Power electronics

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Module - I

Power Semiconductor devices

Power electronics is a subject that deals with the apparatus and equipment working on the principle of electronics but rated at power level rather than signal level.

example - Semiconductor power switches

① Thyristor, GTO etc

② Diodes, mercury are rectifier and thyratrons

Power electronics system today incorporate power semiconductor devices as well as micro electronics integrated circuits.

Advantages of power electronic system

- High efficiency due to low loss in power semiconductor devices
- Long life and less maintenance due to the absence of any moving parts
- Small size less weight which in turns lower installation

Disadvantages -

1. Power electronics converter circuits have a tendency to generate harmonics in the supply system as well as load circuit.
2. Ac to Dc and Dc to Ac converters operate at a low input power factor under certain operating conditions.

3. Power electronic controller have low over-load capacity.
4. The generation of power is different in power electronics converter systems.

Rating of power electronics semiconductor devices are -

1. Power diodes - Available upto 3000, 3500A, 1 KHz.
2. Thyristor (static conductor thyristor) - 6000V, 3500A, 1 KHz.
3. GTO (Gate-turn off thyristor) - 4000V, 3000A, 10 KA.
4. MCTs (Mos controlled thyristors) - 600V, 60A, 20 KA
5. Triac → 1200 V, 300 A, 400 Hz.
6. BJTs → 1200 V, 400 A, 10 KHz
7. Power MOSFETs → 1000 A, 50 A, 100 KHz
8. IGBTs (Insulated gate bipolar transistor) →
   1200 V, 400 A, 20 KHz.

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③ BJTs → 1200V, 400A, 10KHz
④ Power MOSFETs → 500V, 50A, 100KHz
⑤ IGBTs (Insulated gate bipolar transistors) → 1200V, 400A, 20KHz

Based on
(a) turn-on and turn-off characteristics
(b) gate signal requirements

The power semiconductor devices can be classified as

1. <u>Diodes</u>

Diodes are uncontrolled rectifying devices. Their on and off states are controlled by power supply.

2. <u>Thyristors</u>

These are control rectifying devices. They have controlled turn on by gate signal. After the thyristors are turn on by gate signal, they remain latched in on state due to internal regenerative action.

3. <u>Controllable switches</u>

These devices are turn on or turn-off by control signal so different controllable switches are
BJT, MOSFET, IGBT, GTO, SITH, SIT, MCT

<u>Note</u>
* SCR, GTO, SITH and MCT require pulse gate-signal for turning them on, once these devices are on, gate pulse is removed.
* BJT, MOSFET, IGBT, SIT require continuous signal for keeping them in turn-on state.
* Unipolar voltage devices are BJT, MOSFET, IGBT and MCT
  Bipolar voltage " Thyristors and GTOs
* Bi directional current capability devices
  Triac & RCT (reverse conducting thyristor)
* Unidirectional current devices
  Diode, SCR, GTO, BJT, MOSFET, IGBT, SIT, SITH, MCT

<u>Power diodes</u>

Difference between power diode and signal diode

<u>power diode</u>	<u>signal diode</u>
① voltage, current, power ratings	① voltage, current, power ratings are lower.

② power diode operate at lower switching speed. | ② signal diode operate at higher switching speed.

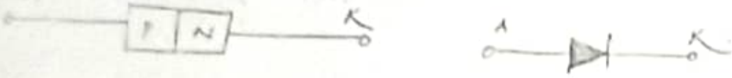
③ complex in structure and operation. | ③ simple in structure and operation

④ n⁻ type layer called drift region between p⁺ layer (anode) and n⁺ layer (substrate) or (cathode) ... is given to support large ... voltages | ④ n⁻ layer is absent in signal diode.

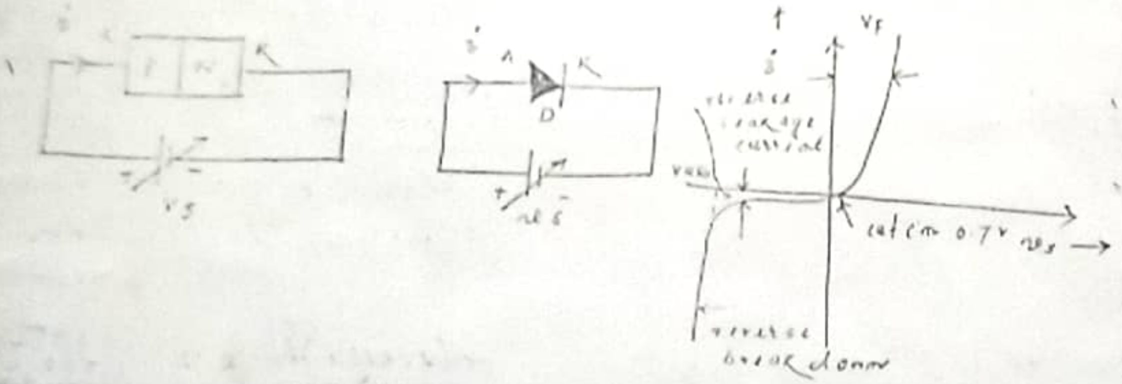
It is used as free wheeling diodes for a.c to d.c conversion, for recovery of trapped energy.

Power diode is a two-layer, two terminal, p-n semiconductor device. It has one p-n junction formed by alloying and diffusing.

The two terminals of diode are anode and cathode



V-I characteristics



When anode is +ve w.r.t cathode diode is in forward biasing mode. But current does not flow due to +ve and ... Vbar's at the junction i.e initially the diode current is zero. The junction break when cut-in voltage is applied to the junction.

Cut in voltage is the voltage ~~is the voltage~~ at which the diode turn on, it is also called thresold voltage. From zero to cut in voltage, forward diode current is very small.

Beyond cut-in voltage, the diode current rises rapidly and the diode is said to conduct.

... si diode cut in voltage is around 0.7 V and when diode conducts there is a forward voltage drop of the order of 0.8 V to 1 V.

When cathode is +ve w.r.t anode, the diode is in reverse biasing mode and a small leakage current of the order of milliamperes or microamperes flows due to minority carriers. The leakage current increases slowly with the reverse voltage until break down or avalanche voltage is reached. At this break down voltage, diode is turned on in the reverse direction. If the current in the reversed direction is not limited by a series resistance, the current will become quite high to destroy the diode.

The reverse avalanche break down of a diode is avoided by operating the diode below specified peak repetitive reverse voltage VRRM

Diode Manufacturers also indicate the value of peak inverse voltage (PIV) of a diode.

PIV is the largest reverse voltage to which a diode may be subjected during its working. PIV is same as VRRM

* power diodes are now available with forward current ratings of 1A to several thousand amperes and with reverse voltage ratings of 50V to 3000V or even.

Diode reverse recovery characteristics

Reverse recovery characteristics shows the variation of current in the diode with time when charges in the two layers recover.

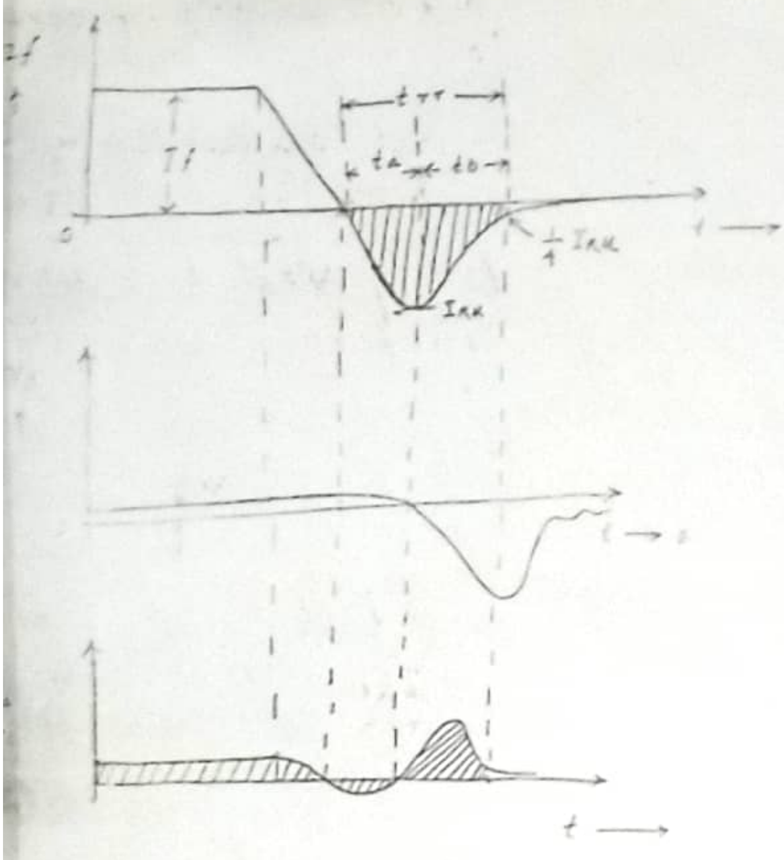
When forward diode current decays to zero, the diode continues to conduct in the reverse direction because of the presence of stored charges in the two layers.

The reverse current flows for a time called reverse recovery time trr.

The diode regains its blocking capability until reverse recovery current decays to zero.

Reverse recovery time (trr)

It is defined as the time between the instant forward diode currents become zero and the instant forward reverse recovery current decays to 25% of its reverse peak value I_{RR}.



he reverse recovery time is divided into two times
and tb

trr = ta + tb

the time between zero crossing of forward
current and peak reverse current IRM

During time ta charge store in depletion layer is
removed.

tb = the time between IRM to 0.25 IRM.

During tb charge from two semiconductor layers
removed.

The shaded area represents the stored charge or
reverse recovery charge QR which must be removed
during the reverse recovery time trr.

Softness factor or s-factor

The ratio tb/ta is called s-factor and it is a
measure of the voltage transients occur during the
diode recovers.

If s-factor is small, diode has large oscillatory
voltages

s-factor = 1, diode is called soft-recovery
diode with low oscillatory voltages.

Types of power diodes

According to reverse recovery characteristics there are 3 types of power diodes.

(a) General purpose diodes
(b) Fast recovery diodes
(c) Schottky diodes

General purpose diodes

If power diodes have high recovery time of the order of about 25 µs then they are called General purpose diodes

current ratings - vary from 1A to several thousand amperes

voltage ratings - vary from 50V to about 5KV.

