LECTURE NOTES

ON

POWER ELECTRONICS

III B.Tech I Semester

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

POWER SEMICONDUCTOR DEVICES

Introduction to the subject :-

Basically, the field of electrical engineering may be divided in to three areas of specialisation namely, (i) electronics
(ii) power
(iii) control

→ In that Electronics deals with the study of semi conductor devices and circuits at low power level

→ power deals with the generation, transmission and distribution of electrical energy with static and rotating Power equipments.

→ control deals with the steady state and dynamic characteristics of closed loop systems.

Def :- power electronics is defined as the use of solid state electronics for the control and conversion of electric power. (control of electric power means, the output voltage can be controlled and conversion of electric power means, ac to dc, dc to ac, dc to dc and ac to ac)

HISTORY OF POWER ELECTRONICS :-

→ The Power electronics history began with the development of mercury arc rectifier in the year 1900. Then the other power devices like metal tank rectifier, grid controlled vacuum tube rectifier, ignitron, phanotron, thyratron and magnetic amplifier, were developed & used gradually for power control applications until 1950.

→ The first SCR (Silicon controlled Rectifier) or Thyristor was invented and developed by Bell lab's in 1956 which was the first PNPN triggering transistor.

→ The second electronic revolution began in the year 1958 with the development of the commercial grade Thyristor by the General Electric company (GE)

Applications of Power Electronics :-

→ 1. control of ac and dc drives in rolling mills, paper and textile mills, traction vehicles, mine winders, cranes ventilation fans etc.

→ 2. Uninterruptible power supplies (UPS) for critical loads such as computers and space applications

→ Machine tool control.

→ power control in metallurgical and chemical processes using arc melting, induction heating and melting, resistance heating, arc welding etc.

→ Static power compensators, transformer tap changers and static contactors for industrial power systems.

→ High voltage Direct current (HVDC) system

→ Illumination controls for lighting in trains, homes and theatres

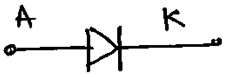
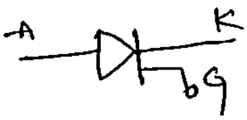
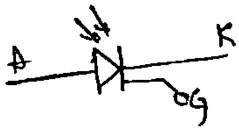
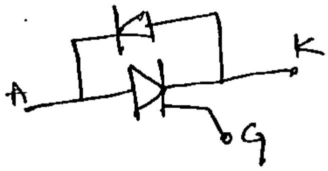
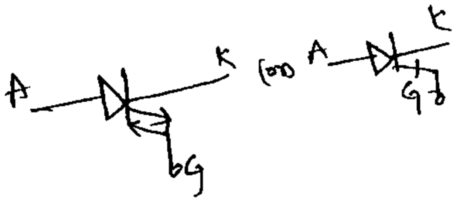
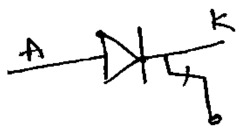
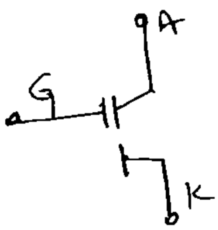
→ Excitation systems for alternator and synchronous condenser.

→ Battery charging

→ Electric Traction

→ Solid state controllers for home appliances

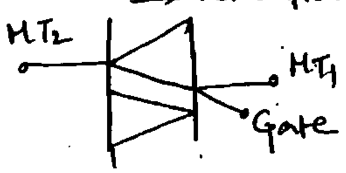
Maximum Ratings of Power semiconductor devices

S.No.	Device	Circuit symbol	Voltage/Current rating	Upper operating frequency (KHz)
1.	Diode		5000 V / 5000A	1.0
2.	Thyristors			
	a) SCR		7000V / 5000 A	1.0
	b) LASCR (Light activated SCR)		6000V / 3000A	1.0
	c) ASCR / RCT (Asymmetrical SCR, Reverse conducting thyristor)		2500V / 400A	2.0
	d) GTO (Gate turn off Thyristor)		5000V / 3000A	2.0
	e) SITH (Static Induction thyristor)		2500V / 500A	100.0
	f) MCT (CMOS controlled Thyristor)		1200V / 40A	20.0
	g) TRIAC		1200V / 1000A	0.5

TRIAC (Bidirectional Triode Thyristor) :-

TRIAC is a five layer device having 3 terminals and 3 Junctions. Its terminals are usually designated as MT_1, MT_2 and gate terminals. The Gate terminal 'G' is nearest to MT_1. MT_1 is always used as a reference terminal where any Voltage (or) currents may be measured w.r.t MT_1 terminal.

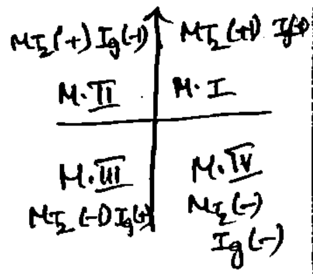
It will block both the +ve and -ve half cycles when gate signal is not applied. The value of the Voltage that should be applied to the TRIAC should be less than forward break over voltage i.e V_{BO1} or V_{BO2}



Symbol of TRIAC

TRIGGERING MODES OF TRIAC :-

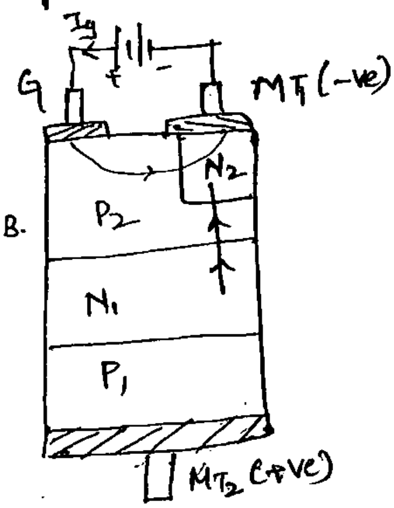
TRIAC can be turned on with +Ve or -ve gate current keeping the MT_2 terminal at positive (or) negative potential.



Mode 1 : MT_2 positive and gate current positive
Mode 2 : MT_2 positive and gate current Negative
Mode 3 : MT_2 Negative and Gate current positive.
Mode 4 : MT_2 Negative and Gate current Negative

Mode 1 :-

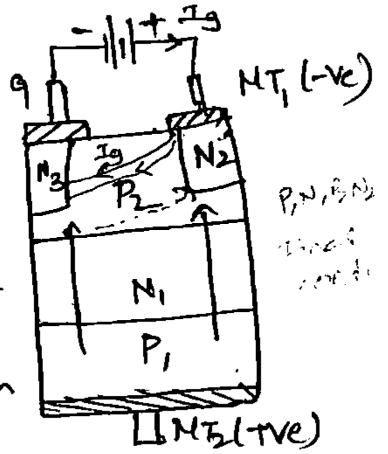
When MT_2 is +ve w.r.t MT_1, Junctions P_1-N_1, P_2-N_2 are F.B and junction N_1-P_2 is R.B. By applying the +ve gate signal w.r.t MT_1 Gate current mainly flows through P_2-N_2 junction.



MT_2 +ve and gate current is also +ve

when the gate current has injected sufficient charge into P_2 layer, P_2 layer is flooded with more electrons. These electrons tries to penetrate into the R.B junction and junction breaks down because of the avalanche phenomenon. Under these conditions, TRIAC will operate in the first quadrant which is sensitive. whenever a conduction is required, give the positive gate signal and +ve voltage w.r.t reference terminal

Mode II :



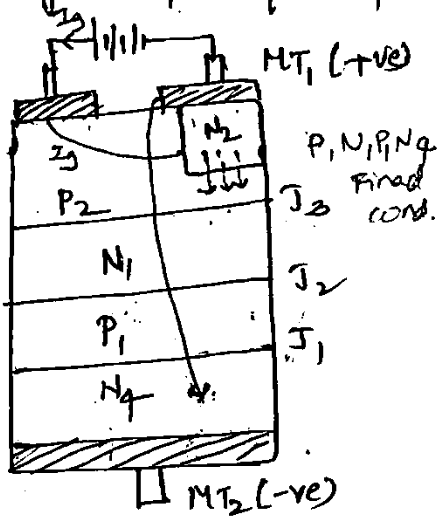
MT_2 is +ve, Gate current negative :

when MT_2 is +ve and gate current is -ve w.r.t terminal MT_1, Gate current starts flowing through the junction $P_2 - N_3$.

Initially, TRIAC starts conducting through $P_1N_1P_2N_3$ auxiliary structure. As the power flows is in the direction $P_1N_1P_2N_3$, the voltage drop across P_2N_3 falls because it is in conduction but P_2N_3 layer's potential rises towards the anode potential of MT_2 terminal. Here, right hand portion of P_2 is clamped at the cathode potential of MT_1 hence, there exists a potential gradient across P_2 layer. Left hand region of P_2 layer is at higher potential and right hand region of P_2 layer is at lower potential which results in the current flow from higher potential to lower potential. Here, TRIAC operates in second quadrant which is less sensitive compared to that of first quadrant.

Mode 3:- MT_2 negative with positive gate current:

when MT_2 is negative and MT_1 is positive, TRIAC may be turned ON by giving a positive ~~gate~~ voltage b/w Gate & terminal MT_1. The external gate current F.B P_2N_2 junction as gate is much more positive than MT_1 terminal. Layer N_2 injects electrons into P_2 layer as shown by dotted lines which is termed as remote gate control and these electrons are collected by the junction P_2N_1

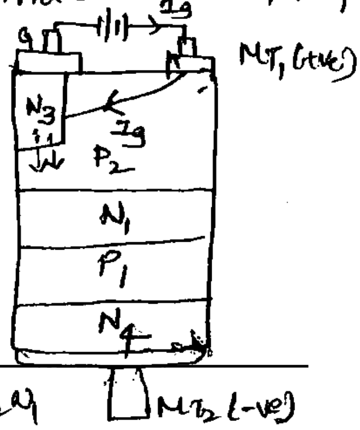


MT_2 is negative but gate current in positive.

→ The main structure which leads to turn ON the device is $P_2N_1P_1N_4$ where N_2 acts as a remote gate. The excess electrons liberated from N_2 are collected by P_2N_1 junction which causes an increase in the current flow through the junction P_2N_1. This device operates in the third quadrant. As the turn ON of the device depends upon the remote gate, it is less sensitive when compared to the mode① and mode② operations of the device.

Mode 4:- MT_2 negative with negative gate current:

Here, when MT_2 is negative and terminal MT_1 is positive, TRIAC may be turned ON by giving negative gate current. The main structure that leads to turn ON the triac is $P_2N_1P_1N_4$ with N_3 acting as a remote gate. External gate current I_g forward biases P_2N_3 junction. Layer N_3 injects electrons into P_2 as shown by dotted lines and these are collected by the junction P_2N_1 which causes an increase of current through P_2N_1



Now, P_2 releases holes which diffuses through N_1 and reaches P_1 layer where a positive space charge builds up in this region. More electrons from N_4 layer diffuses into P_1 which neutralizes the positive space charge. These electrons finally arrives at the junction J_2 which creates a negative space charge in N_1 region resulting more holes being injected from P_2 layer into N_1. This regenerative process takes place until the structure P_2N_1 P_1N_4 gets turned ON and conducts current which may be limited by external load. The device is more sensitive in this mode where the triac operates in 4th quadrant.

→ The Triac can be switched into the ON-state by either +ve (or) -ve gate current, but it is more sensitive if positive current is injected when MT_2 is positive and negative current is injected when MT_1 is +ve.

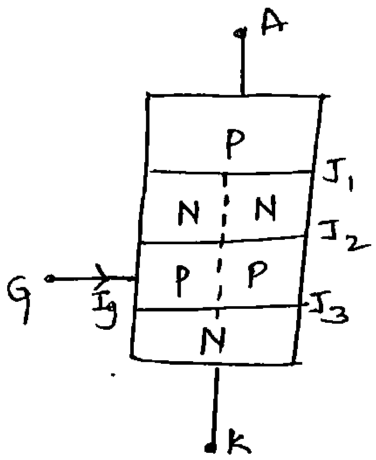


fig (a)

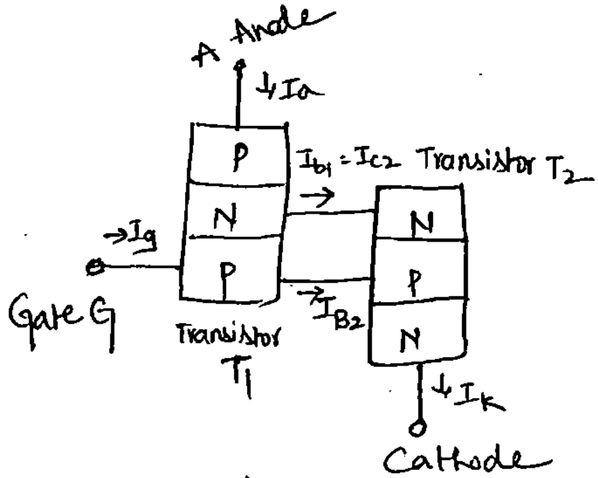


fig (b)

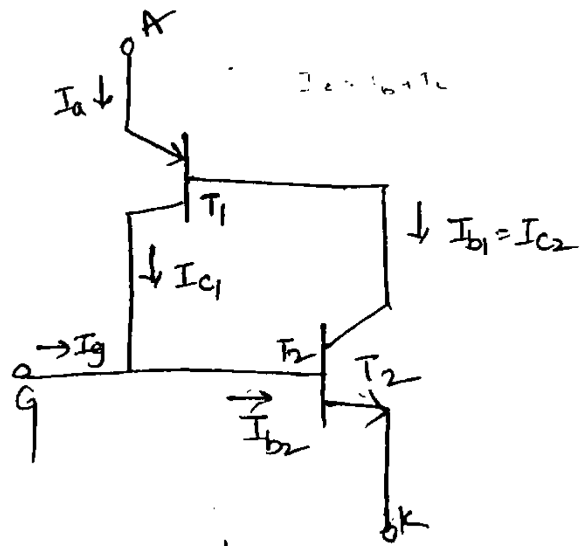


fig (c)

Two Transistor Analogy of SCR

From fig(c), observe that the collector current of transistor T_1 becomes the base current of transistor T_2 and vice versa

$$\therefore \quad I_{c1} = I_{b2} \quad \text{and} \quad I_{b1} = I_{c2}$$

Also, $$I_k = I_a + I_g \quad \text{—(1)}$$

Already we know the relation from transistor analysis

$$I_{b1} = I_{e1} - I_{c1} \quad \text{—(2)} \quad (\because I_{e1} = I_{b1} + I_{c1})$$

Also $$I_{c1} = \alpha I_{e1} + I_{co1} \quad \text{—(3)}$$

$\alpha_1 \rightarrow$ common base current gain of T_1

where I_{co1} is the reverse leakage current of the reverse biased junction ...

substituting eq. ② in eq ③ we get

$$I_{b1} = I_{e1} - \alpha_1 I_{e1} - I_{co1}$$

$$I_{b1} = (1-\alpha_1) I_{e1} - I_{co1}$$

From fig (c) it is evident that the anode current of the device becomes the emitter current of Transistor T_1 that is

$$I_a = I_{e1}$$

$$\therefore \quad I_{b1} = (1-\alpha_1) I_a - I_{co1}$$

Also, $I_{C2} = \alpha_2 I_{e2} + I_{co2}$ — ④

From fig (c). The cathode current of the SCR becomes the emitter current of transistor T_2

$$\therefore \quad I_K = I_{e2}$$

$$I_{c2} = \alpha_2 I_{e2} + I_{co2}$$

$$\therefore \quad I_{c2} = \alpha_2 I_K + I_{co2} \quad — ⑤$$

But $I_{b1} = I_{c2}$ — ⑥

Substitute eq ⑤ & ⑥ in eq. ④, we get

$$(1-\alpha_1) I_a - I_{co1} = \alpha_2 I_K + I_{co2} \quad — ⑦$$

Substitute eq. ① in eq. ⑦ we get

$$(1-\alpha_1) I_a - I_{co1} = \alpha_2 (I_a + I_g) + I_{co2}$$

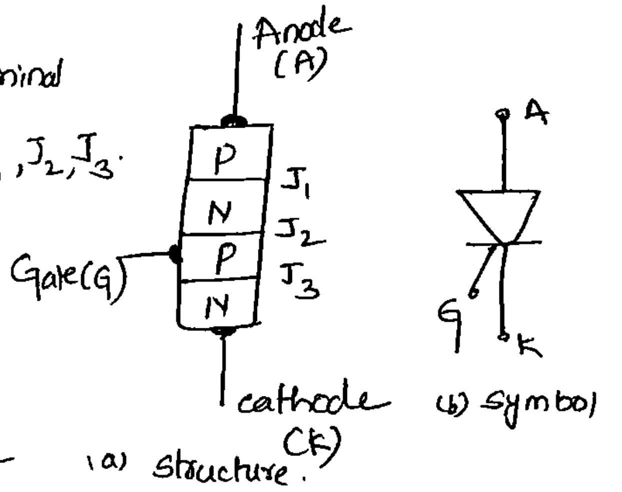
$$(1-\alpha_1-\alpha_2) I_a = \alpha_2 I_g + I_{co2} + I_{co1}$$

$$[1-(\alpha_1+\alpha_2)] I_a = \alpha_2 I_g + I_{co1} + I_{co2}$$

$$\therefore \quad I_a = \frac{\alpha_2 I_g + I_{co1} + I_{co2}}{[1-(\alpha_1+\alpha_2)]}$$

PRINCIPLE OF OPERATION OF SCR :-

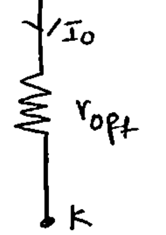
→ SCR is a four layered, three terminal device with three junctions namely J_1, J_2, J_3. It is a PNPN switching device. The four layers in this device are PNPN layers.



→ The three terminals of the device are Anode, cathode and gate. Here, the Anode and cathode terminals are connected to the main power circuit. The gate terminal carries a low level gate current in the direction gate to cathode. Normally, the gate terminal is provided at the p layer near the cathode. This is known as cathode gate.

→ When the end P layer near the anode is made more positive when compared to N layer near the cathode, Junctions J_1 and J_3 gets forward biased where as the middle junction J_2 gets reverse biased. Junction J_2 is known as Junction capacitance as it acts as a capacitor in this mode. Due to the depletion layer formed at this junction, no current flows through the device. But due to the drift of mobile charge carriers a small amount of leakage current flows through the circuit. As the leakage current is negligibly small, the device does not conduct. This state is known as forward blocking state or OFF state of the device as it blocks the forward biased voltage.

→ During the 'OFF' state, an SCR acts as a high Impedance device.

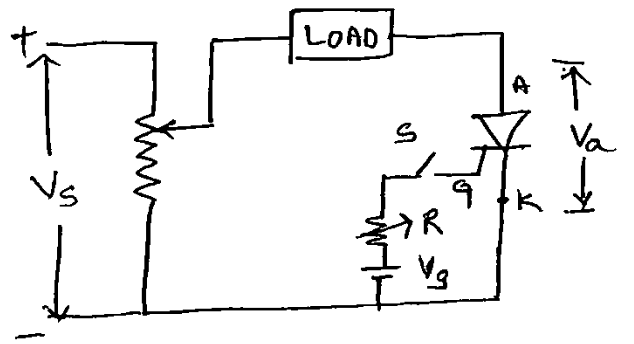


Equivalent ckt during off state.

STATIC V-I CHARACTERISTICS OF AN SCR:-

→ An elementary circuit diagram for obtaining static V-I characteristics of a thyristor is shown in fig.

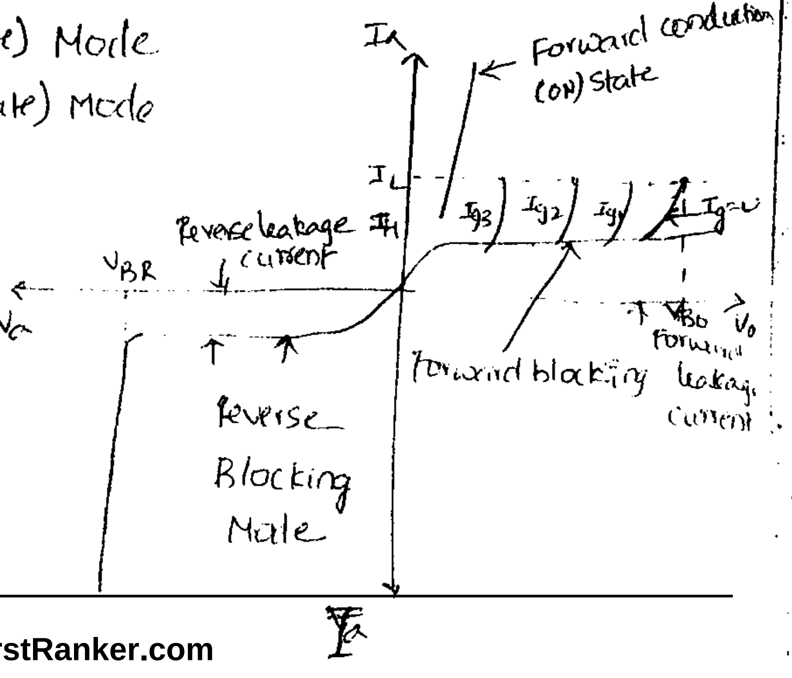
→ The anode and cathode are connected to main source through the load. The gate and cathode are fed from a source V_s which gives positive gate current from gate to cathode



→ V_a is the anode voltage across thyristor terminals A and K and I_a is the anode current. The static V-I characteristic of a thyristor has three basic modes of operation.

a) Reverse blocking Mode
b) Forward blocking (off-state) Mode
c) Forward conduction (ON-state) Mode

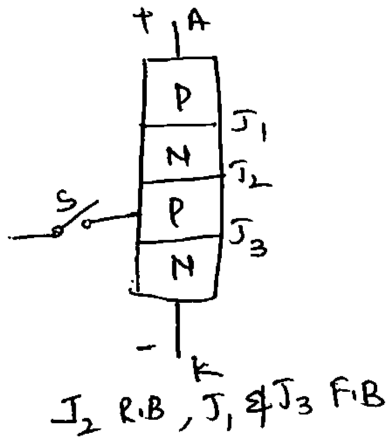
a)



V_{Bo} - Forward breakover voltage
V_{BR} - Reverse breakover voltage
I_g - gate current
I_L - Latching current
I_H - Holding current

b) Forward Blocking Region :-

In this region, the anode is made positive w.r.t cathode and therefore, Junctions J_1 & J_3 are F.B and J_2 remains R.B. Hence the anode current is a small forward leakage current.



→ Incase the forward voltage is increased, then the reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward breakover voltage V_{BO}.

→ when forward voltage is less then V_{BO}, thyristor offers high Impedance. ∴ SCR can be treated as an open switch even in the forward blocking mode.

c) FORWARD CONDUCTION MODE :-

→ In this mode, SCR conducts currents from Anode to cathode with a very small voltage drop across it. A SCR is brought from forward blocking mode to forward conduction mode by turning it ON by exceeding the forward breakover voltage (or) by applying a gate between gate and cathode.

→ In this high conduction Mode, the anode current is determined essentially by the external load impedance. Therefore when the thyristor conducts forward current, it can be regarded as a closed switch.

→ Anode current < latching current, Holding current

RATINGS OF AN SCR :-

→ Rating of an SCR is the safer value which is more than that of its normal working values.

→ thyristor posses several ratings such as Voltage, current, $\frac{di}{dt}$, $\frac{dv}{dt}$, Power, turn on time, turn-off-time etc.

→ Generally subscripts are associated with voltage and current ratings for the convenience in identifying them.

→ First subscript indicates the direction (or) the state

→ 2nd subscript denotes the operating values except for gate G.

W – working value
R – Repetitive Value
S – Surge (or) non repetitive value
T – Trigger

→ 3rd subscript M indicates the maximum value.

[Note: For the ratings less than 3 subscripts the above rules cannot be applied]

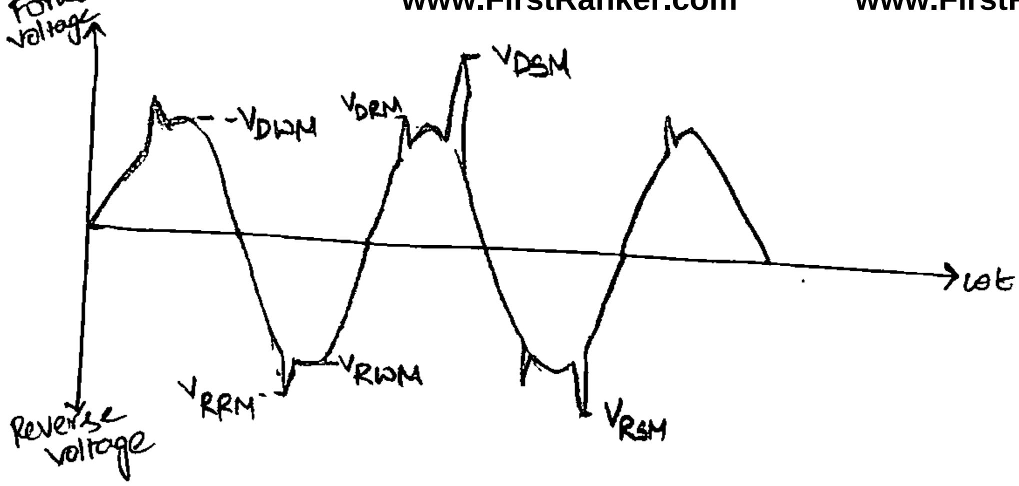
ANODE VOLTAGE RATINGS:-

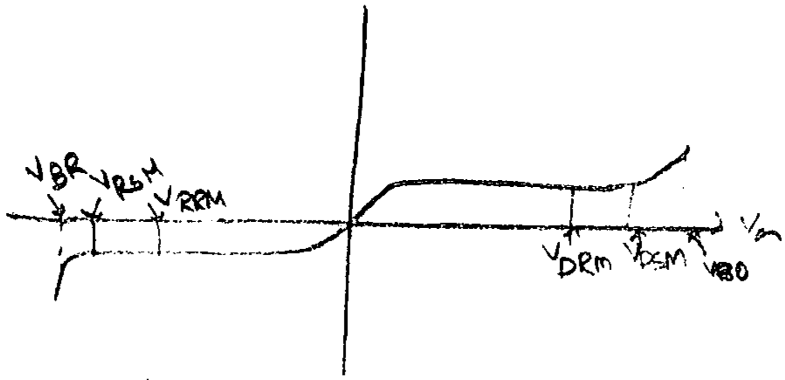
→ Anode voltage ratings indicate the max. ~~voltage~~ voltage values that an SCR can withstand without any breakdown of the junction area with gate circuit open.

→ For A.C supply systems, the source voltage does not appear as a smooth sine wave. It consists of voltage transients ~~rep~~ regularly or randomly

V_{DWM} :- It is the "Peak working forward blocking voltage"

→ It denotes the maximum forward blocking voltage that a thyristor can withstand during turn ON state.





Anode voltage Ratings during the blocking state of an SCR

(2) **V_{DRM}**: It is the "Peak repetitive forward blocking voltage."

→ It specifies the peak transient voltage that an SCR can withstand periodically (or) repeatedly in its forward blocking state.

⇒ wherever the thyristor is in the turn off state, V_{DRM} is obtained. V_{DRM} is an abrupt change in reverse recovery current which accompanies a spike voltage of magnitude $L\frac{di}{dt}$

3. **V_{DSM}**:- It is the "Peak surge or non repetitive forward blocking voltage".

→ It denotes the peak value of the forward surge voltage which does not repeat again. Its value is given as 130% of V_{DRM}

$$V_{DSM} < V_{BO}$$

4) **V_{RWM}**:- It is the "Peak working reverse voltage".

→ It is the maximum permissible reverse voltage ~~that a thyristor~~ can withstand repeatedly ... equal to the peak ...

5. V_{RRM} : It is the "peak repetitive reverse Voltage".
It denotes the peak, reverse transient voltage that occurs repeatedly in the reverse direction at the allowable max. junction temp. Its duration is for a period of fraction of one cycle.

6. V_{RSM} :- It is the "Peak surge or non repetitive reverse Voltage"
It represents the peak value of the reverse surge voltage which does not repeat. Its value is about 130% of V_{RRM}

$$V_{RSM} < V_{BR}$$

7. V_T :- It is the "ON state voltage drop".
It is the drop across the anode and cathode with a specified forward ON state current and junction temp. Its value is of the order of 1 to 1.5 v

8. dv/dt rating :- It indicates the max. rate of rise of the anode voltage which does not trigger the device without any trigger pulse.
→ If dv/dt rating is more than the specified value unwanted triggering of SCR takes place.

9. Gate trigger voltage : (V_{GT}) :- It is defined as the minimum gate voltage required to produce the gate trigger current.

10. Voltage safety factor (V_f) :- To avoid damage to SCR due to undesired conditions, normal operating voltage is kept well below the V_{RSM} value of device.

$$V_f = \frac{V_{RSM}\ (\text{Peak reverse voltage})}{\sqrt{2} \times \text{RMS value of i/p Voltage}}$$

range of this factor : $2 < V_f < 2.5$

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range of this factor ; $2 < V_f < 2.5$

Current ratings of an SCR:

→ The junction temperature of an SCR may increase whenever it carries a current which is more than the rated value. So, the device gets destroyed. In order to the avoid this and for the proper (or) better utilization of SCR, it must carry the current values which are less than rated values.

1. Average ON state current (I_{TAV}) :- As the forward voltage drop across conducting thyristor is very low, the power loss in a thyristor depends mainly on forward average ON state current I_{TAV}.

→ The average current rating of a phase controlled thyristor results in different conduction angles.

→ ~~As the conduction angle decreases~~, ~~the~~

→ The instataneous current increases with the decrease in conduction angle. There by, the voltage drop across the device increases. The average power dissipation may increase raising the junction temp beyond the gate allowable limit.

→ This current rating is of repetitive type and is specified at the maximum junction temp. current rating varies with the different temp.

2. RMS ON state current (I_{RMS}) :-

→ whenever 'SCR' is subjected to high peak currents and low duty cycle waveforms (I_{RMS}) places a very important role

→ In order to prevent the excessive heating in Resistance elements of SCR such as Metallic joints, leads, interfaces, the Vertical rms values must be specified of the specification of

· Surge current rating (I_{TSM})

→ whenever SCR works under its V-I specifications the junction temp. never exceeds and when it is subiected to abnormal conditions the junction temp. raises to such an extent that it damages the devices, in order to avoid this damage, surge current must be known, which indicates maximum permissible non repetitive current which the device can withstand.

→ The frequency of surge current depends upon the switching frequency and the rating is specified in terms of no. of surge cycles with corresponding current peak

$$\text{subcycle current } I_{SB} = I_{TSM} \times \sqrt{\frac{T}{t}}$$

T → Time for one half cycle of switching freq. in seconds

t → duration of subcycle surge in seconds

4) I^2t rating :-

This rating is the measure of the thermal energy that the device can absorb for a short time before the fault is cleared by the fuse.

It is given by the square of the rms value of the current integrated w.r.t time (I^2dt)

5) $\frac{di}{dt}$ rating :-

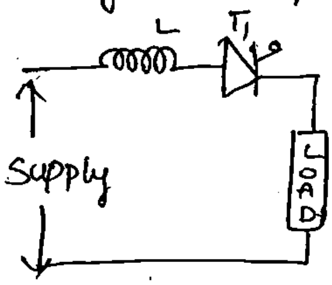
The $\frac{di}{dt}$ rating of a SCR indicates the maximum rate of rise in anode to cathode current.

→ The max. rate of change of current that the device can withstand during its ON state is called its critical rate of rise of current.

→ If rate of rise in anode current is greater than the velocity of charge carriers across the cathode junction, on the account of high current density. which increases the junction temperature beyond the safe limit and the SCR may be damaged.

→ $\frac{dI}{dt}$ range is from 50 to 800 ampere per μseconds.

→ The SCR device can be protected from $\frac{di}{dt}$, a large value of inductor is connected in series with device.



6. <u>Holding current</u> :- (I_H)

→ The holding current may be defined as the minimum value of anode current below which the device stops conducting and returns to its OFF state.

→ usually it is very small in the order of milliamperes.

7. <u>Latching current</u> :- (I_L)

The latching current of a device may be defined as the minimum ON state current required to keep the device in the ON state after the triggering pulse has been removed.

8) <u>Gate current (I_{gmin} and I_{gmax})</u> :-

→ The current which is applied to the gate of the SCR for control purposes, is known as its gate current.

→ The minimum value of current required at the gate for triggering the device is called as the minimum gate current (I_{gmin})

→ ~~The Maximum gate current (I_{gmax}) is the maximum value of current~~
that can be applied to the gate ...

Thyristor Turn ON Methods:

→ when Anode is made positive w.r.t cathode, A thyristor can be turned ON by any one of the following techniques.

1) Forward voltage triggering
2) dv/dt triggering
3) Temperature triggering (Thermal triggering)
4. Light triggering (Radiation triggering)
5. Gate triggering.

1. Forward Voltage triggering:-

when the anode to cathode voltage is increased with the gate circuit open, the junction (J_2) will have an avalanche break down at a voltage called forward break over voltage (V_{BO}). Immediately, the thyristor can be brought from the forward blocking state to forward conduction state. when the SCR is in the ON state, the forward voltage drop across the SCR is of the order of 1 to 1.5 V and increases slightly with load current.

Disadvantages:-

a) A large forward voltage is required to turn ON the SCR
b) At this forward break over voltage the SCR may get damaged.

2) dv/dt triggering :-

when the forward voltage is applied across the device, the junctions J_1 and J_3 are F.B, whereas junction J_2 is R.B. The reverse biased junction (J_2) has the characteristics of a capacitor, due to the space charges existing across the junction.

~~Let V → forward voltage applied across the device~~

Q → charge

Advantages of power electronics converter systems :-

→ 1. High efficiency due to low loss in power semiconductor device.

→ Fast response of power electronic systems as compared to electro-mechanical converter systems.

→ Long life and reduced maintenance due to absence of Mechanical wear.

→ High reliability of power electronic converter systems

→ Small size and low weight require less floor area

→ Lower acoustic noise compared to electromagnetic controllers

→ Mass production of power semiconductor devices has resulted in lower cost of the converter equipment.

→ Flexibility in operation due to digital controls.

Disadvantages :-

→ Power semiconductor converters have a tendency to introduce current and voltage harmonics into the supply systems and controlled systems.

→ Thyristor controllers have low overload capacity.

→ Harmonics in the supply system causes interference with communication systems and distortion of supply system.

→ Regeneration of power is difficult

→ Some converters, such as controlled rectifiers, cycloconverter and ac voltage controller suffer from a low power factor, particularly at low o/p voltages

The charging current is given by

$$i_c = \frac{dv}{dt} \qquad [\because Q = C.V]$$

$$i_c = \frac{d}{dt}(C_j \cdot v)$$

$$= C_j \frac{dv}{dt} + v \frac{dC_j}{dt}$$

The rate of change of capacitance (w.r.t time) is negligible, since the junction capacitance does not vary w.r.t time.

$$\Rightarrow i_c = C_j \cdot \frac{dv}{dt}$$

∴ The rate of change of voltage across the device is large, the device may turn ON even though the voltage appearing across the device is very small.

9) Temperature Triggering :-

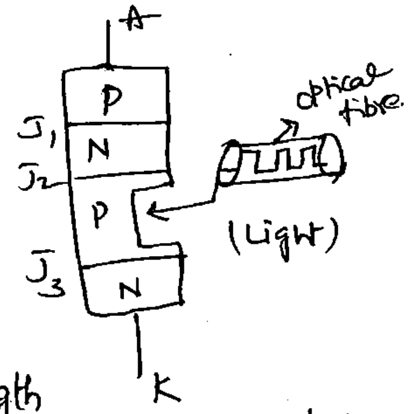
→ In case of semiconductor devices, the width of the depletion layer decreases on increasing the junction temperature.

→ During the forward blocking condition major part of the applied voltage appears across the reverse biased junction (J_2).

→ The voltage across the junction associated with the leakage current, raise the temp. of the junction. Due to this temp., the leakage current further increases. This is a cumulative process, and it may turn ON the SCR at some high temp. and at a voltage which is less than the forward break over voltage.

d) Light triggering : (Radiation triggering):

→ In this method, the energy is imparted by radiation. So this is known as Radiation triggering.



→ SCRs are bombarded with the high energy particles such as neutrons (or) photons. The electron hole pairs are generated in the device with the help of the external energy.

→ A pulse of light with appropriate wave length is guided by the optical fibres. If the intensity of the light thrown on the device exceeds a certain value, the SCR which is in forward blocking state is brought to the forward conduction state.

→ LASCR and LASCS comes under the light triggering (or) radiation triggering

Gate triggering :-

In order to turn ON the thyristor, the most effective method, simple, reliable and efficient is the gate triggering method.

→ When Anode is more positive w.r.t cathode, SCR is F.B. Gate signal is applied between the gate and cathode. Here J_1, J_3 are F.B and J_2 is R.B. Due to the repulsion of the charge carriers from the -ve plate, the charge carriers will penetrate into the junction 2 and it will cross the junction (J_2).

→ In case of the gate triggering, a signal must be applied across the gate cathode. The signal may be D.C voltage, A.C voltage (or) pulse triggering.

(i) D.C gate triggering :- In this method, a D.C voltage of proper magnitude and correct polarity is applied b/w the gate and cathode so that gate cathode junction is F.B and when the applied voltage exceeds the minimum gate triggering voltage, the SCR can be brought from OFF state to ON state.

Disadvantage:-

(i) There is no isolation b/w Power circuit (Anode cathode) and control circuit (Gate cathode circuit)

(ii) Gate signal can be used at the time of turn on, but in the case of D.C gate triggering a continuous gate signal is applied causing more losses at the gate.

2) A.C gate triggering:- In this method an isolation transformer is used to provide an isolation between power ckt and cntrl ckt.

→ In case of A.C circuit, if source voltage is provided for the power circuit and control circuit, SCR is triggered, covering +ve half cycle.

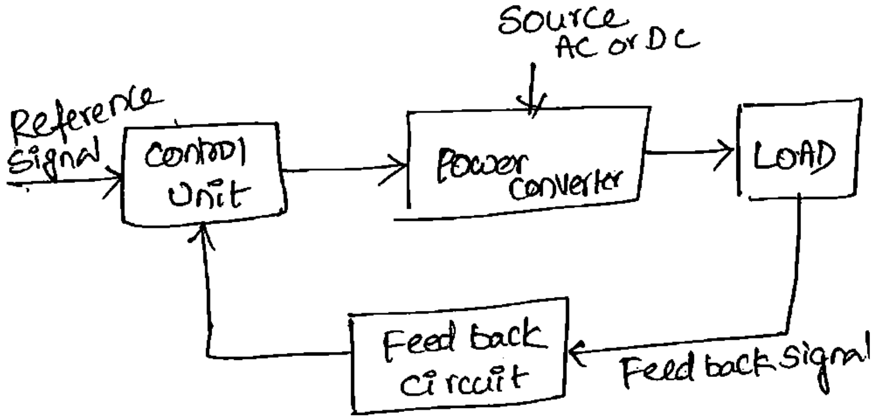
→ During the -ve half cycle SCR is R.B. The gate cathode is subjected to a large reverse voltage, which requires a stepdown transformer. So the cost will increase.

3) pulse triggering :- One of the most efficient method in case of gate triggering is pulse triggering.

→ A pulse transformer is used for the isolation of Power ckt and control ckt. In this method, there is no need of applying continuous gate signal

→ If the gate signals are applied with some periodicity then it is known as carrier frequency gating.

Power Electronics Systems :-



Block diagram of power electronics system.

→ The main power source may be ac or dc supply system. The power converter may be one of the power electronic converter depending upon the applications. The o/p from the power electronic converter may be variable dc or ac voltage, or it may be a variable voltage and frequency.

→ The o/p of the power electronic converter depends upon the requirements of the load.

→ For example, if the load is a 3-ϕ IM, the converter output has variable voltage and variable freq.

→ In case the load is a dc motor only, the converter o/p voltage must be variable.

→ The feed back signal measures a parameter of the load, say speed in case of a rotating m/c and compares it with reference signal.

→ The difference of these two signals, through the control units, controls the instant of turn-on of power devices in the power converter system. In this way the performance can be controlled

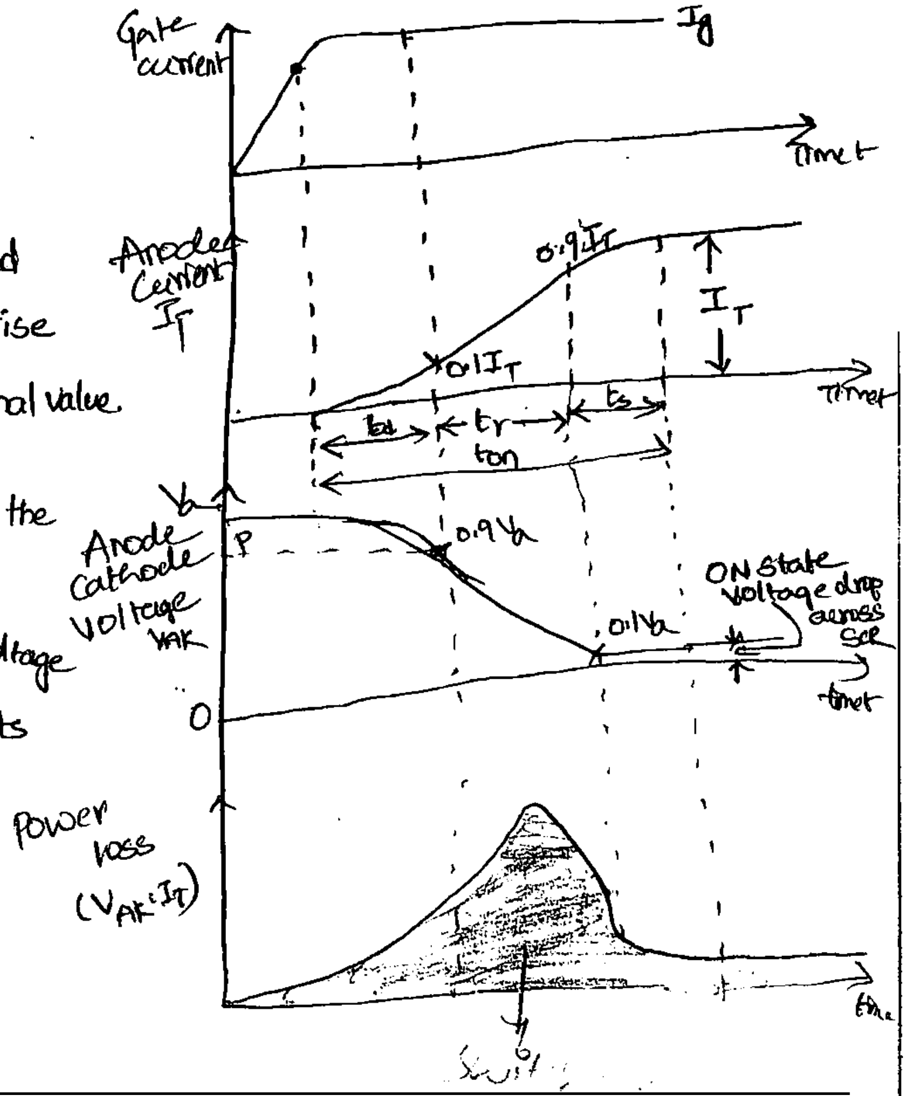
DYNAMIC CHARACTERISTICS ... During T_{ON})

The transition from one state to the other does not take place instantaneously, it takes a finite period of time. The total turn on time t_{ON} of the SCR is subdivided into three distinct periods, called the delay time, rise time and spread time.

(i) Delay time (t_d) :-

This is the time between the instant at which the gate current reaches 90% of its final value and the instant at which the anode current reaches 10% of its final value.

It can also be defined as the time during which anode voltage falls from V_a to $0.9\,V_a$ where V_a is the initial value of anode voltage



(ii) Rise time (t_r) :-

This is the time required for the anode current to rise from 10% to 90% of its final value.

→ It can also be defined as the time required for the forward blocking off state voltage to fall from 0.9 to 0.1 of its initial value

(iii) Spread time (t_s) :-

The spread time is the time required for the forward blocking voltage to fall from 0.1 to its value to the onstate voltage drop (1 to 1.5V). After the spread time, anode current attains steady state values and the voltage drop across SCR is equal to the on-state voltage drop of the order of 1 to 1.5V.

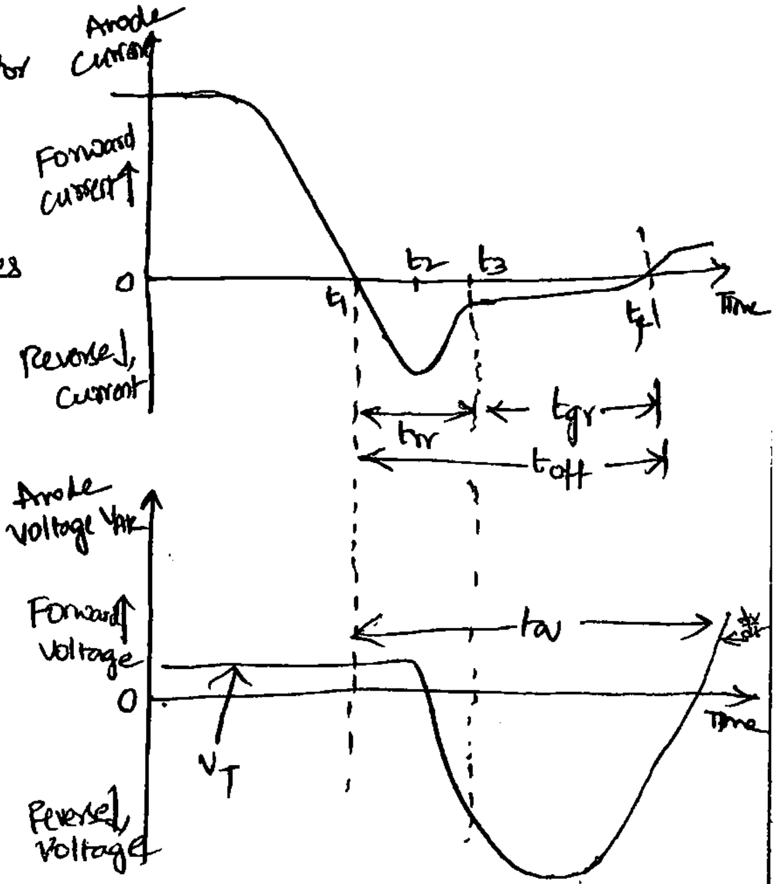
(iv) Turn ON Time (t_{ON}) :-

This is the sum of the delay time, rise time and spread time. This is typically of the order of 1 to 4 μs, depends upon the anode circuit parameter and the gate signal waveshapes.

→ Dynamic characteristics during Turn OFF Mechanism: (Turn off characteristics)

› The turn-off time of the thyristor is defined as the minimum time interval between the instant at which the anode current becomes zero, and the instant at which the device is capable of blocking the forward voltage.

→ the total turn off time is divided into two time intervals i.e, reverse recovery time t_{rr} and the gate recovery time t_{gr}



Reverse Recovery time :-

It is the time taken by the reverse recovery current to remove the excess charge carriers from the outer junctions J_1 & J_3

Gate recovery time :- It is the time taken to remove the excess charge carriers from the middle junction J_{12} by the recombination process.

Types of Power Electronics Converters :-

→ A power electronic converter is made up of some power semi conductor devices controlled by Integrated circuits. This converter converts the input power of one form to output power of some other form.

→ The power electronic converter (or circuits) can be classified into six types

1. Diode rectifiers
2. AC - DC converters (controlled Rectifiers)
3. AC - AC converters.
   (i) AC voltage regulators
   (ii) cyclo converters
4. DC - DC converters (DC choppers)
5. DC - AC converters (Inverters)
6. Static switches.

1. Diode Rectifiers :-

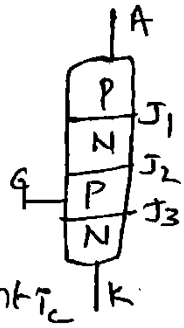
A Diode rectifier circuit converts ac input voltage into fixed dc output voltage. The i/p voltage to the rectifier could be either single phase or three phase.

Applications :-

(a) Electric traction
b) Battery charging
c) uninterruptible power supply (UPS)
d) Power supplies
e) electro chemical processing

Need For Snubber Circuit :-

→ When the Forward voltage is applied across the anode and cathode of the thyristor, the outer two junctions (J_1 & J_3) are forward biased and the inner junction (J_2) is reverse biased. In the reverse biased condition, junction J_2 exhibits the characteristics of a capacitor. Holes from P layer of J_1 accumulate at the junction J_2 and electrons from N layer of J_3 accumulates at the other side of junction J_2. There exists space charge carriers across the junction J_2.

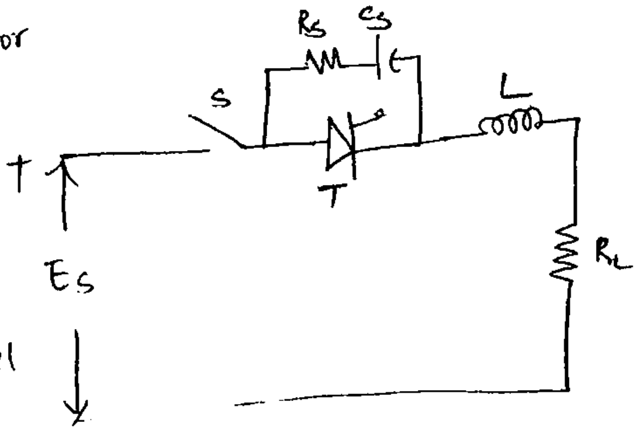


→ If a large amount of voltage is applied with in a short interval of time, charging current i_c flows through SCR. without the application of the gate signal the SCR gets turned ON. It leads to the malfunctioning of the device.

→ So, the rate of rise of voltage across the anode to cathode should be limited. So, an RC network should be connected across the SCR inorder to limit $\frac{dv}{dt}$ rating.

Design Aspects of Snubber circuit :-

→ When the switch 'S' is closed, a sudden voltage appears across the circuit Capacitor C_s. The capacitor behaves as a short circuit.



→ The voltage across the capacitor and thyristor is zero at that instant because they are connected in parallel

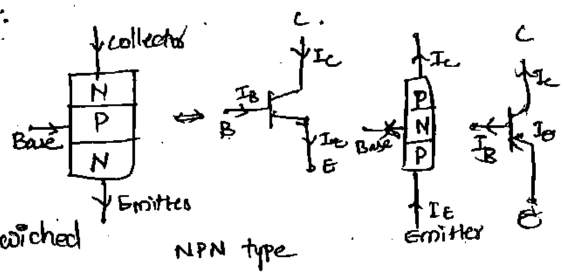
→ As the time goes on, the voltage across the capacitor C_s builds up slowly with less $\frac{dv}{dt}$ rating.

CLASSIFICATION OF POWER TRANSISTORS:-

Power transistors may be classified into three types. they are

1. Bipolar junction Transistors (BJTs)
2. Metal oxide semiconductor field Effect Transistors (MOSFETs)
3. Insulated gate bipolar transistors (IGBTs)

Bipolar Junction Transistors :-

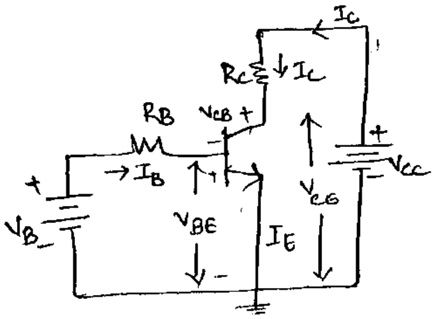


→ It is a three layered device having two junctions npn or pnp semiconductor device.

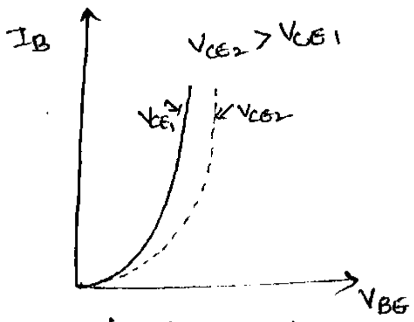
→ whenever the p region is sandwiched by two n regions an npn transistor is formed.

→ whenever the n region is sandwiched by two p regions a pnp transistor is formed.

→ BJT is a device where the current flow in the device is due to the mobility of both the charge carriers i.e electrons and holes.



NPN transistor circuit

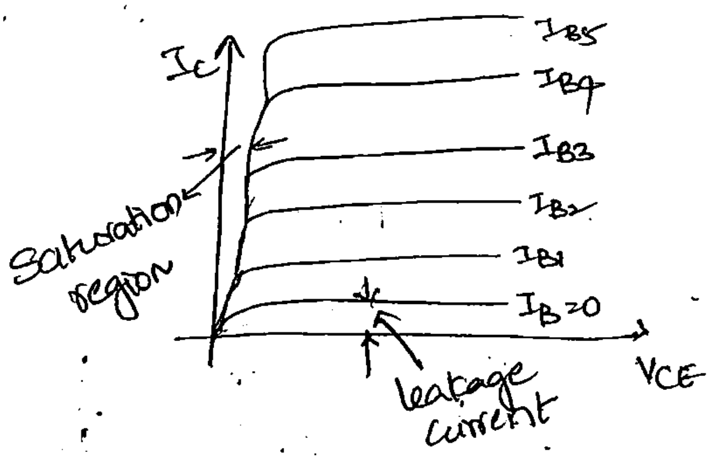


I/P characteristics

→ common emitter configuration of transistor is most commonly used for switching application.

→ I/p characteristics is obtained by plotting the graph b/w the base current I_B and the base emitter voltage V_{BE}.

