SYNERGY INSTITUTE OF ENGINEERING & TECHNOLOGY

Department of Electrical Engineering

LECTURE NOTE

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Degree	**:B. TECH.**
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Branch	**:ELECTRICAL ENGINEERING**
Semester	**:4TH**
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Subject Code	**:REL4C003**
Subject Credit	**: 3**

UNIT–I
Powerswitching devices

Introductiontopowerelectronics:

Power Electronics is a field which combines Power (electric power), Electronics and Control systems.Power engineering deals with the static and rotating power equipment for the generation, transmissionand distribution of electric power. Electronics deals with the study of solid state semiconductor powerdevices and circuits for Power conversion to meet the desired control objectives (to control the outputvoltage and output power). Power electronics may be defined as the subject of applications of solid statepowersemiconductordevices (Thyristors) forthe control and conversion of electric power. Powerelectronics deals with the study and design of Thyristorised power controllers for variety of applicationlike Heat control, Light/Illumination control and Motor control - AC/DC motor drives used in industries,Highvoltagepowersupplies,Vehiclepropulsionsystems,Highvoltagedirectcurrent(HVDC)transmission.

Power Electronics refers to the process of controlling the flow of current and voltage and converting it toa form that is suitable for user loads. The most desirable power electronic system is one whose efficiencyandreliabilityis100%.

Take a look at the following block diagram. It shows the components of a Power Electronic system andhowtheyareinterlinked.

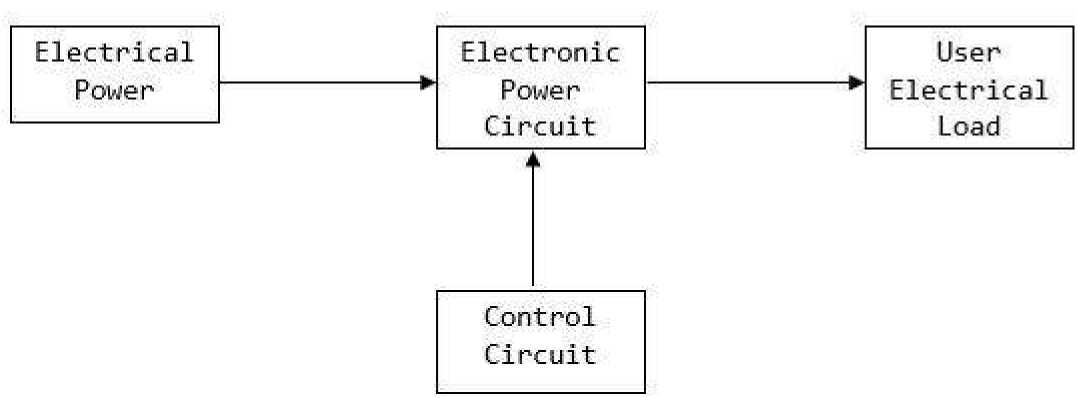


Figure:1.1.BlockdiagramofDCpowersupply

Apowerelectronicsystemconvertselectricalenergyfromoneformtoanotherandensuresthe followingisachieved–

- Maximumefficiency
- Maximumreliability
- Maximumavailability
- Minimumcost
- Leastweight
- Smallsize

ApplicationsofPowerElectronicsareclassifiedintotwotypes–StaticApplicationsandDrive Applications.

StaticApplications

Thisutilizesmovingand/orrotatingmechanicalpartssuchaswelding,heating,cooling,andelectro-platingandDCpower.

DCPowerSupply

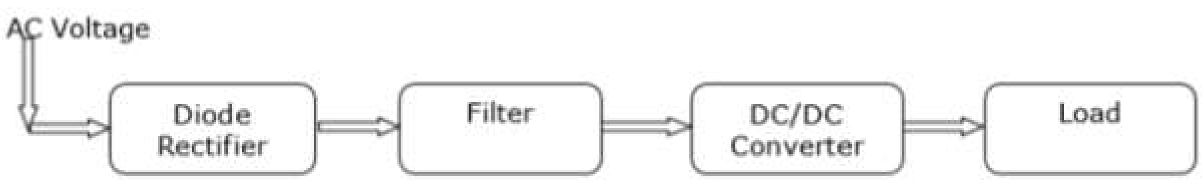


Figure:1.2.BlockdiagramofDCpowersupply

DriveApplications

Driveapplicationshaverotatingpartssuchasmotors.Examplesincludecompressors,pumps,conveyerbeltsanda irconditioningsystems.

AirConditioningSystem

Powerelectronicsisextensivelyusedinairconditionerstocontrolelementssuchascompressors.Aschematicdiagramthats hows howpowerelectronicsisused inairconditioners is shownbelow.

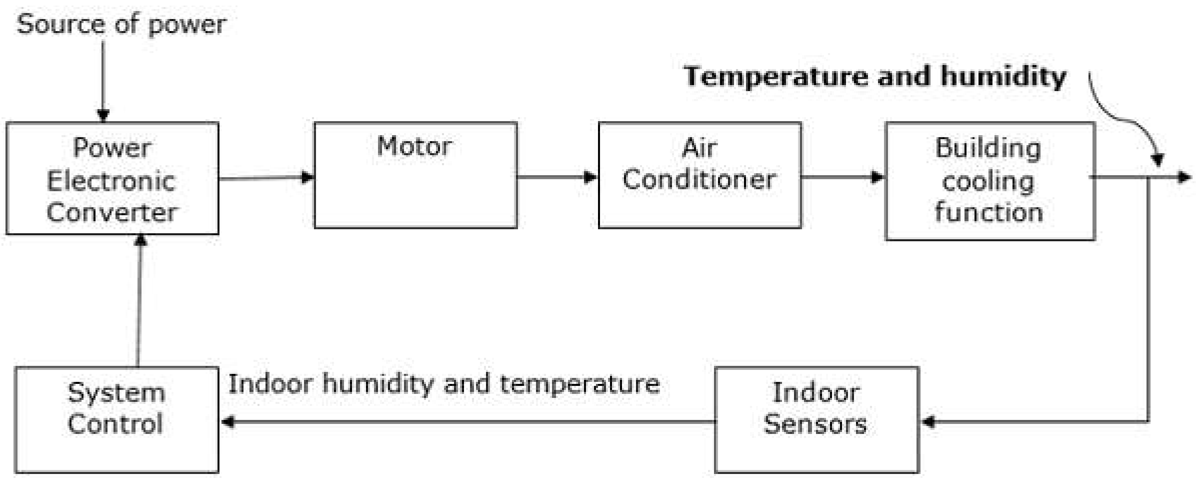


Figure:1.3.Block diagramofAirConditioningSystem

Powerelectronicapplications

CommercialapplicationsHeatingSystemsVentilating,AirConditioners,CentralRefrigeration,Lighting,ComputersandOfficeequipments,Uninterruptible PowerSupplies(UPS),Elevators,andEmergencyLamps

DomesticapplicationsCookingEquipments,Lighting,Heating,AirConditioners,Refrigerators&Freezers,PersonalComputers,EntertainmentEquipments,UPS

Industrial applications Pumps, compressors, blowers and fans Machine tools, arc furnaces, inductionfurnaces,lightingcontrolcircuits,industriallasers,inductionheating,weldingequipments

Aerospace applications Space shuttle power supply systems, satellite power systems, aircraft powersystems.

TelecommunicationsBatterychargers,powersupplies(DCandUPS),mobilecellphonebatterychargers

Transportation Traction controlofelectricvehicles,battery chargersforelectricvehicles,electriclocomotives,streetcars,trolleybuses,automobileelectronicsincludingengine controls

Utility systems High voltage DC transmission (HVDC), static VAR compensation (SVC), Alternativeenergy sources (wind, photovoltaic), fuel cells, energy storage systems, induced draft fans and boiler feedwaterpumps

Typesofpowerelectronicconverters

1. Rectifiers(ACto DCconverters): These convertersconvertconstantac voltage tovariable dcoutputvoltage.
2. Choppers(DCto DCconverters):Dc chopperconvertsfixeddcvoltage to acontrollable dcoutputvoltage.
3. Inverters(DCtoACconverters):Aninverterconvertsfixeddcvoltagetoavariableacoutputvoltage.
4. ACvoltagecontrollers:Theseconvertersconvertsfixedacvoltageto avariableacoutputvoltageatsamefrequency.
5. Cycloconverters:Thesecircuitsconvertinputpoweratonefrequencytooutputpoweratadifferentfrequencythroughonestageconversion.

Powersemiconductordevices

i. PowerDiodes.
ii. Powertransistors(BJT's).
iii. Power MOSFETS.
iv. IGBT's.
v. Thyristors

Thyristorsareafamilyofp-n-p-nstructuredpowersemiconductorswitchingdevices

Powerdiodes

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. P-N junction isformed by alloying, diffusion and epitaxial growth. Modern techniques in diffusion and epitaxialprocessespermitdesired device characteristics.The diodeshave the following advantagesHighmechanical and thermal reliability High peak inverse voltage Low reverse currentLow forwardvoltagedropHighefficiencyCompactness.

Powertransistors

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devicesare used a switching devices and are operated in the saturation region resulting in low on-state voltagedrop. They are turned on when a current signal is given to base or control terminal. The transistorremains on so long as the control signal is present. The switching speed of modern transistors is muchhigherthanthatofthyristorsandisusedextensivelyindc-dcanddc-acconverters.Howevertheir voltage and current ratings are lower than those of thyristors and are therefore used in low to mediumpower applications. Power transistors are classified as follows o Bipolar junction transistors(BJTs) oMetal-oxide semiconductor filed-effect transistors(MOSFETs) o Static Induction transistors(SITs) oInsulated-gatebipolartransistors(IGBTs)

AdvantagesofBJT'S

i. BJT‟shavehighswitchingfrequenciessincetheirturn-onandturn-offtimearelow.
ii. Theturn-onlosses ofaBJT aresmall.
iii. BJThascontrolledturn-onandturn-offcharacteristics sincebasedrivecontrolis possible.
iv. BJTdoesnotrequirecommutationcircuits

DemeritsofBJT

i. Drivecircuit ofBJTiscomplex.
ii. It hastheproblemofchargestoragewhichsetsalimit onswitchingfrequencies.
iii. It cannotbeusedinparalleloperationduetoproblems ofnegativetemperaturecoefficient.

Thyristors–SiliconControlledRectifiers(SCR's)

A silicon controlled rectifier or semiconductor-controlled rectifier is a four-layer solidstate current-controlling device. The name "silicon controlled rectifier" is General Electric's trade name for a type ofthyristor.

SCRs are mainly used in electronic devices that require control of high voltage and power. This makesthemapplicableinmediumandhighACpoweroperationssuchasmotorcontrolfunction.

AnSCRconductswhenagatepulseisappliedtoit,justlikeadiode.Ithasfourlayersofsemiconductors that form two structures namely; NPNP or PNPN. In addition, it has three junctionslabeled as J1, J2 and J3 and three terminals(anode, cathode and a gate). An SCR is diagramaticallyrepresentedasshownbelow.

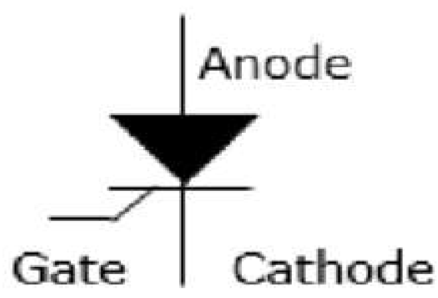


Figure: 1.4.Symbolofthyristor

TheanodeconnectstotheP-type,cathodetotheN-typeandthegatetotheP-typeasshownbelow.

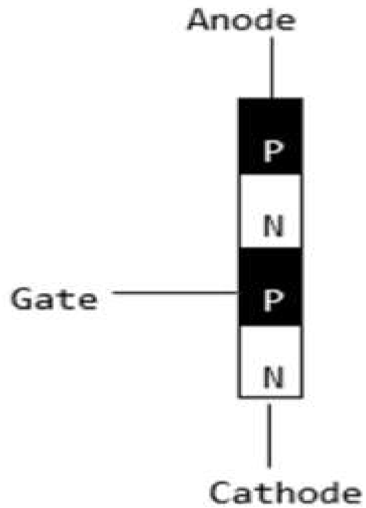


Figure:1.5.Structureofthyristor

In an SCR, the intrinsic semiconductor is silicon to which the required dopants are infused. However,dopingaPNPNjunctionisdependentontheSCRapplication.

ModesofOperationinSCR

- OFF state (forward blocking mode) − Here the anode is assigned a positive voltage, the gate isassigned a zero voltage (disconnected) and the cathode is assigned a negative voltage. As aresult,JunctionsJ1and J3are in forward biaswhile J2isin reverse bias.J2 reachesitsbreakdown avalanche value and starts to conduct. Below this value, the resistance of J1 issignificantlyhighandisthussaidtobeintheoff state.

- ON state (conducting mode) − An SCR is brought to this state either by increasing the potentialdifference between the anode and cathode above the avalanche voltage or by applying a positivesignal at the gate. Immediately the SCR starts to conduct, gate voltage is no longer needed tomaintaintheON stateandis,therefore,switchedoff by−

    - Decreasingthecurrentflowthroughittothelowestvaluecalledholdingcurrent
    - Usingatransistorplacedacrossthejunction.

- Reverse blocking − This compensates the drop in forward voltage. This is due to the fact that alow doped region in P1 is needed. It is important to note that the voltage ratings of forward andreverseblockingareequal.

CharacteristicsofThyristor

A thyristoris a fourlayer3 junction p-n-p-n semiconductordevice consisting of at least three p-njunctions, functioning as an electrical switch for high power operations. It has three basic terminals,namely the anode, cathode and the gate mounted on the semiconductor layers of the device. The symbolicdiagram and the basic circuit diagram for determining the characteristics of thyristoris shown in thefigurebelow,

V-ICharacteristicsofaThyristor

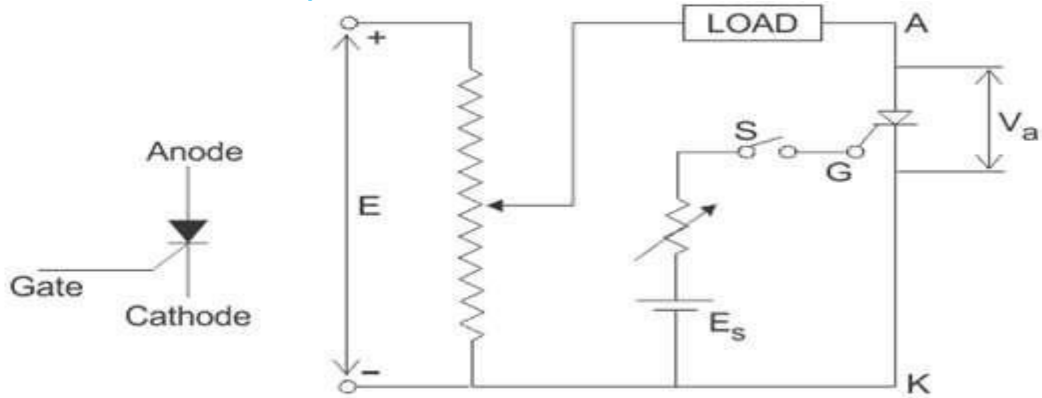


Figure:1.6.CircuitdiagramforcharacteristicsofSCR

From the circuit diagram above we can see the anode and cathode are connected to the supply voltagethrough the load. Another secondary supply E_s is applied between the gate and the cathode terminal whichsuppliesforthe positive gate currentwhen the switch Sisclosed.On giving the supply we gettherequired V-I characteristics of a thyristor show in the figure below for anode to cathode voltage $V_a$andanode current I_a as we can see from the circuit diagram. A detailed study of the characteristics reveal thatthe thyristor has three basic modes of operation, namely the reverse blocking mode, forward blocking(off-state) mode and forward conduction (on-state) mode. Which are discussed in great details below, tounderstandthe overallcharacteristicsof athyristor.

ReverseBlocking ModeofThyristor

Initially for the reverse blocking mode of the thyristor, the cathode is made positive with respect to anodeby supplying voltage E and the gate to cathode supply voltage E_s is detached initially by keeping switch Sopen. For understanding this mode we should look into the fourth quadrant where the thyristor is reversebiased.

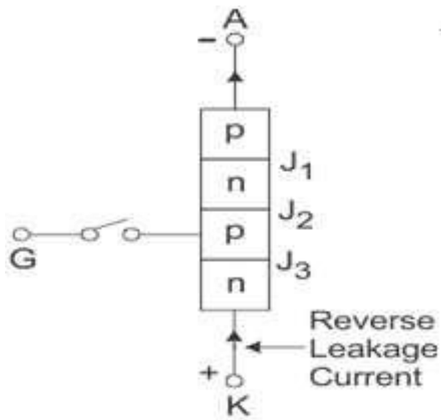


Figure:1.7.ReverseblockingmodeofSCR

Here Junctions J_1 and J_3 are reverse biased whereas the junction J_2 is forward biased. The behavior of thethyristor here is similar to that of two diodes are connected in series with reverse voltage applied acrossthem. As a result only a small leakage current of the order of a few µAmps flows. This is the reverseblocking mode or the off-state, of the thyristor. If the reverse voltage is now increased, then at a particularvoltage, known as the critical breakdown voltage V_{BR}, an avalanche occurs at J_1 and J_3 and the reversecurrent increases rapidly. A large current associated with V_{BR} gives rise to more losses in the SCR, whichresultsinheating.Thismayleadtothyristordamageasthejunctiontemperaturemayexceeditspermissible temperature rise. It should, therefore, be ensured that maximum working reverse voltageacross a thyristor does not exceed V_{BR}. When reverse voltage applied across a thyristor is less than V_{BR},the device offers very high impedance in the reverse direction.The SCR in the reverse blocking modemaythereforebetreatedasopencircuit.

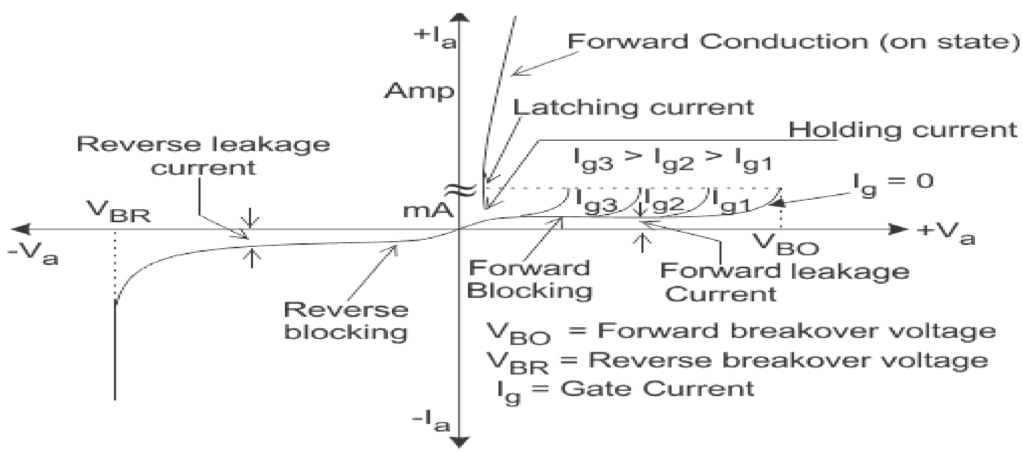


Figure:1.8.V- Icharacteristicsof SCR

ForwardBlocking Mode Nowconsideringtheanodeis positivewithrespecttothecathode,with gatekeptinopencondition.Thethyristorisnowsaidtobeforwardbiasedasshownthefigurebelow.

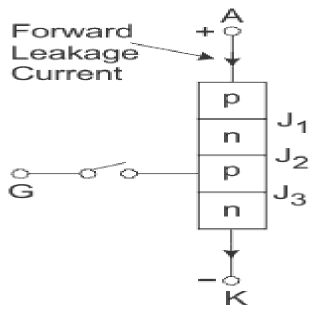


Figure: 1.9.Forwardconnectionof SCR

As we can see the junctions J_1 and J_3 are now forward biased but junction J_2 goes into reverse biasedcondition. In this particular mode, a small current, called forward leakage current is allowed to flowinitially as shown in the diagram forcharacteristics of thyristor.Now,ifwe keepon increasing theforwardbiasedanodetocathode voltage.

In this particular mode, the thyristor conducts currents from anode to cathode with a very small voltagedrop across it. A thyristor is brought from forward blocking mode to forward conduction mode by turningit on by exceeding the forward break over voltage or by applying a gate pulse between gate and cathode.In this mode, thyristor is in on-state and behaves like a closed switch. Voltage drop across thyristor in theon state is of the order of 1 to 2 V depending beyond a certain point, then the reverse biased junction J_2will have an avalanche breakdown at a voltage called forward break over voltage V_{B0} of the thyristor. But,if we keep the forward voltage less than V_{BO}, we can see from the characteristics of thyristor, that thedevice offers high impedance. Thus even here the thyristor operates as an open switch during the forwardblockingmode.

ForwardConductionMode

When the anode to cathode forward voltage is increased,with gate circuitopen,the reverse junction J_2willhaveanavalanchebreakdownatforwardbreakovervoltageV_{BO}leadingtothyristorturnon.Oncethe thyristor is turned on we can see from the diagram for characteristics of thyristor, that the point M atonce shifts toward N and then anywhere between N and K. Here NK represents the forward conductionmodeofthethyristor.Inthismodeofoperation,thethyristorconductsmaximumcurrentwithminimum voltagedrop,thisisknownastheforwardconductionforwardconductionortheturnonmodeofthethyristor.

Two transistoranalogyofSCR

Basic**operatingprincipleofSCR**,canbeeasilyunderstoodbythe**twotransistormodelofSCR**oranalogyofsiliconcontrolledrectifier,as itisalsoacombinationofPandNlayers,showninfigure below

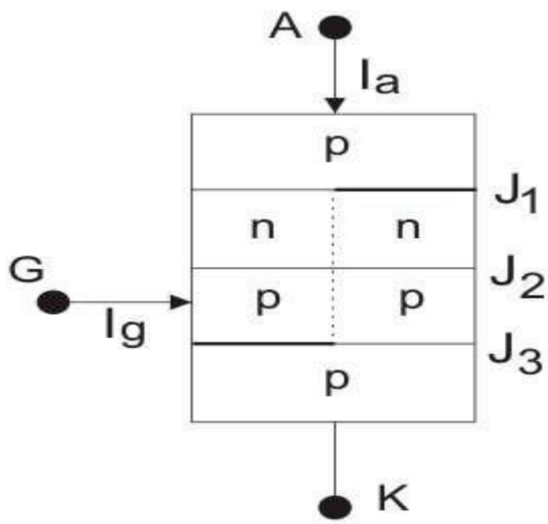


Figure:1.10.Twotransistorstructureof SCR

Thisisapnpnthyristor.Ifwebisectitthroughthedottedlinethenwewill gettwotransistorsi.e.onepnptransistorwithJ_1andJ_2junctionsandanotheris withJ_2andJ_3junctionsasshowninfigurebelow.

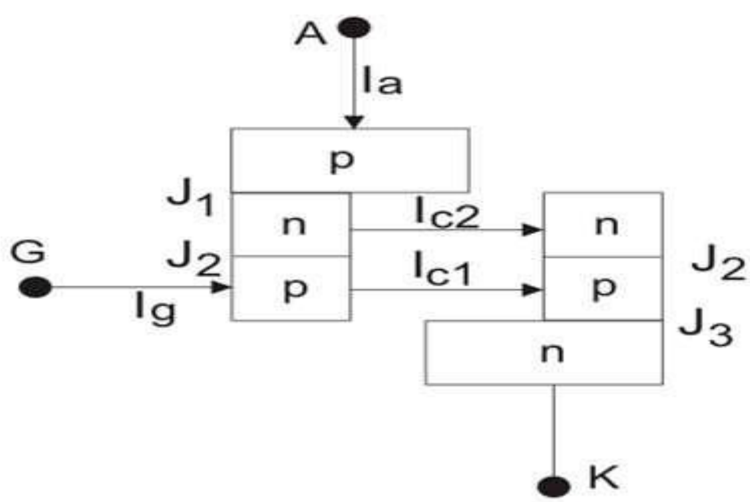


Figure:1.11.TwotransistorstructureofSCR

Whenthetransistorsareinoffstate,therelationbetweenthecollectorcurrentandemittercurrent isshownbelow

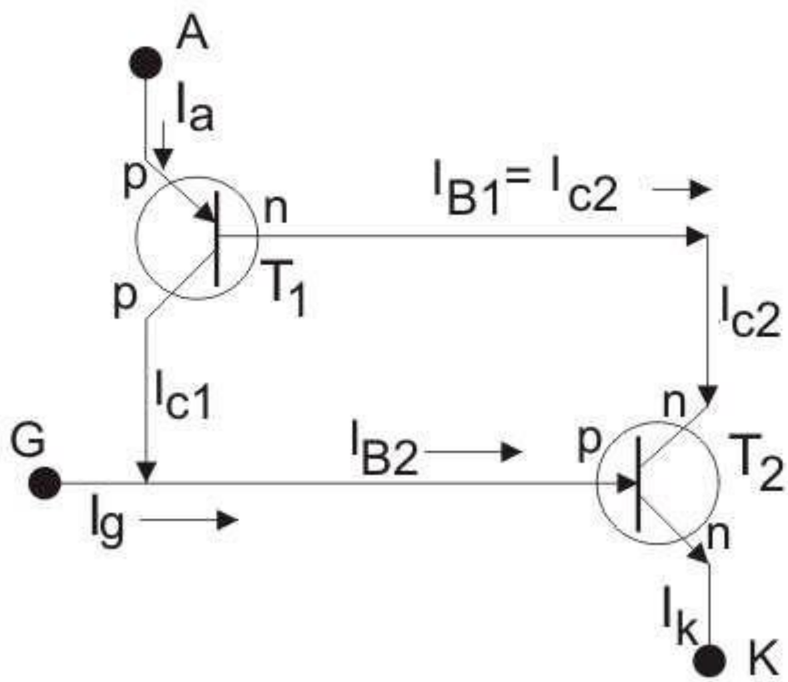


Figure:1.12.Twotransistors connectionofSCR

Here, $I_C$iscollectorcurrent, I_E isemittercurrent, I_{CBO}isforwardleakagecurrent, αiscommonbase forwardcurrentgainandrelationshipbetween$I_C$and$I_B$is $I_C = \beta I_B$ Where,$I_B$is basecurrentandβis common emitterforwardcurrentgain.Let"sfortransistorT_1thisrelationholds

$$I_{C1} = \alpha_1 I_a + I_{CBO1} \ldots\ldots (i)$$

Andthat fortransistorT_2

$I_{C2} = \alpha_2 I_k + I_{CBO2} \ldots\ldots (ii)\ again\ I_{C2} = \beta_2 I_{B2}$ Now,bytheanalysis oftwo transistorsmodel wecangetanodecurrent,

$$I_a = I_{C1} + I_{C2}\ \ [applying\ KCL]$$

Fromequation(i)and(ii),weget, $I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_k + I_{CBO2} \ldots\ldots (iii)$

IfappliedgatecurrentisI$_g$thencathodecurrentwillbe thesummationofanodecurrentandgatecurrenti.e.

$$I_k = I_a + I_g$$

BysubstitutingthisvalueofI$_k$in(iii)weget,

$$I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2}$$
$$I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

Fromthisrelationwecanassurethatwithincreasingthevalueof$(\alpha_1 + \alpha_2)$towardsunity,corresponding anode current will increase. Now the question is how $(\alpha_1 + \alpha_2)$increasing.Here is theexplanationusingtwotransistormodelofSCR.AtthefirststagewhenweapplyagatecurrentI$_g$,itactsas base current of T_2 transistor i.e. $I_{B2} = I_g$ and emitter current i.e. $I_k = I_g$ of the T,$_2$ transistor. Henceestablishmentof the emittercurrentgivesriseα_2 as

$$\alpha_2 = \frac{I_{CBO1}}{I_g}$$

Presenceofbasecurrentwillgeneratecollectorcurrentas

$$I_{C2} = \beta_2 \times I_{B2} = \beta_2 I_g$$

ThisI$_{C2}$isnothingbutbasecurrentI$_{B1}$oftransistorT,$_1$,which willcausetheflowofcollectorcurrent,

$$I_{C2} = \beta_1 \times I_{B1} = \beta_1 \beta_2 I_g$$

I_{C1} andI$_{B1}$leadtoincreaseI$_{C1}$ as

$$I_a = I_{C1} + I_{B1}$$

Andhence,$\alpha_1$increases.Now,newbasecurrentofT$_2$is

$$I_g + I_{C1} = (1 + \beta_1 \beta_2) I_g,$$

Thiswillleadtoincreaseemittercurrent

$$I_k = I_g + I_{C1}$$

andasaresult $\alpha_2$alsoincreasesandthisfurtherincreases

$$I_{C2} = \beta_2(1 + \beta_1\beta_2)I_g.$$

As

$$I_{B1} = I_{C2},$$

α_1 again increases. This continuous positive feedback effect increases$(\alpha_1 + \alpha_2)$towards unity andanode currenttendsto flow atavery large value.The value currentthen canonly be controlled byexternalresistanceof thecircuit.

TurnonmethodsofSCR

The turning on Process of the SCR is known as Triggering. In otherwords, turning the SCR fromForward-Blocking state to Forward-Conduction state is known as Triggering. ThevariousmethodsofSCRtriggeringarediscussedhere.

ThevariousSCRtriggeringmethodsare

- ForwardVoltageTriggering
- ThermalorTemperatureTriggering
- RadiationorLighttriggering
- dv/dtTriggering
- GateTriggering

(a) ForwardVoltageTriggering:-

- Inthismode,anadditionalforwardvoltageisappliedbetweenanodeandcathode.
- When the anode terminal is positive with respect to cathode (V_{AK}), Junction J1 and J3 is forwardbiasedandjunctionJ2isreversebiased.
- NocurrentflowduetodepletionregioninJ2isreverse biased(exceptleakagecurrent).
- AsV_{AK} isfurtherincreased,atavoltageV_{BO} (ForwardBreakOverVoltage)thejunctionJ2undergoes avalanche breakdown and so a current flows and the device tends to turn ON(even whengateisopen)

(b) Thermal (or)TemperatureTriggering:-

- ThewidthofdepletionlayerofSCRdecreaseswithincreaseinjunctiontemperature.
- ThereforeinSCRwhen V_{AR}isverynearitsbreakdownvoltage,thedeviceistriggeredby increasingthejunctiontemperature.
- Byincreasingthejunctiontemperaturethereversebiasedjunctioncollapsesthusthedevicestartstoconduct.

(c) RadiationTriggering (or)LightTriggering:-

- ForlighttriggeredSCRsaspecialterminalnicheismadeinsidetheinnerPlayerinsteadofgateterminal.
- When lightisallowedtostrikethisterminal,freechargecarriersaregenerated.
- Whenintensityoflightbecomesmorethananormalvalue,thethyristorstartsconducting.
- ThistypeofSCRsarecalledasLASCR

(d) dv/dtTriggering:-

- Whenthedeviceisforwardbiased,J1andJ3areforwardbiased,J2isreversebiased.
- JunctionJ2 behavesasacapacitor,duetothechargesexistingacrossthejunction.
- If voltage across the device is V, the charge by Q and capacitance by C then,i_c=dQ/dt

  Q=CV

  i_c=d(CV)/dt

  =CdV/dt+VdC/dt

  asdC/dt=0

  i_c=CdV/dt
- Therefore when the rate of change ofvoltage acrossthe device becomeslarge,the device may turnON,evenifthe voltageacrossthedeviceissmall.

(e) GateTriggering:-

- Thisismost widelyusedSCRtriggering method.
- Applyingapositive voltagebetweengateandcathodecanTurnONaforwardbiasedthyristor.
- When apositive voltage isapplied atthe gate terminal,charge carriersare injected in the innerP-layer,therebyreducingthe depletionlayerthickness.
- Astheappliedvoltageincreases,thecarrierinjectionincreases,thereforethevoltageatwhichforwardbreak-overoccursdecreases.

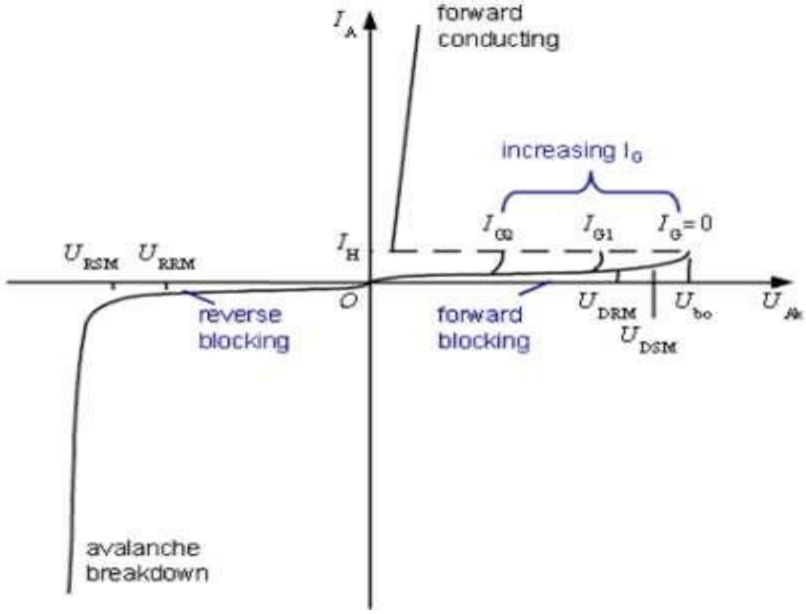


Figure:1.13.V -IcharacteristicsofSCR

- Threetypesofsignalsareusedforgatetriggering.

1. DCgatetriggering:-

- A DC voltage of proper polarity is applied between gate and cathode (Gate terminal is positive withrespecttoCathode).
- WhenappliedvoltageissufficienttoproducetherequiredgateCurrent,thedevicestartsconducting.
- One drawback of this scheme is that both power and control circuits are DC and there is no isolationbetweenthetwo.
- Anotherdisadvantageis thatacontinuous DCsignal has tobeapplied.Sogatepowerlossis high.

2. ACGateTriggering:-

- HereACsourceisusedforgatesignals.
- Thisschemeprovidesproperisolationbetweenpowerandcontrolcircuit.
- Drawbackofthisschemeis thataseparatetransformeris requiredtostepdownacsupply.
- TherearetwomethodsofACvoltagetriggeringnamely(i)RTriggering(ii)RCtriggering

(i) Resistancetriggering:

Thefollowingcircuitshowstheresistancetriggering.

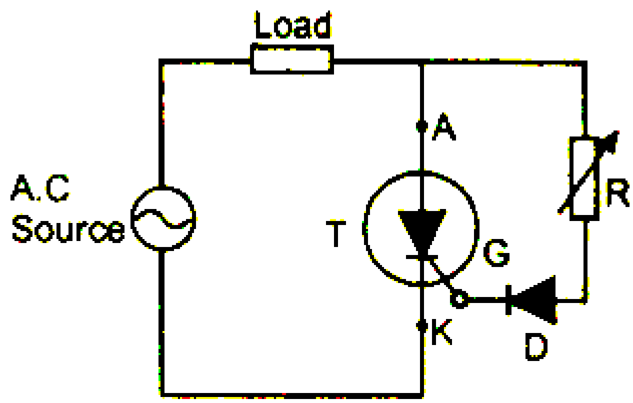


Figure:1.14.Resistancetriggeringcircuit ofSCR

- Inthismethod,thevariableresistanceRisusedtocontrolthegatecurrent.
- DependinguponthevalueofR,whenthemagnitudeofthegatecurrentreachesthesufficientvalue(latchingcurrentof thedevice) theSCRstartstoconduct.
- The diode D is called as blocking diode. It prevents the gate cathode junction from getting damagedinthenegativehalfcycle.
- By considering that the gate circuit is purely resistive, the gate current is in phase with the appliedvoltage.
- Byusingthismethodwecanachievemaximumfiringangleupto90°.

(ii) RCTriggering

Thefollowingcircuitshows theresistance-capacitancetriggering.

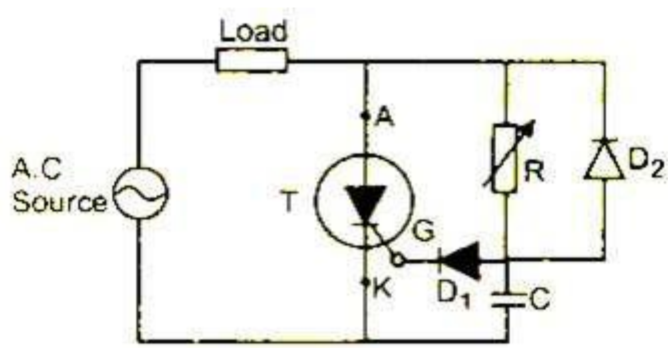


Figure:1.15.ResistanceCapacitancetriggeringcircuitof SCR

- Byusingthismethodwecanachievefiringanglemorethan90°.
- In the positive half cycle, the capacitor is charged through the variable resistance R up to the peakvalueoftheappliedvoltage.
- ThevariableresistorRcontrolsthechargingtimeof thecapacitor.
- Depends upon the voltage across the capacitor, when sufficient amount of gate current will flow inthecircuit,theSCRstartstoconduct.
- In the negative half cycle, the capacitor C is charged up to the negative peak value through thediodeD2.
- DiodeD1isusedtopreventthereversebreakdownofthegatecathode junctioninthenegative halfcycle.

3. PulseGateTriggering:-

- Inthismethodthegatedriveconsistsofasinglepulseappearingperiodically(or)asequenceofhighfrequency pulses.
- Thisisknownascarrierfrequencygating.
- Apulsetransformeris usedforisolation.
- Themainadvantageisthatthereisnoneedofapplyingcontinuoussignals,sothegatelossesarereduced.

Advantagesofpulsetraintriggering:

- Lowgatedissipationathighergatecurrent.
- Smallgateisolatingpulsetransformer
- Low dissipation in reverse biased condition is possible. So simple trigger circuits are possible insomecases
- WhenthefirsttriggerpulsefailstotriggertheSCR,thefollowingpulsescansucceedinlatchingSCR.This importantwhile
- Triggeringinductivecircuitsandcircuits havingbackemf's.

Turnoffmethods ofSCR:

SCRcanbeturnedONbyapplyingappropriatepositivegatevoltagebetweenthegateandcathodeterminals,butitcannotbet urnedOFFthroughthegateterminal.TheSCRcanbebroughtbacktothe forward blocking state from the forward conduction state by reducing the anode or forward current belowtheholdingcurrentlevel.

The turn OFF process of an SCR is called **commutation**. The term commutation means the transfer ofcurrents from one path to another. So the commutation circuit does this job by reducing the forwardcurrenttozerosoastoturnOFFtheSCRor Thyristor.

ToturnOFFtheconductingSCRthebelowconditionsmustbesatisfied.

- TheanodeorforwardcurrentofSCRmustbereducedtozeroorbelowthelevelofholdingcurrentandthen,
- AsufficientreversevoltagemustbeappliedacrosstheSCRtoregainitsforwardblockingstate.

When the SCR is turned OFF by reducing forward current to zero there exist excess charge carriers indifferentlayers.ToregaintheforwardblockingstateofanSCR,theseexcesscarriersmustberecombined. Therefore, this recombination process is accelerated by applying a reverse voltage across theSCR.

SCRTurnOFFMethods

ThereversevoltagewhichcausestocommutatetheSCRiscalledcommutationvoltage.Dependingonthecommutationvoltagelocated,thecommutation methodsareclassifiedintotwomajortypes.
Those are 1) Forced commutation and 2) Natural commutation.Letus discussin brief aboutthesemethods.

ForcedCommutation

In case of DC circuits, there is no natural current zero to turn OFF the SCR. In such circuits, forwardcurrent must be forced to zero with an external circuit to commutate the SCR hence named as forcedcommutation.

This commutating circuit consists of components like inductors and capacitors called as commutatingcomponents. These commutating componentscause to apply a reversevoltage acrossthe SCR thatimmediatelybringthecurrentintheSCRtozero.

Basedonthemannerinwhichthezerocurrentachievedandarrangementofthecommutatingcomponents, forced commutation is classified into different types such as class A, B, C, D, and E. Thiscommutationismainlyusedinchopperandinvertercircuits.

ClassACommutation

Thisisalsoknownasselfcommutation,orresonantcommutation,orloadcommutation.Inthiscommutation, the source of commutation voltage is in the load. This load must be an under damped R-L-CsuppliedwithaDCsupplysothatnaturalzeroisobtained.

The commutating components L and C are connected either parallel or series with the load resistance R asshownbelow withwaveformsofSCRcurrent,voltageandcapacitorvoltage.

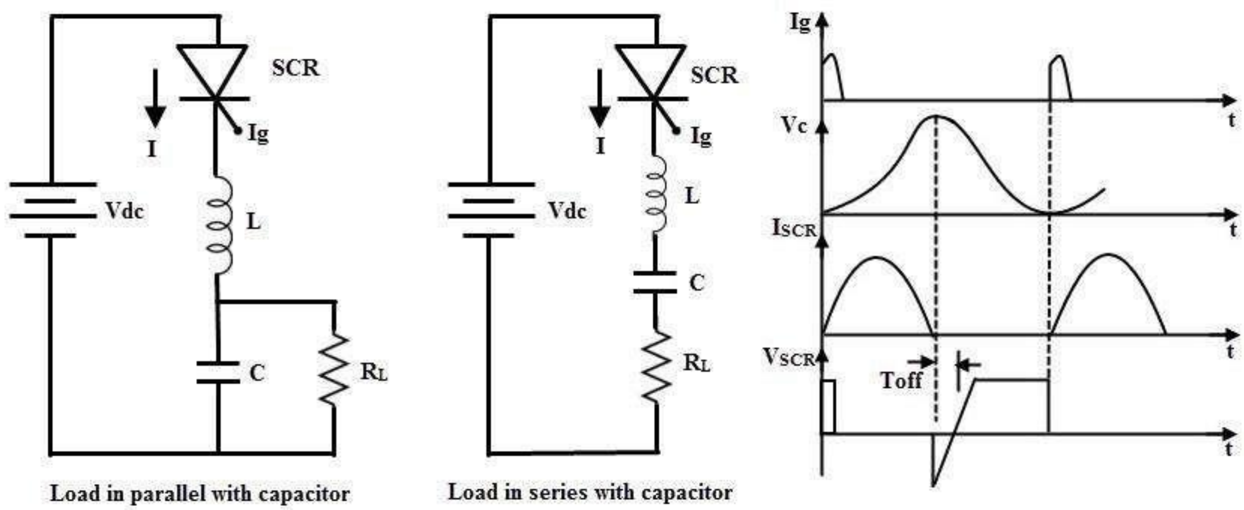


Figure:1.16.ClassACommutationcircuitandwaveforms

Thevalueofloadresistanceandcommutatingcomponentsaresoselectedthattheyforms aunderdampedresonantcircuitto produce natural zero.When the thyristororSCR istriggered,the forward currentsstartsflowingthroughitandduringthisthecapacitorischargeduptothevalueof E.

Once the capacitoris fully charged (more than the supply source voltage) the SCR becomes reversebiased and hence the commutation of the device. The capacitor discharges through the load resistance tomake ready the circuit for the next cycle of operation. The time for switching OFF the SCR depends ontheresonantfrequencywhichfurtherdependsontheLandCcomponents.

This method is simple and reliable. For high frequency operation which is in the range above 1000 Hz,this typeofcommutationcircuits ispreferredduetothehighvaluesofLandCcomponents.

ClassB Commutation

This is also a self commutation circuit in which commutation of SCR is achieved automatically by L andC components, once the SCR is turned ON. In this, the LC resonant circuit is connected across the SCRbut not in series with load as in case of class A commutation and hence the L and C components do notcarrytheloadcurrent.

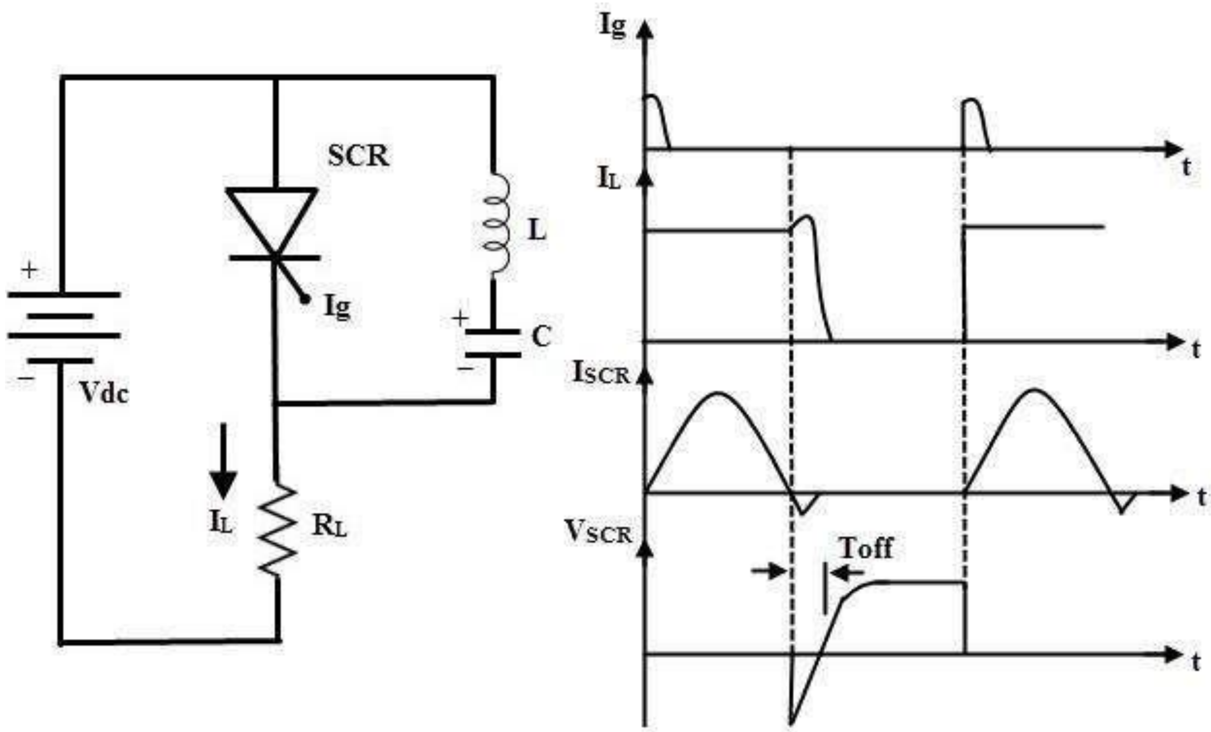


Figure:1.17.ClassB Commutationcircuitandwaveforms

When the DC supply is applied to the circuit, the capacitor charges with an upper plate positive and lowerplate negative up to the supply voltage E. When the SCR is triggered, the current flows in two directions,one is through E+ – SCR – R – E- and anotherone is the commutating current through L and Ccomponents.

Once the SCR is turned ON, the capacitor is starts discharging through C+ – L – T – C-. When thecapacitor is fully discharged, it starts charging with a reverse polarity. Hence a reverse voltage appliedacrosstheSCRwhichcausesthecommutatingcurrentICtoopposeloadcurrentIL.

When the commutating current Ic ishigher than the load current, the SCR will automatically turn OFFandthecapacitorchargeswithoriginalpolarity.

In the above process, the SCR is turned ON for some time and then automatically turned OFF for sometime.Thisisacontinuousprocessandthedesiredfrequencyof ON/OFFdependsonthevaluesofLand C.This typeofcommutationismostlyusedinchoppercircuits.

ClassCCommutation

In this commutation method, the main SCR is to be commutated is connected in series with the load andan additional or complementary SCR is connected in parallel with main SCR. This method is also calledascomplementarycommutation.

In this , SCR turns OFF with a reverse voltage of a charged capacitor. The figure below shows thecomplementarycommutationwithappropriatewaveforms.

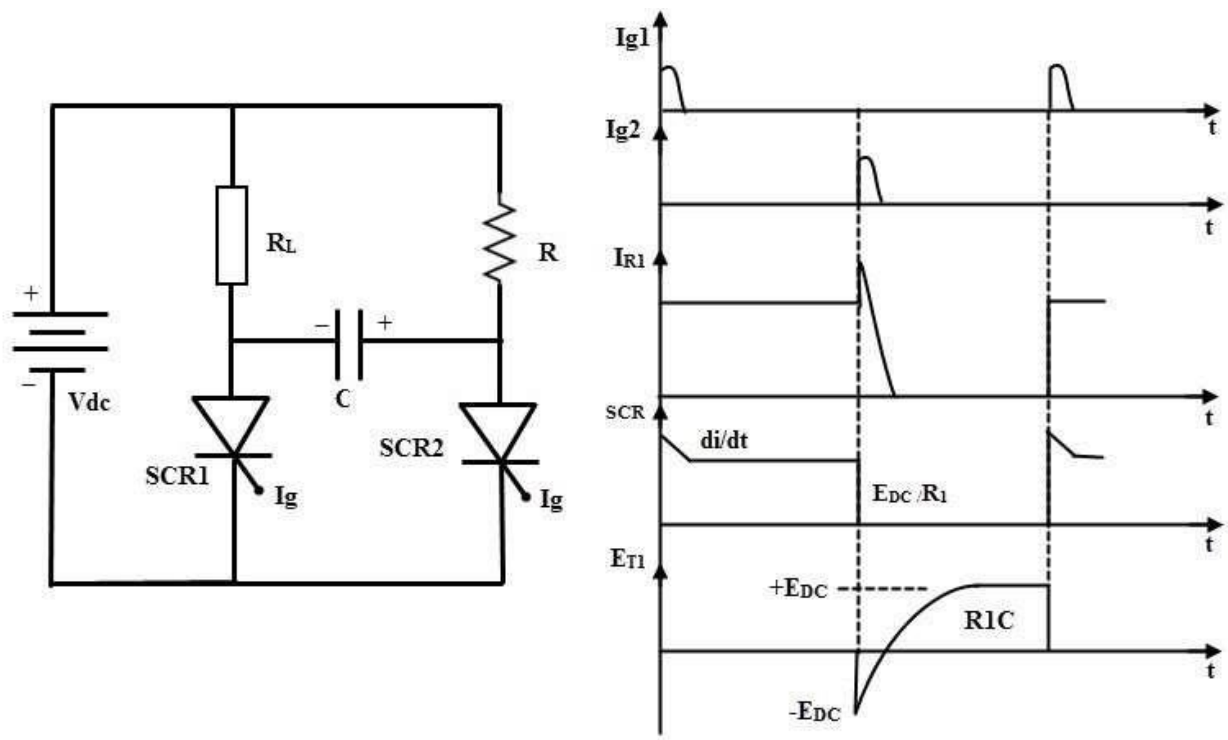


Figure:1.18.ClassCCommutationcircuitandwaveforms

Initially, both SCRs are in OFF state so the capacitor voltage is also zero. When the SCR1 or main SCR istriggered, current starts flowing in two directions, one path is E+– R1 – SCR1 – E- and another path isthe charging current E+– R2- C+ – C- SCR1 – E- . Therefore,the capacitorstarts charging up to thevalueof E.

When the SCR2 is triggered, SCR is turned ON and simultaneously a negative polarity is applied acrossthe SCR1. So this reverse voltage across the SCR1 immediately causes to turn OFF the SCR1. Now thecapacitor starts charging with a reverse polarity through the path of E+ – R1- C+ – C- SCR2 – E-. Andagain,iftheSCR1istriggered,dischargingcurrentofthecapacitorturnsOFFtheSCR2.

This commutation is mainly used in single phase inverters with a centre tapped transformers. The McMurray Bedford inverter is the best example of this commutation circuit. This is a very reliable method ofcommutationanditisalsousefulevenatfrequenciesbelow1000Hz.

ClassDCommutation

This is also called as auxiliary commutation because it uses an auxiliary SCR to switch the chargedcapacitor. In this, the main SCR is commutated by the auxiliary SCR. The main SCR with load resistanceformsthepowercircuitwhilethediodeD,inductorLandSCR2formsthecommutationcircuit.

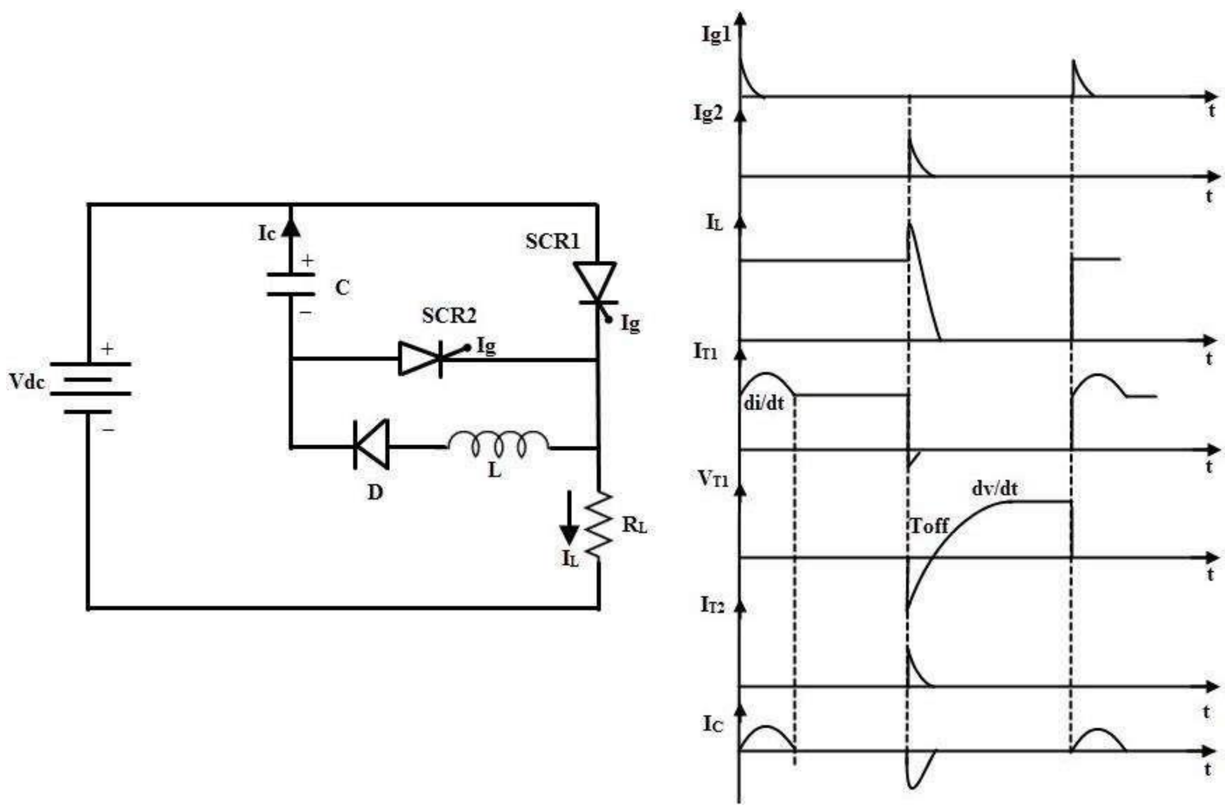


Figure:1.19.ClassDCommutationcircuitandwaveforms

When the supply voltage E is applied, both SCRs are in OFF state and hence the capacitor voltage is zero.In order to charge the capacitor, SCR2 must be triggered first. So the capacitor charges through the pathE+–C+–C-–SCR2-R-E-.

When the capacitor is fully charged the SCR2 becomes turned OFF because no current flow through theSCR2 when capacitor is charged fully. If the SCR1 is triggered, the current flows in two directions; one istheloadcurrentpathE+–SCR1-R-E-andanotheroneiscommutationcurrentpathC+–SCR1-L-D-C.

As soon as the capacitor completely discharges, its polarities will be reversed but due to the presence ofdiode the reverse discharge is not possible. When the SCR2 is triggered capacitor starts dischargingthrough C+ – SCR2- SCR1- C-. When this discharging current is more than the load current the SCR1becomesturnedOFF.

Again, the capacitor starts charging through the SCR2 to a supply voltage E and then the SCR2 is turnedOFF. Therefore, both SCRs are turned OFF and the above cyclic process is repeated. This commutationmethodismainlyusedininvertersandalsousedintheJoneschoppercircuit.

ClassE Commutation

This is also known as external pulse commutation. In this, an external pulse source is used to produce thereverse voltage across the SCR. The circuit below shows the class E commutation circuit which uses apulse transformer to produce the commutating pulse and is designed with tight coupling between theprimaryandsecondarywithasmallairgap.

If the SCR need to be commutated,pulse duration equal to the turn OFF time of the SCR is applied.When the SCR is triggered, load current flows through the pulse transformer. If the pulse is applied to theprimaryofthepulsetransformer,anemforvoltageisinducedinthesecondaryofthepulsetransformer.

This induced voltage is applied across the SCR as a reverse polarity and hence the SCR is turned OFF.Thecapacitoroffersaverylowor zeroimpedancetothehighfrequencypulse.

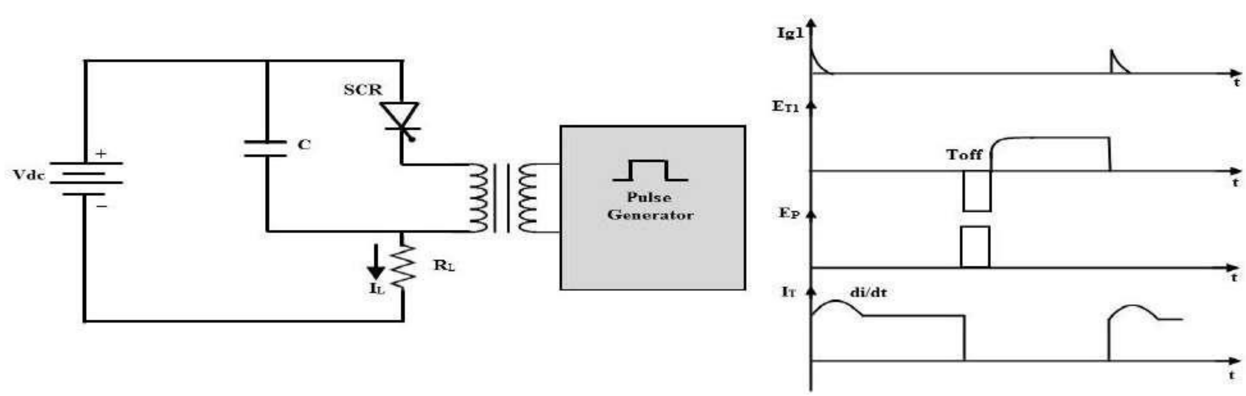


Figure:1.20.ClassECommutationcircuitandwaveforms

NaturalCommutation

In natural commutation, the source of commutation voltage is the supply source itself. If the SCR isconnected to an AC supply, at every end of the positive half cycle the anode current goes through thenatural current zero and also immediately a reverse voltage is applied across the SCR. These are theconditionstoturnOFFtheSCR.

