EE8552 POWER ELECTRONICS

UNIT I POWER SEMI-CONDUCTOR DEVICES

Study of switching devices, SCR, TRIAC, GTO, BJT, MOSFET, IGBT and IGCT- Static characteristics: SCR, MOSFET and IGBT - Triggering and commutation circuit for SCRIntroduction to Driver and snubber circuits.

UNIT II PHASE-CONTROLLED CONVERTERS

2-pulse, 3-pulse and 6-pulseconverters– performance parameters –Effect of source inductance–– Firing Schemes for converter–Dual converters, Applications-light dimmer, Excitation system, Solar PV systems.

UNIT III DC TO DC CONVERTERS

Step-down and step-up chopper-control strategy– Introduction to types of choppers-A, B, C, D and E -Switched mode regulators- Buck, Boost, Buck-Boost regulator, Introduction to Resonant Converters, Applications-Battery operated vehicles.

UNIT IV INVERTERS

Single phase and three phase voltage source inverters (both1200 mode and 1800 mode)– Voltage& harmonic control--PWM techniques: Multiple PWM, Sinusoidal PWM, modified sinusoidal PWM – Introduction to space vector modulation –Current source inverter, Applications-Induction heating, UPS.

UNIT V AC TO AC CONVERTERS

Single phase and Three phase AC voltage controllers–Control strategy- Power Factor Control – Multistage sequence control -single phase and three phase cyclo converters – Introduction to Matrix converters, Applications –welding .

TOTAL : 45 PERIODS

TEXT BOOKS:

1. M.H. Rashid, ‘Power Electronics: Circuits, Devices and Applications’, Pearson Education, Third Edition, New Delhi, 2004.
2. P.S.Bimbra “Power Electronics” Khanna Publishers, third Edition, 2003.
3. Ashfaq Ahmed ‘Power Electronics for Technology’, Pearson Education, Indian reprint, 2003.

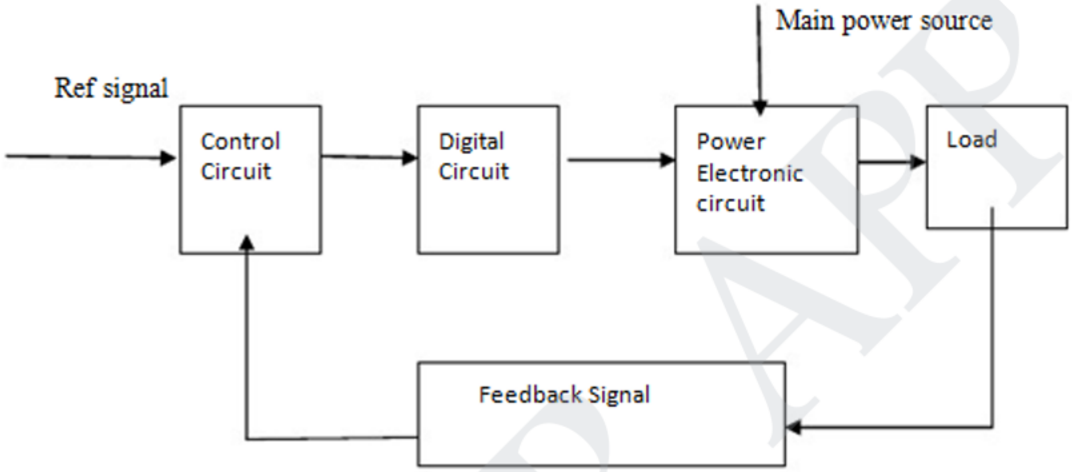
REFERENCES

1. Joseph Vithayathil,’ Power Electronics, Principles and Applications’, McGraw Hill Series, 6th Reprint, 2013.
2. Philip T. Krein, “Elements of Power Electronics” Oxford University Press, 2004 Edition.
3. L. Umanand, “Power Electronics Essentials and Applications”, Wiley, 2010.
4. Ned Mohan Tore. M. Undel and, William. P. Robbins, ‘Power Electronics: Converters, Applications and Design’, John Wiley and sons, third edition, 2003.
5. S.Rama Reddy, ‘Fundamentals of Power Electronics’, Narosa Publications, 2014.
6. M.D. Singh and K.B. Khanchandani, “Power Electronics,” Mc Graw Hill India, 2013.
7. JP Agarwal,” Power Electronic Systems: Theory and Design” 1e, Pearson Education, 2002.

UNIT I
POWER SEMI-CONDUCTOR DEVICES

1.1INTRODUCTION TO POWER ELECTRONICS

The control of electric motor drives requires control of electric power. Power electronics have eased the concept of power control. Power electronics signifies the word power electronics and control or we can say the electronic that deal with power equipment for power control.



Power electronics based on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of power devices have been improved tremendously.

1.2Power Semiconductor Devices

The first SCR was developed in late 1957. Power semiconductor devices are broadly categorized into 3 types:

1. Power diodes
2. Transistors
3. Thyristors

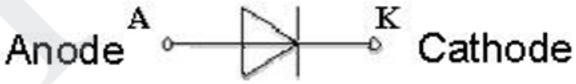
Power diodes

1.3Power diode:

Diode is a two terminal P-N junction semiconductor device, with terminals anode (A) and cathode (C).

Symbol:

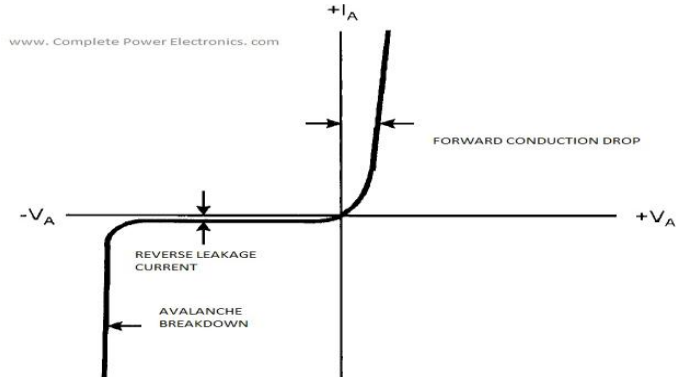
The symbol of the Power diode is same as signal level diode.



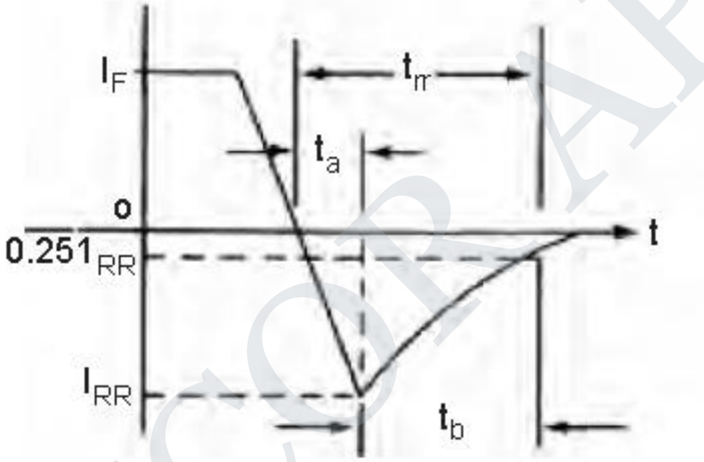
If terminal A experiences a higher potential compared to terminal K, the device is said to be forward biased and a forward current will flow from anode to cathode. This causes a small voltage drop across the device (<1V) called as *forward voltage drop*(V_f), which under ideal conditions is usually ignored. By contrast, when a diode is reverse biased, it does not conduct and the diode then experiences a small current flowing in the reverse direction called the *leakage current*. It is shown below in the VI characteristics of the diode.

The Structure of Power Diode is different from the low power signal diode.

1.3.1Power Diode Characteristics:



The reverse recovery characteristics of the Power diode is shown in the following figure. From the figure, we can understand the turn off characteristic of the diode. The *Reverse recovery time* t_{RR} is the time interval between the application of reverse voltage and the reverse current dropped to 0.25 of I_{RR}.



Parameter t_a is the interval between the zero crossing of the diode current to it reaches I_{RR}. Parameter t_b is the time interval from the maximum reverse recovery current to 0:25 of I_{RR} .

The lower t_{rr} means fast diode switching. The ratio of the two parameters t_a and t_b is known as the *softness factor* SF.

Datasheet Parameters:

For power diodes, a data sheet will give two voltage ratings. One is the repetitive peak inverse voltage (V_{RRM}) and the other is the non repetitive peak inverse voltage. The non repetitive voltage (V_{RM}) is the diode's capability to block a reverse voltage that may occur occasionally due to over voltage surge. The data sheet of a diode normally specifies three different current ratings. They are: (1) Average current; (2) RMS current; and (3) Peak current. A design engineer must ensure that each of these values are never exceeded.

1.3.2 Diode Selection:

A power diode is chosen primarily based on forward current (I_F) and the peak inverse (V_{RRM}) voltage.

1.3.3Diode Protection:

Snubber circuits are essential for diodes used in switching circuits. It can save a diode from overvoltage spikes, which may arise during the reverse recovery process. A very common snubber circuit for a power diode consists of a capacitor and a resistor connected in parallel with the diode

1.3.4Power Diode Applications:

As a rectifier Diode
For Voltage Clamping
As a Voltage Multiplier
As a freewheeling Diode

1.3.5 Types of Power Diode:

Schottky diodes:

These diodes are used where a low forward voltage drop (usually 0.3V) is needed in low output voltage circuits. These diodes are limited in their blocking voltage capabilities to 50 – 100V.

Fast Recovery diodes:

These are used in high frequency circuits in combination with controllable switches where a small reverse recovery time is needed. At power levels of several hundred volts and several hundred amperes, these diodes have t_{rr} ratings of less than a few microsecond.

Line – frequency diodes:

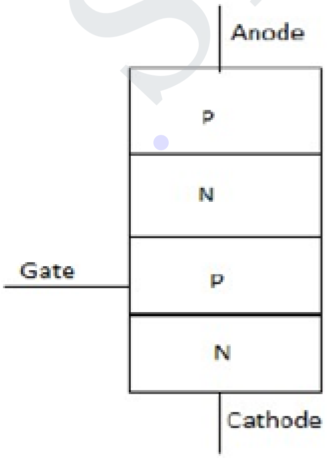
The on state voltage of these diodes is designed to be as low as possible and as a consequence have larger t_{rr}, which are acceptable for line frequency applications. These diodes are available with blocking voltage ratings of several kilovolts and current ratings of several kilo amperes. Moreover, they can be connected in series and parallel to satisfy any voltage and current requirement.

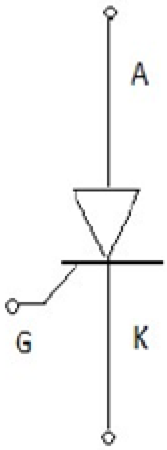
How to test Diode?

We know that fact that resistance of diode in forward biased condition is low and the resistance of diode in reverse biased condition is high. Keep the multimeter in the ohmmeter section. If we measure the resistance of a diode using the connections like red lead to anode and black lead(common) to cathode, a healthy forward biased diode will give low resistance. A high resistance reading in both directions indicates an open(defective device) condition, while a very low resistance reading in both directions will probably indicate a shorted device.

1.4 Thysistor

Thyristor is a four layer three junction pnpn semiconductor switching device. It has 3terminals these are anode, cathode and gate. SCRs are solid state device, so they are compact,possess high reliability and have low loss.

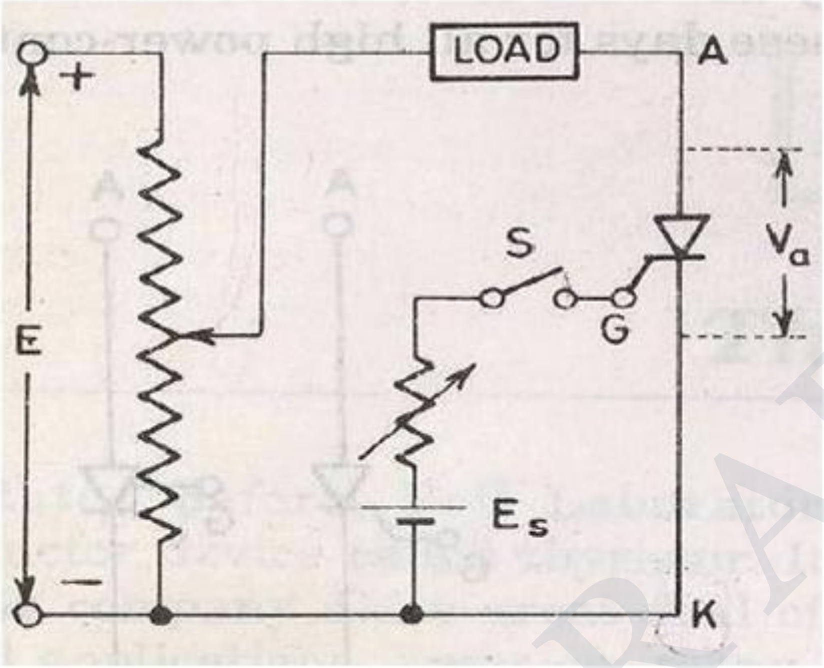




SCR is made up of silicon, it act as a rectifier; it has very low resistance in the forwarddirection and high resistance in the reverse direction. It is a unidirectional device.

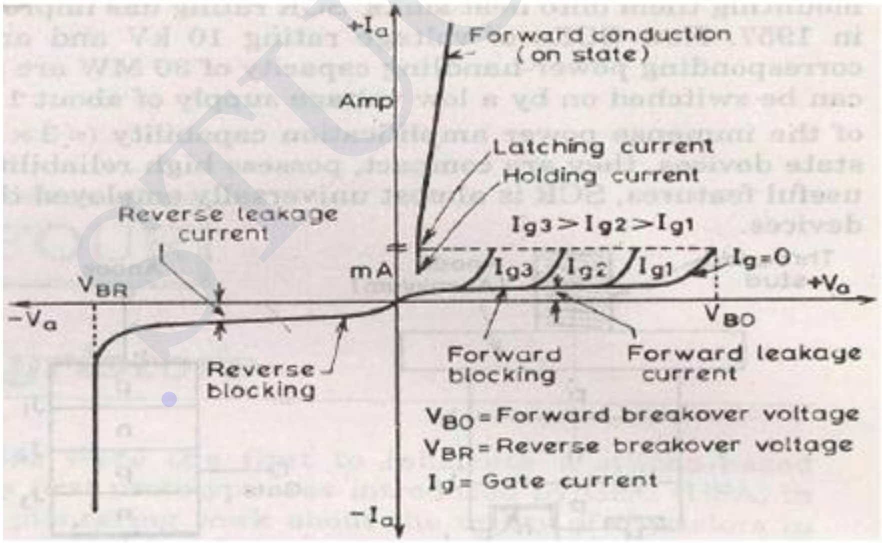
1.4.1Static V-I characteristics of a Thyristor

The circuit diagram for obtaining static V-I characteristics is as shown



Anode and cathode are connected to main source voltage through the load. The gate andcathode are fed from source ES.

A typical SCR V-I characteristic is as shown below:



VBO =Forward breakover voltage
VBR =Reverse breakover voltage
Ig =Gate current
V =Anode voltage across the thyristor terminal A,K.a
Ia =Anode current

It can be inferred from the static V-I characteristic of SCR.

1.4.2Modes of operation

SCR have 3 modes ofoperation:

1. Reverse blocking mode
2. Forward blocking mode (off state)
3. Forward conduction mode (on state)

1. Reverse Blocking Mode

When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased. Junctions$J1$ and $J2$ are reverse biased where junction $J2$ is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.

A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.

Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage VB,an avalanche occurs at $J1$ and $J3$ and the reverse current increases rapidly. As a large current associated with VBR and hence more losses to the SCR. This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

2. Forward Blocking Mode

When anode is positive with respect to cathode, with gate circuit open, thyristor is said tobe forward biased.Thus junction $J1$ and $J3$ are forward biased and $J2$ is reverse biased. As the forwardvoltage is increases junction $J2$ will have an avalanche breakdown at a voltage calledforwardbreakover voltageVB. When forward voltage is less thenVBOthyristor offers highimpedance. Thus a thyristor acts as an open switch in forward blocking mode.

3. Forward Conduction Mode

Here thyristor conducts current from anode to cathode with a very small voltage dropacross it. So a thyristor can be brought from forward blocking mode to forwardconducting mode:

1. By exceeding the forward breakover voltage.
2. By applying a gate pulse between gate and cathode.

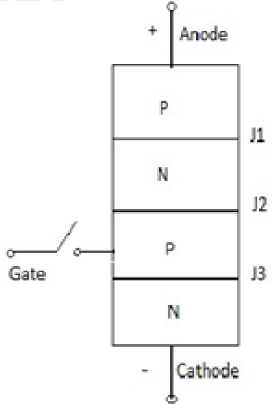
During forward conduction mode of operation thyristor is in on state and behave like aclose switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due toohmic drop across the four layers of the device.

1.4.3 Turn ON methods

Different turn ON methods for SCR

1. Forward voltage triggering
2. Gate triggering
3. dv/dttriggering
4. Light triggering
5. Temperature triggering

1. Forward voltage triggering



A forward voltage is applied between anode and cathode with gate circuit open.
A forward voltage is applied between anode and cathode with gate circuit open.
Junction $J1$ and $J3$ is forward biased.
Juntion$J2$ is reverse biased.

As the anode to cathode voltage is increased breakdown of the reverse biased junction$J2$ occurs. This is known as avalanche breakdown and the voltage at which thisphenomena occurs is called forward breakovervoltage.The conduction of current continues even if the anode cathode voltage reduces belowVBO till Ia will not go belowIh .Where Ih is the holding current for the thyristor.

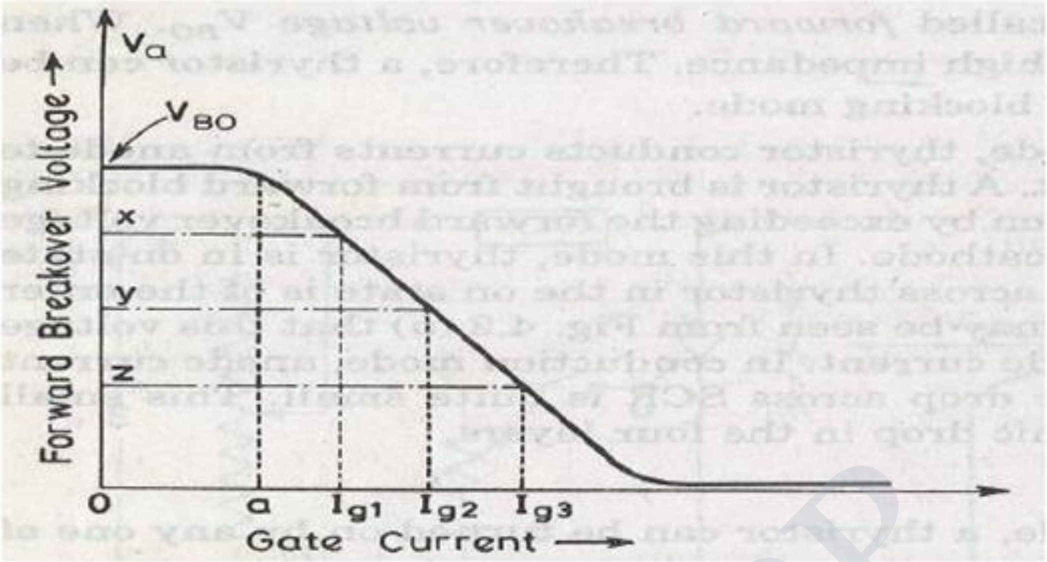
2. Gate triggering

This is the simplest, reliable and efficient method of firing the forward biased SCRs. FirstSCR is forward biased. Then a positive gate voltage is applied between gate and cathode. Inpractice the transition from OFF state to ON state by exceeding VBO is never employed as itmay destroy the device. The magnitude of VB,so forward breakover voltage is taken as finalvoltage rating of the device during the design of SCR application.

First step is to choose a thyristor with forward breakover voltage (say 800V) higher than thenormal working voltage. The benefit is that the thyristor will be in blocking state with normalworking voltage applied across the anode and cathode with gate open. When we require theturning ON of a SCR a positive gate voltage between gate and cathode is applied. The pointto be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gatesupply is given between gate and cathode gate p-layer is flooded with electron from cathoden-layer. Now the thyristor is forward biased, so some of these electron reach junction $J2$ .As aresult width **of**$J2$ breaks down or conduction at $J2$ occur at a voltage less than VBO .As Igincreases VBO reduces which decreases then turn ON time. Another important point isduration for which the gate current is applied should be more then turn ON time. This meansthat if the gate current is reduced to zero before the anode current reaches a minimum valueknown as holding current, SCR can’t turn ONIn this process power loss is less and also low applied voltage is required for triggering.

3. dv/dt triggering

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided.



When SCR is forward biased, junction $J1$ and $J3$ are forward biased and junction $J2$ isreversed biased so it behaves as if an insulator is place between two conducting plate. Here $J1$and $J3$ acts as a conducting plate and $J2$ acts as an insulator. $J2$ is known as junction capacitor.So if we increase the rate of change of forward voltage instead of increasing the magnitude ofvoltage. Junction $J2$ breaks and starts conducting. A high value of changing current maydamage the SCR. So SCR may be protected from high d.

4. Temperature triggering

During forward biased, $J2$ is reverse biased so a leakage forward current always associatedwith SCR. Now as we know the leakage current is temperature dependant, so if we increasethe temperature the leakage current will also increase and heat dissipitation of junction$J2$ occurs. When this heat reaches a sufficient value $J2$ will break and conduction starts.

Disadvantages

This type of triggering causes local hot spot and may cause thermal run away of the device. This triggering cannot be controlled easily.It is very costly as protection is costly.

5. Light triggering

First a new recess niche is made in the inner p-layer. When this recess is irradiated, then freecharge carriers (electron and hole) are generated. Now if the intensity is increased above acertain value then it leads to turn ON of SCR. Such SCR are known as Light activated SCR(LASCR).

Latching current

The latching current may be defined as the minimum value of anode current which at mustattain during turn ON process to maintain conduction even if gate signal is removed.

Holding current

It is the minimum value of anode current below which if it falls, the SCR will turn OFF.

1.4.4Switching characteristics of thyristors

The time variation of voltage across the thyristor and current through it during turn onand turn off process gives the dynamic or switching characteristic of SCR.

Switching characteristic during turn on

Turn on time

It is the time during which it changes from forward blocking state to ON state. Total turnon time is divided into 3 intervals:

1. Delay time
2. Rise time
3. Spread time

Delay time

If Ig and Ia represent the final value of gate current and anode current. Then the delay timecan be explained as time during which the gate current attains 0.9 Ig to the instant anodecurrent reaches 0.1 Ig or the anode current rises from forward leakage current to 0.1 I.

1. Gate current 0.9 Ig to 0.1 I.
2. Anode voltage falls from V to 0.9 $.aa$
3. Anode current rises from forward leakage current to 0.1 I.

Rise time ($\boldsymbol{t}$)

Time during which

1. Anode current rises from 0.1 Ia to 0.9 Ia
2. Forward blocking voltage falls from 0.9V to 0.1 .V is the initial forward blocking anode voltage.

Spread time ($\boldsymbol{t}$)

1. Time taken by the anode current to rise from 0.9Ia to$I$.
2. Time for the forward voltage to fall from 0.1V to on state voltage drop of 1 to 1.5V.oDuring turn on, SCR is considered to be a charge controlled device. A certain amount of charge is injected in the gate region to begin conduction. So higher the magnitude of gate current it requires less time to inject the charges. Thus turn on time is reduced by using large magnitude of gate current.

Switching Characteristics During Turn Off

Thyristor turn off means it changed from ON to OFF state. Once thyristor is ON there isno role of gate. As we know thyristor can be made turn OFF by reducing the anodecurrent below the latching current. Here we assume the latching current to be zeroampere. If a forward voltage is applied across the SCR at the moment it reaches zero thenSCR will not be able to block this forward voltage. Because the charges trapped in the 4-layer are still favourable for conduction and it may turn on the device. So to avoid such acase, SCR is reverse biased for some time even if the anode current has reached to zero.

So now the turn off time can be different as the instant anode current becomes zero to theinstant when SCR regains its forward blocking capability.

$tq = trr + tqr$

Where,

tq is the turn off time, is the reverse recovery time, tqr is the gate recovery time

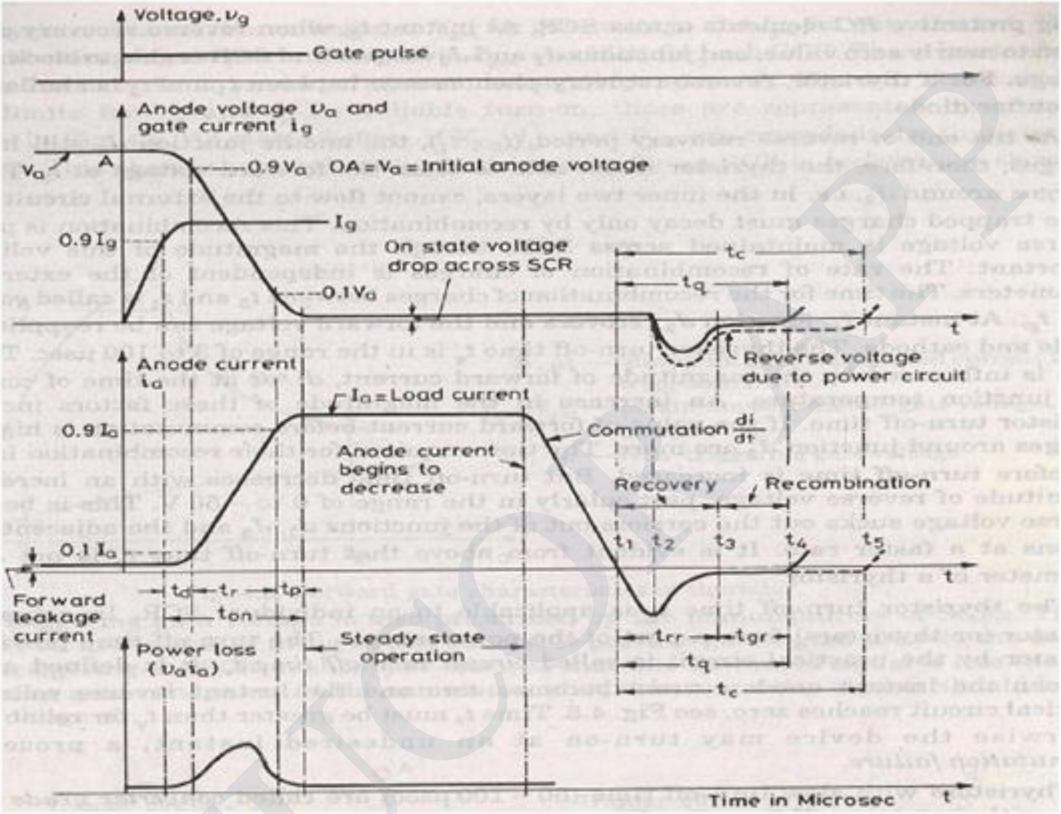
At $t1$ anode current is zero. Now anode current builds up in reverse direction with samedv/dtslope. This is due to the presence of charge carriers in the four layers. The reverserecovery current removes the excess carriers from $J1$ and $J3$ between the instants

$t1$ and$t3$ .At instant $t3$ the end junction $J1$ and $J3$ is recovered. But $J2$ still has trapped charges whichdecay due to recombination only so the reverse voltage has to be maintained for some
more time. The time taken for the recombination of charges between $t3$ and $t4$ is calledgate recovery time tq. Junction $J2$ recovered and now a forward voltage can be appliedacross SCR.

The turn off time is affected by:

1. Junction temperature
2. Magnitude of forward current

Turn off time decreases with the increase of magnitude of reverse applied voltage.



1.5 GTO (Gate turn off thyristor)

A gate turn off thyristor is a pnpn device. In which it can be turned ON like an ordinary SCR by a positive gate current. However it can be easily turned off by a negative gate pulse of appropriate magnitude eexistence.

The salient features of GTO are:

1. GTO turned on like conventional SCR and is turned off by a negative gate signal of sufficient magnitude.
2. It is a non latching device.
3. GTO reduces acoustic and electromagnetic noise.

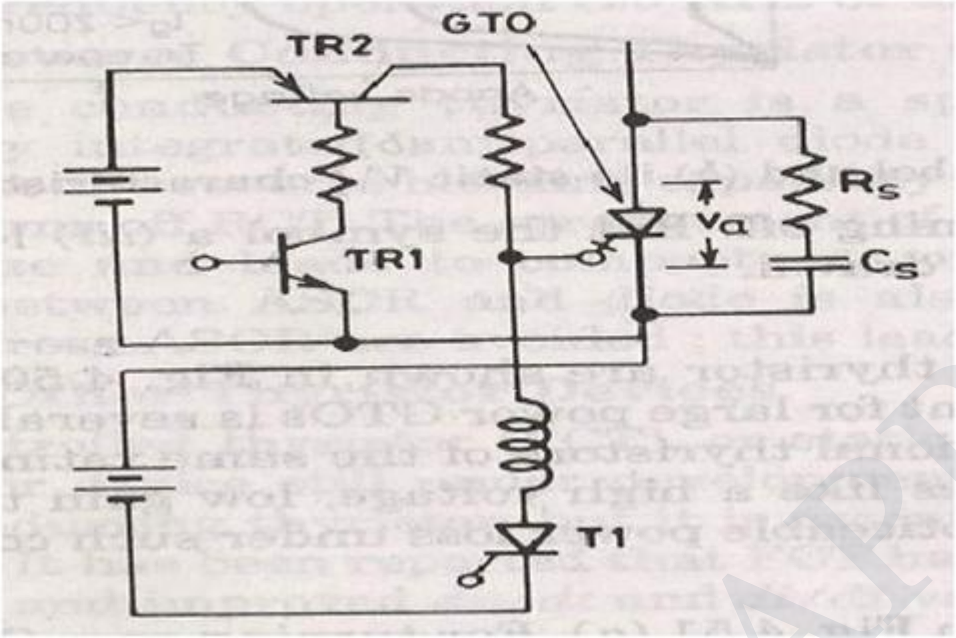
It has high switching frequency and efficiency.A gate turn off thyristor can turn on like an ordinary thyristor but it is turn off by negativegate pulse of appropriate magnitude.

Disadvantage

The negative gate current required to turn off a GTO is quite large that is 20% to 30 % of anode current

Advantage

It is compact and cost less
Switching performance



1. For turning ON a GTO first TR1is turned on.
2. This in turn switches on TR2 so that a positive gate current pulse is applied to turn on theGTO.
3. Thyristor$T$1 is used to apply a high peak negative gate current pulse.

1.5.1 Gate turn-on and turn off characteristic

Gate turn-on

1. The gate turn on characteristics is similar to a thyristor. Total turn on time consists of delay time, rise time, spread time.
2. The turn on time can be reduced by increasing its forward gate current.

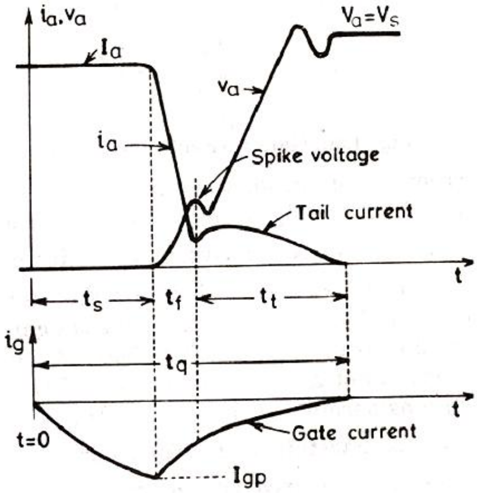
Gate turn off

Turn off time is different for SCR.Turn off characteristics is divied into 3 pd

1. Storage time
2. Fall time
3. Tail time

Tq=ts+tf+tt

At normal operating condition gto carries a steady state current.The turn off process starts as soon as negative current is applied after t=0.



STORAGE TIME

During the storagepd the anode voltage and current remains constant.The gate current risesdepending upon the gate circuit impedance and gate applied voltage.The beginning of pd is as soonas negative gate current is applied.The end of storage pd is marked by fall in anode current andrise in voltage,what we have to do is remove the excess carriers.the excess carriers are removed bynegative carriers.

