

# POWER ELECTRONICS and PLC

5th semester

Electrical Engg

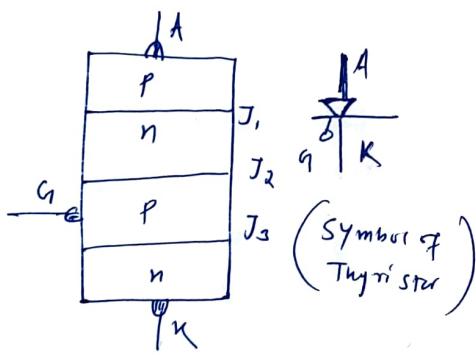
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## Thyristors

Thyristor is ~~is~~ derived from the combination of two words i.e. THYRatron and transITOR. That means thyristor is a solid state device ~~is~~ like transistor and has characteristics like thyatron tube.

Thyristor is a set of power semiconductor device. Inside the set a large no. of power semiconductor elements like SCR, ASCR/RCT, SITH, LASCR, MCT and TRIAC are available. Out of all these ~~are~~ the most widely used element is SCR i.e. why thyristor has become synonymous with SCR.

Thyristor is a four layer, three junction, three terminal p-n-p-n power semiconductor device. The terminals present in thyristors are Anode, Cathode and gate. The terminal connected to outer p-region is called ~~anode~~ anode, the terminal connected to outer n-region is called cathode and inner p-region is called gate.



(Schematic diagram  
of Thyristor)

The Junctions present in SCR are  $J_1$ ,  $J_2$  &  $J_3$ .

The diode, SCR is a uni-directional device & it can be used in power system to control a huge amount of power. In addition to this SCR is a switch. The given switch is operated by a smaller amount of power.

Nowadays SCR rating of 3000A, 1600V, voltage rating 1600V and power handling capacity of 30MW are available.

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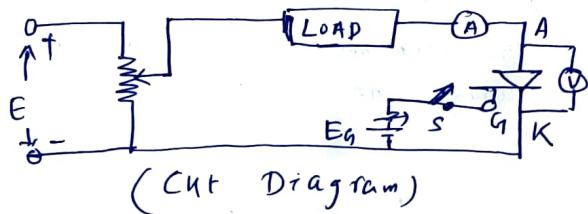
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The given device can be turn-on by a supply current of 1A and low. So the power ~~amplification~~ capacity is large.

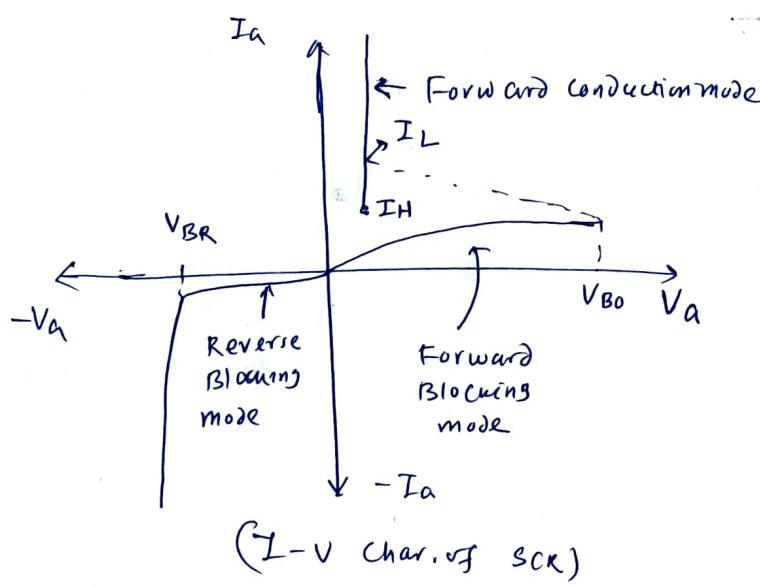
SCR is made up of Silicon. It's operation as a rectifier, the output voltage can be easily controlled by the application of controlling signal.

## Static I-V Char. of SCR

I-V Char. of SCR is nothing but a char. plotted between anode current and anode voltage. In order to obtain the above char., the following cut diagram is used. The I-V char. of SCR is shown in fig 1.



From the I-V char. a SCR has three basic modes of operation, namely reverse blocking mode, forward blocking mode and forward conduction mode.



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## Reverse Blocking mode

In this mode cathode is positive w.r.t. anode and gate is kept open circuited. During this junction J<sub>1</sub> and J<sub>3</sub> are in reverse biased and J<sub>2</sub> is forward biased condition. Hence a very small amount of current called ~~is~~ reverse leakage is flowing from anode to cathode. In this case two diodes are connected in series with reverse voltage applied across them. If the reverse voltage is increased then at a critical breakdown level called reverse breakdown voltage V<sub>BR</sub>, junction J<sub>1</sub> and J<sub>3</sub> lose ~~is~~ their blocking capability. During this large amount of current is ~~is~~ from cathode to anode and this may lead to thyristor damage, so for the safe operation ~~the~~ value of supply voltage should be lesser than V<sub>BR</sub>. Just before V<sub>BR</sub>, thyristor is acting as an open switch in reverse biased condition and the operation is called reverse blocking mode.

## Forward Blocking mode

In this mode anode is the w.r.t. cathode and gate is in open circuit condition. During this J<sub>1</sub> & J<sub>3</sub> are in forward biased and J<sub>2</sub> is in reverse biased condition. Due to reverse biased condition of J<sub>2</sub>, a very small amount of current called leakage is flowing. This kind of operation is called forward blocking mode. Because here thyristor is acting as an open switch in forward biased condition.

## Forward Conduction mode

When anode to cathode forward voltage is increased with gate circuit open, reverse biased junction J<sub>2</sub> will ~~be~~ here

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an avalanche breakdown at a voltage called forward breakover voltage. After this breakdown thyristor gets turn on and such kind of operation is called forward conduction mode. Once SCR gets turn on, a ~~is~~ very small amount of voltage is available across it i.e. 1 to 2V.

## Thyristor Turn-on method

A forward biased thyristor can be turn-on by any of the following techniques:

- (a) Forward voltage triggering (b)  $\frac{dV}{dt}$  triggering (c) temperature triggering (d) Light triggering (e) Gate triggering.

## Forward voltage triggering

When forward voltage is applied between anode and cathode ~~with~~ with gate circuit open, Junction J<sub>2</sub> is in reverse biased. Due to ~~this~~ depletion layer is formed across junction J<sub>2</sub>. The width of layer decreases with increase in anode-cathode voltage. At a particular value of voltage junction J<sub>2</sub> loses its blocking capability and hence device is at on state. Such kind of triggering is called forward voltage triggering. The voltage at which the device at on state is called forward breakover voltage.

## $\frac{dV}{dt}$ triggering

During forward bias ~~cond~~, thyristor is acting as a capacitor. Because J<sub>1</sub> & J<sub>3</sub> are in forward

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biased cond<sup>n</sup>,  $J_2$  is in reverse biased cond<sup>n</sup>. Now ~~if~~ two ~~two~~ conducting materials are separated by a dielectric electric then that material is called ~~dielectric~~ capacitance. If  $C_J$  is the Junction capacitance,  $V_o$  is the Supply voltage then charging current  $\Rightarrow I_c$  is

$$I_c = \frac{dQ}{dt} = \frac{d}{dt}(C_J V)$$

$$I_c = V \frac{dC_J}{dt} + C_J \frac{dV}{dt}$$

$$\Rightarrow I_c = C_J \frac{dV}{dt} \quad [ \text{Because } \frac{dC_J}{dt} = 0 ]$$

$$\text{so } I_c \propto \frac{dV}{dt}$$

If the rate of rise of forward voltage  $\frac{dV}{dt}$  is high, then the device is at on state. This is an unwanted triggering method of SCR.

## Temperature triggering

Semiconductor device has negative temperature coefficient of resistance i.e. with increase in temperature, the resistance of the device starts ~~decreasing~~ decreasing.

Since SCR is a semiconductor device and with increment of temperature the device gets turn-on. Such kind of triggering of SCR is called temperature triggering.

## Light triggering

For Light triggering, a recess is made in inner p-layer of SCR. When the recess is irradiated, free charge

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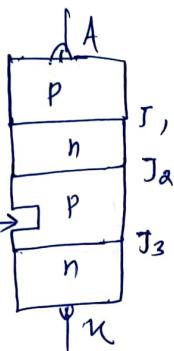
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are generated.

With the help of optical fibre, if proper intensity of light is thrown on the recess, then the forward biased SCR is turn-on. Such kind of turning on device is called Light triggering and semiconductor device form is a LASCR i.e. Light activated SCR.



These are used in HVDC transmission line. For electrical isolation between power and control circuit, LASCR is used.

## Gate Triggering

The main disadvantage of forward voltage triggering is that it has high value of breakdown voltage. So in order to turn-on thyristor at normal voltage, gate triggering method is used.

When gate is positive w.r.t. Cathode, then gate layer is flooded with electrons from the Cathode. This is because n-layer is highly doped as compared to p-layers.

Some of these electrons now reach the Junction J<sub>2</sub>. As a result of this at a lesser value of supply voltage the device is going to be turn-on. Such way of triggering method is called gate triggering.

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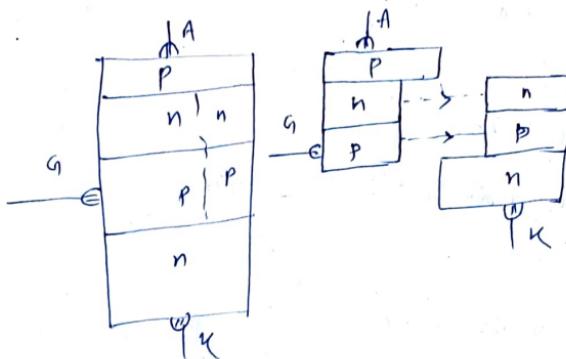
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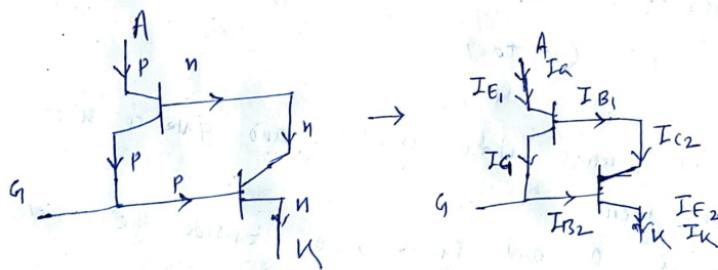
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## TWO Transistor Model of a Thyristor

Thyristor is a four layer, three junction three terminal power semiconductor device. If we bisect the inner two layer, then the device is shown below.



So while moving from Anode to Cathode, we have to pass across two transistors that should be inherently present in the device. The transistors are pnp and npn, so the cut is



From the above figure

$$I_a = I_{F1}, I_{B1} = I_{C2}$$

In the off state of transistor, collector current  $I_c$  is related to emitter current  $I_E$  as

$$I_c = \alpha I_E + I_{CB0}$$

Where  $\alpha$  = Common-base current gain

$I_{CB0}$  = Common base leakage current of collector-base junction.

Let us consider pnp transistor & npn transistors are denoted as  $Q_1$  and  $Q_2$ .

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For  $d_1$ ,

$$I_{C1} = d_1 I_{F1} + I_{CB01}$$

$$I_{C1} = d_1 I_a + I_{CB01} \quad \text{--- (1)}$$

For  $d_2$ ,

$$I_{C2} = d_2 I_{F2} + I_{CB02}$$

$$I_{C2} = d_2 I_K + I_{CB02}$$

Now

$$I_{E1} = \cancel{I_{CB02}} T_u + I_{B1}$$

$$I_a = d_1 I_a + I_{CB01} + d_2 I_K + I_{CB02} \quad \text{--- (2)}$$

$$I_K = I_a + I_g$$

putting  $I_K$  in the above equation

$$I_a = d_1 I_a + I_{CB01} + d_2 (I_a + I_g) + I_{CB02}$$

$$\Rightarrow I_a [1 - (d_1 + d_2)] = d_2 I_g + I_{CB01} + I_{CB02}$$

$$\Rightarrow I_a = \frac{d_2 I_g + I_{CB01} + I_{CB02}}{1 - (d_1 + d_2)} \quad \text{--- (3)}$$

When anode is positive w.r.t. cathode and gate is kept open circuited, then  $d_1 = 0$ ,  $d_2 = 0$  and  $I_g = 0$ , so inside the device  $I_{CB01} + I_{CB02}$  i.e. leakage current is flowing.

When  $I_g$  is of larger magnitude, then from the above figure,  $I_{B2} = I_g$ . Due to application of base signal some collector current and emitter current across  $L_2$  is available. Due to this  $d_2$  starts increasing from zero value to some higher value.

From the above figure,

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

Where  $\beta_2$  = Current gain of  $B_2$ .

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Due to application of large base signal, larger emitter current and collector current are available. This further leads to increment of  $\alpha_1$ .

In the second steps,  $I_{B1} = I_g + I_{C1} = I_g + \beta_1 \beta_2 Z_g$ . So base current is larger value. Due to larger base current larger collector and emitter current available across  $\alpha_2$ . This further leads increment of  $\alpha_2$ . So due to application of gate signal  $\alpha_1$  &  $\alpha_2$  start increasing.

When  $\alpha_1 + \alpha_2$  reaches unity, then the device is at ~~on state~~ on state.

$$I_a = 0$$

Switching char. of SCR  
For reliable and economic design of converter circuit switching char. is taken into consideration.

The time variation of voltage and current in a given SCR during the turn-on and turn-off time is called switching char. switching char. is divided into two parts. and those are switching char. during turn-on and switching char. during turn-off.

Switching char. during turn-on  
A forward biased thyristor can be turn on after the application of positive gate signal. Turn-on time is defined as the time during which thyristor is changing its condition from forward blocking mode to forward conduction mode. Total turn-on time is divided into three intervals i.e. delay time, rise time and spread time.

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## Delay time

Delay time is defined as the time during which anode voltage falls from  $V_a$  to  $0.9V_a$  where  $V_a$  is actual anode voltage.

It may also be defined as the time during which anode current increases from its leakage current to  $0.1 I_a$  where  $I_a$  is the final value of anode current.

This kind of phenomenon takes place where gate current reaches 90% of its final value of triggering.

During delay time, due to non-uniform doping concentration of gate to cathode surface the total amount of anode current is flowing nearer to gate ~~portion~~ only.

## Rise time

The time during which anode current increases from  $0.1 I_a$  to  $0.9 I_a$  is called rise time.

Also,

It is defined as the time during which anode voltage falls from  $0.9 V_a$  to  $0.1 V_a$ .

Rise time is inversely proportional to gate current and anode circuit parameter. For RL cut it is more whereas for RC cut it is small.

If the  $t_r$  is small, then within a quick time period the total anode current can't be spread over the entire gate cathode surface. So within a ~~part~~ limited region the total anode current is flowing. So the local hot spot is formed. Due to local hot spot the device may get damaged.

## Spread time

The time during which anode current increases from 90% of  $I_a$  to full anode current is called spread time. The time during which anode voltage decreases from 10% of its initial value to turn-on voltage is called spread time. Spread time depends upon the area of cathode and on gate structure. After spread time, anode current attains a steady state current.

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The total turn-on time is the summation of delay time, rise time and spread time. The turn-on time depends upon gate signal and anode circuit parameters.

Thyristor is a charge controlled device. In order to turn-on the thyristor, certain amount of charge must be injected into the gate region for the thyristor conduction.

Generally the thyristor turns-on by 3 to 5 times of minimum value of gate current and this kind of turning on of SCR is called hard-firing or over driving. Hard-firing reduces the turn-on time and enhances  $\frac{di}{dt}$  capability.

## Switching char. during Turn-off

Turn-off time is the time during which thyristor changes its condition from forward conduction mode to forward blocking mode. So turn-off process is called commutation process.

In order to turn-off the thyristor, first we have to reduce the anode current to zero value. After that the reverse blocking capability is developed.

So turn-off time is defined as the time between the instant anode current becomes zero and the instant SCR regains forward blocking capability. During turn-off time, the excess charge carrier from the four layers must be removed. This removal includes sweeping out of holes from outer p-layer and electrons from outer n-layer. The carriers around junction J<sub>2</sub> can be removed out by the process of recombination. So total turn-off time is divided into two intervals, reverse recovery time and gate recovery time. The turn-off time is denoted as  $t_{qr} + t_{gr} = t_{rr} + t_{gr}$  where

$t_{rr}$  = Reverse recovery time

$t_{gr}$  = Gate Recovery time,

From the waveform, just after  $t_1$ , anode current became zero. After  $t_2$ , anode current builds in the reverse direction. The reason for reversal of anode current is due to the presence of charge stored in the four layers. The reverse current removes excess of charge carrier from the junction J<sub>1</sub> and J<sub>3</sub> between  $t_1$  and  $t_3$ .

