

GOVERNMENT POLYTECHNIC, DHENKANAL

**LECTURE NOTES ON
POWER ELECTRONICS & PLC**

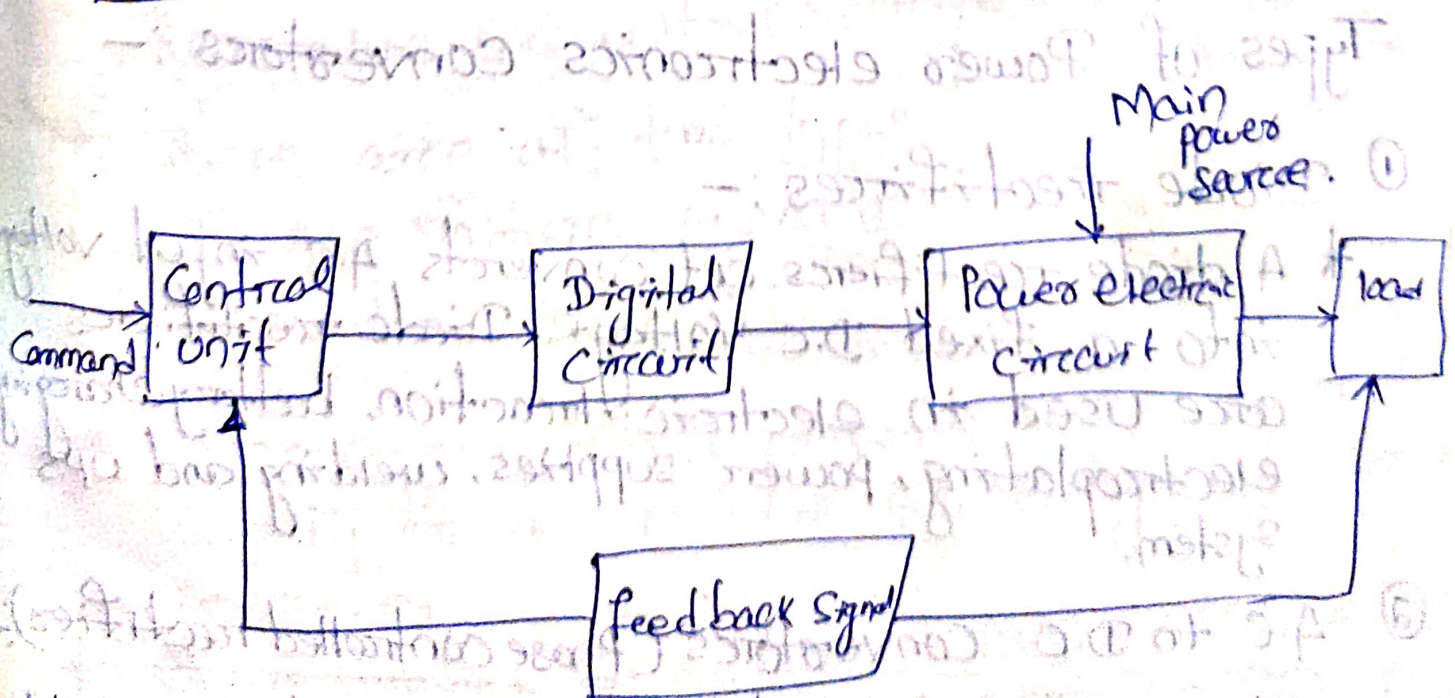
SEMESTER- 5th

**PREPARED BY
DEBIPRASAD PRUTHUIRAJ DHALL**

Power Electronics

- Power electronics may be defined as a subject that deals with the apparatus and equipment working on the principle of electronic but rated at power level rather than signal level.
- Power engineering is mainly concerned with generation, transmission, distribution of electric energy at high efficiency.
- electronics engg. is guided by distortionless, production, transmission and reception of data and signals of very low power level.

Power Electronics System :-



- Main power source may be an A.C supply system or D.C supply system.
- The output from the power electronics ckt may be variable D.C or A.C voltage. Depends on load requirement.
- The feedback component measure a parameter of the load and compares with command
- The difference of the two through the Digital ckt component controls the instant of turn ON OFF semiconductor devices forming the power electronics ckt.
- In this manner, behaviour of the load ckt can be controlled as desired with the adjustment of the command.