FALL TIME

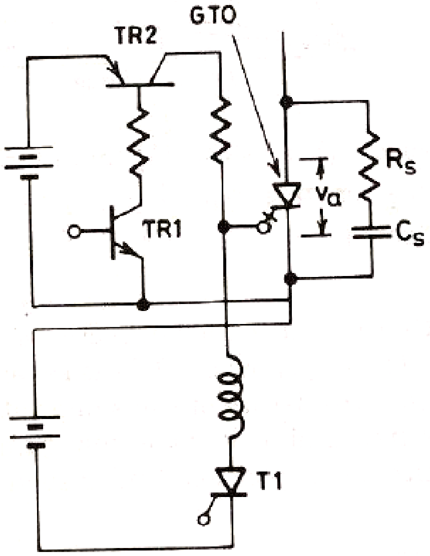
After ts, anode current begins to fall rapidly and anode voltage starts rising.After falling to a certainvalue,then anode current changes its rate to fall.this time is called fall time

SPIKE IN VOLTAGE

During the time of storage and fall timethere is achange in voltage due to abrupt current change.

TAIL TIME

During this time ,the anode current and voltage continues towards the turn off values.The transient overshoot is due to the snubber parameter and voltage stabilizes to steady state value.

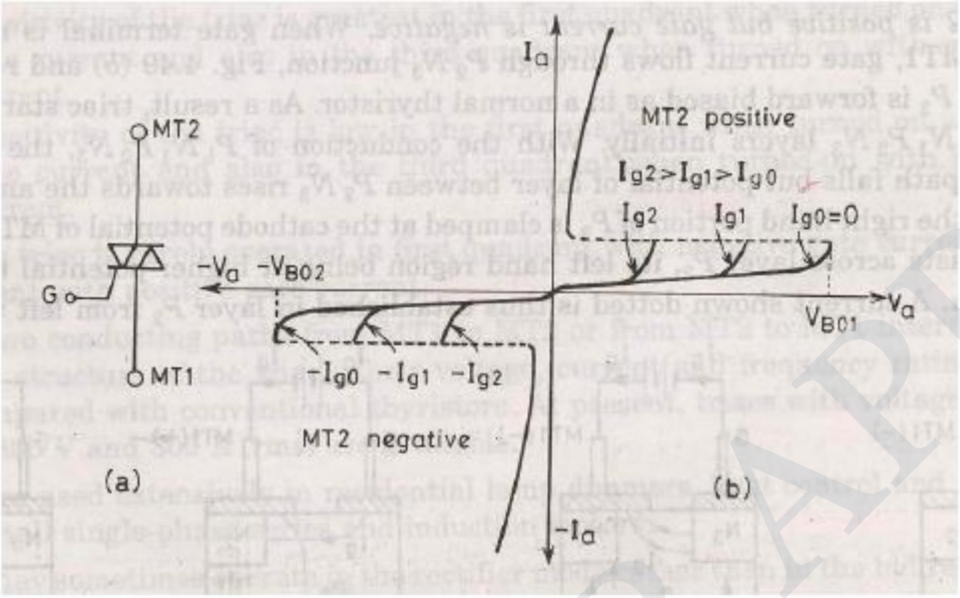


1.6 TRIAC

As SCR is a unidirectional device,the conduction is from anode to cathode and not from cathode to anode. It conducts in both direction.It is a bidirectional SCR with three terminal.

TRIAC=TRIODE+AC

Here it is considered to be two SCRS connected in anti parallel.As it conducts in both direction so it is named as MT1,MT2 and gate G.



SALIENT FEATURES

1.Bi directional triode thyristor

2.TRIAC means triode that works on ac

3.It conduct in both direction

4.It is a controlled device

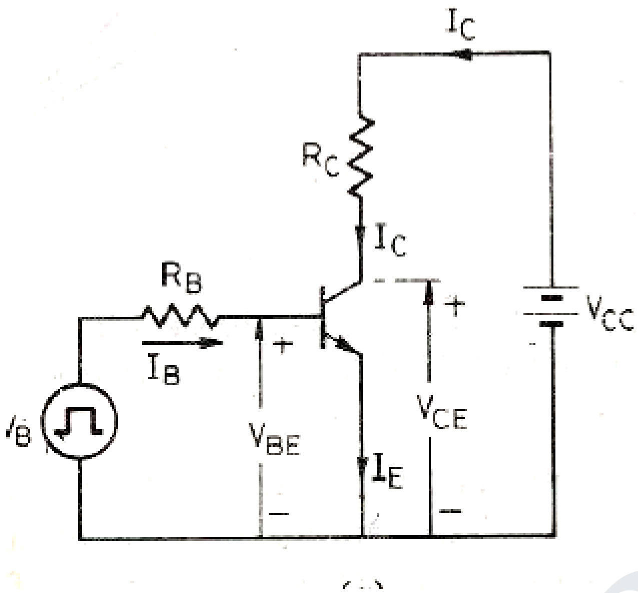
5.Its operation is similar to two devices connected in anti parallel with common gate connection.

6.It has 3 terminals MT1,MT2 and gate G

Its use is control of power in ac.

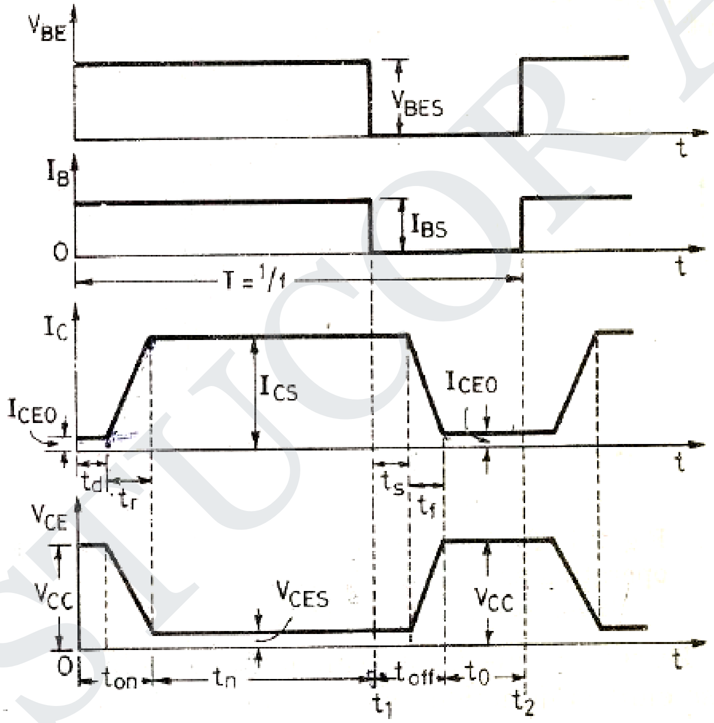
1.7 POWER BJT

Power BJT means a large voltage blocking in the OFF state and high current carrying capability in the ON state. In most power application, base is the input terminal. Emitter is the common terminal. Collector is the output terminal.



1.7.1 Signal level of BJT

n+ doped emitter layer ,doping of base is more than collector.Depletion layer exists more towards the collector than emitter



1.7.2 Power BJT Construction

The maxium collector emitter voltage that can be sustained across the junction, when it is carrying substantial collector current.

Vceo=maxiumcollectorand emitter voltage that can be sustain by the device.

Vcbo=collector base breakdown voltage with emitter open

Primary Breakdown

It is due to convention avalanche breakdown of the C-B junction and its associated large flow of current.The thickness of the depletion region determines the breakdown voltage of the transistor.The base thickness is made as small as possible,in order to have good amplification capability. If the thickness is too small, the breakdown voltage is compromised.So a compromise has to be made between the two.

The Doping Levels

1.The doping of the emitter layer is quite large.
2.The base doping is moderate.
3.n- region is lightly doped.
4.n+ region doping level is similar to emitter.
1.Thickness Of Drift Region-It determines the breakdown length of the transistor.
2.The Base Thicknes -Small base thickness- good amplification capability
Too small base thickness- the breakdown voltage of the transistor has to be compromised. For a relatively thick base,the current gain will be relatively small.so it is increase the gain.Monolithicesigns for darlington connected BJT pair have been deveploed.

Secondary Breakdown

Secondary breakdown is due to large power disspation at localized site within the semi conductor.

Physics OfBJT Operation

The transistor is assumed to operate in active region. There is no doped collector drift region. It has importance only in switching operation, in active region of operation.

B-E junction is forward biased and C-B junction is reverse biased. Electrons are injected into base from the emitter. Holes are injected from base into the emitter.

Quasi Saturation

Intially we assume that, the transistor is in active region. Base current is allowed to increase then lets see what happens.first collector rises in response to base current.So there is a increase voltage drop across the collector load.So C-E voltage drops. Because of increase in collector current, there is a increase in voltage in drift region. This eventually reduces the reverse biased across the C-B junction.so n-p junction get smaller, at some point the junction become forward bised. So now injection of holes from base into collector drift region occurs. Charge neutrality requires the electron to be injected in the drift region of the holes. From where these electron came. Since a large no of electron is supplied to the C-B junction via injection from emitter and subsequent diffusion across the base. As excess carrier build up in the drift region begins to occur quasi saturation region is entered. As the injected carrires increase in the drift region is gradually shotred out and the voltage across the drift region drops. In quasi saturation the drift region is not completely shorted out by high level injection.Hard saturation obtained when excess carrier density reaches the n+ side.

During quasi saturation, the rate of the collector fall.Hard saturation occurs when excess carriers have completely swept across the drift region.

1.8 Thyristor Protection

Over Voltage Protection

Over voltage occurring during the switching operation causes the failure of SCR.

Internal Overvoltage

It is due to the operating condition of SCR.During the commutation of SCR ,when the anode current decays to zero anode current reverses due to stored changes. First the reverse current rises to peak value, then reverse current reduces abruptly with large *didt⁄*. During series inductance of SCR large transient large voltage i.e*Ldidt⁄*.is generated.

External Over Voltage

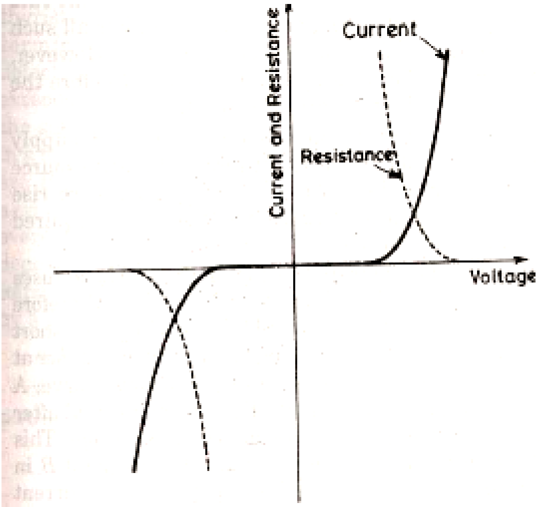
This is due to external supply and load condition. This is because of
1. The interruption of current flow in an inductive circuit.
2. Lightening strokes on the lines feeding the thyristor systems.

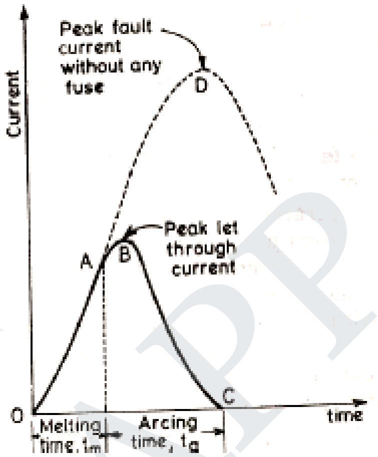
Suppose a SCR converter is fed from a transformer, voltage transient occur when transformer primary will energise or de-energised.

This overvoltages cause random turn ON of a SCR.

The effect of overvoltage is minimized using

1. RC circuits
2. Non linear resistor called voltage clamping device.





Voltage clamping device is a non linearresistor.It is connected between cathode and anode of SCR. The resistance of voltage clamping device decreases with increasing voltages. During normal working condition Voltage clamping (V.C) device has high resistance, drawing only leakage current. When voltage surge appears voltage clamping device offers a low resistance and it create a virtual short circuit across the SCR. Hence voltage across SCR is clamped to a safe value.

When surge condition over voltage clamping device returns to high resistance state.

e.g. of voltage clamping device

1.Seleniumthyrector diodes
2.Metal Oxide varistors
3.Avalanche diode supressors

1.8.1 Over Current Protection

Long duration operation of SCR, during over current causes the

1.junction temp. of SCR to rise above the rated value,causing permanent damage to device.

SCR is protected from overcurrent by using

1.Circuit breakers
2.Fast acting fuses

Proper co-ordination is essential because

1..fault current has to be interrupted before SCR gets damaged.

2. Only faulty branches of the network has to be replaced. In stiff supply network, source has negligible impedance. So in such system the magnitude and rate of rise of current is not limited. Fault current hence junction temp rises in a few miliseconds.

POINTS TO BE NOTED-

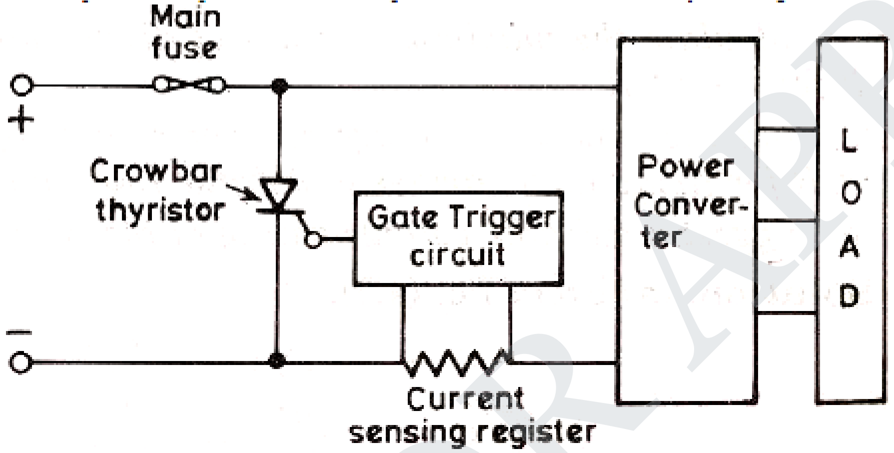
1. Proper coordination between fast acting fuse and thyristor is essential.
2. The fuse is always rated to carry marginal overload current over definite period.
3. The peak let through current through SCR must be less than sub cycle rating of the SCR.

4. The voltage across the fuse during arcing time is called arcing or recovery voltage and is equal to sum of the source voltage and emf induced in the circuit inductance during arcing time.

5. On abrupt interruption of fuse current, induce emf would be high, which results in high arcing voltage.

Circuit Breaker (C.B)
C.B. has long tripping time. So it is used for protecting the device against continuous overload current or against the surge current for long duration. In order that fuse protects the thyristorrealiably the $I2t$ rating of fuse current must be less than that of SCR.
ELECTRONIC CROWBAR PROTECTION

For overcurrent protection of power converter using SCR, electronic crowbar are used. It provide rapid isolation of power converter before any damage occurs.



HEAT PROTECTION-
To protect the SCR
1. From the local spots

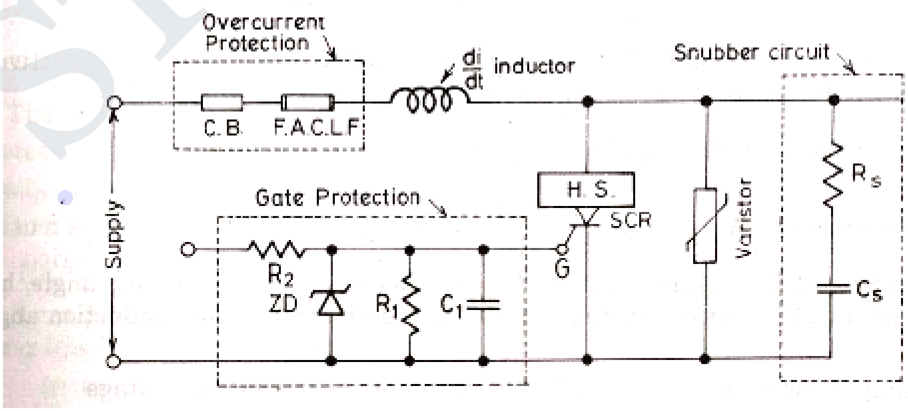
2. Temp rise
SCRs are mounted over heat sinks.

1.9 Gate Protection

Gate circuit should also be protected from

1. Overvoltages

2. Overcurrents



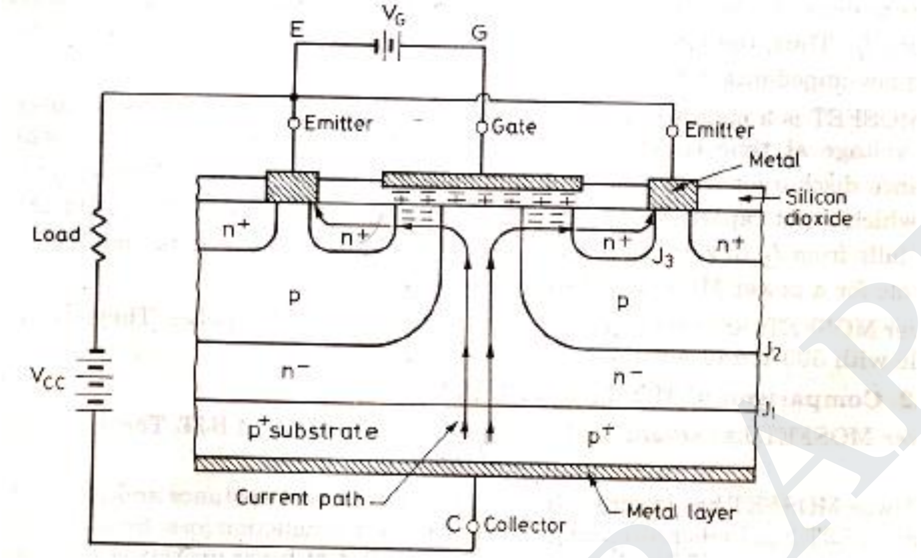
Overvoltage across the gate circuit causes the false triggering of SCR

Overcurrent raise the junction temperature. Overvoltage protection is by zener diode across the gate circuit.

1.10 **INSULATED GATE BIPOLAR TRANSISTOR(IGBT)**

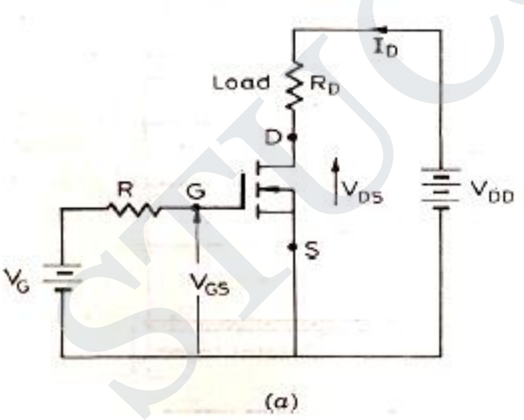
BASIC CONSTRUCTION-

The n+ layer substrate at the drain in the power MOSFET is substituted by p+ layer substrate and called as collector. When gate to emitter voltage is positive,n- channel is formed in the p- region.This n- channel short circuit the n- and n+ layer and an electron movement in n channel cause hole injection from p+subtrate layer to n- layer.

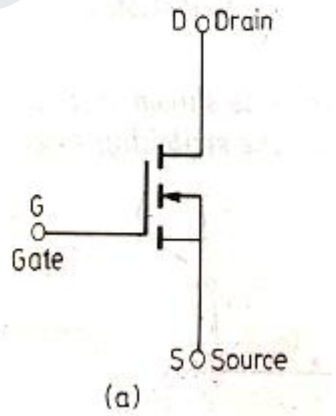


1.11POWER MOSFET

A power MOSFET has three terminal device. Arrow indicates the direction of current flow. MOSFET is a voltage controlled device. The operation of MOSFET depends on flow of majority carriers only.



(Circuit diagram)



(circuit symbol)

1.11.1Switching Characteristics:-

The switching characteristic is influenced by

1. Internal capacitance of the device.
2. Internal impedance of the gate drive circuit.

Total **turn on time** is divided into

1. Turn on delay time
2. Rise time

Turn on time is affected by impedance of gate drive source. During turn on delay time gate to source voltage attends its threshold value .
After tdn and during rise time gate to source voltage rise to $VGsp$, a voltage which is sufficient to drive the MOSFET to ON state.
The turn off process is initiated by removing the gate to source voltage. Turn off time is composed of turn off delay time to fall time.
Turn off delay time To turn off the MOSFET the input capacitance has to be discharged . During tdf the input capacitance discharge from $V1$to $VGsp$. During , fall time ,the input capacitance discharges from $VGsp$ to $VGST$. During tf drain current falls from ID to zero. So when $VGs \leq$, MOFSET turn off is complete.

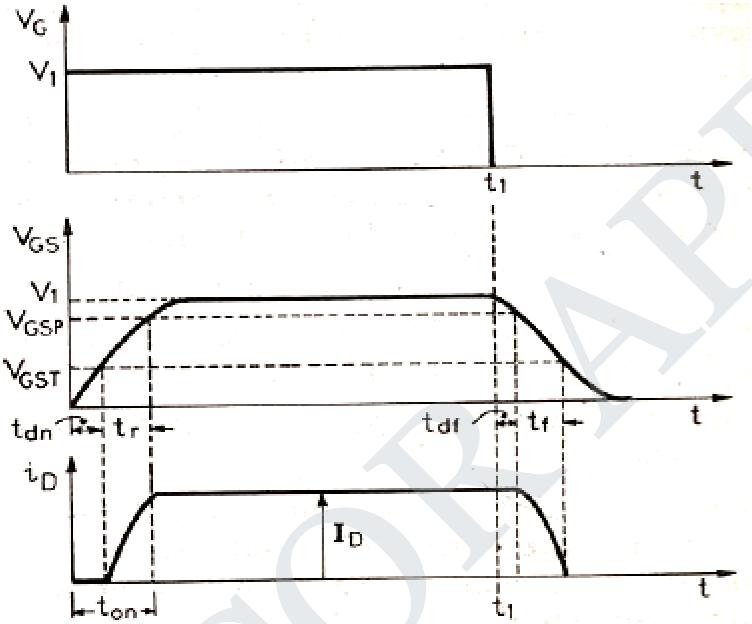


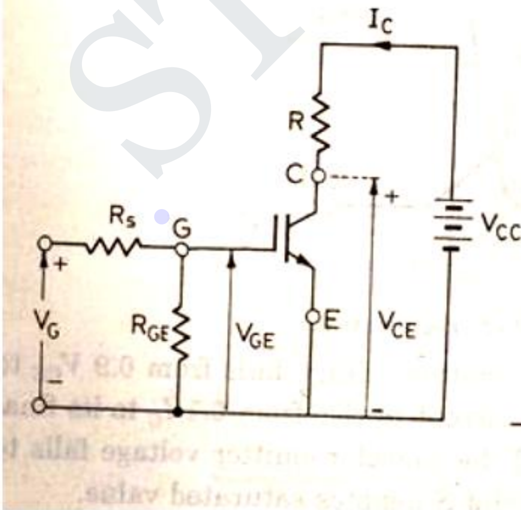
Fig. Switching waveform of power MOSFET

Insulated Gate Bipolar Transistor (IGBT)

IGBT has high input impedance like MOFFSET and low on state power lose as in BJT.

1.11.2 IGBT Characteristics

Here the controlling parameter is gate emitter voltage As IGBT is a voltage controlled device. When VGE is less than $VGET$ that is gate emitter threshold voltage IGBT is in off state.



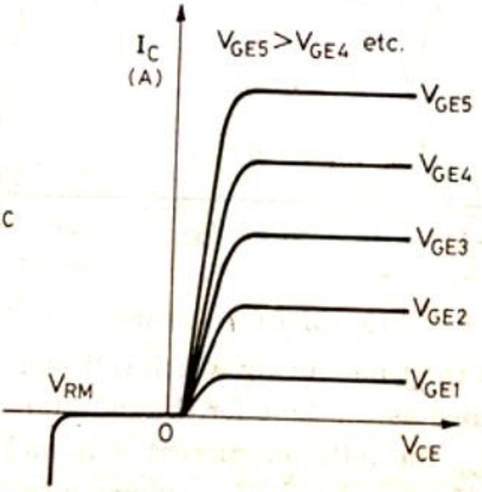


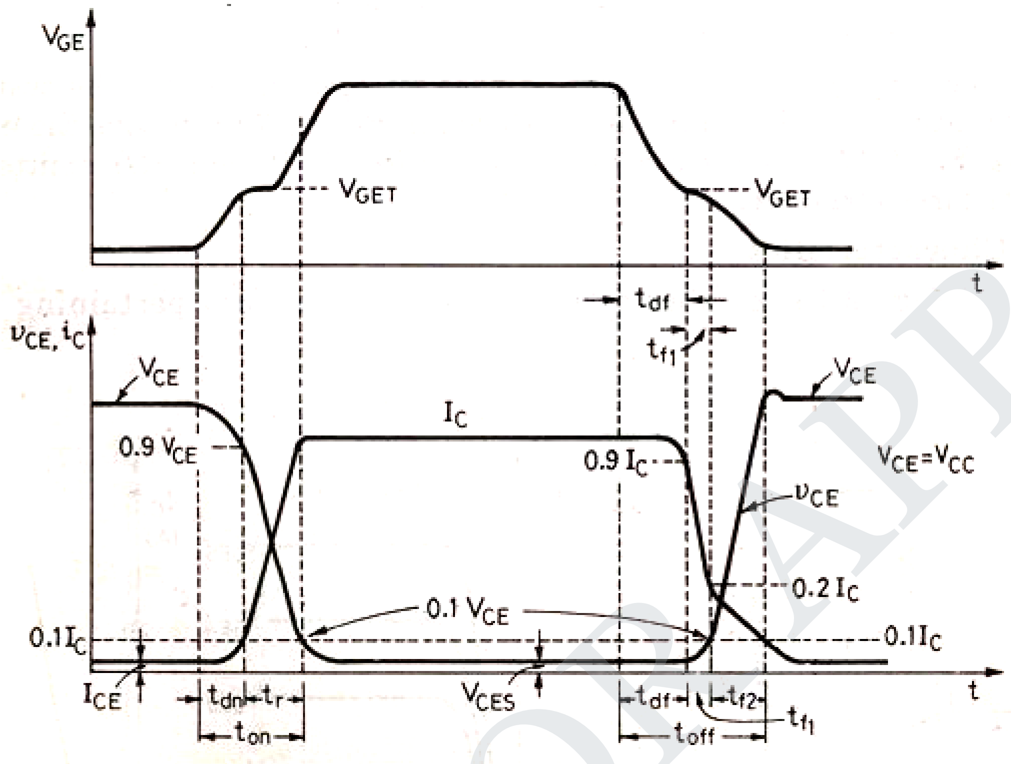
Fig. a Fig. b. Fig. c

Fig. a (Circuit diagram for obtaining V-I characteristics) Fig. b (Static V-I characteristics)

Fig. c (Transfer characteristic)

Switching characteristics: Figure below shows the turn ON and turn OFF characteristics of IGBT

Turn on



Turn on time :

Time between the instants forward blocking state to forward on -state .

Turn on time = Delay time + Rise time

Delay time = Time for collector emitter voltage fall from VCE to 0.9VCE

VCE=Initial collector emitter voltage

tdn=collector current to rise from initial leakage current to 0.1Ic

Ic= Final value of collector current

Rise time:

Collector emitter voltage to fall from 0.9VCE to 0.1VCE. 0.1Ic to Ic

After ton the device is on state the device carries a steady current of Ic and the collector emitter voltage falls to a small value called conduction drop $VCES$.

Turn off time :

1) Delay time tdf

2) Initial fall time $tf1$

3) Final fall time $tf2$

t_{off} =tdf+$tf1$+ $tf2$

tdf= Time during which the gate emitter voltage falls to the threshold value $VGET$. Collector current falls from Ic to 0.9Ic at the end of the tdf collector emitter voltage begins to rise. Turn off time = Collector current falls from 90% to 20% of its initial value Ic OR The time during which collector emitter voltage rise from VCE to 0.1VCE. $tf2$=collector current falls from20% to 10% of Ic. During this collector emitter voltage rise 0.1VCE to final value of VCE.

1.12 Series and parallel operation of SCR

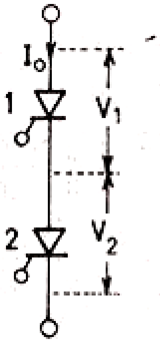
SCR are connected in series for h.v demand and in parallel for fulfilling high current demand. Sting efficiency can be defined as measure of the degree of utilization on SCRs in a string.

String efficiency < 1.

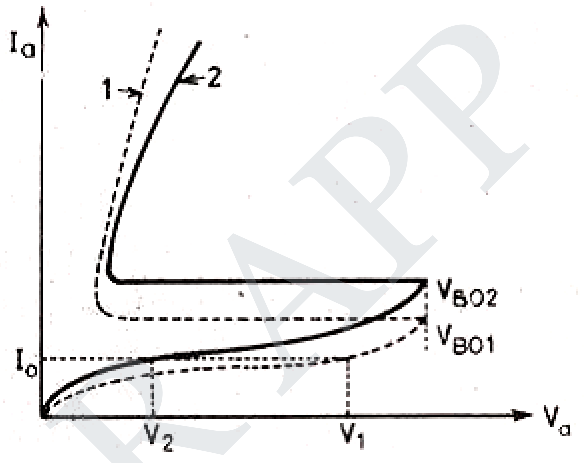
Derating factor (DRF) 1 – string efficiency.

If DRF more then no. of SCRs will more, so string is more reliable.

Let the rated blocking voltage of the string of a series connected SCR is $2V1$ as shown in the figure below, But in the string two SCRs are supplied a maximum voltage of $V1+V2$.



(a)



(b)

$$\eta = V1+V2/2V1$$

Significance of string efficiency .

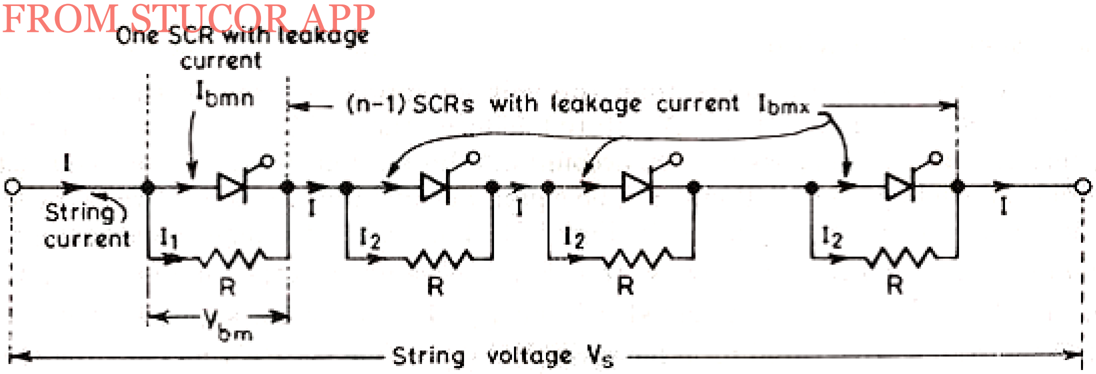
Two SCRs are have same forward blocking voltage ,When system voltage is more then the voltage rating of a single SCR. SCRs are connected in series in a string. There is a inherent variation in characteristics. So voltage shared by each SCR may not be equal. Suppose, SCR1 leakage resistance > SCR2 leakage resistance. For same leakage current $I0$ in the series connected SCRs. For same leakage current SCR1 supports a voltage $V1$, SCR2 supports a voltage $V2$,

$$\text{So string } \eta \text{ for two SCRs} = \frac{V_1+V_2}{2V_2} = \frac{1}{2}\left(1+\frac{V_2}{V_1}\right) < 1 .$$

So, $V_1 > V_2,$

The above operation is when SCRs are not turned ON. But in steady state of operation , A uniform voltage distribution in the state can be achieved by connect a suitable resistance across each SCRs , so that parallel combination have same resistance. But this is a cumbersome work. During steady state operation we connect same value of shunt resistance across each SCRs. This shunt resistance is called ***state equalizing circuit.***

Suppose,



Static-voltage equalization for series-connected string.