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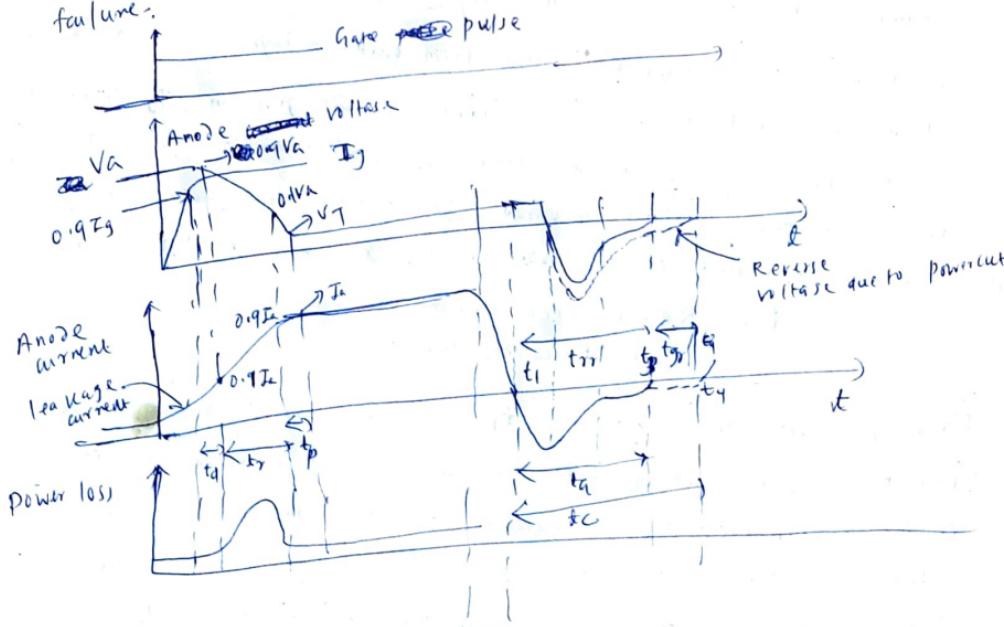
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At  $t_2$ , anode reaches its maximum value. At this instant 60% of the stored charge carriers removed. Just after  $t_2$ , reverse current decays fast in the beginning & then it becomes gradual. The fast decay of anode current causes a reverse voltage across the device due to circuit inductance. The reverse voltage surge appears across the thyristor and device may get damaged. This voltage is called internal overvoltage. In order to remove or internal overvoltage, snubber circuit is used.

After  $t_3$ , middle junction  $J_2$  has trapped charges. Therefore the thyristor is not able to block the forward voltage. So the total amount of charge carriers across  $J_2$  is removed out by the process of recombination. The recombination is possible if reverse voltage is maintained across SCR. The rate of recombination is independent of external circuit. The rate of recombination of charges is called gate recovery time.

The turn-off time is applicable to individual SCR. But thyristor is part of power system. So circuit turn-off time is provided. In general circuit turn-off time is greater than turn-off time of individual SCR i.e.  $t_c > t_{off}$ . If  $t_c < t_{off}$ , then thyristor may turn-on at undesired instant and such kind of failure is known as commutation failure.



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Depending upon the turn-off time, thyristors divided into two parts i.e. converter grade SCR and inverter grade SCR.

Thyristor with slow turn-off time is called converter grade SCR i.e. 50-100 μsec.

Thyristor with fast turn-off time (3-50 μsec) is called inverter grade SCR.

Converter grade SCR is found in ac voltage controllers, phase controlled converters, cyclo converter whereas, inverter grade SCRs are found in inverters, chopper and forced commutated inverter.

## Thyristor Rating

Thyristor ratings indicate the specified limits of voltage, current, temperature within which the device operate safely. Ratings and specification provides a link between user and manufacturer.

### Thyristor voltage rating

Thyristor is subjected forward bias and reverse biased con'tn.

So some voltage ratings are provided in both the condition. In voltage rating of SCR some subscripts letters are provided.

If the first subscript is D, then it represents forward voltage with gate cut open.

If it is T, then it is at on state state.

R → Reverse, F → Forward.

If the second subscript is S → Surge value, W → Working value, R → Repetitive value.

T → Trigger

The third letter M represents maximum value.

The thyristor voltage ratings are -

(i) Upm - peak working forward blocking voltage -

It specifies maximum forward blocking voltage that a thyristor can withstand during working.

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$V_{DPM}$  - peak repetitive forward blocking voltage -; If refers to peak current voltage that a thyristor can withstand repeatedly.

$V_{DSM}$  - peak surge forward blocking voltage -; It refers to peak value of forward surge voltage that does not repeat.

$V_{RWM}$  - peak working reverse voltage

$V_{RRM}$  - peak repetitive reverse voltage

$V_{RSR}$  - peak surge reverse voltage

Both forward and reverse voltage, another thyristor voltages are specified.

$V_T$  - on state voltage drop -; The voltage drop between anode and cathode during on state is called on state voltage drop. Its value is 1 to 1.5V.

Forward dv/dt rating -; This rating is provided in order to avoid the unwanted turn-on.

This value is ~~20~~ 20 - 50 V/μsec.

Voltage safety factor -; The ratio of  $V_{RRM}$  to  $V_m$  is called

voltage safety factor.

$$VSF = \frac{V_{RRM}}{V_m}$$

Its value is 2 to 3.

~~Current Rating~~ Current ratings are provided -

Generally the following current ratings are provided -

(i) Average on state current

(ii) RMS on state current

(iii) Surge current rating (Rating of fews)

(iv)  $I_{AT}$  rating ( $\vee$ ) Holding current ( $i_{H}$ ) Latching Current

(v) dv/dt rating ( $i_e$ ) Gate current [ $i_{Gmin}$  and  $i_{Gmax}$ ]

(vi) Gate current [ $i_{Gmin}$  and  $i_{Gmax}$ ]

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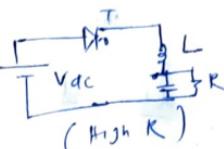
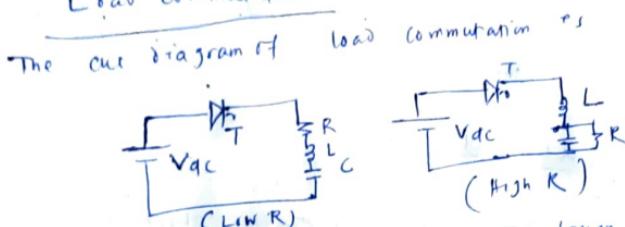
## Commutation

The process of turning off of an thyristor is called commutation.

Generally the following types of commutations are available -

- (i) Load commutation (Class A commutation)
- (ii) Class B commutation (Resonant pulse commutation)
- (iii) Class C      "      (Complementary commutation)
- (iv) Class D      "      (Impulse      "      )      } Forced commutation
- (v) Class E      "      (External pulse      "      )
- (vi) Class F      "      (Line commutation)

## Load commutation



In the above circuit, R, L and C are taken in such a way that they have to maintain an under damped condition. The thyristor is turned on after the application of gate pulse.

$$So \quad V_{dc} = R I(t) + L \frac{di(t)}{dt} + \frac{1}{C} \int i(t) dt$$

By taking Laplace T/F

$$\frac{V_{dc}(s)}{s} = I(s) R + sL I(s) + \frac{1}{C} I(s)$$

$$\Rightarrow I(s) = \frac{\frac{V_{dc}(s)}{s}}{s(R + sL) + \frac{1}{C}}$$

$$\frac{V_{dc}(s)}{s^2 + \frac{R}{L}s + \frac{1}{LC}} = \frac{V_{dc}(s)}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

$$\Rightarrow I(s) = \frac{V_{dc}(s)}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

By taking inverse Laplace transformation

$$i(t) = \frac{V_{dc}}{WL} e^{-\frac{Rt}{2L}} \sin \omega t$$

$$\omega_0 = \frac{R}{2L}$$

When  $\omega t = \pi$

$i(t) = 0$  and hence thyristor is at off state.

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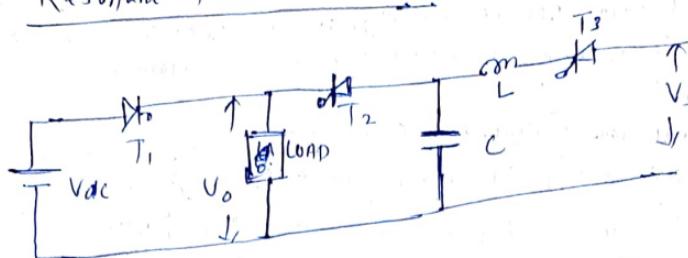
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Resonant pulse commutation



When  $T_1$  is at on state,  $V_0 = V_{dc} - \text{---(1)}$

In order to turn-off thyristor  $T_1$ ,  $T_3$  is at on state.  
After turning on  $T_3$ , the capacitor starts charging with the help of  $V_s$ .

By applying KVL on the cut

$$V_s = L \frac{di}{dt} + \frac{1}{C} \int i dt$$

Taking Laplace Transformation of the above eqn.

$$\frac{V_s}{s} = sL I(s) + \frac{1}{Cs} I(s)$$

$$\Rightarrow I(s) = \frac{\frac{V_s(s)}{s}}{sL + \frac{1}{Cs}} = \frac{V_s(s)}{sL + \frac{1}{Cs}} = \frac{V_s(s)}{sL + \frac{1}{Cs}} = \frac{V_s(s)}{sL + \frac{1}{Cs}} = \frac{V_s(s)}{sL + \frac{1}{Cs}}$$

Taking reverse Laplace T/F

$$I = \frac{V_s}{L} e^{-\frac{t}{LC}}$$

$$I(s) = \frac{V_s(s)}{s(L + \frac{1}{Cs})} = \frac{V_s(s)}{s^2 + \frac{1}{Cs}} = \frac{V_s(s)}{s^2 + \frac{1}{Cs}}$$

$$= \frac{V_s(s)}{s^2 + \frac{1}{Cs}} \times \frac{1}{s^2 + \omega^2} = \frac{V_s(s)}{s^2 + \omega^2} = \frac{V_s(s)}{s^2 + \omega^2}$$

$$\Rightarrow I = \frac{V_s}{L \omega} \sin \omega t - \text{---(1)}$$

capacitor charging voltage

$$V_C = V_s (1 - \cos \omega t)$$

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when  $\omega t = \pi$

$$I = 0$$

$$\text{Capacitor charging voltage } V_C = V_S (1 - \cos \pi) \\ = 2V_S \quad \text{--- (1)}$$

when  $\omega t = \pi$ ,  $T_2$  is at off state.

After turning off  $T_2$ ,  $T_1$  is at on state, by applying gate pulse.

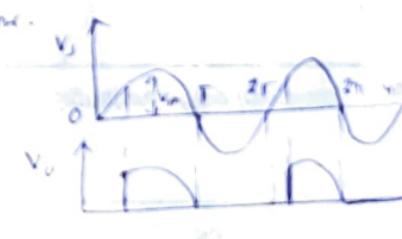
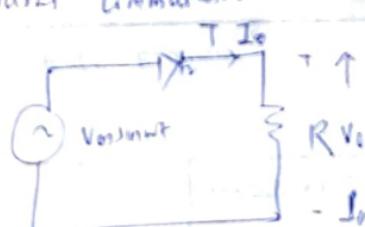
When  $T_2$  is at on state, then across the thyristor  $T_1$ ,  $(V_{dc} - 2V_S)$  amount of reverse voltage is available. Due to this voltage  $T_1$  is at off. In this case  $T_1$  is the main thyristor.

After turning off  $T_1$ , capacitor starts discharging across load and then  $T_2$  is at off state.

In this case  $T_2$ ,  $T_3$  are auxiliary thyristors and  $V_S$  is the auxiliary supply voltage.

## Line Commutation

The process of turning off of an thyristor with the help of supply voltage is known as line commutation. In the line commutation or Natural commutation the nature of the supply voltage is ac one. The circuit diagram of natural commutation is shown below.



Let us consider sinusoidal nature of supply voltage provided with the above circuit.

The supply voltage is at zero value at the end of each half cycle.

When  $\omega t = 0$ , the thyristor is at forward biased condition.

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During the forward biased condition, the thyristor is at on state. Let us consider an instant  $m_s$  at which thyristor is at on state. After turning on of thyristor the rest portion of the supply voltage is available across the load side.

When  $wt = \pi$ , supply voltage is zero. At the zero value of supply voltage thyristor is at off state.

After  $\pi$ , negative half-cycle is available. During -ve half-cycle thyristor is reverse biased condition.

In the turning off process, supply voltage is used > no extra circuit is required. That is why such kind of turn-off process is called natural commutation or line commutation.

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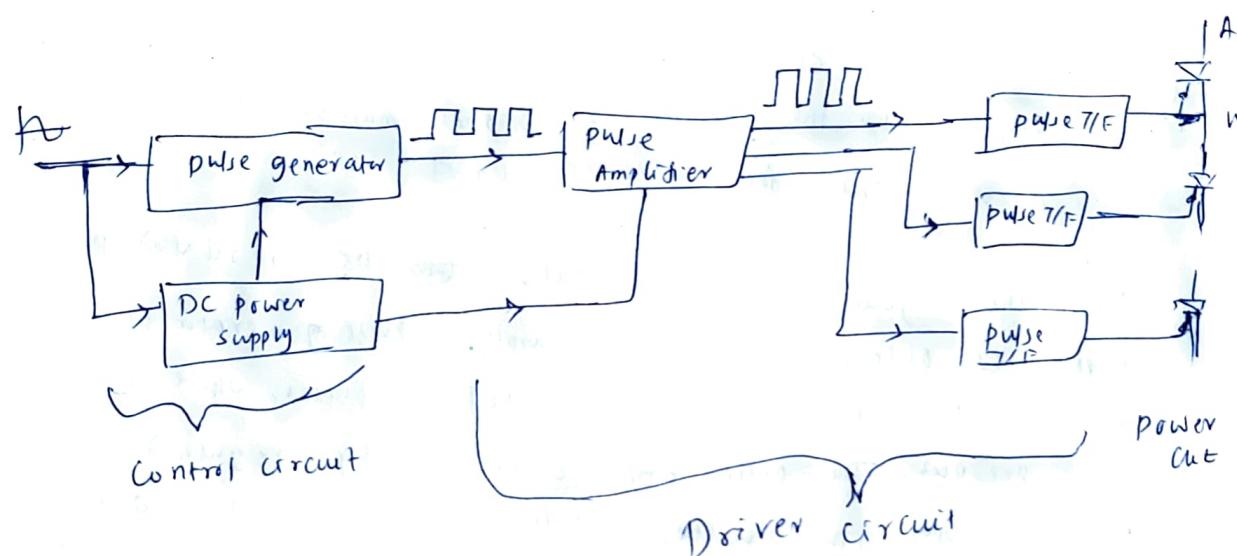
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## Firing Circuit

Turning on or off SCR with the help of gate circuit is known as firing circuit. The layout of firing circuit is shown below.



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The firing cut should fulfill the two following condn. -

- ⑥ In a power cut larger no of SCR are available, so the firing cut has the tendency to generate the gate pulse at the desired instant.

(+) The control cut signal is unable to turn-on the SCR. So the control cut signal must be feed into driver cut for turning on of SCR.

From the layout of firing cut, DC regulated power supply is obtained from AC supply. pulse generator is supplied from both ac and dc voltage pulses, where pulses are produced. The pulse amplifier is feed by regulated power supply. The voltage pulses are feed to pulse amplifier for their amplification. The amplified pulse is feed to pulse with the help of shielded cable. The amplified pulse is feed to Gate to Cathode circuit for the turning on of SCR.

In this case pulse Transformer is acting as an oscillator between gate-cathode cut to high power Anode-Cathode Cut.

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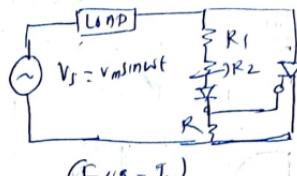
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## Resistance Firing Cut

The circuit diagram of resistance firing cut is given in fig-I.

From the cut  $R_2$  is variable resistance.



If  $R_2$  is zero, then gate current  $I_g$  flows from source, through  $R_3$ , Gate Cathode to Negative plate of supply voltage. This gate current should not exceed maximum permissible value of gate current.

$$\frac{V_m}{R_1} < I_{gm} \text{ or } R_1 > \frac{V_m}{I_{gm}}$$

Resistance  $R$  should have such a value that maximum voltage drop across it does not exceed maximum resistance.

$$\frac{V_m}{R+R_2} \leq V_{gm}$$

$$R \leq \frac{V_{gm} R_2}{V_m - V_{gm}}$$

When  $R_2$  is large, current  $I_g$  is small and voltage drop across  $R$  is small. In this case  $V_g < V_{gt}$  & hence thyristor  $T_1$  is at off state.