DT-19-07-2019

Types of Power electronics converters :-

① Diode rectifiers :-

* A diode rectifier ckt converts A.C input voltage into a fixed D.C voltage. Diode rectifiers are used in electric traction, battery charging, electroplating, power supplies, welding and UPS system.

② A.C to D.C converters (Phase controlled rectifier)

These convert constant A.C voltage to variable D.C output voltage. Used in D.C drives, metallurgy and chemical industries, excitation system for

Synchronous machine.

③ D.C to D.C converters :- (D.C choppers) :-

- * A D.C chopper converts fixed D.C input voltage to controllable/variable D.C output voltage.
- * These are widely used in D.C drives, Subway cars, tractors, Battery driven vehicles.

④ D.C to A.C converters :- (Inverters) :-

- * An inverter converts a fixed D.C input voltage to a variable A.C voltage.
- * Inverters are used in induction motor and synchronous motor drives, UPS, HVDC transmission etc.

⑤ A.C to A.C converters :-

- ↳ These convert fixed AC input voltage into variable A.C output voltage.

- ↳ These are of two types
 - ① A.C voltage regulators
 - ② Cycloconverters

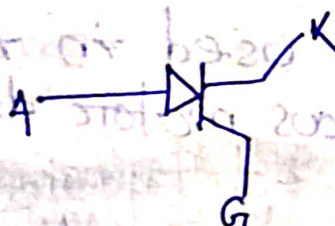
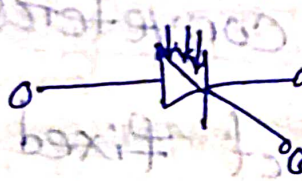
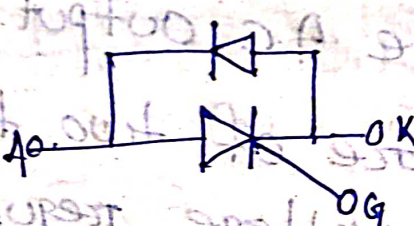
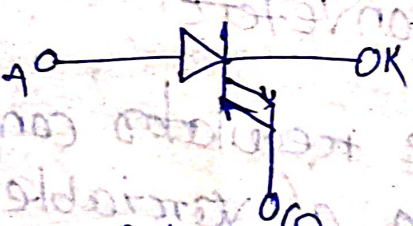
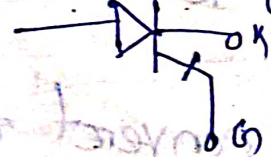
- * A.C voltage regulator converts fixed A.C voltage directly to a variable A.C voltage at same frequency.
- * Cycloconverters convert input power at one frequency to output power at a different frequency.

↳ Uses

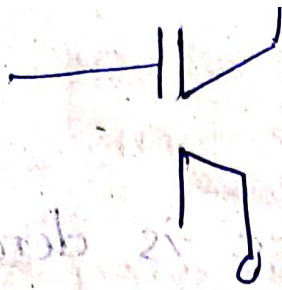
* AC voltage regulator → lighting control, speed control of fans, pump.

* Cycloconverters → slow speed large AC drive.

Power Semiconductor devices :-

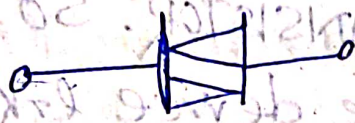
<u>Sl No.</u>	<u>Device</u>	<u>Symbol</u>	<u>Rating</u>
1.	Diode		5000V/5000A.
2.	SCR		7000V/5000A.
3.	LASCR (Light Activated)		6000V/3000A.
4.	ASCR/RCT Asymmetric.		2500V/400A.
5.	GTO Gate turn off		5000V/3000A.
6.	SITH Static induction thyristor		

