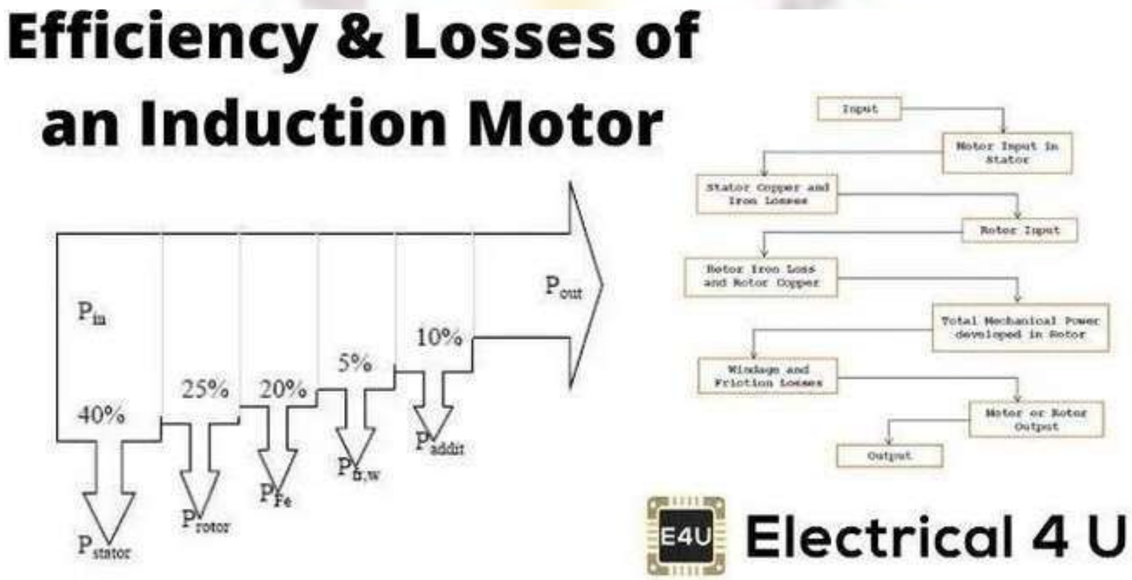
=actualspeedofrotor/Synchronous speedNotefor3-phasesrotorCu.Losses=$3I^2R$

4. Motoroutput=Mechanicalpowerdevelopedinrotor,PmwindageandFrictionlosses.

Ifmotorout put isinB.H.P.

Motor output=B.H.P.x746Watts

Efficiencyofmotor=output/Input=((B.H.P.x746)/Statorinput)x100



EFFICIENCYOFTHREEPHASEINDUCTIONMOTOR

Efficiencyisdefinedastheratiooftheoutputtothatofinput,

$$Efficiency,\ \eta = \frac{output}{input}$$

Rotorefficiencyofthethreephaseinductionmotor,

$$= \frac{rotor\ output}{rotor\ input}$$

=Grossmechanicalpower developed/rotorinput

$$= \frac{P_m}{P_2}$$

Threephaseinductionmotorefficiency,

$$= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

Threephaseinductionmotorefficiency

$$\eta = \frac{P_{out}}{P_{in}}$$

INDUCTIONMOTORSPEEDCONTROL

FromStatorSide

1. By Changing The Applied

Voltage:Fromthetorqueequationofinduction

motor,

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi N_S} \frac{s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Rotorresistance R2isconstantandifslipsissmall then $(sX_2)^2$issosmall thatitcan beneglected.

Therefore,T=sE^{2}2whereE isrotorinducedemfandE a V2Thus,

T a sV^2, which means, if supplied voltage is decreased, the developed torque decreases. Hence,forproviding the same load torque, the slip increases with decrease in voltage, and consequently, thespeeddecreases.Thismethodistheeasiestandcheapest,stillrarelyused,because

1. largechangeinsupplyvoltageisrequiredforrelativelysmallchangeinspeed.
2. largechangeinsupplyvoltagewillresultinalargechangeinfluxdensity,hence,thiswilldisturbthe magneticconditionsofthemotor.

2. ByChanging TheAppliedFrequency

Synchronousspeedoftherotatingmagneticfieldofaninductionmotorisgivenby,

$$Ns = \frac{120\,f}{P} \quad (RPM)$$

where,f=frequencyofthesupplyandP=numberofstatorpoles.

Hence,the synchronousspeedchangeswithchangeinsupplyfrequency.Actual speedof aninduction motor is given as **N = Ns (1 - s)**. However, this method is not widely used. It may be usedwhere, the induction motor is supplied by a dedicated generator (so that frequency can be easilyvaried by changing the speed of prime mover). Also, at lower frequency, the motor current maybecometoo

high due to decreased reactance. And if the frequency is increased beyond the rated value, themaximumtorquedevelopedfallswhilethespeedrises.

3. ConstantV/FControlOfInductionMotor

This is the most popular method for controlling the speed of an induction motor. As in abovemethod, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux willtend to saturate. This will cause excessive stator current and distortion of the stator flux wave.Therefore, the stator voltage should alsobe reducedin proportional to the frequency soas tomaintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of thestator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant.Also, by keeping V/F constant, the developed torque remains approximatelyconstant. This method gives higher run-time efficiency. Therefore, majority of AC speed drivesemploy constant V/F method (or variable voltage, variable frequency method) for the speed control.Along withwiderange ofspeedcontrol,thismethodalso offers'softstart'capability.

4. ChangingTheNumberOfStator Poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence,running speed) can be changed by changing the number of stator poles. This method is generallyused for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of statorpoles. Change in stator poles is achieved by two or more independent stator windings wound fordifferentnumberofpolesinsameslots.

For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles. forsupplyfrequencyof50Hz

i) synchronousspeedwhen4polewindingisconnected,Ns=120*50/4 =1500RPM
ii) synchronousspeed when6

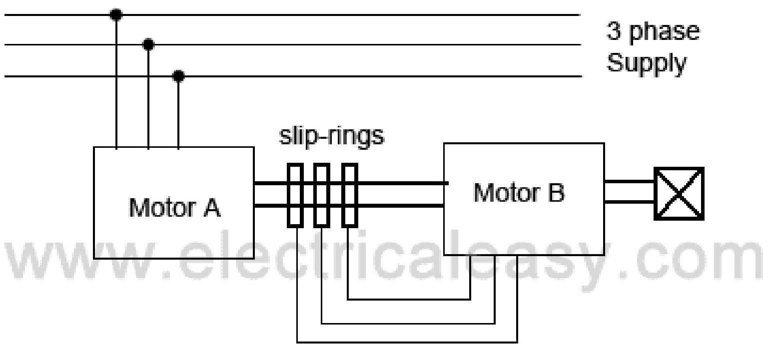
polewindingisconnected,Ns=120*50/6=1000RPMSpeedControlFromRotorSide:

1. RotorRheostatControl

This method is similar to that of armature rheostat control of DC shunt motor. But this method isonly applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cagemotorsisnotpossible.

2. CascadeOperation

In this method of speed control, two motors are used. Both are mounted on a same shaft so that bothrun at same speed. One motor is fed from a 3phase supply and the other motor is fed from theinducedemfinfirstmotorviaslip-rings.Thearrangementisasshowninfollowingfigure.



MotorAiscalledthemainmotorandmotorBiscalledtheauxiliarymotor.Let,Ns1=frequencyofmotorA

Ns2= frequencyofmotorB

P1 = number of poles stator of motor AP2 = number of stator poles of motor

BN = speed of the set and same for both motorsf = frequency of the

supplyNow,slipofmotorA,S1=(Ns1-N)/Ns1.

frequencyoftherotorinducedemfinmotorA,f1=S1fNow,auxiliarymotorBissuppliedwiththerotorinduceemf

therefore,Ns2 = (120f1)/ P2=(120S1f)/P2.nowputtingthevalueofS1= (Ns1-N)/Ns1

$$N_{s2} = \frac{120f(N_{s1} - N)}{P_2 N_{s1}}$$

Atnoload,speedoftheauxiliaryrotoris almostsameasitssynchronousspeed.

i.e.N=Ns2.

fromtheaboveequations,itcanbeobtainedthat

$$N = \frac{120f}{P_1 + P_2}$$

Withthismethod,fourdifferentspeedscanbeobtained

1. whenonlymotorAworks,corresponding speed=.Ns1=120f/P1
2. whenonlymotorBworks,correspondingspeed=Ns2=120f/P2
3. ifcommulativecascadingisdone,speed oftheset= N=120f/(P1+P2)
4. ifdifferentialcascadingisdone,speedoftheset=N=120f(P1-P2)

3.ByInjectingEMFInRotorCircuit

In this method, speed of an induction motor is controlled by injecting a voltage in rotor circuit. It isnecessary that voltage (emf) being injected must have same frequency as of the slip frequency.However, there is no restriction to the phase of injected emf. If we inject emf which is in oppositephase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is inphase withtherotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed canbe controlled. The main advantage of this method is a wide rage of speed control (above normal aswellasbelownormal)canbeachieved.

$$N_s = \frac{120 f}{P} \quad \text{(RPM)}$$

where,f=frequencyofthesupplyandP=numberofstatorpoles.

Hence,the synchronousspeedchangeswithchangeinsupplyfrequency.Actual speedof aninduction motor is given as **N = Ns (1 - s)**. However, this method is not widely used. It may be usedwhere, the induction motor is supplied by a dedicated generator (so that frequency can be easilyvaried by changing the speed of prime mover). Also, at lower frequency, the motor current maybecome too high due to decreased reactance. And if the frequency is increased beyond the ratedvalue,themaximumtorquedevelopedfallswhilethespeedrises.

STARTINGMETHODS OFTHREE-PHASEINDUCTIONMOTOR:

At starting the slip is unity and the motor impedance is quite small with rated applied voltage, thusthe motor current is excessive due to the small motor impedance. This abnormal condition must bebrought within normal limits using starting methods. The starters are used to start the motors in safemode and to protect it from over withdrawn current. For small size motors, there is no need to useany starting method since smaller motors have higher per unit impedances and the starting period israthershort.Inductionmotorsarepracticallyaconstantspeedmotorwhichaccountabout90percentoftheelectricaldrivesusedinindustry.

ThestandardmethodsforstartingofsquirrelcageandwoundrotorInductionmotorsareasfollows:

1)Direct on-Line Starting: This method involves direct switching of three-phase stator on to thesupplymainsasinfigure1.

The motor draws low power factor starting current with (5-7) times of full load current (FLC). Duetothislargecurrentthereisaconsiderablevoltagedropinthepowerutilitywhichcausesundesirable dip in supply voltage thereby affecting the operation of other equipment connected tothe powerutilityaswell.

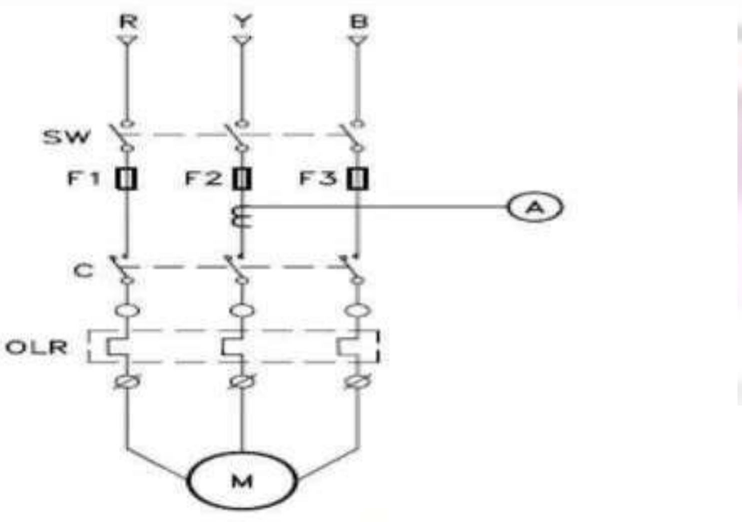


Figure 1 Power Circuit for DOL Starting

II. Autotransformer Starting: This method of starting is illustrated in figure 2, a fraction of 'x'(where x is always less than unity) of the supply voltage is applied to the stator terminals at the timeof starting by means of an Autotransformer. This reduces the starting current of the motor. After themotor has accelerated close to its operating speed, the Autotransformer is disconnected, and full linevoltageis appliedtothestatorwindingsbyconnectingittothesupplymains

IAT= x2IDOL

IDOL=Perphasestartingcurrentondirectswitchingtofullvoltage.IAT=Perphasestartingcurrentbymeans ofAutotransformer.

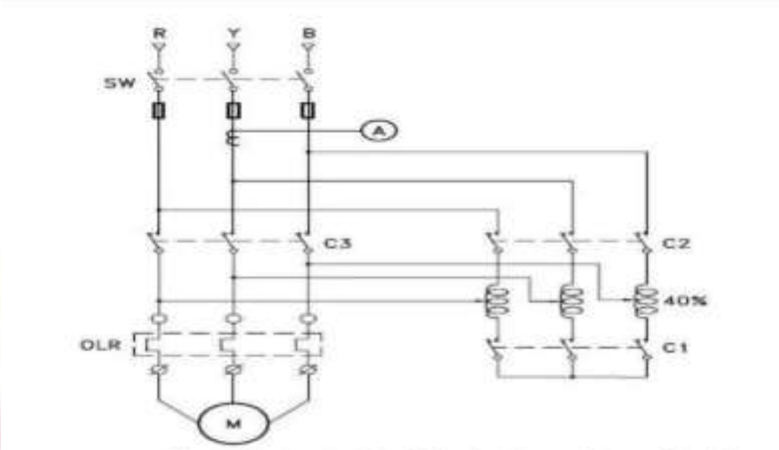


Figure 2 Power Circuit for Autotransformer Starting

III. Star-Delta Starting: This method may be adopted only for those motors which are designedtooperatenormallyindelta.Thesixterminalsfromthestatorwindingmustbeavailableasshownin the figure 3 below. The terminals have been marked as a1, a2 for 'R' phase, b1, b2 for 'Y' phaseand c1, c2 for 'B' phase. The terminals are connected to a TPDT (triple pole double throw) switch.Duringmotorstarting,theTPDTswitchisinposition1,andhencethestatorwindinggetsconnected in star.Once themotor has accelerated toits steady state speed, the TPDT switchchanges over to position 2. Now, the stator winding gets connected in delta. Hence, the motor hasstartedinstarconnectionthereby reducingthestartingcurrentandthenswitchedtodeltaconnectionforitsnormaloperation.

IY-D=IDOL

IY-D=Startinglinecurrentwithstar-deltastarter.

IDOL=Startinglinecurrentwithdirectswitchingindelta.

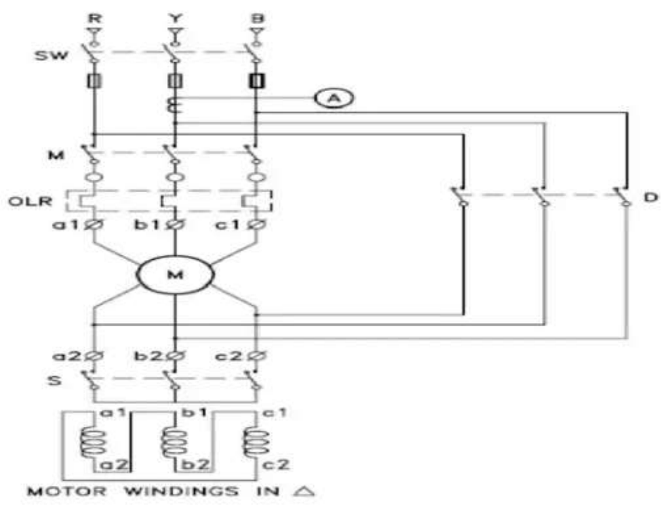


Figure 3 power Circuit for Star-Delta Starting

It is evident from the above that the starting torque available during DOL starting is also reduced toone-thirdincaseofstar-deltastarting.

IV. TheStatorResistance(orInductance)Starting:

A suitable resistance (or inductance) is added in series with the stator and the motor is started withreduced current. As the motor speeds up, this resistance (or inductance) is gradually cut-off andfinallytheratedvoltageis appliedtothe motor,andthemotorachievesfullspeed.

V. Rotor–RheostatStarting:

A suitable resistance is added (at starting) to the wound rotor windings via slip rings and then it isgradually cut, as themotor speeds up. Finally,when the rotor achieves full speed, the addedresistanceisfullycut-off.

VI. ElectronicSoftStarting:

It is based upon the controlled rectifier or 'Thyristor'. By applying a firing pulses to the Thyristor, itswitches from 'off' to 'on' until the current stops flowing through it, which occurs every half cycleof an AC supply. By controlling electronically, the Thyristor turn on point (firing angle), it ispossibletoregulatetheenergypassingthroughit.Figure4showingtheeffectofthe5firingangleof the Thyristor on the output voltage. By startingwith a large delay angle and gradually reducingit,themotorterminalvoltageisincreasedfroma lowvaluetofullvoltage,givingasmooth,steplessstarting.Electronic softstartinghasasimple,reliableandcosteffectivepieceofequipment.

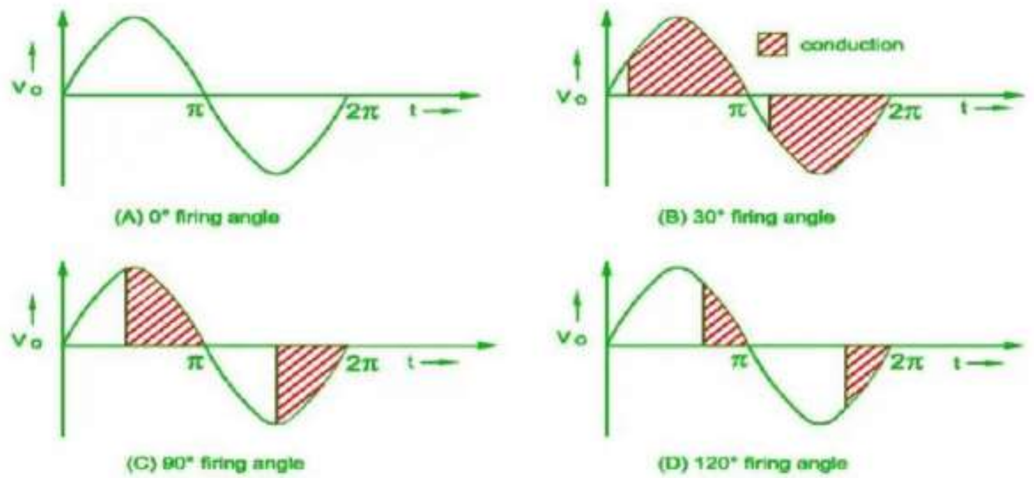


Figure 4 Effect of Firing Angle on Output Voltage

APPLICATIONSOFTHREE-PHASEINDUCTIONMOTORS

- Lifts.C
- ranes.H
- oists.
- Largeexhaustfans.
- Lathemachines.
- Crushers.
- Oil extracting
- mills.extiles.

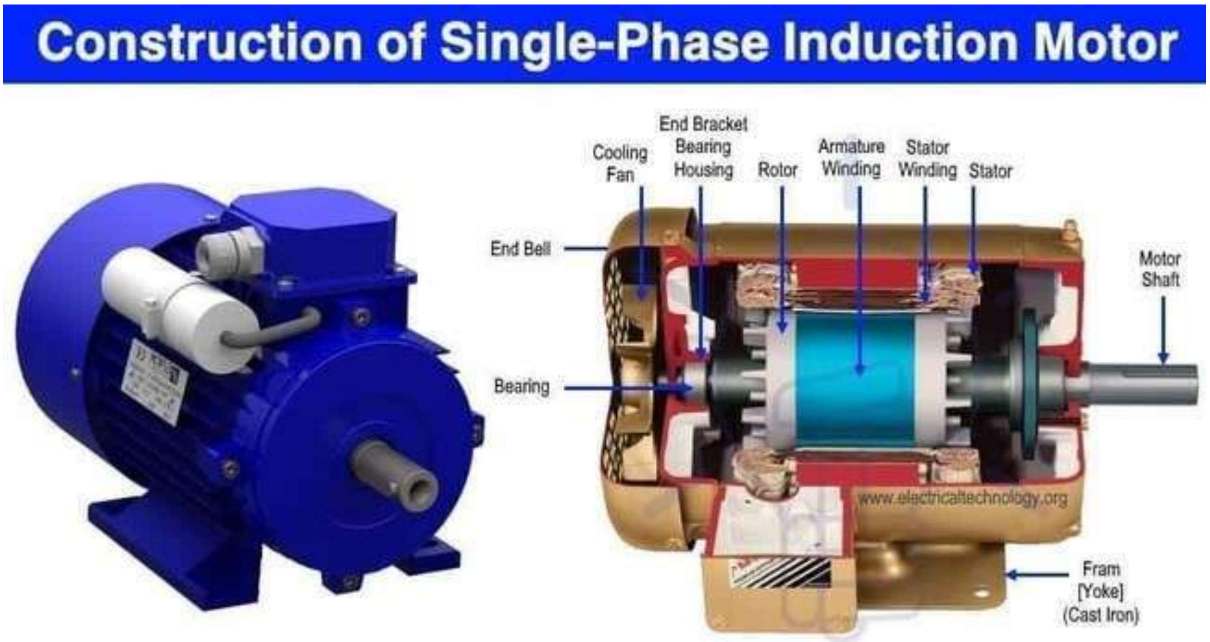
CONSTRUCTION AND WORKING PRINCIPLE OF SINGLE-PHASE INDUCTIONMOTOR:

The single-phasemotors are more preferred over a three-phaseinduction motorfor domestic,commercialapplications.Becauseformutility,onlysingle-phasesupplyisavailable.So,inthistypeofapplication,thethree-phaseinductionmotorcannotbeused.

CONSTRUCTIONOFSINGLE-PHASEINDUCTIONMOTOR

A single phase induction motor is similar to the three phase squirrel cage induction motor exceptthere is single phase two windings (instead of one three phase winding in 3-phase motors) mountedonthestatorandthecagewindingrotorisplacedinsidethestatorwhichfreelyrotateswiththehelpofmountedbearingsonthemotorshaft.

The construction of a single-phase induction motor is similar to the construction of a three-phaseinductionmotor.



Similartoathree-phaseinductionmotor, single-phaseinductionmotoralsohastwomainparts;

- Stator
- Rotor

Stator

In stator, the only difference is in the stator winding. The stator winding is single-phase windinginstead of three-phase winding. The stator core is the same as the core of the three-phase inductionmotor.

In a single-phase induction motor, there are two winding are used in stator except in shaded-poleinduction motor. Out of these two windings, one winding is the main winding and the second isauxiliarywinding.

The stator core is laminated to reduce the eddy current loss. The single-phase supply is given to thestatorwinding(mainwinding)

Rotor

Rotor of single-phase induction motor is the same as a rotor of squirrel cage induction motor.Instead of rotor winding, rotor bars are used and it is short-circuited at the end by end-rings. Hence,it makes a complete path in the rotor circuit. The rotor bars are braced to the end-rings to increasethemechanicalstrengthofthemotor.

The rotor slots are skewed at some angle to avoid magnetic coupling. And it also used to make amotorrunsmoothandquiet.

Thefollowingfigshowsthestatorandrotorofa1-

phaseinductionmotor.WORKINGOFSINGLE-PHASE INDUCTIONMOTOR

Single-phase AC supply is given to the stator winding (main winding). The alternating currentflowingthroughthestatorwindingproducesmagneticflux.Thisfluxisknownas themainflux.

Now we assume that the rotor is rotating and it is placed in a magnetic field produced by the statorwinding. According to Faraday's law, the current start flowing in the rotor circuit it is a close path.Thiscurrentisknownasrotorcurrent.

Duetotherotor current,thefluxproducedaroundtherotorwinding. Thisfluxisknownasrotorflux.

Therearetwofluxes;**mainfluxwhichisproducedbystator**andsecondisthe**rotorflux**

whichisproducedbytherotor.

Interactionbetweenmainfluxandrotorflux,thetorque producedintherotoranditstartsrotating.

The stator field is alternating in nature. The speed of the stator field is the same as synchronousspeed.Thesynchronousspeedofthemotordependsonthenumberofpoleandsupplyfrequency.

It can represent by two revolving fields. These fields are equal in magnitude and rotating in theoppositedirection.

Let say Φ_m is a maximum field induced in the main winding. So, this field is divided into two equal partsandthatis$\Phi_m/2$and$\Phi_m/2$.

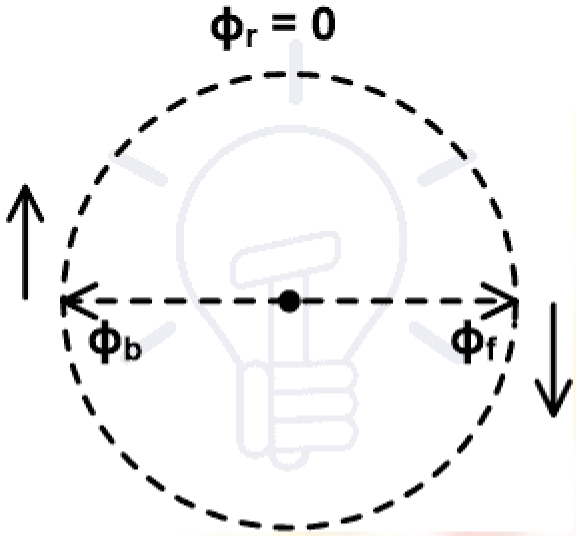
Outofthesetwo fields,onefield$\Phi_f$isrotatingin ananticlockwisedirectionandthesecond field$\Phi_b$isrotatinginaclockwisedirection.Therefore,theresultantfieldiszero.

$$\Phi_r = \frac{\Phi_m}{2} - \frac{\Phi_m}{2}$$

$\Phi_r = \Phi_f - \Phi_b$

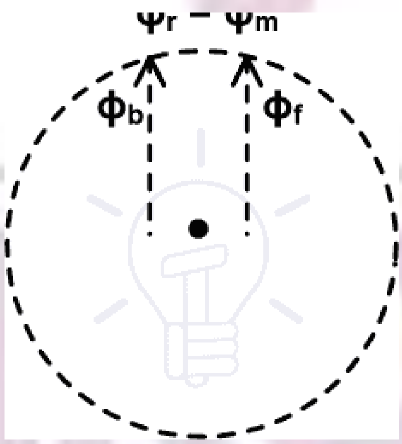
$\Phi_r = 0$

Nowconsidertheresultantfield atdifferentinstants.



Whenamotorstarts,twofieldsareinducedasshownintheabovefigure.Thesetwofieldsarethesamemagnitudeandopposite direction.So,resultantfluxiszero.

Inthiscondition,thestatorfieldcannotcutbyrotorfieldandresultanttorqueiszero.So,therotorcannotrotatebutitproduces humming.



Nowconsiderafterthe rotationof90˚,bothfiledarerotatedandpointinginthesamedirection.Therefore,theresultantfluxisasummationofbothfields.

$$\Phi_r = \frac{\Phi_m}{2} + \frac{\Phi_m}{2}$$

$\Phi_r = \Phi_f + \Phi_b$

$\Phi_r = 0$

In this condition, the resultant filed is equal to the maximum field induced by the stator. Now, bothfieldsrotateseparatelyanditis alternativeinnature.

So, both fields cut by the rotor circuit and EMF induced in the rotor conductor. Due to this EMF,thecurrentstartsflowingintherotorcircuitanditinducesa rotorflux.

Due to the interaction between stator flux and rotor flux motor continues to rotate. T**his theory isknownasDouble RevolvingTheory**or**doublefieldrevolvingtheory**.

Now, from the above explanation, we can conclude that the **single-phase induction motor is notself-starting.**

Tomakethismotorself-startingmotor,weneedstatorfluxrotatinginnatureinsteadofalternatingnature.Thiscanbedonebyvarious methods.

Single-phase induction motor can be classified according to starting methods. Types of Single-phaseInductionMotors

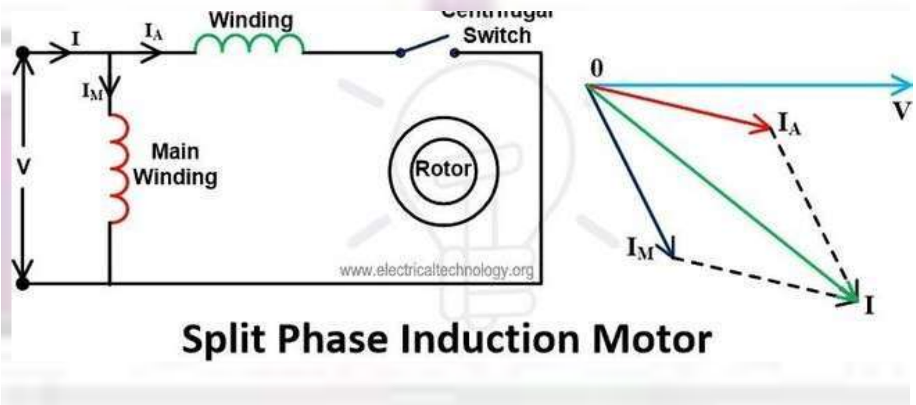
Thesingle-phaseinductionmotors areclassifiedas;

- SplitPhaseInductionMotor
- ShadedPoleInductionMotor
- CapacitorStartInductionMotor
- CapacitorStartCapacitorRunInductionMotor
- PermanentCapacitorInductionMotor

SplitPhaseInductionMotor

In this type of motor, an extra winding is wounded on the same core of the stator. So, there are twowindings in the stator.One winding is known as the main winding or running winding and secondwinding is known as starting winding or auxiliary winding. A centrifugal switch is connected inseries with the auxiliary winding. The auxiliary winding is highly resistive winding and the mainwindingishighlyinductivewinding.Theauxiliarywindinghasfewturnswithasmalldiameter.

The aim of auxiliary winding is to create a phase difference between both fluxes produced by themainwindingandrotorwinding.



Split Phase Induction Motor

The connection diagram is as shown in the above figure. The current flowing through the mainwinding is I_M and current flowing through the auxiliary winding is I_A. Both windings are parallelandsuppliedbyvoltageV.

The auxiliary winding is highly resistive in nature. So, the current IA is almost in phase with supplyvoltageV.

Themainwindingishighlyinductiveinnature.So,thecurrentIMlagsbehindthesupplyvoltagewithalargeangle.

The total stator flux is induced by the resultant current of these two winding.As shown in thephasor diagram, the resultant current is represented as (I). It will create a phase difference betweenfluxesandresultantfluxproducesarotatingmagneticfield.Andthemotorstartsrotating.

Auxiliary winding only uses to start the motor. This winding is not useful in running condition.When the motor reaches 75 to 80 % of synchronous speed, the centrifugal switch opens. So, theauxiliarywindingisoutfromthecircuit.Andmotorruns ononlymainwinding.

The phase difference creates by this method is very small. Hence, the starting torque of this motor ispoor. So, this motor is used in low starting torque applications like a fan, blower, grinder, pumps,etc.

ShadedPoleInductionMotor

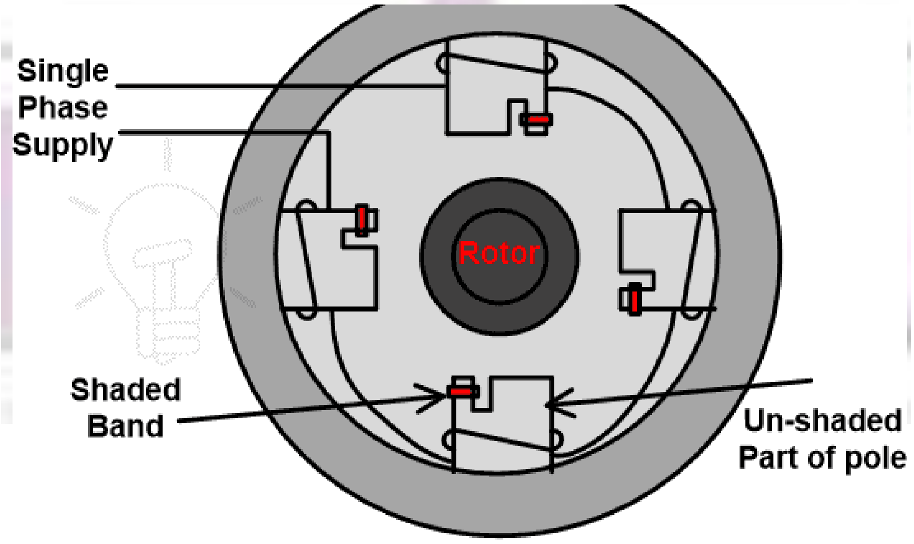
As compared to other types of single-phase induction motor, this motor has a different constructionandworkingprinciple.Thistypeofmotordoesnotrequireauxiliarywinding.