In this case  $V_o$  &  $I_o$  are

small, then

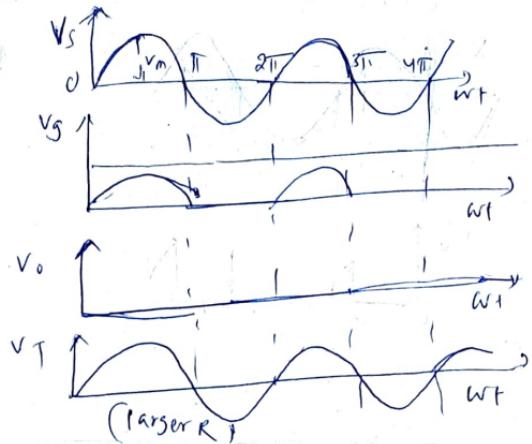
When  $R_2$  is small, then

so when  $V_g = V_{gt}$ , then the thyristor  $T_1$  is at on-state.

In this case the

at zero value. large amount of current  $I_o$  flows.

large amount of current  $I_o$  flows.



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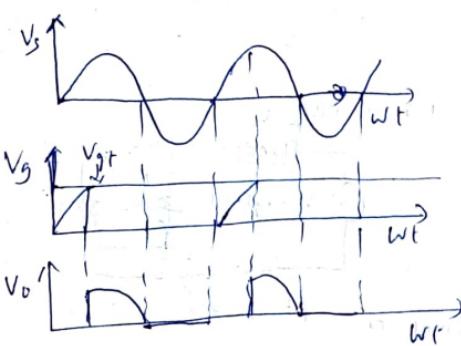
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From the circuit diagram.

$$V_g = V_{gp} \sin \omega t$$

when  $\omega t = d$ ,

$$V_g = V_{gt} \text{ so}$$

$$V_{gt} = V_{gp} \sin d \\ \Rightarrow \sin d = \frac{V_{gt}}{V_{gp}} \Rightarrow d = \sin^{-1} \left( \frac{V_{gt}}{V_{gp}} \right)$$

$$V_{gp} = \frac{V_m R}{R_1 + R_2 + R} \\ d = \sin^{-1} \left[ \frac{V_{gt} (R_1 + R_2 + R)}{V_m R} \right]$$

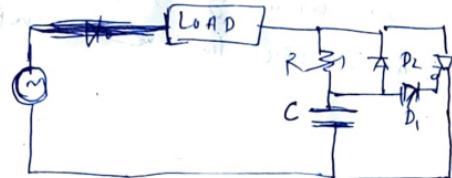
$$d \propto \sin^{-1}(R_2)$$

Since the maximum value of  $\sin^{-1}$  is  $90^\circ$ , since only  $50\%$  of the +ve half-cycle is utilised, rest  $50\%$  is not utilised. In addition to this, the firing angle range increases from  $0$  to  $90^\circ$ .

so in order to increase the range of firing angle  $R-C$  triggering circuit is used.

R-C triggering out

In order to increase the range of firing angle  $R-C$  triggering out is used.



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Let us consider + sinusoidal nature of supply voltage  $v_s$  provided.

During the negative half-cycle of supply the capacitor  $C$  is charged with lower plate positive and upper plate negative and diode  $D_1$  is at on state.

When  $\omega t = -90^\circ$ ,  $V_C = -V_m$ .

When capacitor is charging upto  $-V_m$ , then the same voltage is maintaining when  $\omega t = 0$ .

After  $\omega t = 0$  instant, capacitor is charged with the help of

Variable resistance  $R$ .

When  $V_C$  reaches  $V_{gt}$ , then thyristor is at on state. The current that should be passed through capacitor depends upon

Variable resistance  $R$ .

When  $V_C = V_{gt}$ , then capacitor starts discharging upto

Zero value.

When  $\omega t = \pi$ , supply voltage is zero and the same unit of phenomenon takes place.

Unijunction transistor

In resistance firing cut, firing angle range is limited.

In R-C cut the range of firing angle is increasing.

In R & RC cut, larger pulses are generated. So the

power dissipation is more. In UJT triggering cut  $\Rightarrow$  smaller pulses are generated and used in feedback control systems.

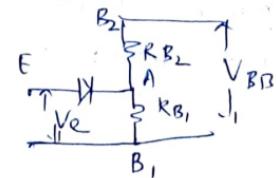
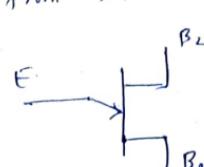
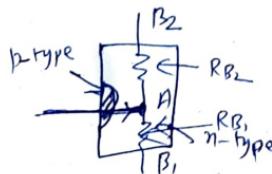
An UJT is made up of n-type Si base to which p-type

emitter is embedded. The n-type base is lightly doped

whereas p-type emitter is heavily doped. UJT has 3 terminals

Emitter, Base  $B_1$  and Base  $B_2$ . Between  $B_1$  and  $B_2$  UJT

behaves like an ordinary resistance.  $R_{B_1}$  and  $R_{B_2}$  are the internal resistances respectively from bases  $B_1$  and  $B_2$  to a point A.



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When a voltage  $V_{BB}$  is applied across the two base terminals  $B_1$  and  $B_2$ , potential of A w.r.t.  $B_1$ ,

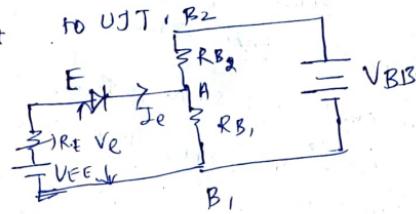
$$V_{AB1} = V_{BB} \times \frac{R_{B1}}{R_{B1} + R_{B2}}$$

Where  $\eta$  is called intrinsic stand off ratio. The value of  $\eta$  lies between 0.51 to 0.52.

Since  $B_2$  is kept nearer to E, so  $R_{B2} < R_{B1}$ . The operation of UJT can be explained with the circuit.

The operation of UJT is similar to that of BJT. DC biasing diagram,

UJT is usually operated with  $B_2$  and E are +ve w.r.t.  $B_1$ . DC voltage  $V_{EE}$  is applied between  $B_2$  and  $B_1$ . DC voltage  $V_{RE}$  is applied between  $E$  and  $B_1$ . RF is considered as input.



$$\text{Now } V_{AB1} = \frac{V_{BB}}{R_{B1} + R_{B2}} R_{B1} = \eta V_{BB}$$

$$\therefore V_{EE} - I_e R_E - V_E = 0$$

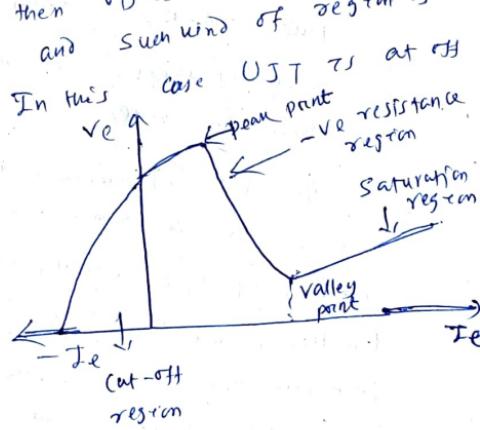
$$\therefore \frac{V_{EE} - V_E}{R_E} = I_e \quad (1)$$

$$V_E = V_D + \eta V_{BB} \quad (2)$$

The magnitude of  $V_E$  can be varied by using  $R_E$ . When  $V_E < \eta V_{BB}$ , then  $V_O$  is at reverse biased region.

In this case  $I_e$  is  $-I_e$  and such kind of regions are called cut-off region. State

By varying  $R_E$ ,  $V_E$  is  $\eta V_{BB}$  by  $V_D$ , then ~~reverse~~ diode is at forward biased condition. This particular point is called peak point.



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At peak point, P-type emitter begins to inject holes from heavily doped emitter E into lower base region B<sub>1</sub>. As N-type base is highly doped, then holes rarely get any chance to recombine with holes. Therefore lower base region B<sub>1</sub> is filled up with additional holes. Therefore lower base region B<sub>1</sub> is filled up with additional holes. Therefore current carriers. As a result R<sub>B1</sub> decreases. Due to this current carriers. As a result R<sub>B1</sub> decreases. Due to this V<sub>E</sub> also decreases.

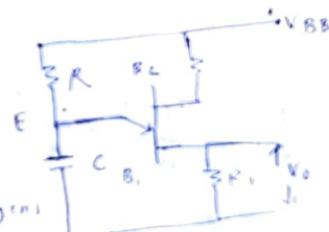
Due to decrease of V<sub>E</sub>, I<sub>E</sub> increases. This increased I<sub>E</sub> injects more holes into B<sub>1</sub> for which R<sub>B1</sub> decreases upto minimum value. The minimum value of R<sub>B1</sub> is called valley point. The region between peak point to valley point is called -ve resistance region. The -ve resistance region is used to find out the triggering circuit.

The valley point is called on-set of +V<sub>ST</sub>. The valley point current is called holding current. At valley point base B<sub>1</sub> is saturated. After B<sub>1</sub> saturation region is obtained.

## VJT Oscillator Triggering

VJT is a highly efficient switch.

When source voltage V<sub>BB</sub> is applied, then capacitor C begins to charge through R.

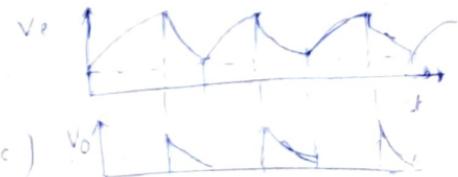


During the charging emitter circuit is open. The capacitor voltage  $V_C = V_{BB}(1 - e^{-t/Rc})$

When V<sub>C</sub> reaches V<sub>p</sub> (peak-point), then E-B<sub>1</sub> breaks down. As a result VJT turns-on and capacitor C rapidly discharges through low resistance R<sub>1</sub> and output voltage is available. The output voltage is used to turn-on the thyristor.

$$Now \quad V_p = nV_{BB} + V_D$$

$$= V_L + V_{BB}(1 - e^{-t/Rc})$$



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From this  $V_D = V_V, \eta = (1 - e^{-t/RC})$

$$t = RC \ln \left( \frac{1}{1-\eta} \right) \quad \text{--- (1)}$$

In this case the value of  $R_1$  is selected in such a way that during the off cond<sup>n</sup> of V<sub>GT</sub>, the voltage drop across  $R_1$  is less than  $V_{gt}$ .

$$\frac{V_{BB} R_1}{R_{BB} + R_1 + R_2} < V_{gt} \quad \text{--- (1)}$$

$$R_2 = \frac{10^4}{\eta V_{BB}} \quad \text{--- (ii)}$$

At peak point  $R_{max} = \frac{V_{BB} - V_p}{I_p}$

The minimum value of  $R$   $R_{min} = \frac{V_{BB} - V_A}{I_V} \quad \text{--- (iii)}$

## Protection of SCR

SCR should be protected from  $\frac{di}{dt}$ ,  $\frac{dv}{dt}$ , over current and over voltage.

$\frac{di}{dt}$  protection - During the rise time of SCR  $\frac{di}{dt}$  is available. If the rise is small, then no spot is formed. Due to formation of hot spot the device may get damaged.

In order to protect this, a smaller inductor ( $L$ ) is used. This inductor has the tendency to provide an opposition for  $\frac{di}{dt}$ .

## $\frac{dv}{dt}$ protection

During the turn-on time  $\frac{dv}{dt}$  is available. In order to avoid unwanted triggering of SCR a snubber circuit is used.

$\frac{dv}{dt}$  Snubber circuit is used. Snubber circuit is the

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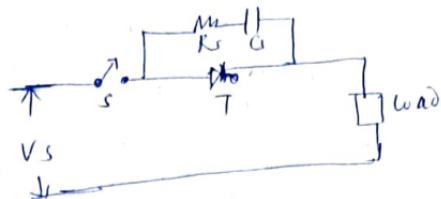
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series combination of resistance and capacitance connected parallelly with the thyristor.

A capacitor  $C_s$  in parallel with device  $s$  is sufficient to prevent unwanted  $\frac{dv}{dt}$  triggering.



When the switch is at on state, capacitor behaves like a short circuit and voltage across SCR is zero, with the passage of time voltage across capacitor builds up at a slow rate than  $\frac{dv}{dt}$ .

The capacitor is charged upto  $V_S$ . When SCR is turned on, capacitor discharges through SCR and sends a current

( $\frac{V_S}{\text{resistance of } C_s + \text{resistance of SCR}}$  during turn-on condition). This current is large and the device gets damaged. So in order to reduce the damage, so in order to reduce the current, resistance  $R_s$  is connected in series with  $C_s$ .

## Over Voltage protection

A thyristor may be subjected to internal and external over-voltage.

Internal overvoltage is caused due to operation of thyristor load circuit or whereas external overvoltage is due to supply lines.

## Internal Over Voltages

During the turning off process if thyristor voltage is available. When 60% of the charged carriers have been removed, then anode current reaches to its maximum value. After this the reverse anode current starts decay. At beginning decay is fast - Due to fast decay of anode current, overvoltage is available. This kind of overvoltage is called internal overvoltage EXAM-50.

## EXAM-50

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## External Over voltages

External over voltages are caused due to interruption of current flow in inductive circuit, due to lightning strokes on lines feeding the converter system, due to energisation or de energisation of transformer feeding converter system,

## Suppression of overvoltages

In order to suppress the internal overvoltage, snubber circuit is used. In order to suppress the external overvoltage, voltage clamping device is used.

Voltage clamping device is a non-linear resistor connected across SCR. V.C. has falling resistance with increasing voltage.

Under normal working condn, the device has high resistance and ~~protects~~ leakage current is passing. When voltage surge appears, V.C. device operates in low resistance region and produces a virtual short cut, dissipating the voltage across SCR is clamped to safe value. The voltage clamping devices are selenium thyrector diodes, metal oxide varistors, avalanche diode suppressors.

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## Over current protection

Thyristors have small thermal time constant. If a thyristor is subjected to faults, short circuit or surge current, then overcurrent is produced. So over-current in thyristor is protected by CB and fast acting fuses.

Depending upon the types of supply system, overcurrent is protected. In weak supply system, fault current is limited by source impedance whereas in stiff supply system fault is not limited by source impedance.

In stiff supply fast acting current limiting fuse is used.

Whenever there is a short circuit (min), then CB or fuse

are used for overcurrent protection of SCR. A CB is used for protecting against continuous overloads for longer duration of time whereas a fast-acting current is used to protect the thyristor of very short duration.

## Electronic Crow-bar protection

Thyristor possesses high surge current. It can be used as an electronic crowbar cut for overcurrent protection of power converter.

A crowbar thyristor is connected across the input dc terminals.

A current sensing register detects the value of current.

In short circuit condition, current sensing resistor senses the current and send a signal to gate triggering circuit. Then gate signal triggers the thyristor to

an on state, so the power converter remains safe in over-current.

## Gate protection

Gate circuit should be protected against overvoltage and overcurrent. Overvoltages across the cut can cause false triggering of SCR whereas overcurrent may raise the junction temperature.

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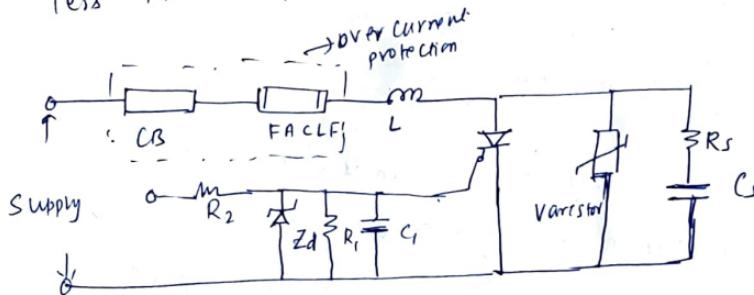
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Protection against the overvoltage is achieved by Zener diode and resistance connected in series to provide protection against over current.

In addition to this the thyristor circuit is a snubber to m noise, firing. Turning on or turning off an SCR may induce trigger pulse in nearby SCR. So in order to avoid such triggering, capacitor and resistor are also connected across gate cathode to bypass noise signal. The capacitor should less than 0.1 μF.