7 MOSCT -



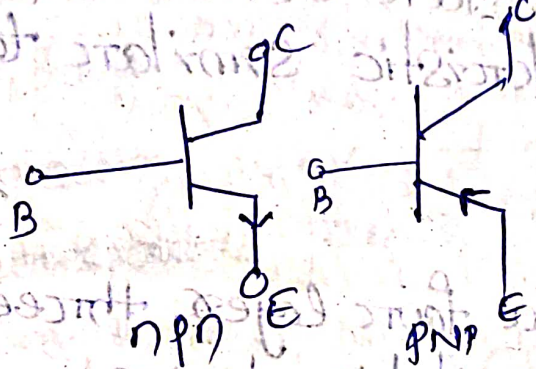
1200 V / 10 A

8. Triac



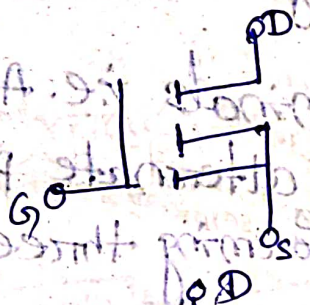
1200 V / 1000 A

9. PNP BJT



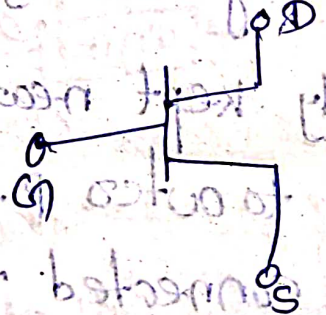
400 V / 400 A

10. MOSFET



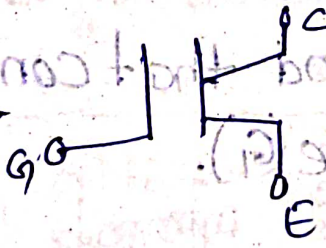
1000 V / 50 A

11. SIT

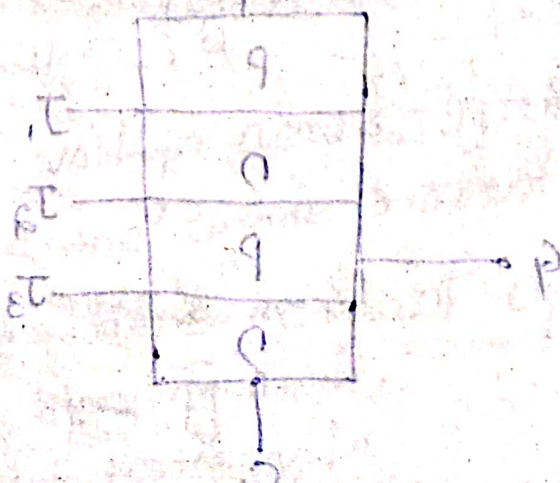


1200 V / 5000 A

12. IGBT



1200 V / 500 A



mode

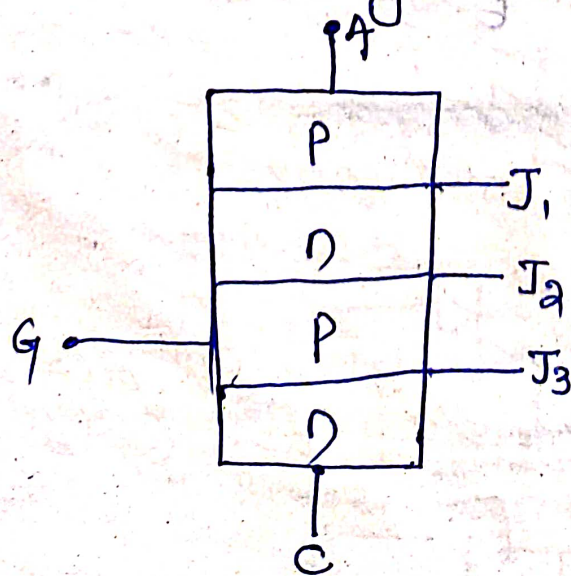
Thyristor

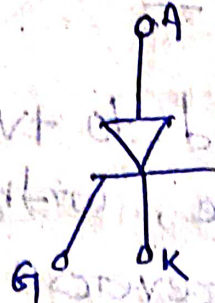
Dt-30.07.2019

- ↳ The name thyristor is derived from THYRATRON + TRANSISTOR. So thyristor is a solid state device like a transistor and its characteristic similar to Thyatron tube.