Applications - Battery charging, electric traction, electroplating, welding and UPS

Fast recovery diodes

If power diodes have low reverse recovery time of about 5 µs or less then the diodes are called fast recovery diodes

current ratings - vary from about 1A to several thousand amperes

voltage ratings - from 50V to about 3KV.

Applications

used in choppers, commutation circuits, switched mode power supplies, Induction heating.

Schottky diodes

If the power diodes use metal to semiconductor junction for rectification instead of p-n junction then the diodes are called schottky diodes.

Diodes are also characterised by very fast recovery time and low voltage drop.

rectified current flow only by Minority carriers and this avoids the turn off delay accompanied with Minority carrier recombination.

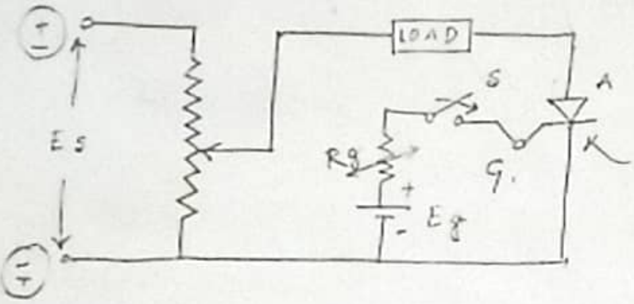
voltage ratings: reverse voltage ratings are limited to about 100V them onto heat sinks

SCRs are solid state devices, they are compact, possess high reliability, and have low loss. Due to these features, SCR is employed these days for all high-power controlled devices.

Static V-I characteristics of SCR

Static V-I characteristics represents the characteristics between anode to cathode voltage V_a versus anode current I_a

circuit diagram



In this circuit diagram ① Anode and cathode of thyristor connected to source through Load to limit the current at conduction state due to low resistance of SCR.

② Gate and cathode terminal is connected to a variable resistance, positive gate voltage through a switch S. Variable resistance is connected to supply different gate currents.

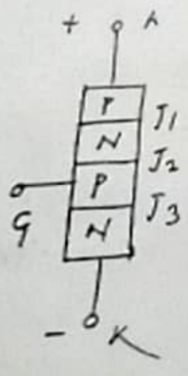
③ A potential divider is connected to supply different source voltage to SCR.

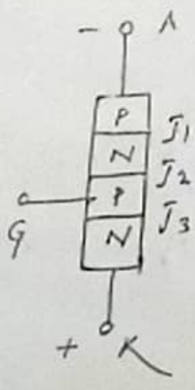
Modes of operation

SCR has three modes of operation, depending upon the polarities of anode, cathode and gate.

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

Description





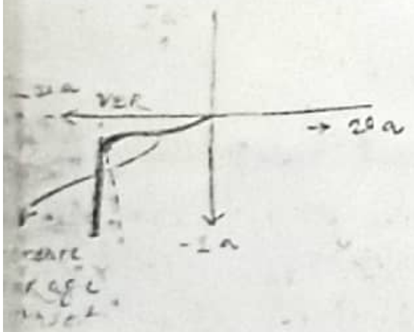
reverse blocking mode

when A is -ve and K is +ve with switch s open then Junctions J_1, J_3 are seen to be reversed biased where J_2 is forward biased since two junctions J_1, J_3 are in reverse biasing mode current flows due to Minority carriers. and to middle junction J_2 current flows due to majority carriers so a small leakage current of the order of few milli amperes or Micro amperes flows depending upon the rating of SCR, that current is called reverse leakage current. It Means the SCR is considered it is in off state. If the reverse voltage is increased then at a critical breakdown voltage (V_{BR}) called reverse break down voltage an avalanche occurs at J_1 and J_3 and reverse current increases rapidly. Large current associated with VBR gives rise to more losses in the SCR. This may lead to damage of thyristor as the junction temperature may exceed its permissible temperature rise limit.

*** note : The Max working reverse voltage across a SCR should not exceed V_{BR}.

when reverse voltage applied across a thyristor < V_{BR} then SCR offers a high impedance in the reverse direction. Hence SCR in reverse blocking modes behaves as an open switch.

characteristics,



when load resistance is present, due to Large anode current, break down at V_{BR} cause More voltage drop across load and V-I characteristics bent to the right of vertical line drawn at V_{BR}. Neither it is vertical

forward blocking mode

when A is +ve and K is -ve, with switch s open; then J_1 and J_3 are forward biased and J_2 is reverse biased. Due to one reverse biasing junction, a small current flows through the SCR called forward leakage current. when the forward voltage is increased then the reverse biased Junction J_2 get avalanche break down at a voltage called forward breakover voltage V_{BO}.

when forward voltage less than V_{BO}, SCR offers high impedance. so the SCR behaves as an open switch in forward blocking mode.

Forward conduction mode

A thyristor brought from forward blocking mode to forward conduction mode by turning it on by exceeding the forward break over voltage or by applying a gate pulse between gate and cathode.

In this mode SCR is in on state and behaves like a closed switch. In on state voltage drop across the SCR is of the order of 1 to 2V depending on the rating of SCR and the voltage drop increases with increase in anode current.

Turn on Methods of SCR

When anode is +ve and cathode is -ve, a SCR can be turned on by any one of the following method

1. forward voltage triggering
2. gate triggering
3. $\frac{dv}{dt}$ triggering
4. Temperature triggering
5. Light triggering

Forward voltage triggering

with gate open when anode to cathode forward voltage is increased, the reverse bias junction J_2 break. This break down is called avalanche break down. and the avalanche break down occur at a voltage called forward break over voltage V_{BO}.

* The on-state is represented by low voltage across SCR and high forward current.

After avalanche break down, junction J_2 looses its reverse blocking capability. Therefore if anode voltage is reduced below V_{BO}, SCR will continue conduction of the current and SCR can only be turn off by reducing the anode current below a certain level.

Holding current - holding current is the Min. value of anode current below which the SCR is turn off.

- Magnitude of V_{BO} ≤ as V_{BR} but less than V_{BR} (and it not) damage the SCR.

so the final voltage rating of SCR during dis is V_{BO}.

Gate triggering

In gate triggering a (+ve) gate voltage is applied to Gate (G) and cathode (K). with the supply of gate current charges are injected into inner p layer and reduce the forward break over voltage required.

The value of forward break over voltage depends upon the magnitude of gate current.

Higher gate current lower V_{BO} and vice versa.

[illegible]

In gate triggering three types of signals used for this purpose

(a) d.c signals (b) pulse signals (c) a.c signals.

- **d.c signals**

In this method of triggering a d.c voltage of proper magnitude and polarity is applied between the gate and cathode of the device in such a way that gate becomes +ve w.r.t cathode when the applied voltage is sufficient to produce the required gate current, the device start conducting.

disadvantage [illegible] signal has to be applied, at [illegible]

Drawback: both power and control circuits are d.c and there is no isolation between the two.

- **A.c signals**

In this method the firing angle control is obtained very conveniently by changing the phase angle of control signal. Here the gate drive is maintained for one half cycle after the device in turn on and a reverse voltage is applied between the gate and the cathode during the negative half cycle. It provides proper isolation between the power and control circuit.

Drawback: A separate transformer is required to step down the [illegible] supply which adds to the cost.

- **pulse signals**

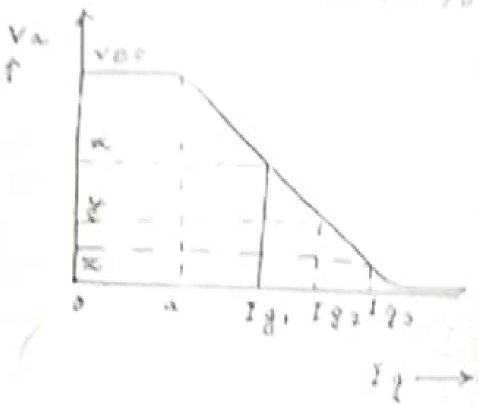
It is the most popular method.

In this method, the gate drive consists of a single pulse appearing periodically or a sequence of high frequency pulses. This is known as carrier frequency gating. A pulse transformer is used for isolation.

Advantage:- There is no need of applying continuous signal and hence the gate losses are very much reduced. Electrical isolation is also provided between the main device signals and the gating signals.

Description

When positive gate current is applied, gate p layer is flooded with electrons from the cathode because N layer is heavily doped as compared to gate p layer. As SCR is forward biased some of these electrons reach junction J_2 as a result width of depletion layer around J_2 is reduced. This causes the junction J_2 to break down at an applied voltage lower than VBO. If the magnitude of gate current is increased, more electrons reach junction J_2 as a result it gets turned on at a much lower forward applied voltage.



For gate current $I_g = 0$, forward voltage is VBO.
For $I_g < 0a$ " " " VBO

So for a SCR for turn on gate current is more than minimum gate current required to turn on.

Typical gate current magnitudes are of the order of 20 to 200mA.

For gate current > 0a, VBO is reduced.

Once SCR conduct reverse bias junction J_2 no longer exists, therefore if gate current is removed conduction of current from anode to cathode remains unaffected.

If gate current is reduced to zero before the anode current attains a certain value then the thyristor will turn off.

Latching current

Latching current is defined as the minimum value of anode current which it must attain during turn-on process to maintain conduction when gate signal is removed.

Latching current is always more than holding current.
Latching current = 2 to 3 times of holding current

$\frac{dv}{dt}$ triggering

When forward voltage applied across anode and cathode the two outer junctions are forward biased but the inner junction is reverse biased. The reverse biased junction has the characteristics of a capacitor due to charges existing across the junction.