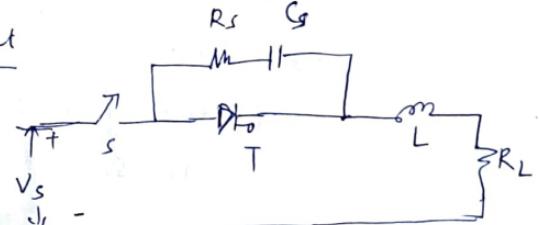


## Design of Snubber Circuit

When ~~closed~~ switch at

on state

$$V_s = (R_s + R_L) t + \frac{1}{C} \int i dt + L \frac{di}{dt}$$



At the switching instant  $\frac{1}{C} \int i dt = 0$ , because capacitor at short-circuit (m).

$$\text{so } V_s = (R_s + R_L)t + L \frac{di}{dt} \quad \text{--- (1)}$$

By solving the above equn

$$i = \frac{V_s}{R_s + R_L} (1 - e^{-t/\tau})$$

$$\tau = \frac{L}{R_s + R_L}$$

$$\frac{de}{dt} = \frac{V_s}{L} e^{-t/\tau}$$

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When  $t = 0$

$\frac{di}{dt} = \frac{V_s}{L}$  and  $\frac{di}{dt}$  reaches to its maximum value.

$$\left( \frac{di}{dt} \right)_{\max} = \frac{V_s}{L}$$

$$L = \frac{V_s}{\left( \frac{di}{dt} \right)_{\max}}$$

At  $t = 0$

$$V_a = R_s t$$

$$\frac{dV_a}{dt} = R_s \frac{di}{dt} \Rightarrow \left( \frac{dV_a}{dt} \right)_{\max} = R_s \left( \frac{di}{dt} \right)_{\max}$$

$$\Rightarrow \left( \frac{dV_a}{dt} \right)_{\max} = R_s \times \frac{V_s}{L}$$

$$\Rightarrow R_s = \frac{L}{V_s} \left( \frac{dV_a}{dt} \right)_{\max}$$

$R_s$  can be obtained from the eqn

$$R_s = 2 \times \sqrt{\frac{L}{C_s}}$$

$$\Rightarrow C_s = \left( \frac{2}{R_s} \right)^2 \times L$$

In this case ~~d~~- damping factor = 0.5 to 1

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## Phase Controlled Converters

Rectification is a process of converting of a.c. voltage into d.c. voltage profile. This conversions can be achieved by variety of circuits.

The rectifier circuits can be classified into 3 types: uncontrolled, fully controlled and half-controlled.

An uncontrolled rectifier circuit uses diode which converts a.c. voltage into a fixed d.c. voltage.

Fully controlled rectifier uses thyristor as rectifying elements and converts a.c. voltage into variable d.c. voltage.

Half-controlled rectifier uses thyristor and diode and control over the d.c. voltage is lesser than fully controlled rectifier circuit.

## Control Techniques

The phase controlled converter to provide either a one quadrant, two-quadrant or four quadrant operation of its d.c. terminals.

Followings are the control techniques of converter.

- (i) phase angle control (ii) extinction angle control
- (iii) pulse width modulation control

### Phase angle control

In a.c. circuit, the SCR can be turned on by gate at any angle w.r.t. applied voltage. The firing angle is measured w.r.t. a given reference, at which firing pulses are provided. "x" represents firing angle. Most efficient method to control turning on angle of thyristors is achieved by changing the firing angle of thyristor, such a method of control is called phase angle control.

### Extinction angle control

Extinction angle control means where the device is at off state. Extinction angle control technique is called extinction angle control.

### PWM Control

In PWM control technique pulse is the control parameter. Depending upon the pulse the output voltage is obtained.

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1f half-wave controlled rectifier with R-load

The circuit diagram of half-wave controlled rectifier with R-load is shown in fig- 2.

Let us consider sinusoidal nature of supply voltage is provided into the circuit.

During the positive half-cycle of the supply voltage, thyristor is in forward biased condition.

During this the thyristor is at on state. The thyristor is triggered by gate pulse.

Let us consider an instant "m" at which gate pulse is provided into the thyristor between  $0\pi$  &  $\pi$ .

At this instant thyristor is

After turning on thyristor, the rest portion of the supply voltage is available across the load side.

When  $wt = \pi$ , supply voltage is at zero value. At the zero value of supply voltage, thyristor is at off state.

After  $\pi$ , -ve half-cycle is available. During this thyristor is at reverse biased condition so the device is at off state available across the load side.

This kind of waveform is

$$\text{From the waveform } V_{av} = \frac{1}{2\pi} \int_0^{\pi} V_m \sin wt dt = \frac{V_m}{2\pi} (1 - \cos d) \quad \text{--- (1)}$$

$$V_{av} = \frac{1}{2\pi} V_m \left[ \frac{\pi - d}{4\pi} + \frac{\sin 2d}{8\pi} \right]^{\frac{1}{2}}$$

$$V_{rms} = \sqrt{V_m^2 \left[ \frac{\pi - d}{4\pi} + \frac{\sin 2d}{8\pi} \right]}$$

1f half-controlled rectifier with R-L load

The circuit diagram of half-controlled rectifier with R-L load is shown below.

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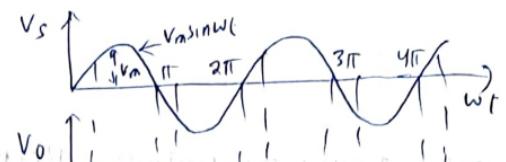
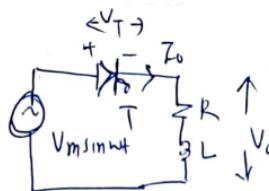
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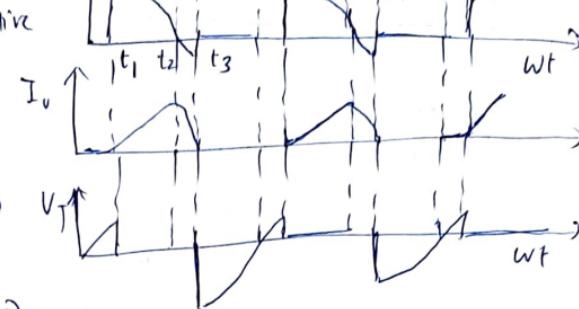
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The operation of the inductive load changes slightly.

At instant  $t_1$ , thyristor is triggered. Now the load

current will increase through the inductive load.



After turning on of SCR, load voltage is available across SCR. Due to inductive load, increase in current is gradual. During the on cond' of SCR, Energy is stored inside inductor during  $t_1$  to  $t_2$ .

At  $t_2$ , supply voltage is at zero value, but the thyristor is conducting during this. This is due to the fact that current through inductance can't be reduced to zero value.

During the -ve half-cycle, energy stored in inductance

is dissipated in load resistor and some part is ~~lost~~. Due to this the current starts fed back to the source. Due to this the current starts decreasing. After complete dissipation of energy, thyristor is at off state. The angle at which thyristor is at off state is called extinction angle. The angle at

which thyristor is at on state is called firing angle. The angle at which thyristor starts conduction is denoted as  $\alpha$  and

The firing angle and conduction angle

$\beta$ .

Average value of output voltage

$$V_{AV} = \frac{V_m}{2\pi} [\cos \alpha - \cos \beta]$$

Effect of Free wheeling Diode  
A bypass diode is connected across ~~the~~ load side to perform ~~the~~ the following two functions -

- ② It prevents reversal of load voltage

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(ii) It transfers the load current away from the main rectifier unit.

## 1. Full-Wave Controlled Rectifier set

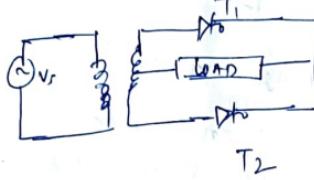
Depending upon the configuration, there are two types of configuration

(i) Mid-point converter

(ii) Bridge converter.

### Mid-Point Converter

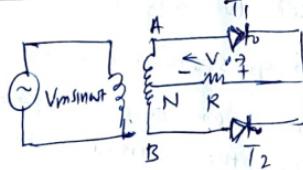
The circuit diagram of mid-point converter is shown below.



It consists of 1d transformer with centre tapped secondary winding. On either side one thyristor is going to be connected. In this case ratio is taken as unity.

primary to each secondary turns

### Mid-point converter with R load



The circuit diagram of mid-point converter with "R" load is shown in the figure.

Let us consider sinusoidal nature of supply voltage  $V_s$  provided onto the primary side. On each secondary side the same amount of voltage is generated.

During the +ve half-cycle of supply voltage, A is at higher potential w.r.t. B point. At this condition  $T_1$  is in forward biased whereas  $T_2$  is in reverse biased.

Let us consider an instant "m" thyristor  $T_1$  is at on state. After turning on of  $T_1$ , the rest portion of the supply voltage is available across  $R_{load}$ . During this T2 is at off state. This kind of phenomenon takes place in between 0 to  $\pi$ .

When  $wt = \pi$ , supply voltage is at zero value.

At this value,  $V_s = 0$  &  $V_o = 0$  hence  $T_1$  is at off state.

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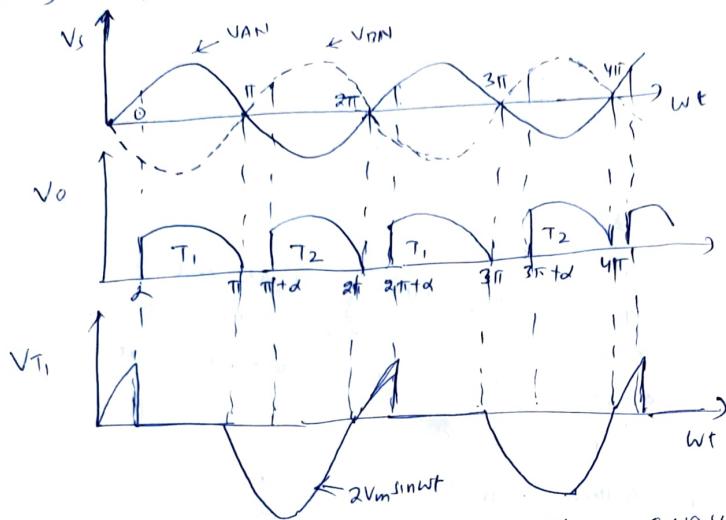
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After  $\pi$ ,  $T_2$  is cut forward biased condition.  $T_2$  can be turn-on by applying gate pulse.

Let us consider an instant "n" at which  $T_2$  is on state and hence the rest portion of supply is available across load. The necessary waveform is shown below



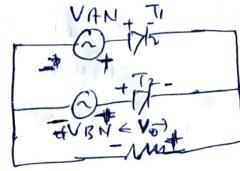
When  $T_1$  is off state, then voltage across  $T_1$

$$V_{AN} - V_{T_1} + V_{T_2} - V_{BN} = 0$$

$$\Rightarrow V_{AN} - V_{T_1} - V_{BN} = 0$$

$$\Rightarrow V_{AN} - V_{BN} = V_{T_1} \quad \text{--- (1)}$$

$V_{T_1} = V_m \sin \omega t - (-V_m \sin \omega t)$ , In this case  $T_2$  is not turn-on consideration or  $V_{T_2} = 0$



$$V_{T_1} = 2V_m \sin \omega t$$

Average value of output voltage

$$V_{AV} = \frac{1}{\pi} \int_{\pi}^{\pi} V_m \sin \omega t d\omega t = \frac{V_m}{\pi} (1 - \cos \omega t) \quad \text{--- (1)}$$

Rms load voltage

$$\text{Rms } V_{rms} = V_m \left[ \frac{\pi - \alpha}{\pi} + \frac{\sin 2\alpha}{4\pi} \right]^{\frac{1}{2}}$$

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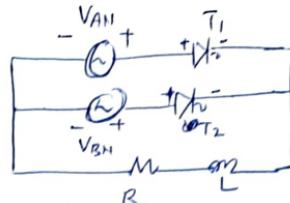
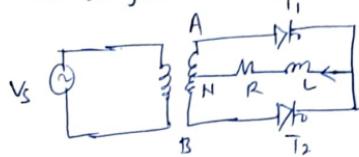
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With Inductive load

The circuit diagram is shown below.



During the positive half-cycle of supply voltage  $T_1$  is forward biased (on).

$T_1$  can be fired by the application of gate pulse. After turning on  $T_1$ , inductor has the tendency to store energy with the help of supply voltage. So from 0 to  $\pi$  energy is stored by the inductor.

When  $wt = \pi$ , supply voltage is at zero value. But the thyristor  $T_1$  is in on state. Because at ~~wt~~ this instant

current across the load side can't drop down to zero value.

After  $\pi$ ,  $T_1$  is in on state.

In addition to this after  $\pi$ ,  $T_2$  is at forward biased condition. So until the application of gate pulse to  $T_2$ ,  $T_1$  is in on state. During this time the energy stored in the inductor dissipates across load resistance  $R$  and feedback into the supply.

After  $\pi + d$ ,  $T_2$  is in on state. After turning on  $T_2$ , once again load current is transferred from  $T_1$  to  $T_2$ . Hence the inductor has the tendency to store the energy from  $\pi + d$  to  $2\pi$ .

After  $2\pi$ ,  $T_2$  is in on state, because of the energy stored by inductor.

After  $2\pi$ ,  $T_2$  is in on state until the application of gate pulse to  $T_1$ . The waveform is shown in the figure below.

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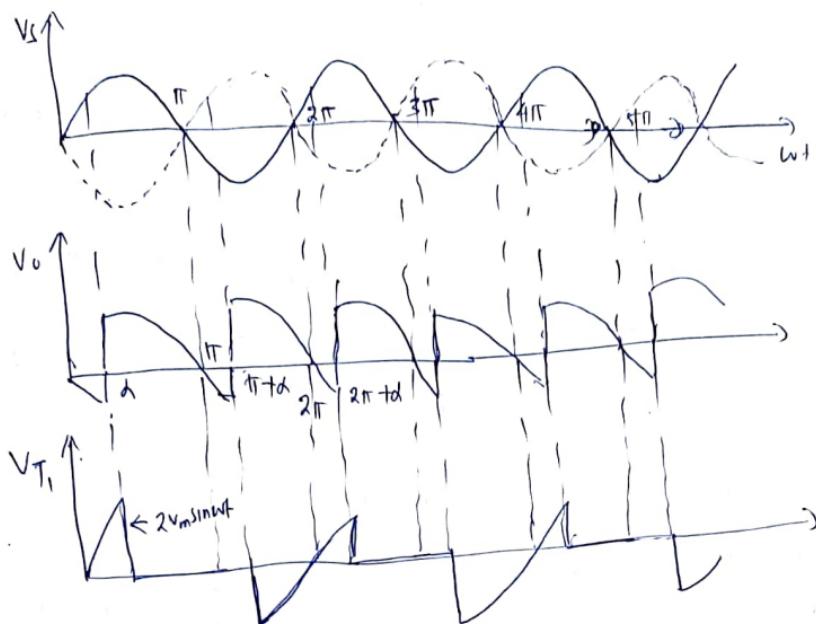
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From the above wave form,

$$(V_o)_{av} = \frac{1}{\pi} \int_{\pi}^{\pi+d} v_m \sin \omega t dt$$

$$= \frac{V_m}{\pi} \left[ -\cos \omega t \right]_{\pi}^{\pi+d} = \frac{V_m}{\pi} \left[ -\cos(\pi+d) + \cos d \right]$$

$$= \frac{2V_m \cos d}{\pi} - 1V$$

Depending upon the firing angle, converting mode and

Inverting mode of operation takes place.

When  $\alpha < 90^\circ$ , Inverting mode operation takes place.

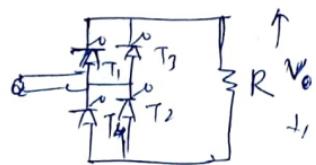
When  $\alpha > 90^\circ$ , Inverting mode operation takes place.

## Pulse Number

Depending upon the output voltage ~~profile~~ profile in a complete cycle pulse number is decided.

## Bridge Configuration

The circuit diagram of bridge configuration is



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In one cycle two thyristors are at turn-on.

Let us consider sinusoidal nature of supply voltage is provided into the bridge configuration which consists of pure resistive load.

During positive half-cycle  $T_1$  and  $T_2$  are at forward biased condition where  $T_3$  and  $T_4$  are at reverse biased condition. After turning on of  $T_1$  and  $T_2$ , the rest portion of the supply voltage is available across the load side.

When  $\omega t = \pi$ , supply voltage is at zero value. At this condition  $T_1$  &  $T_2$  are at off state.  $T_3$  &  $T_4$  are at available.

After  $\pi$ , -ve half-cycle is available.  $T_3$  &  $T_4$  are at forward biased condition. During this  $T_3$  and  $T_4$  are at on state by applying gate pulses into  $T_3$  &  $T_4$ . After turning on  $T_3$  &  $T_4$ , the rest portion of the supply voltage is available across the load side.

When  $\omega t = 2\pi$ , supply voltage is at zero value, ~~at~~ and at zero value of supply voltage  $T_3$  and  $T_4$  are at off state.  $T_1$  &  $T_2$  are at forward biased condition and at value of  $2\pi$ ,  $T_1$  &  $T_2$  are at forward biased condition, the same phenomenon repeats.

After  $2\pi$ , forward biased condition, the current is shown in the waveform of voltage, ~~current~~ current is shown in fig - 3.