This motor has stator salient pole or projecting pole and the rotor is the same as squirrel cageinductionmotor.Thestatorpolesareconstructedspeciallytocreatea rotatingmagneticfield.

A pole of this motor is divided into two parts; shaded part and un-shaded part. It can be created bycuttingpoleintounequaldistances.

A copper ring is placed in the small part of the pole. This ring is a highly inductive ring and it isknown as a shaded ring or shaded band. The part at which shaded ring is paced is known as shadedpartofthepoleandtheremainingpartisanunshadedpart.

Theconstructionofthismotorisasshowninthebelowfigure.



Shaded Pole Induction Motor

When an alternating supply passing through the stator winding, an alternating flux induced in thestator coil. Due to this flux, some amount of flux will link with shaded ring and current will flowthroughashadedring.

According to Len'z law, the current passing through coil is opposite in nature, and flux produceddue tothiscoilwillopposethemainflux.

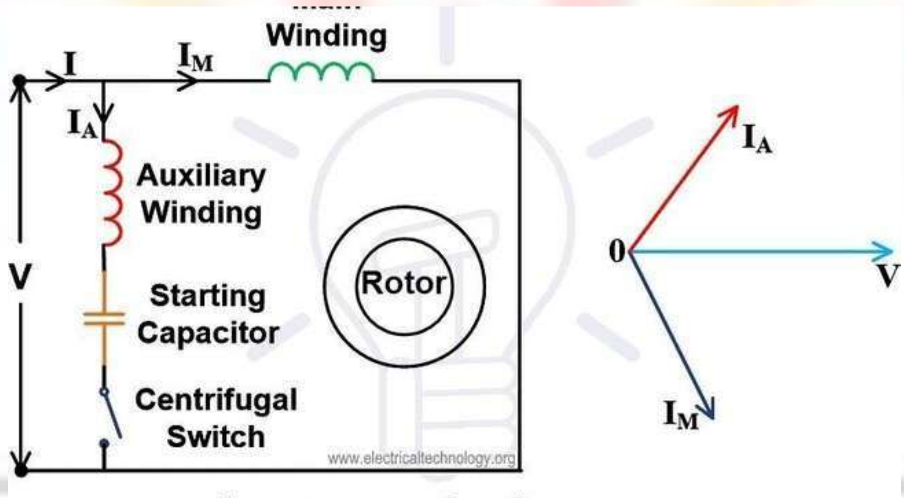
The shaded ring is a highly inductive coil. So, it will oppose the main flux when both fluxes are inthesamedirectionanditwillincreasethemainfluxwhenbothfluxesareintheoppositedirection.

So, it will create a phase difference between the main flux (stator flux) and rotor flux. By thismethod, a phase differenceis very less.Hence,the startingtorque is very less.Itisusedinapplicationsliketoymotor,fan,blower,recordplayer,etc.

CapacitorStartInductionMotor

This type of motor is an advanced version of the Split phase induction motor. The disadvantage ofsplit-phaseinductionislowtorqueproduction.Becauseinthismotor,thephasedifferencecreatedisveryless.

This disadvantage compensates in this motor with the help of a capacitor connected in series withauxiliarywinding.Thecircuitdiagramofthismotoris as showninthebelowfigure.



Capacitor Start Induction Motor

Thecapacitorusedinthismotorisadry-typecapacitor.Thisisdesignedtousewithalternatingcurrent.Butthis capacitorisnotusedforcontinuousoperation.

Inthismethodalso,acentrifugalswitchisusedwhichdisconnectsthecapacitorandauxiliarywindingwhenthemotorruns75-80%ofsynchronousspeed.

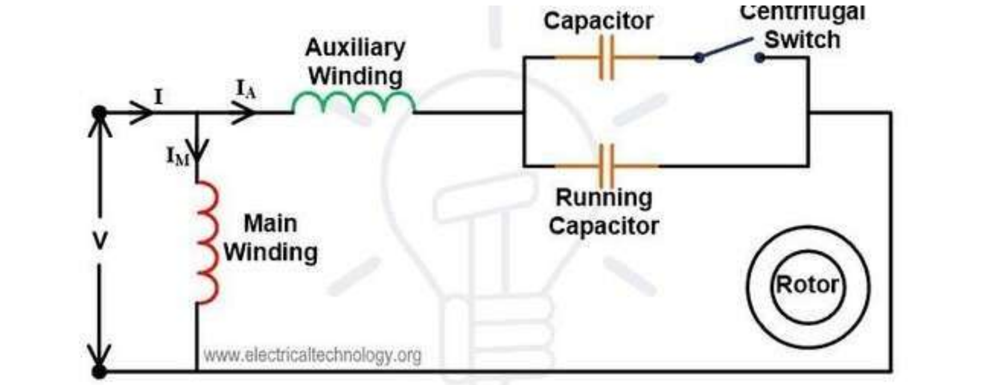
Thecurrentthroughauxiliarywillleadthesupplyvoltagebysomeangle.Thisangleismorethantheangleincreasedinasplit-phaseinductionmotor.
So,thestartingtorqueofthismotorisveryhighcomparedtothesplit-phaseinductionmotor.Thestartingtorqueofthismotoris300%morethanthefullloadtorque.

Duetohighstartingtorque,thismotorisusedintheapplicationswherehighstartingtorqueisrequiredlike,aLathmachine,compressor,drillingmachines,etc.

CapacitorStartCapacitorRunInductionMotor

In this type of motor, two capacitors are connected in parallel with series in auxiliary winding. Outof these two capacitors, one capacitor is used only for starting (starting capacitor) and anothercapacitorisconnectedpermanentlywiththemotor(runningcapacitor).

Thecircuitdiagramofthisfigureisasshowninthebelowfigure



Capacitor Start Capacitor Run Induction Motor

The starting capacitor has high capacitance value and a running capacitor has low capacitancevalue. The starting capacitor is connected in series with a centrifugal switch that will open when the speedofthemotoris70%ofsynchronousspeed.

During running conditions, both running winding and auxiliary winding connected with motor.Thestartingtorqueandefficiencyofthismotorareveryhigh.

Therefore, this can be used in the application where high starting torque is required like

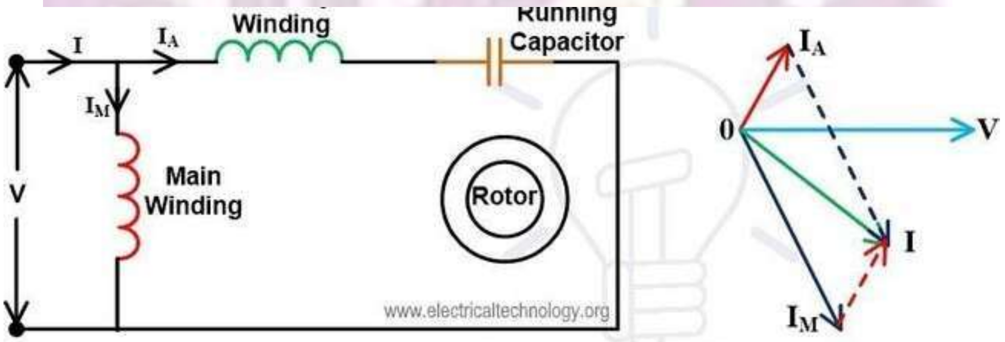
arefrigerator,airconditioner,ceilingfan,compressor, etc.

PermanentCapacitorInductionMotor

The low-value capacitor is connected constantly with the auxiliary winding. Here, the capacitor haslowcapacitance.

The capacitorisused toincrease the startingtorque butitislow comparedto the capacitorstartinductionmotor.

Thecircuitdiagramandphasordiagramofthismotorisasshowninthebelowfigure.



Permanent Capacitor Induction Motor

Thepowerfactorandefficiencyofthismotorareveryhighandalsoithasa highstartingtorquethatis80%offullloadtorque.

Thistypeofmotorisusedintheapplicationlikeanexhaustfan,blower,heater,etc.APPLICATIONS

OFSINGLEPHASEINDUCTIONMOTORS

Singlephasemotorsarenotselfstartingandlessefficientthanthreephaseinductionmotorandavailablein0.5 HPto15HPandstilltheyarewidelyused formultiplepurposessuchas:

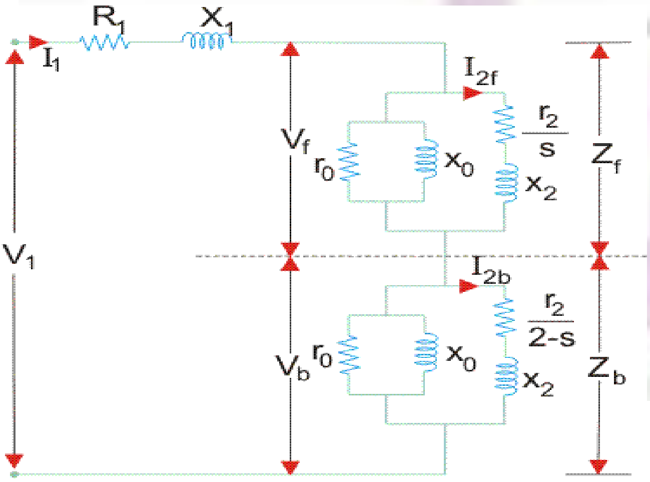
- Clocks
- Refrigerators,freezersandheaters
- Fans,tablefans,ceilingfan,exhaustfans,aircoolersandwatercoolers.
- Blowers
- Washingmachines
- machinetools
- Dryers
- Typewriters,photostatsandprinters
- Waterpumpsandsubmersible
- Computers
- Grinders
- Drillingmachines
- Other Home instrument, equipment and devices

etc.EQUIVALENTCIRCUITOFASINGLEPHASEINDUCTIONMOTOR

Thereisadifferencebetweensinglephaseandthreephaseequivalentcircuits.Thesinglephaseinductionmotorcircuitisgivenbydoublerevolvingfieldtheorywhichstates that-

A stationary pulsating magnetic fieldmight be resolved into two rotating fields, both having equalmagnitudebut oppositein direction.So the nettorque inducedis zeroat standstill.Here,theforwardrotationiscalledtherotationwithslipsandthebackwardrotationisgivenwithaslipof(2
– s).Theequivalentcircuitis-

Inmostofthecasesthecorelosscomponentr0isneglected asthis valueisquitelargeanddoesnot



Induction motor (single phase) equivalent circuit referred to the stator

affectmuchinthecalculation.

Here,$Z_f$showstheforwardimpedanceand$Z_b$showsthebackwardimpedance.

Also,thesumofforwardandbackwardslipis2soincaseofbackwardslip,itisreplacedby(2–s).R1=Resistanceofstatorwinding.

X1=Inductivereactanceofthestatorwinding.Xm=Magnetisingreactance.R2’=Ro

torReactancewithreferredtostator.

X2’=Rotorinductivereactancewithreferredtostator.

DIFFERENCEBETWEENSLIP RING&SQUIRRELCAGEINDUCTIONMOTOR

The squirrel cage induction motor is the most popular type of AC motor. It is very commonly usedin industries because it is very cheap, robust, efficient, and reliable. The slip ring motor has verylittleapplicationinindustries.Rarely5%–10%slip ring motorsareusedinindustriesbecauseithasseveraldisadvantageslikeitrequiredfrequentmaintenance,havingahighcopperloss,etc.

One of the major difference between the slip ring and the squirrel cage motor is that the slip ringmotor has an external resistance circuit for controlling the speed of the motor. Whereas in squirrelcage motor, it is not possible to add any external circuit because the bar of the motor is permanentlyslotted at the end of the ring. Some other differences between them are explained below in thecomparisonchart.

DCMACHINE

The DC machine can be classified into two types namely DC motors**as well as DC** generators. Most of the DC machines are equivalent to AC machines because they include AC currents as well as ACvoltages in them. The output of the DC machine is DC output because they convert AC voltage toDC voltage. The conversion of this mechanism isknown as the commutator, thus these machinesare also named as commutating machines. DC machine is most frequently used for a motor. Themain benefits of this machine include torque regulation as well as easy speed. The **applications ofthe DC machine** is limited to trains, mills, and mines. For example, underground subway cars, aswell as trolleys, may utilize DC motors. In the past, automobiles were designed with DC dynamosforchargingtheirbatteries.

TYPEOFDCMOTORS

The excitation of the DC machine is classified into two types namely separate excitation, as well asself-excitation. In a separate excitation type of dc machine, the field coils are activated with aseparate DC source. In the self-excitation type of dc machine, the flow of current throughout thefield- winding is supplied with the machine. The principal kinds of DC machines are classified intofourtypeswhichincludethefollowing.

- Permanentmagnettypedc motor
- SeparatelyexciteddcmotorC

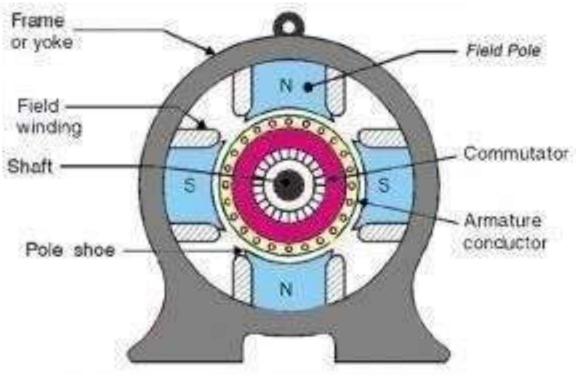
serieswoundmotors

- ShuntwoundDCmotor
- Compound DC

motor.STRUCTIONOFOFDCMACH

INE

TheconstructionoftheDCmachinecanbedoneusingsomeoftheessentialpartslikeYoke,Pole core & pole shoes, Pole coil & field coil, Armature core, Armature winding otherwise conductor,commutator,brushes&bearings.Someofthe**partsoftheDCmachine** isdiscussedbelow.



Constructionc

Yoke

Another name of a yoke is the frame. The main function of the yoke in the machine is to offermechanical support intended for poles and protects the entire machine from moisture, dust, etc. Thematerialsusedinthe yokearedesignedwithcastiron,caststeelotherwiserolledsteel.

PoleandPoleCore

The pole of the DC machine is an electromagnet and the field winding is winding among pole.Whenever field winding is energized then the pole gives magnetic flux. The materials used for thisare cast steel, cast iron otherwise pole core. It can be built with the annealed steel laminations forreducingthepowerdropbecauseoftheeddycurrents.

PoleShoe

Pole shoe in the DC machine is an extensive part as well as to enlarge the region of the pole.Because of this region, flux can be spread out within the air-gap as well as extra flux can be passedthrough the air space toward armature. The materials used to build pole shoe is cast iron otherwisecast steed, and also used annealed steel lamination to reduce the loss of power because of eddycurrents.

FieldWindings

In this, the windings are wounded in the region of pole core & named as field coil. Whenevercurrent is supplied through field winding than it electromagnetics the poles which generate requiredflux.Thematerialusedforfieldwindingsiscopper.

ArmatureCore

Armature core includes a huge number of slots within its edge. The armature conductor is located inthese slots. It provides the low-reluctance path toward the flux generated with field winding. Thematerials used in this core are permeability low-reluctance materials like iron otherwise cast. Thelaminationisusedtodecreasethelossbecauseofthe eddycurrent.

ArmatureWinding

The armature winding can be formed by interconnecting the armature conductor. Whenever anarmature winding is turned with the help of prime mover then the voltage, as well as magnetic flux,gets induced within it. This winding is allied to an exterior circuit. The materials used for this windingareconductingmateriallikecopper.

Commutator

The main function of the commutator in the DC machine is to collect the current from the armatureconductoraswellassuppliesthecurrenttotheloadusingbrushes.Andalsoprovidesuni-directional torque for DC-motor. The commutator can be built with a huge number of segments inthe edge form of hard drawn copper. The Segments in the commutator are protected from the thinmicalayer.

Brushes

Brushes in the DC machine gather the current from the commutator and supply it to the exteriorload. Brushes wear with time to inspect frequently. The materials used in brushes are graphiteotherwisecarbonwhichisinrectangularform.

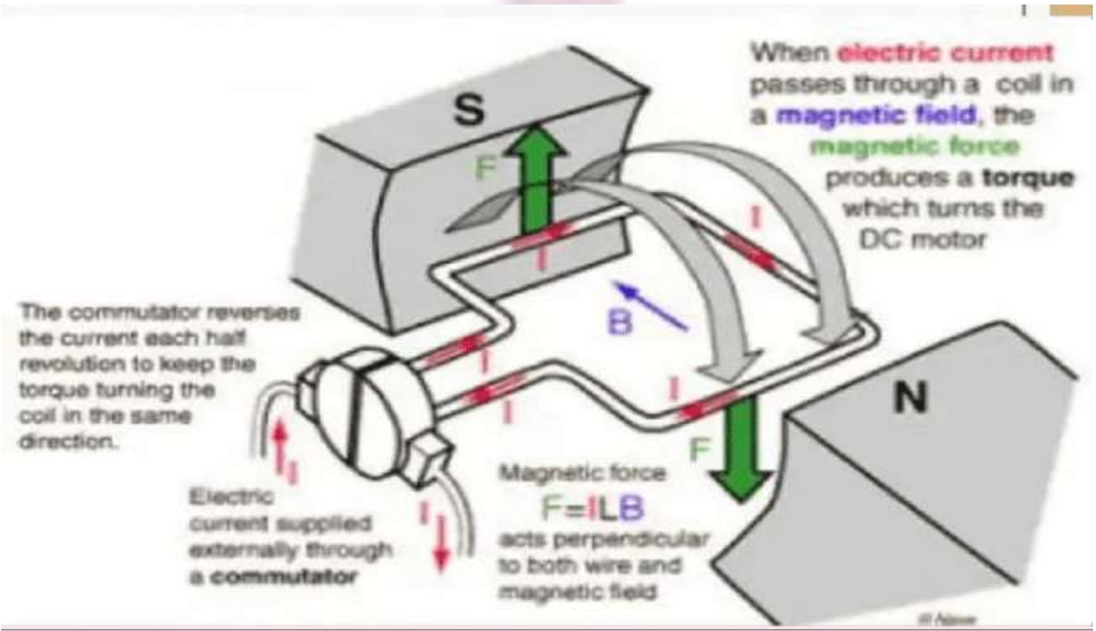
WOPRINCIPLEOF**SEPARATELYEXCITEDDCMOTOR**

A same DC machine can be used as a motor or generator. Construction of a DC motor is same asthat of a DC generator, however, the former converts electrical energy into mechanical energy. Theprinciple of working of a DC motor is that "whenever a current carrying conductor is placed in amagnetic field, it experiences a mechanical force". The direction of this force is given by Fleming'sleft hand rule and it's magnitude is given by F = BIL. When armature windings are connected to aDC supply, current flows in the winding. Magnetic field is provided by field winding excitation. Inthis case, current carrying armature conductors experience force due to the magnetic field, and thisforcewillproduceatorquetorotatethearmature,thusrotatingthemachineshaft.

$\boldsymbol{TA} = (\boldsymbol{ZP}/2\boldsymbol{\pi A})\emptyset \boldsymbol{IA}$

When the armature of the motor is rotating, the conductors are also cutting the magnetic flux linesand hence according to the Faraday's law of electromagnetic induction, an emf induces in thearmature conductors. The direction of this induced emf opposes the supplied armature current (Ia),henceit’scalled**Backemf**andgivenbytheemfequationofDCgenerator;

EA=$K\emptyset\omega m$,whereK=$ZP/2\pi$A



EMFEQUATIONOFDCMACHINE

The **DC machine e.m.f**can be defined as when the armature in the dc machine rotates, the voltagecanbegeneratedwithinthecoils.Inagenerator,thee.m.fofrotationcanbecalledthegeneratedemf,and Er=Eg.Inthe motor,the emfofrotationcanbecalledascounterorbackemf,andEr=Eb.

Let Φis theusefulfluxforeverypolewithinwebersPisthetotalnumberofpolesz is

thetotalnumberofconductorswithinthearmature

nistherotationspeedforanarmatureintherevolutionforeachsecond

A is the no. of parallel lane throughout the armature among the opposite polarity brushes. Z/A is theno.ofarmatureconductorwithinseriesforeachparallellane

Asthefluxfor eachpoleis'Φ',everyconductorslashesaflux'PΦ'withinasinglerevolution.

The voltage produced for each conductor = flux slash for each revolution in WB / Time taken for asinglerevolutionwithinseconds

As 'n' revolutions are completed within a single second and 1 revolution will be completed withina1/nsecond.Thus thetimefora singlearmaturerevolutionisa1/nsec.

ThestandardvalueofproducedvoltageforeachconductorpΦ/

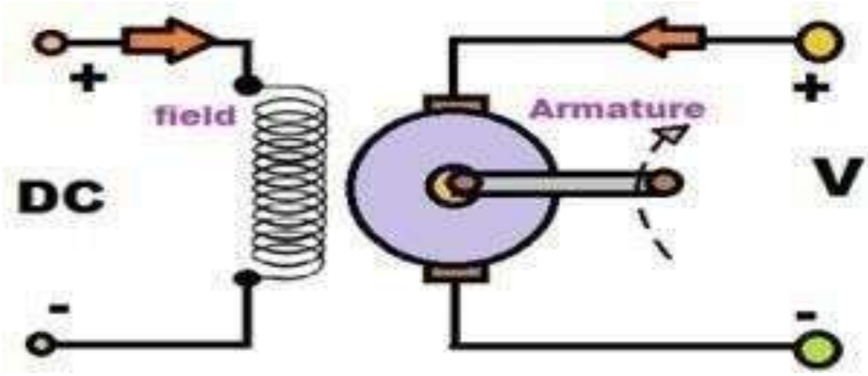
1/n=npΦvolts
Thevoltageproduced(E)canbedecidedwiththeno.ofarmatureconductorswithinseriesIanysinglelaneamongthebrushesthus,thewholevoltageproduced

E=standardvoltageforeachconductorxno.ofconductorswithinseriesforeachlaneE=n.P.Φx

Z/A
Theaboveequationisthee.m.f.theequationoftheDCmachine.

SEPARATELYEXCITEDDCMOTOR

In this section we will discuss about the separately excited dc motor. Like other DC motors, thesemotors also have both stator and rotor. Stator refers to the static part of motor, which consists of thefield windings. And the rotor is the moving armature which contains armature windings or coils.Separately excited dc motor has field coils similar to that of shunt wound dc motor. The namesuggests the construction of this type of motor. Usually, in other DC motors, the field coil and thearmature coil both are energized from a single source. The field of them does not need any separateexcitation. But, in separately excited DCmotor, separate supply Providedfor excitation of bothfield coilandarmaturecoil.Figurebelowshowstheseparatelyexciteddcmotor.



Here, the field coil is energized from a separate DC voltage source and the armature coil is alsoenergized from another source. Armature voltage source may be variable but, independent constantDC voltage is used for energizing the field coil. So, those coils are electrically isolated from eachother,andthis connectionisthespecialtyofthistypeofDCmotor.

OPERATINGCHARACTERISTICSOFSEPARATELY EXCITEDDCMOTOR

Both in shunt wound dc motor and separately excited dc motor field is supplied from constantvoltage so that the field currentis constant. Therefore these two motors have similar speed-armature current and torque – armature current characteristics. In this type of motor flux is assumedtobeconstant.

When theloadincreases,the output torque requiredtodrivetheloadwillincrease.Hence, themotor speed will slow down. Consequently the internal generated voltage drops ($EA = K\emptyset\omega m \downarrow$) ,increasing the armature current in motor $IA = (Vs - EA\downarrow)/RA$. As the armature current increases, thedeveloped torque increase ($Tdev = K\emptyset IA \uparrow$) and finally the developed torque will be equal the loadtorqueatalowermechanicalspeedofrotationωm.

MechanicalLoad $\uparrow\omega m\downarrow, IA\uparrow, Tdev\uparrow$

1) TORQUEVS.ARMATURECURRENT:Generally,thedevelopedtorqueisdirectlyproportional to armature current ($Tdev = K\emptyset IA$) and the relationship is in the form of a straight line, assumingthefieldfluxΦtobeconstantasthesupplyvoltageisconstant.

Since, heavy starting load needs high starting current, shunt motor should never be started on aheavyload.

2) SPEEDVS.ARMATURECURRENT

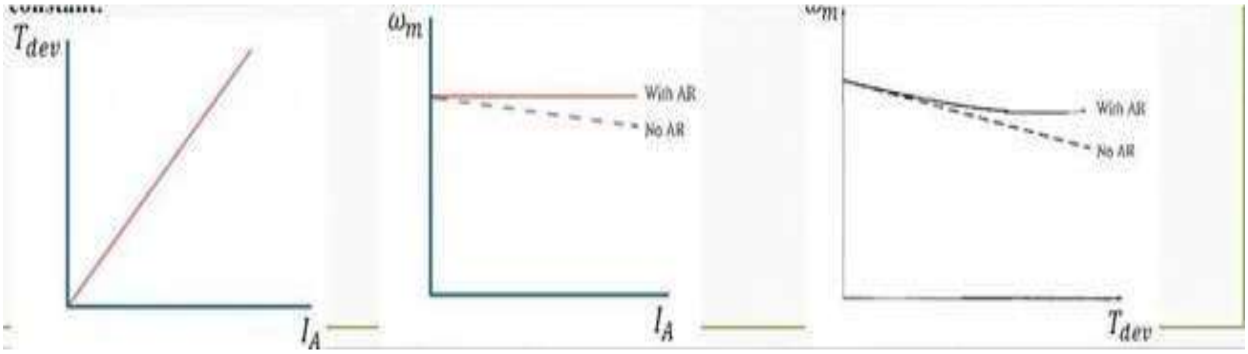
$Vs= EA+IARA and EA=K\emptyset\omega m$»»$Vs= K\emptyset\omega m+ IARA$»»$\omega m=(Vs- IARA)K\emptyset$

As flux Φ is assumed constant, the speed decreases with armature current increase. But practically,due to armature reaction, Φ decreases with increasein armature current, and hence the speeddecrease slightly.Hence,ashuntmotorcanbeassumedasaconstantspeedmotor.

3) TORQUEVS.SPEED

$\omega m=(Vs-TdevRA/K\emptyset)/K\emptyset$

AsfluxΦisassumedconstant,,thespeeddecreaseswithdevelopedtorqueincrease.Butpractically, due to armature reaction, Φ decreases with increase in armature current, and hence thespeed decreaseslightly.Thus,atheavyloads,the motorspeedisalmostconstant.

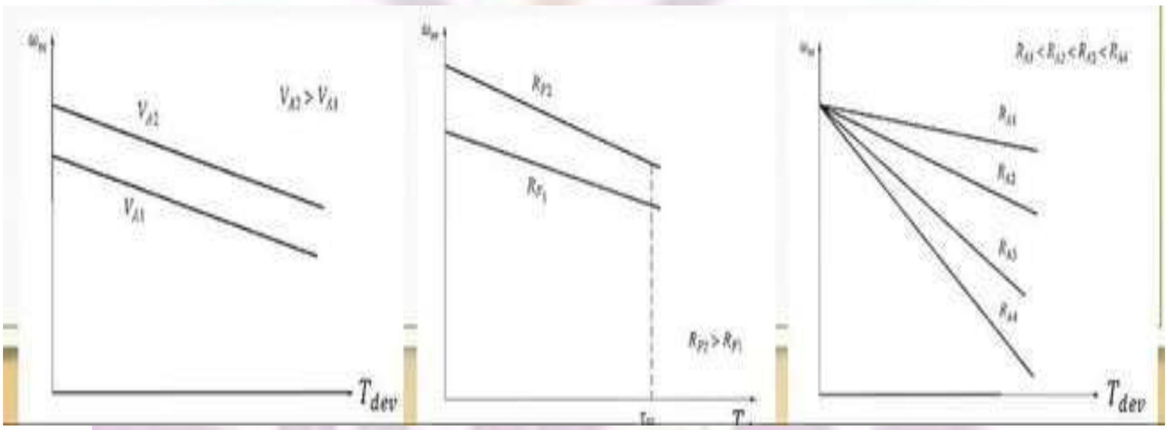


SPEEDCONTROLOFSEPARATELYEXCITED DCMOTOR

Speedofthistypeofdcshuntmotoriscontrolledbythefollowingmethods:

$\omega m=(Vs-IARA)\ /K\emptyset$

1. SUPPLY VOLTAGE CONTROL METHOD:Adjusting the supply voltage applied to thearmature without changing the voltage applied to the field. Hence, the flux is kept constant. This canbe applied to separately excited motors only.Hence, at a certain load, since the flux is fixed,increasingthearmaturevoltage,increasesthemotorspeed.
2. FLUX CONTROL METHOD:Adjusting the field resistance $IF = Vs\ RF$ (and thus the fieldflux). This can be applied to separately excited and shunt motors Hence, for a constant supplyvoltage,atacertainload,increasingthefluxdecreases themotorspeed.
3. ARMATURE RESISTANCE CONTROL METHOD:Inserting a resistor in serieswith the armature circuit. This can be applied to separately excited and shunt motors Hence, for aconstantsupplyvoltageandfixedflux,atacertainload,increasingRAdecreasesthemotorspeed.



ADVANTAGES

Theadvantagesofthismachineincludethefollowing.

- DCmachineslikedcmotorshavevariousadvantageslikestartingtorqueishigh,reversing,fast-starting&stopping,changeablespeedsthroughvoltageinput
- Theseareveryeasilycontrolledas wellas cheaperwhencomparedwithAC
- Speedcontrolisgood
- Torqueishigh
- OperationisSeamless
- Freefromharmonics
- Installationandmaintenanceiseasy

APPLICATIONSOFDCMOTORS

- Separately excited DC motors are often used as actuators in trains and automotive tractionapplications.
- For their constant speed characteristics, shunt DC motors are used in fixed speed applications such asfans.
- Since the series motors can give high torque per ampere (since their toque is directly proportionalto the square of armature current), they can be used in applications that require high starting torque.Examplesoftheseapplicationsinclude;startermotorsincars,andelevatormotors.

SYNCHRONOUSGENERATOR–CONSTRUCTIONANDWORKINGPRINCIPLE

A *synchronous generator* is a synchronous machine which converts mechanical power into ACelectricpowerthroughtheprocessofelectromagneticinduction.

Synchronous generators are also referred to as **alternators** or **AC generators**. The term "alternator"is used since it produces AC power. It is called synchronous generator because it must be driven atsynchronousspeedtoproduceACpowerofthedesiredfrequency.

A synchronous generator can be either *single-phase or poly-phase (generally 3phase)*.

CONSTRUCTIONOFSYNCHRONOUSGENERATORORALTERNATOR

Asalternatorconsistsoftwomainpartsviz.

- **Stator**–Thestatoristhestationarypartofthealternator.It carriesthearmaturewindinginwhichthevoltageisgenerated.Theoutputofthealternatoristakenformthestator.
- **Rotor** – The rotor is the rotating part of the alternator. The rotor produces the main fieldflux.

StatorConstructionofAlternator

Thestatorofthealternatorincludesseveralparts,viz.theframe,statorcore,statororarmaturewindings,andcoolingarrangement.

- The stator frame may be made up of cast iron for small-size machines and of weldedsteelforlarge-sizemachines.
- The stator core is assembled with high-grade silicon content steel laminations. Thesesiliconsteellaminationsreducethehysteresisandeddy-lossesinthestatorcore
- The slots are cut on the inner periphery of the stator core. A 3-phase armature winding isputintheseslots.
- The armature winding of the alternator is star connected. The winding of each phase isdistributed over several slots. When current flows through the distributed armaturewinding,itproducesanessentialsinusoidalspacedistributionofEMF.