This method of commutation is also called as source commutation, or line commutation, or class Fcommutation. This commutation is possible with line commutated inverters, controlled rectifiers, cycloconvertersandACvoltageregulatorsbecausethesupplyisthe ACsourceinalltheseconverters.

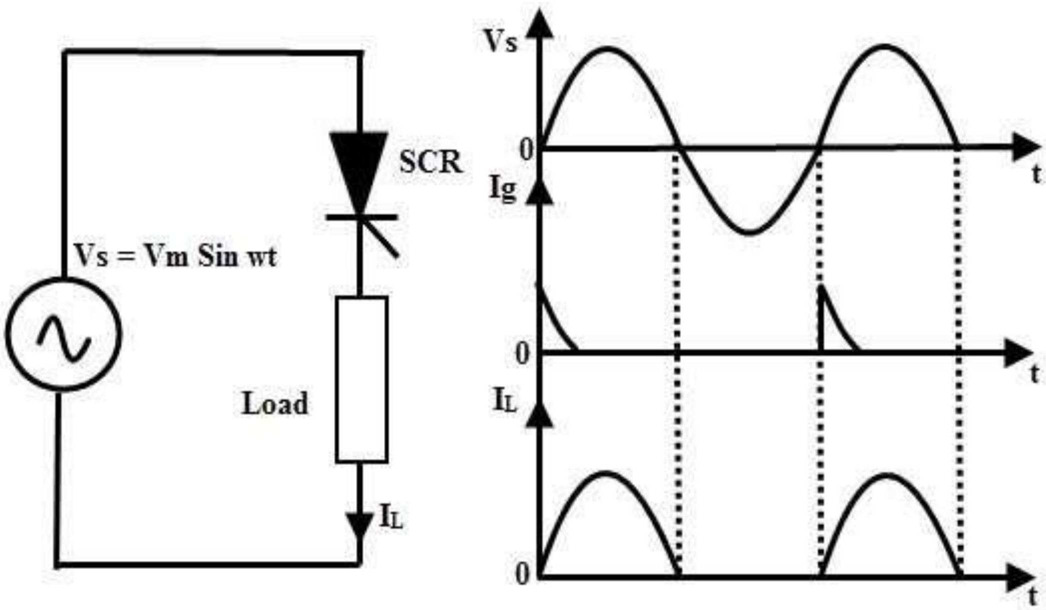


Figure: 1.21.NaturalCommutationcircuitandwaveforms

DynamicTurnOFFSwitchingCharacteristics

The transition of an SCR from forward conduction state to forward blocking state is called as turn OFF orcommutation of SCR. As we know that once the SCR starts conducting, the gate has no control over it tobringbacktoforwardblockingorOFFstate.

To turn OFF the SCR, the current must be reduced to a level below the holding current of SCR. We havediscussedvariousmethodsabovetoturnOFFtheSCRinwhichSCRturnOFFisachievedbyreducing the forward current to zero. But if we apply the forward voltage immediately after the current zero ofSCR,itstartsconductingagainevenwithoutgatetriggering.

This is due to the presence of charge carriers in the four layers. Therefore, it is necessary to apply thereversevoltage,overafinitetimeacrosstheSCRtoremovethechargecarriers.

Hence the turn OFF time is defined as the time between the instant the anode current becomes zero andthe instant at which the SCR retains the forward blocking capability. The excess charge carriers from thefourlayersmustberemovedtobringbacktheSCRtoforwardconductionmode.

This process takes place in two stages. In a first stage excess carriers from outer layers are removed and insecondstageexcesscarriersintheinnertwolayersaretoberecombined.Hence,thetotalturnOFFtimet$_q$isdivided intotwointervals;reverserecoverytimet$_{rr}$andgaterecoverytime t_{gr}.

$$\mathbf{t_q = t_{rr} + t_{gr}}$$

The figure below shows the switching characteristics of SCR during turn ON and OFF. The time t_1 to t_3 iscalled as reverse recovery time; at the instant $t_1$the anode current is zero and builds up in the reversedirection which is called as reverse recovery current. This current removes the excess charge carriers fromouterlayersduringthetime t_1 tot_3.

At instant t_3, junctions J_1 and J_3 are able to block the reverse voltage but, the SCR is not yet able to blockthe forward voltage due to the presence of excess charge carriers in junction J_2. These carriers can bedisappeared only by the way of recombination and this could be achieved by maintaining areversevoltageacrosstheSCR.

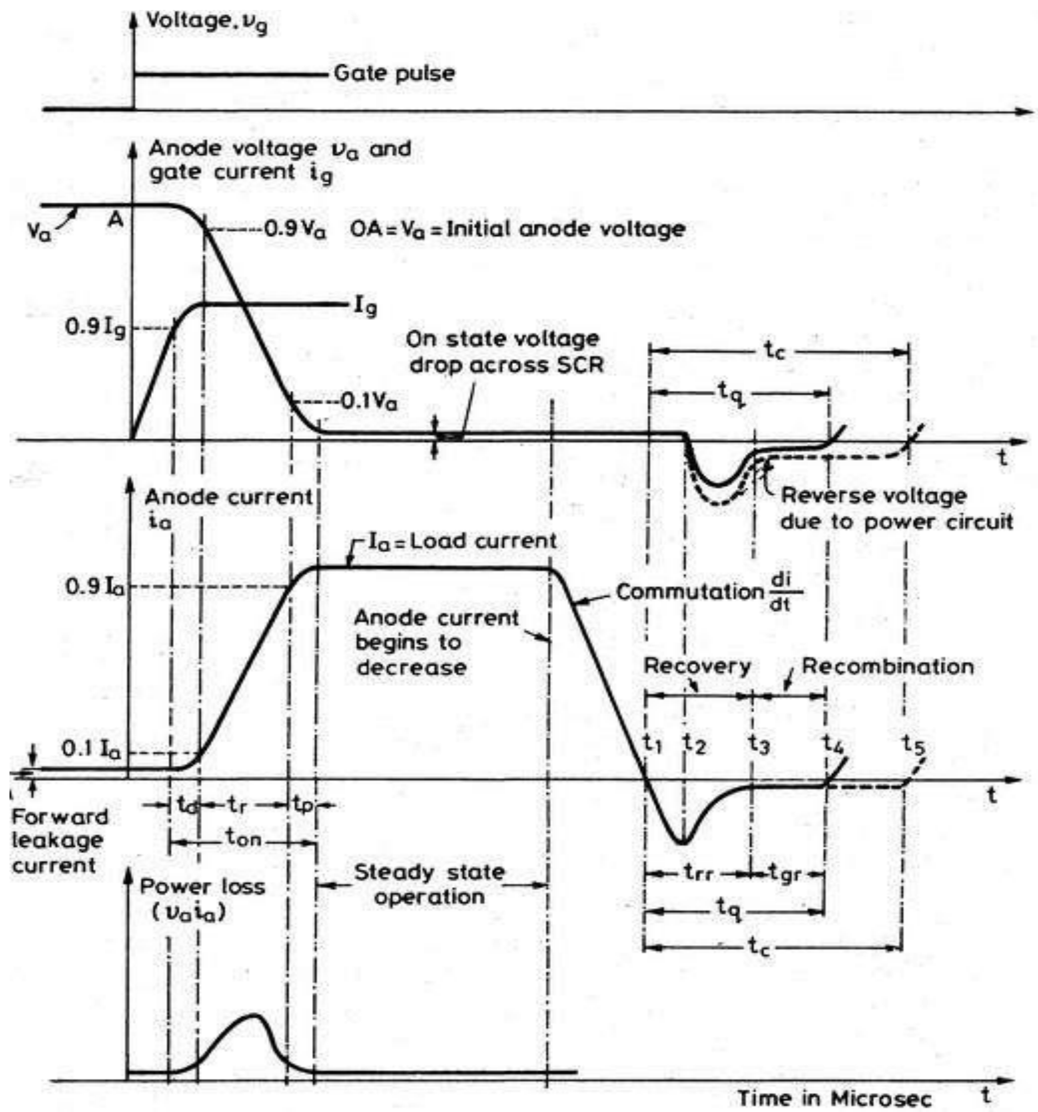


Figure:1.22.Dynamiccharacteristicsof SCR

Hence,duringthetime$t_3$tot_4,therecombinationofchargestakesplaceandattheinstantt_4,junctionJ_2completelyrecovers. Thistimeiscalledgaterecoverytimet_{gr}.

- From the figure the turn OFF time is the time interval between the t_4 and t_1. Generally, this timevariesfrom10to100microseconds.ThisturnOFFtime$t_q$isapplicabletotheindividualSCR.
- The time required by the commutation circuit to apply the reverse voltage to commutate the SCRis called the circuit turn OFF time (t_c). Forasafety margin orreliable commutation, this t_c mustbegreaterthanthet_q otherwisecommutationfailureoccurs.

- The SCRs which have slow turn OFF time as in between 50 to 100 microseconds are called asconverter grade SCRs. These are used in phase controlled rectifiers, cyclo converters, AC voltageregulators,etc.
- The SCRs which have fast turn OFF time as in between 3 to 50 microseconds are inverter gradeSCRs.Thesearecostliercomparedtoconvertergradeandareusedinchoppers,forcecommutatedconvertersandinverters.

ResistanceFiringCircuit

- The circuit below shows the resistance triggering of SCR where it is employed to drive the loadfrom the input AC supply. Resistance and diode combination circuit acts as a gate control circuitrytoswitchtheSCRinthedesiredcondition.
- Asthepositivevoltageapplied,theSCRisforwardbiasedanddoesn"tconductuntilitsgate currentismorethan minimumgatecurrentoftheSCR.
- When the gate current is applied by varying the resistance R2 such that the gate current should bemore than the minimum value of gate current, the SCR is turned ON. And hence the load currentstartsflowingthroughtheSCR.
- The SCR remains ON until the anode current isequal to the holding current of the SCR.And itwill switch OFF when the voltage applied is zero. So the load current is zero as the SCR acts asopenswitch.
- The diode protectsthe gate drive circuitfrom reverse gate voltage during the negative half cycleoftheinput.AndResistanceR1limitsthecurrentflowingthroughthegateterminalanditsvalueissuch thatthegatecurrentshouldnotexceedthe maximumgatecurrent.
- It is the simplest and economical type of triggering but limited for few applications due to itsdisadvantages.
- In this, the triggering angle is limited to 90 degrees only. Because the applied voltage is maximumat 90 degrees so the gate currenthas to reach minimum gate currentvalue somewhere betweenzeroto90degrees.

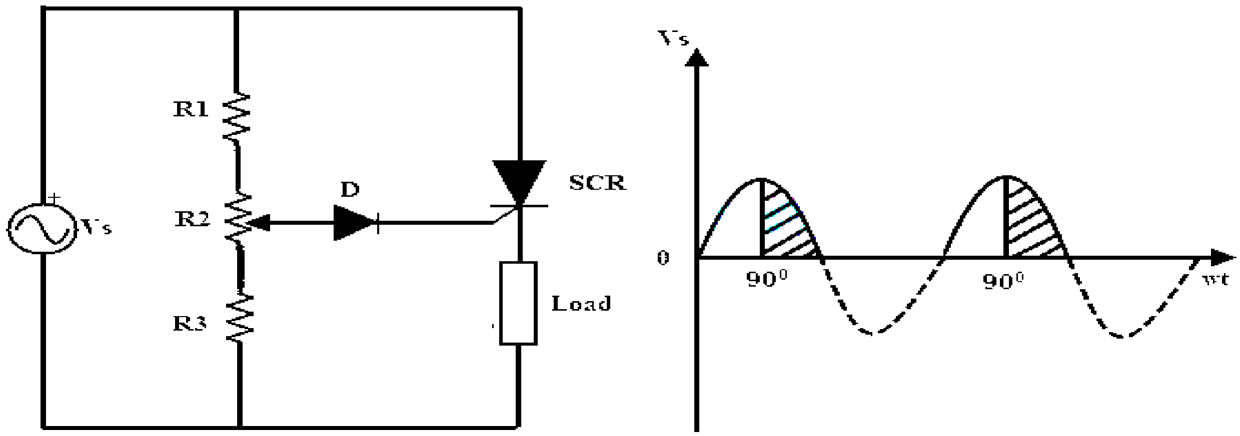


Figure:1. 23.RFiringcircuitforSCRandcorrespondingwaveforms

Resistance–Capacitacne(RC)Firing Circuit

- The limitation of resistance firing circuit can be overcome by the RC triggering circuit whichprovides the firing angle control from 0 to 180 degrees. By changing the phase and amplitude ofthegatecurrent,alarge variationof firingangleisobtainedusingthiscircuit.
- Below figure shows the RC triggering circuit consisting of two diodeswith an RC networkconnectedtoturntheSCR.
- By varying the variable resistance, triggering or firing angle is controlled in a full positive halfcycleof theinputsignal.
- During the negative half cycle of the input signal, capacitor charges with lower plate positivethrough diode D2 up to the maximum supply voltage Vmax. This voltage remains at -Vmax acrossthecapacitortillsupplyvoltageattainszerocrossing.
- During the positive half cycle of the input, the SCR becomes forward biased and the capacitorstartschargingthroughvariableresistancetothetriggeringvoltagevalueof theSCR.
- When the capacitor charging voltage is equal to the gate trigger voltage, SCR is turned ON and thecapacitor holds a small voltage. Therefore the capacitor voltage is helpful for triggering the SCRevenafter90degreesof the inputwaveform.
- In this, diode D1 prevents the negative voltage between the gate and cathode during the negativehalfcycle of the inputthroughdiodeD2.

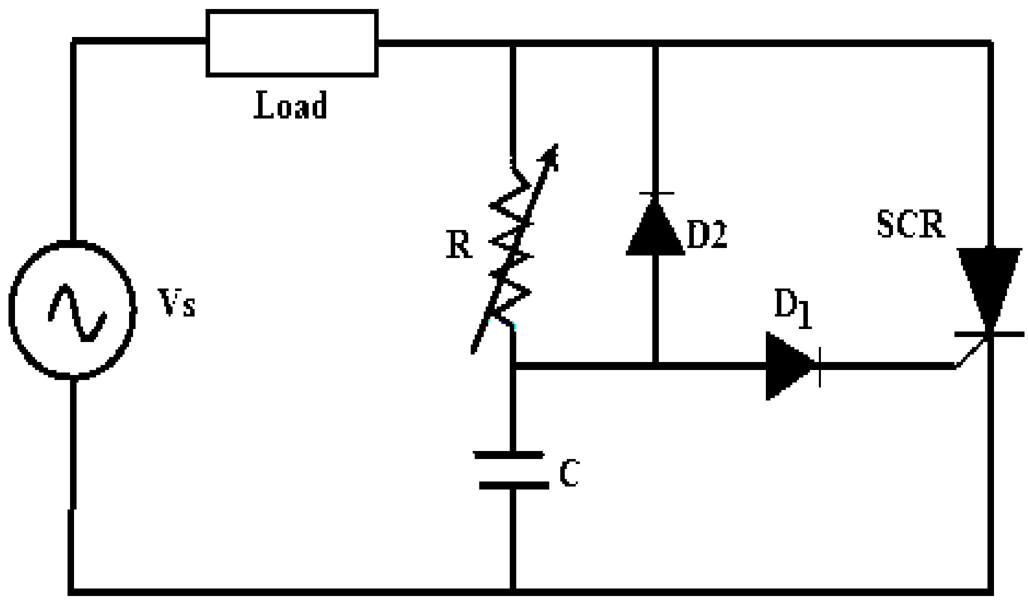


Figure:1.24.RFiringcircuitforSCR

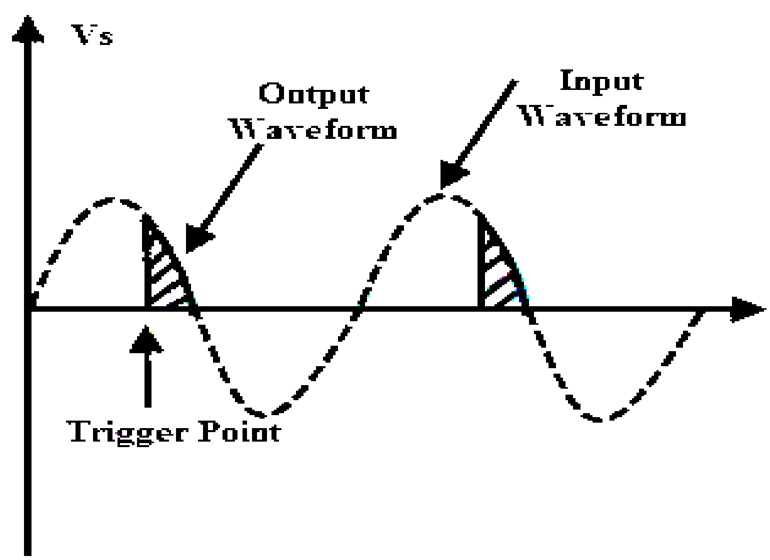


Figure:1.25.RFiringcircuit waveformsofSCR

UJTFiringCircuit

- It is the most common method of triggering the SCR because the prolonged pulsesat the gateusing R and RC triggering methods cause more power dissipation at the gate so by using UJT (UniJunctionTransistor)as triggeringdevicethepowerlossis limitedas it produceatrain ofpulses.
- The RC network is connected to the emitter terminal of the UJT which forms the timing circuit.The capacitor is fixed while the resistance is variable and hence the charging rate of the capacitordependsonthevariableresistancemeansthatthecontrollingoftheRCtimeconstant.
- When the voltage is applied, the capacitor starts charging through the variable resistance. Byvarying the resistance value voltage across the capacitor get varied. Once the capacitor voltage isequal to the peak value of the UJT, it starts conducting and hence produce a pulse output till thevoltage across the capacitor equal to the valley voltage Vv of the UJT. This process repeats andproducesatrainof pulsesatbaseterminal1.
- Thepulse outputatthebaseterminal1isusedtoturnONtheSCRatpredeterminedtime intervals

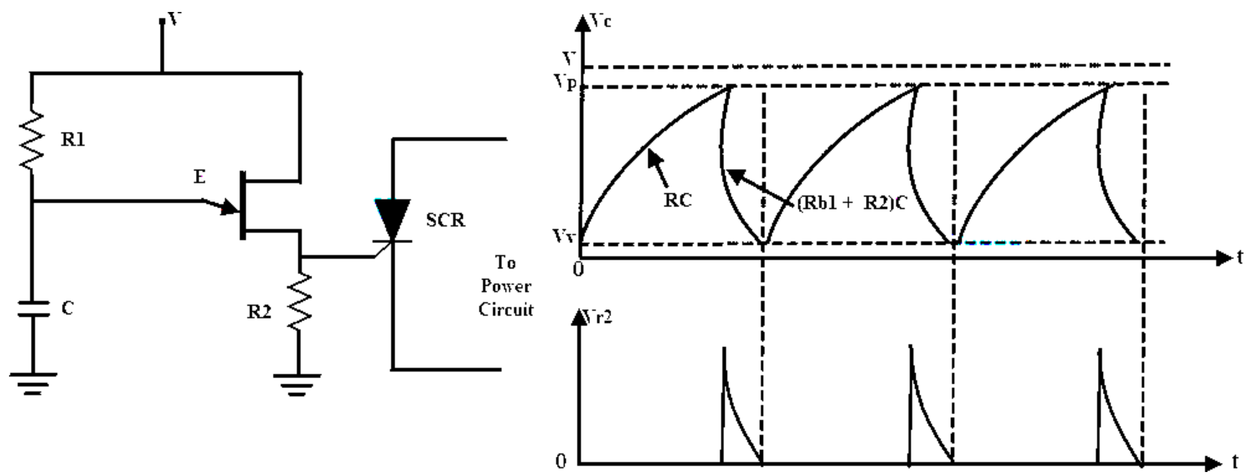


Figure:1. 26.UJTFiringcircuit forSCRandcorrespondingwaveformsSeriesandParallelconnectionsofSCRs

In many power control applications the required voltage and current ratingsexceed the voltage andcurrentthatcan be provided by asingle SCR.Undersuch situationsthe SCRs are required to beconnected in series or in parallel to meet the requirements. Sometimes even if the required rating isavailable, multiple connections are employed for reasons of economy and easy availability of SCRs oflower ratings. Like any other electrical equipment, characteristics/properties of two SCRs of same makeand ratings are never same and this leads to certain problems in the circuit. The mismatching of SCRs isduetodifferencesin

(i) turn-ontime

(ii) turn-offtime

(iii) Leakagecurrentinforwarddirection

(iv) Leakagecurrentinreversedirectionand

(v) Recoveryvoltage.

SeriesConnectionof anSCR

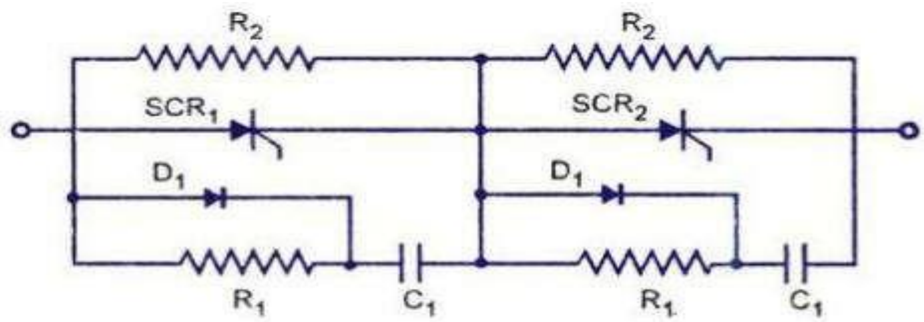


Figure:1.27.SeriesconnectionofSCRs

(i) UnequaldistributionofvoltageacrossSCRs

(ii) Differenceinrecoverycharacteristics.

Care must be taken to share the voltage equally.Forsteady-state conditions,voltage sharing isachieved by using a resistance or a Zener diode in parallel with each SCR. For transient voltagesharing a low non-inductive resistor and capacitor in series are placed across each SCR, as shown infigure. Diodes D1 connected in parallel with resistor Rl, helps in dynamic stabilization. This circuitreducesdifferencesbetweenblockingvoltagesofthetwodeviceswithinpermissiblelimits.Additionally the R-C circuit can also serve the function of „snubber circuit,,. Values of R1 and C1 canprimarily be calculated for snubber circuit and a check can be made for equalization. If ΔQ is thedifference in recovery charge of two devicesarising outofdifferentrecovery currentfordifferenttimeandΔVisthepermissible differenceinblockingvoltagethen

C1=ΔQ/ΔV

The value of resistance Rx should be sufficient to over damp the circuit. Since the capacitor C1 candischargethroughtheSCRduringturn-on,therecanbeexcessivepowerdissipation,buttheswitchingcurrentfromC1islimitedbytheresistorR1Thisresistancealsoservesthepurposeof damping out „ringing" which is oscillation of C1 with the circuit inductance during commutation. Allthe SCRs connected in series should be turned-on at the same time when signals are applied to theirgatessimultaneously.

String efficiency= $\frac{\text{Voioractualcurrentratingofthewholestring}}{\text{NoofSCRsinstring}\times\text{VoiorcurrentratingofindividualSCR}}$

This phenomenon increases the reliability of the string, but reduces the utilization of each SCR. Thusstring efficiency decreases. Reliability of string is measured by derating factor (DRF) which is givenbytheexpression

DRF=1-stringefficiency

ParallelConnectionofanSCR

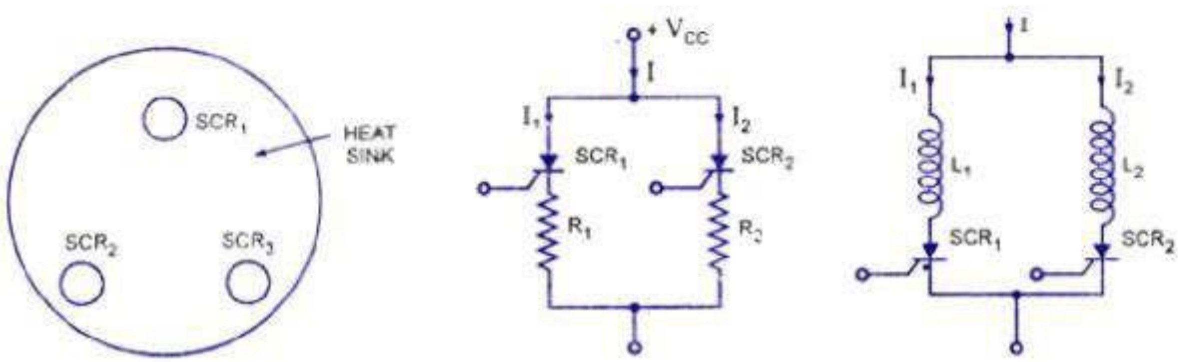


Figure:1.28.ParallelconnectionofSCRs

When the load current exceeds the SCR current rating, SCRs are connected in parallel to share theload current. But when SCRs are operated in parallel, the current sharing between them may not beproper. The device having lowerdynamic resistance will tend to share more current. This will raisethe temperature of that particular device in comparison to other, thereby reducing further its dynamicresistance and increasing current through it. This process is cumulative and continues till the devicegets punctured. Some other factors which directly or indirectly add to this problem are difference inturn-ontime,delaytime,fingervoltageandloopinductance.

Arrangement of SCRs in the cubicle also plays vital role. When the SCRs are connected in parallel, itmust be ensured that the latching current level of the all the SCRs is such that when gate pulse isapplied,allofthemturn-onandremainonwhenthegatepulseisremoved.Furthertheholding currents of the devices should not be so much different that at reduced load current one of the devicegets turned-off because of fall of current through it blow its holding current value. This is particularlyimportantbecauseonincreaseinloadcurrent,thedevicewhichhasstoppedconductingcannotstar tintheabsence ofgatepulse.

Another point to be considered is the on-state voltage across the device. For equal sharing of currentsby the devices voltage drop across the parallel paths must be equal. For operation of all the SCRsconnected in parallel at the same temperature, it becomes necessary to use a common heat sink fortheir mounting, as illustrated in figure. Resistance compensation used for dc circuits is shown infigure. In this circuit the resistors Rx and R2 are chosen so as to cause equal voltage drop in botharms. Inductive compensation used for ac circuits is shown in figure The difference in characteristicsdue to different turn-on time, delay time, finger voltage, latching current, holding current can beminimized by using inductive compensation. Firing circuits giving high rate of rise can be used toreduce mismatch of gate characteristics and delay time. Current sharing circuits must be designed soas to distribute current equally at maximum temperature and maximum anode current. This is done toensurethatthedevicessharecurrentequallyunderworstoperatingconditions.Mechanicalarrangement of SCRs also plays an important role in reducing mismatching. Cylindrical constructionisperhapsthebestfromthispointof view.

Derating:

Even with all the measures taken, it is preferable to derate the device for series/parallel operation.Another reason for derating is poor cooling and heat dissipation as number of devices operates in thesame branch of the circuit. Normal derating factors are 10 to 15% for parallel connection of SCRsdepending upon the number of devices connected in parallel. Higher voltage safety factor is takenwhenSCRsareconnectedinseries.

NumericalProblems:

1. Thetriggercircuitofathyristorhasasourcevoltageof15Vandtheloadlinehasaslopeof-120Vperampere. TheminimumgatecurrenttoturnontheSCRis25mA.Compute
    i. Sourceresistancerequiredinthegatecircuit
    ii. Thetriggervoltageandtriggercurrentforanaveragegatepowerdissipationof0.4watts

Solution:

i. Theslopeofloadlinegivestherequiredgatesourceresistance.Fromtheloadline, seriesresistancerequiredinthegatecircuitis120Ω

ii. Here$V_g I_g$=0.4W

Forthegatecircuit$E_s = R_s I_g + V_g$

$$15 = 120 I_g + 0.4/I_g$$

$$120 I_g^2 - 15 I_g + 0.4 = 0$$

ItssolutiongivesIg=38.56mAor86.44mA

$$V_g \frac{0.4\times1000}{38.56} = 10.37\text{V}$$

$$= V_g = \frac{0.4\times1000}{86.44} = 4.627\text{V}$$

Sochoosethe valueforIgwhichgiveslessvoltageIg=86.44mAandV_g=4.627Vfromminimumgatecurrentof 25mA.

2. For an SCR the gate-cathode characteristic has a straight line slope of 130. For trigger sourcevoltage of 15V and allowable gate power dissipation of 0.5 watts, compute the gate sourceresistance.
3. SCRs with a rating of 1000V and 200A are available to be used in a string to handle 6kV and 1kA.Calculatethenumberofseriesandparallel unitsrequiredincasede-ratingfactoris0.1and0.2

4. It isrequiredto operate250ASCRin parallelwith 350ASCRwith theirrespectiveon statevoltage drops of 1.6V and 1.2V. Calculate the value of resistance to be inserted in series witheachSCRsothat thesharethetotalloadof600Ainproportiontotheircurrent ratings.

Snubbercircuit

Due to overheating, over voltage, over current or excessive change in voltage or current switching devicesand circuit components may fail. From over current they can be protected by placing fuses at suitablelocations. Heat sinks and fans can be used to take the excess heat away from switching devices and othercomponents. Snubber circuits are needed to limit the rate of change in voltage or current (**di/dt** or **dv/dt**)and over voltage during turn-on and turn-off. These are placed across the semiconductor devices forprotection as well as to improve the performance. Static **dv/dt** is a measure of the ability of a thyristor toretain a blocking state under the influence of a voltage transient. These are also used across the relays andswitchestopreventarcing.

NecessityofUsingtheSnubberCircuit

These are placed across the various switching devices like transistors, thyristors, etc. Switching from ONto OFF state results the impedance of the device suddenly changes to the high value. But this allows asmall current to flow through the switch. This induces a large voltage across the device. If this currentreduced at faster rate more is the induced voltage across the device and also if the switch is not capable ofwithstanding this voltage the switch becomes burn out. So auxiliary path is needed to prevent this highinducedvoltage

Similarly when the transition is from OFF to ON state, due to uneven distribution of the current throughthe area of the switch overheating will takes place and eventually it will be burned. Here also snubber isnecessarytoreducethecurrentatstartingbymakinganalternatepath.

Snubbersinswitching modeprovides oneormoreofthefollowingfunctions

- Shapetheloadlineofabipolarswitchingtransistortokeep itinitssafeoperatingarea.
- Reducingthevoltagesandcurrentsduringturn-ONandturn-OFF transientconditions.
- Removesenergyfromaswitchingtransistoranddissipatetheenergyinaresistortoreducejunctiontemperature.
- Limitingtherateofchange ofvoltageandcurrentsduringthetransients.
- Reduceringingtolimit thepeakvoltageonaswitching transistorandloweringtheirfrequency.

DesignofRCSnubberCircuits:

There are many kinds of snubbers like RC, diode and solid state snubbers but the most commonly usedoneisRCsnubbercircuit.Thisisapplicableforboththerateofrisecontrolanddamping.

This circuitis a capacitor and series resistor connected across a switch. For designing the Snubbercircuits. The amount of energy is to dissipate in the snubber resistance is equal to the amount of energy isstoredinthecapacitors.AnRCSnubberplacedacrosstheswitchcanbeusedtoreducethepeakvoltageat turn-off and to lamp the ring. An RC snubber circuit can be polarized or non-polarized. If you assumethesourcehasnegligibleimpedance,the worstcasepeakcurrentinthesnubbercircuitis

I= Vo/RsandI= C.dv/dt

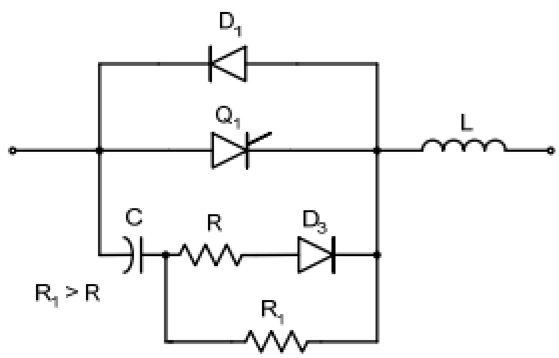


Figure:1.29.Forward-PolarizedRCSnubberCircuit

For an appropriate forward-polarized RC snubber circuit a thyristor or a transistor is connected with ananti-parallel diode. R will limit the forward **dv/dt** and R1 limits the discharge current of the capacitorwhentransistorQ1isturnedon.Theseareusedasovervoltagesnubberstoclampthevoltage.

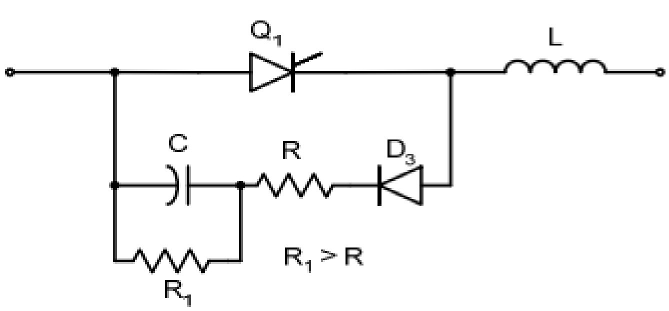


Figure:1. 30.Reverse PolarizedRCSnubberCircuit

Reverse polarized snubber circuit can be used to limit the reverse **dv/dt**. R1 will limit the dischargecurrentof the capacitor.

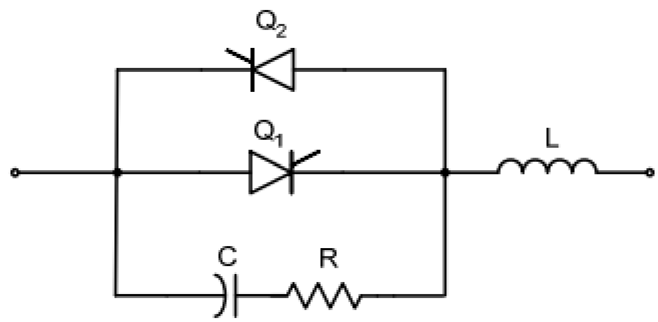


Figure:1. 31.Anun-polarizedsnubbercircuit

An un-polarized snubber circuit is used when a pair of switching devices is used in anti-parallel. Fordetermining the resistor and capacitor values a simple design technique can be used. For this an optimumdesignisneeded.Henceacomplexprocedurewillbeused.Thesecanbeusedtoprotectandthyristors.

Capacitorsselection:

Snubber capacitors are subjected to high peak and RMS currents and high **dv/dt**. An example is turn-onand turn-off current spikes in a typical RCD snubber capacitor. The pulse will have high peak and RMSamplitudes. The snubber capacitor has to meet two requirements. First, the energy stored in the snubbercapacitor must be greater than the energy in the circuit"s inductance. Secondly, the time constant ofsnubber circuits should me small compared to shortest on time expected, usually 10% of the on time. Byallowing the resistor to be effective in the ringing frequency this capacitor is used to minimize thedissipation at switching frequency.The bestdesign is selecting the impedance of the capacitoris samethatof resistorattheringingfrequency.

Resistorsselection:

It is important that R in the RC snubber, have low self inductance. Inductance in R will increase the peakvoltageanditwilltendtodefeatthepurposeofthesnubber.LowinductancewillalsobedesirableforRin snubber but it is not critical since the effect of a small amount of inductance is to slightly increase thereset time of C and it will reduce the peak current in switch at turn-on. The normal choice of R is usuallythecarboncompositionormetalfilm.TheresistorpowerdissipationmustbeindependentoftheresistanceR becauseitdissipatestheenergystoredinthesnubbercapacitorineachtransitionofvoltageinthecapacitor.Ifweselect theresistorasthatthecharacteristicimpedance,theringingiswelldamped.

When comparing the Quick design to optimum design, the required snubber resistor's power capabilitywillbereduced.Usuallythe"Quick"designiscompletelyadequateforfinaldesign.Goingtothe"Optimum" approach is only if power efficiency and size constraints dictate the needfor optimumdesign.

PowerBipolarJunctionTransistor(BJT)

PowerBJTisusedtraditionallyformanyapplications.However,IGBT(Insulated-GateBipolarTransistor) and MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) have replaced it formost of the applications but still they are used in some areas due to its lower saturation voltage over theoperating temperature range. IGBT and MOSFET have higher input capacitance as compared to BJT.Thus, in case of IGBT and MOSFET, drive circuit must be capable to charge and discharge the internalcapacitances.

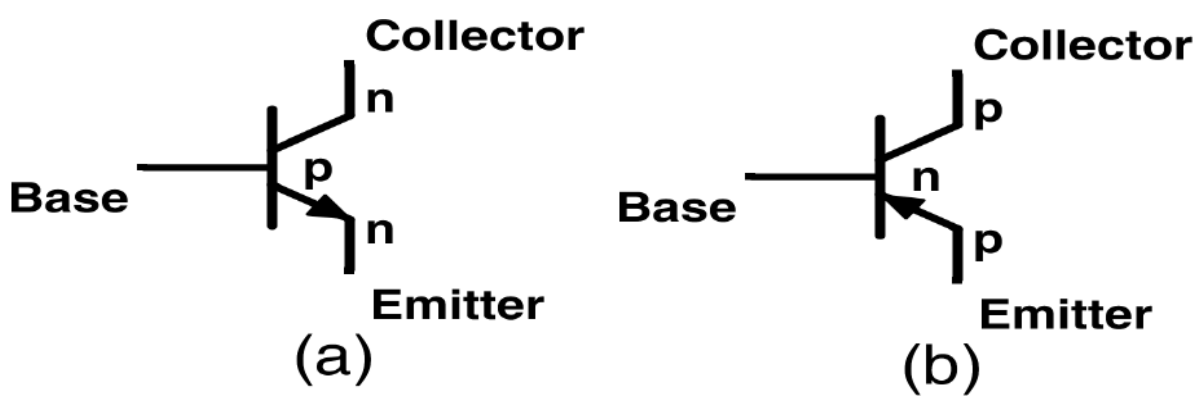


Figure:1.32.Symboloftransistor

The BJT is a three-layer and two-junction npn or pnp semiconductor device as given in Fig. 32. (a) and(b).

AlthoughBJTshavelowerinputcapacitanceascomparedtoMOSFETorIGBT,BJTsareconsiderably slower in response due to low input impedance. BJTs use more silicon for the same driveperformance.

In the case of MOSFET studied earlier, power BJT is different in configuration as compared to simpleplanar BJT. In planar BJT, collector and emitter is on the same side of the wafer while in power BJT itis on the opposite edges as shown in Fig. 33. This is done to increase the power-handling capability ofBJT.

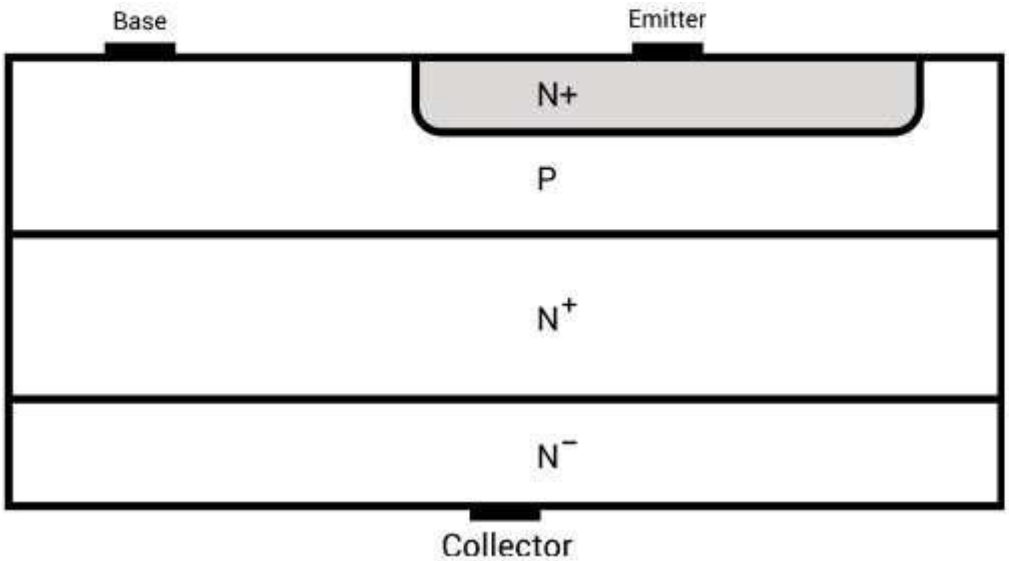


Figure:1.33.Structureoftransistor

Powern-p-ntransistorsarewidelyusedinhigh-voltageandhigh-currentapplicationswhichwillbediscussedlater.

InputandoutputcharacteristicsofplanarBJTforcommon-emitterconfigurationareshown inFig.34.Thesearecurrent-voltagecharacteristicscurves.

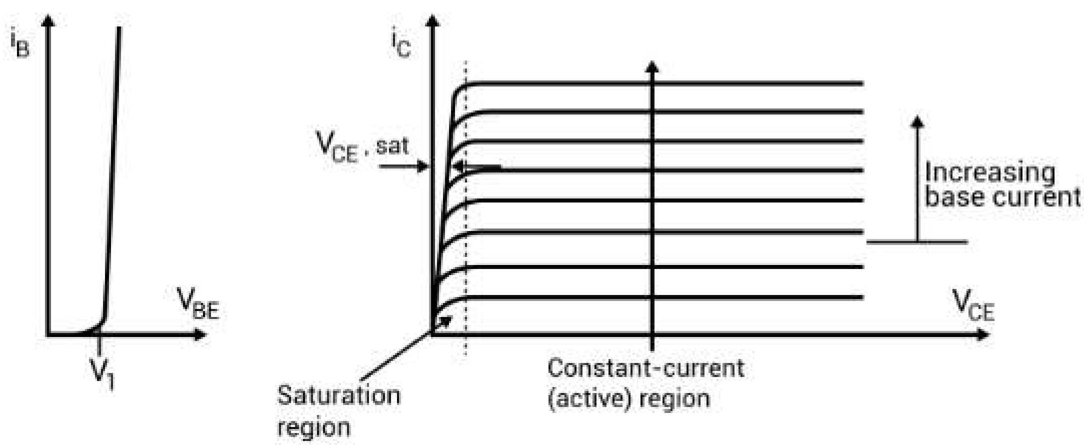


Figure:1.34.Input andoutput characteristics ofBJT

Metal-OxideSemiconductorField-EffectTransistor (Power)

MOSFET is a voltage-controlled majority carrier (or unipolar) three-terminal device. As compared tothe simple lateral channel MOSFET for low-power signals, power MOSFET has different structure. Ithas a vertical channel structure where the source and the drain are on the opposite side of the siliconwafer as shown in Figure. This opposite placement of the source and the drain increases the capabilityofthepowerMOSFETtohandle largerpower.

N-channel enhancement typeMOSFETismorecommon duetohighmobilityofelectrons.

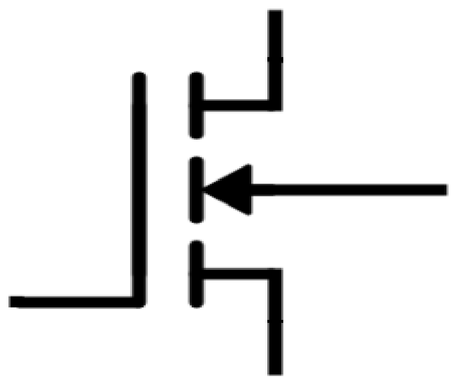


Figure: 1.35.SymbolofMOSFET

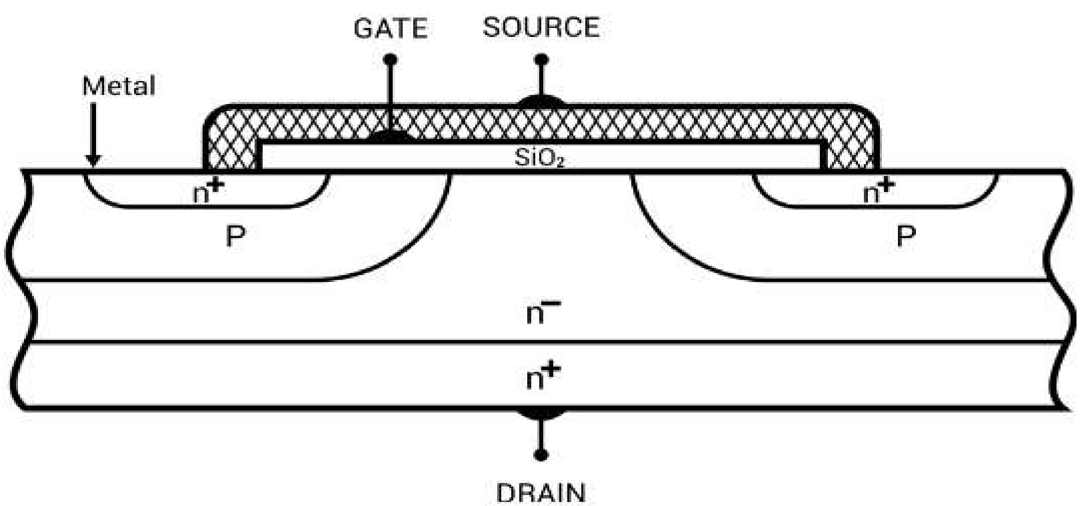


Figure: 1.36.Structureof MOSFET

Basiccircuitdiagramandoutputcharacteristicsofann-channelenhancementpowerMOSFETwithloadconnectedareinFig.37andFig.38respectively.

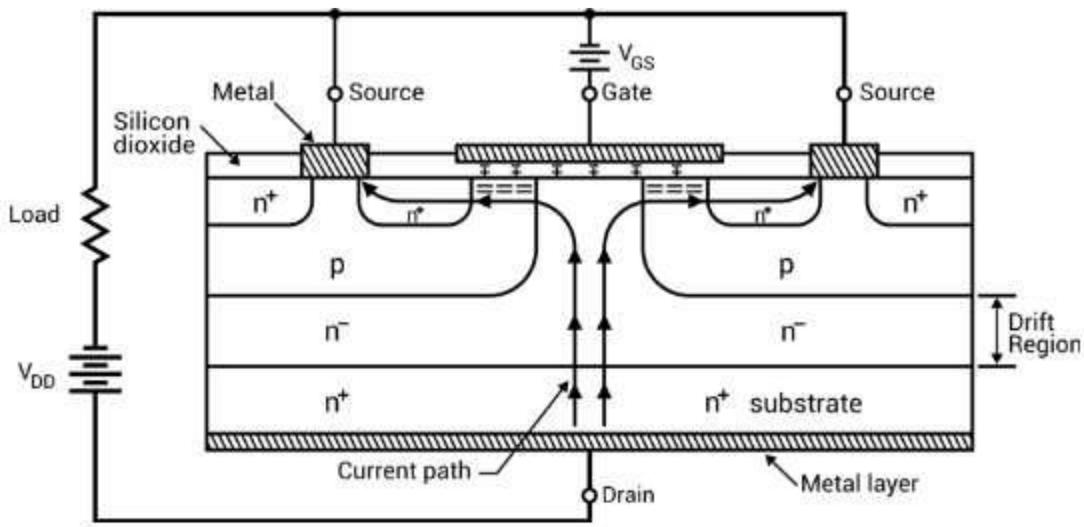


Figure:1.37.Basiccircuit diagramofn-channelenhancement power MOSFET

Drift region shown in Fig. 37 determines the voltage-blocking capability of the

MOSFET.WhenV_{GS}=0,

⇒V_{DD} makes itreversebiasedandnocurrentflows

fromdraintosource.WhenV_{GS}>0,

⇒ElectronsformthecurrentpathasshowninFig.37.Thus,currentfromthedraintothesourceflows.Now,ifwewill increasethegate-to-sourcevoltage,draincurrentwillalsoincrease.

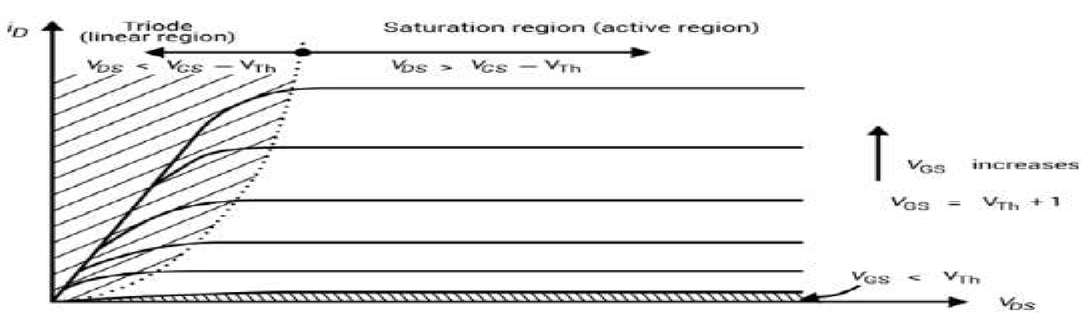


Figure:1.38.Output characteristicsof ann-channelenhancement powerMOSFET

ForlowervalueofV$_{DS}$,MOSFETworksinalinearregionwhereithasaconstantresistanceequaltoV$_{DS}$ / I$_{D}$. For a fixed value of V$_{GS}$ and greater than threshold voltage V$_{TH}$, MOSFET enters a saturationregionwherethevalueof the draincurrenthasa fixedvalue.

Besides the output characteristics curves, transfer characteristics of power MOSFET is also shown inFig.39.

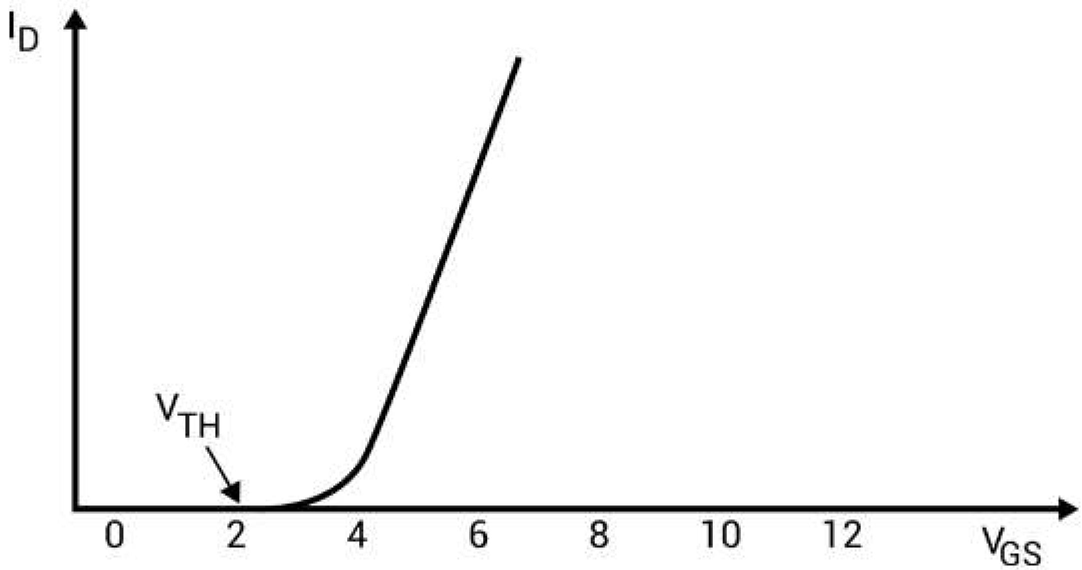


Figure:1.39.Transfercharacteristicsof ann-channelenhancementpowerMOSFET

Insulated-GateBipolarTransistor(IGBT)

IGBT combines the physics of both BJT and power MOSFET to gain the advantages of both worlds. Itis controlled by the gate voltage. It has the high input impedance like a power MOSFET and has lowon-state power loss as in case of BJT.There is no even secondary breakdown and not have longswitching time as in case of BJT. It has better conduction characteristics as compared to MOSFET dueto bipolar nature. It has no body diode as in case of MOSFET but this can be seen as an advantage touse external fast recovery diode for specific applications. They are replacing the MOSFET for most ofthehighvoltageapplicationswithlessconductionlosses.Itsphysicalcross-sectionalstructuraldiagram and equivalent circuit diagram is presented in Fig. 40 to Fig. 41. It has three terminals calledcollector,emitterandgate.

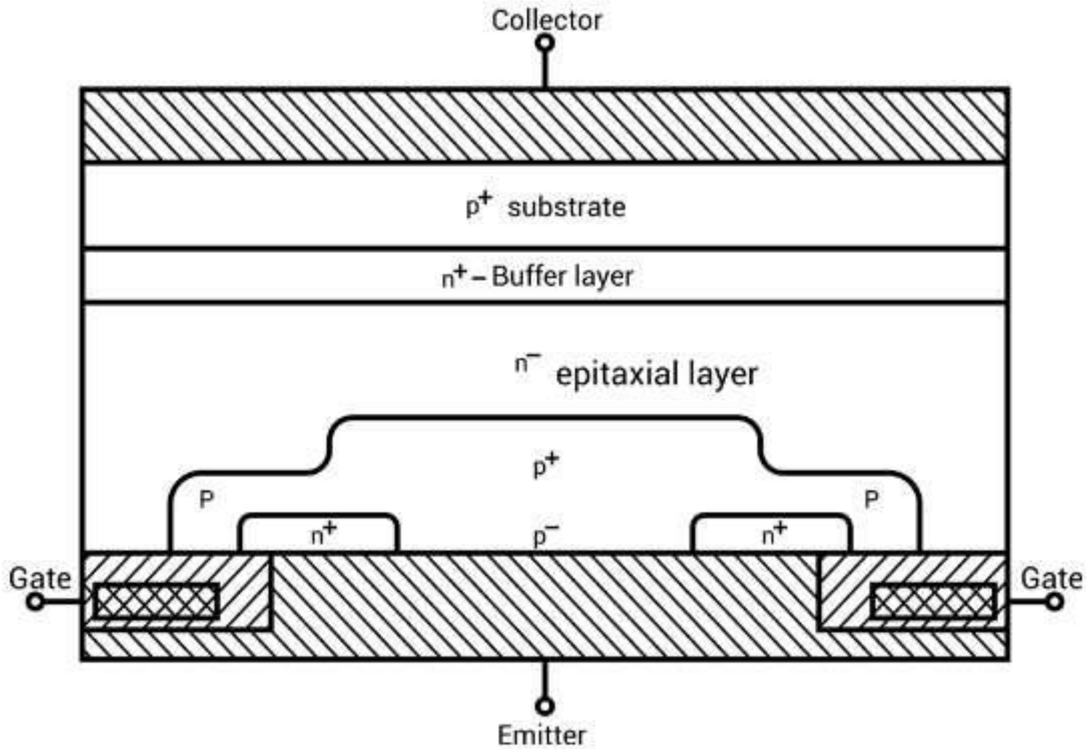


Figure: 1.40.Cross-sectionalstructural diagramofIGBT

There is a p+ substrate which is not present in the MOSFET and responsible for the minority carrierinjection into the n-region. Gain of NPN terminal is reduced due to wide epitaxial base and n+ bufferlayer.

TherearetwostructuresofIGBTsbasedondopingofbufferlayer:

a) Punch-throughIGBT:Heavilydopednbufferlayer➔lessswitchingtime

b) Non-Punch-throughIGBT:Lightlydopednbufferlayer➔greatercarrierlifetime➔increasedconductivityofdriftregion ➔reducedon-statevoltage drop

(Note:➔meansimplies)

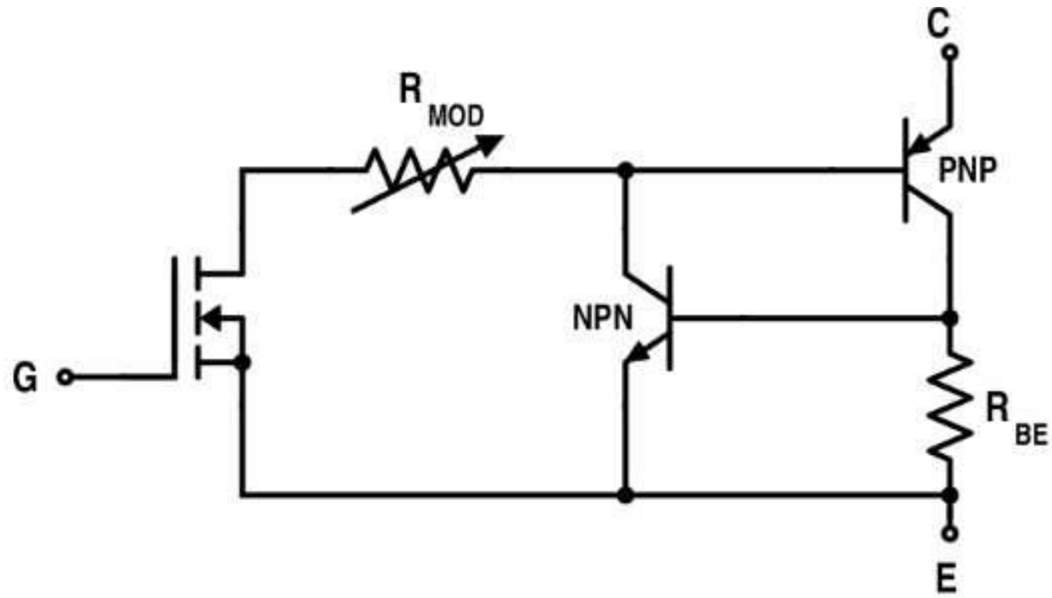


Figure: 1.41.Equivalentdiagramof IGBT

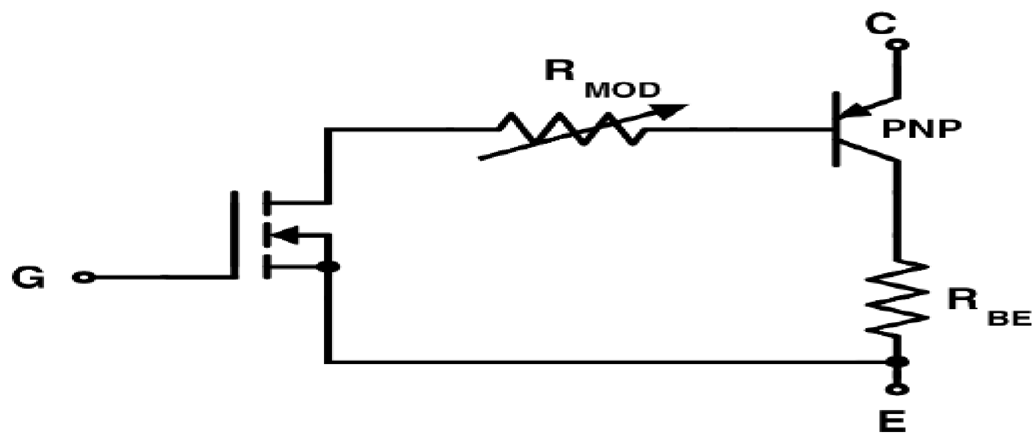


Figure:1.42.Simplified Equivalent diagramof IGBT

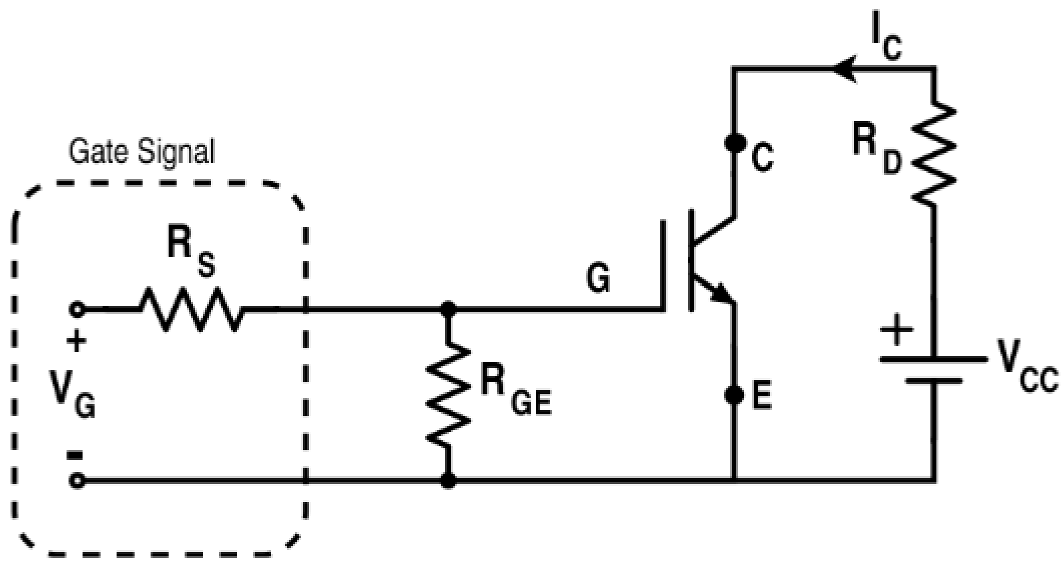


Figure:43.Equivalent diagramofIGBT

BasedonthiscircuitdiagramgiveninFig.43,forwardcharacteristicsandtransfercharacteristicsareobtainedwhic haregiveninFig.44andFig.45.ItsswitchingcharacteristicisalsoshowninFig.45.