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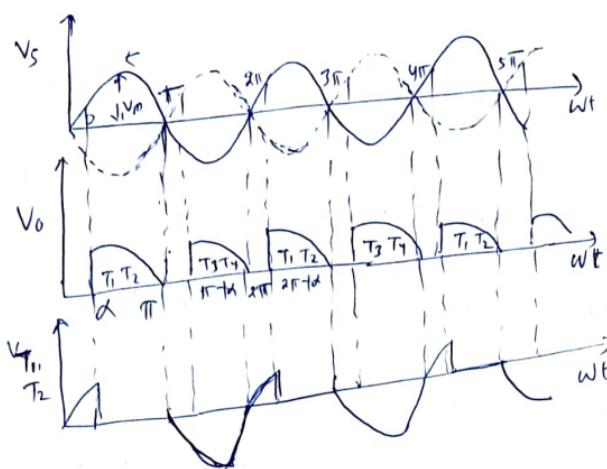
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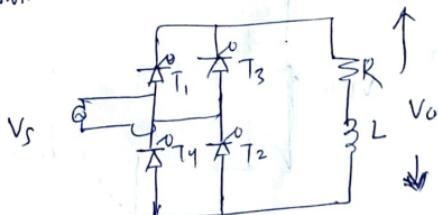
From the waveform

$$(V_o)_{av} = \frac{1}{\pi} \int_0^{\pi} V_m \sin \omega t dt$$

$$= \frac{V_m}{\pi} [1 + \cos \omega t] \Big|_0^{\pi}$$

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

Fully controlled bridge cut with R-L load  
The cut diagram of fully controlled bridge cut with R-L load  
is shown in



Thyristor T<sub>1</sub> and T<sub>2</sub> are fired in the +ve half-cycle whereas T<sub>3</sub> and T<sub>4</sub> are fired in -ve half-cycle. A large value of inductor L is used in order to

reduce the ripple.

During the positive half-cycle of supply voltages T<sub>1</sub> and T<sub>2</sub> are at on state. During the turning on comm<sup>on</sup> inductor has the tendency to store some amount of energy.

When  $\omega t = \pi$ , supply voltage is at zero value. At this value T<sub>1</sub> and T<sub>2</sub> are at on state and hence total energy stored in L will dissipate across R and some energy ~~will~~ feedback into the supply.

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After  $wt = \pi$ ,  $T_3 \& T_4$  are at forward biased condn. so until the application of gate pulse into  $T_3 \& T_4$ ,  $T_1$  and  $T_2$  are at on state. During this condn current starts decreasing from higher value to lower value.

After the application of gate pulse at  $\pi + d$ ,  $T_3 \& T_4$  are at on-state. After turning on once again the inductor has the tendency to store energy during  $\pi + d$  to  $2\pi$ . At  $2\pi$  supply voltage  $v_s$  is at zero value. At the zero value of supply voltage,  $T_3 \& T_4$  are at on state. After  $2\pi$   $T_3 \& T_4$  are at off state. During this time  $T_1$  and  $T_2$  are at forward biased condn; so due to energy stored by inductor  $T_3 \& T_4$  are at on state until the application of gate pulse into  $T_1 \& T_2$ .

The necessary waveforms are

$$(V_o)_{av} = \frac{1}{\pi} \int_{\pi+d}^{2\pi} V_m \sin \omega t dt$$

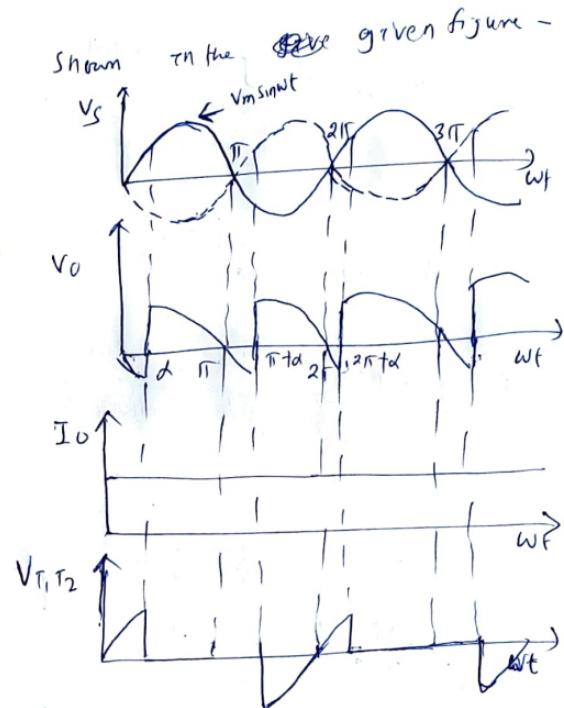
$$= \frac{V_m}{\pi} [-\cos \omega t]_{\pi+d}^{2\pi}$$

$$= \frac{2V_m}{\pi} \cos d - ①$$

Depending upon the firing angle  $d$  converter operation and inverter operation takes place.

When  $d < 90^\circ$ , converter operation takes place.

When  $d > 90^\circ$ , inverter operation takes place.



## 3<sup>ph</sup> Half-Wave Rectifier circuit with R-load

The circuit diagram of a 3<sup>ph</sup> half-wave rectifier circuit with R-load is shown in the given figure.

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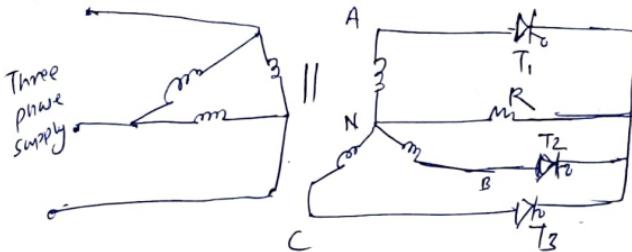
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The three phase supply voltages are

$$V_{AN} = V_m \sin \omega t$$

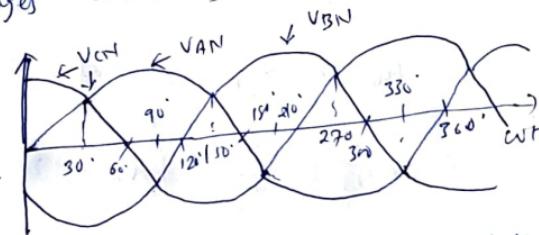
$$V_{BN} = V_m \sin(\omega t - 120^\circ)$$

$$V_{CN} = V_m \sin(\omega t + 120^\circ)$$

With the help of supply voltages all the thyristors are on state.

The phase voltages are

When  $\omega t = 0$ , then C phase supply voltage is at higher potential. So the thyristor present across "C" phase



So  $T_3$  is at on state.

After this up to the overlapping point between  $V_{AN}$  &  $V_{CN}$ ,  $T_3$  is at on state.

At overlapping instant,  $V_{AN} = V_{CN}$ . Now If we apply a gate pulse to  $T_1$ , then  $T_1$  is also on state. Just before this  $T_1$  is at reverse bias condn. The overlapping instant is called zero value of firing angle.

Each thyristor can conduct for a period of  $120^\circ$ . So for continuous conduction it lies between  $0$  to  $30^\circ$ .

Thyristor  $T_1$  can conduct for  $30^\circ + \alpha$  to  $150^\circ + \alpha$ .

At  $150^\circ + \alpha$   $T_2$  can conduct and conduct for  $150^\circ + \alpha$  to

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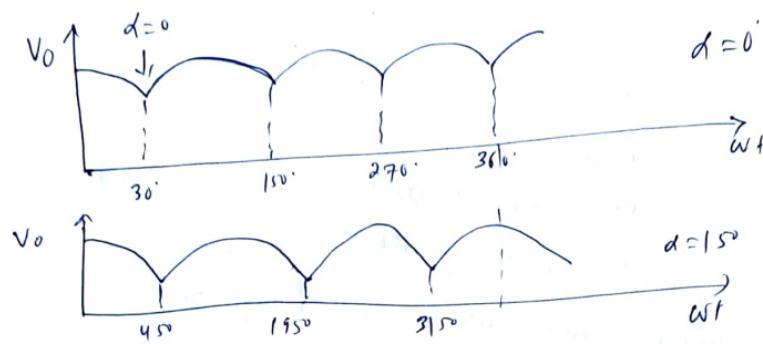
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270° fd.

At 270° fd,  $T_3$  can conduct and conduct for a period of 30° fd. This kind of conduction takes place when  $\alpha$  lies between  $0 < \alpha < 30^\circ$ . So the output voltage is



so the average value of output voltage is

$$(V_o)_{AV} = \frac{1}{\frac{2\pi}{3}} \int_{d+30^\circ}^{d+150^\circ} V_m \sin wt dwt$$

$$= \frac{3}{2\pi} V_m [-\cos wt]_{d+30^\circ}^{d+150^\circ} = \frac{3\sqrt{3}}{2\pi} V_m \cos d$$

For discontinuous conduction

$$(V_o)_{AV} = \frac{3}{2\pi} \int_{d+30^\circ}^{180^\circ} V_m \sin wt dwt$$

$$= \frac{3}{2\pi} V_m [-\cos (wt)]_{d+30^\circ}^{180^\circ}$$

$$= \frac{3V_m}{\pi} [1 + \cos(d+30^\circ)]$$

Avg load current

$$I_d = \frac{3V_m}{2\pi R} [1 + \cos(30^\circ + d)]$$

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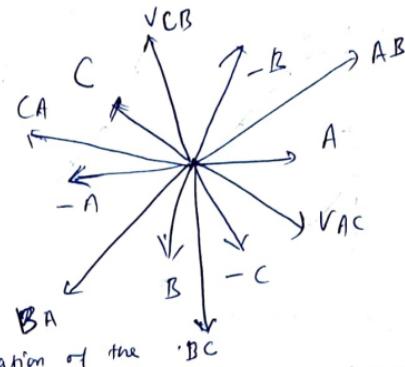
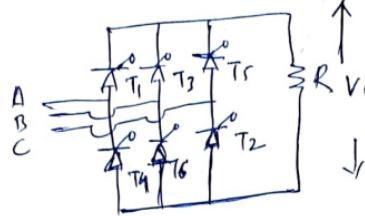
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## 3.4 Full wave Converter circuit with R-load

The circuit diagram of 3.4 full wave converter circuit with R-load is shown in figure



In order to understand the operation of the above circuit, the following points are taken into consideration.

- (i) Each device should be triggered at firing angle  $\alpha$ .
- (ii) Each SCR can conduct for 120°.
- (iii) SCR must be triggered in the sequence  $T_1, T_2, T_3, T_4, T_5, T_6$ .
- (iv) The phase shift between triggering of two adjacent SCRs is 60°.
- (v) At any instant, two SCR can conduct. That means one positive group and one -ve group of SCR are in conduction mode. There are six pairs of SCR  $(T_1, T_2), (T_2, T_3), (T_3, T_4), (T_4, T_5), (T_5, T_6)$ .
- (vi) The incoming SCR commutates the outgoing SCR.

In order to remember all these things one table is there.

SLNO	WT	Incoming SCR	Conducting pair	Outgoing SCR	Line voltages
1.	30°A	$T_1$	$(T_6, T_1)$	$T_6$	$V_{AB}$
2.	90°A	$T_2$	$(T_1, T_2)$	$T_1$	$V_{AC}$
3.	150°A	$T_3$	$(T_2, T_3)$	$T_2$	$V_{BC}$
4.	210°A	$T_4$	$(T_3, T_4)$	$T_3$	$V_{DA}$
5.	270°A	$T_5$	$(T_4, T_5)$	$T_4$	$V_{CA}$
6.	330°A	$T_6$	$(T_5, T_6)$		$V_{CB}$

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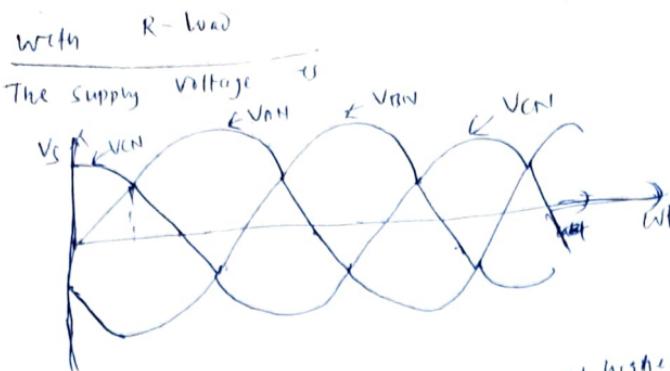
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When  $wt = 0^\circ$ , then C phase is at higher potential where as B is at lower potential. So the thyristor that should be

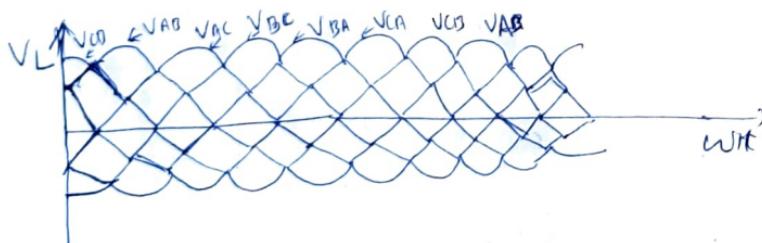
available across C & B are are at on state. So due to turning on  $T_3, T_7$  &  $T_6, T_5$  are at on state. Due to turning on  $T_3, T_7$  line voltage  $V_{CB}$  is available across load side.

At overlapping point,  $T_1$  is at reverse biased. APP by applying gate pulse

At  $wt = 30^\circ$ ,  $VAN = VCN$ , so  $T_1$  is at on state. Due to turning on  $T_1, T_8, T_6$  are on state & hence across load VAB amount of voltage is available.

At overlapping instant if we are able to turn-on thyristor, then thyristors are triggered in the sequences of  $T_1, T_2, T_3, T_4, T_5 \& T_6$ .

The output voltages are line voltages and the waveform of line voltages are -



The ten output voltages are like this.

When ~~wt = 30°~~, across load side VAB amount of voltage is not available. In this case  $T_6, T_1$  are at on state.

$$\text{So } V_{AD} = \cancel{V_{AB}} V_{AN} - V_{BN} = V_m \sin wt - V_m \sin (wt - 120^\circ)$$

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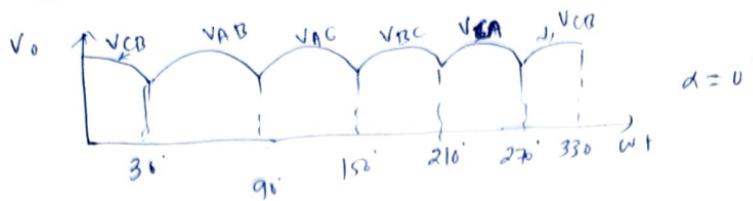
When  $\alpha = 90^\circ$  ( $d = 0^\circ$ )

$T_1, T_2$  are on state. So the voltage  $V_{AC}$  is available.

$$V_{AC} = V_m \sin \omega t - V_m \sin(\omega t + 120^\circ)$$

So at the overlapping instant different thyristors are turn on state.

The output voltage at the overlapping instant is



The average value of output voltages are

$$\begin{aligned}
 (V_o)_{av} &= \frac{1}{2\pi/6} \int_{d+30^\circ}^{d+90^\circ} V_{AB} \, d\omega t \\
 &= \frac{6}{2\pi} \int_{d+30^\circ}^{d+90^\circ} \sqrt{3} V_m \sin(\omega t + 30^\circ) \, d\omega t \\
 &= \frac{3\sqrt{3}}{\pi} \int_{d+30^\circ}^{d+120^\circ} V_m \sin(\omega t + 30^\circ) \, d\omega t \\
 &= \frac{3\sqrt{3} V_m}{\pi} \int_{d+60^\circ}^{d+120^\circ} \sin \omega t \, d\omega t \\
 &= \frac{3\sqrt{3} V_m}{\pi} [\cos(d+60^\circ) - \cos(d+120^\circ)] \\
 &= \frac{3\sqrt{3} V_m}{\pi} [3\sqrt{3} \cos d]
 \end{aligned}$$

Average load current

$$I_d = \frac{3\sqrt{3} V_m}{\pi R} \cos d$$

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Discontinuous conduction When  $d > 60^\circ$  then discontinuous conduction takes place.

$$\text{so } V_o = \frac{6}{\pi R} \int_{\alpha+30^\circ}^{180^\circ} \sqrt{3} V_m \sin(\omega t + 30^\circ) d\omega t$$

$$= \frac{3\sqrt{3} V_m}{\pi} \int_{\alpha+60^\circ}^{180^\circ} \sin(\omega t + \alpha) d\omega t$$

$$= \frac{3\sqrt{3} V_m}{\pi} [1 + \cos(\alpha + 60^\circ)]$$

$$\text{gt } \alpha = 120^\circ \quad (V_o)_{av} = \frac{3\sqrt{3} V_m}{\pi} [1 + \cos 180^\circ] = 0$$

$$(V_o)_{av} = \frac{3\sqrt{3} V_m}{\pi} [1 + \cos(120^\circ)]$$

$$\text{so } d_{max} = 120^\circ$$

$$\text{Avg load current} = \frac{3\sqrt{3} V_m}{\pi R} [1 + \cos(\alpha + 60^\circ)]$$

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## AC Voltage Regulator

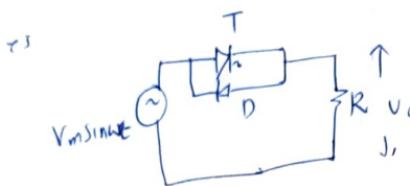
The device which converts fixed ac voltage into variable ac voltage is known as a.c. voltage regulator.