If the entire anode to cathode forward voltage Va appear across the junction and if the charge is Q then a charging current i flow denoted by

$$i = \frac{dQ}{dt} = \frac{d}{dt}(CVa) \quad \text{where } C = \text{capacitance of middle junction}$$

$$= C\frac{dVa}{dt} + Va\frac{dC}{dt}$$

since C is const

$$i = C\frac{dVa}{dt}$$

The charging current play the role of gate current and turn on the SCR. If $\frac{dva}{dt}$ is more then charging current increase and turn on the SCR

Temperature triggering

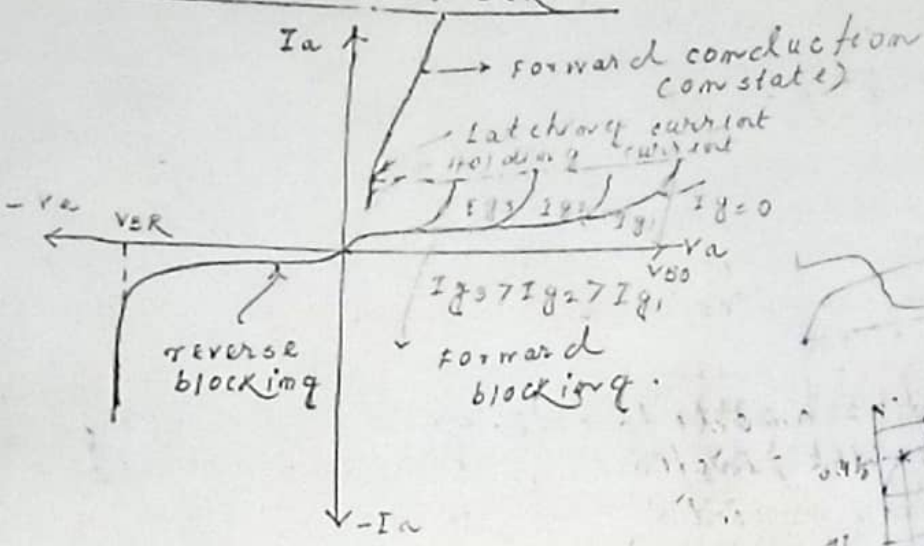
For a semiconductor material, the width of depletion is reduced by increasing the junction temperature. Similarly for SCR, when anode to cathode voltage is nearer to VBO, by increasing the temperature of middle junction to a certain value the reverse biased junction collapse and making the SCR conduct.

Light triggering

In this method of triggering energy is imparted by radiation. A recess is made in the inner p-layer and energy particles called photons are bombarded. with the help of electron-hole pairs external energy, electron-hole pairs are generated in the device and increase the no of charge carriers and turn on the

ex:- LASCR (Light activated SCR).

V-I characteristics of SCR



Switching characteristics of SCR

The static characteristics of SCR gives no indication abo. the speed at which the SCR is switched from from forward blocking state to the conducting state and vice-versa. So the time variation or speed is given by switching characteristics.

The time variations of voltage across the SCR and the current through it during turn-on or turn off process is called switching, dynamics or transient characteristics.

Switching characteristics during turn-on :-

A forward biased thyristor or SCR is turn on by apply a positive gate voltage between gate and cathode. So there is a transition time from off state to on state.

The transition time is called turn on time.

So **turn on time** is defined as the time during which changes from forward blocking state to final on state.

Turn on time is divided into three intervals

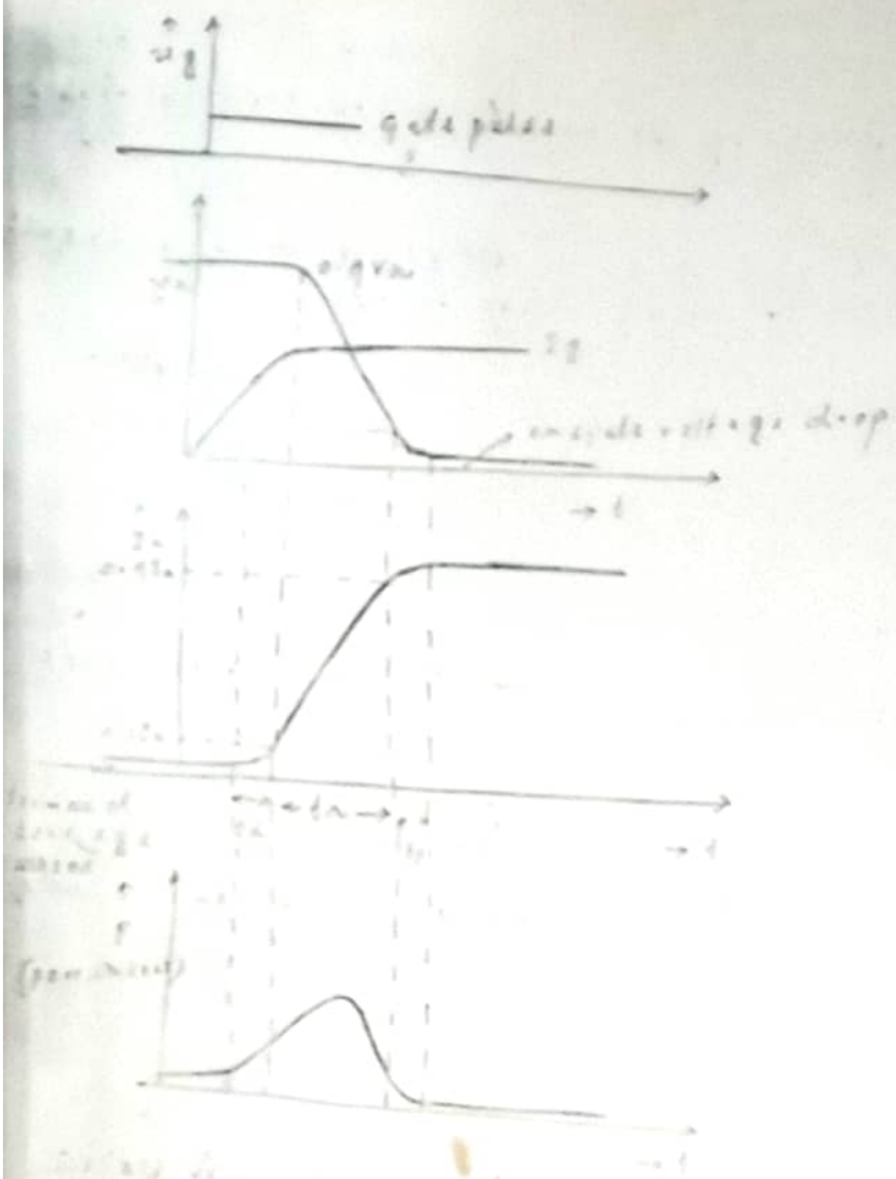
(a) Delay time td
(b) rise time tr
(c) spread time tp

Delay time (td)

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

or

It is the time during which anode voltage falls from Va to 0.9Va



Delay time can be decreased by applying high gate current and more forward voltage between anode and cathode. [illegible] is a fraction of a microsecond.

Rise time (t_r)

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

or

It is the time during which forward anode voltage falls from 90% to 10% of its final value.

Rise time (t_r) is inversely proportional to the magnitude of gate current and its build up rate i.e t_r is reduced [illegible] and steep current pulses are applied to the gate.

[illegible] depends upon type of circuit. For R-L ckt t_r is [illegible] for R-C ckt t_r is less.

During rise time, turn on losses in the SCR are the highest due to high (V_a) and high (I_a) occurring together in SCR. As these losses occur only over a small conduction region, local hot spots may formed and the device may get damaged.

Spread time (t_p)

It is the time taken by the anode current to rise from 0.9 Ia to Ia

or

It is the time for the forward blocking voltage to fall from 0.1 Va to on state voltage drop of 1 to 1.5 V.

During spread time conduction spread to the entire cross section of cathode.

After spread time anode attains its steady state value and voltage drop across the SCR is the on state voltage drop of 1 to 1.5 V

* t_r - range (1 - 4 μ sec)
* Total turn on time depends upon anode circuit parameter and the gate signal wave shapes

When gate current is several times higher than minimum gate current required to turn on then the thyristor is called hard fired.

Hard firing reduces turn on time and enhances di/dt capability

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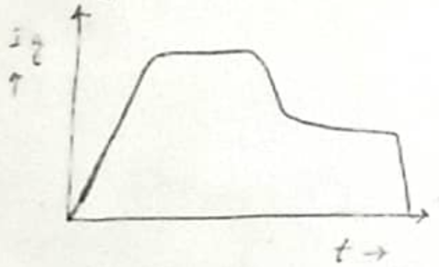
Typical gate current waveform



The initial high value of gate current is reduced to a lower value after staying for several microseconds in order to avoid unwanted turn off of the device.

Switching characteristics during turn off

Once the SCR conduct the gate loses control over it and the device can be brought back to the blocking state only by reducing the forward current to a level below holding current.

So the process of turning off the SCR from on state to blocking state is called commutation process.

If forward voltage is applied to the SCR at the moment its anode current falls to zero, the device will not be able to block this forward voltage as the holes and electrons in the four layers are still favourable for conduction. The device though is therefore turn on even though gate signal is not applied. Due to this reason the SCR is

D.c choppers

There are different techniques available for obtaining variable d.c voltage from fixed d.c voltage. Because speed control of some drives require variable d.c voltage.

The techniques are.

1. Resistance control.
2. Motor - Generator set.
3. A.c link chopper (Inverter-rectifier).
4. D.c chopper (d.c to d.c power converters).

Resistance control

In this method, a variable resistance is inserted between source & Load. For a given output voltage, different values of resistances are needed for different values of Load current.

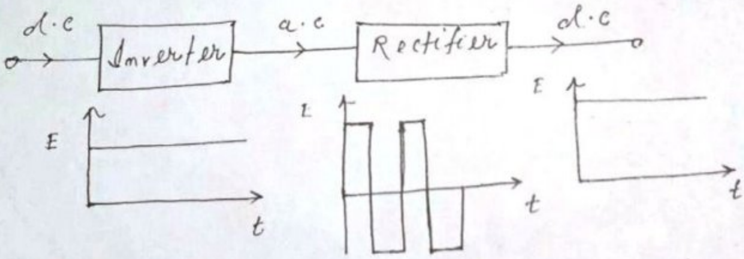
But in this method energy Loss is more.

Motor-generator set

seperately excited generator is used to supply variable voltage an to motor for variable speed. The voltage can be vary from zero to rated value.

But the set up is costly, slower in response and Less effecient because of the generator field time constant.

A.c link chopper



In this method, d.c is first converted to a.c by an inverter. A.c is then stepup/step down by a transformer and then rectified back to d.c by a rectifier.

Advantage.

transformer provides isolation between load and source.

disadvantage.

This technique is costly and less effecient.

D.c chopper

A d.c chopper is a static device or switch used to obtain variable d.c voltage from a source of constant d.c voltage.