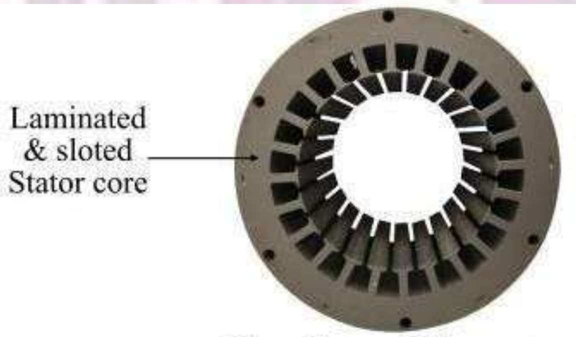


Fig. - Stator of Alternator

RotorConstructionofAlternator

The rotor of the alternator carries the fieldwinding which is supplied with direct current throughtwo slip rings by a separate DC source (also called exciter). The exciter is generally a small DCshuntgeneratormountedontheshaftofthealternator.

Forthealternator,therearetwotypesofrotorconstructionsareusedviz.*thesalient-poletype*and *thecylindricalrotortype*.

SalientPoleRotor

The term *salient means projecting*. Hence, a *salient pole rotor* consists of poles projecting out fromthe surface of the rotor core. This whole arrangement is fixed to the shaft of the alternator as shownin the figure. The individual field pole windings are connected in series such that when the fieldwindingisenergisedbytheDCexciter,theadjacentpoleshaveoppositepolarities.

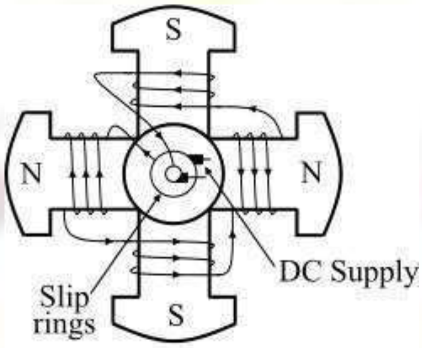
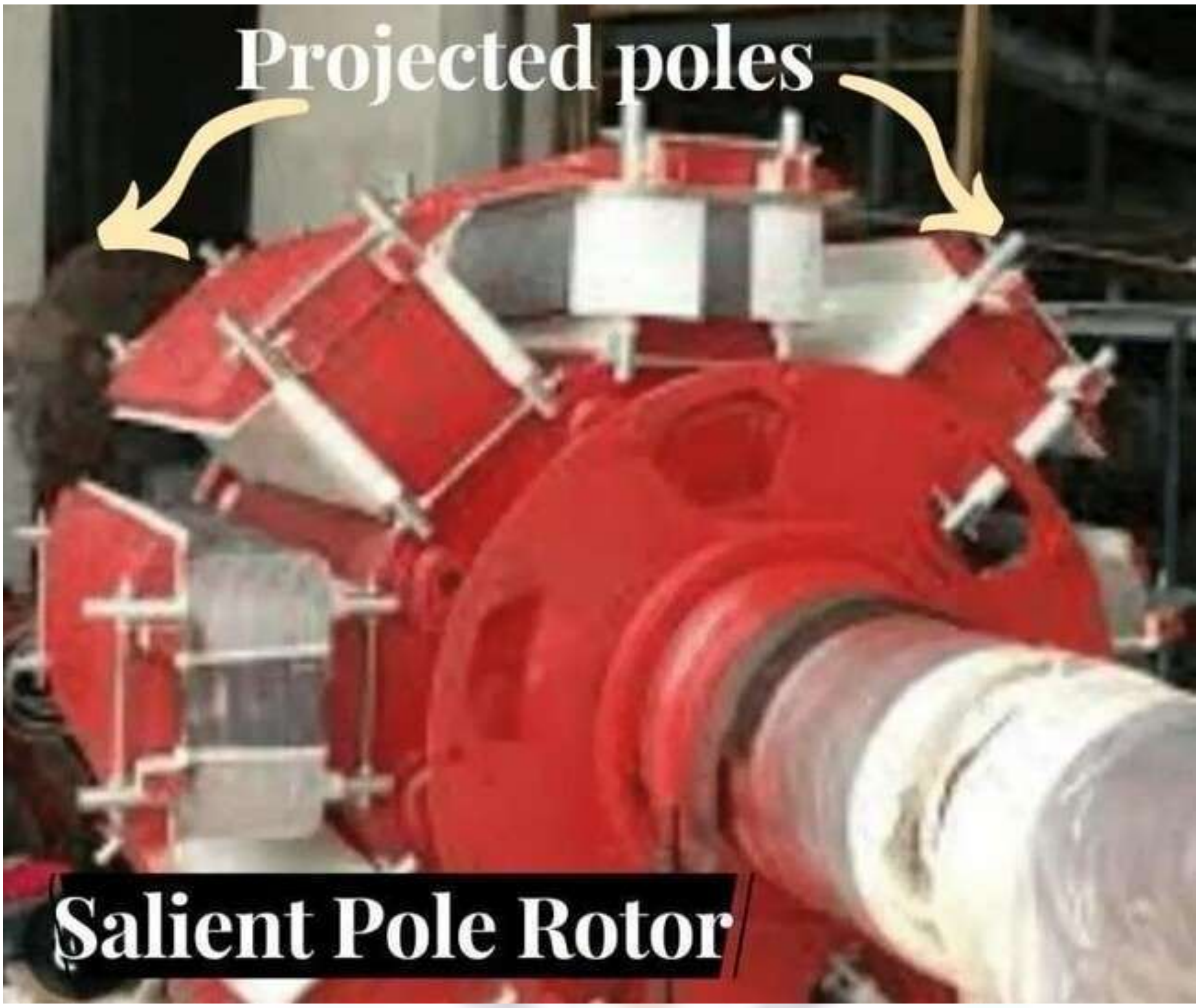


Fig. - Salient Pole Rotor



Thesalientpoletyperotorisusedinthelowandmediumspeed(from 120to400RPM)alternators such as those driven by the diesel engines or water turbines because of the followingreasons −

- Theconstructionofsalientpoletyperotorcannotbemadestrongenoughtowithstandthe mechanicalstresses towhichtheymaybesubjectedathigherspeed.
- If the salientfield pole type rotoris driven athigh speed,then itwould cause windagelossandwouldtendtoproducenoise.

Low speed rotors of the alternators possess a large diameter to provide the necessary space forthepoles.Asaresult,thesalientpoletyperotorshavelarge diameterandshortaxiallength.

CylindricalRotor

Thecylindricalrotorsaremadefromsolidforgingsofhigh-gradenickel-chrome-molybdenumsteel.

- Theconstructionofthecylindricalrotorissuchthattherearenophysicalpolestobeseenasinthesalientpolerotor.
- Inabouttwo-thirdoftheouterperipheryofthecylindricalrotor,slotsarecutatregularintervalsandparalleltotherotorshaft.
- ThefieldwindingsareplacedintheseslotsandisexcitedbyDCsupply.Thefieldwindingisof*distributedtype*.
- Theunslottedportionoftherotorformsthepolefaces.
- Itisclearfromthefigureofthecylindricalrotorthatthepolesformedarenon-salient,i.e.,theydonotprojectoutfromtherotorsurface.

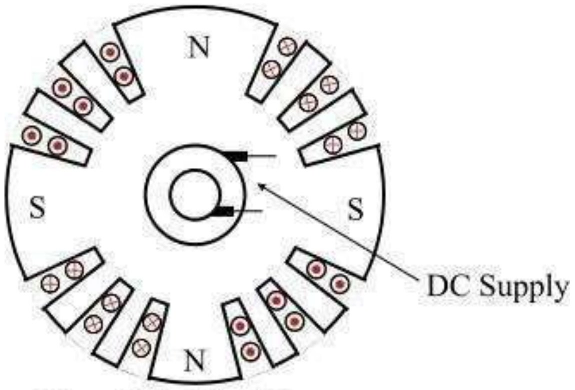


Fig. - Cylindrical Rotor

The cylindrical type rotor construction is used in the high-speed (1500 to 3000 RPM) alternatorssuchasthosedrivenbysteamturbinesbecauseofthefollowingreasons−

- Thecylindricaltyperotorconstructionprovidesagreatermechanicalstrengthandpermitsmore accuratedynamicbalancing.
- Itgivesnoiselessoperationathighspeedsbecauseoftheuniformairgap.
- Thefluxdistributionaroundtheperipheryoftherotorisnearlyasinewaveandhenceabetter EMF waveformisobtained.

Acylindricalrotoralternatorhasacomparativelysmalldiameterandlongaxiallength.Thecylindrical rotor alternators are called **turbo-alternators** or **turbo-generators**. The alternator withcylindricalrotorhavealwayshorizontalconfigurationinstallation.

WORKINGPRINCIPLEANDOPERATIONOFALTERNATOR

An alternator or synchronous generator works on the principle of electromagnetic induction, i.e.,when the flux linking a conductor changes, an EMF is induced in the conductor. When the armaturewinding of alternator subjected to the rotating magnetic field, the voltage will be generated in thearmaturewinding.

Whentherotor fieldwindingofthealternator isenergisedfromtheDCexciter,thealternateNandSpoles are developed on the rotor. When the rotor is rotated in the anticlockwise direction by a primemover,thearmatureconductorsplacedon thestatorarecutbythemagneticfieldoftherotor poles. As a result, the EMF is induced in the armature conductors due to electromagnetic induction.This induced EMF is alternating one because the N and S poles of the rotor pass the armatureconductors alternatively.

Thedirectionof thegeneratedEMFcanbedeterminedbytheFleming'srightruleandthefrequencyofitisgivenby,

$f=NsP/120$

- NsisthesynchronousspeedinRPM
- Pisthenumberofrotorpoles.
- The magnitude of the generated voltage depends upon the speed ofrotationoftherotorandtheDCfieldexcitationcurrent.Forthebalancedcondition, the generated voltage in each phase of the windingis the same butdifferinphaseby120°electrical.

E.M.FEQUATIONOFSYNCHRONOUSGENERATOR

Thee.m.fequationofthisgeneratorisshownbelow.

$E_{ph}=4.44K_cK_d\Phi fT_{ph}$ Volts

Where,

'P'ispoles

'ϕ'isFluxforeachpoleinWebers'N'isthespeedinrpm(revolutionperminute)'f'isthe frequencyinHz

'Tph'isthenumberofturnsconnectedinseriesperphase'Kc'isthespanfactorofthecoil

'Kd'

isthedistributionfactorofthecoil.

ApplicationsofSynchronousGenerator

Theapplicationsofsynchronousgeneratorincludethefollowing.

- Itisusedinthesystemswhereverstablespeedisnecessary.
- It isusedtopreservethepowerfactor(PF)ofthesystem.
- It is used in power generation plants because of stable frequency.

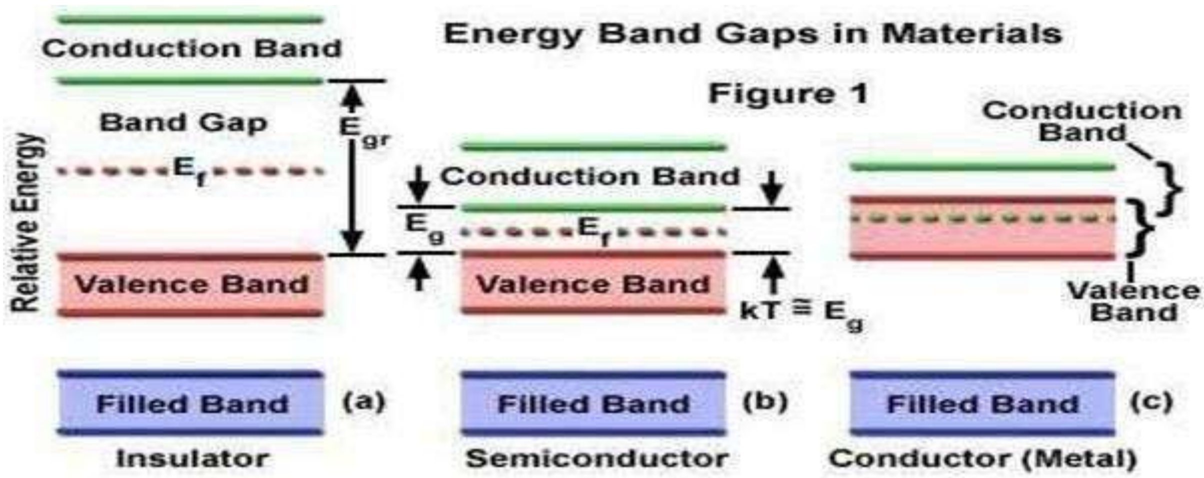
UNITIV

PNJUNCTIONDIODE

4.1 INTRODUCTION:

We start our study of nonlinear circuit elements. These elements (diodes and transistors) are madeofsemiconductors.Abriefdescriptionofhowsemiconductordevicesworkisrstgiventounderstandtheirivcharacteristics.Youwillseearigorousanalysisof semiconductorsinthebreadthcourses.

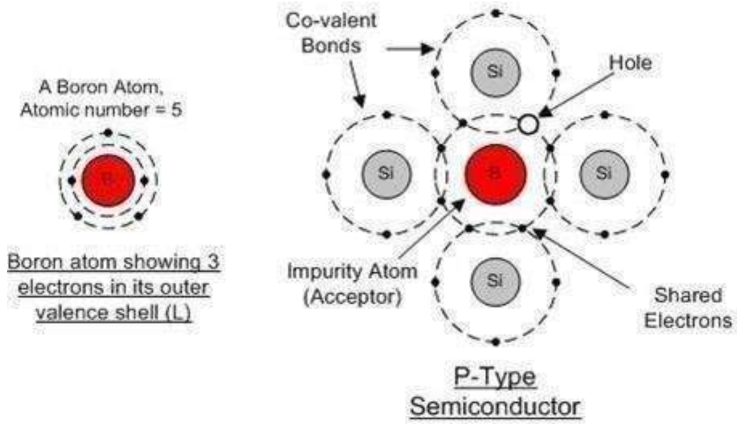
4.1.1 EnergyBandsinSolids:

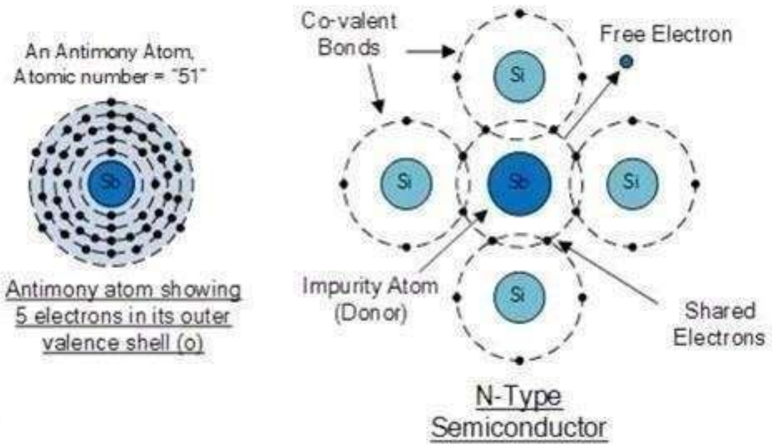


4.1.2 Semiconductors:

Semiconductor material are mainly made of elements from group IVB of the periodic table like C(diamond), Si, Ge, SiC.These material have 4 electrons in their outer most electronic shell. Each atomcan form a \covalent" bond with four of its neighbors sharing one electron with that atom. In thismanner, each atom \sees" eight electrons in its outer most electronic shell (4 of its own, and one fromeach neighbor), completely lling that shell. It is also possible to form this type of covalent bond bycombining elements from group IIIB (sharing three electrons) with element from group VB (sharingveelectrons).ExamplesofthesesemiconductorsareGaAsorAlGaAsandareusuallycalled \3-5" semiconductors. We focus mostly on Si semiconductors in this class. Figure below shows thiscovalentbond structure for Si. A pair of electrons and holes are slow shown. Note that Si form atetrahedron structure and an atom in the center of the tetrahedron share electrons with atoms on theeach vertex. Figure below is atwo-dimensional representation of such astructure. The leftgure is forapureSisemiconductorandanelectron-holepairisdepicted.Bothelectronsandholesarecalled\mobile" carriersastheyareresponsibleforcarryingelectric current.

If we add a small amount of an element from group VB, such as P, to the semiconductor, wecreate a n-type semiconductor and the impurity dopant is called a n-type dopant. Each of these newatoms also form a covalent bond with four of its neighbors. However, as a n-type dopant has 5 valanceelectron, the extra electron will be located in the \empty" energy band. As can be seen, thereis no holeassociated with this electron. In addition to electrons from the n-type dopant, there are electron-hairpair in the solid from the base semiconductor (Si in he above gure) which are generated due totemperature e ects. In a n-type semiconductor, the number of free electrons from the dopant is muchlarger than the number of electrons from electron-hole pairs. As such, a n-type semiconductor isconsiderably more conductive than the base semiconductor (in this respect, a n-type semiconductor ismorelikea\resistive"metalthanasemiconductor).





Insummary,inan-typesemiconductortherearetwochargecarriers:\holes"fromthebasesemiconductor (called the \minority" carriers) and electrons from both the n-type dopant and electron-holepairs(calledthe\majority" carrier).

Similarly, we can create a p-type semiconductorby adding an element from group IIIB, suchas B, to the semiconductor. In this case, the p-type dopant generate holes. We will have two chargecarriers:majoritycarriersare\holes"fromthep-typedopantandelectron-holepairsandminoritycarriersareelectronsfromthebasesemiconductor(fromelectron-holepairs).

The charge carriers (electrons and holes) move in a semiconductor through two mechanisms: First,charge carriers would move from regions of higher concentration to lower concentration in order toachieve a uniform distribution throughout the semiconductor. This process is called **Diff usion**" and ischaracterized by the diffusion coefficient, D. Second, charge carriers move under the influence of anelectricfield.Thismotioniscalledthedriftandischaracterizedbythe mobility.

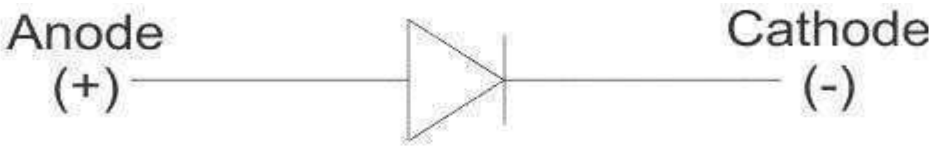
4.2 DIODEWORKINGPRINCIPLE

Whatis aDiode?
A diode is a device which only allows unidirectional flow of current if operated within a ratedspecifiedvoltagelevel.Adiodeonlyblockscurrentinthereversedirectionwhilethereversevoltageis within a limited range otherwise reverse barrier breaks and the voltage at which this breakdownoccursiscalledreversebreakdownvoltage.Thediodeactsasavalveintheelectronicandelectricalcircuit. A P-N junction is the simplest form of the diode which behaves as ideally short circuit whenit is in forward biased and behaves as ideally open circuit when it is in the reverse biased. Besidesimple PN junction diodes, there are different types of diodes although the fundamental principle ismoreorlesssame.Soaparticulararrangementofdiodescanconvert AC topulsatingDC,andhence,itis

sometimes also called as a rectifier. The name diode is derived from "di-ode" which means a devicehavingtwoelectrodes.

4.2.1 SymbolofDiode

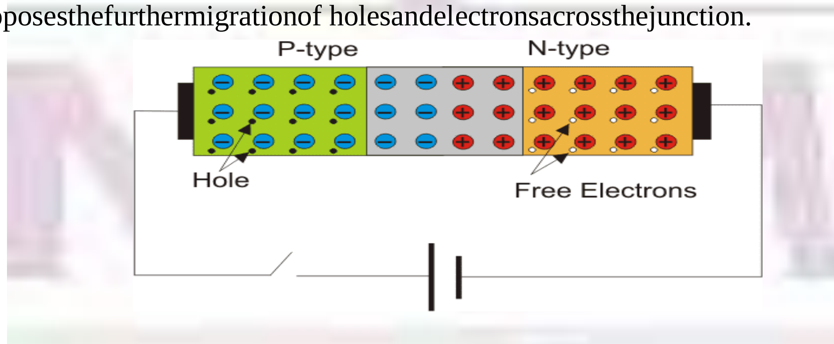
Thesymbolofadiodeisshownbelow,thearrowheadpointsinthedirectionofconventionalcurrentflow.



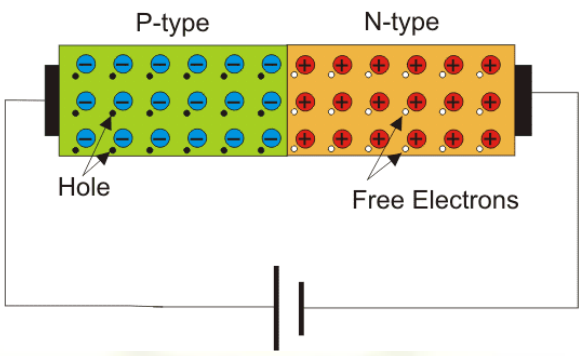
A simple **PN junction diode** can be created by doping donor impurity in one portion and acceptorimpurity in other portion of a silicon or germanium crystal block. These make a p n junction at themiddleportionoftheblockbeside whichoneportionisptype(whichisdopedbytrivalentoracceptorimpurity) and other portion is n type (which is doped by pentavalent or donor impurity). It can also beformed by joining a p-type (intrinsic semiconductordoped with a trivalent impurity) and n-typesemiconductor (intrinsic semiconductor doped with a pentavalent impurity) together with a specialfabrication technique such that a p-n junction is formed. Hence, it is a device with two elements, the p-typeformsanodeandthen-typeformsthecathode.Theseterminalsarebroughtouttomaketheexternalconnections.

4.2.2 WorkingPrinciple ofDiode

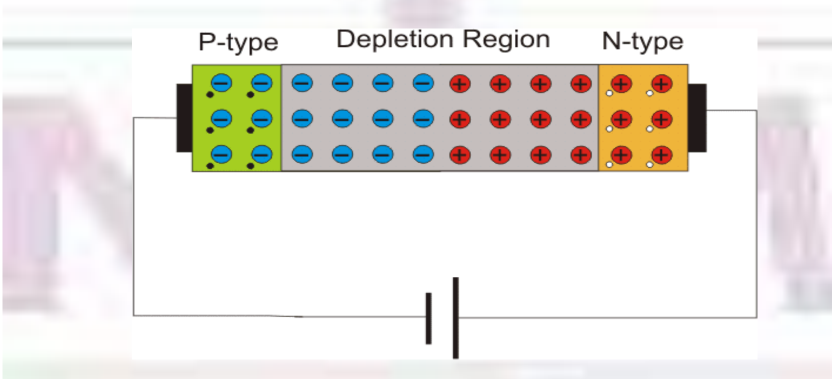
The n side will have a large number of electrons and very few holes (due to thermal excitation)whereas thepsidewillhaveahighconcentrationofholesandveryfewelectrons.Duetothis,aprocesscalleddiffusiontakesplace.Inthisprocessfreeelectronsfromthensidewilldiffuse(spread)intothep side and combine with holes present there, leaving a positive immobile (not moveable) ion in the nside. Hence, few atoms on the p side are converted into negative ions. Similarly, few atomson the n-sidewill getconvertedtopositiveions.Duetothislargenumberofpositiveionsandnegativeionswillaccumulate on the n-side and p-side respectively. This region so formed is called asdepletion region.Duetothepresenceofthesepositiveandnegativeionsastaticelectricfieldcalledas"barrierpotential"is created across the p-n junction of the diode. It is called as "barrier potential" because it acts as abarrierandopposesthefurthermigrationof holesandelectronsacrossthejunction.



InaPNjunctiondiodewhentheforwardvoltageisappliedi.e.positiveterminalofasourceisconnectedto the p-type side, and the negative terminal of the source is connected to the n-type side, the diode issaidtobeinforwardbiasedcondition.Weknowthatthereisabarrierpotentialacrossthejunction.Thisbarrier potential is directed in the opposite of the forward applied voltage. So a diode can only allowcurrent to flow in the forward direction when forward applied voltage is more than barrier potential ofthe junction. This voltage is called forward biased voltage. For silicon diode, it is0.7 volts. Forgermaniumdiode,itis0.3volts.Whenforwardappliedvoltageismorethanthisforwardbiasedvoltage,there willbeforwardcurrentinthediode,andthediodewillbecomeshort circuited. Hence, there will be no more voltage drop across the diode beyond this forward biasedvoltage, and forward current is only limited by the external resistance">resistance connected in serieswith the diode. Thus, if forward applied voltage increases from zero, the diode will start conductingonly after this voltage reaches just above the barrier potential or forward biased voltage of the junction.The time taken by this input voltage to reach that value or in other words the time taken by this inputvoltagetoovercometheforwardbiasedvoltageiscalledrecoverytime.

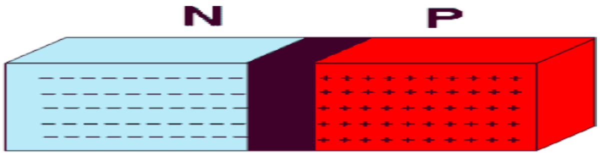


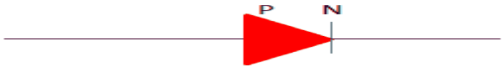
Now if the diode is reverse biased i.e. positive terminal of the source is connected to the n-type end,and the negative terminal of the source is connected to the p-type end of the diode, there will be nocurrent through the diode except reverse saturation current. This is because at the reverse biasedcondition the depilation layer of the junction becomes wider with increasing reverse biased voltage.Although there is a tiny current flowing from n-type end to p-type end in the diode due to minoritycarriers. This tiny current is called reverse saturation current. Minority carriers are mainly thermallygenerated electrons and holes in p-type semiconductor and n-type semiconductor respectively. Now ifreverse applied voltage across the diode is continually increased, then after certain applied voltage thedepletion layer will destroy which will cause a huge reverse current to flow through the diode. If thiscurrent is not externally limited and it reaches beyond the safe value, the **diode** may be permanentlydestroyed. This is because, as the magnitude of the reverse voltage increases, the kinetic energy of theminority charge carriers also increase. These fast moving electrons collide with the other atoms in thedevice to knock-off some more electrons from them. The electrons so released further release muchmore electrons from the atoms by breaking the covalent bonds. This process is termed as carriermultiplication and leads to a considerable increase in the flow of current through the p-n junction. TheassociatedphenomenoniscalledAvalancheBreakdown.



4.3 DIODECHARACTERISTICS

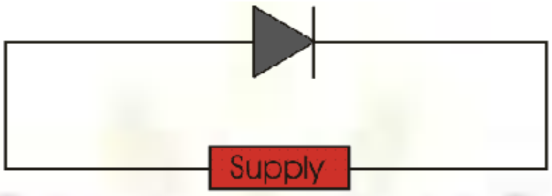
Semiconductor materials (Si, Ge) are used to form variety of electronic devices. The most basic deviceis diode. Diode is a two terminal P-N junction device. P-N junction is formed by bringing a P typematerial in contact with N type material.When a P-type material is brought in contact with N-typematerial electrons and holes start recombining nearthe junction. This result in lack ofcharge carriersatthejunctionandthusthejunctioniscalleddepletionregion.Symbol ofP-Njunctionisgivenas:





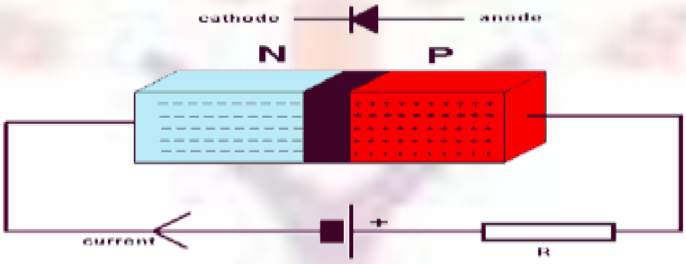
Biasedi.e.whenvoltageisappliedacrosstheterminalsofP-Njunction,itiscalleddiode.

Diode is unidirectional device that allows the flow of current in one direction only depending on thebiasing.



4.3.1 ForwardBiasingCharacteristicofDiode

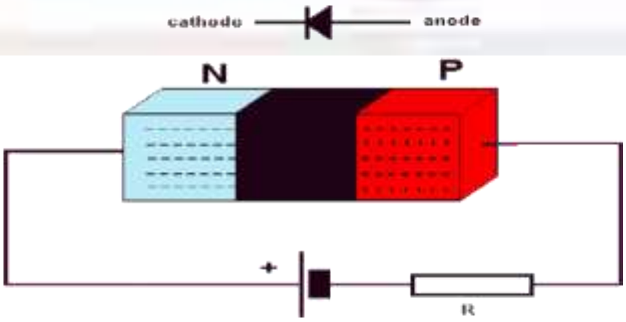
When, P terminal is more positive as compared to N terminal i.e. P- terminal connected to positiveterminal of battery and N-terminal connected to negative terminal of battery, it is said to be forwardbiased.



Positive terminal of the battery repels majority carriers, holes, in P-region and negativeterminal repelselectrons in the N-region and push them towards the junction.This result in increasein concentration of charge carriers near junction, recombination takes place and width of depletionregion decreases. As forward bias voltage is raised depletion region continues to reduce in width, andmoreandmorecarriers recombine.Thisresultsinexponential riseofcurrent.

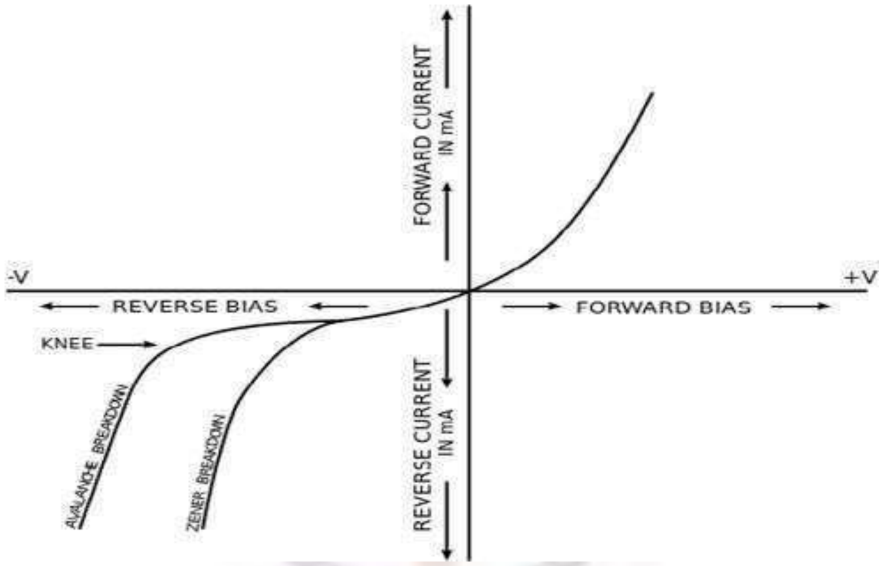
4.3.2 ReverseBiasingCharacteristicofDiode

In reverse biasing P- terminal is connected to negative terminal of the battery and N- terminal topositiveterminalofbattery.ThusappliedvoltagemakesN-side morepositivethanP-side.