AC voltage regulators are used in domestic and industrial heating, transformer tap changing, lighting control, speed control of 1φ and 3φ a.c. motor and starting of induction motor.

AC voltage regulators are divided into two types -

- (i) Half-wave control
- (ii) Full-wave control

Half-Wave A.C. Voltage Regulator  
The cut diagram of half-wave a.c. voltage regulator



From the cut diagram, one Thyristor is connected in anti-parallel with diode.

Let us consider sinusoidal nature of supply voltage with maximum  $V_m$  is provided into the cut. During the positive half the thyristor is turn-on with the help of gate pulse. After turning on, the rest portion of the supply voltage is available across the load side.

When  $\omega t = \pi$ , thyristor T is at off state.

After  $\pi$ , diode D is at state. After turning on of diode -ve supply voltage is available across the load. This kind of phenomenon takes after turns on load. This kind of phenomenon takes after turns on load. The a.c. voltage can be controlled by thyristor and diode. So the a.c. voltage can be converted into variable a.c. voltage. The cut waveform is shown below.

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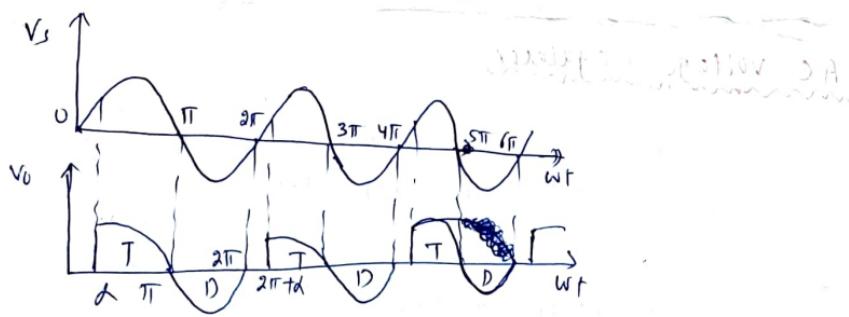
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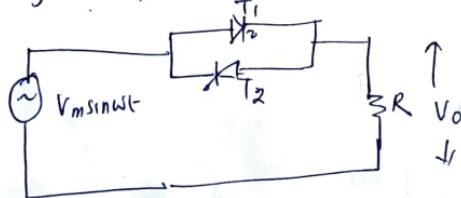
From this the ~~the~~ RMS value of output voltage

$$V_{RMS} = \left[ \frac{1}{2\pi} \int_0^{2\pi} V_m^2 \sin^2 \omega t dt \right]^{\frac{1}{2}}$$

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

## Full-wave A.C. voltage regulator

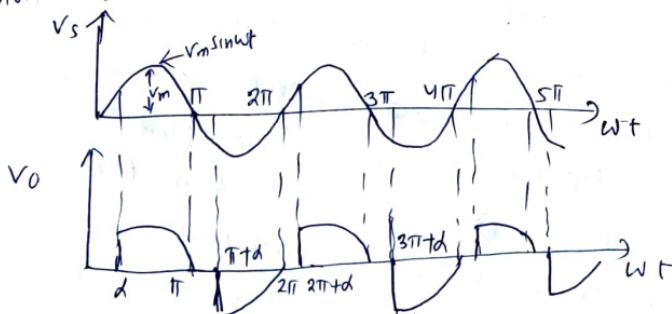
The circuit diagram of full-wave AC voltage regulator is



From the figure two thyristors are connected in antiparallel.

In both the half-cycles T<sub>1</sub> and T<sub>2</sub> are at ~~off~~ on state.

During turn on of both thyristors positive and negative half-cycles are available across the load. The cut wave form is shown below



The  $\text{V}_{RMS}$  value is

$$V_{RMS} = \left[ \frac{1}{2\pi} \int_0^{2\pi} V_m^2 \sin^2 \omega t dt \right]^{\frac{1}{2}}$$

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$$V_{m \text{ max}} = \frac{V_m}{\sqrt{2}} \left[ \frac{1}{\pi} \left\{ (\pi - \alpha) + \frac{\sin \alpha}{2} \right\} \right]^{\frac{1}{2}}$$

## Cycloconverter

The device which converts input power at one frequency into output at different frequency is called cyclo converter.

Cycloconverters are of two types.

(i) Step up Cycloconverter

(ii) Step down "

- cycloconverters are used in -
- (i) speed control of a.c. drives
  - (ii) Induction heating
  - (iii) Static var compensation
  - (iv) Use as a power supply for aircraft or shipboards.

Cycloconverters are of two types -

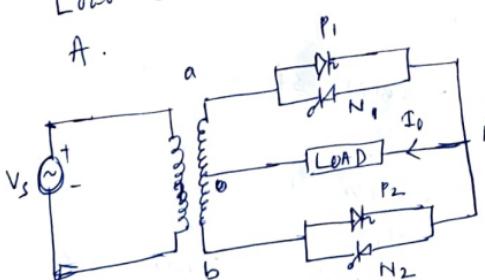
Depending upon the configuration

(i) Mid point Cyclo converter

(ii) Bridge Cycloconverter

## Mid point Cyclo Converter

It consists of a single phase transformer with mid tap on the secondary winding and four thyristor. Two of these thyristor P<sub>1</sub> and P<sub>2</sub> are for positive group and other two N<sub>1</sub> and N<sub>2</sub> for negative group. Load is connected between secondary winding mid point and terminals A and A'.



During the positive half-cycle a is +ve w.r.t. b. So P<sub>1</sub> & N<sub>2</sub> are in forward biased state. SCR P<sub>1</sub> is turned on at wt=0 and positive output voltage is available across load side. At instant wt<sub>1</sub>, P<sub>1</sub> is forced off and thyristor N<sub>2</sub> is at on state.

commutated off and forward biased due to turning on of N<sub>2</sub>, -ve voltage is available across load side.

At wt<sub>2</sub>, N<sub>2</sub> is off and P<sub>1</sub> is on state. Similarly at wt<sub>3</sub> P<sub>1</sub> is off & N<sub>2</sub> is on from wt<sub>3</sub> to π.

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Let that just after  $\pi$ ,  $P_2$  and  $N_1$  are at forward biased condition.

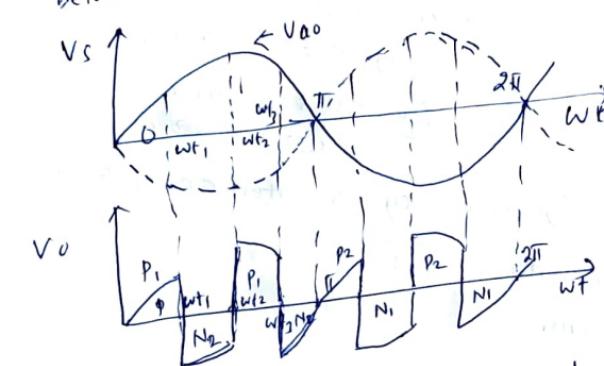
At  $wt = \pi$ ,  $P_2$  is at on state &  $N_1$  is at off state.  
At  $wt = \pi$ ,  $P_2$  is turn-on for why? At  $wt = \pi$ ,  $N_1$  is turn-off &  $P_2$  is at off state.

$N_1$  is turn-on for why to  $w_{t5}$ .  
At  $w_{t5}$ ,  $P_1$  is turn-on &  $N_1$  is at turn-off.

$P_1$  can conduct for  $w_{t5}$  to  $w_{t6}$ .

At  $w_{t6}$ ,  $P_1$  is off and  $N_1$  is turn-on & conduct for  $w_{t6}$  to  $2\pi$ . necessary output voltage waveform is given

The below



From the waveform,  $f_o = f_{in} = \frac{1}{T}$

$$f_o = \frac{1}{T_0}$$

$$T_0 = \frac{T}{4}$$

$$\text{so } f_o = \frac{1}{T_0} = \frac{1}{T/4} = 4 \times \frac{1}{T} = 4 \times f_{in}$$

Thus  $W_n$  of cycloconverter is called step-up cycloconverter.

## Step-down cycloconverter

during the +ve half-cycle

From the Ckt,  $P_1$  and  $N_2$  are forward biased Cndn. When  $wt = 0$ ,  $P_1$  is at on state. After turning on  $P_1$ , rest portion of supply voltage is available across load side.

$$\text{so } V_o = V_s$$

When  $wt = \pi$ ,  $P_1$  is at off state.

At this instant  $P_2$  is a turn-on Cndn. so once again positive voltage is available across load side.

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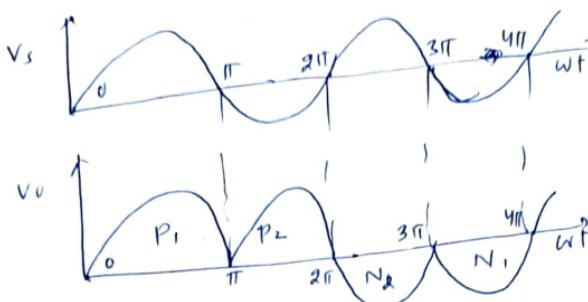
$P_2$  is turn-on condition from  $\pi$  to  $2\pi$ .

When  $wt = 2\pi$ ,  $N_2$  is turn-on (on). So -ve voltage is available.

$N_2$  is turn-on state from  $2\pi$  to  $3\pi$ .

when  $wt = 3\pi$ ,  $N_1$  is at on condn.

After this  $N_1$  is conducting for  $3\pi$  to  $4\pi$ . So two kinds of phenomenon takes place from by turning on the four thyristors. The waveform is given below



From the above waveform

$$T_0 = 2\pi, \text{ so } f_0 = \frac{1}{T_0}$$

$$= \frac{1}{2\pi} = \frac{1}{2} \times f_{in}$$

$$f_0 = \frac{f_{in}}{2} \quad (1)$$

this kind of converter  
is called step down cyclo-converter.

cyclo-converter

The device which converts fixed dc voltage into variable DC voltage is known as chopper.

Choppers are used in - sub-way cars, trolley buses, battery operated vehicles, battery charging etc. Depending upon the conversion process, choppers are classified into two types

those are AC link chopper and DC

chopper.

AC link chopper - In AC link chopper  
into AC by inverter circuit.

DC is converted

Then AC is stepped up or

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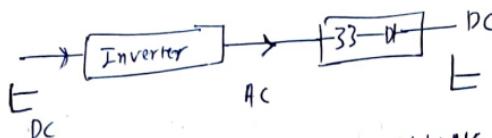
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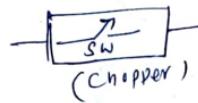
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Stepped down by a transformer which is then converted into DC by rectifier circuit. The block diagram is



AC link chopper is costly, bulky and less efficient. Because conversion is done in two stages.

In DC link chopper fixed DC is converted to variable DC by chopper circuit. In chopper, semi-conductor devices are available and during the turning on and turning off DC can be converted into variable DC. The chopper is represented by a switch which is presented inside the dotted rectangle.



## Basic Chopper Classification

According to input / output voltage levels choppers are of two types

- (i) Step-down chopper
- (ii) Step-up chopper.

According to the direction of output voltages and currents choppers are of following types -

- ① CLASS A CHOPPER
- (ii) CLASS B "
- (iii) CLASS C "
- (iv) CLASS D "
- (v) CLASS E "

According to circuit operation following types of choppers are available.

- (1) First quadrant chopper
- (2) Two quadrant "
- (3) Four quadrant chopper.

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According to commutation process, choppers are of following types -

- (i) Voltage Commutated Choppers
- (ii) Current Commutated "
- (iii) Load Commutated or "
- (iv) Impulse "

## Chopper operation

Chopper is a high speed on/off switch. It connects load with source when it is on state and disconnects load from source whenever it is at off state.

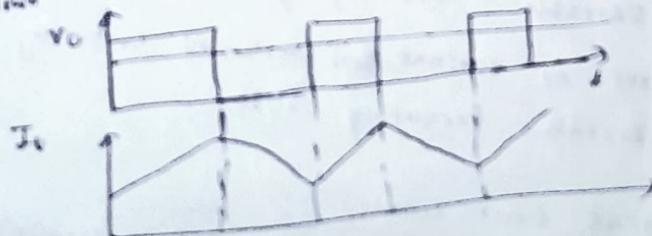
Generally a chopper is represented by a switch inside the dotted rectangle. In chopper circuit, it consists of one power semi-conductor device like SCR, BJT, IGBT, MOSFET.

The basic chopper circuit diagram is



When chopper is at on state,  $V_o = V_d$ . In this case  $I_d$  is at OFF state so the current starts increasing from smaller value to higher value.

When chopper is off state,  $E_d$  is at on state and current is gained by the capacitor present in the load circuit of chopper. Starts decreased. During this current starts decreasing from higher value to lower value. The maximum waveform of the current is shown below



From the above waveform

$$(V_o)_{avg} = V_d \times \frac{T_{on}}{T_{on} + T_{off}} = V_d \times d$$

where  $d$  = duty cycle.

The above circuit is a Step-Down Chopper circuit.

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Duty cycle is nothing but the ratio of turn on time to total time.  
In the stepdown chopper  $d < 1$ .

$$V_o = v_s \times T_m \times \frac{1}{T} \quad \text{---(i)}$$

$$V_o = v_s \times T_{on} \times f \quad \text{---(ii)}$$

$$(I_o)_{AV} = \frac{V_o}{R} = \frac{d \cdot v_s}{R}$$

$$(V_o)_{RMS} = E_{ds} \times \sqrt{\frac{T_m}{T}} \quad \text{---(iii)}$$

$$= E_{dc} \times \sqrt{d}$$

Control Strategies  
The average value of output voltage can be controlled by —

- (r) Time ratio control
- (r2) Current limit control

## Time Ratio Control (TRC Control)

In time ratio control, duty cycle is varied. During this either frequency remains constant or frequency is varying.

- (r) Constant Frequency System -: In constant frequency system  $T_{on}$  is varied but frequency remains constant. Such kind of technique is called constant frequency system or pulse-width modulation system.

(r2) Variable frequency system -: In this case either  $T_{on}$  or  $f_{eff}$  is constant. This method of controlling  $d$  is called variable frequency system.

## Current limit control

The chopper is at on state when current is reaching minimum value. The chopper is at off state when current is reaching maximum value. By controlling the maximum and minimum value the output voltage is controlled. Such kind of control technique is called current limit control.

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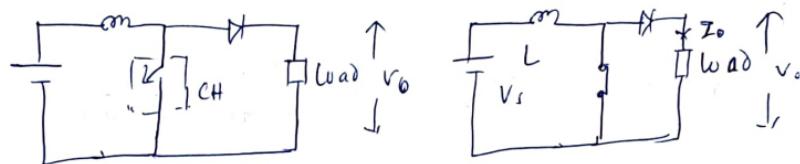
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## Step-up Chopper

The circuit diagram of Step-up Chopper is



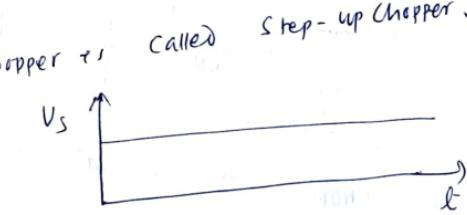
When chopper is at on state  $V_o = 0$ . In this case inductor stores energy during the turn-on period.

When chopper is at off state, the energy starts dissipated across the load. Due to this the polarity of inductor from higher value to lesser value.

Now by applying KVL

$$V_s + L \frac{di}{dt} - V_o = 0 \Rightarrow V_o = V_s + L \frac{di}{dt} \quad (\text{when CH is at off state})$$

such kind of chopper is called Step-up chopper.  
From the cut; energy remains same.



Energy input to inductor during the turn-on time,  $T_{on}$

$$= W_{in}$$

$$= (\text{Voltage across } L) \times (\text{Avg current}) \times T_{on}$$

$$= V_s \times \left( \frac{I_1 + I_2}{2} \right) \times T_{on}$$

Energy released by inductor during the turn-off time

$$W_{out} = (\text{Voltage across } L) \times (\text{Avg current}) \times T_{off}$$

$$= (V_o - V_s) \times \left( \frac{I_1 + I_2}{2} \right) \times T_{off}$$

$$\text{Now } V_s \times \left( \frac{I_1 + I_2}{2} \right) \times T_{on} = (V_o - V_s) \times \left( \frac{I_1 + I_2}{2} \right) \times T_{off}$$

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$$V_s \times T_{on} = V_o T_{off} - V_s T_{off}$$

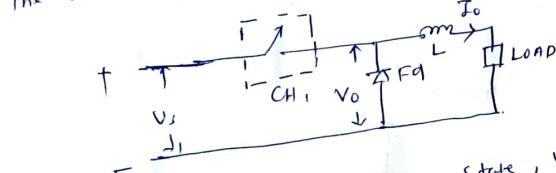
$$V_o T_{off} = V_s (T_{on} + T_{off}) = V_s \times T$$

$$\Rightarrow V_o = \frac{V_s \times T}{T_{off}} = \frac{V_s \times T}{T - T_{on}} = \frac{V_s}{(1-d)}$$

In step-up chopper  $d > 1$ .