Let SCR1 has lower leakage current I , It will block a voltage comparatively larger than other SCRs.

Voltage across SCR1 is $Vbm = I1R$. Voltage across (n-1)SCR is (n-1) I2R, so the voltage equation for the series circuit is

$$Vs = I_1R + (n-1)I_2R = V_{bm} + (n-1)R\,(I - I_{bmx})$$

$$\text{As } I_1 = I - I_{bmn}$$

$$I_2 = I - I_{bmx}$$

$$\text{So, } Vs = V_{bm} + (n-1)R\ [I_1 - (I_{bmx} - I_{bmn})]$$

$$\text{If } \Delta I_b = I_{bmx} - I_{bmn}$$

$$\text{Then } Vs = V_{bm} + (n-1)R\,(I_1 - \Delta I_b)$$

$$Vs = V_{bm} + (n-1)R\,I_1 - (n-1)R\,\Delta I_b$$

$$RI_1 = V_{bm}$$

$$\text{So, } Vs = Vbm + (n-1)\,Vbm - (n-1)R\,\Delta I_b$$

$$= n\,V_{bm} - (n-1)R\,\Delta I_b$$

$$\Rightarrow R = \frac{nV_{bm} - V_S}{(n-1)\Delta I_b}$$

SCR data sheet usually contain only maximum blocking current ,bmx

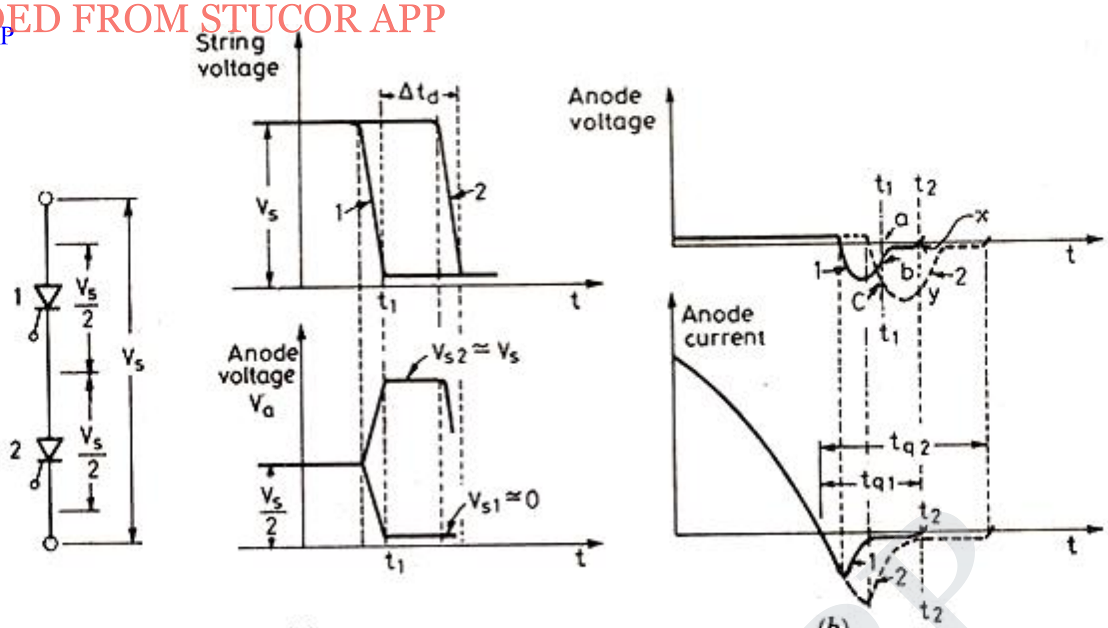
so we assume $Ibmn=0$

So $\Delta Ib = Ibmx$

So the value of R calculated is low than actually required.

SCRs having unequal dynamic characteristics*:*

It may occur that SCRS may have unequal dynamic characteristics so the voltage distribution across the SCR may be unequal during the transient condition.



(a) (b)

Unequal voltage distribution for two series connected SCRs during (a) turn-on and (b) turn-off.

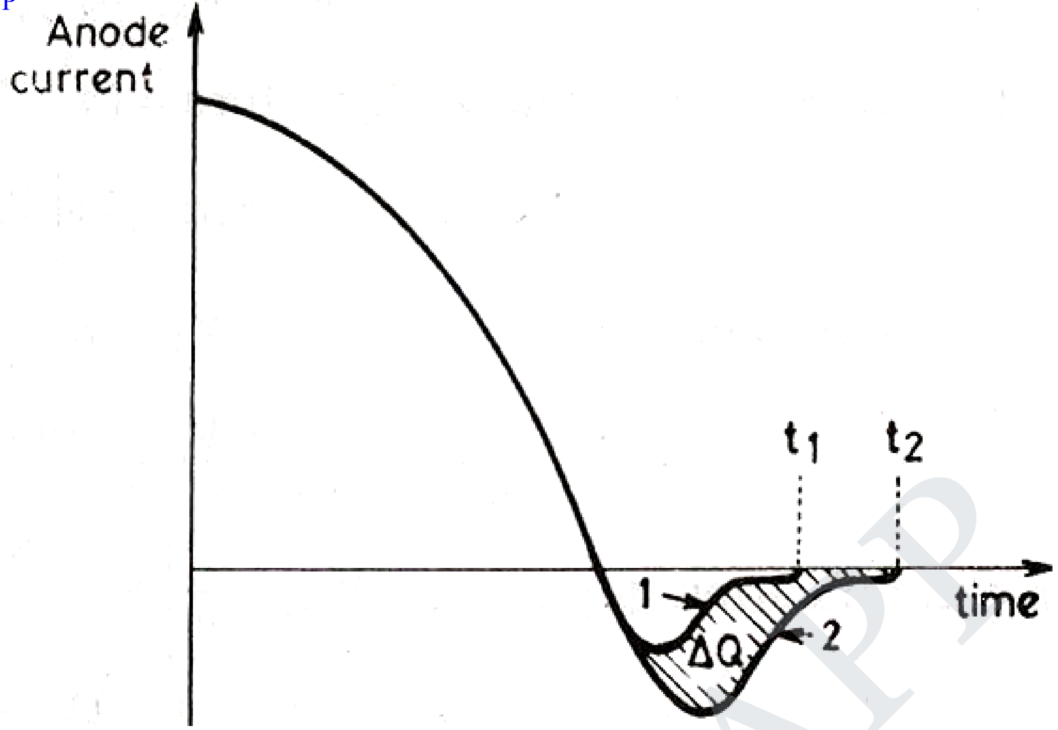
SCR 1 and SCR 2 have different dynamic characteristics. Turn ON time of SCR 2 is more than SCR 1 by time Δ . As string voltage is VS so voltage shared by each SCRs be $VS/2$. Now both are gated at same time so SCR 1 will turn ON at $t1$ its voltage fall nearly to zero so the voltage shared by SCR 2 will be the string voltage if the break over voltage of SCR 2 is less than VS then SCR 2 will turn ON .

* In case VS is less than the breakoverer voltage, SCR 2 will turn ON at instant 2. SCR 1 assumed to have less turn off $tq1$ time then SCR 2, so $tq1<tq2$. At $t2$ SCR 1 has recovered while SCR 2 is developing recovery voltage at $t1$ both are developing different reverse recovery voltage. At $t2$ SCR 1 has recovered while SCR2 is developing reverse recovery voltage .

Conclusion :

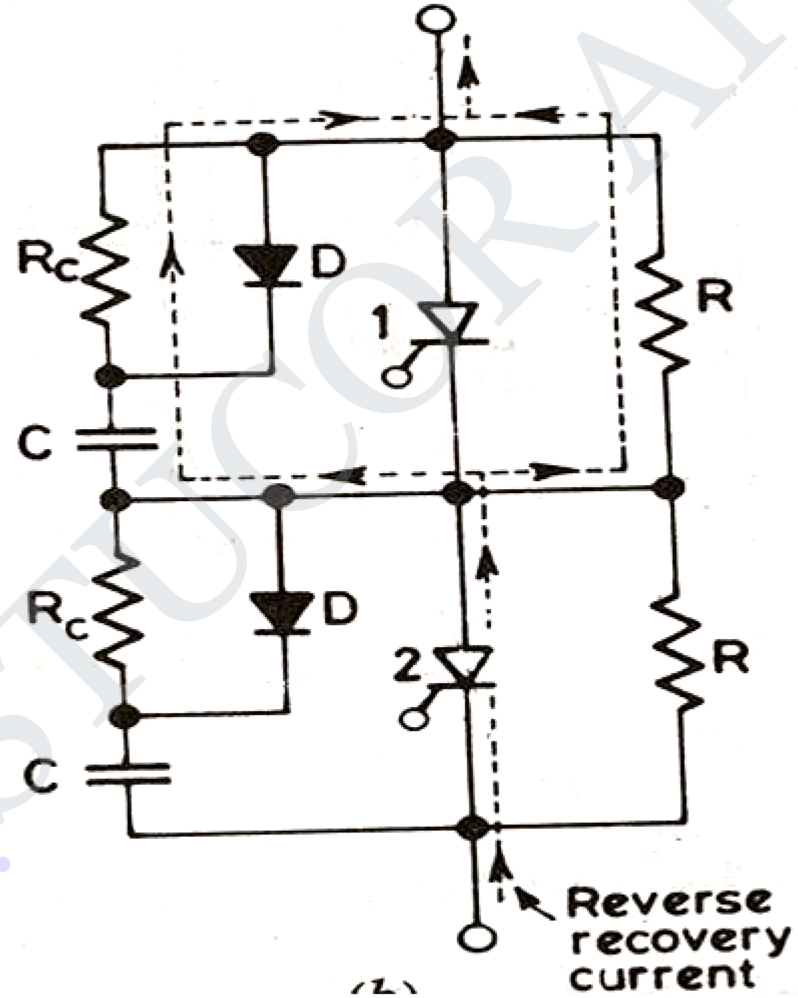
* Series connected SCR develop different voltages during turn ON and turn OFF process. Till now we connect a simple resistor across the diode for static voltage equalizing circuit .

* During turn ON and turn OFF capacitance of reverse biased junction determine the voltage distribution across SCRs in a series connected string . As reverse biased junction have different capacitance called *self capacitance*, the voltage distribution during turn ON and turn Off process would be different.


Anode current
time
t1
t2
1
2
ΔQ

Under transient condition equal voltage distribution can be achieved by employing shunt capacitance as this shunt capacitance has the effect of that the resultant of shunt and self capacitance tend to be equal. The capacitor is used to limits the dv/dt across the SCR during forward blocking state. When this SCR turned ON capacitor discharges heavy current through the SCR . The discharge current spike is limited by damping resistor .Rc also damps out high frequency oscillation that may arise due to series combination of ,C and series inductor . Rc& C are called *dynamic equalizing circuit* Diode D is used during forward biased condition for more effective charging of the capacitor. During capacitor discharge Rc comes into action for limiting current spike and rate of change of current *di/dt*.

The R, Rc& C component also provide path to flow reverse recovery current. When one SCR regain its voltage blocking capability. The flow of reverse recovery current is necessary as it facilitates the turning OFF process of series connected SCR string. So C is necessary for both during turn ON and turn OFF process. But the voltage unbalance during turn OFF time is more predominant then turn ON time. So choice of C is based on reverse recovery characteristic of SCR .



SCR 1 has short recovery time as compared to SCR 2. ΔQ is the difference in reverse recovery charges of two SCR 1 and SCR 2. Now we assume the SCR 1 recovers fast .i.e it goes into blocking state so charge ΔQ can pass through C . The voltage induced by $c1$ is $\Delta Q/C$,where is no voltage induced across $C2$. The difference in voltage to which the two shunt capacitor are charged is $\Delta Q/C$ .Now thyristor with least recovery time will share the highest transient voltage say Vbm, So, $V_{bm} - V_2 = \Delta_Q/C$

So, $V_2 = V_{bm} - \Delta_Q/C$

As $V_1 = V_{bm}$

$$V_S = V_1 + V_2$$

$$= V_{bm} + (V_{bm} - \Delta_Q/C)$$

$$V_S = 2V_{bm} - \Delta_Q/C$$

$$\Rightarrow \frac{1}{2}\left(V_s + \frac{\Delta_Q}{C}\right) = V_{bm}$$

$$\Rightarrow V_2 = V_{bm} - \Delta_Q/C$$

$$\frac{1}{2}[V_S - \Delta_Q/C]$$

Now suppose that there are *n* series SCRs in a string. Let us assume that if top SCR has similar to characteristic SCR 1. Then SCR 1 would support a voltage Vbm

* If the remaining (*n-1)* SCR has characteristic that of SCR 2 .Then SCR 1 would recover first and support a voltage Vbm . The charge *(n-1)* ΔQ from the remaining *(n -1)* SCR would pass through C.

$$V1 = Vbm$$

$$V2 = Vbm - \Delta Q/C$$

Voltage across (*n-1)* slow thyristors

$$V = (n\text{-}1)\ (Vbm - \Delta Q/C)$$

So, $VS = V1 + (n-1)\ V2$

$$= Vbm + (n-1)\ (Vbm - \Delta Q/C)$$

By simplifing we get ,

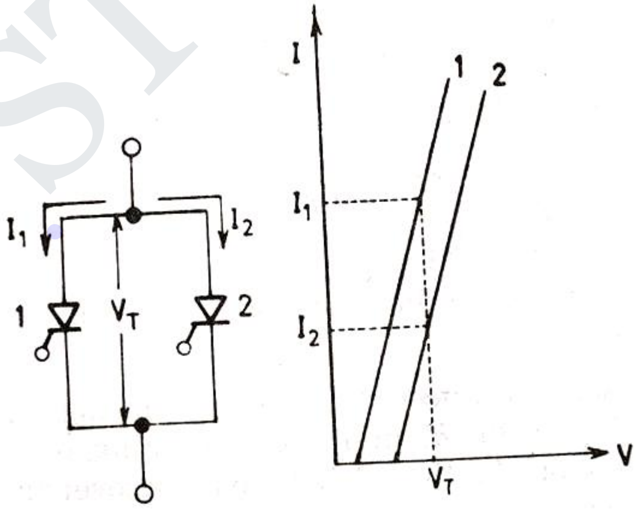
$$Vbm = 1n\ [Vs + (n-1)\ \Delta Q/C\ ]$$

$$C = [\ (n-1)\ \Delta Q/(\ nVbm - VS)$$

$$V2 = (VS - \Delta Q/C\ )/\ n\ .$$

1.12 Parallel operation of SCR:

When current required by the load is more than the rated current of single thyristor , SCRs are connected in parallel in a string .



For equal sharing of current, SCRs must have same $V-I$characteristics during forward conduction. VT across them must be same. For same , SCR 1 share $I1$and SCR 2 share I2 .

If $I1$ is the rated current

$I2 < I1$

The total current $I1+I2$ and not rated current $2I1$.Type equation here.

Thus string efficiency ,

$\frac{I_1+I_2}{2I_1} = \frac{1}{2}(1+\frac{I_2}{I_1})$

Middle conductor will have more inductance as compared to other two nearby conductor. As a result less current flow through the middle conductor. Another method is by magnetic coupling.

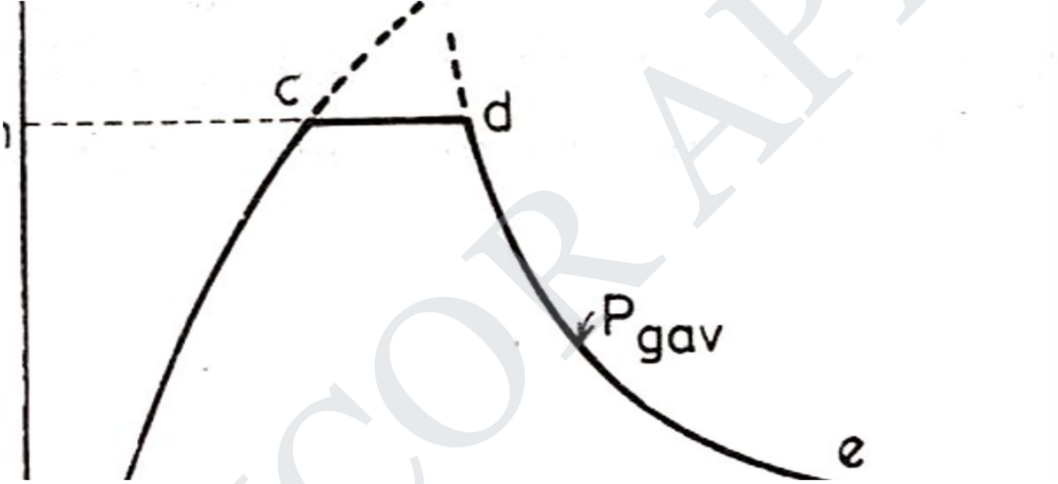
Thyristor gate characteristics:-

Vg = +ve gate to cathode voltage.

Ig= +ve gate to cathode current.

As the gate cathode characteristic of a thyrister is a p-n junction, gate characteristic of the device is similar to diode.

Curve 1 the lowest voltage value s that must be applied to turn on the SCR.



Curve 2 highest possible voltage values that can be safely applied to get circuit.

Vgm= Maximum limit for gate voltage .

Igm= Maximum imilt for gate current.

Pgav = Rated gate power dissipation for each SCR.

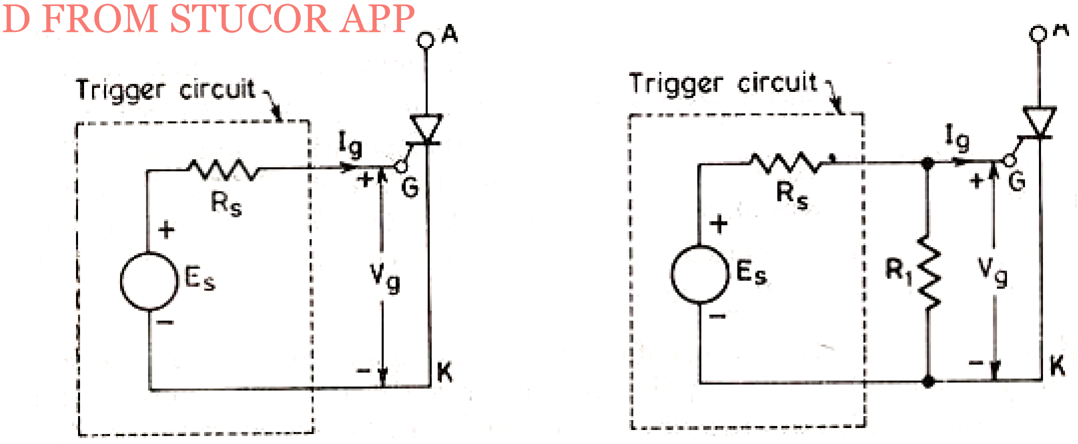
These limits should not be crossed in order to avoid the permanent damage of the device junction $J3$.

OY = Minimum limit of gate voltage to turn ON .

OX = minimum limit of gate current to turn ON.

If Vgm, Igm,gav are exceeded the thyristor will damage so the preferred gate drive area of SCR is bcdefghb.

oa = The non triggering gate voltage , If firing circuit generates +ve gate signal prior to the desired instant of triggering the SCR.It should be ensured that this un wanted signal should be less than the non –triggering voltage oa.



(a) (b)

$ES = Vg + IgRS$

ES =Gate source voltage

Vg = Gate cathode voltage

Ig = Gate current

RS = Gate source resistance

RS = The internal resistance of the trigger source

$R1$ is connected across the gate cathode terminal, which provides an easy path to the flow of leakage current between SCR terminal. If I ,gmn are the minimum gate current and gate voltage to turn ON the SCR.

$$ES = (Igmn + Vgmn/ R1)\ RS + Vgmn$$

Glossary

1. Doping:

It is the amount of impurity added to a pure semiconductor.

2. Substrate:

It is the base or starting material for a semiconductor device.

3. Depletion Region:

The semiconductor device has two regions, one region doped with p-type impurity and the second doped with n-type impurity. The free electrons in the n-type material diffuse across the junction into the p-type; similarly the holes in the p-type material diffuse across the junction into the n-type material. Due to this, a form of uncovered acceptor and donor ions are left uncovered with immobile charges across the junction.

4. Drift region:

It is a region where the immobile acceptor and donor ions break.

5. Barrier Potential:

The potential/ voltage required to break the depletion region is known as barrier potential. At 25^{o}C the barrier potential is 0.3V for germanium and 0.7V for silicon.

6. Break down voltage:

The voltage at which the pn junction breaks and the device starts conducting.

7. Biasing:

It is the application of voltage to a semiconductor device.

8. Forward Bias:

The forward bias is applied to a semiconductor device by connecting the positive terminal of the battery to p-type material and the negative terminal of the battery to n-type material.

9. Reverse Bias:

The reverse bias is applied to a semiconductor device by connecting the positive terminal of the battery to n-type material and the negative terminal of the battery to p-type material.

10. On-State voltage drop:

When the power semiconductor device is turned-on, voltage across the device drops to 0.6 v (for Silicon material) to o.3 v (for Germanium).

11. Off-State voltage drop:

When the power semiconductor device is turned-off, voltage across the device is nothing but the applied source voltage

12. Latching current:

It is the minimum value of anode current, above which the SCR starts conducting.

13. Holding current:

It is the minimum value of anode current, below which the SCR turns-off.

14. Active region:

A power BJT operates under active region when the emitter-base junction is forward biased and the collector-base junction is reverse biased.

15. Cut-off region:

A power BJT operates under cut-off region when both the emitter-base junction and the collector-base junctions are reverse biased. Hence no collector current and transistor is in off position.

16. Saturation region:

A power BJT operates under saturation region when both the emitter-base junction and the collector-base junctions are forward biased.

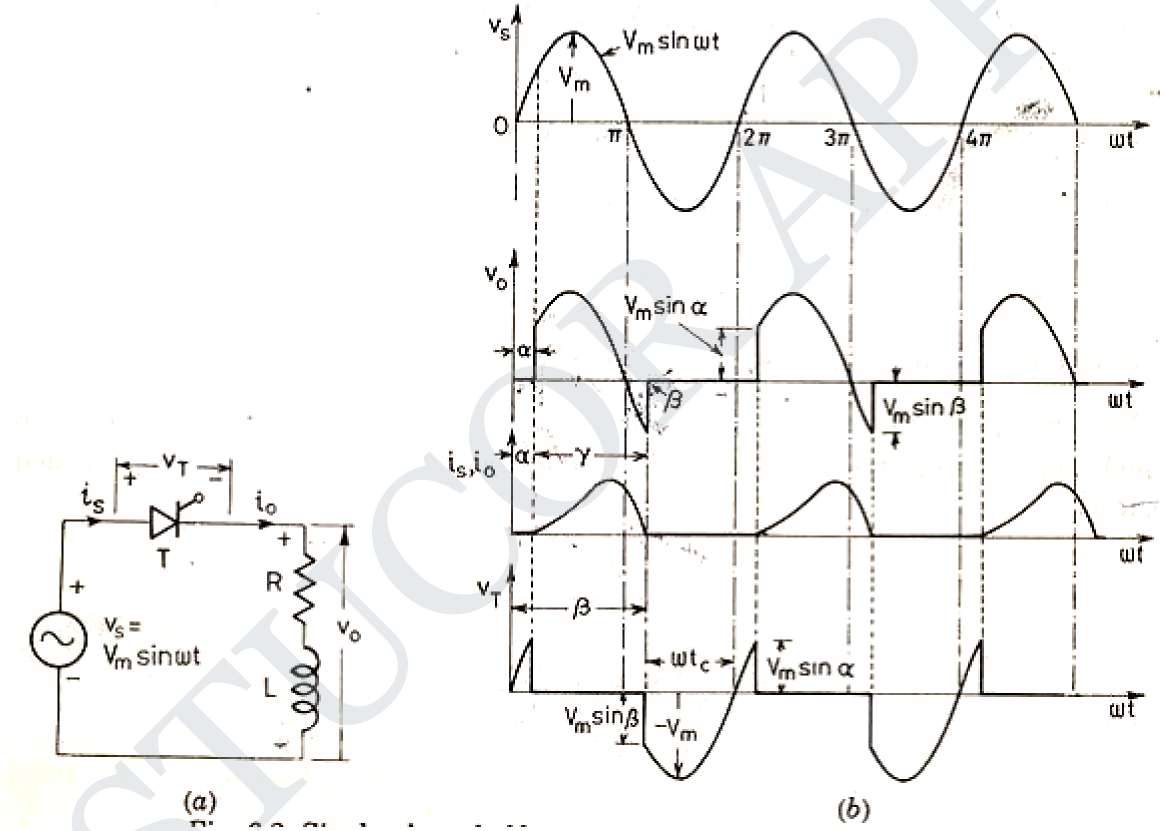
UNIT II
PHASE-CONTROLLED CONVERTERS

2.1 Introduction

`Rectifier are used to convert A.C to D.C supply.

`Rectifiers can be classified as single phase rectifier and three phase rectifier. Single phase rectifier are classified as 1-Φ half wave and 1-Φ full wave rectifier. Three phase rectifier are classified as 3-Φ half wave rectifier and 3-Φ full wave rectifier. 1-Φ Full wave rectifier are classified as1-Φmid point type and 1-Φ bridge type rectifier. 1-Φ bridge type rectifier are classified as 1-Φ half controlled and 1-Φ full controlled rectifier. 3-Φ full wave rectifier are again classified as 3-Φmid point type and 3-Φ bridge type rectifier. 3-Φ bridge type rectifier are again divided as 3-Φ half controlled rectifier and 3-Φ full controlled rectifier.

2.2Single phase half wave circuit with R-L load



Output current *io*rises gradually. After some time *io* reaches a maximum value and then begins to decrease.

At π, *vo*=0 but *io* is not zero because of the load inductance L. After π interval SCR is reverse biased but load current is not less then the holding current.

At β>π, *io* reduces to zero and SCR is turned off.

At 2π+β SCR triggers again

α is the firing angle

β is the extinction angle.

$v = \beta - \alpha = conduction\ angle$

Analysis for V_T.

At $\omega t = \square, V_T = V_m sin\square$

During $= \square\ to\ \square$, $V_T = 0$;

When $= \square$, $V_T = V_m sin\square$;

$$V_m \sin \omega t = Ri_0 + L\frac{di_0}{dt}$$

$$i_s = \frac{V_m}{\sqrt{R^2 + X^2}}\sin(\omega t - \phi)$$

Where,

$$\phi = \tan^{-1}\frac{X}{R}$$

$$X = \omega L$$

Where $\square$ is the angle by which I_s lags V_s.

The transient component can be obtained as

$$Ri_t + L\frac{di_0}{dt} = 0$$

So $i_t = Ae^{-(Rt/L)}$

$i_0 = i_s + i_t$

$$\frac{V_m}{z}\sin(\ \omega t - \square) + Ae^{-(Rt/L)}$$

Where $z = \sqrt{R^2 + X^2}$

At $\alpha = \omega t, i_o = 0$;

$$0 = \frac{V_m}{z}\sin(\ \alpha - \square) + Ae^{-(R\alpha/L\omega)};$$

$$A = \frac{-V_m}{z}\sin(\ \alpha - \square)e^{(R\alpha/L\omega)}$$

$$i_o = \frac{V_m}{z}\sin(\ \omega t - \square) - \frac{V_m}{z}\sin(\ \alpha - \square)e^{-R(\omega t - \alpha)/L\omega}$$

Therefore,

$\omega t = \beta, i_0 = 0;$

So $\sin(\beta - \alpha) = \sin(\alpha - \square)e^{-(\beta-\alpha)/(\omega L)}$

β can obtained from the above equation.

The average load voltage can be given by

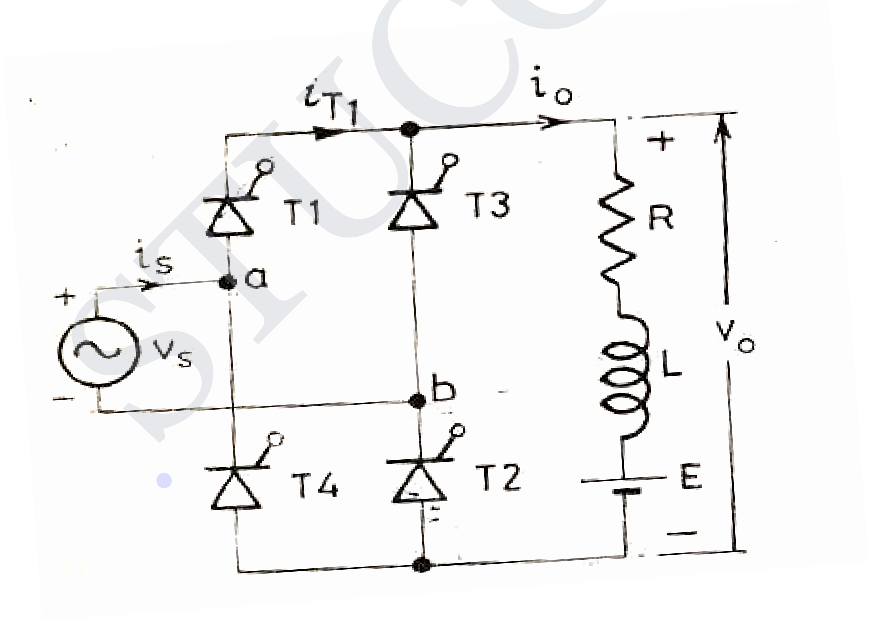
$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin\omega t d(\omega t)$$

$$\frac{V_m}{2\pi}(\cos(\alpha) - \cos(\beta))$$

Average load current

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

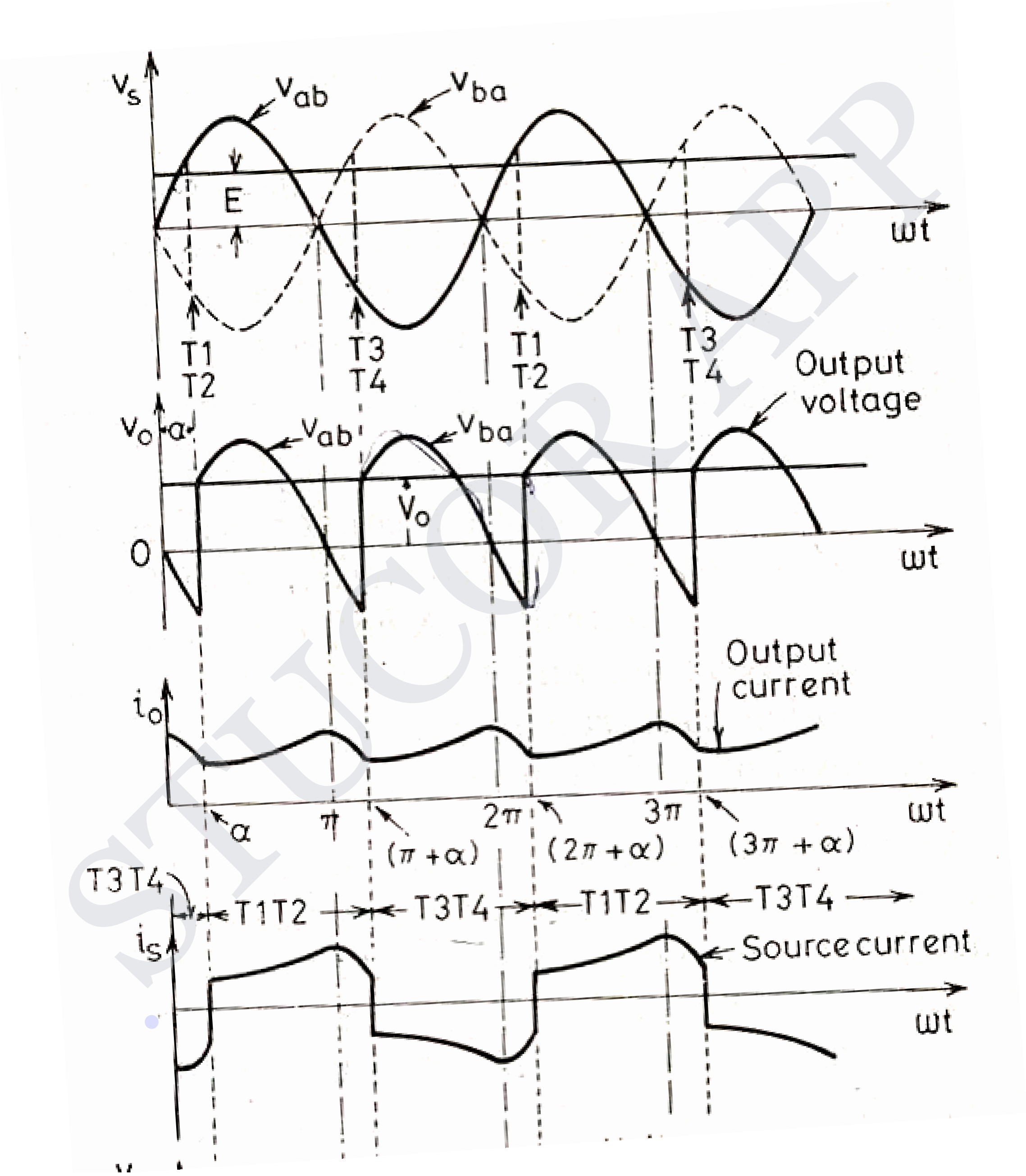
2.3 Single phase full converter



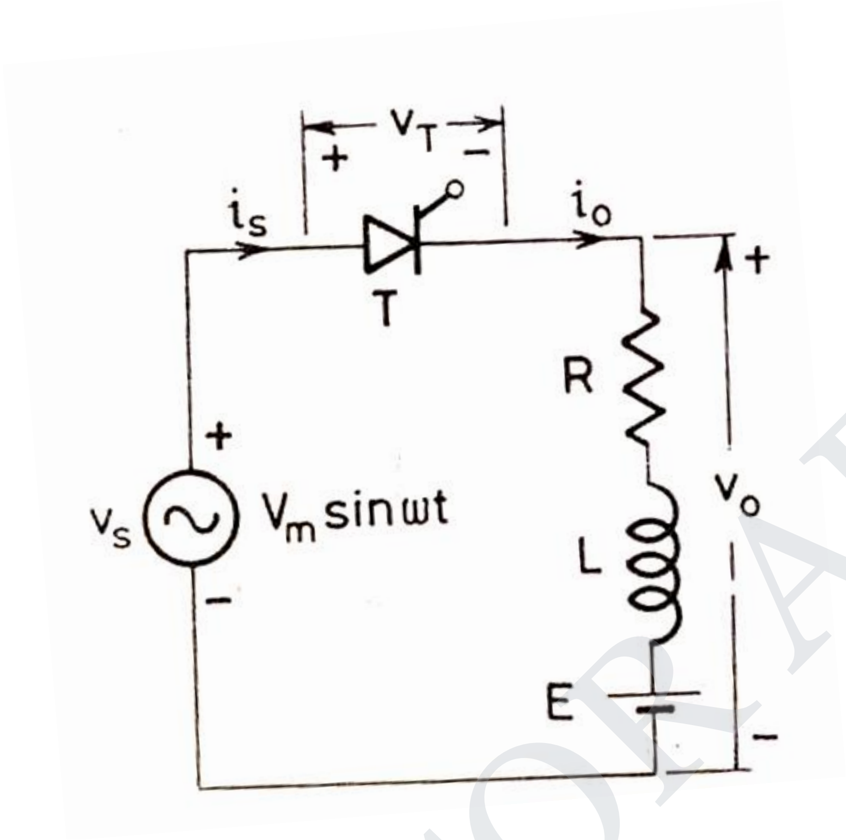
$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\beta} V_m \sin(\omega t)\,d(\omega t)$$

$$= \frac{2V_m}{\pi}\cos\alpha$$

T_1,T_2 triggered at α and π radian latter T_3, T_4 are triggered.