Negative terminal of the battery attracts majority carriers, holes, in P-region and positive terminalattracts electrons in the N-region and pull them away from the junction. This result in decrease inconcentration of charge carriers near junction and width of depletion region increases. A small amountof current flow due to minority carriers, called as reverse bias current or leakage current. As reversebias voltage is raised depletion region continues to increase in width and no current flows. It can beconcluded that diode acts only when forward biased. Operation of diode can be summarized in formofI-V**diodecharacteristics**graph. Forreversebiasdiode,$V<0, I_D=I_S$Where,V=supplyvoltageI_D =diodecurrentI_S=reversesaturationcurrentForforwardbias,$V>0, I_D=I_S(e^{V/NV_T}-1)$

Where,
V_T=volt'sequivalentoftemperature=KT/Q=T/11600Q=electronic charge=$1.632X10^{-19}$ C
K=Boltzmann'sconstant=$1.38X10^{-23}$
N=1,forGe
=2,forSi



As reverse bias voltage is further raised, depletion region width increases and apoint comes when junction breaks down. This results in large flow of current. Breakdown is the kneeof**diodecharacteristics**curve.Junctionbreakdowntakesplaceduetotwophenomena

4.3.3 AvalancheBreakdown(forV>5V)

Under very high reverse bias voltage kinetic energy of minority carriers become so large that theyknock out electrons from covalent bonds, which in turn knock more electrons and this cycle continuesuntilandunlessjunctionbreakdowns.

4.3.4 ZenerEffect(forV<5V)

Under reverse bias voltage junction barrier tends to increase with increase in bias voltage. This resultsin very high static electric field at the junction. This static electric field breaks covalent bond and setminority carriers free which contributes to reverse current. Current increases abruptly and junctionbreaksdown.

P-NJUNCTIONDIODEAND CHARACTERISTICSOFP-NJUNCTION

Thevolt-amperecharacteristicsofadiodeexplainedbythefollowingequations:

$$I = I_S(e^{V_D/(\eta V_T)} - 1)$$

Where
I=currentflowinginthediode,I_0=

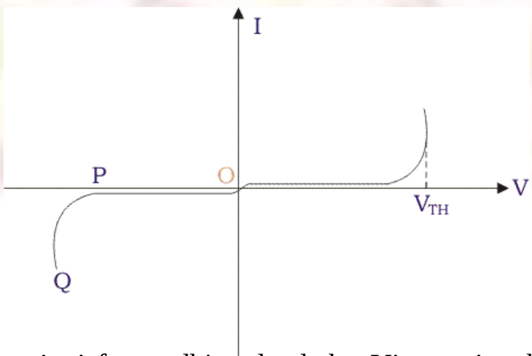
reversesaturationcurrent

V_D=Voltageappliedtothediode

V_T=volt-equivalentoftemperature=kT/q=T/11,600=26mV(@roomtemp)

η=1(forGe)and2(forSi)

It is observed that **Ge** diodes has smaller cut-in-voltage when compared to **Si**diode. The reverse saturation current in **Ge** diode is larger in magnitude whencomparedtosilicondiode.

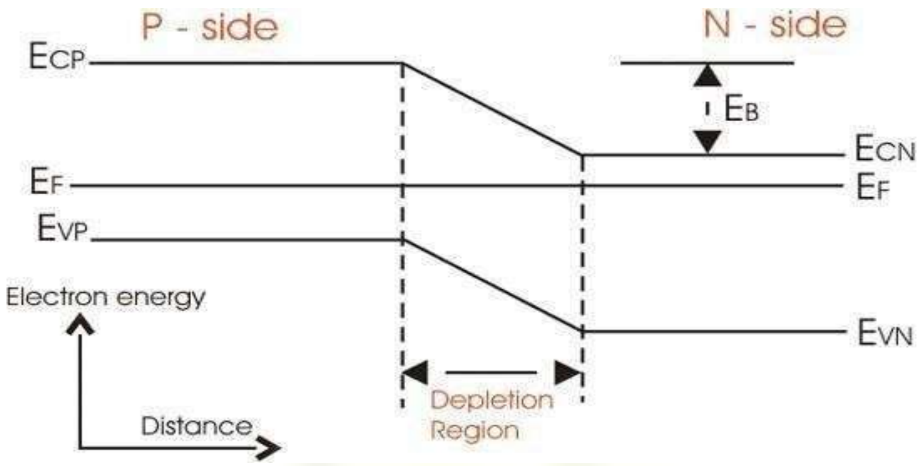


When,Vispositivethejunctionisforwardbiasedandwhen Visnegative,thejunctionisreversingbiased.WhenVisnegativeandless thanVTH,thecurrentisverysmall.ButwhenVexceedsVTH,the current suddenly becomes very high. The voltage VTH is known as threshold or cut in voltage.For Silicon diode VTH = 0.6 V. At a reverse voltage corresponding to the point P, there is abruptincrementinreversecurrent.ThePQportionofthecharacteristicsisknownasbreakdownregion.

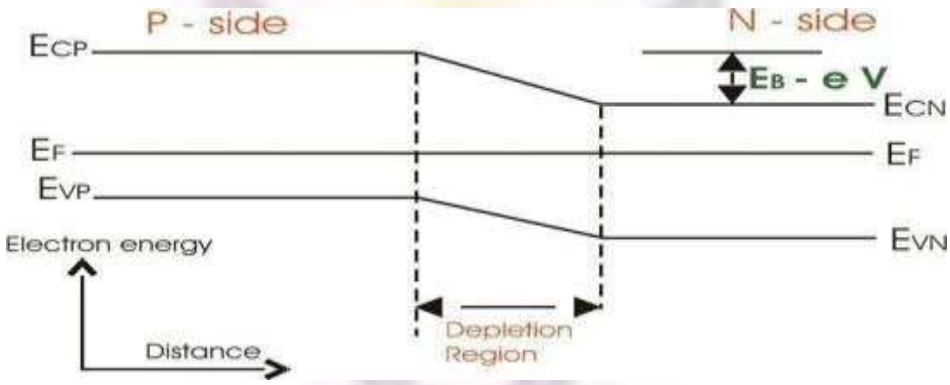
4.4 P-NJunctionBandDiagram

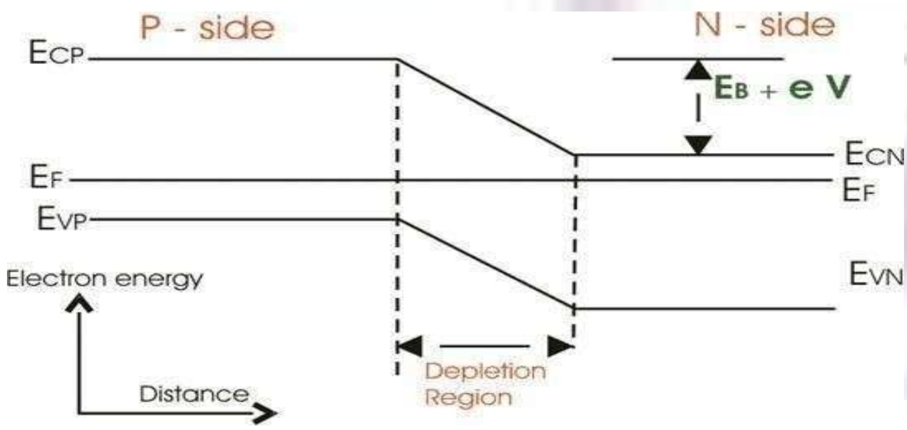
For an n-type semiconductor, the Fermi level E_F lies near the conduction band edge. $E_C$butforanp-typesemiconductor,$E_F$liesnearthevalancebandedgeE_V.

Now, when a p-n junction is built, the Fermi energy E_F attains a constant value. In thisscenario the p- sides conduction band edge. Similarly n–side valance band edge will be athigher level than E_{cn}, n- sides conduction band edge of p - side. This energy difference isknownasbarrierenergy.TheBarrierenergyis$E_B=E_{cp}-E_{cn}=E_{vp}-E_{vn}$



IfweapplyforwardbiasvoltageV,acrossjunctionthenthebarrierenergydecreasesbyanamount ofeVandifVisreversebiasisappliedthebarrierenergyincreasesbyeV.





2.4. Diode Current Equation

The mathematical equation, which describes the forward and reverse characteristics of a semiconductor diode is called the **diode current equation.**

Let I = Forward (or reverse) diode current,

I_{RS} = Reverse saturation current,

V = External voltage (It is positive for forward bias and negative for reverse bias),

η = A constant

= 1 for germanium diodes, 2 for silicon diodes for relative *low value of diode current* (*i.e.*, at or below the knee of the curve)

= 1 for germanium and silicon for *higher levels of diode current* (*i.e.*, in the rapidly increasing section of the curve), and

V_T = Volt-equivalent of temperature. Its value is given by the relation, $\frac{T}{11600}$,

where T is the absolute temperature

= 26 mV at room temperature (300 K).

For a *forward-biased diode*, the current equation is given by the relation,

$$I = I_{RS} \left[e^{V/(\eta \times V_T)} - 1\right] \qquad ...(i)$$

Substituting the value of V_T = 26 mV or 0.026 V (at room temperature) in eqn. (*i*), we get

$$I = I_{RS} (e^{40V/\eta})$$

$\therefore$ Diode current at or below the knee, for *germanium*,

$$I = I_{RS} (e^{40V} - 1) \qquad (\because \eta = 1)$$

and, for *silicon*,

$$I = I_{RS} (e^{20V} - 1) \qquad (\because \eta = 2)$$

When the value of applied voltage is greater than unity (*i.e.*, for the diode current in the rapidly increasing section of curve), the equation of diode current for germanium or and silicon,

$$I = I_{RS} \cdot e^{20V} \qquad (\because \eta = 2)$$

The current equation for a reverse biased diode may be obtained from eqn. (*i*) by *changing the sign of the applied voltage (V)*. Thus the *diode current for reverse bias*,

$$I = I_{RS} \left[e^{-V/(\eta \times V_T)} - 1\right]$$

When $V >> V_T$, then the term $e^{-V/(\eta \times V_T)} << 1$. Therefore $I = I_{RS}$. Thus the *diode current under reverse bias is equal to the reverse saturation current as long as the external voltage is below its breakdown value.*

4.5.1 APPLICATIONSOFDIODES

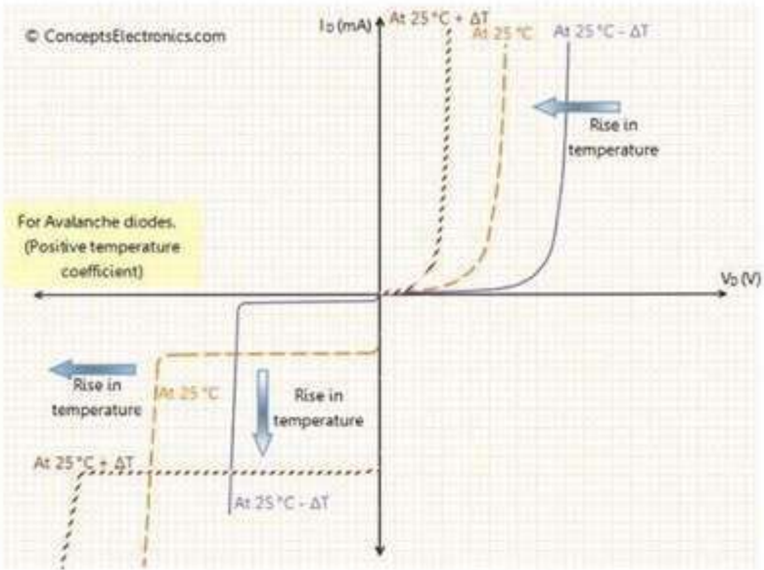
- Rectifyingavoltage,suchasturningACintoDCvoltages
- Isolatingsignalsfromasupply
- VoltageReference
- Controllingthesizeofasignal
- Mixingsignals
- Detectionsignals
- Lighting
- Lasersdiodes

Effect of temperature on PN junction diode.

- PN junction diode parameters like cut in voltage , forward current in the forward bias and reverse current, reverse breakdown voltage and reverse saturation current in the reverse bias are dependent on temperature.
- The current that a PN junction diode can conduct at a given voltage is dependent upon the operating temperature. An increased temperature will result in a large number of broken covalent bonds increasing the large number of majority and minority carriers. Rise in temperature generates more electron-hole pair thus conductivity increases and thus increase in current.This amounts to a diode current larger than its previous diode current. The above phenomenon applies both to forward and reverse current.
- Mathematically diode current is given by

$$I = I_{RS}\ [e^{V/(\eta \times V_T)} - 1]$$

Hence from equation we conclude that the current should decrease with increase in temperature but exactly opposite occurs, there are two reasons:



Effect of temperature on avalanche diodes

Forward bias region :

- The effect of increased temperature and decrease in temperature on the forward characteristics curve of a PN junction diode is as shown in above figure. It may be noted that the forward characteristics of silicon diode shift to the left at rate of 2.5 m V per centigrade degree increase in temperature and shift towards right at rate of 25 m V per centigrade degree decrease in temperature.
- The cut-in voltage decreases as the temperature increases. The diode conducts at smaller voltage at large temperature.
- The cut-in voltage increases as the temperature decreases. The diode conducts at larger voltage at lower temperature.

Example:

At 25° C $V_D = 0.7V$

for 100° C Rise in temp. i.e., at 25+100=125°C

now we will find new V_D at 125° C then 100*2.5mV =0.25 V

the new V_D will be reduce by 0.25 V

therefore new V_D = 0.7- 0.25= **0.45 V**

At 25° C $V_D = 0.7V$

for 100° C decrease in temp. i.e., at 25-100= -75°C

now we will find new V_D at 75° C then 100*2.5mV =0.25 V

the new V_D will be increase by 0.25 V

therefore new V_D = 0.7+ 0.25= **0.95 V**

Reverse bias region:

- The effect of increased temperature and decrease in temperature on the reverse characteristics curve of a PN junction diode is as shown in above figure. It may be noted that in the reverse bias region characteristics reverse current of silicon diode shift downwards with the increase in temperature and shift upward with decrease in temperature.
- In the reverse bias region the reverse current of diode doubles for every 10°C rise in temperature.

. Example:

- For 100° C Rise in temp. i.e., at 25+100=125°C

25° C ⟶ 10nA

35° C ⟶ 20nA

45° C ⟶ 40nA

55° C ⟶ 80nA

.
.
.
.
.
.

125° ⟶ 10240n A **(OR)** 10.24 μ A

Therefore for 100° C Rise in temp. i.e., at 25+100=125°C the reverse saturation current increases to greater than 10nA

- For 100° C decrease in temp. i.e., at 25-100 = -75°C the reverse saturation current reduces to less than 10nA

Static and Dynamic Resistance of a Diode

Static forward resistances (R_F). A diode has a definite value of resistance when forward biased. It is given by the *ratio of the D.C. voltage across the diode to D.C. current flowing through it.*

Mathematically, $R_F = \dfrac{V_F}{I_F}$

R_F may be obtained *graphically* from the diode forward characteristics as shown in Fig. From the operating point P, the static forward resistance,

$$R_F = \frac{0.8}{16} = 0.05\ \Omega.$$

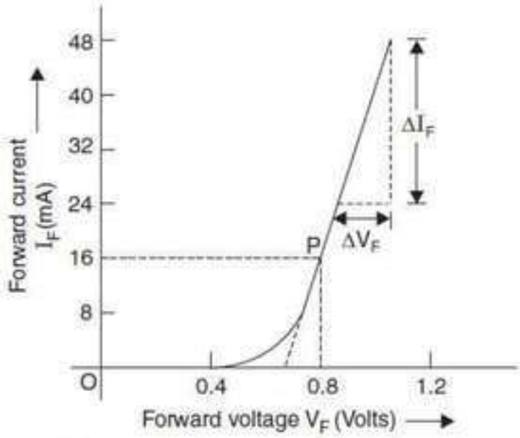


Fig. Static and dynamic forward resistances of a diode from the characteristic curve.

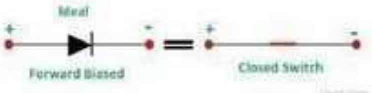
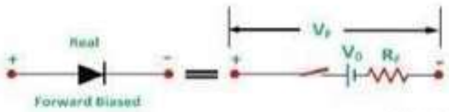
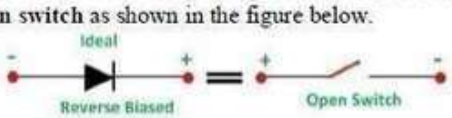
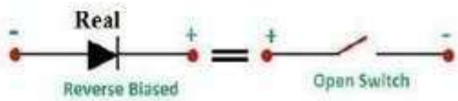
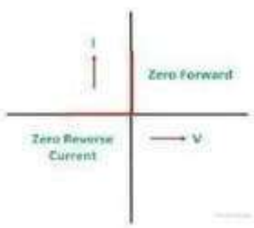
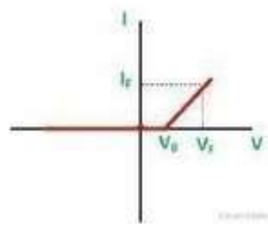
Dynamic or A.C. resistance. In practice we don't use static forward resistance, instead, we use the dynamic or A.C. resistance. The A.C. resistance of a diode, at a particular D.C. voltage, is *equal to the reciprocal of the slope of the characteristic at that point ;* *i.e,* the A.C. resistance,

$$r_{A.C.} = \frac{1}{\Delta I_F/\Delta V_F} = \frac{\Delta V_F}{\Delta I_F} = \frac{\text{Change in voltage}}{\text{Resulting change in current}}.$$

Owing to the non-linear shape of the forward characteristic, the value of A.C. resistance of a diode is in the range of 1 to 25 Ω. Usually it is *smaller than D.C. resistance of a diode.*

Reverse resistance. When a diode is *reverse biased*, besides the forward resistance, it also possesses another resistance known as *reverse resistance.* It can be either D.C. or A.C. depending upon whether the reverse bias is direct or alternating voltage. Ideally, the reverse resistance of a diode is infinite. However, in actual practice, the reverse resistance is never infinite. It is *due to the existence of leakage current* in a reverse biased diode.

Ideal Diode and Practical Diode

Ideal Diode	Practical Diode
1)A diode is said to be an **Ideal Diode** when it is forward biased and acts like a perfect conductor, with zero voltage across it. Similarly, when the diode is reversed biased, it acts as a perfect insulator with zero current through it.	1)A **Practical diode** contains barrier potential V_0 (0.7 V for silicon and 0.3 V for Germanium) and a forward resistance R_F of about 25 ohms. When a diode is forward biased and conducts a forward current I_F flows through it which causes a voltage drop I_FR_F in the forward resistance. Hence, the forward voltage V_F applied across the Practical diode for conduction, has to overcome the following. (i) Potential barrier (ii) Drop in forward resistance i.e., $V_F = V_0 + I_FR_F$
2) When the Ideal diode is forward biased it acts like a **closed switch** as shown in the figure below. An Ideal diode also acts like a switch  Diode resistance is zero i.e., R_D=0 from ohms law $V_D = I_DR_D$ Therefore V_D=0	2)The **equivalent circuit** of the Practical diode under forwarding bias condition is shown below.This circuit shows that a Practical diode still acts as a switch when forward biased, but the voltage required to operate this switch is V_F  $V_F = V_0 + I_FR_F$
3) Where as, if the diode is reversed biased, it acts like an **open switch** as shown in the figure below.  Diode resistance is infinity i.e., $R_D=\infty$ from ohms law $V_D = I_DR_D$ Therefore ,I_D=0	3)For all the practical purposes, a diode is considered to be an open switch when reversing biased. It is because the value of reverse resistance is so high (R_R > 100 MΩ) that is considered to be an infinite for all practical purposes. 
4) The **V-I characteristics** of the Ideal diode are shown in the figure below  	4)The **V-I characteristic** of the Practical diode is shown below. 

Equivalent Diode Circuits

An equivalent circuit is nothing but a combination of elements that best represents the actual terminal characteristics of the device. In simple language, it simply means the diode in the circuit can be replaced by other elements without severely affecting the behavior of circuit.

The diode can be modeled in three different ways depending on the accuracy required. Three models with increasing accuracy are listed below:

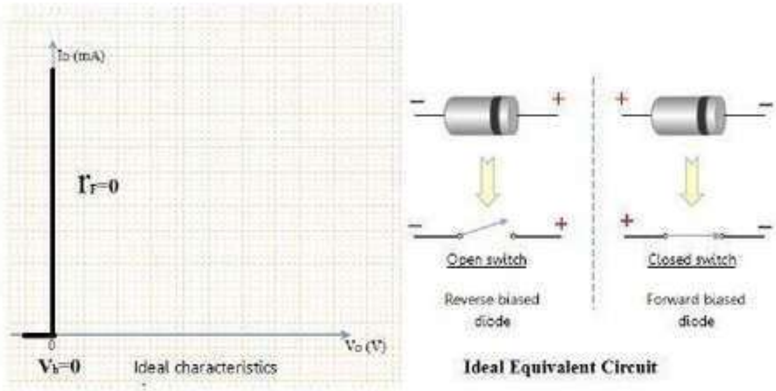
1. Ideal Diode Equivalent Circuit:
2. Constant voltage drop (or) Simplified Equivalent Circuit
3. Piece-Wise Linear Equivalent Circuit

1. Ideal Diode Equivalent Circuit:

Figure indicates that the voltage drop across the diode is zero for any value of diode current. The ideal diode does not allow any current to flow in reverse biased condition. The current flowing through the diode is zero for any value of reverse biased voltage. Taking this into consideration, the ideal diode can be modeled as open or closed switch depending on the bias voltage.

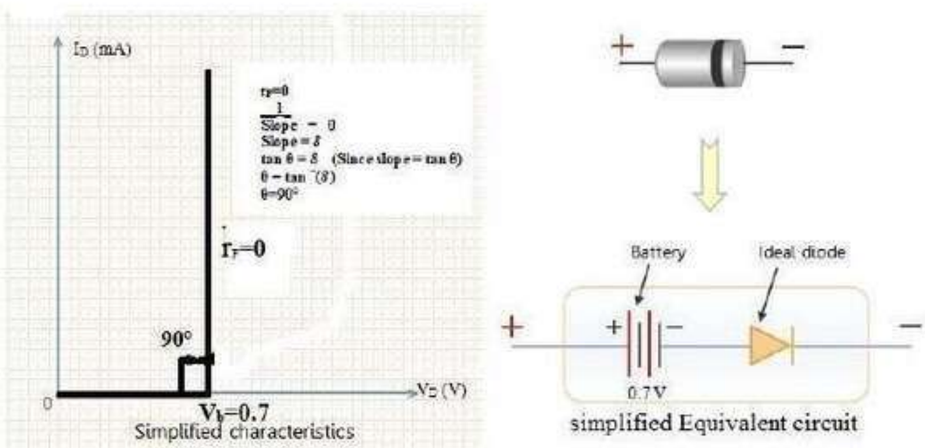
a) Ideal diode allows the flow of forward current for any value of forward bias voltage. Hence, Ideal diode can be modeled as closed switch under forward bias condition. This is shown in the figure.

b) Ideal diode allows zero current to flow under reverse biased condition. Hence it can be modeled as open switch. This is indicated in the figure.



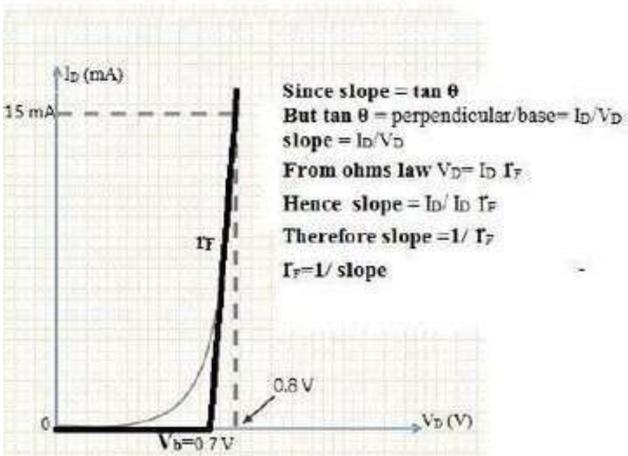
2. Constant Voltage Drop (or) Simplified Equivalent Circuit

The equivalent circuit in this case consists of a battery and an ideal diode. Consider the horizontal line from (0 to 0.7 V) in the curve. The horizontal line indicates that the current flowing through diode is zero for voltages between 0 and 0.7 V. To model this behavior, we put a battery of 0.7 V in the equivalent diode model. This does not mean that diodes are a source of voltage. When you measure the voltage across an isolated diode, the instrument will show zero value. The battery simply indicates that it opposes the flow of current in forward direction until 0.7 V. As the voltage becomes larger than 0.7 V, the current starts flowing in forward direction.

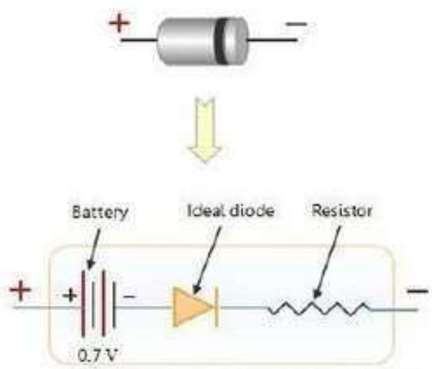


3. Piece-Wise Linear Equivalent Circuit

The piece-wise linear circuit, as the name suggests, is a model in which the characteristics of diode is approximated by "piece-wise linear" line segments. Now consider the straight line in the piece-wise linear characteristics. This straight line indicates constant slope. Slope in the V-I graph indicates resistance. So we add a resistor in the diode model. The value of resistance can be found from the graph. We can see from the graph that the diode current changes from 0 to 15 mA for a voltage change from 0.7 to 0.8 V. Thus the average value of resistance is (0.8 V-0.7 V)/(15 mA - 0 mA) = 6.67 Ω. Thus the value of resistance in the equivalent model is approximately 6.67 Ω. The figure given below shows piece-wise linear characteristics of diode along with its model.



Piecewise-linear characteristics



Piecewise linear Equivalent Circuit

In the graph shown on left, the actual characteristics of diode is superimposed by piece-wise linear characteristics (shown in amber color). It is clear that the piece-wise linear characteristics do not exactly represent the characteristics of diode, especially near the knee of the curve. However it provides a good first approximation to the actual characteristics of the diode. Piece- wise linear characteristics can be obtained by replacing the diode in the circuit with a resistor, a battery and an ideal diode. This is shown in the right side of the above figure.

ZENER DIODE

A properly doped P-N junction crystal diode which has a sharp breakdown voltage is known as ***Zener diode.***

The voltage-regulator diode is commonly called a **'Zener' diode.** It is a *voltage limiting diode* that has some applications in common with the older voltage-regulator gas tubes but serves a much wider field of application, because the devices cover a wide spectrum of voltages and power levels.

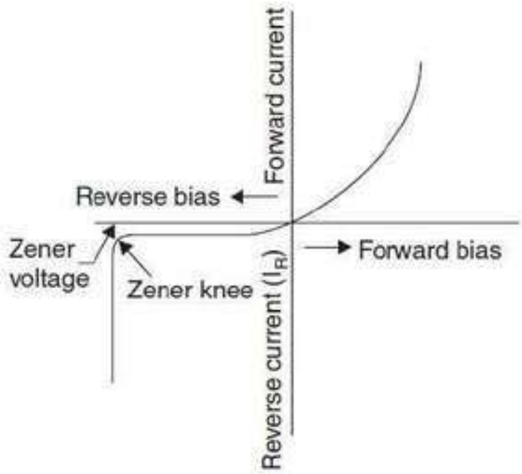


Fig.

Performance/Operation

The electrical performance of a zener diode is based on the *avalanche characteristics* of the *P-N* junction. When a source of voltage is applied to a diode in the *reverse direction* (negative to anode), a reverse current I_R is observed (see Fig.). As the reverse potential is increased beyond the "*Zener knee*" avalanche breakdown becomes well developed at zener voltage V_Z. At voltage V_Z, the high counter resistance drops to a low value and the junction current increases rapidly. The current must of necessity be limited by an external resistance, since the voltage V_Z developed across the zener diode remains essentially constant. *Avalanche breakdown of the operating zener diode is not destructive as long as the rated power dissipation of the junction is not exceeded.*

Externally, the zener diode looks much like other silicon rectifying devices, and electrically it is capable of rectifying alternating current.

The following points about the *Zener diode* are worth noting :

(*i*) It looks like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.

(*ii*) It is always reverse connected *i.e.*, it is *always reverse biased.*

(*iii*) It has sharp breakdown voltage, called Zener voltage V_Z.

(*iv*) When forward biased, its characteristics are just those of ordinary diode.

(*v*) It is not immediately burnt just because it has entered the breakdown region (The current is limited only by both external resistance and power dissipation of Zener diode).

- The location of Zener region can be controlled by varying the doping levels. An *increase in doping, producing an increase in the number of added impurities, will decrease the Zener potential.*

- Zener diodes are available having Zener potentials of 1.8 to 200 V with power ratings from $\frac{1}{4}$ to 50 W. *Because of its higher temperature and current capability, silicon is usually preferred in the manufacture of Zener diodes.*

. Equivalent Circuit of Zener Diode

The complete equivalent circuit of the Zener diode in the Zener region includes a small dynamic resistance and D.C. battery equal to the Zener potential, as shown in Fig. :

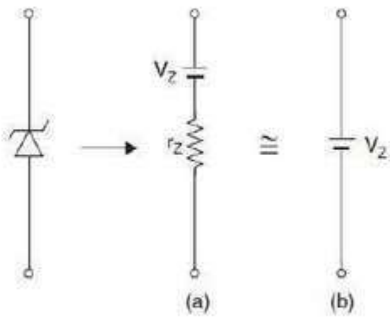


Fig. Zener equivalent circuit : (a) Complete ; (b) Approximately.

"ON" state. When reverse voltage across a Zener diode is equal to or more than breakdown voltage V_Z, the current increases very sharply. In this region curve is almost vertical ; it means that voltage across Zener diode is constant at V_Z even though the current through it changes. Therefore, in the breakdown region, an ideal Zener diode (this assumption is fairly reasonable as the impedance of Zener diode is *quite small in the breakdown region*) can be represented by a battery of voltage V_Z as shown in Fig. (*b*). Under such conditions, the Zener diode is said to be in the "ON" state.

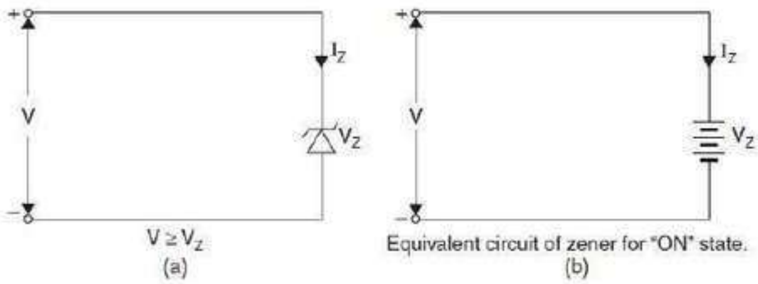
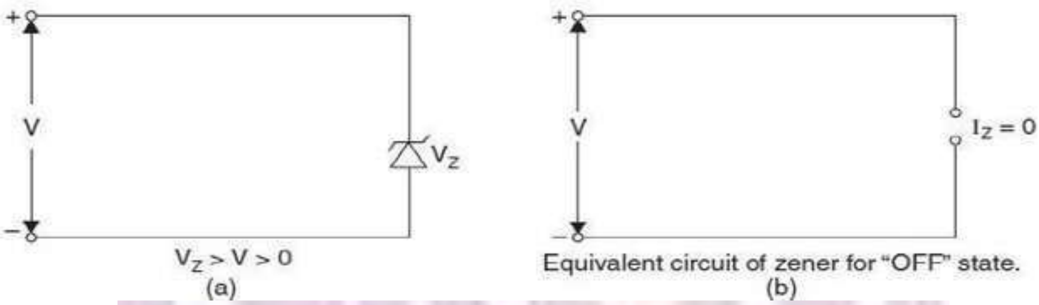


Fig.

"OFF" state. When the reverse voltage across the Zener diode is less than V_Z but greater than 0 V, the Zener diode is in the "OFF" stage. Under such conditions, the Zener diode can be represented by an open circuit as shown in Fig. (*b*).