→ In the i/p characteristics curve, we observe that whenever V_{CE} is increased, the base current gets decreased.



o/p characteristics

→ o/p characteristics of BJTs are obtained by plotting a graph b/w collector current I_C and collector emitter voltage V_{CE}. whenever $I_B = 0$, there exists a small leakage current as the voltage V_{CE} value is increased

POWER MOSFETS :-

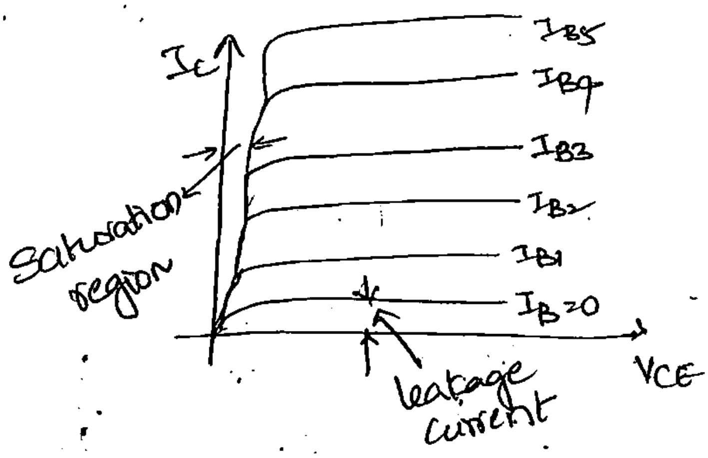
→ MOSFET stands for Metal oxide semiconductor, field effect transistor. It has 3 terminals i.e. gate, source and drain.

→ It is a voltage controlled device and is available for high voltage and current ratings.

→ MOSFETs are becoming popular in low to medium power applications and ~~beeee~~ high frequency power electronic circuits, since the turn on time is very less.

→ In the case of transistor secondary breakdown take place. But in the case of MOSFETs, it doesnot have the problem of secondary breakdown, as it operates in the safe operating area.

→ In the o/p characteristics curve, we observe whenever V_{CE} is increased, the base current gets decreased.



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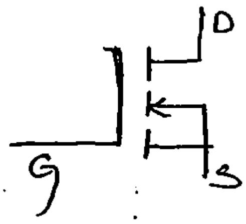
→ In the case of transistor secondary breakdown take place. But in the case of MOSFETs, it doesnot have the problem of secondary breakdown, as it operates in the safe operating area.

→ The switching times are very short, with range of few tens of nano secs to a few hundred nano sec. depending upon the type of device.

→ It is used in high current applications



Symbol of Power MOSFET.

Types of power MOSFET :-

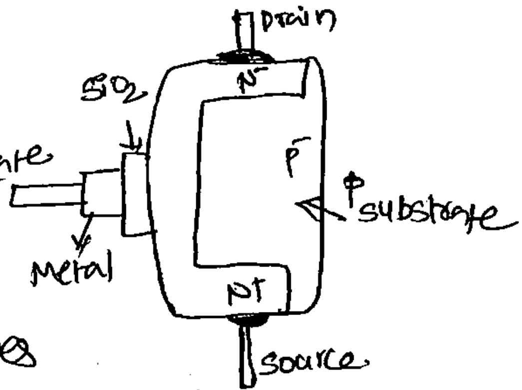
The two main types of Power MOSFETs are

1. Depletion MOSFET
2. Enhancement MOSFET

Each type are further classified as

(i) n channel MOSFET
(ii) p channel MOSFET

→ n channel enhancement MOSFET is more common because of higher mobility of electrons.



Basic structure of N channel power MOSFET

→ The bottom layer is n^+ substrate. Gate and treated as a source.

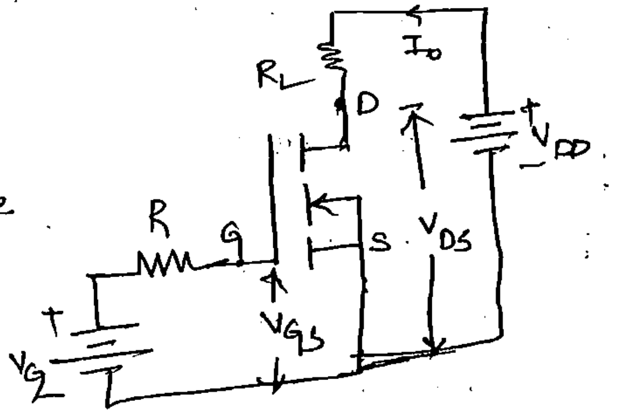
The n^- layer is called the drain drift region. This drift region determines the breakdown voltage of the device, a metal layer is deposited to form the drain terminal.

→ P^- regions are diffused in the epitaxially grown n^- layer SiO_2 (silicon dioxide) layer is added which is then etched so as to fit metallic source and gate terminals.

Operation :-

When the Gate source Voltage V_{GS} is zero, and drain source Voltage V_{DD} is present, then $n^- - p^-$ junctions are reverse biased and no current flows from drain to source. So, the device acts as a open switch.

→ when Gate terminal is made +ve w.r.t source, an electric field is created and electrons form n-channel in the p^- region. Now, the current flows from Drain to source. when gate voltage V_{GS} is increased drain current I_D also increases. i.e., o/p current can be controlled by gate voltage.



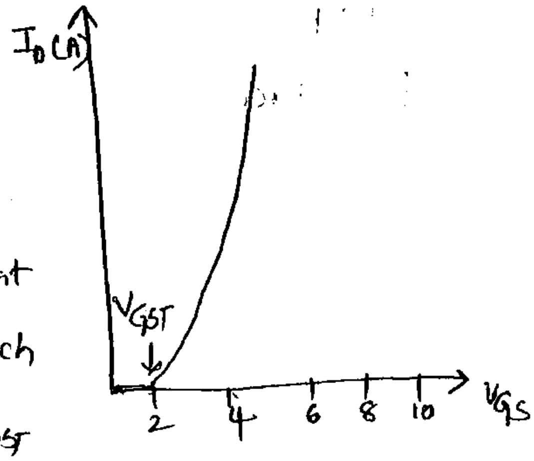
N channel Power MOSFET Circuit diagram

so Power MOSFET is also called as Voltage controlled device. Here the controlling Parameter is gate source voltage V_{GS}.

Static characteristics :-

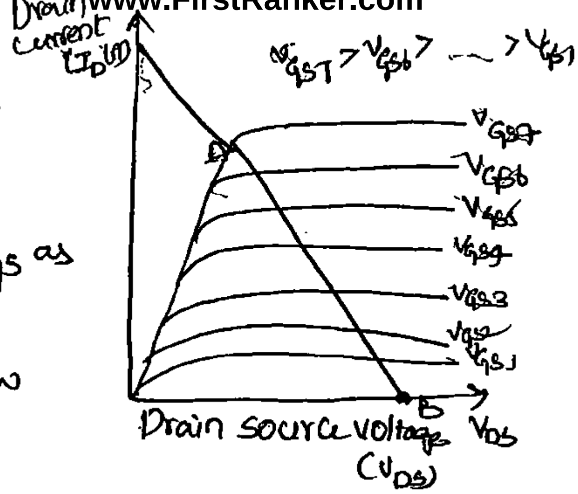
(a) Transfer characteristics :-

This characteristic shows the variation of drain current I_D as a function of gate source Voltage V_{GS}. It is seen that there is threshold voltage V_{GST} below which the device is OFF. The magnitude of V_{GST} is of the order of 2 to 3 V.



Transfer characteristics for n-channel Power MOSFET

Output characteristics :



→ Power MOSFET o/p characteristics indicate the variation of drain current I_D as a function of drain-source voltage V_{DS} as a parameter.

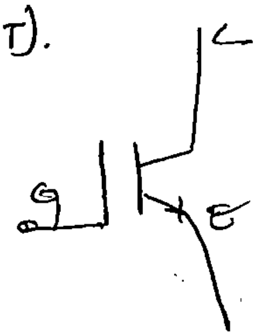
→ For low values of V_{DS}, the graph b/w $I_D - V_{DS}$ is almost linear. $R_{DS} = \frac{V_{DS}}{I_D}$.

→ For given V_{GS}, if V_{DS} is increased, o/p characteristics is relatively flat indicating that drain current is nearly constant.

MOSFET	BJT
1. Power MOSFET has lower switching losses.	1. BJT has higher switching losses
2. It has more conduction losses	2. It has low conduction losses
3. It is a voltage controlled device.	3. It is a current controlled device.
4. It is a unipolar device	4. It is a bipolar device
5. Power MOSFET operate at switching frequencies in the MHz range.	5. BJT operate at switching frequencies in kHz range.
6. MOSFET has positive temp. coefficient	6. BJT has negative temp coefficient
7. Secondary breakdown doesnot occur in MOSFET	7. BJT has secondary breakdown.
8. MOSFETs are available with ratings upto 500V, 140A	8. BJTs are available with ratings upto 1200V and 800A.

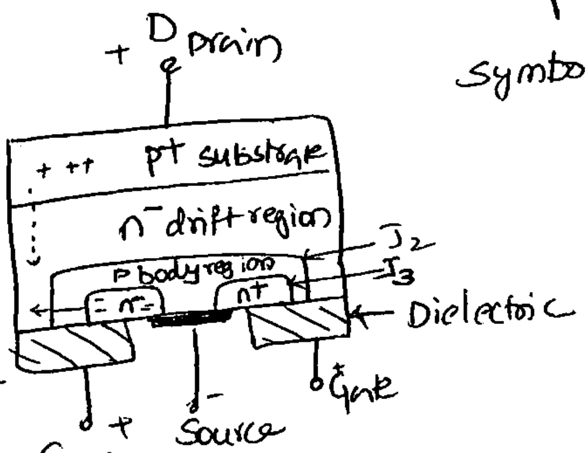
IGBT (Insulated Gate Bipolar Transistor):

→ IGBT has high i/p Impedance like a MOSFET and low ON state power loss as in a BJT. IGBT is also known as Metal oxide insulated Gate Transistor (MOSIGT), conductively - Modulated Field effect transistor (COMFET) or gain Modulated FET (GEMFET). It is also called insulated Gate transistor (IGT).



Symbol

Structure of IGBT:-



Structure of IGBT

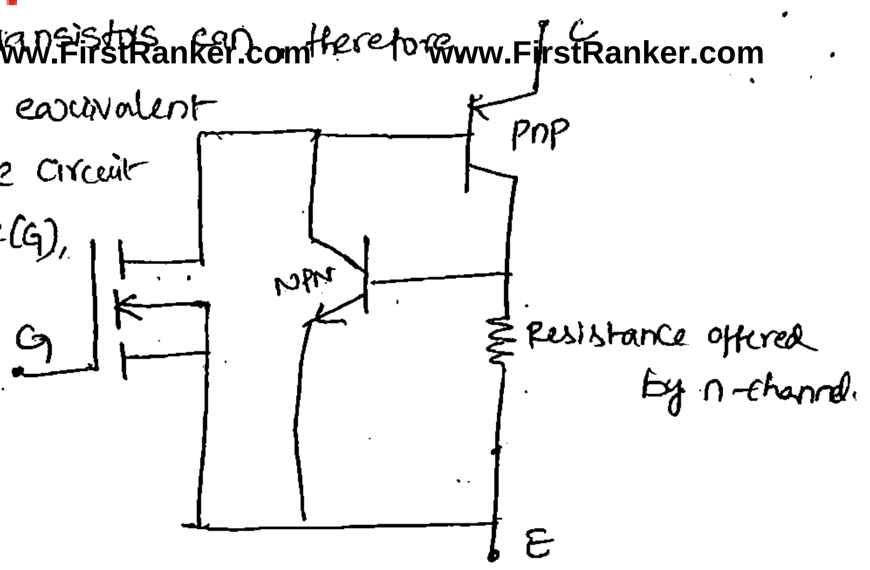
→ The IGBT structure is very close to the n-channel MOSFET. The major difference b/w the structure of the n-channel MOSFET and IGBT is that a highly doped p+ type substrate is provided with IGBT

→ From the basic structure, n+ p body region, n⁻ forms the power MOSFET. The n⁻ drift region forms the drain. The next part will constitute the three layers $p^+ n^- p$, that forms a BJT b/w the drain and source terminals $p n^- p^+$ regions will behave as collector, base and emitter (E) of pnp transistor resp.

Drift current: The transport of the charges in a device under the influence of the electric field is known as drift current

Diffusion current: The transport of charges in a device under the influence of the non uniform concentration gradient is termed as diffusion current

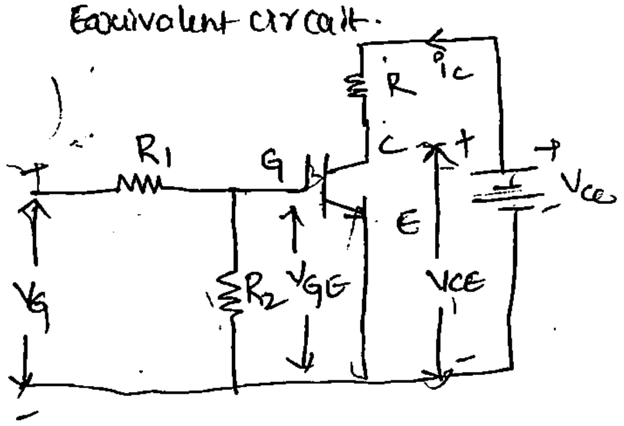
→ The two pnp and npn transistors can therefore be connected to give the equivalent circuit of an IGBT. The circuit symbol for IGBT with gate(G), emitter(E) and collector(C) as its three terminals



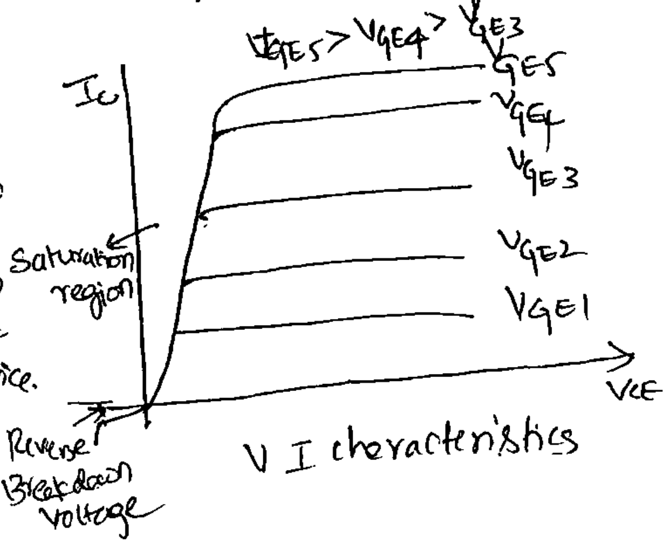
Equivalent circuit.

IGBT Static characteristics:-

→ Static V-I characteristics of an IGBT (n-channel type) shows the plot of collector current I_C Vs collector emitter voltage V_{CE} for various values of gate emitter voltages. In the forward direction, the shape of the o/p characteristics is similar to that of BJT. But here the controlling parameter is gate emitter voltage V_{GE} because IGBT is a voltage controlled device.

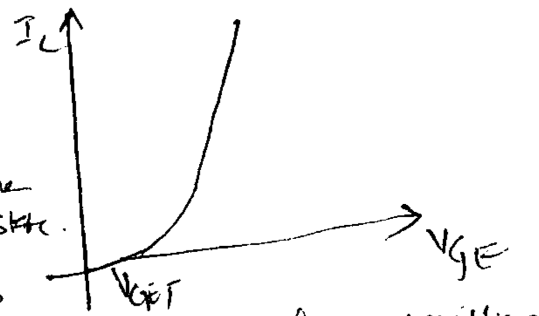


IGBT circuit diagram



V I characteristics

→ The transfer characteristic of an IGBT is a plot of collector current I_C Vs. gate emitter voltage V_{GE}. This characteristics is same as power MOSFET. when V_{GE} is less than V_{GET}, IGBT is in the off state.



Transfer Characteristic

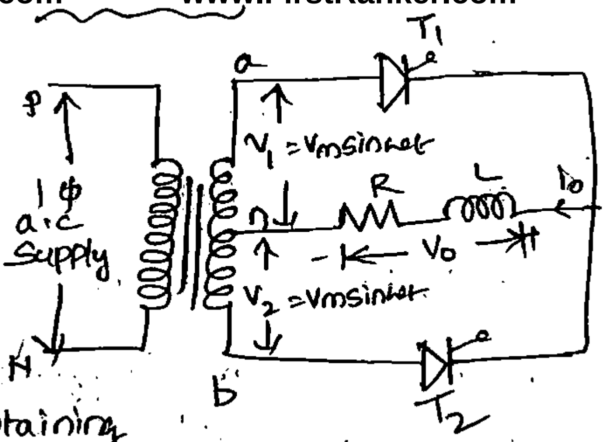
→ when the device is OFF, junction J_2 blocks forward voltage and in case reverse voltage appears across collector and emitter junction J_1 blocks it.

IGBT Applications:

→ IGBTs are widely used in medium power applications such as dc and ac motor drives, UPS systems, power supplies and drives for solenoids, relays and contactors.

MOSFETs	IGBTs
→ In the power MOSFET, the decrease in the electron mobility with increasing temp. results in a rapid increase in the ON state resistance of the channel and hence the ON state drop.	→ In IGBTs, the increase in voltage drop is very small.
2. The ON state voltage drop increases by a factor of 3 between room temp. and 200°C	2. Here with the identical conditions, the increment in the ON state voltage drop is very small.
3. All highest temp., max. current rating goes down to 1/3 value	3. At high ambient temp., IGBTs extraordinarily well suited
4. Current sharing in multiple Paralleled MOSFETs is comparatively poor than IGBTs	4. Current sharing in multiple Paralleled IGBTs is far better than Power MOSFET
5. The turn ON transients are identical to IGBTs	5. Turn ON transients are identical to MOSFETs
6. Power MOSFET is suited for ~~applications that require low blocking~~ voltages and high operating frequencies	6. IGBT is the preferred device for applications that require high blocking voltages and lower operating frequencies

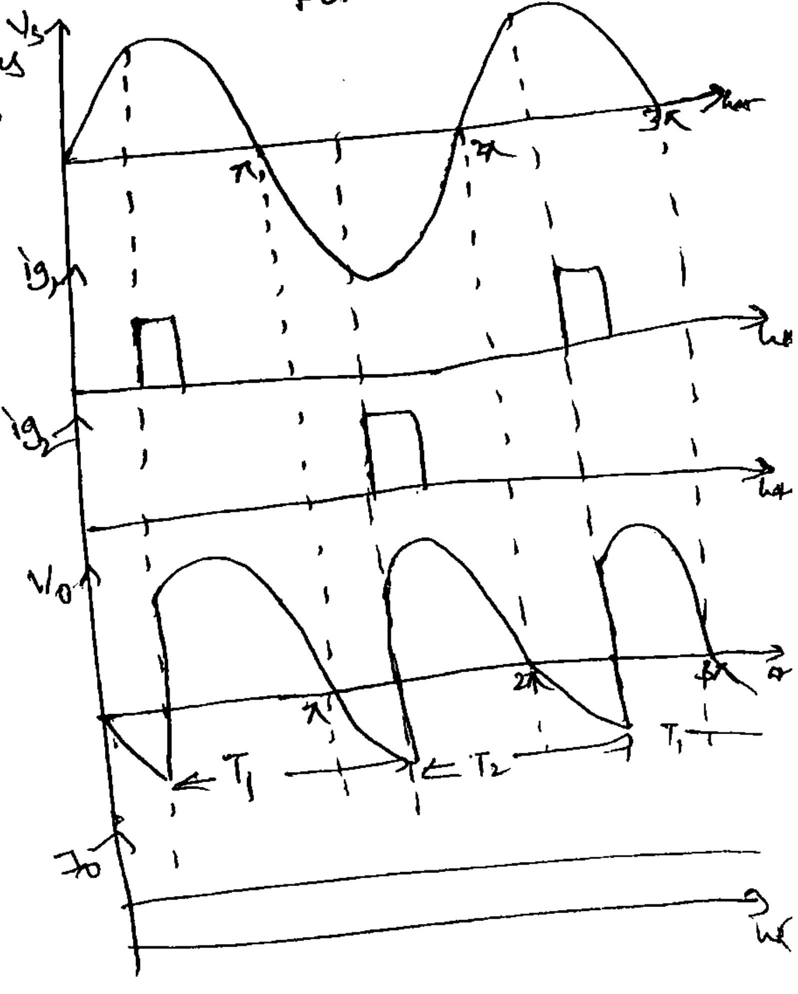
1φ Full wave mid point converter with RL load :-



→ In this, the SCR T_1 can be triggered into the ON state at any time after V_1 goes positive. once SCR T_1 is turned ON, current builds up in the inductive load, maintaining SCR T_1 in the ON state upto the period when V_1 goes negative.

→ once V_1 goes negative, V_2 becomes +ve and the triggering of SCR T_2, turns ON which takes up the load current. The Peak inverse voltage that appears across the thyristor is $2V_m$. The load current may be continuous (or) discontinuous, depending on the load Inductance value.

For $\alpha = 60°$



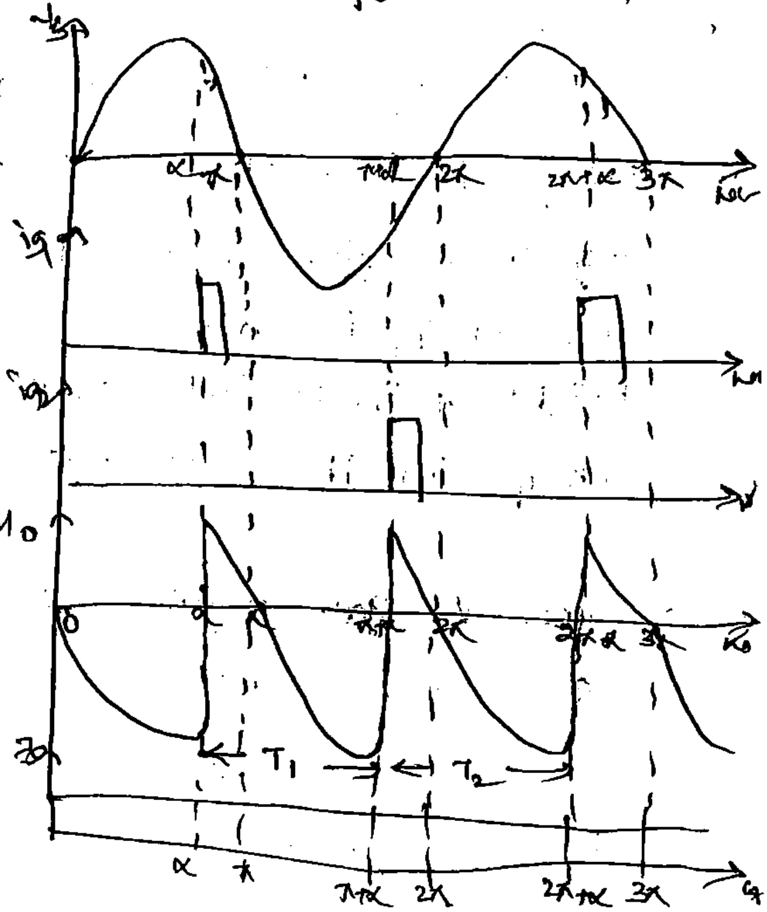
The load current is continuous if inductance value is greater than its critical value.
It is discontinuous if inductance value is less than its critical value.

The average load voltage V_{dc} can be obtained as

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

$$\boxed{V_{dc} = \frac{2V_m}{\pi}\cos\alpha}$$

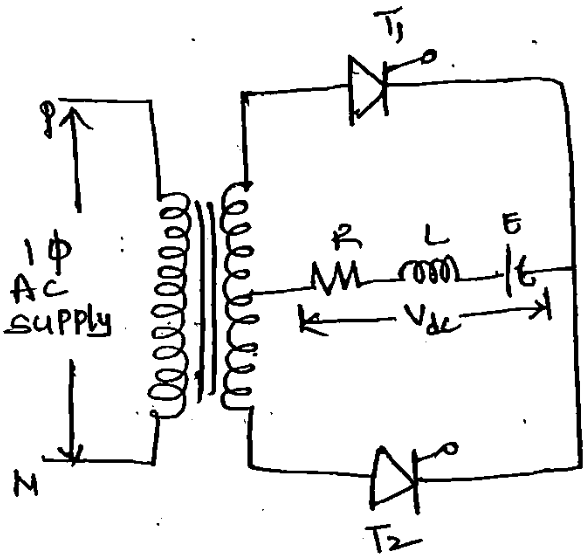
→ The inductance is sufficiently large, so that each thyristor conducts for a period of 180°. Both SCRs are triggered with the same delay angle; hence they share the load current equally



→ Due to large inductance in the circuit and continuous current conduction occurs. i.e, the thyristors continue to conduct even when their anode voltages are negative w.r.t cathode.

1-φ Full wave mid point converter with RLE load :-

→ Voltage E may be due to a battery in the load circuit (or) may be back emf in a dc motor.



→ SCR T_1 is triggered and π radians later, SCR T_2 is gated. The load inductance should be large and load current is assumed continuous.

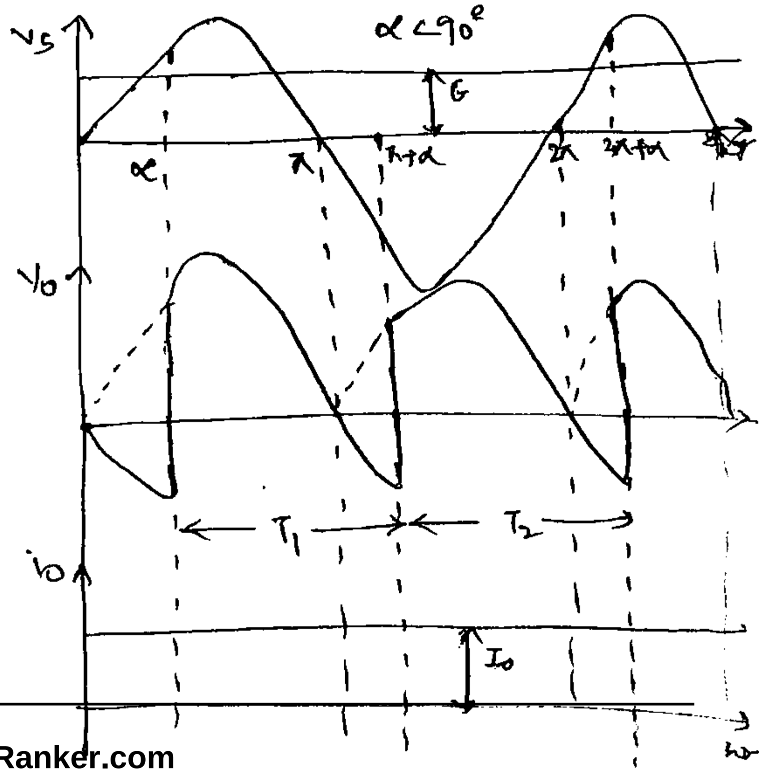
→ After $\omega t = 0$, SCR T_1 is F.B only when source voltage $V_m \sin \omega t$ exceeds E. Thus SCR T_1 is triggered at firing angle $\omega t = \alpha$ such that $V_m \sin \alpha > E$. At $\omega t = \alpha$, SCR T_1 is triggered and conducts upto $\pi + \alpha$.

At $\omega t = \pi + \alpha$, SCR T_1 is turned off by natural commutation and SCR T_2 is triggered. During the period $\pi + \alpha$ to $2\pi + \alpha$, T_2 conducts.

The Average output voltage

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

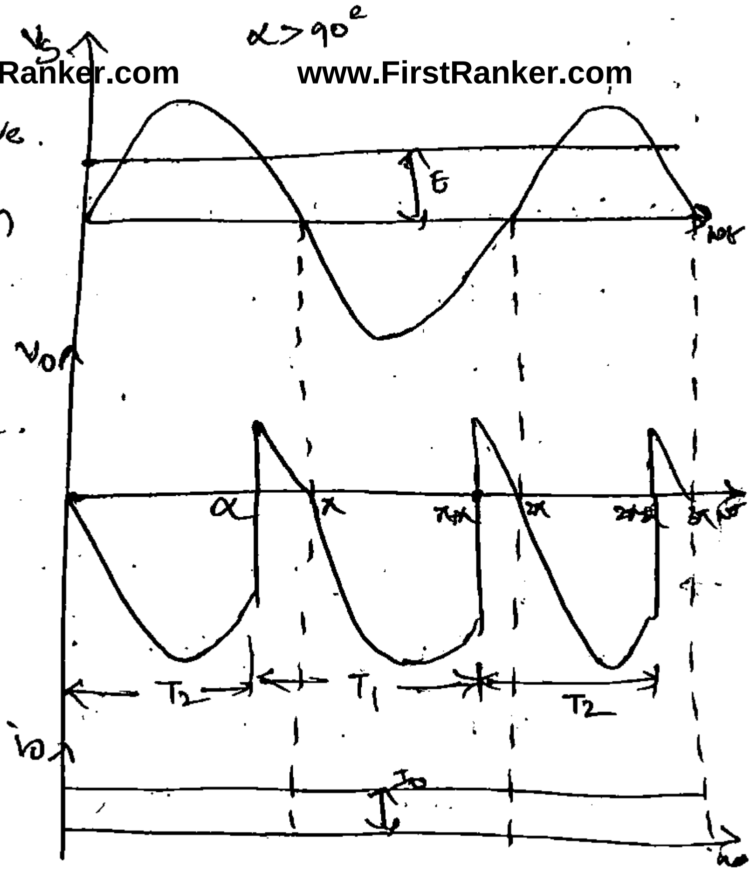
$$\therefore V_{dc} = \frac{2V_m}{\pi} \cos \alpha.$$



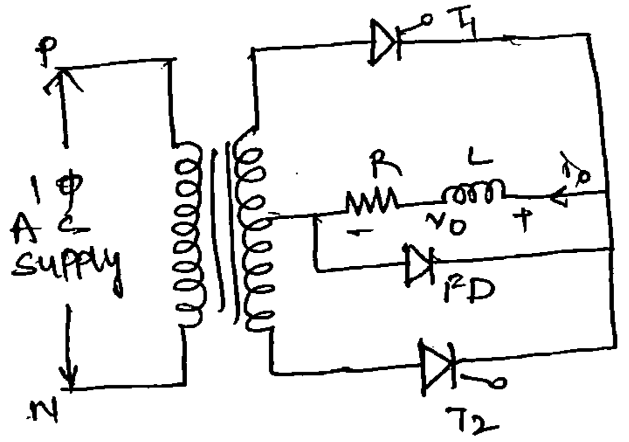
If $\alpha < 90^\circ$, the o/p voltage is +ve. Therefore, the power flows from source to load.

If $\alpha > 90^\circ$, the o/p voltage is -ve. Therefore the power flows from load to source.

∴ The full converter with firing angle greater than 90° is called line commutated inverter.



Full wave mid point converter with free wheeling diodes:-



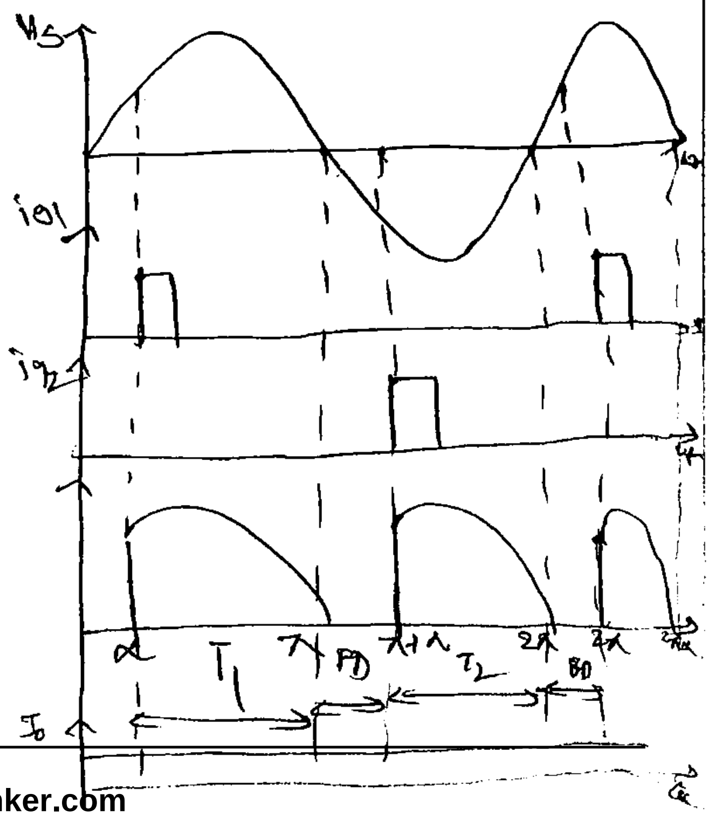
The fig. shows full wave converter with inductive load and free wheeling diode.

A free wheeling diode is connected across the load. The thyristors are triggered with a delay angle α.
The α is varied to obtain a variable dc voltage at the load.

→ As the i/p voltage goes through zero at 180°, the load voltage cannot be negative since the FD starts conducting and clamps the load voltage to zero.

→ A constant load current is maintained by free wheeling the current through the load.

→ The inductive energy of the load circulates current through the feedback diode which decays depending on the time constant of the load.



The avg. load voltage is

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

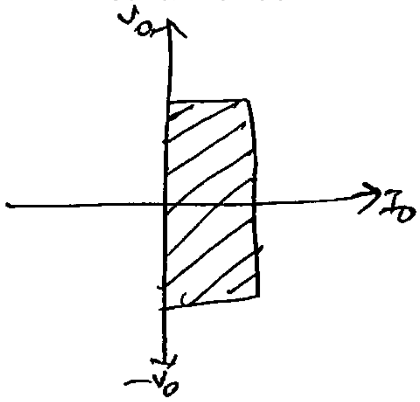
$$\boxed{V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)}$$

The dc load current is given by

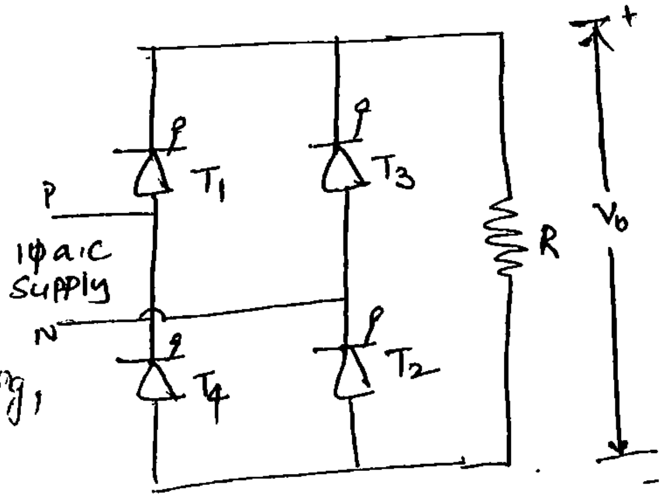
$$I_{dc} = \frac{V_{dc}}{R} = \frac{V_m}{\pi R}(1+\cos\alpha)$$

1-φ FULL WAVE CONTROLLED BRIDGE RECTIFIER :-

→ 1-φ Full wave controlled rectifier is also called as two quadrant converter. A fully controlled converter (or) full converter uses thyristors only and there is a wider control over the level of dc o/p voltage. Here, the o/p voltage is either positive (or) negative but o/p current is always positive.

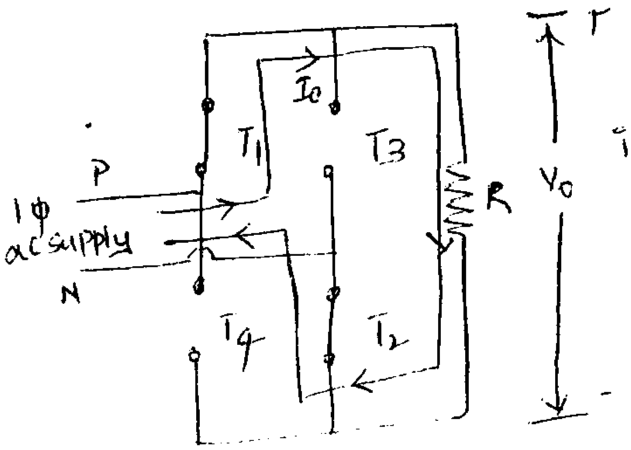


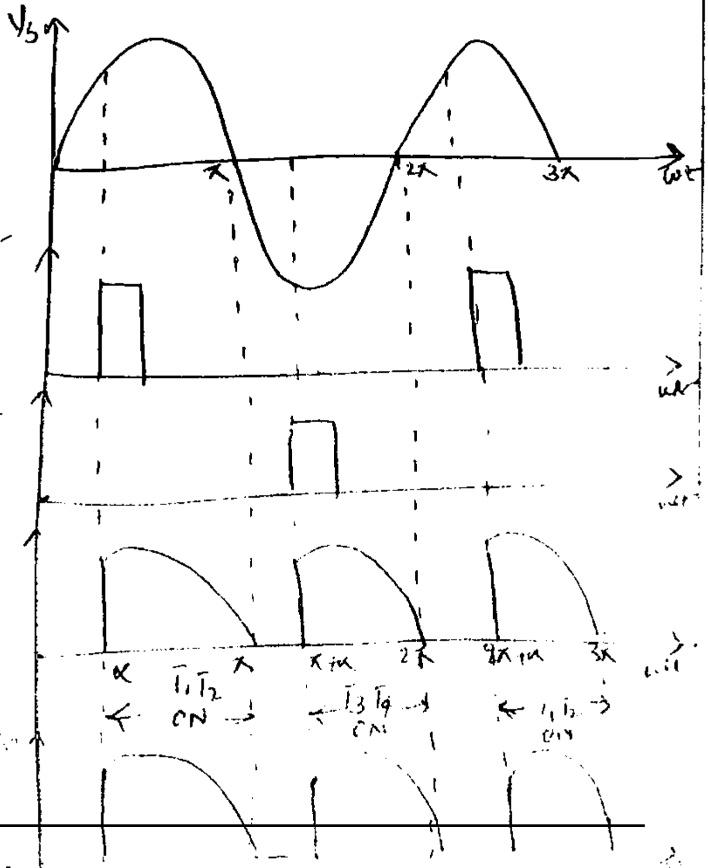
For R load :-



During the +ve half cycle, SCRs T_1 & T_2 are F.B and if they are triggered simultaneously.

At $\omega t = \alpha$, SCR T_1 & T_2 are conducting, then current flows through the path P – T_1 – R – T_2 – N





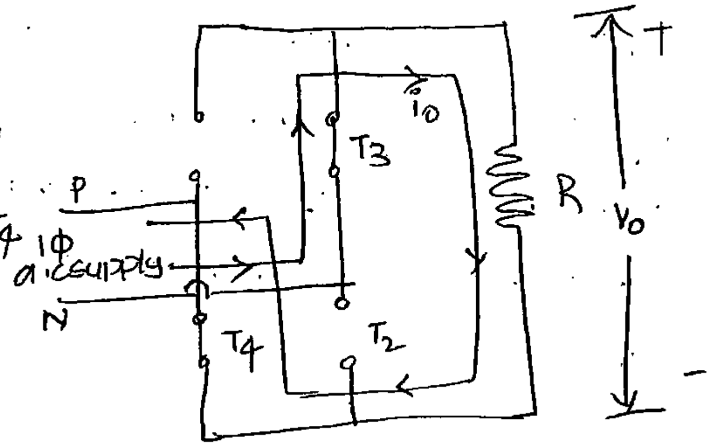
$\alpha < \omega t < \pi$, T_1, T_2 ON

At $\omega t = \pi$, supply voltage falls to zero and the current also goes to zero. Hence SCRs T_1 & T_2 turned OFF

During negative half cycle (π to 2π) SCRs T_3 & T_4 are F.B and if they are triggered simultaneously. At $\omega t = \pi + \alpha$, SCRs T_3 & T_4 are conducting, then current flows through the path

N − T_3 − R − T_4 − P.

At $\omega t = 2\pi$, supply voltage and current goes to zero. SCRs T_3, T_4 are turned OFF.



$\pi + \alpha < \omega t < 2\pi$, T_3, T_4 ON

Average o/p voltage (V_{dc}):

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

$$\boxed{V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)}$$

Average load current (I_{dc})

$$I_{dc} = \frac{V_{dc}}{R}$$

$$\boxed{\therefore I_{dc} = \frac{V_m}{\pi R}(1+\cos\alpha)}$$

RMS load voltage (V_{rms}):

$$V_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2\omega t \, d(\omega t)\right]^{1/2}$$

$$= V_m\left[\frac{1}{\pi}\int_{\alpha}^{\pi} \sin^2\omega t \, d(\omega t)\right]^{1/2}$$

$$= V_m\left[\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) d(\omega t)\right]^{1/2}$$

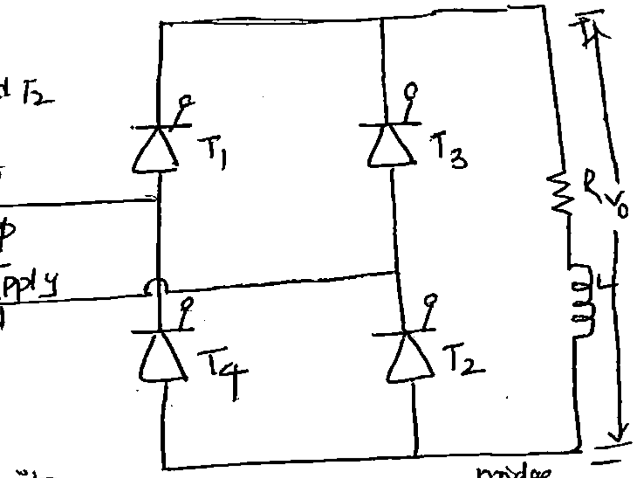
$$= V_m\left[\frac{1}{2\pi}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_{\alpha}^{\pi}\right]^{1/2}$$

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

$$\therefore V_{rms} = V_m\left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2} \quad I_{rms} = \frac{V_{rms}}{R}$$

Full wave controlled Bridge Rectifier with RL load :-

→ conduction does not takes place until the thyristors are triggered, T_1 and T_2 must be fired together from the same firing angle. Simultaneously T_3 & T_4 are triggered in the next half cycle.



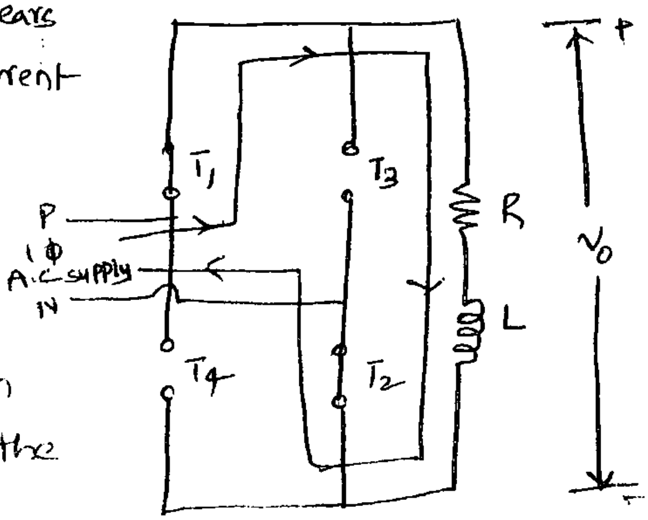
1-ϕ Full controlled bridge converter with RL load.

→ Inductance L is used in this circuit to reduce the ripple. A large value of inductor L is used for continuous steady current in the load. A small value of L will produce a discontinuous load current for large firing angles.

→ The voltage waveform at the dc terminals consists of steady dc component and an ac ripple component having a fundamental frequency equal to twice that of supply freq.

At firing angle $\omega t = \alpha$ i.e. 60°, Thyristors T_1, T_2 are triggered. Current flows through the path $P - T_1 - RL - T_2 - N$. Supply voltage from this instant appears across the load and flows the current through the load.

The load current I_0, is assumed to be continuous. The load current flows from source to load which is taken as positive, along with the applied voltage



$\alpha < \omega t < \pi + \alpha$; T_1, T_2 ON

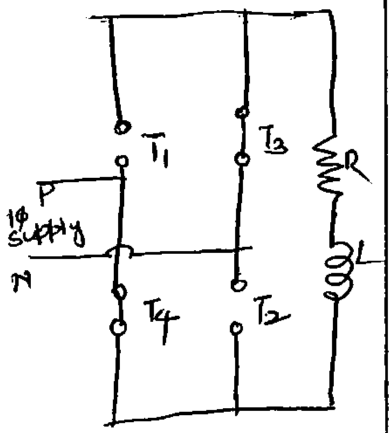
At $\omega t = \pi$, source voltage reverses, the current is maintained in the same direction of constant magnitude.

because of large inductance L which keeps the thyristors T_1 and T_2 in conducting state and hence, the negative supply voltage appears across the load.

→ At $\omega t = \pi+\alpha$, T_3 & T_4 are triggered, the negative line voltage reverse biases T_1 through T_3, and T_2 through T_4 of commutating thyristors T_1 & T_2.

The current flow path is

$N - T_3 - R_L - T_4 - P$



$\pi+\alpha < \omega t < 2\pi+\alpha$

This continues in every half cycle, the line current is positive when T_1, T_2 are conducting and negative when T_3, T_4 are conducting.

Average o/p voltage:

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t) = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi+\alpha}$$

$$= \frac{V_m}{\pi}\left[\cos\alpha - \cos(\pi+\alpha)\right] = \frac{2V_m}{\pi}\cos\alpha$$

By varying the firing angle (0° to 180°), the average load voltage can be varied continuously, from +ve max to -ve max., assuming continuous load current flow at the output (d.c) terminals. Because the average load voltage is reversible even though the current flow in the o/p terminals is unidirectional.

Here two modes of operation are possible in fully controlled rectifier bridge circuit because the power flow in the converter can be in either direction.

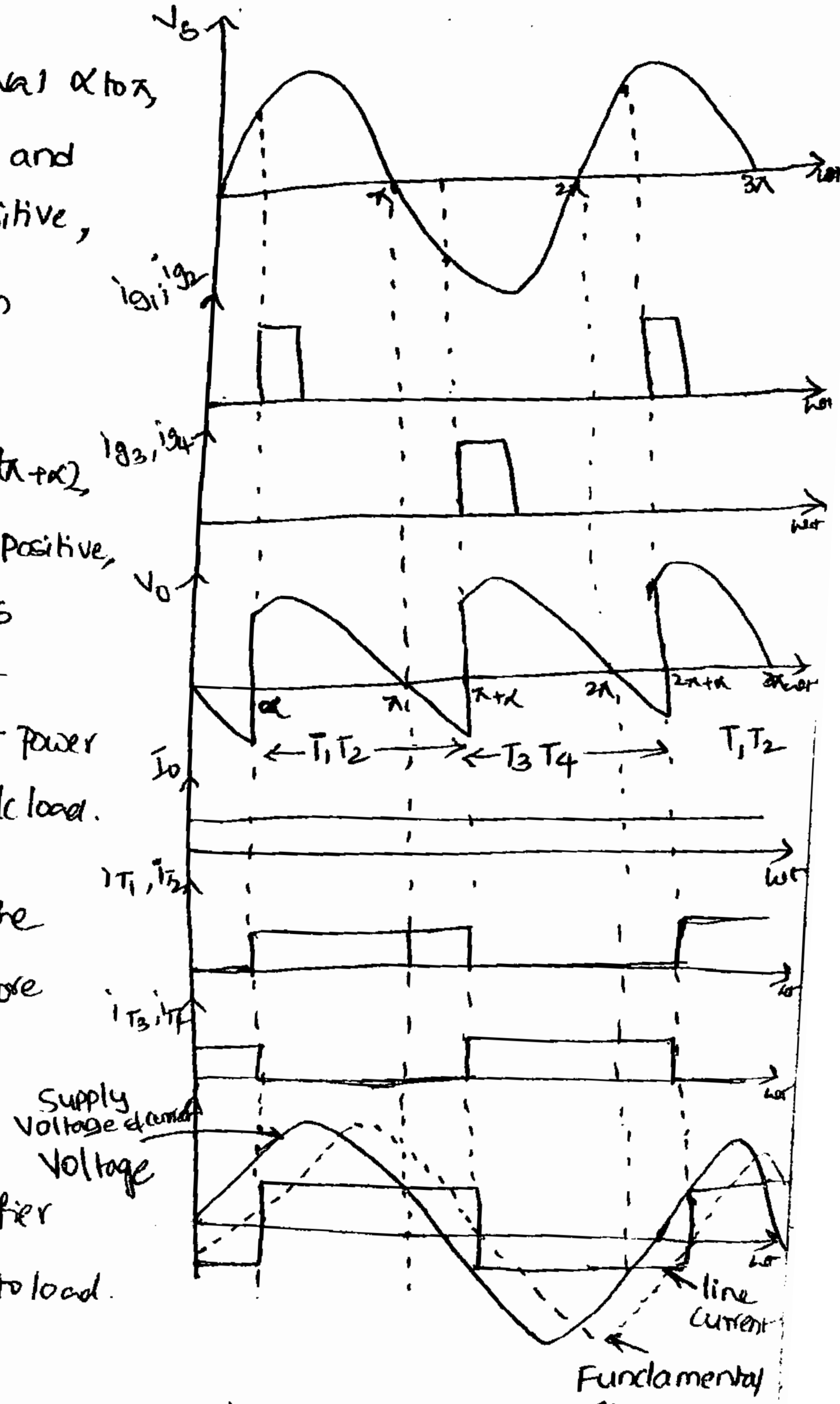
Mode 1: Rectification Mode:-

→ During the interval α to π, both supply voltage V_s and supply current I_s are positive, therefore power flows from ac source to load.

→ During the interval π to $(\pi+\alpha)$, V_s is negative but I_s is positive, therefore the load returns some of its energy to the supply system. But the net power flow is from ac source to dc load.

→ If $\alpha < 90°$, the voltage at the load terminals is +ve, therefore the power flows from ac side to dc side and the converter operates as a rectifier i.e power flows from source to load.

Rectification Mode:



Voltage and current waveforms 1φ Full controlled rectifier with RL load.

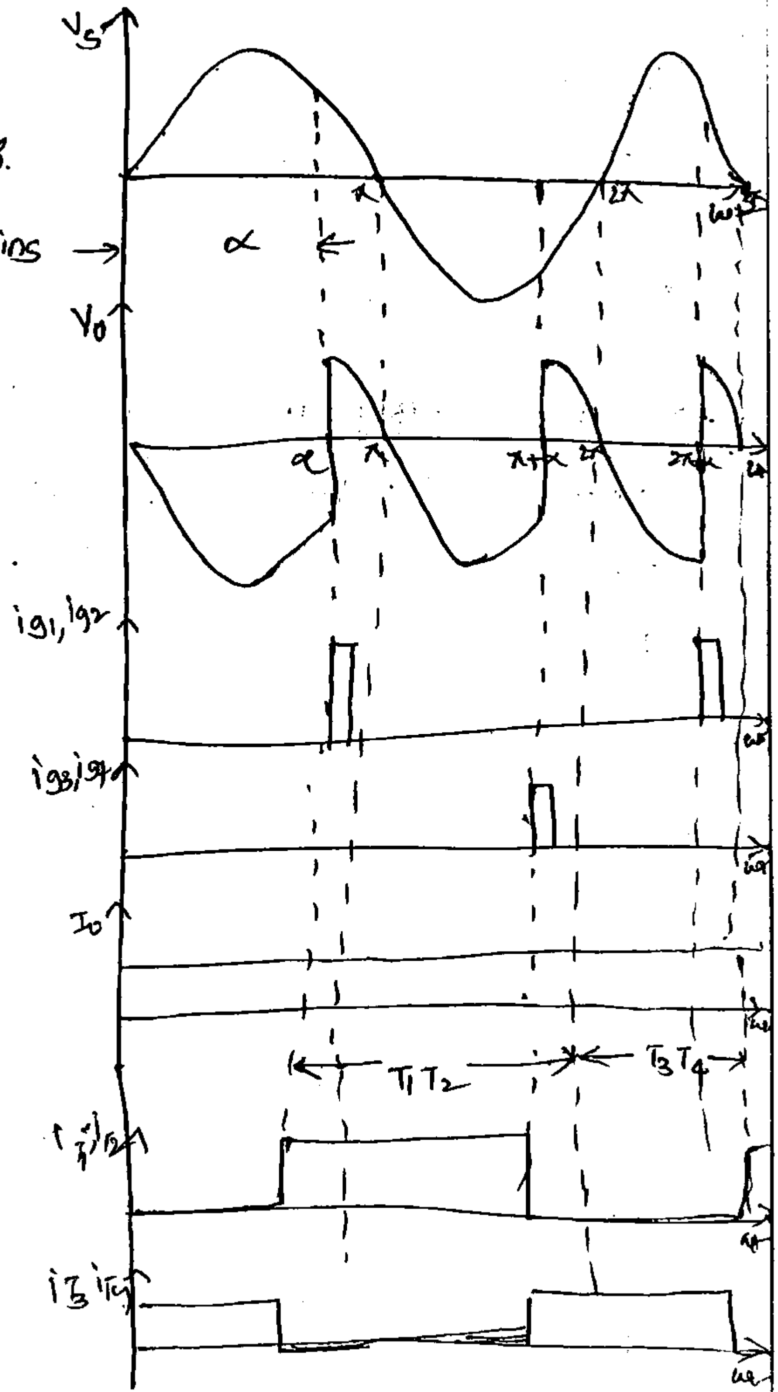
Mode II : Inversion Mode

For $\alpha = 120^\circ$

The firing pulse are retarded by an angle of 120° i.e., $\alpha = 120^\circ$.

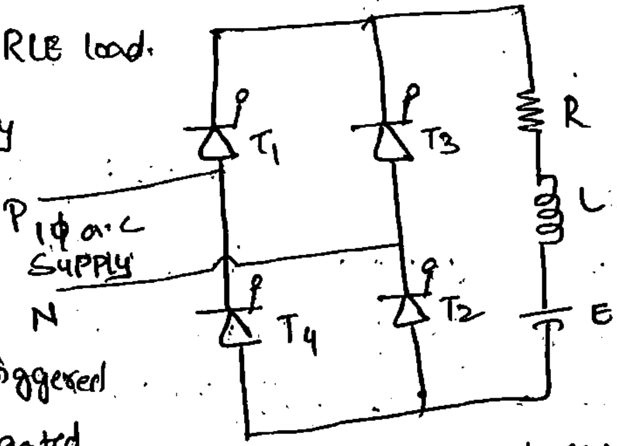
The o/p voltage waveform contains a mean negative component.