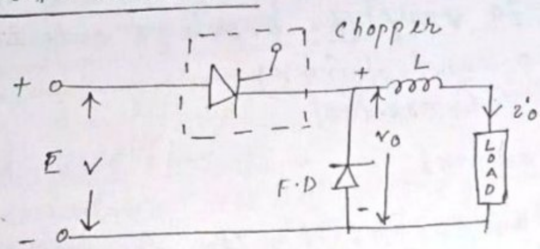
Advantages

saving in power, more efficiency, faster response, smooth control, Lower Maintenance, small size, Lower cost from other techniques.

principle of operation of chopper

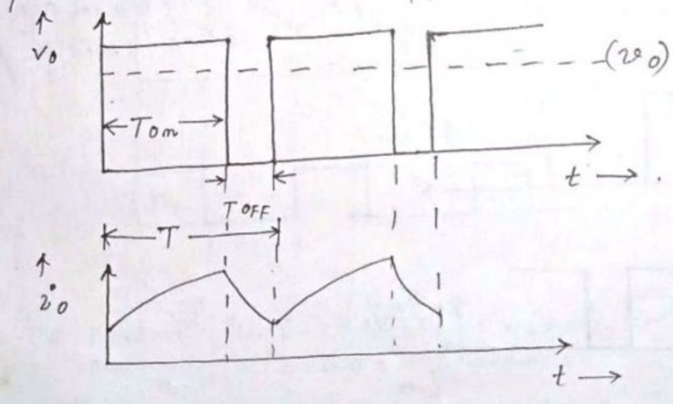
A chopper is a thyristor on/off switch. It connects and disconnects load from source and produces a chopped load voltage from a constant input supply voltage.

Basic circuit



A chopper is represented by an SCR inside a dotted square.

It is triggered periodically and is kept conducting for a period Ton and is blocked for a period TOFF. The chopped load voltage is as below



During the period Ton, when chopper is on, the supply terminals are connected to load. During the interval TOFF, when chopper is off load current flows through the freewheeling diode F.D. As a result, Load terminals are short circuited by F.D and load voltage is therefore zero during TOFF.

Now average load voltage v_0 is given by

$$E_0 = \frac{v_0 \times T_{ON}}{T_{ON} + T_{OFF}}$$

(1)

where T_{ON} - on-time of the chopper.

T_{OFF} = Off-time of the chopper.

$T = T_{ON} + T_{OFF}$ = chopping period.

If δ = duty cycle then

$$\delta = \frac{T_{ON}}{T}$$

$$\therefore \boxed{E_0 = V_0 \cdot \delta}$$

Thus the load voltage can be controlled by varying the duty cycle of the chopper.

Control strategies

Two types of control strategies are employed in d.c choppers to vary the average output voltage.

1. Time-ratio control (TRC)
2. current-limit control.

Time-ratio control

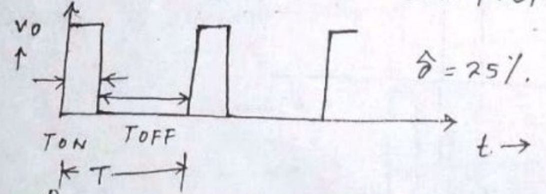
In time ratio control, $\frac{T_{ON}}{T}$ is varied. $\frac{T_{ON}}{T}$ is affected in two ways

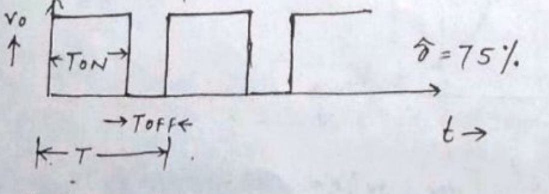
(a) by variable frequency operation

(b) by constant frequency operation.

constant frequency operation / pulse width modn control

In this type of control strategy, the on time T_{ON} is varied but the chopping frequency $f = 1/T$ is kept const. This control is also called pulse width modulation control.





variable frequency system / freq modn control

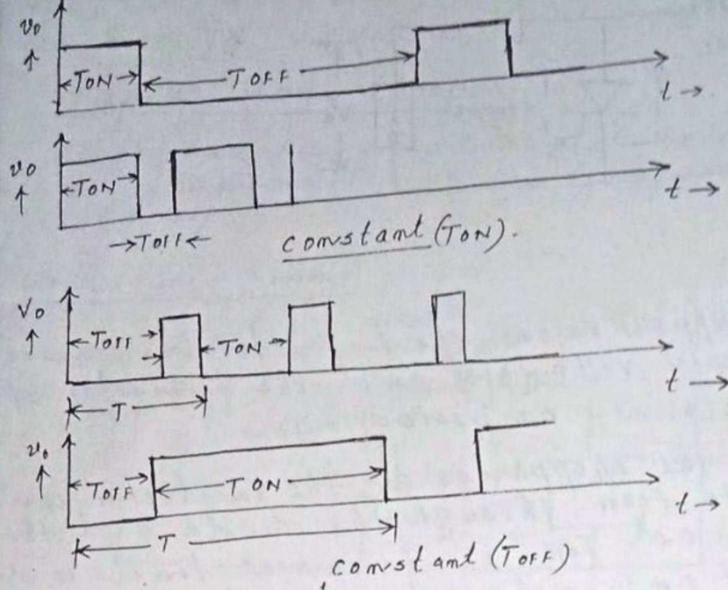
In this type of control strategy, chopping frequency is varied either by varying

(a) turn on time (T_{ON})

or

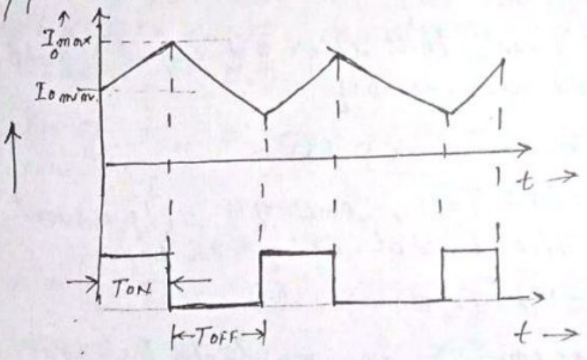
(b) turn off time (T_{OFF}).

This type of control strategy is called frequency modulation control.



current Limit control

In current limit control strategy, the chopper is switched ON and OFF so that the current in the Load is maintained between two limits. when the current exceeds upper Limit, the chopper is switched off. During off period, Load current freewheels and decreases exponentially. when it reaches the Lower Limit, the chopper is switched on.



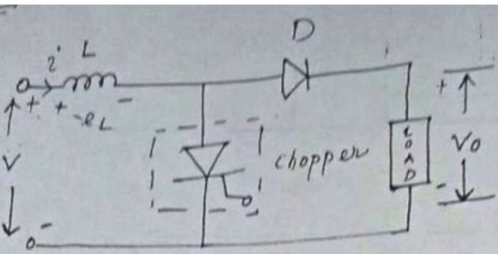
The current limit control is used only when the Load has energy storage elements.

The difference between I_{0max} & I_{0min} decides the switching frequency.

step-up choppers

The basic chopper circuit gives a Maximum voltage V_0 Less than supply voltage V_0. so the chopper configuration is called step-down chopper.

But if the chopper configuration produce voltage higher than the Input voltage at Load. This is called step up chopper.



principle

When chopper is on, the inductor L is connected to the supply voltage V and the inductor stores energy during on period, Ton.

When the chopper is off, the inductor current is forced to flow through the diode and the load for a period Toff. As the current tends to decrease polarity of e.m.f induced in inductor L is reversed to that of shown in fig. and voltage across the load V_o becomes

$$V_o = V + L\frac{di}{dt} \quad \text{--- (1)}$$

i.e the inductor voltage adds to the source voltage to force the inductor current into the load. and energy is released by the inductor

During time Ton, the energy input to the inductor from source is given by

$$W_i = V i \, T_{on} \quad \text{--- (2)}$$

During the time Toff, energy released by inductor to the load is given by

$$W_o = (V_o - V) i \, T_{off} \quad \text{--- (3)}$$

If the system is assumed to be lossless then the two energies are equal.

$$\therefore V i \, T_{on} = (V_o - V) i \, T_{off}$$

$$\therefore V_o = V \frac{T_{ON} + T_{off}}{T_{OFF}} \Rightarrow V_o = V \frac{T}{T - T_{ON}} = V \frac{1}{\frac{T}{T} - T_{ON}/T}$$

But $\delta = \frac{T_{ON}}{T}$

$$\therefore \boxed{V_o = V \frac{1}{1-\delta}} \quad \text{---- (4)}$$

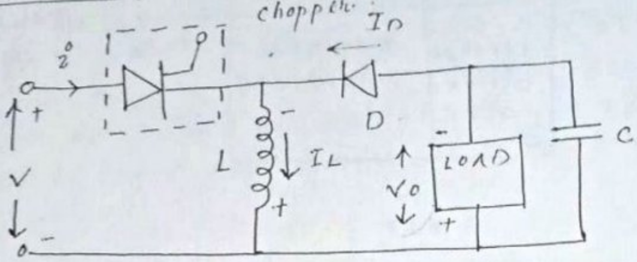
For $\delta = 0$, $V_o = V$ and $\delta = 1$, $V_o = \infty$

Hence for variation of duty cycle δ in the range $0 < \delta < 1$, the output voltage V_0 vary in the range $V < V_0 < \infty$.

step-up/down chopper

A chopper can also be used both in step-up and step-down modes by continuously varying its duty cycle.

circuit diagram



principle

When the chopper is on, the supply current flows through the path (V_+ − CH − L − V_-). Hence inductor L stores the energy during the TON period.

When the chopper CH is OFF, the inductor current tends to decrease and polarity of e.m.f induced in L is reversed. The inductance energy discharges in the load through the path ($L+$ − Load − D − L_-)

During TON, energy stored in inductance is given by

$$W_i = V i T_{ON} \quad \ldots \quad (1)$$

During TOFF, the energy fed to the load is

$$W_0 = E\, V_0 i\, T_{OFF} \quad \ldots \quad (2)$$

For a lossless system,

$$W_i = W_0$$

i.e. $V i T_{ON} = V_0 i T_{OFF}$

$$\Rightarrow V_0 = V \cdot \frac{T_{ON}}{T_{OFF}} \quad \ldots \quad (3)$$

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

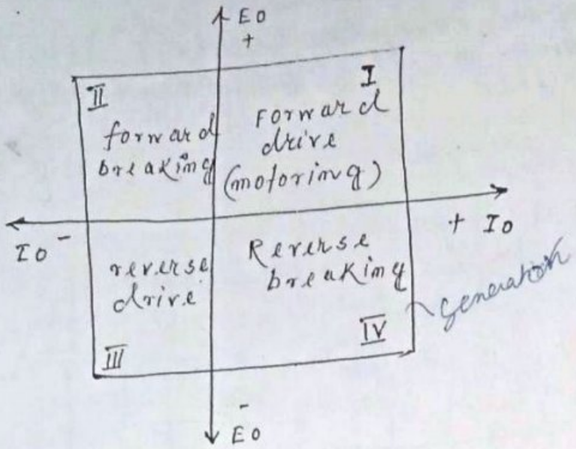
But $\delta = \frac{T_{ON}}{T}$.

$$\therefore V_0 = V \cdot \frac{1}{\frac{1}{\delta} - 1} = V \cdot \frac{\delta}{1 - \delta} \quad \ldots \quad (4)$$

For $0 < \delta < 0.5$, the step-down chopper operation is achieved and for $0.5 < \alpha < 1$, step-up chopper operation is achieved.