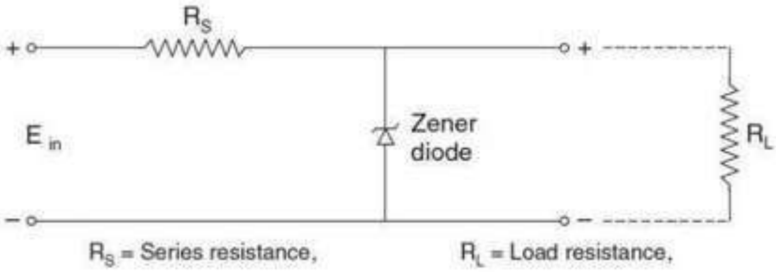


3.3. Applications of Zener Diode

Zener diode serves in the following variety of *applications* :

1. **Voltage reference or regulator element :**

The primary use of a zener diode is as a *voltage reference or regulator element*. Fig. 22 shows the fundamental circuit for the Zener diode employed as a shunt regulator. In the circuit, diode element and load R_L draw current through the series resistance R_S. If E_{in} increases, the current through the Zener element will increase and thus maintain an essentially fixed voltage across R_L. This ability to maintain the desired voltage is determined by the temperature coefficient and the diode impedance of the zener device.



R_S = Series resistance, R_L = Load resistance

Fig. 22. Basic Zener-diode regulator circuit.

2. **Shunt transistor regulator :**

The Zener diode may also be used to control the reference voltage of a transistor regulated power supply. An example of this in a shunt transistor regulator is shown in Fig. 23, where Zener element is used to control the operating point of the transistor. The advantage of this circuit over that shown in Fig. 22 are *increased power handling capability and a regulating factor improved by utilizing the current gain of the transistor.*

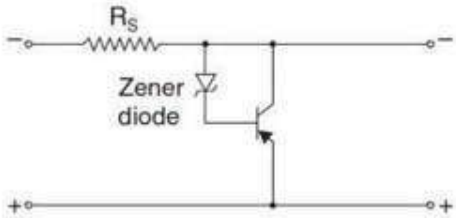


Fig. 23. Shunt transistor regulator.

3. **Audio or r-f applications :**

The Zener diode also finds use in audio or *r-f* (radio frequency) applications where a source of stable reference voltage is required, as in bias supplies. Frequently, *Zener diodes are connected in series package,* with, for example, one junction operating in the reverse within a single direction and possessing a positive temperature V_Z coefficient ; the remaining diodes are connected to operate in the forward direction and exhibit negative temperature V_Z coefficient characteristics. The net result

3.22. Zener Diode Regulator

The major application of zener diode in the electronic circuit is as a voltage regulator. It provides a constant voltage to the load from a source whose voltage may vary over sufficient range. The zener diode of zener voltage V_z is reverse connected across the load R_1 across which constant voltage is desired. A resistor R is connected in series with the circuit which absorbs the output voltage fluctuation so as to maintain constant voltage (V_0) across the load.

Let a variable voltage Vin be applied across the load R_1. When the value of Vin is less than zener voltage V_z of the zener diode. No current flows through it and the same voltage appears across the load. When the input voltage Vin is more than V_z this will cause the zener diode to conduct a large current I_z.

In the above discussion it has been seen that when a zener diode of zener voltage V_z is connected in reverse direction parallel to the load. It maintains a constant voltage across the load equal yp V_z and hence stablises the output voltage.

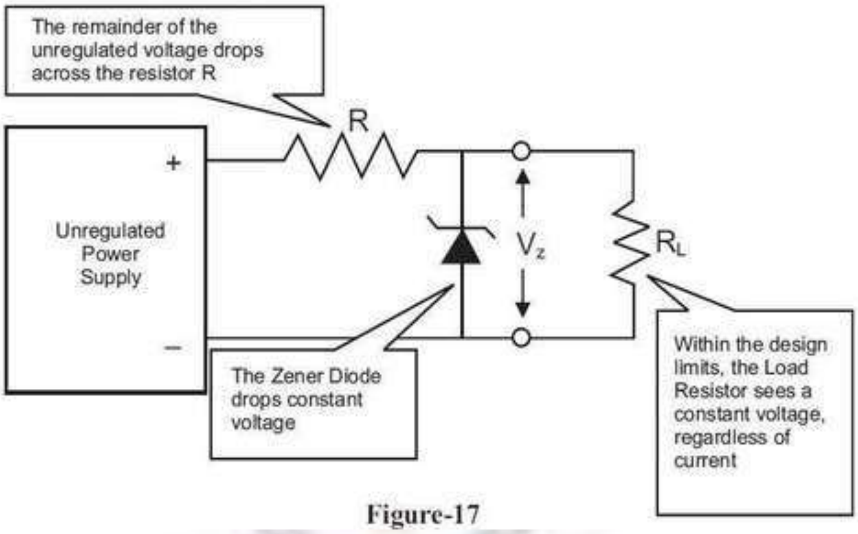


Figure-17

Example 4. *Determine the current flowing through the Zener diode for the circuit shown in Fig. 24, if R_L = 4000 Ω, input voltage is 50 volts, R_S = 1800 Ω and output voltage is 32 volts.*

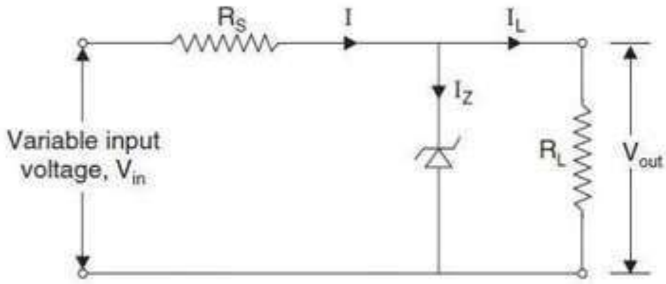


Fig. 24

Solution. Input voltage, V_{in} = 50 V

Output voltage, V_{out} = 32 V

Voltage drop in series resistor, $R_S = V_{in} - V_{out} = 50 - 32 = 18$ V

Current through series resistance, $I = \dfrac{V_{in} - V_{out}}{R} = \dfrac{18}{1800}$ = .01 A or 10 mA

Load current, $I_L = \dfrac{V_{out}}{R_L} = \dfrac{32}{4000}$ = 0.008 A or 8 mA

Current through Zener diode, $\mathbf{I_Z} = I - I_L = 10 - 8 =$ **2 mA. (Ans.)**

Example 5. *Determine the maximum and minimum values of Zener current if in the circuit shown in Fig. 24 the load resistance, R_L = 4000 Ω, series resistance = 8000 Ω, output voltage = 32 V and source voltage varies between 100 V and 128 V.*

Solution. Refer to Fig. 23. *Given :* R_L = 4000 Ω ; R = 8000 Ω ; V_{out} = 32 V ;

Load current, $I_L = \dfrac{V_{out}}{R_L} = \dfrac{32}{4000}$ = 0.008 A or 8 mA

The Zener current will be maximum when input voltage is maximum *i.e.*, 128 V

Corresponding current through series resistance,

$$I = \frac{V_{in(max)} - V_{out}}{R_S} = \frac{128 - 32}{8000} = 0.012 \text{ A or } 12 \text{ mA}$$

Corresponding Zener current, $(\mathbf{I_Z})_{\mathbf{max.}} = I - I_L = 12 - 8 =$ **4 mA. (Ans.)**

The Zener current will be minimum when input voltage is minimum *i.e.*, 100 V.

Corresponding, current through series resistance,

$$I' = \frac{V_{in(min)} - V_{out}}{R_S} = \frac{100 - 32}{8000} = 0.0085 = 8.5 \text{ mA}$$

Corresponding Zener current, $(\mathbf{I_Z})_{\mathbf{min.}} = I' - I_L = 8.5 - 8 =$ **0.5 mA. (Ans.)**

Example 6. *In the simple Zener-diode based voltage regulator shown in Fig. 25, a 5.6 V, 0.25 W Zener diode is used. For reliable operation, the minimum I_Z should be 1 mA. The load R_L varies between 20 Ω and 50 Ω. Find the range of R_S for reliable and safe operation of the voltage regulator.*

Solution. (*i*) Let R_S = 20 Ω

$$I = \frac{5.6}{20} = 0.28 \text{ A}$$

$$R_S = \frac{10 - 5.6}{0.28 + 0.001} = 15.66\ \Omega \approx 16\ \Omega.$$

(*ii*) Let, R_S = 50 Ω

$$I = \frac{5.6}{50} = 0.112 \text{ A}$$

$$R_S = \frac{10 - 5.6}{0.112 + 0.001} = 38.93\ \Omega \approx 39\ \Omega.$$

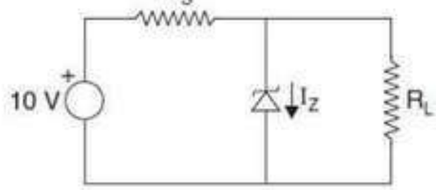


Fig. 25

∴ **R ranges from 16 Ω to 39 Ω. (Ans.)**

Diode Junction capacitance:

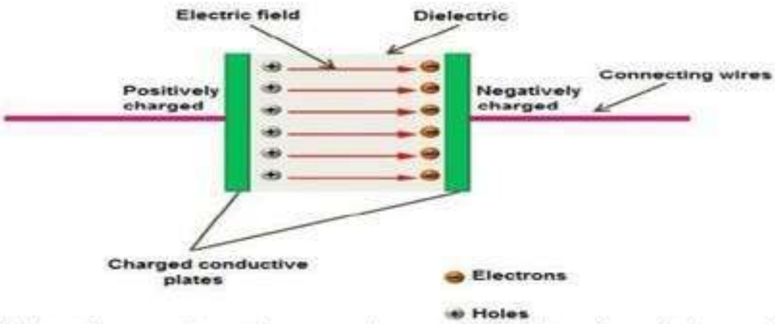
In a p-n junction diode, two types of capacitance take place. They are,

- Transition capacitance (C_T)
- Diffusion capacitance (C_D)

(a) Transition capacitance (C_T):

We know that capacitors store electric charge in the form of electric field. This charge storage is done by using two electrically conducting plates (placed close to each other) separated by an insulating material called dielectric.

The conducting plates or electrodes of the capacitor are good conductors of electricity. Therefore, they easily allow electric current through them. On the other hand, dielectric material or medium is poor conductor of electricity. Therefore, it does not allow electric current through it. However, it efficiently allows electric field.



When voltage is applied to the capacitor, charge carriers starts flowing through the conducting wire. When these charge carriers reach the electrodes of the capacitor, they experience a strong opposition from the dielectric or insulating material. As a result, a large number of charge carriers are trapped at the electrodes of the capacitor. These charge carriers cannot move between the plates. However, they exerts electric field between the plates. The charge carriers which are trapped near the dielectric material will stores electric charge. The ability of the material to store electric charge is called capacitance.

In a basic capacitor, the capacitance is directly proportional to the size of electrodes or plates and inversely proportional to the distance between two plates.

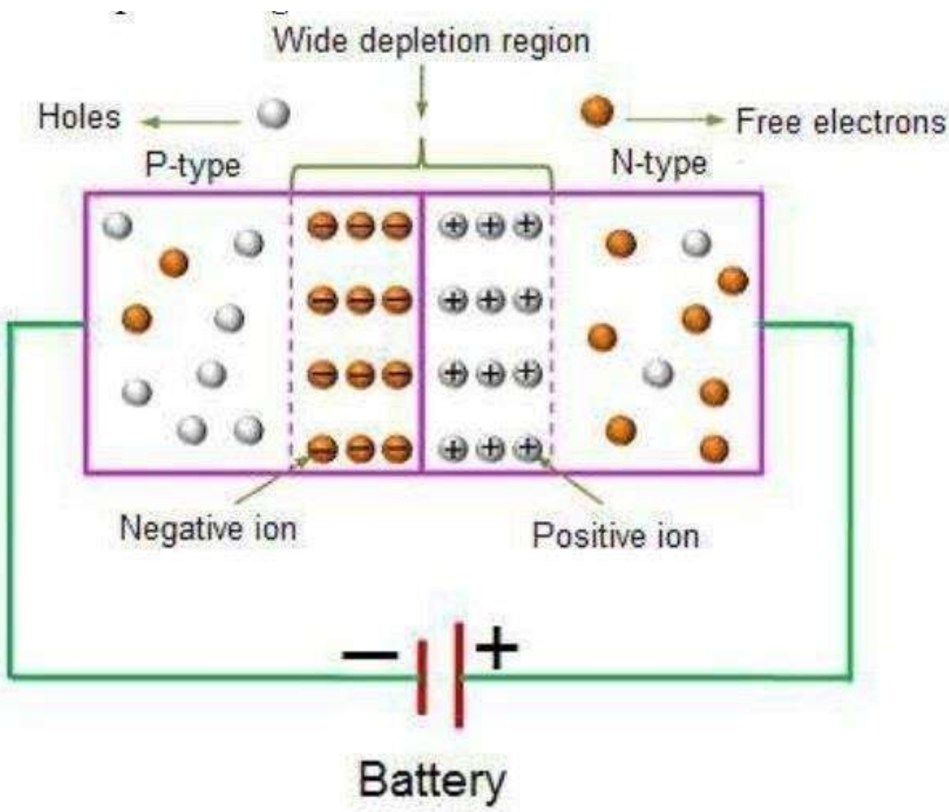
Just like the capacitors, a reverse biased p-n junction diode also stores electric charge at the depletion region. The depletion region is made of immobile positive and negative ions.

In a reverse biased p-n junction diode, the p-type and n-type regions have low resistance. Hence, p-type and n-type regions act like the electrodes or conducting plates of the capacitor. The depletion region of the p-n junction diode has high resistance. Hence, the depletion region acts like the dielectric or insulating material. Thus, p-n junction diode can be considered as a parallel plate capacitor.

In depletion region, the electric charges (positive and negative ions) do not move from one place to another place. However, they exert electric field or electric force. Therefore, charge is stored at the depletion region in the form of electric field. The ability of a material to store electric charge is called capacitance. Thus, there exists a capacitance at the depletion region.

The capacitance at the depletion region changes with the change in applied voltage. When reverse bias voltage applied to the p-n junction diode is increased, a large number of holes(majority carriers) from p-side and electrons (majority carriers) from n-side are moved away from the p-n junction. As a result, the width of depletion region increases whereas the size of p-type and n-type regions (plates) decreases.

We know that capacitance means the ability to store electric charge. The p-n junction diode with narrow depletion width and large p-type and n-type regions will store large amount of electric charge whereas the p-n junction diode with wide depletion width and small p-type and n-type regions will store only a small amount of electric charge. Therefore, the capacitance of the reverse bias p-n junction diode decreases when voltage increases.



In a forward biased diode, the transition capacitance exist. However, the transition capacitance is very small compared to the diffusion capacitance. Hence, transition capacitance is neglected in forward biased diode.
The amount of capacitance changed with increase in voltage is called transition capacitance. The transition capacitance is also known as depletion region capacitance, junction capacitance or barrier capacitance. Transition capacitance is denoted as C_T.

The change of capacitance at the depletion region can be defined as the change in electric charge per change in voltage.

$$C_T = dQ / dV$$

Where,

C_T = Transition capacitance
dQ = Change in electric charge
dV = Change in voltage

The transition capacitance can be mathematically written as,

$$C_T = \varepsilon A / W$$

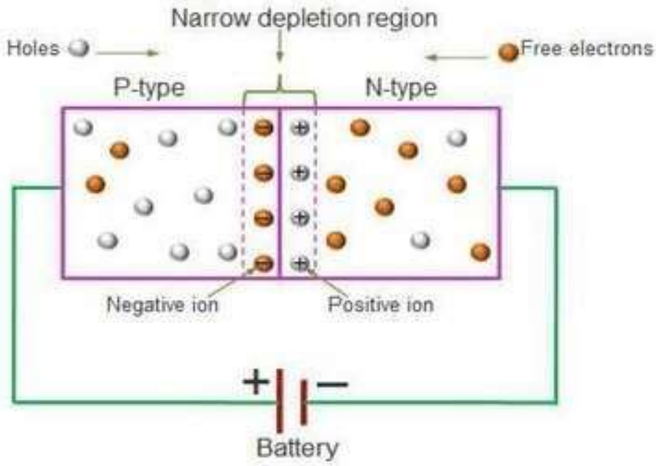
Where,

ε = Permittivity of the semiconductor
A = Area of plates or p-type and n-type regions
W = Width of depletion region

Diffusion capacitance (C_D):

Diffusion capacitance occurs in a forward biased p-n junction diode. Diffusion capacitance is also sometimes referred as storage capacitance. It is denoted as C_D.
In a forward biased diode, diffusion capacitance is much larger than the transition capacitance. Hence, diffusion capacitance is considered in forward biased diode.
The diffusion capacitance occurs due to stored charge of minority electrons and minority holes near the depletion region.

When forward bias voltage is applied to the p-n junction diode, electrons (majority carriers) in the n-region will move into the p-region and recombines with the holes. In the similar way, holes in the p-region will move into the n-region and recombines with electrons. As a result, the width of depletion region decreases.



The electrons (majority carriers) which cross the depletion region and enter into the p-region will become minority carriers of the p-region similarly; the holes (majority carriers) which cross the depletion region and enter into the n-region will become minority carriers of the n-region.

The accumulation of holes in the n-region and electrons in the p-region is separated by a very thin depletion region or depletion layer. This depletion region acts like dielectric or insulator of the capacitor and charge stored at both sides of the depletion layer acts like conducting plates of the capacitor.
Diffusion capacitance is directly proportional to the electric current or applied voltage. If large electric current flows through the diode, a large amount of charge is accumulated near the depletion layer. As a result, large diffusion capacitance occurs.
In the similar way, if small electric current flows through the diode, only a small amount of charge is accumulated near the depletion layer. As a result, small diffusion capacitance occurs.
When the width of depletion region decreases, the diffusion capacitance increases. The diffusion capacitance value will be in the range of nano farads (nF) to micro farads (μF).
The formula for diffusion capacitance is

$$C_D = dQ / dV$$

Where,

C_D = Diffusion capacitance
dQ = Change in number of minority carriers stored outside the depletion region
dV = Change in voltage applied across diode

4.5 HALFWAVERECTIFIERS

Rectifiers are the circuits used to convert alternating current (AC) into direct current (DC). Half-WaveRectifiersaredesignedusingadiode(D)andaloadresistor(R_L)asshowninFigure1.Intheserectifiers, only one-half of the input waveform is obtained at the output i.e. the output will compriseof either positive pulses or the negative pulses only. The polarity of the output voltage so obtained(across R_L) depends on the direction of the diode used in the circuit of half-wave rectifier. This isevident from the figure as Figure 1a shows the output waveform consisting of only positive pulseswhiletheFigure1bhasonlynegativepulsesinitsoutputwaveform.

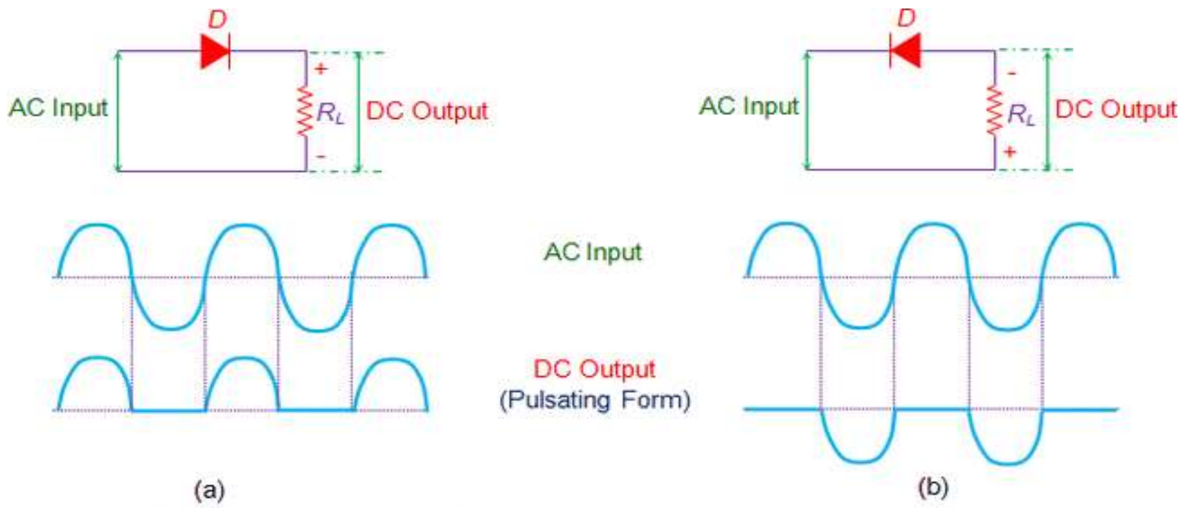


Figure 1 Half Wave Rectifier with Input and Output Waveforms

This is because, in Figure 1a the diode gets forward biased only during the positive pulseoftheinputwhichcausesthecurrenttoflowacrossR_L,producingthe outputvoltage.

Furtherforthesamecase,iftheinputpulsebecomesnegative,thenthediodewillbereversebiasedand hence there will be no current flow and no output voltage. Similarly for the circuit shown inFigure1b,thediodewillbeforwardbiasedonlywhentheinput pulseisnegative, andthustheoutputvoltagewillcontainonlythenegativepulses.Furtheritistobenotedthattheinputtothehalf-waverectifier can be supplied even via the transformer. This is advantageous as the transformer providesisolationfromthepowerlineaswellashelpsinobtainingthe desiredlevelofDCvoltage.Next,onecan connect a capacitor across the resistor in the circuit of half wave rectifier to obtain a smootherDC output (Figure 2). Here the capacitor charges through the diodeD during the positive pulse oftheinputwhileitdischargesthroughtheloadresistor$R_L$whentheinputpulsewillbenegative.Thustheoutputwaveformofsucharectifierwillhaveripplesinitasshowninthefigure.

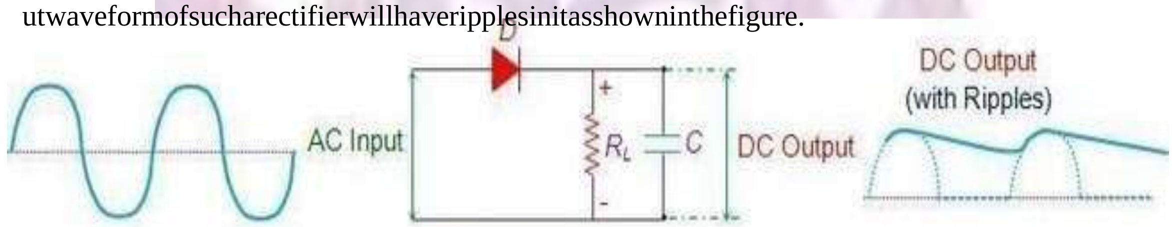


Figure 2 Half-Wave Rectifier with a RC Filter

Differentparametersassociated withthehalfwaverectifiersare

1. **PeakInverseVoltage(PIV):**Thisisthemaximumvoltagewhichshouldbewithstoodbythediodeunderreversebiasedconditionandisequaltothepeakoftheinputvoltage,Vm.
2. **AverageVoltage:**ThisistheDCcontentofthevoltageacrosstheloadandisgivenbyVm/π.Similarly DCcurrentisgivenasIm/π,whereImisthemaximumvalueofthecurrent.

3. **Ripple Factor (r):** It is the ratio of root mean square (rms) value of AC component to the DCcomponentintheoutputandisgivenby

$$r = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

Further,forhalf-waverectifier,rmsvoltageisgivenasVm/2whichresultsintheripplefactorof1.21.

4. **Efficiency:**Itis theratioofDCoutputpowertotheACinputpowerandisequalto40.6%.
5. **TransformerUtilizationFactor:**ItistheratioofDCpowerdeliveredtotheloadtotheACratingof thetransformersecondaryandisequalto0.287.

6. **FormFactor:**Thisistheratioofrmsvaluetotheaveragevalueandisthusequalto 1.57forhalf-waverectifier.
7. **PeakFactor:**Itistheratioofpeakvaluetothermsvalueandisequalto2.

Half wave rectifiers are advantageous as they are cheap, simple and easy to construct. These are quiterarely used as they have high ripple content in their output. However they can be used in non-criticalapplications like those of charging the battery. They are also less preferred when compared to otherrectifiers as they have low output power, low rectification efficiency and low transformer utilizationfactor. In addition, if AC input is fed via the transformer, then it might get saturated which inturn resultsin magnetizing current, hysteresis loss and/or result in the generation of harmonics. Lastly it is importantto note that the explanation provided here applies only for the case where the diode is ideal. Althoughfor a practical diode, the basic working remains the same, one will have to consider the voltage dropacross thediodeaswellasitsreversesaturationcurrentintoconsiderationduringtheanalysis.

4.6 CENTRETAPFULLWAVERECTIFIERS

The circuits which convert the input alternating current (AC) into direct current (DC) are referred toasrectifiers.Ifsuchrectifiersrectifyboththepositiveaswell asnegativepulsesoftheinputwaveform,then they are called Full-Wave Rectifiers. Figure 1 shows such a rectifier designed usinga multiplewinding transformer whose secondary winding is equally divided into two parts with a provision forthe connection at its central point (and thus referred to as the centre-tapped transformer), two diodes(D_1andD_2)andaloadresistor(R_L).HeretheACinputisfedtotheprimarywindingofthetransformerwhile an arrangement of diodes and the load resistor which yields the DC output, is made across itssecondaryterminals.

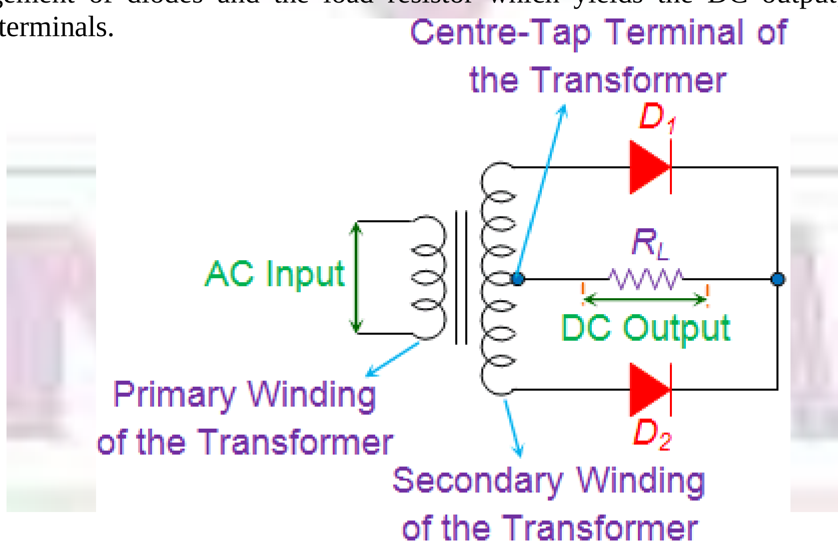


Figure 1 Full Wave Rectifier

The circuit can be analyzed by considering its working during the positive and the negative inputpulsesseparately.

Figure 2a shows the case where the AC pulse is positive in nature i.e. the polarity at the top of theprimarywindingispositivewhileitsbottomwillbenegativeinpolarity.Thiscausesthetoppartof thesecondarywindingtoacquireapositivechargewhilethecommoncentre-tapterminalofthetransformerwillbecomenegate

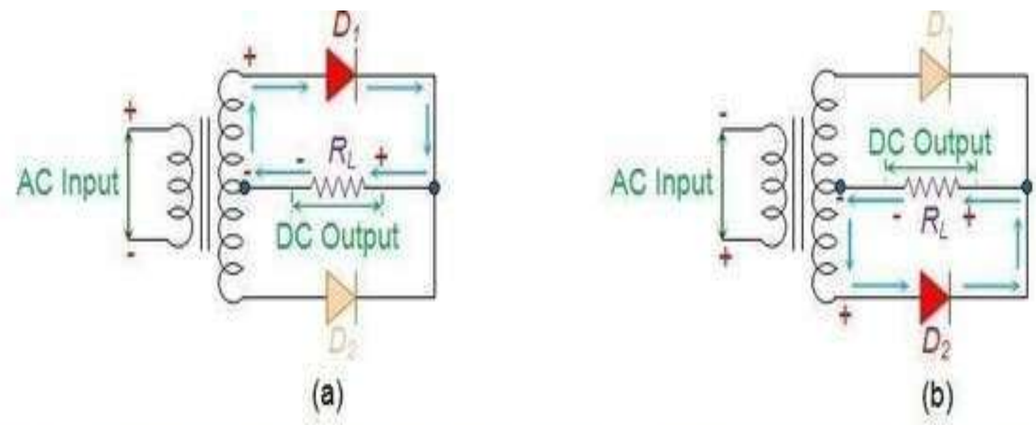


Figure 2 Conduction Path of Full Wave Rectifier for (a) Positive Input Pulse (b) Negative Input Pulseve.

This causes the diode D_1 to be forward biased which inturn causes the flow of current through R_L alongthe direction shown in Figure 2a. However at the same time, diode D_2 will be reverse biased and henceacts like an open circuit. This causes the appearance of positive pulse across the R_L, which will be theDCoutput.Next,iftheinputpulsebecomesnegativeinnature,thenthetopandthebottomoftheprimarywindi ng will acquire the negative and the positive polarities respectively. This causes the bottom of thesecondary winding to become positive while its centre-tapped terminal will become negative. Thus thediode D_2 gets forward biased while the D_1 will get reverse biased which allows the flow of current asshown in the Figure 2b. Here the most important thing to note is the fact that the direction in which thecurrent flowsvia$R_L$willbeidenticalineithercase(bothforpositiveaswellasfornegativeinput pulses).Thuswegetthepositiveoutput pulseevenforthecaseofnegativeinputpulse(Figure3),whichindicatesthatboththehalfcyclesoftheinputACare rectified.

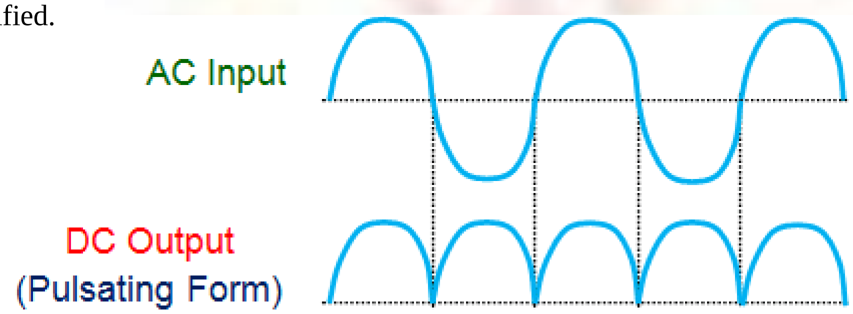


Figure 3 Input and Output Waveforms of Full Wave Rectifier

Such circuits are referred to as (i) Centre-Tapped **Full Wave Rectifiers** as they use a centre-tappedtransformer,(ii)Two-DiodeFull-WaveRectifiers becauseoftheuseoftwodiodesand/or(iii)Bi-PhaseCircuits due to the fact that in these circuits, the output voltage will be the phasor addition of thevoltages developed across the load resistor due to two individual diodes, where each of them conductsonly for a particular half-cycle. However as evident from Figure 3, the output of the rectifieris not pureDC but pulsating in nature, where the frequency of the output waveform is seen to be double of that atthe input. In order to smoothen this, one can connect a capacitor across the load resistor as shown bythe Figure 4. This causes the capacitor to charge via the diode D_1 as long as the input positive pulseincreases in its magnitude. By the time the input pulse reaches the positive maxima, the capacitor wouldhavechargedtothesame magnitude.Next,aslongastheinputpositivepulsekeeps decreasing,thecapacitortriestoholdthechargeacquired(beinganenergy-storageelement).