2.4 Single phase half wave circuit with RLE load



The minimum value of firing angle is

$$V_m \sin(\omega t) = E$$

So,

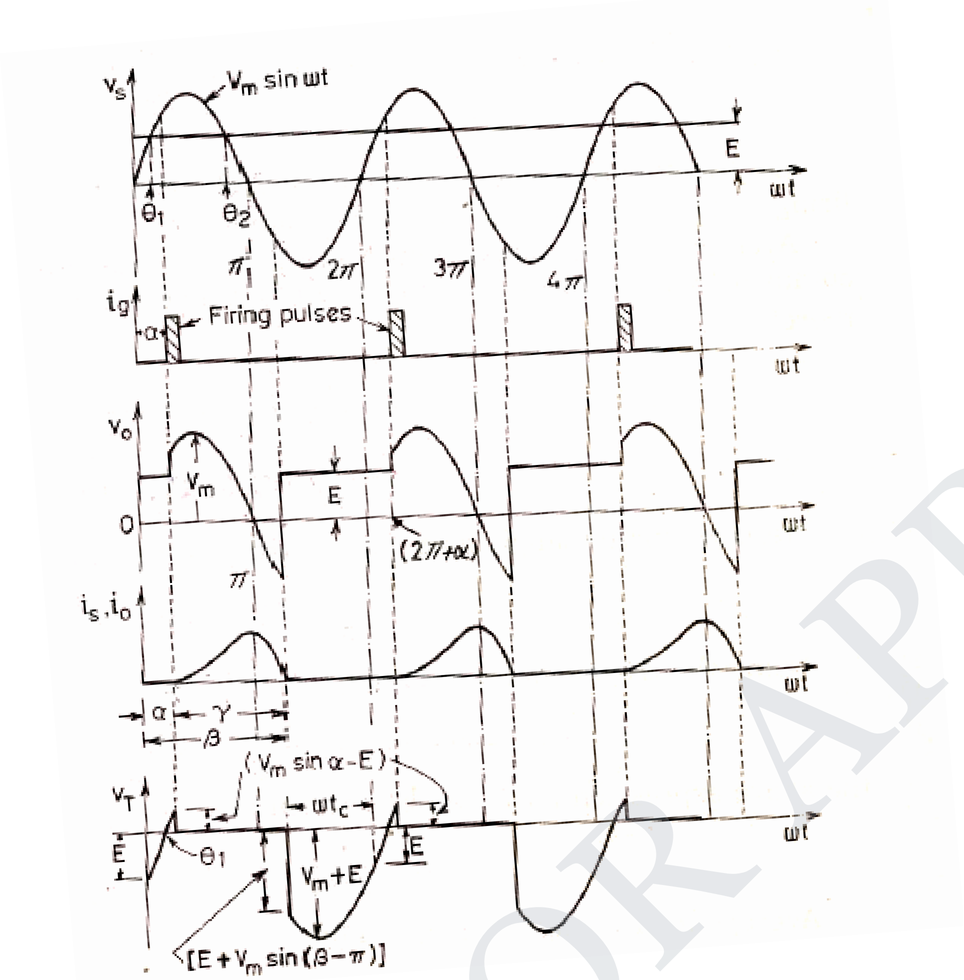
$$\theta_1 = \sin^{-1}\frac{E}{V_m}$$

Maximum value of firing angle

$$\theta_2 = \pi - \theta_2$$

The voltage differential equation is

$$V_m \sin(\omega t) = Ri_0 + L\frac{di_0}{dt} + E$$



$$i_s = i_{s1} + i_{s2}$$

Due to source volt

$$i_{s1} = \frac{V_m}{Z}\sin(\omega t - \phi)$$

Due to DC counter emf

$i_{s2} = -(E/R)$

$i_t = Ae^{-(R/L)t}$

Thus the total current is given by

$i_{s1} + i_{s2} + i_t$

$$= \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R} + Ae^{-(R/L)t}$$

$$i_{s0} = \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R} + Ae^{-(R/L)t}$$

$At\ \omega t = \alpha, i_0 = 0$

$$A = [\frac{E}{R} - \frac{V_m}{Z}\sin(\alpha - \phi)]\,\mathrm{e}^{-R\alpha/L\omega}$$

So

$$i_0 = \frac{V_m}{Z}[\sin(\omega t - \phi) - \sin(\alpha - \phi)e^{\{\frac{-R}{\omega L}(\omega t - \alpha)\}} - \frac{E}{R}[1 - e^{\{\frac{-R}{\omega L}(\omega t - \alpha)\}}]$$

Average voltage across the inductance is zero. Average value of load current is

$$\mathrm{I}_0 = \frac{1}{2\pi R}\int_{\alpha}^{\beta}(V_m \sin\omega t - E)\,\mathrm{d}(\omega t)$$

$$= \frac{1}{2\pi R}[V_m(\cos\alpha - \cos\beta) - \mathrm{E}(\beta - \alpha)]$$

Conduction angle $\nu = \beta - \alpha$

$\Rightarrow \beta = \alpha + \nu$

$$\mathrm{I}_0 = \frac{1}{2\pi R}[V_m(\cos\alpha - \cos(\alpha + \nu)) - \mathrm{E}(\nu)]$$

$$\cos A - \cos\mathrm{B} = 2\sin\frac{A+B}{2}\sin\frac{A-B}{2}$$

So

$$\mathrm{I}_0 = \frac{1}{2\pi R}[2V_m\sin(\alpha + \frac{\nu}{2})\sin\frac{\nu}{2} - E.\nu]$$

$$v = E + I_0R$$

$$= \mathrm{E} + \frac{1}{2\pi}[2V_m \sin(\alpha + \frac{v}{2}) \sin\frac{v}{2} - E.v]$$

$$= \mathrm{E}(1 - \frac{v}{2\pi}) + [\frac{V_m}{\pi}\sin(\alpha + \frac{v}{2}) \sin\frac{v}{2}]$$

If load inductance L is zero then

$$\beta = \theta_2$$

And $v = \beta - \alpha = \theta_2 - \alpha$

But $\theta_2 = \pi - \theta_1$

So $\beta = \theta_2 = \pi - \theta_1$

And $v = \pi - \theta_1 - \alpha$

So average current will be

$$\mathrm{I}_0 = \frac{1}{2\pi R}[V_m(\cos\alpha - \cos(\pi - \theta_1)) - E(\pi - \theta_1 - \alpha)]$$

So $V_0 = E + I_0R$

$$= \frac{V_m}{2\pi}(\cos\alpha + \cos\theta_1) + \frac{E}{2}(1 + \frac{\theta_1 + \alpha}{\pi})$$

For no inductance rms value of load current

$$\mathrm{I}_0 = [\frac{1}{2\pi R^2}\int_{\alpha}^{\pi-\alpha}(V_m \sin(\omega t) - E)^2 d(\omega t)]^{1/2}$$

Power delivered to load

$$P = I_{or}^2 R + I_0 E$$

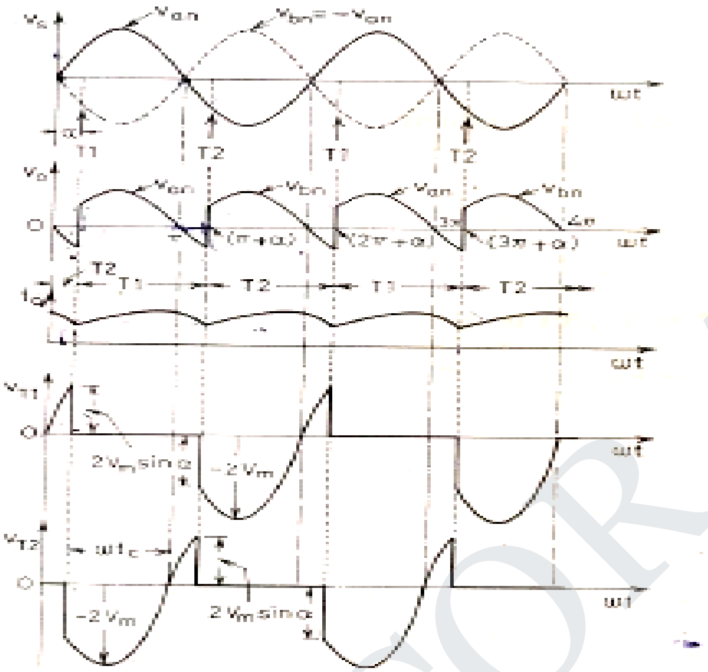
Supply power factor

$$Pf = \frac{I_{or}^2 R + I_0 E}{V_s I_{or}}$$

2.5 Single phase full wave converter:

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin(\omega t)\, d(\omega t)$$

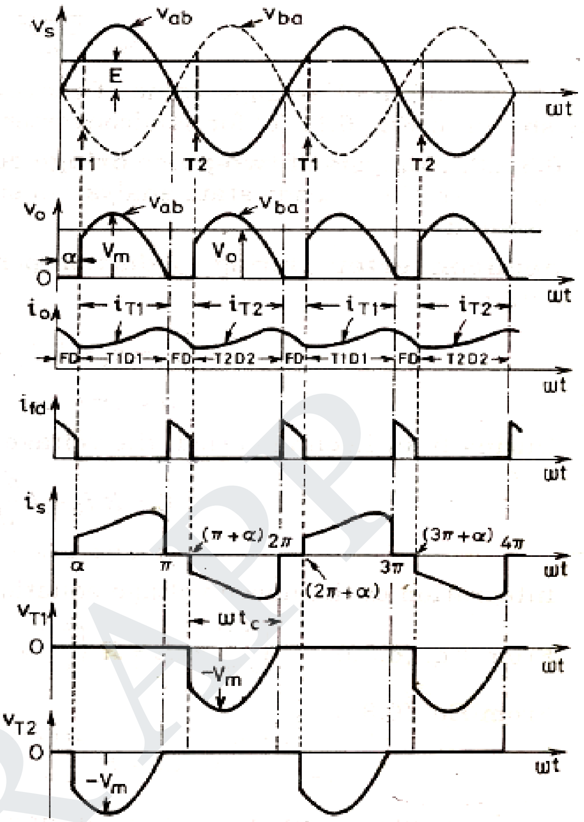
$$= \frac{2V_m}{\pi}\sin\alpha$$

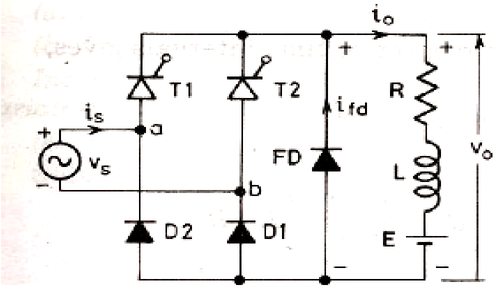


$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)\, d(\omega t)$$

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

2.6 Single phase semi converter:





steady state analysis

$$V_s = Ri_o + L\frac{di_0}{dt} + E$$

$$V_0 = RI_0 + E$$

$$V_0 = \frac{2V_m}{\pi}\cos\alpha$$

So in case of DC motor load

$$V_0 = r_a I_a + \alpha_m \omega_m$$

So $$\omega_m = \frac{\frac{2V_m}{\pi}\cos\alpha - r_a I_a}{\alpha_m}$$

$$T = \alpha_m I_a$$

$$\Rightarrow I_a = \frac{T_e}{\alpha_m}$$

Put $$I_a = \frac{T_e}{\alpha_m}$$

So $$\omega_m = \frac{(\frac{2V_m}{\pi})\cos\alpha}{\alpha_m} - \frac{r_a T_e}{\alpha_m^2}$$

Glossary

1. Rectification:

The conversion of ac to dc is known as rectification.

2. Semi-converters:

It combines the features of both controlled rectifiers (using SCR) and uncontrolled rectifiers (using diodes). The polarity of output voltage can be either positive ornegative.

3. Commutation:

It is the process of turning-off of a power semiconductor device.

4. Freewheeling diode:

A power diode connected parallel across the load to prevent the reversal of load voltage in order to improve the input power factor.

5. Ripple:

AC component present in the DC output voltage.

6. Delay angle:

It is defined as the angle between the zero crossing of the input voltage and the instant the thyristors is fired.

7. Overlap period:

The period during which both the incoming and outgoing thyristors conducts simultaneously is called overlap period.

8. Overlap angle/ commutation angle:

The angle for which both devices share conduction is known as overlap angle.

9. Input Displacement Angle:

It is the angular displacement between the fundamental component current to the line to neutral voltage of the input ac source.

10. Displacement factor:

It is defined as the cosine of the input displacement angle.

11. Distortion factor:

It is defined as the ratio of RMS amplitude of the fundamental component to the total RMS amplitude.

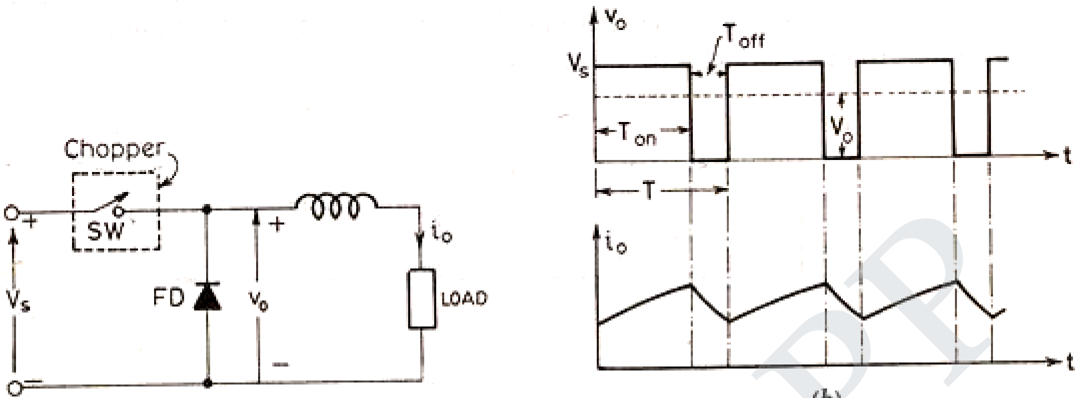
12. Harmonic Factor:

It is defined as the ratio of the total harmonic content to the fundamental component.

UNIT III
DC TO DC CONVERTER

3.1 INTRODUCTION

A chopper is a static device that converts fixed DC input voltage to variable output voltage directly. Chopper are mostly used in electric vehicle, mini haulers.
Chopper are used for speed control and braking. The systems employing chopper offer smooth control, high efficiency and have fast response



(a) (b)

The average output voltage is

$$V_a = \frac{1}{T}\int_0^{t1} V_0 dt = \frac{1}{T}V_s(t_1) = ft_1V_s = \alpha V_s$$

The average load current

$$I_a = \frac{V_a}{R} = \frac{\alpha V_s}{R}$$

Where, T=chopping period

Duty cycle of chopper =

$$\alpha = \frac{t_1}{T}$$

f=chopping frequency

The rms value of output voltage is

$$V_0 = \left(\frac{1}{T}\int_0^{\alpha} V_0^2 dt\right)^{\frac{1}{2}} = \sqrt{\alpha}V_s$$

If we consider the converter to be loss less then the input power is equal to the output power and is given by

$$P_i = \frac{1}{T}\int_0^{\alpha T} V_0 i\,dt = \frac{1}{T}\int_0^{\alpha T} \frac{V_o^{2}}{R}\,dt$$

$$= \frac{1}{T}\frac{V_s^2}{R}(\alpha T) = \frac{\alpha V_s^2}{R}$$

The effective input resistance seen by the P source is

$$P_i = \frac{V_s}{I_a} = \frac{V_s}{\frac{\alpha V_s}{R}} = \frac{R}{\alpha}$$

The duty cycle α can be varied by varying t_1 , T of frequency.

Constant frequency operation:

1)The chopping period T is kept constant and on time is varied.
The pulse width modulation ,the width of the pulse is varied.
2) Variable frequency operation, the chopping frequency f is varied.
Frequency modulation, either on time or off time is kept constant.
This type of control generate harmonics at unpredictable frequency and filter design is often difficult.

3.2 TYPES OF CHOPPER:

3.2.1FIRST QUADRANT OR TYPE A CHOPPER:

When switch ON

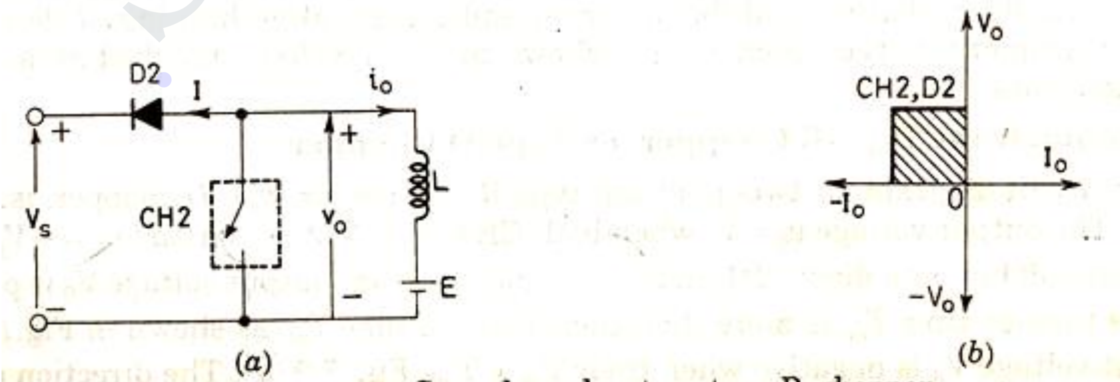
$$V_0 = V_s.$$

Current i_o flows in the same direction when switch off.

V_o=0, i_o=0

So, average value of both the load and the current are positive.

3.2.3 SECOND QUADRANT OR TYPE B CHOPPER:



Second-quadrant, or type-B, chopper.

When switch are closed the load voltage E drives current through L and switch. During on T
L stores energy.
When switch off 0 V
exceeds source voltage s V

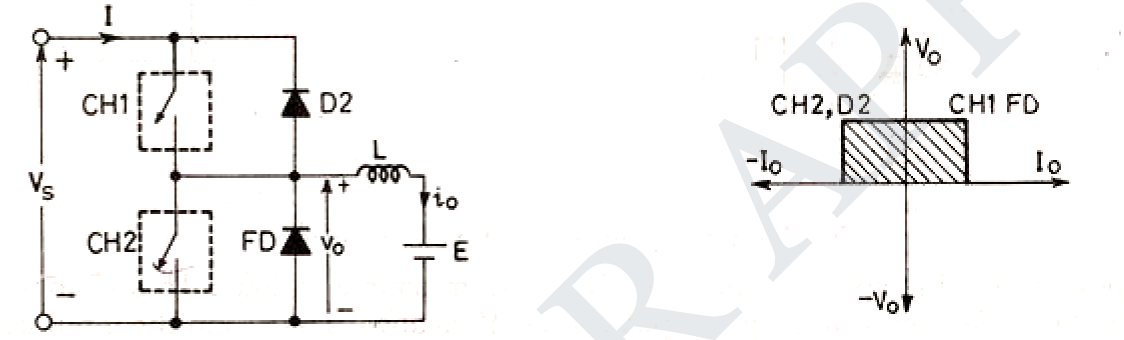
$$V_0 = E + L\frac{di}{dt}$$

.
Diode D_2 is forward biased.power is fed back to supply. As $V_0$is more than sourse voltage. So such chopper is called step up chopper.

$$V_0 = E + L\frac{di}{dt}$$

So current is always negative and V_0 is always positive.

3.3.4 TWO QUADRANT TYPE A CHOPPER OR, TYPE C CHOPPER:

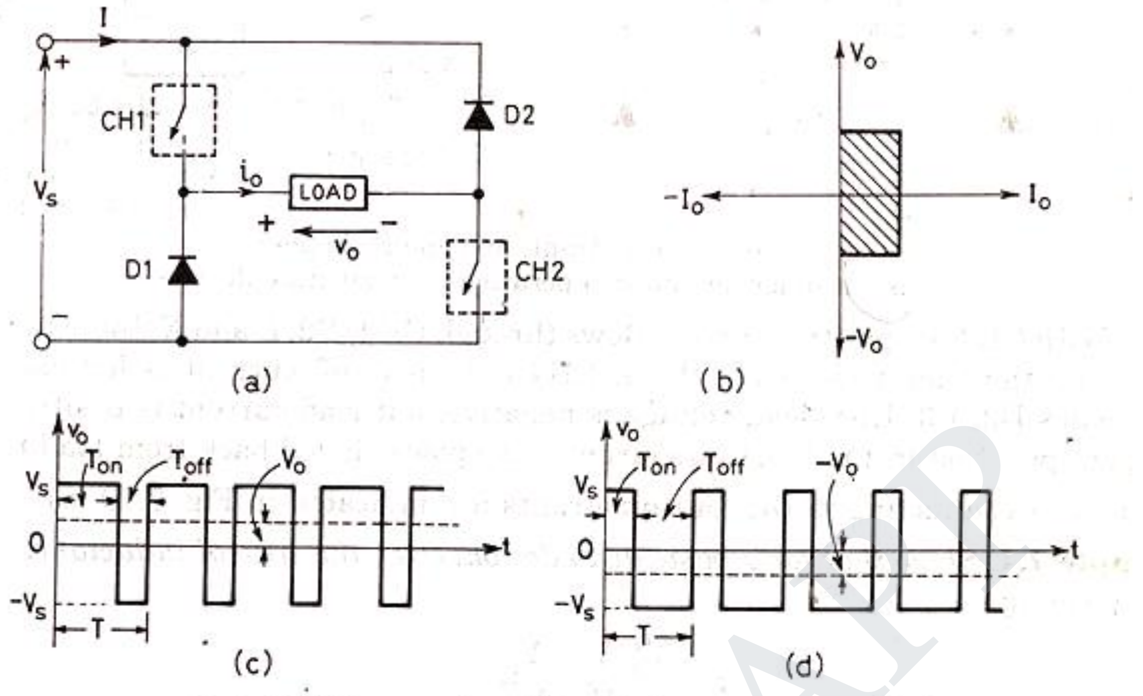


(a) (b)

Two-quadrant type-A chopper, or type-C chopper.

Both the switches never switch ON simultaneously as it lead direct short circuit of the supply.
Now when sw2 is closed or FD is on the output voltage V_0 is zero.
When sw1 is ON or diode D conducts output voltage is V_0 is +Vs'
CURRENT ANANLYSIS:
When CH1 is ON current flows along i0. When CH1 is off current continues to flow along i0 as FD is forward biased. So i0 is positive.
Now when CH2 is ON current direction will be opposite to i0. When sw2 is off D2 turns ON.
Load current is –i0. So average load voltage is always positive. Average load current may be positive or negative.

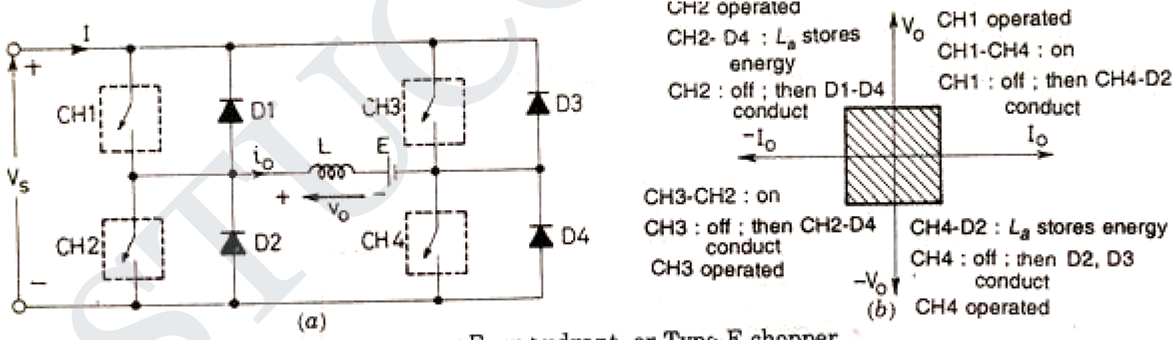
3.3.5 TWO QUADRANT TYPE B CHOPPER, OR TYPE D CHOPPER:



(*a*) and (*b*) Two-quadrant type-B chopper, or type-D chopper
(*c*) V_0 is positive, $T_{on} > T_{off}$ and (*d*) V_0 is negative, $T_{on} < T_{off}$.

When CH1 and CH2 both are on then V0=Vs.
When CH1 and CH2 are off and D1 and D2 are on V 0=-Vs.
The direction of current is always positive because chopper and diode can only conduct in the direction of arrow shown in fig.
Average voltage is positive when Ton>Toff

3.3.6 FOUR QUADRANT CHOPPER, OR TYPE E CHOPPER



Four-qudrant, or Type-E chopper
(*a*) circuit diagram and (*b*) operation of conducting devices.

FIRST QUADRANT:
CH4 is kept ON
CH3 is off
CH1 is operarted
V0=Vs
i0 = positive
when CH1 is off positive current free wheels through CH4,D2
so V0 and I2 is in first quadrant.

SECOND QUADRANT:
CH1,CH3,CH4 are off.
CH2 is operated.

Reverse current flows and I is negative through L CH2 D4 and E.
When CH2 off D1 and D4 is ON and current id fed back to source. So is more than source voltage

$$E + L\frac{di}{dt}$$ is more than source voltage V_s.

As i0 is negative and V0 is positive, so second quadrant operation.

THIRD QUADRANT:

CH1 OFF, CH2 ON
CH3 operated. So both V0 and i0 is negative.
When CH3 turned off negative current freewheels through CH2 and D4.

FOURTH QUADRANT:

CH4 is operated other are off.
Positive current flows through CH4 E L D2.
Inductance L stores energy when current fed to source through D3 and D2.V0 is negative.

3.4 STEADY STATE ANALYSIS OF PRACTICAL BUCK CHOPPER:

The voltage across the inductor L is e_l=Ldi/dt.

$$V_s - V_a = L\frac{d(i_2 - i_1)}{t_1} = L\frac{\Delta i}{t_1}$$

$$t_1 = \frac{\Delta i L}{V_s - V_a}.$$

The inductor current falls linearly from I_2 to I_1 in time t_2 as V_s=0.

So

$$-V_a = \frac{L(i_1 - i_2)}{t_2}$$

If I_2-I_1=ΔI then

$$-V_a = -\frac{L\Delta I}{t_2}$$

$$t_2 = \frac{L\Delta I}{V_a}.$$

ΔI=I_2-I_1= peak to peak ripple current.

$$\Delta I = \frac{(V_s - V_a)t_1}{L} = \frac{V_a t_2}{L}$$

Now t_1=αT, t_2=(1-α)T

$$V_a = V_s\frac{t_1}{T} = \alpha V_s$$

A<1 so it is a step down or buck converter.

If the circuit is lossless then V_sI_s=V_a I_a=αVsI_a

I_s=α I_a.