Chopper configuration

Chopper may be classified according to the number of quadrants of the output voltage (Eo) - output current (Io) diagram in which they are capable of operating.



The classification depends upon the polarity of output voltage & current.

① If the load is a seperately excited motor of constant field then +ve voltage and +ve current in the 1st quadrant give rise to forward drive (quadrant - I)

② reversing the polarity of both the armature voltage and current results in a reverse drive (quadrant - III)

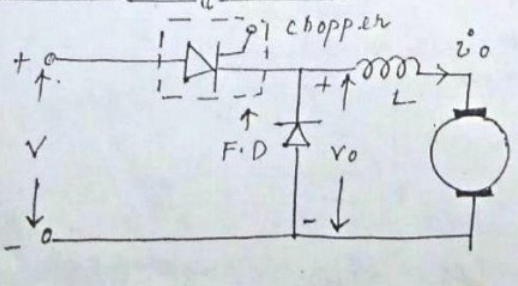
③ In quadrant II & IV, the direction of energy flow is reversed and the motor operates as a generator breaking rather than driving.

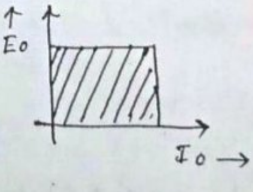
For the different chopper configuration a d.c motor assumed as a load.

In I & III quadrants, a resistance may be serve as a load but if the load mode is generating mode then the load should be capable of delivering sustained power.

Type - A chopper (1st quadrant)

circuit diagram





principle

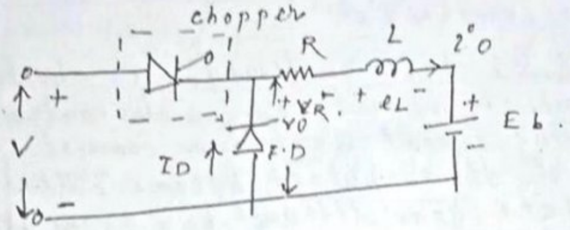
When chopper is on $V_0 = V$ and the current flow in the direction as shown. When the chopper is off, $V_0 = 0$ but the current i_0 flows in the load in the same direction through the free wheeling diode F.D. Therefore both average load voltage V_0 and i_0 are positive and thus power flows from source to load.

Therefore this configuration is used for motoring operation of d.c Motor Load.

Type-A chopper is also called as step-down chopper as average output voltage V_0 is less than the d.c input voltage V. It is also called motoring chopper.

Description with R-L-E Load

circuit :-

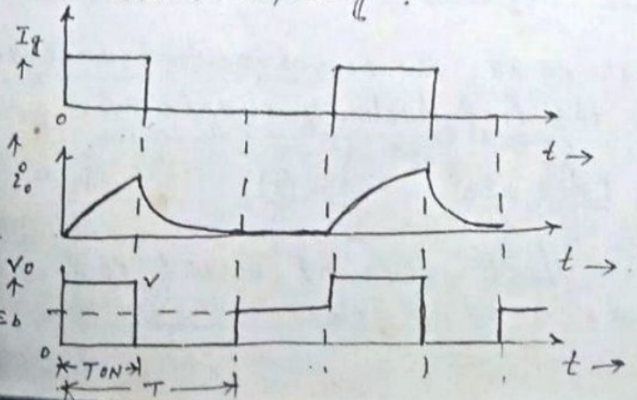


Let the chopper is connected to R, L, E_b Load. It has two modes of operation.

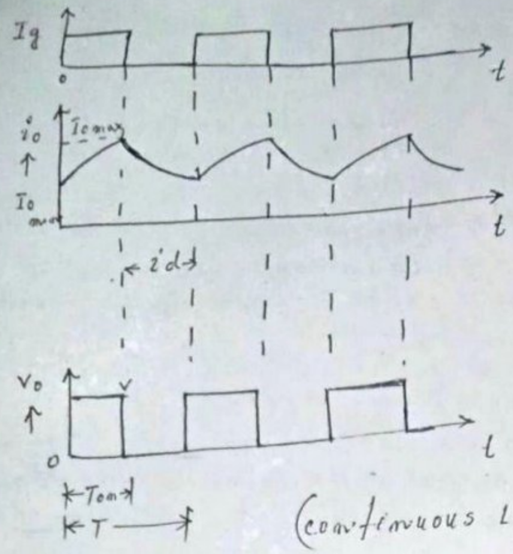
When chopper is on, supply voltage V appears at the terminals of the armature circuit and i_0 increase untill it reached the steady state value i.e

$$i_0 = E \quad \frac{V - E_b}{R} \qquad (1)$$

The average current I_0 in the circuit can be controlled by commuting chopper before the current has reached the value i_0, and allow it to decay through diode F.D either to zero or to some lower value that it had attained while CH_1 was conducting.



(Discontinuous Load)



(continuous Load current)

If the process of turning chopper on and off is repeated at regular intervals, then average value io is controlled.

In fig (a) turn on time Ton is shorter than chopping period T, which results in a discontinuous current. Therefore the current waveform consists of series of pulses and these pulses become identical when steady state conditions has been reached.

In fig(b) If turn on time is Longer in relation to T the Load current will not decay to zero during the interval $T_{on} < t < T$ but will merely decrease until chopper is again turn on. Thus in steady state current flow continuously.

Mode-1

$0 \le t \le T_{on}$

when chopper is on, current flows through the path ($V_+ - R - L - E_b - V_-$). For this mode of operation the differential eqn is.

$$V = Ri_o + L\frac{di_o}{dt} + E_b \quad \text{--- (1)}$$

Mode-2

$T_{on} \le t \le T$.

when chopper is off, the Load current continuously flowing through the free wheeling diode F.D.

$$0 = Ri_o + \frac{L di_o}{dt} + E_b \quad \text{--- (2)}$$

for mode-1 initial value of current is I_{omin} and for mode-2 it is I_{omax}.

by taking Laplace transformation of eqn ① and ②

$$\left(\frac{V-E_b}{s}\right) = R I_o(s) + L[sI_o(s) - I_{o\,min}] \quad ③$$

$$-E_b/s = R I_o(s) + L[sI_o(s) - I_{o\,max}] \quad ④$$

by taking Inverse Laplace of eqn ③

$$i_o(t) = \left(\frac{V-E_b}{R}\right)(1-e^{-R/Lt}) + I_{o\,min}\, e^{-R/Lt}, \quad 0 \le t \le T_{on} \quad ⑤$$

and by taking Laplace transformation of eqn ④

$$i_o(t) = -\frac{E_b}{R}(1-e^{-t/\tau}) + I_{o\,max}\, e^{-t/\tau}; \quad T_{on} \le t \le T. \quad ⑥$$

At $t = T_{on}$, $i_o(t) = I_{o\,max}$.

& at $t = T_{off}$, $i_o(t) = I_{o\,min}$

subsituting these values in eqn ⑤ and ⑥ respectively and solving we get

$$\boxed{I_{o\,max} = \frac{V}{R}\left[\frac{1-e^{-T_{on}/\tau}}{1-e^{-T/\tau}}\right] - E_b/R}$$

where $\tau = L/R$

and

$$\boxed{I_{o\,min} = \frac{V}{R}\left[\frac{e^{T_{on}/\tau}-1}{e^{T/\tau}-1}\right] - \frac{E_b}{R}}$$

steady state ripple

when load current i_o varies between $I_{o\,max}$ and $I_{o\,min}$ then ripple current $(I_{o\,max} - I_{o\,min})$.

$$(I_{o\,max} - I_{o\,min}) = \frac{V}{R}\left[\frac{(1-e^{-T_{on}/\tau})(1-e^{-(T-T_{on})/\tau})}{(1-e^{-T/\tau})}\right]$$

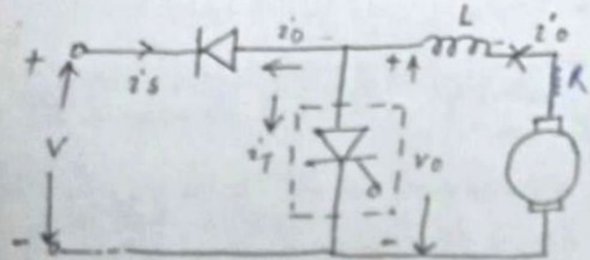
∴ p.u ripple current

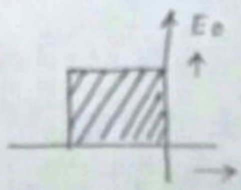
$$\frac{I_{o\,max}-I_{o\,min}}{(V/R)} = \frac{(1-e^{-\alpha T/\tau})(1-e^{-(1-\alpha)T/\tau})}{(1-e^{-T/\tau})}$$

where $\alpha = T_{on}/T$.