The principles of step-up chopper can be employed for the regenerative braking of dc motors.

Type A chopper or First quadrant chopper is

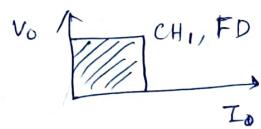


When chopper CH<sub>1</sub> is at on state,  $V_o = V_s$ . In this cond.

FD is at off state. During such cond., current is flowing in positive part of  $V_s$ ,  $CH_1, L, \text{load}$  to  $-V_s$ .

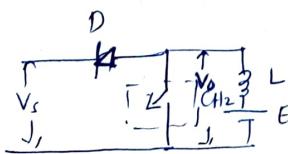
When CH<sub>1</sub> is at off state,  $V_o = 0$ , then FD is at on state. Energy stored inside inductor freewheels through load.

During the operation,  $V_o$  and  $I_o$  are positive. So it is called first quadrant chopper.



Second quadrant chopper

The circuit diagram of second quadrant chopper is



From the cut, load contains a dc source E like a battery or dc motor.

When CH<sub>2</sub> is at on state,  $V_o = 0$ . Here voltage E drives the current through L.

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Inductance L stores energy during turning on comm. of chopper C H<sub>2</sub>.

When C H<sub>2</sub> is at off state, energy is dissipated & hence

$$V_o = t + \frac{L di}{dt} - ①$$

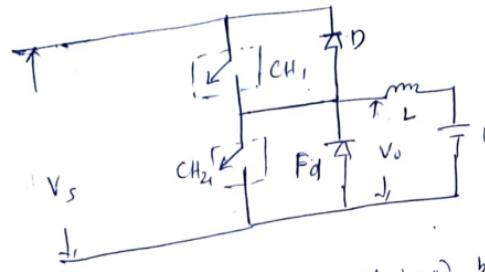
Due to this the diode D<sub>2</sub> is at on state and allows the power to flow to the source.

In this V<sub>O</sub> > V<sub>S</sub> and hence such kind of chopper is called step-up chopper. In this case V<sub>O</sub> is ~~positive~~ positive

and I<sub>O</sub> is negative. So such kind of chopper is called second quadrant chopper.

Two quadrant or Type-C chopper

The circuit diagram of two quadrant chopper is



Type C - Chopper is obtained by combining the type A and type B chopper in parallel. The output voltage V<sub>O</sub> is always positive due to Fd. When CH<sub>1</sub> on or FD on, then V<sub>O</sub> = 0

When CH<sub>2</sub> on or D on, output voltage is +ve.

When CH<sub>1</sub> on or D on, output voltage is -ve. The load current however be negative when CH<sub>2</sub> or FD is at on state.

When CH<sub>1</sub> and FD operate together as type A chopper whereas CH<sub>2</sub> & D<sub>2</sub> operate together as type B chopper.

Chopper.

This type of chopper operation is used in regenerative braking of DC motor.

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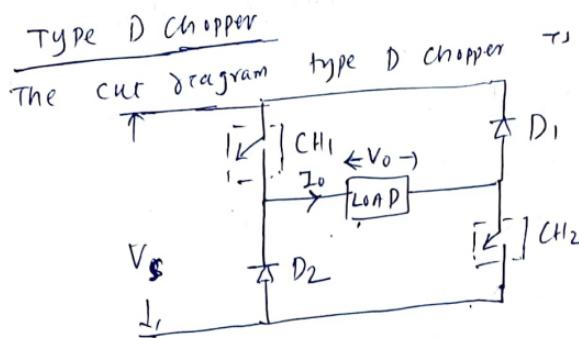
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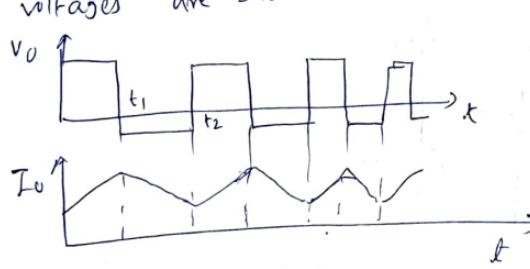


When \$CH\_1\$ and \$CH\_2\$ are at on state, \$V\_o = V\_s\$.

When \$D\_1\$ and \$D\_2\$ are at on state, \$V\_o = -V\_s\$.

When both choppers are at off state, \$D\_1\$ and \$D\_2\$ are at on (com).

Average output voltage is +ve when chopper turn-on time is more than turn-off time. The direction of current is always positive. ~~Waveforms of the~~ waveforms of the voltages are shown below



$$\Rightarrow V_o = V_s \left[ \frac{T_m - T_{OFF}}{T} \right] \quad \text{---(1)}$$

Avg. value of output

Voltage is

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

$$= \frac{1}{T} \left[ \int_0^{T_m} V_s dt + \int_{T_m}^T -V_s dt \right]$$

$$= \frac{1}{T} [ V_s T_m - V_s T_{OFF} ]$$

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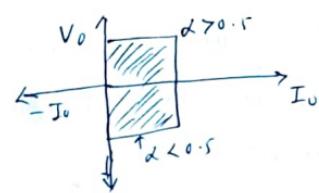
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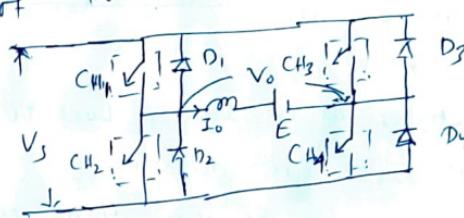
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- (1) If  $T_{on} > T_{off}$ ,  $\alpha > 0.5$ ,  $V_o$  is +ve.
- (2) If  $T_{on} < T_{off}$ ,  $\alpha < 0.5$ ,  $V_o$  is -ve.
- (3) If  $T_{on} = T_{off}$ ,  $V_o = 0$ .



## Four quadrant chopper, Type E chopper

The circuit diagram of Four quadrant chopper



For First quadrant operation,  $CH_4$  is at ~~on~~ on state.  
In this case  $CH_1$  and  $D_2$  are operated.

In this case  $CH_1$  is at on state,  $V_o = V_s$ .  
When  $CH_1$  is at off state,  $V_o = 0$  and current by pass-through

When  $CH_2$  is at off state,  $D_2$  to load side are positive.

In this case  $V_o, I_o$  are positive.  $CH_1, CH_3$  are at on state.

For second quadrant operation -  $CH_4$  is at off state.  
 $CH_2$  and  $CH_3$  are at on state.  
When  $CH_2$  is at on state, reverse current flows through ~~through~~  $L$ ,  $CH_2$ ,  $D_4$  and  $E$ . Inductance  $L$  stores energy during on condn of  $CH_2$ .

When  $CH_2$  is turned off, current is fed back into the source through  $D_1$ .

Such kind of operation of chopper is second quadrant operation. In this during off condn of chopper  $CH_2$ ,  $V_o = E + \frac{Ldi}{dt}$  and is +ve and  $I_o$  is negative.

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## Third quadrant operation

For the third quadrant operation polarity of load emf  $E$  is reversed.

For third quadrant operation,  
CTH<sub>2</sub> is cut on state.

CH<sub>3</sub> and D<sub>4</sub> are at operating mode.

When CTH<sub>3</sub> is at on state, Load  $r$  is connected into source.  
So  $V_o$  and  $I_o$  are negative.

When CTH<sub>3</sub> is at off state, then current freewheels through CTH<sub>2</sub> and D<sub>4</sub>.

Such kind of operation is called third quadrant operation.

## Fourth quadrant operation

In such cases, D<sub>2</sub> is at on state.

CH<sub>4</sub> and D<sub>3</sub> are at operating mode.

When CTH<sub>4</sub> is at on state, L stored energy & hence  $V_o = 0$ .

In this case current is +ve.

When CTH<sub>4</sub> is at off state, D<sub>3</sub> is at on condn &

Current is flowing from load, D<sub>3</sub>, V<sub>S</sub> to, D<sub>2</sub> to load.

Such kind of operation is called fourth quadrant operation.

## Inverters

The device which converts dc voltage into ac voltage at desired frequency is called an inverters.

Inverters are used in - adjustable speed ac drives, induction heating, standby air - craft power supplies, UPS, ~~switches~~, hVdc transmission lines.

Inverters can be broadly classified into two types - voltage source inverter and current source inverters.

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Voltage Source Inverter is one in which dc has small or negligible impedance. A voltage source inverter has stiff dc voltage.

A current source inverter has stiff dc ~~as~~ current source <sup>pp.</sup>. Current remains constant and can't be affected by load.

In VSI forced commutation is usually required.

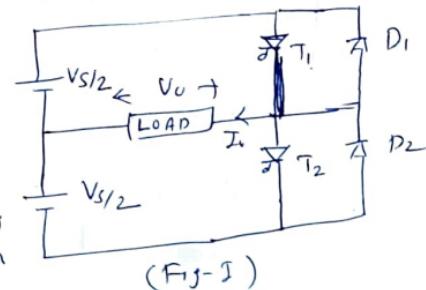
Depending upon the connection of semi-conductor devices, inverters are classified as - (1) Bridge inverters (2) series inverters (3) parallel inverter.

## 1 & Half-Bridge voltage source inverters

The circuit diagram of 1 & half-bridge voltage source inverter is shown on the figure-I

The operation of the circuit can be divided into two parts

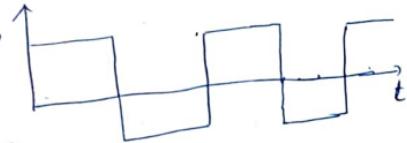
- (1) When  $T_1$  is ON and conducting for  $0 < t < T/2$ ,
- (2) When  $T_2$  is ON and conducting for  $T/2 < t < T$ ,



When  $T_1$  is ON,  $V_o = VS/2$ . At  $T/2$  time period gate signal is removed. After removal of gate signal  $T_1$  is at off state.

Signal  $T_1$  is at off state. After turning on  $T_2$  at this instant  $T_2$  is at on state. Such kind of waveform is available across load side during the turning on of the different devices.

It is here assumed that thyristors are going to be turn-off after the removal of gate signal.



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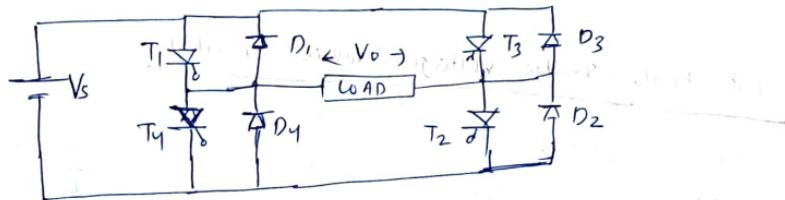
Rms Value of output voltage

$$V_{rms} = \left[ \frac{1}{\pi T_2} \int_0^{T_2} e^2 dt \right]^{\frac{1}{2}}$$

$$= \left( \frac{V_s^2}{T} \times \frac{T}{4} \right)^{\frac{1}{2}} = \frac{V_s}{2}$$

Single phase Full Bridge inverter

The circuit diagram of full bridge inverter cuts are -



The operation of the above devices are as follows -

- (I) mode-I ( $0 < t < T/2$ ) :- In this mode  $T_1$  &  $T_2$  are at on state. After turning on  $T_1$  and  $T_2$ ,  $V_0 = V_s$ .
- (II) mode-II ( $T/2 < t < T$ ): At  $T/2$ ,  $T_3$  and  $T_4$  are turned on and  $T_1$  and  $T_2$  are at off state. During this  $V_0 = -V_s$ .

~~For pure resistive load, feedback diodes  $D_1$ ,  $D_2$ ,  $D_3$  and  $D_4$  are not taken into consideration.~~

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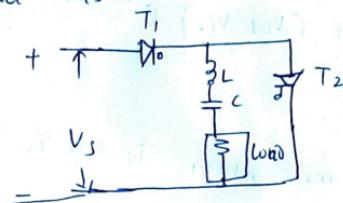
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## Series Inverter

The inverters in which commutating components are connected parallelly with the load is called series inverter. The series cut must be under damped. The inverter cut is operated at high frequencies.

The Series inverter cut is



## Analyses of Basic Series Inverter Cut

The operation of the inverter cut in three diff. modes are -

### mode-I

When  $T_1$  is on,  $T_2$  is at off state. In this case capacitor is assumed to be initially charged to voltage  $V_{CO}$ .

After turning on  $T_1$ ,

$$R\tau + L \frac{di}{dt} + \frac{1}{C} \int v dt = V_s + V_{CO}$$

By solving the above eqn

$$v(t) = \frac{V_s + V_{CO}}{\omega_r L} e^{-\delta t} \sin \omega_r t$$

$$\text{Where } \omega_r = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

$$\approx \sqrt{\omega_0^2 - \delta_0^2}$$

$\omega_0$  = Natural frequency of oscillation

$$\delta_0 = \frac{R}{2L} \text{ damping factor}$$

From the figure

$$V_C = V_s - V_R - V_L$$

$$= V_s - (V_s + V_{CO}) e^{-\delta t} \frac{\omega_0}{\omega_r} \cos(\omega_r t - \phi)$$

$$\text{Where } \phi = \tan^{-1} \left( \frac{\delta}{\omega_r} \right)$$

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When  $\omega t = \pi$ ,  $\tau(t) = 0$  so capacitor is charged to  $V_C$ , and

$$V_{C1} = V_s - (V_s + V_{CO}) e^{-\delta\pi/\omega_r} \frac{\omega_0}{\omega_r} \cos(\pi - \Psi)$$

$$V_{C1} = V_s + (V_s + V_{CO}) e^{-\delta\pi/\omega_r}$$

Mode-II  
During this mode, both  $T_1$  and  $T_2$  are off. Therefore

$$V_C = V_{G1}, V_L = 0$$

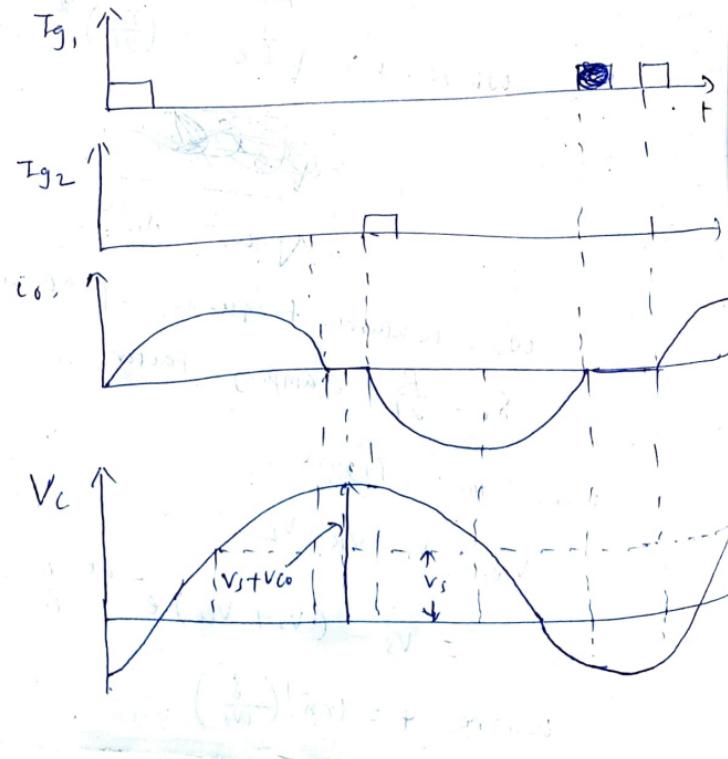
Mode-III  
During this mode,  $T_2$  is switched on. Therefore

$$R_C + L \frac{di}{dt} + \frac{1}{C} \int v dt = V_{C1}$$

During this mode, capacitor is discharged through  $R$ .

$$\tau(t) = \frac{V_{C1}}{\omega_r L} e^{-\delta t} \sin \omega_r t$$

The waveform of the load current,  $V_C$  and  $V_L$  are sketched.



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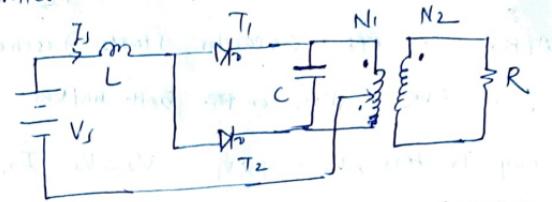
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## Parallel Inverter

The circuit diagram of parallel inverter is



The operation of the parallel inverter is defined as follows -

### Mode-I

In this mode thyristor  $T_1$  is conducting and current flows in the upper half of primary winding. Thyristor  $T_2$  is at off state. The current establishes magnetic flux that links both half of primary winding. In other words the total voltage is  $2V_s$ . This voltage charges the commutating capacitor  $C$  to  $2V_s$  with upper plate positive.