If $\alpha > 90^\circ$,



Full wave controlled bridge rectifier with RLE load:-

It consists of 4 SCRs and an RLE load. Voltage E may be due to a battery in the load circuit (or) may be back emf in a dc motor

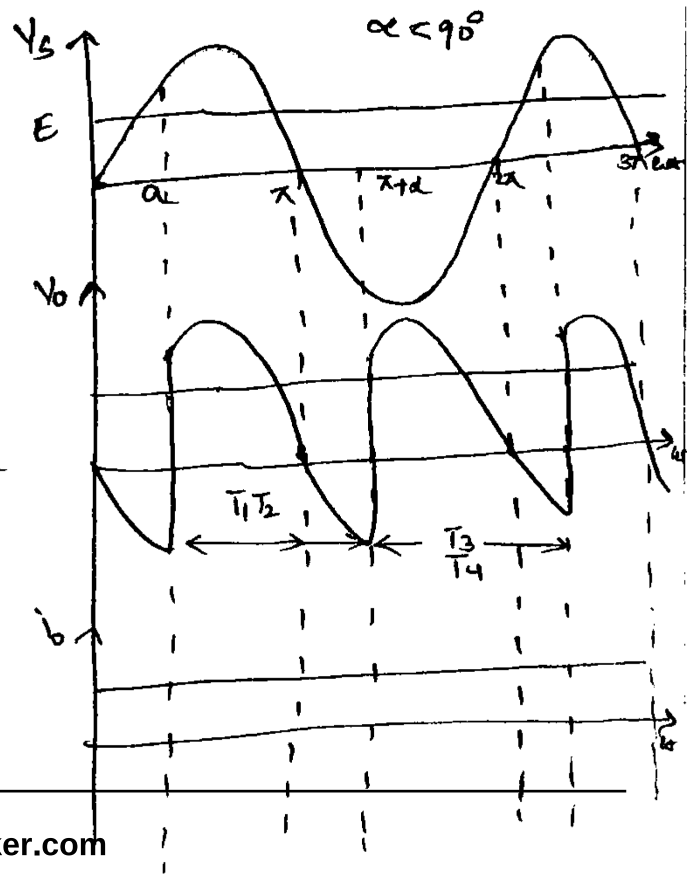


→ SCRs T_1 & T_2 are simultaneously triggered and π radians later, T_3 & T_4 is gated together. Here, the load inductance should be large and load current is assumed continuous.

→ At $\omega t = 0$, SCR T_1 & T_2 is F.B only when source voltage $V_m \sin\omega t$ exceeds E. Thus SCR T_1 & T_2 are triggered at firing angle $\omega t = \alpha$ such that $V_m \sin\alpha > E$.

→ At $\omega t = \alpha$, SCR T_1 & T_2 comes to ON state. T_1 & T_2 conducts upto $\pi+\alpha$. During the period α to $\pi+\alpha$, T_1 & T_2 conducts.

→ At $\omega t = \pi+\alpha$, SCR T_1 & T_2 turns OFF by natural commutation and SCR T_3, T_4 is triggered. During the period ($\pi+\alpha$ to $2\pi+\alpha$) T_3 & T_4 ON state and load current is transferred from $T_1 T_2$ to T_3, T_4



→ During α to π, both V_s & I_s are positive, therefore power flows from ac source to load.

→ During the period π to π+α, V_s is negative but I_s is positive, therefore the load returns some of its energy to supply system.

The avg. o/p voltage

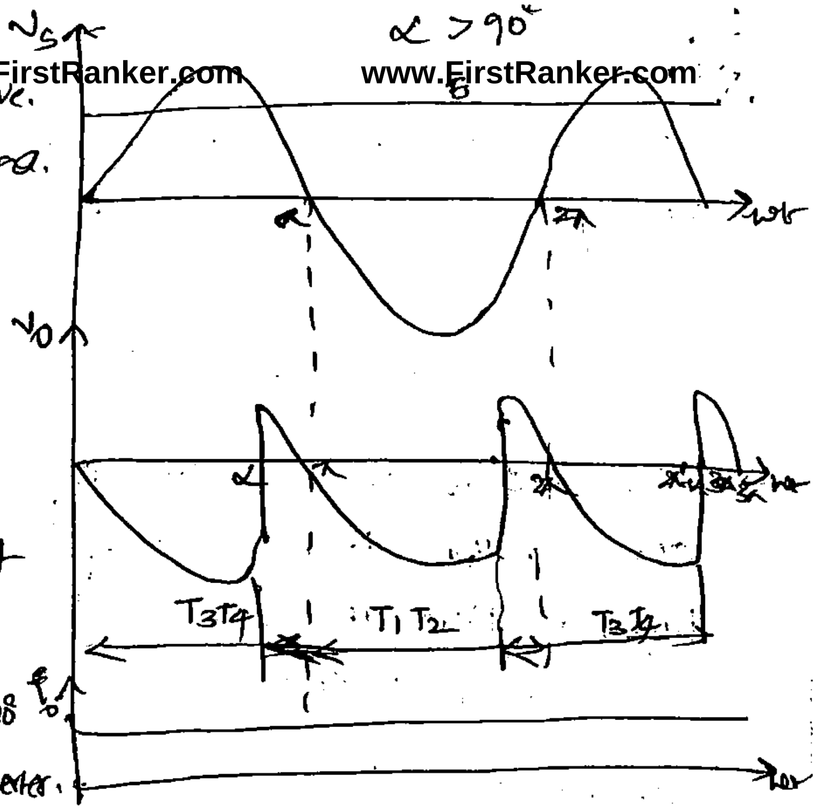
$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d(\omega t)$$

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

If $\alpha < 90°$, the o/p voltage is +ve.

∴ power flows from source to load.

If $\alpha > 90°$, the o/p voltage is -ve, therefore power flows from load source. This operation of full converter is known as inverter operation of the convertor.



→ The full converter with $\alpha > 90°$ is called line commutated inverter. This operation is used in the regenerative braking mode of a dc motor.

AC VOLTAGE CONTROLLERS & CYCLO CONVERTERS

AC VOLTAGE CONTROLLERS :-

→ A.C Voltage controllers are thyristor based devices, which converts fixed alternating voltage directly to variable alternating voltage without change in frequency.

→ By connecting a TRIAC (or) two SCR's connected in antiparallel b/w the source and load., the voltage applied to the load can be controlled by varying the firing angles. So, A.c voltage controllers are known as phase controlled devices.

→ A.C. Voltage controllers are used in closed loop control system.

Applications :-

1) Domestic heating
2) Static V.A.R compensators
3) speed control of 1ϕ and 3ϕ IM
4) ON-load transformer tap changing

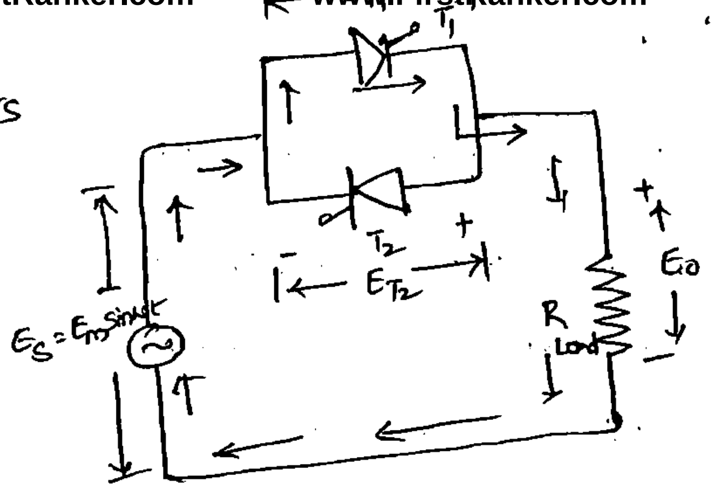
→ TRIAC is used for low and medium Power applications.
SCRs is used for high power applications.

Advantages :- (By using SCR & TRIAC)

1. High Efficiency
2. Flexibility in control
3. Compact in size
4. Less maintenance.

Voltage Regulator with Resistive Load :-

→ It consists of two thyristors connected in antiparallel to eachother. Here, the load considered is of purely resistive.



Mode 1 : $(0 < \omega t < \pi)$:

During +ve half cycle of the supply voltage, thyristor T_1 is in the Forward biased condition where as 'T_2' is in the R.B whenever gate signal has been given to thyristor 'T_1' at $\omega t = \alpha$, it starts conducting and load current follows the path

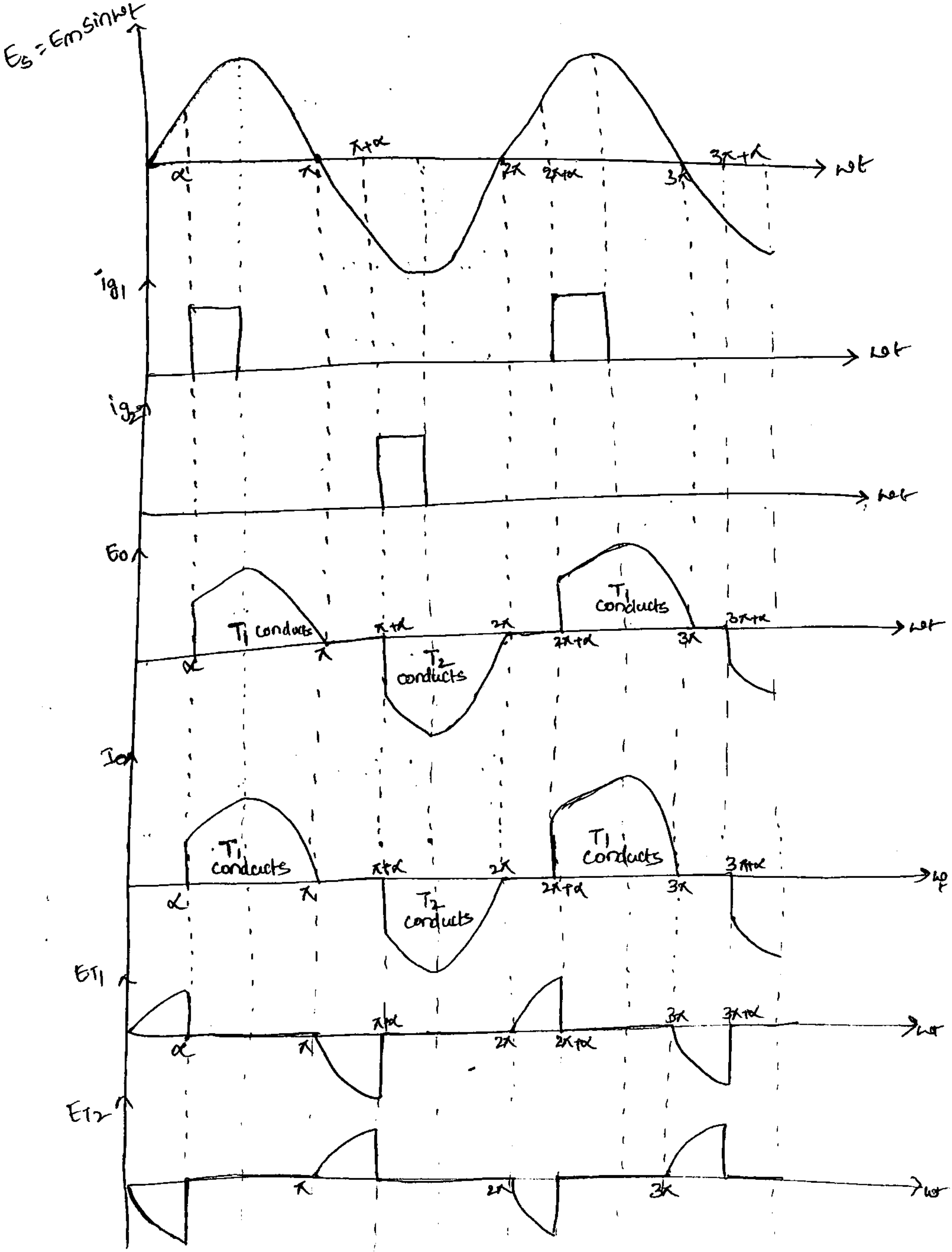
$$E_s^+ - T_1 - \text{load} - E_s^-$$

During +ve half cycle of supply voltage, the power gets delivered from source to load during the period α to π. At π, both E_0 & I_0 falls to zero. At this instant, T_1 is subjected to R.B and therefore it gets turned OFF naturally.

Mode 2 : $(\pi < \omega t < 2\pi)$

During -ve half cycle of supply voltage, T_2 is in F.B condition and T_1 is in R.B condition. At $\omega t = \pi + \alpha$, the gate signal has been given to the thyristor T_2, it gets turned ON and conducts from $(\pi + \alpha$ to $2\pi)$. At $\omega t = 2\pi$, T_2 gets R.B

The o/p waveforms of A.C voltage controllers with R load is as follows:



Derivation of avg. o/p voltage :-

$$E_{o\,avg} = \frac{1}{2\pi}\int_{\alpha}^{\pi} E_m \sin\omega t \, d(\omega t)$$

$$= \frac{E_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$= \frac{E_m}{2\pi}\left[-\cos\pi + \cos\alpha\right]$$

$$= \frac{E_m}{2\pi}\left[1 + \cos\alpha\right]$$

$$= \frac{\sqrt{2}\,E_s}{2\pi}\left[1 + \cos\alpha\right]$$

RMS output voltage :-

$$E_{o\,RMS} = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi} E_m^2 \sin^2\omega t \, d\omega t\right]^{1/2}$$

$$= \left[\frac{E_m^2}{\pi}\int_{\alpha}^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right]\right]^{1/2}$$

$$= \frac{E_m}{\sqrt{\pi}}\left[\frac{1}{2}(\pi-\alpha) - \frac{1}{2\times 2}(\sin 2\omega t)_{\alpha}^{\pi}\right]^{1/2}$$

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

$$= \frac{E_s}{\sqrt{\pi}}\left[\pi-\alpha + \frac{1}{2}\sin 2\alpha\right]^{1/2} \qquad \left[\because E_s = \frac{E_m}{\sqrt{2}}\right]$$

$$\therefore E_{o\,RMS} = \frac{E_s}{\sqrt{\pi}}\left[\pi-\alpha + \frac{\sin 2\alpha}{2}\right]^{1/2}$$

RMS load current :

$$I_{o\,rms} = \frac{E_{o\,rms}}{R}$$

(iii) Power delivered to the load $= \frac{E_{orms}^2}{R}$

(iv) I/p Power factor $(\cos\phi) = \frac{\text{Power delivered to load}}{\text{apparent power}}$

$$= \frac{E_0 I_0 \cos\phi_0}{E_s I_s}$$

$$\therefore \cos\phi = \frac{E_0 I_0}{E_s I_s} \quad \because \cos\phi_0 = 1 \text{ for R load}$$

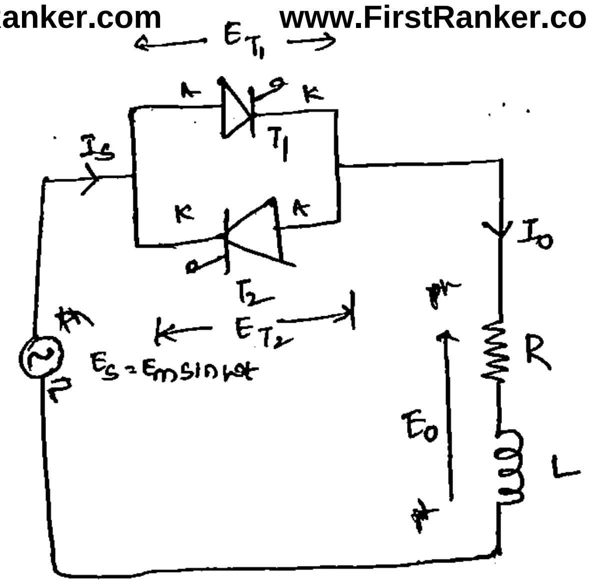
$$= \frac{E_0}{E_s} \quad \text{as} \quad I_s = I_0$$

or

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

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

AC VOLTAGE CONTROLLER WITH INDUCTIVE (RL) load:-



Ac voltage controller with RL load.

The principle of operation of A.C voltage controller with RL load may be explained in two modes.

Mode 1: $(0 < \alpha < \pi)$:-

During the +ve half cycle of the supply voltage, T_1 is in the F.B condition. where as T_2 is in the R.B condition. when gate pulse is given to thyristor T_1 at $\omega t = \alpha$, it starts conducting and the load current flows through the following path

$$E_s^+ - T_1 - R - L - E_s^-$$

At $\omega t = \pi$, V_s & V_L becomes zero but load current doesn't fall to zero due to the presence of inductance in the load circuit. After some time at the instant $\beta > \pi$, load current becomes zero and hence thyristor T_1 gets turned off. which is already in Reverse biased condition. β is known as extinction angle. Now a voltage of magnitude $E_m \sin\beta$ appears as reverse Bias across the thyristor T_1, and as forward bias across the thyristor T_2. From β to $\pi+\alpha$, no current exists.

∴ Both the thyristors are in the OFF state.

During the negative half cycle of the supply Voltage, T_1 is in the reverse biased condition and T_2 is in the Forward biased condition. when gate signal is given to the thyristor T_2, it gets turned ON and load current follows the path

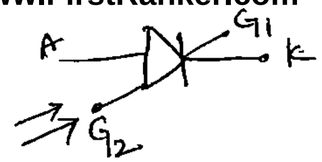
$$E_s^+ - L - R - T_2 - E_s^-$$

This load current traces the negative half cycle of the supply Voltage. At the instant $\omega t = 2\pi$, T_2 must be turned OFF as the V_s & V_L is zero and it gets R.B at $\omega t = 2\pi$. But it does not turned OFF due to the presence of inductance in the load circuit. At $(\pi + \alpha + \gamma)$, $i_{T_2} = 0$ and T_2 gets turned OFF as it is already in the R.B

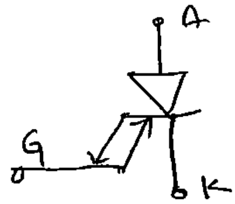
From $(\pi + \alpha + \gamma)$ to $(2\pi + \alpha)$ no current exists in the Power circuit as both the thyristors are in OFF state. Again at $(2\pi + \alpha)$, T_1 is turned ON and current starts building up as before.

→ Here ϕ is the input displacement angle or load phase angle. It is defined as the angle between the fundamental component of the ac line current and the associated line to natural Voltage.

8. PUT – Programmable Unijunction Transistor



9. GTO – Gate Turn off thyristors



SCR :- Silicon controlled Rectifier

Merits :-

1. It can be able to block large voltages and can carry large current through it. It has high power handling capacity.
2. It requires low power circuit for turning ON the thyristor.
3. The life time of SCR is long and it is reliable
4. The weight of SCR is light and it is the fastest semiconductor switching device.
5. It is a static device, and it has no moving Parts
6. It can be operated upto a switching frequency of 10KHz

Demerits :-

1. The forward voltage drop, across the conducting device is about 1V or 2V
2. The current density of it is limited to About 150 A/cm²
3. Forced commutation circuit is necessary for turning OFF the thyristor
4. Thermal time constant is very short
5. There will be some conducting loss, and power loss due to dissipations

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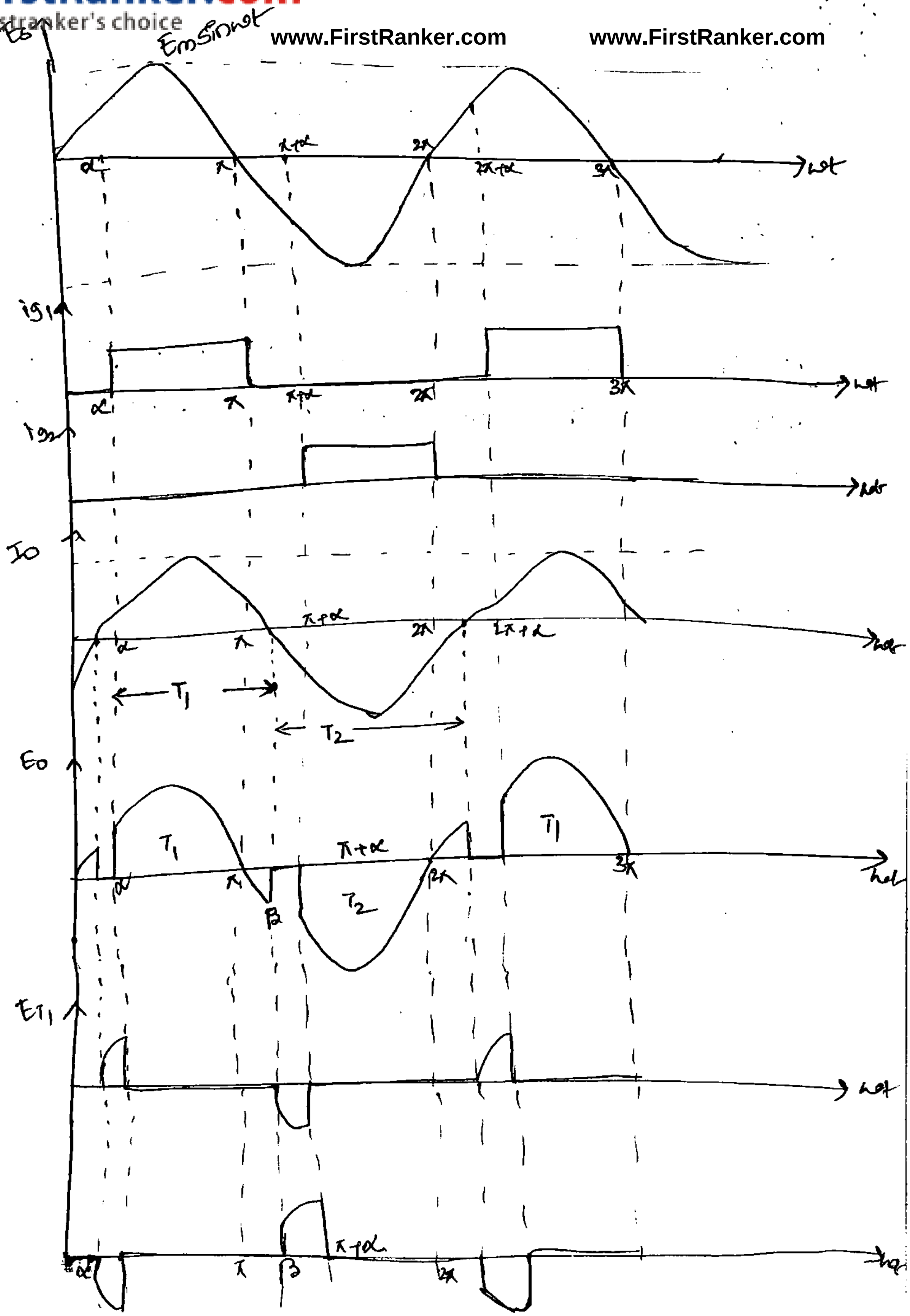


For α > φ for discontinuous conduction mode.

α & ϕ :

(i) RMS o/p voltage :

$$V_{orms} = \left[\frac{2}{2\pi}\int_{\alpha}^{\beta} V_m^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2}$$

$$= \left[\frac{1}{\pi}\int_{\alpha}^{\beta} 2V_s^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2}$$

$$= \left[\frac{V_s^2}{\pi}\int_{\alpha}^{\beta} 1 - \cos 2\omega t \, d(\omega t)\right]^{1/2}$$

$$\therefore V_{orms} = V_s\left[\frac{1}{\pi}\left(\beta - \alpha + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2}\right)\right]^{1/2}$$

(ii) Expression for load current i_o

the KVL for the circuit gives

For $\alpha \le \omega t \le \beta$,

$$V_s = V_m \sin \omega t = R i_o + L\frac{di_o}{dt}$$

The solution of this eq. is

$$i_o = \frac{V_m}{Z}\sin(\omega t - \phi) + A e^{-(R/L)t} \quad —①$$

where $Z = \sqrt{R^2 + (\omega L)^2}$

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

Constant A can be obtained from the initial condition according to which $i_o = 0$ at $\omega t = \alpha$ i.e $t = \frac{\alpha}{\omega}$

$$\therefore 0 = \frac{V_m}{Z}\sin(\alpha - \phi) + A e^{-R\alpha/\omega L}$$

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

Substitute A value in eq. ①

$$i_o = \frac{V_m}{Z}\left[\sin(\omega t - \phi) - \sin(\alpha - \phi)\exp\left\{\frac{R}{L}\left(\frac{\alpha}{\omega} - t\right)\right\}\right] \quad —②$$

From the Graph, it becomes clear that the load current i_0 again falls to zero at an angle $\omega t = \beta$. Substitute this condition in eq ②, we get.

$$\sin(\beta - \phi) = \sin(\alpha - \phi) \exp\left[\frac{R}{L}\left(\frac{\alpha - \beta}{\omega}\right)\right]$$

Extinction angle β can be determined by the solution of the transcendental eq. once β is known, the conduction angle γ

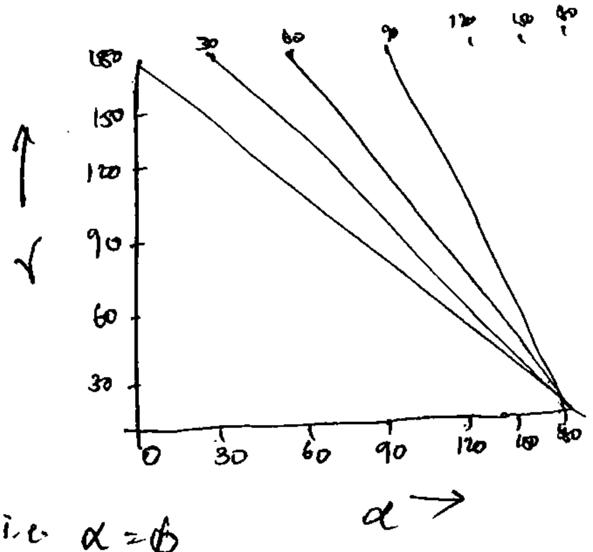
$$\gamma = \beta - \alpha$$

Case (ii) $\alpha = \phi$

with progressive decrease in α, γ may become equal to π. i.e $\gamma = \pi$

From 0 to α – T_2 ON
From α to $\pi + \alpha$ – T_1 ON
From $\pi + \alpha$ to $2\pi + \alpha$ – T_2 ON and so on

→ In this the load current will never become zero and load always connected to source i.e. load voltage = source voltage



From the Graph

0 to ϕ – T_2 ON

ϕ to $(\pi + \phi)$ – T_1 ON

$(\pi + \phi)$ to $(2\pi + \phi)$ – T_2 ON

Here delay angle of thyristor is ϕ i.e. $\alpha = \phi$

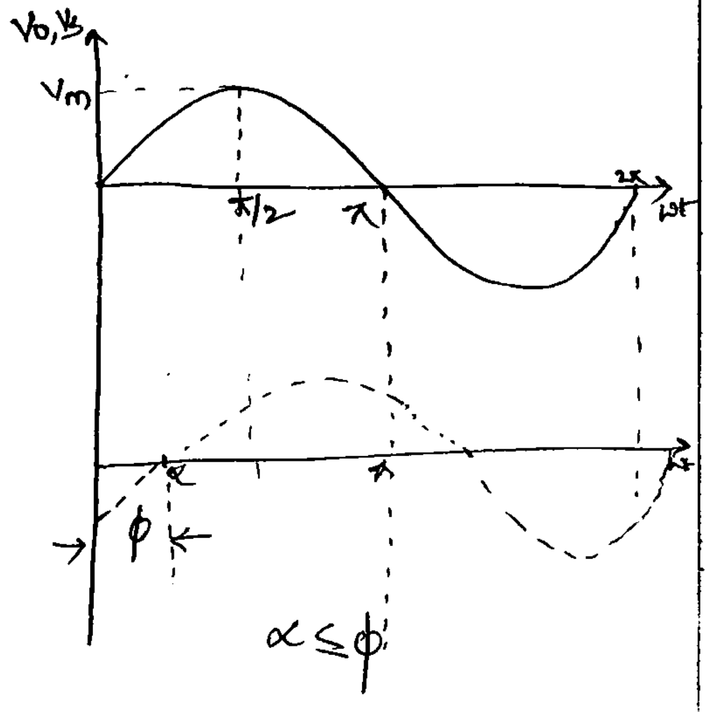
ii) $(\alpha < \phi)$:

Now, α can be decreased below ϕ, SCR T_2 will not get turned ON because it is reverse biased. SCR T_1 will get turned ON only at ϕ when $i_{T_2} = 0$. Now SCR T_1 will conduct from ϕ to $(\pi+\phi)$

SCR T_2 will be triggered at an angle $(\pi+\alpha) < (\pi+\phi)$. A SCR T_1 is conducting a voltage drop in T_1 will apply across SCR T_2; as a result SCR T_2 will not turned ON at $(\pi+\alpha)$. $i_{T_1} = 0$ at $(\pi+\phi)$. SCR T_2 will conduct from $(\pi+\phi)$ to $(2\pi+\phi)$ and so on.

Thus a reduction of α below ϕ is not able to control the o/p voltage and current. The ac o/p Power can be controlled only for $\alpha > \phi$.

Thus the control ~~angle~~ range of delay (or) firing angle is $\phi < \alpha < \pi$



Harmonics of output quantities and input current:

The output quantities (voltage e_0 and current i_0) and input current is non sinusoidal. These waveforms can be described by Fourier series. As the positive and negative half cycles are identical, d.c component and even harmonics are absent.

The output voltage e_0, can be represented by Fourier series

$$e_0 = \sum_{n=1,3,5}^{\infty} A_n \sin \omega t + \sum_{n=1,3,5}^{\infty} B_n \cos \omega t \quad \text{—(1)}$$

where $A_n = \frac{2}{\pi} \int_0^{\pi} e_0(\omega t) \sin n\omega t \, d(\omega t)$ —(2)

and $B_n = \frac{2}{\pi} \int_0^{\pi} e_0(\omega t) \cos n\omega t \, d(\omega t)$ —(3)

The load voltage e_0 during the first half cycle is

$$e_0 = E_m \sin \omega t \,, \quad \alpha < \omega t < \pi \quad \text{—(4)}$$

Substitute eq.(4) in eq.(2) & eq.(3) gives.

$$A_n = \frac{2E_m}{\pi} \int_{\alpha}^{\pi} \sin \omega t \sin n\omega t \, d(\omega t)$$

$$= \frac{E_m}{\pi} \int_{\alpha}^{\pi} [\cos(n-1)\omega t - \cos(n+1)\omega t] \, d(\omega t)$$

$$= \frac{E_m}{\pi} \left[\frac{\sin(n+1)\alpha}{(n+1)} - \frac{\sin(n-1)\alpha}{(n-1)} \right] \quad \text{—(5)}$$

$$B_n = \frac{2E_m}{\pi}\int_{\alpha}^{\pi} \sin\omega t \cdot \cos n\omega t \; d(\omega t)$$

$$= \frac{E_m}{\pi}\int_{\alpha}^{\pi}\left[\sin(n+1)\omega t - \sin(n-1)\omega t\right] d(\omega t)$$

$$= \frac{E_m}{\pi}\left[\frac{\cos(n+1)\alpha - 1}{(n+1)} - \frac{\cos(n-1)\alpha - 1}{n-1}\right] \quad \text{--- (6)}$$

where $E_m = \sqrt{2}\, E_s$ and E_s = RMS value of source voltage.

For $n = 1, 3, 5, \ldots$ $\cos(n+1)\pi = 1$ and $\cos(n-1)\pi = 1$

→ The peak amplitude of the n^{th} harmonic output voltage E_{nm} and its phase ϕ_n are given by, $E_{nm} = \sqrt{A_n^2 + B_n^2}$ --- (7)

and $\phi_n = \tan^{-1}\frac{B_n}{A_n}$ --- (8)

$I_{nm} = \frac{E_{nm}}{R}$ = n^{th} harmonic load current --- (9)

equations (5) to (9) can be used to evaluate the magnitude of harmonics for which $n = 3, 5, \ldots$ It cannot be used to calculate the fundamental component because substitution of $n = 1$ in eq. (5) & (6) leads to undefined expressions.

→ The fundamental component which has the same frequency as the supply voltage can be obtained from eq. (2) & eq. (3) by substituting $n = 1$ & for e_0 from eq. (1).

$$A_1 = \frac{2}{\pi}\int_{\alpha}^{\pi} E_m \sin^2 \omega t \; d(\omega t) = \frac{E_m}{\pi}\left(\frac{\sin 2\alpha}{2} + \pi - \alpha\right) \quad \text{--- (6)}$$

and $$B_1 = \frac{2}{\pi}\int_{\alpha}^{\pi} E_m \sin \omega t \cos \omega t \; d(\omega t) = \frac{E_m}{\pi}\left[\frac{\cos 2\alpha - 1}{2}\right]$$

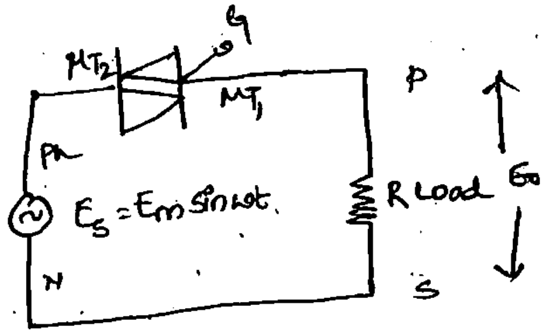
$\therefore$ The value of E_{1m} and ϕ_1 for the fundamental frequency is given by

$$E_{1m} = \sqrt{A_1^2 + B_1^2} = \frac{E_m}{\pi}\left[\left(\frac{\sin 2\alpha}{2} + (\pi-\alpha)\right)^2 + \left(\frac{\cos 2\alpha - 1}{2}\right)^2\right]^{1/2}$$

$I_{1m} = \frac{E_{1m}}{R}$ is the amplitude of fundamental component of load (or source current.

and $$\phi_1 = \tan^{-1}\frac{B_1}{A_1} = \tan^{-1}\left(\frac{\cos 2\alpha - 1}{\sin 2\alpha + 2(\pi-\alpha)}\right)$$

TRIAC with R LOAD:-



During the positive half cycle of the ac supply voltage, MT_2 is positive w.r.t MT_1

Mode 1: $(0 < \omega t < \pi)$

At $\omega t = \alpha$, give the gate signal (positive gate signal) w.r.t MT_1. TRIAC can be brought into conduction state after giving the gate pulse at $\omega t = \alpha$. The load current follows the path.

$$E_S^{Ph} - MT_2 - MT_1 - P - Load - S - E_S^{N}$$

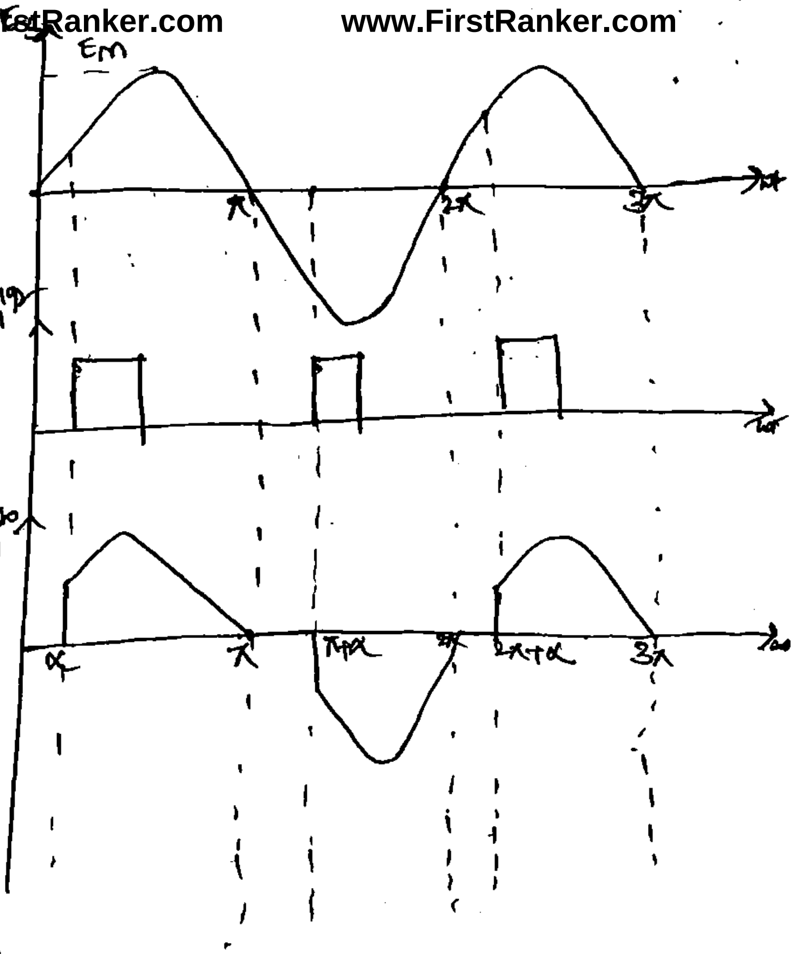
At $\omega t = \pi$, the source voltage becomes zero, at that instant the load o/p voltage and load current becomes zero. so, the current flowing through triac is less than the holding current. Hence, the TRIAC gets commutated.

Mode 2:- During the -ve half cycle of the ac supply voltage, MT_2 is -ve w.r.t MT_1. At $\omega t = \pi + \alpha$, give the gate signal (positive gate signal) w.r.t MT_2. TRIAC can be brought into the conduction state by applying the +ve gate signal. The load current follows the path

$$E_S^{N} - S - load - P - MT_1 - MT_2 - E_S^{Ph}$$

At $\omega t = 2\pi$, the source voltage and load o/p voltage becomes zero and at that instant, load current becomes zero. Here, the current flowing through triac is less than the holding current which results the commutation of TRIAC.

Derivation of RMS Load Voltage:-



$$E_{ORMS}^2 = \frac{2}{2\pi}\int_\alpha^\pi E_m^2 \sin^2\omega t\, d\omega t$$

$$= \frac{2E_m^2}{2\pi}\int_\alpha^\pi \left[\frac{1-\cos 2\omega t}{2}\right] d\omega t$$

$$= \frac{E_m^2}{2\pi}\left[\pi-\alpha-\left[\frac{\sin 2\omega t}{2}\right]_\alpha^\pi\right]$$

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

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

$$\therefore E_{ORMS} = \sqrt{\frac{E_m^2}{2\pi}\left[\pi-\alpha+\frac{\sin 2\alpha}{2}\right]}$$

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

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

$$I_{ORM} = \frac{E_{ORMS}}{R}$$

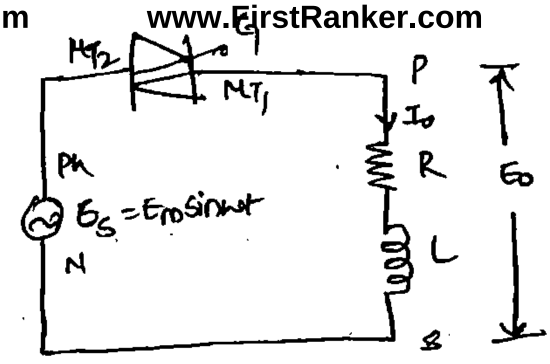
Power delivered to load $= \frac{E_{ORMS}^2}{R}$

I/p power factor $= \frac{E_0 I_0 \cos\phi}{E_s I_s}$ $\because \cos\phi = 1$ for resistive load and $I_s = I_0$

$\therefore$ I/p Power factor $\cos\phi_0 = \frac{E_0}{E_s}$

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

With RL LOAD :-



Triac with RL Load.

Mode 1 : $(0 < \omega t < \beta)$

During the positive half cycle of the supply voltage, triac is in the FB condition. whenever the gate signal is given to the triac T, it conducts. Power flows from source to load. The load current follows the path

$$E_s^{Ph} - MT_2 - MT_1 - P - R - L - S - E_s^N$$

At the instant $\omega t = \pi$, the source voltage and load voltage becomes zero. But, due to the presence of load inductance, the load current does not become zero at this instant. At the instant $\beta > \pi$, the load current becomes zero and hence the triac gets turned OFF. From β to $\pi + \alpha$, no current flows in this Mode, MT_2 as the triac is in the off state. is more positive w.r.t MT_1

Mode 3 :- $(\beta < \omega t < 2\pi)$

As the triac is a bidirectional device, it is in the forward biased condition in the negative half cycle of the supply voltage also. whenever gate signal is given, it conducts and the power flows from load to source. Hence, the load current follows the path as below

$$E_s^{N} - S - L - R - P - MT_1 - MT_2 - E_s^P$$

Comparison Between SCRs & TRIACS :-

SCR	TRIAC
1. For the triggering of SCRs Positive gate signal is required.	1. TRIAC can be triggered by using either positive or negative gate signal.
2. Number of heat sinks required in the case of SCRs (connected in antiparallel) is high. But the heat sinks are slightly smaller in size as compared to that of TRIAC	2. TRIAC requires a single heat sink of larger size.
3 SCRs are available in larger ratings when compared to TRIAC	3. TRIACS are having smaller rating because of the commutation Problem.
4. SCRs have $\frac{dv}{dt}$ rating comparatively high when compared to triac's $\frac{dv}{dt}$ rating.	4. TRIACs have low $\frac{dv}{dt}$ rating compared to SCRs.
5) Reliability is high (the instant at which the SCR should be triggered at a given firing angle α)	5. Reliability is low.
6. It requires two fuse	6. It requires a single fuse for protection.

CYCLO CONVERTERS:-

A Device which converts input power at one frequency to the o/p power at a different frequency with one stage conversion is called a cyclo converter.

Cyclo converters are of two types:

1. step up cyclo converter
2. Step down cyclo converter

In stepup cyclo converter, the o/p frequency (f_o) is greater than supply frequency (f_s) i.e. $f_o > f_s$.

In step down cyclo converter, the o/p frequency (f_o) is less than supply frequency (f_s) i.e $f_o < f_s$.

Depending upon phases, there are three types of cycloconverters. They are

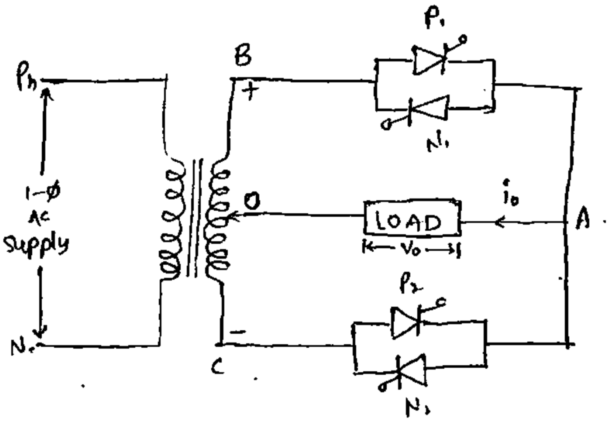
a) $1\phi - 1\phi$ cyclo converter
b) $3\phi - 1\phi$ cyclo converter
c) $3\phi - 3\phi$ "

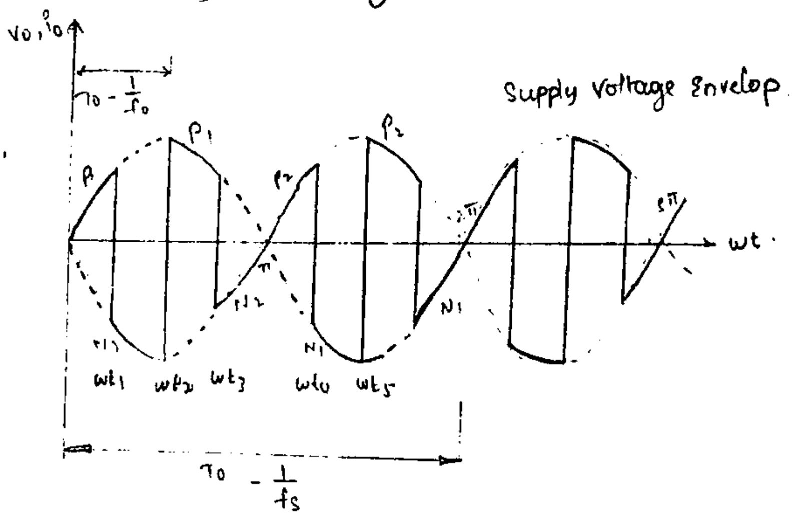
According to the type of connections there are mainly two types. They are.

a) Mid point type cyclo converter
b) Bridge type cyclo converter.

1φ - 1φ STEP-UP CYCLO CONVERTER MID POINT TYPE CYCLO CONVERTER WITH R LOAD :-

It consists of a Single phase transformer with centre-tap on the secondary winding and Four SCRs. Two of these SCRs, P_1 & P_2 are for positive group and the other two N_1, N_2 are for negative group. Resistive load is connected between Secondary winding mid-point 'O' and terminal 'A' as shown in fig.





From the figure shown,

During the +ve half cycle of (0 – π) supply voltage, terminal B is positive with respect to terminal 'c'. During this Both SCRs P_1 and N_2 are forward biased from $\omega t = 0 - \pi$

At instant ωt_1, P_1 is turned off by forced commutation and forward-Biased SCR N_2 is turned ON, so that load voltage is negative envelop of the supply voltage. i.e. o/p Voltage and current is -ve.

At instant ωt_2, SCR N_2 is turned off by forced commutation and SCR P_1 is turned on. Thus the load voltage is +ve and follows the +ve Envelop of supply voltage.

During -ve Half cycle (π - 2π), terminal C is +ve with respect to B.

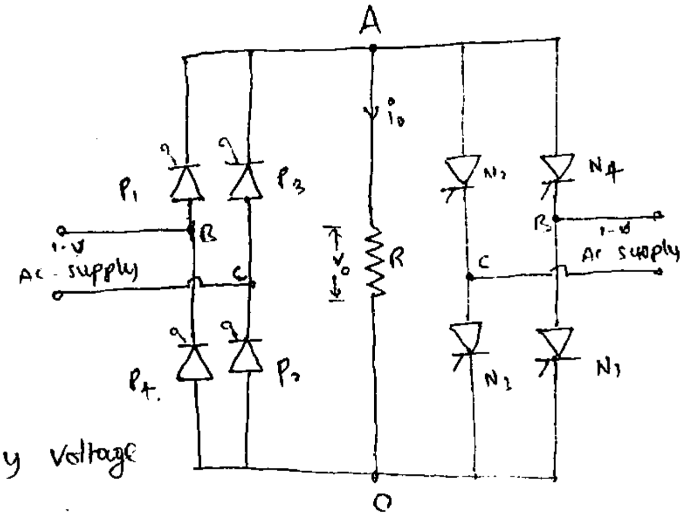
~~During the period SCR P_2 and N_1 get forward biased~~

At $\omega t = \pi$, N_2 is turned OFF by Forced commutation and P_2 is turned ON. At ωt_4, P_2 is turned OFF and SCR N_1 is turned ON.

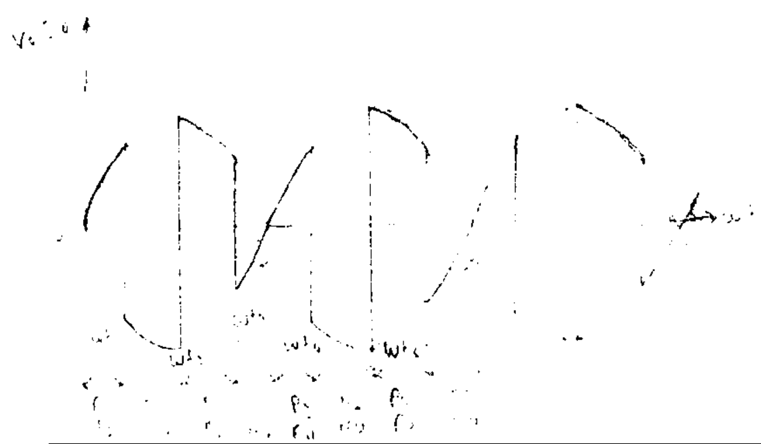
In this way for positive first half cycle P_1, N_2 and P_2, N_1 for second Half cycle are employed. By switching these SCR's Alternatively output frequency is higher than the supply frequency and is given as $\boxed{f_0 = 4 f_s}$. Thus output frequency is four times to the supply frequency.

BRIDGE TYPE STEP-UP CYCLO CONVERTER:-

It consists a total of 8 SCR's. P_1 to P_4 and N_1 to N_4 i.e, Four for +ve group and remaining four for -ve group.



When 'B' is +ve w.r.t 'C' During +ve half cycle $(0-\pi)$ of supply voltage SCR pairs $P_1 P_2$ and $N_1 N_2$ are forward Biased.



at instant $\omega t = 0$, $P_1 P_2$ are turned ON and at ωt_1, $P_1 P_2$ SCR's are turned OFF and pair $N_1 N_2$ are turned ON. and again at ωt_3 $P_1 P_2$ are turned ON by forced commutation [illegible] $N_1 N_2$.

and at ωt_5 P_1P_2 are turned OFF and N_1N_2 are turned ON.

During Second Half cycle SCR pair P_3P_4 and N_3N_4 are forward Biased. From $\omega t = \pi$ to $\omega t = 2\pi$, the switching of SCR pairs as follows. From $\omega t = \pi$ to ωt_4 P_3P_4 are turned ON. at ωt_4 N_3N_4 are turned ON. at ωt_5 again P_3P_4 are turned ON.

Such that for first half cycle $(0-\pi)$ of supply voltage P_1P_2 & N_1N_2 are switched alternatively and for second half cycle $(\pi-2\pi)$, P_3P_4 and N_3N_4 are switched.

Thus frequency modulated output voltage across load terminal are obtained.

1-ϕ to 1-ϕ STEP DOWN CYCLO CONVERTER.

Resistive type It is a 1-ϕ cyclo converter whose input and output are single phase AC. The input AC voltage supply frequency is converted into lower frequency AC output. There are mainly two configurations for this type, which are

i) Center-tapped (mid point type) transformer configuration and

ii) Bridge configuration.

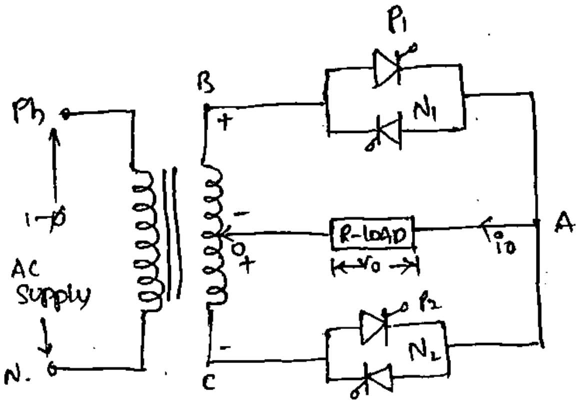
MID POINT cyclo converter:-

There are four thyristors, namely P_1, N_1, P_2 and N_2. out of the four SCR's, SCR's P_1 and P_2 are responsible for generating the +ve halves [illegible] positive group). The other two N_1 and N_2 [illegible] are responsible for producing the negative halves. This configuration is meant for generating 1/3 of the input frequency,

i.e. $f_0 = \frac{1}{3} f_s$

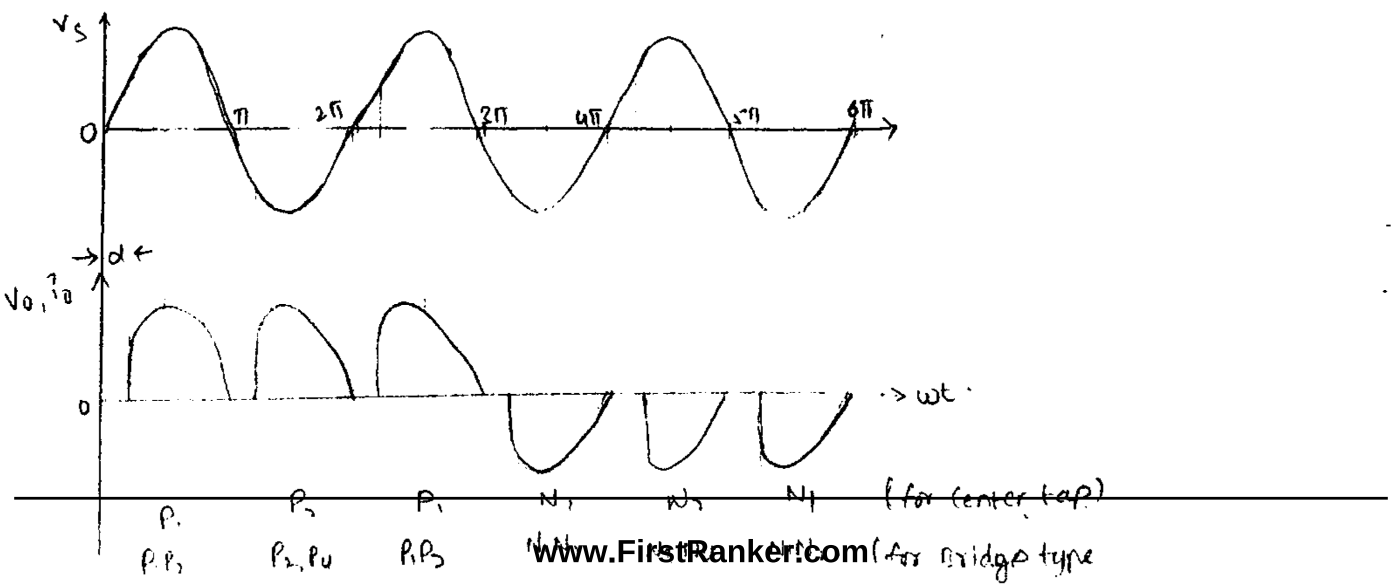
1-ø TO 1-ø STEP DOWN CYCLO CONVERTER WITH R-LOAD:-

The circuit will be as shown in the figure. During the 1st +ve halfcycle from (0-π), when point B is +ve with respect to C, then SCR P_1 being in forward Bias condition.



When firing angle 'α' is applied, then the current flowing path is as from "B - P_1 - A - R-load - 0".

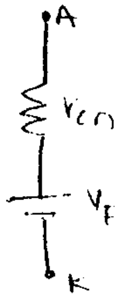
During second half cycle i.e. from (π - 2π) SCR P_1 is automatically line commutated and SCR P_2 is triggered simultaneously. Then path for current flow in this direction will be from "positive C - SCR P_2 - R-load - 0".



→ whenever the N layer near the cathode when compared to the player near anode, junctions J_1 & J_3 gets reverse biased. Now the middle junction J_2 gets forward biased. As the junctions J_1 & J_3 are in reverse biased condition, they does not allow any amount of current to flow through the device. Due to the drift of charges a small amount of leakage currents flows which is not sufficient to conduct the device. This state is known as reverse blocking state or OFF state of the device as it blocks the reverse biased voltage.

By increasing the voltage across the Anode and cathode, the width of the depletion layer at the junction J_2 may be reduced. At some particular voltage, the junction J_2 gets disappeared. This is due to the breakdown of junction by large voltage gradient. This phenomena is known as Avalanche breakdown. As the junctions J_1 and J_3 are already in the forward biased condition, there exists a free carrier movement from Anode to cathode. As a result, the device starts conducting and hence it is said to be in the conducting state or ON state.