second quadrant or type-B chopper

circuit diagram



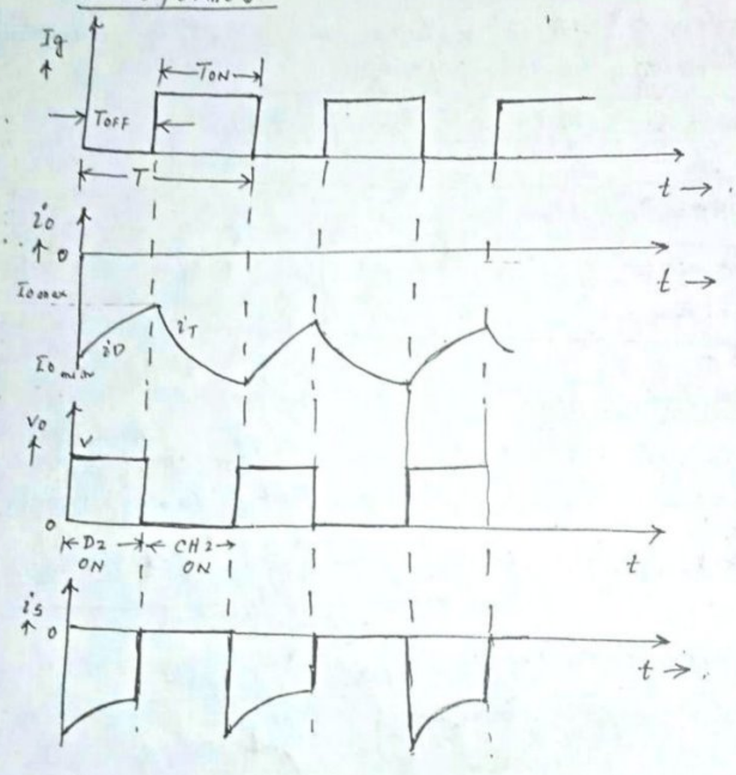


principle:

In this case the Load must contain a d.c source E_b, like a battery or a (d.c motor).

when chopper is on, $v_0 = 0$, but E_b drives current through L and chopper. Inductance L stores energy during Ton period. when CH is off, $V_0 = E_b + L\frac{di}{dt}$ exceeds source voltage V_s. As a result diode D_2 is forward biased and begins conduction, thus allowing power to flow to the source. chopper may be on or off, currents I_0 flows out of the Load, current i_0 is therefore treated as negative. since Here $v_0 > V$, it is called step-up chopper.

wave forms



Let i_0 has value I_{0min} at $t = 0$. For interval $0 < t < T_{OFF}$ diode D_2 conducts and $v_0 = V$ so the voltage eqn becomes.

$$L\frac{di_0}{dt} + Ri_0 = V - E_b \quad \cdots (1)$$

$$\therefore i_0(t) = \left(\frac{V - E_b}{R}\right)\left(1 - e^{-t/\tau}\right) + I_{0min}\, e^{-t/\tau} \quad \cdots (2)$$

At $t = T_{OFF}$, I_0 reached max. magnitude I_{0max} where $I_{0min} < I_{0max} < 0$.

so from eqn (2)

$$\checkmark\; I_{o\,max} = \left(\frac{V - E_b}{R}\right)\left(1 - e^{-T_{OFF}/\tau}\right) + I_{o\,min}\, e^{-T_{OFF}/\tau} \quad \text{(3)}$$

At $t = T_{OFF}$, chopper CH_2 is turned on and at T_{OFF}, V_o becomes zero and $i_o = i_{max}$

During interval $T_{OFF} < t < T$, voltage eqn becomes

$$\frac{di_o}{dt'} + \frac{R i_o}{L} = -\frac{E_b}{L} \quad \text{where } t' = t - T_{OFF} \quad \text{(3)}$$

$$\text{and } I_o = \frac{-E_b}{R}\left(1 - e^{-t'/\tau}\right) + I_{o\,max}\, e^{-t'/\tau} \quad \text{(4)}$$

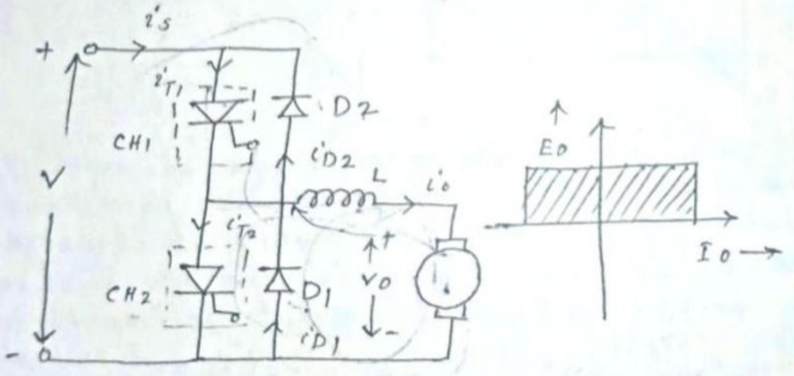
At the end of the cycle when $t = T$ or $t' = T - T_{OFF}$, i_o must be returned to its initial value $I_{o\,min}$

$$\checkmark\; I_{o\,min} = \frac{-E_b}{R}\left(1 - e^{-(T-T_{OFF})/\tau}\right) + I_{o\,max}\, e^{-(T-T_{OFF})/\tau} \quad \text{(5)}$$

Type-C chopper (1st & 2nd)

Type-C chopper is obtained by operating type-A and type-B chopper in parallel.

circuit



This circuit has both one quadrant and two quadrant operation.

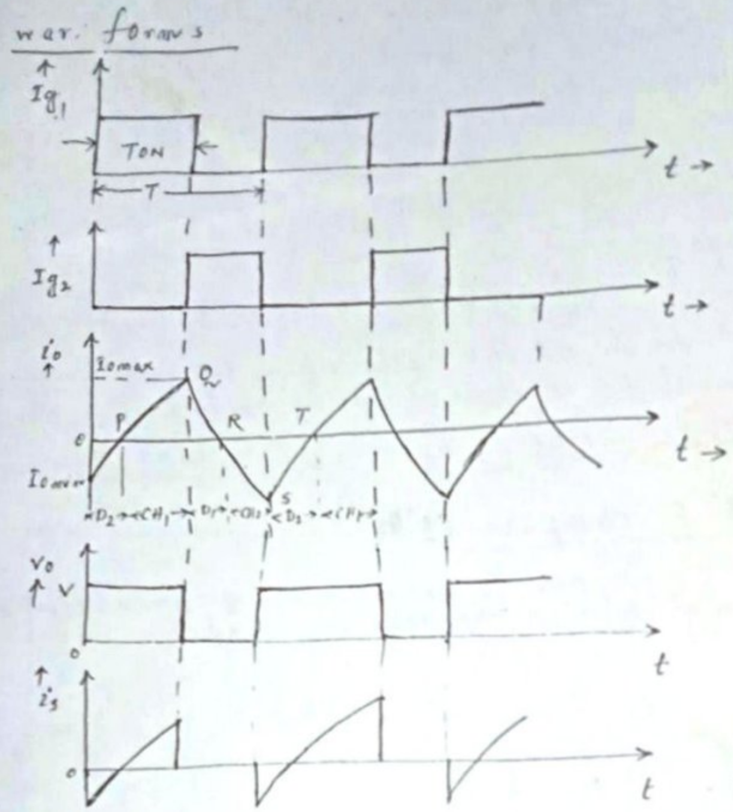
For 1st quadrant operation, CH_1 and D_1 performs the functions and if average load current I_o is high enough, CH_2 and D_2 do not conduct, even though CH_2 receives a gating signal.

For 2nd quadrant operation, CH_2 and D_2 perform the functions and if the average load current I_o has a sufficiently large negative value, CH_1 and D_1 do not conduct, even though CH_1 receives a gating signal.

principle:

Initially, when both the chopper are off, both the diodes D_1 and D_2 becomes OFF and therefore Load is isolated from the supply.

wave forms

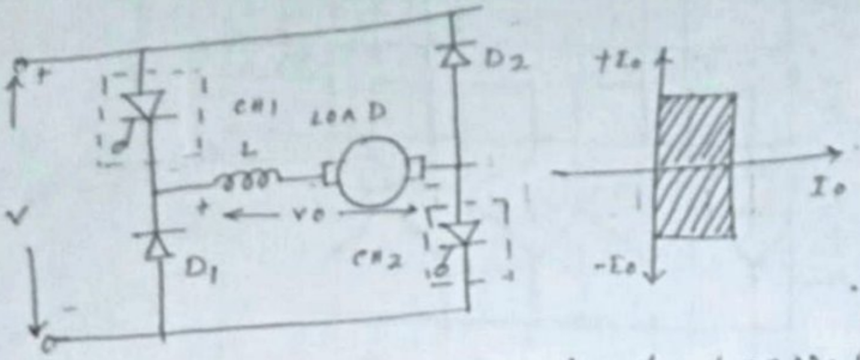


At point P, chopper CH_1 is triggered and it starts to conduct. The Load current is positive and Load receives power from the supply and output voltage $V_O = V$. At point Q, CH_1 is turn off and inductance L forces the Load current to flow through D_1 till $L\frac{di}{dt}$ equals to E_b, and Load current i_o becomes zero. So Diode conducts from Q to R.

At point R, if gate signal to chopper CH_2 is available the back e.m.f E_b of the motor forces current in the opposite direction through L and CH_2. This continues until CH_2 is turn-off and CH_1 is turn-On. Now when CH_2 is turn-off, the energy of the inductance forces current through Diode D_2 to the supply. The input current becomes negative. During this period CH_1 cannot conduct due to reverse bias but come into conduction when the input current reduces to zero, provided gate signal is available to CH_1 and both the Load and input current become positive.

Type-D chopper (Type 4th)

circuit diagram



Type D chopper is a two quadrant chopper permits either to change voltage polarity while maintaining current polarity or vice-versa.

It has two modes of operation and two gating

① Ton > T/2 represent one mode and signals overlap.

② other mode for which Ton < T/2 and only one chopper is turn on at any instant or none of the chopper is turn on. Here load current is assumed to be continuous.

Mode-1 (Ton > T/2)

when both the choppers are turn on, the current flows through the path V - CH1 - Load - CH2 - V. There for both the diodes are turn off. The supply voltage V is applied to the load circuit and Load current io increases.

when only one chopper turn on, that chopper and one of the diode short circuit the load branch and provide a path in which some of the energy stored in inductance L may be dissipated in maintaining a decreasing load current io.