The thyristor  $T_2$  is forward biased through  $T_1$  by capacitor voltage  $2V_s$ .

In this case steady state current  $I_0$  flows through  $V_s, L, T_1$  upper half of primary winding.

During this mode,  $V_L = V_s$ ,  $V_C = 2V_s$ ,  $E_0 = I_0$ .

Mode-II  
Thyristor  $T_2$  is turned on by applying gate pulse. After turning on  $T_2$ , reverse bias voltage is available across  $T_1$ , therefore it is at off. So no current is flowing through  $T_1$ , therefore no current flows in primary winding,  $V_s$  and  $L$ .

During this capacitor  $-I_0$  is established. Capacitor current continues to flow till the capacitor charged from  $+2V_s$  to  $-2V_s$ .

Mode-III  
When  $V_C$  becomes  $-2V_s$ , lower plate is positive.

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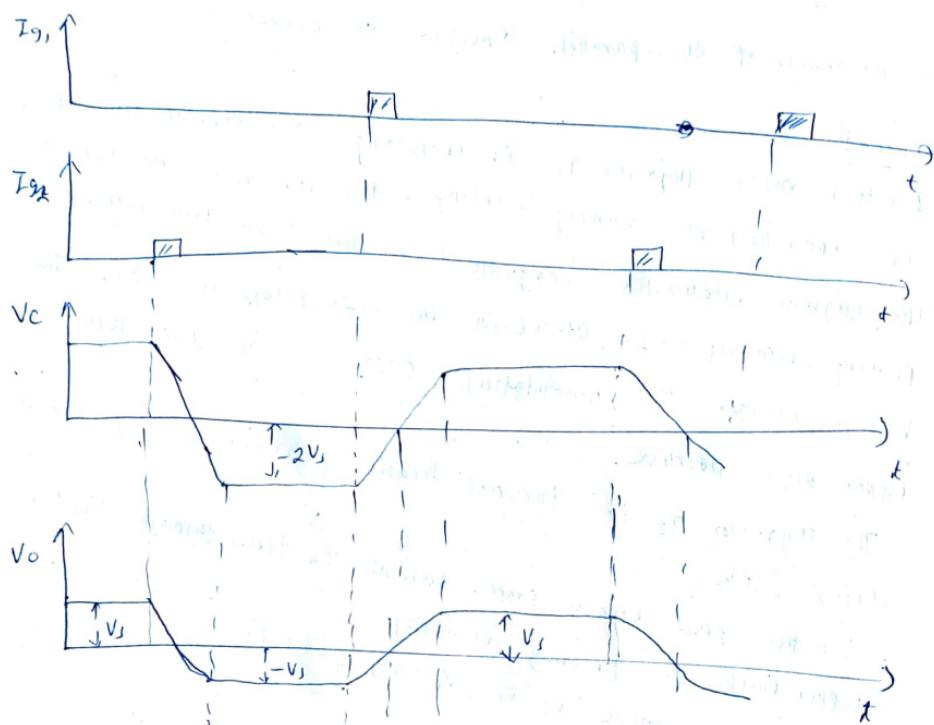
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Since  $T_1$  can be turned on at any time, capacitor voltage  $+2V_s$  applies a reverse bias across  $T_2$  therefore it is turned off. After  $T_2$  off, capacitor starts discharging. Now current  $I_C$  in the m.m.f. on both halves remains same. When  $I_C$  decays to zero,  $V_C = +2V_s$ ,  $V_o = V_s$ ,  $I_{T_1} = I_0 = \frac{V_s}{R}$



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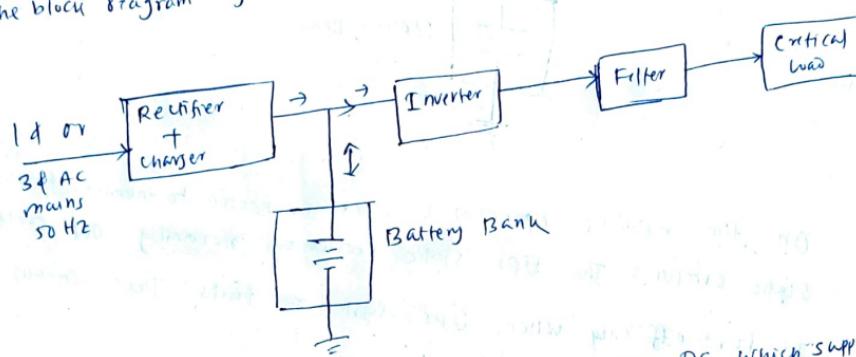
## Applications of Power Electronic Circ.

Power electronics circs are used in SMPS, UPS system, electrochemical process, heating and lighting, static VAR compensation, active filtering, HVDC system, photo-voltaic system and variable frequency motor drives.

### UPS (Uninterruptible power supply)

UPS are used in medical intensive care system, chemical plant process control, major computer installation.

The block diagram of UPS power system



A rectifier converts 1φ or 3φ a.c. voltage into DC which supplies power into the inverter and battery bank. The inverter gets DC voltage ~~when~~ from the main supply is ON and from the battery when battery bank is OFF.

Inverter converts d.c. voltage into a.c. voltage and through filter it is supplied into the load. If PWM inverter is used, then filter can be eliminated. A static switch connects and disconnect the battery from input of inverter depending upon the a.c. mains.

Depending the arrangement of basic blocks, UPS systems are classified as - (i) On-line UPS system or Inverter preferred (ii) Off-line UPS system or line ~~preferred~~ UPS system (iii) Line interactive UPS system.

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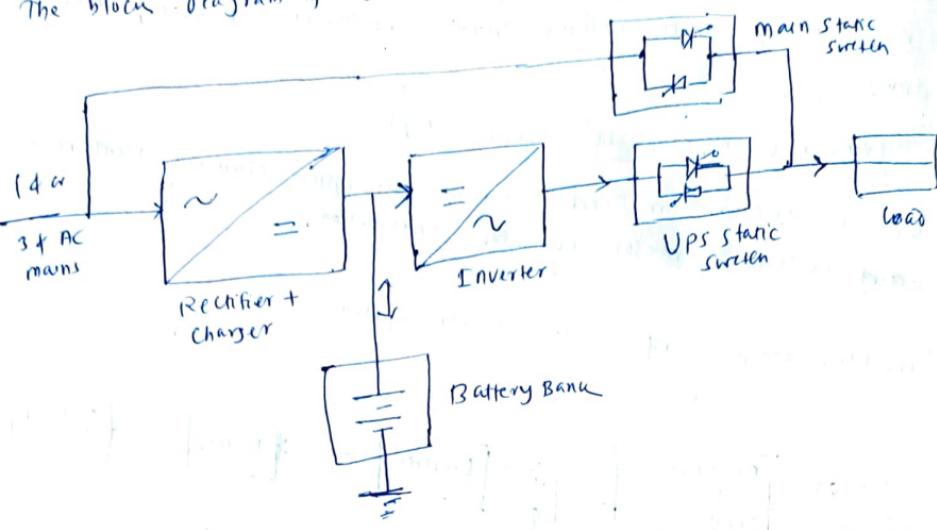
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## On-line UPS

The block diagram of On-line UPS system is



On the mode of operation load is connected to inverter through UPS static switch. The UPS static switches normally ON switch. It turns off only when UPS system fails. The various operating modes are -

Mode-I - When AC mains is ON, rectifier will carry power to inverter as well as to the battery. Therefore it acts as rectifier cum charger. So the ratings are usually higher. The inverter is connected to the load through UPS static switch. Battery will be charged through this mode.

Mode-II - If the power supply fails suddenly, then the battery bank now supplies power to inverter without any interruption and delay. There will be not any change in inverter as well as load. After restoration of power supply, the charger supplied inverter and recharges the battery automatically first in constant current mode and then in potential mode. Various rates of battery recharges may be set depending upon the application.

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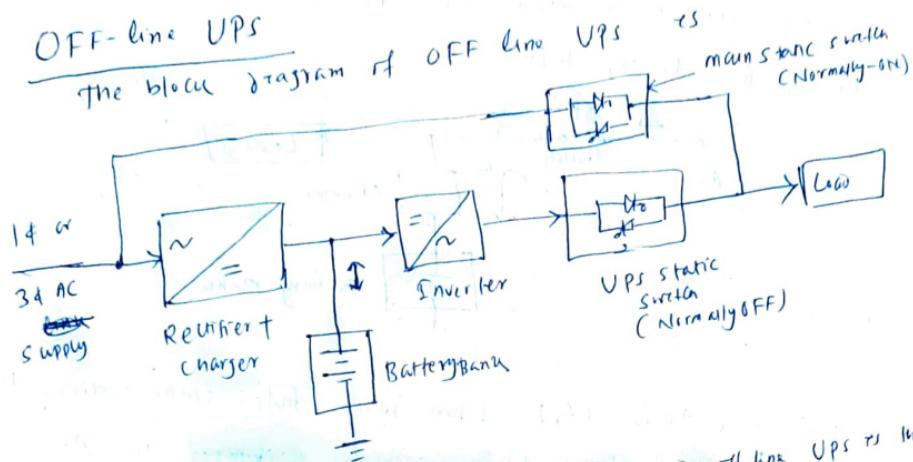
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Mode-II  
 In case If UPS fails, then normally "OFF" mains static switch is turned on which automatically transfers a.c. line to load.  
 This type of system is more popular because it can provide isolation of critical load from the a.c. line.  
 This system protects the critical load against surges, spikes, lightning strikes, frequency and voltage variations.

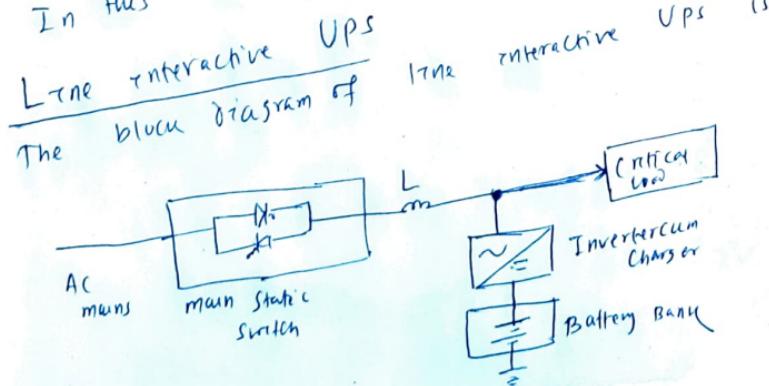


The main difference between on-line UPS and off-line UPS is that main static switches at on state. It can connect a.c.main directly to the load when main is ON.

During this battery is going to be charged with the help of rectifier cut. by using main supply. So the size of battery and power rating is lower than on-line UPS.

Under the main supply failure, UPS static switches at on state and connect the load to the UPS output.

In this case there is no isolation between load and mains.



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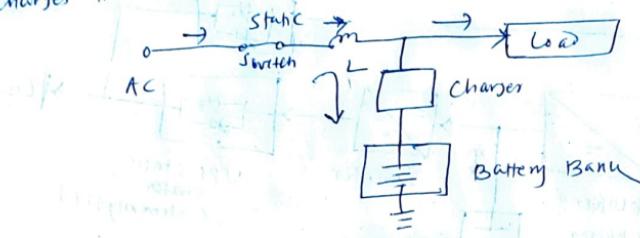
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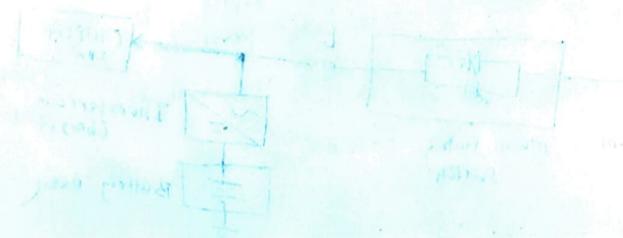
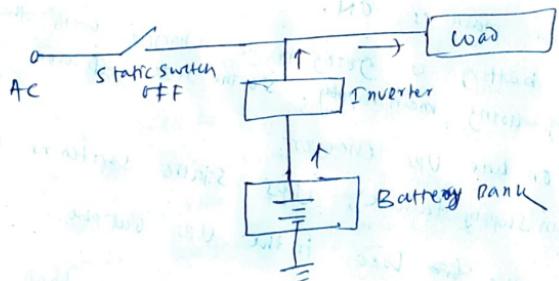
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heart of this system is a battery-charger cum inverter which acts as a inverter. In this system critical load is supplied from commercial supply through static switch and inductance L. The operation of the system can be divided into following modes -

- (i) mode 1 (Mains ON) - When mains is ON, Static switch is closed and load gets connected directly to the ac main through inductance L. The inverter or charger block operates as a charger and charges the battery bank.



- (ii) mode-2 (Mains OFF) - When mains fails, static switch turns off and the charger block operates as ~~inverter~~ a inverter supplies power to the load through inverter and battery



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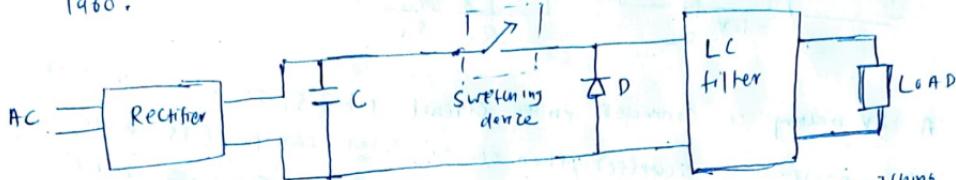
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## SMPs (switch mode power supply)

SMPs is an electronic switching device to obtain d.c. power which has negligible a.c. ripple. These are useful for low and medium power range up to ~~50~~ 50 W d.c. These are developed by NASA in 1960.



The capacitor C provides smooth control over rectifier. The switching device, chops the output voltage waveform and LC filter does the final filtering.

If the switching rate is high, filtering component is small. The diode D provides continuous conduction to inductor when switch is open.

The inductor provides negligible impedance to d.c. The SMPs can be classified into the following groups -

(i) Flyback SMPs

(ii) Feed-Forward SMPs

(iii) push-pull SMPs

(iv) Bridge SMPs.

## Advantage of SMPs

(i) Smaller in size, lighter weight and possess higher efficiency.

(ii) SMPs is less sensitive to input voltage variation.

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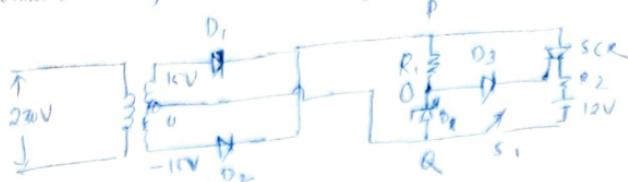
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## Battery Charger

Automatic battery charger using SCR is shown in figure-



A 12V battery is connected in the circuit when  $S_1$  is closed, the single phase 220V is sufficient, then it is stepped down to  $(15 - 0.15)V$  by a centre-tapped transformer. Diodes  $D_1$  and  $D_2$  forms full wave rectifier. Due to this pulsating dc is available across P and Q.

When SCR is off, cathode is held at potential of  $0^{\circ}$  V point since it is sufficient level such that forward biased diode  $D_2$  can gate-cause junction of SCR. Due to this the SCR is at on state.

When SCR is on charging current flows through battery. During each positive half-cycle of dc voltage SCR is triggered. Charging current is passed till the end of that half-cycle. During zero diode  $D_2$ , maximum voltage at Q is held at 12V. Due to the charging process, battery voltage rises to 12V.

When battery is fully charged cathode voltage is at 12V. Therefore  $D_2$  can't be at forward biased condition. Hence SCR is not triggered.

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## DC motor speed control

We know, For a particular motor

$$V_t = E_b + I_a R_a$$

$$\Rightarrow E_b = V_t - I_a R_a$$

$$\therefore \frac{\phi Z N P}{.60 A} = V_t - I_a R_a$$

$$K \& N = V_t - I_a R_a$$

$$\therefore N = \frac{V_t - I_a R_a}{K \& P}$$

The speed can be controlled by - (1) Armature terminal voltage, (2) Field flux control method (called armature voltage control)

Base speed is defined as the speed at which the motor is rotating under ~~normal~~ rated ~~terminal~~ voltage, rated field current and rated armature current.

Speed below base speed can be obtained by armature-voltage control whereas speed above base speed can be obtained by field flux control method.

$$\text{we know } T = K \& I_a$$

During armature control method,  $I_a$  and If remain constant

so  $\therefore T = \text{constant}$ . and hence armature control method

is called constant torque method.

We know

$$P = E_b I_a = (V - I_a R_a) I_a$$

In field control method,  $V$  &  $I_a$  remain const. so field control method is called constant power method.

The speed of 14 dc drive can be controlled by

(1) 1φ ~~half-wave converter~~ drives

(2) 1φ ~~semi-converter~~ drives

(3) 1φ Full converter drives

(4) 1φ dual converter

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