The equivalent circuit of an SCR during the 'ON' state is represented with a low resistance (i.e), on state resistance (r_{on}) in series with a forward voltage drop 'V_F'. Generally the forward voltage drop (V_T) may be varied 1 or 2 volts depending upon the rating of SCR.



Equivalent ckt during ON state.

V_T – Voltage drop across SCR when rated ~~Current is carried by it~~

Next moment, again point B becomes positive and point C becomes negative, thus the conduction takes place in the same path of first half cycle i.e., $\omega(0-\pi)$. At instant $\omega = 2\pi$ SCR P_3 is automatically line commutated and SCR P_1 is triggered simultaneously.

Thus, it is seen that the direction of flow of current through the load remains same in all the three half cycle, or in other words, the three positive half-cycles are being obtained across the load to produce one combined positive half-cycle as output.

Similarly, in the next negative half-cycle, i.e. $\omega(3\pi - 4\pi)$, instead of SCR P_3, point 'C' is +ve w.r.to point B. But here instead of SCR N_1 (which is also in conducting mode) is forward biased and is gated. The path from current flow is from

point B^- – SCR – R-load –
. Point C^+ – R-load – SCR N_1 and back to negative point B^-.

Thus, the direction of flow of current through the load is reversed.

In the same way during half cycle $\omega(4\pi - 5\pi)$ instead of SCR P_1, SCR N_2 is triggered and the conduction path is as

[illegible] point A^+ – R-load – SCR N_2 – [illegible]

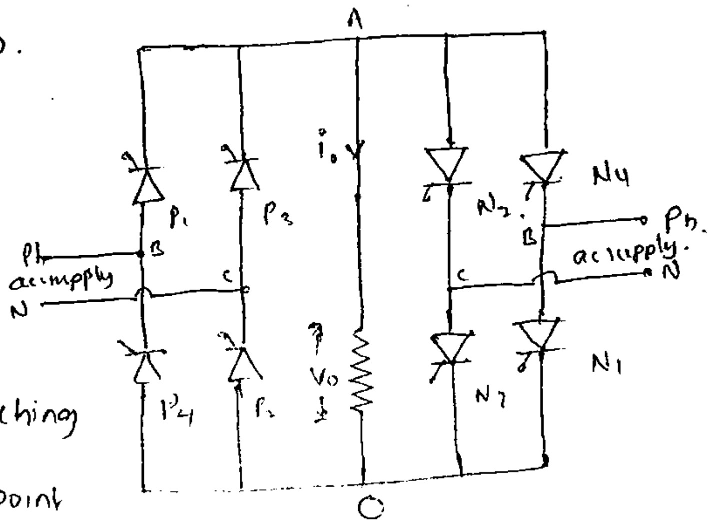
Similarly, During the half cycle $\omega t(5\pi - 6\pi)$, instead of SCR P_3, SCR N_1 is triggered. Thus the conduction path through the load again remains same direction

i.e, O^+ - R-load - SCR N_2 - C^-

There fore three cycles of the input, a.c have been combined to produce one cycle of the output. This clearly indicates that the i/p frequency is reduced to 1/3 at the output across the load. The output voltage magnitude can be changed by varying the firing angle of the SCRs.

1-φ STEP DOWN BRIDGE TYPE CYCLO CONVERTER WITH R-LOAD:-

In case of Bridge type converter also. The procedure is same to that of mid-point type.



But in this type converter During the half cycle's the SCR switching is different when compared to MID-point type. and is as follows.

During $\omega t(0-\pi)$ - P_1, P_2 are triggered.

During $\omega t(\pi - 2\pi)$ - P_3, P_4 are triggered

During $\omega t(2\pi - 3\pi)$ - P_1, P_2 are triggered.

During $\omega(3\pi - 4\pi)$, SCR's N_3, N_4 are triggered.

During $\omega(4\pi - 5\pi)$, SCR_s N_1, N_2 are triggered.

During $\omega(5\pi - 6\pi)$, SCR's N_3, N_4 are triggered.

Thus, In Bridge type also, First three cycles of the input a.c. have been combined to produce one cycle at the output. i.e, the input frequency is reduced to $\frac{1}{3}$ time $\therefore$ $f_0 = \frac{1}{3} f_s$

for this type of conversion, The conduction path is as follows.

$\omega(0 - \pi)$, B – SCR P_1 – A – R.LOAD – O – SCR P_2 – C.

$\omega(\pi - 2\pi)$, C – SCR P_3 – A – R.LOAD – O – SCR P_4 – B

$\omega(2\pi - 3\pi)$, B – SCR P_1 – A – R.LOAD – O – SCR P_2 – C.

$\omega(3\pi - 4\pi)$, B – SCR N_4 – O – R.LOAD – A – SCR N_2 – C.

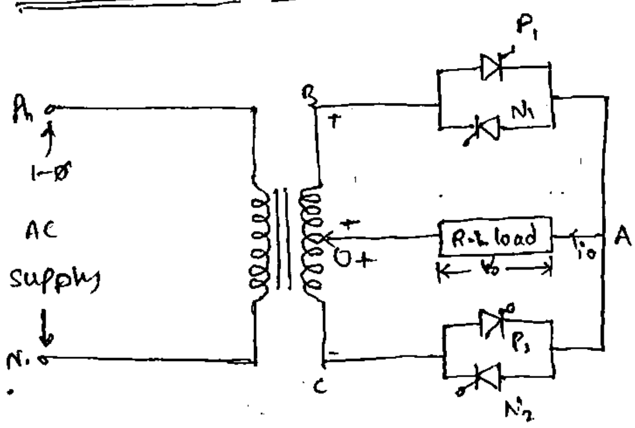
$\omega(4\pi - 5\pi)$, C – SCR N_3 – O – R.LOAD – A – SCR N_4 – B.

$\omega(5\pi - 6\pi)$, B – SCR N_1 – O – R.LOAD – A – SCR N_2 – C.

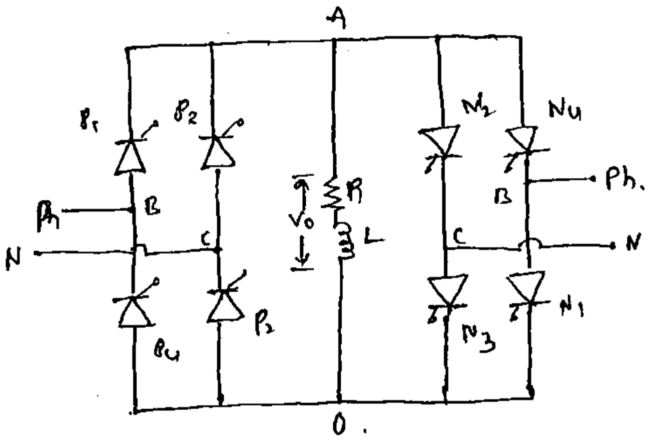
1-φ STEP DOWN CYCLO CONVERTER WITH R L LOAD:-

This type of cyclo converter will be described both for discontinuous as well as continuous load which depends upon the choosing the Inductor Value.

(a) Discontinuous load current :-



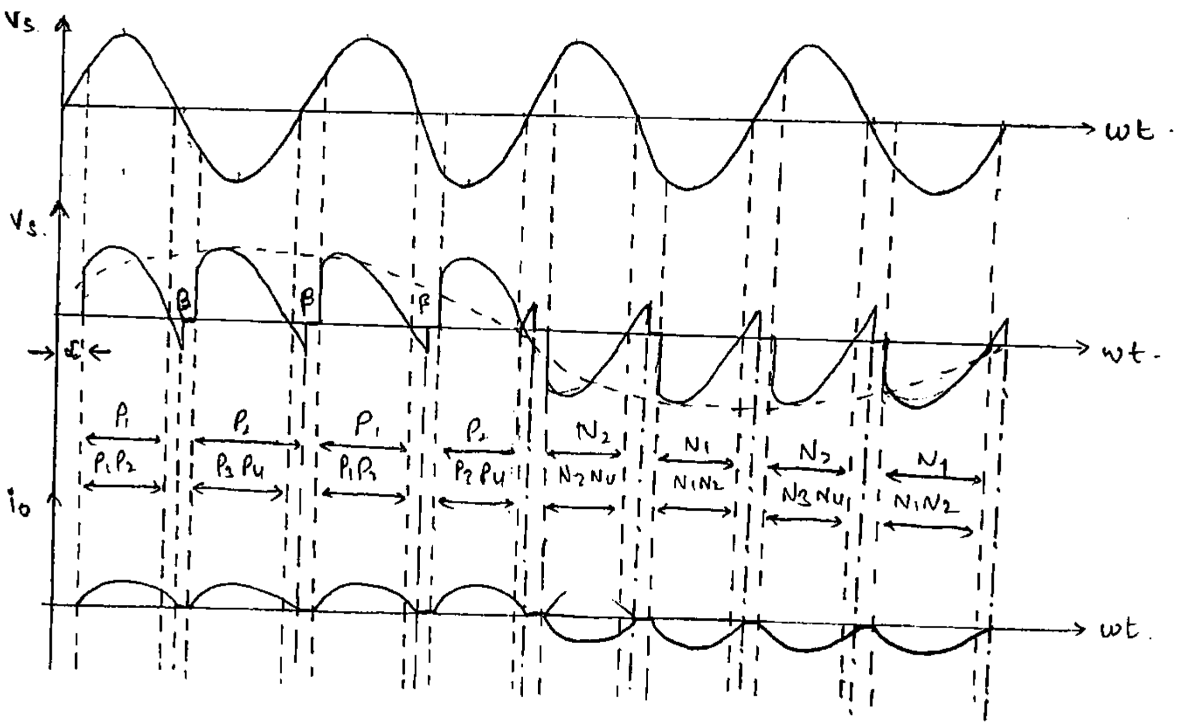
Mid-point type



Bridge-type

When point B is positive with respect to point 'O', forward Biased SCR P_1 is triggered at $\omega t = \alpha$, with this, load current starts building up in the positive direction from point 'A' to point 'O'. Load current I_o becomes zero at $\omega t = \beta > \pi$ But less than $(\pi+\alpha)$. Thus at $\omega t = \beta$, SCR P_1 is naturally commutated, which is already reverse biased after π.

After half cycle, point C is positive with respect to 'O'. Now forward biased SCR P_3 is triggered at $\omega t = (\pi+\alpha)$. Load current is again positive from point A to 'O' and builds up. At $\omega t = (\pi+\beta)$, current decays to zero and SCR P_3 is naturally commutated. At $(2\pi+\alpha)$, SCR P_1 is again turned ON. The load current seen to be discontinuous, as shown in the figure.



After four positive halfcycles of load voltage and load current, Thyristor N_2 (after P_2, N_2 should be fired) is gated at $(4\pi+\alpha)$. When point 'O' is positive with respect to point 'C'.

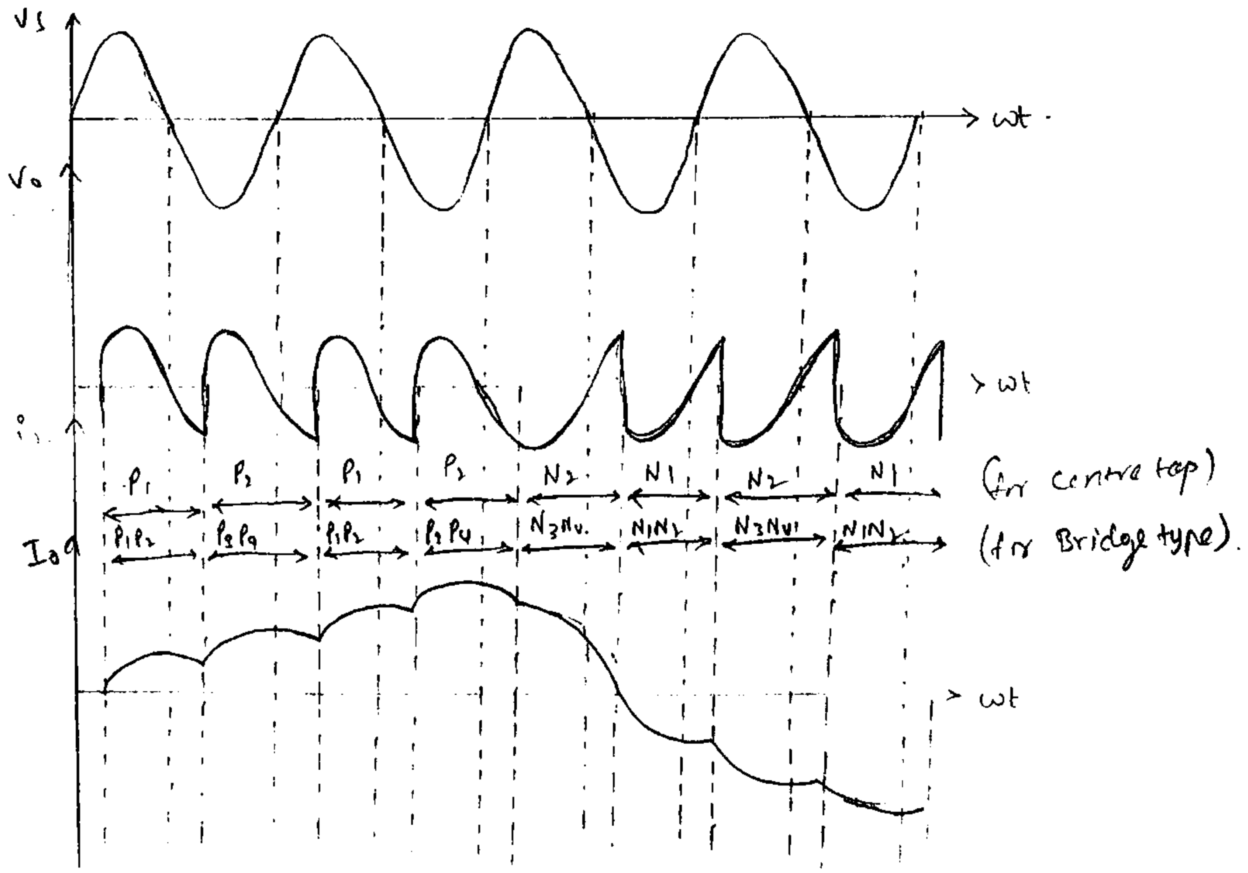
As SCR N_2 is forward biased, it starts conducting but load current direction is reversed, it is now from point O to A. After SCR N_2 is turned ON, load current builds up in the negative direction in the Inductor. In the next half cycle point O is positive with respect to point B. but before SCR N_1 is fired, current i_o decays to zero and SCR N_2 is naturally commutated. Now, when SCR N_1 is gated at $(5\pi+\alpha)$, current i_o again builds up but it decays zero before SCR N_3 in sequence is again gated.

This also repeats in next cycles until four half cycles of ac input.

mean output voltage and current waveforms are also shown.

It can be observed that the frequency of output voltage and current is $\boxed{f_0 = \frac{1}{4} f_s}$

(b) <u>Continuous load current</u>:-



During this type also the procedure is same as that of discontinuous current type. But here the difference is due to high value of inductance, there is no β ~~value~~ exists. It is equal to (π/n rad) where n is the number of that ~~halfcycle~~. half cycle.

Hence conduction of current is takes place until the next SCR triggered. Then continuous current is obtained at output.

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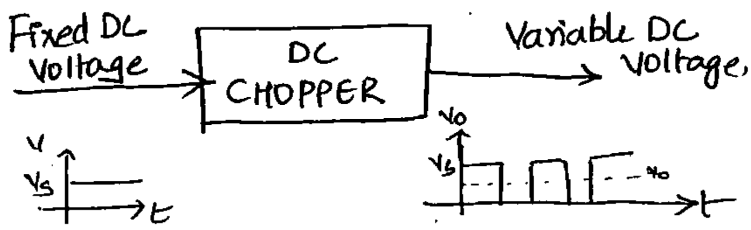
Introduction:-

A dc chopper is a high speed static switch used to obtain variable d.c voltage from constant dc voltage. It is also known as dc to dc converter.



Applications :-

1. Battery operated vehicles
2. Traction motors control in electric traction
3. Trolly cars
4. Marine hoists
5. Mine haulers
6. Electric Braking

Advantages:-

1. High efficiency
2. Smooth acceleration.
3. Fast dynamic response
4. Regeneration

The Average output voltage can be controlled by opening and closing the semiconductor switch periodically. The various control strategies for varying duty cycle 'α' are as follows.

1. Time Ratio Control Method (TRC) 2. Current Limit control method (CLC)

Time Ratio control Method :-

In this, the value of $\frac{T_{ON}}{T}$ is varied. This may be effected in two ways.

(i) Constant Frequency system :-

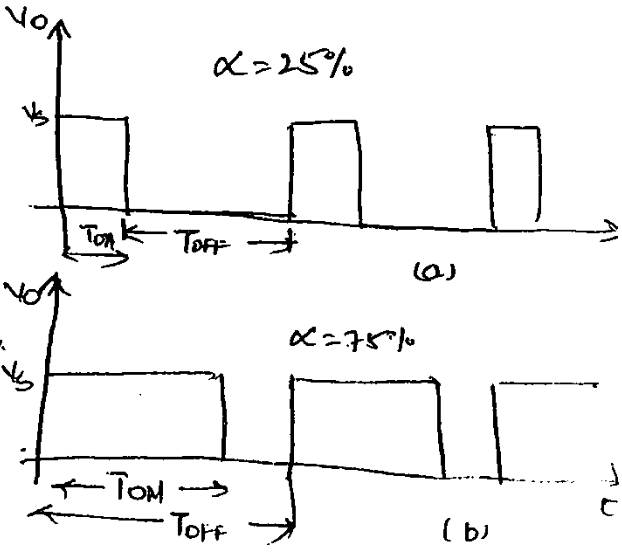
In this control method the ON time T_{ON} is varied but chopping frequency f (or chopping period T) is kept constant. The width of the pulse is varied and this type of control is known as Pulse width modulation (PWM). Here chopping period T is constant.

In Fig(a), $T_{ON} = \frac{1}{4}T$, So that $\alpha = 25\%$

In Fig(b), $T_{ON} = \frac{3}{4}T$, So that $\alpha = 75\%$

Ideally α can be varied from zero to unity.

∴ o/p voltage can be varied from zero to V_s



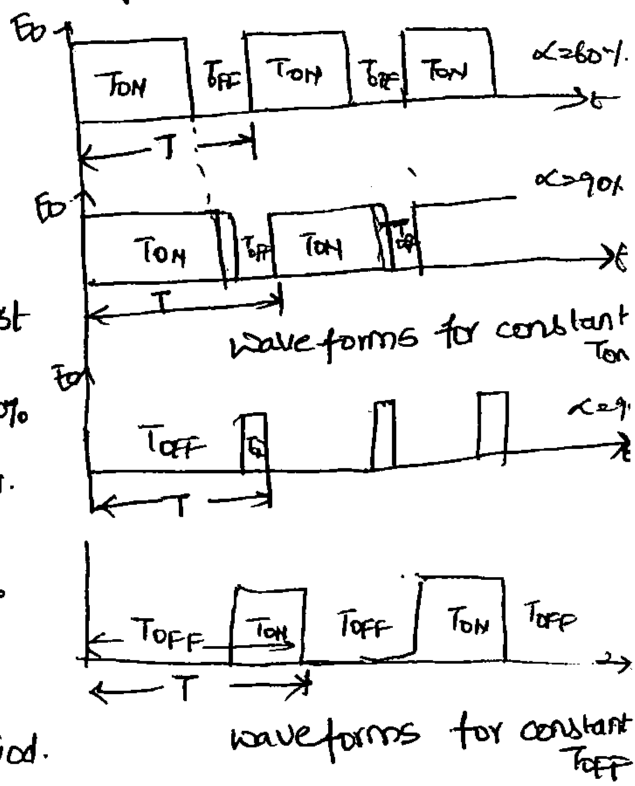
Principle of Pulse-width modulation [Constant T]

→ The constant frequency control gives low ripple and requires

(b) Variable frequency system:

It is also known as frequency modulation control as frequency ($f = 1/T$) is varied by keeping (a) ON time (T_{ON}) as constant or (b) OFF time (T_{OFF}) as constant.

Principle of frequency modulation may be illustrated as follows for different duty cycles.



Disadvantages of pulse width modulation scheme:-

1) TON cannot be reduced to zero for most of the commutation techniques as below 10% duty cycle, commutation failure may occur.

As a result, low range of α control is not possible in PWM which can be achieved by increasing the chopping period.

Disadvantages of Frequency modulation scheme:-

1. Filter design becomes a problem as the chopping freq. has to be varied over a wide Range, for control of o/p voltage in this scheme.

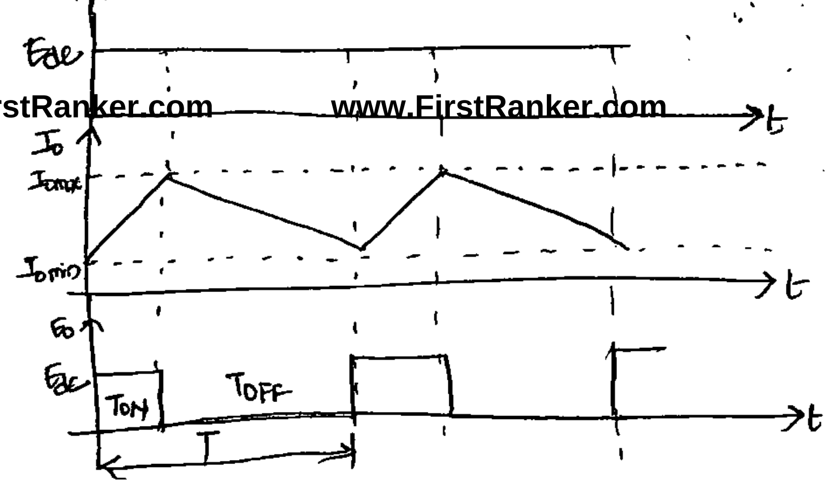
2. There is a possibility of interference with signalling and telephone lines as the frequency variation would be wide for control of α.

3. The undesirable feature i.e. discontinuity of load current may occur due to large off time in this scheme.

→ Due to above disadv. ~~constant frequency scheme is Preferred to frequency modulation scheme.~~

2) Current limit control :-

In this, the chopper operates between prescribed current limits. Here, chopper is switched ON and OFF so that the load current may be maintained between two limits.



Current limit control waveforms

→ When the current exceeds the upper limit, the chopper gets turned OFF whereas it gets turned ON when the current reaches the lower limit.

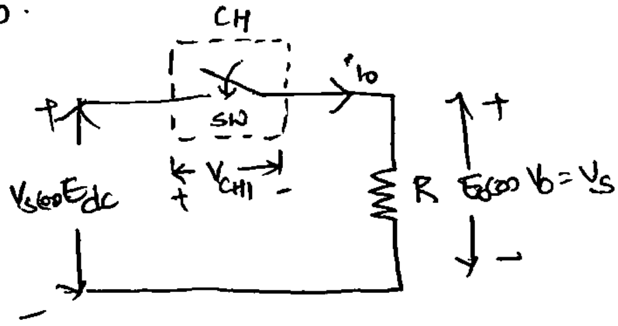
→ Current limit control is possible either with a constant frequency or with constant TON. Discontinuity of power flow cannot occur as the chopper operates between two prescribed limits. The difference between Iomax and Iomin decides the chopping frequency.

→ If the difference between Iomax and Iomin limits is minimum, the ripple in the load current gets reduced, which in turn increases the chopper frequency thereby increasing the switching losses.

PRINCIPLE OF OPERATION OF STEP-DOWN CHOPPER WITH R LOAD [BUCK CONVERTER] :-

A chopper is a high speed semiconductor ON/OFF switch.

The chopper is represented by a switch (SW) inside a dotted rectangle which may be turn ON (or) turn OFF as desired.

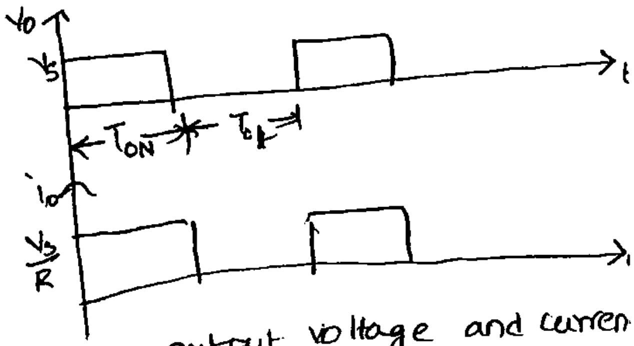


DC chopper with R Load

→ When switch is closed for a time T_{ON}, the i/p voltage V_s appears across the load. The current path is

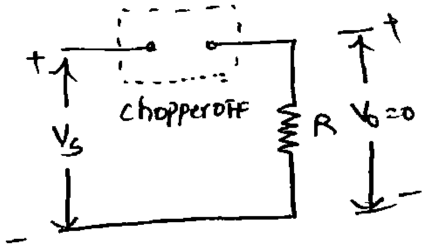
$V_s^+ - CH - R - V_s^-$

The o/p voltage across load resistance R during T_{ON} period is supply voltage.



output voltage and current waveforms

→ If the switch remains off for a time T_{OFF}, the voltage across the load is zero. Here, the o/p voltage V_o is a chopped voltage derived from supply voltage V_s. Hence the name chopper.



→ The chopper switch can be implemented by using Power BJT, Power MOSFET, GTO and forced commutation thyristors.

Average o/p voltage V_o is given by

$$V_o = \frac{1}{T}\int_0^T V_s\,dt$$

$$= \frac{1}{T}\left[\int_0^{T_{ON}} V_s\,dt + \int_{T_{ON}}^{T} V_s\,dt\right]$$

During T_{ON} to T Period (i.e, off period T_{OFF}) o/p voltage is zero

$$\frac{1}{T}\int_0^{T_{ON}} V_s\,dt = V_s\frac{T_{ON}}{T} \qquad \left[V_o = V_s\,\alpha\right]$$

$\alpha \rightarrow$ Duty cycle

Average load current I_o is given by

$$I_o = \frac{V_o}{R} = \alpha \cdot \frac{V_s}{R}$$

The RMS Value of o/p voltage

$$V_{orms} = \left[\frac{1}{T} \int_0^{T_{ON}} V_s^2 \, dt \right]^{1/2}$$

$$= \left[\frac{V_s^2}{T} (T_{ON}) \right]^{1/2}$$

$$= V_s \cdot \sqrt{\frac{T_{ON}}{T}}$$

$$\therefore V_{orms} = V_s \sqrt{\alpha}$$

Assume a loss less chopper, the i/p power to the chopper is the same as the o/p power and is given by.

$$P_i = \frac{1}{T} \int_0^{T_{ON}} V_s I_s \, dt$$

$$= \frac{1}{T} \int_0^{T_{ON}} V_s \cdot \frac{V_s}{R} \, dt = \frac{V_s^2}{R} \left[\frac{T_{ON}}{T} \right]$$

$$\therefore P_i = \alpha \cdot \frac{V_s^2}{R}$$

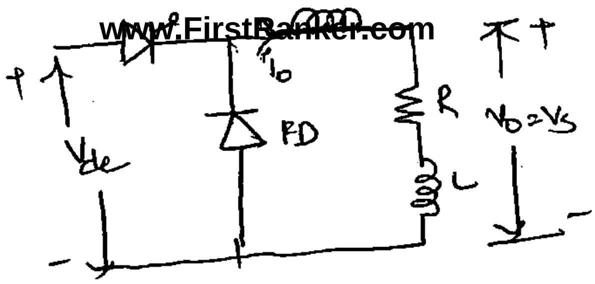
The effective i/p Resistance seen by the source is

$$R_i = \frac{V_s}{I_o} = \frac{V_s}{\alpha V_s / R} = \frac{R}{\alpha}$$

$$\therefore R_i = R/\alpha$$

The duty cycle α can be varied from 0 to 1 by varying T_{ON}, T or f.

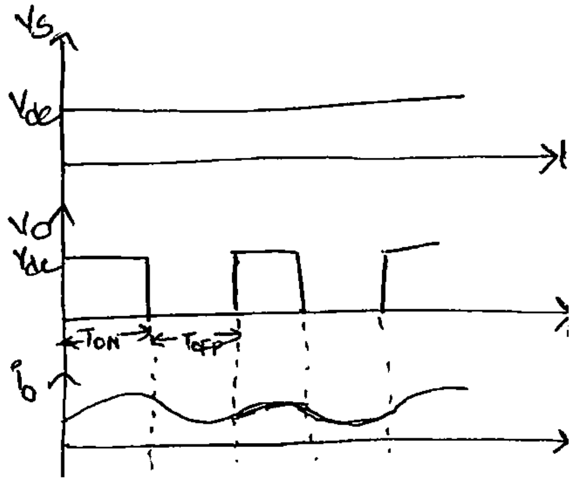
STEP DOWN CHOPPER WITH RL LOAD:



→ In this, the chopping device is SCR. Freewheeling diode is used for continuous current operation.

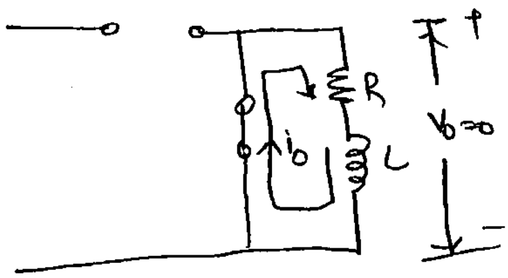
→ Dc Voltage is applied to chopper circuit. SCR is triggered and comes to the ON state. During the ON time of the chopper inductor stores the energy. So, the o/p voltage and current is positive. The current path is

V_{dc}^{+} – chopper – RL load – V_{dc}^{-}



i/p & o/p voltages & o/p current

→ During the OFF time of the chopper T_{OFF}, the load current flows through the Freewheeling diode FD. As a result, load terminals are short circuited by FD and load voltage is zero.



→ By varying ON and OFF time of the chopper, the o/p voltage can be varied.

Average o/p voltage $\therefore V_o = \alpha V_s$

$\alpha \rightarrow$ duty cycle $= \frac{T_{ON}}{T}$

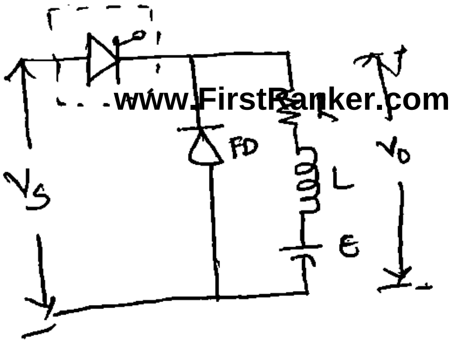
Average load current $I_o = \frac{V_o}{R}$

In this, the load current expression is determined to know

(i) the current profiles over periodic time T

(ii) the current ripple

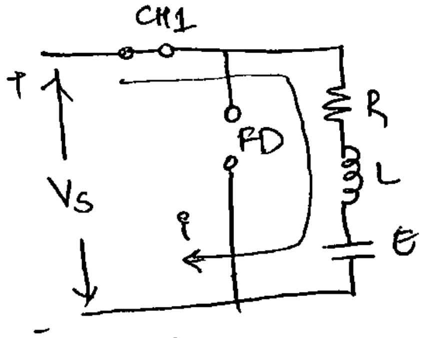
(iii) whether the current is continuous (or) discontinuous.



Type A chopper circuit diagram.

For RLE load, E is the load voltage which may be a dc motor (or) a battery. When CH1 is ON, the equivalent circuit is as follows.

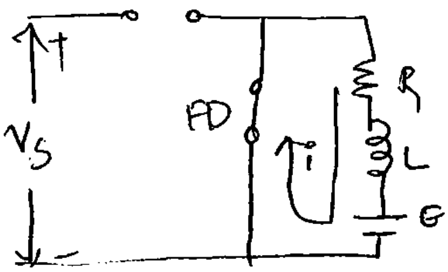
$$V_s = iR + L\,di/dt + E \quad —(1) \quad \text{for } 0 \le t \le t_{ON}$$



CH1 ON

When CH1 is OFF, the load current continues flowing through the free-wheeling diode.

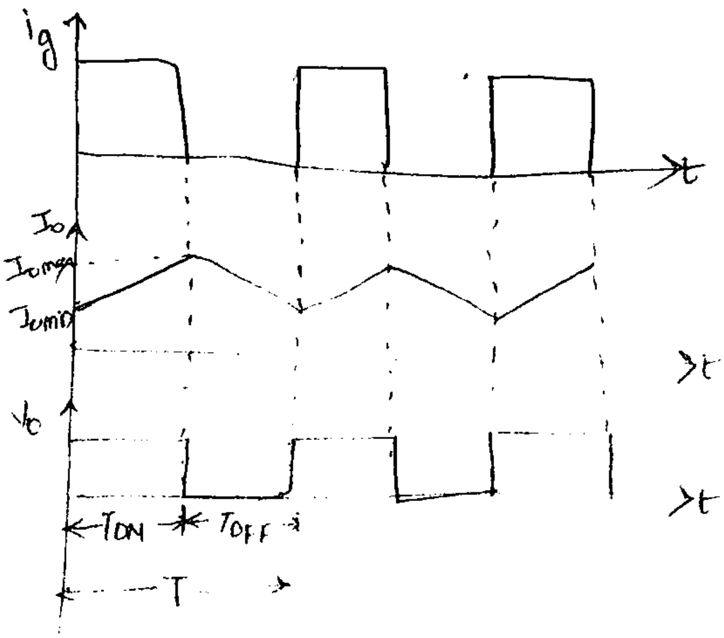
$$0 = iR + L\,di/dt + E \quad —(2) \quad \text{for } T_{ON} \le t \le T$$



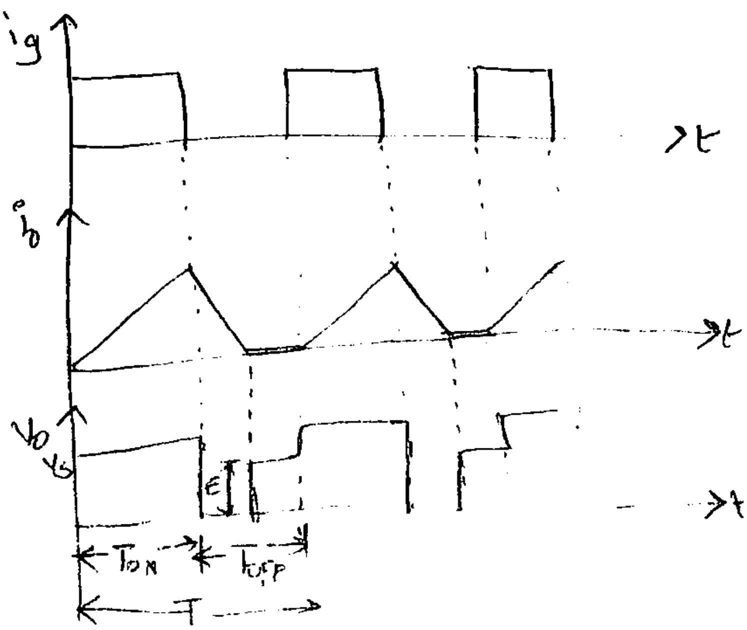
CH1 OFF

Solution for eq (1) & (2) may be obtained by using Laplace transform.

$$R\,I(s) + L\,[s\,I(s) - I_{omin}] = \frac{V_s - E}{V_s}$$



Continuous load current



Discontinuous load current

$$I(s) = \frac{V_s - E}{s(R+Ls)} + \frac{L \cdot I_{omin}}{(R+Ls)}$$

$$I(s) = \frac{V_s - E}{Ls\left(s+\frac{R}{L}\right)} + \frac{I_{omin}}{\left(s+\frac{R}{L}\right)}$$

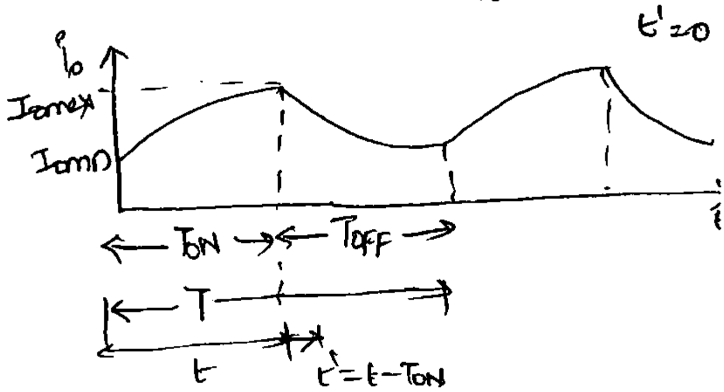
Laplace inverse of the above expression is

$$i(t) = \frac{V_s - E}{R}\left(1-e^{-R/L\, t}\right) + I_{omin}\, e^{-R/L\, t} \quad \text{for } 0 \le t \le T_{ON}$$

$$\therefore\ i(t) = \frac{-E}{R}\left(1-e^{-R/L\, t'}\right) + I_{omax}\, e^{-R/L\, t'} \quad \text{for } T_{on} \le t \le T$$

where $t' = t - T_{ON}$ when $t = T_{ON}$, $t' = 0$

for $t = T$, $t' = T - T_{ON} = T_{OFF}$



The variation of current $i(t)$ from I_{omin} to I_{omax} for $0 \le t \le T_{ON}$

at $t = T_{ON}$, $i(t) = I_{omax}$

$$\therefore\ I_{omax} = \frac{V_s - E}{R}\left[1-e^{-T_{ON}/T_a}\right] + I_{omin}\, e^{-T_{ON}/T_a} \quad —③ \qquad \text{where } T_a = \frac{L}{R}$$

at $t' = T_{OFF} = T - T_{ON}$, $i(t') = I_{omin}$

$$\therefore\ I_{omin} = \frac{-E}{R}\left(1-e^{-(T-T_{ON})/T_a}\right) + I_{omax}\, e^{-(T-T_{ON})/T_a} \quad —④$$

eq.③ & eq.④ can be solved for I_{omax} and I_{omin}

$$I_{omax} = \frac{V_s}{R}\left(1-e^{-T_{ON}/T_a}\right) - \frac{E}{R}\left(1-e^{-T_{ON}/T_a}\right) + I_{omin}\, e^{-T_{ON}/T_a}$$

$$I_{omin} = \frac{V_s}{R}\left[1-e^{-T_{ON}/T_a}\right] - \frac{E}{R} + \frac{E}{R} e^{-T_{ON}/T_a} - \frac{E}{R} e^{-T_{ON}/T_a} + \frac{E}{R} e^{-(T-T_{ON})/T_a} e^{-T_{ON}/T_a} + I_{omax}\, e^{-(T-T_{ON})/T_a} e^{-T_{ON}/T_a}$$

$$I_{omax} = \frac{V_s}{R}\left[1-e^{-T_{ON}/T_a}\right] - \frac{E}{R}\left[e^{-T/T_a}\right] + I_{omax}e^{-T/T_a}$$

(or)

$$I_{omax}\left(1-e^{-T/T_a}\right) = \frac{V_s}{R}\left[1-e^{-T_{ON}/T_a}\right] - \frac{E}{R}\left[e^{-T/T_a}\right]$$

$$I_{omax} = \frac{V_s}{R}\left[\frac{1-e^{-T_{ON}/T_a}}{1-e^{-T/T_a}}\right] - \frac{E}{R} \quad \text{--- (5)}$$

Substitution of eq (5) in eq (4)

$$I_{omax} = -\frac{E}{R} + \frac{E}{R}e^{-(T-T_{ON})/T_a} + \frac{V_s}{R}\left(\frac{1-e^{-T_{ON}/T_a}}{1-e^{-T/T_a}}\right)e^{-(T-T_{ON})/T_a} - \frac{E}{R}e^{-(T-T_{ON})}$$

$$= \frac{V_s}{R}\left[\frac{1-e^{-T_{ON}/T_a}}{1-e^{-T/T_a}}\right]\frac{e^{T_{ON}/T_a}}{e^{T/T_a}} - \frac{E}{R}$$

$$I_{omin} = \frac{V_s}{R}\left(\frac{e^{T_{ON}/T_a}-1}{e^{T/T_a}-1}\right) - \frac{E}{R}$$

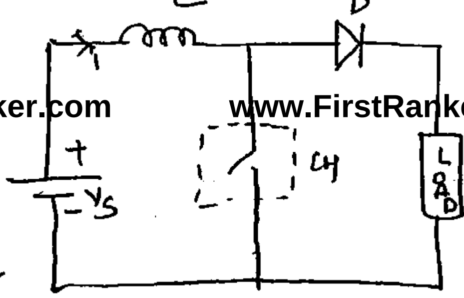
In case CH_1 conducts continuously, then $T_{ON} = T$

$$\therefore I_{omax} = I_{omin} = \frac{V_s - E}{R}$$

$\therefore$ The average load current $I_o = \frac{I_{omin} + I_{omax}}{2}$

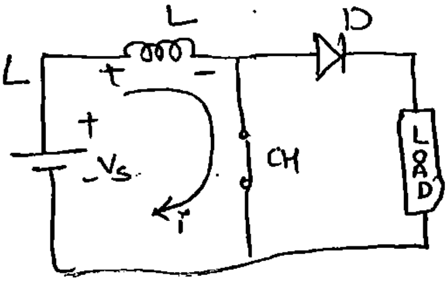
STEP UP CHOPPERS :-

The average o/p voltage V_0 is greater than the i/p voltage V_s, i.e. $V_0 > V_s$. This chopper is called step up chopper (or) Boost converter.



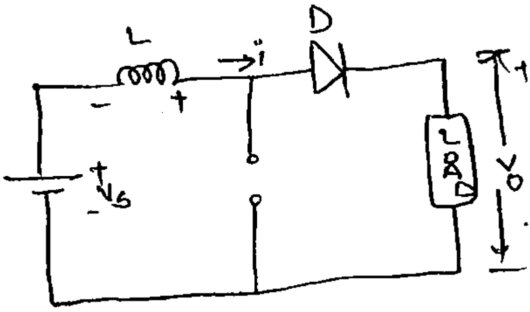
Step up chopper

→ In this chopper, a large value of inductor L in series with source voltage V_s. When the chopper is ON, the inductor L is connected to the supply V_s and inductor stores energy during ON period T_{ON}. The current through the load could increase from I_{omin} to I_{omax} and $V_L = V_s$



L stores energy.

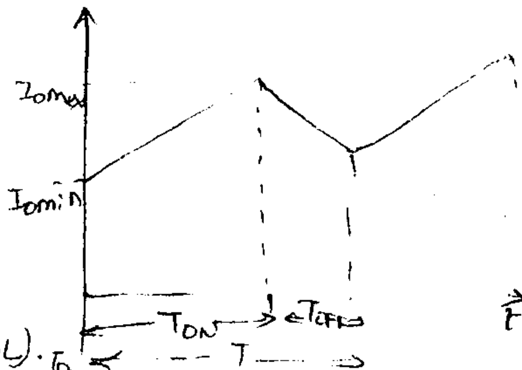
→ when the chopper is OFF, the inductor current is forced to flow through the diode and load for a time T_{off}. As the current tends to decrease polarity of the emf induced in L is reversed.



$L\frac{di}{dt}$ is added to V_s.

As a result voltage across the load becomes $V_s + L\frac{di}{dt}$

i.e. the inductor voltage adds to the source voltage to force the inductor current into the load. In this manner, the energy stored in the inductor is released to the load i.e current decreases from I_{omax} to I_{omin}.



The energy input to inductor from the source during the period T_{ON} is

W_i = (Voltage across L).(Avg. current through L).T_{ON}

$= V_s \left(\frac{I_{omin} + I_{omax}}{2}\right) T_{ON}$ ... (1)

During the time T_{OFF}, when chopper is OFF, energy released by the inductor to load is given by.

$$W_o = (\text{Voltage across } L)(\text{Avg. current through } L) \cdot T_{OFF}$$

$$= (V_o - V_s)\left(\frac{I_{omin} + I_{omax}}{2}\right) \cdot T_{OFF} \quad -(2)$$

Considering the system to be lossless and in the steady state, These two energies will be equal.

$$V_s\left(\frac{I_{omin} + I_{omax}}{2}\right) T_{ON} = (V_o - V_s)\left(\frac{I_{omin} + I_{omax}}{2}\right) T_{OFF}$$

$$V_s \cdot T_{ON} = (V_o - V_s)\, T_{OFF}$$

$$V_s T_{ON} + V_s T_{OFF} = V_o T_{OFF}$$

$$V_s (T_{ON} + T_{OFF}) = V_o \cdot T_{OFF}$$

$$V_o = V_s \cdot \frac{T_{ON} + T_{OFF}}{T_{OFF}}$$

$$V_o = V_s \cdot \frac{T}{T - T_{ON}}$$

$$V_o = V_s \cdot \frac{1}{T/T - T_{ON}/T}$$

$$\boxed{V_o = V_s \cdot \frac{1}{1-\alpha}}$$

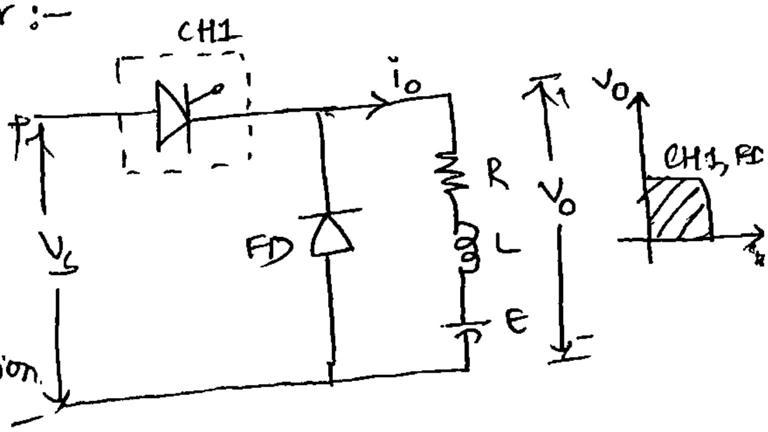
For $\alpha = 0$, $V_o = V_s$; and $\alpha = 1$ $V_o = \infty$ (infinity)

CONFIGURATION :-

Depending on the direction of current and voltage choppers can be classified into 5 types.

1) Type A chopper (or) First quadrant chopper
2) Type B chopper (or) second quadrant chopper
3) Type C chopper (or) Two quadrant type A chopper
4) Type D chopper (or) Two quadrant type B chopper.
5) Type E chopper (or) Four quadrant chopper.

First quadrant (or) Type-A chopper :-

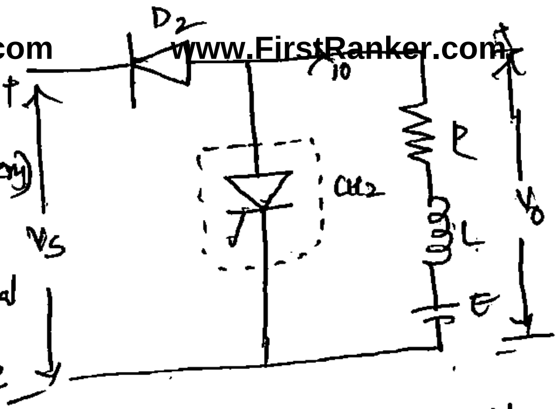


when chopper CH1 is ON, o/p voltage is equal to supply voltage i.e, $V_o = V_s$ and current I_o flows in the arrow direction i.e, positive direction.

when CH1 is OFF, o/p voltage is equal to zero i.e, $V_o = 0$ but I_o in the load continues flowing in the same direction through free wheeling diode FD. Here average o/p voltage and load current always positive.

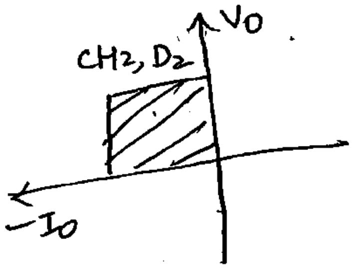
Type A chopper power flows from source to load. It is also called as step down chopper because average o/p voltage V_o is less than the input dc voltage V_s

2nd quadrant (or) type B chopper:



In this chopper, the load must contain the dc source E, like a dc motor (or a battery)

→ when CH_2 is ON, o/p voltage is equal to zero i.e, $V_0 = 0$ but load voltage E drives current through L and CH_2. During ON time of chopper (T_{ON}), inductor L stores energy.

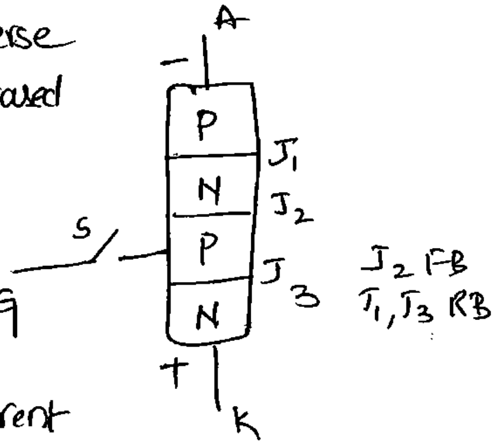


→ when CH_2 is OFF, o/p voltage $V_0 = \left(E + L\frac{di}{dt}\right)$ exceeds source Voltage V_s. As a result, diode D_2 is F.B and conducts, thus allowing power to flow to the source. chopper CH_2 may be ON or OFF, load current I_0 flows out of the load. Here load current I_0 is treated as -ve.

→ The power flows from load to source because o/p voltage V_0 is always positive and load current I_0 is -ve. As load voltage V_0 is greater than the source voltage V_s, type B chopper is called as step up chopper (or) boost converter.

It is also known as regenerative chopper.

1) Reverse Blocking Mode :- when cathode is made positive w.r.t anode with switch S open, thyristor is reverse biased i.e. Junctions J_1, J_3 are reverse biased whereas junction J_2 is forward biased.



→ The device behaves like two diodes connected in series with reverse voltage applied across them. A small leakage current of the order of few milliamperes (or) few microamperes depending upon the SCR rating flows. This is reverse blocking mode (or) OFF state of the SCR.

→ If the reverse voltage is increased, then at a critical breakdown level called reverse breakdown voltage V_{BR}, an avalanche will occur at J_1 & J_3 increasing the current sharply.

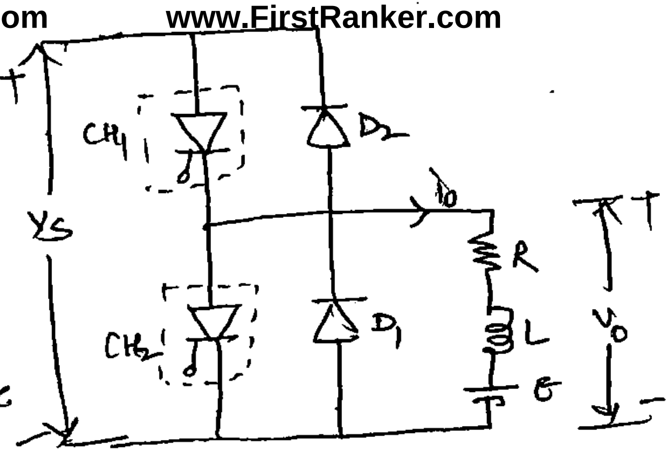
→ If this current is not limited, power dissipation will increase to a dangerous level that may destroy the device. If the reverse voltage applied across the device is below this critical value, the device will behave as a high impedance device (i.e, essentially open) in the reverse direction.

→ The inner two regions of the SCR are lightly doped compared to the outer layers. Hence, the thickness of the J_2 depletion layer during the forward biased conditions will be greater than the total thickness of two depletions layers at J_1 & J_3 when the device is reverse biased.

→ The forward breakover voltage V_{Bo} is generally higher than the reverse break over voltage V_{BR}

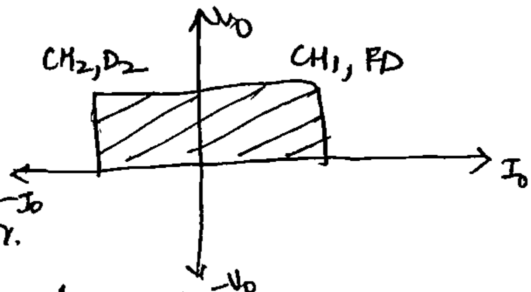
$V_{Bo} > V_{BR}$

Two quadrant type A chopper (or) Type - C chopper :-



> Type C chopper is obtained by connecting type A and type B chopper in parallel. Here, the o/p Voltage V_0 is always positive but the load current I_0 is positive as well as negative.

> When chopper CH1 (or) FD conduct, the o/p voltage and load current is always +Ve. In other words, CH1 and FD operate together as type A chopper in 1st quadrant.

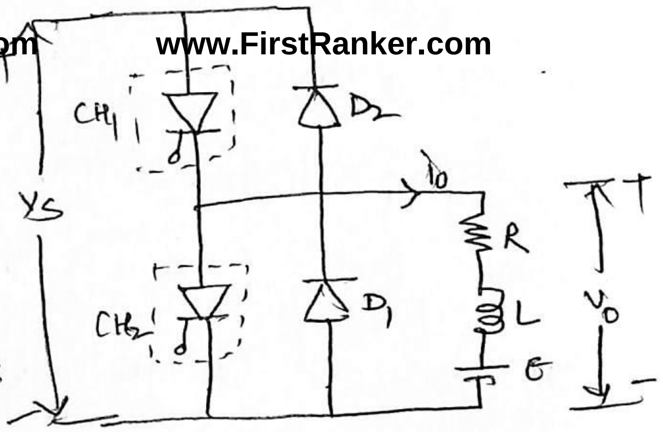


When chopper CH_2 (or) diode D_2 conduct, the o/p voltage is positive but the load current is negative. In otherwords CH_2 and D_2 operate together as type B chopper in second quadrant.

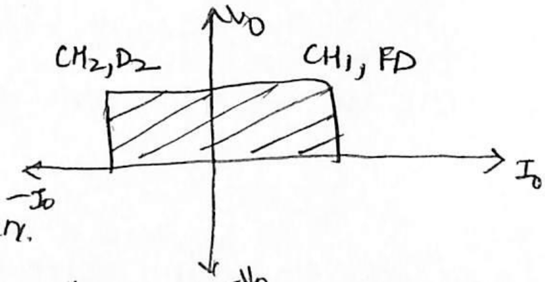
> Average load voltage is always positive but average load current may be +ve (or) -ve. ∴ power flow may be from source to load (1st quadrant operation) or from load to source (2nd quadrant operation).

> Choppers CH1 & CH_2 should not be on simultaneously otherwise direct short circuit will occur. This type of chopper is used for motoring and regenerative braking of dc motors.

> Type C chopper is obtained by connecting type A and type B chopper in parallel. Here, the o/p voltage V_0 is always positive but the load current I_0 is positive as well as negative.