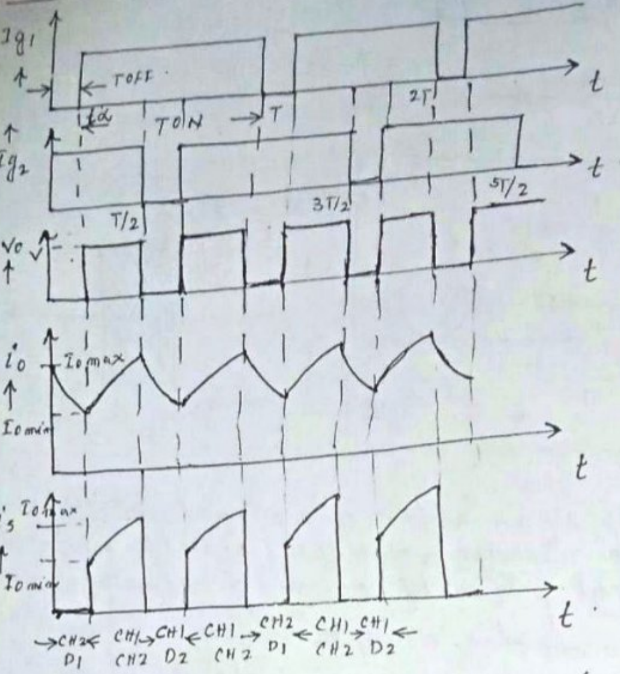
circuit analysis

For steady state operation, it is necessary in this mode that V > Eb. since one cycle of the load circuit variables take place in time T/2, two durations are to be considered.

① Interval 0<t<tx, let us assume that load current is continuous.

At t=0; let io = Iomax.

Mode-1 wave forms



For this duration CH2 is only turned-on and current flows through CH2 & D1.

so voltage eqn becomes.

$$R i_0 + L\frac{di_0}{dt} + E_b = 0 \quad \ldots\ldots (1)$$

soln with initial condn becomes.

$$i_0 = -\frac{E_b}{R}\left(1 - e^{-t/\tau}\right) + I_{o\,max}\, e^{-t/\tau}, \quad 0 < t < t_\alpha \quad (2)$$

where $\tau = L/R$ sec.

At $t = t_\alpha$, $i_0 = I_{o\,min}$

$$\therefore I_{o\,min} = -\frac{E_b}{R}\left(1 - e^{-t_\alpha/\tau}\right) + I_{o\,max}\, e^{-t_\alpha/\tau} \ldots (3)$$

(ii) Interval $t_\alpha < t < T/2$

Let $t' = t - t_\alpha$.

Now both the choppers are turn on.

∴ voltage equation becomes.

$$R i_0 + L\frac{di_0}{dt'} + E_b = V \quad \ldots\ldots (1)'$$

soln with initial condn becomes.

$$i_0 = \left(\frac{V - E_b}{R}\right)\left(1 - e^{-t'/\tau}\right) + I_{o\,min}\, e^{-t'/\tau}, \quad t_\alpha < t < T/2 \quad (2)'$$

At $t = T/2$, $i_0 = i_{o\,max}$

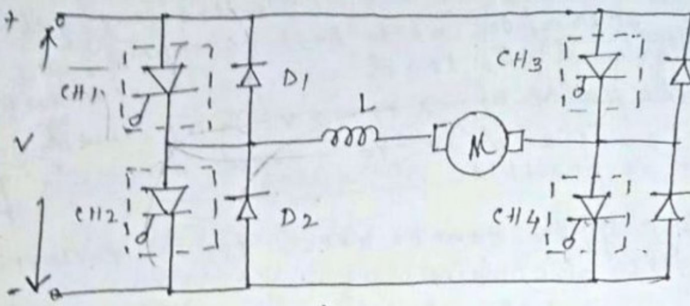
$$\therefore I_{o\,max} = \left(\frac{V - E_b}{R}\right)\left(1 - e^{-(T/2 - t_\alpha)/\tau}\right) + I_{o\,min}\, e^{-(T/2 - t_\alpha)/\tau} \quad (3)'$$

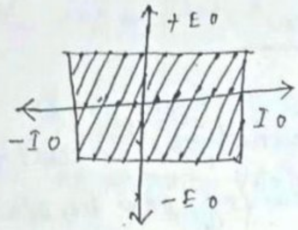
Type-E chopper or (four quadrant chopper)

Type-E chopper is the parallel combination of two type-C chopper.

In this chopper configuration with motor load, the sense of rotation can be reversed without reversing the polarity of excitation.

circuit diagram





In the above figure

① CH_1, CH_4, D_2 and D_3 constitute one type C.

② CH_2, CH_3, D_1, D_4 form another C-type.

principle

when CH_4 is turn on, then the combination CH_4, D_4 forms a short circuit.

chopper CH_3 should not be turned on at the same time as CH_4 because that would short circuit the source.

when CH_4 continuously on, and CH_3 always off, operation of CH_1 and CH_2 make E_0 +ve and I_0 reversible and operation in the 1st and second quadrant is possible.

on the other hand, with CH_2 continuously on and CH_1 always off, operation of CH_3 and CH_4 make E_0 negative and I_0 reversible and operation in the third and fourth quadrants is possible.

explanation

when choppers CH_1 and CH_4 are turned on, current flows through the path, $V_+ \rightarrow CH_1 \rightarrow$ Load $\rightarrow CH_4 \rightarrow V_-$. since both E_0 and I_0 are positive we get 1st quadrant operation when both the choppers CH_1 and CH_4 are turn off, load dissipates its energy through the path Load $\rightarrow D_3 \rightarrow V_+ \rightarrow V_- \rightarrow D_2 \rightarrow$ Load. In this case E_0 is negative while I_0 is positive so fourth quadrant operation is possible.

when choppers CH_2 and CH_3 are turned on, current flows through the path $V_+ \rightarrow CH_3 \rightarrow$ Load $\rightarrow CH_2 \rightarrow V_-$. since both E_0 and I_0 are negative, we get third quadrant operation when both choppers CH_2 and CH_3 are turned off; load dissipates its energy through the path $D_1 \rightarrow V_+ \rightarrow V_- \rightarrow D_4$ — Load. In this case E_0 +ve and I_0 -ve, and second quadrant operation is possible.

Type-E chopper can be used for a reversible regenerative d.c drive.

chopper commutation

A chopper consists of a Main power SCR switch together with the commutation circuitry to turn it off.

The commutation circuitry can be classified as

① forced commutation
② Load commutation

Forced commutation

In this type of commutation, current through the thyristor is forced to become zero to turn it off. It is accomplished in two ways.

① voltage commutation :-

In this scheme a charged capacitor momentarily reverse-biases the conducting SCR and turns it off.

② current commutation

In this scheme, a current pulse is forced in the reverse direction through the conducting SCR. As the net current becomes zero, the thyristor is turn off.

Load commutation

In this type of commutation, the load current flowing through the SCR either become zero (as in natural or line commutation) or then through diode D1

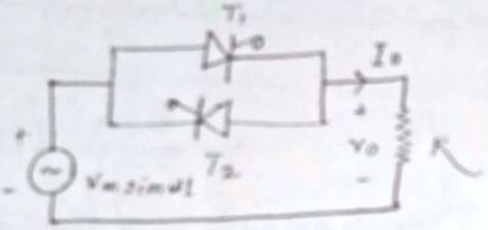
when T1 is turn off the load current flows through F.D

Since the volt-time integral to saturate the core is constant, the on period of T1 is fixed. The on period is a function of Lc and the average output voltage can be altered only by varying the operating frequency.

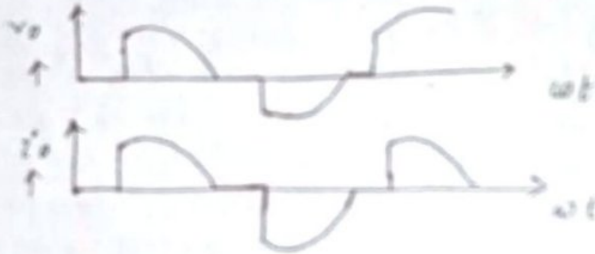
cyclo converter

A.C voltage controllers

It is a thyrister based device which convert fixed A.C voltage to variable a.c voltage with fixed frequency.



wave forms



cyclo converter

A device which converts input power at one frequency to output power at a different frequency with one-stage conversion is called a cyclo-converter.

So a cyclo-converter is a one-stage frequency changer.

cyclo-converters are of two types

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

In step-down cyclo-converter output frequency fo is less than supply frequency fs
i.e $f_o < f_s$

But in step-up cyclo-converter
$f_o > f_s$.

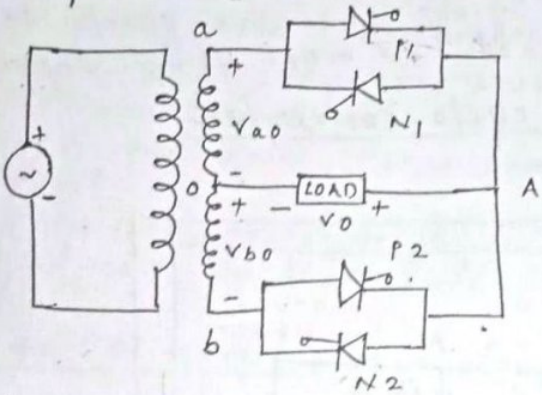
Applications

① speed control of high-power a.c drives.
② Induction heating.
③ static VAR generation
④

principle of operation

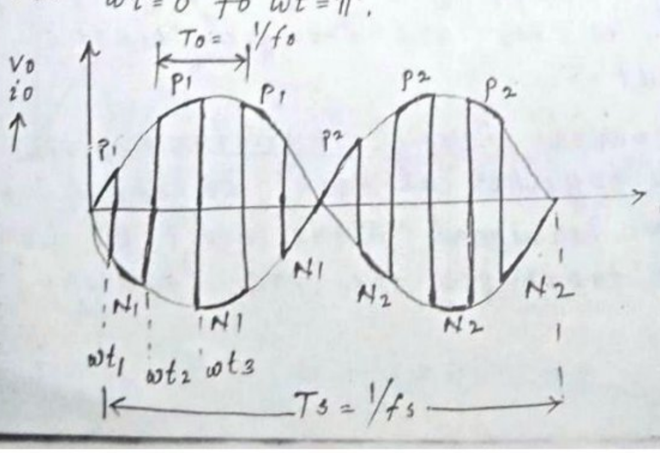
single phase to single-phase circuit step-up cyclo-converter.