Now switching period T can be expressed as

$T=1/f= t_1+ t_2=\Delta IL/(V_s-V_a) + \Delta IL/(V_a)$

$=\Delta ILV_s/V_a(V_s-V_a)$

So peak to peak ripple current

$$\Delta I = \frac{V_a(V_s - V_a)}{fLV_s}$$

$$\Delta I = \frac{V_a\alpha(1-\alpha)}{fL}$$

The peak to peak voltage of the capacitor is

$$\Delta V_c = \frac{\Delta I}{8fc}$$

So from above equation

$$\Delta V_c = \frac{V_a(V_s - V_a)}{8Lcf^2V_s} \cdot \frac{V_s\alpha(1-\alpha)}{8Lcf^2}$$

Condition for continuous inductor current and capacitor voltage :

If I_L is the average inductor current

$\Delta I_L = 2I_L$ ....as

$V_a = \alpha V_s$

$$\frac{V_s\alpha(1-\alpha)}{fL} =$$

As $\frac{I_2 - I_1}{2} = I_L$

So $\Delta I = 2I_L$

$$\frac{V_s\alpha(1-\alpha)}{fL}$$ .....eq (2)

$$\frac{V_s\alpha(1-\alpha)}{fL} = 2I_L = 2I_a = \frac{2\alpha V_s}{R}$$ .....eq(4)

As $V_a = \alpha V_s$ so $I_a = \frac{\alpha V_s}{R}$

$$2I_a = \frac{2\alpha V_s}{R}$$

So equation 4 gives

$$L_c = \frac{(1-\alpha)R}{2f}$$

Which is the critical value of inductor

$$\Delta V_c = 2V_a$$

$$2V_a = \frac{V_s\alpha(1-\alpha)}{8Lcf^2} = 2\alpha V_s$$

$$c = \frac{1-\alpha}{16Lf^2}$$

Peak to peak ripple voltage of capacitor:

$$\Delta V_c = V_c - V_c(t=0)$$

$$= \frac{1}{c}\int_0^{t_1} I_c dt = \frac{1}{c}\int_0^{t_1} I_a = \frac{I_a t_1}{c}$$

So $t_1 = \frac{V_a - V_s}{V_{af}}$

$$t_1 = \frac{V_a - V_s}{V_{af}}$$

$$\Rightarrow 1-\alpha = \frac{V_s}{V_a}$$

$$\Rightarrow 1-\frac{t_1}{T} = \frac{V_s}{V_a}$$

$$\Rightarrow t_1 = \frac{V_a - V_s}{V_a f}$$

So $\Delta V_c = \frac{I_a}{c}(\frac{V_a - V_s}{V_{af}})$

$$\Rightarrow \Delta V_c = \frac{I_a \alpha}{fc}$$

Condition for continuous imductor current and capacitor voltage:

If I_L= average inductor current then

$$I_L = \frac{\Delta I}{2}$$

$$\Delta I = \frac{V_s \alpha}{fL} = 2I_L = 2I_a = \frac{2V_s}{(1-\alpha)R}$$

As $V_a = \frac{V_s}{1-\alpha}$

$$\Rightarrow 2I_a = \frac{2V_s}{(1-\alpha)\mathrm{R}}$$

So $\Delta I_L = 2I_L = 2I_a = \frac{2V_s}{(1-\alpha)R} = \frac{V_s \alpha}{fL}$

$$\Rightarrow L_c = \frac{\alpha(1-a)R}{2f}$$

$$\Delta V_c = 2V_a$$

$$\frac{I_a \alpha}{cf} = 2V_a = 2I_a R$$

$$c = \frac{\alpha}{2fR}$$

Glossary

1. Chopper:

It is a dc-dc converter which converts fixed dc voltage to variable dc voltage.

2. Duty Cycle:

The output voltage of the chopper can be controlled by varying (On and Off of the semiconductor switch) the duty cycle of the chopper.

3. Time-Ratio control:

It is achieved by varying the T_{on} / T control.

4. Current Limit control:

In this control strategy chopper is switched On and Off so that the current in the load is maintained between two limits. (Min. current when the chopper is On and Max. current when the chopper is Off)

5. Step-up Chopper:

When the output voltage is greater than the input ($E_0>E_{dc}$), it corresponds to step-up operation.

6. Breaking:

It is the process of stopping the machine which is under motion.

7. Commutation:

It is the process of turning-off of a power semiconductor device.

8. Forced commutation:

In this process, current through a power semiconductor device is forced to become zero to turn-off.

9. Voltage commutation:

In this process, a charged capacitor momentarily reverse biases the conducting device and it turns off.

10. Current commutation:

In this process, a current pulse is forced in the reverse direction through the conducting device. Now the net current (forward and reverse current direction devices) becomes zero and the device is turned off.

11. Load commutation: In this process, the load current flowing through the device either becomes zero or is transferred to another device from the conducting device.

13. Harmonic Factor:

It is defined as the ratio of the total harmonic content to the fundamental component.

14. Ac regulators:

It converts fixed ac supply voltage and frequency to variable ac voltage without change in supply frequency.

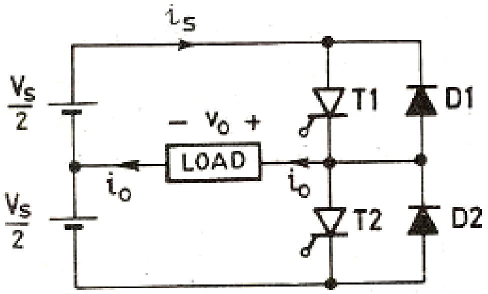
15. Cyclo-converters:

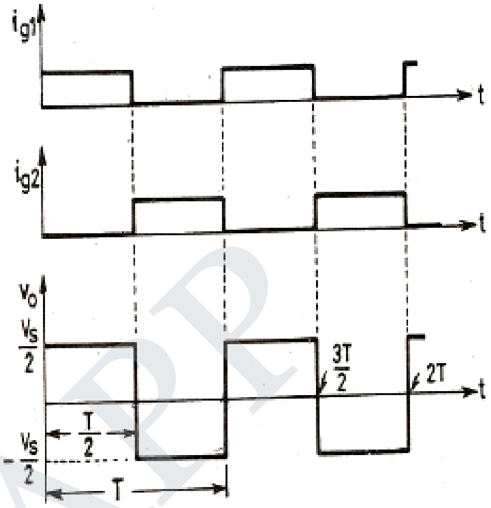
It converts fixed ac supply voltage and frequency to variable ac load frequency without change in supply voltage.

UNIT IV
INVERTERS

The device that converts dc power into ac power at desired output voltage and frequency is called an inverter.

4.1 Single phase voltage source inverters





$$V_o(rms) = \frac{1}{T_0/2}\int_0^{T_0/2}\frac{V_S^2}{4}\,dt = \frac{V_S}{2}$$

$$V_0 = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n\cos(n\omega t) + b_n\sin(n\omega t))$$

Due to symmetry along x-axis

$$a_0 = 0\ ,\ a_n = 0$$

$$b_n = \frac{4V_S}{n\pi}$$

The instantaneous output voltage

$$v_0 = \sum_{n=1,3,5\ldots}^{\infty}\frac{2V_S}{n\pi}\sin(nwt)$$

=0, n=2,4.....

The rms value of the fundamental output voltage

$$V_{01} = \frac{2V_S}{\sqrt{2}\pi} = 0.45V_S$$

So if $V_0 = \sum_{n=1,3,5...}^{\infty} \frac{2V_S}{n\pi}\sin(nwt)$

$$=\sum_{n=1,3,5....}^{\infty} \frac{2V_S}{n\pi\sqrt{R^2+(n\omega L)^2}}\sin(n\omega t-\theta_n)$$

$$P_{01} = (I_{01})^2R = \left[\frac{2V_S}{\sqrt{2}\pi\sqrt{R^2+(\omega L)^2}}\right]^2\mathrm{R}$$

DC Supply Current

Assuming a lossless inverter, the ac power absorbed by the load must be equal to the average power supplied by the dc source.

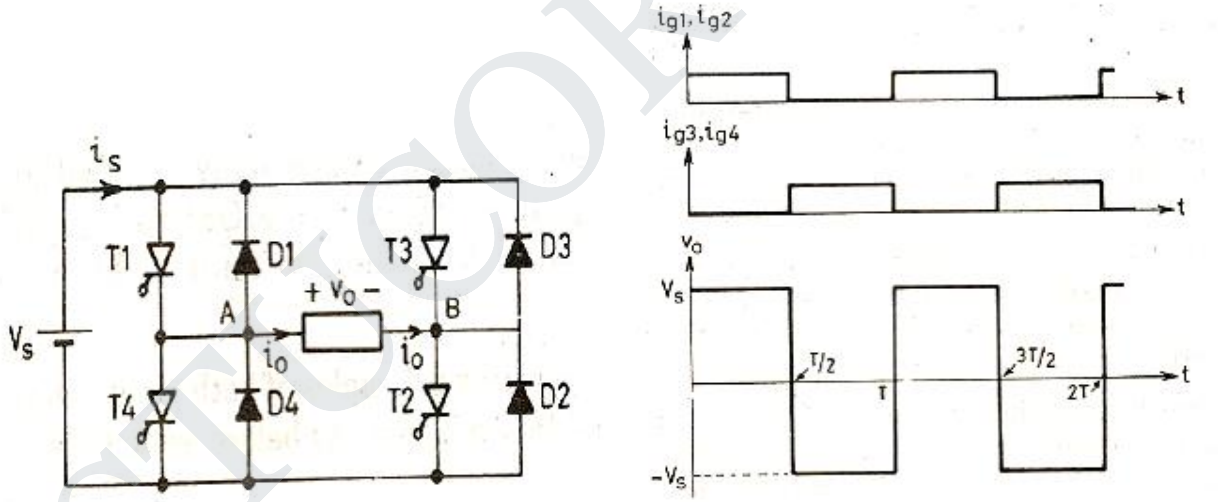
$$\int_0^T i_s(t)dt = \frac{1}{V_S}\int_0^T \sqrt{2}V_{01}\sin(\omega t)\,\sqrt{2}I_0\sin(\omega t-\theta_1)\,dt=I_S$$

V_{01} =Fundamental rms output output voltage

I_0=rms load current

θ_1=the load angle at the fundamental frequency

4.2 Single phase full bridge inverter



For n=1, $V_1 = \frac{4V_S}{\sqrt{2}V_S}$=$0.9V_S$ (The rms of fundamental)

Instantaneous load current i_0 for an RL load

$$i_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_S}{n\pi\sqrt{R^2+(n\omega L)^2}}\sin(n\omega t - \theta_n)$$

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

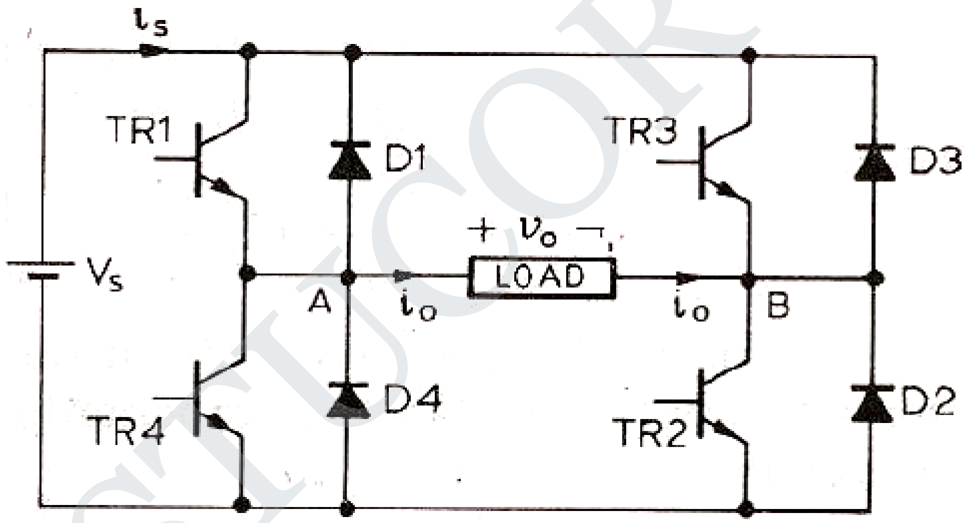
The rms output voltage is

$$V_0 = \left(\frac{2}{T_0}\int_0^{T/2} V_S^2\right)^{1/2} = V_S$$

The instantaneous output voltage in a fourier series

$$v_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_S}{n\pi}\sin(n\omega t)$$

Single phase bridge inverter



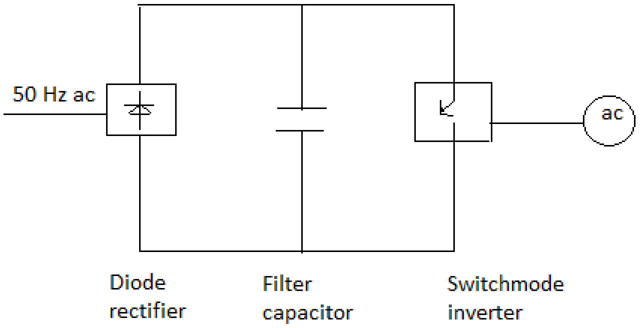
4.3 Types Of Inverter

Inverters are of the two types

1) VSI

2) CSI

4.3.1 Pulse width model



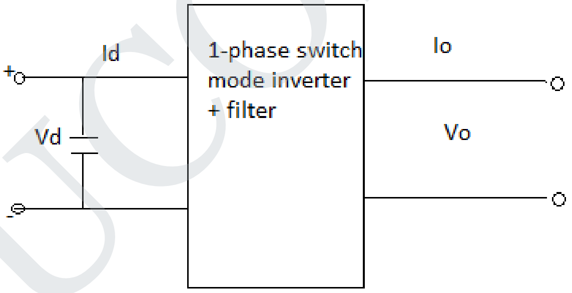
The VSI can be further divided into general 3 categories:

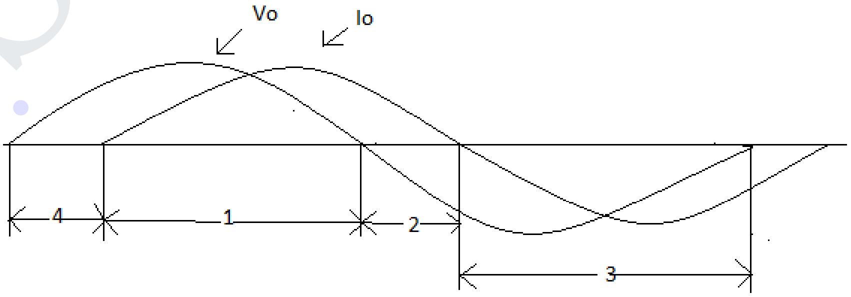
1.Pulse width modulated inverters
2.Square wave inverters
3.Single phase inverter with voltage cancellation

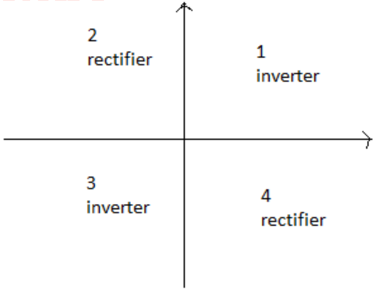
4.3.1.1 Pulse width modulated inverters

The input dc voltage is of constant magnitude . The diode rectifier is used to rectify the line voltage. The inverter control the magnitude and frequency of the ac output voltage. This is achieved by PWM technique of inverter switches and this is called PWM inverters. The sinusoidal PWM technique is one of the PWM technique to shape the output voltage to as close as sinusoidal output.

Basic concepts of switch mode inverter







During interval 1 $v0$and $i0$ both are positive
During interval 3 $v0$ and $i0$ both are negative
Therefore during 1 and 3 the instantaneous power flow is from dc side to corresponding to inverter mode of operation.
In contrast during interval 2 and 4 $v0$ and $i0$ are of opposite sign i.e. power flows from ac side to dc side corresponding to rectifier mode of operation.

4.3.1.2 Pulse width modulated switching scheme

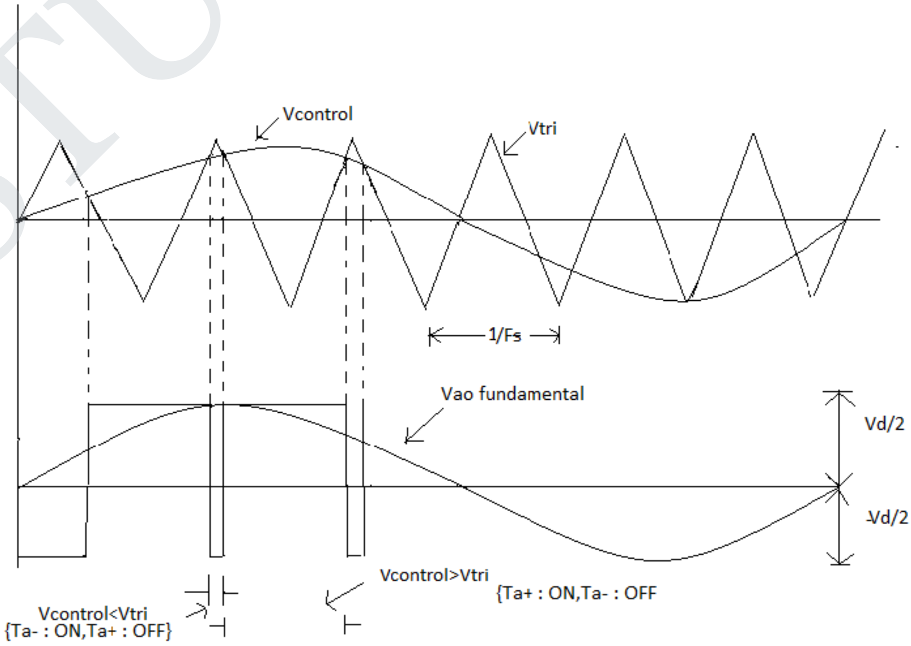
We require the inverter output to be sinusoidal with magnitude and frequency controllable. In order to produce sinusoidal output voltage at desired frequency a sinusoidal control signal at desired frequency is compared with a triangular waveform as show. The frequency of the triangular waveform established the inverter switching frequency. The triangular waveform is called carrier waveform. The triangular waveform establishes switching frequency , which establishes with which the inverter switches are applied.

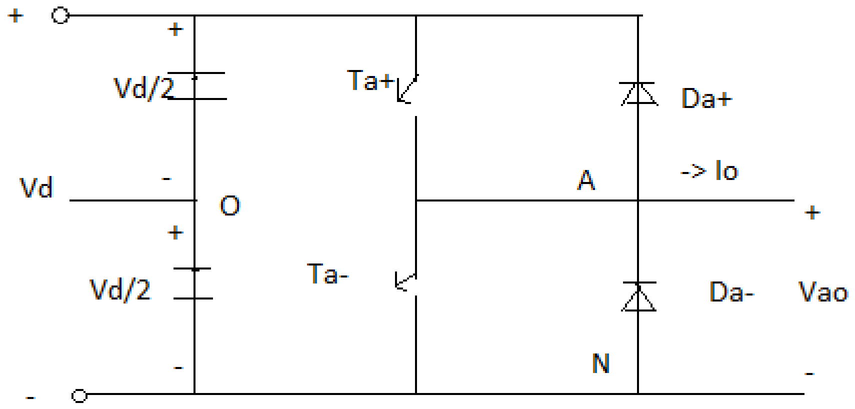
The control signal has frequency fs and is used to modulate the switch duty ratio. $f1$ is the desired fundamental frequency of the output voltage.
The amplitude modulation ratio ma is defined as

$$m_a = \frac{V_{control}}{V_{tri}}$$

$Vcontrol$ is the peak amplitude of control signal.
$Vtri$peak amplitude of triangular signal.
The frequency modulation ratio mf

$$m_f = \frac{f_s}{f_1}$$





When $V_{control} > V_{tri}$ T_A^+ is ON $V_{AO} = \frac{1}{2}V_d$

$V_{control} < V_{tri}$ T_A^- is ON $V_{AO} = \frac{1}{2}V_d$

So the following inferences can be drawn

The peak amplitude of fundamental frequency is m_a times $\frac{1}{2}V_d$

$V_{AO} = m_a \frac{v_d}{2}$

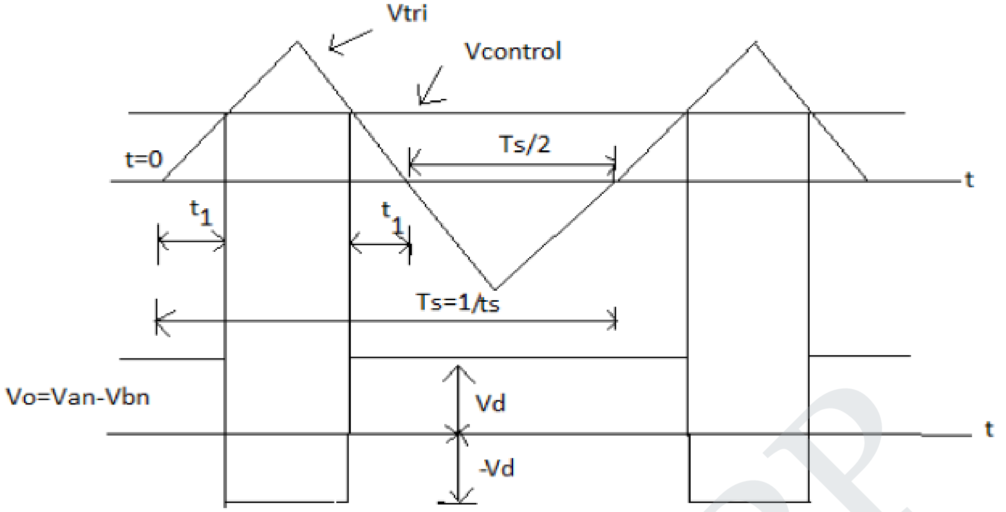
$V_{AO} = \frac{V_{control}}{\hat{V}_{tri}} * \frac{V_d}{2}$ $V_{control} \leq \hat{V}_{tri}$

<u>The foregoing arguments shown why $V_{control}$ is chosen to be sinusoidal to provide sinusoidal output voltage with fewer harmonics</u>

Let the $V_{control}$ vary sinusoidal with frequency f_1,which is the desired frequency of the inverter output voltage.

Let $V_{control} = \hat{V}_{control} \sin\omega_1 t$

$\hat{V}_{control} \leq \hat{V}_{tri}$



$\frac{\hat{v}_{tri}}{t_1}=\frac{\hat{V}_{tri}}{T_S/4}$

At t=t_1 , $v_{tri}=v_{control}$

So $\frac{v_{control}}{t_1}=\frac{\hat{V}_{tri}}{T_S/4}$

$t_1=\frac{\hat{v}_{control}}{\hat{V}_{tri}}*\frac{T_S}{4}$

$T_{on}=2t_1+\frac{T_S}{2}$

$D_1=\frac{T_{on}}{T_S}=\frac{2t_1+\frac{T_S}{2}}{2}$

$=\frac{1}{2}+\frac{2t_1}{T_S}$

$D_1=\frac{1}{2}+\frac{1}{2}(\frac{\hat{v}_{control}}{\hat{V}_{tri}})$

4.3.1.3 Three phase inverter

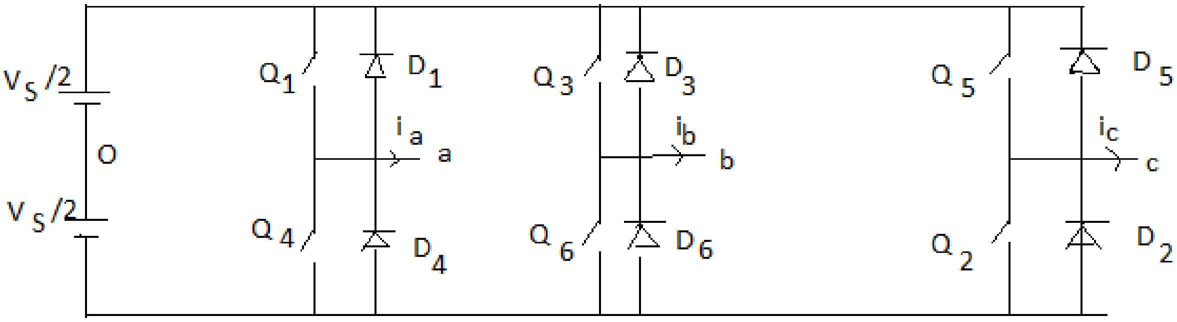
When three single-phase inverters are connected in parallel a three phase inverter is formed.

The gating signal has to be displaced by 1200 with respect to each other so as achieve three phase balanced voltages.

A 3-phase output can be achieved from a configuration of six transistors and six diodes.

Two type of control signal can be applied to transistors, they are such as 180 or 120 conduction.

4.4 180-degree conduction

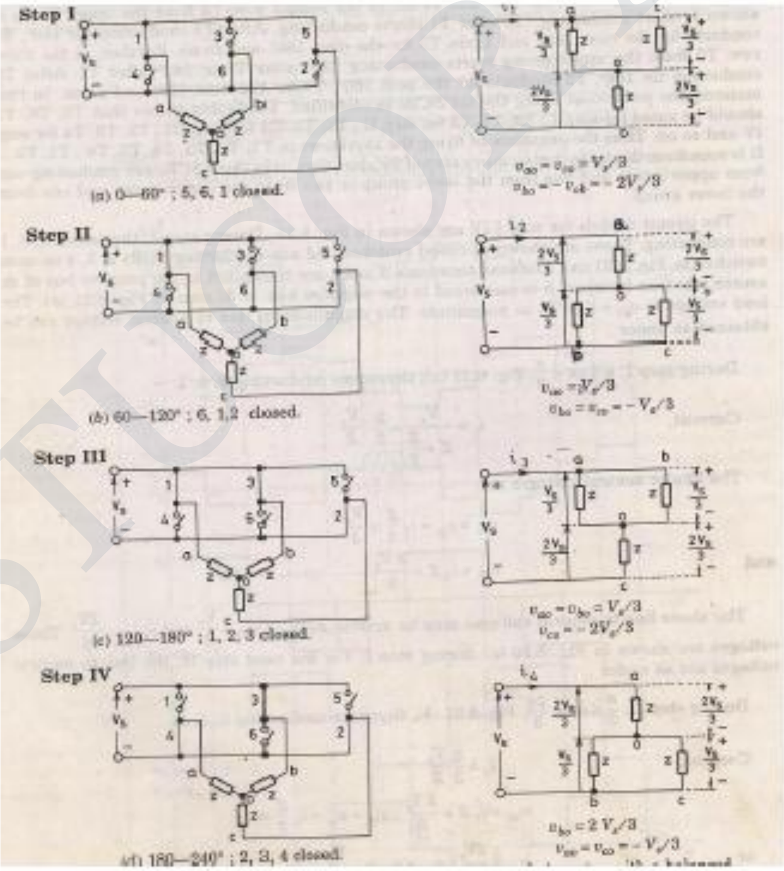


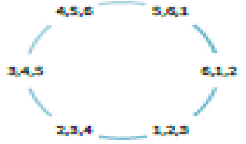
When When$Q1$ is switched on, terminal a is connected to the positive terminal of dc input voltage.

When $Q4$ is switched on terminal a is brought to negative terminal of the dc source.

There are 6 modes of operation is a cycle and the duration of each mode is 600.

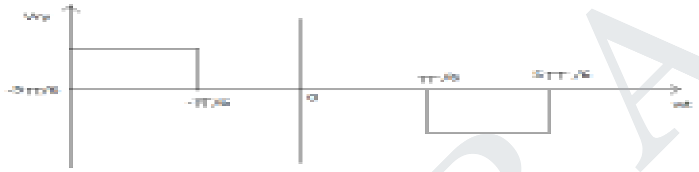
The conduction sequence of transistors is 123,234,345,456,561,612. The gating signals are shifted from each other by 600 to get 3-φ balanced voltages.Switching states for the three phase voltage inverters





V_{RN}	V_{YN}	V_{BN}	V_{RY}	V_{YB}	V_{BR}	V_1
$\frac{V}{3}$	$\frac{-2V}{3}$	$\frac{V}{3}$	V_{dc}	$-V_{dc}$	0	$\frac{2}{\sqrt{3}}(330^\circ)$
$\frac{2V}{3}$	$\frac{-V}{3}$	$\frac{-V}{3}$	V_{dc}	0	$-V_{dc}$	$\frac{2}{\sqrt{3}}(30^\circ)$
$\frac{V}{3}$	$\frac{V}{3}$	$\frac{-2V}{3}$	0	V	-V	$\frac{2}{\sqrt{3}}(90^\circ)$
$\frac{-V}{3}$	$\frac{2V}{3}$	$\frac{-V}{3}$	-V	V	0	$\frac{2}{\sqrt{3}}(150^\circ)$
$\frac{-2V}{3}$	$\frac{V}{3}$	$\frac{V}{3}$	-V	0	0	$\frac{2}{\sqrt{3}}(210^\circ)$
$\frac{-V}{3}$	$\frac{-V}{3}$	$\frac{2V}{3}$	0	-V	0	$\frac{2}{\sqrt{3}}(270^\circ)$

Fourier analysis



If we go for harmonic analysis $V_{RY}=\sum_{n=1,3,5...}^{\infty}\frac{4V}{n\pi}\sin\frac{n\pi}{3}\sin n(\omega t+\pi/6)$

$$V_{YB}=\sum_{n=1,3,5...}^{\infty}\frac{4V_s}{n\pi}\sin\frac{n\pi}{3}\sin n(\omega t-\pi/2)$$

$$V_{BR}=\sum_{n=1,3,5...}^{\infty}\frac{4V_s}{n\pi}\sin\frac{n\pi}{3}\sin n(\omega t-\pi/6)$$

All even harmonics are zero all triple n harmonics are zero.

The rms nth component of the line voltage is

$=\frac{4V}{\sqrt{2}n\pi}\sin\frac{n\pi}{3}=\frac{4V}{\sqrt{2}\pi}\sin(60)$

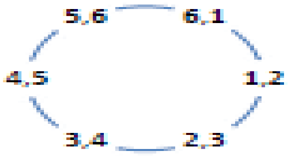
For n=1

$=0.7797V_s$

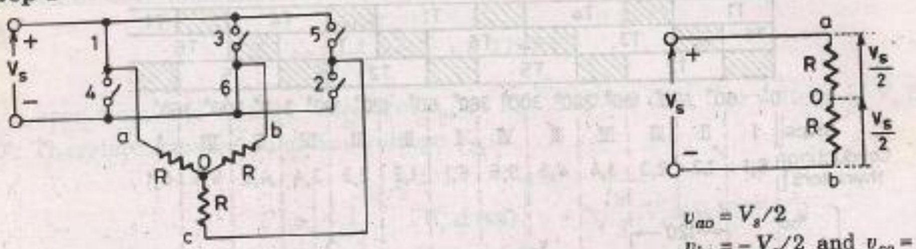
Three phase 120^0 mode VSI

The circuit diagram is same as that for 180^0 mode of conduction.

Here each thyristor conducts for 120^0.There are 6 steps each of 60^0 duration, for completing one cycle of ac output voltage.