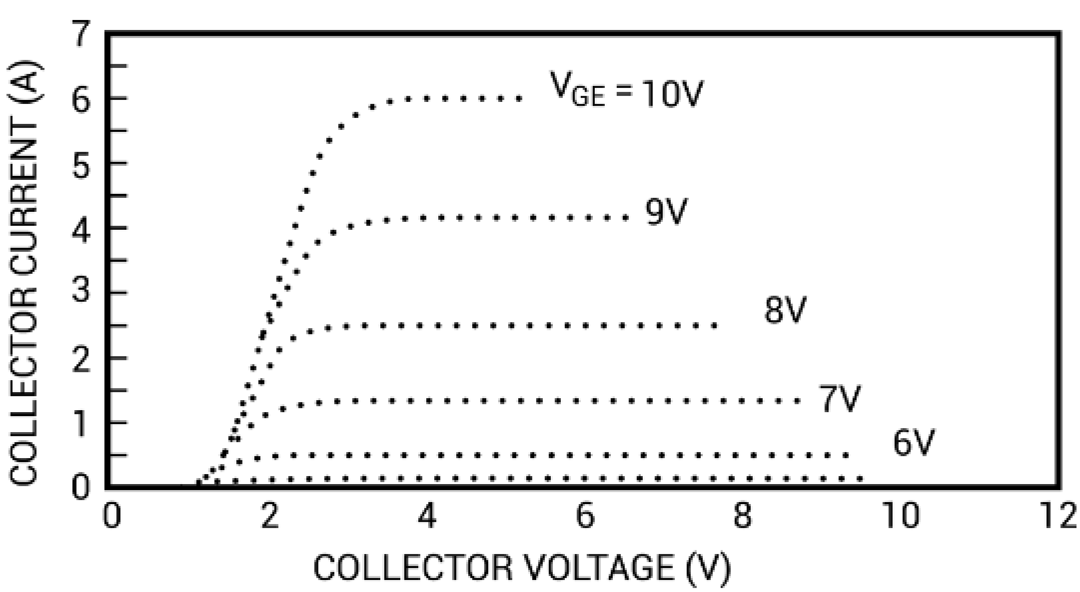


Figure:1.44.Forwardcharacteristicsof IGBT

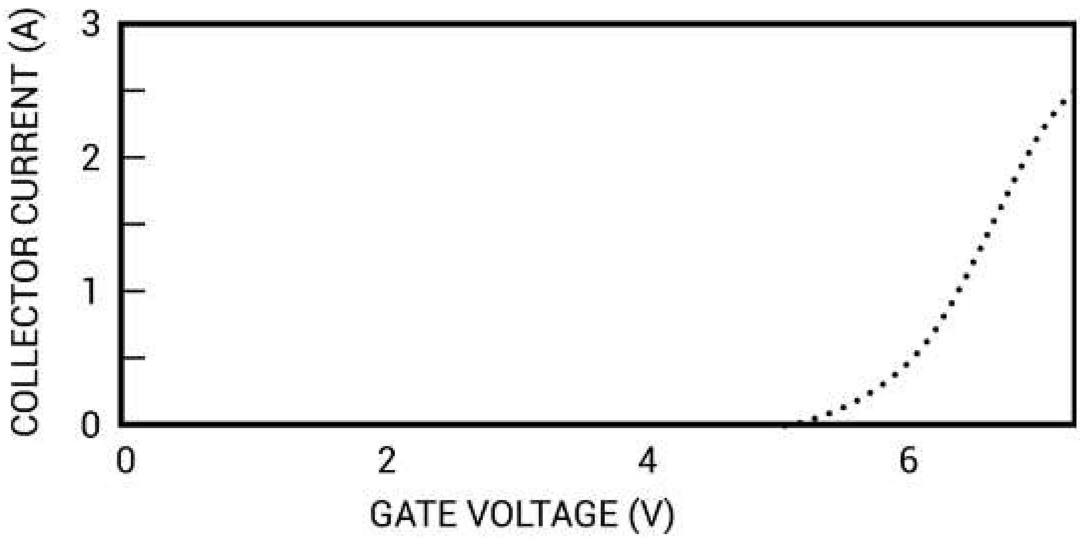


Figure:1.45.Transfercharacteristicsof IGBT

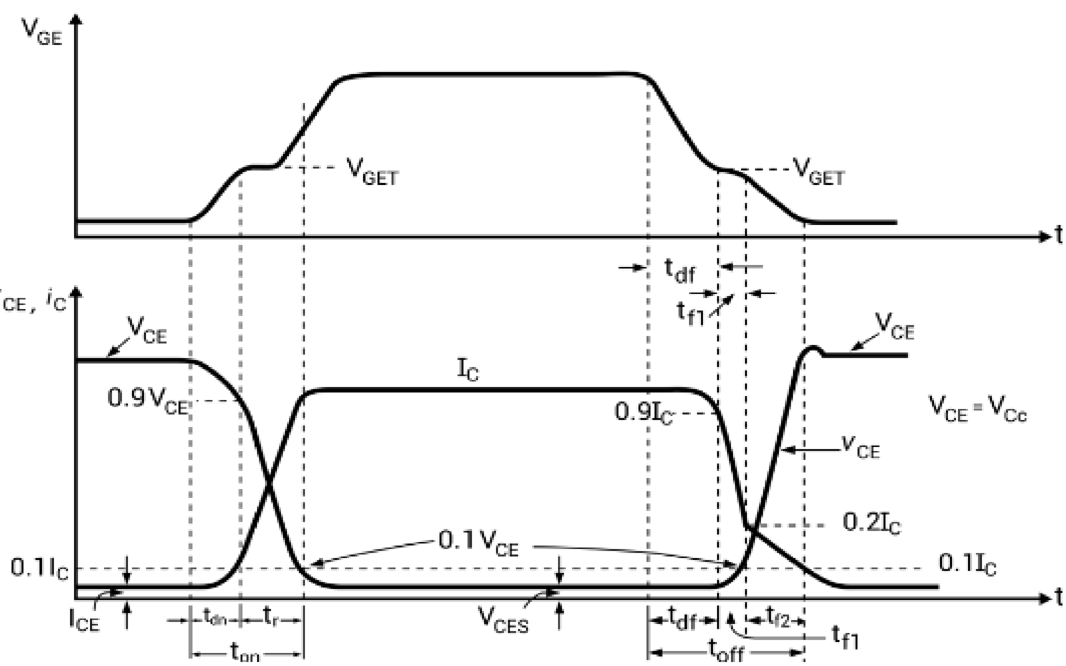


Figure: 1.46.DynamiccharacteristicsofIGBT

(Note:T_{dn}:delaytime;T_r:rise time ;T_{df}: delay time ;T_{f1}: initialfalltime;T_{f2}:finalfalltime)

GTO(GateTurn-offThyristor)

GTO can be turned on with the positive gate current pulse and turned off with the negative gate currentpulse. Its capability to turn off is due to the diversion of PNP collector current by the gate and thusbreakingtheregenerativefeedbackeffect.

Actually the design of GTO is made in such a way that the pnp current gain of GTO is reduced. Ahighly doped n spot in the anode p layer form a shorted emitter effect and ultimately decreases thecurrent gain of GTO for lower current regeneration and also the reverse voltage blocking capability.This reduction in reverse blocking capability can be improved by diffusing gold but this reduces thecarrierlifetime.Moreover,itrequiresaspecialprotection.

ThesymbolforGTO isshowninFig.46.

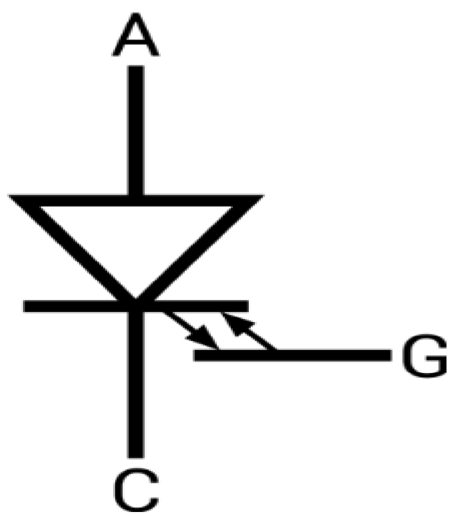


Figure:1.47.Symbolof GTO

Overall switching speed of GTO is faster than thyristor (SCR) but voltage drop of GTO is larger. ThepowerrangeofGTOisbetterthanBJT,IGBTor SCR.

The static voltage current characteristics of GTO are similar to SCR except that the latching current ofGTO islarger(about2A) ascomparedtoSCR(around100-500mA).

ThegatedrivecircuitrywithswitchingcharacteristicsisgiveninFig.48andFig.49.

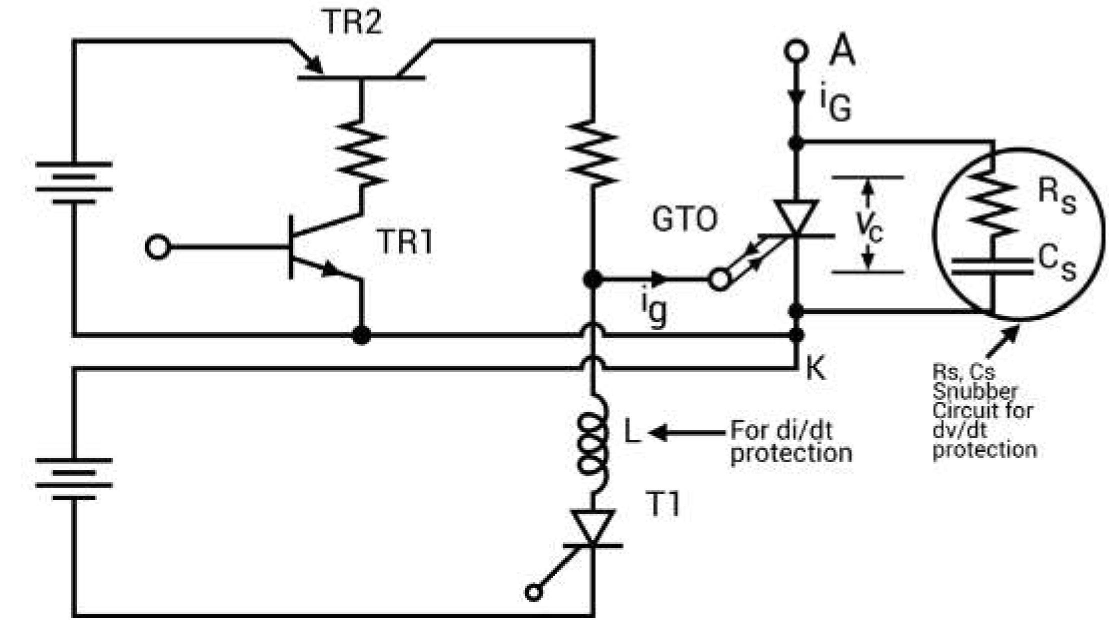


Figure:1.48.GateDriveCircuit forGTO

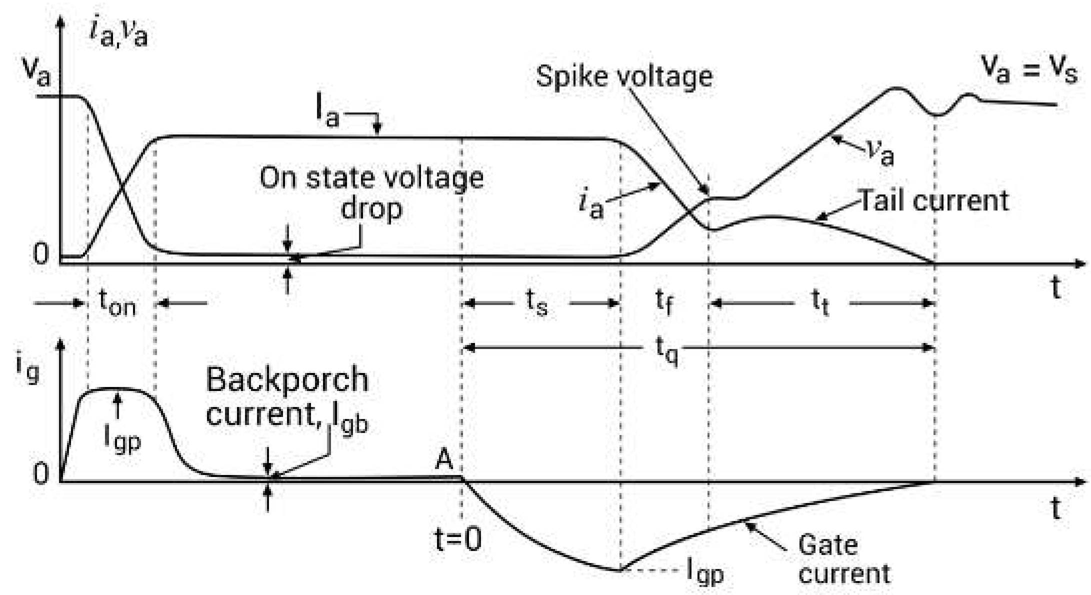


Figure:1.49.SwitchingcharacteristicsforGTO

SCRSpecificationsandRatings:

ThemainspecificationsoftheSCRareitsvoltageratingandcurrentrating.Inthispost,letusseevariousratingsofthyristor.

VoltageRatings

PeakInveseVoltage(V_{PIV})

The peak inverse voltage is defined as the maximum voltage which SCR can safely withstand in its OFFstate. Theappliedvoltageshouldneverbeexceededunderanycircumstances.

OnStateVoltage:

The voltage which appears across the SCR during its ON state is known as its ON state Voltage. Themaximum value of voltage which can appear across the SCR during its conducting state is called itsmaximumonstatevoltage.Usuallyitwillbe1Vto4V.

FingerVoltage:

The minimum voltage, which is required between the anode and cathode of an SCR to trigger it toconductionmode,iscalleditsfingervoltage.

RateofRise ofVoltage(dV/dt)

Therateatwhichthevoltageacrossthedevicerises(forforwardcondition)withouttriggeringthedevice,isknownasitsrateof riseofvoltage.

VoltageSafetyFactor:

The normal operating voltage of the SCR is kept well below its peak inverse voltage(V_{PIV}) to avoidpuncture of SCR due to uncertain conditions. The operating voltage and peak inverse voltage are relatedbyvoltagesafetyfactorV_f

V_f=Peakinversevoltage/(2

xRMSvalueofinputvoltage)Normaly$V_f$valueliesbetween2and2.5

CurrentRatings:

Thecurrentcarryingcapacityofthedeviceis knownas itscurrent

rating.Itcanbeoftwotypes.

1. Continuous
2. Intermittent

MaximumaverageONstatecurrent(I_{mac}):

This is the average value of maximum continuous sinusoidal ON state current with conduction angle180deg,atfrequency40to60Hz,whichshouldnotbeexceededevenwithintensivecooling.

Maximumrms ON-statecurrent:(I_{mrc})

It is the rms value of the maximum continuous sinusoidal ON state current at the frequency 40 to 60 Hzandconductionangle180deg,whichshouldnotbeexceededevenwithintensivecooling.

Maximumsurge-ONstateCurrent (I_{msc})

It is the maximum admissible peak value of a sinusoidal half cycle of tem milliseconds duration at afrequencyof50Hz.

LatchingCurrent(I_I)

Itistheminimumcurrent,whichisrequiredtolatchthedevicefromitsOFFstatetoitsON state.Inotherwords,itisthe minimumcurrentrequiredtotriggerthedevice.

HoldingCurrent(I_H)

It is theminimumcurrentrequiredtoholdtheSCRconducting.Inotherwords,It istheminimumcurrent,belowwhichthedevicestopsconductingandreturnstoitsOFFstate.

GateCurrent:

Thecurrentwhichisappliedtothegateofthe deviceforcontrolpurposesisknownasgatecurrent.

MinimumGate Current:

Theminimumcurrent requiredat thegatefortriggering thedevice.

MaximumGateCurrent:

The maximum current which can be applied to device safely. Current higher than this will damage thegateterminal.

GatePowerLoss:

Themeanpowerloss,whichoccursduetoflowofgatecurrentbetweenthegateandthemainterminals.

TurnONtime:

Thetimetakenby thedevicebeforegetting latchedfromitsOFFstateto ONstate.Inotherwords,itisthe time for which the device waits before achieving its full conduction. Usually it will be 150 to 200µsec.**TurnOFFtime:**

After applying reverse voltage, the device takes a finite time to get switched OFF. This time is called asturn-OFFtimeofthedevice.Usuallyitwillbe200µsec.

Rateofriseofcurrent(dI/dt)

Therateatwhichthe currentflowinginthedevicerisesisknownasitsrateof rise(dI/dt)of current.

ComparisonbetweenBJTand MOSFET:

Sl No	BJT	MOSFET
1	Itis aBipolarDevice	It is majoritycarrierDevice
2	CurrentcontrolDevice	VoltagecontrolDevice.
3	Outputiscontrolledbycontrollingbasecurrent	Output is controlledbycontrollinggatevoltage
4	Negativetemperaturecoefficient	Positivetemperaturecoefficient
5	SoparallelingofBJTis difficult.	Soparallelingofthis deviceiseasy.
6	Dive circuit is complex. It should provideconstantcurrent(Basecurrent)	Dive circuit is simple. It should provideconstantvoltage(gatevoltage)
7	Losses arelow.	LossesarehigherthanBJTs.
8	Sousedinhighpowerapplications.	Usedinlowpowerapplications.
9	BJTshavehighvoltageandcurrentratings.	They havelessvoltageandcurrentratings.
10	Switchingfrequencyis lowerthanMOSFET.	Switchingfrequencyishigh.

UNIT–II
Thyristorrectifiers

Phasecontroltechnique –SinglephaseLinecommutatedconverters

Unlike diode rectifiers, PCRs or phase controlled rectifiers has an advantage of regulating the outputvoltage. The diode rectifiers are termed as uncontrolled rectifiers. When these diodes are switched withThyristors, then it becomes phase control rectifier. The o/pvoltage can be regulated by changing thefiring angle of the Thyristors. The main application of these rectifiers is involved in speed control of DCmotor.

WhatisaPhaseControlledRectifier?

The term PCR or Phase controlled rectifier is a one type of rectifier circuit in which the diodes areswitched by Thyristors or SCRs (Silicon Controlled Rectifiers). Whereas the diodes offer no control overthe o/p voltage, the Thyristors can be used to differ the output voltage by adjusting the firing angle ordelay. A phase control Thyristor is activated by applying a short pulse to its gate terminal and it isdeactivated due to line communication or natural. In case of heavy inductive load, it is deactivated byfiringanotherThyristoroftherectifierduringthenegativehalfcycleofi/pvoltage.

TypesofPhaseControlledRectifier

The phase controlled rectifier is classified into two types based on the type of i/p power supply. And eachkindincludesasemi,fullanddualconverter.

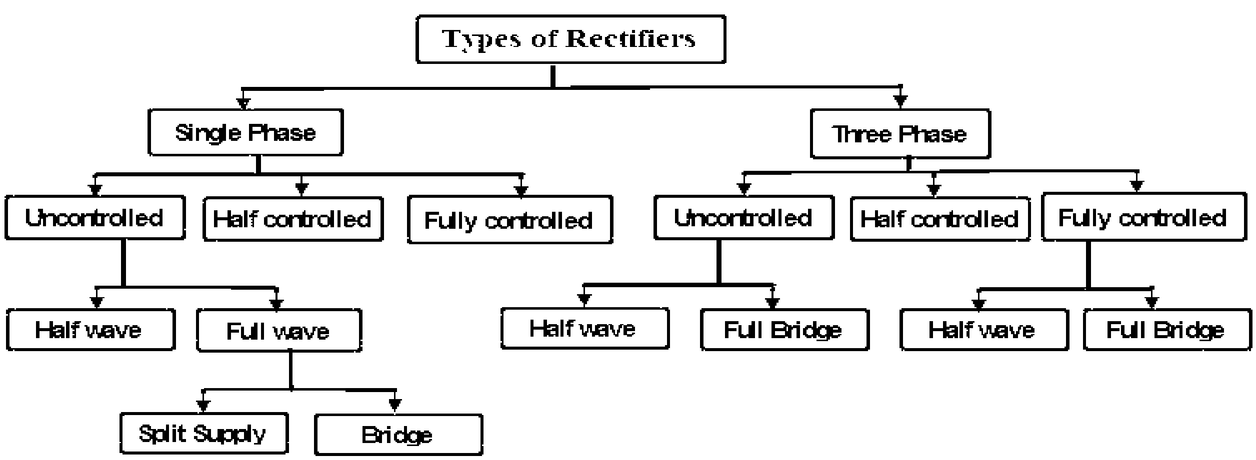


Figure:2.1.Classificationofrectifiers

Single-phaseControlledRectifier

This type of rectifier which works from single phase AC i/p power

supplySinglePhaseControlledRectifiers areclassified into differenttypes

HalfwaveControlledRectifier: Thistype ofrectifierusesasingle Thyristordevice to providedo/pcontrolonlyinone halfcycle ofinputACsupply,anditofferslowDCoutput.

FullwaveControlledRectifier: ThistypeofrectifierprovideshigherDCoutput

- FullwavecontrolledrectifierwithacentertappedtransformerrequirestwoThyristors.
- Fullwavebridgecontrolledrectifiersdo notneedacentertappedtransformer

Three-phaseControlledRectifier

ThistypeofrectifierwhichworksfromthreephaseACi/ppowersupply

- Asemiconverteris aonequadrantconverterthat hasonepolarityofo/p voltageandcurrent.
- A full converter is a a two quadrants converter that has polarity of o/p voltage can be either +ve or –vebut,thecurrentcanhave onlyonepolaritythatiseither+veor-ve.
- Dualconverterworks infourquadrants–botho/p voltageando/pcurrentcan havebooththepolarities.

OperationofPhaseControlledRectifier

The basic working principle of a PCR circuit is explained using a single phase half wave PCR circuit withaRLloadresistiveshowninthefollowingcircuit.

A single phase half wave Thyristor converter circuit is used to convert AC to DC power conversion. Thei/p AC supply is attained from a transformer to offer the required AC supply voltage to the Thyristorconverter based on the o/p DC voltage required. In the above circuit, the primary and secondary ACsupplyvoltagesaredenotedwithVPandVS.

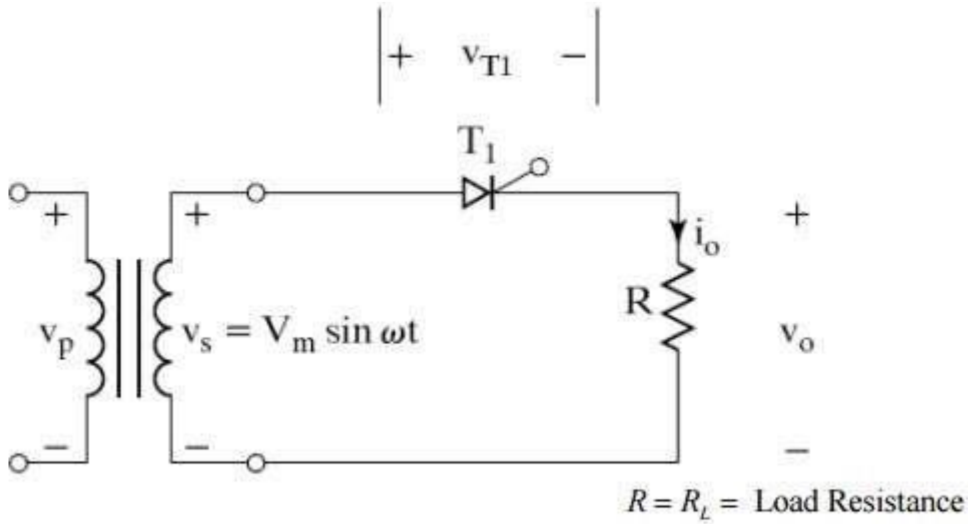


Figure:2.2.Singlephasehalf waverectifiercircuit

During the +ve half cycle of i/p supply when the upper end of the transformer secondary winding is at a +vepotentialwithrespecttothelowerend,theThyristorisinaforwardbiasedstate.

The thyristor is activated at a delay angle of ωt =α, by applying an appropriate gate trigger pulse to thegate terminal of thyristor. When the thyristor is activated at a delay angle of ωt =α, the thyristor behaviorsand assuming a perfect thyristor. The thyristor acts as a closed switch and the i/p supply voltage actsacross the load when it conducts from ωt =α to π radians For a purely resistive load, the load current iothatflowswhenthethyristorT1ison,isgivenbytheexpression.

Io=vo/RL,for $\alpha \leq \omega t \leq \pi$

ApplicationsofPhaseControlledRectifier

Phase controlled rectifier applications include paper mills, textile mills using DC motor drives and DCmotorcontrolinsteelmills.

- ACfedtractionsystemusingaDCtraction motor.
- Electro-metallurgicalandElectrochemicalprocesses.
- Reactorcontrols.
- Magnetpower supplies.
- Portablehandinstrumentdrives.

- Flexiblespeedindustrialdrives.
- Batterycharges.
- HighvoltageDCtransmission.
- UPS(Uninterruptiblepowersupplysystems).

OperationofhalfconverterwithR andRLloads

SinglePhaseHalfWaveControlledRectifierwith'R'load:

As shown in figure below primary of transformer is connected to ac mains supply with which SCRbecomesforwardbias inpositivehalfcycle.T1 is triggeredatananglеα,T1 conductsandvoltageisappliedacrossR.

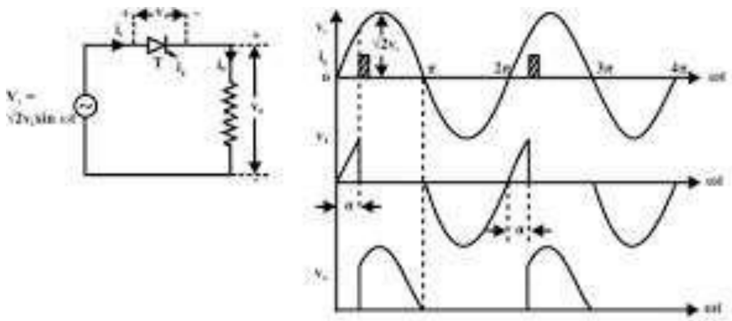


Figure:2.3 SinglephasehalfwaverectifierwithRloadwithwaveforms

Theloadcurrent$i_0$flowsthrough„R" thewaveformsforvoltage& currentareasshownabove.Asloadisresistive, Outputcurrentis givenas,

$$I_o = \frac{V_o}{R}$$

Henceshapeofoutputcurrent is sameas output voltage
As T1 conducts onlyinpositivehalfcycleas itisreversedbias in negativecycle,theripplefrequency ofoutputvoltage is-
fripple= 50 Hz (supply

frequency)Averageoutputvoltageis

givenas,

$$V_0(Avg)=\frac{1}{T}\int_0^T V_0(wt)\,dwt$$

i.eAreaunderonecycle.

ThereforeT=2π&Vo(ωt)=Vmsinωtfromα toπ&forrestoftheperiodVo(ωt)=0

$$\therefore V_0(Avg)=\frac{1}{2\pi}\int_0^{2\pi} V_m sin(wt)\,dwt$$
$$=\frac{V_m}{2\pi}[-coswt]_\alpha^\pi$$
$$=\frac{V_m}{2\pi}(1+cos\alpha)$$

Power transferredtoload,

$$P_0(Avg)=\frac{V_0^2(Avg)}{R}$$

Thus,power&voltagecanbecontrolledbyfiringangle.

SinglePhaseHalfWaveControlledRectifierwith‘RL’load:

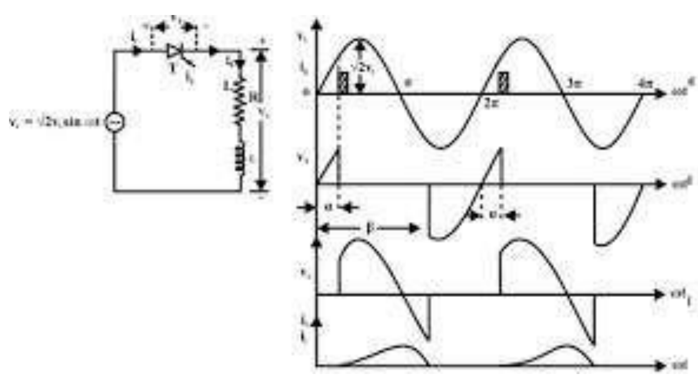


Figure: 2.4 Singlephasehalfwaverectifierwith RLloadwith waveforms

Figureaboveshowsthesinglephasehalfwaverectifierwith RLLoad.

- NormallymotorsareinductiveloadsL

=armatureoffieldcoilinductance

R=Resistanceof coil.

- Inpositivehalfcycle,SCRstarts conductionat firingangle"α".
- DropacrossSCR is small&neglectedsooutput voltageisequaltosupplyvoltage.
- Dueto,,R_L‟load,currentthroughSCRincreasesslowly.
- At,,π‟,supplyvoltageisatzerowhereloadcurrentisatitsmaxvalue.
- Inpositivehalfcycle, inductorstoresenergy&thatgeneratesthevoltage.
- Innegativehalfcycle,thevoltagedevelopedacross inductor,forwardbiasesSCR&maintainsitsconduction.
- Basicallywiththepropertyofinductanceitopposeschangeincurrent.
- Output current&supplycurrentflows insameloop,soallthetimei_o=i_s.
- Afterπtheenergyof inductorisgiventomains&thereisflowof,,io‟.Theenergyreducesasifgets consumedbycircuitsocurrentalsoreduces.
- At,,β‟energystoredininductanceisfinished,hence,,i_o‟becomeszero&,,T1‟turnsoff.
- ,,i_o‟becomeszerofrom,,β‟to,,2π+α‟henceitisdiscontinuousconduction.

Theaverage outputvoltage $V_0=\frac{1}{2\pi}\int_{\alpha}^{\beta} Vm\sin w(wt)=\frac{Vm}{2\pi}(\cos\alpha-\cos\beta)$

$$I_0=\frac{Vm}{2\pi R}(\cos\alpha-\cos\beta)$$

RMSloadvoltageV_{0r}= $\left\{\frac{1}{2\pi}\int_{\alpha}^{\beta} Vm^2 \sin^2 wt\, d(wt)\right\}^{1/2}$

$$=\frac{V}{2\sqrt{\pi}}\left[(\beta-\alpha)-\frac{1}{2}\{\sin 2\beta-\sin 2\alpha\}\right]^{1/2}$$

Singlephasehalfcontrolledconverterwith RLEload

The diode D2 and D4 conducts for the positive and negative half cycle of the input voltage waveformrespectively. On the other hand T1 starts conduction when it is fired in the positive half cycle of the inputvoltage waveform and continuous conduction till T3 is fired in the negative half cycle. Fig. shows thecircuit diagram and the waveforms of a single phase half controlled converter supplying an R–L – Eload.

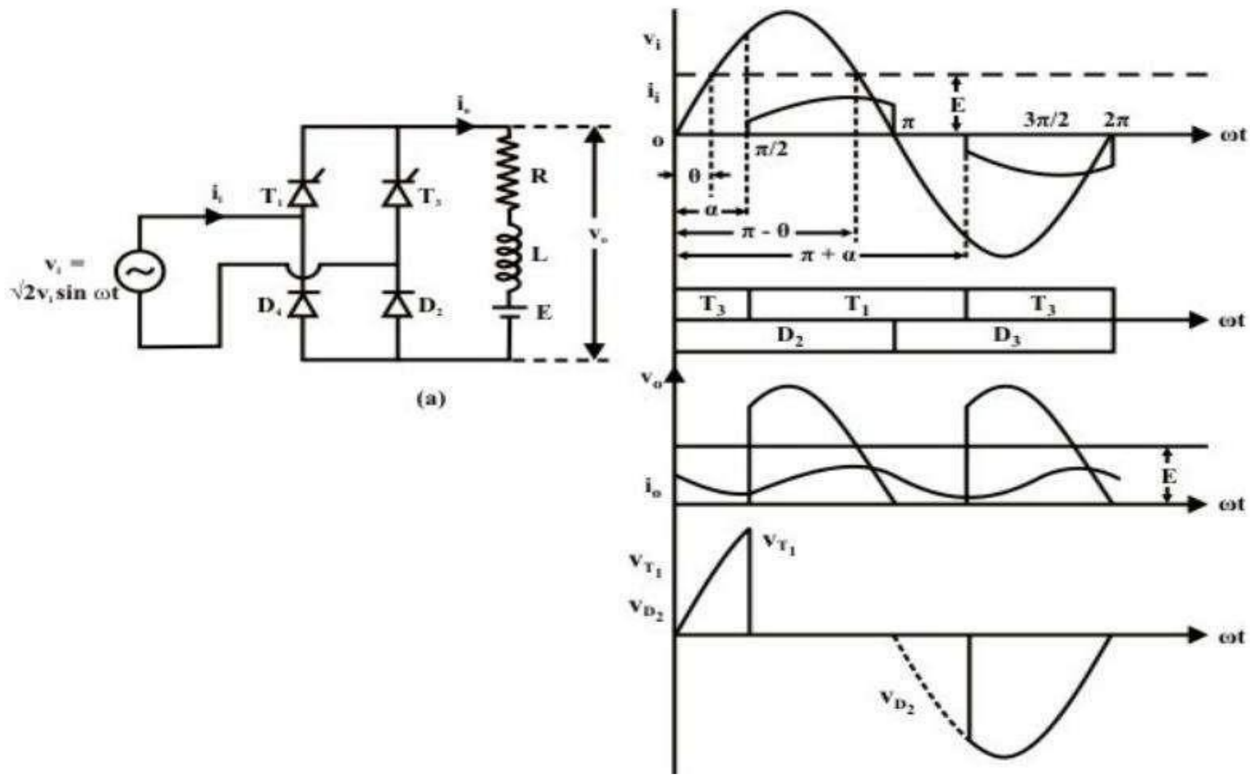


Figure:2.5 singlephasehalfcontrolledconverterwithRLE load

ReferringtoFigT1D2startsconductionatωt=α.Outputvoltageduringthisperiodbecomesequalto vi. At ωt = π as vi tends to go negative D4 is forward biased and the load current commutates from D2 toD4 and freewheels through D4 and T1. The output voltage remains clamped to zero till T3 is fired at ωt =π + α. The T3 D4 conduction mode continues upto ωt = 2π. Where upon load current again free wheelsthrough T3 and D2 while the load voltage is clamped to zero. From the discussion in the previousparagraph it can be concluded that the output voltage (hence the output current) is periodic over half theinputcycle.Hence

$$V_{oav} = \frac{1}{\pi}\int_{o}^{\pi} v_o d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_i \sin \omega t \, d\omega t = \frac{\sqrt{2}V_i}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2}V_i}{\pi R}(1+\cos\alpha - \pi \sin\theta)$$

Singlephasehalfcontrolledconverterwith RLE loadandfreewheelingdiode

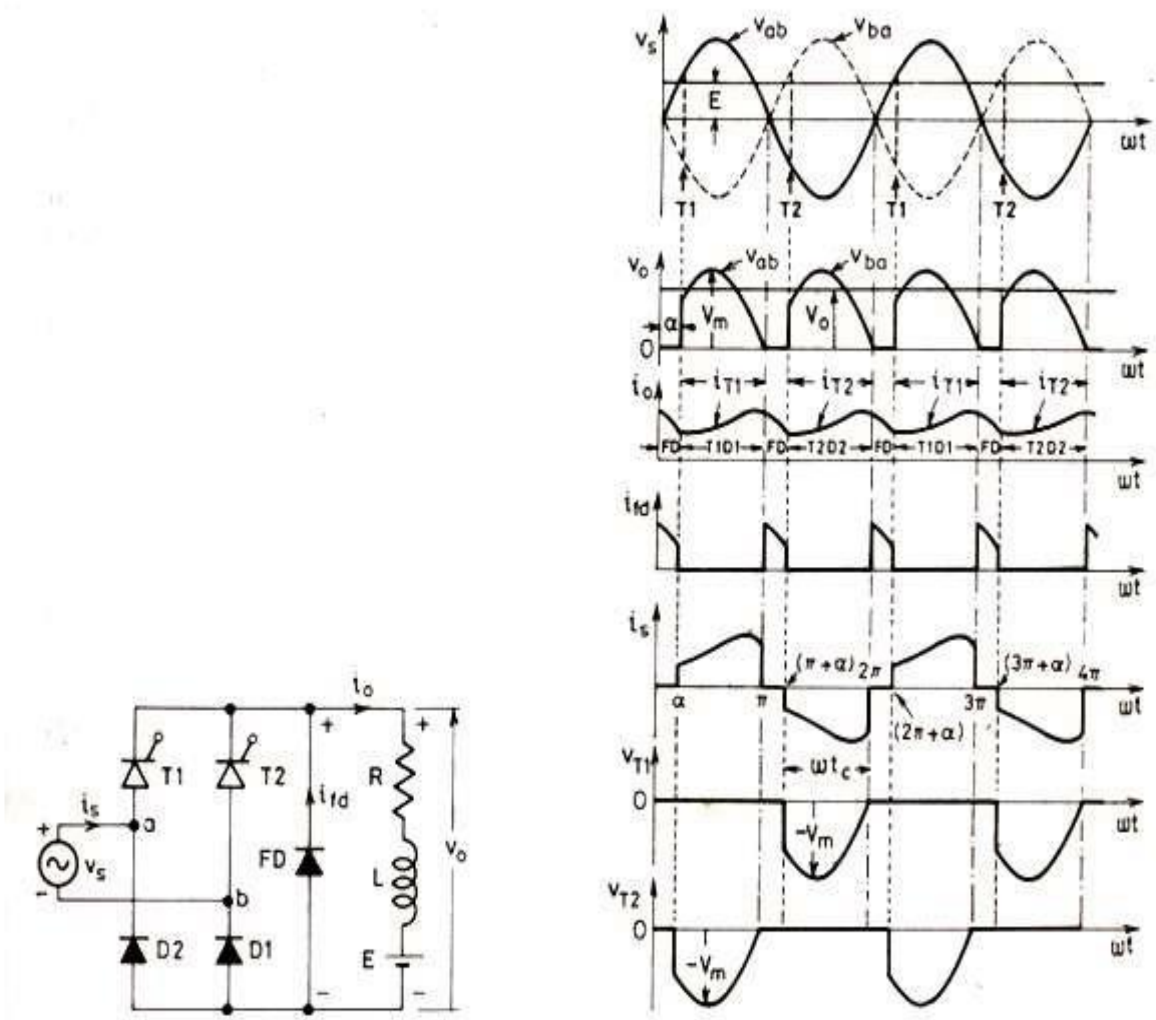


Figure:2.6singlephasehalfcontrolledconverterwithRLEloadandfreewheeling diode

Numericalproblems

1. A single phase 230V, 1 Kwheater is connected across 1 phase 230V, 50Hz supply through anSCR.Forfiringangledelayof45^{0}and90^0,calculatethepowerabsorbedintheheaterelement.

   Solution:Heaterresistance R=230^2/1000Ω

   ThermsvalueofvoltageisV_{or}= $\frac{Vm}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}$

   $$=\frac{\sqrt{2}\times 230}{2\sqrt{\pi}}\left[(\pi-\frac{\pi}{4})+\frac{1}{2}\sin 90\right]^{1/2}=155.071V$$

   Powerabsorbedbytheheaterelementforα = 45^{0}is

   $$\frac{Vor^2}{R}=\left[\frac{155.071}{230}\right]^2\times 1000=454.57W$$

   forα = 90^{0}therms voltageis

   $$V_{or}=\frac{\sqrt{2}\times 230}{2\sqrt{\pi}}\left[(\pi-\frac{\pi}{2})+\frac{1}{2}\sin 180\right]^{1/2}=115V$$

   Powerabsorbedbytheheaterelementforα = 90^{0}is

   $$\frac{Vor^2}{R}=\left[\frac{115}{230}\right]^2\times 1000=250W$$

2. A resistive load of 10Ω is connected through a half-wave controlled rectifier circuit to 220V, 50Hz, single phase source. Calculate the power delivered to the load for a firing angle of 60°. Findalsothevalueofinputpowerfactor
3. AsinglephasesemiconverterdeliverstoRLEloadwith R=5Ω,L=10mHandE=80V.Thesourcevoltage is 230V, 50Hz. For continuous conduction, Find the average value of output current forfiringangle =50°.

Singlephasefullwavecontrolledrectifier

SinglePhaseFullWaveControlledRectifierwith‘R’load:

FigurebelowshowstheSinglephaseFullWaveControlledRectifierswithRload

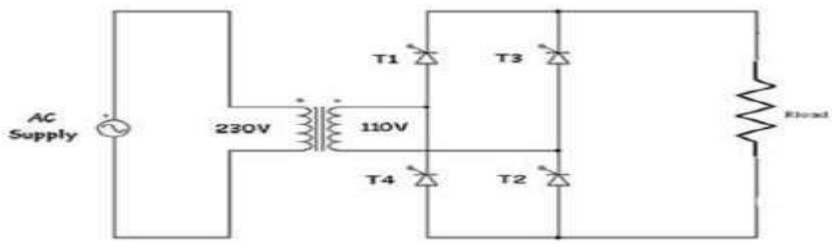


Figure: 2.7 singlephasefullconvertercircuitwithRload

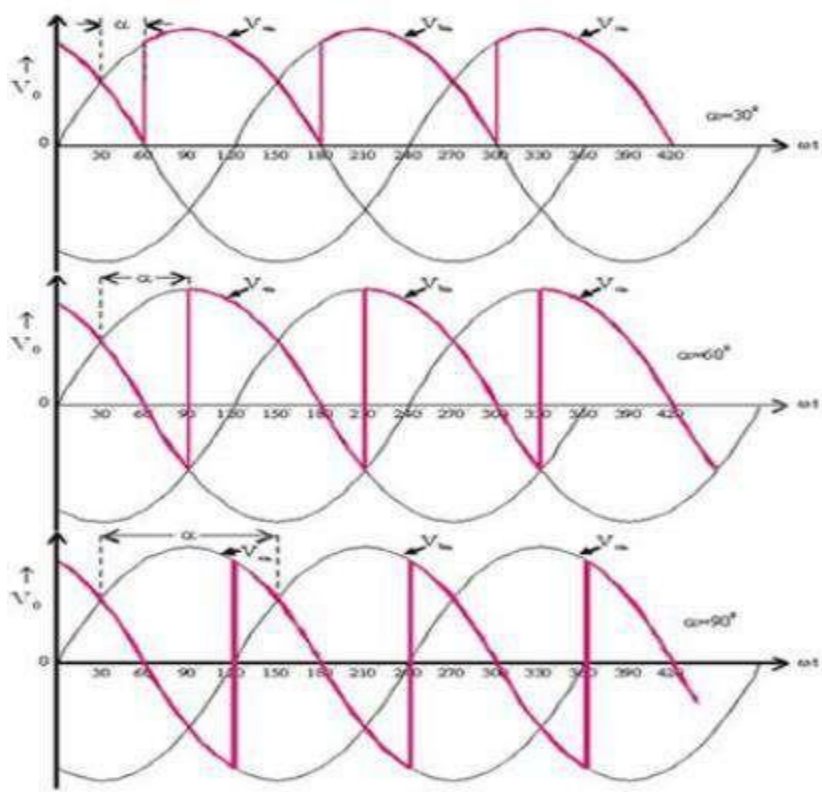


Figure:2.8singlephasefullconvertercircuit withRloadinputandoutputwaveforms

• The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally thisisusedinvariousapplicationssuchasbatterycharging, speedcontrolofDC motorsandfrontendofUPS(UninterruptiblePowerSupply) andSMPS(SwitchedModePowerSupply).

• All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firingsignals thataregiven.Turn-offhappenswhenthecurrentthroughthedevicereacheszeroanditisreverse biasedatleastfordurationequaltotheturn-offtimeofthedevicespecifiedinthedatasheet.

• Inpositivehalf cycleThyristorsT1&T2arefiredatanangleα.

• WhenT1&T2conductsV

o=VsIO=is=Vo/R=Vs/R

• Innegativehalfcycleofinput voltage,SCR‟sT3&T4aretriggeredatanangleof(π+α)

• Hereoutputcurrent &supplycurrentareinoppositedirection

∴is=-io

T3&T4becomesoffat2π.

$$V=\frac{1}{\pi}\int_{0}^{\pi+\alpha} Vm\sin w(wt) = \frac{2Vm}{\pi}\cos\alpha$$

SinglePhaseFullWaveControlledRectifierwith‘RL’load:

FigurebelowshowsSinglephaseFullWaveControlledRectifierswithRLload.

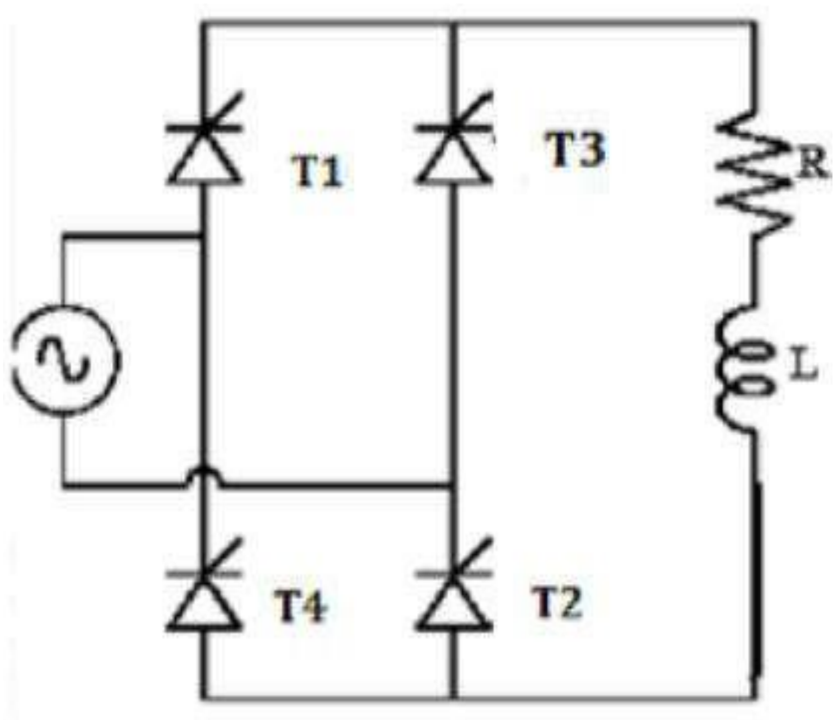


Figure:2.9 singlephasefullconvertercircuitwithRLload

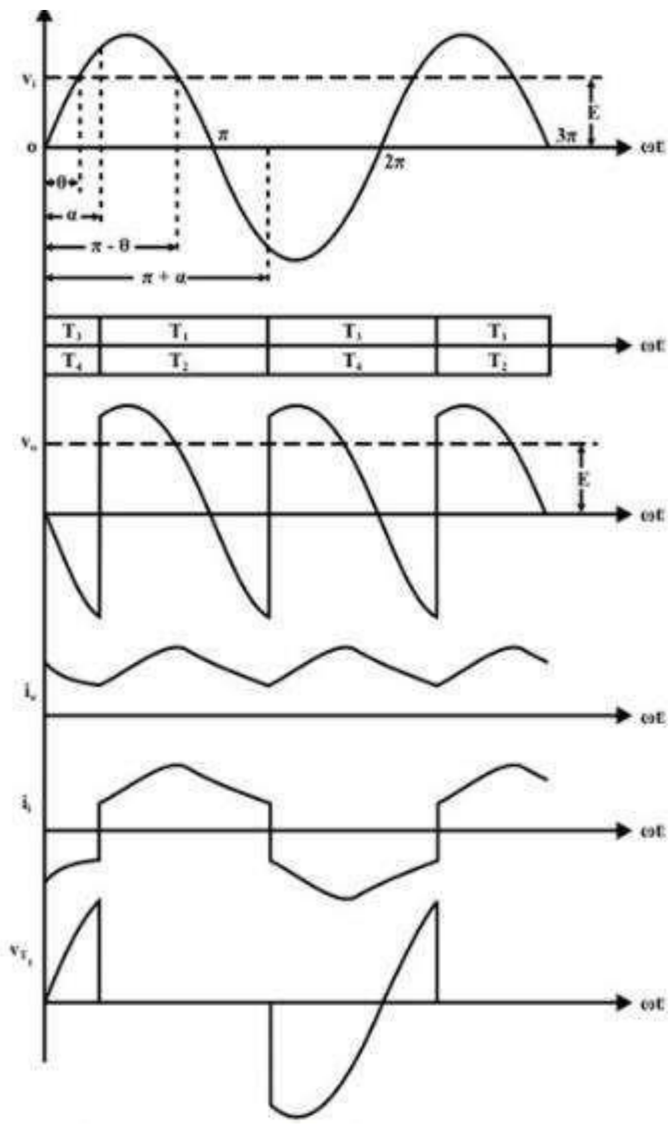


Figure:2.10singlephasefullconvertercircuit withRLloadinputandoutputwaveforms

Operationofthismodecanbedividedbetweenfourmodes

Mode1 (αtoπ)

• Inpositivehalfcycleofappliedacsignal,SCR‟sT1&T2areforwardbias&canbeturnedonatan angleα.

• Loadvoltageisequaltopositiveinstantaneousacsupplyvoltage.Theloadcurrent is positive,ripple free, constant andequaltoIo.

• Duetopositivepolarityofload voltage&loadcurrent,loadinductancewillstoreenergy.

Mode2 (π toπ+α)

• Atwt=π, inputsupplyisequaltozero&afterπitbecomesnegative. Butinductanceopposesany changethroughit.

• Inorderto maintainaconstantloadcurrent&alsoinsamedirection.Aselfinducedemfappearsacross „L‟asshown.

• Duetothisinducedvoltage,SCR‟sT1 &T2areforwardbais inspitethenegativesupplyvoltage.

• Theloadvoltageis negative& equaltoinstantaneous acsupplyvoltagewhereas loadcurrentispositive.

• Thus,loadactsassource&stored energyininductanceisreturnedbacktotheacsupply.

Mode3 (π+αto2π)

• Atwt=π+αSCR‟sT3&T4areturnedon&T1,T2arereversedbias.

• Thus,processofconductionistransferredfromT1,T2toT3,T4.

• Loadvoltageagainbecomes positive&energyis storedin inductor

• T3,T4conductinnegative halfcyclefrom(π+α)to2π

• Withpositiveloadvoltage& loadcurrentenergygetsstored

Mode4(2π to2π+α)

• Atwt=2π, inputvoltagepassesthroughzero.

• Inductiveloadwilltrytoopposeanychangeincurrentifin orderto maintain loadcurrentconstant&inthesame direction.

• Inducedemfispositive&maintainsconductingSCR‟sT3&T4withreversepolarityalso.

• Thus VL is negative & equal to instantaneous ac supply voltage. Whereas load current continues to bepositive.

• Thusloadactsassource&storedenergyininductanceisreturnedbacktoacsupply

• Atwt=αor2π+α,T3&T4arecommutatedandT1,T2areturnedon.

$$V=\frac{1}{\pi}\int_{0}^{\pi+\alpha} Vm\sin w(wt)=\frac{2Vm}{\pi}\cos\alpha$$

Singlephasefullycontrolledconverterswith RLEload

Thecircuitdiagramofafullwavebridgerectifierusing thyristors inshowninfigurebelow.It consists offourSCRswhichareconnectedbetweensinglephase ACsupplyandaload.

ThisrectifierproducescontrollableDC byvaryingconductionofallSCRs.

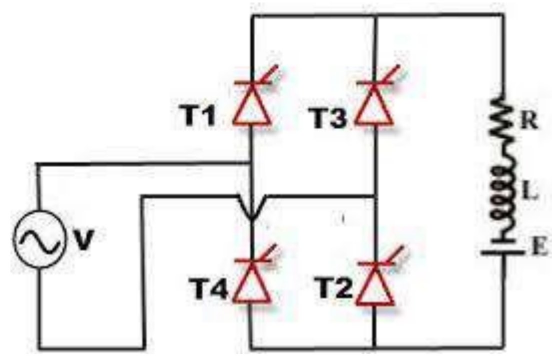


Figure:2.11singlephasefullconvertercircuitwithRLEload

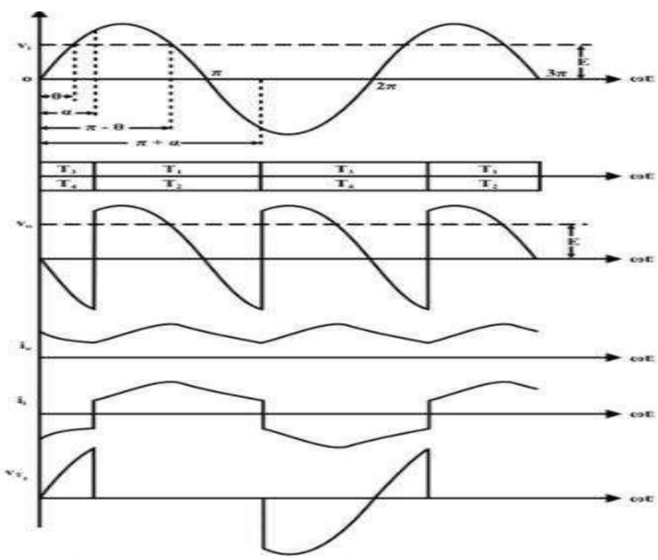


Figure:2.12singlephasefullconvertercircuitwithRLEloadinputandoutputwaveforms

In positive half-cycle of the input, Thyristors T1 and T2 are forward biased while T3 and T4 are reversebiased.ThyristorsT1andT2aretriggeredsimultaneouslyatsomefiringangleinthepositivehalfcycle,andT3andT4aretriggeredinthe negativehalf cycle.

Theloadcurrentstartsflowingthroughthemwhentheyareinconductionstate.TheloadforthisconvertercanbeRLor RLEdependingontheapplication.

Byvaryingtheconductionofeachthyristorinthebridge,theaverageoutput ofthisconvertergetscontrolled.Theaveragevalueofthe outputvoltage istwicethatofhalf-waverectifier.