> When chopper CH1 (or) FD conduct, the o/p voltage and load current is always +ve. In other words, CH1 and FD operate together as type A chopper in 1st quadrant.



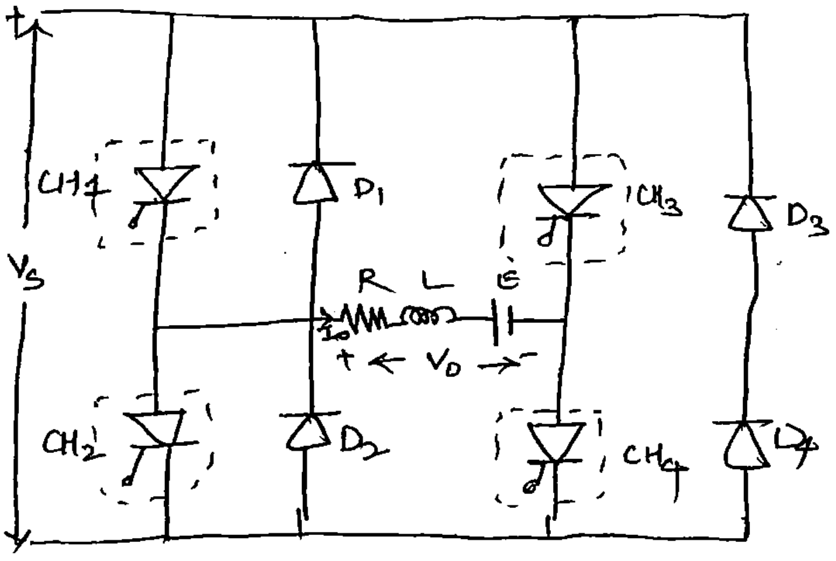
When chopper CH2 (or) diode D2 conduct, the o/p voltage is positive but the load current is negative. In otherwords CH2 and D2 operate together as type B chopper in second quadrant.

> Average load voltage is always positive but average load current may be +ve (or) -ve. ∴ power flow may be from source to load (1st quadrant operation) or from load to source (2nd quadrant operation).

> Choppers CH1 & CH2 should not be on simultaneously otherwise direct short circuit will occur. This type of chopper is used for motoring and regenerative braking of dc motors.

Four quadrant chopper (or) type E chopper:-

It consists of 4 power semiconductor switches CH1 to CH4 and 4 power diodes D_1 to D_4 in antiparallel.



Four quadrant [or] type E chopper

First quadrant:-

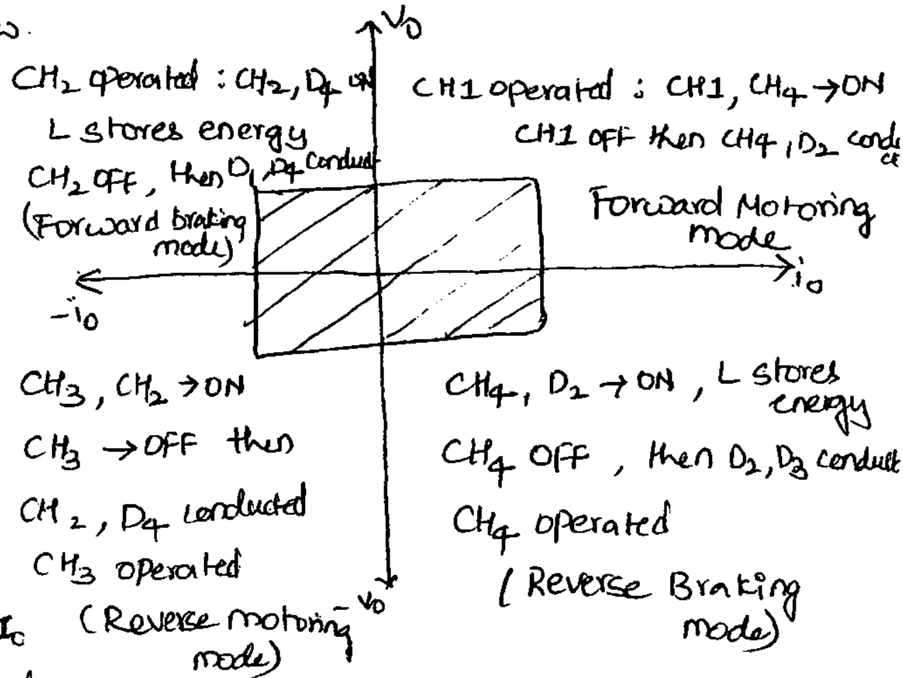
For first quadrant operation, CH4 is kept ON, CH_3 is kept OFF and CH1 is operated.

With CH1, CH4 ON, load voltage is equal to supply voltage i.e $V_o = V_s$. and load current I_o begins to flow.

Here both o/p voltage V_o and load current I_o are positive giving 1^{st} quadrant operation.

When CH1 is turned OFF, positive current freewheels through CH4, D_2 in this way.

both o/p voltage V_o, load current I_o can be controlled in the 1^{st} quadrant.



Second quadrant:-

Here CH_2 is operated and CH_1, CH_3 and CH_4 are kept off. With CH_2 ON, reverse (or negative) current flows through L. CH_2, D_4 & E. During the ON time of CH_2 the inductor L stores energy. When CH_2 is turned off, current is fed back to source through Diodes D_1, D_4. note that there $(E + L\,di/dt)$ is greater than the source voltage V_s. As the load voltage V_o is +ve and load current is -ve. Power flows from load to source. Second quadrant gives forward braking mode.

Quadrant :-

In this CH1 is kept OFF, CH_2 is kept ON and CH_3 is operated. Polarity of load emf E must be reversed for this Quadrant operation. with CH3 ON, load gets connected to source V_S so that both o/p voltage V_0, load current I_0 are -ve. It is also known as reverse motoring mode. when CH_3 is turned OFF, -ve current freewheels through CH_2, D_4. In this way, o/p voltage V_0 and load current I_0 can be controlled in the third quadrant

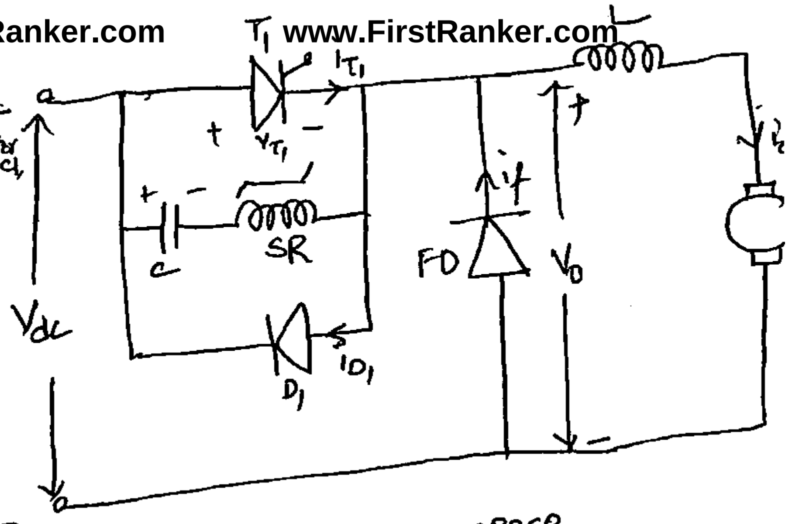
Fourth quadrant :-

In this CH_4 is operated and other devices are kept OFF. Load emf E must have its polarity reversed. with CH_4 ON, the +ve current flows through CH_4, D_2, L and E. During the ON time of CH_4 inductor L stores energy.

When CH_4 is turned OFF, current is feedback to source through D_2, D_3. Here load voltage is -ve, but load current is +ve leading to the choppers operation in the 4^{th} quadrant. Power flows from load to source. The 4^{th} quadrant operation gives reverse braking mode.

MORGAN CHOPPER :-

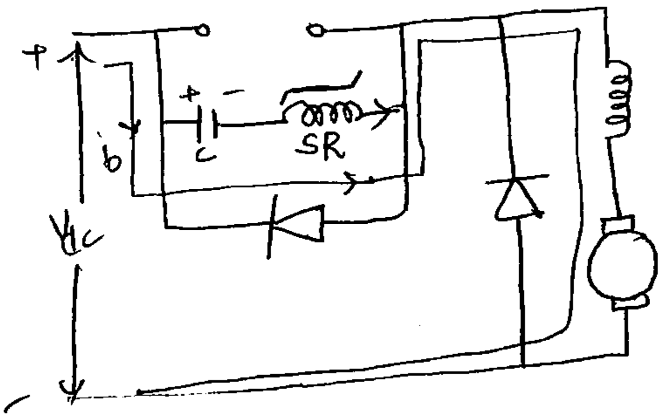
It consists of one SCR, saturable reactor in the commutation circuit and diode D_1. The exciting current of the saturable reactor is very small and is assumed to be negligible when it is saturated. The load consists of dc motor.



MORGAN CHOPPER

Operation :-

When the SCR T_1, is off state, capacitor 'C' will charge to the supply voltage V_{dc}. The saturable reactor is placed in the positive saturation condition. Now the charging path is V_{dc}^{+} − C − SR − Load − V_{dc}^{-}.



→ SCR T_1 is triggered at time $t = t_1$. When SCR T_1 is turned ON, the capacitor voltage applied across the SR. Then SR flux is driven from +ve saturation to negative saturation. The capacitor voltage is maintained constant with the same polarity, till the negative saturation point will be reached.

the SR flux reaches the -ve saturation, the capacitor discharges through the thyristor T_1 and the post saturation inductor of SR. It forms as resonant circuit. The discharging time $= \pi\sqrt{L_s \cdot C}$

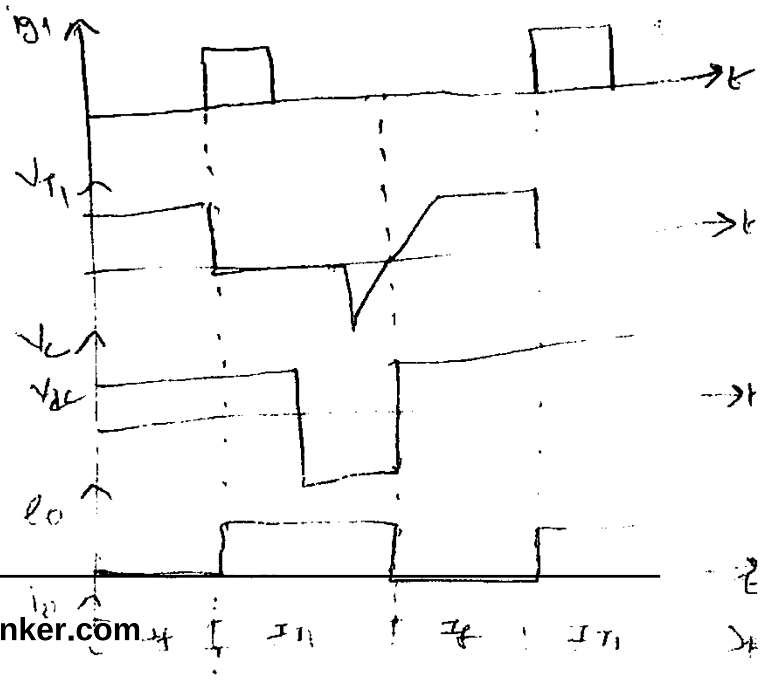
where L_s = Post saturation Inductance of the reactor.

→ The discharging time of the capacitor is very small and the polarity of the capacitor is reversed very quickly. Now the capacitor voltage is $-V_{dc}$ and is impressed on the SR in the reverse direction and cores changes from -ve saturation to the +ve saturation.

→ After a fixed time interval the reactor flux reaches the +ve saturation. Then the capacitor discharges through SCR T_1 in the reverse direction, ~~the~~ turning it off and then through diode D_1.

→ When SCR T_1 is comes to the OFF state, the load current flows through the freewheeling diode FD. Since the volt-time integral to saturate the core is constant, the on time of the SCR T_1 is fixed.

The ON time is a function of $L_s C$ and average o/p voltage can be varied only by varying operating freq. The o/p voltage is decreased by decreasing the frequency and increases by increasing the freq.



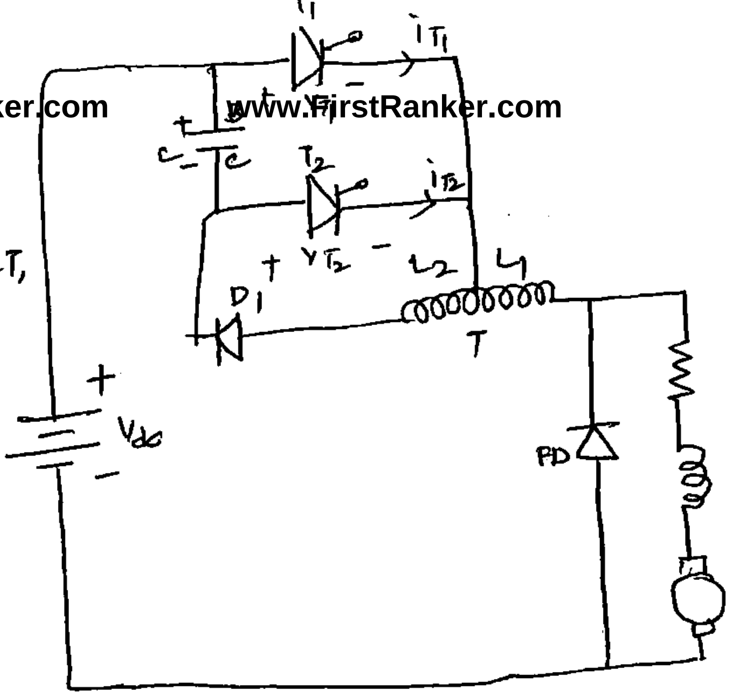
Advantages:-

By using saturable reactor in place of linear reactor

1) The circuit cost is low because of using one SCR

2) For off time, saturable inductance is low and for ON time, it is high.

CHOPPER :-



In this circuit consists of SCRs T_1 and T_2, diode D_1, autotransformer T, capacitor and dc motor load. Here, SCR T_1 is main thyristor. SCR T_2, diode D_1 capacitor c and auto transformer forms the commutating circuit for the main SCR T_1. In this circuit, the tapped transformer T through a portion of which the load current flows. Here the auto transformer forms L_1 and L_2 are closely coupled so that the capacitor always gets sufficient energy to turn OFF the main thyristor T_1

→ The main SCR is ON for a long period, then the dc motor rotate and reach the max. steady state speed. If the main SCR T_1 is turned OFF, the dc motor will not rotate. The main SCR T_1 is turned ON and OFF in periodically, the motor will rotate at some speed between max. ~~to~~ and zero.

→ First, we assume the capacitor c is charged to the supply voltage V_{dc}. Main SCR T_1 is triggered at $t = t_1$, the main thyristor T_1 comes to ON state. Now the current flows through the path

$$C_B - T_1 - L_2 - D_1 - C_c$$

→ Now, the capacitor charges in the reverse direction i.e bottom plate c is +ve and top plate B is -ve. Now the diode D_1 comes to ~~the OFF state due to capacitor voltage i.e the bottom plate is -ve~~

...ce, Capacitor C retains its charge until the thyristor T_2 is triggered.

→ At $t = t_3$, T_2 is triggered and comes to the ON state. Now the current path is $C_c - T_2 - T_1 - C_B$. The capacitor voltage C reverse biases the main SCR T_1 and it comes to the OFF state. Now the capacitor charges in the +ve direction i.e upper plate B is +ve and lower plate C is −ve. SCR T_2 is turned OFF due to the current through it falls below the holding current. Again SCR is triggered and the cycle is repeated.

→ At t_5, the capacitor bottom plate reaches a max. value. Since at t_5, the capacitor C is charged to a voltage greater than V_{dc}. Now D_1 is again F.B. The capacitor C discharges to a value lower than V_{dc}.

The time duration b/w t_3 & t_4 is the circuit turn OFF time presented to SCR T_1.

Advantages:-

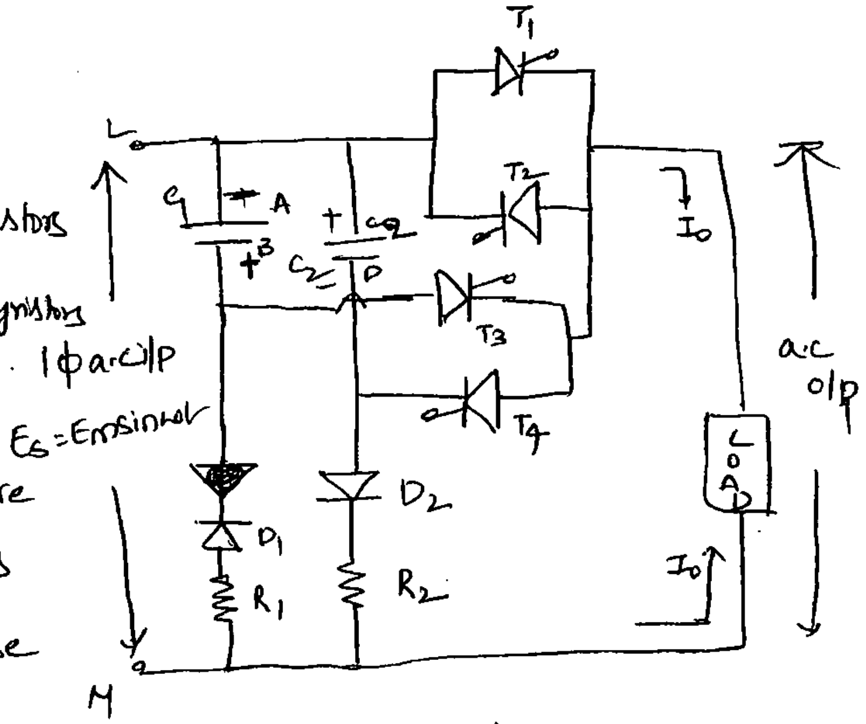
1. It allows the use of higher voltage and lower μF commutating capacitor.
2. There is no starting problem and any one of SCRs can be turned ON initially.
3) There is a greater flexibility in control because both the ON time and OFF time can be varied individually.

The desired ac voltage magnitudes may be obtained by two methods

1. By using stepup and stepdown transformers, in which the change in voltage depends upon the transformation ratio(k) of the transformer.

2. By using Ac choppers.

Ac choppers are those voltage changing or voltage varying circuits which employ semiconductor devices as static switches.



Circuit Description :-

It consists of two main thyristors T_1, T_2 and two auxiliary thyristors T_3 & T_4. C_1 & C_2 are commutating capacitors where as diodes D_1 and D_2 provides the charging path for these capacitors. Thyristors T_1 & T_3 may be used for producing the positive alternation and thyristors T_2 & T_4 for negative alternation of i/p a.c voltage.

Principle of operation :-

Mode 0 :- In this mode, during +ve half cycle of a.c supply voltage, capacitor C_2 gets charged whose path is

$L - C_2 - D_2 - R_2 - M$

During -ve half cycle, the capacitor C_1 gets charged through the path

$M - R_1 - D_1 - C_1 - L$

For commutation of the main SCRs T_1 & T_2, the voltage across these capacitors may be used.

Mode 1:-

During the positive half cycle of the supply voltage, T_1 is F.B which may be triggered at the instant T_1 with a firing angle α. The current flows through the path

$$L - T_1 - Load - N$$

At the instant t_2, the auxiliary thyristor T_3 may be turned ON so that the capacitor C_1 gets discharged through it. It's path may be given as

$$C_B - T_3 - T_1 - C_A.$$

whenever discharging current becomes more than the forward current of T_1, thyristor T_1 gets commutated. The auxiliary thyristor T_3 may be turned OFF naturally at the instant t_3 as the current passes through natural zero. Hence, SCRs T_1 & T_3 forms the first pair for producing the positive alternation of the i/p ac voltage.

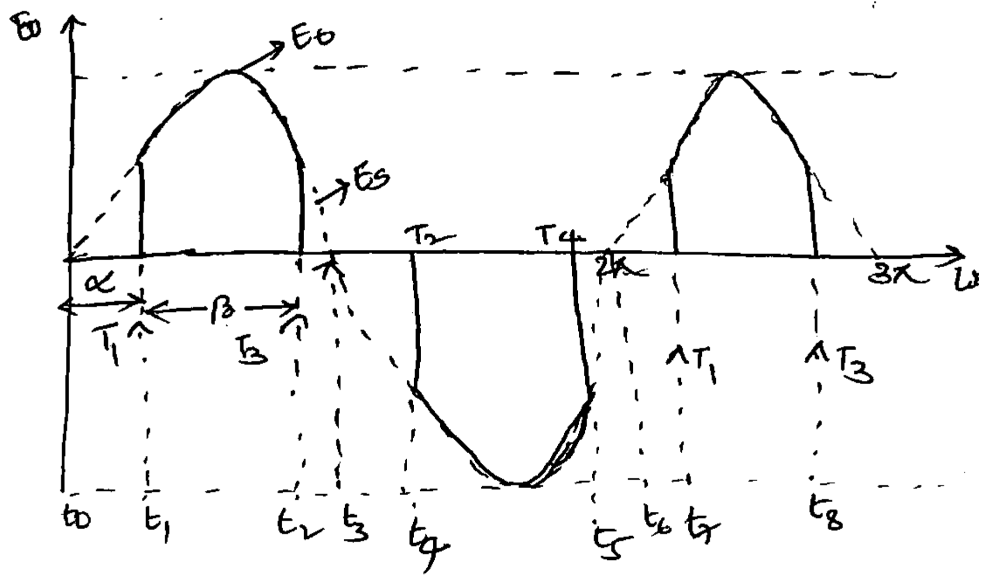
Mode 2:- During -ve half cycle of the supply voltage, thyristor T_2 is forward biased which may be triggered at the instant t_4. The load current follows the path.

$$N - Load - T_2 - L$$

when the instantaneous voltage reaches the instant t_5, auxiliary thyristor T_4 may be triggered. As soon as the auxiliary thyristor gets turned ON the capacitor C_2 gets discharged whose discharging current path is

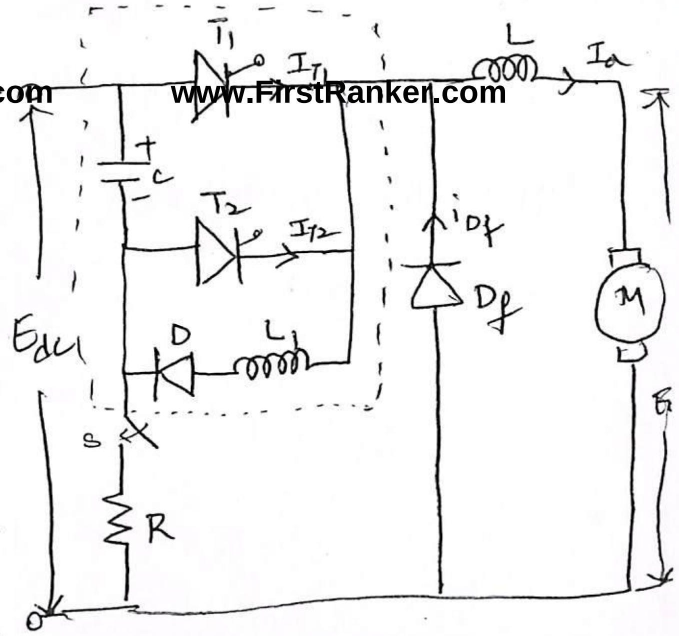
$$C_C - T_2 - T_4 - C_D$$

When this discharging current becomes more than the load current, SCR T_2 becomes turned OFF. At the instant t_6, SCR T_4 gets automatically turned OFF due to natural zero. Again at instant t_7, SCR T_1 gets triggered and the above process repeats.



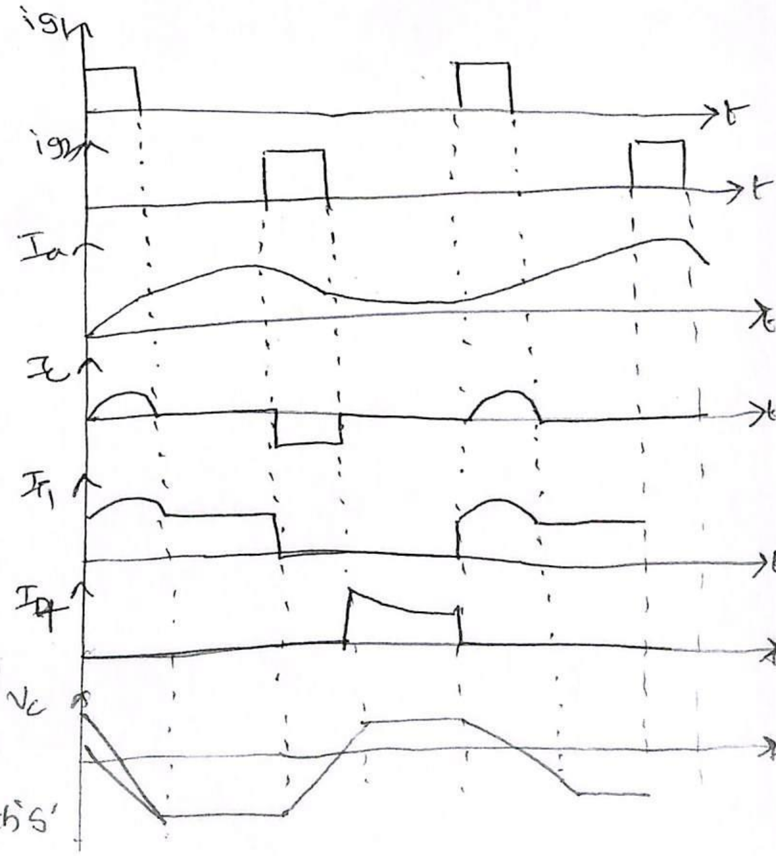
Supply voltage & o/p voltage waveforms in A.C. chopper

It consists of a main thyristor T_1.



The commutating circuit elements of thyristor T_1 are the auxiliary thyristor T_2, capacitor 'c', inductor L_1 and diode D. At the time of charging, the capacitor 'C', resistor 'R' is placed in series with the switch which are connected across the dc supply.

It consists of a freewheeling diode D_f.



Mode 1:-

During this mode, the capacitor 'c' gets charged to a voltage of E_{dc} by closing the switch 'S'. It's charging path is

$$E_{dc}^{+} - C^{+} - C^{-} - S - R - E_{dc}^{-}$$

whenever the capacitor gets charged to a voltage of E_{dc} with upper plate +ve and lower plate -ve, current through the resistance is zero. Hence, the switch 'S' may be opened.

Mode 2:- whenever thyristor 'T_1' is triggered, it comes into the conduction state from forward blocking state. During this mode, two currents flow through the thyristor T_1: One is the load current (I_o) and the other is the capacitor discharging current(I_c)

... current path may be given as

$$E_{dc}^{+} - T_1 - Load - E_{dc}^{-}$$

capacitor discharging current (I_c) follows the path

$$c^{+} - T_1 - L_1 - D - c^{-}$$

Mode 3:- During this mode, the capacitor 'c' gets charged with the reverse polarity i.e., with lower plate +ve and upper plate -ve. Now, the auxiliary thyristor 'T_2' gets into the F.B condition.

Mode 4:- During this mode, auxiliary thyristor T_2 is triggered inorder to commutate the main thyristor 'T_1'. As the thyristor 'T_2' gets into the F.B condition, and gets into the conduction state when it is triggered. Now, the capacitor discharging current flows through the auxiliary thyristor (T_2). It's path may be given as

$$c^{+} - T_2 - T_1 - c^{-}$$

wherever, the cathode potential of thyristor T_1 becomes more w.r.t anode potential, T_1 gets turned off.

During the off state of the thyristor 'T_1', due to the presence of stored energy in the inductor, current flows through the load whose path may be given as

$$L^{+} - load - D_f - L^{-}$$

Diode 'D' is known as blocking diode.

→ A device which converts the power to a power of desired o/p voltage and frequency is called an inverter. The o/p voltage can be fixed or variable at a fixed (or) variable frequency.

→ For low and medium power o/p's, transistorised inverters can be used

→ For high power o/p's, SCRs can be used.

Applications:-

1. Variable speed a c motor drives
2. Uninterruptible power supplies (UPS)
3. Induction heating, standby power supplies
4. HVDC transmission lines
5. Aircraft power supplies etc.

→ For low and medium power applications, square wave (or) quasi square wave voltages can be obtained as inverter o/p.

→ For high power applications, low distorted sinusoidal waveforms can be obtained as inverter o/p.

Types of Inverters:-

Thyristor inverters can be classified according to the method of commutation, method of connections (or) according to the control systems used.

Based on commutation, the inverters can be classified as,

i) Line commutated inverters (iii) Self commutated inverters
(ii) Load commutated inverters (iv) Forced commutated inverters

→ Based on method of connections, the inverters can be classified as:

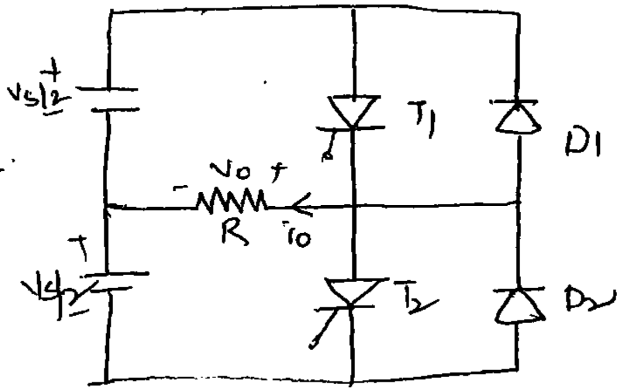
(i) Series Inverter
(ii) Parallel Inverter
(iii) Bridge Inverter
- 1-ϕ half bridge Inverter
- 1-ϕ Full bridge Inverter
- 3-ϕ Bridge Inverter.

→ Based on the no. of phases of the load inverters can be classified as

(i) 1-ϕ Inverters
(ii) 3-ϕ Inverters.

→ Inverters can also be broadly classified into two types as
i) Voltage source Inverters (VSI) or Voltage Fed Inverters (VFI)
ii) Current source Inverters (CSI) or Current Fed Inverters (CFI)

1-ϕ Half bridge Inverters:-



1-ϕ half bridge Inverter with R load

The circuit consists of two thyristors T_1 & T_2 and diodes D_1 & D_2 and three wire d.c supply $V_s/2$. In this each thyristor conducts for the duration of its gate signal and get commutated as soon as the pulse is removed. The circuit is designed such that T_1 & T_2 are not turned ON at the same time. If T_1 & T_2 are turned ON at the same time it will cause direct short circuit of the voltage source.

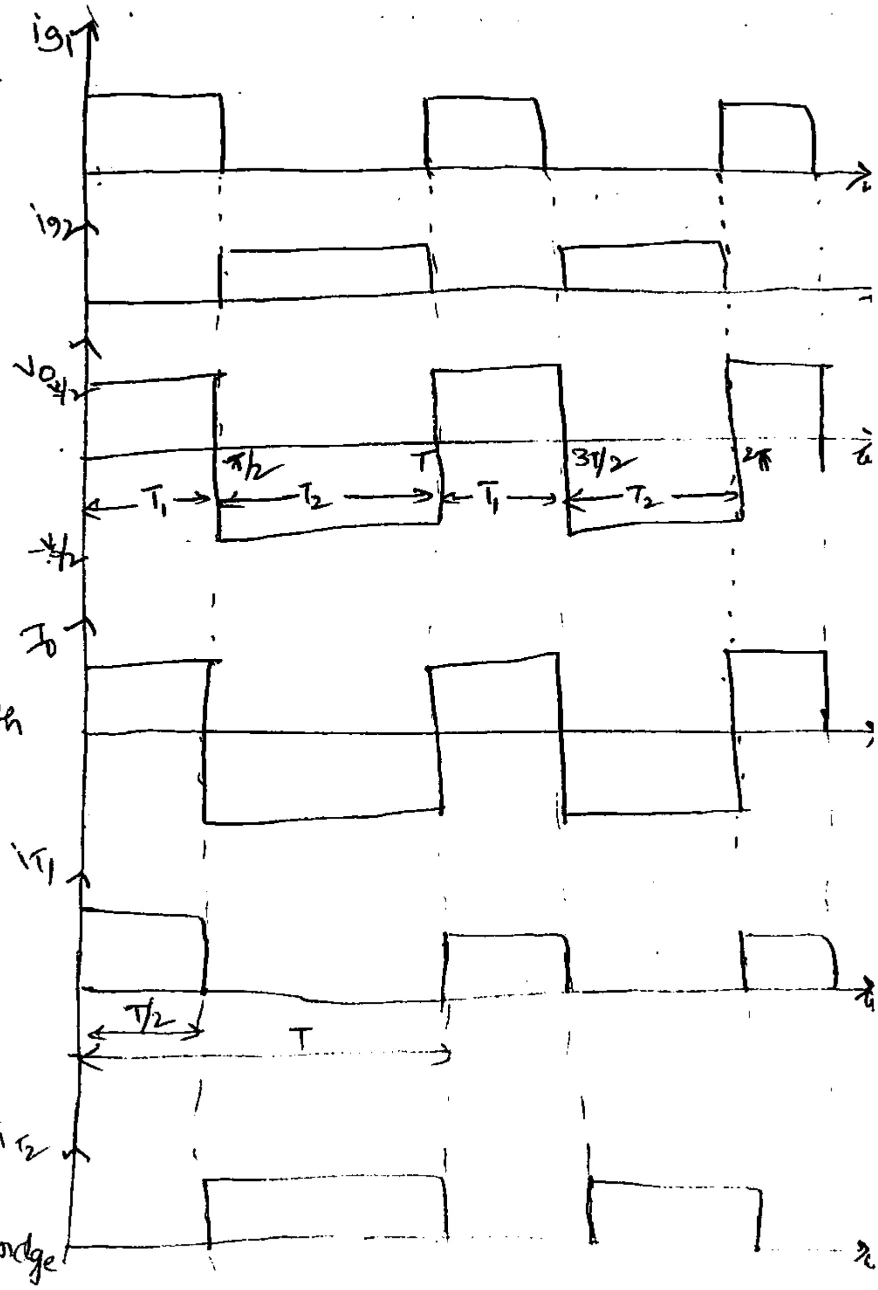
→ During the time 0 to $T/2$ thyristor T_1 is turned ON by applying the gate signal i_{g1}. The voltage across the resistive load is $V_s/2$ due to the upper voltage source $V_s/2$.

– T₁ thyristor is turned OFF by forced commutation and T_2 is turned on. During the time $T/2$ to T thyristor T_2 conducts. The voltage across the resistive load is $(-V_s/2)$ due to the lower voltage source $V_s/2$. Thus the load voltage V_0 is an alternating voltage waveform of amplitude $V_s/2$ and freq. $1/T$ Hz. The o/p freq. can be changed by changing T.

→ For resistive load the load voltage V_0 and load current i_0 are inphase with each other

→ For inductive load the load current i_0 will not be in phase with load voltage V_0.

→ The diodes D_1 & D_2 which are connected in antiparallel with the thyristors carries the current when the thyristor are turned OFF. These diodes D_1 & D_2 are called feedback diodes

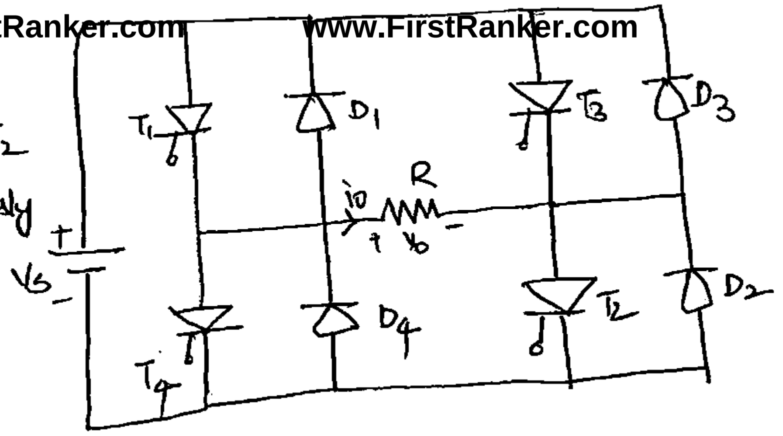


Voltage & current waveforms for 1-ϕ half bridge inverter with R load

→ The main drawback of the half bridge inverter is that it requires a 3 wire dc supply. This drawback can be overcomed by 1-ϕ full bridge inverters.

Full Bridge Inverter :-

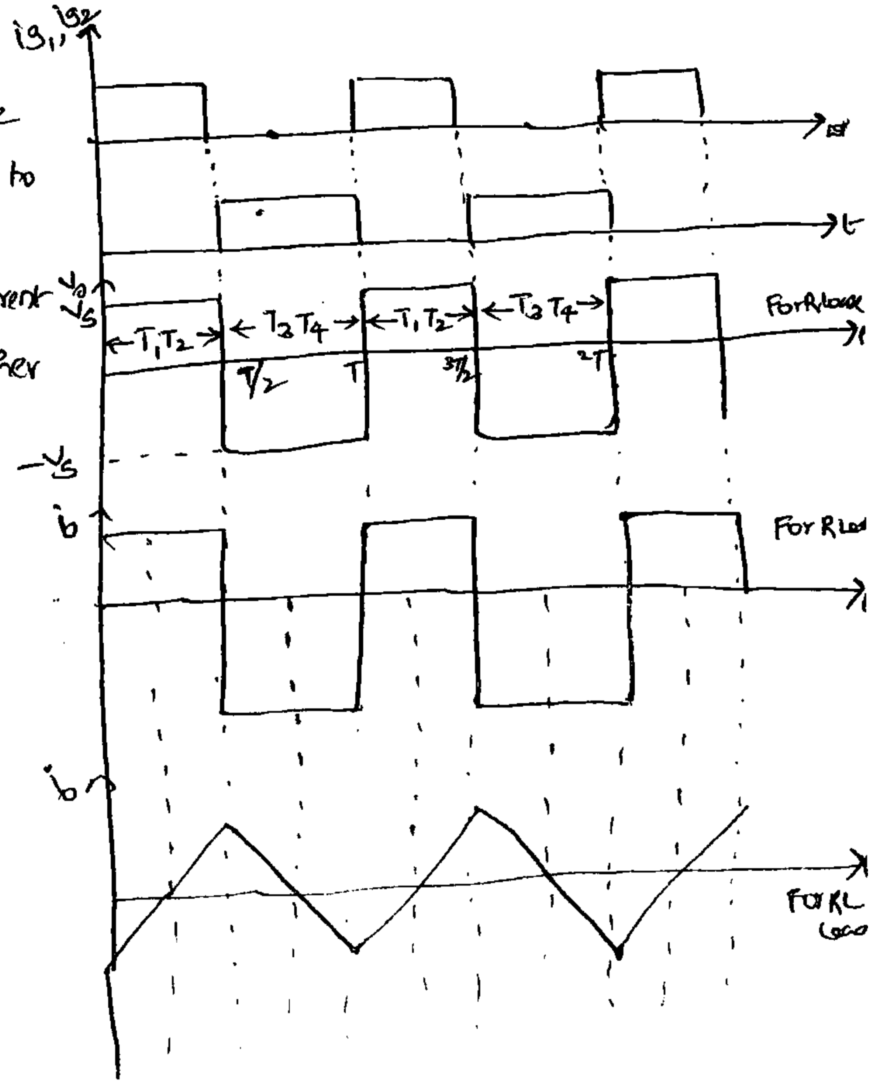
It consists of 4 thyristors and 4 freewheeling diodes. Thyristors T_1 & T_2 should be turned ON simultaneously at freq. $f = \frac{1}{T}$ and thyristors T_3 & T_4 should be turned ON 180° out of phase with T_1 & T_2.



→ Freq. of o/p voltage can be controlled by varying the time period T. when T_1 & T_2 conducts, load voltage is +ve i.e., V_s when the thyristor T_3 & T_4 conducts, the load voltage is -ve i.e ($-V_s$). The load voltage waveform is rectangular and is not affected by the nature of the loa

→ The amplitude of o/p voltage and o/p power of 1-φ full bridge inverter is doubled when compared to 1-φ half bridge inv.

→ The load voltage V_o and load current i_o will be in phase with eachother for resistive load.

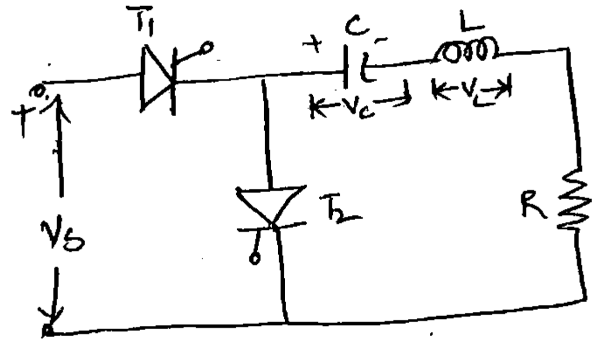


SERIES INVERTER :-

In series Inverters, the commutating elements, viz L and C are connected in series with the load. This constitutes a series R-L-C resonant circuit. If the load is purely resistive, it only has resistance in the circuit. In case of load being inductive (or) capacitive in nature, its inductance (or) capacitance part is added to the commutating elements of thyristorised series inverter produces an approximately sinusoidal waveform at a high o/p freq., ranging from 200 Hz to 100 KHz.

Applications:- Ultrasonic generators, Induction heating, sonar transmitter, Fluorescent lighting, etc.

→ Circuit Description:-



Circuit diagram for Basic series Inv.

It consists of two SCRs T_1 & T_2 which are used to produce the two halves (positive & negative resp.) in the o/p. The commutating elements, L and C are connected in series with the load R to form the R-L-C circuit. The values of L & C are chosen that, they form an underdamped circuit and is necessary to produce the required oscillations.

$R^2 < \frac{4L}{C}$ condition is satisfied by selecting L & C

The operation can be divided into 3 modes.

Mode 1:-
when a d.c voltage V_s is applied to the circuit and SCR T_1 is triggered by giving pulse to its gate. As soon as SCR T_1 is triggered, it starts conducting and current flows

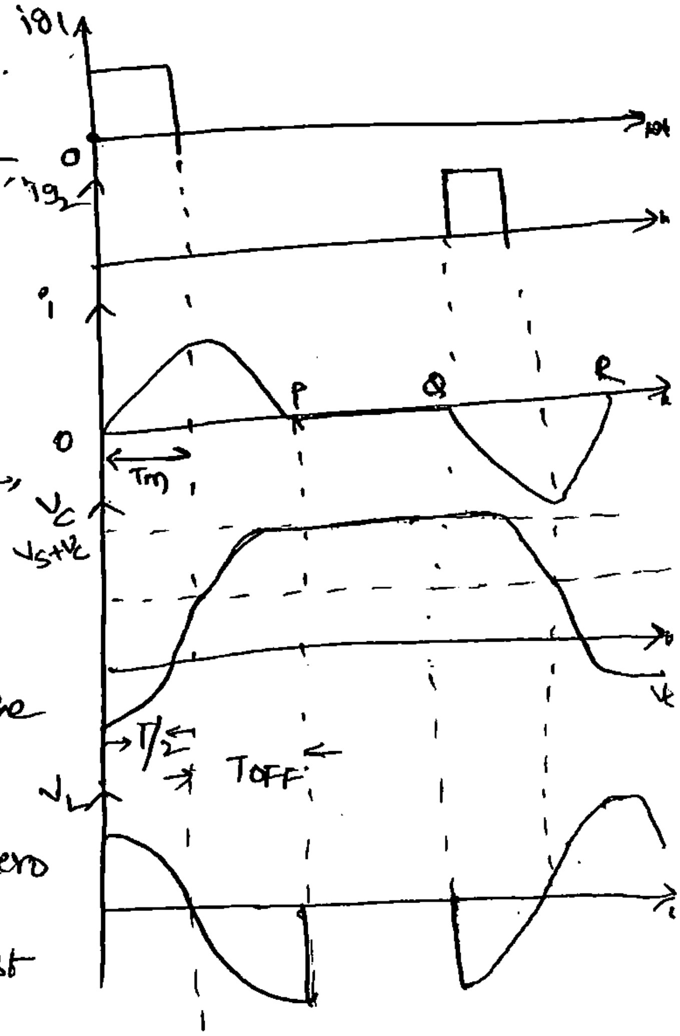
through the R-L-C circuit

→ Capacitor C gets charged upto supply voltage V_s with +ve Polarity on its left plate and -ve polarity on its right plate.

The load current is of alternating nature due to the underdamped circuit formed by the commutating elements L & C.

→ It starts building up in the +ve half, goes gradually to its peak value, then starts returning and again becomes zero.

→ when the current reaches its peak value, the voltage across the capacitor is the supply voltage V_s. After this the current starts decreasing but the capacitor voltage still increases and finally the current becomes zero but the capacitor retains the highest voltage, i.e, $(V_s + V_c)$ where V_c is the initial voltage across the capacitor at the instant SCR T_1 is turned ON.



Voltage & current waveforms for series Inv.

At P, SCR T_1 is automatically turned OFF due to the current flowing through it becomes zero.

Mode 2:- During this mode, the load current remains at zero for a sufficient time (T_{off}). ∴ both SCRs T_1 & T_2 are OFF. During this period PQ, capacitor voltage will be held constant.

The +ve polarity of the capacitor C appears on the anode of SCR T_2, it is in conducting mode and hence triggers immediately. At Q, SCR T_2 is triggered. When SCR T_2 starts conducting, capacitor C gets discharged through it.

Thus, the current through the load flows in the opposite direction forming the -ve alternation. This current builds up to the -ve max. and then decreases to zero at point R, SCR T_2 will be Turned OFF. Now, the capacitor Voltage reverses to some value depending upon the values of R, L & C.

Again SCR T_1 is triggered after some time delay (T_{OFF}) and in the same way other cycles are produced. It produces the alternating o/p almost sinusoidal in nature. Here, the supply from the dc source is intermittent in nature. +ve cycle of the a.c o/p is drawn from the d.c i/p source, whereas for the -ve cycle the current is drawn from the capacitor.

⇒ It is necessary to maintain a time delay b/w the point when one thyristor is turned OFF and other thyristor is triggered. If this is not done, both the thyristors will start conducting simultaneously resulting in a short circuit occur in the dc i/p source. The time delay (T_{OFF}) must be more than the turn off time of the SCRs. The o/p freq is given by

$$f = \left[\frac{1}{T/2 + T_{OFF}}\right] Hz$$

T → time period for oscillation.

$$\frac{T}{2} = \frac{\pi}{\sqrt{1/LC - R^2/4L^2}}$$

T_{OFF} → time delay b/w turn off of one thyristor and turn on of the other thyristor.

Latching current :- once the SCR is conducting, a forward current that is greater than the minimum value, called the latching current.

Latching current :-

once the SCR is conducting a forward current is greater than the minimum value; called the latching current, the gate signal is no longer reasuired to maintain the device in its ON state. Removal of the gate current doesnot affect the conduction of anode current.

$I_a > I_L \rightarrow ON$

Holding current :-

The SCR will return to its original forward blocking state if the anode current falls below a low level, called the holding current (I_h)

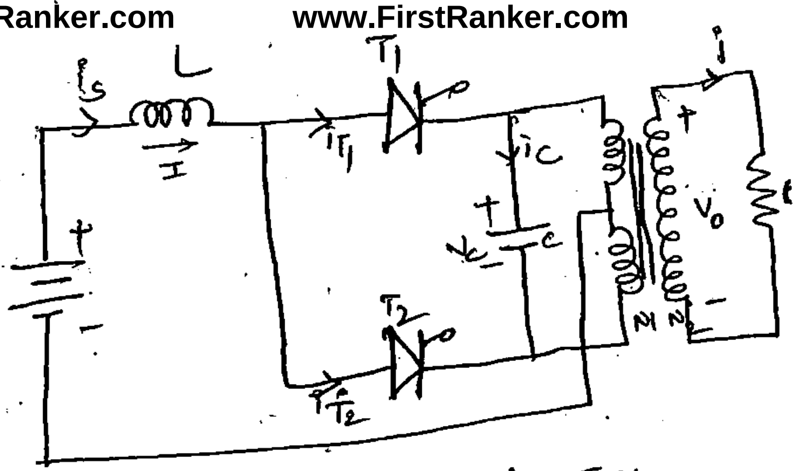
$I_a < I_h \rightarrow OFF$.

TWO TRANSISTOR MODEL OF SCR (TWO TRANSISTOR ANALOGY) :-

→ The operation of an SCR can be explained in a better cooy by considering it in terms of two transistors. This analogy is called two transistor analogy.

→ The two transistor model is obtained by bisecting the middle layer into two halves. A thyristor can be considered to be a combination of PNP and NPN transistors.

PARALLEL CAPACITOR INVERTER :-



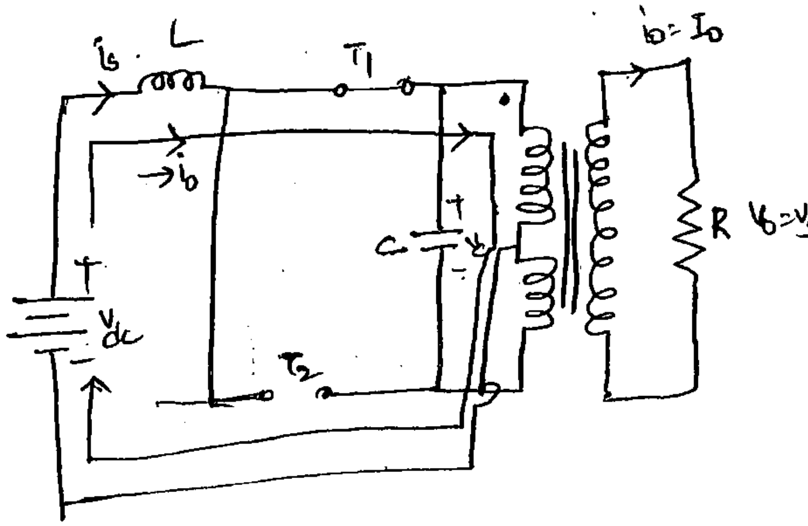
Basic parallel Inv.

Here, capacitor is used for commutation of two SCRs. It consists of two SCRs T_1 & T_2, an inductor L an o/p transformer and a commutating capacitor C.

The transformer turns ratio from primary half to secondary winding is to be assumed unity. The inductance is connected in series with supply voltage because the source current becomes constant.

During this operation of this inv. circuit, commutating capacitor C comes in parallel with load in the o/p transformer. Due to this reason, it is called parallel inverter.

Mode 1 :-



When SCR T_1, is conducting and a current flows in the upper half of primary wdg. Here SCR T_2, is OFF. this current produces magnetic flux. this flux links with both the halves of the primary winding i.e total voltage across primary winding is $2V_{dc}$.

Now, the commutating capacitor charges to a voltage of $2V_{dc}$. The upper plate is +ve and lower plate is −ve.

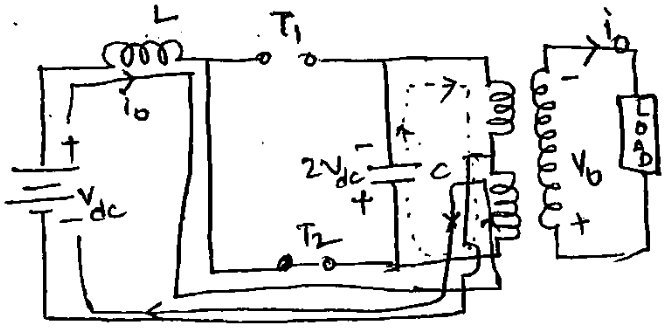
→ ... is rev. B. through SCR T_1 by the capacitor voltage $2V_{dc}$

A steady state current I_0 flows through V_{dc}^+ − L − T_1 − upper half of Pri wdg. − V_{dc}^-

$\therefore v_0 = V_{dc}$; $V_c = 2V_{dc}$; $i_0 = I_0$, $V_{T_1} = 0$; $i_c = 0$; $i_{T_1} = I_0$

Mode II :-

At t=0, SCR T_2 is triggered and comes to the ON state. The capacitor voltage $2V_{dc}$ is applied reverse bias across SCR T_1 and it comes to OFF state. Now the current path is V_{dc}^+ − L − T_2 − lower half of primary wdg. − V_{dc}^-



→ At the same time, commutating capacitor voltage $2V_{dc}$ is applied across the primary winding. Due to this, capacitor current i_c is established.

The capacitor current path C^+ − transformer primary winding − C^-.

→ Before SCR T_2 is ON state, i.e. at $t=0^-$, mmf in upper half of primary winding is I_0N_1 and zero in the lower half of primary wdg.. Soon after SCR T_2 is ON state i.e, at $t=0^+$, mmfs linking with both upper and lower halves primary wdg. It cannot change suddenly.