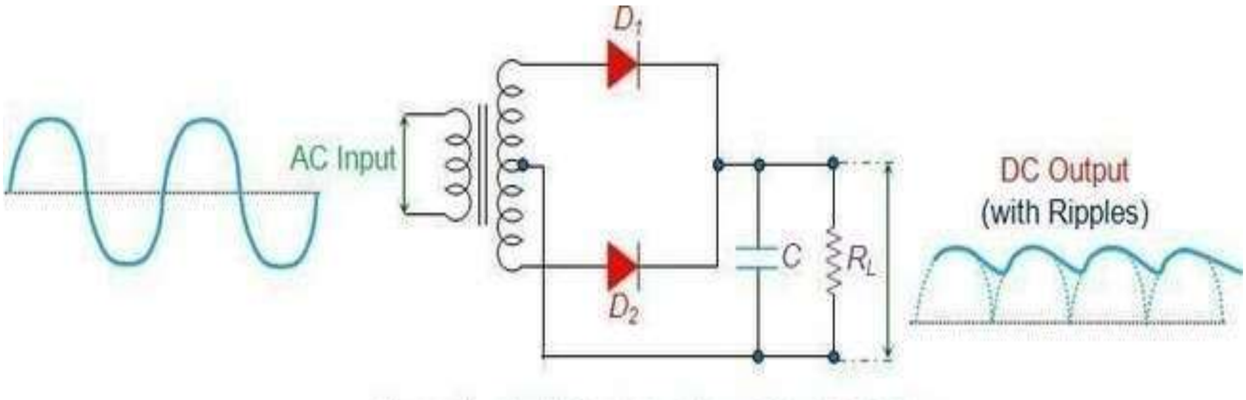


Figure 4 Full-Wave Rectifier with a RC Filter

Howevertherewillbevoltage-lossassomeamountofchargegetslostthroughthepathprovidedbythe load resistor (nothing but discharging phenomenon). Further, as the input pulse starts to go lowtoreachthenegativemaxima,thecapacitoragainstartstochargeviathepathprovidedbythediodeD_2 and acquires an almost equal voltage but with opposite polarity. Next, as the input voltage startsto move towards 0V, the capacitor slightly discharges via R_L. This charge-discharge cycle of thecapacitor causes the ripples to appear in the output waveform of the full-wave rectifier with RC filterasshowninFigure4.

Differentparametersandtheirvaluesforthecentre-tappedfull-waverectifiersare

1. **Peak Inverse Voltage (PIV):** This is the maximum voltage which occurs across the diodeswhentheyarereversebiased.Hereitwillbeequaltotwicethepeakoftheinputvoltage,$2V_m$.
2. **Average Voltage:** It is the DC voltage available across the load and is equal to $2V_m/\pi$. ThecorrespondingDCcurrentwillbe$2I_m/\pi$,whereIisthemaximumvalueofthecurrent.
3. **Ripple Factor (r):** This is the ratio of the root mean square (rms) value of AC component to thedc component at the output. It is given by and will be equal to 0.482 as the rms voltage for a full-waverectifierisgivenas

$$r = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

$$V_m/\sqrt{2}$$

4. **Efficiency:**ThisistheratioofDCoutput powertotheACinputpowerandisequalto81.2%.
5. **Transformer Utilization Factor (TUF):** This factor is expressed as the ratio of DC powerdeliveredtotheloadtotheAC ratingofthetransformersecondary.Forthefull-waverectifierthiswillbe0.693.
6. **FormFactor:**Thisistheratioofrmsvaluetotheaveragevalueandisequalto1.11.
7. **Peak Factor:** It is the ratio of peak value to the rms value and is equal to √2 for the full-waverectifiers.

Further it is to be noted that the two-diode full-wave rectifier shown in Figure 1 is costly and bulkyinsizeasitusesthecomplexcentre-tappedtransformerinitsdesign.Thusonemayresorttoanothertype of full-wave rectifier called Full-Wave Bridge Rectifier (identical to Bridge Rectifier) whichmight or might not involve the transformer (even if used, will not be as complicated as a centre-tapone). It also offers higher TUF and higher PIV which makes it ideal forhigh power applications.However it is to be noted that the full wave bridge rectifier uses four diodes instead of two, whichin turn increases the magnitude of voltage drop across the diodes, increasing the heating loss. **Fullwave rectifiers** are used in general power supplies, to charge a battery and to provide power to thedevices like motors, LEDs, etc. However due to the ripple content in the outputwaveform,theyarenot preferred for audio applications. Further these are advantageous when compared to half-wave rectifiersas they have higher DC output power, higher transformer utilization factor and lower ripple content,which can be made more smoother by using π-filters. All these merits mask-up its demerit of beingcostly in comparison to the half-wave rectifiers due to the use of increased circuit elements. At last, itis to be noted that the explanation provided here considers the diodes to be ideal in nature. So, incaseof practical diodes, one will have to consider the voltage drop across the diode, its reverse saturationcurrent and other diode characteristics into account and reanalyze the circuit. Nevertheless the basicworkingremainsthesame.

4.10FULLWAVEBRIDGERECTIFIERS

BridgeRectifiersarethecircuitswhichconvert alternatingcurrent(AC)intodirectcurrent(DC)usingthe diodes arranged in the bridge circuit configuration. They usually comprise of four or more numberof diodes which cause the output generated to be of the same polarity irrespective of the polarity at theinput. Figure 1 shows such a bridge rectifier composed of four diodes D_1, D_2, D_3 and D_4 in which theinputissuppliedacrosstwoterminalsAandBinthefigurewhiletheoutputiscollectedacrosstheloadresistor $R_L$connectedbetweentheterminalsCandD.

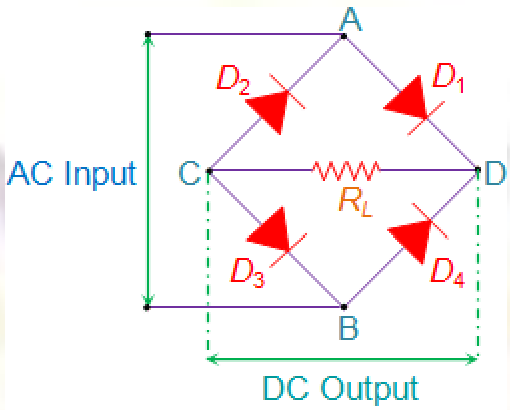


Figure 1 Bridge Rectifier

NowconsiderthecasewhereinthepositivepulseappearsattheACinputi.e. theterminalAispositivewhiletheterminalBisnegative.ThiscausesthediodesD1andD3togetforwardbiasedandatthesametime,thediodesD_2andD_4willbereversebiased.

Asaresult,thecurrentflowsalongtheshort-circuitedpathcreatedbythediodesD_1andD_3(consideringthe diodes to be ideal), as shown by Figure 2a. Thus the voltage developed across the load resistor $R_L$will be positive towards the end connected to terminal D and negative at the end connected to theterminalC.

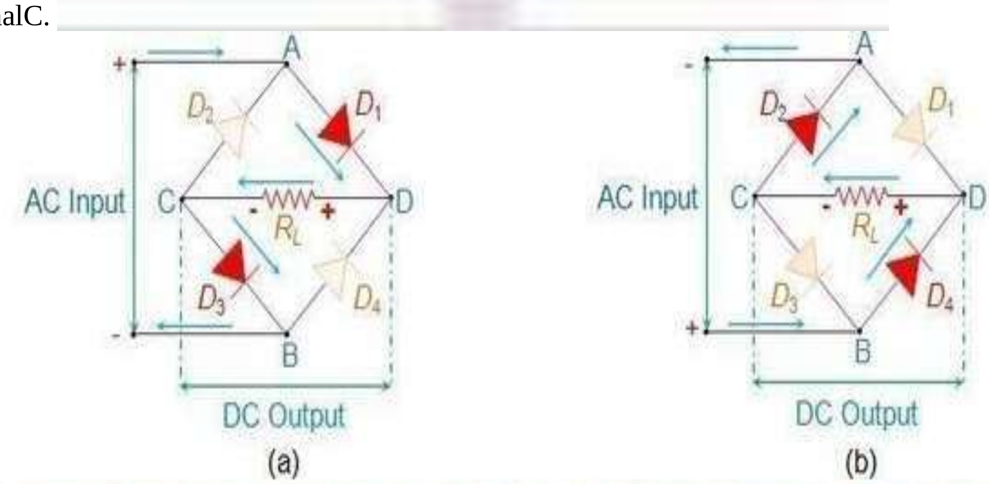


Figure 2 Current Path Through the Bridge Rectifier for (a) Positive half-cycle (b) Negative Half-Cycle

Next if the negative pulse appears at the AC input, then the terminals A and B are negative and positiverespectively.This forwardbiasesthediodesD_2andD_4, whilereversebiasingD_1andD_3whichcauses thecurrent to flow in the direction shown by Figure 2b. At this instant, one has to note that the polarity ofthe voltage developed across R_L is identical to that produced when the incoming AC pulse was positiveinnature.Thismeansthatforbothpositiveandnegativepulse,theoutputofthebridgerectifierwillbe

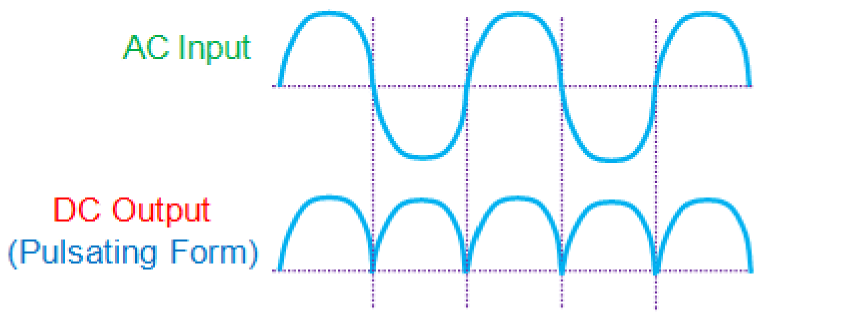


Figure 3 Input-Output Waveforms of a Bridge Rectifier

identicalinpolarityasshownbythe waveformsinFigure3.

Howeveritistobenotedthatthebridgerectifier'sDCwillbepulsatinginnature.Inordertoobtainpureformof DC,onehastousecapacitorinconjunctionwiththebridgecircuit(Figure4).

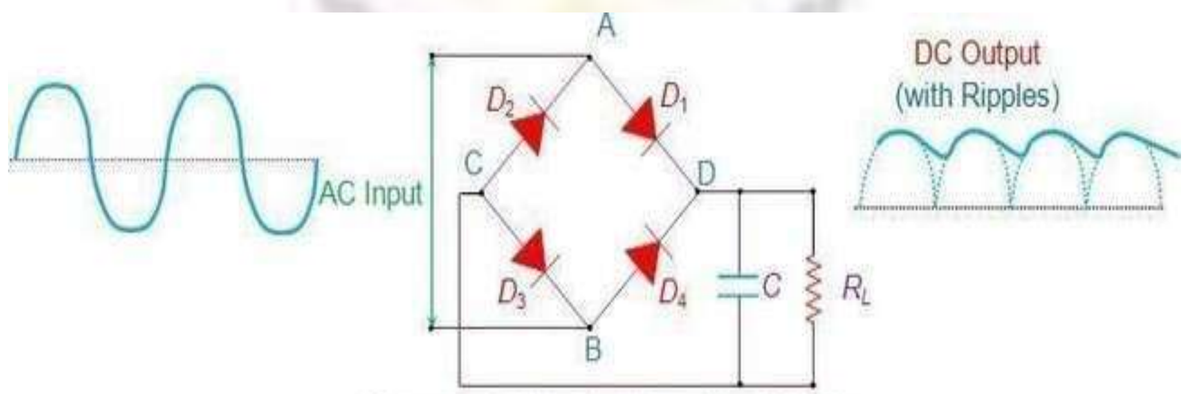


Figure 4 Bridge Rectifier with a RC Filter

In this design, the positive pulse at the input causes the capacitor to charge through the diodes D_1 andD_3. Howeveras the negative pulse arrives at the input, the charging action of the capacitorceases andit starts to discharge via R_L. This results in the generation of DC output which will have ripples in it asshown in the figure. This ripple factor is defined as the ratio of AC component to the DC component inthe output voltage. In addition, the mathematical expression for the ripple voltage is given by theequation

$$V_r = \frac{I_l}{fC}$$

Where,$V_r$representstheripplevoltage.

$I_l$representstheloadcurrent.

frepresentsthefrequencyoftheripple whichwillbetwicetheinputfrequency.CistheCapacitance.

Further, the **bridge rectifiers** can be majorly of two types, viz., Single-Phase Rectifiers and Three-Phase Rectifiers. In addition, each of these can be either Uncontrolled or Half-Controlled or Full-Controlled. Bridge rectifiers for a particular application are selected by considering the load currentrequirements. These bridge rectifiers are quite advantageous as they can be constructed with or withoutatransformerandare suitableforhighvoltageapplications.Howeverhere twodiodeswillbeconducting for every half-cycle and thus the voltage drop across the diodes will be higher. Lastly onehastonotethat apartfromconvertingACtoDC,**bridgerectifiers**arealsousedtodetect theamplitudeofmodulatedradiosignalsandtosupplypolarizedvoltageforweldingapplications.

3.23.1. Filters Circuit

An electronic circuit or device which blocks the a.c. components but allows the d.c. components of the rectifiers to pass to the load is called a filter circuit.

Types of filter circuit:-

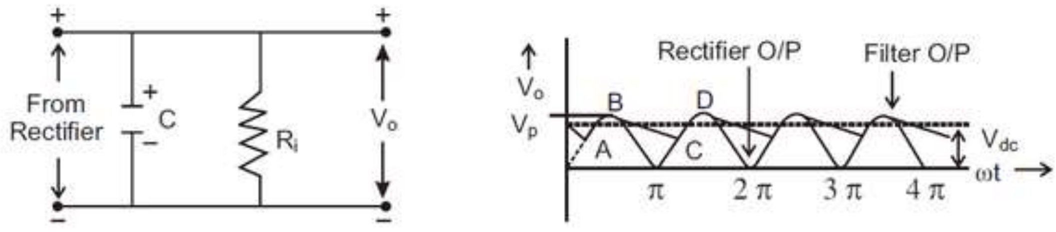
(i) Shunt Capacitor Filter

(ii) Series Inductor Filter

(iii) Choke Input (LC) Filter

(iv) Capacitor Input (pi) Filter

(i) Shunt Capacitor Filter



a) Capacitor Filter b) Waveform

Figure-18

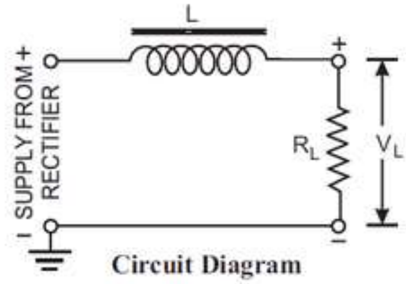
Working

The working of a shunt capacitor filter can be explained with the help of a wave diagram shown in fig.18 the dotted pulsating wave shows the output of a full wave rectifier. When the rectifier voltage is increasing the capacitor is charged to +Vm. at point b the rectifier voltage tries to fall but the charged capacitor immediately tries to send the current back to rectifier. In the process the rectifier diodes are reverse biased and stop giving supply to the load. Thus the capacitor discharges (B to C) through the load. The capacitor continues to discharge until the source voltage becomes more than the capacitor voltage. The diode again starts conducting and the capacitor is again charged to peak value +Vm (point). During this time the rectifier supplies the charging current I and the load current.

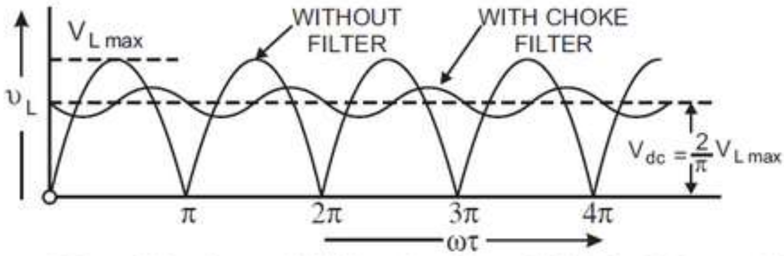
From above it is clear that capacitor not only remove the a.c. component but also improves the output voltage. The smoothless and magnitude of output voltage depends upon the time constant CR. The longer the time period the steadier is the output voltage. This can be achieved by using a large value of capacitor.

However the maximum value of the capacitance that can be employed is limited by the current that can be safely handled by the diode. The diodes employed in the rectifier circuit can deliver maximum current as per their rating. Therefore the size of the capacitor has to be limited so that it may not draw current more than the rating of the diodes.

(ii) Series Inductor Filter



Circuit Diagram



Output Voltage Waveforms Full-Wave Rectifier with Series Inductor Filter
Figure-19

A series inductor filter is shown. In this case an inductor is just connected in series with load. The inductor has the inherent property to oppose the change of current. This property of inductor utilised here to suppress the a.c. component (ripples) from the output of the rectifier.

The reactance (X=2 pi fL) of the inductor is large for high frequencies and offers more opposition to them but it allows the d.c. component of the rectifier output. Hence an inductance blocks the a.c. components but allows the d.c. components to reach the load. Thus it smooths out the rectifier output as shown fig.-19.

(iii) Choke Input LC Filter

A choke input LC filter is shown fig.-20. In this case an inductor is connected in series and a capacitor is parallel with the load.

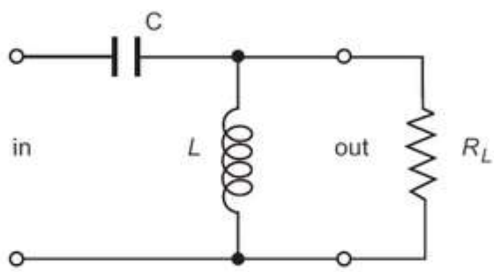
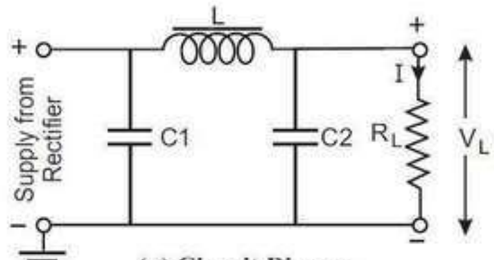


Figure-20

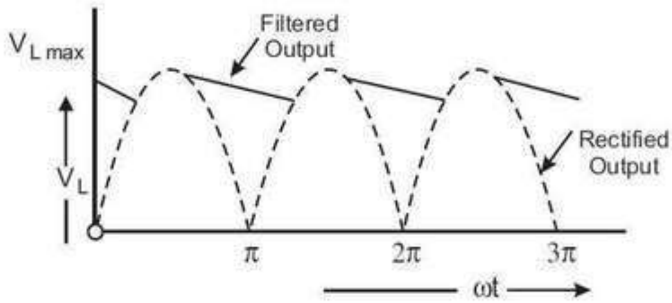
The output of a full wave rectifier contains a.c. components of a fundamental frequencies 100 Hz. The inductor offers a high opposition to the a.c component and blocks it but allows the d.c. component to pass through the low reactance of the capacitor. Hence almost pure d.c. reaches at the load. Although the output of this filter is almost d.c. but still it contains small a.c. component. To improve it further one or more sets of LC filter may be applied further.

(iv) Capacitor Input (PIE) Filter

A capacitor input filter is shown fig.-21(a). In this case an additional capacitor C, is connected in the beginning across the output terminals of the rectifier. Since its shape is like the Greek letter (PIE) it is named as pie rectifier.



(a) Circuit Digram



(b) Rectified and Filtered Output Voltage Waveform Full-Wave Rectifier with Capacitor Input Filter
Figure-21

The filter action of three components C1,L and C2 is described below:

(I) **Action of C1:** It provides an easy path to the a.c. components and by pass it and blocks d.c. components which continues its journey through the inductor choke. It also increases the magnitude of Vav because of its charging and discharging action.

(II) **Action of L:** It provides an easy path to d.c. component but blocks the a.c. components because of its high reactance.

(III) **Action of C2:** Any a.c component which the inductor has failed to block is by passed by this capacitor and only pure d.c. appears across the load.

UNITV

BIPOLARJUNCTIONTRANSISTORANDJFET

5.1 INTRODUCTION

- Thetransistorwasinvented in1947byJohnBardeen,WalterBrattainandWilliamShockleyatBellLaboratoryinAmerica.Atransistorisasemiconductordevice,commonlyusedas anAmplifieroranelectricallyControlledSwitch.

- Therearetwotypesoftransistors:

1) UnipolarJunctionTransistor
2) BipolarJunctionTransistor

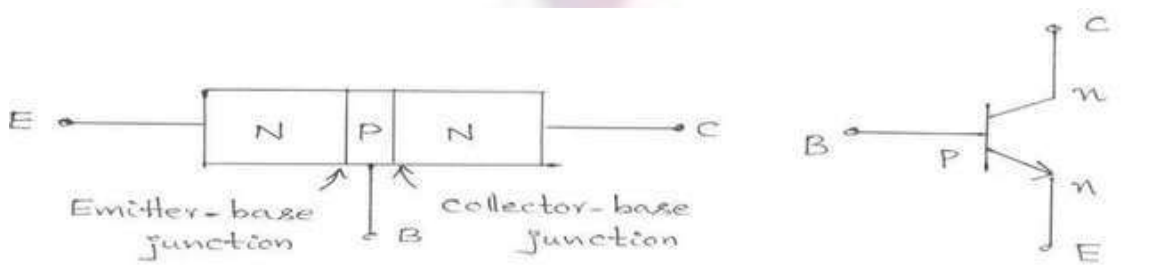
- In Unipolar transistor, the current conduction is only due to one type of carriers i.e.,majority charge carriers. The current conduction in bipolar transistor is because of boththetypesofchargecarriersi.e.,holesandelectrons.Henceitiscalled asBipolarJunctionTransistoranditis referredtoasBJT.

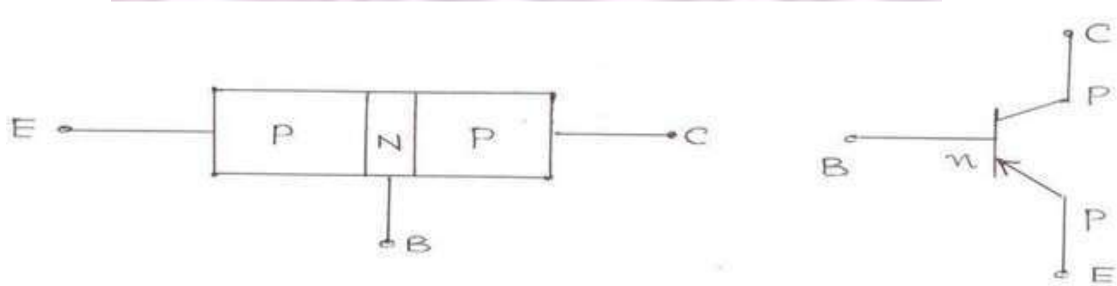
- BJT is a semiconductor device in which one type of semiconductor material is sandwitched between two opposite types of semiconductor i.e., an n-type semiconductor issandwichedbetweentwop-typesemiconductorsorap-typesemiconductorissandwichedbetweentwon-typesemiconductor.

- HencetheBJTsareoftwotypes.Theyare:

1) n-p-nTransistor
2) p-n-pTransistor

ThetwotypesofBJTsareshowninthefigurebelow.





- The arrow head represents the conventional current direction from p to n. Transistor hasthreeterminals.

1)Emitter 2)Base 3)Collector

- Transistorhastwop-njunctions.Theyare:
1) Emitter-BaseJunction
2) Collector-BaseJunction

Emitter: Emitterisheavilydopedbecauseitistoemitthechargecarriers.

Base: The charge carriers emitted by the emitter should reach collector passing through thebase. Hence base should be very thin and to avoid recombination, and to provide morecollectorcurrentbaseislightlydoped.
Collector: Collector has to collect the most of charge carriers emitted by the emitter. Hencetheareaofcrosssectionofcollectorismorecomparedtoemitteranditismoderatelydoped.

Transistorcanbeoperatedinthreeregions.
1) Activeregion.
2) Saturationregion.
3) Cut-Offregion.

ActiveRegion: Forthetransistortooperateinactiveregionbasetoemitterjunctionis forwardbiasedandcollectortobasejunctionis reversebiased.

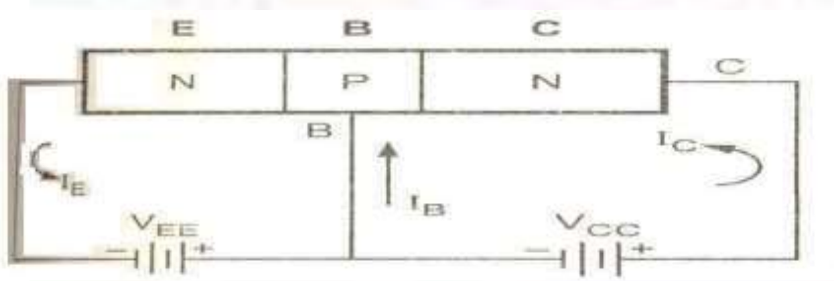
Saturation Region: Transistor to be operated in saturation region if both the junctions i.e.,collectortobasejunctionandbasetoemitterjunctionareforwardbiased.

Cut-Off Region: For the transistor to operate in cut-off region both the junctionsi.e., basetoemitterjunctionandcollectortobasejunctionarereversebiased.

Transistorcanbeusedas
1)Amplifier2)Switch
Forthetransistortoactasanamplifier,itshouldbeoperatedinactiveregion.Forthetransistorto act as a switch, it should be operated in saturation region for ON state, and cut- off regionforOFFstate.

5.2 TRANSISTOROPERATION:

Workingof aN-P-NTransistor:

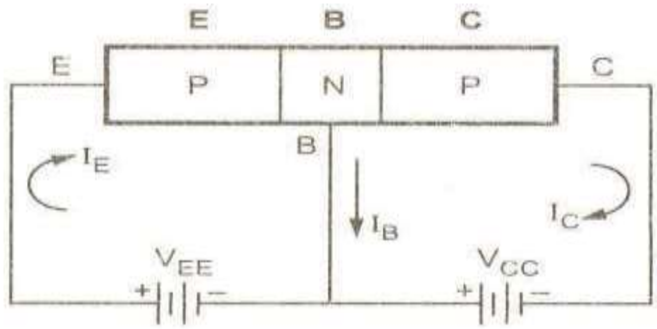


The n-p-n transistor with base to emitter junction forward biased and collector base junctionreversebiasedis asshowninfigure.
As the base to emitter junction is forward biased the majority carriers emitted by the n typeemitter i.e., electrons have a tendency to flow towards the base which constitutes the emitterCurrent I_E. As the base is p-type there is chance of recombination of electrons emitted by theemitter with the holes in the p-type base. But as the base is very thin and lightly doped

onlyfewelectronsemittedbythen-typeemitterlessthan5%combineswiththeholes inthep-typebase, the remaining more than 95% electrons emitted by the n-type emitter cross over into thecollectorregionconstitutethecollectorcurrent.

Thecurrentdistributionsareasshowninfig$I_E=I_B+I_C$

WorkingofaP-N-PTransistor:



The p-n-p transistor with base to emitter junction is forward biased and collector to basejunction reverse biased is as show in figure. As the base to emitter junction is forward biasedthe majority carriers emitted by the type emitter i.e., holes have a tendency to flow towards thebase which constitutes the emitter current IE. As the base is n-type there is a chance ofrecombination of holes emitted by the emitter with the electrons in the n-type base.Butasthebaseusverythinandlightlydopedonly fewelectronslessthan5%combinewiththeholesemitted by the p-type emitter, theremaining 95% charge carriers cross over into the collectorregiontoconstitutethecollectorcurrent.Thecurrentdistributionsareshown infigure.

$$I_E=I_B+I_C$$

5.1 TRANSISTORCIRCUITCONFIGURATIONS:

Followingarethethreetypesoftransistorcircuitconfigurations:

1) Common-Base(CB)
2) Common-Emitter(CE)
3) Common-Collector(CC)

Here the term ‘Common’ is used to denote the transistor lead which is common to the input and outputcircuits. The common terminal is generally grounded.It should be remembered that regardless the circuitconfiguration,theemitterisalwaysforward-biasedwhilethecollectorisalwaysreverse-biased.

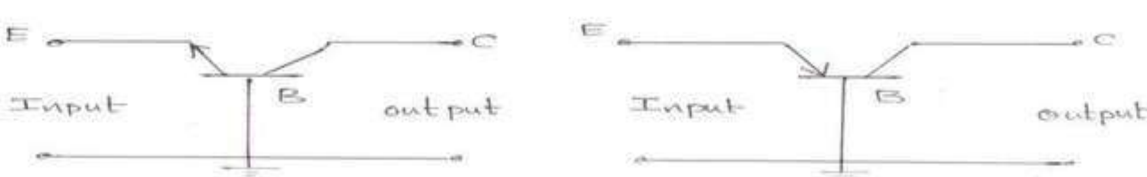


Fig. Common–BaseConfiguration

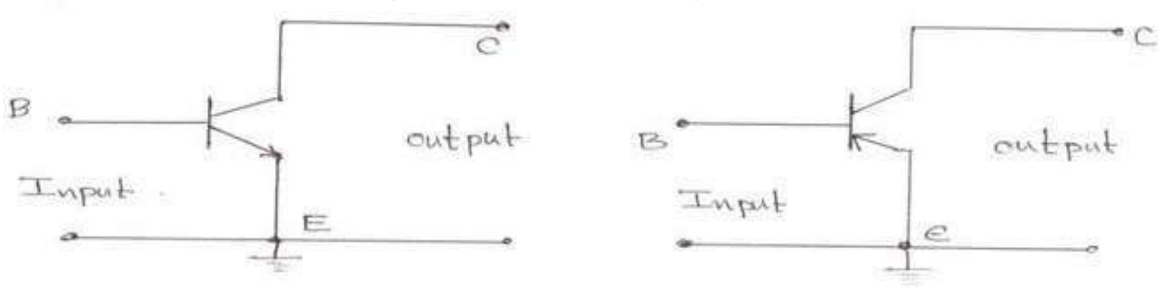


Fig.Common–EmitterConfiguration

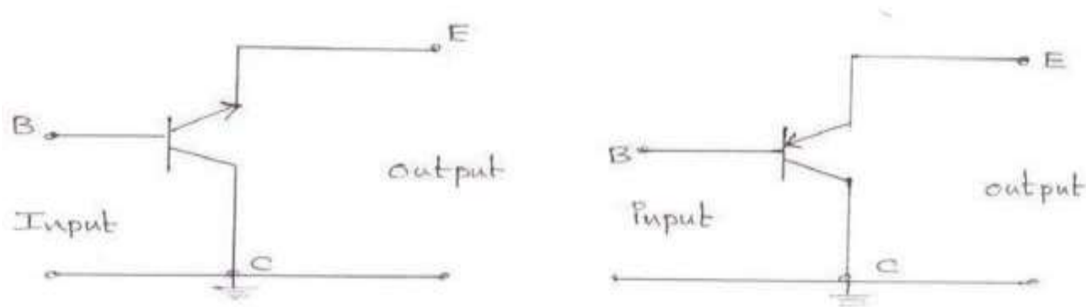


Fig.Common–CollectorConfiguration

5.1.1 Common–Base(CB)Configurations:

Inthisconfiguration,theinputsignalisappliedbetweenemitterandbasewhiletheoutput istakenfromcollector and base. As base is common to input and output circuits, hence the name common-baseconfiguration.Figureshow thecommon-baseP-N-Ptransistorcircuit.

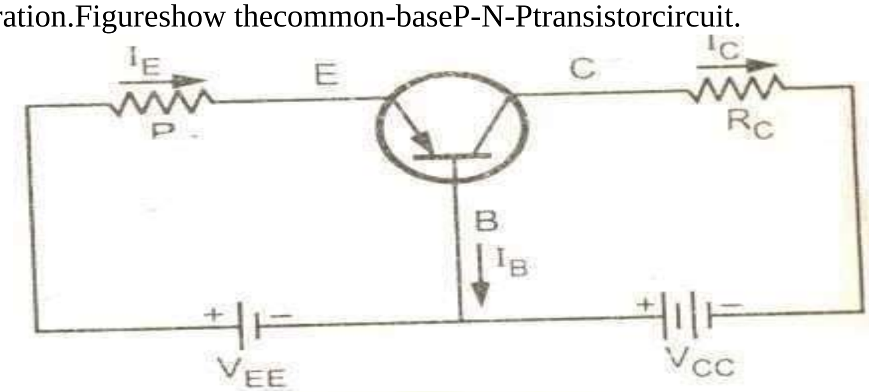


Fig.Common– BasePNPtransistoramplifier.