Theaverageoutputvoltageis

$$V_0=\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinw(wt)=\frac{2Vm}{\pi}cos\alpha$$

Linecommutatedconverters

Forsinglephasehalfwaveconverter

1. AverageDCloadvoltage:(V_{oavg})

$$V_{oavg}=V_0=\frac{1}{T}\int_0^T Vmsinw(wt) \qquad \text{whereTistimeperiod}$$

$$V_{oavg}=\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} Vmsinw(wt)+\int_{\pi}^{2\pi+\alpha} 0(wt)\right]$$

$$=\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} Vmsinw(wt)\right]$$

$$=\frac{Vm}{2\pi}[-coswt]_{\alpha}^{\pi}$$

$$=\frac{Vm}{2\pi}[cos\pi-cos\alpha]$$

$$=\frac{V}{2\pi}[1+cos\alpha]$$

Ifα=0$V_{oavg\ max}=\frac{Vm}{\pi}$

Ifα=180V_{oavg}= 0

2. AverageDCloadcurrentisgivenas

$$I_{oavg}=\frac{V0avg}{R}$$

$$I_{oavg}=\frac{V}{2\pi R}[1+cos\alpha]$$

3. RMSload voltage

$$V_{rms}=\left\{\frac{1}{T}\int_0^T Vm^2 sin^2 wtd(wt)\right\}^{1/2}$$

$$V_{rms}=\left\{\frac{1}{2\pi}\int_{\alpha}^{M} Vm^2 \sin^2 wtd(wt)\right\}^{1/2}$$

$$V_{rms}=\frac{Vm}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}$$

If $\alpha=0$ $V_{rms}=\frac{Vm}{2}$

If $\alpha=180$ $V_{rms} = 0$

TheRMSvoltagemaybevariedfrom0to$\frac{Vm}{2}$byvaryingαfrom180to0

4. Powerdeliveredtotheresistiveloadis given

P_L=(RMSloadvoltage)(RMSloadcurrent)

$=V_{rms} X I_{rms}$

$=\frac{Vrms^2}{R}=Irms^2XR$

5. Inputvoltamperes=(RMSsourcevoltage)(RMS linecurrent)

$=V_s I_{rms}$

$=V_s\frac{\sqrt{2}Vs}{R2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}$

$=\frac{Vs^2}{\sqrt{2\pi}XR}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}$

6. Inputpowerfactor:Itisdefinedastheratiooftotalmeaninputpowertothetotalrmsinputvoltamperes

$$\text{Inputpowerfactor}=\frac{\frac{\sqrt{2}Vs}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}}{Vs}$$

$$=\frac{1}{\sqrt{2\pi}}\left[(\pi-\alpha)+\frac{1}{2}\sin 2\alpha\right]^{1/2}$$

7. Formfactor:Formfactorisdefinedastheratioof

RMSvoltagetotheaverageDCvoltageFormFactor=$\frac{Vrms}{Vavg}$

8. EffectivevalueoftheACcomponentoftheoutputvoltage

$$V_{ac}=[Vrms^2-Vavg^2]^{1/2}$$

9. Ripplefactor(R_f)

ItisdefinedastheratioofACcomponenttotheDC.WhererippleistheamountofACcomponentpresentinDCcomponent

$$R_f=\frac{Vac}{Vavg}=\frac{[Vrms^2-Vavg^2]^{1/2}}{Vavg}=[(\frac{Vrms}{Vavg})^2-1]^{1/2}=\sqrt{FF^2-1}$$

10. TransformerUtilizationFactor(TUF):

It isdefinedastheratioofoutput DC powertothevoltampererating ofthetransformer

$$TUF=\frac{Pdc}{VAratingofsecondarywinding\ ofthetransformer}$$

11. Rectifierefficiency:

It is definedastheratioofoutput DCpowertotheinputacpower

$$\eta=\frac{VavgIavg}{VrmsIrms}$$

12. Peakinversevoltage(PIV):

ItisdefinedasthemaximumvoltagethatanSCRcanbesubjectedtointhereversebiasedcondition

InthecaseofHalfwaverectifieritisV_m

Effectofsourceinductanceinsinglephaserectifier

Fig. below shows a single phase fully controlled converter with source inductance. For simplicity it hasbeenassumedthatthe converteroperatesinthe continuousconductionmode.Further,ithasbeenassumed that the load current ripple is negligible and the load can be replaced by a dc current source themagnitudeofwhichequalstheaverageloadcurrent.Fig.showsthecorrespondingwaveforms

ItisassumedthattheThyristorsT3andT4wereconductingatt=0.T1andT2arefiredatωt=α.If therewerenosourceinductanceT3andT4wouldhavecommutatedassoonasT1andT2areturnedON.

The inputcurrentpolaritywouldhave changedinstantaneously.However,if asource inductance ispresent the commutation and change of input current polarity cannot be instantaneous. s. Therefore, whenT1 and T2 are turned ON T3 T4 does not commutate immediately. Instead, for some interval all fourThyristorscontinuetoconductasshowninFig.2.14.Thisintervaliscalled“overlap”interval.

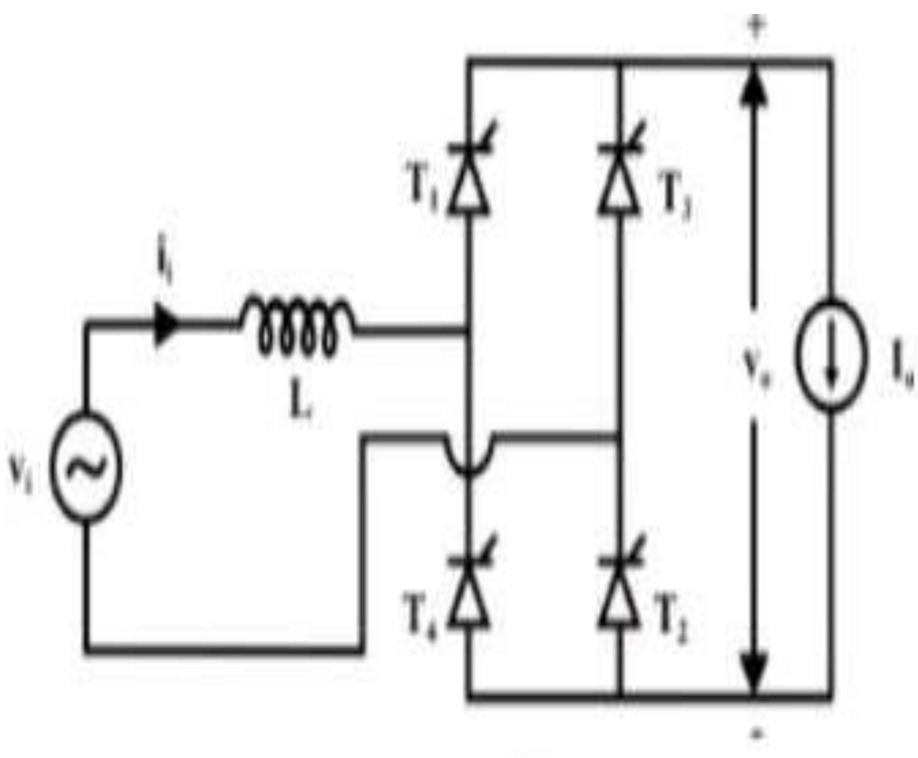


Figure:2.13 singlephasefullconvertercircuitwithsourceinductance

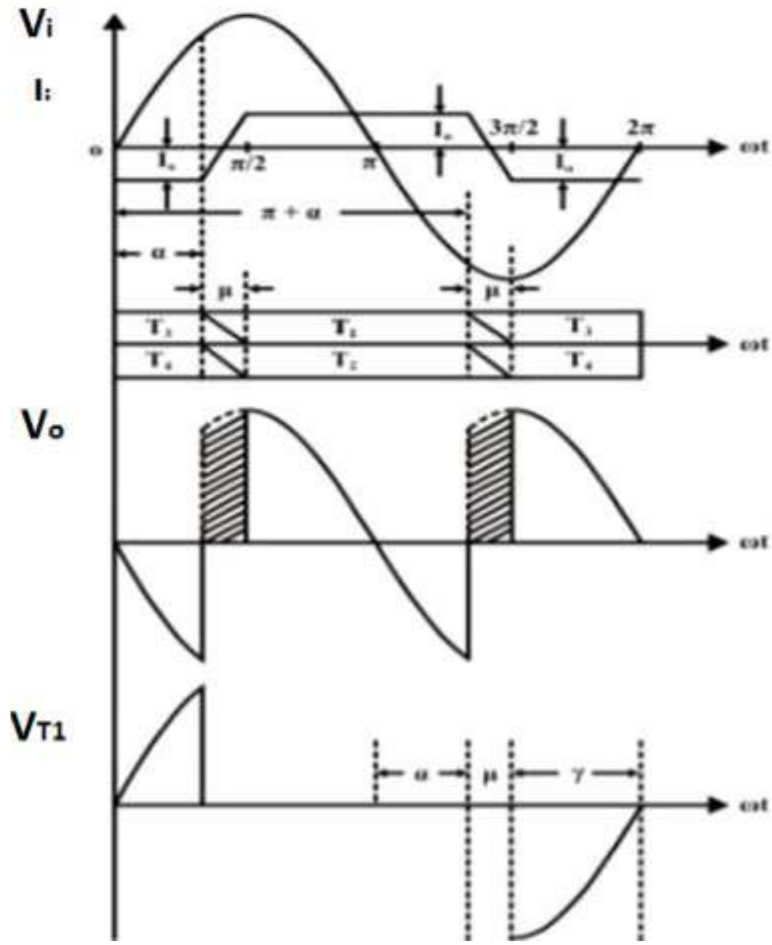


Figure:2.14singlephasefullconverteroutput waveformswithsourceinductance

1. Duringoverlapintervaltheloadcurrentfreewheelsthroughthethyristorsandtheoutputvoltageis clamped to zero. On the other hand, the input current starts changing polarity as the currentthrough T1 and T2 increases and T3 T4 current decreases. At the end of the overlap interval thecurrent through T3 and T4 becomes zero and they commutate, T1 and T2 starts conducting thefullloadcurrent
2. The same process repeats during commutation from T1 T2 to T3T4 at $\omega t = \pi + \alpha$. From Fig. 2.14it is clear that, commutation overlap not only reduces average output dc voltage but also reducesthe extinction angle γ which may cause commutation failure in the inverting mode of operation ifαisverycloseto180º.
3. Inthefollowinganalysisanexpressionoftheoverlapangle"μ"willbedetermined.Fromthe equivalentcircuitoftheconverterduringoverlapperiod.

$$L\frac{di_i}{dt} = v_i \ \ for \ \ \alpha \le \omega t + \mu$$

$$i_i(\omega t = \alpha) = -I_0$$

$$i_i = I - \frac{\sqrt{2}V_i}{\omega L}cos\omega t$$

$$\therefore i_i|_{\omega t-\alpha} = I - \frac{\sqrt{2}V_i}{\omega L}cos\alpha = -I_0$$

$$I = \frac{\sqrt{2}V_i}{\omega L}\cos\alpha - I_0$$

$$\therefore \qquad i_i = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu \quad i_i = I_0$

$$I_0 = \frac{\sqrt{2}V_i}{\omega L}(\cos\alpha - \cos(\alpha+\mu)) - I_0$$

$$\therefore \qquad \cos\alpha - \cos(\alpha+\mu) = \frac{\sqrt{2}\omega L}{V_0}I_0$$

$$V_0 = \frac{I}{\pi}\int_{\alpha}^{\alpha+\pi} V_i d\,\omega t$$

or $$V_0 = \frac{I}{\pi}\int_{\alpha+\mu}^{\alpha+\pi}\sqrt{2}v_i \sin\,\omega t d\,\omega t$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos(\alpha+\mu) - \cos(\pi+\alpha)$$

$$= \frac{\sqrt{2}v_i}{\pi}[\cos\alpha + \cos(\alpha+\mu)]$$

$$\therefore V_0 = 2\sqrt{2}\frac{v_i}{\pi}[cos\alpha - cos(\alpha+\mu)]$$

$$\therefore V_0 = \frac{2\sqrt{2}}{\pi}v_i cos\alpha - \frac{2}{\pi}\omega L I_0$$

TheEquationcanberepresentedbythefollowingequivalentcircuit

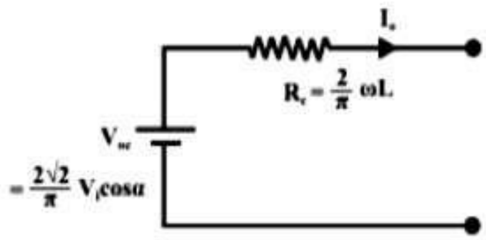


Figure:2.15Equivalentcircuitofthegivenequation

Equivalent circuitrepresentationofthesinglephasefullycontrolledrectifierwithsourceinductance

The simple equivalent circuit of Fig. 2.15 represents the single phase fully controlled converter withsource inductance as a practical dc source as far as its average behavior is concerned. The open circuitvoltage of this practical source equals the average dc output voltage of an ideal converter (without sourceinductance)operatingatafiringangleofα.Thevoltagedropacrosstheinternalresistance“RC”represents the voltage lost due to overlap shown in Fig. 2.14 by the hatched portion of the Vo waveform.Therefore, this is called the “Commutation resistance”. Although this resistance accounts for the voltagedrop correctly there is no power loss associated with this resistance since the physical process of overlapdoesnotinvolveanypowerloss.Thereforethisresistanceshouldbeusedcarefullywherepowercalculation isinvolved.

Numericalproblems

1. For the single phase fully controlled bridge is connected to RLE load. The source voltage is 230V, 50 Hz. The average load current of 10A continuous over the working range. For R= 0.4 Ω andL =2mH,Compute(a)firingangleforE= 120V(b)firingangleforE=-120V(c)incaseoutputcurrentisconstantfindtheinputpowerfactorsforbothpartsaandb

Solution:

a) ForE=120thefullconverterisoperatingas acontrolledrectifier

$$\frac{2Vm}{\pi}\cos\alpha = E + I_0 R$$

$$\frac{2\sqrt{2}.230}{\pi}\cos\alpha = 120 + 10X0.4 = 124V$$

$$\alpha = 53.21^0$$

Forα= 53.21^0powerflowsfromacsourcetoDCload.

b) ForE= -120thefullconverterisoperatingasacontrolledrectifier

$$\frac{2Vm}{\pi}\ cos\alpha = E + I_0 R$$

$$\frac{2\sqrt{2}.230}{\pi}\ cos\alpha = -120 + 10X0.4 = -116V$$

$$\alpha = 124.1^0$$

Forα=124.1^{0}powerflowsfromDCsourcetoac load.

c) Forconstantloadcurrent, rmsvalueofloadcurrentis

$$I_{or} = I_o = 10A$$

$$V_s I_{or} cos\Phi = EI_o + I^2 R_{or}$$

For α=53.21^0 $\qquad cos\Phi = \frac{120\times10+10^2\times0.4}{230\times10} = 0.5391lag$

For α=124.1^0 $\qquad cos\Phi = \frac{120\times10-10^2\times0.4}{230\times10} = 0.5043lag$

2. A single phase two pulse converter feeds power to RLE load with R= 6Ω, L= 6mH, E= 60V, ACsource voltage is 230V, 50Hz for continuous condition. Find the average value of load current forafiringangleof50^o.Incaseoneofthe4SCRsgets opencircuited.Findthenewvalueofaverageloadcurrentassumingthe outputcurrentascontinuous.
3. Forthesinglephasefullycontrolledbridgeconverter havingloadof„R‟,determinetheaverageoutput voltage, rms output voltage and input power factor if the supply is 230V, 50 Hz, singlephaseACandthefiringangleis60degrees

Operationofthreephasehalfwaverectifierwith R andRLloads

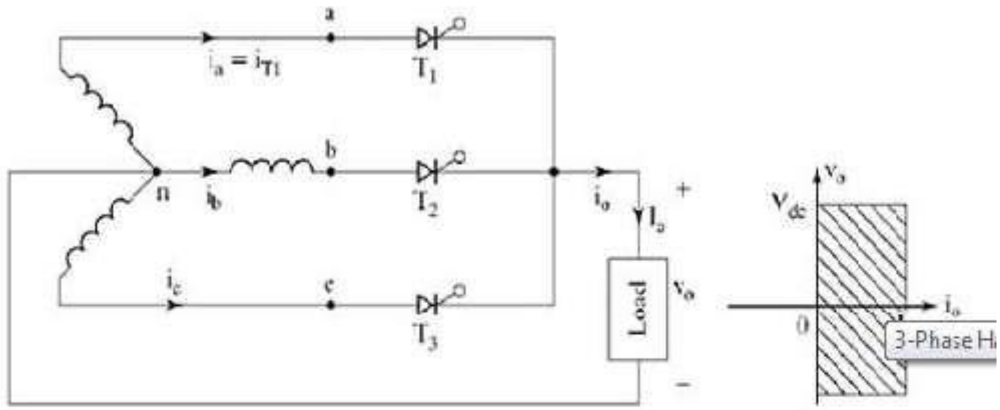


Figure:2.16circuitdiagramthreephasehalf waverectifier

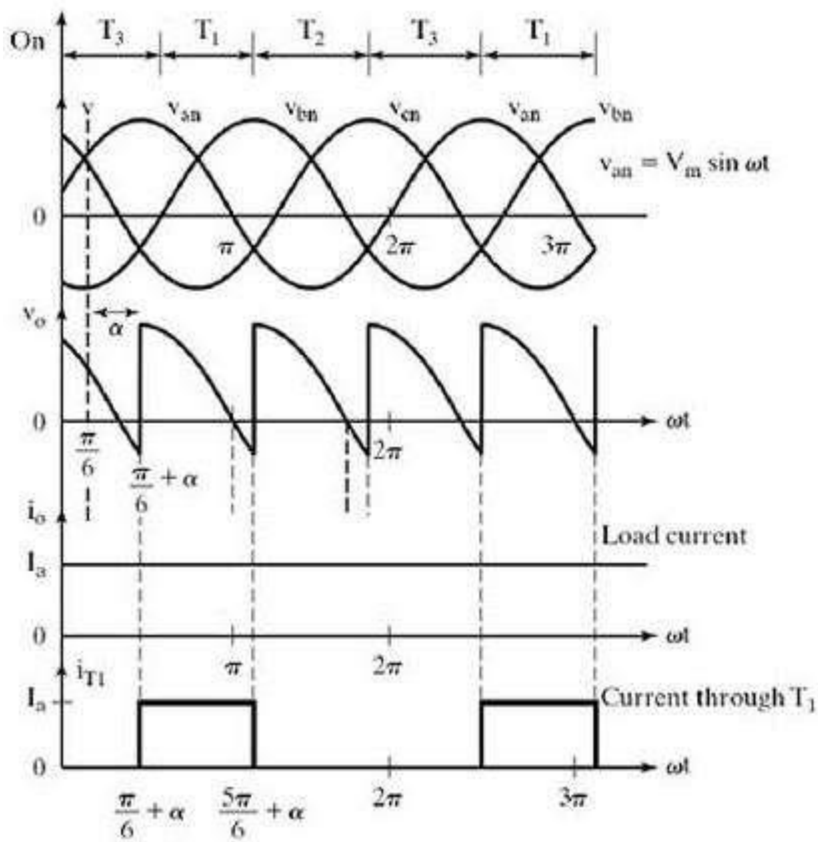


Figure:2.17input andoutputwaveformsofthreephasehalf waverectifier

Threephasesupply voltageequations

Wedefinethreelineneutral

voltages(3phasevoltages)asfollows$V_{RN}=V_{an}=V_m\sin wt$where$V_m$isthem

aximumvoltage

$V_{YN}=V_{bn}=V_m\sin(wt-\frac{2\pi}{3})$

$V_{BN}=V_{cn}=V_m\sin(wt-\frac{4\pi}{3})$

The3-phasehalfwaveconvertercombinesthreesinglephasehalfwavecontrolledrectifiersinone single circuit feeding a common load. The thyristor T_1 in serieswith one of the supply phasewindings*'a-n'* acts asone halfwave controlled rectifierThe second thyristor T_2 in serieswith thesupplyphasewinding*'b-n'* actsasthesecondhalfwavecontrolledrectifier.ThethirdthyristorT_3inserieswiththesupplyphasewindingactsast hethirdhalfwavecontrolledrectifier.

The3-phaseinputsupplyisappliedthroughthestarconnectedsupplytransformerasshowninthe figure.The commonneutral pointofthe supplyisconnectedtoone endofthe loadwhile theotherendoftheloadconnectedtothecommoncathodepoint.

WhenthethyristorT_1 istriggeredat$\omega t=(\prod/6+\alpha)=(30°+\alpha)$,thephasevoltage$V_{an}$appearsacrosstheloadwhen$T_1$conducts.Theloadcurrentflows throughthesupplyphasewinding*'a-n'*andthroughthyristorT_1aslongasT_1conducts.
WhenthyristorT_2istriggeredat$\omega t=(5\prod/6\alpha)$,$T_1$becomesreversebiasedandturns-off.Theloadcurrent flows through the thyristor and through the supply phase winding*'b-n'* .
WhenT_2conductsthephasevoltagev_{bn}appearsacrosstheloaduntilthethyristorT_3istriggered.
WhenthethyristorT_3istriggeredat$\omega t=(3\prod/2+\alpha)=(270°+\alpha)$,$T_2$isreversedbiasedandhence$T_2$turns-off.ThephasevoltageV_{an}appearsacrosstheloadwhenT_3conducts.
WhenT_1istriggeredagainatthebeginningofthenextinputcyclethethyristorT_3turnsoffasitisreversebiasednaturallyassoonasT_1istriggered.Thefigure showsthe 3-phaseinputsupplyvoltages,theoutputvoltagewhichappearsacrosstheload,andtheloadcurrentassumingaconstantandripplefreeloadcurrentforahighlyinductiveloadandthecurrentthroughthethyristorT_1.
For a purelyresistive loadwhere the loadinductance „L=0‟ andthe triggerangle $\alpha>(\prod/6)$, theloadcurrentappearsasdiscontinuousloadcurrentandeachthyristorisnaturallycommutatedwhenthepolarity ofthecorrespondingphasesupplyvoltagereverses.Thefrequencyofoutputripplefrequencyfora3-phasehalfwaveconverterisf_s,where$f_s$istheinputsupplyfrequency.3

The 3-phasehalfwaveconverterisnotnormallyusedinpracticalconvertersystemsbecauseofthedisadvantagethatthesupplycurrent waveformscontaindccomponents(i.e.,thesupplycurrentwaveformshaveanaverageordcvalue).

Toderiveanexpressionfortheaverageoutputvoltageofa3-phasehalfwaveconverter forcontinuousloadcurrent

Thereferencephasevoltageis$v_{RN}=v_{an}=V_m sin\omega t$.Thetriggerangleismeasuredfromthecrossoverpointsofthe3-phasesupplyvoltagewaveforms.WhenthephasesupplyvoltageV_{an}beginsitspositivehalfcycleat$\omega t=0$,thefirstcrossoverpointappearsat$\omega t=(\prod/6)$*radians*30°.

Thetriggerangleαforthethyristor T_1ismeasuredfromthe cross over point at . Thethyristor T_1isforwardbiasedduringtheperiod$\omega t=30°$to 150° , when the phase supplyvoltage v_{an}hashigheramplitudethantheotherphase supplyvoltages.HenceT_1can betriggeredbetween30°to150°.Whenthethyristor T_1istriggeredatatriggerangleα,theaverageordcoutputvoltageforcontinuousloadcurrentiscalculatedusingtheequation

$$V_{avg}= \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} Vmsinwtd(wt)$$

$$=\frac{3Vm}{2\pi}\left[(-cos\alpha)_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha}\right]$$

$$= -\frac{\frac{3\sqrt{3}}{Vm2}}{\pi}\ cos\alpha$$

$$=\frac{3Vml}{2\pi}\ cos\alpha$$

Operationofthreephasehalfcontrolledrectifierwith RandRLloads

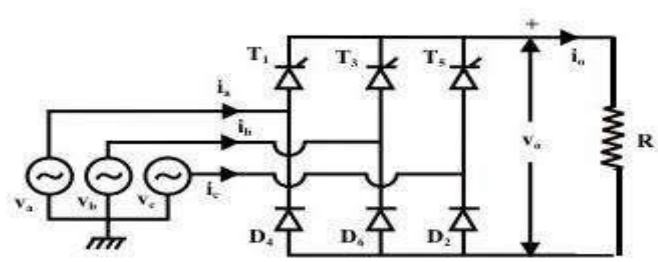


Figure: 2.18circuit diagramthreephasehalfcontrolledrectifier

ThreephasehalfwavecontrolledrectifieroutputvoltagewaveformsfordifferenttriggerangleswithRload

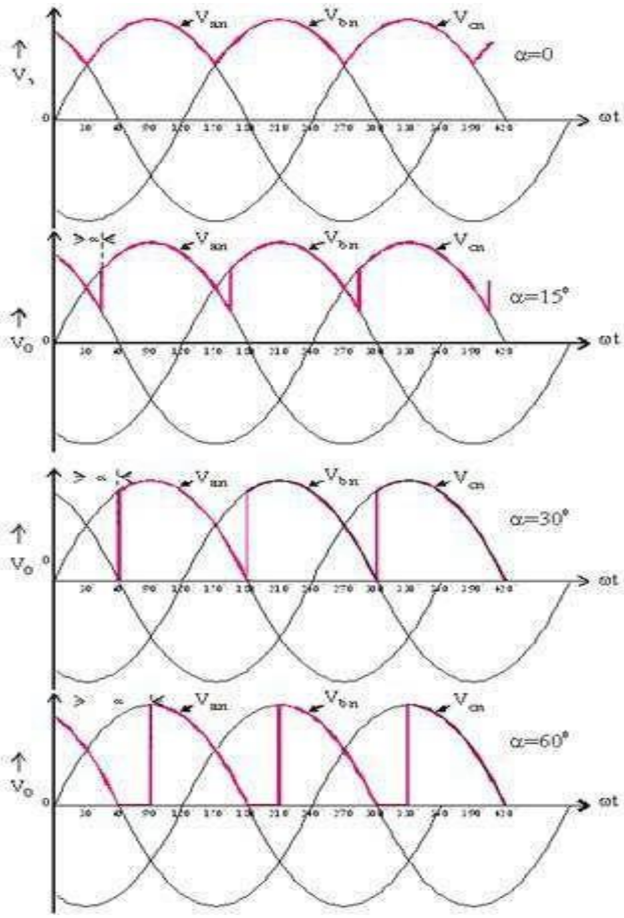


Figure:2.19input andoutput waveformsofthreephasehalfcontrolledrectifierwithRload

Three single phase half wave converters can be connected to form a three phase half wave converter.Similarly three phase semi converter uses 3 SCRs T1, T3 & T5 and 3 diodes D2, D4&D6 In the circuitshown above when any device conducts, line voltage is applied across load. so line voltage are necessaryto draw Phase shift between two line voltages is 60 degree & between two phase voltages it is 120 degreeEach phase & line voltage is sine wave with the frequency of 50 Hz.R,Y,Barephase voltageswithrespectto„N‟.

Inthecaseofa three-phasehalfwavecontrolledrectifierwithresistiveload,thethyristorT_1istriggeredatω$t=(30°+\alpha)$and T_1conductsuptoω$t=180°=$*&pron;* radians.Whenthephasesupplyvoltagedecreasestozeroat, theload current falls to zeroand thethyristorT_1turns off.ThusT_1conductsfrom$\omega t=(30°+\alpha)$*to*$(180°)$.

Hencetheaveragedcoutputvoltagefora3 -pulseconverter(3-phasehalfwavecontrolledrectifier)iscalculatedbyusingtheequation

TheaverageoutputvoltageV$_{avg}$= $\frac{3}{\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}}$ Vmlsinwtd(wt)+$\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha}$Vmlsinwtd(wt)

$$=\frac{3Vml}{2\pi}\ (1+cos\alpha)$$

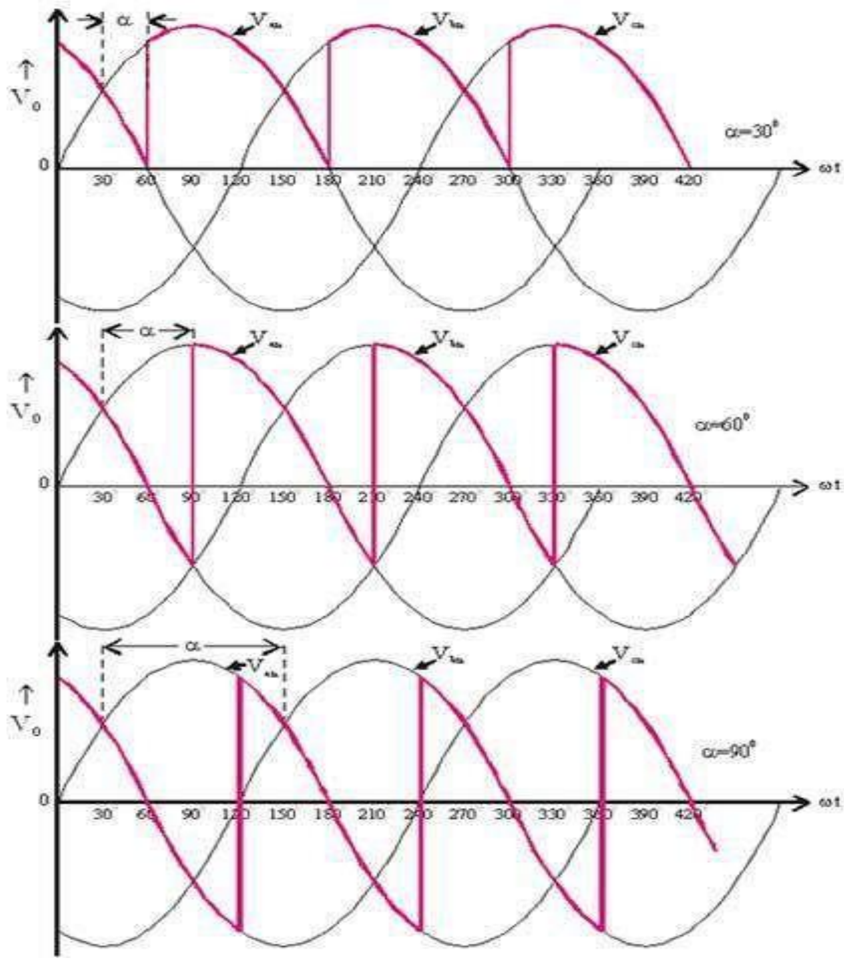


Figure:2.19 Inputandoutputwaveformsofthreephasehalfcontrolledrectifierwith RLload

Numerical Problemsonthreephaserectifiers:

1. Athreephasesemiconverterfeedspowertoaresistiveloadof10Ω.Forafiringangledelayof 30^0theloadtakes5Kw.Findthemagnitudeof perphaseinputsupplyvoltage.

Solution:

$$V_{or} = \left[\frac{3}{2\pi}\left[\int_{-(\frac{\pi}{6}-\alpha)}^{\frac{\pi}{6}} Vml^2\sin^2 wt\,d(wt) + \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}+\alpha} Vml^2\sin^2 wt\,d(wt)\right]\right]^{1/2}$$

$$V_{or}^2 = \frac{3Vml^2}{4\pi}\left[\left|wt+\frac{sin2wt}{2}\right|_{-(\frac{\pi}{6}-\alpha)}^{\frac{\pi}{6}} + \left|wt+\frac{sin2wt}{2}\right|_{-(\frac{\pi}{6})}^{\frac{\pi}{6}+\alpha}\right]$$

$$V_{or} = \frac{Vml}{2}\sqrt{\frac{3}{\pi}}\left[\frac{2\pi}{3}+\frac{\sqrt{3}}{2}(1+cos2\alpha)\right]^{1/2}$$

For$\alpha=30^0$

$P=V^2/R$

$$5000x10=\frac{2V_s^2 3}{4}\left[\frac{2\pi}{3}+\frac{\sqrt{3}}{2}(1+cos60)\right]$$

V_s =175.67VandV$_{ph}$=101.43V

2. Athree-phasehalf-wavecontrolledrectifierhas asupplyof200V/phase.Determinetheaverageload voltage for firing angle of 0^o, $30^o$and 60^o assuming a thyristor volt drop of 1.5V andcontinuousloadcurrent
3. A three phase half wave converter is supplying a load with a continuous constant current of 50Aoverafiringanglefrom0^oto60^0.Whatwillbethepowerdissipatedbytheloadattheselimitingvalues of firingangle.Thesupplyvoltageis415V(line).

Operationofthreephasefully controlledrectifierwithRandRLloads

Threephasefullconverterisafullycontrolledbridgecontrolledrectifierusingsixthyristorsconnectedintheformofafullwavebridgeconfiguration.Allthesixthyristorsarecontrolledswitcheswhichareturnedonataappropriatetimesbyapplyingsuitablegatetriggersignals.

Thethreephasefullconverterisextensivelyusedinindustrialpowerapplicationsuptoabout120kWoutputpowerlevel,wheretwoquadrantoperationsisrequired.Thefigureshowsathreephasefullconverterwithhighlyinductiveload.Thiscircuitisalsoknownasthreephasefullwavebridgeorasasixpulseconverter.

Thethyristorsaretriggeredatanintervalof(∏/3)radians(i.e.atanintervalof30°).Thefrequencyofoutputripplevoltageis6$f_s$andthefilteringrequirementislessthanthatofthreephasesemiandhalfwaveconverters.

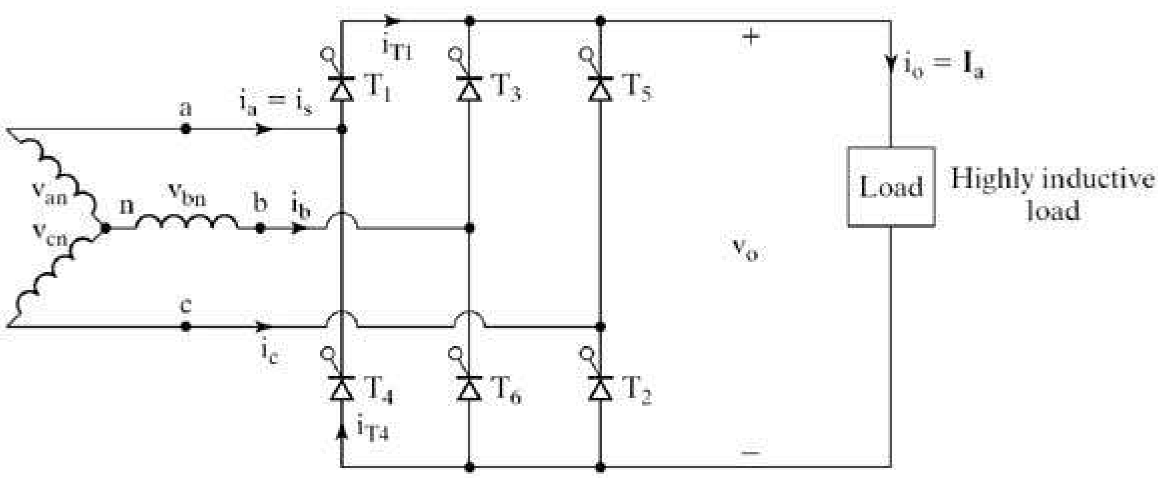


Figure: 2.20circuitdiagramthreephasefullycontrolledrectifierwithRand RLload

Atω$t=(∏/6+\alpha)$,thyristoris alreadyconductingwhenthe thyristoris turnedonby applyingthegatingsignaltothegateof.Duringthetimeperiodω $t=(∏/6+\alpha)$ to(∏/2+α),thyristorsandconducttogetherandthelinetolinesupplyvoltageappearsacrosstheload.

Atω$t=(∏/2+\alpha)$,thethyristorT_2istriggeredandT_6isreversebiasedimmediatelyandT_6turnsoffdue to natural commutation. During the time period ω$t=(∏/ +\alpha)$ to $(5∏/6 +\alpha)$,thyristorT_1andT_2conducttogetherandthelinetolinesupplyvoltageappearsacrosstheload.

Thethyristorsarenumberedinthecircuitdiagramcorrespondingtotheorderinwhichtheyaretriggered.Thetriggersequence(firingsequence)ofthethyristorsis12,23,34,45,56,61,12,23,andsoon.Thefigureshowsthewaveformsofthreephaseinputsupplyvoltages,outputvoltage,thethyristorcurrentthroughT_1andT_4,thesupplycurrentthroughtheline„a‟.

Wedefinethreelineneutral

voltages(3phasevoltages)asfollows$V_{RN}=V_{an}=V_m\sin wt$where$V_m$isthem

aximumvoltage

$V_{YN}=V_{bn}=V_m\sin(wt-\frac{2\pi}{3})$

$V_{BN}=V_{cn}=V_m\sin(wt-\frac{4\pi}{3})$

Thecorrespondinglinetolinevoltages are

$V_{RY}=V_{ab}=V_{an}-V_{bn}=\sqrt{3}V_m\sin(wt+\frac{\pi}{6})$

$V_{YB}=V_{bc}=V_{bn}-V_{cn}=\sqrt{3}V_m\sin(wt-\frac{\pi}{2})$

$V_{BR}=V_{ca}=V_{cn}-V_{an}=\sqrt{3}V_m\sin(wt+\frac{\pi}{2})$

Toderiveanexpressionfortheaverageoutputvoltageofthreephasefullconverterwithhighlyinductiveloadassum ingcontinuousandconstantloadcurrent

Theoutputloadvoltageconsistsof6voltagepulsesoveraperiodof2∏radians,hencethe averageoutputvoltageiscalculatedas

$$V_{avg}=\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} V_o d(wt)$$

$$V_o=V_{ab}=\sqrt{3}V_m\sin(wt+\frac{\pi}{6})$$

$$V_{avg}=\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha}\sqrt{3}V_m\sin(wt+\frac{\pi}{6})d(wt)$$

$$=\frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

$$=\frac{3V_{ml}}{\pi}\cos\alpha$$

TheRMSvalueoftheoutputvoltageisfoundfrom

$$V_{orms} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vo^2 d(wt)\right]^{1/2}$$

$$= \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vab^2 d(wt)\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3Vm^2 sin^2(wt+\frac{\pi}{6}) d(wt)\right]^{1/2}$$

$$= \sqrt{3}V\left(\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}cos2\alpha\right)^{1/2}$$

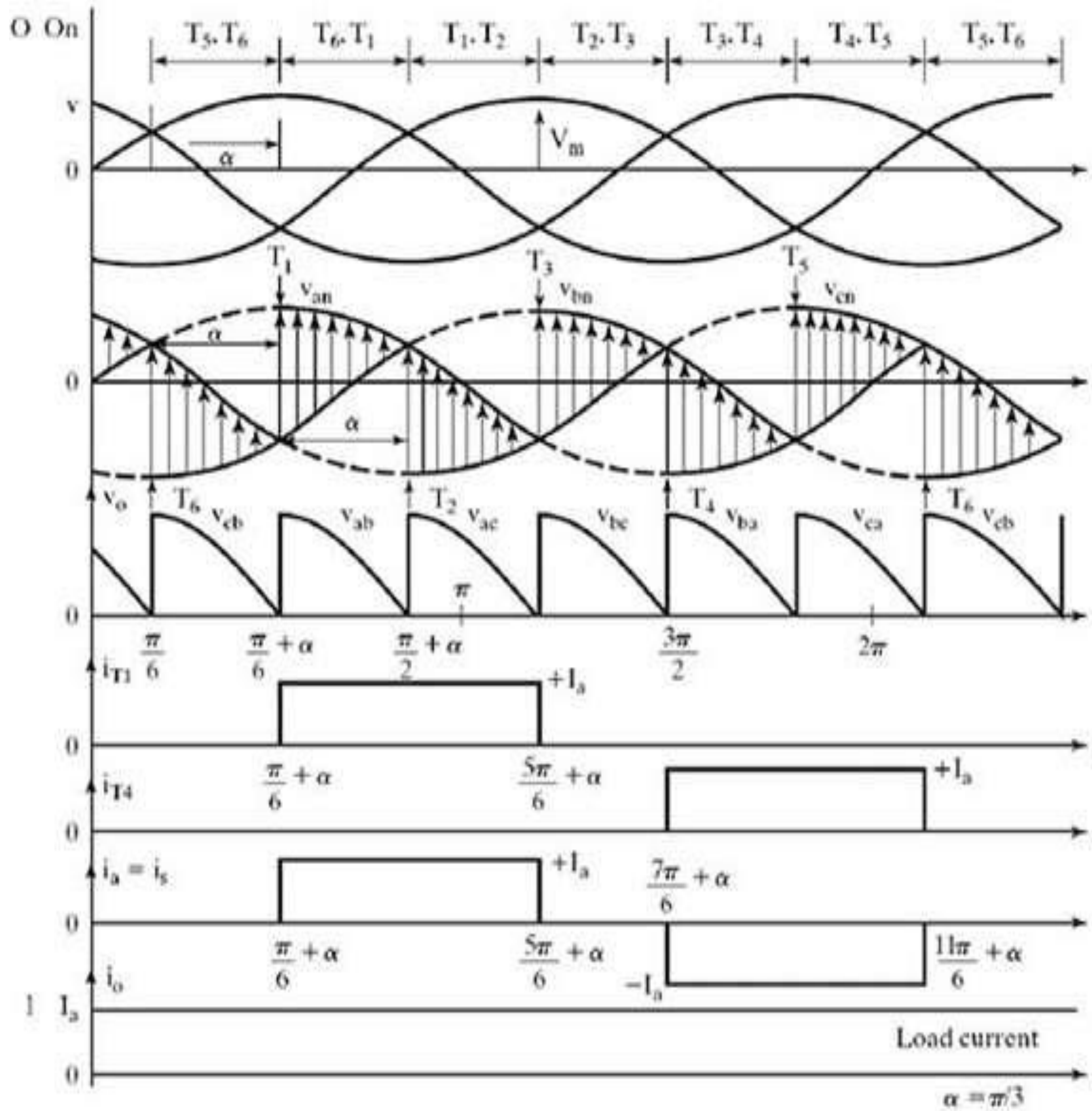


Figure:2.21Inputandoutputwaveformsofthree phasefully controlledrectifier

Operationofthreephasehalfwaverectifier withRLEloads

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolledconverterbysixthyristorsasshowninFigure

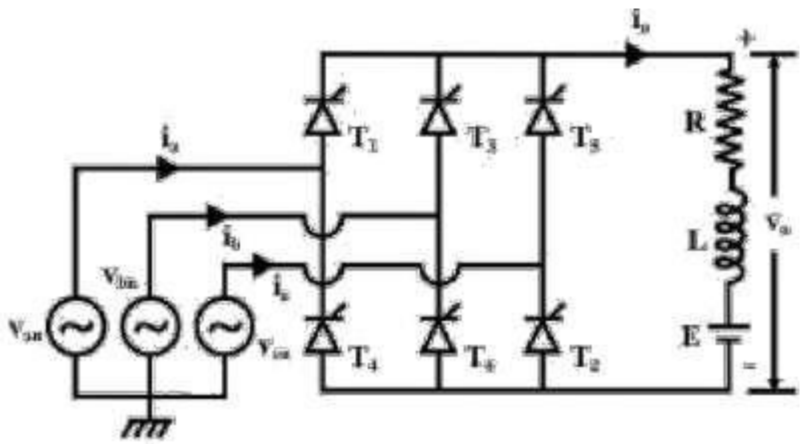


Figure:2.22circuitdiagramofthreephasefullycontrolledrectifierwithRLE load

For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from thebottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter onlyone devicefromthesetwogroupswillconduct.

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the inputcycle. Now the thyristors are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60°interval betweeneach firing.Therefore thyristorson thesame phase leg are fired atan interval of 180°andhencecannotconductsimultaneously.Thisleavesonlysixpossibleconductionmodefortheconverter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, T5T6,T6T1. Each conductionmode isof 60° duration and appears in the sequence mentioned.Each of theseline voltages can be associated with the firing of a thyristor with the help of the conduction table-1. ForexamplethethyristorT1isfiredatthe end ofT5T6conductioninterval.DuringthisperiodthevoltageacrossT1wasvac.ThereforeT1isfiredα angleafterthepositivegoingzerocrossingofvac.similarobservationcanbemadeaboutotherthyristors.

Fig. 2.23 shows the waveforms of different variables. To arrive at the waveforms it is necessary to drawthe conduction diagram which shows the interval of conduction for each thyristor and can be drawn withthehelpofthephasordiagramoffig.2.22.Iftheconverterfiringangleisαeachthyristorisfired“α” angle after the positive going zero crossing of the line voltage with which it‟s firing is associated. Oncetheconductiondiagram isdrawnallothervoltagewaveformscanbedrawnfrom thelinevoltagewaveforms and from the conduction table of fig. 2.22. Similarly line currents can be drawn from theoutput current and the conduction diagram. It is clear from the waveforms that output voltage and currentwaveforms areperiodicoveronesixthoftheinputcycle.Thereforethisconverterisalsocalled

the “six pulse” converter. The input current on the other hand contains only odds harmonics of the inputfrequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation ofthisconverterinmore details.

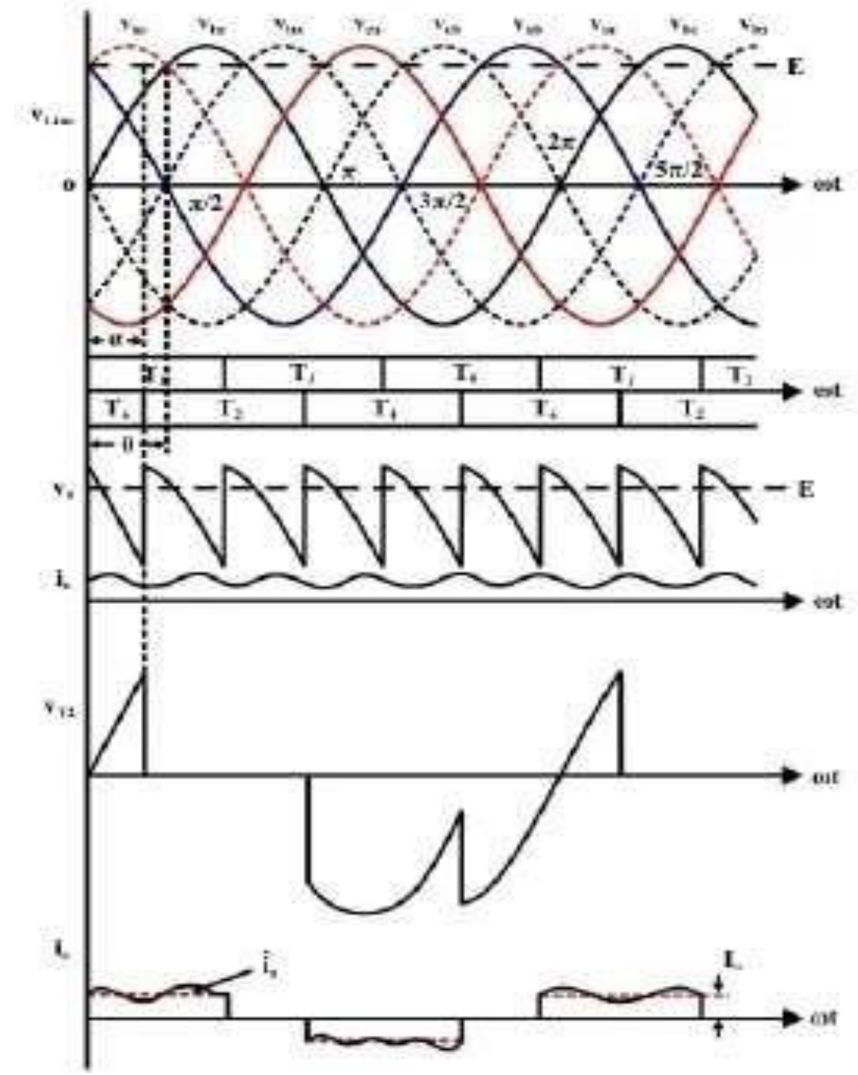


Figure:2.23 Inputandoutputwaveformsofthreephase fullycontrolledrectifierinrectifiermode

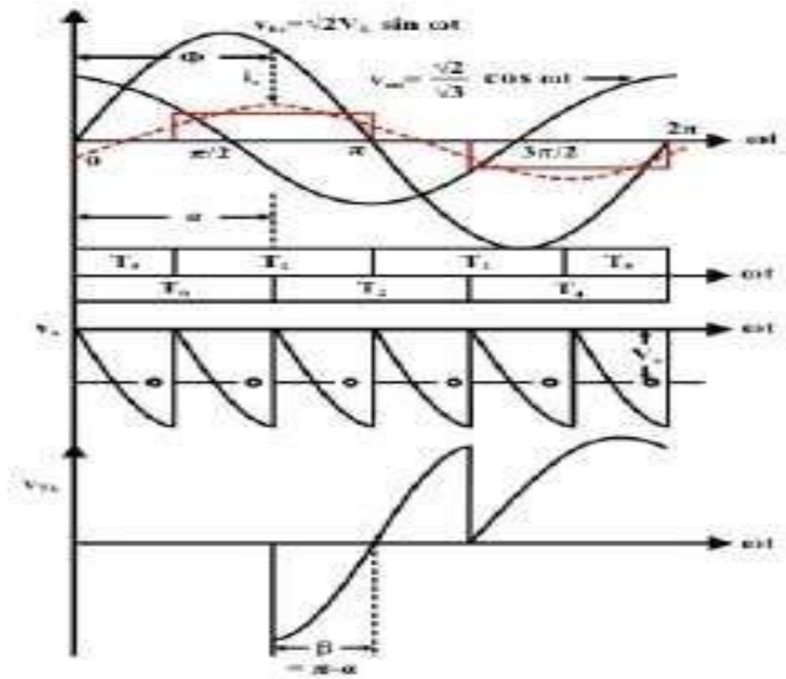


Figure:2.24Inputandoutputwaveformsofthreephase fullycontrolledrectifierininversionmode

Effectofsourceinductanceinthreephaserectifiers

The three phase fully controlled converter was analyzed with ideal source with no internal impedance.When the source inductance is taken into account, the qualitative effects on the performance of theconverteris similartothatinthecaseofasinglephaseconverter.Fig.2.25shows suchaconverter.Asinthe case of a single phase converter the load is assumed to be highly inductive such that the load can bereplacedbyacurrentsource.

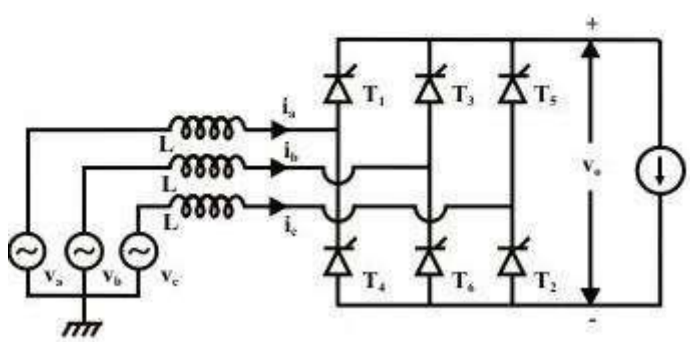


Figure: 2.25circuitdiagramforthreephaserectifierwith sourceinductance

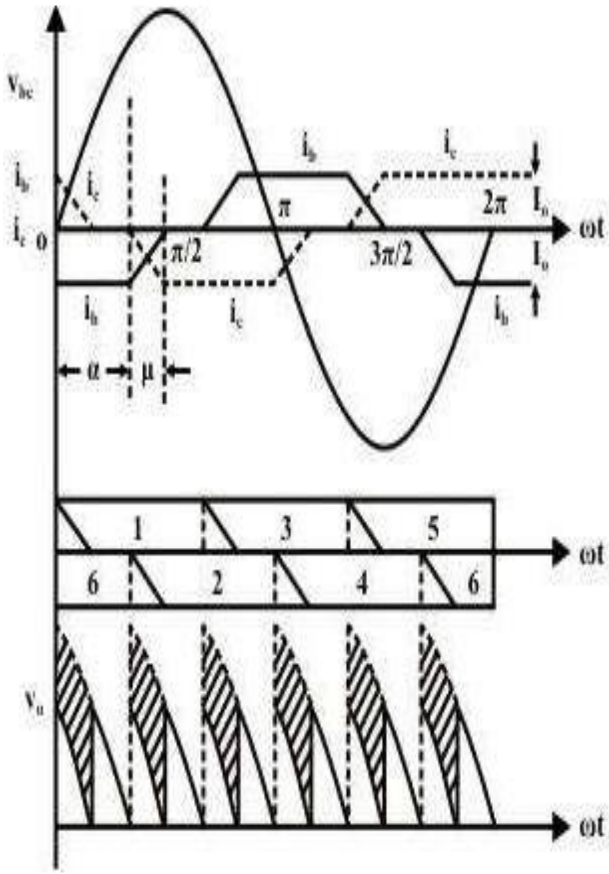


Figure:2.26waveformsforthree phaserectifierwithsourceinductance

As in the case of a single phase converter, commutations are not instantaneous due to the presence ofsource inductances. It takes place over an overlap period of "μ_1" instead. During the overlap period threethyristors instead of two conducts. Current in the outgoing thyristor gradually decreases to zero while theincoming thyristor current increases and equals the total load current at the end of the overlap period. Ifthe duration of the overlap period is greater than 60º four thyristors may also conduct clamping the outputvoltage to zero for some time. However, this situation is not very common and will not be discussed anyfurther in this lesson. Due to the conduction of two devices during commutation either from the top groupor the bottom group the instantaneous output voltage during the overlap period drops (shown by thehatched portion of Fig. 2.26 resulting in reduced average voltage. The exact amount of this reduction canbecalculatedasfollows.

In the time interval $\alpha < \omega t \leq \alpha + \mu$, T_6 and T_2 from the bottom group and T_1 from the top group conducts.Theequivalentcircuitof theconverterduringthisperiodisgivenbythecircuitdiagramofFig.2.27

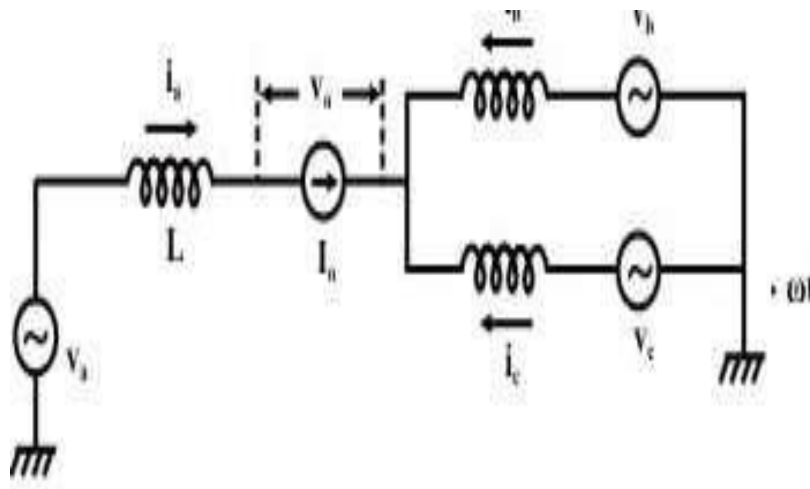


Figure:2.27Equivalentcircuitofwaveformswithsourceinductance

Therefore, in the interval $\alpha < \omega t \leq \alpha + \mu$

$$v_b = L\frac{di_b}{dt} - L\frac{di_c}{dt} + v_c$$

or, $$v_{bc} = L\frac{d}{dt}(i_b - i_c)$$

but $i_b + i_c + I_o = 0$ $\quad \therefore \quad \frac{di_b}{dt} = -\frac{di_c}{dt}$

$$\therefore \quad 2L\frac{d}{dt}i_b = v_{bc} = \sqrt{2}V_L \sin\omega t$$

$$\therefore \quad i_b = C - \frac{\sqrt{2}V_L}{2\omega L}\cos\omega t$$

at $\omega t = \alpha$, $\quad i_b = -I_0$ $\quad \therefore \quad C = \frac{\sqrt{2}V_L}{2\omega L}\cos\alpha - I_0$

$$\therefore \quad i_b = \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos\omega t) - I_0$$

at $\omega t = \alpha + \mu$, $\quad i_b = 0$

$$\therefore \quad \frac{\sqrt{2}V_L}{2\omega L}(\cos\alpha - \cos(\alpha + \mu)) = I_0$$

Or, $$\cos\alpha - \cos(\alpha + \mu) = \frac{\sqrt{2}\omega L}{V_L}I_0$$

.

for $\mu \le 60°$. It can be shown that for this condition to be satisfied

$$I_0 \le \frac{V_L}{\sqrt{2}\omega L}\cos\left(\alpha - \frac{\pi}{3}\right)$$

To calculate the dc voltage

For $\alpha \le \omega t \le \alpha + \mu$

$$v_0 = v_a - v_b + L\frac{di_b}{d_t} = \frac{3}{2}v_a$$

for $\alpha + \mu \le \omega t \le \alpha + \frac{\pi}{3}$ $\qquad v_0 = v_{ac}$

$$\therefore \qquad V_0 = \frac{3}{\pi}\left[\int_\alpha^{\alpha+\mu}\frac{3}{2}v_a\, d\omega t + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_\alpha^{\alpha+\mu}\left(v_{ac} + \frac{3}{2}v_a - v_{ac}\right) + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_\alpha^{\alpha+\frac{\pi}{3}} v_{ac}\, d\omega t + \int_\alpha^{\alpha+\mu}\left(\frac{v_a}{2} + v_c\right)d\omega t\right]$$

$$= \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3}{2\pi}\int_\alpha^{\alpha+\mu} v_{bc}\, d\omega t$$

$$\text{or} \qquad V_0 = \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}\int_\alpha^{\alpha+\mu}\sin\omega t\, d\omega t$$

$$= \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}[\cos\alpha - \cos(\alpha+\mu)]$$

$$V_0 = \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3}{\pi}\omega L\, I_0$$

Introductiontodualconverters

Dual converter, the name itself says two converters. It is really an electronic converter or circuit whichcomprisesoftwoconverters.Onewillperform asrectifierandtheotherwillperform asinverter.Therefore,we can say thatdouble processeswilloccurat amoment.Here,two full convertersarearranged in anti-parallel pattern and linked to the same dcload. These converters can provide fourquadrantoperations.Thebasicblockdiagramisshownbelow

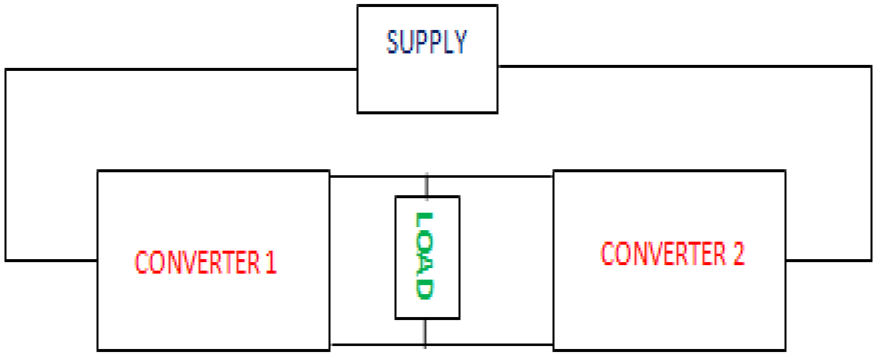


Figure:2.28Blockdiagramof dualconverter

ModesofOperationofDualConverter

Therearetwofunctionalmodes:Non-circulatingcurrentmodeandcirculatingmode.

NonCirculatingCurrentMode

- Oneconverterwillperformatatime.Sothereisnocirculatingcurrentbetweentheconverters.
- Duringtheconverter1operation,firingangle(α_1)willbe0<α_1< 90^o;V_{dc}andI_{dc}arepositive.
- Duringtheconverter2operation,firingangle(α_2)willbe0<α_2< 90^o;V_{dc}andI_{dc}arenegative.