$\therefore$ At $t=0^+$, $i_1 = I_0$. At this condition, lower half mmf is zero and upper half mmf is equal to mmf at $t=0^-$

→ After $t=0^+$, commutating capacitor C discharges and current i_c is such that it supplies the load current i_0 equals the primary and secondary ampere turns of the transformer. Now the capacitor is charged to $-2V_{dc}$ at time $t=t_1$. The capacitor upper plate is -ve and lower plate is +ve ~~The capacitor is~~ fully charged. the ... current is zero i.e. $I = 0$

The current path is V_{dc}^{+} – L – T_2 – lower half of the primary wdg – V_{dc}^{-}

Mode III :-

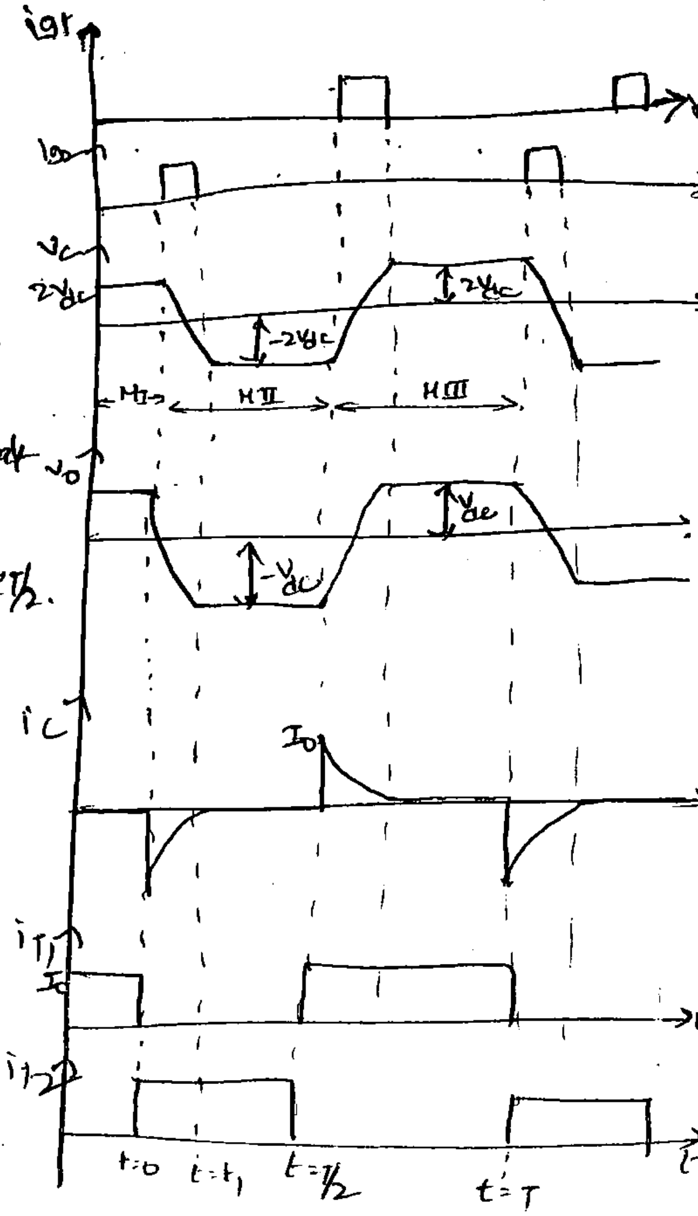
Now, the capacitor voltage is $-2V_{dc}$. SCR T_1 is F.B due to capacitor voltage. At $t = T/2$, SCR T_1 is triggered and it comes to the ON state. At the same time, SCR T_2 is turned OFF due to capacitor voltage i.e. the capacitor voltage act as reverse bias of the SCR T_2.

Now the load current path is

V_{dc}^{+} – L – T_1 – upper half of pri. wdg – V_{dc}^{-}

At the same time, capacitor is discharged through transformer. The capacitor current path is C^{+} – transformer primary wdg – C^{-}

The capacitor current i_c is +ve upper half mmf and lower half mmf remain unchanged from their values just before $T/2$.

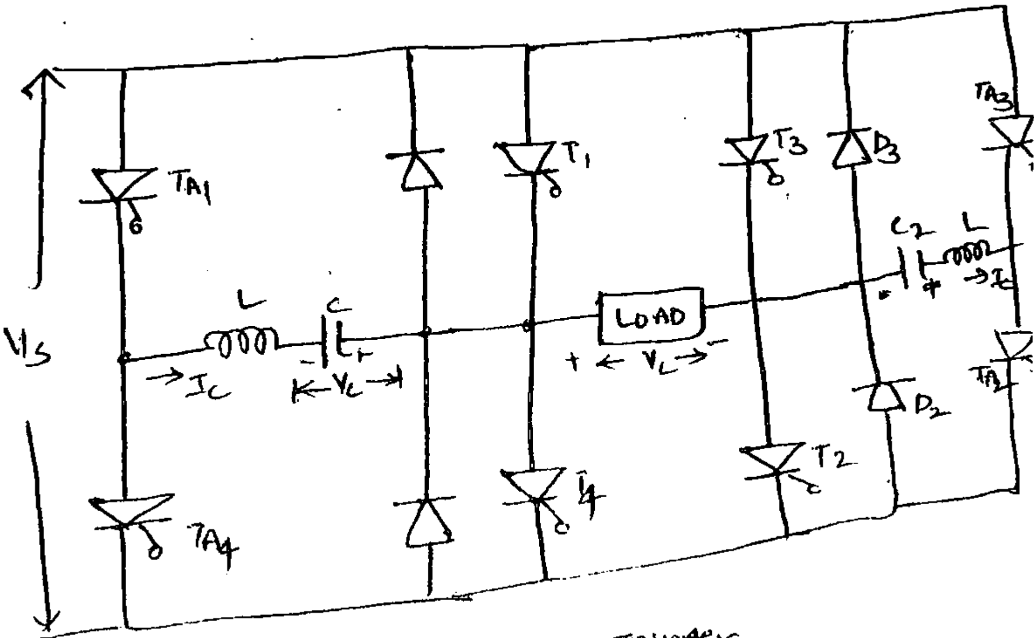


McMurray Inverter [Auxiliary commutated Inverter]

The McMurray inverter is an impulse commutated inverter which relies on an LC circuit and an auxiliary SCR for commutation in the load circuit. This commutation scheme was first reported by W. McMurray and therefore, it is called "MC Murray Scheme". It is also known as "auxiliary commutations scheme" because it requires an additional thyristor for the turning off of each main thyristor.

The circuit consists of the main SCRs. T_1, T_2, T_3 & T_4, the freewheeling diodes D_1, D_2, D_3 & D_4, the auxiliary SCRs TA_1, TA_2, TA_3 & TA_4 and the commutating components L and C. When the SCR pair T_1 & T_2 conducts, load is connected across the dc supply causing a positive voltage across the load. When SCR pair T_3 & T_4 conducts, a negative voltage is produced across the load. Thus, alternatively making the pair of SCRs to conduct, an alternating voltage is produced across the load.

→ In any inverter circuit, the commutating circuit has to be properly designed. The operation of the circuit will be described for a lagging P.f load with the following assumptions.



1-φ McMurray Inverter.

(i) Load current remains constant during the commutation interval.

iii) SCRs and diodes are ideal ...

Inductor L and capacitors are ideal in that they have no resistance.

Mode 1:-

This mode begins when the SCR pair T_1, T_2 is triggered when thyristors T_1, T_2 become turned ON, the supply current flows through the path $V_s^+ - T_1 - L_1 - T_2 - V_s^-$ and hence +ve load voltage V_L is obtained. The commutating capacitors C_1, C_2 are already charged to a voltage V_c.

Mode 2:-

This mode begins when SCRs TA_1, TA_2 are triggered to turn OFF the main SCRs T_1, T_2 which were conducting. When SCRs TA_1, TA_2 have been turned ON, capacitors C_1 & C_2 start discharging. Capacitor C_1 forms the discharging loop $C_{1+} - T_1 - TA_1 - L - C_{1-}$ and capacitor C_2 forms the discharging loop $C_{2+} - L - TA_2 - T_2 - C_{2-}$ and therefore, current I_c rises taking part of the load current from T_1, T_2. Voltage drop across T_1, T_2 reverse biases D_1, D_2. Current I_c can flow only through T_1, T_2 and not through D_1, D_2.

As load current I_L is constant, an increase in I_c causes a corresponding decrease in I_{T_1} & I_{T_2}.

At instant t_1, the capacitor current I_c rises to I_L and currents I_{T_1} & I_{T_2} become zero. As a result, main SCR T_1 & T_2 become turned OFF at time t_1.

After as resonant current I_c exceeds I_L, the excessive current $I_c - I_L = I_{D1} = I_{D2}$ circulates through feed back diodes D_1, D_2. The resonating oscillation continues through the path $C_{1+} - D_1 - T_{A1} - L - C_1$ & $C_{2+} - L - T_{A2} - D_2 - C_{2-}$ respectively. The voltage drop across D_1, D_2 R.B T_1, T_2 to bring it to forward blocking capability. The commutating current I_c rises to a peak value (I_{cp}) when the capacitor voltage (V_c) is zero, and then decreases as the capacitor is charged in the reverse direction. At time t_2, I_c falls back to the load current I_L and diodes D_1, D_2 stop conducting.

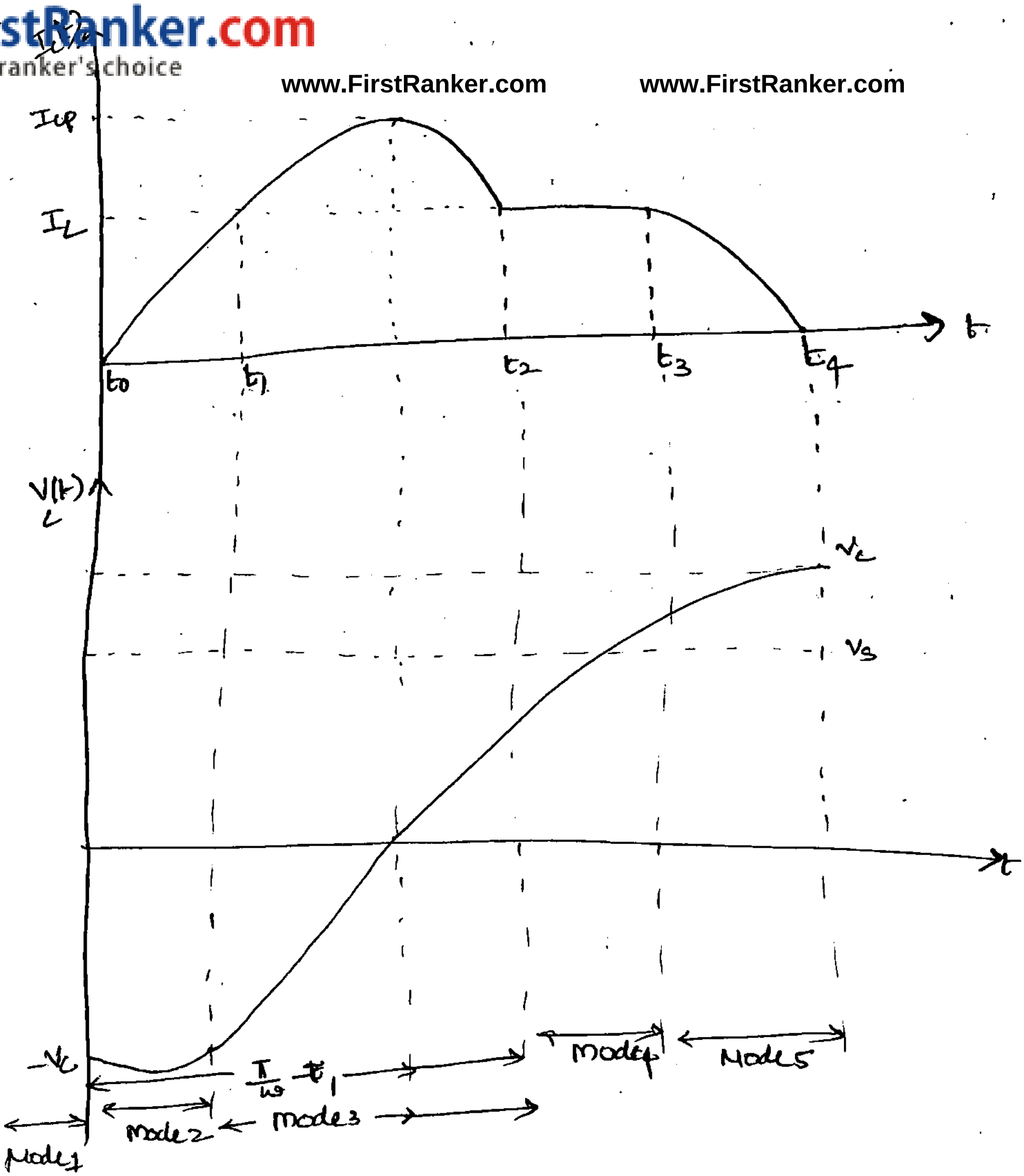
Mode 4 :-

This mode starts when diodes D_1 & D_2 stops conducting. The capacitor recharges through the load at an approximate constant current of I_L. This mode ends when the capacitor voltage becomes equal to the dc supply V_s at $t = t_3$ and tends to overcharge due to the energy stored in inductor L.

Mode 5 :

This mode starts when the capacitor voltage tends to be greater than V_s, and diodes D_4 & D_3 become F.B. The energy stored in L is transferred to the capacitor, causing it to be overcharged w.r.t the supply voltage V_s. This mode ends when the capacitor current falls again to zero and the capacitor voltage is reversed to that of original polarity and now the circuit is ready for the next cycle.

During the next half cycle, SCR pair T_3 & T_4 is triggered and -ve half cycle of voltage is produced across the load.

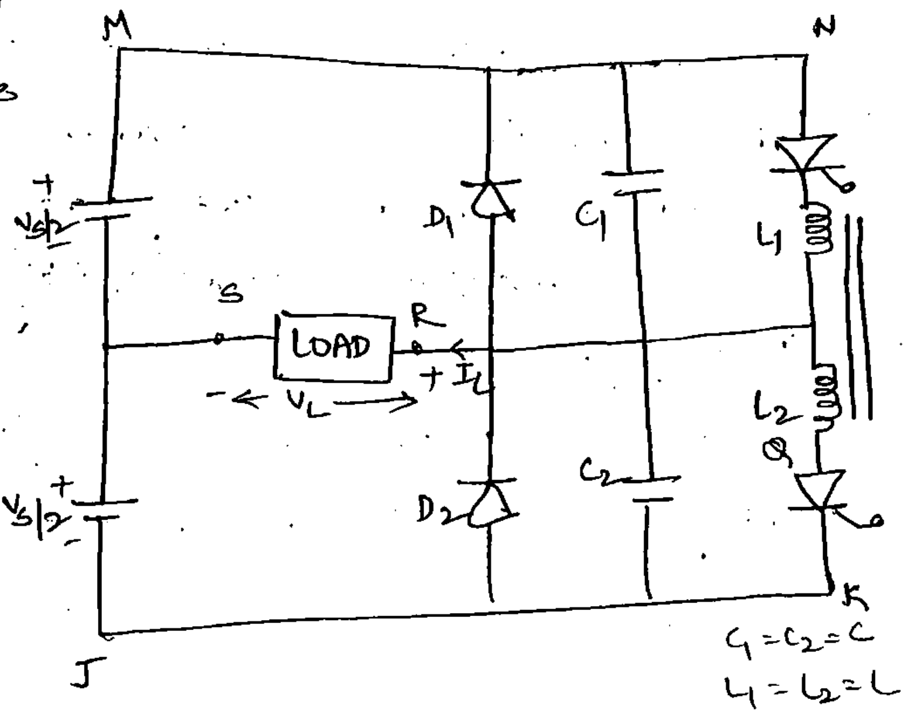


Voltage and current waveforms for 1-φ McMurray Inverter.

McMurray - BEDFORD HALF BRIDGE INVERTER [Complementary commutated Inverters]

Mc. Murray - Bedford Inverter is a complementary impulse commutated inverter. This means that if two inductors are tightly coupled, triggering of one SCR turns-off another SCR in the same arm.

This circuit configuration uses less no. of thyristors compared to the half bridge McMurray inverter. In this the number of inductors and capacitors are higher.



McMurray Bedford half bridge Inv.

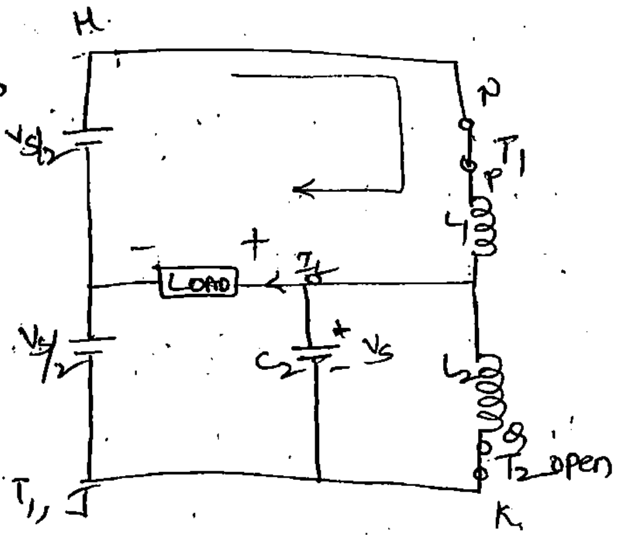
This circuit consists of main SCRs T_1, T_2, and feed back diodes D_1, D_2. commutation circuitry consists of two capacitors C_1, C_2 and magnetically coupled inductors L_1 & L_2 having the same inductance L and the same no. of turns. Inductors L_1 & L_2 are wound on a core with an air gap so as to avoid saturation. Values of these inductors are of the order of microhenries.

The simplifying assumptions for this inverter circuit are the same as for the McMurray inverter

... can be studied in different modes.

Mode 1 :- This mode starts when SCR T_1 is triggered.

when SCR T_1 is turned on, upper de source supplies load current I_L to the load. As the load current is almost constant, Voltage drop across commutating inductance $L_1 \left(= L_1 \frac{di}{dt}\right)$ is negligible.

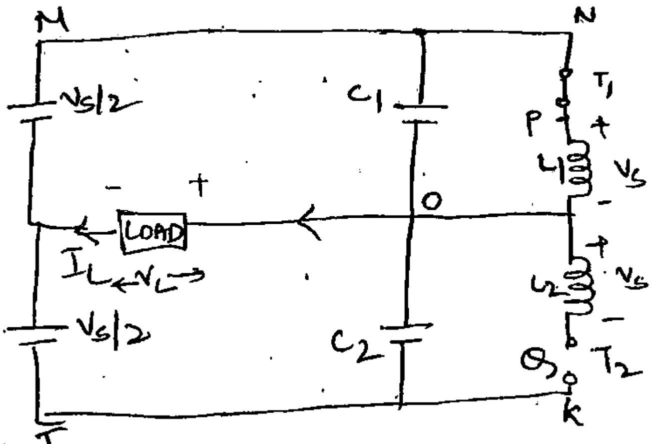


With zero voltage drop across L_1 & T_1, Voltage across C_1 is zero and voltage across C_2 is V_s. The potential of all the three nodes O, P, Q w.r.t J is V_s.

Mode 1 before t=0

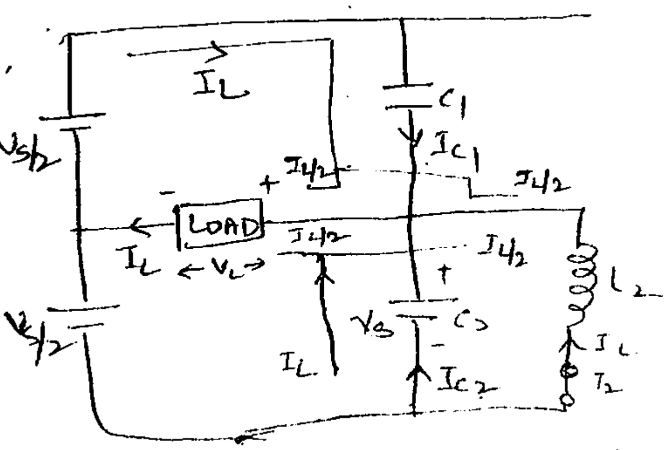
Mode 2 :-

This mode starts when SCR T_2 is triggered (at instant t=0) to turn off the SCR T_1 which was conducting. When SCR T_2 is turned on, node Q gets connected to K to J i.e., to the -ve supply terminal.



Mode 2 before t=0

Since the voltage across C_1 & C_2 cannot change instantaneously, a voltage V_s appears across L_2.

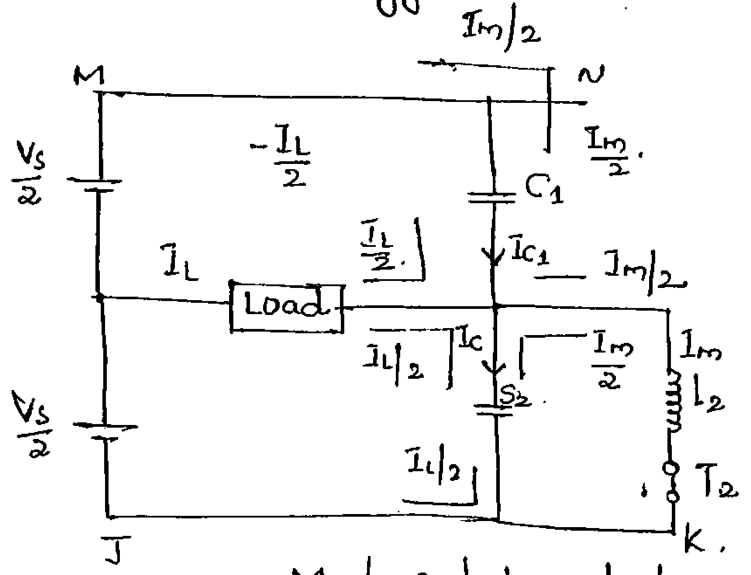


→ As inductors L_1 & L_2 are magnetically coupled, an equal Voltage is induced across L_1 with point P positive. Voltage V_{T_1} across SCR T_1 can be found by applying KVL to the loop NMJKQPN

Mode 2 before t at

$$V_{T_1} = V_{NP} = -\frac{V_s}{2} - V$$

...d current which was flowing through SCR T_1 & L_1, now transfers to winding L_2 and SCR T_2 in order to maintain energy stored in inductance.

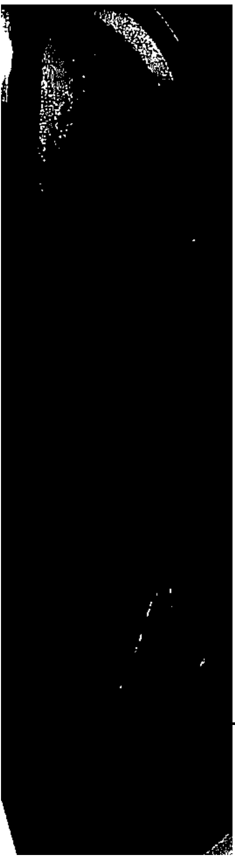


Mode 2 before $t < t_1$.

Mode 3: This mode begins at instant t_1, where capacitor C_1 is charged to supply voltage V_s and therefore no current can flow through C_1 i.e., $I_{C_1} = 0$. After one-fourth of a cycle from $t=0$ i.e., at t_1, $V_{C_2} = 0$.

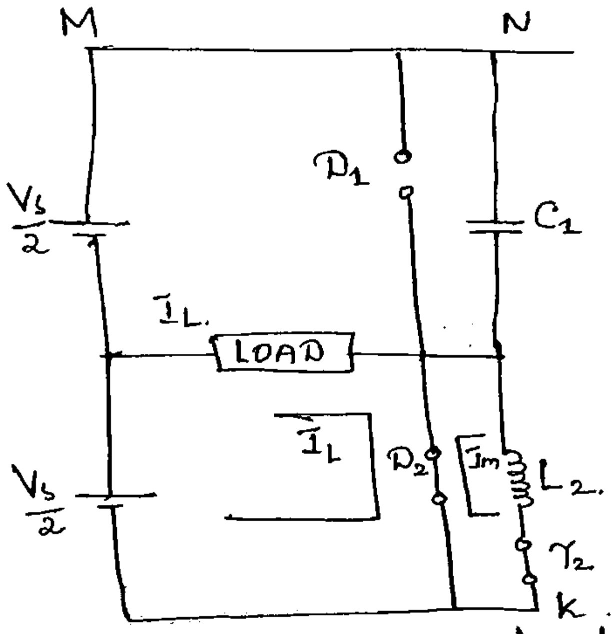
Just after t_1, current $\left(\frac{I_L + I_m}{2}\right)$ through C_2 tends to charge it with bottom plate +ve. ∴ at t_1, diode D_2 gets forward biased. Thus now entire current $(I_L + I_m)$ is transferred to diode D_2 so that both capacitive currents become zero $(I_{C_1} = I_{C_2} = 0)$ just after t_1 as shown in figure. Diode current $I_{D_2} = I_0 + I_m$ is also shown in figure.

At instant t_1, energy stored in inductor L_2 is dissipated in closed circuit I_{T_2} decays to zero and as a result, thyristor T_2 is turned off at t_2 as shown in figure. To speed



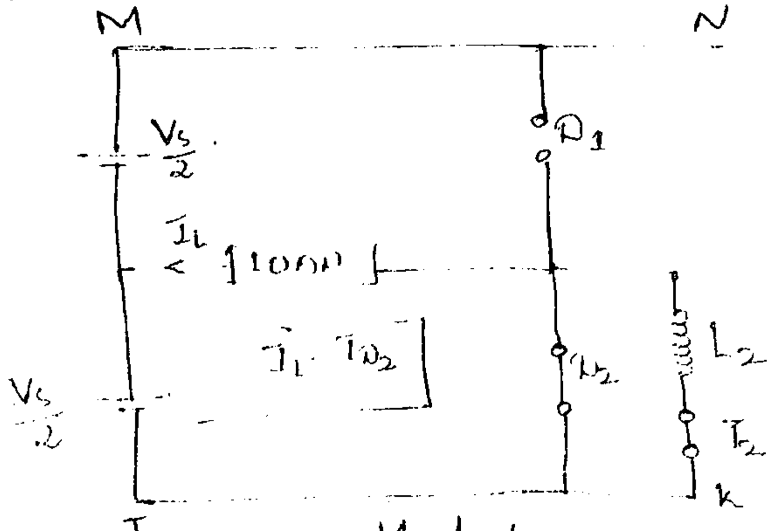
up dissipation of stored energy is L_2, a small resistance is placed in series with diode D_2.

As I_{T_2} decays from I_m at t_1 to zero at t_2, I_{D_2} also decays from $(I_L + I_M)$ at t_1 to $i_L = UV$ at t_2.



Mode 3 at t_1.

Mode 4: When current I_{T_2}, through L_2 and T_2 has decayed to zero, equivalent circuit is as shown in figure. A load current $I_L = I_{D_2}$ still continues flowing through diode D_2 as I_{D_2} during $(t_3 - t_2)$ interval as shown in figure.



Mode 4.

Finally, load current I_L through diode D_2 and load decays to zero at t_3 and is then reversed. As soon as i_L, equal to I_{D_2} tends to reverse diode D_2 is blocked. The R.B. across SCR T_2 due to voltage drop in diode D_2 no longer exists. ∴ SCR T_2 already gated during interval $(t_3 - t_2)$ gets turned on to carry load current in reversed direction as shown in figure.

The magnitude of commutating circuit parameters L and C, for minimum trapped energy, is given by

$$\boxed{L = 2.35 \frac{V_s \cdot t_q}{I_{LM}}}$$

and $$\boxed{C = 2.35 \frac{I_{LM} t_q}{V_s}}$$

where t_q = SCR turn-off time.

I_{LM} = maximum load current to be commutated.

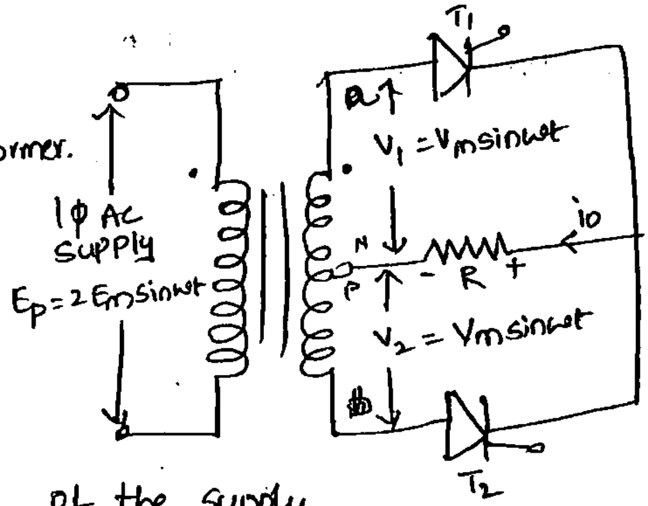
UNIT - IV

SINGLE PHASE FULLY CONTROLLED CONVERTERS

→ Depending upon the type of SCR configuration, 1-ϕ Full wave controlled rectifiers are classified into two types. They are (i) Mid point type converter
(ii) Bridge type converter.

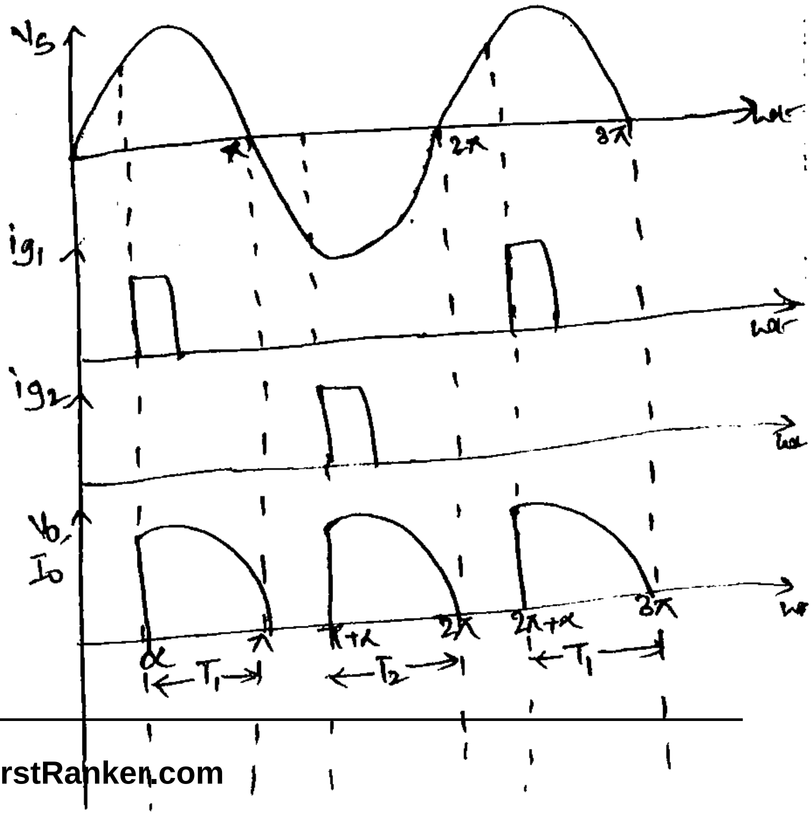
1-ϕ Full wave controlled rectifier with mid point type :- For R Load

It consists of two SCRs and a centre tapped transformer. These converter is also known as two pulse converter because two triggering pulses are to be generated during every cycle of the supply.



→ Generally, these rectifiers are used for low ratings.

→ The input signal is coupled through the transformer to the centre tapped secondary.



Assume that the leakage current of transistor T_1 and T_2 to be negligible small, we have

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

→ If $(\alpha_1+\alpha_2) = 1$, the value of anode current becomes infinite, i.e., the anode current suddenly attains a very high value, approaching infinity. (or) In other words that the device suddenly latches into conduction (ON) state from the non conduction (OFF) state. This characteristic of the device is known as its regenerative action.

The operational differences between thyristor family and transistor family of devices are

(i) once a SCR is turned on by a gate signal, it remains latched in ON state due to internal regenerative action. For a transistor must be given a continuous base signal to remain in on state.

(ii) In order to turn off a thyristor, a reverse voltage must be applied across its anode cathode terminals. However, a transistor turns off when its base signal is removed

THYRISTOR TURNOFF PROCESS:

Thyristor turn off process is a process where the SCR transfers its state from ON state to OFF state. This is also known as commutation process.

Commutation may be of two types:

1. Natural or line commutation
2. Forced commutation.

Natural commutation:-

→ It is a turnoff process where the SCR gets into the OFF state whenever the supply voltages passes through natural zero. ~~This~~ whenever Additional commutation circuitry is not reauired, whenever an A.C i/p is given this may be obtained.

→ This type of commutation process is used in A.C voltage regulators, step down cycloconverters, class F commutation.

Forced commutation:-

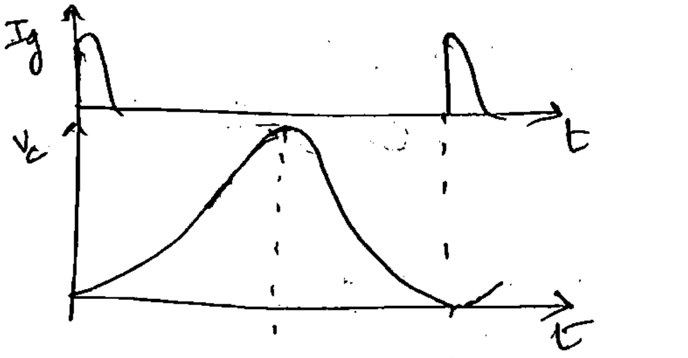
→ It is a turnoff process where the SCR gets into the turnOFF state whenever the current flowing through the SCR is made zero for sometime by using external devices.

→ The commutating elements generally employed are inductor and capacitor. This type of commutation process is used for D.C i/p circuits.

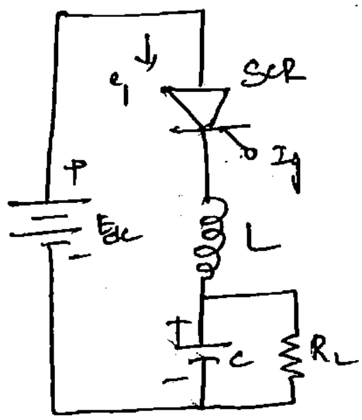
→ Forced commutation may be classified into different methods depending upon the way in which the current through the SCR becomes zero.

A - Self Commutation by Resonating the Load :-

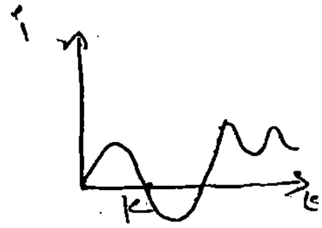
→ It is also known as Resonant commutation and is obtained by L-C circuit in series with the load.



voltages and currents in class A [Load is parallel with capacitor]



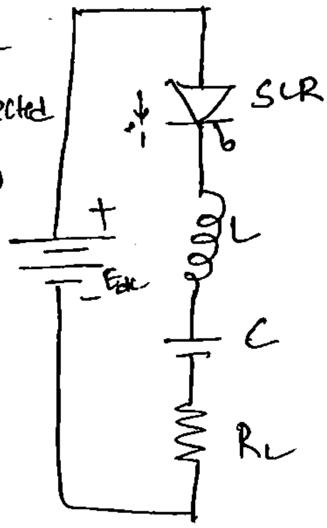
Load in parallel with capacitor



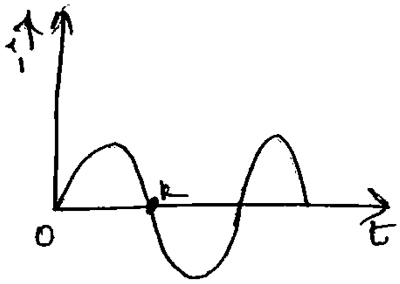
current produced in parallel capacitor

→ In this process of commutation, the forward current passing through the device is reduced to less than the level of holding current of the device. Hence, this method is also known as the current commutation method.

→ The Load Resistance R_L and the commutating components L & C are selected that their combination forms an underdamped resonant circuit.



Load in series with capacitor



waveform of the current produced in series capacitor

Operation :-

→ when the circuit is excited by a D.C source and the SCR is triggered, the SCR carries only the charging current of capacitor C. This charging current decays to a value which is less than the holding current ~~of the device, the 'C' gets charged to the supply voltage E_{dc}~~

This simultaneously switches

→ Beyond point 'k', the current is reversed in nature which assures definite commutation of the device.

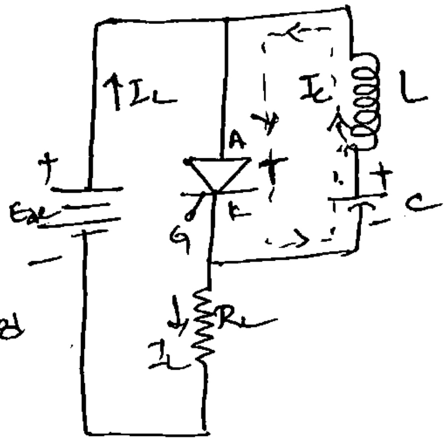
→ The time for switching off the device is determined by the resonant frequency which in turn depends on the values of the commutating components L and C and the total load resistance.

→ This is most suitable for high frequency operation i.e. above 1000 Hz.

Applications) series Inverter.

class B commutation :-

→ It is a self commutation process by an LC circuit. The resonating LC circuit is connected across the SCR but not in series with load. It is also known as resonant pulse commutation.



Mode 1 :-

Initially whenever source voltage E_{dc} is applied to the commutation circuit the capacitor 'c' gets charged to the supply voltage E_{dc} ~~with~~ ~~upper plate state~~

→ charging of capacitor is done like this

$$E_{dc+} - L - C_+ - C_- - E_{dc-}$$

Mode 2: when gate pulse is given to the circuit two currents flow in the circuit (i) load current i_L (ii) capacitor discharging current (I_C)

The load current I_L follows the path $E_{dc}^{+} - T - R_L - E_{dc}^{-}$

During this ON period of the thyristor 'T' capacitor gets discharged through the path $C_+ - L - T - C_-$

Mode 3:-
when the capacitor 'C' becomes completely discharged its polarity gets reversed. Due to the reverse voltage across the capacitor the commutating current develops. Now the commutating current I_C must follow the path ~~[illegible]~~

$C_+ - T - L - C_-$. It opposes the load current I_L.

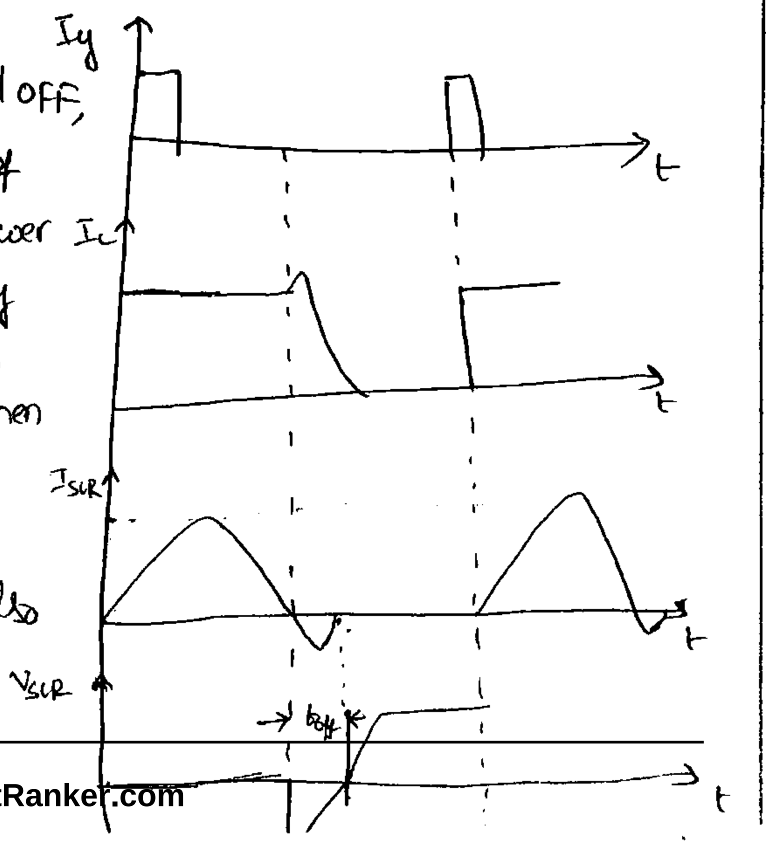
→ SCR is a unidirectional device, it does not allow the commutating current to flow through it.

→ whenever the commutating current I_C becomes more than the load current I_L the SCR gets turned OFF.

Net forward current is $I_{T_1} = I_L - I_C$

Mode 4:-
Again when the thyristor gets turned OFF, the capacitor charges to a voltage of E_{dc} with upper plate +ve and lower plate -ve. Thus, when it is fully charged the thyristor will be again in forward blocking state and when it is triggered it gets into the turn ON state.

→ Class B commutation process is also a self commutation process.



Applications:- DC chopper circuits.

Complementary Commutation :-

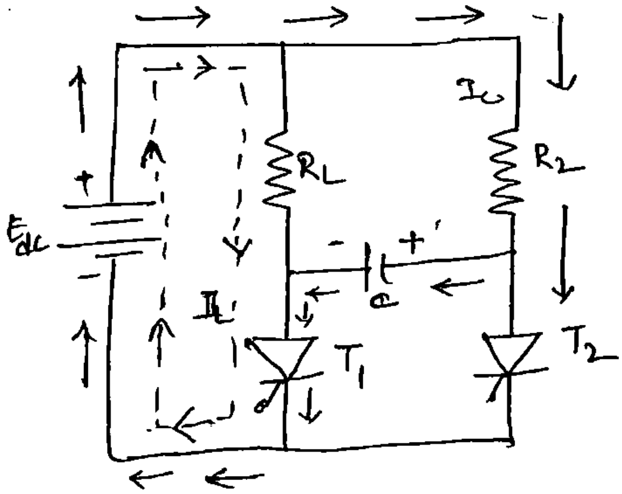
→ It is also known as complementary commutation process as the commutation of the main thyristor occurs due to turn ON of auxilary Thyristor (T_2)

Circuit description:-

It consist of main thyristor T_1 and an auxilary thyristor T_2. Here, the commutating components are the capacitor 'C' and an thyristor T_2.

→ It consists of R_L (load Resistance) placed in series with the main thyristor (T_1) and the resistor R. The thyristor 'T_2' is connected in parallel to the thyristor T_1.

Mode 0 :- Initially, the thyristors T_1 & T_2 are in the OFF state and the voltage across the capacitor is zero.



$T_1 \rightarrow$ OFF and $E_c = 0$
$T_2 \rightarrow$ OFF

Mode 1:-

T_1 gets triggered when the triggering pulse is given to it. Hence, when the thyristor is in the ON state the two currents will flow

1. Load current I_L and
2. charging current I_c

$$I_L \rightarrow E_{dc}^{+} - R_L - T_1 - E_{dc}^{-}$$

$$I_c \rightarrow E_{dc}^{+} - R_2 - C_{+} - C_{-} - T_1 - E_{dc}^{-}$$

Now, the capacitor 'c' gets charged to the supply voltage E_{dc}

$T_1 \rightarrow$ ON state and $E_c = E_{dc}$
$T_2 \rightarrow$ OFF state

19

whenever a triggering pulse is given to T_2 it gets into the conduction state. As soon as the T_2 attains the conduction state the reverse voltage will be applied across the thyristor T_1 as the -ve polarity of the capacitor gets connected to anode of the thyristor and +ve polarity of the capacitor gets connected to the thyristor (T_1) cathode terminal.

→ In this way the commutation of the main thyristor (T_1) by using auxiliary thyristor (T_2) occurs.

Now, the charging path of the capacitor is given as

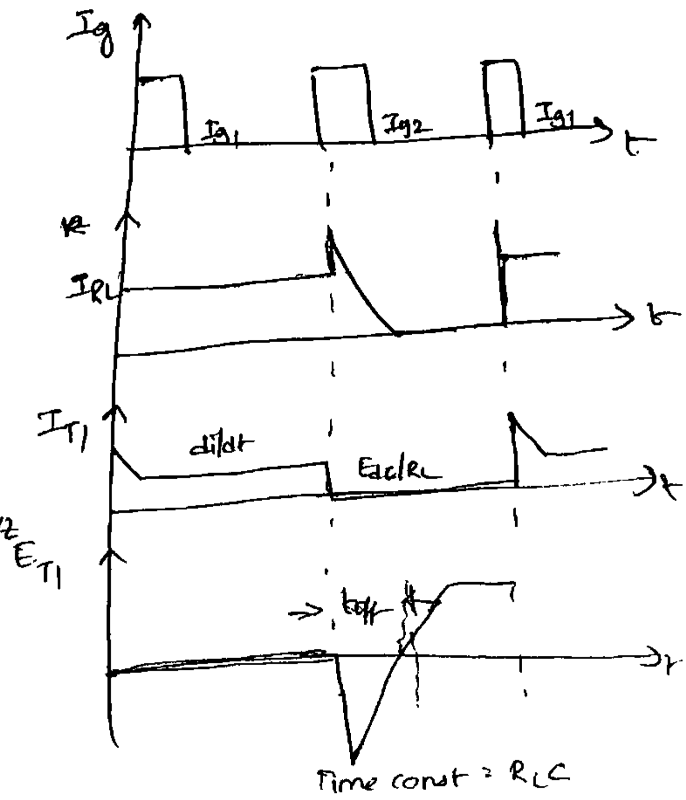
$$E_{dc}+ - R_L - C_+ - C_- - T_2 - E_{dc}-$$

→ Polarity of the capacitor 'c' gets reversed

$T_1 \rightarrow$ OFF state
$T_2 \rightarrow$ ON state
$E_c \Rightarrow -E_{dc}$

Mode 3:- Now, again when thyristor T_1 is triggered, T_2 gets turned OFF

$T_1 \rightarrow$ ON state
$T_2 \rightarrow$ OFF state
$E_c \rightarrow E_{dc}$



→ This type of commutation is very useful for the frequencies below 1kHz

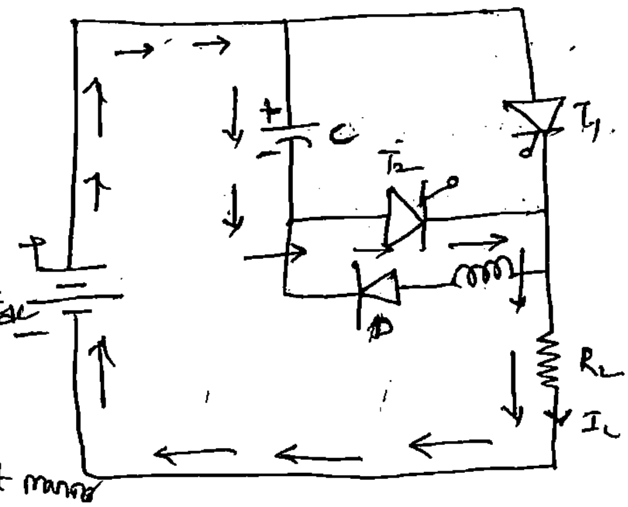
→ Application:-

MC. Murray bed ford inverter.

Class D commutation:

→ It is also known as Impulse commutation, voltage commutation, auxiliary commutation and parallel capacitor commutation.

Circuit description:



→ It consists of main thyristor T_1 and an auxiliary thyristor T_2, inductor L and diode D. The power circuit consists of the main thyristor T_1 and the load Resistance R_L. Inductor L is introduced in order to ensure the polarity of the capacitor 'c' in a correct manner.

operation :-

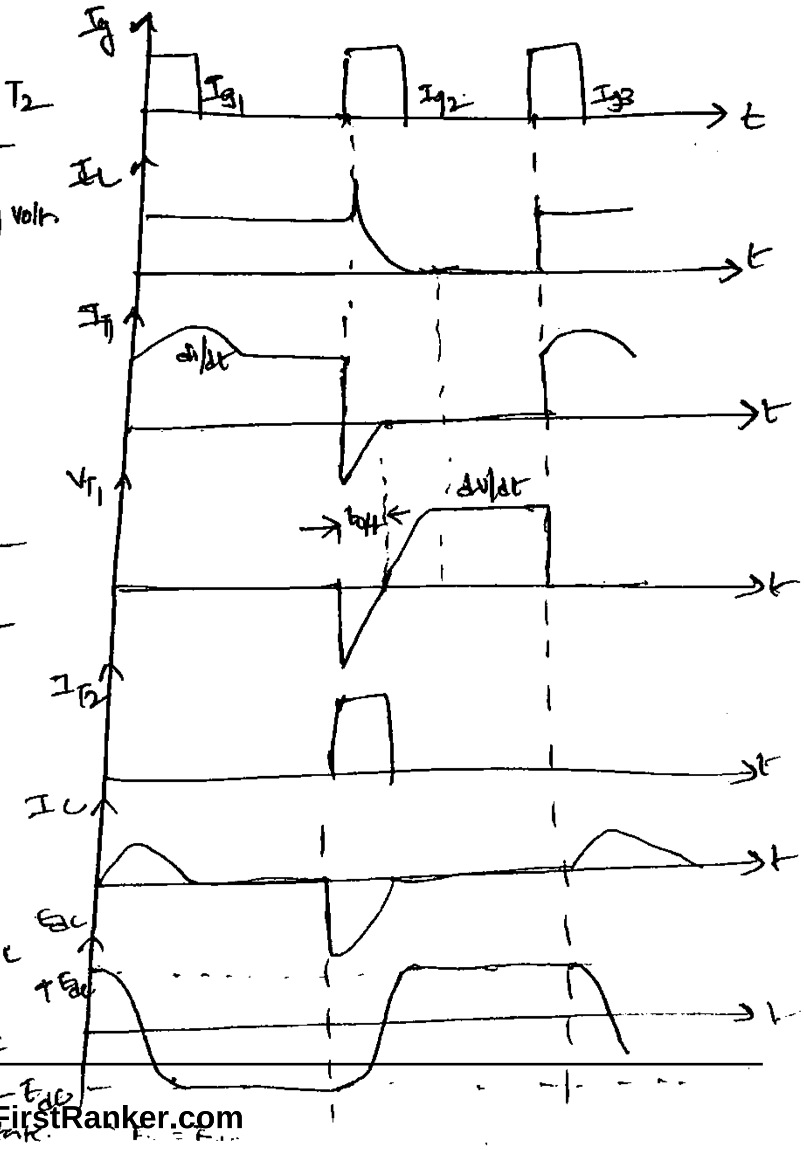
Mode 0 :-

Initially the thyristors T_1 & T_2 are in the off state, no current flow is observed through the supply volt.

T_1 — OFF State

T_2 — OFF State

$E_c = 0$



Mode 1 :- Inorder to charge the capacitor 'c' to a voltage of E_{dc} initially auxiliary thyristor T_2 is triggered. The capacitor gets charged as follows

$E_{dc}^{+} - C^{+} - C^{-} - T_2 - R_L - E_{dc}^{-}$

→ $V_c \uparrow$ $I_{T_2} \downarrow$

→ whenever C is fully charged the ~~auxiliary thyristor T_2 gets turned OFF~~

T_1 — OFF

T_2 — OFF

Initially T_1 — ON state

The current flows in the two different paths whenever the main thyristor T_1 is triggered.

a) I_L path

$$E_{dc}^{+} - T_1 - R_L - E_{dc}^{-}$$

b) Commutation current

$$C^{+} - T_1 - L - D - C^{-}$$

→ whenever 'c' gets completely discharged, its polarity will be reversed. Discharging of capacitor 'C' in reverse direction is not possible due to the presence of blocking diode D

Mode 3:—

→ capacitor starts discharging through the path $C_{+} - T_2 - T_1 - C -$ whenever the auxiliary thyristor T_2 is triggered

→ $I_{C T_1} > I_L$ → T_1 gets turned OFF

T_1 — OFF
T_2 — ON   same repeated as

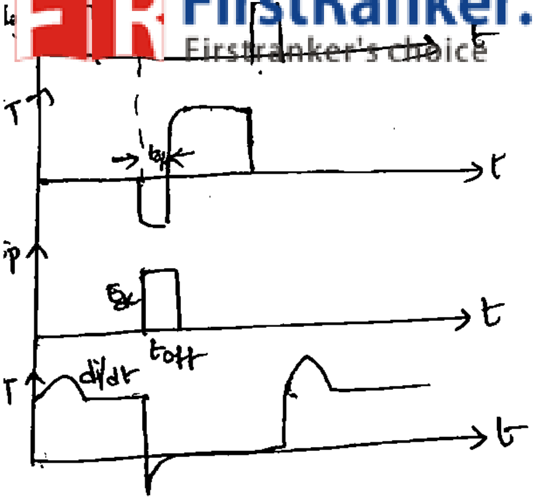
Application:- Jones chopper circuit.

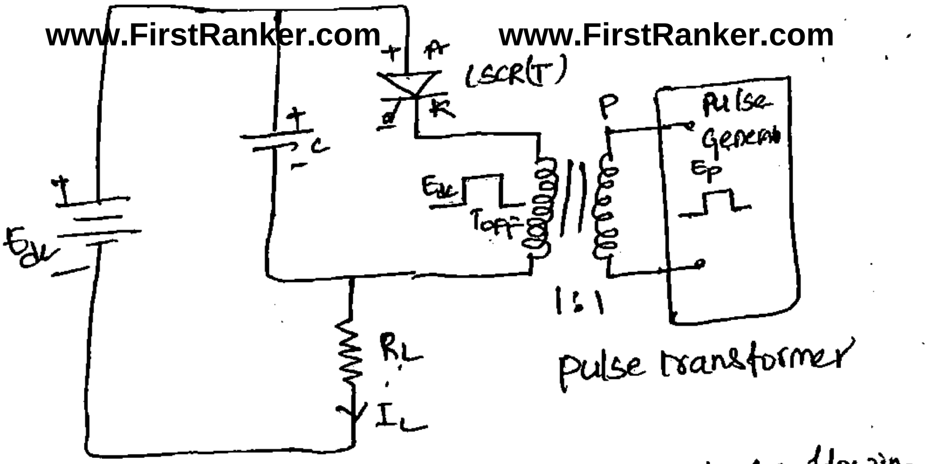
CLASS E commutation:- (or) External pulse commutation.

→ The reverse voltage is applied to the current carrying SCR by using an external pulse supply. There should be a tight coupling b/w the primary and secondary of the pulse transformer.

→ The commutating pulse is applied to the circuit by using pulse transformer externally.

→ whenever the commutation of the thyristor T is required the pulse duration equal to or slightly more then the turn OFF time ~~or according to commutation time specifications is required.~~





Mode 0:-

Whenever the SCR (T) is triggered, the current starts flowing through the pulse transformer and the load Resistance R_L

$$E_{dc}^{+} - T - P.T - R_L - E_{dc}^{-}$$

Mode 1:-

→ whenever a pulse of magnitude E_p is applied across the primary of the P.T, the voltage gets induced in the secondary of the P.T. This induced voltage appears as a reverse voltage $-E_p$ across the thyristor T and hence it gets turned OFF.

→ T – off → I_L = zero

→ Here, as the pulse introduced is of high frequency, the impedance offered by capacitor is almost negligible

$$X_C = \frac{1}{2\pi f_c} = \frac{1}{0} = \infty$$

commutation :- (or) A.C line commutation

→ In this type of commutation process the supply voltage given is an alternating one. Applying the gate signal for the T_1 the SCR comes into the conduction state.

→ At the instant $\omega t = \pi$, supply voltage is zero, load voltage is zero. current flowing through the SCR is reduced to zero.

→ The load current can be seen only during the +ve half cycle. During the negative half cycle of the supply voltage, the SCR will be turned OFF due to the negative polarity across it, $I_L = 0$

Necessary condition:-

The duration of the half cycle should be more than the commutation period of SCR. The max. possible frequency with which this circuit can be operated is determined by the commutation period of SCR.