Dt-31.07.2019

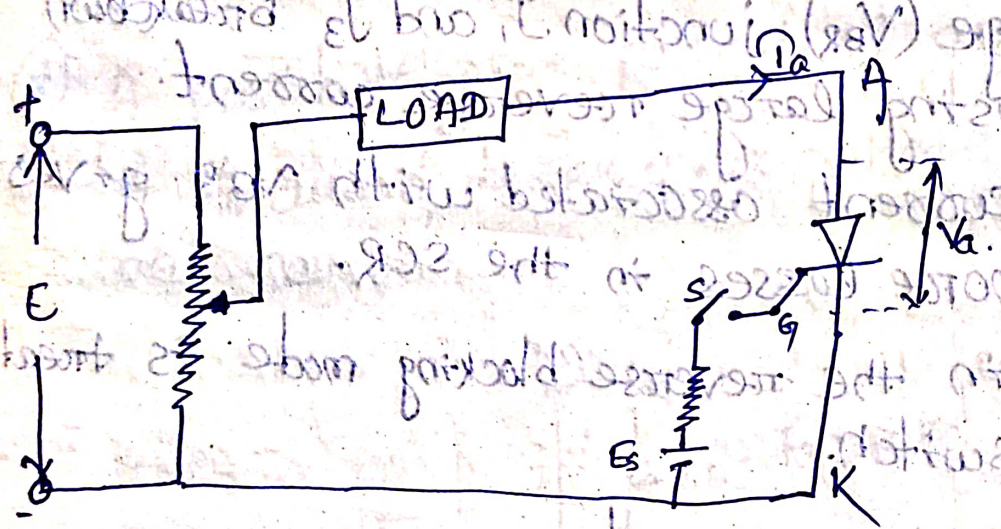
- ↳ Thyristor is a four layer, three junction p-n-p-n semiconductor switching device.
- ↳ It has three terminals i.e. Anode, cathode, and gate. Four layers of alternate p-type and n-type Silicon semiconductor forming three junction J_1 , J_2 and J_3 .
- ↳ Gate terminal is usually kept near cathode terminal.
- ↳ The terminal connected to outer p-region is called anode (A). The terminal connected to outer n-region is called cathode (K) and that connected to inner p-region is called gate (G).





- * Like the diode SCR is an unidirectional device, that block current flow from cathode to anode.
- * SCR voltage rating: 10KV and rms current rating 3000A. with corresponding power handling capacity 30MW.
- * Thyristor is also called as SCR (silicon controlled rectifier).

Static V-I characteristics of SCR



- The circuit diagram shown is used for obtaining static V-I characteristic of thyristor.
- V_a is the anode voltage across thyristor terminal A and K and I_a is the anode current.
- Thyristor has three basic mode of operation.
 - Reverse blocking mode.
 - Forward blocking mode.
 - Forward conduction mode.

Reverse blocking mode :-

- when cathode is connected to +ve and anode is connected to -ve, with switch 'S' open, then thyristor is reverse biased.
- So junction J_1 and J_3 are reversed biased and J_2 forward biased.
- A small leakage current of few mA flows, ~~this~~ from cathode to anode. This mode is called reverse blocking mode and also called off state of the thyristor.
- If the reverse voltage is increased, then at a critical breakdown level called reverse breakdown voltage (V_{BR}) junction J_1 and J_3 breakdown occurs causing large reverse current.
- A large current associated with V_{BR} gives rise to more losses in the SCR.
- The SCR in the reverse blocking mode is treated as open switch.

* Forward blocking mode :-

- when anode is ~~not~~ connected +ve and cathode is connected to -ve then thyristor is said to be forward biased.
- So junction J_1 and J_2 are forward bias but junction J_3 is reversed biased. In this mode a small current flow is called forward leakage current flow.