CirculatingCurrentMode

- TwoconverterswillbeintheON conditionatthesametime.Socirculatingcurrentispresent.
- Thefiringanglesareadjustedsuchthatfiringangleofconverter1(α_1)+firingangleofconverter2 (α_2)= 180^o.
- Converter 1 performs as a controlled rectifierwhen firing angle be 0<α_1< 90^o and Converter 2performs as an inverter when the firing angle be 90^o<α_2< 180^o. In this condition, V_{dc} and I_{dc} arepositive.
  - Converter 1 performs as an inverter when firing angle be 90^o<α_1< 180^o and Converter 2 performsas a controlled rectifier when the firing angle be 0<α_2< 90^{o}In this condition, V_{dc} and I_{dc} arenegative.
  - Thefourquadrant operationis shownbelow

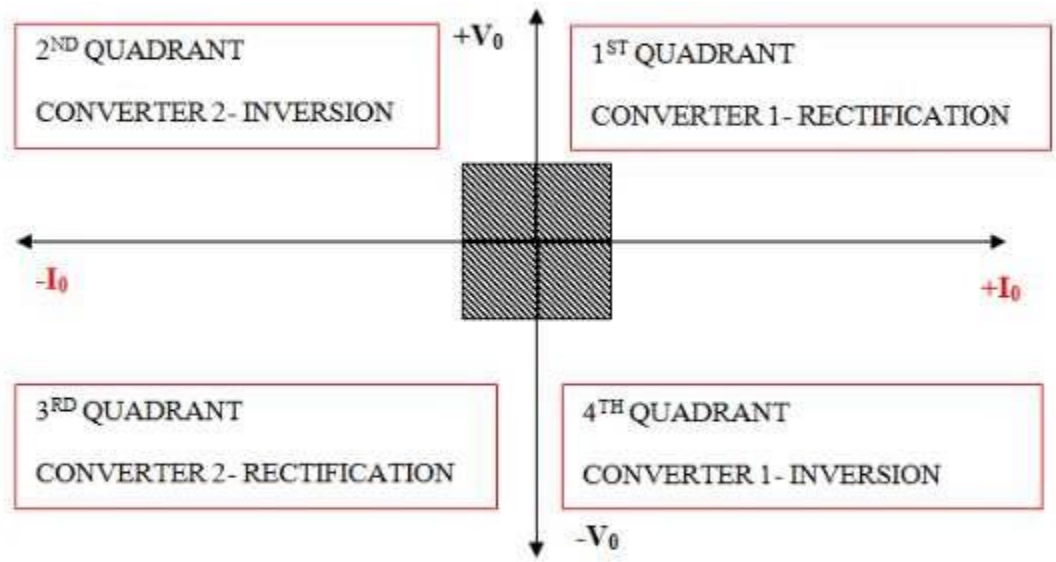


Figure:2.29Four quadrantoperationsofdual converter

IdealDualConverter

The term „ideal" refers to the ripple free output voltage. For the purpose of unidirectional flow of DCcurrent, two diodes(D_1 and D_2) are incorporated between the converters. However, the direction ofcurrent can be in any way. The average output voltage of the converter 1 is V_{01} and converter 2 is V_{02}. Tomake the output voltage of the two converters in same polarity and magnitude, the firing angles of theThyristorshavetobecontrolled.

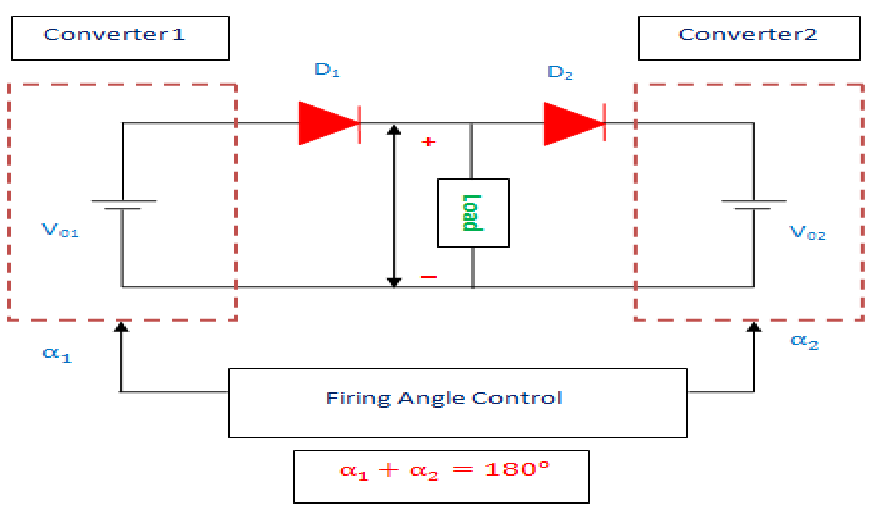


Figure:2.30Idealdualconverter

SinglePhaseDualConverter

The source of this type of converter will be single-phase supply. Consider, the converter is in non-circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by themethod of rectification. It is then given to the load after filtering. Then, this DC is provided to theconverter 2 as input. This converter performs as inverter and converts this DC to AC. Thus, we get AC asoutput.Thecircuitdiagramisshownbelow.

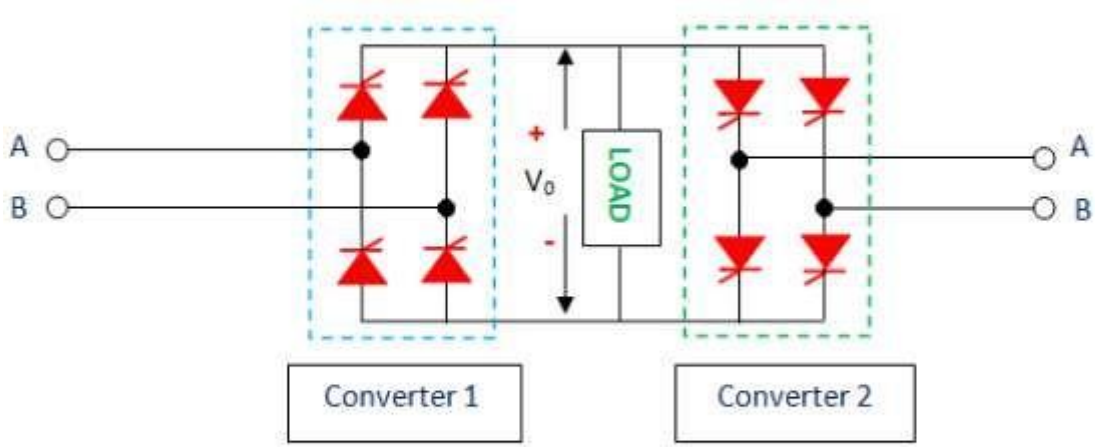


Figure:2.31Single phaseDual converter

AverageoutputvoltageofSingle-phaseconverter= $\frac{2V_m Cos\ \alpha}{\pi}$

AverageoutputvoltageofThree-phaseconverter= $\frac{3V_{ml} Cos\ \alpha}{\pi}$

Forconverter 1,theaverageoutputvoltage, $V_{01} = V_{max} Cos\alpha_1$

Forconverter 2,theaverageoutputvoltage, $V_{02} = V_{max} Cos\alpha_2$

$$V_0 = V_{01} = -V_{02}$$
$$V_{max} Cos\alpha_1 = -V_{max} Cos\alpha_2$$
$$Cos\alpha_1 = Cos(180^o - \alpha_2)\ or\ Cos\alpha_2 = Cos(180^o + \alpha_2)$$

Outputvoltage, $\alpha_1 + \alpha_2 = 180^o\ And\ \alpha_1 - \alpha_2 = 180^o$

Thefiringanglecanneverbegreaterthan180°.So, $\alpha_1 + \alpha_2 = 180^o$

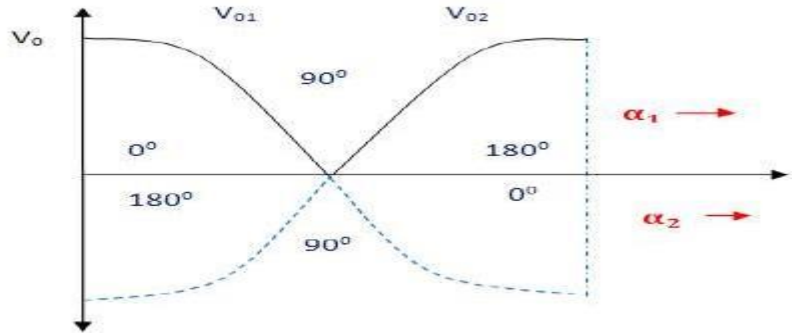


Figure:2.32output voltagevariationwithfiringangle

Three PhaseDualConverter

Here, three-phase rectifierand three-phase inverterare used. The processes are similar to single-phasedual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC.This DC is filtered and given to the input of the second converter. It will do the DC to AC conversion andthe output that we get is the three-phase AC. Applications where the output is up to 2 megawatts. Thecircuitisshownbelow.

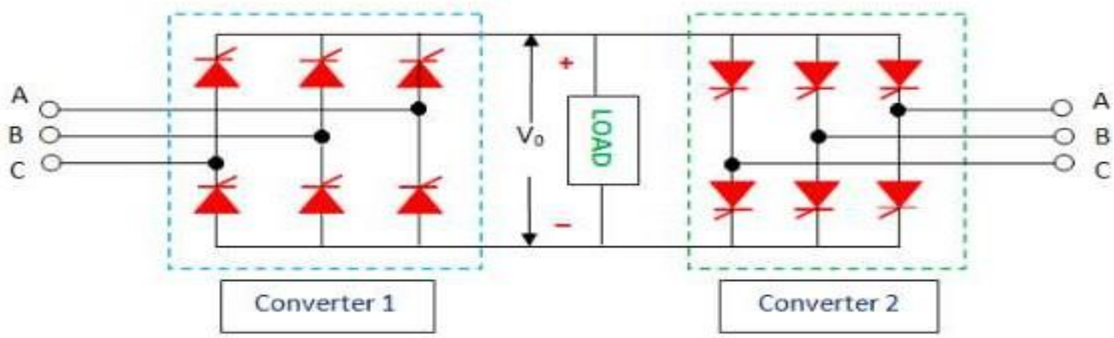


Figure:2.33Threephasedualconverter

ApplicationofDualConverter

- DirectionandSpeedcontrolofDCmotors.
- ApplicablewherevertherereversibleDC isrequired.
- IndustrialvariablespeedDCdrives.

UNIT– III
ACvoltagecontrollersandCycloconverters

IntroductiontoACvoltagecontrollers

ACvoltagecontrollers **(**aclinevoltagecontrollers**)**areemployedtovarytheRMSvalueofthealternatingvoltageappliedtoaloadcircuitbyintroducingThyristorsbetweentheloadandaconstantvoltageacsource.TheRMSvalueofalternatingvoltageappliedtoaloadcircuitiscontrolled by controlling the triggering angle of the Thyristors in the AC VoltageControllercircuits**.**

Inbrief,anACVoltageControllerisatypeofthyristorpowerconverterwhichisusedtoconvertafixedvoltage,fixed frequencyac inputsupply toobtain avariable voltageacoutput. The RMSvalueoftheacoutputvoltageandtheacpowerflowtotheloadiscontrolledbyvarying(adjusting)thetriggerangle,„α"

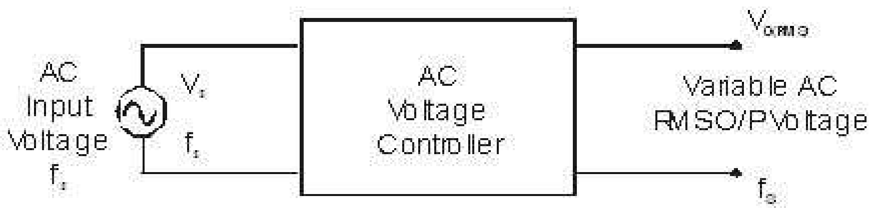


Figure: 3.1Blockdiagramof ACvoltagecontroller

Controlstrategies:

Therearetwodifferenttypesofthyristorcontrolusedinpracticetocontroltheacpowerflow

1. On-Offcontrol
2. Phasecontrol

Thesearethetwoacoutput voltagecontroltechniques.InOn-OffcontroltechniqueThyristorsare usedasswitchestoconnectthe loadcircuittothe ac supply(source)forafewcyclesoftheinput acsupply and thentodisconnectitforfewinputcycles.The Thyristors thus act as ahighspeedcontactor(orhighspeedacswitch).

Phasecontrol

InphasecontroltheThyristorsareusedasswitchestoconnecttheloadcircuittotheinputacsupply,forapartofeveryinputcycle.Thatis theac supplyvoltageischoppedusing Thyristorsduringapartofeachinputcycle.

Thethyristorswitchisturnedonforapartofeveryhalfcycle,sothatinputsupplyvoltageappearsacrosstheloadandthenturnedoffduringtheremainingpartofinputhalfcycletodisconnecttheacsupplyfromtheload.

Bycontrollingthephaseangleorthetriggerangle„α‟(delayangle),theoutputRMSvoltage acrosstheloadcanbecontrolled.

Thetriggerdelayangle„α‟isdefinedasthephaseangle(thevalueofωt)atwhichthethyristor turnsonandtheloadcurrentbeginstoflow.

ThyristorAC VoltageControllersuseaclinecommutation oracphasecommutation.ThyristorsinACVoltageControllersarelinecommutated(phasecommutated)sincetheinputsupplyisac.Whentheinputacvoltagereversesandbecomesnegativeduringthenegativehalfcyclethecurrentflowingthroughtheconductingthyristordecreasesandfallstozero.Thus theONthyristornaturallyturnsoff,whenthedevicecurrentfallstozero.

PhasecontrolThyristorswhicharerelativelyinexpensive,convertergradeThyristorswhichareslowerthanfastswitchinginvertergradeThyristorsarenormallyused.

Forapplicationsupto400Hz,if Triacsare availabletomeetthevoltageandcurrentratingsof aparticularapplication,Triacsaremorecommonlyused.

Duetoaclinecommutationornaturalcommutation,thereisnoneedofextracommutationcircuitryorcomponentsandthecircuitsforACVoltageControllersareverysimple.
Duetothenatureoftheoutputwaveforms,theanalysis,derivationsofexpressionsforperformanceparametersarenotsimple,especiallyforthe phase controlled AC VoltageControllerswithRLload.Buthowevermostofthe practicalloadsare ofthe RLtype andhenceRLloadshouldbeconsideredintheanalysisanddesignofACVoltageControllerscircuits.

Typeofacvoltagecontrollers

Theacvoltagecontrollersareclassifiedintotwotypesbasedonthetypeofinputacsupplyappliedtothecircuit.

- SinglePhaseACControllers
- ThreePhaseACControllers

SinglePhaseACControllersoperatewithsinglephaseacsupplyvoltageof230VRMSat50Hzinourcountry.
ThreePhaseACControllers operatewith3phaseacsupplyof400VRMSat50Hzsupplyfrequency.

Performanceparameters ofacvoltagecontrollers

- RMS Output (Load) Voltage

$$V_{O(RMS)} = \left[\frac{n}{2\pi(n+m)} \int_0^{2\pi} V_m^2 \sin^2 \omega t . d(\omega t) \right]^{1/2}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{n}{(m+n)}} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

$$V_{O(RMS)} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

Where $V_S = V_{i(RMS)}$ = RMS value of input supply voltage.

- Duty Cycle

$$k = \frac{t_{ON}}{T_O} = \frac{t_{ON}}{(t_{ON} + t_{OFF})} = \frac{nT}{(m+n)T}$$

Where, $k = \frac{n}{(m+n)}$ = duty cycle (d).

- RMS Load Current

$$I_{O(RMS)} = \frac{V_{O(RMS)}}{Z} = \frac{V_{O(RMS)}}{R_L}; \quad \text{for a resistive load } Z = R_L.$$

- Output AC (Load) Power

$$P_O = I_{O(RMS)}^2 \times R_L$$

- Input Power Factor

$$PF = \frac{P_O}{VA} = \frac{\text{output load power}}{\text{input supply volt amperes}} = \frac{P_O}{V_S I_S}$$

$$PF = \frac{I_{O(RMS)}^2 \times R_L}{V_{i(RMS)} \times I_{in(RMS)}}; \qquad I_S = I_{in(RMS)} = \text{RMS input supply current.}$$

The input supply current is same as the load current $I_{in} = I_O = I_L$

Hence, RMS supply current = RMS load current; $I_{in(RMS)} = I_{O(RMS)}$.

$$PF = \frac{I_{O(RMS)}^2 \times R_L}{V_{i(RMS)} \times I_{in(RMS)}} = \frac{V_{O(RMS)}}{V_{i(RMS)}} = \frac{V_{i(RMS)}\sqrt{k}}{V_{i(RMS)}} = \sqrt{k}$$

$$PF = \sqrt{k} = \sqrt{\frac{n}{m+n}}$$

Applicationsofacvoltagecontrollers

- Lighting/Illuminationcontrolinacpowercircuits.
- Inductionheating.
- Industrialheating&Domesticheating.
- Transformerstap changing(on load transformertapchanging).
- Speedcontrolofinductionmotors(singlephaseandpolyphaseacinductionmotorcontrol).
- ACmagnetcontrols.

SinglephaseACvoltagecontrollerwithRload

AC to AC voltage converters operates on the AC mains essentially to regulate the output voltage. Portionsof the supply sinusoid appear at the load while the semiconductor switches block the remaining portions.Several topologies have emerged along with voltage regulation methods, most of which are linked to thedevelopmentof thesemiconductordevices.

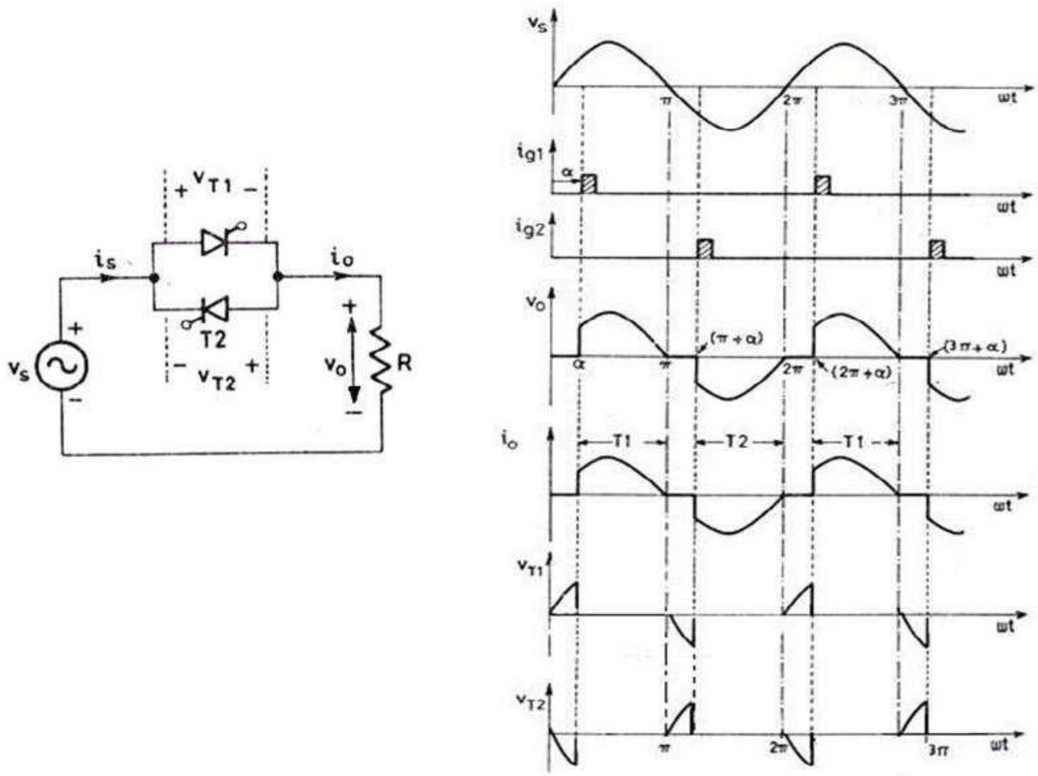


Figure:3.2Circuit diagramandoutputwaveformsof ACvoltagecontrollerwithRload

Fig.2.35illustratestheoperationofthePACconverterwitharesistiveload.Thedevice(s)istriggeredata phase-angle 'α' in each cycle. The current follows the voltage wave shape in each half and extinguishesitself at the zero crossingsof the supply voltage. In the two-SCR topology, one SCR is positively biasedin each half of the supply voltage. There is no scope for conduction overlap of the devices. A single pulseis sufficient to trigger the controlled devices with a resistive load. In the diode-SCR topology, two diodesare forward biased in each half. The SCR always receives a DC voltage and does not distinguish thepolarity of the supply. It is thus always forward biased. The bi-directional TRIAC is also forward biasedforbothpolaritiesof thesupplyvoltage.

ThermsvoltageVrmsdecidesthepowersuppliedtotheload.Itcanbecomputedas

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} 2V^2 \sin^2 \omega t \quad d\omega t}$$
$$= V\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}$$

PowerFactor

The power factor of a nonlinear deserves a special discussion. Fig. 2.35 shows the supply voltage and thenon-sinusoidal load current. The fundamental load/supply current lags the supply voltage by the φ1,'Fundamental Power Factor' angle. Cosφ1 is also called the 'Displacement Factor'. However this does notaccount for the total reactive power drawn by the system. This power factor is inspite of the actual loadbeingresistive!Thereactivepowerisdrawnalsoythetrigger-angle dependentharmonics.Now

$$power \quad factor = \frac{average \quad power}{apparent \quad voltamperes} = \frac{P}{VI_L}$$
$$= \frac{VI_{L1}\cos\phi_1}{VI_L}$$
$$distortion \quad factor = \frac{I_{L1}}{I_L}$$

The Average Power, P drawn by the resistive load is

$$P = \frac{1}{2\pi}\int_0^{2\pi} vi_L \quad d\omega t \quad = \frac{1}{\pi}\int_{\alpha}^{\pi} \frac{2V^2}{R}\sin^2 \omega t \quad dwt$$
$$= \frac{2V^2}{R\pi}\left[\pi - \frac{\alpha}{2} + \frac{\sin 2\alpha}{2}\right]$$

SinglephaseACvoltagecontrollerwithRL load

With inductive loads the operation of the PAC is illustrated in Fig 2. 36. The current builds up from zeroin each cycle. It quenches not at the zero crossing of the applied voltage as with the resistive load but afterthat instant. The supply voltage thus continues to be impressed on the load till the load current returns tozero. A single-pulse trigger for the TRIAC) or the anti parallel SCR has no effect on the devices if it (orthe anti-parallel device) is already in conduction in the reverse direction. The devices would fail toconduct when they are intended to, as they do not have the supply voltage forward biasing them when thetrigger pulse arrives. A single pulse trigger will work till the trigger angle α > φ, where φ is the powerfactor angle of the inductive load. A train of pulses is required here. The output voltage is controllableonly between triggering angles φ and 180°. The load current waveform is further explained in Fig. 26.6.The current is composed of two components. The first is the steady state component of the load current, i_{ss}andthesecond,i_{tr}isthetransientcomponent.

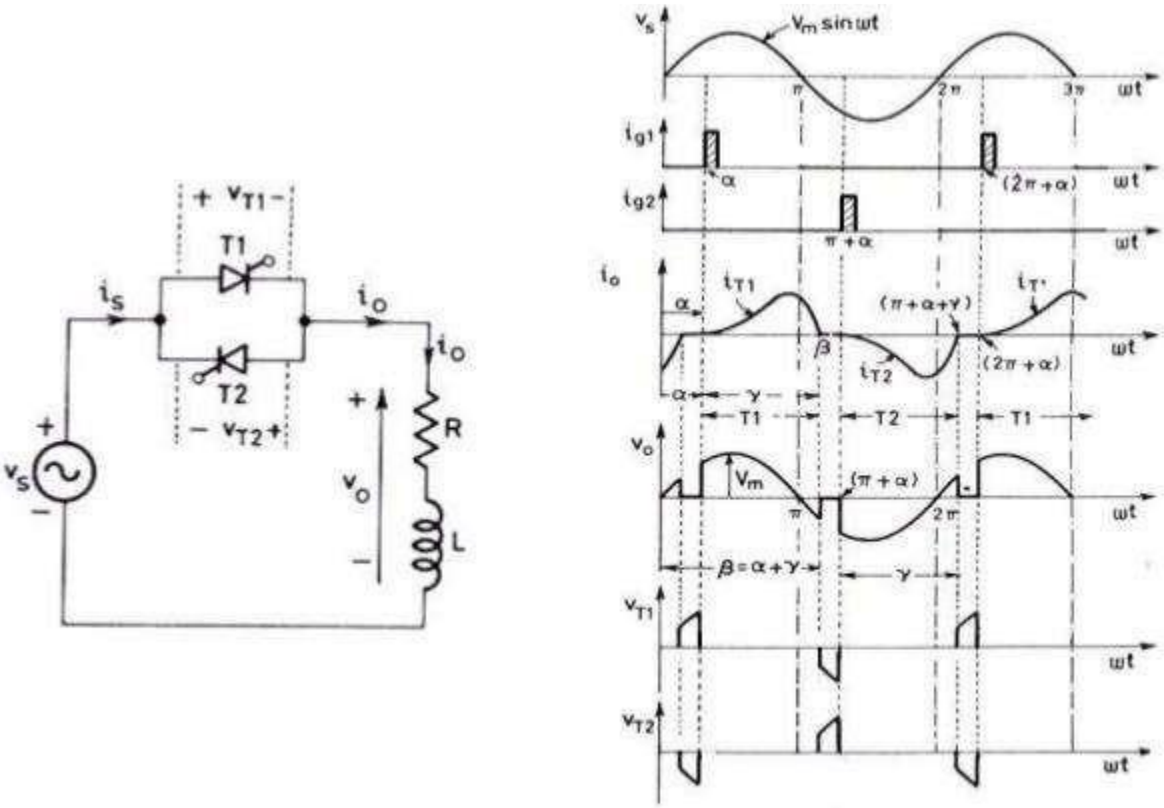


Figure: 3.3Circuitdiagramandoutputwaveformsof ACvoltagecontrollerwithRLload

With an inductance in the load the distinguishing feature of the load current is that it must always startfrom zero. However, if the switch could have permanently kept the load connected to the supply thecurrentwould have become asinusoidalone phase shifted from the voltage by the phase angle of theload, φ. This current restricted to the half periods of conduction is called the 'steady-state component' ofload current iss. The 'transient component' of load current itr, again in each half cycle, must add up to zerowiththisisstostartfromzero.Thisconditionsetstheinitialvalueofthetransientcomponenttothatofthe steady state at the instant that the SCR/TRIAC is triggered. Fig. 2. 36 illustrates these relations. Whenadevice isinconduction,theloadcurrentisgovernedbytheequation

$$L\,{}^{di}\!/_{dt} + Ri = v_s$$

$$i_{load} = \frac{\sqrt{2}V}{Z}\left[\ \sin(\omega t - \phi) + \sin(\alpha - \phi)e^{-\frac{R}{L}\left(\alpha/\omega - t\ \right)}\ \right]$$

Since at t = 0, i_{load} = 0 and supply voltage v_s = √2Vsinωt the solution is of the form the instant when theloadcurrentextinguishesiscalledtheextinctionangleβ.Itcanbeinferredthattherewouldbeno transients in the load current if the devices are triggered at the power factor angle of the load. The loadcurrentI thatcaseisperfectlysinusoidal.

ModesofoperationofTRIAC

The triac is an important member of the thyristor family of devices. It is a bidirectional device that canpass the current in both forward and reverse biased conditions and hence it is an AC control device. Thetriac is equivalent to two back to back SCRs connected with one gate terminal as shown in figure. Thetriac is an abbreviation for a TRIode AC switch. TRI means that the device consisting of three terminalsandAC meansthat itcontrolstheAC powerorit canconduct inbothdirections ofalternatingcurrent.

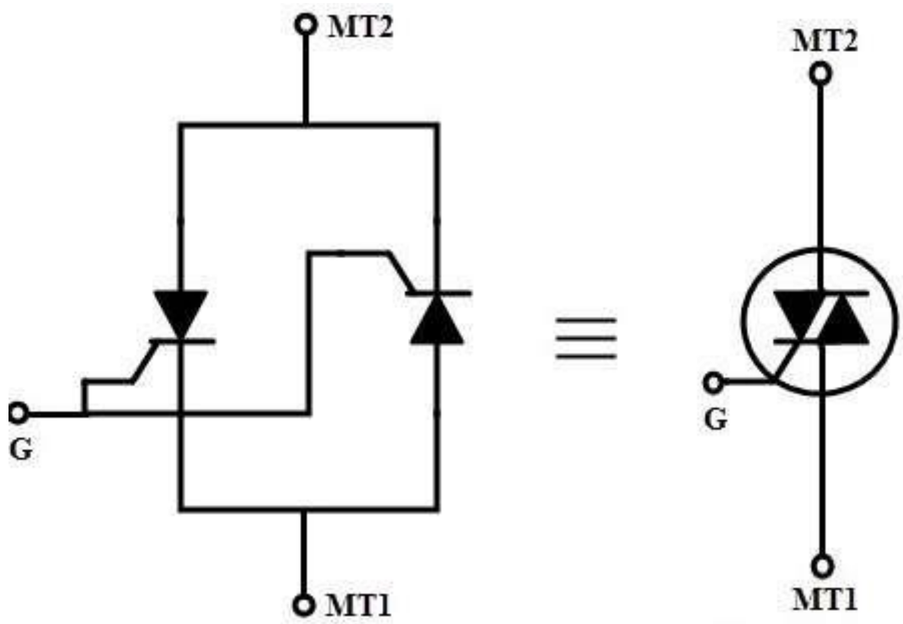


Figure: 3.4TwothyristoranalogyandcircuitsymbolofTRIAC

The triac has three terminals namely Main Terminal 1(MT1), Main Terminal 2 (MT2) and Gate (G) asshown in figure. If MT1 is forward biased with respect to MT2, then the current flows from MT1 to MT2.Similarly, if the MT2 is forward biased with respect to MT1, then the current flows from MT2 to MT1.The above two conditions are achieved whenever the gate is triggered with an appropriate gate pulse.Similar to the SCR, triac is also turned by injecting appropriate current pulses into the gate terminal. Onceit is turned ON, it looses its gate control over its conduction. So traic can be turned OFF by reducing thecurrenttozerothroughthe mainterminals.

ConstructionofTRIAC

A triac is a five layer, three terminal semiconductor device. The terminals are marked as MT1, MT2 asanode and cathode terminals in case of SCR. And the gate is represented as G similar to the thyristor. Thegate terminal is connected to both N4 and P2 regions by a metallic contact and it is near to the MT1terminal. The terminal MT1 is connected to both N2 and P2 regions, while MT2 is connected to both N3and P1 regions. Hence, the terminals MT1 and MT2 connected to both P and N regions of the device andthus the polarity of applied voltage between these two terminals decides the current flow through thelayersof the device.

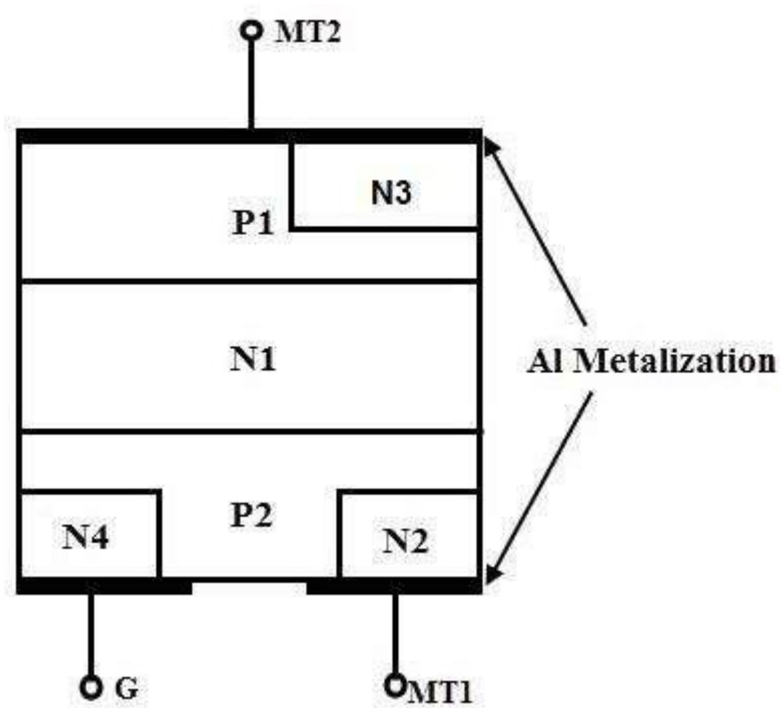


Figure:3.5constructionofTRIAC

With the gate open, MT2 is made positive with respect to MT1 for a forward biased traic. Hence traicoperates in forward blocking mode until the voltage across the triac is less than the forward break overvoltage. Similarly for a reverse biased triac, MT2 is made negative with respect to MT1 with gate open.Until the voltage across the triac is less than the reverse break over voltage, device operates in a reverseblockingmode.Atraiccanbemadeconductiveby eitherpositiveornegativevoltageatthegateterminal.

WorkingandOperationofTRIAC

It is possible to connect various combinations of negative and positive voltages to the triac terminalsbecause it is a bidirectional device. The four possible electrode potential combinations which make thetriactooperatefourdifferentoperatingquadrantsormodesaregivenas.

1. MT2ispositivewithrespecttoMT1withagatepolaritypositivewithrespecttoMT1.
2. MT2ispositivewithrespecttoMT1withagatepolaritynegativewithrespecttoMT1.
3. MT2isnegativewithrespecttoMT1withagatepolaritynegativewithrespecttoMT1.
4. MT2isnegativewithrespecttoMT1withagatepolaritypositivewithrespecttoMT1.

In general, latching current is higherin second quadrant ormode whilst gate trigger current is higher inthe fourth mode compared with other modes for any triac. Most of the applications, negative triggeringcurrent circuit is used that means 2 and 3 quadrants are used for a reliable triggering in bidirectionalcontrol and also when the gate sensitivity is critical. The gate sensitivity is highest with modes 1 and 4 aregenerallyemployed.

Mode1:MT2isPositive,PositiveGateCurrent

When the gate terminal is made positive with respect to MT1, gate current flows through the P2 and N2junction. When this current flows, the P2 layer is flooded with electrons and further these electrons arediffused to the edge of junction J2 (or P2-N1 junction). These electrons collected by the N1 layer builds aspace charge on the N1 layer. Therefore, more holes from the P1 region are diffused into the N1 region toneutralize the negative space charges. These holes arrive at the junction J2 and produce the positive spacecharge in the P2 region, which causes more electrons to inject into P2 from N2. This results a positiveregenerationandfinallythe maincurrentflowsfromMT2toMT1throughtheregionsP1-N1–P2–N2.

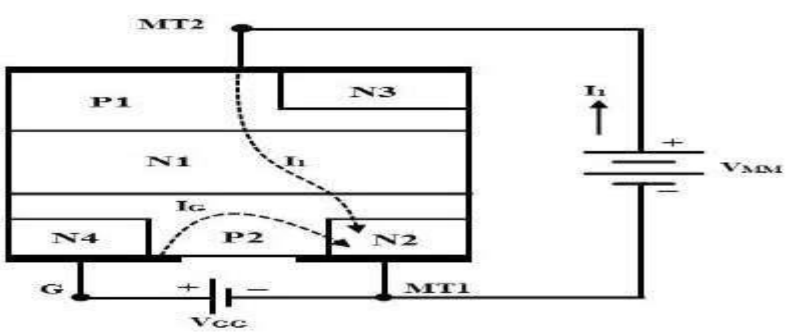


Figure: 3.6Mode1operationof TRIAC

Mode2:MT2isPositive,NegativeGateCurrent

When MT2 is positive and the gate terminal is negative with respect to MT1, gate current flows throughtheP2-N4junction.ThisgatecurrentforwardbiasestheP2-N4junctionforauxiliaryP1N1P2N4structure. This results the triac to conduct initially through the P1N1P2N4 layers. This further raises thepotential between P2N2 towards the potential of MT2. This causes the current to establish from left toright in the P2 layer which forward biases the junction P2N2. And hence the main structure P1N1P2N2begins to conduct. Initially conducted auxiliary structure P1N1P2N4 is considered as a pilot SCR whilelater conducted structure P1N1P2N2 is considered as main SCR. Hence the anode current of pilot SCRserves as gate current to the main SCR. The sensitivity to gate current is less in this mode and hence moregatecurrentisrequiredtoturnthetriac.

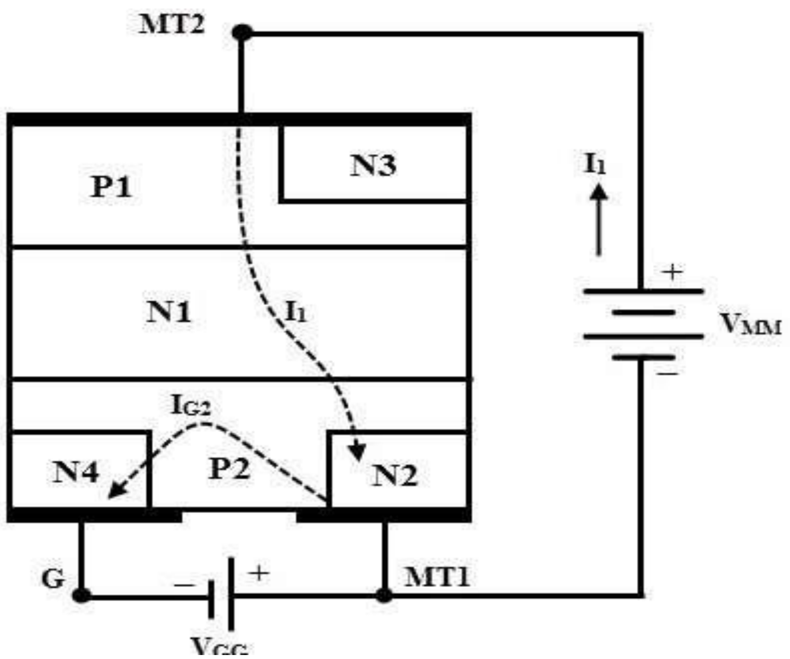


Figure:3.7Mode2operationof TRIAC

Mode3:MT2isNegative,PositiveGateCurrent

In this mode, MT2 is made negative with respect to MT1 and the device is turned ON by applying apositive voltage between the gate and MT1 terminal. The turn ON is initiated by N2 which acts as aremote gate control and the structure leads to turn ON the triac is P2N1P1N3. The external gate currentforward biasesthe junction P2-N2.N2 layerinjectsthe electronsinto the P2 layerwhich are thencollectedbyjunctionP2N1.Thisresulttoincreasesthecurrentflowthrough P2N1junction.

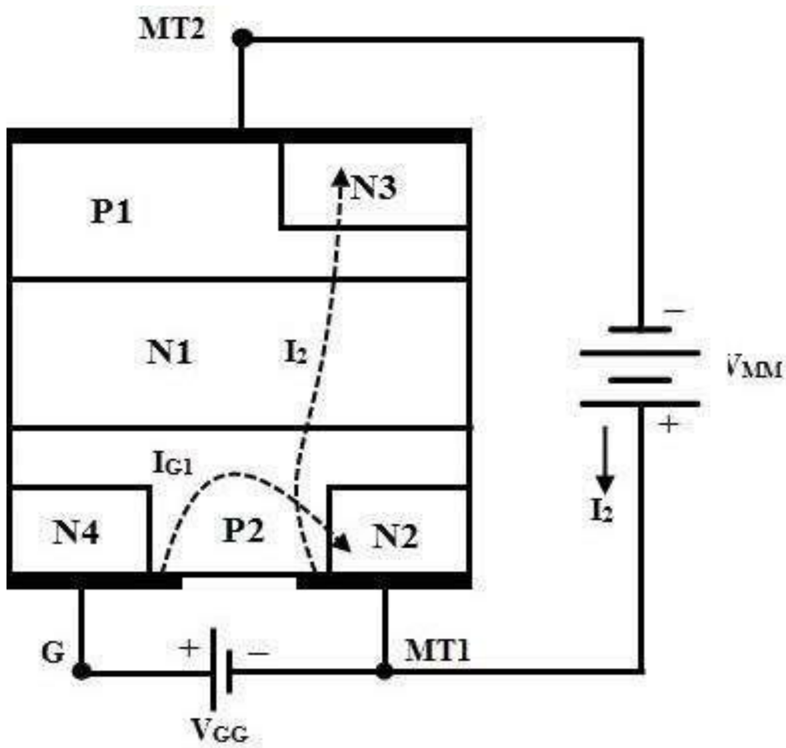


Figure:3.8Mode3operationof TRIAC

The holes injected from layer P2 diffuse through the N1 region. This builds a positive space charge in theP region. Therefore, more electrons from N3 are diffused into P1 to neutralize the positive space charges.Hence, these electrons arrive at junction J2 and produce a negative space charge in the N1region whichresults to inject more holes from the P2 into the region N1. This regenerative process continues till thestructure P2N1P1N3 turns ON the triac and conducts the external current. As the triac is turned ON by theremotegateN2,thedeviceislesssensitivetothepositivegatecurrentinthismode.

Mode4:MT2isNegative, NegativeGateCurrent

In thismode N4 acts as a remote gate and injects the electrons into the P2 region.The external gatecurrent forward biases the junction P2N4. The electrons from the N4 region are collected by the P2N1junction increase the current across P1N1 junction. Hence the structure P2N1P1N3 turns ON by theregenerative action.The triac ismore sensitive in thismode comparedwith positive gate currentinmode3.

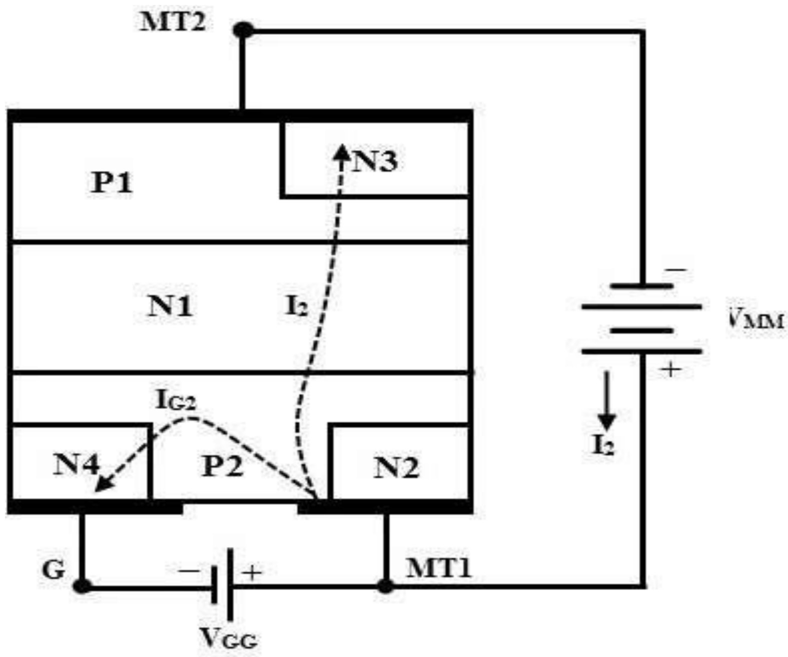


Figure:3.9Mode4operationof TRIAC

From the above discussion, it is concluded that the modes 2 and 3 are less sensitive configuration whichneeds more gate current to trigger the triac, whereas more common triggering modes of triac are 1 and 4which have greater sensitivity. In practice the more sensitive mode of operation is selected such that thepolarityof the gate istomatchwiththepolarityof theterminalMT2.

CharacteristicsofTRIAC:

The traic function like a two thyristors connected in anti-parallel and hence the VI characteristics of triacin the 1st and 3rd quadrants will be similar to the VI characteristics of a thyristors. When the terminalMT2 is positive with respect to MT1 terminal, the traic is said to be in forward blocking mode. A smallleakage currentflowsthrough the device provided thatvoltage acrossthe device islowerthan thebreakover voltage. Once the breakover voltage of the device is reached, then the triac turns ON as shownin below figure. However, it is also possible to turn ON the triac below the VBO by applying a gate pulseinsuchthatthecurrentthroughthe deviceshouldbe morethanthelatchingcurrentofthetriac.

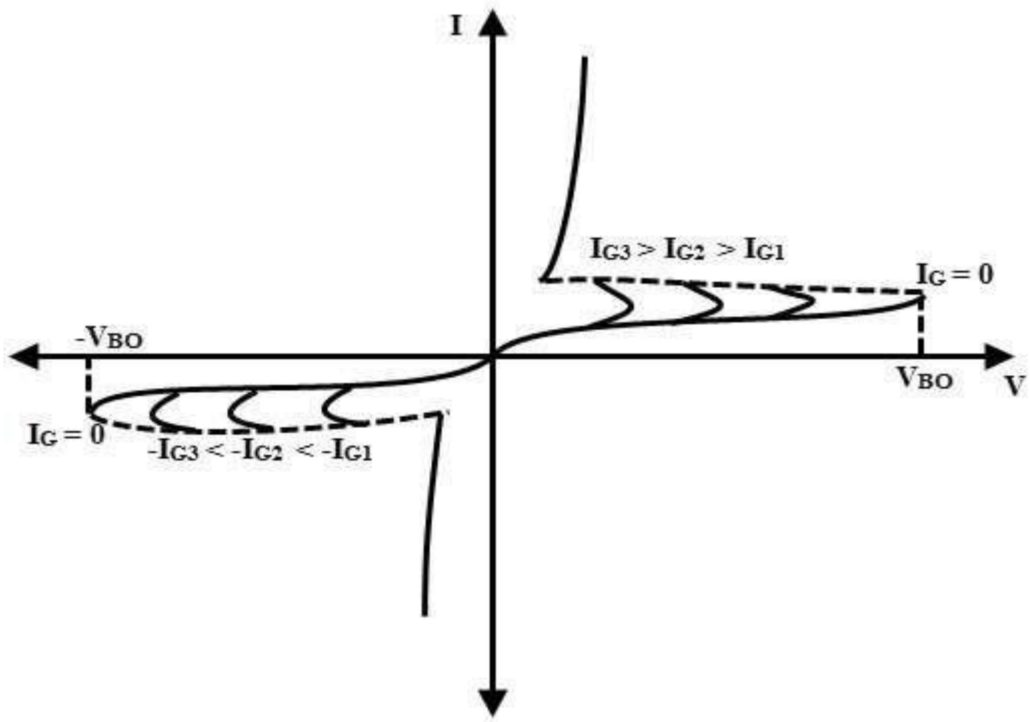


Figure: 3.10 V-IcharacteristicsofTRIAC

Similarly, when the terminal MT2 is made negative with respect to MT1, the traic is in reverse blockingmode. A small leakage current flows through the device until it is triggered by breakover voltage or gatetriggering method.Hence the positive ornegative pulse to the gate triggers the triac in both directions.Thesupplyvoltageatwhichthetriacstartsconductingdependsonthegatecurrent.Ifthegateiscurrentis being greater, lesser will be the supply voltage at which the triac is turned ON. Above discussed mode -1 triggering is used in the first quadrant whereas mode-3 triggering is used in 3rd quadrant. Due to theinternal structure of the triac, the actual values of latching current, gate trigger current and holding currentmay be slightly different in different operating modes. Therefore, the ratings of the traics considerablylowerthanthethyristors.

AdvantagesofTRIAC

Triaccanbetriggeredbybothpositiveandnegativepolarityvoltagesappliedatthegate.

- It canoperateandswitchbothhalfcycles ofanACwaveform.
- As compared with the anti-parallel thyristor configuration which requires two heat sinks of slightlysmaller size, a triac needs a single heat sink of slightly larger size. Hence the triac saves both spaceandcostinACpowerapplications.

- In DC applications, SCRs are required to be connected with a parallel diode to protect againstreverse voltage. But the triac may work without a diode, a safe breakdown is possible in eitherdirection.

DisadvantagesofTRIAC

- Theseareavailableinlowerratings as comparedwiththyristors.
- A careful consideration is required while selecting a gate trigger circuit since a triac can betriggeredinbothforwardandreversebiasedconditions.
- Thesehavelowdv/dtratingascomparedwiththyristors.
- Thesehaveverysmallswitchingfrequencies.
- Triacsarelessreliablethanthyristors.

NumericalProblems

1. Asinglephasevoltagecontrollerisemployedforcontrollingthepowerflowfrom230V,50Hzsource intoaloadcircuitconsisting ofR=3 Ωand ωL=4 Ω.Calculate

(i) therangeoffiringangle

(ii) themaximumvalueofrms loadcurrent

(iii) themaximumpowerandpowerfactor

(iv) Themaximumvalues ofaverageandrms thyristorcurrents.

Solution:

i. Forcontrollingtheloadtheminimumvalueoffiringangleα =loadphaseangle

$$\varphi = tan^{-1}\frac{wL}{R} = tan^{-1}\frac{4}{3} = 53.13°$$

Themaximumpossible valueofαis180^0

Sothefiringanglecontrolrangeis53.13°≤α≤180°

ii. Themaximumvalueofrmsvalueofloadcurrentoccurs whenα= Φ= 53.13^0

But atthis valueoffiringangle,thepowercircuitofacvoltagecontrollerbehaves asifloadisdirectlyconnectedtoacsource.Therefore maximumvalueof rmsloadcurrentis

$$I_0 = \frac{230}{\sqrt{R^2+(wL)^2}} = \frac{230}{\sqrt{3^2+4^2}} = 46A$$

iii. Maximumpower=$I_0^2 xR$=46^2x3= 6348W

Powerfactor=$\frac{I_0^2 xR}{VsIo} = \frac{46x3}{230} = 0.6$

iv. Averagethyristorcurrentismaximumwhenα=Φandconductionangle$\gamma = M$

$$I_{TAVG} = \frac{1}{2\pi}\int_{\alpha}^{\alpha+\pi} \frac{Vm}{Z} \sin(wt-\varphi)\,d(wt)$$

$$= \frac{Vm}{\pi Z} = \frac{\sqrt{2}\times 230}{\pi\times\sqrt{3^2+4^2}} = 20.707A$$

Similarlymaximumvalueofthyristor currentis

$$I_{Trms} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\alpha+\pi} \frac{Vm^2}{Z^2} \sin^2(wt-\alpha)\,d(wt)\right\}^{1/2}$$

$$= \frac{Vm}{2Z} = \frac{\sqrt{2}\times 230}{2\times\sqrt{3^2+4^2}} = 32.527A$$

2. AnacvoltagecontrollerusesaTRIAC forphaseanglecontrol ofaresistiveloadof100Ω.Calculatethe value of delay angle for having an rms load voltage of 220 volts. Also calculate the rms value ofTRIACcurrent.Assumethermssupplyvoltagetobe230V.

3. Theacvoltagecontrolleruseson-offcontrolforheatingaresistiveloadofR=4 ohms andtheinputvoltageisVs=208V,60Hz.If thedesiredoutputpowerisP_O=3KW,determinethe

(a) dutycycleδ

(b) inputpower factor

Sketchwaveforms forthedutycycleobtained in(a)

IntroductiontoCycloconverters

The Cycloconverterhas been traditionally used only in very high powerdrives,usually above onemegawatt,wherenoothertypeofdrivecanbeused.Examplesarecementtubemilldrivesabove5MW,the13MWGerman-Dutchwindtunnelfandrive,reversiblerollingmilldrivesandshippropulsiondrives.Thereasonsforthisarethatthe traditional Cycloconverter requiresalargenumberofthyristors,atleast36andusuallymoreforgoodmotorperformance,togetherwithaverycomplexcontrolcircuit,andithassomeperformancelimitations,theworstofwhichisanoutputfrequencylimitedto aboutonethirdtheinputfrequency.

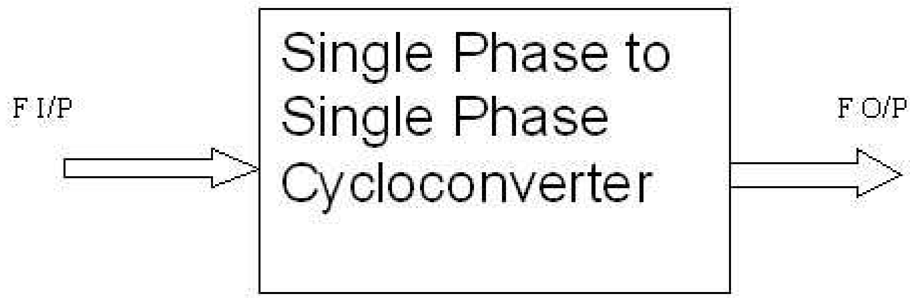


Figure3.11Blockdiagramofcycloconverters

The Cycloconverterhasfourthyristorsdividedintoapositive andnegativebankoftwo thyristorseach.When positive currentflowsin theload,theoutputvoltageiscontrolled by phase controlofthetwopositivebankthyristorswhilstthenegativebankthyristorsarekeptoffandviceversawhennegativ ecurrentflowsintheload.Anidealizedoutputwaveformforasinusoidalloadcurrent and a 45 degrees load phase angle is shown in Figure3.11. It is important to keep the nonconductingthyristorbankoffatalltimes,otherwisethemainscouldbeshortedviathetwothyristorbanks,result inginwaveformdistortionandpossibledevicefailurefromtheshortingcurrent.Amajorcontrolproblemofthe Cycloconverter ishowtoswapbetweenbanksintheshortestpossible time to avoiddistortionwhilstensuring the twobanksdo notconduct at the sametime.Acommonadditiontothepowercircuitthatremovesthe requirementtokeeponebankoffisto place acentre tappedinductorcalled acirculatingcurrentinductor betwe en the outputsof thetwo banks.Both banks can now conduct togetherwithout shorting the mains.Also, the circulatingcurrentintheinductorkeepsbothbanksoperatingallthetime,resultinginimprovedoutputwaveforms. Thistechniqueisnotoftenused,though,becausethecirculatingcurrent inductortendstobeexpensiveandbulkyandthecirculatingcurrentreducesthepowerfactorontheinput

In a 1-**φ** Cycloconverter**,**theoutputfrequencyisless than the supply frequency.These convertersrequirenaturalcommutationwhichisprovidedbyACsupply.Duringpositivehalfcycleofsupply,Thyr istorsP1 and N2 areforwardbiased.FirsttriggeringpulseisappliedtoP1 andhenceitstartsconducting. Asthesupplygoesnegative,P1 getsoffandinnegativehalfcycleofsupply, P2 and N1 areforwardbiased. P2 istriggeredandhenceitconducts.Inthenextcycleofsupply,N2inpositivehalfcycleandN1 innegativehalfcycleare triggered.Thus,wecanobservethatheretheoutputfrequencyis1/2timesthesupplyfrequency.

OperationPrinciples

ThefollowingsectionswilldescribetheoperationprinciplesoftheCycloconverterstartingfromthesimplestone,single-phasetosingle-phase(1f-1f)Cycloconverter.

Single-phasetoSingle-phase(1Φ-1Φ)Cycloconverter

To understand the operation principles of Cycloconverters,the single-phase to single-phase Cycloconverter(Fig.3.12)shouldbestudiedfirst.Thisconverterconsistsofback-to-backconnectionoftwofull-waverectifiercircuits.Fig3.13showstheoperatingwaveformsforthisconverterwitharesistiveload.

ZeroFiringangle,i.e.thyristorsactlikediodes.NotethatthefiringanglesarenamedasαPforthepositiveconverterandαN forthenegativeconverter.Theinputvoltage,vsisan acvoltage atafrequency,fiasshowninFig.3.13.Foreasyunderstandingassumethatallthethyristorsarefiredatα=0°

Considertheoperationofthe Cycloconverter toget one-fourthoftheinputfrequencyattheoutput.Forthefirsttwocyclesofvs,thepositiveconverteroperatessupplyingcurrenttotheload.Itrectifiestheinputvoltage;therefore,theloadsees4positivehalfcyclesasseeninFig. 3.13.In thenexttwocycles,thenegativeconverteroperatessupplyingcurrenttotheloadinthereversedirection.Thecurrentwaveformsarenotshowninthefiguresbecausetheresistiveloadcurrentwillhavethesamewaveformasthevoltagebutonlyscaledbytheresistance.Note thatwhenoneoftheconvertersoperatestheotheroneisdisabled,sothatthereisnocurrentcirculatingbetweenthetworectifiers.

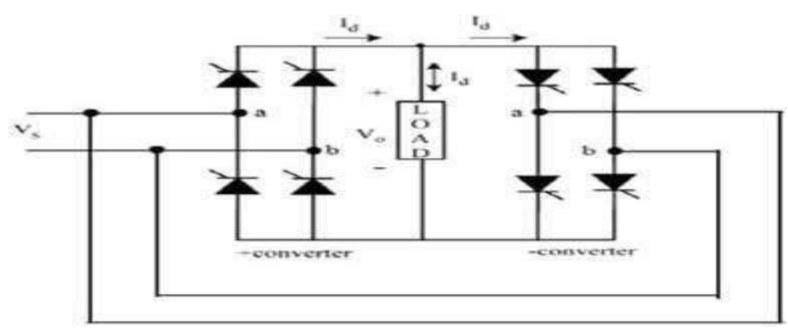


Figure3.12circuit diagramofcycloconverter

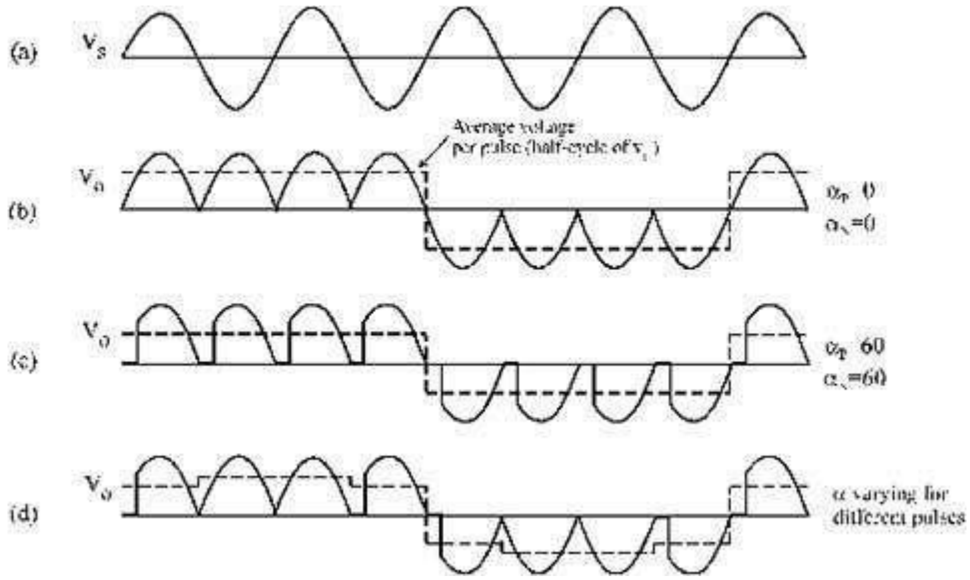


Figure 3.13Inputandoutputwaveformsofcycloconverter

Singlephase midpointCycloconverters

Basically,thesearedividedintotwo maintypes,andaregivenbelow

Step-downcyclo-converter

It actslikeastep-downtransformerthat providestheoutput frequencyless thanthat ofinput,fo<fi.