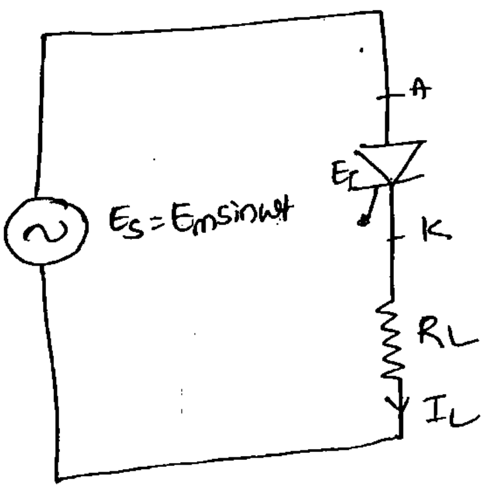
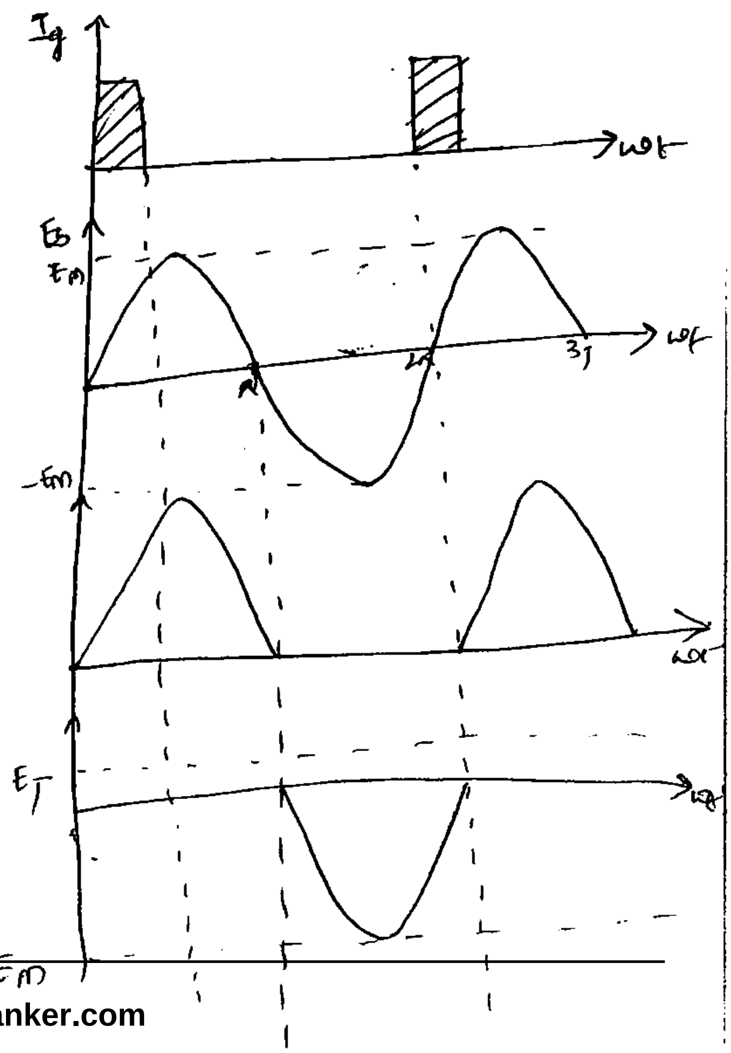


fig (a)



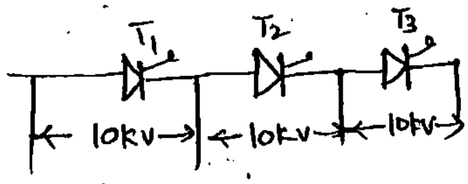
Series operation of SCRs :-

→ The maximum power which can be controlled by the SCR is determined by its rated forward blocking voltage, and by its rated current. Today SCR with voltage and current rating of 10kV and 3.5 kA are available in market.

Series connection :-

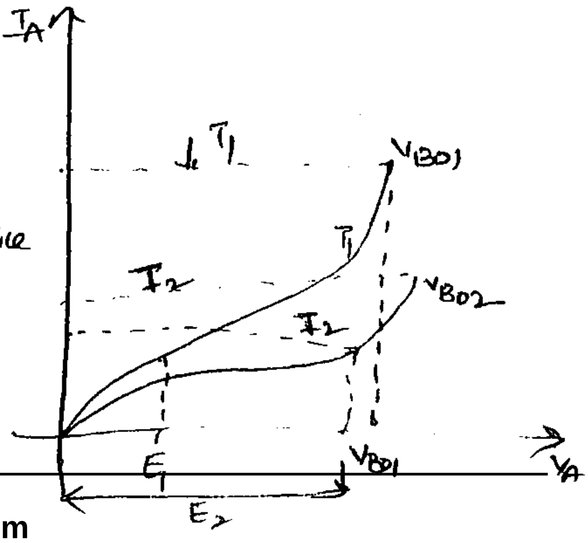
For high voltage applications ; two or more SCR's are connected in series, to increase the voltage rating.

For example in a HVDC n/w, the voltage that should be blocked should be 30 kV. A single SCR cannot block 30kV. so, three SCR's are connected in series to block the 30kV.



Series operation of the SCR's :-

The thyristors of the same class (current rating, voltage rating, manufactured by the same company) are to be connected in series in the series operation of SCRs. The static V-I characteristics of SCRS of the same type are not identical.

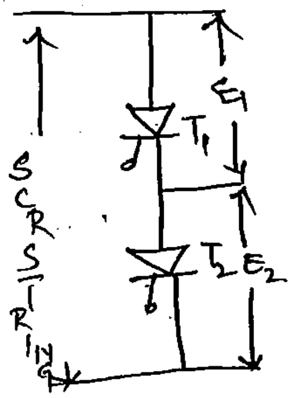


→ The problems that may arise due to the series connected SCR's are

1. Unequal voltage distribution across the device
2. Difference in the reverse recovery characteristics.

Unequal Voltage distribution

Let us consider two SCR's connected in series. Even though the two SCRs are connected in series, they don't have the same static V-I characteristics of the SCR. V_{BO_1}, V_{BO_2} are the forward break over voltages of T_1 & T_2 respectively.



→ For the same amount of leakage current I_o, the leakage resistance for T_1 is $\left(\frac{E_1}{I_o}\right)$

The leakage resistance for T_2 is $\left(\frac{E_2}{I_o}\right)$

$$\text{i.e., } R_1 = \frac{E_1}{I_o}, \quad R_2 = \frac{E_2}{I_o}$$

→ The SCR(T_1) will block less voltage (E_1) and SCR(T_2) will block rated voltage (E_2), because leakage resistance is high. The rated voltage that each SCR should block is E_2.

String efficiency :-

It is the measure of the degree of utilization of SCR's in a string. This ratio is always less than one.

$$\%\eta = \frac{\text{Actual voltage / current rating of whole string}}{[\text{Individual voltage / current rating of one SCR}]\,[\text{no. of SCRs in string}]}$$

De-rating Factor :- The measure of the reliability of the string is given by a factor called derating factor (DRF)

$$DRF = 1 - \text{String efficiency}.$$

→ If DRF is more, the no. of devices used in the string will be more and increases the reliability of the string.

string η in the case of series connection string, for two SCRs

$$\eta = \frac{E_1 + E_2}{2E_2} \leq 1$$

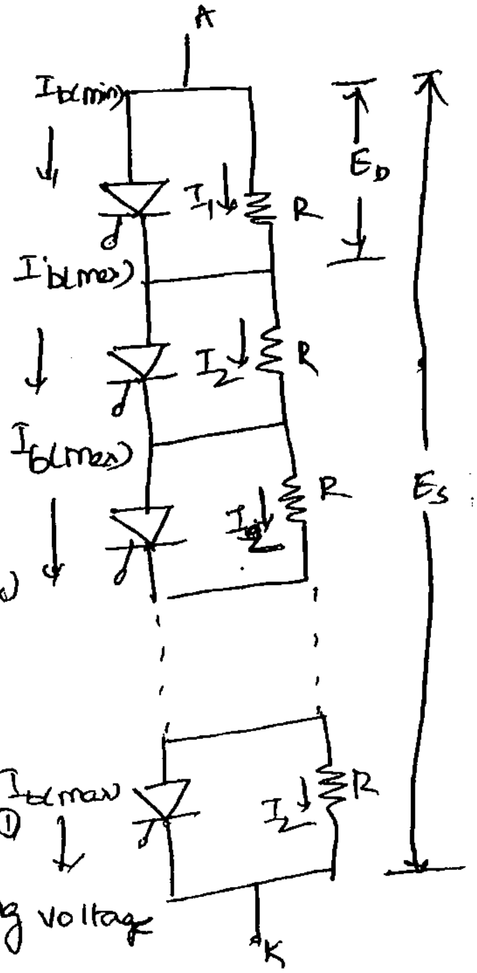
→ The reason for the unequal voltage distribution across the SCRs is the leakage resistance. An external resistance should be connected in parallel, so that, the parallel combination will have the same resistance. This is known as static equalizing network.

Static Equalizing network :-

In order to have uniform voltage distribution, different values of resistance are selected, so that

$$[(\text{Junction Resistance}) \times R_1] \text{ of } T_1 = [(\text{Junction Resistance}) \times R_2] \text{ of } T_2$$

→ But in practical application, same value of (R) is selected in order to have uniform voltage distribution



Let n_s → no. of SCRs connected in string.
E_D → Voltage drop across the resistance (R)

→ Range of blocking current is defined as $I_{b(max)} - I_{b(min)} = \Delta I_b$.

→ The current flowing through the SCR T_1 is $I_{b\,min}$, and remaining SCRs is ($I_{b\,max}$)

$$I_{b(min)} + I_1 = I_{b(max)} + I_2$$

$$I_{b(max)} - I_{b(min)} = I_1 - I_2 = \Delta I_b \quad -①$$

Let E_D be the maximum permissible blocking voltage

Then $E_D = I_1 \times R$ — ②

For the whole string, $E_s = E_D + (n_s - 1) R \cdot I_2$ — ③

$I_2 = I_1 - \Delta I_b$

Take T_1 has the fastest recovery and the remaining thyristor (n_s-1) will have the slowest recovery.

Let ΔQ_{max} be the maximum permissible difference of the reverse recovery charge of SCRs

Let ΔE_{max} be the maximum permissible difference in voltage

$$\Delta E_{max} = \frac{\Delta Q_{max}}{C} \qquad \left[\because C = \frac{q}{V}\right]$$

Let us take, E_D as the permissible voltage for the fast recovery SCRs (T_1), then the voltage across the (n_s-1) SCR will be $(E_D - \Delta E_{max})$

$\therefore$ String voltage, $E_s = E_D + (n_s-1)(E_D - \Delta E_{max})$

$$= E_D + n_s E_D - n_s \Delta E_{max} - E_D + \Delta E_{max}$$

$$E_s = n_s E_D + \Delta E_{max} - n_s \cdot \Delta E_{max}$$

$$n_s \Delta E_{max} - \Delta E_{max} = n_s E_D - E_s$$

$$\Delta E_{max}(n_s - 1) = n_s E_D - E_s$$

$$\frac{\Delta Q_{max}}{C}(n_s-1) = n_s E_D - E_s$$

$$\therefore C \geq \frac{(n_s-1)\Delta Q_{max}}{n_s E_D - E_s}$$

Parallel operation of thyristors

→ Thyristors are connected in parallel, whenever the load current demanded is more than the single current rating of an SCR. Then SCRs are said to be connected in Parallel.

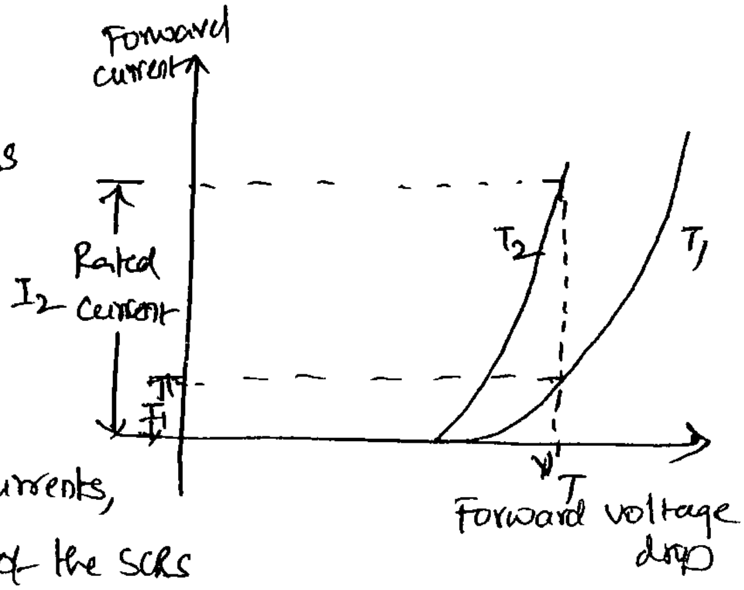
→ SCRs can be connected in Parallel, if they have the same forward voltage drop characteristics.

→ Let us take 2 SCRs T_1 and T_2. Even though the two SCRs are of the same rating, they do not have the same forward voltage drop characteristics. For the same forward voltage drop V_T, T_1 carries a current of I_1 and T_2 carries a current of I_2.

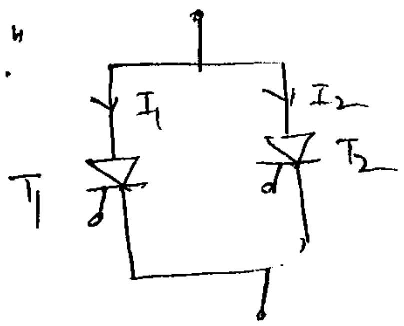
→ Let us take I_2 as the rated current of each SCR. Therefore T_2 carries rated current, while T_1 carries less than the rated current.

∴ The string efficiency in the case of parallel connected SCRs is

$$\eta = \frac{I_1 + I_2}{2I_2} < 1$$



→ The unequal distribution of currents, in the parallel connection of the SCRs leads to the problem of "Thermal Runaway."



Thermal Runaway :-

→ Let us take SCR (T_2) carries rated current (I_2) which is greater than I_1. when large current flows through T_2, its power dissipation ($I_2^2 \times R_{jun.Res}$) will be more. This leads to raising of the temp. in the junction. semiconductor, switching devices will have "-ve ~~temp~~ coefficient of Resistance".

→ with the increase in temp., the junction resistance of T_2 is reduced. The current flowing through the SCR (T_2) increases. This becomes a repetitive process and the SCR (T_2) gets damaged.

Remedy :-

→ In order to maintain the same temperature, SCRs must be placed in heat sinks. when they are connected in parallel.

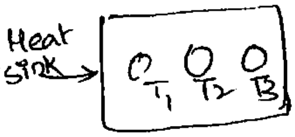
There are two types of heat sinks

a) Unsymmetrical Arrangement
b) Symmetrical Arrangement.

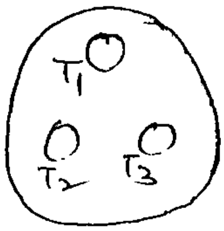
→ In the unsymmetrical Arrangement, whenever the SCRs are carrying the rated current, there will be fluxes produced in the current carrying conductors. There are two types of flux linkages

a) Internal flux linkages b) External flux linkages

→ The middle SCR (T_2) will have both type of linkages and the inductance of T_2 is high [$\because L = \frac{N\phi}{I}$]



Unsymmetrical



Symmetrical

∴ The current flowing through the SCR's (T_2) is reduced. This leads to the unequal distribution of current in the unsymmetrical arrangement.

→ ~~This problem can be eliminated by using symmetrical~~ arrangement of heat sinks

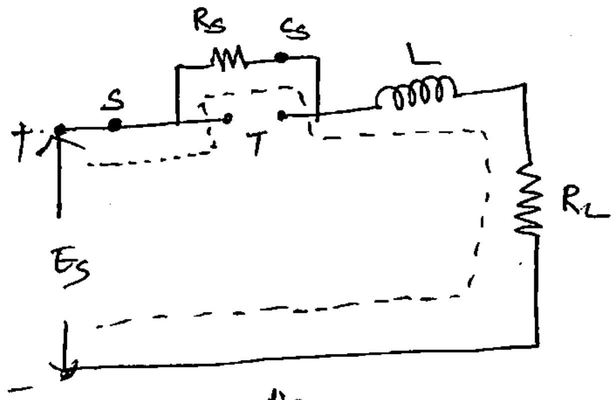
→ When the SCR is turned 'ON' by gate pulse the capacitor which is charged to a voltage of E_S will discharge through SCR and the current is given by

$$i_s = \frac{E_S}{R_T}$$

R_T → Resistance offered by the thyristor during forward conduction state.

→ This current can be set to a safe value by keeping a resistance R_S in series with the capacitor C_S.

→ When the switch S is closed, capacitor behaves as a short circuit and SCR is in forward blocking state.



eq. ckt after closing the switch

Applying KVL to the closed path

$$E_S = i_s (R_S + R_L) + L\frac{di}{dt}$$

This is the first order linear differential eq. The solution of the circuit current at any instant is given by

$$i = I\left(1 - e^{-t/\tau}\right) \quad \text{—(1)} \quad \text{where } I = \frac{E_S}{(R_S + R_L)}$$

Time constant $\tau = \frac{L}{(R_S + R_L)}$

t = time in secs measured from the instant of closing the switch.

Differentiate eq. (1) w.r.t time

$$\frac{di}{dt} = \frac{1}{\tau}\left[I e^{-t/\tau}\right]$$

$$= \left(\frac{E_S}{R_S + R_L}\right)\frac{1}{\tau} e^{-t/\tau}$$

$$\frac{di}{dt} = \frac{E_S}{(R_S + R_L)} \cdot \left(\frac{R_L + R_S}{L}\right) e^{-t/\tau}$$

$$\therefore \frac{di}{dt} = \frac{E_S}{L} e^{-t/\tau}$$

Calculation of L:-

At $t = 0$, $\frac{di}{dt}$ is max

Hence, $\frac{di}{dt}\Big|_{max} = \frac{E_s}{L}$ — ②

$$L = \frac{E_s}{\left(\frac{di}{dt}\right)_{max}}$$

Calculation of R_s :-

Voltage across the SCR may be given as

$$E_t = R_s \cdot i$$

differentiating w.r.t time, we get

$$\left(\frac{dE_t}{dt}\right)_{max} = R_s \left[\frac{di}{dt}\right]_{max}$$

From eq. ②
$$\left(\frac{dE_t}{dt}\right)_{max} = R_s \cdot \frac{E_s}{L}$$

$$R_s = L\left(\frac{dE_t}{dt}\right)_{max} \times \frac{1}{E_s}$$

Calculation of C_s :

As the above RLC circuit is a criticaly damped circuit

$$R_s = 2\xi\sqrt{\frac{L}{C_s}}$$ (where ξ is known as damping factor)

$$C_s = \left(\frac{2\xi}{R}\right)^2 L$$

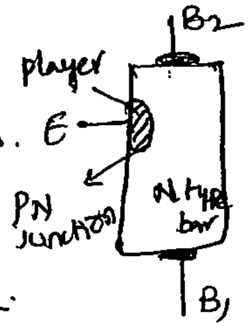
→ UJT :

(Uni-Junction Transistor) : As the name indicates, it is a unijunction (PN) device consisting of three terminals namely Emitter E, base B_1 and base B_2.

→ Applications :- Oscillators, Timing circuits and SCR/TRIAC firing circuits as a switch

Operation :-

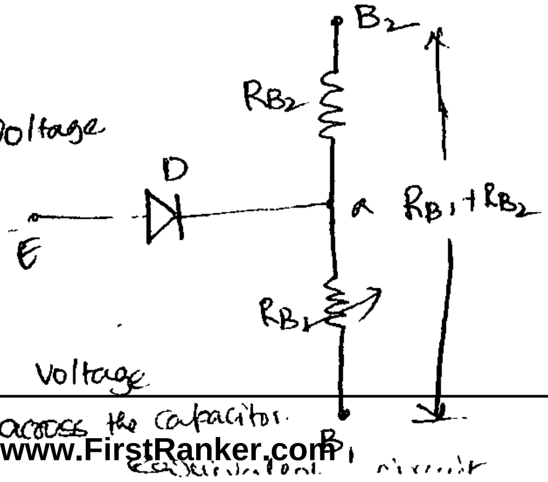
→ It consists of a lightly doped, N type silicon bar provided with ohmic contacts at both the ends. A small heavily doped P-layer is alloyed into one side of the N type bar closer to the base B_2.

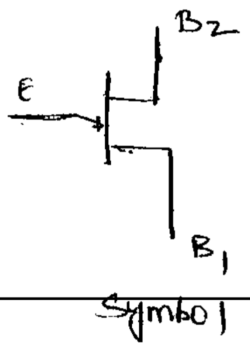


The player is considered as the emitter 'E' of UJT which forms a PN junction with N type bar.

→ A resistance R_{BB}, known as inter base resistance exists b/w the bases B_1 and B_2. splitting the resistance R_{BB} gives the resistance from Base B_1 to emitter of UJT and resistance from Base B_2 to UJT emitter given as R_{B_1} & R_{B_2} resp.

→ As the emitter is closer to base B_2, $R_{B_2} < R_{B_1}$. Usually, base B_2 and emitter E of UJT are biased positive when compared to B_1. Here, B_1 is considered as reference terminal throughout the operation and all the voltages are measured w.r.t B_1.

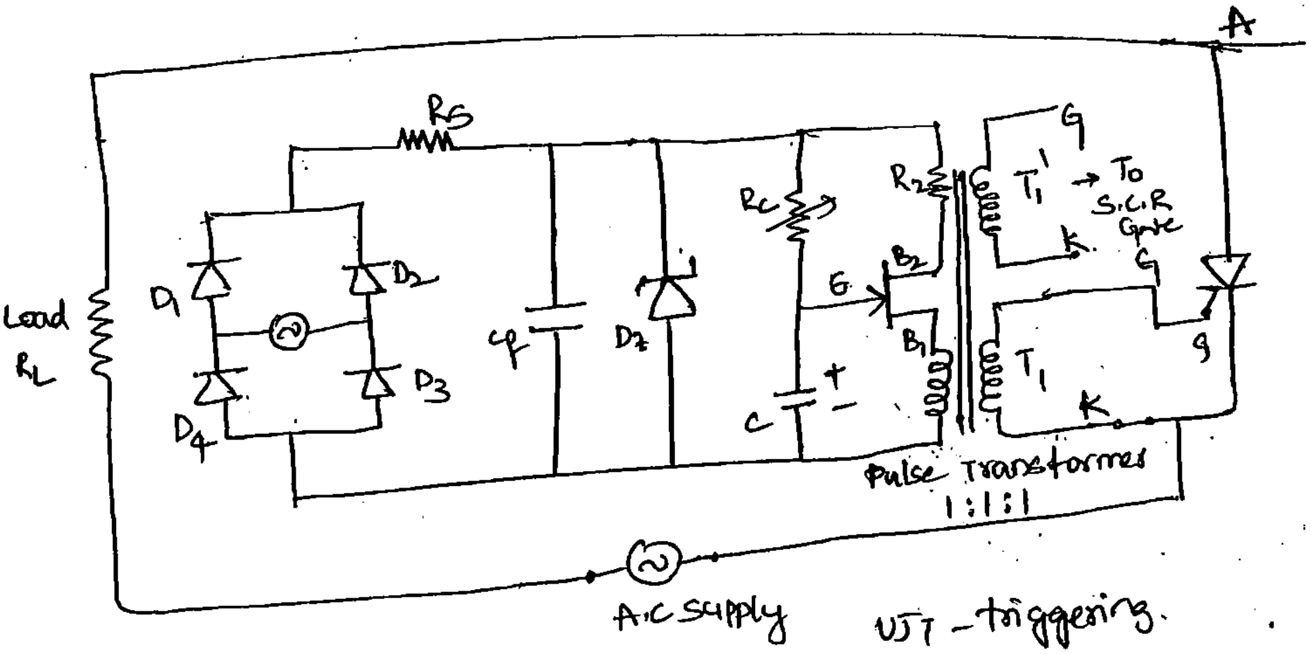




→ V_{BB} source is a fixed D.C Voltage source and hence, provides a constant voltage across B_1 and B_2.

→ V_{EE} ~~source is a~~ variable D.C Voltage source which may be applied across the capacitor.

UJT Firing circuit :-

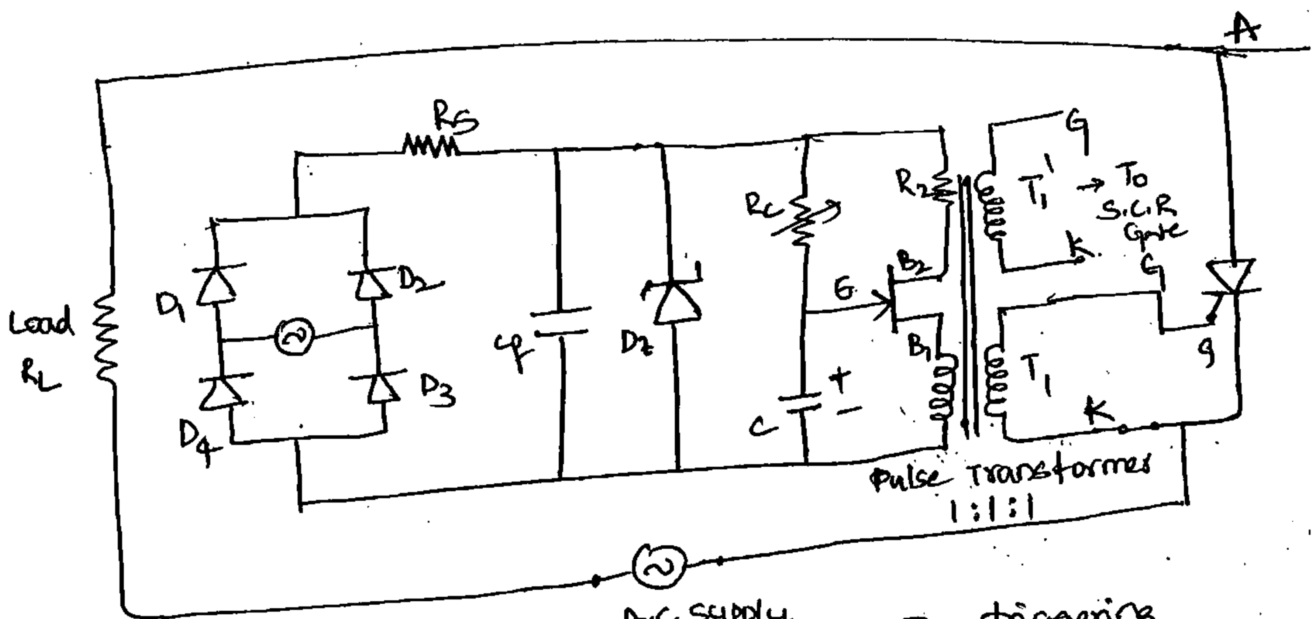


UJT - triggering.

→ The synchronised UJT Triggering circuit consists of a full bridge diode rectifier which is used to convert A.C into D.C. Edc value. A suitable value of resistor (R_s) is chosen to lower Edc value. The filter capacitor C_f is used to reduce the ripple in the D.C voltage. The zener diode (D_z) is used for clipping the rectified voltage to a fixed voltage V_z. This fixed voltage is applied to the charging circuit R_cC. R_c is a control resistor. When the R_c is very low, the time required to charge the capacitor to a triggering voltage of UJT is less, which corresponds to zero degree firing angle.

→ Conversely, if the control resistor is varied to a maximum value, the time required to charge the capacitor to a triggering voltage of UJT is more, which corresponds to the maximum firing angle (180°)

UJT Firing circuit:-



UJT - triggering.

→ The synchronised UJT Triggering circuit consists of a full bridge diode rectifier which is used to convert A.C into D.C. A suitable value of resistor (R_s) is chosen to lower E_{dc} value for the zener diode. The filter capacitor C_f is used to reduce the ripple in the D.C voltage. The zener diode (D_z) is used for clipping the rectified voltage to a fixed voltage V_z. This fixed voltage is applied to the charging circuit R_cC. R_c is a control resistor. When the R_c is very low, the time required to charge the capacitor to a triggering voltage of UJT is less, which corresponds to zero degree firing angle.

→ Conversely, if the control resistor is varied to a maximum value, the time required to charge the capacitor to a triggering voltage of UJT is more, which corresponds to the maximum firing angle (180°)

But practically the firing can be controlled upto 150°.

As soon as the capacitor reaches the triggering voltage of UJT, the UJT gets turned ON. Hence capacitor 'C' discharges through emitter of the UJT and the primary wdg of the pulse transformer. The windings of pulse transformer have secondary pulse voltages of their secondaries.

→ The pulses at the two secondary winding feed the same in phase pulses, to the two thyristors of the full wave circuit so the SCR(T), which is in the forward biased condition, turns ON.

→ This method of controlling the o/p power, by varying the control resistor(R_c) is called as Ramp control, open loop control (or) manual control.

→ As the zener diode voltages goes to zero at the end of each half cycle achieves the synchronization of the trigger circuit with the supply voltage across the SCRs.

2) AC to D.C converters (Controlled Rectifiers) :-

A controlled rectifier converts fixed a.c voltage to a variable d.c voltage. This o/p voltage can be controlled by varying the firing angle or delay angle of thyristors. These are also fed from 1-ϕ (or) 3-ϕ.

Applications :-

a) dc drives
b) metallurgical and chemical Industries
c) excitation systems

3. AC to AC converters :-

These converts fixed ac input voltage to variable a.c output voltage. There are 2 types:

(i) Ac voltage controllers (AC voltage regulators) :-

These converters convert fixed ac i/p voltage to a variable ac o/p voltage without change in supply frequency. Ac voltage controllers employ two thyristors in antiparallel or a TRIAC. The o/p voltage is controlled by varying the firing angle of thyristors.

Applications :-

a) Lighting control
b) Speed control of fans, Pumps
c) Transformer tap changer
d) ac drives.

SINGLE PHASE CONTROLLED CONVERTERS:

Introduction :-

Rectification (or) conversion:

Rectification is a process of converting A.C Voltage (or) current to D.C Voltage (or) current. Many industrial applications require controllable D.C power.

Applications :-

1. High voltage D.C Transmission
2. Electro metallurgical process.
3. Magnetic power supplies.
4. Electro plating
5. Battery Charging.
6. Speed control of D.C drives, traction etc.

→ This conversion can be achieved by variety of circuits, based on the switching devices. The commonly used switching devices are
1) Diode 2) Transistor 3) MOSFETS 4) IGBTs 5) Thyristor
6) IPM (Intelligent power Modules)

PHASE ANGLE CONTROL TECHNIQUE :-

→ All the rectifier circuits can be classified as controlled rectifiers and uncontrolled rectifiers.

→ Diode is an uncontrolled rectifier where as remaining all the devices are controlled rectifiers.

→ The uncontrolled rectifier uses only power diodes and the output voltage is fixed in amplitude and it is a function of supply voltage only

→ In case of controlled rectifiers, thyristors are mainly used for high power applications where the DC output voltage is a function of ac supply voltage amplitude and the instant at which the SCR starts conducting for a given firing angle 'α'. The o/p voltage can be varied by varying the firing angle. This is known as phase angle control.

Firing angle (α):

It may be defined as an angle between the instant at which the thyristor would conduct, if it was a diode and the instant at which it is triggered.

In AC circuits, the thyristor gets turned on by giving a gate signal at any angle as per the requirement of the desired output w.r.t the applied voltage.

LINE COMMUTATED RECTIFIERS:-

Commutation is a process which occurs whenever the current through SCR falls below the holding current.

There are two types of commutations process

(1) line (or) natural commutation; (2) Forced commutation.

A rectifier is said to be naturally commutated (or) line commutated whenever the supply voltage passes through a natural zero

Phase controlled rectifiers are line commutated as the supply voltages becomes zero at $\omega t = \pi, 2\pi$.

The o/p voltage and current becomes zero at these instants when the load [illegible] resistive [illegible]

(3) Cyclo converters :-

Cyclo converters convert input power at one frequency to output power at a different frequency.

Applications :-

a) speed control of large ac drives like rotary kilns, etc
b) static variable speed constant frequency generators for air craft.

4) DC to DC converters (DC choppers) :-

A DC chopper converts fixed d.c i/p voltage to variable d.c output voltage. The o/p voltage can be controlled by ON and OFF time of the thyristors.

Applications :-

a) dc drives
b) subway cars
c) battery operated vehicles
d) trolley trucks

5.) DC to AC converter (Inverter) :-

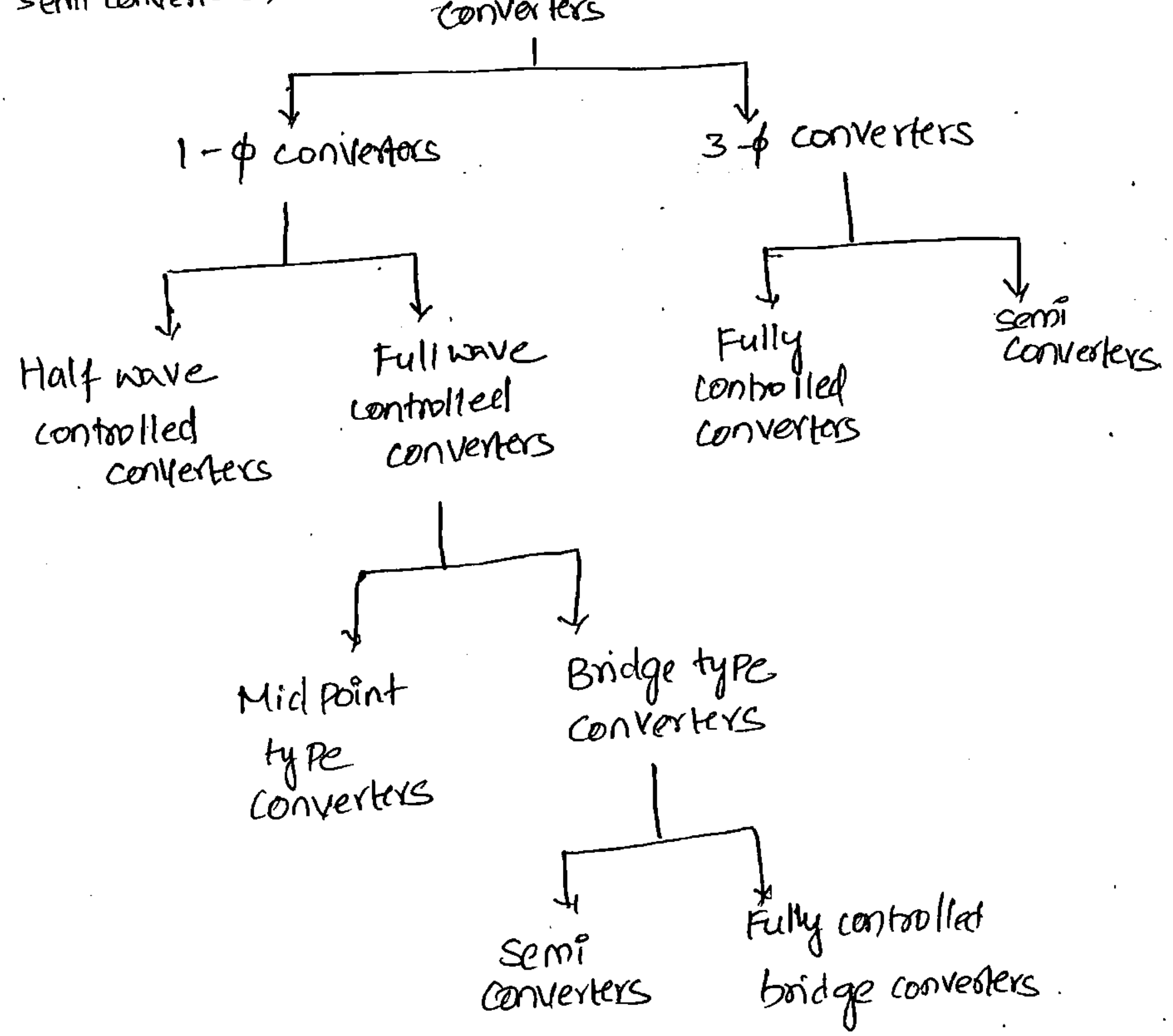
An inverter converts a fixed dc i/p voltage to fixed (or variable) ac output voltage with variable frequency. The o/p voltage can be controlled by varying the ON time of the thyristors.

Applications :-

a) uninterruptible power supply (UPS)
b) Induction motor and synchronous motor drives
c) high voltage DC transmission (HVDC)
d) Induction heating.

classification of converters

1) 1-ϕ, 3-ϕ
2) semi converters, full converters, Dual converters.



Uncontrolled converters :

uncontrolled converter contains only diodes and the D.C o/p voltage is fixed in amplitude by the amplitude of A.C supply.

uncontrolled converter permits power to flow only from the A.C system to the D.C load. The inversion process is not possible.

2. 1-ϕ (or) 3-ϕ converters :

Depending upon the i/p supply, the converters are classified as 1-ϕ (or) 3-ϕ converters. If the o/p is greater than few kV, they are usually fed from the 3-ϕ supply.

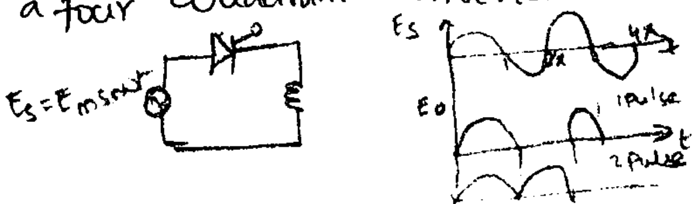
3. **Semi converter** :- In semi converter only one polarity of the voltage and the current are present at the D.C terminals.

A semi converter is a one quadrant converter. It contains mixture of diodes and thyristors allowing more limited control over the D.C output voltage level than the full controlled rectifier. It permits the power flow from A.C system to D.C load.

A semi converter is also known as half wave controlled converter.

4) Full converters :- These are two quadrant converters. Fully controlled rectifier uses only thyristors as the rectifying elements. In these converters, power can be transmitted from A.C side to D.C side (conversion) and from D.C side to A.C side (Inversion)

5) Dual converter : If the two full converters are connected back to back, it is called dual converter. The o/p current and voltage may be positive (or) negative. Dual converters are normally used in high power applications. It is a four quadrant converter.



PULSE NUMBER :-

Pulse number :- Depending upon the pulse number, converters are classified into 1 pulse, 2 pulse, 3 pulse, 6 pulse and 12 pulse converters.

Def :- It is defined as the no. of pulsations present in the o/p voltage in a given alternating cycle of voltage.

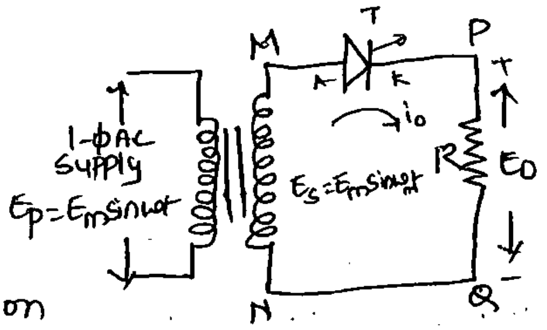
Here, the o/p voltage contains one pulse present in one cycle of alternating voltage. So it is one pulse converter.

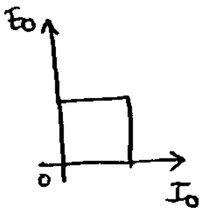
1. 1ϕ midpoint type, bridge type rectifiers — 2 pulse converters
2. 3ϕ semi converters — 3 pulse or 6 pulse
3. 3ϕ fully controlled rectifiers — 6 pulse

→ pulse number indicates directly the ripple frequency i.e.

∴ the ripple frequency in the case of 2 pulse converters is 2 times the supply frequency.

Single phase half wave controlled converter with R Load :-





→ The circuit consists of an SCR in series with source and load. The supply to the converter is given by isolation transformer whose secondary voltage is given as $E_s = E_m \sin\omega t$, where $E_m = \sqrt{2}\, E_{rms}$.

→ SCR should be selected in such a way that the peak voltage of the source never exceeds the forward and reverse blocking voltage rating of an SCR. The load is assumed is purely resistive. It is known as half controlled rectifier as the supply voltage is rectified during the positive half cycles only.

→ In this circuit, the load current and load voltage have the same polarity throughout the circuit operation, so it is known as one quadrant converter.

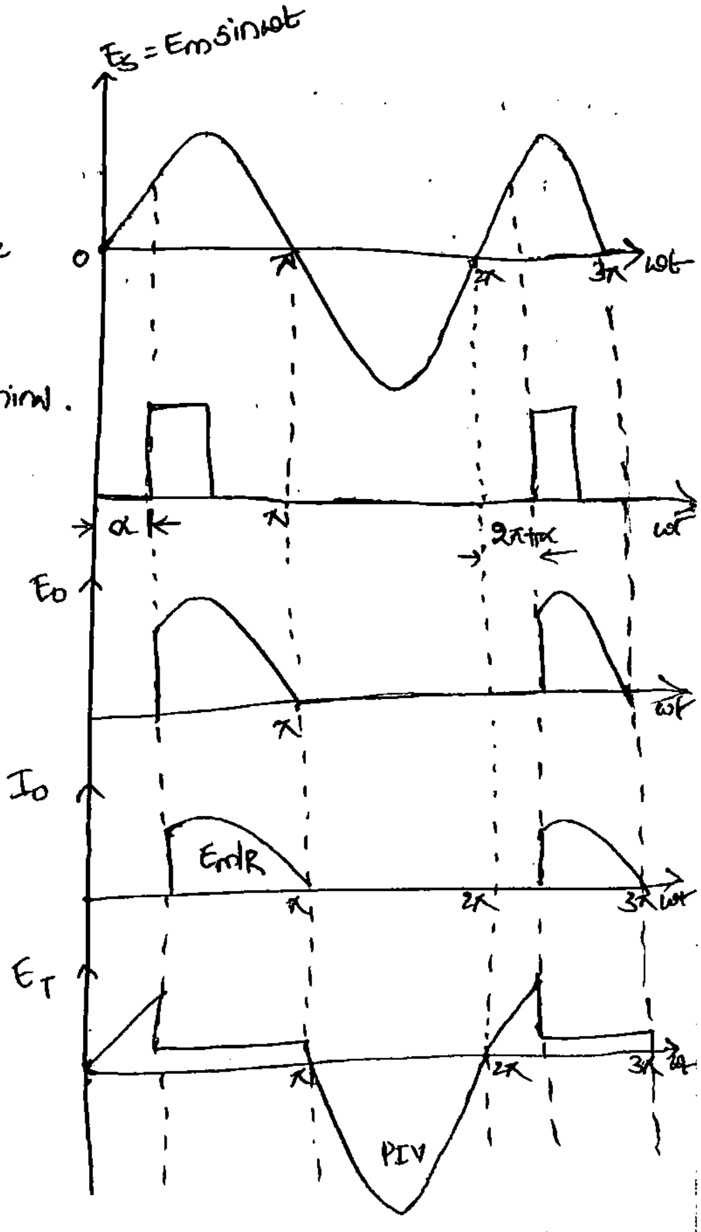
Mode 1 :- During the positive half cycle of the supply voltage, anode terminal of SCR is more positive w.r.t cathode terminal. Here, the SCR is said to be in the forward blocking state.

→ whenever a gate signal is given to the thyristor at some firing angle say α, it gets triggered and moves into conduction state. The power gets transferred from supply to load during +ve cycle

→ Load voltage follows the supply voltage from α to π. The angle during which the SCR conducts is known as conduction angle given by π−α

In this mode, load current follows the path

M − T − P − load − Q − N



SCR is R.B from π to 2π.

Half wave controlled converter wave forms with R load

Mode 2 :-

During the negative half cycle of the supply voltage, the cathode terminal becomes more +ve w.r.t anode terminal. As a result, the thyristor (T) gets R.B and blocks the −ve half cycle of the supply voltage. Thus, the voltage appeared across load becomes zero.

1. Average D.C load Voltage $(E_0)_{Avg}$:

$$\therefore \quad E_{avg} = \frac{1}{T}\int_0^T E_m \sin \omega t \, d(\omega t) \quad [T \text{ is timeperiod}]$$

$$(E_0)_{Avg} = \frac{1}{2\pi}\left[\int_\alpha^\pi E_m \sin\omega t \, d(\omega t) + \int_\pi^{2\pi+\alpha} 0 \times d(\omega t)\right]$$

$$= \frac{1}{2\pi}\int_\alpha^\pi E_m \sin \omega t \, d(\omega t)$$

$$= \frac{E_m}{2\pi}\left[-\cos\omega t\right]_\alpha^\pi$$

$$= \frac{E_m}{2\pi}(-1)\left[\cos\pi - \cos\alpha\right]$$

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

(i) If $\alpha = 0$ $\quad E_{0(max)} = \frac{E_m}{\pi}$

(ii) If $\alpha = \pi$ $\quad E_0 = 0$

2. Average D.C load current is given as

$$\therefore \quad I_0 = \frac{E_0}{R}$$

$$I_0 = \frac{E_m}{2\pi R}(1+\cos\alpha)$$

3. RMS Load Voltage E_{RMS}

$$\therefore \quad E_{RMS} = \left[\frac{1}{T}\int_0^T (E_m \sin\omega t)^2 \, d(\omega t)\right]^{1/2}$$

(or) $$E_{RMS} = \left\{\frac{1}{2\pi}\left[\int_\alpha^\pi (E_m \sin\omega t)^2 d(\omega t) + \int_\pi^{2\pi+\alpha} 0\right]\right\}^{1/2}$$

$$= \left[\frac{E_m^2}{2\pi}\int_\alpha^\pi \sin^2\omega t \, d(\omega t)\right]^{1/2}$$

$$= \left[\frac{E_m^2}{2\pi}\int_\alpha^\pi \frac{(1-\cos 2\omega t)}{2}\, d(\omega t)\right]^{1/2}$$

$$= \left\{\frac{E_m^2}{2\pi}\left[\frac{\omega t}{2} - \frac{\sin 2\omega t}{4}\right]_\alpha^\pi\right\}^{1/2}$$

$$= \left\{\frac{E_m^2}{2\pi}\left[\frac{\pi-\alpha}{2} - \left\{\frac{\sin 2\pi - \sin 2\alpha}{4}\right\}\right]\right\}^{1/2}$$

$$= \left\{\frac{E_m^2}{2\pi}\left[\frac{\pi-\alpha}{2} + \frac{\sin 2\alpha}{4}\right]\right\}^{1/2}$$

(or) $$E_{rms} = E_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8}\right]^{1/2}$$

(i) If $\alpha = 0$

$$E_{RMS(max)} = \frac{E_m}{2}$$

(ii) If $\alpha = \pi$ $\quad E_{Rms} = 0$

→ The RMS voltage may be varied from 0 to $\frac{E_m}{2}$ by varying α from π to 0.

4) Power delivered to the resistive load is given as

$$\therefore P_L = (\text{RMS load Voltage})(\text{RMS load current})$$

$$P_L = (E_{RMS})(I_{RMS})$$

$$= \frac{E^2_{RMS}}{R}$$

$$= I^2_{RMS} \cdot R$$

5) Input Volt amperes = (RMS source voltage)(RMS line current)

$$= E_s I_{RMS}$$

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

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

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

6. Input power factor : It is defined as the ratio of total mean input power to the total rms i/p volt amperes.

$$\therefore \text{Input power factor} = \frac{\text{Power delivered to the load}}{\text{Input volt amperes}}$$

$$= \frac{E_{RMS}\, I_{RMS}}{E_s\, I_{RMS}}$$

$$= \frac{E_{RMS}}{E_s}$$

$$\therefore \text{I/p P.f} = \frac{\frac{\sqrt{2}E_s}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]^{1/2}}{E_s}$$

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

7. Form Factor (F_F) : Form Factor is defined as the ratio of RMS voltage (E_{RMS}) to the average D.C voltage E_o

$$\therefore \text{Form Factor} = \frac{E_{RMS}}{E_o}$$

8. Effective value of the A.C component of the output voltage is

$$E_{ac} = \left[(E_{RMS})^2 - E_o^2\right]^{1/2}$$

... Ripple factor (R_f): It is defined as the ratio of A.C component to the D.C component where ripple is the amount of A.C component present in D.C component

$$R_f = \frac{E_{ac}}{E_0} = \frac{(E_{RMS}^2 - E_0^2)^{1/2}}{E_0} = \left[\left(\frac{E_{RMS}}{E_0}\right)^2 - 1\right]^{1/2}$$

$$\therefore R_f = \sqrt{(F.F)^2 - 1}$$

10. Transformer Utilization Factor (TUF): It is defined as the ratio of output D.C power to the volt ampere rating of the transformer.

$$TUF = \frac{P_{dc}}{\text{VA rating of secondary winding of transformer}}$$

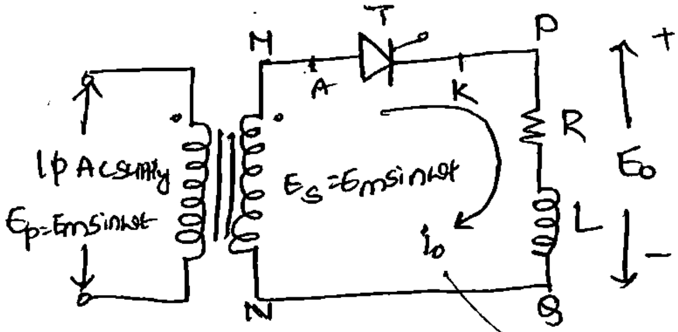
11. Rectifier Efficiency: It is defined as the ratio of output D.C power to i/p a.c power.

$$\eta = \frac{E_0 I_0}{E_{RMS} I_{RMS}}$$

12. Peak Inverse Voltage (PIV): It is defined as the maximum voltage that an SCR can be subjected to in the reverse biased condition.

In the case of Half wave converter it is E_m.

Half wave converter with RL load :-



Mode 1 :-

During the +ve half cycle of the supply voltage, anode terminal is more +ve w.r.t cathode terminal. The SCR is in the F.B condition. when the gate signal is given to the SCR, it starts conducting and the load voltage traces the supply voltage. The load current flows in the direction

M-T-P- RL load - QN

The energy gets stored in the inductor during the interval $\omega t = \alpha$ to π. At $\omega t = \pi$, source voltage becomes zero and load voltage is zero. But, the load current does not become zero due to the presence of inductance in the load circuit, which does not allow sudden changes of current. Hence, the SCR does not get commutated at the instant $\omega t = \pi$. It gets commutated at some other point denoted by β after $\omega t = \pi$. β is known as extinction angle.

Extinction angle (β) : It is defined as the angle measured from the reference point to the instant at which the current extinguishes to zero.

Conduction angle (γ) :- It is defined as the angle, during the period in which the SCR is in conduction state

The relation b/w α, β and γ is given by

$$\beta = \alpha + \gamma$$

During the negative half cycle, at $\omega t = \beta$ current flowing through the SCR becomes zero. Hence, it is naturally commutated. The load o/p voltage and load current is zero. The thyristor is R.B from $\omega t = \beta$ to 2π. Hence, circuit turnoff time is given as $\omega t_c = 2\pi - \beta$ i.e. $t_c = \frac{2\pi - \beta}{\omega}$

Discontinuous conduction :-

The extinction angle (β) may be calculated when $\alpha < \omega t < \beta$

By applying the KVL across the loop.

$$E_m \sin \omega t = R i_0 + L \frac{di_0}{dt}$$

Load current (I_0) consists of two components known as steady state and transient components.

$$I_0 = I_{ss} + I_t$$

∵ It is a first order non linear differential equation, the solution contains Particular integral and complementary function.

Complementary function corresponds to transient current

Particular Integral corresponds to steady state current.

$$\therefore I_{ss} = \frac{E_m}{Z} \sin(\omega t - \phi) \quad \text{where } Z = \sqrt{R^2 + (\omega L)^2}$$

$$\phi = \tan^{-1}\left(\frac{X_L}{R}\right) \quad \text{where } X_L = \omega L$$

ϕ is the phase angle b/w I_s and E_s.

Transient component is given by $I_t = A e^{-t/\tau}$ where $\tau = \frac{L}{R}$

$$I_t = A e^{-tR/L}$$

$$\therefore \text{Total current } I_0 = I_{ss} + I_t = \frac{E_m}{Z} \sin(\omega t - \phi) + A e^{-tR/L} \quad \text{---(1)}$$

where $Z = \sqrt{R^2 + (\omega L)^2}$

6. Static switches :-

The power semiconductor devices can be operated as static switches. If the supply to these switches is dc the switches are called as dc switches.

If the supply given is ac then the switches are called ac switches.

Static switches have many advantages over mechanical and electromechanical circuit breakers.

CLASSIFICATION OF POWER SEMICONDUCTOR DEVICES:-

Silicon controlled Rectifier (SCR) was introduced first in 1957. The power semi conductor devices can be classified on the basis of

(i) Turn ON and Turn Off characteristics
(ii) Gate signal requirements
(iii) Voltage and current capability.