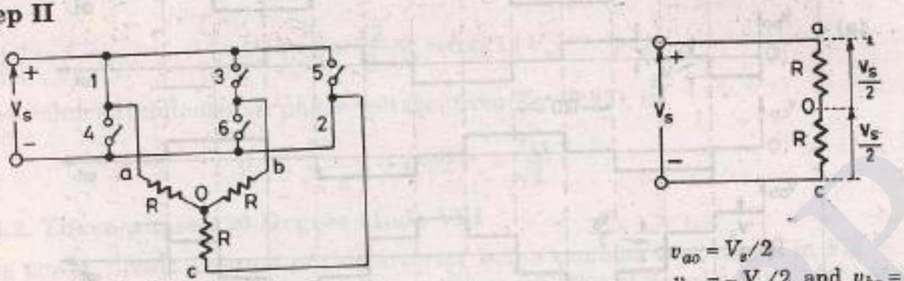
Step I



$v_{ao} = V_s/2$
$v_{bo} = -V_s/2$ and $v_{co} = 0$

(*a*) 0—60° ; 6, 1 closed

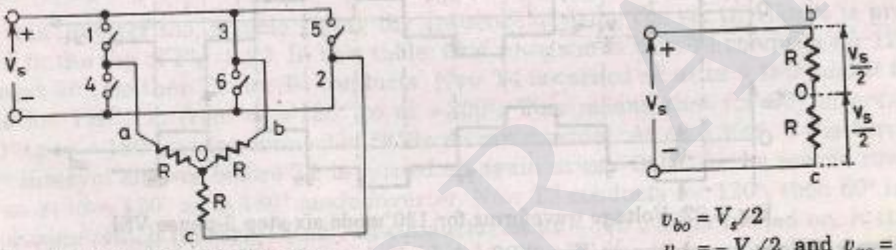
Step II



$v_{ao} = V_s/2$
$v_{co} = -V_s/2$ and $v_{bo} = 0$

(*b*) 60—120° ; 1, 2 closed

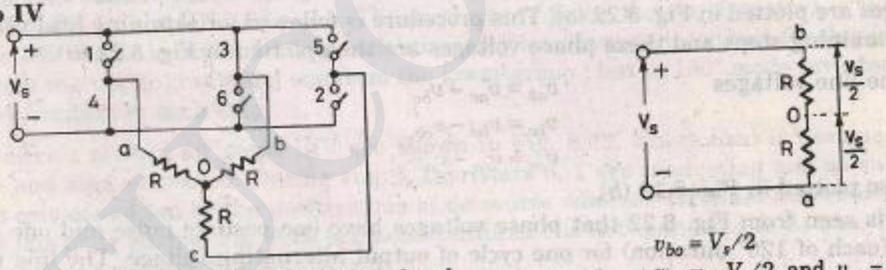
Step III



$v_{bo} = V_s/2$
$v_{co} = -V_s/2$ and $v_{ao} = 0$

(*c*) 120—180° ; 2, 3 closed

Step IV



$v_{bo} = V_s/2$
$v_{ao} = -V_s/2$ and $v_{co} = 0$

(*d*) 180—240° ; 3, 4 closed

Step 1: 6,1 conducting

$$V_{an} = \frac{V_S}{2}, V_{yn} = \frac{-V_S}{2}, V_{cn}=0$$

Step 2: 1,2 conducting

$V_{an} = \frac{V_S}{2}, V_{bn} = 0, V_{cn} = \frac{-V_S}{2}$

Step 3: 2,3 conducting

$V_{an} = 0, V_{bn} = \frac{V_S}{2}, V_{cn} = \frac{-V_S}{2}$

Step 4: 3,4 conducting

$V_{an} = \frac{-V_S}{2}, V_{bn} = \frac{V_S}{2}, V_{cn} = 0$

Step 5: 4,5 conducting

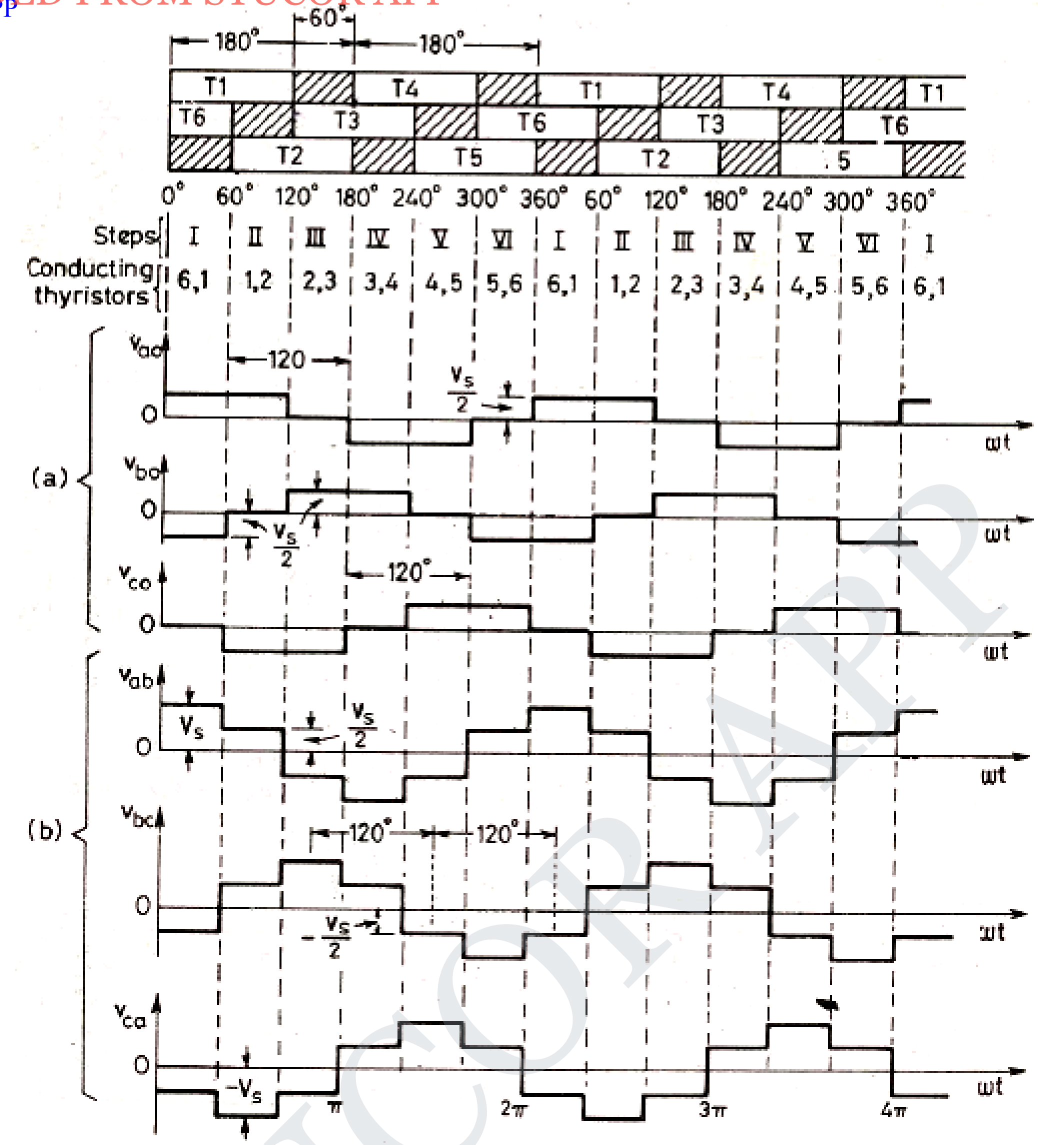
$V_{an} == \frac{-V_S}{2}, V_{yn} = 0, V_{bn} = \frac{V_S}{2}$

Step 6: 5,6 conducting

$V_{an} = 0, V_{bn} = \frac{-V_S}{2}, V_{cn} = \frac{V_S}{2}$

120^0 conduction mode

Step	Thyristor conducting	V_{Rn}	V_{Yn}	V_{Bn}	$\vec{v}$
1	6,1	$V_s/2$	$-V_s/2$	0	$\frac{\sqrt{3}V_S}{2}(-30^0)$
2	1,2	$V_s/2$	0	$-V_s/2$	$\frac{\sqrt{3}V_S}{2}(30^0)$
3	2,3	0	$V_s/2$	$-V_s/2$	$\frac{\sqrt{3}V_S}{2}(90^0)$
4	3,4	$-V_s/2$	$V_s/2$	0	$\frac{\sqrt{3}V_S}{2}(150^0)$
5	4,5	$-V_s/2$	0	$V_s/2$	$\frac{\sqrt{3}V}{2}(210^0)$
6	5,6	0	$-V_s/2$	$V_s/2$	$\frac{\sqrt{3}V}{2}(-30^0)$


180°
60°
180°
T1
T4
T1
T4
T1
T6
T3
T6
T3
T6
T2
T5
T2
5
0°
60°
120°
180°
240°
300°
360°
60°
120°
180°
240°
300°
360°
Steps
I
II
III
IV
V
VI
I
II
III
IV
V
VI
I
Conducting thyristors
6,1
1,2
2,3
3,4
4,5
5,6
6,1
1,2
2,3
3,4
4,5
5,6
6,1
(a)
v_ao
120
V_s/2
O
ωt
v_bo
V_s/2
v_co
120°
(b)
v_ab
V_s
V_s/2
v_bc
120°
120°
V_s/2
v_ca
−V_s
π
2π
3π
4π

Glossary

1. Inverters:

Inverters are those which convert fixed dc voltage to variable ac output voltage and frequency.

2. Harmonics:

Harmonics are generated in the power electronic circuit due to the frequent turn-on and turn-off of the semiconductor devices. Due to this disturbances in the circuit, it causes fluctuations in the supply voltage, torque pulsations, low power factor, , increase of losses, less efficiency, etc.

3. PWM Technique:

In this technique, a fixed dc voltage is applied to the inverter as a input and a controlled ac output voltage is obtained by adjusting the ON and OFF period of the inverter devices.

4. Single-PWM:

In this scheme, there is only one pulse per half cycle and the width of the pulse is varied to control the inverter output voltage.

5. Multiple-PWM:

In this scheme, there are several pulses in each half cycle and the width of the pulse is varied to control the inverter output voltage. This method permits reduction in harmonic content up to low output voltage.

6. Comparator:

OP-amp acts as a comparator, which compares the carrier triangular signal and a dc reference signal.

7. Pulse Generator:

It generates trigger pulses/firing pulses; in order to turn-on the switching/power semiconductor devices.

8. Voltage source inverter:

In VSI the input dc voltage remains constant at low input impedance irrespective of ac voltage delivered to load.

9. Utility Factor:

It is the ratio of power delivered by the three-phase inverter when the load is 3-Φ balanced to the total power rating of all switching devices of the bridges.

10. Current source inverter:

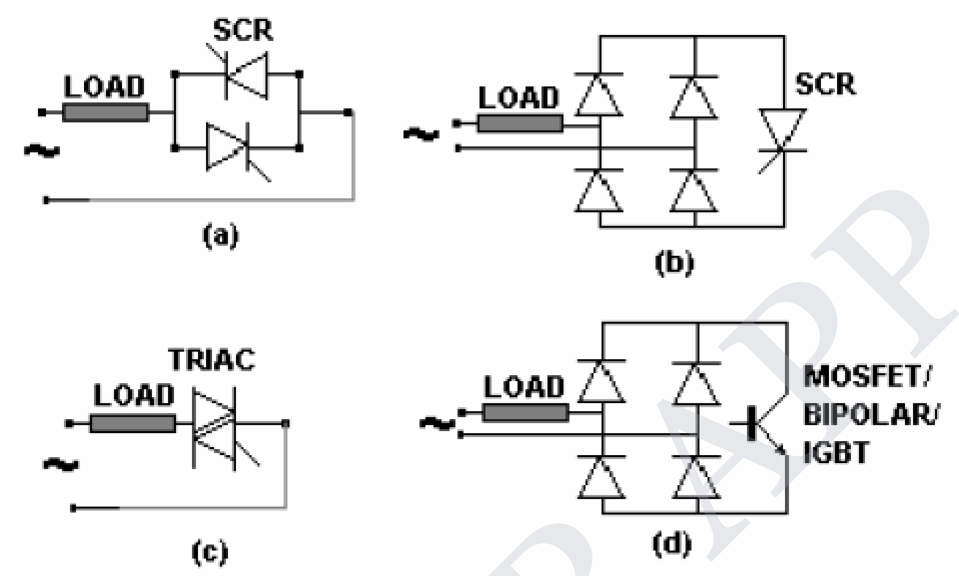
In CSI the input dc current from the dc source is maintained at an effectively constant level at high input impedance irrespective of load.

UNIT V

AC TO AC CONVERTERS

5.1 Introduction

AC to AC voltage converters operates on the AC mains essentially to regulate the output voltage. Portions of 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 the development of the semiconductor devices.



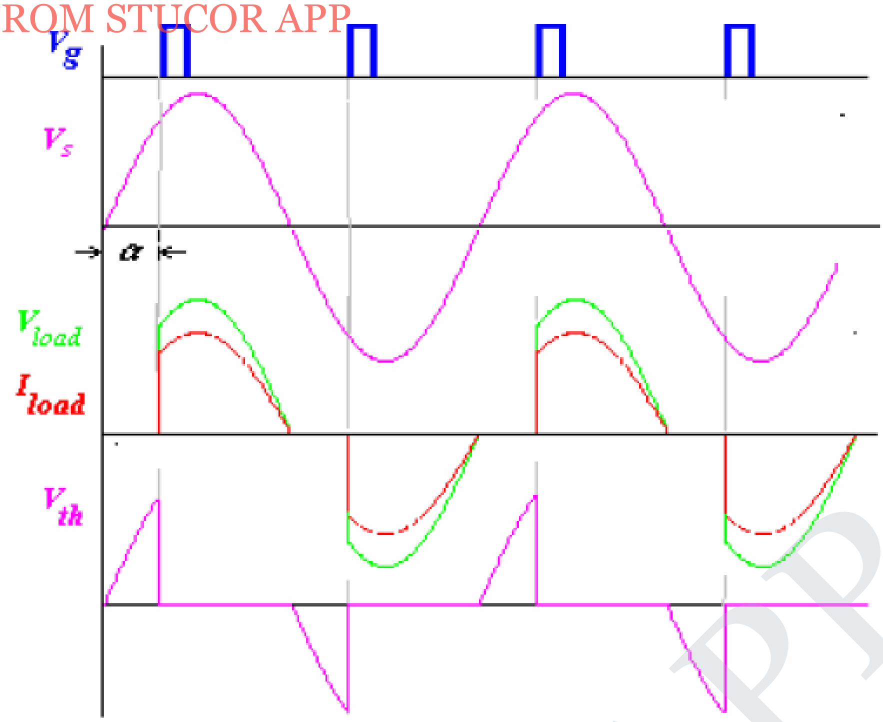
Some single phase AC-AC voltage regulator topologies. (a) Back-to-back SCR; (b) One SCR in (a) replaced by a four-diode full wave diode bridge; (c) A bi-directionally conducting TRIAC; (d) The SCR in (b) replaced by a transistor.

They are called Phase Angle Controlled (PAC) AC-AC converters or AC-AC choppers. The TRIAC based converter may be considered as the basic topology. Being bi-directionally conducting devices, they act on both polarities of the applied voltage. However, $dv/dt_{re-applied}$ their ratings being poor, they tend to turn-on in the opposite direction just subsequent to their turn-off with an inductive load. The 'Alternistor' was developed with improved features but was not popular. The TRIAC is common only at the low power ranges. The (a) and (b) options are improvements on (c) mostly regarding current handling and turn-off-able current rating.

A transistorised AC-AC regulator is a PWM regulator similar to the DC-DC converters. It also requires a freewheeling path across the inductive load, which has also got to be bi-directional. Consequently, only controlled freewheeling devices can be used.

Operation with resistive loads

The device(s) is triggered at a phase-angle 'α' in each cycle. The current follows the voltage wave shape in each half and extinguishes itself at the zero crossings of the supply voltage. In the two-SCR topology, one SCR is positively biased in each half of the supply voltage. There is no scope for conduction overlap of the devices. A single pulse is sufficient to trigger the controlled devices with a resistive load. In the diode-SCR topology, two diodes are forward biased in each half. The SCR always receives a DC voltage and does not distinguish the polarity of the supply. It is thus always forward biased. The bi-directional TRIAC is also forward biased for both polarities of the supply voltage.

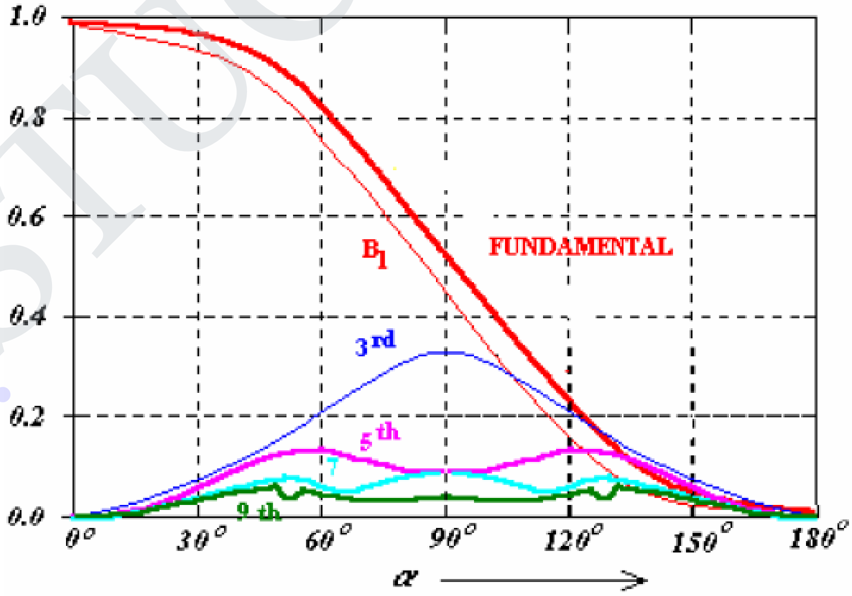


Operation of a Phase Angle Controlled AC-AC converter with a resistive load

The rms voltage V_{rms} decides the power supplied to the load. It can be computed as

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

$$= V\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}$$



The rms output voltage and the most important harmonics versus triggering angle α.

As is evident from the current waveforms, the PAC introduces significant harmonics both into the load and the supply. This is one of the main reasons why such controllers are today not acceptable. The ideal waveform as shown in Fig 26.2 is half wave symmetric. However it is to be achieved by the trigger circuits. The controller in Fig. 26.4 ensures this for the TRIAC based circuit. While the TRIAC has a differing characteristic for the two polarities of biasing with the 32V DIAC - a two terminal device- triggering is effected when the capacitor voltage reaches 32 V. This ensures elimination of DC and even components in the output voltage.

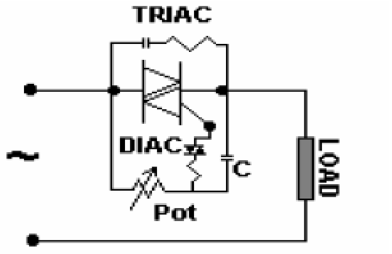


Fig. 26.4 DIAC based trigger circuit for a TRIAC to ensure symmetrical triggering in the two halves of the supply.

For the SCR based controllers, identical comparators for the two halves of the AC supply, which generates pulses for the two SCRs ensures DC and even harmonic free operation.

The PAC operates with a resistive load for all values of α ranging from 0^{o} The fundamental current, i_f can be represented as

$$i_f = \frac{\sqrt{2}V}{R\pi}\left[\left(\pi - \frac{\alpha}{2} + \frac{\sin 2\alpha}{2}\right)\sin \omega t - \left(\frac{1}{2} - \frac{\cos 2\alpha}{2}\right)\cos \omega t\right]$$

In machine drives it is only the fundamental component, which is useful. However, in resistance heating type of application all harmonics are of no consequence. The corrupted supply current nevertheless is undesirable.

Power Factor

The power factor of a nonlinear deserves a special discussion. Fig. 26.2 shows the supply voltage and the non-sinusoidal load current. The fundamental load/supply current lags the supply voltage by the φ_1, 'Fundamental Power Factor' angle. Cosφ_1 is also called the 'Displacement Factor'. However this does not account for the total reactive power drawn by the system. This power factor is inspite of the actual load being resistive! The reactive power is drawn also y the trigger-angle dependent harmonics. 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

$$P = \frac{1}{2\pi}\int_0^{2\pi} vi_L \quad d\omega t \quad = \frac{1}{\pi}\int_\alpha^\pi \frac{2V^2}{R}\sin^2 \omega t \quad dwt$$

$$= \frac{2V^2}{R\pi}\left[\pi - \frac{\alpha}{2} + \frac{\sin 2\alpha}{2}\right]$$

The portion within square brackets in Eq. 26.5 is identical to the first part of the expression within brackets in Eq. 26.1, which is called the Fourier coefficient 'B1'.

The rms load voltage can also be similarly obtained by integrating between α and π and the result can be combined

$$power \quad factor = per-unit \quad rms \quad load-current$$

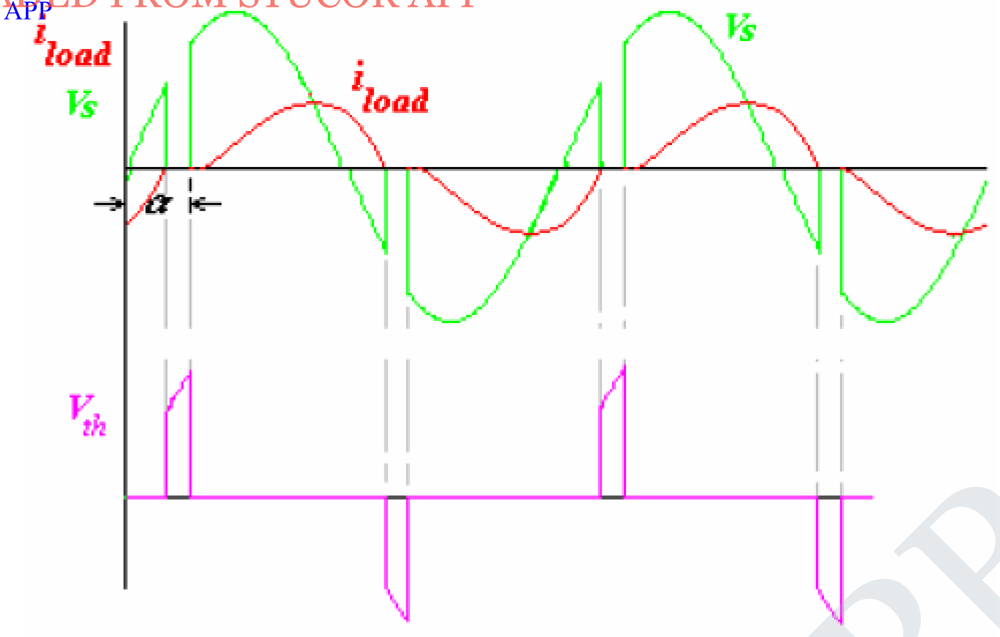
$$= \sqrt{per-unit \quad load \quad power}$$

$$= \sqrt{B_1 \quad p.u..}$$

Operation with inductive loads

With inductive loads the operation of the PAC is illustrated in Fig 26.5. The current builds up from zero in each cycle. It quenches not at the zero crossing of the applied voltage as with the resistive load but after that instant. The supply voltage thus continues to be impressed on the load till the load current returns to zero. A single-pulse trigger for the TRIAC 26.1 (c) or the anti-parallel SCR (b) has no effect on the devices if it (or the anti-parallel device) is already in conduction in the reverse direction. The devices would fail to conduct when they are intended to, as they do not have the supply voltage forward biasing them when the trigger pulse arrives. A single pulse trigger will work till the trigger angle α > φ, where φ is the power factor angle of the inductive load. A train of pulses is required here. The output voltage is controllable only between triggering angles φ and 180^o.

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} and the second, i_{tr} is the transient component.



Operation of a single phase PAC with an inductive load

With an inductance in the load the distinguishing feature of the load current is that it must always start from zero. However, if the switch could have permanently kept the load connected to the supply the current would have become a sinusoidal one phase shifted from the voltage by the phase angle of the load, φ. This current restricted to the half periods of conduction is called the 'steady-state component' of load current i_{ss}. The 'transient component' of load current i_{tr}, again in each half cycle, must add up to zero with this i_{ss} to start from zero. This condition sets the initial value of the transient component to that of the steady state at the instant that the SCR/TRIAC is triggered. Fig. 26.6 illustrates these relations.

When a device is in conduction, the load current is governed by the equation

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

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

Since at $t = 0$, $i_{load} = 0$ and supply voltage $v_s = \sqrt{2}V\sin\omega t$ the solution is of the form

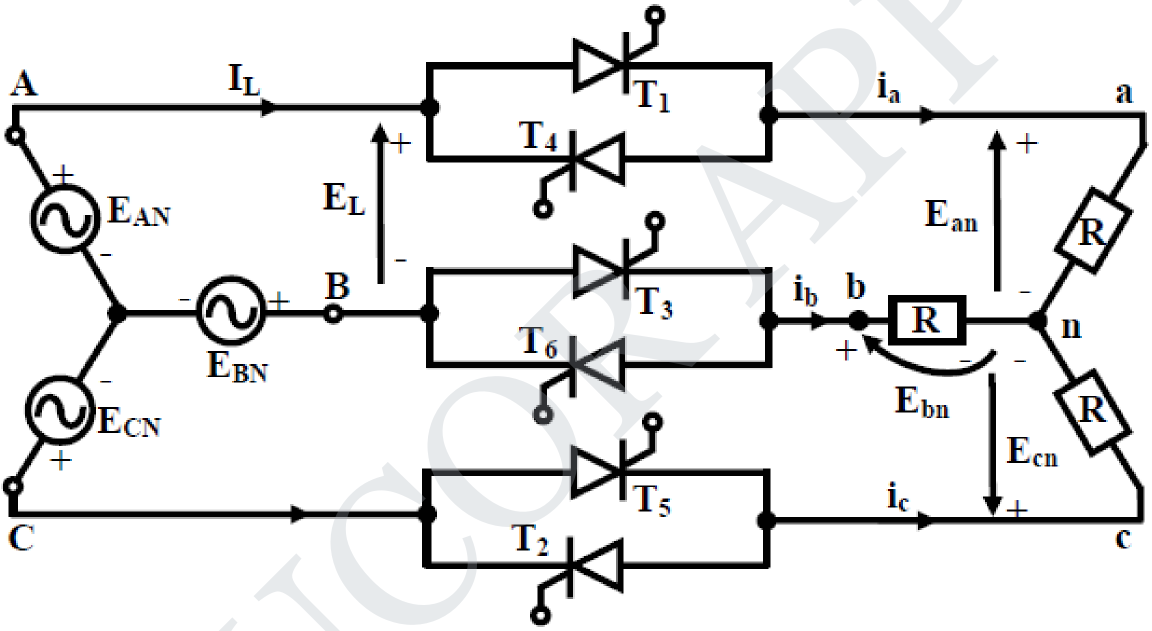
The instant when the load current extinguishes is called the extinction angle β. It can be inferred that there would be no transients in the load current if the devices are triggered at the power factor angle of the load. The load current I that case is perfectly sinusoidal.

Three-phase AC Regulators

There are many types of circuits used for the three-phase ac regulators (ac to ac voltage converters), unlike single-phase ones. The three-phase loads (balanced) are connected in star or delta. Two thyristors connected back to back, or a triac, is used for each phase in mo most of the circuits as described. Two circuits are first taken up, both with balanced resistive (R) load

5.2 Three-phase, Three-wire AC Regulator with Balanced Resistive Load

The circuit of a three-phase, three-wire ac regulator (termed as ac to ac voltage converter) with balanced resistive (star-connected) load is shown in Fig. 27.1. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. Please note the numbering scheme, which is same as that used in a three-phase full-wave bridge converter or inverter, described in module 2 or 5. The thyristors are fired in sequence (Fig. 27.2), starting from 1 in ascending order, with the angle between the triggering of thyristors 1 & 2 being (one-sixth of the time period (°60*T*) of a complete cycle). The line frequency is 50 Hz, with *fT*/1==20 ms. The thyristors are fired or triggered after a delay of α from the natural commutation point. The natural commutation point is the starting of a cycle with period, (6/60*T*=°) of output voltage waveform, if six thyristors are replaced by diodes. Note that the output voltage is similar to phase-controlled waveform for a converter, with the difference that it is an ac waveform in this case. The current flow is bidirectional, with the current in one direction in the positive half, and then, in other (opposite) direction in the negative half. So, two thyristors connected back to back are needed in each phase. The turning off of a thyristor occurs, if its current falls to zero. To turn the thyristor on, the anode voltage must be higher that the cathode voltage, and also, a triggering signal must be applied at its gate.



Three-phase, three-wire ac regulator

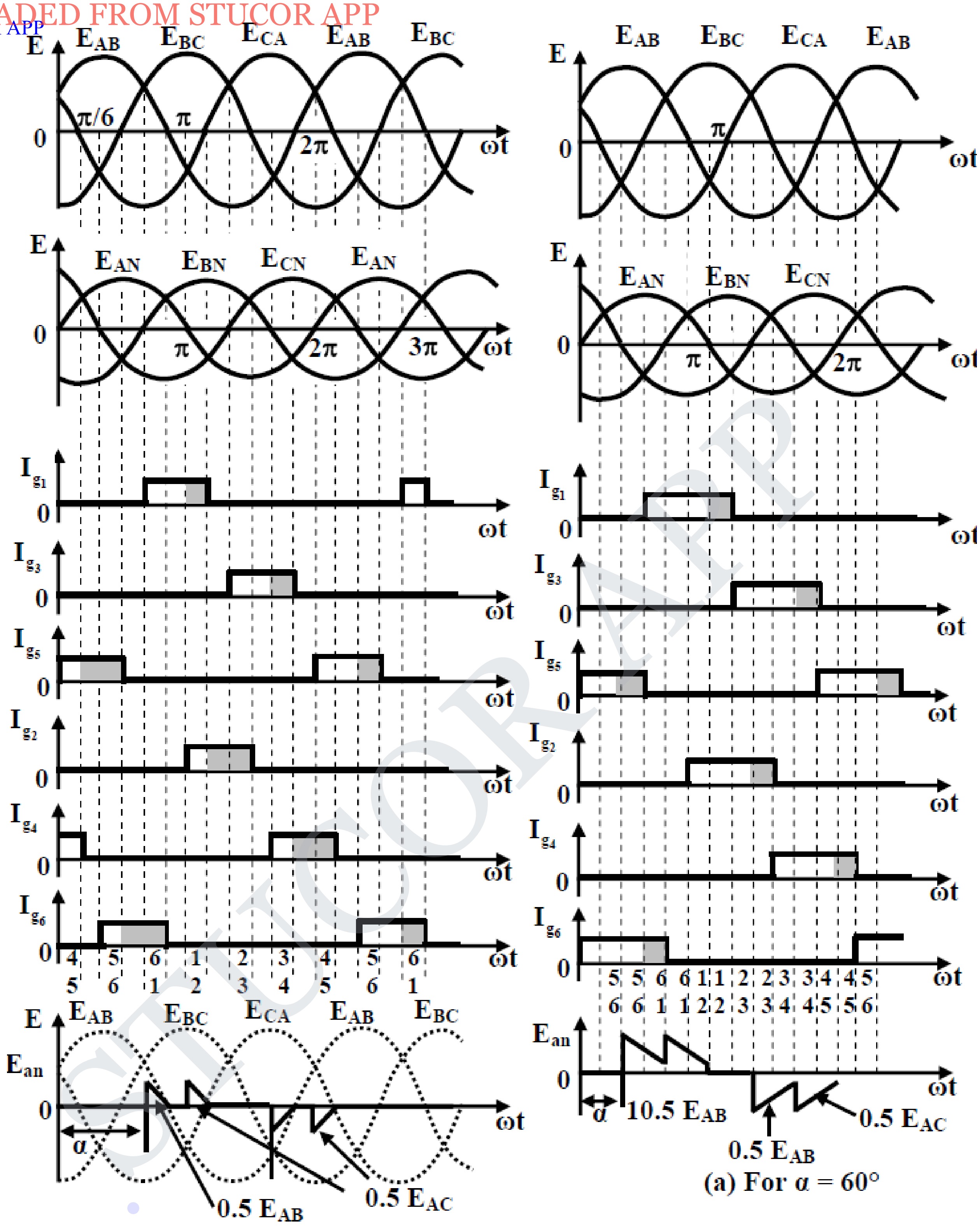
The procedure for obtaining the expression of the rms value of the output voltage per phase for balanced star-connected resistive load, which depends on range of firing angle, as shown later, is described. If E_s is the rms value of the input voltage per phase, and assuming the voltage, E_{AN} as the reference, the instantaneous input voltages per phase are,

$$e_{AN} = \sqrt{2}\,E_s \sin\omega t,\quad e_{BN} = \sqrt{2}\,E_s \sin(\omega t - 120°)\quad \text{and}\quad e_{CN} = \sqrt{2}\,E_s \sin(\omega t + 120°)$$

Then, the instantaneous input line voltages are,

$$e_{AB} = \sqrt{6}\,E_s \sin(\omega t + 30°),\quad e_{BC} = \sqrt{6}\,E_s \sin(\omega t - 90°)\quad \text{and}$$

$$e_{CA} = \sqrt{6}\,E_s \sin(\omega t + 150°)$$



(b) For α = 120°

(a) For α = 60°

Waveforms for three-phase three-wire ac regulator

The waveforms of the input voltages, the conduction angles of thyristors and the output voltage of one phase, for firing delay angles (α) of (a) and (b) are shown in Fig. 27.2. For °60°120)6/(600πα°≤≤°, immediately before triggering of thyristor 1, two thyristors (5 & 6) conduct. Once thyristor 1 is triggered, three thyristors (1, 5 & 6) conduct. As stated earlier, a thyristor turns off, when the current through it goes to zero. The conditions alternate between two and three conducting thyristors.

At any time only two thyristors conduct for $60^\circ \le \alpha \le 90^\circ$ .Although two thyristors conduct at any time for $90^\circ \le \alpha \le 150^\circ$, there are periods, when no thyristors are on. For $\alpha \ge 150^\circ$, there is no period for which two thyristors are on, and the output voltage becomes zero at $\alpha = 150^\circ (5\pi/6)$. The range of delay angle is $0^\circ \le \alpha \le 150^\circ$.

The expressions of the rms value of the output voltage per phase for balanced star-connected resistive load are as follows. Please note that $\theta = \omega t$.