CurrentAmplificationFactor(α):

Whennosignalisapplied,thentheratioofthecollectorcurrenttothe emittercurrentiscalleddcalpha(α_{dc})ofatransistor.

$$\alpha_{dc} = \frac{\Delta I_C}{\Delta I_E}$$

(Negative sign signifies that I_E flows into transistor while I_C flows out of it). ' α' of a transistor is ameasure of the quality of a transistor. Higher is the value of 'α ', better is the transistor in the sensethat collector current approaches the emitter current. By considering only magnitudes of the currents,I_C=**α** $I_E$andhenceI_B=I_E-I_C

Therefore,

$$I_B = I_E - \boldsymbol{\alpha} I_E = I_E(1 - \boldsymbol{\alpha})$$

For all practical purposes, $\alpha_{dc} = \alpha_{ac} = \alpha$ and practical values in commercial transistors rangefrom0.9to0.99.

TotalCollectorCurrent:

Thetotalcollectorcurrentconsistsofthefollowingtwoparts
i) $I_E$currentduetomajoritycarriers
ii) I_{CBO}currentduetominoritycarriers

Totalcollectorcurrent$I_C=\alpha I_E+I_{CBO}$
Thecollectorcurrentcanalsobeexpressedas$I_C=\alpha(I_B+I_C)+I_{CBO}$$(Q I_E=I_B+I_C)$

$$\Rightarrow I_C(1-\alpha)=\alpha I_B+I_{CBO}$$

$$\Rightarrow I_C=\left(\frac{\alpha}{1-\alpha}\right)I_B+\left(\frac{1}{1-\alpha}\right)I_{CBO}$$

5.1.2 COMMON-EMITTER(CE)CONFIGURATION:

In this configuration, the input signal is applied between base and emitter and the output istaken from collector and emitter. As emitter is common to input and output circuits, hence thenamecommonemitterconfiguration.

FigureshowstheCommon-EmitterP-N-Ptransistor circuit.

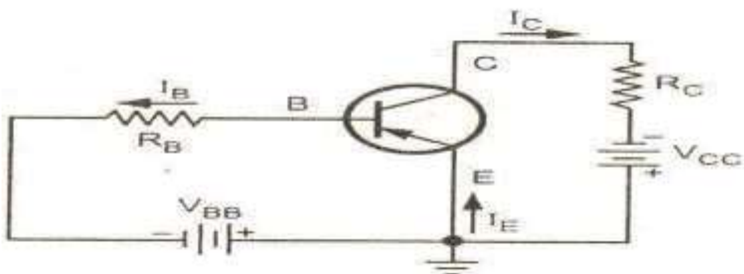


Fig.Common-EmitterPNPtransistoramplifier.

CurrentAmplification Factor(β):

When nosignalisapplied,thentheratioofcollectorcurrenttothebasecurrentiscalleddcbeta(β_{dc}) ofatransistor.

$$\beta_{dc}=\beta=\frac{I_C}{I_B} \quad ....(1)$$

When signal is applied, the ratio of change in collector current to the change in base current is defined as base current amplification factor. Thus,

$$\beta_{dc}=\beta=\frac{\Delta I_C}{\Delta I_B} \quad ....(2)$$

From equation (1), $I_C=\beta I_B$

Almost in all transistors, the base current is less than 5% of the emitter current. Due to this fact, 'β' ranges from 20 to 500. Hence this configuration is frequently used when appreciable current gain as well as voltage gain is required.

TotalCollectorCurrent:

TheTotalcollectorcurrent$I_C=\beta I_B+I_{CEO}$..................(3)
WhereI_{CEO}istheleakagecurrent.

But, we have, $I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO}$ ....(4)

Comparing equations (3) and (4), we get

$$\beta = \frac{\alpha}{1-\alpha} \text{ and } I_{CEO} = \frac{1}{1-\alpha} I_{CBO} \quad \text{...........(5)}$$

Relation between α and β:

We know that $\alpha = \frac{I_C}{I_E}$ and $\beta = \frac{I_C}{I_B}$

$I_E = I_B + I_C$ (or) $I_B = I_E - I_C$

Now
$$\beta = \frac{I_C}{I_E - I_C} = \frac{\frac{I_C}{I_E}}{1 - \frac{I_C}{I_E}} = \frac{\alpha}{1-\alpha} \quad \text{................ (6)}$$

$$\Rightarrow \beta(1-\alpha) = \alpha \quad \text{(or)} \quad \beta = \alpha(1+\beta)$$

$$\Rightarrow \alpha = \frac{\beta}{1+\beta} \quad \text{................ (7)}$$

It can be seen that $1 - \alpha = \frac{1}{1+\beta}$ .... (8)

5.1.3 COMMON–COLLECTOR(CC)CONFIGURATION:

In this configuration, the input signal is applied between base and collector and the output istaken from the emitter. As collector is common to input and output circuits, hence the namecommoncollectorconfiguration.Figureshowsthecommoncollector PNPtransistor circuit.

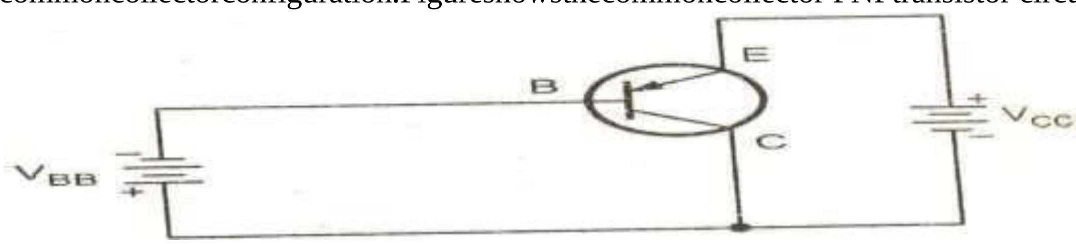


Fig.CommonCollectorPNPtransistoramplifier.

CurrentAmplificationFactor(γ):

Whenno signalisapplied,thentheratioofemittercurrenttothebasecurrentiscalledasdcgamma(γ_{dc})ofthetransistor.

$$\gamma_{dc} = \gamma = \frac{I_E}{I_B} \quad \text{............... (1)}$$

5.4 CHARACTERISTICSOFCOMMON-BASE CIRCUIT:

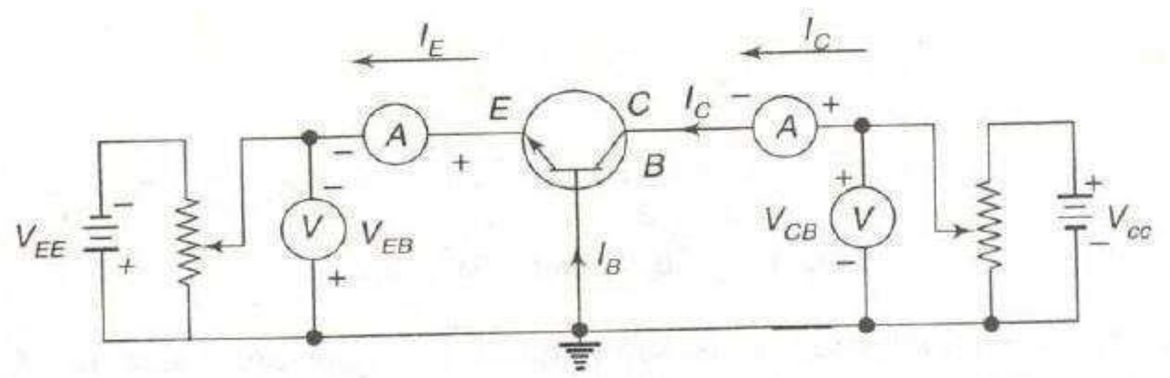


Fig. Circuit to determine CB static characteristics.

InputCharacteristics:

To determine the input characteristics, the collector-base voltage V_{CB} is kept constant at zerovolts and the emitter current I_E is increased from zero in suitable equal steps by increasing V_{EB}.This is repeated for higher fixed values of V_{CB}. A curve is drawn between emitter current IEandemitter-base voltage V_{EB}atconstantcollector-basevoltageV_{CB}. Theinputcharacteristicsthusobtainedareshowninfigurebelow.

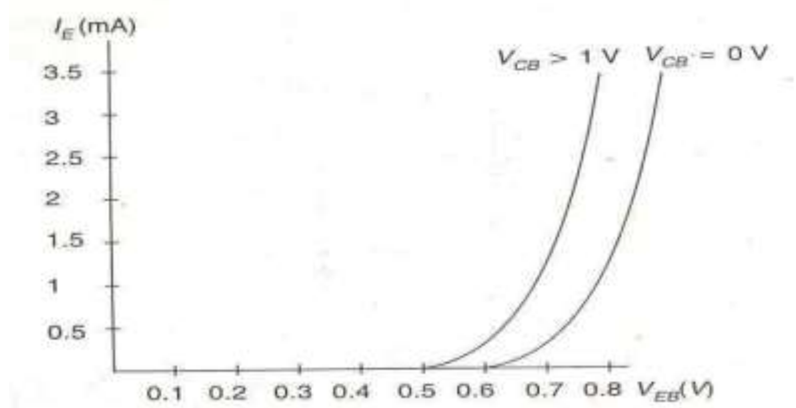
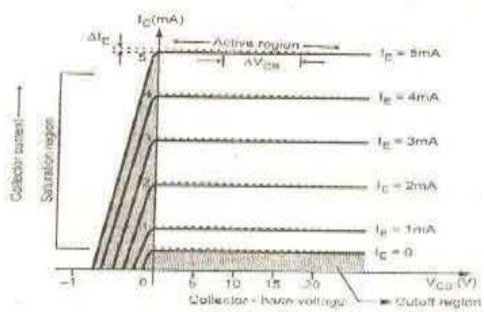


Fig.CBInputCharacteristics.

OutputCharacteristics:

To determine the output characteristics, the emitter current I_E is kept constant at a suitable valueby adjusting the emitter-base voltage V_{EB}. Then V_{CB} is increased in suitable equal steps and thecollector current I_C is noted for each value of I_E. Now the curves of I_C versus V_{CB} are plotted forconstantvaluesof$I_E$andtheoutputcharacteristicsthusobtainedisshowninfigurebelow.



q Fig.CBOutputCharacteristics

From the characteristics, it is seen that for a constant value of I_E, I_C is independent of V_{CB} and the curves are parallel to the axis of V_{CB}. Further, I_C flows even when V_{CB} is equal to zero. As the emitter-base junction is forward biased, the majority carriers, i.e., electrons, from the emitter are injected into the base region. Due to the action of the internal potential barrier at the reverse biased collector-base junction, they flow to the collector region and give rise to I_C even when V_{CB} is equal to zero.

It is the slope of CB output characteristics I_C versus V_{CB}.

5.5 CHARACTERISTICS OF COMMON-EMITTER CIRCUIT:

The circuit diagram for determining the static characteristic curves of the an N-P-N transistor in the common emitter configuration is shown in figure below.

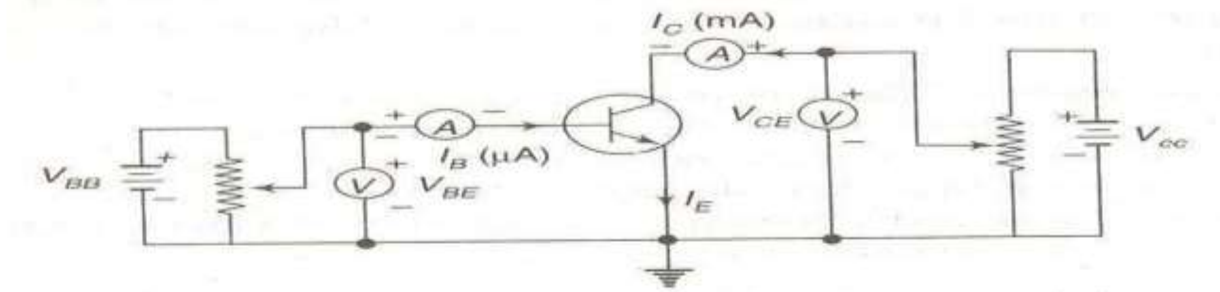


Fig. Circuit to determine CE Static characteristics.

Input Characteristics:

To determine the input characteristics, the collector to emitter voltage is kept constant at zero volts and base current is increased from zero in equal steps by increasing V_{BE} in the circuit. The value of V_{BE} is noted for each setting of I_B. This procedure is repeated for higher fixed values of V_{CE}, and the curves of I_B versus V_{BE} are drawn. The input characteristics thus obtained are shown in figure below.

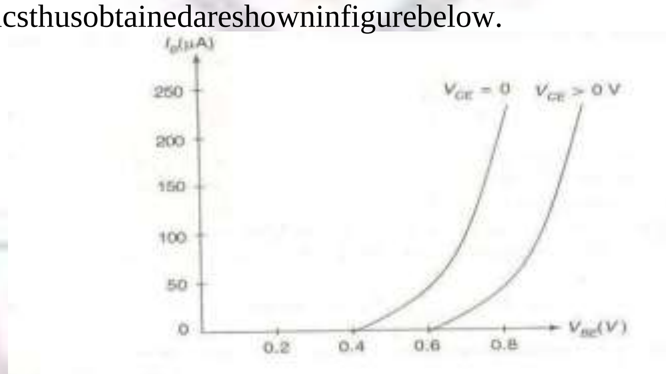


Fig. CE Input Characteristics.

When V_{CE}=0 , the emitter-base junction is forward biased and he junction behaves as a forward biased diode. When V_{CE} is increased, the width of the depletion region at the reverse biased collector-base junction will increase. Hence he effective width of the base will decrease. This effect causes a decrease in the base current I_B. Hence, to get the same value of I_B as that for V_{CE}=0, V_{BE} Should be increased. Therefore, the curve shifts to the right as V_{CE} increases.

OutputCharacteristics:

To determine the output characteristics, the base current $I_B$is kept constant at a suitable value byadjusting base-emitter voltage, V_{BE}. The magnitude of collector-emitter voltage V_{CE} is increased insuitable equal steps from zero and the collector current I_C is noted for each setting of V_{CE}. Now thecurves of $I_C$versus V_{CE} are plotted for different constant values of I_B. The output characteristics thusobtainedareshowninfigurebelow.

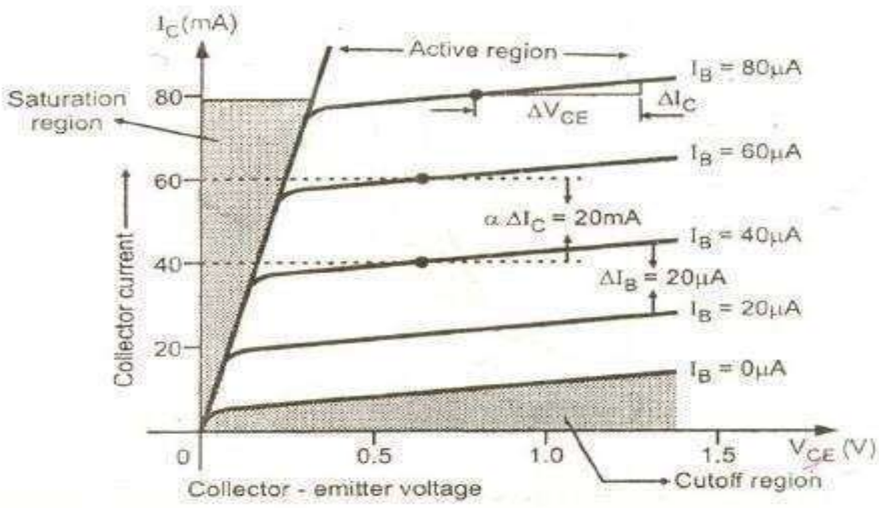


Fig.CEOutputcharacteristics

Theoutput characteristics ofcommonemitterconfigurationconsist ofthreeregions:Active,SaturationandCut-offregions.

ActiveRegion:

Theregionwherethecurvesareapproximatelyhorizontalisthe“Active”regionoftheCEconfiguration.Inthe activeregion,thecollectorjunctionisreversebiased.AsV_{CE}isincreased,reversebias increase. This causes depletion region to spread more in base than in collector, reducing thechangesofrecombinationinthebase.Thisincreasethevalueofadc.ThisEarlyeffectcausescollectorcurrent to rise more sharply with increasing V_{CE} in the active region of output characteristics of CEtransistor.

SaturationRegion:

If V_{CE} is reduced to a small value such as 0.2V, then collector-base junction becomes forward biased,sincetheemitter-basejunctionisalreadyforwardbiasedby0.7V.TheinputjunctioninCEconfiguration is base to emitter junction, which is always forward biased to operate transistor in activeregion. Thus input characteristics of CE configuration are similar to forward characteristics of p-njunctiondiode.Whenboththejunctionsareforwards biased, the transistor operates in the saturation region, which is indicated on the output characteristics.Thesaturationvalue ofV_{CE},designatedV_{CE}(Sat),usuallyrangesbetween0.1Vto0.3V.

Cut-OffRegion:

When the input base current is made equal to zero, the collector current is the reverse leakage currentICEO. Accordingly, in order to cut off the transistor, it is not enough to reduce IB=0. Instead, it isnecessary to reverse bias the emitter junction slightly. We shall define cut off as the condition wherethecollectorcurrentisequaltothereversesaturationcurrentICOandthe emittercurrentiszero.

5.5Characteristics ofcommoncollectorcircuit:

The circuit diagram for determining the static characteristics of an N-P-N transistor in the commoncollectorconfigurationisshowninfig.below.

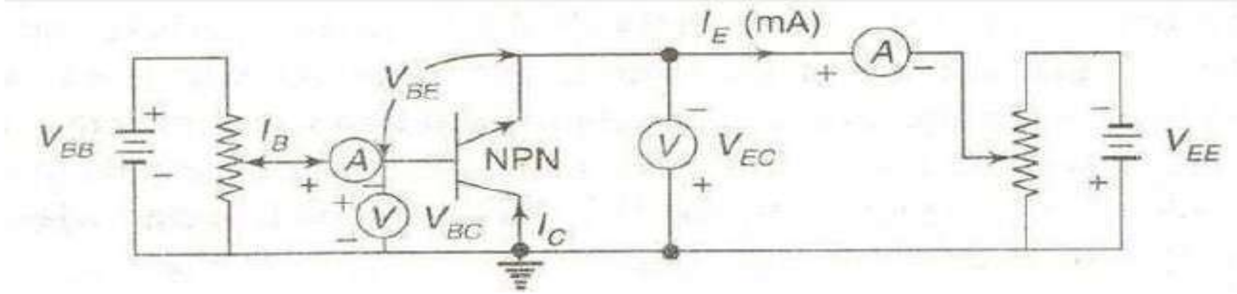


Fig.Circuit todetermineCC staticcharacteristics.

InputCharacteristics:

Todeterminetheinputcharacteristic,V_{EC}iskeptatasuitablefixedvalue.Thebasecollector voltage VBC is increased in equal steps and the corresponding increase in $I_B$is noted. This is repeatedfordifferentfixedvaluesofV_{EC}.PlotsofV_{BC}versus$I_B$fordifferentvaluesofV_{EC}showninfigureare theinputcharacteristics.

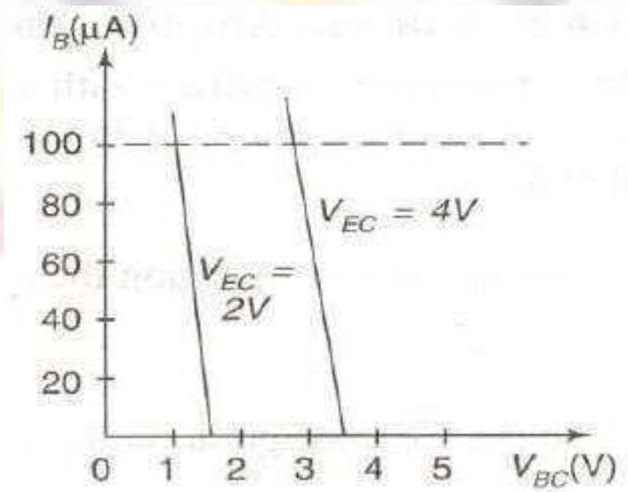


Fig.CCInputCharacteristics.

OutputCharacteristics:

Theoutputcharacteristicsshowninfigurebelowarethesameasthoseofthecommonemitterconfiguration.
Fig.CCoutputcharacteristics.

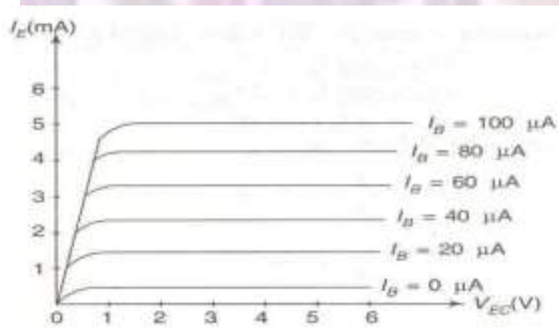
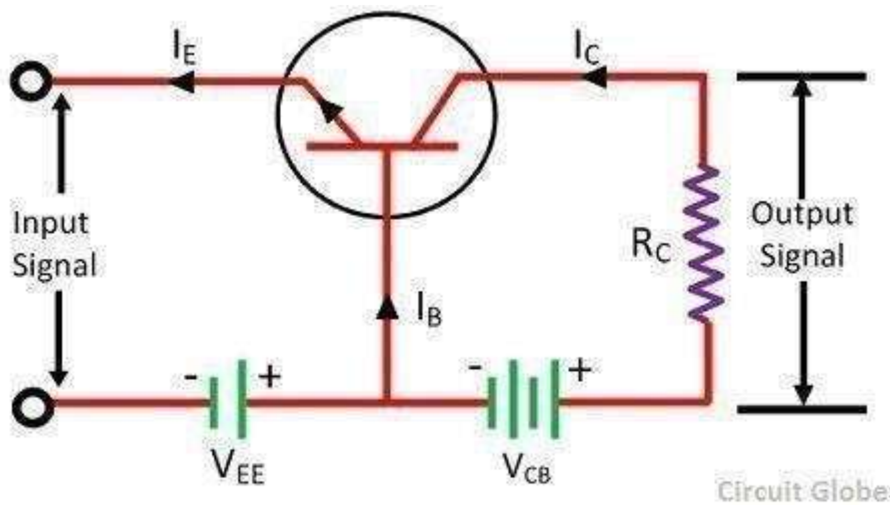


Fig.CCoutputcharacteristics.

TransistorasanAmplifier:

The transistor raises the strength of a weak signal and hence acts an amplifier. The transistor amplifiercircuit is shown in the figure below. The transistor has three terminals namely emitter, base andcollector.The emitter and base of the transistor are connected in forward biased and the collector base region is inreversebias.TheforwardbiasmeanstheP-regionofthetransistor isconnectedtothepositiveterminalofthe supply and the negative region is connected to the N-terminal and in reverse biasjust opposite of it hasoccurred.



The input signal or weak signal is applied across the emitter base and the output is obtained to the loadresistor R_C which is connected in the collector circuit. The DC voltage V_{EE} is applied to the input circuitalong with the input signal to achieve the amplification. The DC voltage V_{EE} keeps the emitter-basejunction under the forward biased condition regardless of the polarity of the input signal and is known asabiasvoltage.

Inthecollectorcircuit,aloadresistor$R_C$ofhighvalueisconnected.Whencollectorcurrentflowsthroughsuchahighresistance,itproducesalargevoltagedropacross it.Thus, aweaksignal(0.1V)appliedtotheinputcircuitappearsintheamplifiedform(10V)inthecollector circuit.

FIELDEFFECTTRANSISTOR

INTRODUCTION

1. TheFieldeffecttransistorisabbreviatedasFET,itisananothersemiconductordevicelike a BJTwhichcanbeusedasanamplifierorswitch.
2. TheFieldeffecttransistorisavoltageoperateddevice.WhereasBipolarjunctiontransistorisacurrentcontrolleddevice.UnlikeBJTaFETrequiresvirtuallynoinputcurrent.
3. Thisgivesitanextremelyhighinputresistance,whichisitsmostimportantadvantageoverabipolartransistor.
4. FETisalsoathreeterminaldevice,labeledassource,drainandgate.
5. ThesourcecanbeviewedasBJT'semitter,thedrainascollector,andthegateasthecounterpartofthebase.
6. Thematerialthatconnectsthesourcetodrainisreferred toasthechannel.
7. FEToperationdependsonlyontheflowofmajoritycarriers,thereforetheyarecalledunipolardevices.BJT operationdependsonbothminorityandmajoritycarriers.
8. AsFEThasconductionthroughonlymajoritycarriersitislessnoisythanBJT.
9. FETsaremucheasiertofabricateandareparticularlysuitableforICsbecausetheyoccupylessspacethanBJTs.
10. FETamplifiershavelowgainbandwidthproductduetothejunctioncapacitiveeffectsandproducemoresignaldistortionexceptforsmallsignaloperation.
11. The performance of FET is relatively unaffected by ambient temperature changes. As ithas a negative temperature coefficient at high current levels, it prevents the FET fromthermal breakdown. The BJT has a positive temperature coefficient at high current levelswhichleads tothermalbreakdown.

CLASSIFICATIONOFFET:

Therearetwomajorcategoriesoffieldeffecttransistors:

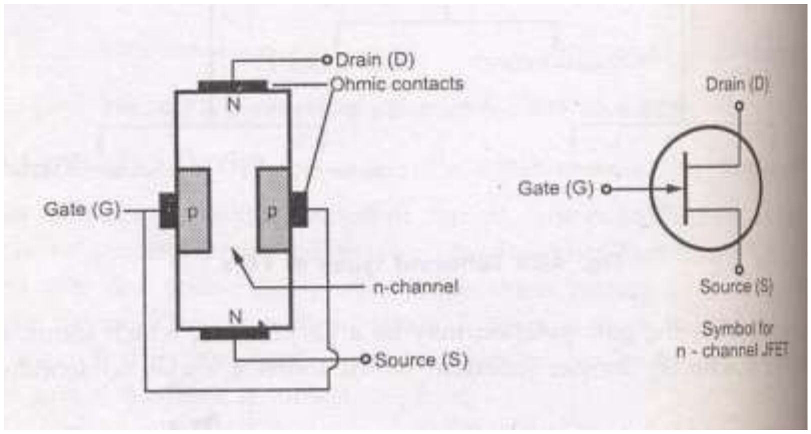
1. JunctionFieldEffectTransistors
2. MOSFETs

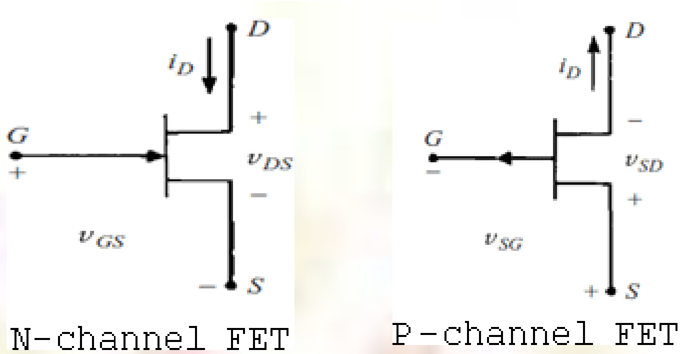
1. JunctionFieldEffectTransistors

- Junction FieldEffectTransistorsarefurthersubdividedin toP- channel andN-channeldevices.
- When the channel is of N-type the JFET is referred to as an N-channel JFET ,whenthechannelisofP-typetheJFETisreferredtoasP-channelJFET.

CONSTRUCTIONOFN-CHANNELJFET

ApieceofN-typematerial,referredtoaschannelhastwosmallerpiecesofP-typematerialattached to its sides, forming PN junctions. The channel ends are designated as thedrain and source . And the two pieces of P-type material are connected together and theirterminal is called the gate. Since this channel is in the N-type bar, the FET is known as N-channelJFET.





TheschematicsymbolsfortheP-channelandN-channelJFETsareshowninthefigure

OPERATIONOFN-CHANNELJFET:-

TheoveralloperationoftheJFETisbasedonvaryingthewidthofthechanneltocontrolthedraincurrent.

A piece of N type material referred to as the channel, has two smaller pieces of Ptype material attached to its sites, farming PN –Junctions. The channel's ends are designated thedrain and the source. And the two pieces of P type material are connected together and theirterminaliscalledthegate.Withthegateterminalnotconnectedandthepotentialappliedpositiveatth edrainnegativeatthesourceadraincurrent$I_D$flows.

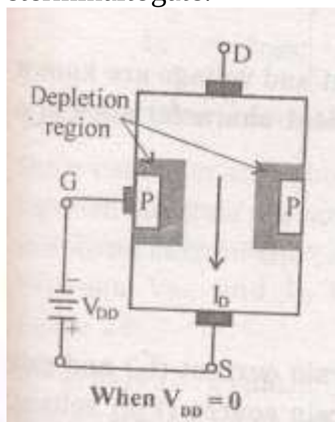
When the gate is biasednegative with respective to the source the PN junctions are reversebiased and depletion regions are formed. The channel is more lightly doped than the P type gateblocks, so the depletion regions penetrate deeply into the channel. Since depletion region is aregion depleted of charge carriers it behaves as an Insulator. The result is that the channel isnarrowed. Its resistance is increased and $I_D$is reduced. When the negative gate bias voltage isfurtherincreased,thedepletionregionsmeetatthecenterandIdiscutoffcompletely.

Therearetwowaystocontrolthechannelwidth

1. ByvaryingthevalueofV$_{GS}$
2. AndbyVaryingthevalueofV$_{DS}$holdingV$_{GS}$constant

Byvaryingthevalue ofV_{GS}:-

We can vary the width of the channel and in turn vary the amount of draincurrent.ThiscanbedonebyvaryingthevalueofV_{GS}.Thispointisillustrated inthefigbelow.Here we are dealing with N channel FET. So channel is of N type and gate is of P type thatconstitutes a PN junction. This PN junction is always reverse biased in JFET operation .Thereverse bias is applied by a battery voltage V_{GS}connected between the gate and the sourceterminali.epositiveterminalofthebatteryis connectedtothesourceandnegativeterminaltogate.



1) When a PN junction is reverse biased the electrons and holes diffuse across junction byleaving immobile ions on the N and P sides , the region containing these immobile ionsisknownas depletionregions.
2) IfbothPandNregionsareheavilydopedthenthedepletionregionextendssymmetricallyonbothsides.
3) ButinNchannelFETPregionisheavilydopedthanNtypethusdepletionregionextendsmoreinNregionthanPregion.
4) So when no $V_{DS}$is applied the depletion region is symmetrical and the conductivitybecomesZero.Since therearenomobilecarriersinthejunction.
5) Asthereversebiasvoltageisincreasesthethicknessofthedepletionregionalsoincreases. i.e.theeffectivechannelwidthdecreases.
6) ByvaryingthevalueofV_{GS}wecanvarythewidthofthechannel.

2 Varying thevalueofV_{DS}holdingV_{GS}constant:-

1) When no voltage is applied to the gate i.e. V_{GS}=0 ,$V_{DS}$is applied between source anddrain the electrons will flow from source to drain through the channel constituting draincurrentI_D.
2) WithV_{GS}=0forI_D=0thechannelbetweenthegatejunctionsisentirelyopen.Inresponsetoasmall appliedvoltageV_{DS},theentire bar actsasasimple semiconductorresistorandthe current$I_D$increaseslinearlywithV_{DS}.
3) Thechannelresistancesarerepresentedas$R_D$and$R_S$asshowninthefig.

4) This increasingdraincurrent$I_D$producesavoltagedropacrossrdwhichreversebiasesthegate tosource junction,(R_D> R_S).Thus the depletion regionisformed which is notsymmetrical.