(i) Turn ON and Turn OFF characteristics:-

a) Uncontrolled turn on and OFF (e.g. diode)
b) controlled turn ON and uncontrolled turn OFF (e.g. SCR)
c) Controlled turn ON and OFF characteristics (e.g. BJT, MOSFET, GTO IGBT)

(ii) Gate signal requirements :-

a) Continues Gate signal requirement (e.g. MOSFET, BJT, IGBT)
b) Pulse Gate requirement (e.g. SCR, GTO)

(iii) Voltage and current capability:-

a) Bipolar voltage withstanding capability (e.g., SCR, GTO)
b) Unipolar voltage " (e.g. BJT, MOSFET, IGBT)

Constant A can be obtained by applying boundary conditions at $\omega t = \alpha$,

$$I_0 = 0$$
$$t = \alpha/\omega$$

Hence, eq. (1) becomes $0 = \frac{E_m}{Z}\sin\left(\omega \cdot \frac{\alpha}{\omega} - \phi\right) + A e^{\frac{\alpha}{\omega}\cdot\frac{R}{L}}$

$$-\frac{E_m}{Z}\sin(\alpha-\phi) \cdot e^{\frac{R\alpha}{\omega L}} = A$$

$$\therefore A = -\frac{E_m}{Z}\sin(\alpha-\phi)\, e^{\frac{R\alpha}{\omega L}}$$

Substituting 'A' value in eq. (1), we get

$$I_0 = \frac{E_m}{Z}\sin(\omega t-\phi) - \frac{E_m}{Z}\sin(\alpha-\phi)\, e^{\frac{R\alpha}{\omega L}} \cdot e^{-tR/L}$$

$$\therefore I_0 = \frac{E_m}{Z}\sin(\omega t-\phi) - \frac{E_m}{Z}\sin(\alpha-\phi)\, e^{-\frac{R}{\omega L}(\omega t-\alpha)} \quad \text{--- (2)}$$

at $\omega t = \beta$, $t = \frac{\beta}{\omega}$, $I_0 = 0$

$\therefore$ eq. (2) becomes

$$0 = \frac{E_m}{Z}\sin\left(\omega\cdot\frac{\beta}{\omega}-\phi\right) - \frac{E_m}{Z}\sin(\alpha-\phi)\, e^{-\frac{R}{\omega L}\left(\omega\cdot\frac{\beta}{\omega}-\alpha\right)}$$

(or) $$0 = \frac{E_m}{Z}\sin(\beta-\phi) - \frac{E_m}{Z}\sin(\alpha-\phi)\, e^{-\frac{R}{\omega L}(\beta-\alpha)}$$

$$\therefore \sin(\beta-\phi) = \frac{\frac{E_m}{Z}\cdot\sin(\alpha-\phi)\, e^{-\frac{R}{\omega L}(\beta-\alpha)}}{E_m/Z}$$

$$\sin(\beta-\phi) = \sin(\alpha-\phi)\, e^{-\frac{R}{\omega L}(\beta-\alpha)}$$

The solution gives the values of 'β' because all the parameters α, ϕ, R, L are known. By knowing the value of 'β', E_0 can ~~be calculated.~~

1. Average o/p voltage :-

$$(E_0)_{Avg} = \frac{1}{2\pi}\int_{\alpha}^{\beta} E_m \sin\omega t \, d(\omega t)$$

$$= \frac{E_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\beta}$$

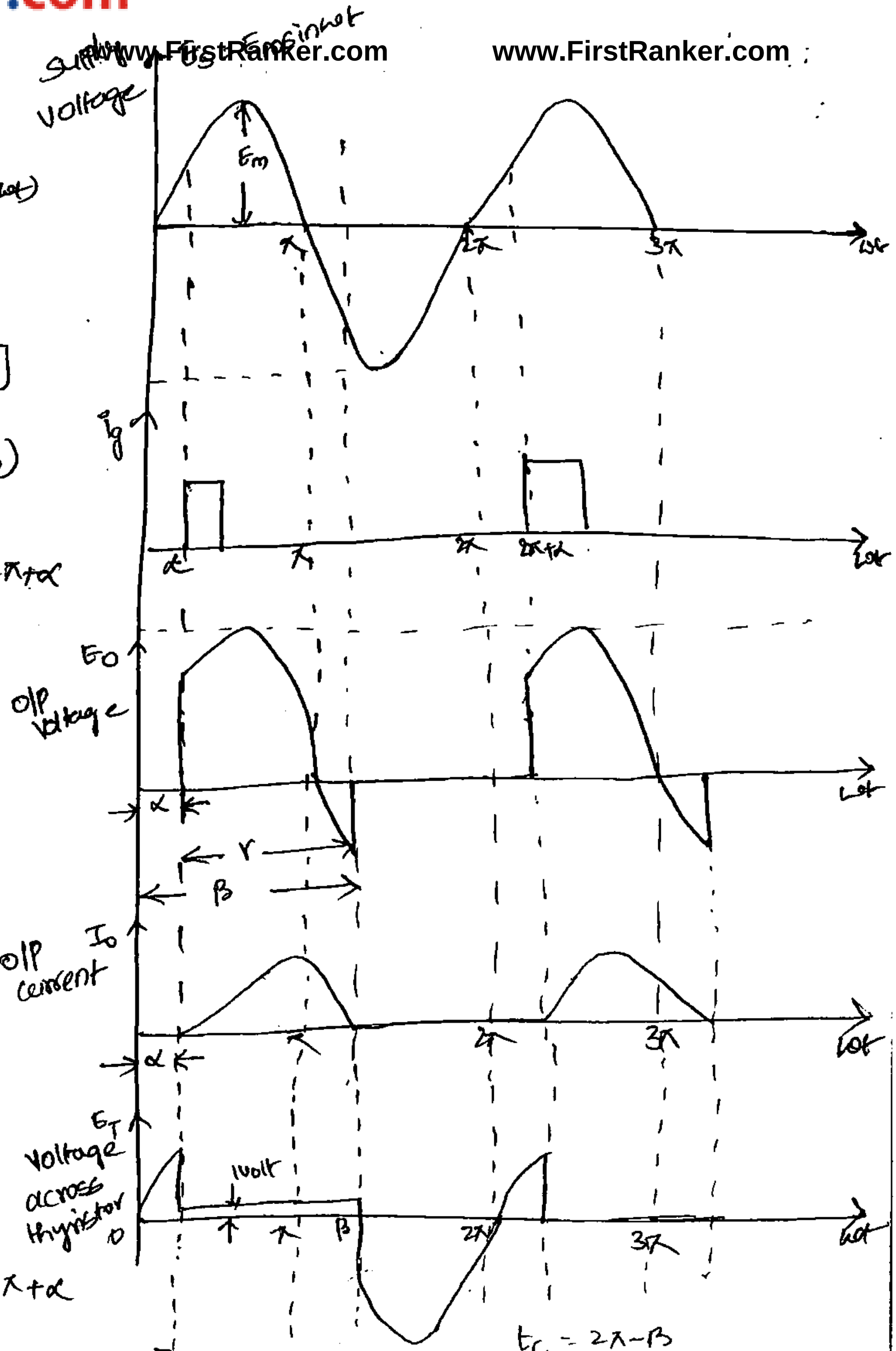
$$= \frac{E_m}{2\pi}\left[-\cos\beta + \cos\alpha\right]$$

$$\therefore (E_0)_{Avg} = \frac{E_m}{2\pi}(\cos\alpha - \cos\beta)$$

For continuous conduction, $\beta = \pi + \alpha$

$$\therefore E_0 = \frac{E_m}{2\pi}\left(\cos\alpha - \cos(\pi+\alpha)\right)$$

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



1. Avg. o/p current eq:

$$\therefore (I_0)_{Avg} = \frac{E_0}{R}$$

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

For continuous conduction $\beta = \pi + \alpha$

$$I_0 = \frac{E_m}{2\pi R}\left(\cos\alpha - \cos(\pi+\alpha)\right)$$

$$= \frac{E_m}{\pi R}\cos\alpha.$$

RMS output voltage is given as

$$E_{RMS} = \left[\frac{1}{2\pi} \int_{\alpha}^{\beta} E_m^2 \sin^2 \omega t \; d(\omega t) \right]^{1/2}$$

$$= \left[\frac{E_m^2}{2\pi} \int_{\alpha}^{\beta} \frac{1-\cos 2\omega t}{2} \; d(\omega t) \right]^{1/2}$$

$$= \left[\frac{E_m^2}{2\pi} \left[\frac{\omega t}{2} - \frac{\sin 2\omega t}{4} \right]_{\alpha}^{\beta} \right]^{1/2}$$

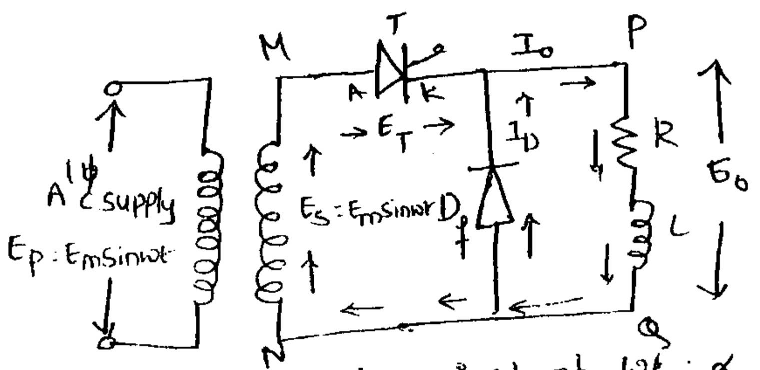
$$E_{RMS} = \left[\frac{E_m^2}{2\pi} \left[\frac{\beta - \alpha}{2} - \frac{\sin 2\beta}{4} + \frac{\sin 2\alpha}{4} \right] \right]^{1/2}$$

$$= \left[\frac{E_m^2}{4\pi} \left\{ (\beta - \alpha) - \frac{1}{2} \left(\sin 2\beta - \sin 2\alpha \right) \right\} \right]^{1/2}$$

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

EFFECT OF FREEWHEELING DIODE :-

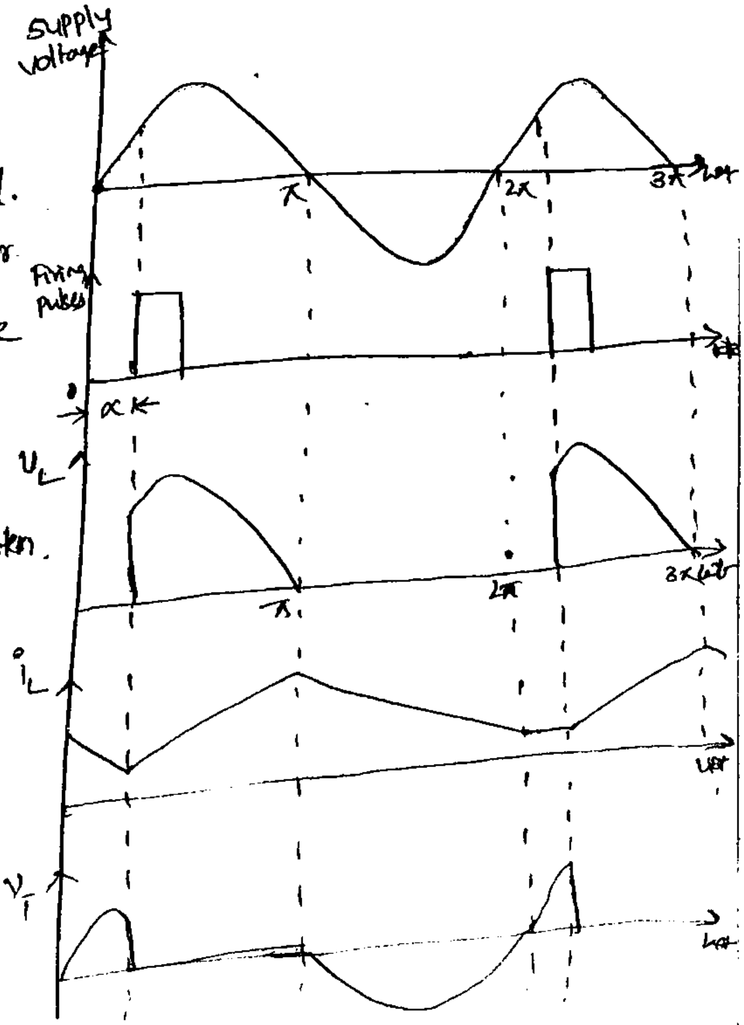
→ Free wheeling diode is also known as a commutating diode because it transfers the load current away from the rectifier circuit. This is also called as fly wheel diode or byepass diode.



Mode 1 :- During the +ve half cycle of the supply voltage, thyristor T_1 is F.B Give the gate signal to the SCR at the instant $\omega t = \alpha$. The load current follows the path M - T - P - load - Q - N. During this interval the energy gets stored in the inductor.

At the instant $\omega t = \pi$, load voltage becomes zero but load current does not become zero due to the presence of inductor in the load circuit.

Mode 2 (Effect of Freewheeling diode): During the +ve half cycle, voltage is induced in the inductor. At the instant ($\omega t = \pi$), ~~in order to maintain the current~~ this induced voltage in inductance will change its polarity as the di/dt changes its sign and diode D_f will start conducting as soon as the induced voltage ~~with~~ is of sufficient magnitude, thereby enabling the inductance to discharge its stored energy into the resistance. Here, the load current free wheels through the free wheeling diode.



Advantages of D_f :-

1) Load current waveform is improved. As a result, load performance is better.

2) Freewheeling diode prevents negative swing voltage except for a small diode voltage drop.

3) It improves the i/p P.f of the system.

→ with freewheeling diode, no power will be transferred from load to source because it eliminates the reversal of voltage.

→ without freewheeling diode, the energy will be returned from the load to source during the -ve portion of the E_s. Hence, the ratio of reactive power flow from the i/p to the power consumed in the load with D_f will be less, when

when compared to without freewheeling diode.

so, $\left(\frac{EI\sin\phi}{EI}\right)$ is less in Free wheeling diode circuit

$EI\sin\phi$ is less

$\sin\phi$ is less

ϕ is less

$\therefore$ $\cos\phi$ is more.

So, the freewheeling diode improves the P.f.

1. Average o/p voltage:

$$E_0 = \frac{1}{2\pi}\int_{\alpha}^{\pi} E_m \sin\omega t \, d(\omega t)$$

$$= \frac{E_m}{2\pi}\left(-\cos\omega t\right)_{\alpha}^{\pi}$$

$$= \frac{E_m}{2\pi}\left(1 + \cos\alpha\right]$$

2. Average o/p current:

$$I_0 = \frac{E_m}{2\pi R}(1+\cos\alpha)$$

3. RMS load voltage:

$$E_{RMS} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} E_m^2 \sin^2\omega t \, d(\omega t)\right]^{1/2}$$

$$= \left[\frac{E_m^2}{2\pi}\left[\frac{(\pi-\alpha)}{2} + \frac{\sin 2\alpha}{4}\right]\right]^{1/2}$$

$$E_{RMS} = E_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8}\right]^{1/2}$$

Problems:

→ A resistive load of 10Ω is connected through a half wave SCR circuit to 220V, 50 Hz, single phase source. Calculate the power delivered to the load for a firing angle of 60°. Find also the value of i/p P.f.

sol:

$V_s = 220V$

$f = 50Hz$

$R = 10\Omega$

$\alpha = 60°$; $V_m = \sqrt{2}\, V_s = \sqrt{2} \times 220 = 311.12V$

Power delivered to the load $= V_{rms} . I_{rms}$

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

$$= \frac{311.12}{2}\left(\frac{1}{\pi}\left(\pi - 60 \times \frac{\pi}{180} + \frac{\sin 2\times 60}{2}\right)\right)^{1/2}$$

$$V_{rms} = 139.38\ V$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{139.38}{10} = 13.938A$$

$$P_{ac} = 139.38 \times 13.938 = 1943 W$$

$$I/P\ P.f = \frac{V_{rms}}{V_s} = \frac{139.38}{220} = 0.633\ (lag)$$

2) A 1-φ half wave converter is operated from a 120V, 60 Hz supply. If the load is resistive of value 10Ω and delay angle is $\alpha = \pi/3$. Determine (i) the efficiency (ii) Form factor (iii) Ripple Factor (iv) Transformer utilization factor (v) Peak inverse voltage of thyristor

sol:

$V_s = 120V$, $R = 10\Omega$, $\alpha = \pi/3$

$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

$$= \frac{\sqrt{2} \times 120}{2\pi}(1 + \cos \pi/3)$$

$$V_{dc} = 40.5V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{40.5}{10} = 4.05\,A$$

$$V_{rms} = \frac{V_m}{2}\left[\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2} = \frac{\sqrt{2}\times 120}{2}\left(\frac{1}{\pi}\left(\pi - \frac{\pi}{3} + \frac{\sin 2\times 60}{2}\right)\right)^{1/2}$$

$$= 76.11\,V$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{76.11}{10} = 7.611\,A$$

$$P_{dc} = V_{dc} I_{dc} = 40.5 \times 4.05 = 164.025\,W$$

$$P_{ac} = V_{rms} I_{rms} = 76.11 \times 7.611 = 579.2\,W$$

(i) Rectification efficiency (η):

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{164.025}{579.2} \times 100 = 28.32\%$$

(ii) Form Factor (FF)

$$FF = \frac{\text{RMS Value}}{\text{Avg. value}} = \frac{76.11}{40.5} = 1.88$$

(iii) Ripple Factor

$$RF = \sqrt{(FF)^2 - 1} = \sqrt{(1.88)^2 - 1} = 1.59$$

(iv) TUF ($\because I_s = I_{rms}$)

$$TUF = \frac{P_{dc}}{V_s I_s}$$

$$= \frac{164.025}{120 \times 7.611} = 0.1981$$

(v) PIV $V_m = \sqrt{2}\, V_s$

$$\sqrt{2} \times 120 = 169.7\,V$$

→ A 1-φ HW controlled rectifier has a purely resistive load R and delay angle is $\alpha = \pi/2$. Find (i) the rectification efficiency (ii) Form Factor (iii) Ripple Factor (iv) TUF (v) PIV of the thyristor.

→ Design a circuit to produce an average voltage of 40V across a 100Ω load resistor from a 120V rms, 60Hz ac source. Determine the power absorbed by the resistance and the p.f

HWRL
→ A 230V, 50Hz, 1 pulse SCR controlled converter is triggered at a firing angle of 40° and the load current extinguishers at an angle of 210°. Find the average o/p voltage and average load current for R = 5Ω and L = 2mH.

Sol:-

Average output voltage

$$V_{dc} = \frac{V_m}{\pi}(\cos\alpha - \cos\beta)$$

$$= \frac{\sqrt{2}\times 230}{\pi}[\cos 40 - \cos 210)$$

$$= 84.477\,V$$

Average load current

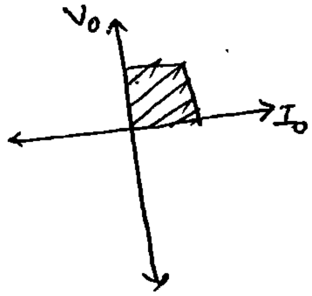
$$I_d = \frac{V_{dc}}{R} = \frac{84.477}{5} = 16.895\,A$$

Two pulse converters :-

Two pulse converter can be classified as

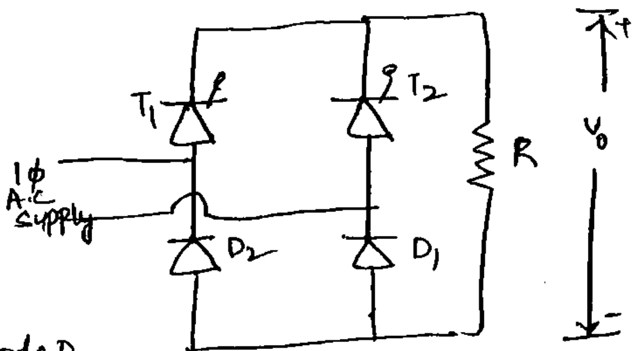
1) 1ϕ Full wave Controlled rectifier (Two quadrant converter)
   a) Mid point converter
   b) Bridge converter.
2) 1ϕ Half controlled rectifier (semi converter) (one quadrant converter)

1-ϕ Half controlled Bridge Rectifier :-



→ A semi converter uses a mixture of diodes and thyristors and there is a limited control over the level of dc o/p voltage. A semi converter is one quadrant converter.

1-ϕ half controlled bridge rectifier with R Load :-

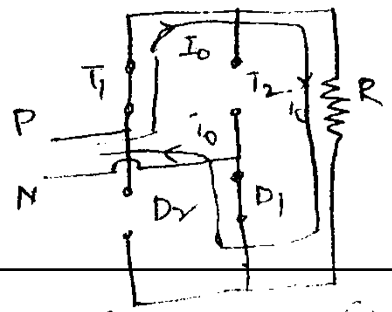


Half controlled bridge rectifier with resistive load

→ This circuit consists of two SCR's T_1 & T_2, two diodes D_1 and D_2.

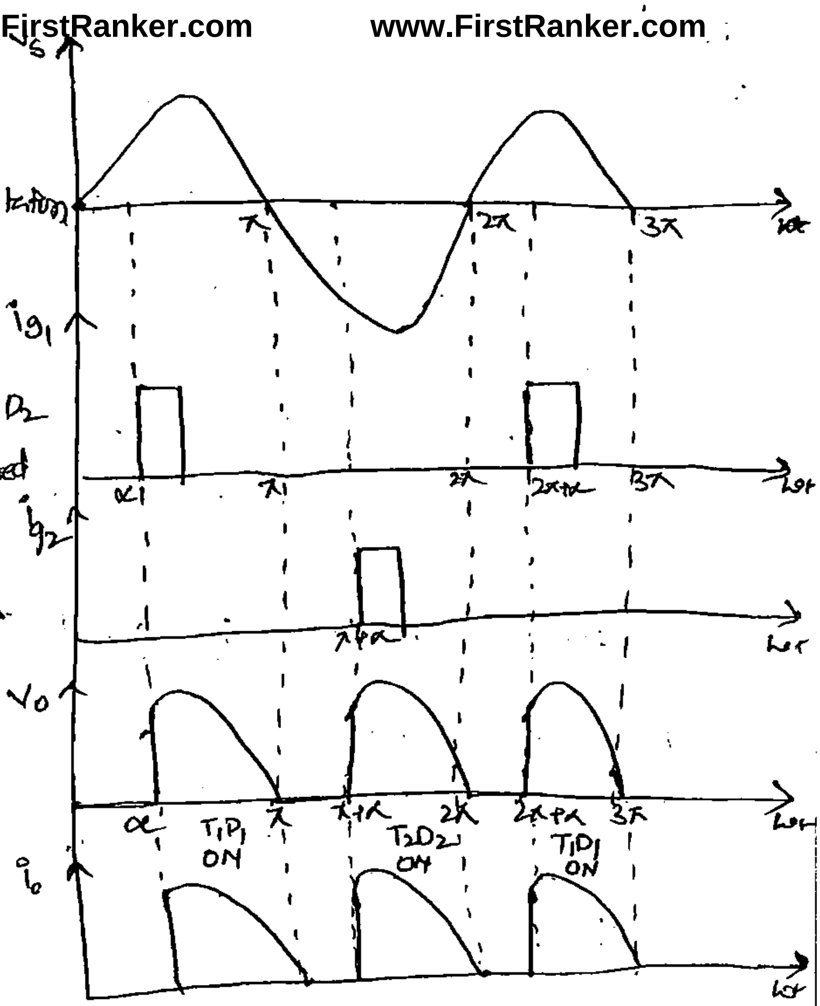
→ During the +ve half cycle of the ac supply, SCR T_1 and diode D_1 are F.B when the SCR T_1 is triggered at a firing angle $\omega t = \alpha$, the SCR T_1 & Diode D_1 comes into ON State. Now, the load current flows through the path $P - T_1 - R - D_1 - N$

during this period, we can get o/p voltage and current are +ve.



Current flow, (α to π)

At $\omega t = \pi$, the load voltage and load current reaches to zero, then SCR T_1 & diode D_1 comes to OFF state due to natural commutation.

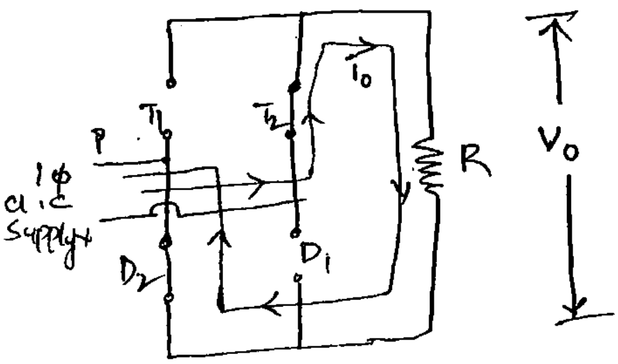


→ During the -ve half cycle of the ac supply, SCR T_2 and diode D_2 are F.B. when SCR T_2 is triggered at a firing angle $\omega t = \pi + \alpha$, the SCR T_2 and diode D_2 comes to ON state. Now, the load current flows through the path

$N - T_2 - R - D_2 - P$

→ During this period, we can get positive o/p voltage and +ve o/p current.

Voltage & current waveforms for 1φ Half controlled Rectifier with R load.



→ At $\omega t = 2\pi$; the load voltage and load current reaches to zero then SCR T_2 and diode D_2 comes OFF state due to natural commutation. During the period ($\pi+\alpha$ to 2π) SCR T_2 and Diode D_2 are conducting.

Current path ($\pi+\alpha$ to 2π)

c) Bidirectional current capability. (e.g., TRIAC, RCT)

d) Unidirectional current capability. (e.g., SCR, GTO, BJT, MOSFET, IGBT, diode)

→ Based on these above characteristics, the power semiconductor devices can be classified as

a) Diodes: These are uncontrolled rectifying devices. Their ON & OFF states r controlled by power supply.

b) Thyristors: These have controlled turn on by Gate signal. These can be turned off by the Power circuit.

c) Controllable switches :- These devices are turned on and turned off by the application of control signals.

Ex: BJT, MOSFET, SIT (Static Induction Transistor), IGBT, MCT (MOS controlled thyristor)

→ TRIAC & RCT (Reverse conducting thyristor) possess bidirectional current capability. where as all other remaining devices (diode, SCR, GTO, BJT, MOSFET, IGBT, SIT, SITH and MCT) are unidirectional current devices.

(i) Average load voltage:

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \; d(\omega t) = \frac{V_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)$$

(ii) Average load current:

$$I_{dc} = \frac{V_{dc}}{R}$$

$$I_{dc} = \frac{V_m}{\pi R}(1+\cos\alpha)$$

(iii) RMS load voltage:

$$V_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2\omega t \,.\, d(\omega t)\right]^{1/2}$$

$$= \left[\frac{V_m^2}{\pi}\int_{\alpha}^{\pi} \sin^2\omega t \; d(\omega t)\right]^{1/2}$$

$$= V_m\left[\frac{1}{\pi}\int_{\alpha}^{\pi} \frac{1-\cos 2\omega t}{2} \; d(\omega t)\right]^{1/2}$$

$$= V_m\left[\frac{1}{2\pi}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_{\alpha}^{\pi}\right]^{1/2}$$

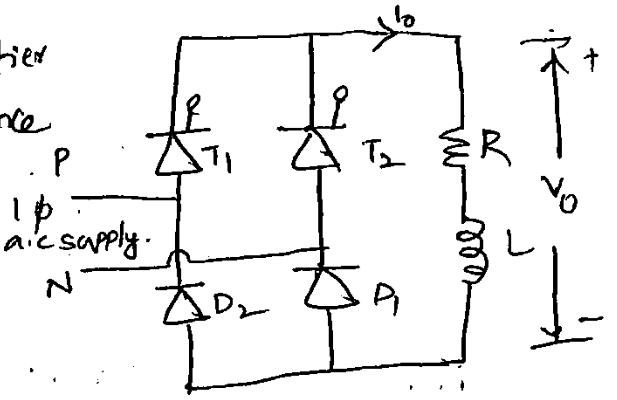
$$V_{rms} = V_m\left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2}$$

(iv) RMS load current :-

$$I_{rms} = \frac{V_{rms}}{R}$$

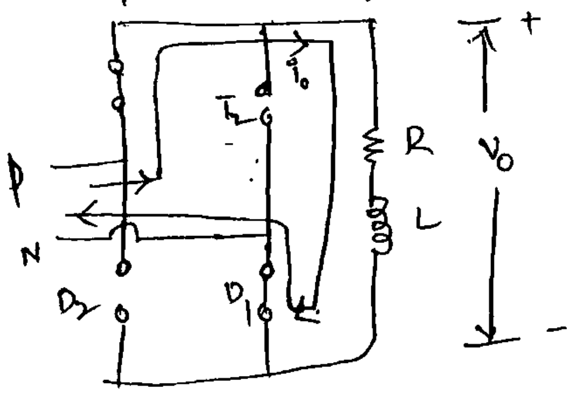
Half controlled bridge rectifier with RL load:-

Consider a half controlled bridge rectifier with inductive load. Here the inductance value should be large so the load current should be continuous.

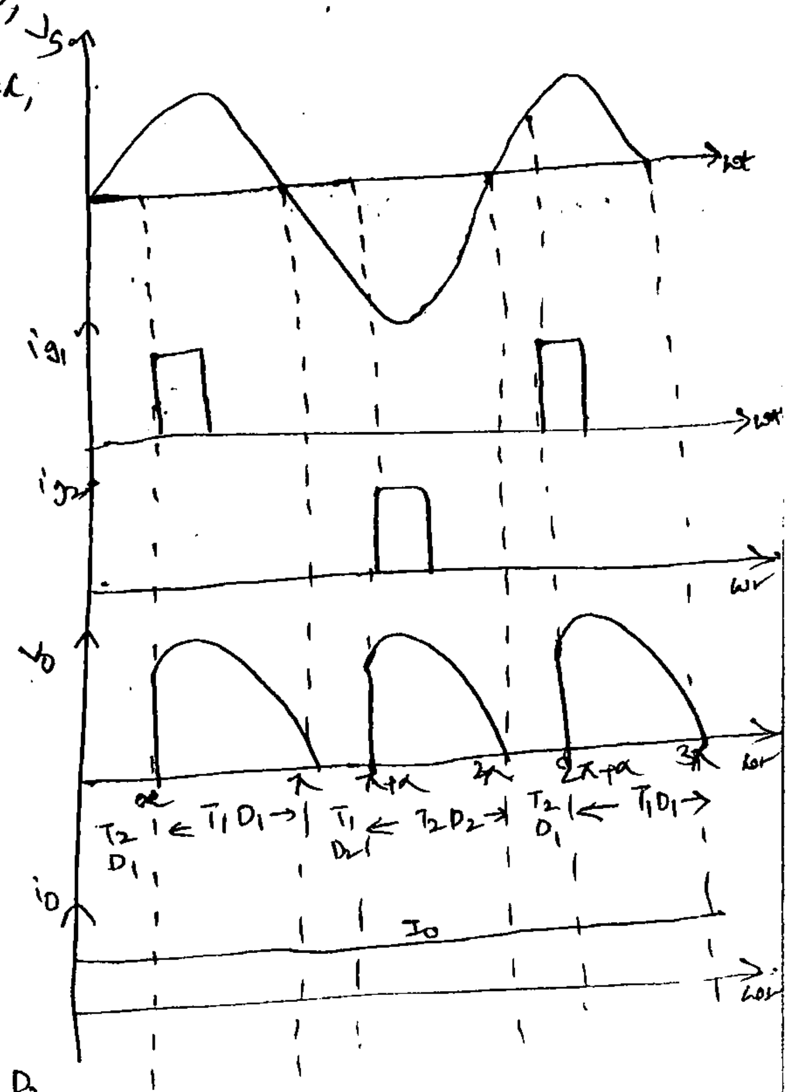


→ During the +ve half cycle (0 to π), SCR T_1 and D_1 are F.B. At $\omega t = \alpha$, SCR T_1 and Diode D_1 comes to the ON state. Now the current flows through the path

P – T_1 – RL – D_1 – N



Current path (α to π)



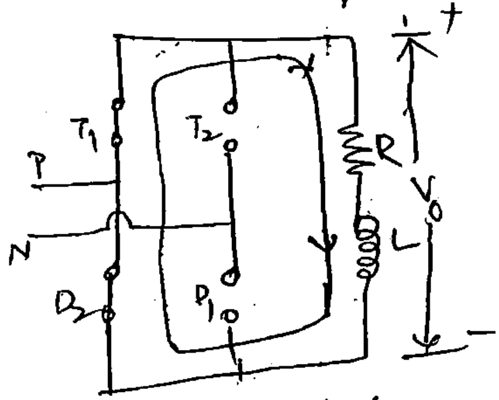
Voltage and current waveforms for 1ϕ half controlled rectifier with RL load.

→ Now, when the supply voltage reverses at $\omega t = \pi$, the diode D_2 is F B since diode D_1 is already conducting. Then D_2 comes to the ON state and the load current ~~passes~~ passes through D_2 and T_1.

The Diode D_1 is reverse biased due to supply voltage and it turns off thus the load current through the path.

L − D_2 − T_1 − R during the interval (π to π+α).

During this period o/p voltage should be zero because of closed current path.



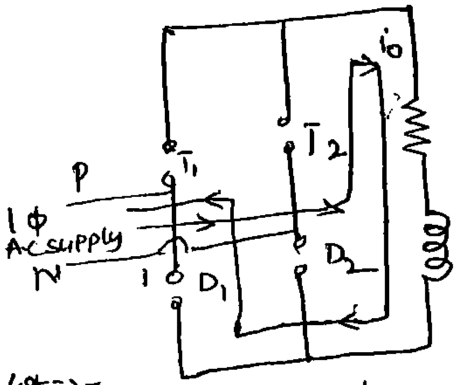
Current path (π to π+α)

→ During the −ve half cycle, at the instant (π+α), a triggering pulse is applied to the F.B SCR T_2. SCR T_2 is turned ON as, the supply voltage R.B T_1 and then it OFF by the Natural commutation.

During the period (π+α) to 2π, SCR T_2 and diode D_2 are conducting.

Load current path as follows:

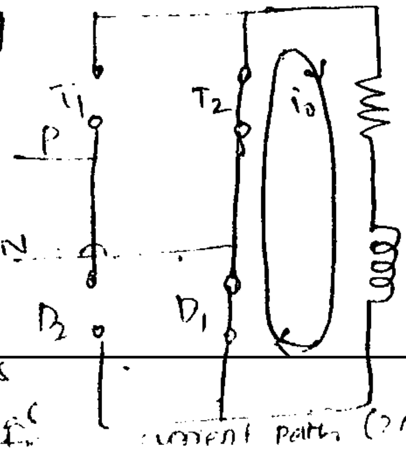
N − T_2 − RL − D_2 − P



current path (π+α to 2π)

→ when the supply voltage reverses at ωt=2π, the diode D_1 F.B since diode D_2 is already conducting. Then diode D_1 comes to ON state and load current passes through D_1 and T_2. The diode D_2 is R.B due to supply voltage and it turns OFF. Thus the load current freewheels through the path L − D_1 − T_2 − R during the interval from 2π to 2π+α

→ During this period, o/p current is positive but o/p voltage is zero due to closed circuit.

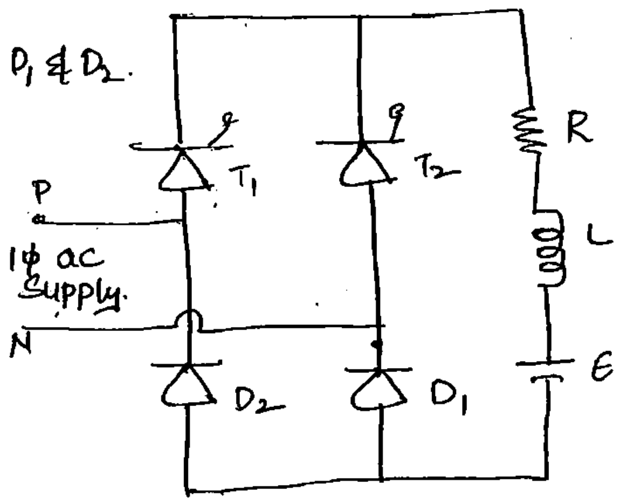


current path (2π to 2π+α)

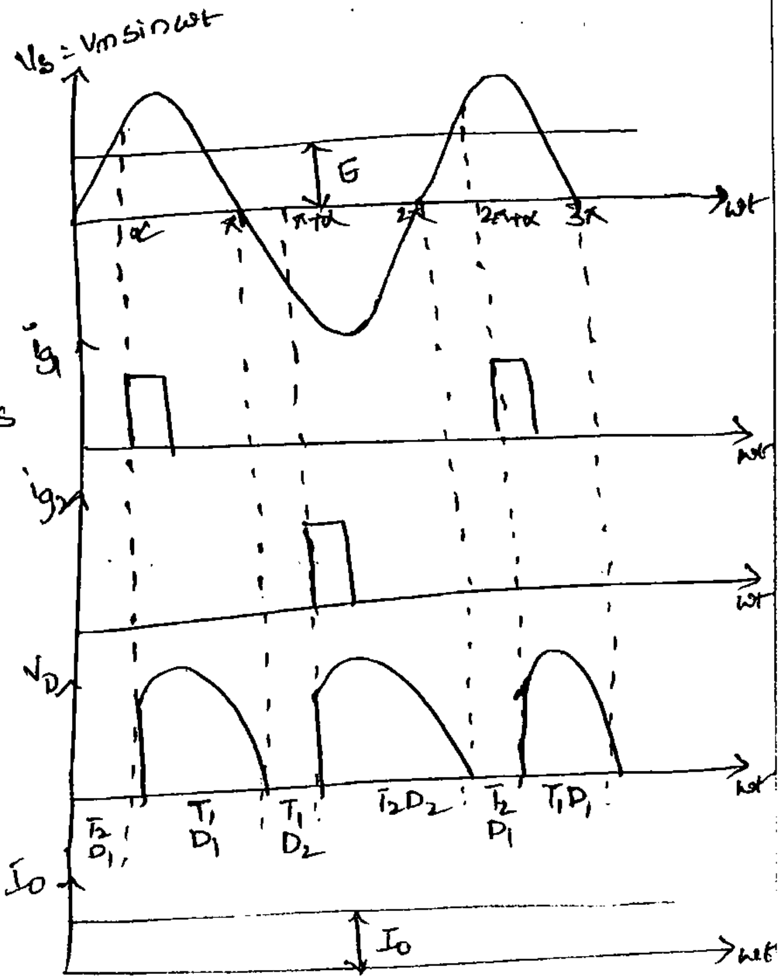
→ Here the conduction period of diodes & thyristors are equal, therefore the ...

1-ϕ Half controlled rectifier with RLE load:-

→ This circuit consists of two SCRs T_1 & T_2, two diodes D_1 & D_2. The load consists of RLE type. Here the load inductance should be large and load current is assumed continuous.



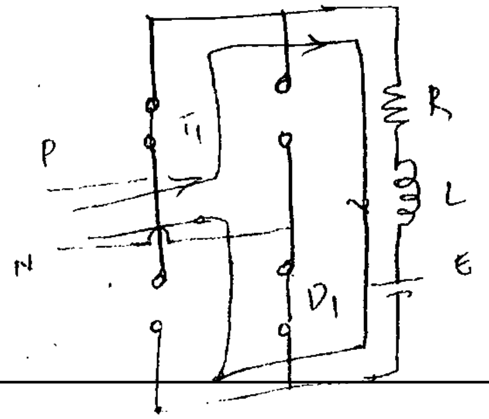
→ At $\omega t = 0$, SCR T_1 is F.B only. when source voltage exceeds E. Thus SCR, T_1 is triggered at firing angle $\omega t = \alpha$, SCR T_1 & D_1 comes to the ON state.



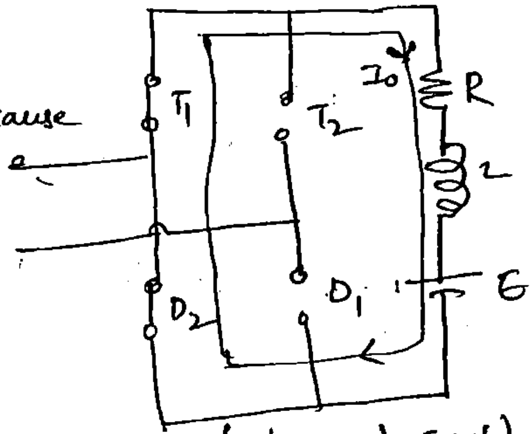
For the period α to π, I_o flows thru.

$$P - T_1 - RLE - D_1 - N$$

During that period positive voltage and positive current are attained



→ During the period π to (π+α), o/p voltage is negative and Diode D_2 is F.B and diode D_1 is R.B. The Diode D_2 comes to the ON state and the load current passes through D_2 and T_1. Thus load current freewheels through the path RLE – D_2 – T_1 – RLE. During this period o/p voltage should be zero. because of closed current path.

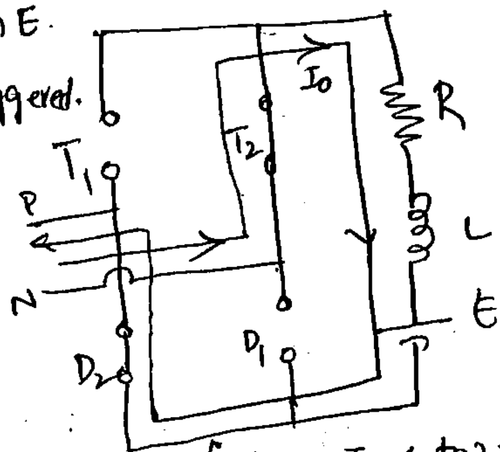


(ωt = π to π+α)

→ During the –ve half cycle, T_2 is F.B only. when source voltage is more than E. At ωt = π+α, V_s exceeds E, T_2 is triggered. The current flows through the path

N – T_2 – RLE – D – P_2.

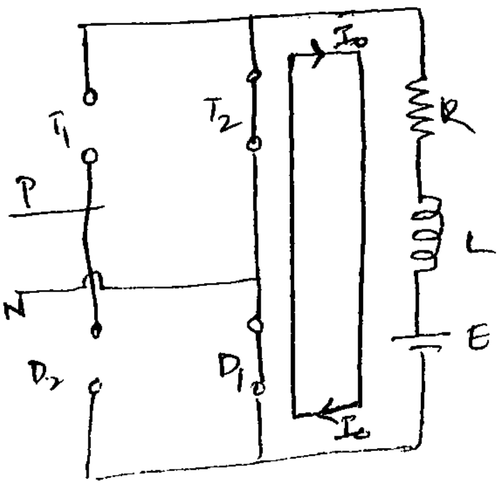
During this period +ve o/p voltage and current are obtained



(ωt = π+α to 2π)

→ When the V_s reverses at ωt = 2π, D_1 is F.B since D_2 is already conducting. Then D_1 comes to ON state and load current passes through D_1 & T_2. D_2 is R.B due to V_s and it turns off. Thus load current free wheels thru the path

RLE – D_1 – T_2 – RLE



(2π to 2π+α)

→ o/p voltage is zero and o/p current is +ve due to closed loop

The Average o/p Voltage is

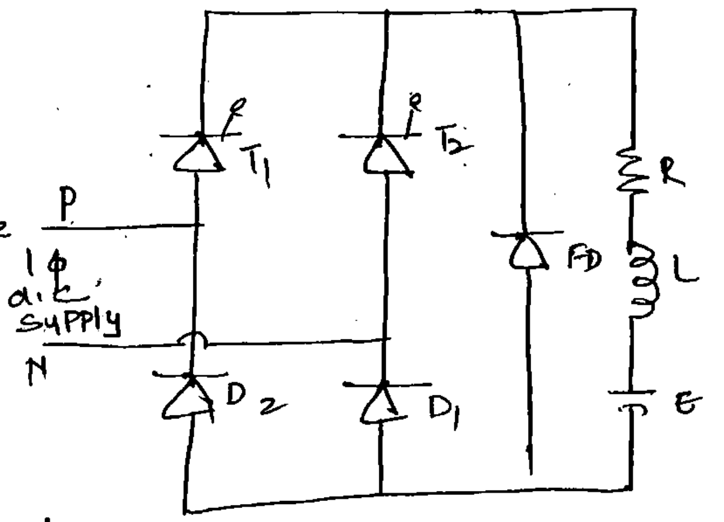
$$V_d = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t)$$

$$V_d = \frac{V_m}{\pi}(1+\cos\alpha)$$

∴ Average load current $I_{dc} = \frac{V_{dc}}{R}$

1-ϕ Half controlled Rectifier with RLE load and Freewheeling diode:-

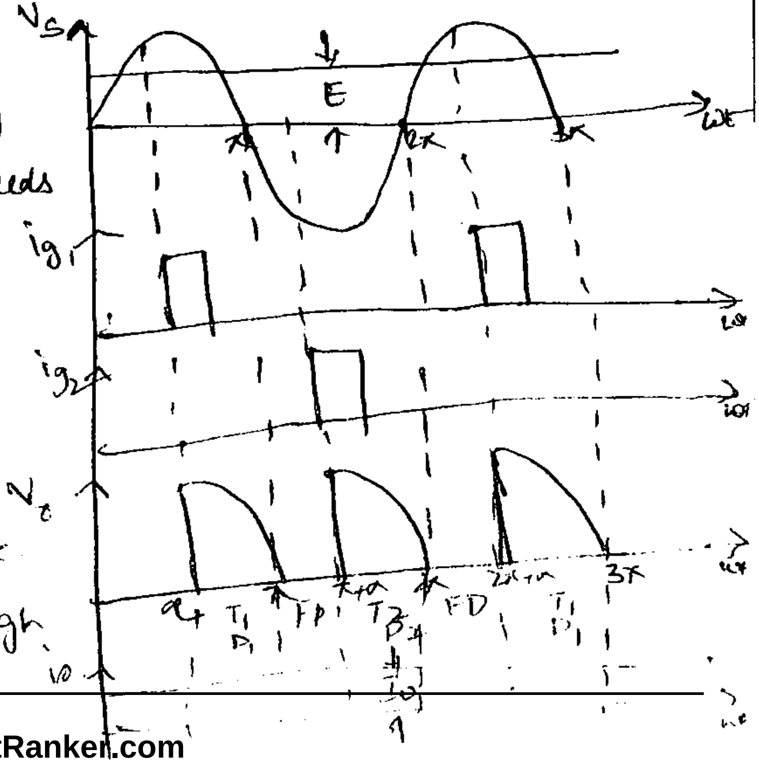
→ This circuit consists of two SCRs T_1 & T_2, two diodes D_1 and D_2. a free wheeling diode is connected across the load. The load consists of RLE type. Here the load inductance should be large and load current is assumed continuous



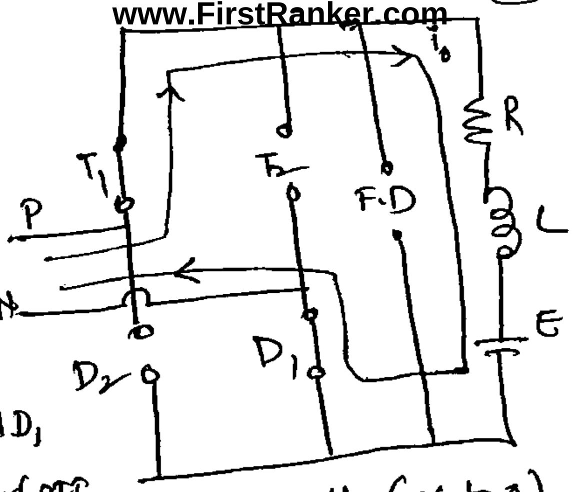
→ After ωt = 0, SCR T_1 is F.B only when source voltage $V_m \sin\omega t$ exceeds E, Thus SCR T_1 is triggered at firing angle ωt = α such that $V_m \sin\alpha > E$.

At α, T_1 & D_1 comes to ON state. i_o flows through the for (α to π)

P - T_1 - RLE - D_1 - N.



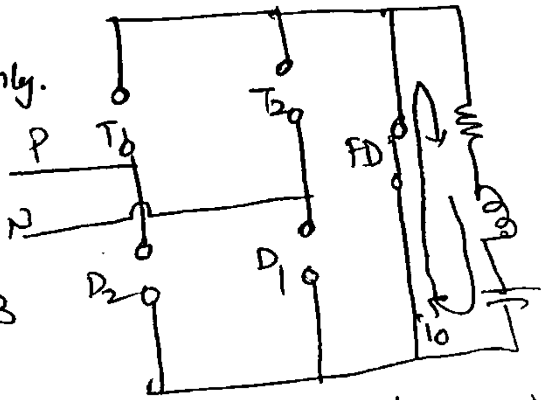
→ During the period from (π to $\pi+\alpha$), the i/p voltage is -ve and F.D is F.B. FD conducts to provide the continuity of current in the inductive load. The load current is transferred from T_1 and D_1 to F.D. and SCR T_1 & D_1 are turned off.



Current path (α to π)

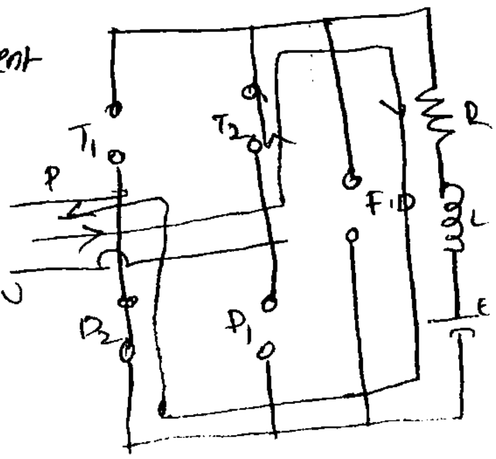
The current path is (RLE – FD – RLE)

→ During the -ve half cycle, T_2 is F.B only. when source voltage is more than E. At $\omega t = \pi + \alpha$, V_s exceeds E, T_2 is triggered. Soon after ($\pi+\alpha$), FD is R.B and is therefore turned OFF. Now the load current transferred from FD to T_2, D_2. The current flows through the Path: N – T_2 – RLE – D_2 – P.



Current path (π to $\pi+\alpha$)

→ During this period (($\pi+\alpha$) to 2π) we can get +ve Voltage & curr. At $\omega t = 2\pi$, FD is F.B and o/p current is transferred from T_2 & D_2 to FD.



The Avg. dc o/p voltage is

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

$$V_{dc} = \frac{V_m}{\pi} (1 + \cos\alpha)$$

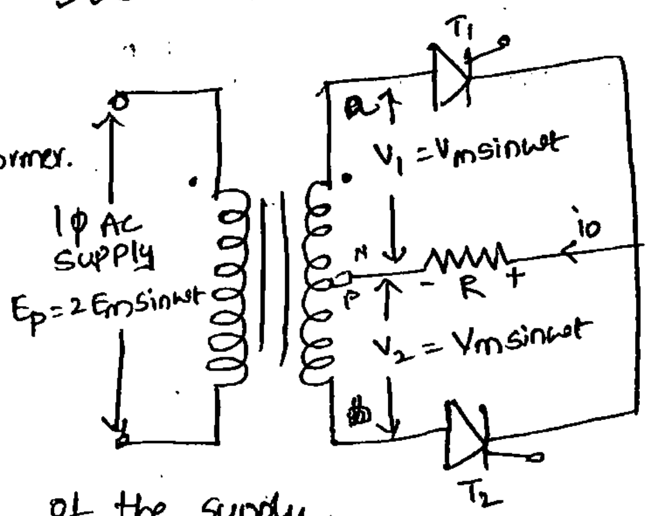
SINGLE PHASE FULLY CONTROLLED CONVERTERS

→ Depending upon the type of SCR configuration, 1-φ Full wave controlled rectifiers are classified into two types.

They are (i) Mid point type converter
(ii) Bridge type converter.

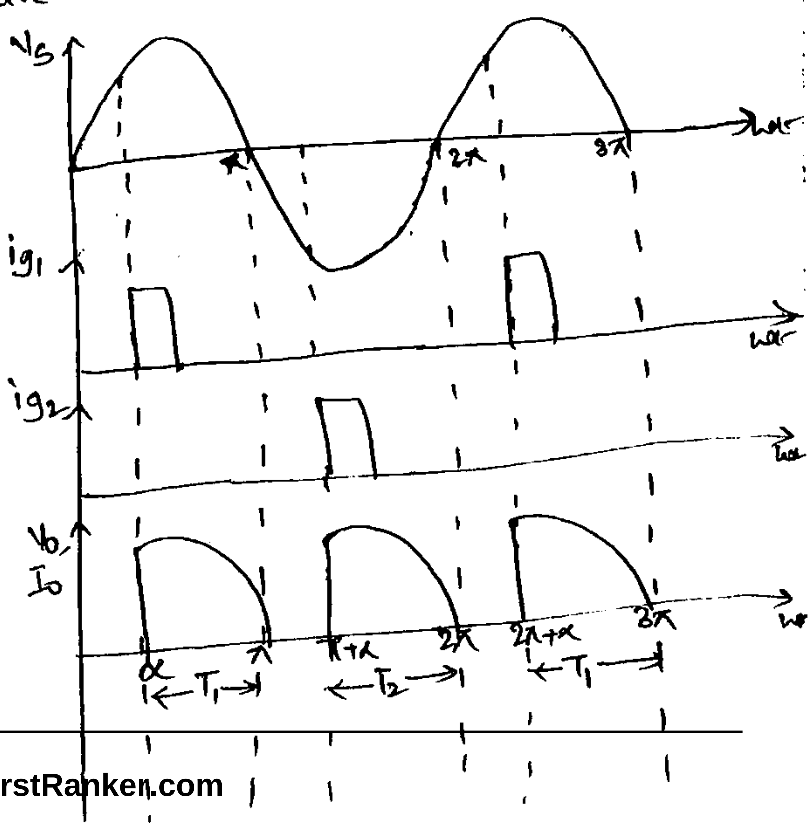
1-φ Full wave controlled rectifier with mid point type :- For R Load

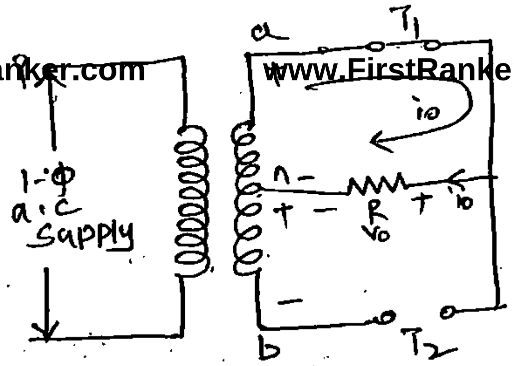
It consists of two SCRs and a centre tapped transformer. These converter is also known as two pulse converter because two triggering pulses are to be generated during every cycle of the supply.



→ Generally, these rectifiers are used for low ratings.

→ The input signal is coupled through the transformer to the centre tapped secondary.

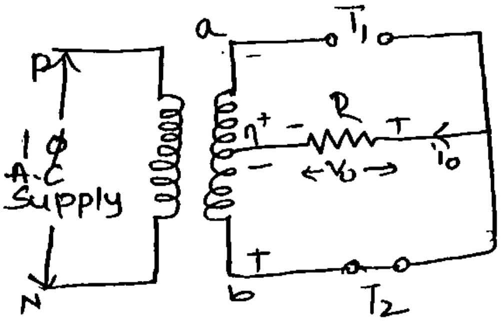




During the +ve half cycle (0 to π), when terminal a of the transformer is positive w.r.t terminal b (or) the secondary winding terminal a is positive w.r.t n. During this period, T_1 is F.B and T_2 is R.B

→ At a firing angle α, T_1 is triggered and the current path is (a – T_1 – R – n). This current continuous to flow upto angle π when the line voltage reverses its polarity and T_1 is turned off due to line commutation.

→ During the –ve half cycle (π to 2π), the terminal b of the transformer is +ve w.r.t n. SCR T_2 is F.B. At ωt = π+α, SCR T_2 is triggered, current would flow from terminal b, through T_2, the resistive load and back to the centre tap transformer. The current path is (b – T_2 – R – n)



→ Here, both SCRs T_1 & T_2 are triggered with the same firing angle, hence they share the load current equally.