For $0^\circ \le \alpha \le 60^\circ$:

$$E_0 = \left[\frac{1}{2\pi} \int_0^{2\pi} (e_{AN})^2 \, d\theta \right]^{\frac{1}{2}}$$

$$= \sqrt{6}\, E_s \left\{ \frac{2}{2\pi} \left[\int_{\alpha}^{\pi/3} \frac{\sin^2\theta}{3} d\theta + \int_{\pi/2}^{\pi/2+\alpha} \frac{\sin^2\theta}{4} d\theta + \int_{\pi/3+\alpha}^{2\pi/3} \frac{\sin^2\theta}{3} d\theta + \int_{\pi/2}^{\pi/2+\alpha} \frac{\sin^2\theta}{4} d\theta + \int_{2\pi/3+\alpha}^{\pi} \frac{\sin^2\theta}{3} d\theta \right] \right\}^{\frac{1}{2}}$$

$$= \sqrt{6}\, E_s \left[\frac{1}{\pi} \left(\frac{\pi}{6} - \frac{\alpha}{4} + \frac{\sin 2\alpha}{8} \right) \right]^{\frac{1}{2}}$$

For $60^\circ \le \alpha \le 90^\circ$:

$$E_0 = \sqrt{6}\, E_s \left\{ \frac{2}{2\pi} \left[\int_{\pi/2-\pi/3+\alpha}^{5\pi/6-\pi/3+\alpha} \frac{\sin^2\theta}{4} d\theta + \int_{\pi/2-\pi/3+\alpha}^{5\pi/6-\pi/3+\alpha} \frac{\sin^2\theta}{4} d\theta \right] \right\}^{\frac{1}{2}}$$

$$= \sqrt{6}\, E_s \left[\frac{1}{\pi} \left(\frac{\pi}{12} - \frac{3\sin 2\alpha}{16} + \frac{\sqrt{3}\cos 2\alpha}{16} \right) \right]^{\frac{1}{2}} = \sqrt{6}\, E_s \left[\frac{1}{\pi} \left(\frac{\pi}{12} + \frac{\sqrt{3}\sin(2\alpha + 30^\circ)}{8} \right) \right]^{\frac{1}{2}}$$

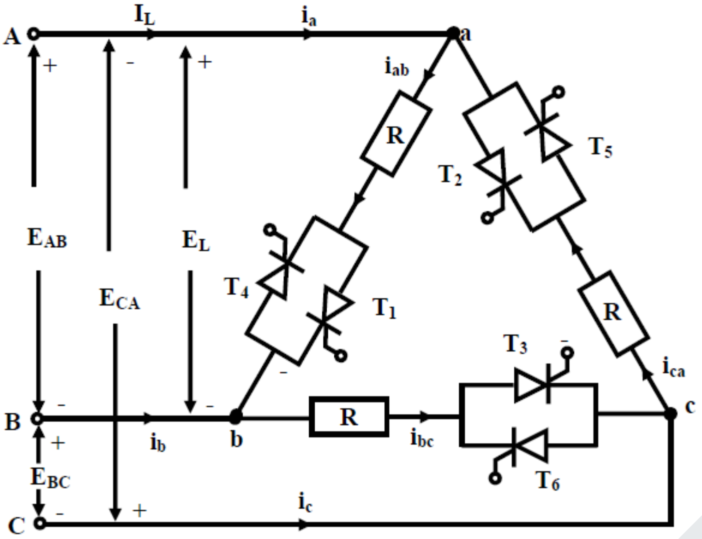
For $90^\circ \le \alpha \le 150^\circ$:

$$E_0 = \sqrt{6}\, E_s \left\{ \frac{2}{2\pi} \left[\int_{\pi/2-\pi/3+\alpha}^{\pi} \frac{\sin^2\theta}{4} d\theta + \int_{\pi/2-\pi/3+\alpha}^{\pi} \frac{\sin^2\theta}{4} d\theta \right] \right\}^{\frac{1}{2}}$$

$$= \sqrt{6}\, E_s \left[\frac{1}{\pi} \left(\frac{5\pi}{24} - \frac{\alpha}{4} + \frac{\sin 2\alpha}{16} + \frac{\sqrt{3}\cos 2\alpha}{16} \right) \right]^{\frac{1}{2}} = \sqrt{6}\, E_s \left[\frac{1}{\pi} \left(\frac{5\pi}{24} - \frac{\alpha}{4} + \frac{\sin(2\alpha + 60^\circ)}{8} \right) \right]^{\frac{1}{2}}$$

5.3Three-phase Delta-connected AC Regulator with Balanced Resistive Load

The circuit of a three-phase, delta-connected ac regulator (termed as ac to ac voltage converter) with balanced resistive load is shown in Fig. 27.3. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. As stated earlier, the numbering scheme may be noted. It may be observed that one phase of the balanced circuit is similar to that used for single-phase ac regulator described in the previous lesson (26) of the module. Since the phase current in a balanced three-phase system is only (3/1) of the line current, the current rating of the thyristors would be lower than that if the thyristors are placed in the line.

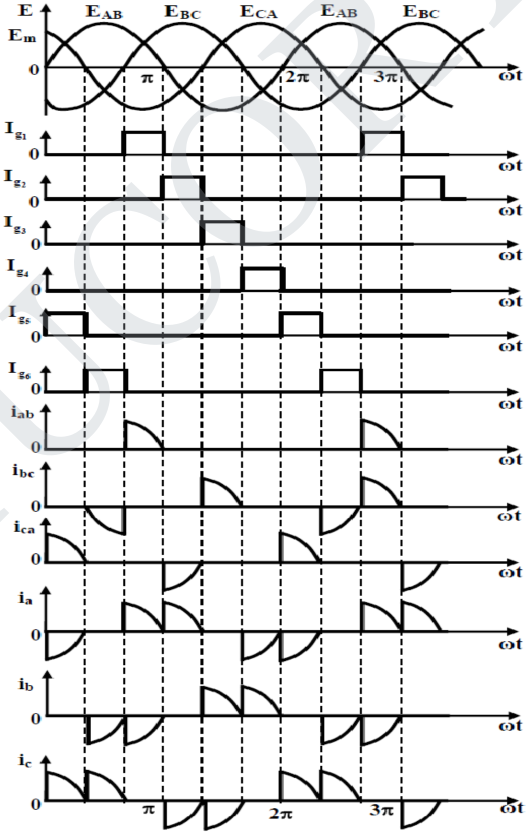


Delta connected three-phase ac regulator

Assuming the line voltage E_{AB} as the reference, the instantaneous input line voltages are,

$e_{AB} = \sqrt{2}\, E_s \sin \omega t$, $e_{BC} = \sqrt{2}\, E_s \sin(\omega t - 120°)$ and $e_{CA} = \sqrt{2}\, E_s \sin(\omega t + 120°)$

It may be noted that E_s is the rms value of the line voltage in this case. The waveforms of the input line voltages, phase and line currents, and the thyristor gating signals, for $\alpha = 120°$ are shown in Fig. 27.4.



For $\alpha = 120°$

Waveforms for three-phase delta-connected ac regu

The rms value of the output phase voltage is obtained as

$$E_0 = \left[\frac{1}{2\pi}\int_{\alpha}^{2\pi}(e_{AB})^2\,d\theta\right]^{\frac{1}{2}} = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi}2(E_s)^2\sin^2\theta\,d\theta\right]^{\frac{1}{2}} = E_s\left[\frac{1}{\pi}\left(\pi-\alpha+\frac{1}{2}\sin 2\alpha\right)\right]^{\frac{1}{2}}$$

When $\alpha = 0^0$, the maximum value of the output voltage is obtained, and the control range of delay angle is $0° \le \alpha \le 180° (\pi)$.

The line currents, which can be determined from the phase current, are,

$i_a = i_{ab} - i_{ca}$, $i_b = i_{bc} - i_{ab}$ and $i_c = i_{ca} - i_{bc}$.

From Fig. 27.4, it can be observed that the line currents depend on the delay angle, and may be discontinuous. The rms value of line and phase currents in this case can be determined by numerical solution or Fourier analysis.

If I_n is the rms value of the nth harmonic component of a phase current, the rms value of the phase current is obtained from

$$I_{ab} = \left[I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2 + I_{11}^2 + \cdots + I_n^2\right]^{\frac{1}{2}}$$

For delta connection, the triplen harmonic components (i.e., those of order, $n = 3m$, where m is an odd integer) of the phase currents flow around the delta, and would not appear in the line. This is due to the fact that these harmonic currents are like the zero sequence component, being in phase in all three phases of the load. So, the rms value of the line current is,

$$I_a = \sqrt{3}\left[I_1^2 + I_5^2 + I_7^2 + I_{11}^2 + \cdots + I_n^2\right]^{\frac{1}{2}}$$

As a result, the rms value of the line current would not follow the normal relationship of a three-phase system such that $I_a < \sqrt{3}\, I_{ab}$.

5.4 AC voltage control techniques.

There are two different types of thyristor control used in practice to control the ac power flow

- On-Off control
- Phase control

These are the two ac output voltage control techniques.

In On-Off control technique Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles. The Thyristors thus act as a high speed contactor (or high speed ac switch).

5.4.1PHASE CONTROL

In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle. The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load.

By controlling the phase angle or the trigger angle ‘α’ (delay angle), the output RMS voltage across the load can be controlled.

The trigger delay angle ‘α’ is defined as the phase angle (the value of ωt) at which the thyristor turns on and the load current begins to flow. Thyristor ac voltage controllers use ac line commutation or ac phase commutation. Thyristors in ac voltage controllers are line commutated (phase commutated) since the input supply is ac. When the input ac voltage reverses and becomes negative during the negative half cycle the current flowing through the

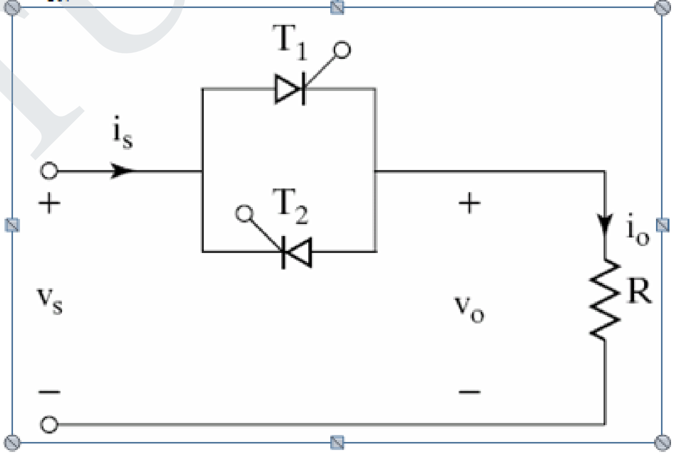
conductingthyristor decreases and falls to zero. Thus the ON thyristor naturally turns off, when the device current falls to zero.

Phase controlThyristors which are relatively inexpensive, converter gradeThyristors which are slower than fast switching inverter grade Thyristors are normallyused.Forapplicationsupto 400Hz, if Triacs are available to meet the voltage andcurrent ratings of a particular application, Triacs are more commonly used.Due to ac line commutation or natural commutation, there is no need of extracommutation circuitry or components and the circuits for ac voltage controllers arevery simple.

Due to the nature of the output waveforms, the analysis, derivations ofexpressions for performance parameters are not simple, especially for the phasecontrolled ac voltage controllers with RL load. But however most of the practicalloads are of the RL type and hence RL load should be considered in the analysis anddesign of ac voltage controller circuits.

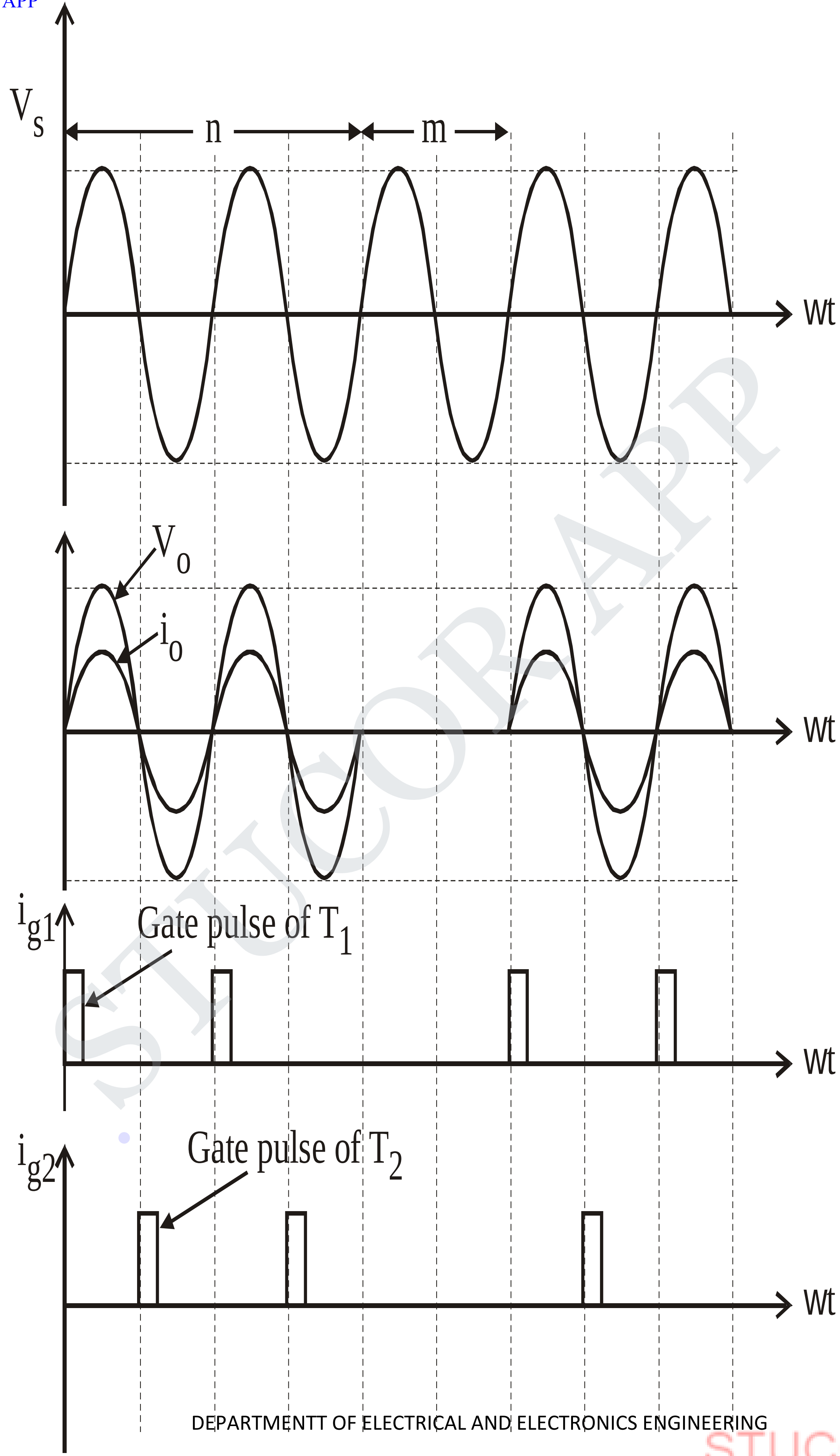
5.4.2PRINCIPLE OF ON-OFF CONTROL TECHNIQUE (INTEGRALCYCLECONTROL)

The basic principle of on-off control technique is explained with reference to a single phase full wave ac voltage controller circuit shown below. The thyristor switches T_1 and T_2 are turned on by applying appropriate gate trigger pulses to connect the input ac supply to the load for ‘n’ number of input cycles during the time interval t_{ON}. The thyristor switches T_1 and T_2 are turned off by blocking the gate trigger pulses for ‘m’ number of input cycles during the time interval t_{OFF}. The ac controller ON time t_{ON} usually consists of an integral number of input cycles.



$R = R_L =$ **Load Resistance**

Fig.: Single phase full wave AC voltage controller circuit


V_s
n
m
wt
V_o
i_o
wt
i_{g1}
Gate pulse of T_1
wt
i_{g2}
Gate pulse of T_2
wt

5.5 Full Bridge Ac voltage controller.

It is possible to design a single phase full wave ac controller with a common cathode configuration by having a common cathode point for T_1 and T_2 & by adding two diodes in a full wave ac controller circuit as shown in the figure below

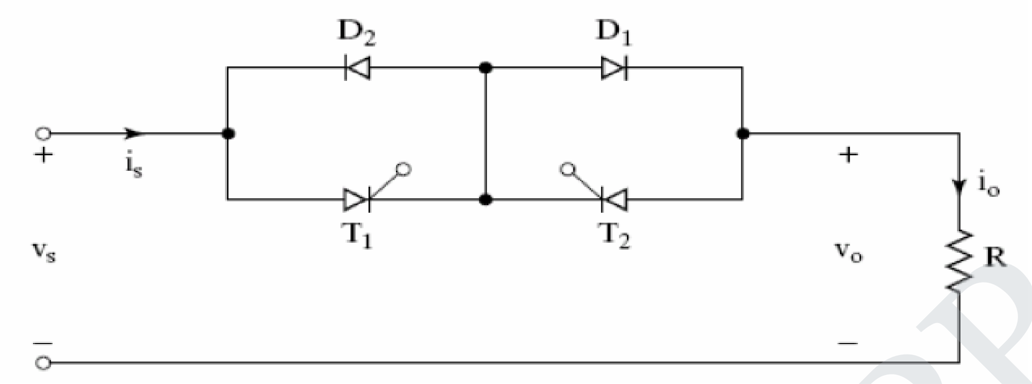


Fig.: Single phase full wave ac controller with common cathode (Bidirectional controller in common cathode configuration)

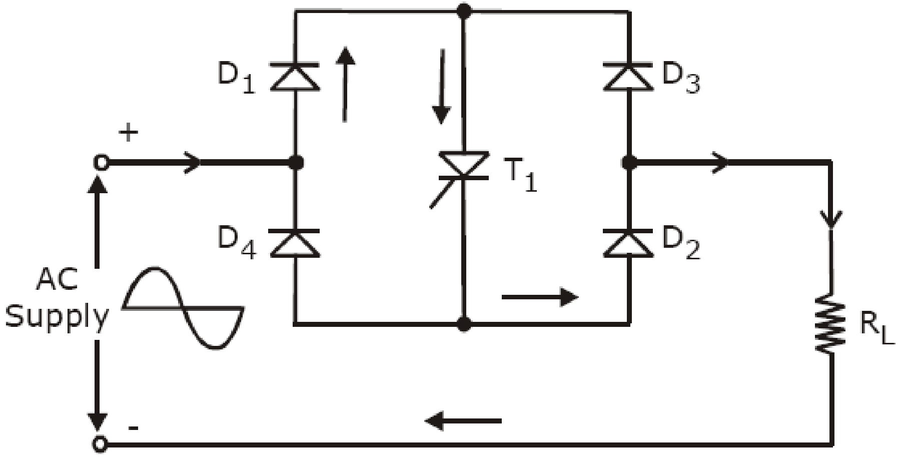
Thyristor T_1 and diode D_1 are forward biased during the positive half cycle of input supply. When thyristor T_1 is triggered at a delay angle α, Thyristor T_1 and diode D_1 conduct together from $\omega t = \alpha$ to π during the positive half cycle.

The thyristor T_2 and diode D_2 are forward biased during the negative half cycle of input supply, when trigged at a delay angle α, thyristor T_2 and diode D_2 conduct together during the negative half cycle from $\omega t = (\pi + \alpha)$ to 2π.

In this circuit as there is one single common cathode point, routing of the gate trigger pulses to the thyristor gates of T_1 and T_2 is simpler and only one isolation circuit is required.

But due to the need of two power diodes the costs of the devices increase. As there are two power devices conducting at the same time the voltage drop across the ON devices increases and the ON state conducting losses of devices increase and hence the efficiency decreases.

SINGLE PHASE FULL WAVE AC VOLTAGE CONTROLLER USING A SINGLE THYRISTOR



A single phase full wave ac controller can also be implemented with one thyristor and four diodes connected in a full wave bridge configuration as shown in the above figure. The four diodes act as a bridge full wave rectifier. The voltage across the thyristor T_1 and current through thyristor T_1 are always unidirectional. When T_1 is triggered at $\omega t = \alpha$, during the positive half cycle $(0 \leq \alpha \leq \pi)$, the load current flows through D_1, T_1, diode D_2 and through the load. With a resistive load, the thyristor current (flowing through the ON thyristor T_1), the load current falls to zero at $\omega t = \pi$, when the input supply voltage decreases to zero at $\omega t = \pi$, the thyristor naturally turns OFF.

In the negative half cycle, diodes $D_3 \,\&\, D_4$ are forward biased during $\omega t = \pi$ to 2π radians. When T_1 is triggered at $\omega t = (\pi + \alpha)$, the load current flows in the opposite direction (upward direction) through the load, through D_3, T_1 and D_4. Thus D_3, D_4 and T_1 conduct together during the negative half cycle to supply the load power. When the input supply voltage becomes zero at $\omega t = 2\pi$, the thyristor current (load current) falls to zero at $\omega t = 2\pi$ and the thyristor T_1 naturally turns OFF. The waveforms and the expression for the RMS output voltage are the same as discussed earlier for the single phase full wave ac controller.

But however if there is a large inductance in the load circuit, thyristor T_1 may not be turned OFF at the zero crossing points, in every half cycle of input voltage and this may result in a loss of output control. This would require detection of the zero crossing of the load current waveform in order to ensure guaranteed turn off of the conducting thyristor before triggering the thyristor in the next half cycle, so that we gain control on the output voltage.

In this full wave ac controller circuit using a single thyristor, as there are three power devices conducting together at the same time there is more conduction voltage drop and an increase in the ON state conduction losses and hence efficiency is also reduced.

The diode bridge rectifier and thyristor (or a power transistor) act together as a bidirectional switch which is commercially available as a single device module and it has relatively low ON state conduction loss. It can be used for bidirectional load current control and for controlling the RMS output voltage.

SINGLE PHASE FULL WAVE AC VOLTAGE CONTROLLER (BIDIRECTIONAL CONTROLLER) WITH RL LOAD

In this section we will discuss the operation and performance of a single phase full wave ac voltage controller with RL load. In practice most of the loads are of RL type. For example if we consider a single phase full wave ac voltage controller controlling the speed of a single phase ac induction motor, the load which is the induction motor winding is an RL type of load, where R represents the motor winding resistance and L represents the motor winding inductance.

A single phase full wave ac voltage controller circuit (bidirectional controller) with an RL load using two thyristors T_1 and T_2 (T_1 and T_2 are two SCRs) connected in parallel is shown in the figure below. In place of two thyristors a single Triac can be used to implement a full wave ac controller, if a suitable Traic is available for the desired RMS load current and the RMS output voltage ratings.

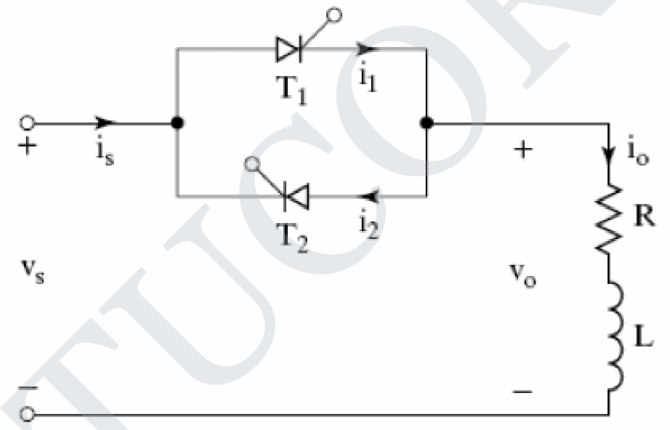


Fig: Single phase full wave ac voltage controller with RL load

The thyristor T_1 is forward biased during the positive half cycle of input supply. Let us assume that T_1 is triggered at $\omega t = \alpha$, by applying a suitable gate trigger pulse to T_1 during the positive half cycle of input supply. The output voltage across the load follows the input supply voltage when T_1 is ON. The load current i_O flows through the thyristor T_1 and through the load in the downward direction. This load current pulse flowing through T_1 can be considered as the positive current pulse.

Due to the inductance in the load, the load current i_O flowing through T_1 would not fall to zero at $\omega t = \pi$, when the input supply voltage starts to become negative.

The thyristor T_1 will continue to conduct the load current until all the inductive energy stored in the load inductor L is completely utilized and the load current through T_1 falls to zero at $\omega t = \beta$, where β is referred to as the Extinction angle, (the value of ωt) at which the load current falls to zero. The extinction angle β is measured from the point of the beginning of the positive half cycle of input supply to the point where the load current falls to zero.

The thyristor T_1 conducts from $\omega t = \alpha$ to β. The conduction angle of T_1 is $\delta = (\beta - \alpha)$, which depends on the delay angle α and the load impedance angle ϕ. The waveforms of the input supply voltage, the gate trigger pulses of T_1 and T_2, the thyristor current, the load current and the load voltage waveforms appear as shown in the figure below.

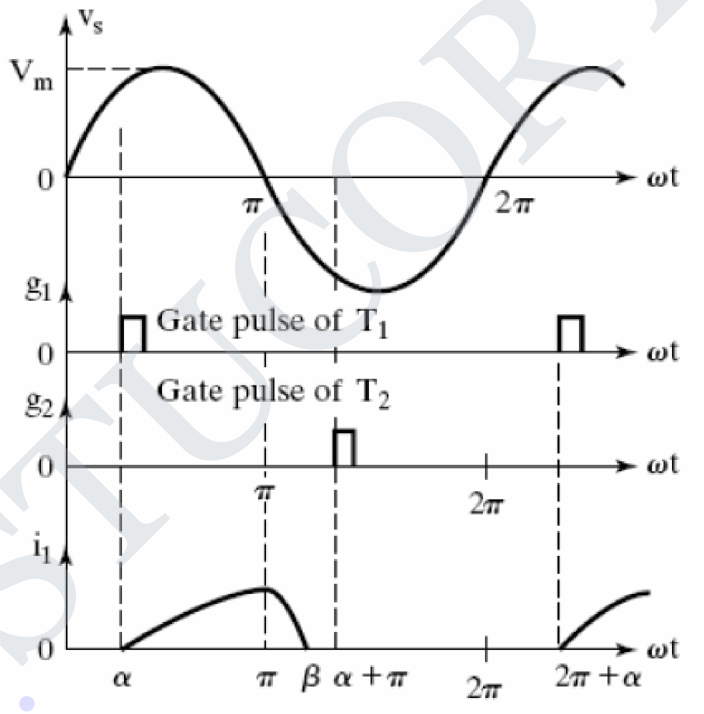


Fig.: Input supply voltage & Thyristor current waveforms

β is the extinction angle which depends upon the load inductance value.

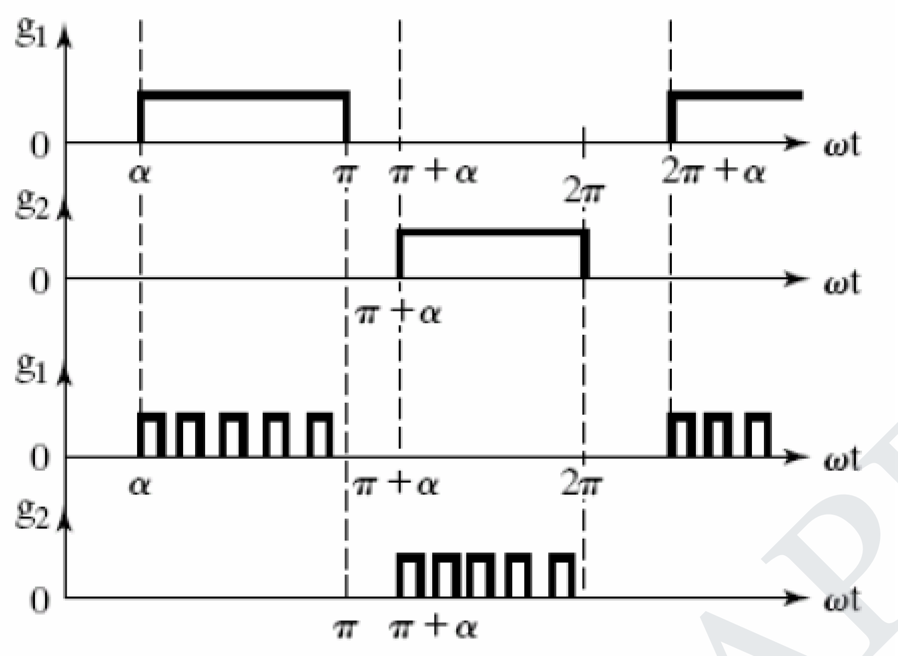
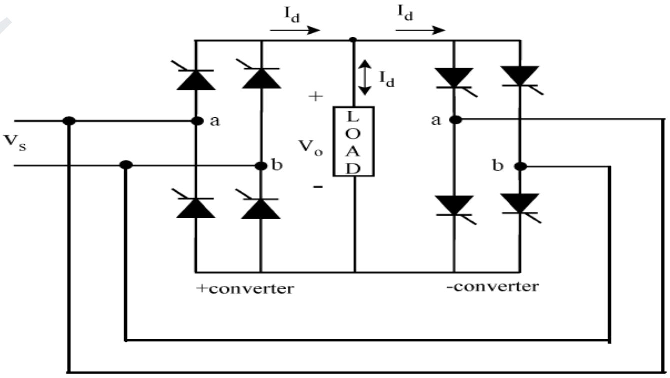
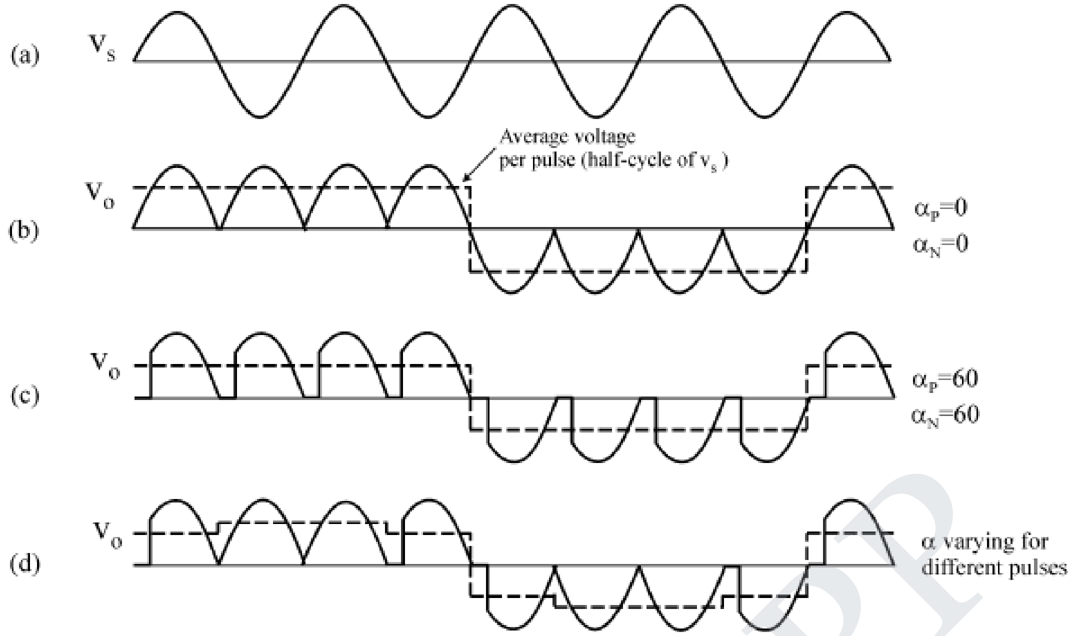


Fig.: Gating Signals

5.6 Single phase cycloconverter.

This converter consists of back-to-back connection of two full-wave rectifier circuits. The input voltage, vs is an ac voltage at a frequency, Foreasyunderstanding assume that all the thyristors are fired firing angle, i.e. thyristors act likediodes. Note that the firing angles are named as P for the positive converter and forthenegative converter. Consider the operation of the cycloconverter to get one-fourth of the input frequency at the output. For the first two cycles of vs, the positive converter operates supplying current to the load. It rectifies the input voltage; therefore, the load sees 4 positive half cycles. In the next two cycles, the negative converter operates supplying current to the load in the reverse direction. The current waveforms are not shown in the figures because the resistive load current will have the same waveform as the voltage but only scaled by the resistance. Note that when one of the converters operates the other one is disabled, so that there is no current circulating between the two rectifiers

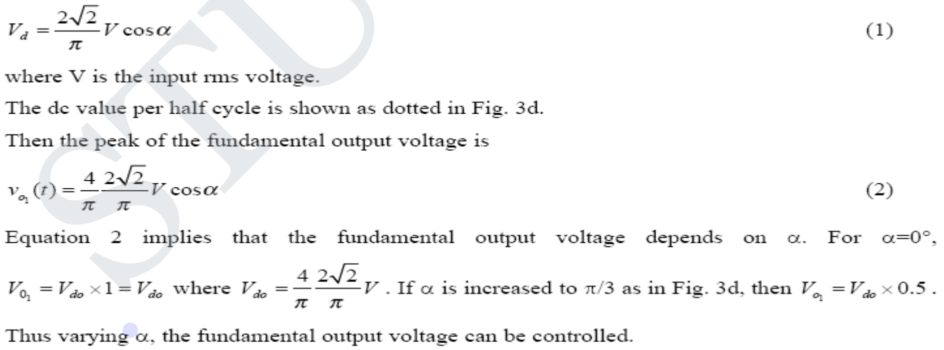




The frequency of the output voltage, vo in Fig. 3b is 4 times less than that of vs, the input voltage, i.e. fo/fi=1/4. Thus, this is a step-down cycloconverter. On the other hand, cycloconverters that have fo/fi>1 frequency relation are called step-up cycloconverters. Note that step-down cycloconverters are more widely used than the step-up ones.