5) Thedepletionregion i.e.developedpenetratesdeeperintothechannelnear drainandlesstowardssourcebecauseVR_D>>VR_S.Soreversebiasishigher neardrainthanatsource.

6) As a result growing depletion region reduces the effective width of the channel. EventuallyavoltageV_{DS}isreached atwhichthechannelispinchedoff.Thisisthevoltagewherethecurrentldbeginstoleveloffandapp roachaconstantvalue.

7) So,byvaryingthevalueofV_{DS}wecanvarythewidthofthechannelholdingV_{GS} Constant.

WhenbothV_{GS}andV_{DS}isapplied:-

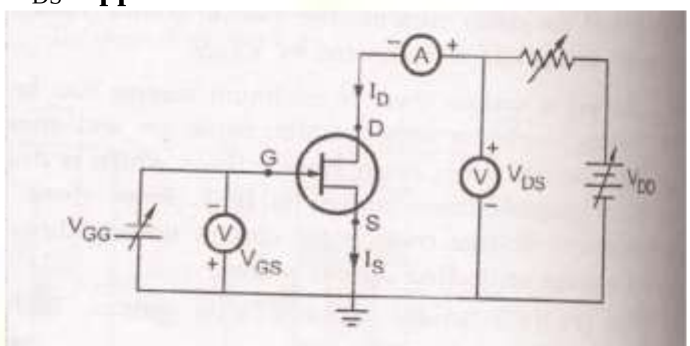
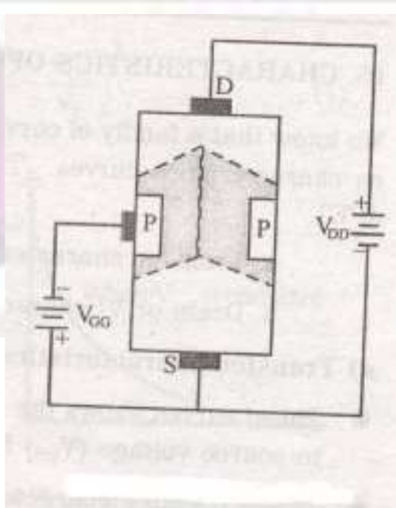


Fig. 4.45 Experimental setup to plot JFET characteristics

It is of course in principle not possible for the channel to close Completely and there byreduce the current Id to Zero for,if such indeed, could be the case the gate voltage V_{GS}isappliedinthedirectiontoprovideadditionalreversebias

1) When voltage is applied between the drain and source with a battery V_{DD}, the electronsflow from source to drain through the narrow channel existing between the depletionregions. This constitutes the drain current I_D, its conventional direction is from drain tosource.
2) The value of drain current is maximum when no external voltage is applied between gateandsourceandis designatedbyI_{DSS}.



3) When V_{GS} isincreasedbeyondZerothedepletionregionsarewidened.Thisreducestheeffectivewidthofthechannelandthereforecontrolstheflowofdraincurrentthroughthechannel.
4) When V_{GS} isfurtherincreasedastageisreachedatwhichtodepletionregionstoucheachother that means the entire channel is closedwith depletion region. This reducesthedraincurrenttoZero.

CHARACTERISTICSOFN-CHANNELJFET:-

Thefamily of curves thatshows the relation between currentandvoltage are known ascharacteristiccurves.

ThearetwoimportantcharacteristicsofaJFET.

1) DrainorVICharacteristics
2) Transfercharacteristics

1. DrainCharacteristics:

Draincharacteristicsshowstherelationbetweenthedraintosourcevoltage V_{DS} and drain current Id. In order to explain typical drain characteristics let us consider thecurve with V_{GS}=0V.

1) When V_{DS} isappliedanditisincreasingthedraincurrent I_D alsoincreaseslinearlyuptokneepoint.
2) ThisshowsthatFETbehaveslikeanordinaryresistor.Thisregioniscalledasohmicregion.
3) I_D increaseswithincreaseindraintosourcevoltage. Herethedraincurrentis increasedslowlyas comparedtoohmic region.

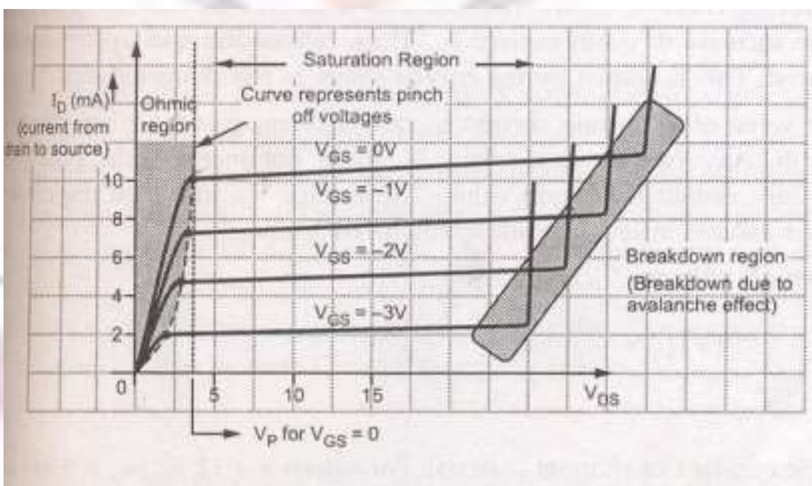


Fig. 4.44 Drain V-I characteristics of n-channel JFET

4) Itisbecauseofthefactthatthereisanincreasein V_{DS}.This inturnincreasesthereversebiasvoltageacrossthegatesourcejunction.Asaresultofthisdepletionregiongrowsinsizetherebyreducingtheeffectivewidthofthechannel.

5) All the drain to source voltage corresponding to point the channel width is reduced to aminimumvalueandisknownas pinchoff.

6) Thedrain tosourcevoltageatwhich channel pinch off occursis calledpinch offvoltage(V_P).

PINCHOFFRegion:

1) Thisistheregionshownbythecurveassaturation region.
2) It is also called as saturation region or constant current region. Because of the channelis occupied with depletion region , the depletion region is more towards the drain andless towards the source, so the channel is limited, with this only limited number ofcarriers are only allowed to cross this channel from source drain causing a current thatis constant in this region. To use FET as an amplifier it is operated in this saturationregion.
3) InthisdraincurrentremainsconstantatitsmaximumvalueI_{DSS}.
4) The drain current in the pinch off region depends upon the gate to source voltage andisgivenbytherelation

$$I_D=I_{DSS}[1-V_{GS}/V_P]^2$$

Thisisknownasshokley'srelation.

BREAKDOWNREGION:

1) The region is shown by the curve .In this region, the drain current increases rapidly asthe draintosourcevoltageisincreased.
2) Itisbecauseofthegatetosourcejunctionduetoavalancheeffect.
3) The avalanche break down occurs at progressively lower value of V_{DS}because thereverse bias gate voltage adds to the drain voltage thereby increasing effective voltageacrossthegatejunction

   Thiscauses

   1. Themaximumsaturationdraincurrentissmaller
   2. Theohmicregionportiondecreased.
4) It is important to note that the maximum voltage V_{DS}which can be applied to FET isthe lowestvoltagewhichcausesavailablebreakdown.

2. TRANSFERCHARACTERISTICS:

These curves shows the relationship between drain current $I_D$and gate to sourcevoltageV_{GS} fordifferentvalues ofV_{DS}

1) Firstadjustthedraintosourcevoltagetosomesuitablevalue,thenincreasethegatetosource voltageinsmallsuitablevalue.
2) Plot thegraphbetween gatetosourcevoltagealongthehorizontalaxisandcurrentIDontheverticalaxis.Weshallo btainacurvelikethis.

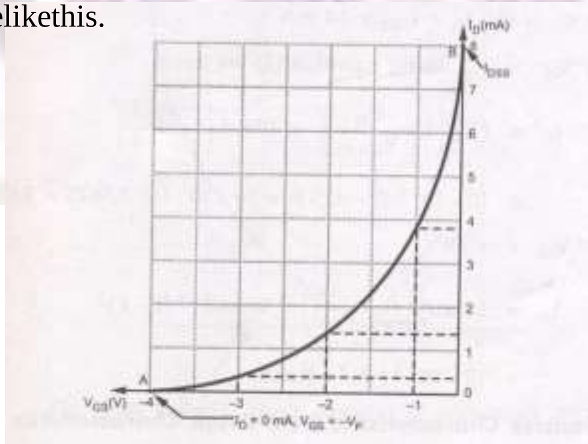


Fig. 4.48 Transfer characteristics of n-channel JFET

3) As we know that if $V_{GS}$is more negative curves drain current to reduce . where $V_{GS}$is made sufficiently negative, $I_D$is reduced to zero. This is caused by the widening ofthe depletion region to a point where it is completely closesthe channel. The valueofV_{GS}atthecutoffpointisdesignedasV_{GSoff}

4) The upper end of the curve as shown by the drain current value is equal to I_{DSS}thatiswhenV_{GS}=0thedraincurrentismaximum.

5) WhilethelowerendisindicatedbyavoltageequaltoV_{GSoff}

6) IfV_{GS}continuouslyincreasing,thechannelwidthisreduced,thenI_D=0

7) Itmaybenotedthatcurveispartoftheparabola;itmaybeexpressedas

$$I_D=I_{DSS}[1-V_{GS}/V_{GSoff}]^2$$

DIFFERENCEBETWEENV_PANDV_{GSoff}:

1)

$V_P$isthevalueofV_{GS}thatcausestheJFETtobecomeconstantcurrentcomponent,ItismeasuredatV_{GS}=0Vandhasaconstantdraincurrentof$I_D=I_{DSS}$.

.WhereV_{GSoff}isthevalueofV_{GS}thatreduces$I_D$toapproximatelyzero.

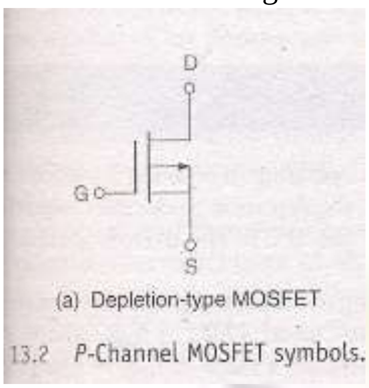
<u>WhythegatetosourcejunctionofaJFETbealwaysreversebiased?</u>

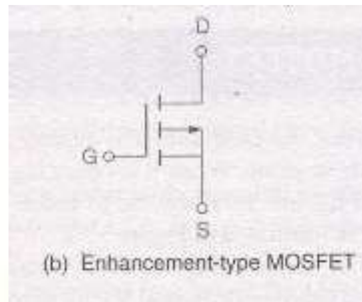
The gate to source junction of a JFET is never allowed to become forward biasedbecause the gate material is not designed to handle any significant amount of current. If thejunctionisallowedtobecomeforwardbiased,currentisgeneratedthroughthegatematerial.Thiscurrentmaydestroythecomponent.

There is one more important characteristic of JFET reverse biasing i.e. J FET ‘shave extremely high characteristic gate input impedance. This impedance is typically in the highmega ohm range. With the advantage of extremely high input impedance it draws no currentfromthe source. The high input impedance of the JFET has led to its extensive use in integrated circuits.The low current requirements of the component makes it perfect for use in ICs. Where thousandsof transistors must be etched on to a single piece of silicon. The low current draw helps the IC toremainrelativelycool,thusallowingmorecomponentstobeplacedinasmallerphysicalarea.

MOSFET:

- Wenowturnourattentiontothe Insulated Gate FETorMetalOxideSemiConductorFETwhichishavingthegreatercommercialimportancethan thejunctionFET.
- MostMOSFETShowever aretriodes,withthesubstrateinternallyconnectedtothesource.Thecircuitsymbolsusedbyseveral manufacturersareindicatedintheFigbelow.



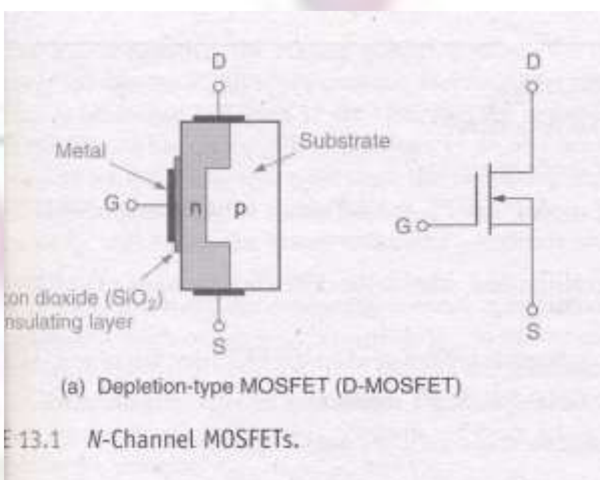


(a) DepletiontypeMOSFET (b)EnhancementtypeMOSFET

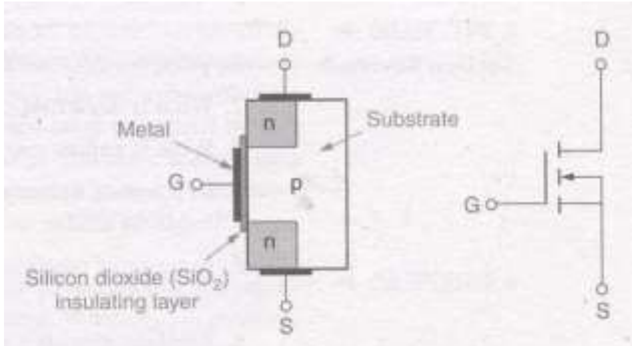
Both ofthemareP-channel

- HerearetwobasictypesofMOSFETS

  (1)Depletiontype (2)Enhancement typeMOSFET.
- D-MOSFETScanbeoperated inboththedepletionmodeandtheenhancementmode.
- EMOSFETSarerestrictedtooperateinenhancement mode.Theprimarydifferencebetweenthemis theirphysicalconstruction.
- Theconstructiondifferencebetweenthetwoisshowninthefiggivenbelow.



AswecanseetheDMOSFEThavephysicalchannelbetweenthesourceanddrainterminals(Sha dedarea)



(b) Enhancement-type MOSFET (E-MOSFET)

The E MOSFET on the other hand has no such channel physically. It depends on the gate voltage toformachannelbetweenthesourceandthedrainterminals.

Both MOSFETS have an insulating layer between the gate and the rest of the component. Thisinsulating layer is made up of SIO_2 a glass like insulating material. The gate material is made up of metalconductor .Thus going from gate to substrate, we can have metal oxide semi conductor which is wherethetermMOSFETcomesfrom.

Since the gate is insulated from the rest of the component, the MOSFET is sometimesreferredtoas aninsulatedgateFETorIGFET.

ThefoundationoftheMOSFETiscalledthesubstrate.Thismaterialisrepresentedinthe schematicsymbolbythecenterline thatis connectedtothesource.

Inthesymbolforthe MOSFET, thearrowisplacedonthe substrate.AswithJFETanarrowpointinginrepresentsanN-channeldevice,whileanarrowpointingoutrepresentsp-channeldevice.

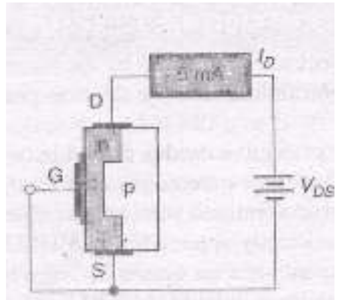
CONSTRUCTIONOFANN-CHANNELMOSFET:

The N- channel MOSFET consists of a lightly doped p type substance into which two heavilydopedn+regionsarediffusedasshownintheFig.Thesen+sections,whichwillactassourceanddrain.

A thin layer of insulation silicon dioxide (SIO_2) is grown over the surface of the structure, andholes are cut into oxide layer, allowing contact with the source and drain. Then the gate metal area isoverlaid on the oxide, covering the entire channel region.Metal contacts are made to drain and sourceand the contact to the metal over the channel area is the gate terminal.The metal area of the gate, inconjunction with the insulating dielectric oxide layer and the semiconductor channel, forms a parallelplate capacitor. The insulating layer of Sio2 Is the reason why this device is called the insulated gatefieldeffecttransistor.Thislayerresultsinanextremelyhighinputresistance(1010to10power 15ohms)forMOSFET.

DEPLETIONMOSFET

ThebasicstructureofD–MOSFETisshowninthefig.AnN-channelisdiffusedbetweensourceanddrainwiththe device anappreciabledraincurrentI_{DSS}flowsfoezerogatetosourcevoltage,V_{GS}=0.



(a) $I_D = I_{DSS}$ when $V_{GS} = 0$ V

Depletion modeoperation:-

1) The above fig shows the D-MOSFET operating conditions with gate and source terminals shortedtogether(V_{GS}=0V)

2) At this stageI_D=I_{DSS}whereV_{GS}=0V,withthisvoltage V_{DS},anappreciabledraincurrentI_{DSS} flows.

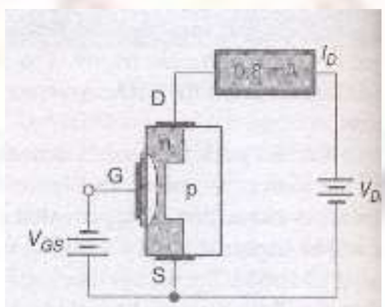
3) Ifthegatetosourcevoltageismadenegativei.e.V_{GS}isnegative.Positivechargesareinducedinthechan nelthroughtheSIO$_2$ofthegatecapacitor.

4) Since the current in a FET is due to majority carriers(electrons for an N-type material) , theinducedpositivechargesmakethechannellessconductiveandthedraincurrent dropsasV_{GS}ismademorenegative.

5) Theredistributionofchargeinthechannelcausesaneffectivedepletionofmajoritycarriers,whichac countsforthedesignationdepletionMOSFET.

6) ThatmeansbiasingvoltageV$_{GS}$depletesthechanneloffreecarriersThiseffectivelyreducesthewidthoft hechannel,increasingitsresistance.

7) NotethatnegativeV_{GS}hasthesameeffectontheMOSFETasithasontheJFET.



(b) $I_D < I_{DSS}$ when V_{GS} is negative

8) Asshowninthefigabove,thedepletionlayergeneratedbyV_{GS}(representedbythewhitespacebetween the insulating material and the channel) cuts into the channel, reducing its width. As aresult,I_D<I_{DSS}.Theactualvalueof$I_D$dependsonthevalueofI_{DSS},V_{GSOFF}andV_{GS}

EnhancementmodeoperationoftheD-MOSFET:-

1) ThisoperatingmodeisaresultofapplyingapositivegatetosourcevoltageV_{GS}tothedevice.

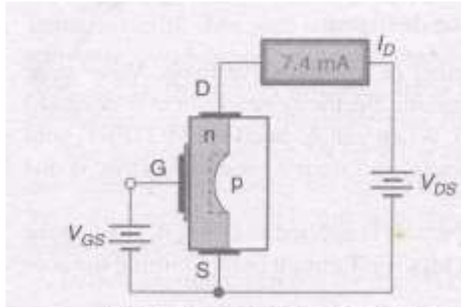
2) WhenV_{GS}ispositivethechanneliseffectivelywidened.This reducestheresistanceofthechannelallowing$I_D$toexceedthevalue ofI_{DSS}

3) WhenV_{GS}isgivenpositivethemajoritycarriersinthep-typeareholes.TheholesinthePtypesubstratearerepelledbythe+vegatevoltage.

4) At the same time, the conduction band electrons (minority carriers) in the P type material areattractedtowardsthechannelbythe+gatevoltage.

5) Withthebuildupofelectronsnearthechannel,theareatotherightofthephysicalchanneleffectively becomes anNtypematerial.

6) Theextendedntypechannelnowallowsmorecurrent, $I_D > I_{DSS}$



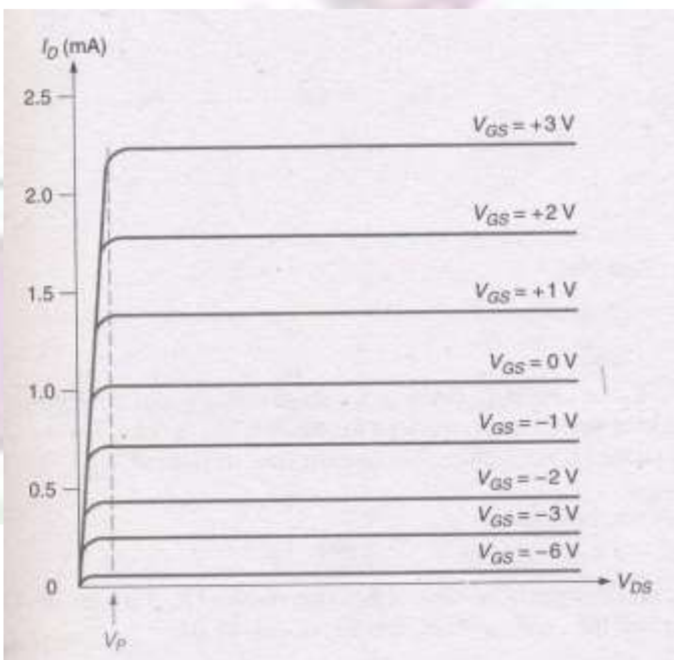
(c) $I_D > I_{DSS}$ when V_{GS} is positive

FIGURE 13.4 D-MOSFET operation.

CharacteristicsofDepletionMOSFET:-

Thefig.showsthedraincharacteristicsfor theNchanneldepletiontypeMOSFET

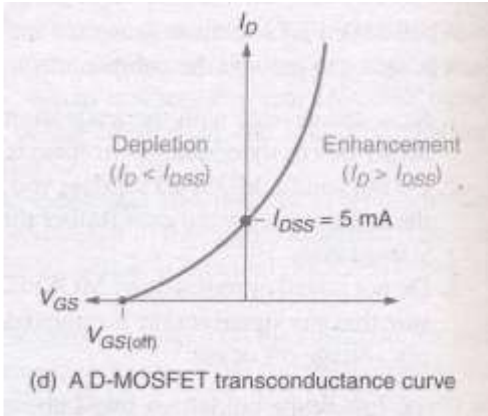
1) ThecurvesareplottedforbothV$_{GS}$positiveandV$_{GS}$negative voltages
2) WhenV$_{GS}$=0andnegativetheMOSFEToperatesindepletionmodewhenV$_{GS}$ispositive,theMOSFEToperates inthe enhancementmode.
3) ThedifferencebetweenJFETandDMOSFETisthatJFETdoesnotoperateforpositivevaluesofV$_{GS}$.
4) WhenV$_{DS}$=0,thereisnoconductiontakesplacebetweensourcetodrain,ifV$_{GS}$<0andV$_{DS}$ >0thenId increaseslinearly.
5) ButasV$_{GS}$,0inducespositivechargesholesinthechannel,andcontrolsthechannelwidth.Thusthe conduction betweensourcetodrainismaintainedasconstant,i.e.I$_D$isconstant.
6) IfV$_{GS}$>0thegateinducesmoreelectronsinchannelside,itisaddedwiththefreeelectronsgenerated by source. again the potential applied to gate determines the channel width andmaintainsconstantcurrentflowthroughitasshowninFig



6 MOSFET drain curves.

TRANSFERCHARACTERISTICS:-

Thecombinationof3operatingstatesi.e.V_{GS}=0V,V_{GS}<0V,V_{GS}>0VisrepresentedbytheD MOSFETtransconductancecurveshowninFig.



(d) A D-MOSFET transconductance curve

1) HereinthiscurveitmaybenotedthattheregionABofthecharacteristicssimilartothatofJFET.

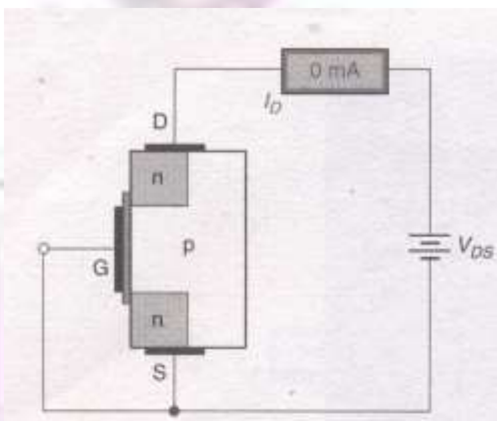
2) ThiscurveextendsforthepositivevaluesofV_{GS}

3) NotethatI_D=I_{DSS}forV_{GS}=0VwhenV_{GS}isnegative,I_D<I_{DSS}whenV_{GS}=V_{GS}(off),$I_D$isreduced to approximately 0mA.Where $V_{GS}$is positive I_D>I_{DSS}.So obviously Idss is not themaximumpossiblevalueof$I_D$foraMOSFET.

4) Thecurvesaresimilar toJFETsothettheDMOSFET havethesametransconductanceequation.

E-MOSFETS

The E MOSFET is capable of operating only in the enhancementmode.The gate potential must bepositivew.r.ttosource.



(a) I_D = 0 mA when V_{GS} = 0 V

1) whenthevalueofV_{GS}=0V,thereisnochannelconnectingthesourceanddrainmaterials.

2) Asaresult,therecanbenosignificantamountofdraincurrent.

3) When V_{GS}=0, the Vdd supply tries to force free electrons from source to drain but thepresenceofp-regiondoesnotpermittheelectronstopassthroughit.ThusthereisnodraincurrentatV_{GS}=0.

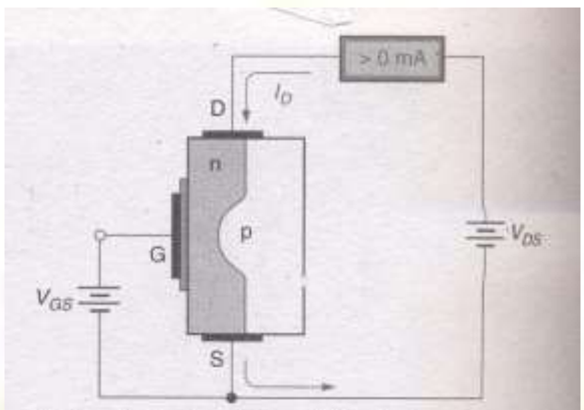
4) If V_{GS}ispositive,itinducesanegativechargeintheptypesubstratejustadjacenttotheSIO$_2$

layer.

5) As the holes are repelled by the positive gate voltage, the minority carrier electrons attractedtowardthisvoltage.ThisformsaneffectiveNtypebridgebetweensourceanddrainprovidinga pathfordraincurrent.

6) This+vegatevoltageformaachannelbetweenthesourceanddrain.

7) ThisproducesathinlayerofNtypechannelinthePtypesubstarate.ThislayeroffreeelectronsiscalledNtypeinversionlayer.



(b) $I_D > 0$ mA when V_{GS} is sufficient to form a channel.

8) The minimum V_{GS}which produces this inversion layer is called threshold voltage and isdesignatedbyV_{GS}(th).This isthepointatwhichthedeviceturnsoniscalledthethresholdvoltageV_{GS}(th)

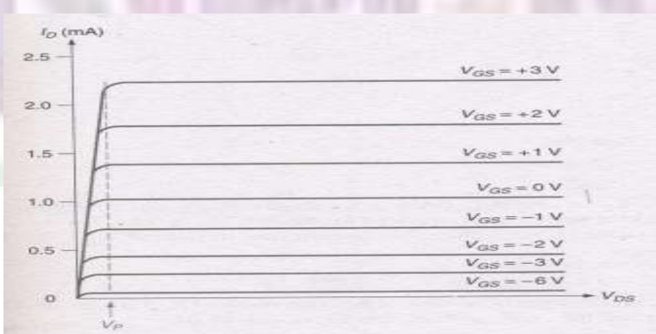
9) Whenthevoltage$V_{GS}$is$<V_{GS}$(th)nocurrentflowsfromdraintosource.

10) How ever when the voltage $V_{GS}>V_{GS}$(th) the inversion layer connects the drain to sourceandwe getsignificantvalues ofcurrent.

CHARACTERISTICSOFEMOSFET:

1. DRAINCHARACTERISTICS:

Thevoltampere draincharacteristicsofanN-channelenhancementmodeMOSFETaregivenin.



6 MOSFET drain curves.

2. TRANSFERCHARACTERISTICS:

1) ThecurrentI_{DSS}at$V_{GS}\leq 0$isverysmallbeinfoftheorderofafewnanoamps.
2) AsV_{GS}ismade+ve,thecurrent$I_D$increasesslowlyat forst,andthenmuchmorerapidlywithanincreaseinV_{GS}.
3) ThestandardtransconductanceformulawillnotworkfortheEMOSFET.
4) TodeterminethevalueofI$_D$atagivenvalueofVGswemustusethefollowingrelation

$$I_D=K[V_{GS}-V_{GS(Th)}]^2$$

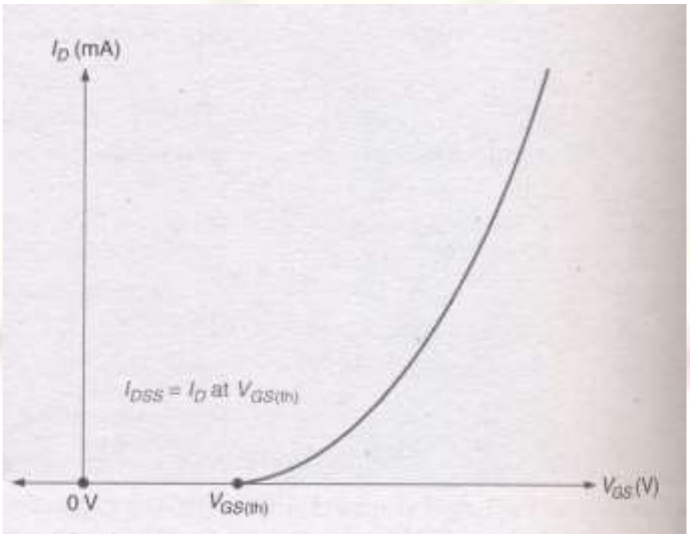
WhereKisconstantfortheMOSFET.foundas

$$K=\frac{Id(on)}{[vgs(on)-Vgs(Th)]2}$$

Fromthedataspecificationsheets,the2N7000hasthefollowingratings.

I_D(on)=75mA(minimum).And

V_{GS}(th)=0.8(minimum)



E-MOSFET transconductance curve.

APPLICATIONOFMOSFET

Oneoftheprimarycontributionstoelectronicsmadeby MOSFETscanbefoundintheareaofdigital(computer electronics). The signals in digital circuits are made up of rapidly switching dc levels.This signal is called as a rectangular wave ,made up of two dc levels (or logic levels). Theselogiclevelsare0Vand+5V.

A group of circuits with similar circuitry and operating characteristics is referred to as a logic family.All the circuits in a given logic family respond to the same logic levels, have similar speed andpower-handling capabilities , and can be directly connected together. One such logic family iscomplementaryMOS(orCMOS)logic.Thislogicfamilyismadeupentirelyof MOSFETs.

COMPARISONOFMOSFETWITH JFET

a. Inenhancement anddepletiontypesofMOSFET,thetransverseelectricfieldinducedacross an insulating layer deposited on the semiconductor material controls theconductivityofthechannel.

b. IntheJFETthetransverseelectricfieldacrossthereversebiasedPNjunctioncontrolstheconductivityofthechannel.

c. The gate leakage current in a MOSFET is of the order of 10^{-12}A. Hence the inputresistance of a MOSFET is very high in the order of 10^{10} to 10^{15} Ω. The gate leakagecurrentofaJFETisoftheorderof10^{-9}A.,anditsinputresistanceisoftheorderof10^{8}Ω.

d. The output characteristics of the JFET are flatter than those of the MOSFET, and hencethe drainresistanceofa JFET(0.1to1MΩ)ismuchhigherthanthat ofa MOSFET(1to50kΩ).

e. JFETsareoperatedonlyinthedepletionmode.ThedepletiontypeMOSFETmaybeoperatedinbothdepletionandenhancementmode.

f. ComparingtoJFET,MOSFETsareeasiertofabricate.

g. Special digital CMOS circuits are available which involve near zero power dissipationand very low voltage and current requirements. This makes them suitable for portablesystems.