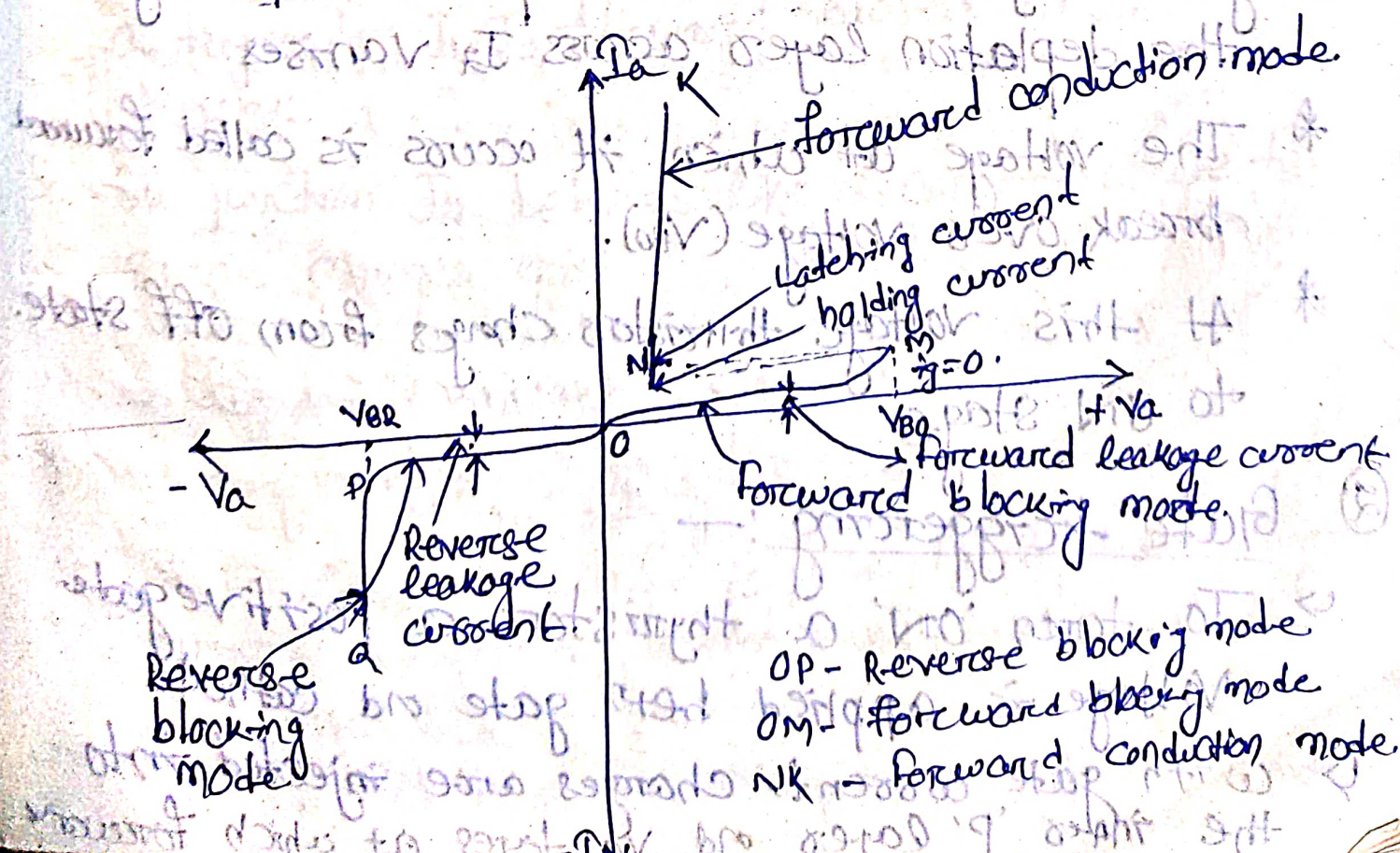
As this current is small, SCR is treated as open switch.

* Forward conduction mode :-

- when +ve anode to cathode voltage is increased with gate open, reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward break over voltage (V_{BO}).
- After this breakdown thyristor gets turned ON.
- A thyristor can be brought from forward blocking mode to forward conduction mode by applying

(i) A positive gate pulse betⁿ gate and cathode.

(ii) A forward break over voltage across anode and cathode.



Turn-on Methods of Thyristor:-

→ with Anode +ve and cathode -ve, a thyristor can be turned on by following methods.