Step-upcyclo-converter

It providestheoutput frequency morethanthat ofinput,fo>fi.

In case of step-down cyclo-converter, the output frequency is limited to a fraction of input frequency,typically it is below 20Hz in case 50Hz supply frequency. In this case, no separate commutation circuitsareneededasSCRsarelinecommutateddevices.

But in case of step-up cyclo-converter, forced commutation circuits are needed to turn OFF SCRs atdesired frequency. Such circuits are relatively very complex. Therefore, majority of cyclo-converters areofstep-downtypethatlowersthefrequencythaninputfrequency.

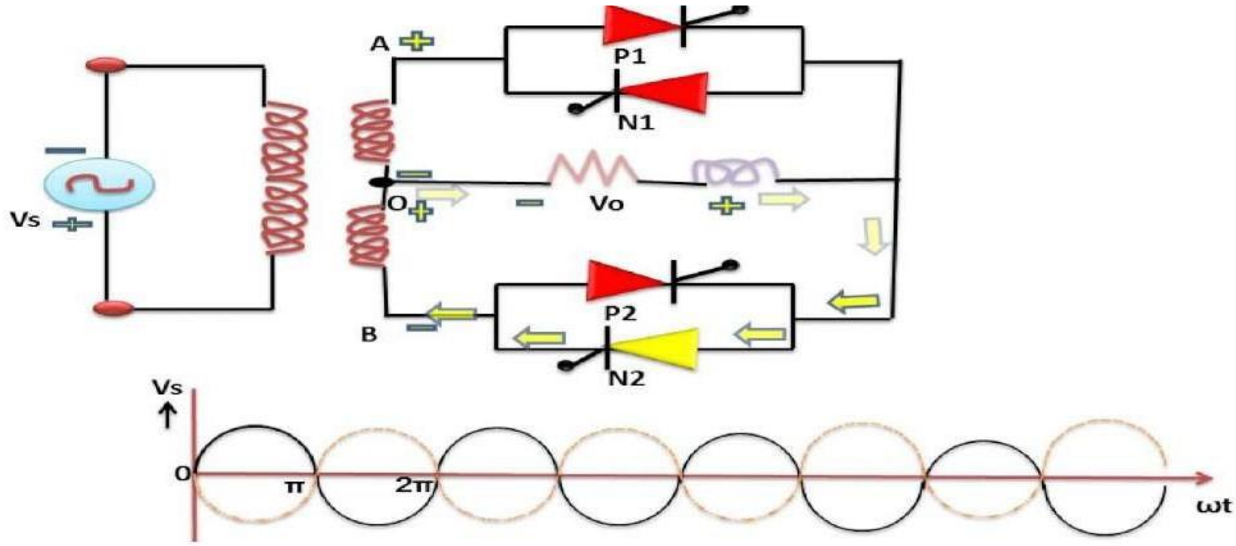


Figure 3.14circuitdiagramofmidpointcycloconverter

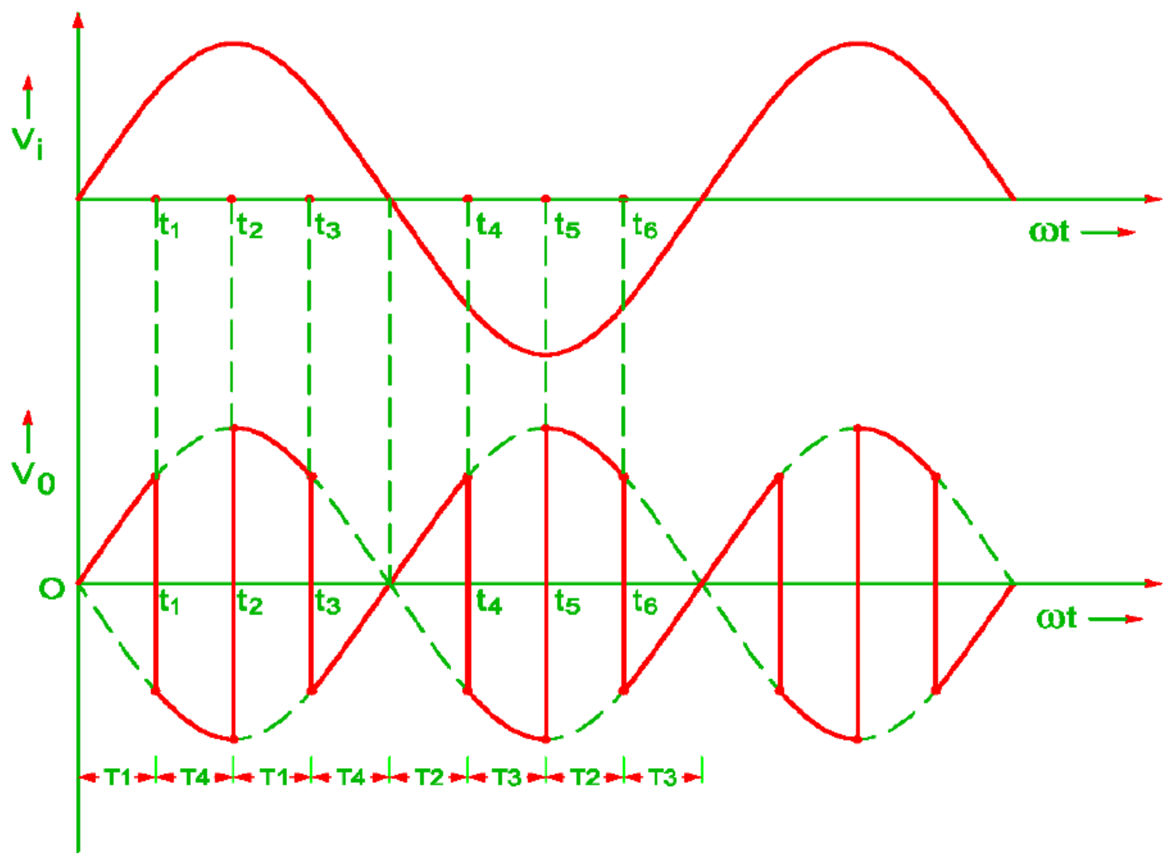


Figure3.15Inputandoutputwaveformsofmidpointcycloconverter

It consists of single phase transformer with mid tap on the secondary winding and four thyristors. Two ofthese thyristors P1, P2 are for positive group and the other two N1, N2 are for the negative group. Load isconnected between secondary winding midpoint 0 and the load terminal. Positive directions for outputvoltageandoutputcurrentare markedinfigure3.14

In figure 3.14 during the positive half cycle of supply voltage terminal a is positive with respect toterminal b. therefore in this positive half cycle, both p1 and N2 are forward biased from wt= 0 to Π. Assuch SCR P1 is turned on at wt = 0 so that load voltage is positive with terminal A and 0 negative. Nowthe load voltage is positive.At instant t1 P1 is force commutated and forward biased thyristor N2 isturned on so that load voltage is negative with terminal 0 and A negative. Now the load voltage isnegative.NowN2isforcecommutatedandP1isturnedontheloadvoltageispositivethisisacontinuousprocessan dwillgetstepupcycloconverteroutput

BridgeconfigurationofsinglephaseCyclo converter

The equivalent circuit of a cyclo-converter is shown in figure below. Here each two quadrant phasecontrolledconverteris representedbyavoltagesourceofdesiredfrequencyandconsiderthattheoutputpowerisgeneratedbythealternatin gcurrentandvoltageatdesiredfrequency.

Thediodes connectedinserieswith eachvoltagesourcerepresenttheunidirectionalconduction ofeachtwo quadrant converter. If the output voltage ripples of each converter are neglected, then it becomesidealandrepresentsthe desiredoutputvoltage.

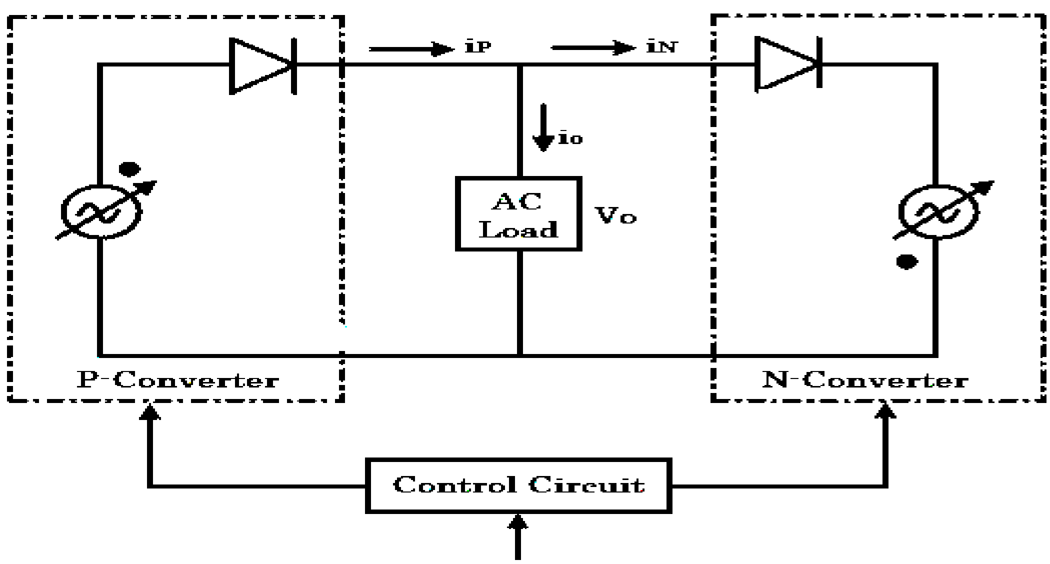


Figure3.16Blockdiagramofbridgetypecycloconverter

Ifthefiringanglesofindividualconvertersaremodulatedcontinuously,eachconverterproducessamesinusoidalv oltagesatitsoutputterminals.

So the voltages produced by these two converters have same phase, voltage and frequency. The averagepowerproducedbythecyclo-convertercanfloweithertoorfromtheoutputterminals as theloadcurrentcanflowfreelytoandfromtheloadthroughthepositiveandnegativeconverters.

Therefore,it ispossibletooperatetheloadsofanyphaseangle(orpowerfactor),inductiveorcapacitivethroughthecyclo-convertercircuit.

Duetotheunidirectionalpropertyofloadcurrent foreachconverter,itis obviousthatpositiveconvertercarriespositivehalf-cycleofloadcurrentwithnegativeconverterremaininginidleduringthisperiod.

Similarly, negativeconvertercarriesnegativehalfcycleoftheloadcurrentwithpositiveconverterremaininginidleduringthi speriod,regardlessofthephaseofcurrentwithrespecttovoltage.

Thismeansthateachconverteroperatesbothinrectifyingandinvertingregionsduringtheperiodofitsassociatedha lf cycles.

The figure below shows ideal output current and voltage waveforms of a cyclo-converter for lagging andleadingpowerfactorloads.Theconductionperiodsofpositiveandnegativeconvertersarealsoillustratedinthe figure.

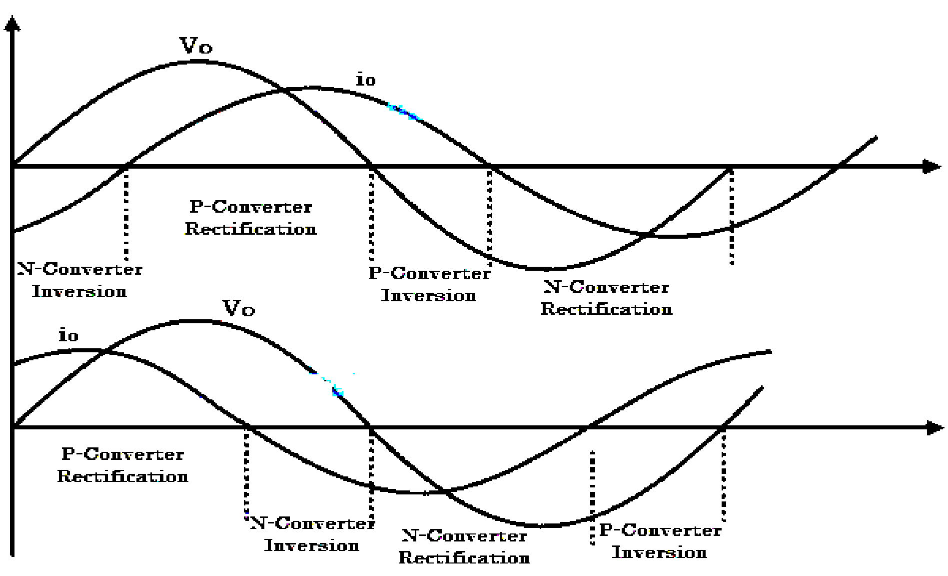


Figure3.17cycloconverterwaveforms

Thepositiveconverteroperateswhenevertheloadcurrentispositivewithnegativeconverterremaininginidle.In thesamemannernegativeconverteroperatesfornegativehalfcycleofloadcurrent.

Bothrectificationandinversionmodes ofeachconverterareshowninfigure.Thisdesired output voltageisproducedbyregulatingthefiringangletoindividualconverters.

Single-phasetosingle-phasecyclo-converters

Thesearerarelyusedinpractice;however,thesearerequiredtounderstandfundamentalprinciple ofcyclo-converters.

Itconsistsof two full-wave,fully controlled bridge thyristors,where each bridge has4thyristors, andeach bridge is connected in opposite direction (back to back) such that both positive and negative voltagescan be obtained as shown in figure below. Both these bridges are excited by single phase, 50 Hz ACsupply.

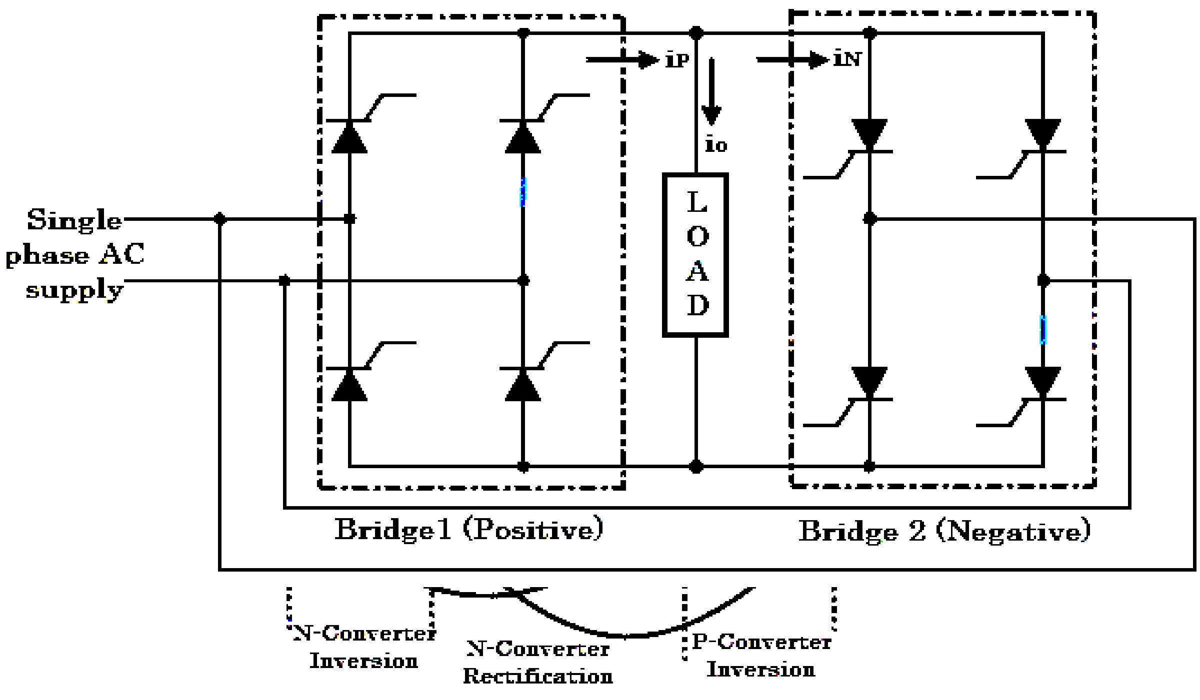


Figure 3.18Circuitdiagramofbridgetypecycloconverter

During positive half cycle of the input voltage, positive converter (bridge-1) is turned ON and it suppliestheloadcurrent.Duringnegativehalfcycleoftheinput,negativebridgeis turnedONand itsupplies loadcurrent.Bothconvertersshouldnotconducttogetherthatcauseshortcircuitattheinput.

To avoid this, triggering to thyristors of bridge-2 is inhibited during positive half cycle of load current,whiletriggeringis appliedtothethyristors ofbridge-1 attheirgates.Duringnegativehalfcycleofloadcurrent,triggeringtopositivebridgeisinhibitedwhileapplyingt riggeringtonegativebridge.

By controlling the switching period of thyristors, time periods of both positive and negative half cyclesarechangedandhencethefrequency.Thisfrequencyoffundamentaloutputvoltagecanbeeasilyreducedins teps,i.e.,1/2,1/3,1/4andsoon.

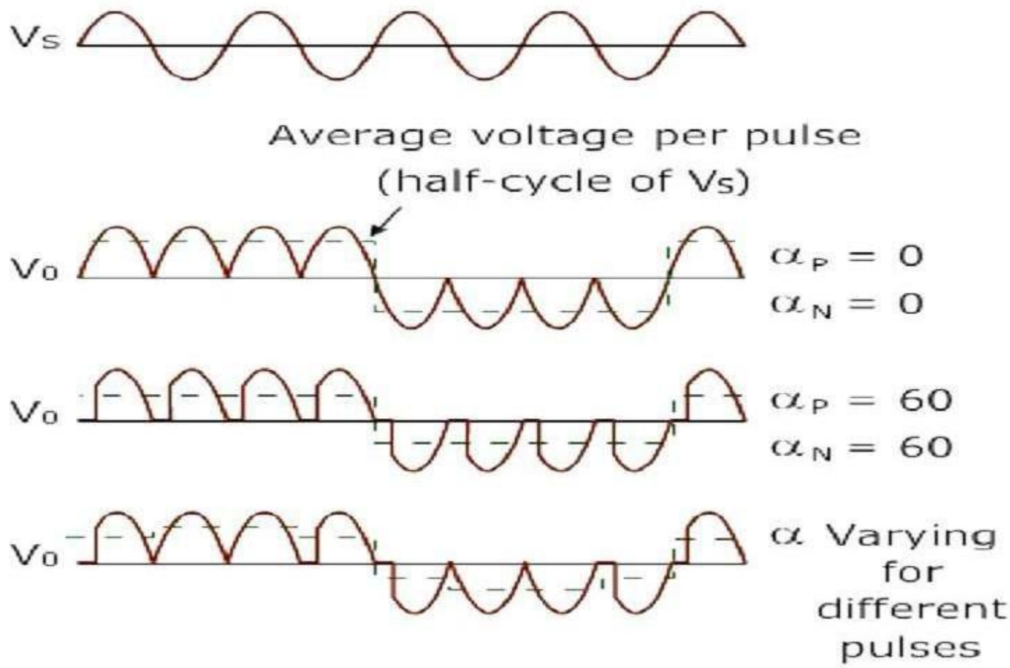


Figure 3.19Inputandoutputwaveformsofbridge typecycloconverter

The above figure shows output waveforms of a cyclo-converter that produces one-fourth of the inputfrequency. Here, forthefirst twocycles,thepositiveconverteroperatesandsuppliescurrent totheload.

It rectifies the input voltage and produce unidirectional output voltage as we can observe four positivehalfcyclesinthefigure.Andduringnext twocycles,thenegativeconverteroperatesandsuppliesloadcurrent.

Herecurrentwaveforms arenotshownbecauseitis aresistiveloadinwherecurrent(withlessmagnitude)exactlyfollowsthevoltage.

Here one converter is disabled if another one operates, so there is no circulating current between twoconverters.Sincethediscontinuousmodeofcontrolschemeis complicated,mostcyclo-converters are operates oncirculatingcurrentmodewherecontinuouscurrentisallowedtoflowbetweentheconverterswithareactor.

This circulatingcurrenttypecyclo-convertercanbeoperatedonwithbothpurelyresistive(R)andinductive(R-L)loads.

NumericalProblems:

1. A single-phase to single-phase cycloconverter is supplying and inductive load comprising of aResistance of 5Ω and an inductance of 40 mH from a 230 V, 50 Hz single-phase supply It isRequired to provide an output frequency which is 1/3 of the input frequency. If the converters areOperated as semi converter such that $0 \leq \alpha \leq \pi$ and firing delay angle is120°. Neglecting theHarmoniccontentof loadvoltage,determine:
   (a) rmsvalueof outputvoltage.
   (b) rmscurrentofeachthyristorand
   (c) inputpowerfactor.

   Solution:

$$E = 230 \text{ V}, f_1 = 50 \text{ Hz}, \alpha_p = \frac{2\pi}{3}$$

$$f_0 = 50/2 = 16.2/3 \text{ Hz}, R = 5\Omega, L = 40 \text{ mH}.$$

$$\omega_0 = 2\pi \times 50/3 = 104.72 \text{ rad/s}.$$

$$X_L = \omega_o L = 104.72 \times 40 \times 10^{-3} = 4.188\ \Omega$$

$$Z_L = \sqrt{5^2 + (4.188)^2} = 6.52\ \Omega.$$

$$\theta = \tan^{-1}(\omega_o L/R) \equiv 40°.$$

(a) For $O \leq \alpha \leq \pi$, *rms* value of output voltage,

$$E_o = E \cdot \left[\frac{1}{\pi}\left(\pi - \alpha_p + \frac{\sin 2\alpha_p}{2}\right)\right]^{1/2}$$

$$= 230 \cdot \left[\frac{1}{\pi}\left\{\left(\pi - \frac{2\pi}{3}\right) + \frac{\sin 240}{2}\right\}\right]^{1/2}$$

$$= 101.6 \text{ V}$$

(b) RMS value of load current, $I_o = \frac{E_o}{Z_L}$

$$= \frac{101.6}{4.188} = 24.26 \text{ A}$$

The *rms* current through each converter group is

$$I_P = I_N = \frac{I_o}{\sqrt{2}} = 17.1542 \text{ A.}$$

and the *rms* current through each thyristor

$$I_{Trms} = \frac{I_p}{\sqrt{2}} = \frac{17.1542}{\sqrt{2}} = 12.13 \text{ A.}$$

(c) *rms* input current, $I_i = I_o = 24.26$ A.

The volt-amp rating $= E \,.\, I_i = 230 \times 24.26 = 5580$ VA

The output power, $P_o = E_o \,.\, I_o \cos\theta = 101.6 \times 24.26 \times \cos 40°$

$= 1888.1$ watts.

$$\therefore \quad \text{Power factor} = \frac{P_o}{E \cdot I_i} = \frac{1888}{5580}$$

$= 0.3384$ (lagging)

Now, $$\text{P.F.} = \frac{m_f}{\sqrt{2}} \,.\, \cos\phi$$

$$m_f = \cos(180 - \alpha_p) = \cos 60° = 0.5$$

$$\cos\phi = \cos 40 = 0.766.$$

Hence, $$P_f = \frac{0.5}{\sqrt{2}} \,.\, \cos 40 = 0.27$$

2. In a standard A single-phase bridge-type cyclo-converter has input voltage of 230V, 50Hz andload of R=10Ω. Output frequency is one-third of input frequency. For a firing angle delay of 30^o,Calculate (i) rms value of output voltage (ii) rms current ofeach converter (iii) rms current ofeachthyristor(iv) inputpowerfactor.
3. A single-phase to single-phase mid-point cyclo-converter is delivering power to a resistive load.The supply transformer has turns ratio of 1: 1: 1. The frequency ratio is fo/fs = 1/5. The firingangle delay α for all the four SCRs are the same. Sketch the time variations of the followingwaveforms for α = 0° and α = 30°(a) Supply voltage (b) Output current and (c) Supply current.Indicatetheconductionof variousthyristorsalso.

UNIT–IV
DC–DCconverters

IntroductiontoChoppers

A chopper uses high speed to connect and disconnect from a source load. A fixed DC voltage is appliedintermittently to the source load by continuously triggering the power switch ON/OFF. The period oftime for which the power switch stays ON or OFF is referred to as the chopper‟s ON and OFF statetimes,respectively.

Choppers are mostly applied in electric cars, conversion of wind and solar energy, and DC motorregulators.

SymbolofaChopper

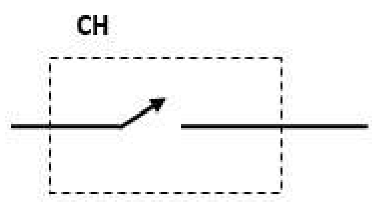


Figure:3.1symbol ofchopper

ControlstrategiesofChopper

InDC-DCconverters,theaverageoutputvoltageiscontrolledbyvaryingthealpha(α)value.Thisis achievedbyvaryingtheDutyCycle oftheswitchingpulses.Dutycyclecanbevariedusuallyin2ways:

1. TimeRatioControl
2. CurrentLimitControl

In this post we shall look upon both the ways of varying the duty cycle. Duty Cycle is the ratio of „OnTime‟to„TimePeriodofapulse‟.

Time Ratio Control: As the name suggest, here the time ratio (i.e. the duty cycle ratio Ton/T) is varied.Thiskindof controlcanbeachievedusing2ways:

• PulseWidthModulation(PWM)•FrequencyModulationControl(FMC)

PulseWidthModulation(PWM)

In this technique, the time period is kept constant, but the „On Time" or the „OFF Time" is varied. Usingthis, the duty cycle ratio can be varied. Since the ON time or the „pulse width" is getting changed in thismethod,soitispopularlyknownasPulsewidthmodulation.

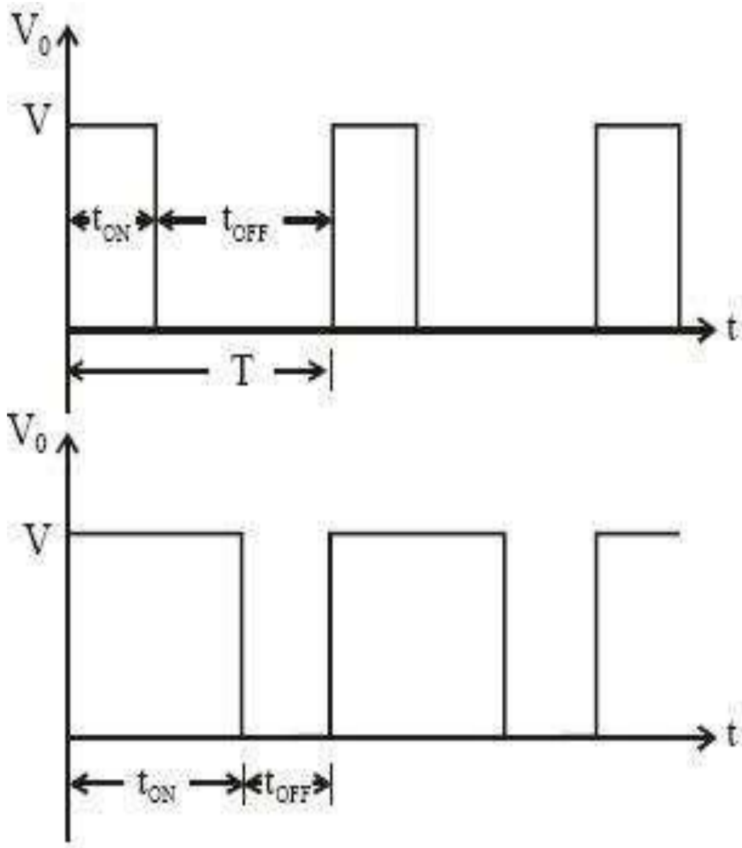


Figure:3.2pulse widthmodulationwaveforms

FrequencyModulationControl(FMC)

In this control method, the „Time Period" is varied while keeping either of „On Time" or „OFF time" asconstant. In thismethod, since the time period gets changed, so the frequency also changes accordingly,sothismethodisknownasfrequencymodulationcontrol.

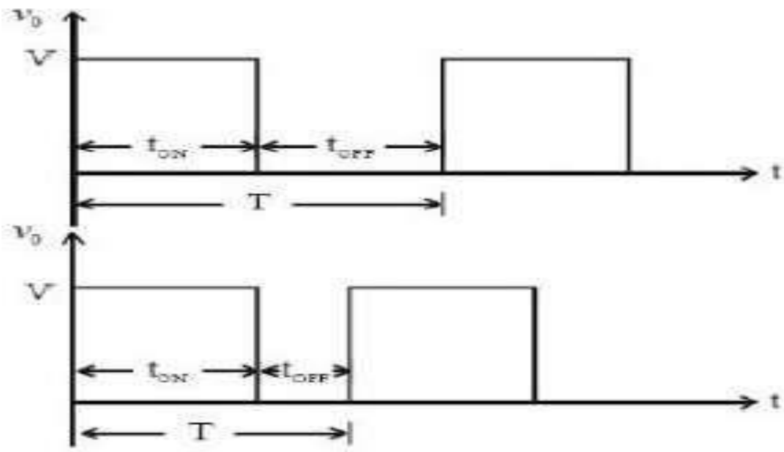


Figure:3.3Frequencymodulationwaveforms

CurrentLimitControl:

Asisobviousfromitsname,inthiscontrolstrategy, aspecificlimitisappliedonthecurrentvariation.

In this method, current is allowed to fluctuate or change only between 2 values i.e. maximum current (Imax) and minimum current (I min). When the current is at minimum value, the chopper is switched ON.After this instance, the current starts increasing, and when it reaches up to maximum value, the chopper isswitchedoffallowingthecurrenttofallbacktominimumvalue.This cyclecontinues againandagain.

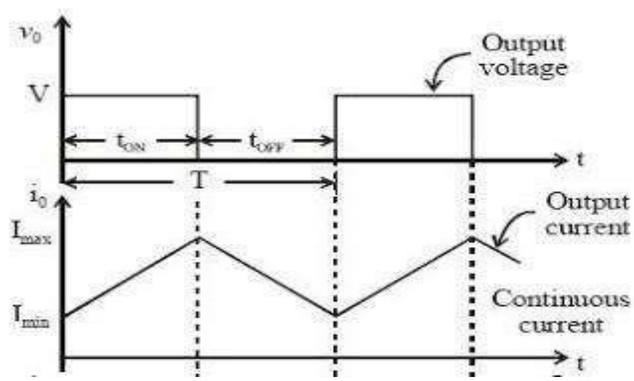


Figure:3.4currentlimitcontrolwaveforms

ClassificationofChoppers

Dependingonthevoltageoutput,choppersareclassifiedas−

1. StepUpchopper (boostconverter)
2. StepDownChopper(Buckconverter)

3. StepUp/DownChopper (Buck-boostconverter)

Dependinguponthedirectionoftheoutputcurrentandvoltage,theconverterscanbeclassifiedintofiveclassesnam ely

1. ClassA[One-quadrantOperation]
2. ClassB[One-quadrantOperation]
3. ClassC[Two-quadrantOperation]
4. ClassDChopper [Two-quadrantOperation]
5. ClassEChopper[Four-quadrantOperation]

StepDownChopper

Thisisalsoknownasabuckconverter.Inthischopper,theaveragevoltageoutput$V_O$islessthantheinputvoltageV_S. WhenthechopperisON,V_O=$V_S$andwhenthechopperisoff,V_O=0

Whenthechopperis ON −

$$VS=(VL+V0),VL=VS-V0,$$

$$Ldi/dt=VS-V0,L$$

$$\Delta i/TON=Vs+V0$$

$$VS=(VL+V0),VL$$

$$=VS-V0,$$

$$Ldi/dt=VS-V0,L$$

$$\Delta i/TON=Vs+V0$$

Thus,peak-to-peakcurrent loadis givenby,

$$\Delta i=\frac{Vs-V0}{L}TON$$

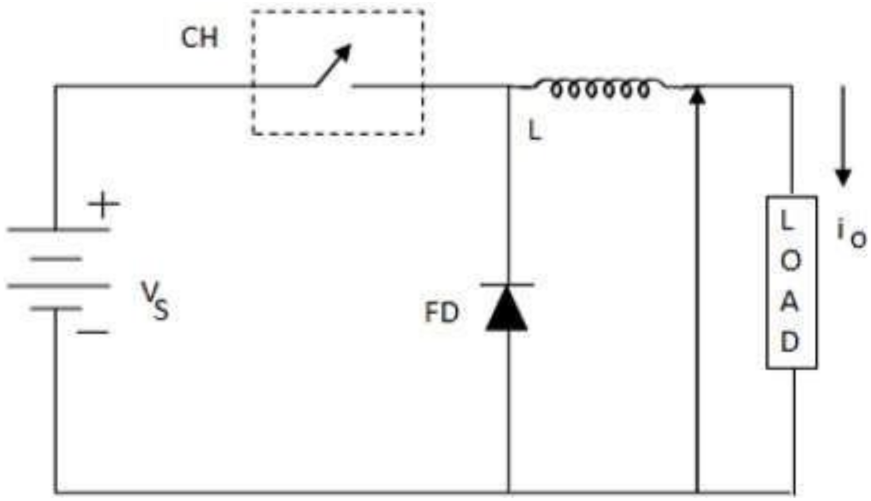


Figure:3.5Stepdownchopper

Where**FD**isfree-wheeldiode.

WhenthechopperisOFF,polarityreversalanddischargingoccursattheinductor.Thecurrentpassesthroughthefree-wheeldiodeandtheinductortothe load.Thisgives,

Ldi/dt=V0

Rewritten as

LΔi/TOFF=V0LΔi/TOFF=

V0Δi=V0TOFF/L

Fromtheabove equations

$$\frac{V_S - V_0}{L} T_{ON} = \frac{V_0}{L} T_{OFF}$$
$$\frac{V_S - V_0}{V_0} = \frac{T_{OFF}}{T_{ON}}$$
$$\frac{V_S}{V_0} = \frac{T_{ON} - T_{OFF}}{T_{ON}}$$

$$V_0 = \frac{T_{ON}}{T} V_S = DV_S$$

$$\Delta i = \frac{V_S - DV_S}{L} DT, \text{ from } D = \frac{T_{ON}}{T}$$
$$= \frac{V_S - (1-D)D}{Lf}$$
$$f = \frac{1}{T} = \text{chopping frequency}$$

CurrentandVoltageWaveforms

Thecurrentandvoltagewaveformsaregivenbelow−

Forastepdownchopperthevoltageoutputisalwayslessthanthevoltageinput.Thisisshownbythewaveformbelow.

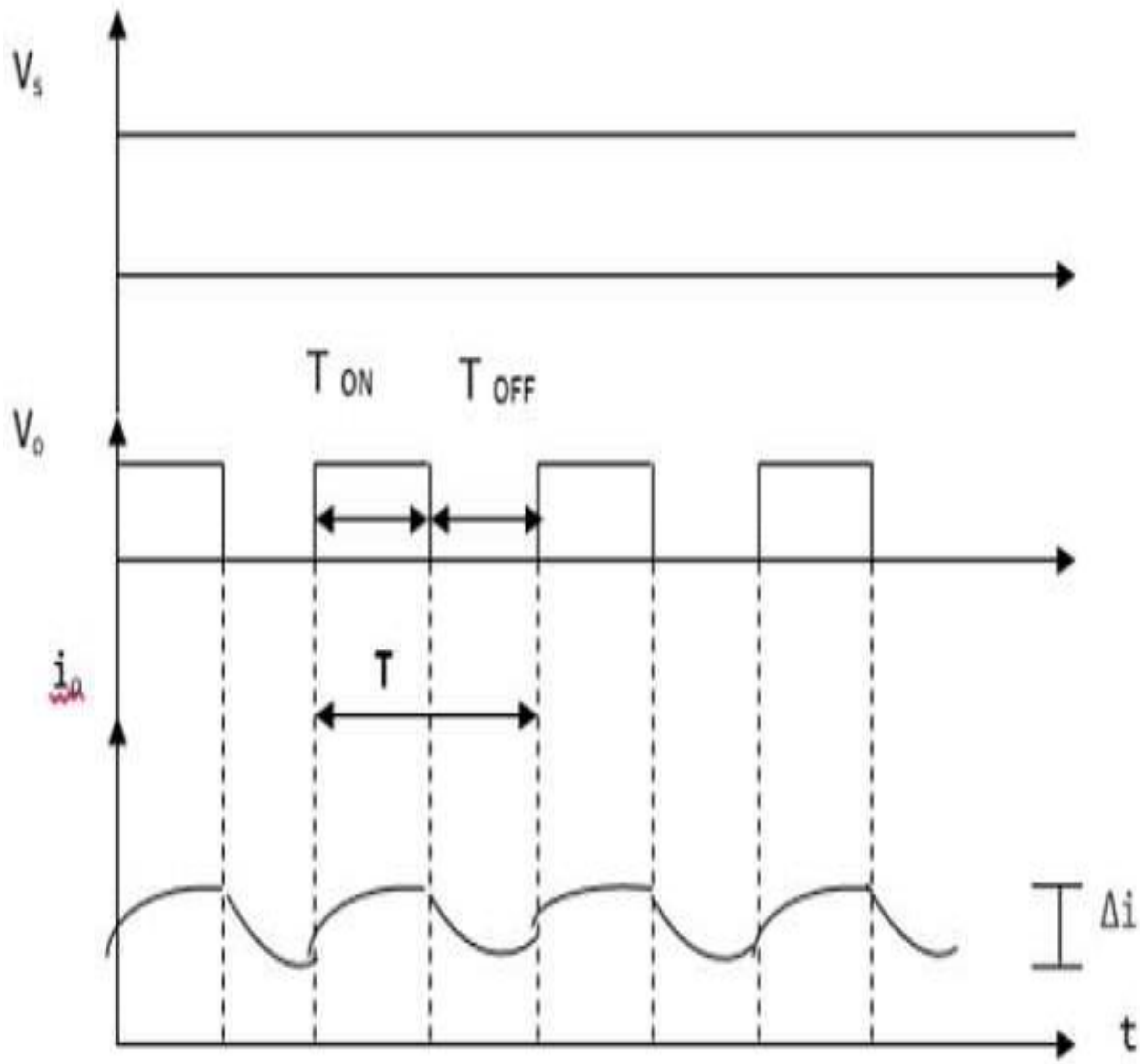


Figure:3.6Inputandoutputwaveforms

StepUpChopper

Theaveragevoltageoutput(V_o)inastepupchopperisgreaterthanthevoltageinput(V_s).Thefigurebelowshowsaconfigurationof astepupchopper.

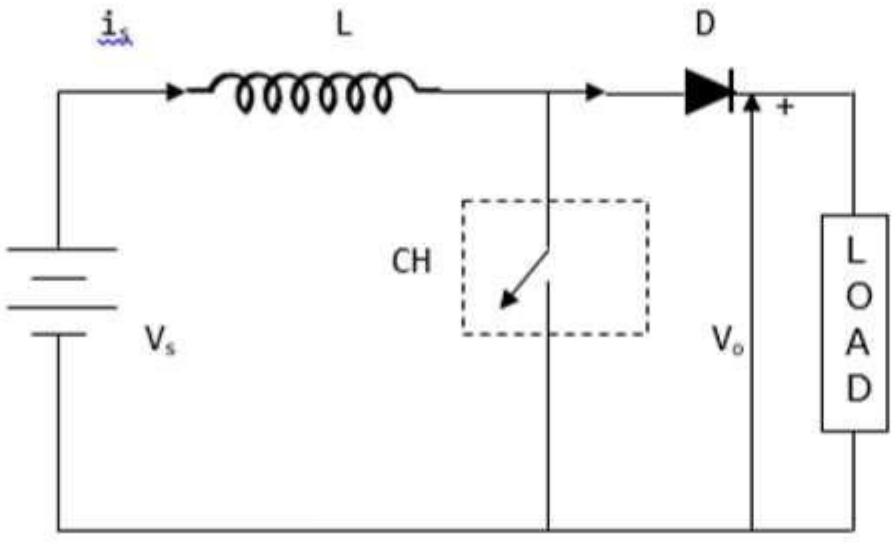


Figure:3.7circuit diagramof stepupchopper

CurrentandVoltageWaveforms

V_0(averagevoltageoutput)ispositivewhenchopperisswitchedONandnegativewhenthechopperisOFFasshowninthe waveformbelow.

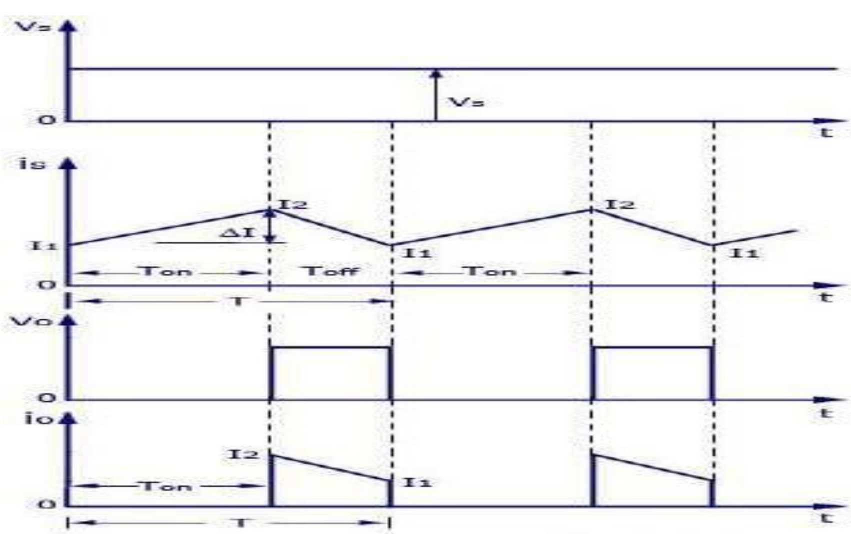


Figure:3.8Inputandoutputwaveformsofstepupchopper

Where

T_{ON} – time interval when chopper is

ONT_{OFF}–timeintervalwhenchopper

isOFFV_L–Loadvoltage

V_s –Sourcevoltage

T – Chopping time period = T_{ON} +

$T_{OFF}$$V_o$isgivenby−

$$V0=\frac{1}{T}\int_0^{Ton} Vs\,dt$$

Whenthechopper(CH)isswitchedON,theloadisshortcircuitedand,therefore,thevoltageoutputfortheperiodT_{ON} iszero.Inaddition,theinductoris charged duringthis time.ThisgivesV_S = V_L

$$Vs=L\frac{di}{dt},\frac{\Delta i}{Ton}=\frac{Vs}{L}$$

$$\Delta i=\frac{Vs}{L}\times Ton$$

Δi=istheinductorpeaktopeakcurrent.Whenthechopper(CH)isOFF,dischargeoccursthroughthe inductorL.Therefore,thesummationoftheV$_s$and V$_L$isgivenas follows −

$$V0=VS+VL,VL=V0-VS$$

$$L\frac{di}{dt}=Vo-Vs$$

$$L\frac{\Delta i}{Toff}=Vo-Vs$$

$$\Delta i=\frac{Vo-Vs}{L}Toff$$

EquatingΔifromonstatetooff state

$$\frac{Vs}{L}\times Ton=\frac{Vo-Vs}{L}Toff$$

$$Vo = \frac{TVs}{Toff}$$

$$Vo = \frac{Vs}{1-D}$$

StepUp/StepDownChopper

Thisis alsoknownasabuck-boost converter.Itmakesitpossibletoincreaseorreducethevoltageinputlevel.The diagrambelowshowsabuck-boostchopper

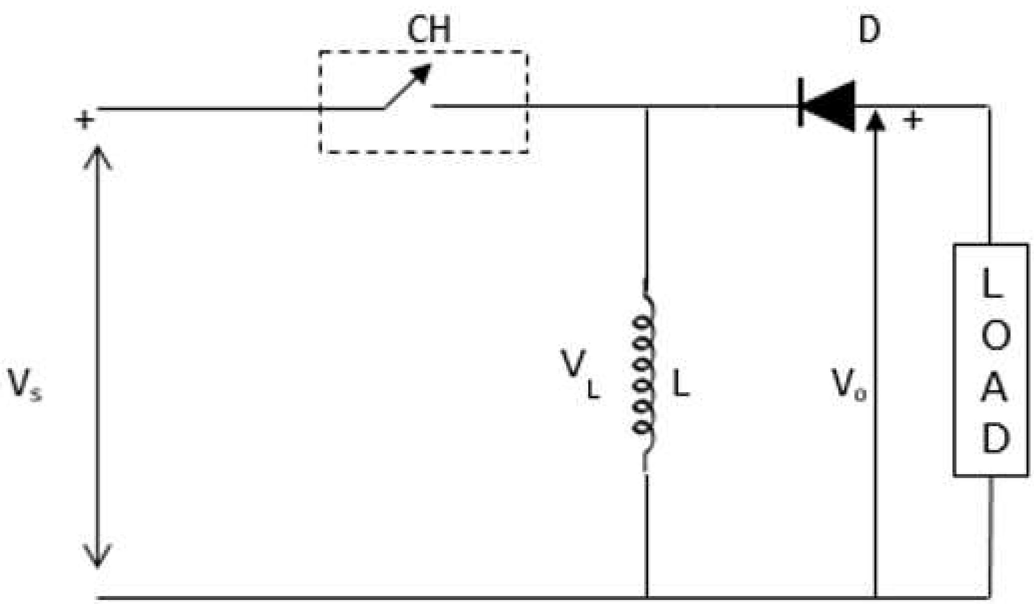


Figure:3.9circuitdiagramof stepupchopper

WhenthechopperIs switchedON,theinductorLbecomes chargedbythesourcevoltageV_s.Therefore,$V_s = V_L$.

$$Vs = L\frac{di}{dt} \quad \frac{\Delta i}{Ton} = \frac{Vs}{L}$$

$$\Delta i = \frac{Vs}{L} Ton \times \frac{T}{T}$$

$$\Delta i = \frac{DVs}{Lf}$$

WhenthechopperisswitchedOFF,theinductor"spolarityreversesandthiscausesittodischarge throughthediodeandthe load.

Hence,

$$V0=-VL$$

$$L\ \frac{di}{dt}=-VL$$

$$\frac{\mathrm{L\Delta i}}{\mathrm{Toff}}=-\mathrm{VL}$$

$$\Delta i=-\frac{VLToff}{L}$$

Bycomparingtheaboveequations

$$\frac{DVs}{Lf}=-\ \frac{VLToff}{L}$$

$$V_0=\frac{DVs}{1-D}$$

PrincipleofoperationofclassAchopper

ClassAChopperisafirstquadrantchopper

• Whenchopperis ON,supplyvoltageVis connectedacross the load.

• WhenchopperisOFF,vO =0andtheloadcurrentcontinuestoflowinthesamedirectionthroughthe FWD.

• Theaveragevaluesofoutputvoltageandcurrent arealwayspositive.ClassAChopperis afirst quadrantchopper

• Whenchopperis ON,supplyvoltageVisconnectedacrosstheload.

• WhenchopperisOFF,vO =0andtheloadcurrentcontinuestoflowinthesamedirectionthroughthe FWD.

• Theaveragevaluesofoutputvoltageandcurrentarealways positive.

• ClassAChopperis astep-downchopperinwhichpoweralwaysflowsformsourcetoload.

• It is usedtocontrolthespeed ofdcmotor.

• The output current equations obtained in step down chopper with R-L load can be used to study theperformanceof ClassAChopper.

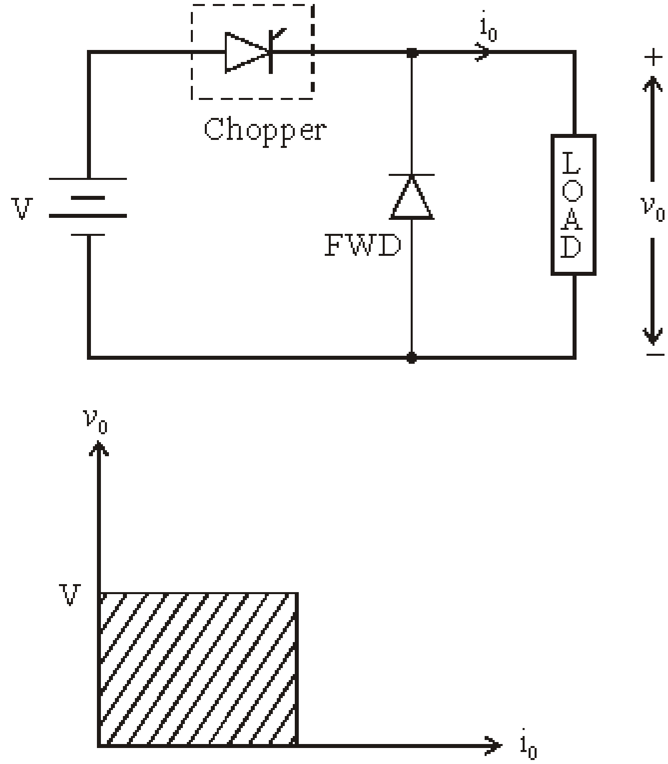


Figure:3.10 circuitdiagramandquadrantoperationofTypeAchopper

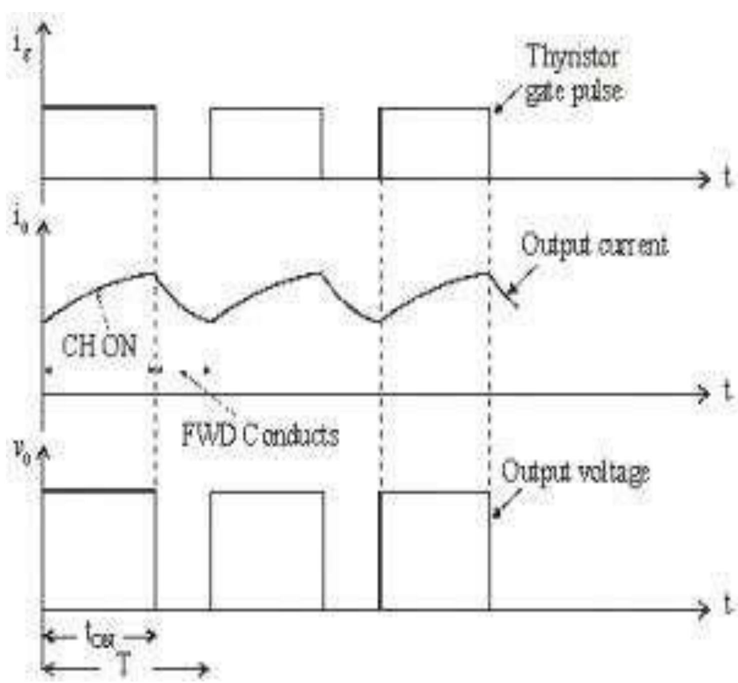


Figure:3.11OutputvoltageandcurrentwaveformsoftypeAchopper

Voltage equation for the circuit shown in figure is

$$V = i_O R + L\frac{di_O}{dt} + E$$

Taking Laplace Transform

$$\frac{V}{S} = RI_O(S) + L\left[S I_O(S) - i_O(0^-)\right] + \frac{E}{S}$$

At $t = 0$, initial current $i_O(0^-) = I_{\min}$

$$I_O(S) = \frac{V-E}{LS\left(S+\frac{R}{L}\right)} + \frac{I_{\min}}{S+\frac{R}{L}}$$

Taking Inverse Laplace Transform

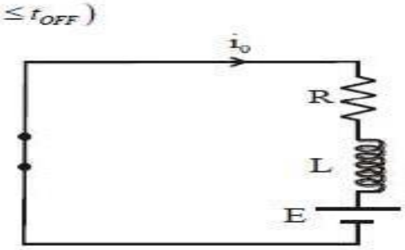
$$i_O(t) = \frac{V-E}{R}\left[1 - e^{-\left(\frac{R}{L}\right)t}\right] + I_{\min} e^{-\left(\frac{R}{L}\right)t}$$

This expression is valid for $0 \le t \le t_{ON}$, i.e., during the period chopper is ON.

At the instant the chopper is turned off, load current is

$$i_O(t_{ON}) = I_{\max}$$

When Chopper is OFF $(0 \le t \le t_{OFF})$



Voltage equation for the circuit shown in figure is

$$0 = Ri_O + L\frac{di_O}{dt} + E$$

Taking Laplace transform

$$0 = RI_O(S) + L\left[SI_O(S) - i_O(0^-)\right] + \frac{E}{S}$$

Redefining time origin we have at $t = 0$, initial current $i_O(0^-) = I_{\max}$

Therefore $$I_O(S) = \frac{I_{\max}}{S+\frac{R}{L}} - \frac{E}{LS\left(S+\frac{R}{L}\right)}$$

Taking Inverse Laplace Transform

$$i_O(t) = I_{\max} e^{-\frac{R}{L}t} - \frac{E}{R}\left[1 - e^{-\frac{R}{L}t}\right]$$

The expression is valid for $0 \le t \le t_{OFF}$, i.e., during the period chopper is OFF. At the instant the chopper is turned ON or at the end of the off period, the load current is

$$i_O(t_{OFF}) = I_{\min}$$

TO FIND $I_{\max}$ AND $I_{\min}$

At $t = t_{ON} = dT$, $i_O(t) = I_{\max}$

ClassBChopper

ClassBChopperisastep-upchopper

- Whenchopperis ON,Edrives acurrent throughLandR inadirection oppositetothat showninfigure.
- DuringtheONperiodofthechopper,theinductanceL stores energy.
- WhenChopperisOFF,diodeDconducts,andpartoftheenergystoredininductorL isreturnedtothe supply.
- Averageoutputvoltageispositive. Averageoutputcurrentisnegative.
- ThereforeClassBChopperoperates insecondquadrant.
- Inthischopper, powerflowsfromloadtosource.
- ClassBChopperisusedforregenerativebrakingofdcmotor.

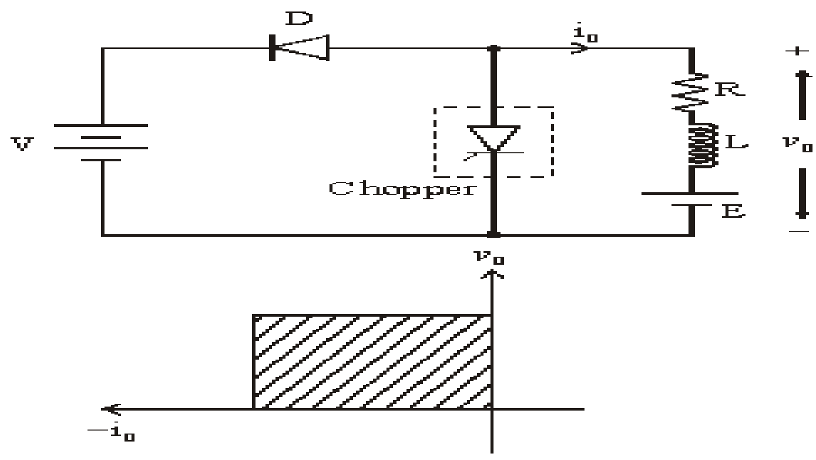


Figure:3.12 circuitdiagramandquadrantoperationofTypeBchopper

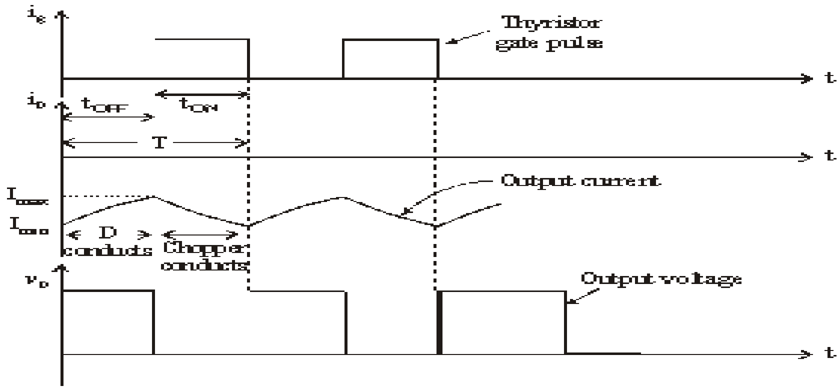


Figure:3.13OutputvoltageandcurrentwaveformsoftypeB

chopper**ClassCchopper**

ClassCChoppercanbeusedasastep-uporstep-downchopper

• ClassCChopperisacombinationofClass AandClassBChoppers.

• For firstquadrantoperation, CH1isONorD2conducts.

• Forsecondquadrantoperation, CH2isONorD1conducts.

• WhenCH1isON,theloadcurrent ispositive.

• Theoutputvoltageisequalto„V"&theloadreceivespowerfromthesource.

• WhenCH1is turnedOFF,energystoredininductanceL forcescurrenttoflowthroughthediodeD2 andtheoutput voltageiszero.

• Currentcontinuestoflowinpositivedirection.

• WhenCH2 is triggered,thevoltageE forces currenttoflowinoppositedirectionthroughLandCH2 .

• Theoutput voltageis zero.

• OnturningOFFCH2,theenergystoredintheinductancedrivescurrentthroughdiodeD1 andthe supply

• OutputvoltageisV,theinput currentbecomesnegativeandpowerflows fromloadtosource.

• Averageoutput voltageispositive

• Averageoutputcurrentcantakebothpositiveandnegativevalues.

• ChoppersCH1&CH2 shouldnotbeturnedONsimultaneouslyas itwouldresultinshortcircuitingthe supply.

• ClassCChoppercanbeusedbothfordcmotorcontrolandregenerativebrakingofdcmotor.