The frequency of vo can be changed by varying the number of cycles the positive and the negative converters work. It can only change as integer multiples of fi in 1f-1f cycloconverters.

With the above operation, the 1f-1f cycloconverter can only supply a certain voltage at a certain firing angle a. The dc output of each rectifier is:



$$V_d = \frac{2\sqrt{2}}{\pi} V \cos\alpha \qquad (1)$$

where V is the input rms voltage.

The dc value per half cycle is shown as dotted in Fig. 3d.

Then the peak of the fundamental output voltage is

$$v_{o_1}(t) = \frac{4}{\pi} \frac{2\sqrt{2}}{\pi} V \cos\alpha \qquad (2)$$

Equation 2 implies that the fundamental output voltage depends on α. For α=0°, $V_{0_1} = V_{do} \times 1 = V_{do}$ where $V_{do} = \frac{4}{\pi} \frac{2\sqrt{2}}{\pi} V$. If α is increased to π/3 as in Fig. 3d, then $V_{o_1} = V_{do} \times 0.5$.

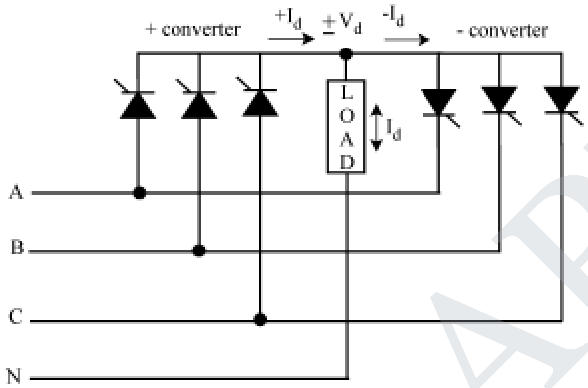
Thus varying α, the fundamental output voltage can be controlled.

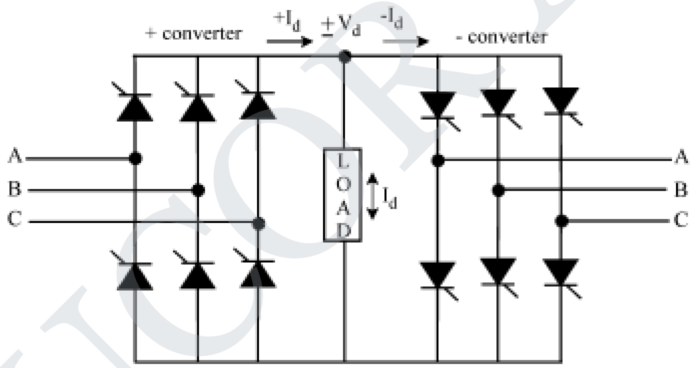
Thus varying a, the fundamental output voltage can be controlled.

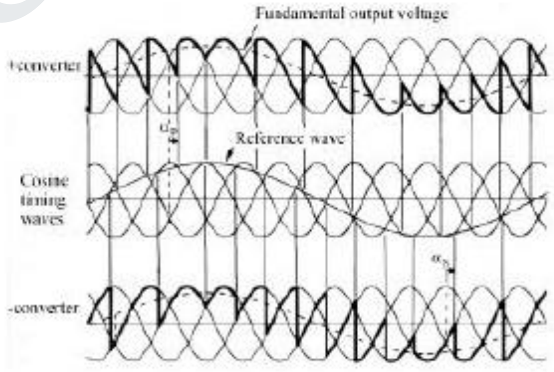
Constant a operation gives a crude output waveform with rich harmonic content. The dotted lines in Fig. 3b and c show a square wave. If the square wave can be modified to look more like a sine wave, the harmonics would be reduced. For this reason a is modulated as shown in Fig. 3d. Now, the six-stepped dotted line is more like a sinewave with fewer harmonics. The more pulses there are with different a's, the less are the harmonics.

5.7 Three Phase Cycloconverter.

There are two kinds of three-phase to single-phase (3f-1f) cycloconverters: 3f-1f half-wave cycloconverter (Fig. 4) and 3f-1f bridge cycloconverter (Fig. 5). Like the 1f-1f case, the 3f-1f cycloconverter applies rectified voltage to the load. Both positive and negative converters can generate voltages at either polarity, but the positive converter can only supply positive current and the negative converter can only supply negative current. Thus, the cycloconverter can operate in four quadrants: (+v, +i) and (-v, -i) rectification modes and (+v, -i) and (-v, +i) inversion modes. The modulation of the output voltage and the fundamental output voltage







The polarity of the current determines if the positive or negative converter should be supplying power to the load. Conventionally, the firing angle for the positive converter is named aP, and that of the negative converter is named aN. When the polarity of the current changes, the converter previously supplying the current is disabled and the other one is enabled. The load always requires the fundamental voltage to be continuous. Therefore, during the current polarity reversal, the average voltage supplied by both of the converters should be equal. Otherwise, switching from one converter to the other one would cause an undesirable voltage jump. To prevent this problem, the converters are forced to produce the same average voltage at all times. Thus, the following condition for the firing angles should be met

$$\alpha_P + \alpha_N = \pi \qquad (3)$$

The fundamental output voltage in Fig. 6 can be given as:

$$v_{o_1}(t) = \sqrt{2}V_o \sin\omega_o t \qquad (4)$$

where V_o is the rms value of the fundamental voltage

At a time t_o the output fundamental voltage is

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin\omega_o t_o \qquad (5)$$

The positive converter can supply this voltage if α_P satisfies the following condition.

$$v_{o_1}(t_o) = \sqrt{2}V_o \sin\omega_o t_o = V_{do}\cos\alpha_P \qquad (6)$$

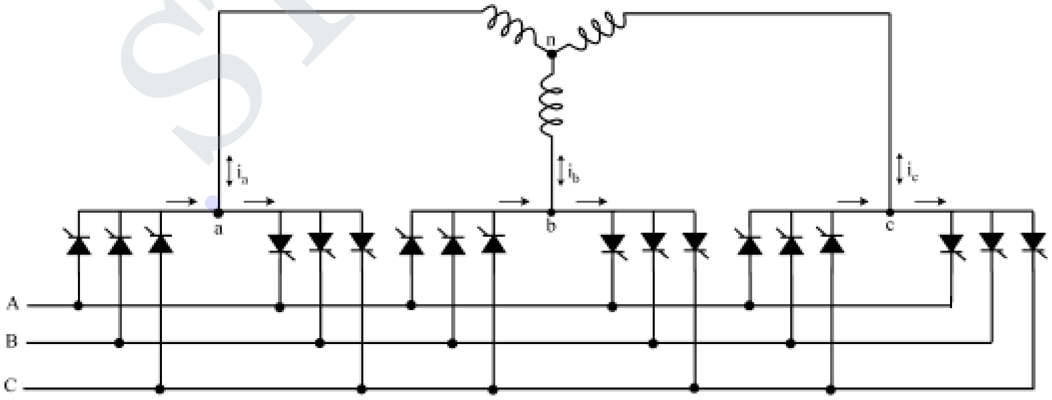
where $V_{do} = \sqrt{2}V_o \frac{p}{\pi}\sin\frac{\pi}{p}$ (p=3 for half wave converter and 6 for bridge converter)

From the α condition (3)

$$v_{o_1} = V_{do}\cos\alpha_P = -V_{do}\sin\alpha_N \qquad (7)$$

5.8 Three-Phase to Three-Phase (3f-3f) Cycloconverter:

If the outputs of 3 3f-1f converters of the same kind are connected in wye or delta and if the output voltages are 2p/3 radians phase shifted from each other, the resulting converter is a three- phase to three-phase (3f-3f) cycloconverter. The resulting cycloconverters are shown in Figs. 7 and 8 with wye connections. If the three converters connected are half-wave converters, then the new converter is called a 3f-3f half-wave cycloconverter. If instead, bridge converters are used, then the result is a 3f-3f bridge cycloconverter. 3f-3f half-wave cycloconverter is also called a 3-pulse cycloconverter or an 18-thyristor cycloconverter. On the other hand, the 3f-3f bridge cycloconverter is also called a 6-pulse cycloconverter or a 36-thyristor cycloconverter. The operation of each phase is explained in the previous section.



The three-phase cycloconverters are mainly used in ac machine drive systems running three- phase synchronous and induction machines. They are more advantageous when used with a synchronous machine due to their output power factor characteristics. A cycloconverter can supply lagging, leading, or unity power factor loads while its input is always lagging. A synchronous machine can draw any power factor current from the converter. This characteristic operation matches the cycloconverter to the synchronous machine. On the other hand, induction machines can only draw lagging current, so the cycloconverter does not have an edge compared to the other converters in this aspect for running an induction machine. However, cycloconverters are used in Scherbius drives for speed control purposes driving wound rotor induction motors.

Cycloconverters produce harmonic rich output voltages, which will be discussed in the following sections. When cycloconverters are used to run an ac machine, the leakage inductance of the machine filters most of the higher frequency harmonics and reduces the magnitudes of the lower order harmonics.

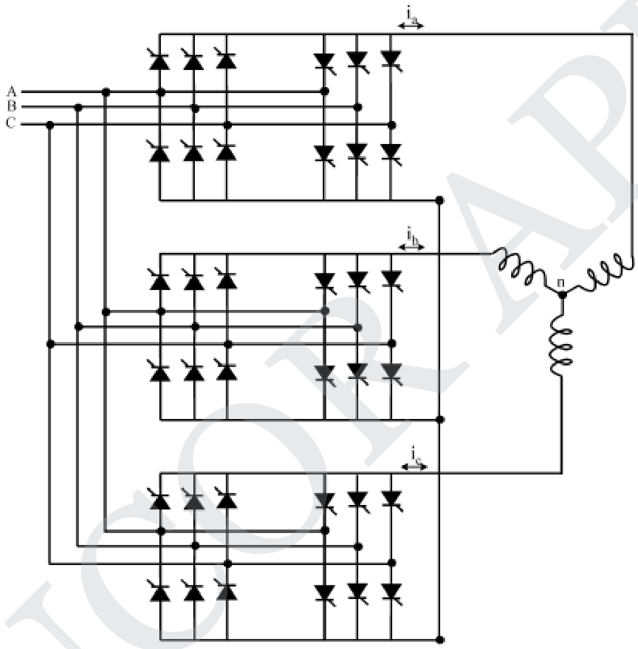
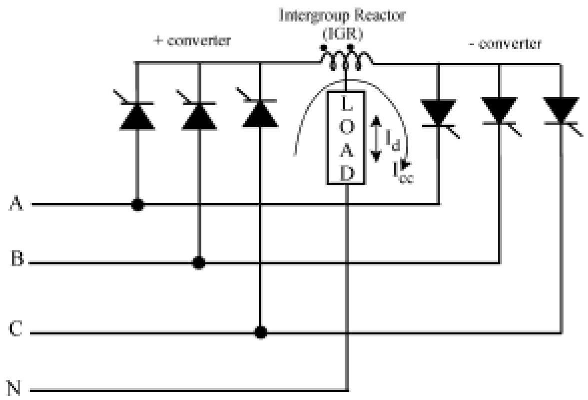


Fig. 8 3ϕ-3ϕ bridge cycloconverter

5.8.1Blocked Mode and Circulating Current Mode:

The operation of the cycloconverters is explained above in ideal terms. When the load current is positive, the positive converter supplies the required voltage and the negative converter is disabled. On the other hand, when the load current is negative, then the negative converter supplies the required voltage and the positive converter is blocked. This operation is called the blocked mode operation, and the cycloconverters using this approach are called blocking mode cycloconverters.

However, if by any chance both of the converters are enabled, then the supply is short-circuited. To avoid this short circuit, an intergroup reactor (IGR) can be connected between the converters as shown in Fig. 9. Instead of blocking the converters during current reversal, if they are both enabled, then a circulating current is produced. This current is called the circulating current. It is unidirectional because the thyristors allow the current to flow in only one direction. Some cycloconverters allow this circulating current at all times. These are called circulating current cycloconverters.



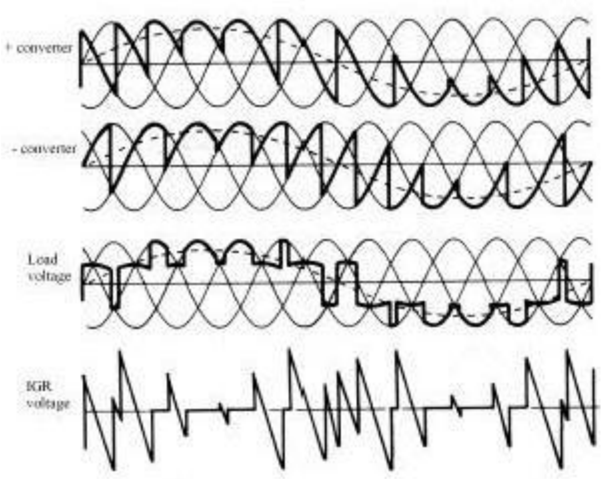
Blocking Mode Cycloconverters:

The operation of these cycloconverters was explained briefly before. They do not let circulating current flow, and therefore they do not need a bulky IGR. When the current goes to zero, both positive and negative converters are blocked. The converters stay off for a short delay time to assure that the load current ceases. Then, depending on the polarity, one of the converters is enabled. With each zero crossing of the current, the converter, which was disabled before the zero crossing, is enabled. A toggle flip-flop, which toggles when the current goes to zero, can be used for this purpose. The operation waveforms for a three-pulse blocking mode cycloconverter are given in Fig.

The blocking mode operation has some advantages and disadvantages over the circulating mode operation. During the delay time, the current stays at zero distorting the voltage and current waveforms. This distortion means complex harmonics patterns compared to the circulating mode cycloconverters. In addition to this, the current reversal problem brings more control complexity. However, no bulky IGRs are used, so the size and cost is less than that of the circulating current case. Another advantage is that only one converter is in conduction at all times rather than two. This means less losses and higher efficiency.

5.8.2Circulating Current Cycloconverters:

In this case, both of the converters operate at all times producing the same fundamental output voltage. The firing angles of the converters satisfy the firing angle condition (Eq. 3), thus whenone converter is in rectification mode the other one is in inversion mode and vice versa. If both of the converters are producing pure sine waves, then there would not be any circulating current because the instantaneous potential difference between the outputs of the converters would be zero. In reality, an IGR is connected between the outputs of two phase controlled converters (in either rectification or inversion mode).

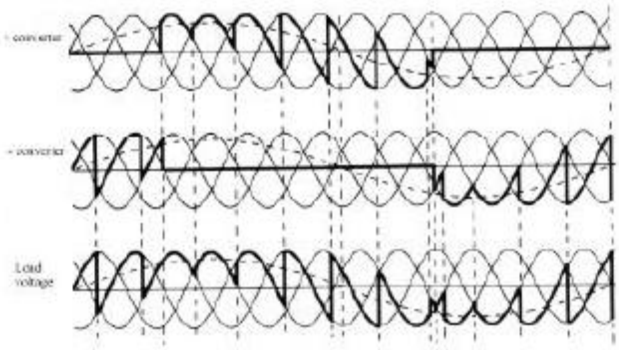


The voltage waveform across the IGR can be seen in Fig. 11d. This is the difference of the instantaneous output voltages produced by the two converters. Note that it is zero when both of the converters produce the same instantaneous voltage. The center tap voltage of IGR is the voltage applied to the load and it is the mean of the voltages applied to the ends of IGR, thus the load voltage ripple is reduced.

5.8.2.1Circulating mode

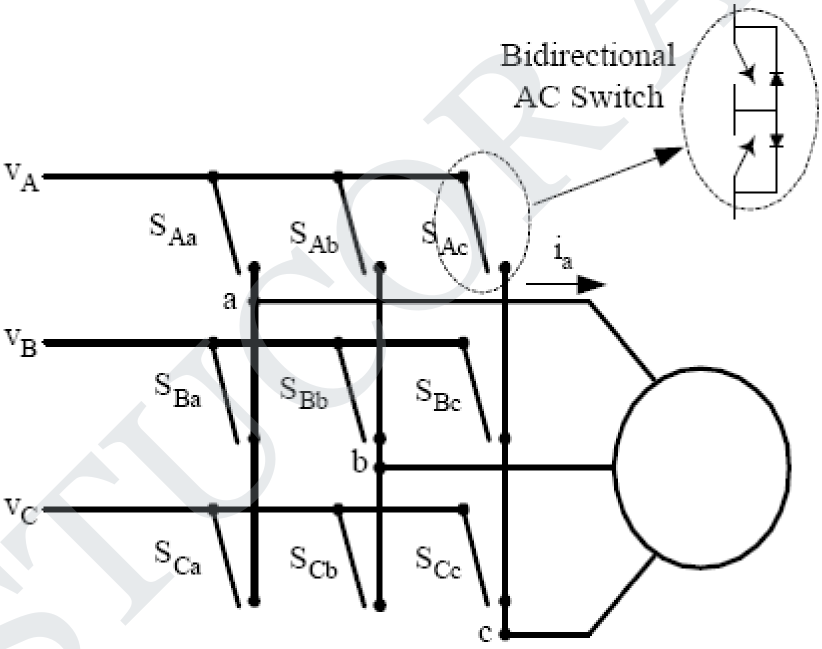
The circulating current cycloconverter applies a smoother load voltage with less harmonics compared to the blocking mode case. Moreover, the control is simple because there is no current reversal problem. However, the bulky IGR is a big disadvantage for this converter. In addition to this, the number of devices conducting at any time is twice that of the blocking mode converter. Due to these disadvantages, this cycloconverter is not attractive.

The blocked mode cycloconverter converter and the circulating current cycloconverter can be combined to give a hybrid system, which has the advantages of both. The resulting cycloconverter looks like a circulating mode cycloconverter circuit, but depending on the polarity of the output current only one converter is enabled and the other one is disabled as with the blocking mode cycloconverters. When the load current decreases below a threshold, both of the converters are enabled. Thus, the current has a smooth reversal. When the current increases above a threshold in the other direction, the outgoing converter is disabled. This hybrid cycloconverter operates in the blocking mode most of the time so a smaller IGR can be used. The efficiency is slightly higher than that of the circulating current cycloconverter but much less than the blocking mode cycloconverter. Moreover, the distortion caused by the blocking mode operation disappears due to the circulating current operation around zero current. Moreover, the control of the converter is still less complex than that of the blocking mode cycloconverter.



5.9 Matrix converter.

The matrix converter is a fairly new converter topology, which was first proposed in the beginning of the 1980s. A matrix converter consists of a matrix of 9 switches connecting the three input phases to the three output phases directly as shown in Fig. 12. Any input phase can be connected to any output phase at any time depending on the control. However, no two switches from the same phase should be on at the same time, otherwise this will cause a short circuit of the input phases. These converters are usually controlled by PWM to produce three-phase variable voltages at variable frequency.



This direct frequency changer is not commonly used because of the high device count, i.e. 18 switches compared to 12 of a dc link rectifier-inverter system. However, the devices used are smaller because of their shorter ON time compared to the latter.

5.9.1Single-Phase to Three-Phase (1f-3f) Cycloconverters:

Recently, with the decrease in the size and the price of power electronics switches, single-phase to three-phase cycloconverters (1f-3f) started drawing more research interest. Usually, an H-bridge inverter produces a high frequency single-phase voltage waveform, which is fed to the cycloconverter either through a high frequency transformer or not. If a transformer is used, it isolates the inverter from the cycloconverter. In addition to this, additional taps from the transformer can be used to power other converters producing a high frequency ac link. The single-phase high frequency ac (hfac) voltage can be either sinusoidal or trapezoidal. There might be zero voltage intervals for control purposes or zero voltage commutation. Fig. 13 shows the circuit diagram of a typical hfac link converter. These converters are not commercially available yet. They are in the research state.

Among several kinds, only two of them will be addressed here:

5.9.2 Integral Pulse Modulated (1f-3f) Cycloconverters

The input to these cycloconverters is single-phase high frequency sinusoidal or square waveforms with or without zero voltage gaps. Every half-cycle of the input signal, the control for each phase decides if it needs a positive pulse or a negative pulse using integral pulse modulation. For integral pulse modulation, the command signal and the output phase voltage are integrated and the latter result is subtracted from the former. For a positive difference, a negative pulse is required, and vice versa for the negative difference. For the positive (negative) input half-cycle, if a positive pulse is required, the upper (lower) switch is turned on; otherwise, the lower (upper) switch is turned on.

Therefore, the three-phase output voltage consists of positive and negative half-cycle pulses of the input voltage. Note that this converter can only work at output frequencies which are multiples of the input frequency.

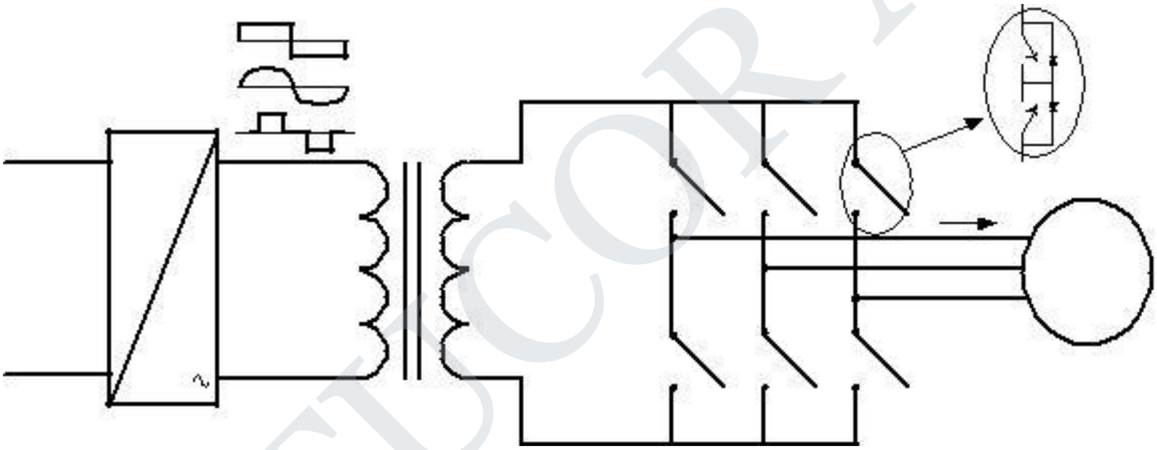


Fig. 13 High frequency ac link converter (1f hf inverter + (1f-3f) Cycloconverter)

5.9.3Phase-Controlled (1f-3f) Cycloconverter

This cycloconverter converts the single-phase high frequency sinusoidal or square wave voltage into three-phase voltages using the previously explained phase control principles. The voltage command is compared to a sawtooth waveform to find the firing instant of the switches. Depending on the polarity of the current and the input voltage, the next switch to be turned on is determined. Compared to the previous one, this converter has more complex control but it can work at any frequency.

Glossary

1. Triggering/Firing circuit:

It is used to give a trigger pulse to initiate the thyristor to the state of conduction.

2. Zero-crossing detector:

It is an Operational amplifier, which converts the sine wave to a square wave. The output of the zero-crossing detector is fed to an integrator.

3. Integrator:

An Operational amplifier with a feedback capacitor is said to act as an integrator. The output of the integrator is similar to that of a saw tooth waveform.

4. Pulse amplifier:

Pulses obtained from the control circuit magnitude is less, hence it is insufficient to trigger the high current rated thyristors. This can be overcome by feeding the control circuit to a pulse amplifier which strengthens the weak control signals and later it is fed to the thysristor gate cathode terminals.

5. Isolation Transformer:

Thyristor anode-cathode voltage is high, where as gate circuit voltage is low. Hence necessary isolation must be given to the control circuit (gate circuit) and power circuit. This can be done by using an isolation transformer, whose turns ratio is 1:1 unlike the power transformers.

Question Bank

UNIT – I
POWER SEMI-CONDUCTOR DEVICES

1. What is meant by thyristor converter system?
2. What is the difference between power diode and signal level diode?
3. Define reverse recovery time in diodes.
4. Define safe operating area.
5. What are the different methods to turn on the thyristor?
6. Define latching and holding current.
7. List the advantages of GTO over SCR?
8. Distinguish between SCR, TRIAC and GTO.
9. What is snubber circuit?
10. What is the drawback of SCR over BJT?
11. What is DIAC and how it differs from SCR?
12. Draw the symbol of TRIAC, GTO, MOSFET and IGBT.
13. Compare MOSFET and BJT.
14. Why IGBT is very popular now a day?
15. IGBT and MOSFET is voltage controlled device why?
16. Why MOSFETs are preferred for high frequency applications?
17. List the important features of IGBT.
18. Define circuit turn-off time
19. Why circuit turn-off time should be greater than the thyristor turn-off time?
20. What is the basis for selection of power semiconductor device for a particular application?

PART- B

1. i**.** Enumerate the importance of series and parallel operation of an SCR with relevant sketches.
   ii .Discuss the various methods of turning on of SCR.
   iii. Explain the two transistor analogy of SCR.
   iv.Explain about the dV/dt and di/dt protection in an SCR.
2. Draw the symbol and structure of TRIAC. Explain all the four triggering modes of operation with neat sketch.
3. i. Explain the construction, operation and switching characteristics of SCR.
   ii. Explain the construction, operation and switching characteristics of BJT.
   iii. Explain about the secondary breakdown in BJT.
4. i. Explain the construction, operation and switching characteristics of MOSFET.
   ii. Explain the construction, operation and switching characteristics of IGBT.

UNIT – II
PHASE CONTROLLED CONVERTER
PART A

1. What is meant by phase controlled rectifier?
2. Mention some of the applications of controlled rectifiers.
3. Classify controlled rectifiers.
4. Define delay or firing angle.
5. Define extinction angle.
6. Differentiate between line and forced commutation.
7. What is commutation angle or overlap angle?
8. What is the function of freewheeling diode in controlled rectifiers?
9. List the advantages of freewheeling diodes.

10. What is the inversion mode of rectifiers?
11. Why the power factor of semi converter is greater than full converter?
12. What is meant by input power factor in controlled rectifier?
13. What are the advantages of six pulse converter?
14. Distinguish between two and four quadrant converters.
15. What are ac voltage controllers and give few applications?
16. List the merits and demerits of ac voltage controllers.
17. List the strategies available for control of ac voltage controllers.
18. Distinguish between ON-OFF and integral cycle control.
19. What are the two types of ac voltage controllers? Which one of these is preferred, why?
20. What is meant by full wave or bidirectional ac voltage controller?

PART- B

1. Explain the principle of operation and derive the expressions for average output voltage and RMS output voltage of the following,
   a. Single-phase half controlled rectifier feeding R load
   b. Single-phase full controlled rectifier feeding RL load
   c. Single-phase two quadrant and two pulse converter operating on rectification and Inversion modes.
2. Explain the operation of three-phase half and full converter rectifier feeding RL load. With the aid of neat waveforms and also derive the expression for average output voltage.
3. Explain the effect of source impedance on the performance of converters.
4. Explain the operation of Single-phase ac voltage controller having only thyristors feeding resistive load by on-off and phase control. Derive the expression for rms value of output voltage in both cases.
5. Explain the principle of operation of Single-phase ac voltage controllers with necessary circuit and waveforms.

UNIT III
DC TO DC CONVERTER
PART- A

1. What is chopper and list its applications?
2. What are the advantages of dc chopper?
3. Define duty cycle.
4. What are the two types of control strategies used in choppers?
5. What is meant by frequency modulation control in dc chopper?
6. What is meant by pulse width modulation control in dc chopper?
7. What are the types of TRC?
8. What is current limit control?
9. Differentiate between step-up and step-down chopper.
10. What is continuous current operation?
11. Draw the circuit diagram of Buck-Boost chopper.
12. Why voltage commutated chopper is extensively used?
13. What are four quadrant choppers?
14. What is meant by Cycloconverters? List its types.
15. What are the applications of Cycloconverters?

PART- B

1. Explain the operation of step-up and step down choppers. Also derive the expressions for the output voltage.
2. With the aid of power circuit explain the Class A to Class E copper configurations.
3. Derive an expression for duty ratio of buck boost converter.

4. With relevant sketches explain the operation of a voltage, current and load commutated chopper.
5. Explain the operation of the following,
   a. Single phase to single phase bridge type Cycloconverters
   b. Three phase to single phase Cycloconverters.

UNIT IV
INVERTERS
PART- A

1. What are inverters, list its applications.
2. How inverters are classified based on the commutation circuitry?
3. How the output frequency is varied in an inverter?
4. Why diodes should be connected in anti parallel with the thyristors in inverter circuits?
5. Why thyristors are not preferred for inverters?
6. What is inverter gain?
7. Mention the methods available for the output voltage control of inverters.
8. What is meant by PWM control?
9. List the different types of PWM techniques.
10. What are the advantages of PWM techniques in inverters?
11. Compare VSI and CSI.
12. What are the applications of CSI?
13. What are the drawbacks of the presence of harmonics in inverters?
14. What are the methods of reduction of harmonic content?

PART- B

1. Explain the operation of single-phase half bridge inverter with aid of relevant waveforms and derive the instantaneous output voltage.
2. Explain the operation of single-phase full bridge inverter with aid of relevant waveforms and derive the instantaneous output voltage.
3. i. Explain the principle of operation of current source inverter.
   ii. Explain the principle of operation of auto sequential 1Ø current sourceinverter?
4. i. Explain three-phase 180^0 degree conduction mode of inverter.
   ii. Explain three-phase 120^0 degree conduction mode of inverter.
5. What is the need for controlling the output voltage of inverters and state the different methods of voltage control of single phase inverters. Describe the single phase sinusoidal PWM control with relevant waveforms.
6. Write short notes on, Harmonic reduction.

UNIT V AC TO AC CONVERTERS

1.What is the difference betweenON-OFF control and phase control?
2. What is the advantage of ON-OFF control?
3. What is the disadvantage ofON-OFF control?
4. What is the duty cycle in ON-OFF control method?
5. What is meant by unidirectional or half-wave ac voltage controller?
6. What are the disadvantages of unidirectional or half-wave ac voltage controller?
7. What is meant by bidirectional or half-wave ac voltage controller?
8. What is the control range of firing angle in ac voltage controller with RL load?
9. What type of gating signal is used in single phase ac voltage controller with RL load?
10. What are the disadvantages of continuous gating signal?
11. What is meant by high frequency carrier gating?
12. What is meant by sequence control ofac voltage regulators?

13. What are the advantages ofsequence control of ac voltage regulators?
14. What is meant by cyclo-converter?
15. What are the two types of cyclo-converters?
16. What is meant by step-up cyclo-converters?
17. What is meantby step-down cyclo-converters?
18. What are the applications of cyclo-converter?
19. What is meant by positive converter groupin a cyclo converter?
20. What is meant by negative converter group in a cyclo converter?

PART-B

1. Draw the circuit diagramof 1_capacitor commutated currentsource inverter and explain its operation with equivalent circuits for different modes and necessary waveforms.
2. Explain the operation of multistage controlof AC voltagecontrollers withneat diagram.
3. Explain the operation of 1_ ACvoltage controller with RL load.
4. Explain the operation of sequence control of AC voltagecontroller..

5 Explain the operation of 1_ sinusoidal AC voltagecontroller..