① Forward voltage triggering

② Gate triggering

③ $\frac{dv}{dt}$ triggering

④ Temperature triggering

⑤ Light triggering

① Forward Voltage Triggering:-

* If forward voltage across anode-cathode is gradually increased, at a particular stage the depletion layer across J_a vanishes.

* The voltage at which it occurs is called forward break over voltage (V_{bo}).

* At this voltage thyristor changes from off state to ON stage.

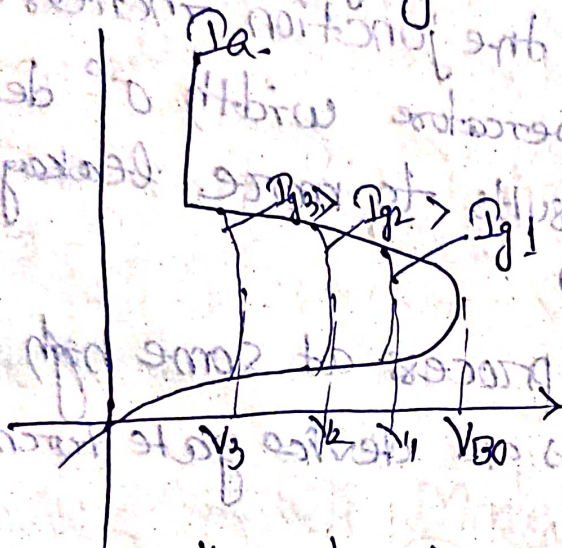
② Gate triggering:-

→ To turn 'ON' a thyristor, a positive gate voltage is applied betⁿ gate and cathode.

→ With gate current, charges are injected into the inner 'p' layers and voltages at which forward

break over occurs is reduced.

→ Higher the gate current, lower is the forward break over voltage.



→ Once the thyristor is conducting if the gate current is removed the conduction of current from anode to cathode is unaffected.

③ $\frac{dv}{dt}$ triggering : —

→ With forward voltage across anode and cathode of a thyristor J_1, J_3 forward biased and J_2 reverse biased.

→ So junction J_2 behaves like a capacitor due to space charges exist.

→ Current through capacitor

$$I_c = C_j \frac{dV_a}{dt}$$

→ If forward voltage is suddenly applied, a charging current through a junction, capacitance C_j may turn on the SCR.

→ If $\frac{dV_a}{dt}$ is high the charging current I_c is more.

④ Temperature triggering :-

- During forward blocking junction T_j is associated with high voltage with leakage current as a result temperature of the junction increased.
- with increase in temperature width of depletion layer decreases so, results to more leakage current and more junction temp.
- with the cumulative process at some high temp. depletion layer vanishes and device gets turned ON.

⑤ Light triggering :-

- A recess is made in the inner P_1 layer.
- when this recess is irradiated, free charge carriers are generated near the junction.
- If the intensity of light exceeds a certain value forward biased SCR is turned ON. This is called light activated SCR, (LASCR).

Latching current :-

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

Holding current :-

- It is defined as the minimum value of anode current below which it must fall to turn off the thyristor.