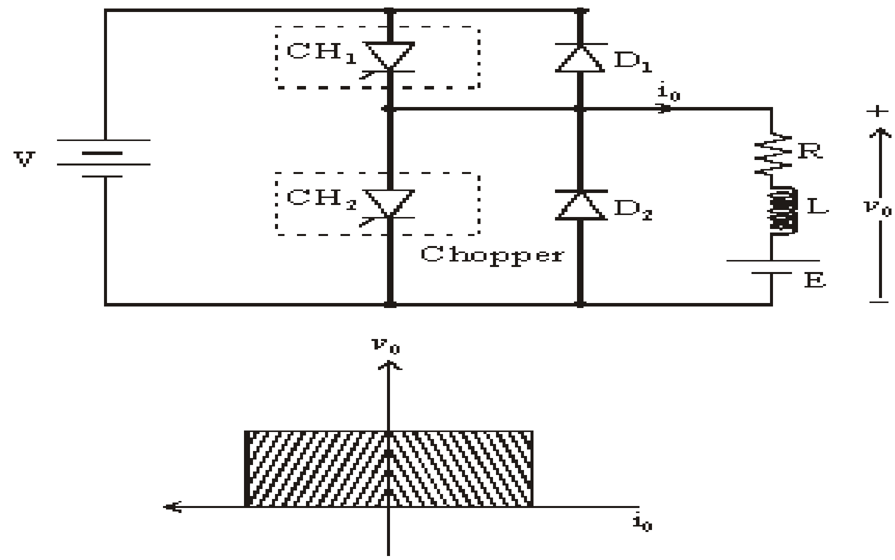


Figure:3.14 circuitdiagramandquadrantoperationofTypeCchopper

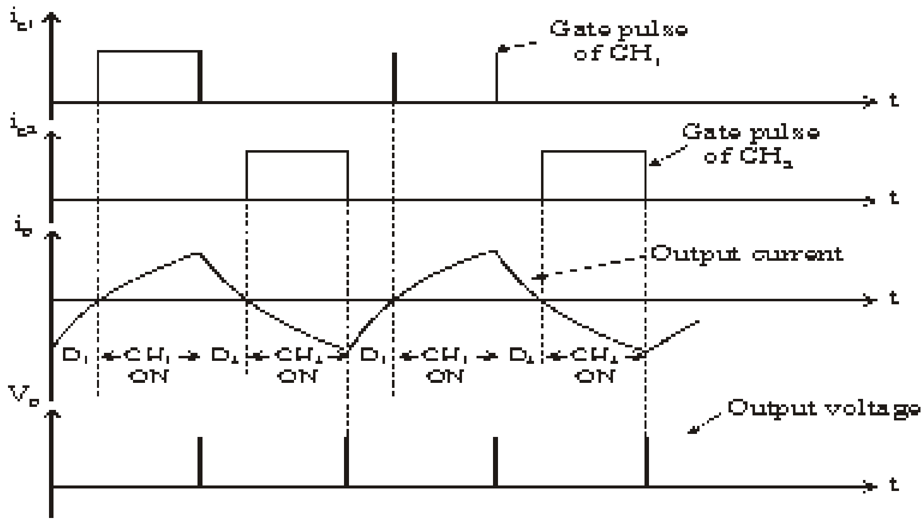


Figure:3.15OutputvoltageandcurrentwaveformsoftypeCchopper

ClassDchopper

• ClassDisatwo quadrantchopper.

• WhenbothCH1 andCH2aretriggeredsimultaneously,theoutputvoltagevO=Vandoutputcurrent flows throughtheload.

• WhenCH1andCH2areturnedOFF,theloadcurrentcontinuestoflowinthesamedirectionthrough load,D1andD2,dueto the energystoredintheinductorL.

• OutputvoltagevO=–V.

• Averageloadvoltageis positiveifchopperON timeismorethantheOFFtime

• AverageoutputvoltagebecomesnegativeiftON<tOFF.

• Hencethedirectionofloadcurrentisalways positivebutloadvoltagecanbepositiveornegative.

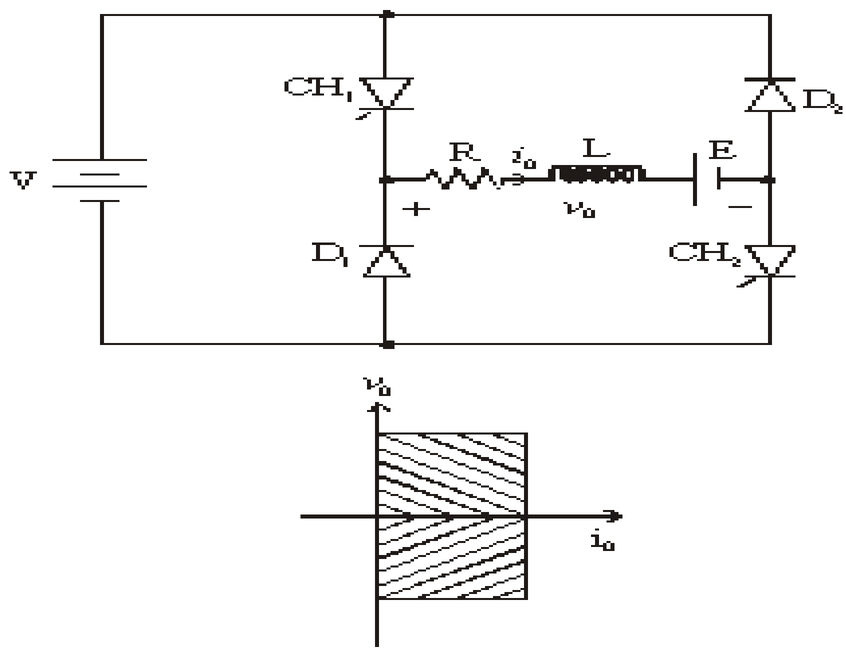


Figure:3.16 circuitdiagramandquadrantoperationofTypeDchopper

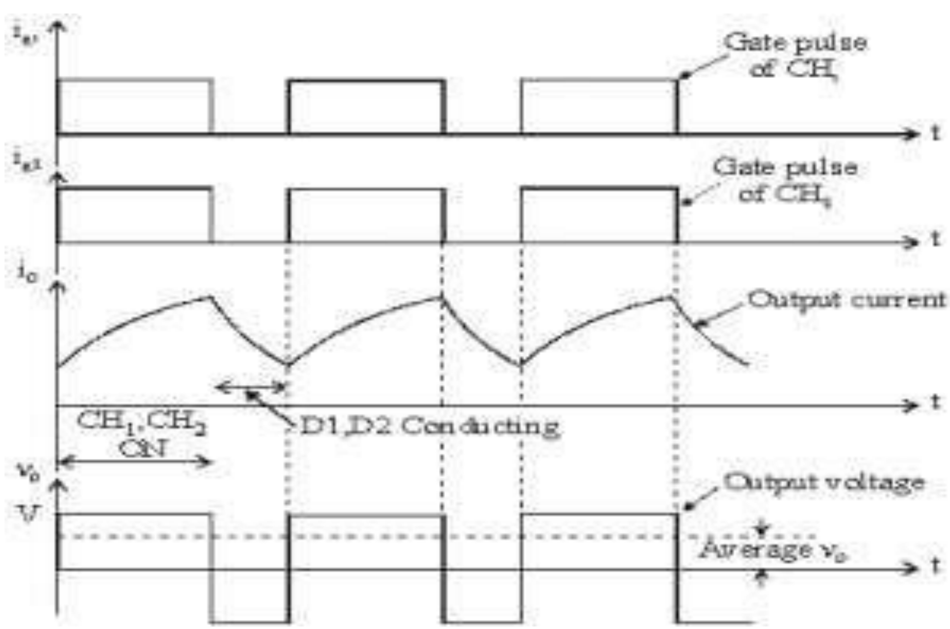


Figure:3.17OutputvoltageandcurrentwaveformsoftypeDchopper

ClassEChopper

• ClassEisafourquadrantchopper

• WhenCH1 andCH4aretriggered,outputcurrentiOflows inpositivedirectionthroughCH1andCH4,andwithoutputvoltagevO=V.

• Thisgivesthefirstquadrantoperation.

• WhenbothCH1andCH4areOFF,theenergystoredintheinductorLdrives iO throughD2andD3inthesame direction,butoutputvoltage vO=-V.

• Thereforethechopperoperatesinthefourthquadrant.

• WhenCH2 andCH3aretriggered,theloadcurrent iOflowsin oppositedirection&output voltagevO =-V.

• SincebothiOand vOarenegative,thechopperoperates inthird quadrant.

• WhenbothCH2andCH3areOFF,the loadcurrentiO continuestoflowinthesamedirectionD1and D4 andtheoutputvoltagevO= V.

• ThereforethechopperoperatesinsecondquadrantasvOispositivebutiOis negative.

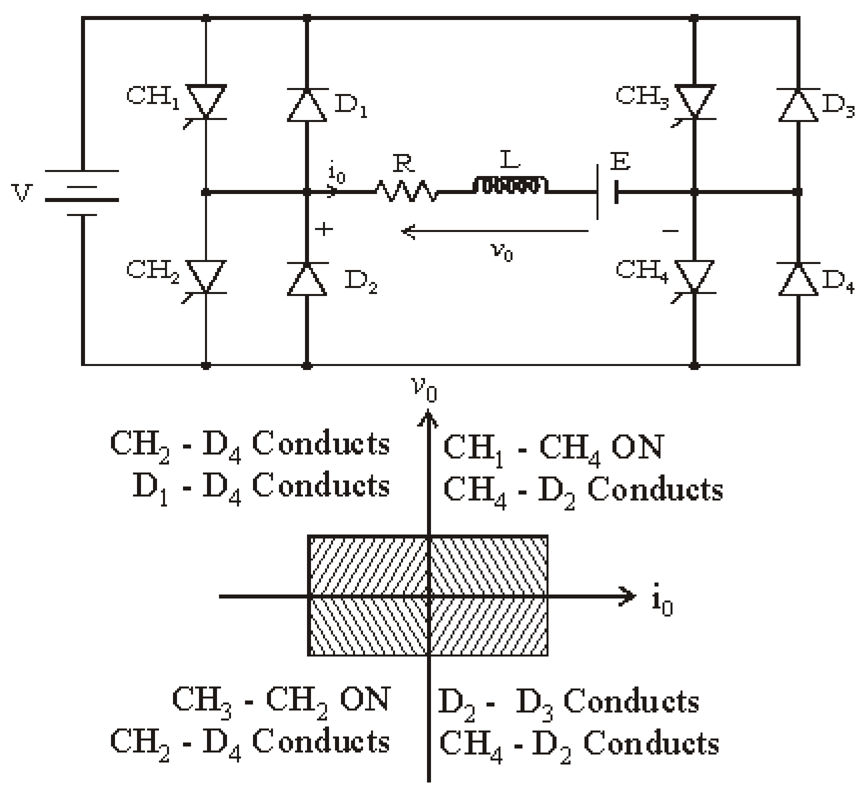


Figure:3.18 circuitdiagramandquadrantoperationofTypeEchopper

Numericalproblems

1. Astepupchopperhasan inputvoltageof150V.Thevoltageoutputneededis450V.Given,thatthe thyristorhasaconductingtimeof150µseconds.Calculatethechoppingfrequency.

Solution−

Thechoppingfrequency(f)

$$f = \frac{1}{T}$$

Where **T** – Chopping time period = $T_{ON} + T_{OFF}$

Given – $V_S = 150V$ $V_0 = 450V$ $T_{ON} = 150\mu sec$

$$V_0 = V_{S(\frac{T}{T-T_{ON}})}$$

$$450 = 150\frac{T}{T-150^{-6}}\ T = 225\mu sec$$

Therfore, $f = \frac{1}{225*10^{-6}} = 4.44KHz$

Thenewvoltageoutput,onconditionthattheoperationisatconstantfrequencyafterthehalvingthepulsewidth.

Halvingthepulsewidthgives−

$$T_{ON} = \frac{150 \times 10^{-6}}{2} = 75\mu sec$$

The frequency is constant thus,

$$f = 4.44KHz$$

$$T = \frac{1}{f} = 150\mu sec$$

The voltage output is given by –

$$V_0 = V_S\left(\frac{T}{T - T_{ON}}\right) = 150 \times \left(\frac{150 \times 10^{-6}}{(150-75) \times 10^{-6}}\right) = 300Volts$$

2. In a type A chopper, the input supply voltage is 230 V the load resistance is 10Ω and there is avoltage drop of 2 V across the chopper thyristor when it is on. For a duty ratio of 0.4, calculate theaverageandrmsvaluesoftheoutputvoltage.Alsofindthechopperefficiency
3. A step-up chopper supplies a load of 480 V from 230 V dc supply. Assuming the non conductionperiodof thethyristortobe50microsecond,findthe ontimeof thethyristor

Buckregulator

Withpowerbeingakeyparameterin manydesigns,stepdown or"buck"regulators arewidelyused.

Although a resistor would enable voltage to be dropped, power is lost, and in applications such as themanybatterypowereditemsusedtoday,powerconsumptionisacrucialelement.

As a result step down switch mode converters or as they are more commonly termed, buck regulators arewidelyused.

Linear stepdown

Themostbasicformofstepdowntransitionistousearesistorasapotentialdividerorvoltagedropper.Insome casesazenerdiode mayalsobeusedtostabilizethevoltage.

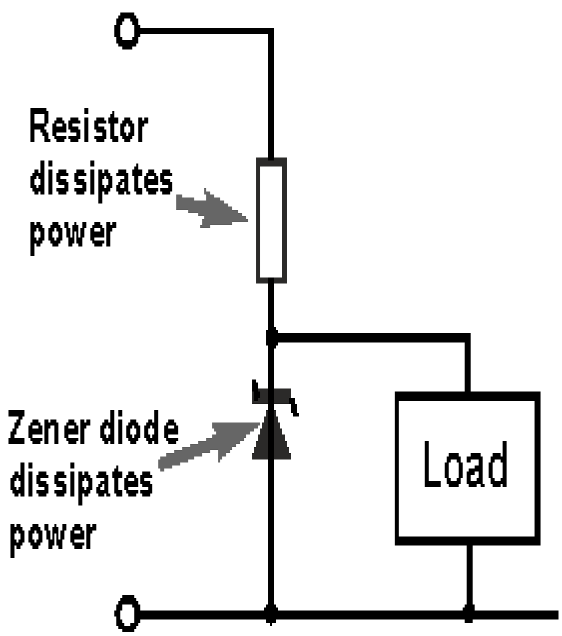


Figure:3.19Potential dividercircuits

The issue with this form of voltage dropper or step down converter is that it is very wasteful in terms ofpower. Any voltage dropped across the resistor will be dissipated as heat, and any current flowing throughthezenerdiodewillalsodissipateheat.Bothoftheseelementsresultonthelossofvaluableenergy.

Basicbuckconverterorregulator

The fundamental circuit for a step down converter or buck converter consists of an inductor, diode,capacitor,switchanderror amplifierwithswitchcontrolcircuitry.

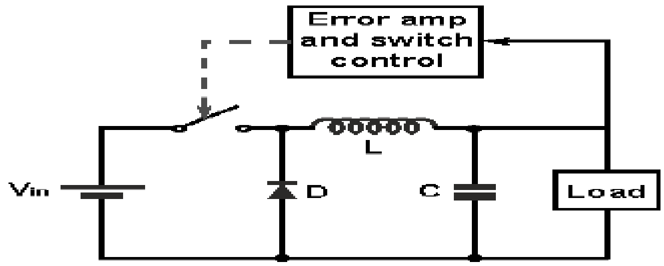


Figure:3.20circuit diagramofBuckregulator

The circuit for the buck regulator operates by varying the amount of time in which inductor receivesenergyfromthesource.

In the basic block diagram the operation of the buck converter or buck regulator can be seen that theoutput voltage appearing across the load is sensed by the sense / error amplifier and an error voltage isgeneratedthatcontrolstheswitch.

Typically the switch is controlled by a pulse width modulator, the switch remaining on of longer as morecurrent is drawn by the load and the voltage tends to drop and often there is a fixed frequency oscillator todrivetheswitching.

Buckconverteroperation

When the switch in the buck regulator is on, the voltage that appears across the inductor is Vin - Vout.Using the inductorequations, the current in the inductor will rise at a rate of (Vin-Vout)/L. At this timethediodeDisreversebiasedanddoesnotconduct.

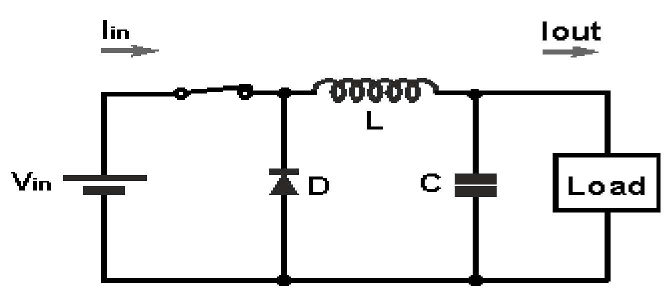


Figure:3.21circuitdiagramofBuckregulatorduringswitchoncondition

When the switch opens, current must still flow as the inductor works to keep the same current flowing. Asa result current still flows through the inductor and into the load. The diode, D then forms the return pathwithacurrentIdiode equaltoIoutflowingthroughit.

With the switch open, the polarity of the voltage across the inductor has reversed and therefore the currentthroughtheinductordecreaseswithaslopeequalto-Vout/L.

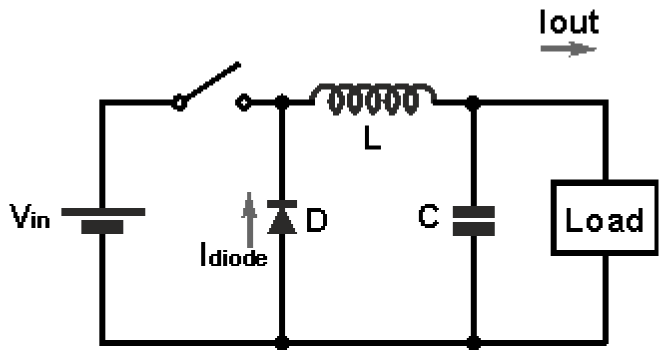


Figure:3.22circuitdiagramofBuckregulatorduringswitchoffcondition

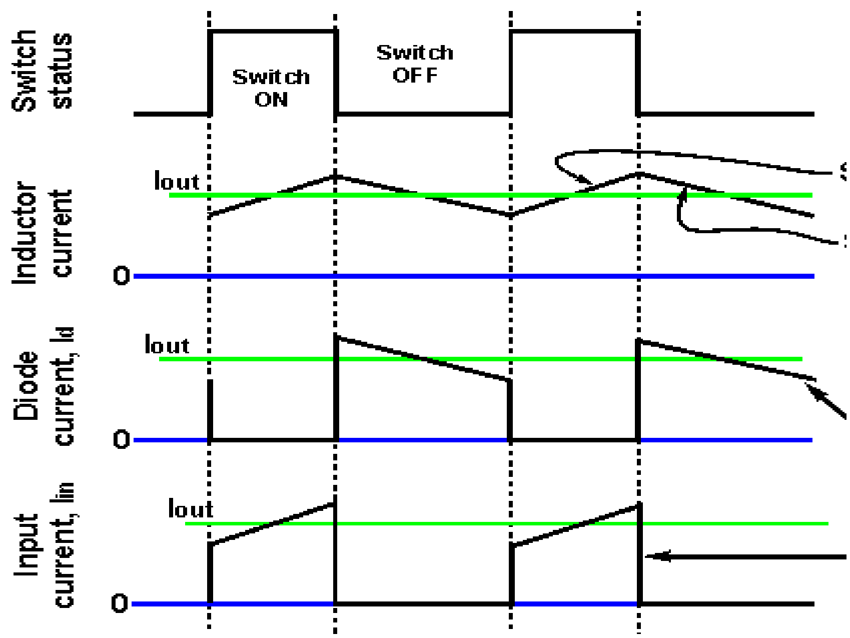


Figure:3.23InputandoutputwaveformsofBuckregulator

In the diagram of the current waveforms for the buck converter / switching regulator, it can be seen thatthe inductor current is the sum of the diode and input / switch current. Current either flows through theswitchorthediode.

It is also worth noting that the average input current is less than the average output current. This is to beexpected because the buck converter circuit is very efficient and the input voltage is greater than theoutput voltage. Assuming a perfect circuit, then power in would equal power out, i.e. Vin· In = Vout ·Iout. While in a real circuit there will be some losses, efficiency levels greater than 85%are to beexpectedforawell-designedcircuit.

It will also be seen that there is a smoothing capacitor placed on the output. This serves to ensure that thevoltage does not vary appreciable, especially during and switch transition times. It will also be required tosmoothanyswitchingspikesthatoccur.

Boostregulator

Oneoftheadvantagesofswitchmodepowersupplytechnologyisthatitcanbeusedtocreateastepuporboostconverter/regulator.

Boost converters or regulators are used in many instances from providing small supplies where highervoltagesmaybeneededtomuchhigherpowerrequirements.

Often there are requirements for voltages higher than those provided by the available power supply - voltagesforRFpoweramplifierswithinmobilephonesisjustoneexample.

Step-upboostconverterbasics

The boost converter circuit has many similarities to the buck converter. However the circuit topology forthe boost converter is slightly different. The fundamental circuit for a boost converter or step up converterconsists ofaninductor,diode,capacitor,switchand erroramplifierwithswitchcontrolcircuitry.

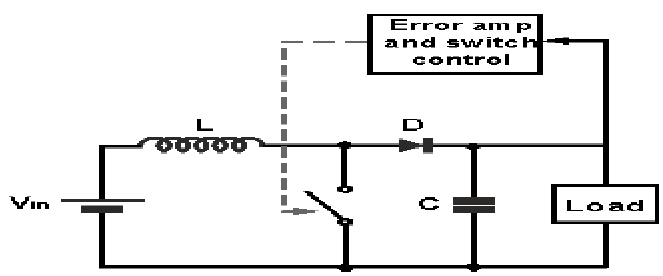


Figure:3.24circuit diagramofBoost regulator

The circuit for the step-up boost converter operates by varying the amount of time in which inductorreceivesenergyfromthesource.

In the basic block diagram the operation of the boost converter can be seen that the output voltageappearing across the load is sensed by the sense / error amplifier and an error voltage is generated thatcontrolstheswitch.

Typically the boost converter switch is controlled by a pulse width modulator, the switch remaining on oflonger as more current is drawn by the load and the voltage tends to drop and often there is a fixedfrequencyoscillatortodrivetheswitching.

Boostconverteroperation

Theoperationoftheboost converterisrelativelystraightforward.

When the switch is in the ON position, the inductor output is connected to ground and the voltage Vin isplacedacrossit.TheinductorcurrentincreasesatarateequaltoVin/L.

Whentheswitchis placedintheOFFposition,thevoltageacrosstheinductorchangesandisequaltoVout-Vin.Currentthatwasflowingintheinductordecaysatarateequalto(Vout-Vin)/L.

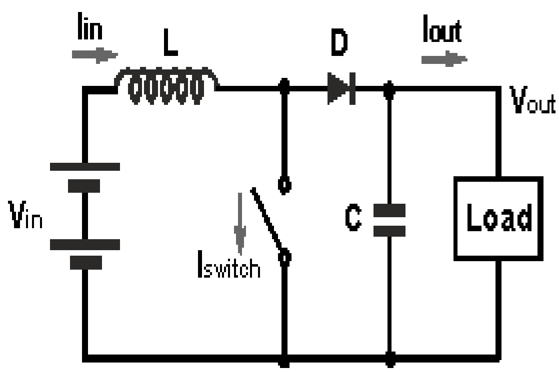


Figure:3.25circuitdiagramofBoostregulatorduring switchoffcondition

Referringtotheboostconvertercircuitdiagram,thecurrentwaveformsforthedifferentareasofthecircuitcanbeseenasbelow.

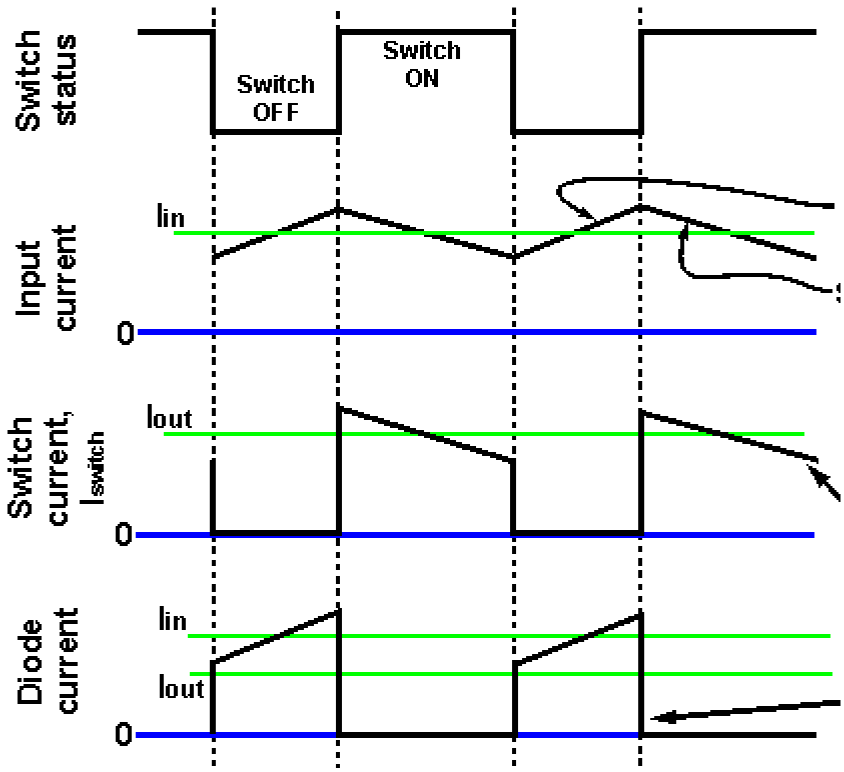


Figure:3.26Inputandoutputwaveforms ofBoostregulator

It can be seen from the waveform diagrams that the input current to the boost converter is higher than theoutput current. Assuming a perfectly efficient, i.e. lossless, boost converter, the power out must equal thepower in, i.e. Vin· Iin = Vout · Iout. From this it can be seen if the output voltage is higher than the inputvoltage,thentheinputcurrentmustbehigherthanthe outputcurrent.

In reality no boost converter will be lossless, but efficiency levels of around 85% and more are achievableinmostsupplies.

Buckboostregulator

A simple buck converter can only produce voltages lower than the input voltage, and a boost converter,only voltages higher than the input. To provide voltages over the complete range a circuit known as abuck-boostconverterisrequired.

There are many applicationswhere voltageshigherand lowerthan the inputare required.In thesesituationsabuck-boostconverterisrequired.

Buck-BoostConverterbasics

The buck-boost DC-DC converter offers a greater level of capability than the buck converter of boostconverterindividually,itas expected itextracomponentsmay be required to provide the leveloffunctionalityneeded.

Thereareseveralformatsthatcanbeusedforbuck-boostconverters:

- ***+Vin, -Vout:***This configuration of a buck-boost converter circuit uses the same number ofcomponents as the simple buck or boost converters. However this buck-boost regulator or DC-DCconverter produces a negative output for a positive input. While this may be required or can beaccommodated foralimited numberof applications,it is not normally the most convenientformat.

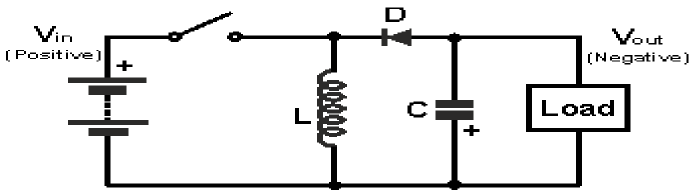


Figure:3.27circuitdiagramofbuckboostregulator

- When the switch in closed, current builds up through the inductor. When the switch is opened theinductorsuppliescurrentthroughthediodetotheload.

  Obviouslythepolarities(includingthediode)withinthebuck-boostconvertercanbereversedtoprovideapositiveoutputvoltagefromanegativeinputvoltage.

- ***+Vin, +Vout:*** The second buck-boost converter circuit allows both input and output to be thesame polarity. However to achieve this, more components are required. The circuit for this buckboostconverterisshownbelow.

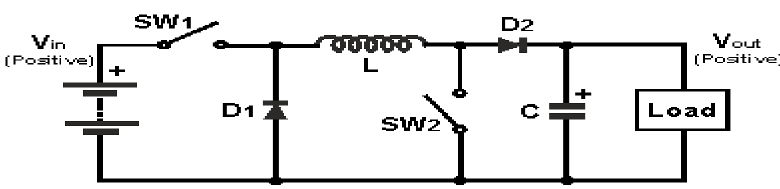


Figure:3.28circuit diagramof buckboost regulatorwithtwoswitches

In this circuit, both switches act together, i.e. both are closed or open. When the switches are open, theinductor current builds. At a suitable point, the switches are opened. The inductor then supplies current totheloadthroughapath incorporatingbothdiodes,D1andD2.

Numericalprobelms

1. In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz. Supplyvoltage is 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2ohms.

   Solution:

   $I_{dc} = 30\text{ Amps},\ f = 250\text{ Hz},\ V = 110\text{ V},\ R = 2\Omega$

   Chopping period, $T = \frac{1}{f} = \frac{1}{250} = 4\times10^{-3} = 4\text{ msecs}$

   $$I_{dc} = \frac{V_{dc}}{R} \text{ and } V_{dc} = dV$$

   Therefore $I_{dc} = \frac{dV}{R}$

   $$d = \frac{I_{dc}R}{V} = \frac{30\times2}{110} = 0.545$$

   Chopper ON period, $t_{ON} = dT = 0.545\times4\times10^{-3} = 2.18\text{ msecs}$

   Chopper OFF period, $t_{OFF} = T - t_{ON}$

   $$t_{OFF} = 4\times10^{-3} - 2.18\times10^{-3}$$

   $$t_{OFF} = 1.82\times10^{-3} = 1.82\text{ msec}$$

2. A step up chopper has input voltage of 220 V and output voltage of 660 V. If the non-conductingtime of thyristor chopper is 100 micro sec compute the pulse width of output voltage. In case thepulsewidthishalvedforconstantfrequencyoperation,findthe new outputvoltage
3. A chopper operating from 220V dc supply with for a duty cycle of 0.5 and chopping frequency of1KHz drives an R L load with R = 1Ω , L=1mH and E = 105V. Find whether the current iscontinuousandalsofindthe valuesofI_{max} and$I_{min.}$

UNIT–VINVERTERS

IntroductiontoInverters

The word „inverter" in the context of power-electronics denotes a class of power conversion (or powerconditioning) circuits that operates from a dc voltage source or a dc current source and converts it into acvoltage or current. The inverter does reverse of what ac-to-dc converter does (refer to ac to dc converters).Even though input to an inverter circuit is a dc source, it is not uncommon to have this dc derived from anac source such as utility ac supply. Thus, for example, the primary source of input power may be utility acvoltage supply that is converted to dc by an ac to dc converter and then „inverted" back to ac using aninverter. Here, the final ac output may be of a different frequency and magnitude than the input ac of theutilitysupply

AsinglephaseHalfBridgeDC-ACinverterisshowninFigurebelow

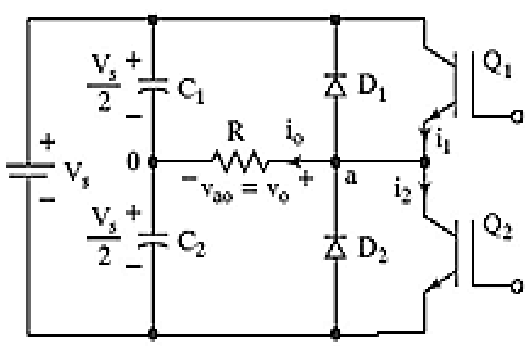


Figure:5.1SinglephaseHalfBridgeDC-ACinverterwith R load

Theanalysis oftheDC-ACinverters is donetakingintoaccounts thefollowingassumptions andconventions.

1) Thecurrententeringnodeais consideredtobepositive.

2) Theswitches S1andS2areunidirectional,i.e.theyconduct currentinonedirection.

3) ThecurrentthroughS1isdenotedasi1andthecurrentthroughS2isi2.

The switching sequence is so design is shown in Figure below. Here,switch S1 is on for the timeduration0≤t≤T1andtheswitchS2isonforthetimedurationT1≤t≤T2.WhenswitchS1isturnedon,theinstant aneousvoltageacrossthe loadisvo=Vin/2

WhentheswitchS2isonlyturnedon,thevoltageacrosstheloadis
vo=-Vin/2.

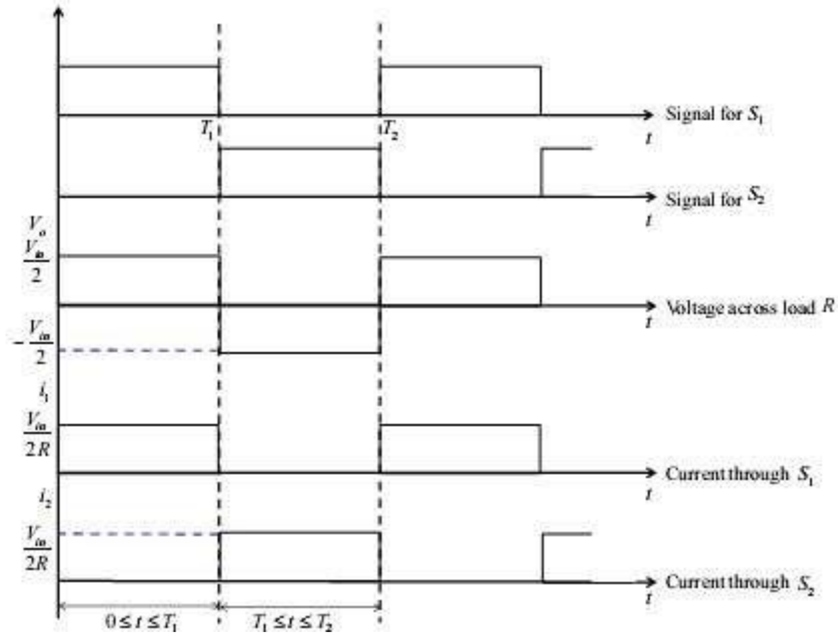


Figure: 5.2SinglephaseHalfBridgeDC-ACinverteroutput waveforms

Ther.m.svalueofoutputvoltagevoisgivenby,

$$V_{o,rms} = \left(\frac{1}{T_1} \int_0^{T_1} \frac{V_{in}^2}{4} dt \right) = \frac{V_{in}}{2}$$

Theinstantaneousoutputvoltagevoisrectangularinshape.Theinstantaneousvalueofvocanbe expressedinFourierseriesas,

$$v_o = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)$$

Due tothequarterwave symmetryalongthetimeaxis,thevaluesofa0andanarezero.Thevalueofbnisgivenby,

$$b_n = \frac{1}{\pi} \left[\int_{\frac{-\pi}{2}}^{0} \frac{-V_{in}}{2} d(\omega t) + \int_0^{\frac{\pi}{2}} \frac{V_{in}}{2} d(\omega t) \right] = \frac{2V_{in}}{n\pi}$$

Substitutingthevalueofbnfromaboveequation,weget

$$v_o = \sum_{n=1,3,5,...}^{\infty} \frac{2V_{in}}{n\pi} \sin(n\omega t)$$

Thecurrentthroughtheresistor(iL)is givenby,

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{1}{R} \frac{2V_{in}}{n\pi} \sin(n\omega t)$$

HalfBridgeDC-ACInverterwithLLoadandR-LLoad

TheDC-ACconverterwithinductiveloadisshowninFigurebelow.Foraninductiveload,theloadcurrentcannotchangeimmediatelywiththeoutputvoltage.

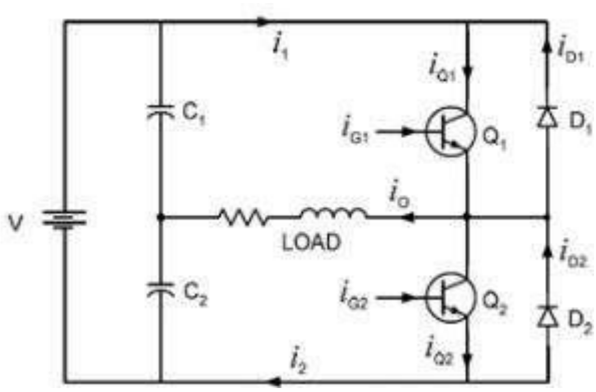


Figure:5.3SinglephaseHalfBridgeDC-ACinverterwith RLload

The working of the DC-AC inverter with inductive load is as follow is:Case 1: In the timeinterval 0<=t<= T1 the switch S1 is on andthe current flows through the inductorfrom points a to b. When the switch S1 is turned off (case 1) at t-T1, the load current would continue toflowthroughthecapacitorC2anddiodeD2untilthecurrentfallstozero,asshowninFigurebelow.

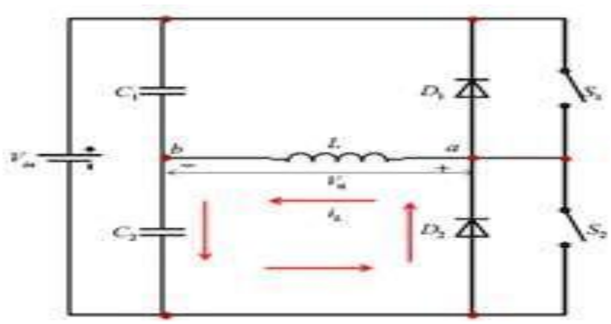


Figure: 5.4SinglephaseHalfBridgeDC-ACinverterwithLload

Case 2: Similarly, when S2 is turned off at t = T1 , the load current flows through the diode D1 andcapacitorC1untilthecurrentfallstozero,asshowninFigurebelow.

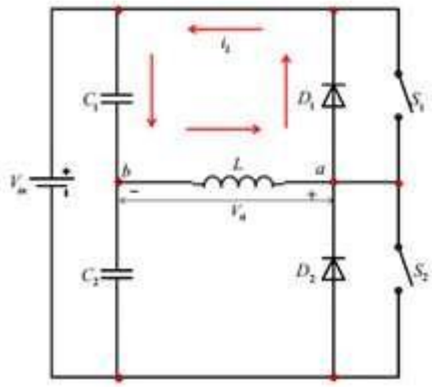


Figure:5.5SinglephaseHalfBridgeDC-ACinverterwithLload

When the diodes D1 and D2 conduct, energy is feedback to the dc source and these diodes are known asfeedback diodes. These diodes are also known as freewheeling diodes. The current for purely inductiveloadisgivenby,

$$i_L = \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{\omega nL} \frac{2V_{in}}{n\pi} \sin\left(n\omega t - \frac{\pi}{2}\right)$$

Similarly,fortheR– Lload.Theinstantaneous loadcurrent isobtainedas,

$$i_L = \sum_{n=1,3,5,\ldots}^{\infty} \frac{2V_{in}}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin\left(n\omega t - \theta_n\right)$$

Where,

$$\theta_n = \tan^{-1}\left(\frac{n\omega L}{R}\right)$$

Operationofsinglephasefullbridgeinverter

AsinglephasebridgeDC-ACinverterisshowninFigurebelow.TheanalysisofthesinglephaseDC-ACinverters is done taking into account following assumptions and conventions.
1) The current entering node a in Figure 8 is considered to be positive.
2) Theswitches S1,S2,S3andS4 areunidirectional,i.e.theyconductcurrentinonedirection.

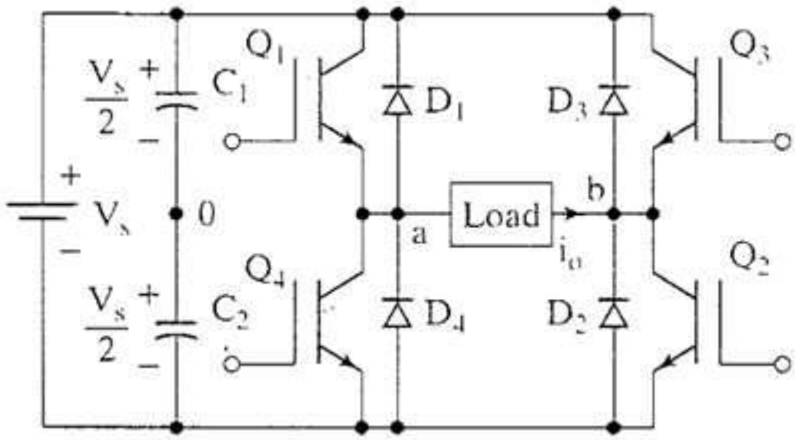


Figure: 5.6 SinglephaseFullBridgeDC-ACinverterwithR load

WhentheswitchesS1andS2areturnedonsimultaneouslyforaduration0≤t≤T1,ththeinput voltageVinappearsacrosstheloadandthecurrentflowsfrompointatob.

Q1–Q2ON,Q3–Q4OFF==>vo=Vs

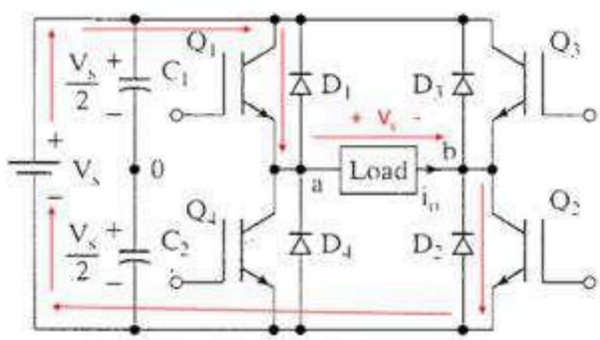


Figure: 5.7 SinglephaseFullBridgeDC-ACinverterwithR load

IftheswitchesS3andS4turnedondurationT1≤ t≤T2,thevoltageacrosstheloadtheloadisreversed andthecurrentthroughtheloadflowsfrompointbtoa.Q1–
Q2OFF,Q3–Q4ON==>vo=-Vs

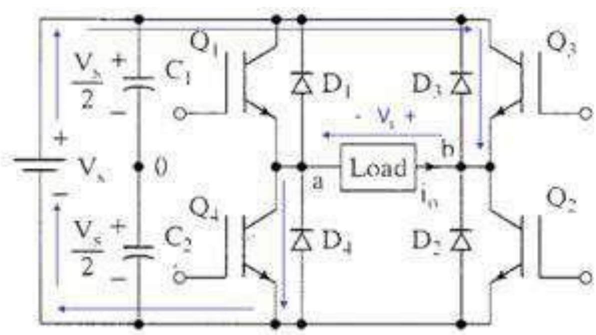


Figure:5.8 SinglephaseFullBridgeDC-ACinverterwithRloadcurrentdirections

ThevoltageandcurrentwaveformsacrosstheresistiveloadareshowninFigurebelow

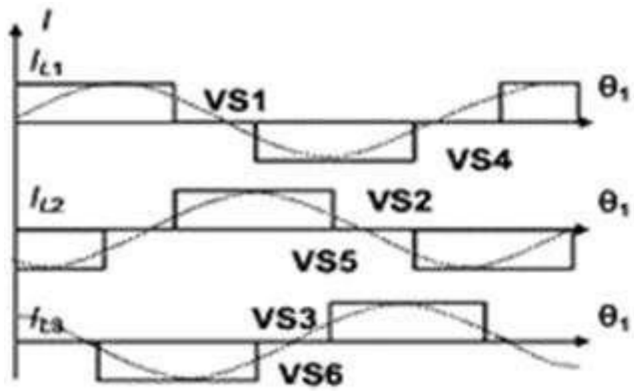


Figure: 5.9SinglephaseFullBridgeDC-ACinverterwaveforms

SinglePhaseFullBridgeInverterforR-L load:

A single-phase square wave type voltage source inverter produces square shaped output voltage for asingle-phase load. Such inverters have very simple control logic and the power switches need to operateat much lower frequencies compared to switches in some other types of inverters.The first generationinverters, using thyristor switches, were almost invariably square wave inverters because thyristorswitches could be switched on and off only a few hundred times in a second. In contrast, the present dayswitches like IGBTs are much faster and used at switching frequencies of several kilohertz. Single-phaseinvertersmostlyusehalfbridgeorfullbridgetopologies.Powercircuits ofthesetopologies areshown ininFigurebelow.

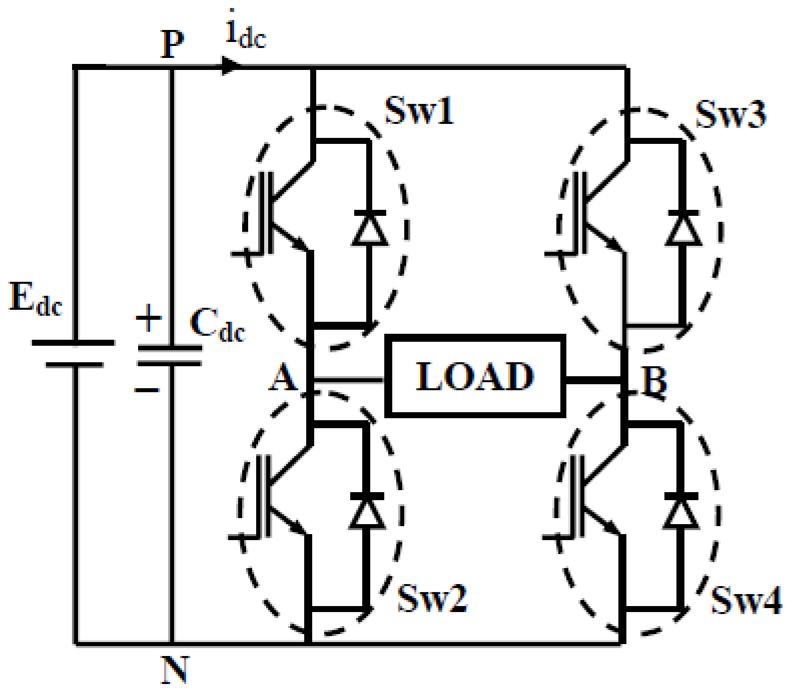


Figure: 5.10 SinglephaseFullBridgeDC-ACinverterwithLload

The above topology is analyzed under the assumption of ideal circuit conditions. Accordingly, it isassumed that the input dc voltage (Edc) is constant and the switches are lossless. In full bridge topologyhas two such legs. Each leg of the inverter consists of two series connected electronic switches shownwithin dotted lines in the figures. Each of these switchesconsists of an IGBT type controlled switchacrosswhichanuncontrolleddiodeisputinanti-parallelmanner.Theseswitchesarecapableofconducting bi-directional current but they need to block only one polarity ofvoltage.The junction pointoftheswitchesineachlegoftheinverterservesasone outputpointfortheload.

Seriesinverter:

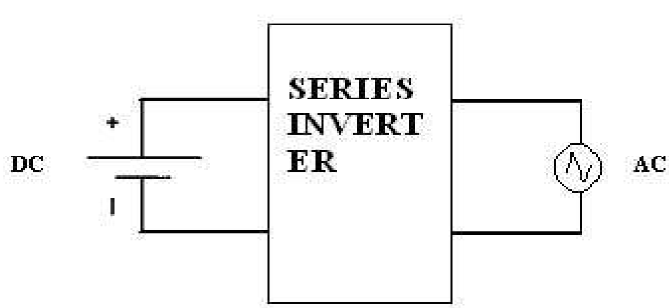


Figure: 5.11Blockdiagramof seriesinverter

In seriesinverter,the commutatingelementsL andCare connectedinserieswiththe load.Thisconstitutes aseriesRLCresonantcircuit.TheTwo SCRs are used to producethehalves(positiveandnegativehalfcycle)intheoutput.

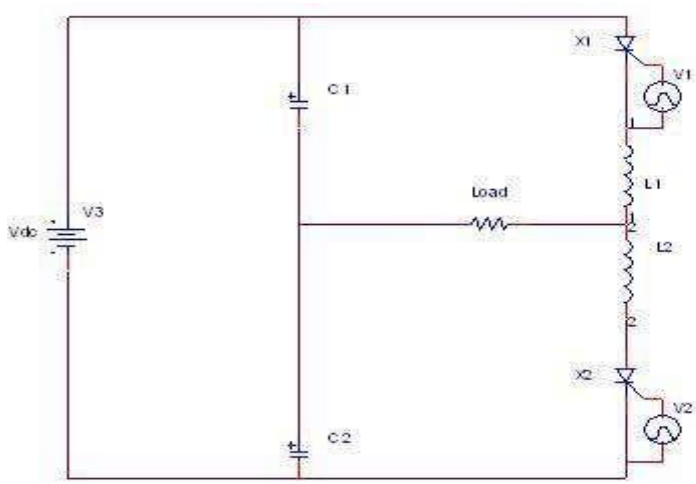


Figure:5.12 Circuitdiagramof seriesinverter

In the firsthalfof the outputcurrents whenSCR T1 is triggered itwillallow the currentto flowthroughL1,andload, andC2thuscharging.The capacitorC1whichisalreadychargedattheseinstantdischargesthrough SCR1,L1 and theLoad.Hence50%ofthecurrentisdrawnfrom theinputsourceand50%fromthecapacitor.SimilarlyinthesecondhalfoftheoutputcurrentC1willbechargedand C2willdischargethroughtheload,L2and SCR**2**,Again50%oftheloadcurrentisobtainedfromtheDCinputsourceandrestfromthecapacitor.The SCRsT1andT2arealternativelyfiredtogetACvoltageandcurrent.

Operationofparallelinverter

The singlephaseparallelinvertercircuitconsistsoftwo SCRsT1andT2,aninductorL,anoutputtransformerand acommutating capacitor C. The outputvoltage and currentare Vo and Iorespectively. The function of Lis to make the source currentconstant. During the working of thisinverter, capacitor C comes in**parallel**with the load via the transformer. So it is calleda**parallelinverter**.

Theoperationofthisinvertercanbeexplainedinthefollowingmodes.

ModeI

Inthismode, SCR T1isconductingand a current flow in the upper half of primarywinding. SCR T2isOFF.As aresult anemfVsisinducedacross upperaswellaslowerhalfoftheprimarywinding.

Inotherwordstotalvoltageacrossprimarywindingis2Vs.NowthecapacitorCchargestoavoltageof2Vswithupperplateaspositive.

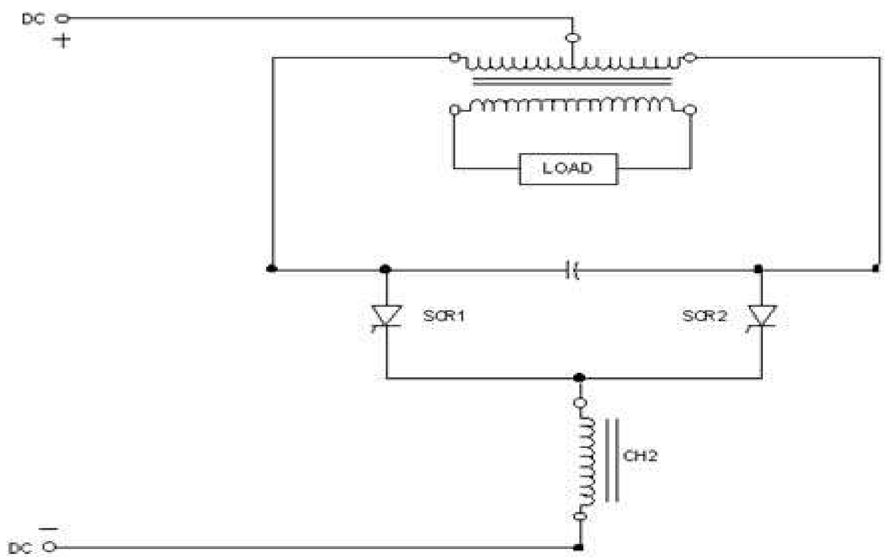


Figure:5.13Circuit diagramof parallelinverter

ModeII

Attimeto,T2isturnedONbyapplyingatriggerpulsetoitsgate.Atthistimet=0,capacitorvoltage2Vsappearsasareversebiasacross T1,itisthereforeturnedOFF.AcurrentIobeginstoflowthroughT2andlowerhalfofprimarywinding.Nowthecapacitorhascharged(upperplateasnegative)from+2Vsto-2Vsattimet=t1.LoadvoltagealsochangesfromVsatt=0to–Vsatt=t1.

ModeIII

Whencapacitorhaschargedto–Vs,T1maybetunedONatanytimeWhenT1istriggered,capacitorvoltage2Vsappliesareversebiasacross T2,itisthereforeturnedOFF.AfterT2isOFF,capacitorstartsdischarging,andchargedtotheoppositedirection,theupperplateaspositive.

ParalleledCommutatedInverter

Fig 1: is a schematic of the classical parallel commutated square wave inverterbridge.It is beingincludedhereforillustrativepurposessincemostothercircuitsutilizethiscircuitoravariationthereof.Thewaveformgeneratedandsuppliedtotheloadisbasicallyasquarewavehavingapeaktopeakamplitudeoftwicethe DCsupplyvoltageandaperiodthatisdeterminedbytherelateatwhich SCRs1through4aregatedon.The SCRsareturnedoninpairsbysimultaneouslyapplyingsignalstothegateterminalsofSCRs1and4orSCRs2and3.If SCRs1and 4happento bethefirst twoswitchedonacurrentwillflowfrom thepositiveterminalofthesourcethroughnegativeterminalofthesource.Thiswillestablishalefttoright,plustominusvoltagerelationshipontheload. Simultaneously,theleftterminalofcapacitorC1willbechargedpositivelywithrespecttotherightnegativeterminal.Thesteady-stateloadcurrentthroughthevariouscomponents isdeterminednearlycompletelybytheimpedanceoftheload.Chokes1and2and SCRs1and4presentverylowsteady-statedrops andthereforenearly all thesourcevoltageappears across theload.Conductionof SCRs1 and4willcontinue tothe endofthe halfcycle,atwhichpointthegatesare removedfrom SCRs1and4remaininconductionalongwith SCRs2and3thathavenowbeenturnedon.Ifitwerenotforchokes1 and2,theactionofturningonthesecondsetof SCRswouldplaceverylowimpedanceandthereforemomentarilypreventthesourcefrombeingshort-circuited. Capacitor C1 now discharges with a current which flows into the cathode ofSCR 1through SCR 2inaforwarddirectionbacktothenegativeterminalofthe capacitor.Thisdirectionofcurrentflowcauses SCR 1tobecome non-conductiveprovidedthat thereversecurrentthroughthe SCR isofsufficientdurationforthe SCR toagainbecomeblocking.C1simultaneouslydischargesthroughSCR 3inaforwarddirectionandthrough SCR 4inareversedirection.Thiswillcause SCR 4tobecomenon-conductivejustthesame SCR 1.Thisentiresequenceisreferredtoascommutationandtypicallyinamoderninverterwouldoccurina periodoftimelessthan50microseconds.Duringthisinterval,chokes1and2musthavesufficienttransientimpedan cetopreventasignificantincreaseincurrentfromtheDCsource.

Diodes1,2,3and4servetwofunctions.Thefirstistoreturnanystoredenergythatmaybe"kickedback"fromtheload tothesource.Theyalsoservetopreventthechokefromgeneratingahightransientvoltageimmediatelyaftercomm utation.

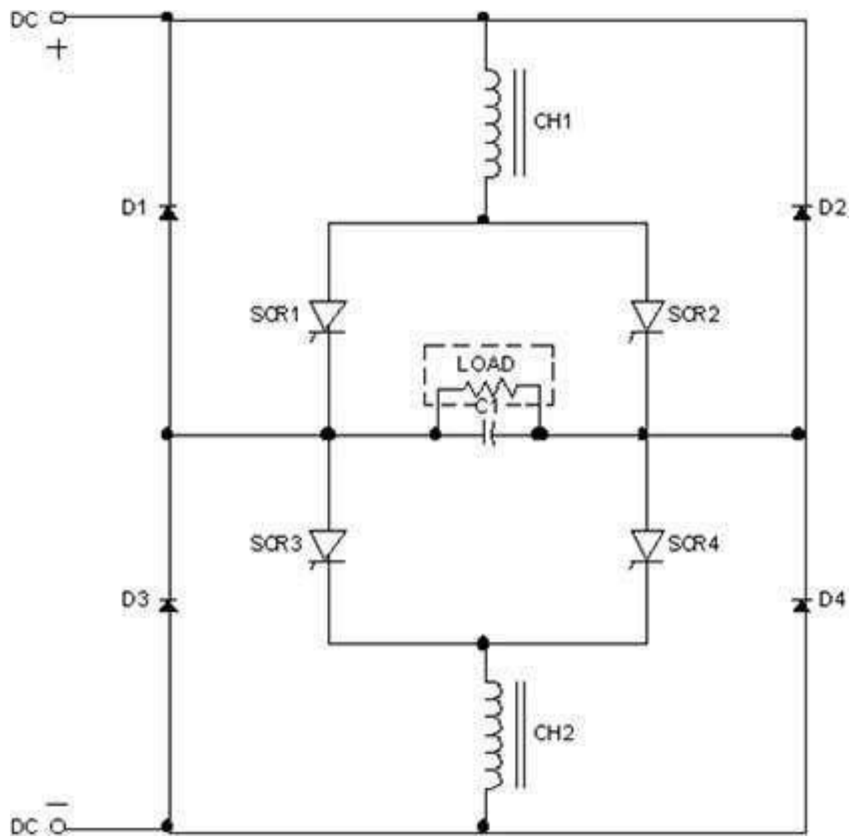


Figure:5.14Circuitdiagramof parallelcommutated inverter

Three PhaseDC-ACConverters

Three phase inverters are normally used for high power applications. The advantages of a three phaseinverterare:

• Thefrequencyoftheoutputvoltagewaveformdependsontheswitchingrateoftheswtichesandhence canbevaried overawiderange.

• Thedirectionofrotationofthemotorcanbereversedbychangingtheoutputphasesequenceoftheinverter.

• Theac outputvoltagecanbecontrolledbyvaryingthedc linkvoltage.

The general configuration of a three phase DC-AC inverter is shown in **Figure** Two types of controlsignalscanbeappliedtotheswitches:

• 180°conduction

• 120°conduction

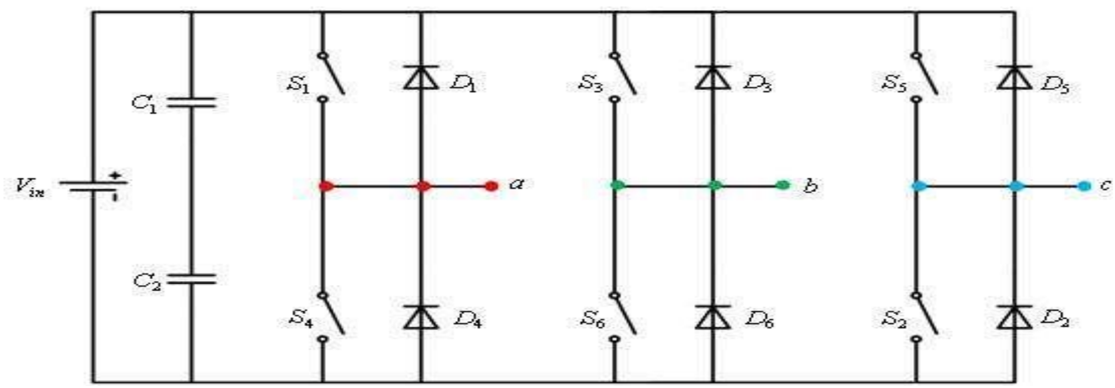


Figure:5.15Circuitdiagramofthreephasebridgeinverter

180-DegreeConductionwithStarConnectedResistiveLoad

The configuration of the three phase inverter with star connected resistive load is shown in **Figure.** Thefollowingconventionisfollowed:

- •Acurrentleavinganodepoint***a***,***b*** or***c***andenteringtheneutralpoint***n***is assumedtobepositive.