① Mid point cyclo-converter



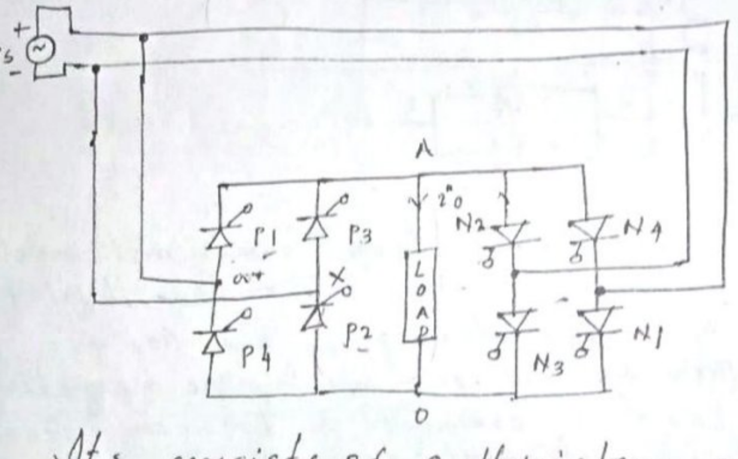
It consists of a 1φ-transformer with mid-tap on the secondary winding & four thyristors. Two of these thyristors P_1, P_2 are for +ve group and other two N_1, N_2 are for the negative group. Load is connected between secondary winding & mid point o and terminal A.

During the +ve half cycle of supply voltage terminal A is +ve w.r.t b & In this positive half cycle, both SCRs P_1 and N_2 are forward biased from $\omega t = 0$ to $\omega t = \pi$.



As SCR P1 is turn on at wt=0° so that load voltage is positive with A. The load voltage now follows the positive envelope of the supply voltage. At Imst ant wt1, P1 is forced commutated and forward biased. N2 is turn on so that load voltage is negative with terminal 0 +ve and A -ve. The load or output voltage now traces the negative envelope of the supply voltage. At wt2, N2 is force commutated and P1 is turn on, the load voltage is now positive and follows the +ve envelop of supply voltage. After wt=π, terminal b is +ve w.r.t terminal a. both SCRs P2 and N1 are therefore forward biased from wt=π to 2π. At wt =π, N2 is force commutated and forward biased SCR P2 is turn on. At $wt = \frac{1}{2f_s} + \frac{1}{2f_0}$, P2 is force commutated and SCR N1 is turned on. so by switching +ve group and -ve group, output frequency is increased i.e more than input.

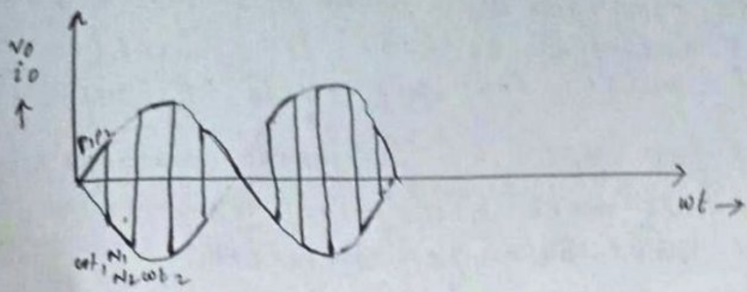
Bridge-type cyclo-converter



It consists of 8 thyristors, P1 to P2 i.e four for +ve group and N1 to N2 remaining four for -ve group.

When a is +ve w.r.t x i.e during positive half cycle of supply voltage, thyristor pairs P1, P2 and N1, N2 are forward biased from wt = 0° to wt = π.

When forward biased thyristors P1, P2 are turned on together at wt=0° so load voltage is +ve with terminal 'A' +ve w.r.t 0. Load voltage now traverses the +ve envelope of supply voltage.



At ωt_1, pair P_1, P_2 is force commutated and forward biased pair N_1, N_2 is turn on. with this Load voltage is -ve with terminal O positive w.r.t A. Load voltage now follows the negative envelope of source voltage. At ωt_2 N_1, N_2 are force commutated and P_1, P_2 are turned on. The Load voltage is now positive and follows the +ve envelope of source voltage.

After $\omega t = \pi$, thyristor pairs P_3, P_4 and N_3, N_4 are forward biased, these can therefore be turned on and force commutated from $\omega t = \pi$ to $\omega t = 2\pi$

In this process high frequency modulated output can be obtained.

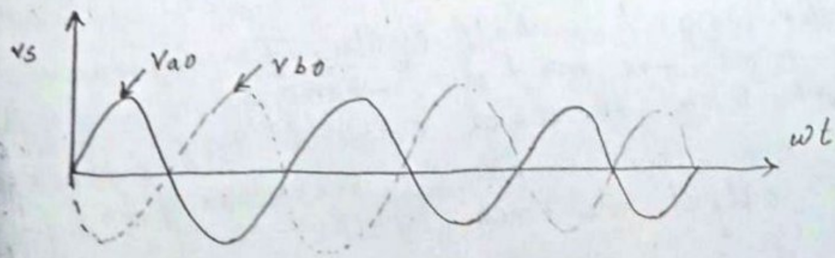
1ϕ to 1ϕ circuit - step down cyclo-converter

A step-down cyclo-converter does not required forced commutation. It needs only Line or natural commutation which is provided by a.c supply.

Mid point cyclo-converter

Let the Load is Inductive so this type of cyclo-converter can be described for both discontinuous and continuous Load current.

Discontinuous Load current



1ϕ- Full wave controlled rectifiers

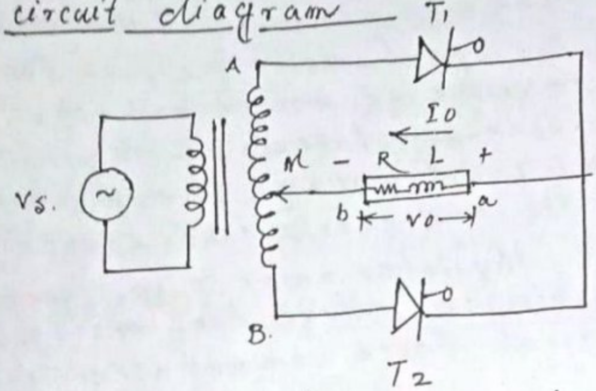
Full wave controlled rectifiers are also called two pulse rectifier because It generates two output d.c pulse for one cycle of supply voltage

There are two types of full wave controlled rectifiers

1. Full wave Mid point converter.
2. Full wave bridge converter.

1ϕ full wave Mid point converter with R-L Load

circuit diagram



In this converter a 1ϕ-transformer with centre tapped secondary is used.

Two thyristors are connected for control in both half cycles of supply voltage.

- principle.

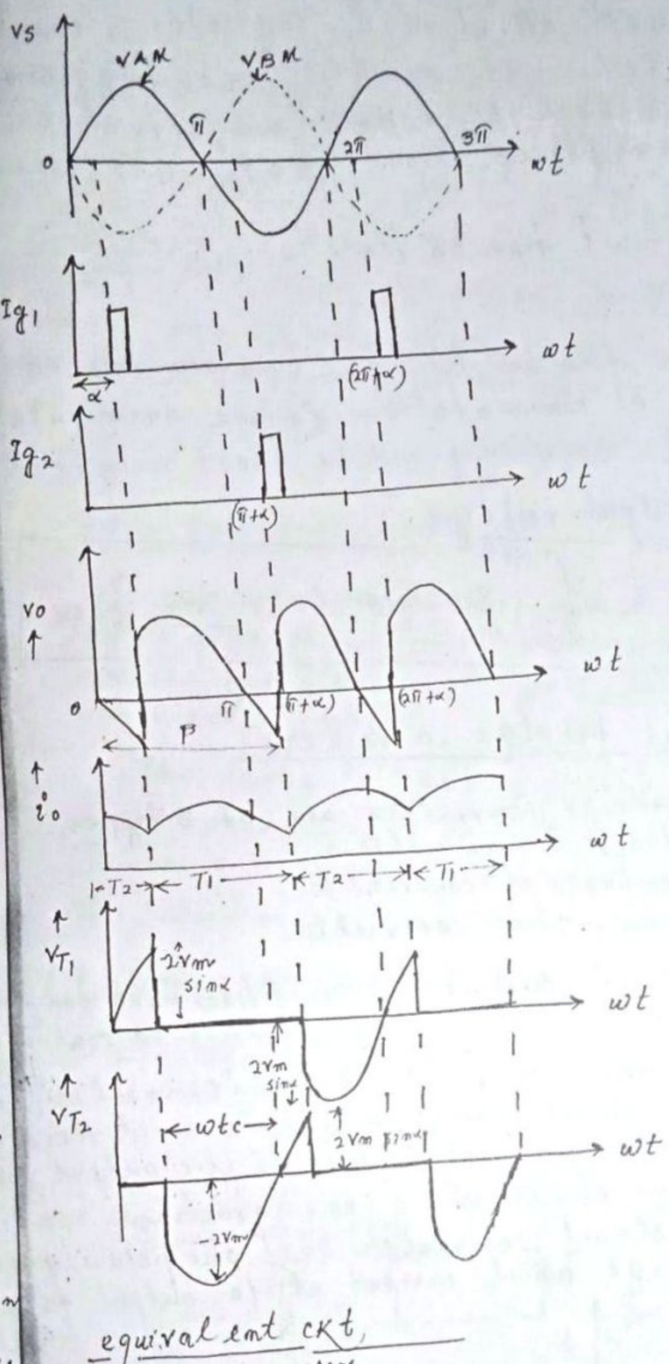
During the +ve half cycle of supply terminal A is +ve w.r.t M, which Makes T_1 forward biased. If thyristor is fired at an angle $\omega t = \alpha$ then Load current flows in the Loop A, a, b and M, A. Due to the Inductance of Load, currents continues to flow until $\omega t = \beta$, which is called extinction angle. (Assuming continuous conduction)

For $\alpha \leq \omega \leq \beta$ Load voltage is equal to source voltage.

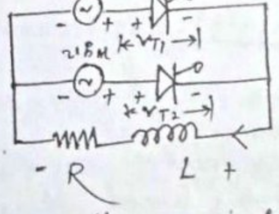
In the negative half cycle, T_2 is forward biased when B is +ve w.r.t M, when T_2 is triggered at $\omega t = \pi + \alpha$ ω Load current flows through the Loop B, a, b, M, B. so It develops two pulses in the output in each cycle.

waveforms

Here $V_{BK} = -V_{AK}$



equivalent ckt,



from the equivalent It is seen that

$v_{AK} = v_m \sin \omega t$

$v_{BK} = - v_{AK} = -v_m \sin \omega t$

and $V_{AB} = V_{AK} + (V_{BK}) \times (-1) = V_{AK} + V_{KB} = 2V_m \sin \omega t$