• Allthethreeresistancesareequal, $R_a = R_b = R_c = R$.

Inthismodeofoperationeachswitchconductsfor180°.Hence,atanyinstantoftime ***threeswitches*** remain ***on*** . When S_1 is ***on*** , the terminal ***a*** gets connected to the positive terminal of input DCsource. Similarly, when S_4 is ***on*** , terminal ***a*** gets connected to the negative terminal of input DC source.There are six possible modes of operation in a cycle and each mode is of 60° duration and the explanationofeachmode isasfollows:

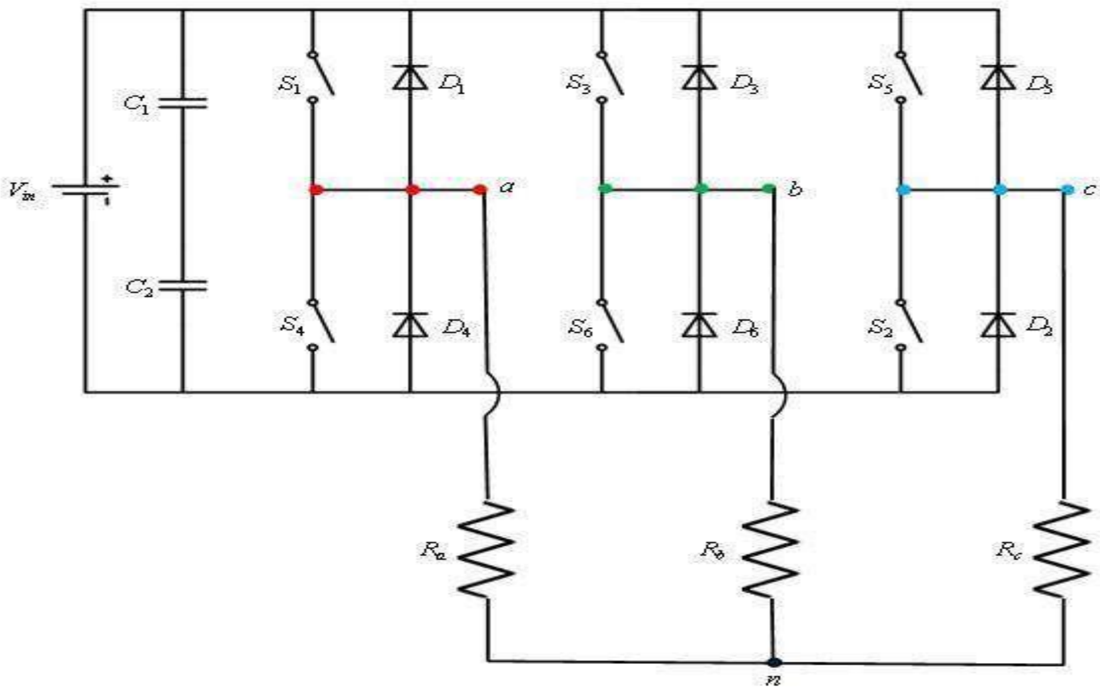


Figure:5.16Circuitdiagramofthreephasebridgeinverterwithstarconnectedload

Mode1: Inthismodetheswitches S_5, S_6 and S_1 areturned ***on*** fortimeinterval $0 \leq \omega t \leq \frac{\pi}{3}$ .Asaresult ofthisthe terminals ***a*** and ***c*** are connected to the positive terminal ofthe inputDCsource and theterminal ***b*** is connected to the negative terminal of the DC source. The current flowthrough R_a, R_b and R_c is shown in Figure and the equivalent circuit is shown in Figure**.** The equivalentresistanceof the circuitshownin***Figure***is

$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2} \tag{1}$$

Thecurrent *i* deliveredbytheDCinputsourceis

$$i = \frac{V_{in}}{R_{eq}} = \frac{2}{3}\frac{V_{in}}{R} \tag{2}$$

Thecurrents i_a and i_b are

$$i_a = i_c = \frac{1}{3}\frac{V_{in}}{R} \tag{3}$$

Keepingthecurrentconventioninmind,thecurrent$i_b$is

$$i_b = -i = -\frac{2}{3}\frac{V_{in}}{R} \tag{4}$$

Havingdeterminedthecurrents through eachbranch,thevoltageacrosseachbranchis

$$v_{an} = v_{cn} = i_a R = \frac{V_{in}}{3};\ v_{bn} = i_b R = -\frac{2V_{in}}{3} \tag{5}$$

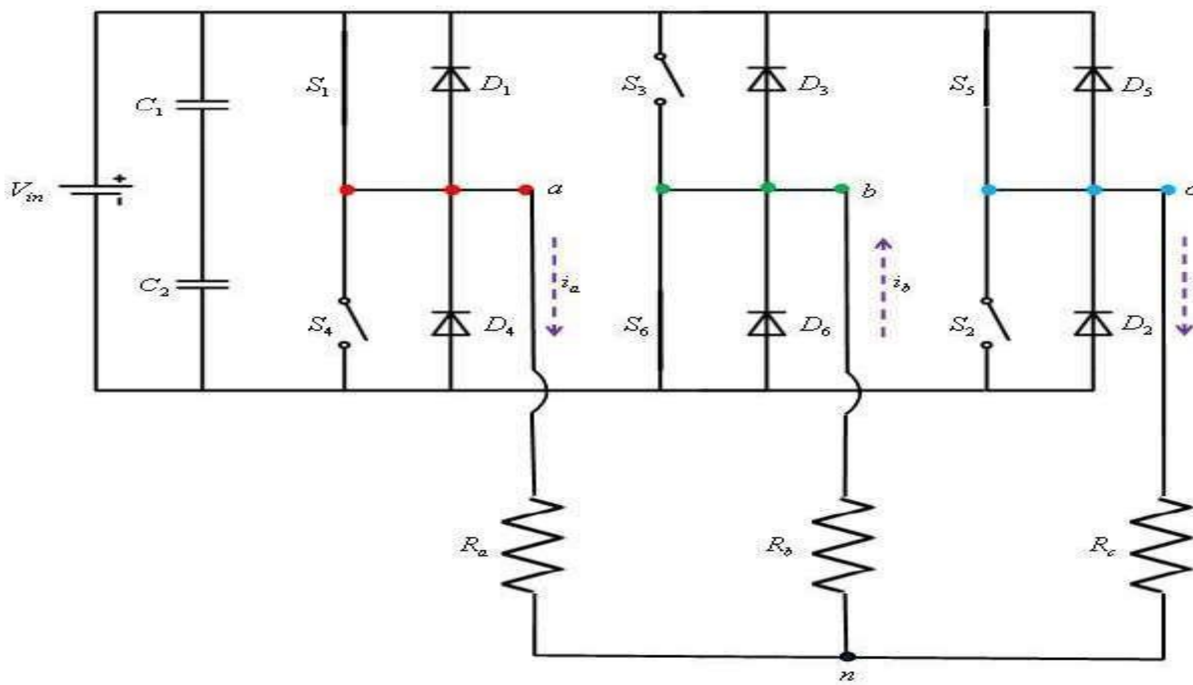


Figure:5.17Mode 1operationof threephasebridgeinverter withstarconnectedload

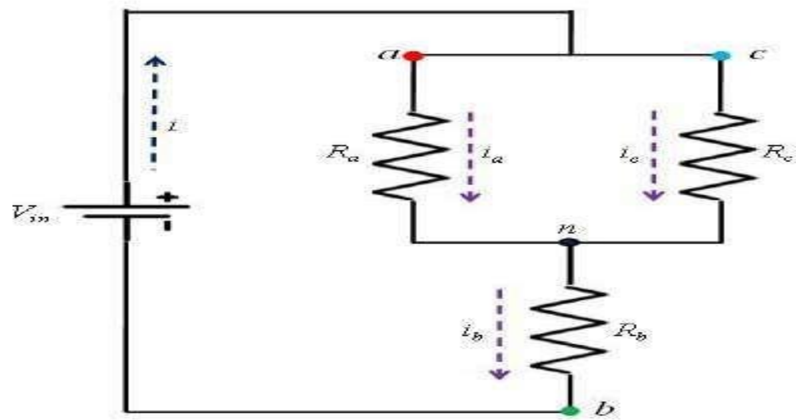


Figure:5.18 Currentflow inMode1operation

Mode2: InthismodetheswitchesS_6,S_1andS_2 areturned***on***fortimeinterval $\frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3}$ .Thecurrentflowandtheequivalentcircuitsareshownin**Figure**and**Figure**respectively.Followingthe reasoning givenfor***mode1*** ,thecurrentsthrougheachbranchandthevoltagedropsaregivenby

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\ i_a = -\frac{2}{3}\frac{V_{in}}{R} \tag{6}$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\ v_{an} = -\frac{2V_{in}}{3} \tag{7}$$

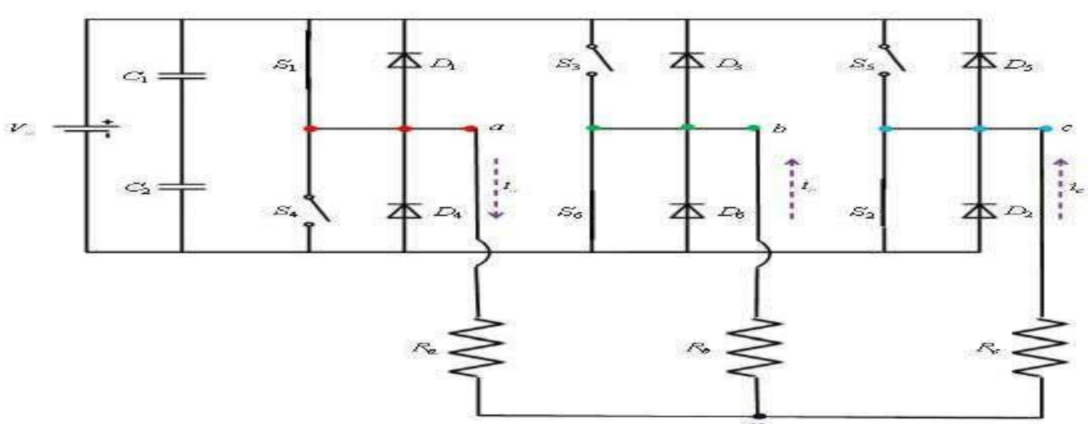


Figure:5.19Mode 2operationof threephasebridgeinverter withstarconnectedload

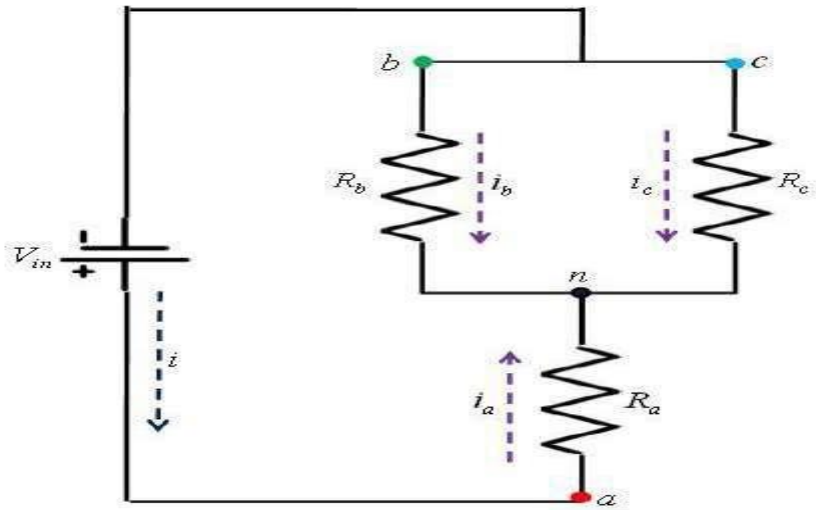


Figure:5.20 Currentflow inMode2operation

Mode3: InthismodetheswitchesS$_1$,S$_2$andS$_3$are***on***for $\frac{2\pi}{3} \le \omega t \le \pi$ .Thecurrentflowandtheequivalentcircuitsareshownin**Figure**and**figure**respectively.Themagnitudesofcurrents andvoltages

are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R} \tag{8}$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3} \tag{9}$$

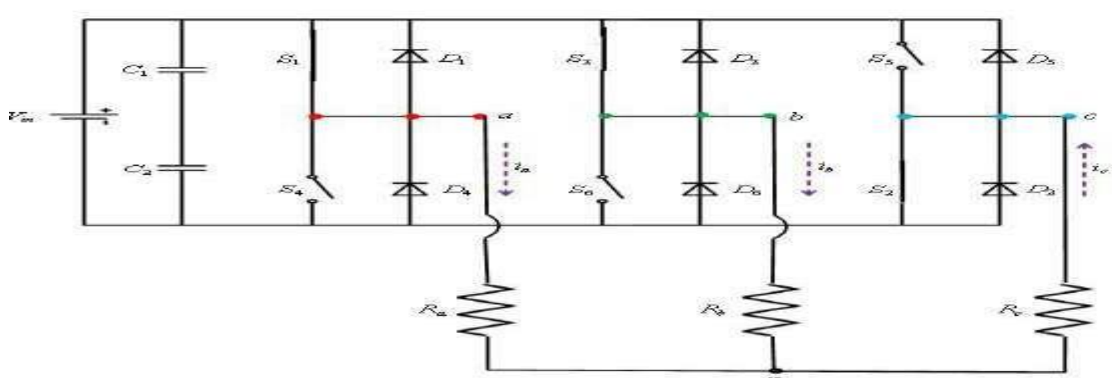


Figure:5.21Mode 3operationof threephasebridgeinverter withstarconnectedload

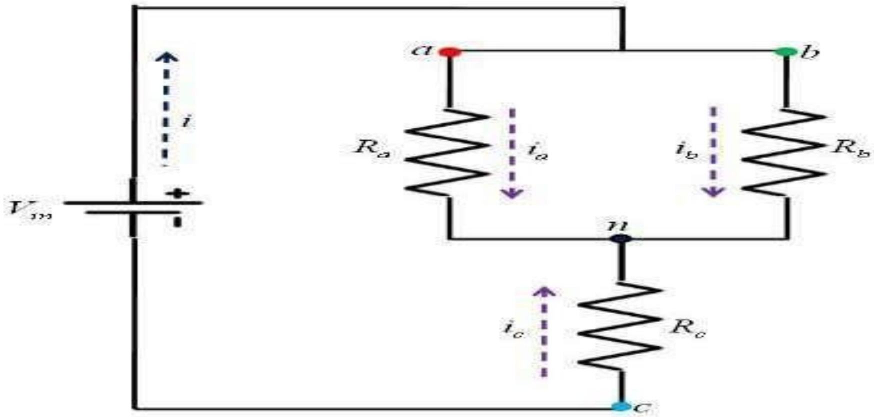


Figure:5.23 Currentflow inMode3operation

Formodes4,5 *and*6theequivalentcircuitswillbesameasmodes1,2*and* 3respectively.Thevoltagesandcurrentsforeachmodeare:

$$\left.\begin{aligned} i_a = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} = -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{formode4} \qquad (10)$$

$$\left.\begin{aligned} i_b = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} = -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{formode5} \qquad (11)$$

$$\left.\begin{aligned} i_a = i_b = -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} = -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{formode6} \qquad (12)$$

Theplotsofthephasevoltages(v_{an},v_{bn}andv_{cn})andthecurrents(i_a, $i_b$andi_c)areshowninFigureHavingknownthephasevoltages,the linevoltagescanalsobedeterminedas:

$$v_{ab} = v_{an} - v_{bn}$$
$$v_{bc} = v_{bn} - v_{cn}$$
$$v_{ca} = v_{cn} - v_{an} \qquad (13)$$

Theplotsoflinevoltagesarealsoshownin **Figure**andthephaseandlinevoltagescanbeexpressedintermsof Fourierseriesas:

$$v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin(n\omega t)$$
$$v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{2n\pi}{3}\right)$$
$$v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1 + \sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{4n\pi}{3}\right) \qquad (14)$$

$$v_{ab} = v_{an} - v_{bn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t + \frac{n\pi}{6}\right)$$
$$v_{bc} = v_{bn} - v_{cn} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{n\pi}{2}\right)$$
$$v_{ca} = v_{cn} - v_{an} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{7n\pi}{6}\right) \qquad (15)$$

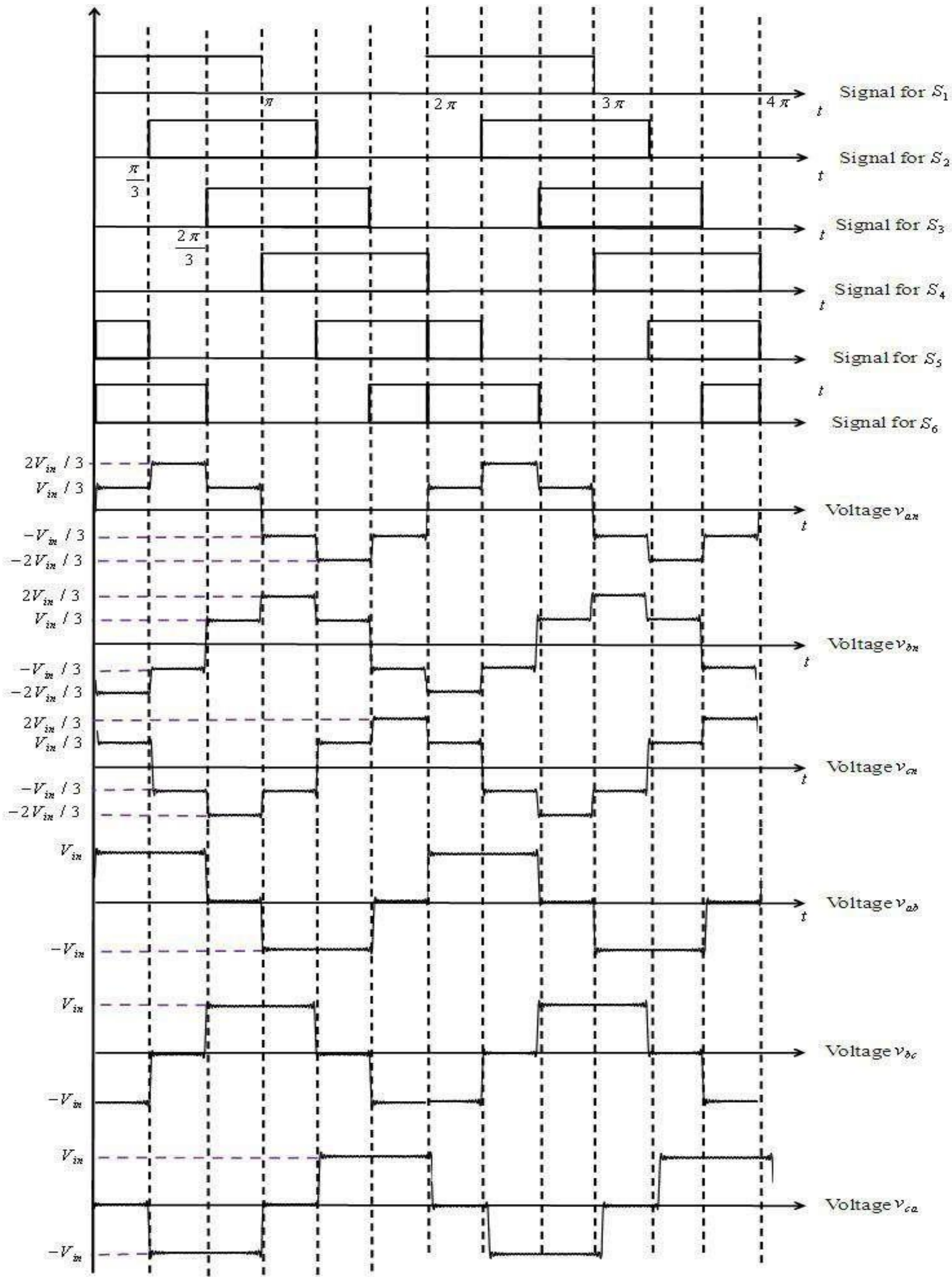


Figure: 5.24Lineandphasevoltagesof threephasebridgeinverter

ThreePhaseDC-ACConverterswith120degreeconductionmode

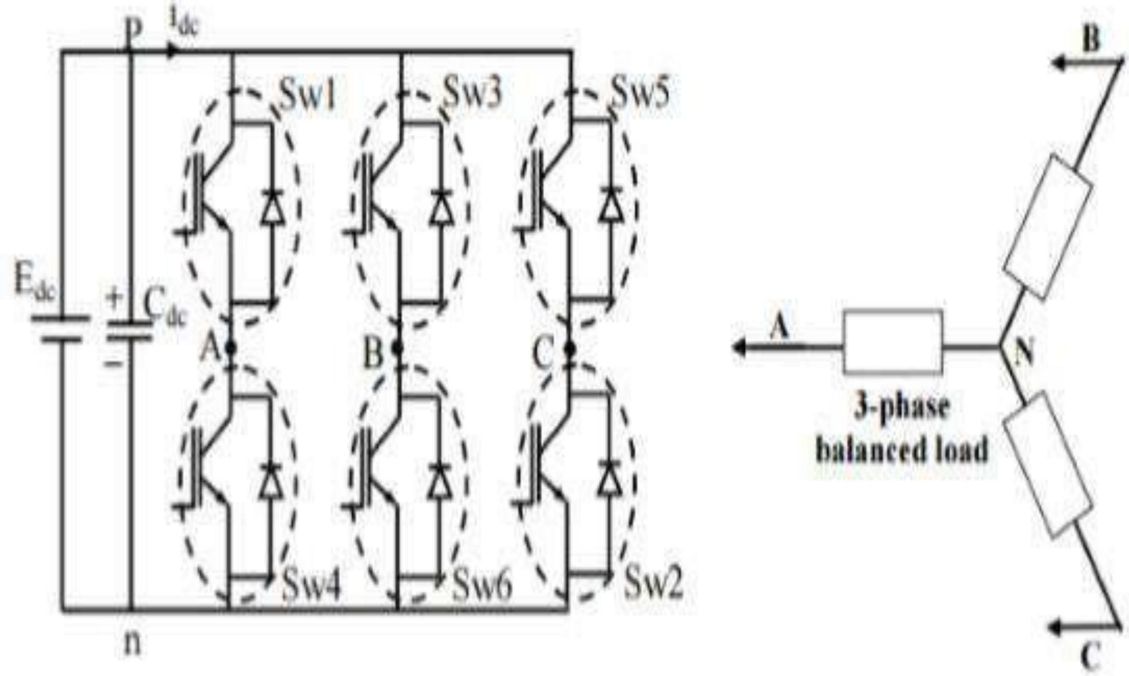


Figure:5.25Circuitdiagramofthreephasebridgeinverter

120°modeofconduction

Inthismodeofconduction,eachelectronicdeviceisinaconductionstatefor120°.Itismostsuitablefor a delta connection in a load because it results in a six-step type of waveform across any of its phases.Therefore,atanyinstantonlytwodevicesareconductingbecauseeachdeviceconductsatonly120°.

The terminal A on the load is connected to the positive end while the terminal B is connected to thenegativeendofthesource.TheterminalContheloadisinaconditioncalledfloatingstate.Furthermore,thephas evoltagesareequaltothe loadvoltagesasshownbelow.

Phasevoltages=LinevoltagesV

$_{AB}$ =V

V_{BC}=−V/2

V_{CA}= −V/2

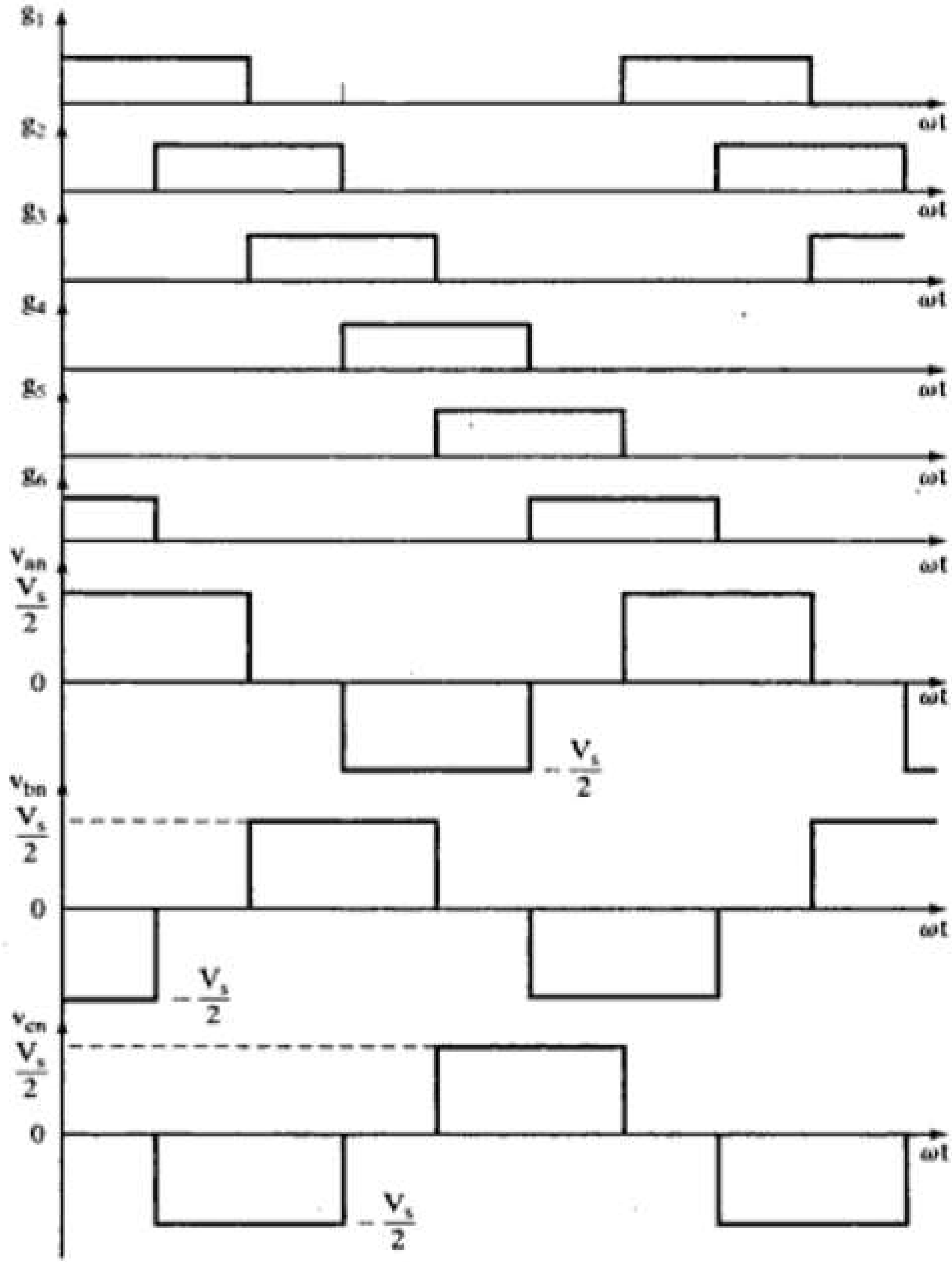


Figure: 5.26Lineandphasevoltagesof threephasebridge inverter

Voltagecontroltechniquesforinverters

Pulsewidthmodulationtechniques

PWM is a technique thatis used to reduce the overall harmonic distortion (THD)in aload current.Ituses a pulse wave in rectangular/square form that results in a variable average waveform value f(t), afterits pulse width has been modulated. The time period for modulation is given by T. Therefore, waveformaveragevalueisgivenby

$$y= \frac{1}{T_0}\int^{T} f(t)dt$$

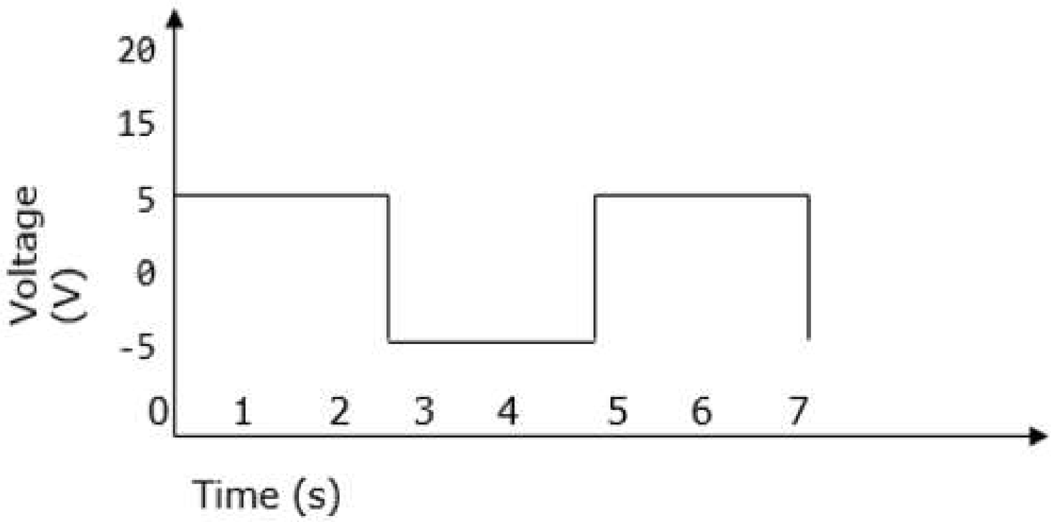


Figure: 5.27Squarewaveformusedfor PWMtechnique

SinusoidalPulseWidthModulation

In a simple source voltage inverter, the switches can be turned ON and OFF as needed. During eachcycle, the switch is turned on or off once. This results in a square waveform. However, if the switch isturnedonforanumberoftimes,aharmonicprofilethatisimprovedwaveformis obtained.

The sinusoidal PWM waveform is obtained by comparing the desired modulated waveform with atriangular waveform of high frequency. Regardless of whether the voltage of the signal is smaller orlarger than that of the carrier waveform, the resulting output voltage of the DC bus is either negative orpositive.

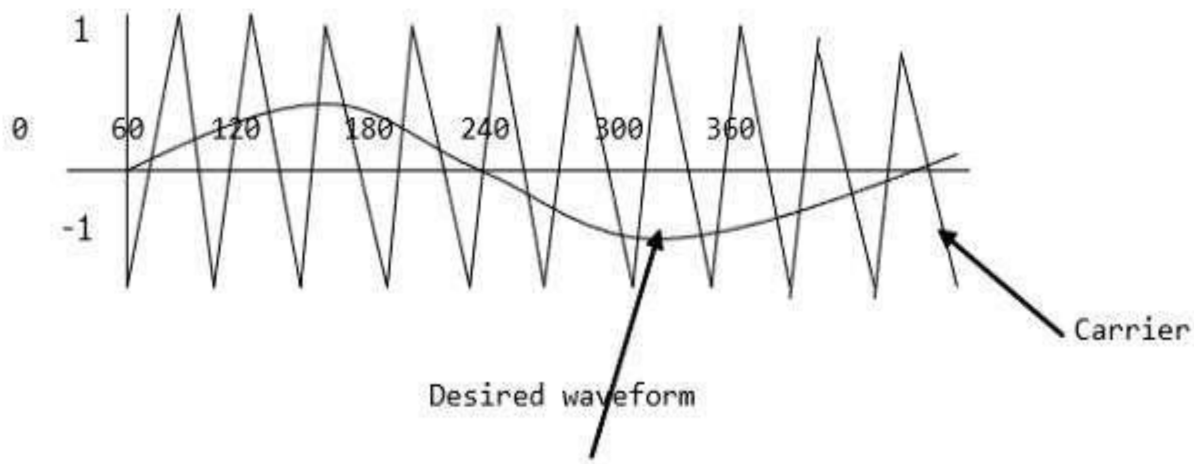


Figure:5.28Sinusoidal PWMwaveform

The sinusoidal amplitude is given as A_m and that of the carrier triangle is give as A_c. For sinusoidal PWM,themodulatingindexmisgivenbyA_m/A_c.

ModifiedSinusoidalWaveformPWM

A modified sinusoidal PWM waveform is used for power control and optimization of the power factor.The main concept is to shift current delayed on the grid to the voltage grid by modifying the PWMconverter. Consequently, there is an improvement in the efficiency of power as well as optimization inpowerfactor.

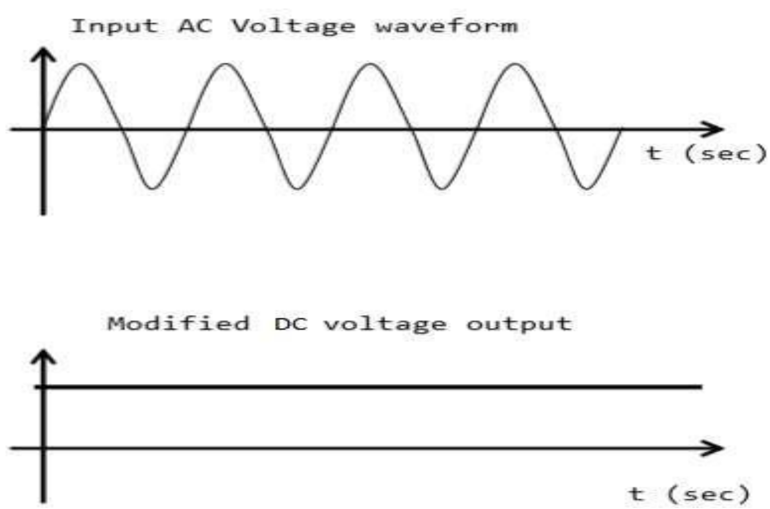


Figure:5.29ModifiedsinusoidalPWMwaveform

MultiplePWM

The multiple PWM has numerous outputs that are not the same in value but the time period over whichthey are produced is constant for all outputs. Inverters with PWM are able to operate at high voltageoutput.

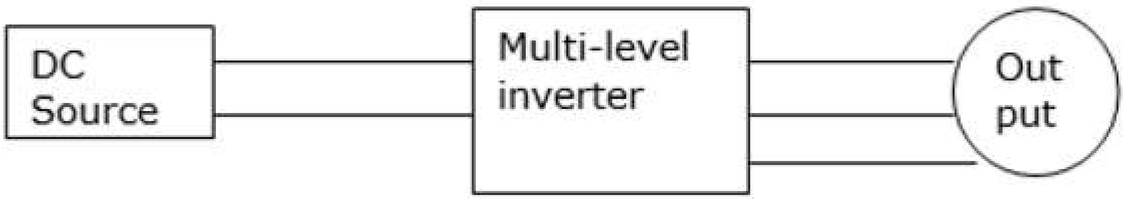


Figure:5.30Blockdiagramof multiplePWMtechnique

Thewaveformbelowis asinusoidalwaveproducedbyamultiplePWM

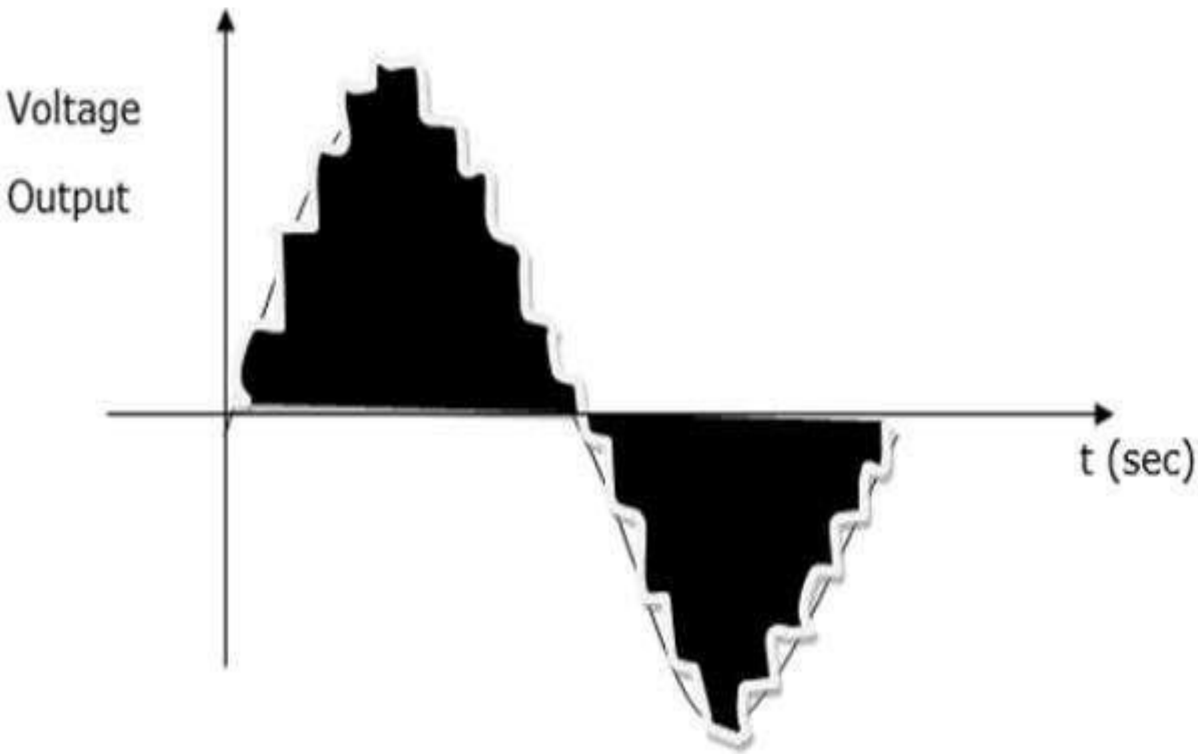


Figure:5.31Waveformof multiplePWMtechnique

VoltageandHarmonicControl

A periodic waveform that has frequency, which is a multiple integral of the fundamental power withfrequency of 60Hz is known as a harmonic. Total harmonic distortion (THD) on the other hand refers tothetotalcontributionofallthe harmoniccurrentfrequencies.

Harmonicsarecharacterizedbythepulsethatrepresentsthenumberofrectifiersusedinagivencircuit. Itiscalculatedasfollowsh

=(n×P)+1or−1

Where**n**− is aninteger1,2,3,4….n

P−Numberofrectifiers

Harmonicshaveanimpactonthevoltageandcurrentoutputandcanbereducedusingisolationtransformers,linereactors,redesignofpowersystemsandharmonicfilters.

Operationofsinusoidalpulsewidthmodulation

The sinusoidal PWM (SPWM) method also known as the triangulation, sub harmonic, or sub oscillationmethod,is very popularin industrial applications. The SPWM is explained with reference to Figure,whichisthe half-bridgecircuittopologyforasingle-phaseinverter.

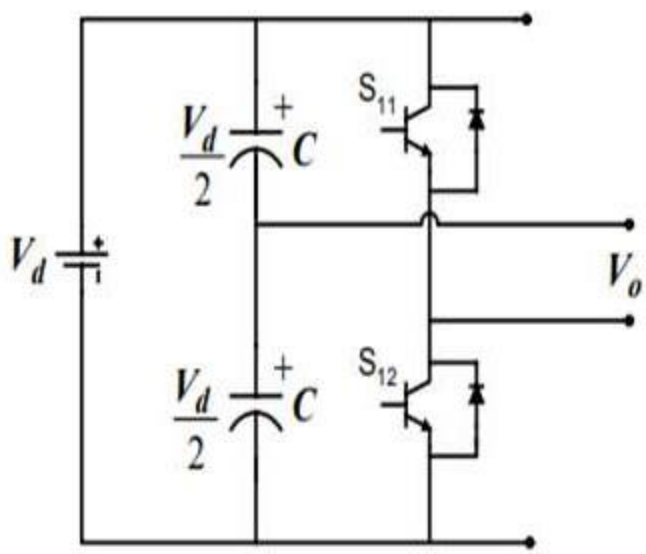


Figure: 5.32 schematicdiagramofHalfbridgePWMinverter

For realizing SPWM, a high-frequency triangular carrier wave is compared with a sinusoidal reference ofthe desired frequency. The intersection of and waves determines the switching instants and commutationof the modulated pulse. The PWM scheme is illustrated in Figure, in which v_c the peak value of triangularcarrier wave and v_r is that of the reference, or modulating signal. The figure shows the triangle andmodulation signalwith some arbitrary frequency andmagnitude.In the inverterof Figure the switchesand are controlled based on the comparison of control signal and the triangular wave which are mixed in acomparator. When sinusoidal wave has magnitude higher than the triangular wave the comparator outputishigh,otherwise itislow.

$$v_r > v_c \qquad S_{11} \text{ is on}, \ V_{out} = \frac{V_d}{2}$$

and

$$v_r < v_c \qquad S_{12} \text{ is on}, \ V_{out} = -\frac{V_d}{2}$$

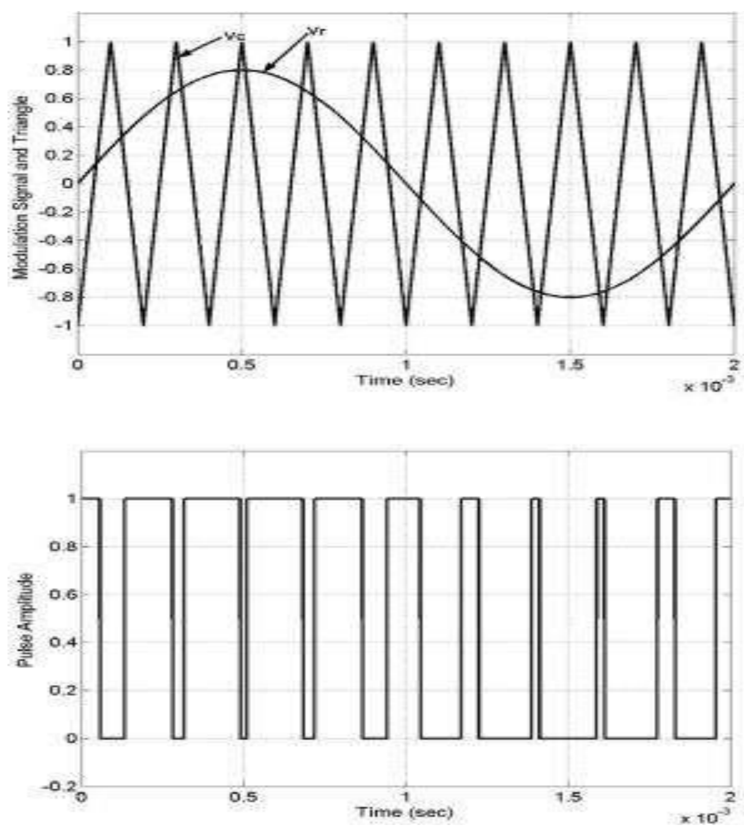


Figure:5.33 Sine-TriangleComparisonandswitchingpulsesofhalf bridgePWMinverter

The comparator output is processes in a trigger pulse generator in such a manner that the output voltagewaveofthe inverterhas apulse width in agreementwith the comparatoroutput pulsewidth.Themagnitude ratio of V_r/V_C is called the modulation index (MI) and it controls the harmonic content of theoutput voltage waveform. The magnitude of fundamental component of output voltage is proportional toMI . The amplitude of the triangular wave is generally kept constant. The frequency modulation ratio isdefinedas

$$M_{F}=\frac{fr}{fm}$$

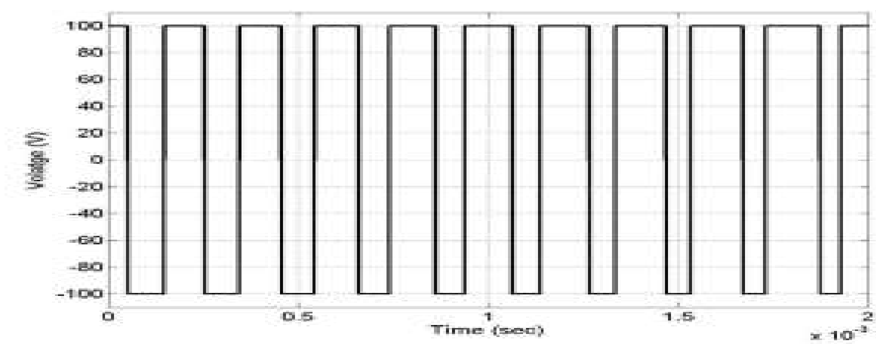


Figure:5.34OutputvoltageoftheHalf-Bridgeinverter

Operationofcurrentsourceinverterwithidealswitches Single-phaseCurrentSource Inverter

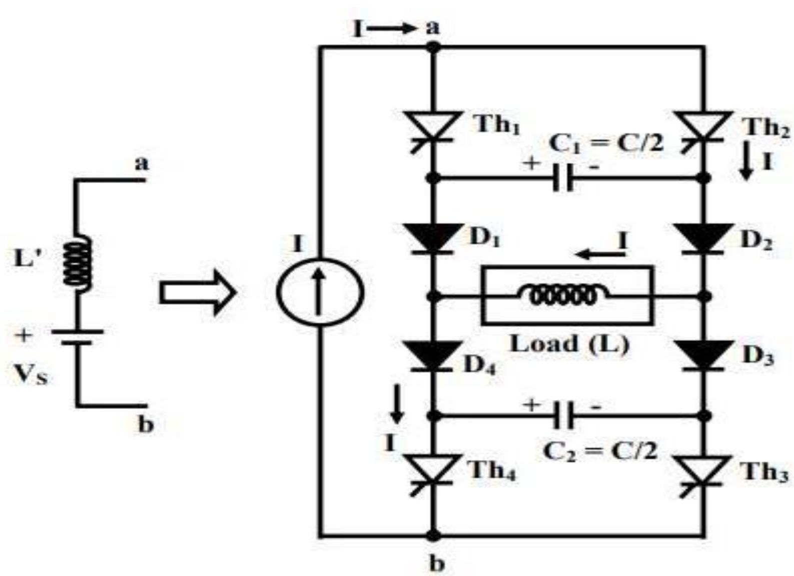


Figure:5.35Singlephasecurrentsourceinverter(CSI)ofASCItype

The circuit of a Single-phase Current Source Inverter (CSI) is shown in Fig. 5.35. The type of operation istermed as Auto-Sequential Commutated Inverter (ASCI). A constant current source is assumed here,which may be realized by using an inductance of suitable value, which must be high, in series with thecurrent limited dc voltage source. The thyristor pairs, Th1 & Th3, and Th2 & Th4, are alternatively turnedON to obtain anearly square wave currentwaveform. Two commutating capacitors − C1 inthe upperhalf, and C2 in the lower half, are used. Four diodes, D1–D4 are connected in series with each thyristor topreventthecommutatingcapacitorsfromdischargingintotheload.Theoutputfrequencyoftheinverteris controlled in the usual way,i.e.,by varying the halftime period,(T/2), at which the thyristors in pairare triggered by pulses being fed to the respective gates by the control circuit, to turn them ON, as can beobserved from the waveforms (Fig. 5.36). The inductance (L) is taken asthe load in this case, thereason(s)forwhich need notbestated,being wellknown.Theoperationis explainedbytwo modes.

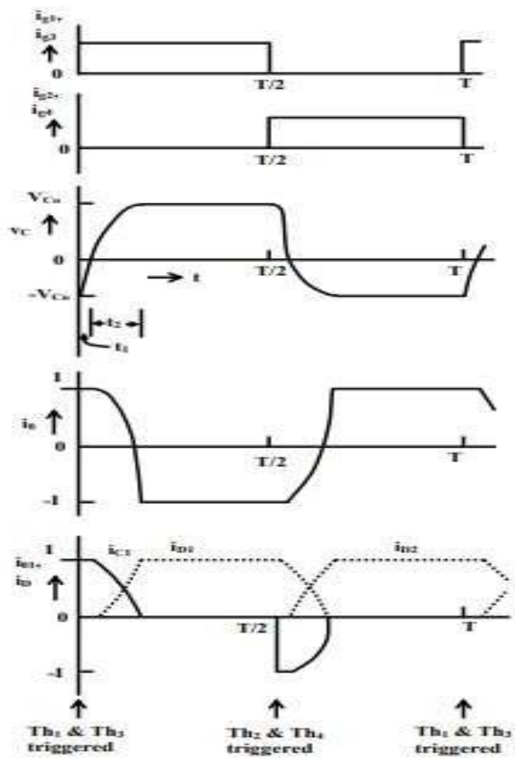


Figure:5.36outputwaveformsofSinglephasecurrentsource inverter

Mode I: The circuit for this mode is shown in Fig. 5.37. The following are the assumptions. Starting fromthe instant, , the thyristor pair, Th − t = 0 2 & Th4, is conducting (ON), and the current (I) flows throughthe path, Th2, D2, load (L), D4, Th4, and source, I. The commutating capacitors are initially chargedequally with the polarity as given, i.e., . This mans that both capacitors have right hand plate positive andlefthandplatenegative.Iftwocapacitorsarenotchargedinitially,theyhavetopre-charge.

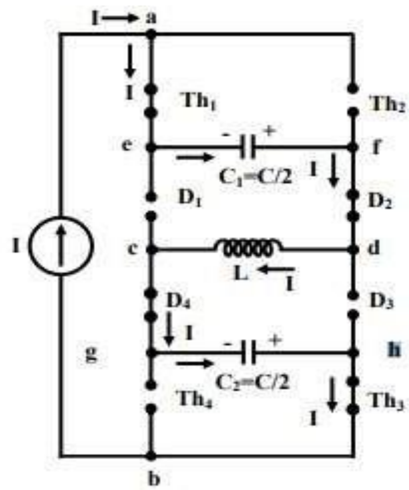


Figure: 5.37ModeIoperation of CSI

ModeII: Thecircuitforthismodeisshowninthe Fig.5.38.Diodes,D2&D4,arealreadyconducting,butat = tt 1 , diodes, D1 & D3, get forward biased, and start conducting. Thus, at the end of time t1, all fourdiodes, D1–D4 conduct. As a result, the commutating capacitors now get connected in parallel with theload(L).

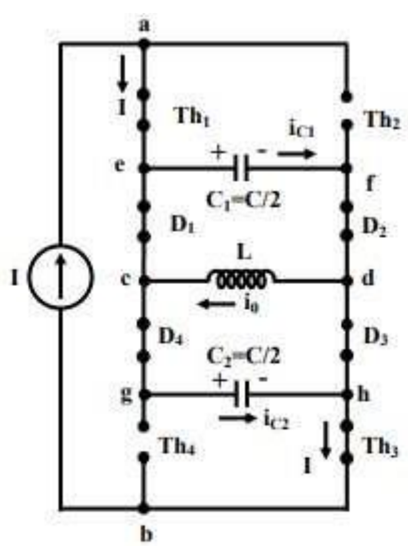


Figure:5.38ModeIIoperationof CSI

LoadCommutatedCSI

Two commutating capacitors, along with four diodes, are used in the circuit for commutation from onepair of thyristors to the second pair. Earlier, also in VSI, if the load is capacitive, it was shown that forcedcommutation may not be needed. The operation of a single-phase CSI with capacitive load (Fig. 5.39) isdiscussed here. It may be noted that the capacitor, C is assumed to be in parallel with resistive load (R).The capacitor, C is used for storing the charge, or voltage, to be used to force-commutate the conductingthyristor pair as will be shown. As was the case in the last lesson, a constant current source, or a voltagesourcewithlargeinductance,isusedastheinputtothecircuit.

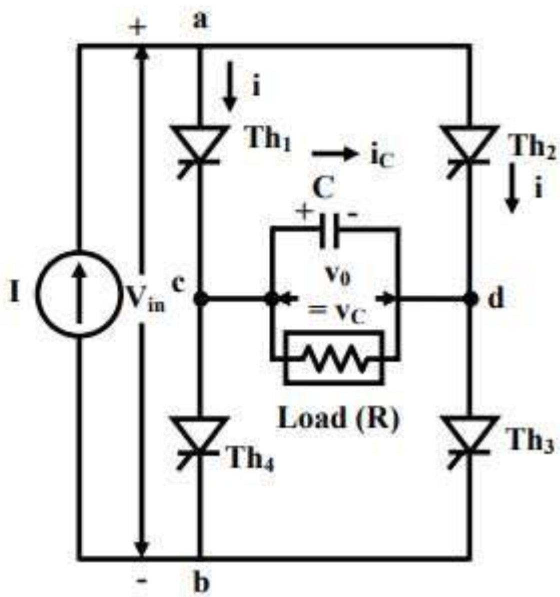


Figure:5.39CircuitdiagramofloadcommutatedCSI

Thepowerswitchingdevicesusedhereisthesame,i.e.fourThyristorsonlyinafull-bridgeconfiguration. The positive direction for load current and voltage is shown in Fig. 5.40 Before t = 0, thecapacitor voltage is , i.e. the capacitor has left plate negative and right plate positive. At that time, thethyristor pair, Th2 & Th4 was conducting. When (at t = 0), the thyristor pair, Th1 & Th3 is triggered bythe pulses fed at the gates, the conducting thyristor pair, Th2 & Th4 is reverse biased by the capacitorvoltageC=−Vv1,andturnsoffimmediately.ThecurrentpathisthroughTh1,load(parallelcombinationofR&C),Th3,andthesource.ThecurrentinthethyristorsisI$_{Ti}$,theoutputcurrentis

Iac=I

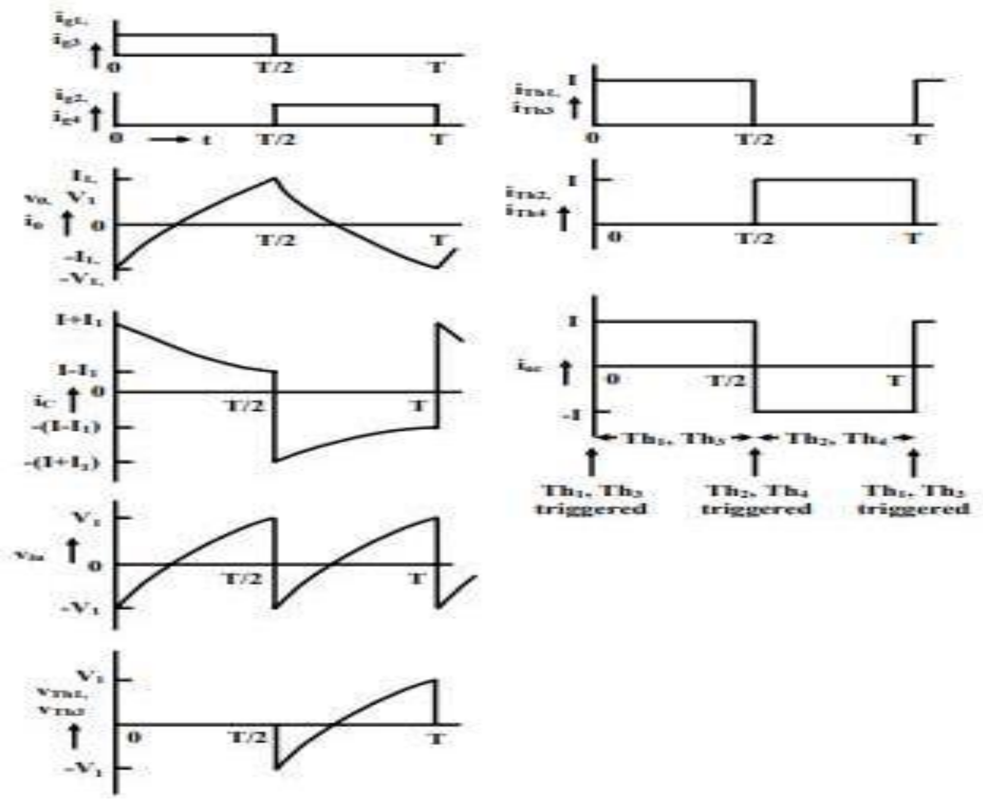


Figure:5.40 VoltageandcurrentwaveformsofloadcommutatedCSI

NumericalProblems

1. Asingle-phasehalfbridgeinverterhasaresis loadof2.4 Wandthed.c.inputvoltageof48V.Determine:-

   (i) RMSoutputvoltageatthefundamentalfrequency

   (ii) OutputpowerP_0

   (iii) Averageandpeakcurrentsofeachtransistor

   (iv) Peakblockingvoltageofeachtransistor.

   (v) Totalharmonicdistortionanddistortionfactor.

   (vi) Harmonicfactoranddistortionfactoratthelowest orderharmonic.

Solution:

(i) RMSoutputvoltageoffundamentalfrequency,E_1 =0.9¥48=43.2 V.

(ii) RMS output voltage, Eorms = E = 48

V.Outputpower=E^2/R = $(48)^2/2.4$ =960W.

(iii) Peaktransistorcurrent=Ip=Ed/R=48/2.4

=20A.Averagetransistorcurrent=Ip/2=10A.

(iv) Peakreverseblockingvoltage,

VBR = 48 V.

(v) RMS harmonic voltage

$$En = \left[\sum_{n=3,5,7}^{8} E_n^2\right]^{1/2}$$

$$= (E^2_{orms} - E_1{}^2_{rms})^{1/2}$$

$$= [(48)^2 - (43.2)^2]^{1/2}$$

$$= 20.92 \text{ V.}$$

$\therefore$ $$\text{THD} = \frac{20.92}{43.2} = 48.43\%.$$

(vi) $$\text{D.F.} = \frac{\left[\sum_{n=3,5,7}^{\infty}\left(E_n/n^2\right)^2\right]^{1/2}}{0.9}$$

$$= \frac{0.03424}{0.9} = 3.8\%$$

(vii) Lowest order harmonic is the third harmonic. RMS value of third harmonic is

$$E_{3rms} = E_{1rms}/3$$

$\therefore$ $$\text{H.F}_3 = E_{3rms}/E_{1rms} = 33.33\%$$

and $$\text{D.F.}_3 = (E_{3rms}/3^2)/E_{1rms}$$

$$= 1/27 = 3.704\%.$$

2. A single phase full bridge inverter has a resistive load of R = 10 Ω and the input voltage V_{dc} of100 V.Findtheaverageoutputvoltageandrmsoutputvoltageatfundamentalfrequency.
3. A single PWM full bridge inverter feeds an RL load with R=10Ω and L= 10 mH. If the sourcevoltage is 120V, find out the total harmonic distortion in the output voltage and in the loadcurrent.Thewidthofeachpulseis120° andthe outputfrequencyis50Hz.