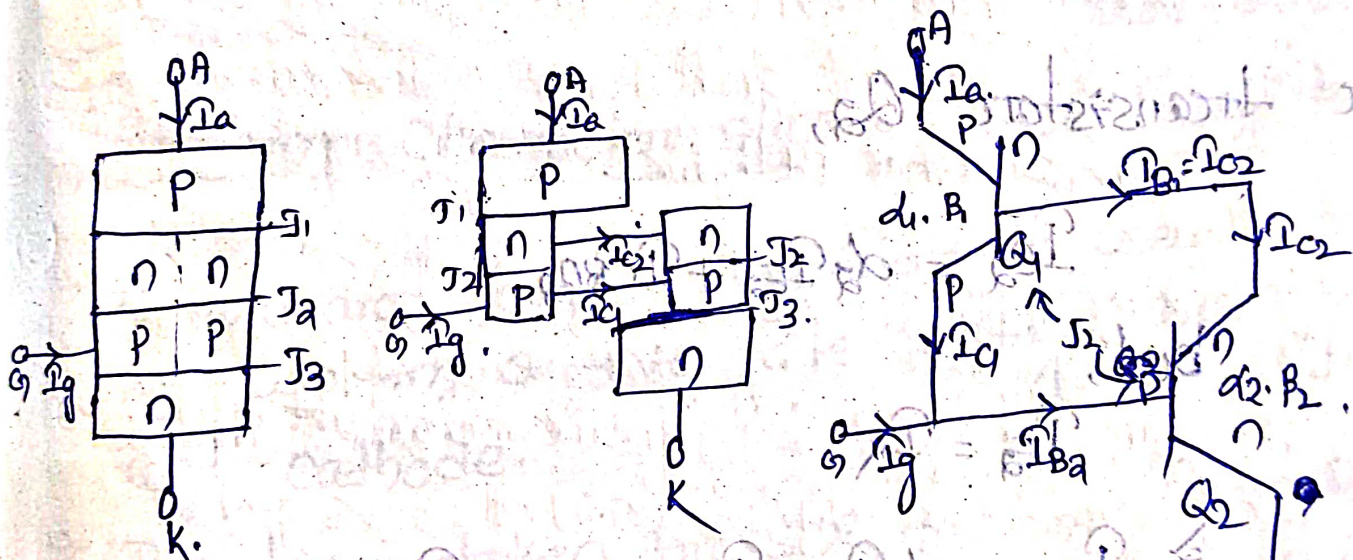
↳ Holding current is almost taken as 0.

* Latching current is associated with turn on process and holding current is associated with turn off process.

* Latching current is higher than holding current. 2-2.5 times.

DL-07.08.2019

Two transistor Model of thyristor:



↳ The thyristor operation can be explained with the use of its two transistor model.

↳ Junction J_1 and J_2 constitute P-n-P transistor and junction J_2 - J_3 make n-p-n transistor.

↳ In off state of a transistor the collector current I_C is related to emitter current I_E as

$$I_C = \alpha I_E + I_{CBO}$$

I_{CBO} = Common base leakage current of Q_1

α = Common base current gain.

For transistor Q_1 ,

$$I_{C1} = \alpha_1 I_{E1} + I_{CBO1}$$

$$\Rightarrow I_{E1} = I_a$$

$$\Rightarrow I_{C1} = I_{C1}$$

$$\Rightarrow I_{C1} = \alpha_1 I_a + I_{CBO1} \quad \text{--- (1)}$$

For transistor Q_2 ,

$$I_{C2} = \alpha_2 I_{E2} + I_{CBO2}$$

but,

$$I_{E2} = I_K$$

$$\Rightarrow I_{C2} = \alpha_2 I_K + I_{CBO2} \quad \text{--- (2)}$$

$$\therefore I_a = I_{C1} + I_{C2}$$

$$\Rightarrow I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 I_K + I_{CBO2} \quad \text{--- (3)}$$

when gate current is applied,

$$I_K = I_a + I_g$$

putting the value of I_K in eqn (3)

$$\Rightarrow I_a = \alpha_1 I_a + I_{CBO1} + \alpha_2 (I_a + I_g) + I_{CBO2}$$

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

* If emitter current of two component transistor can be increased so that $\alpha_1 + \alpha_2$ reaches unity I_a will tend to become high there by turning on the device

Date- 09.08.2019
Switching Characteristics of SCR during turn-ON:

- A forward biased thyristor is usually turn-on by applying a +ve gate voltage betn gate and cathode.
- The time taken for SCR to change from forward blocking state to forward conduction state is called turn on time.
- Turn on time is divided into 3 intervals
 - ① Delay time (T_d)
 - ② Rise time (T_r)
 - ③ Spread time (T_s)

① Delay time (T_d) :-

→ It is measured from the instant gate current reaches $0.9 I_g$ to the instant at which anode current reaches $0.1 I_a$.

→ I_g = final value of gate current

I_a = final value of anode current.

→ The time taken for anode voltage to fall from V_a to $0.9 V_a$ is called delay time.

→ The delay time can be decreased by applying high gate current and more forward voltage betⁿ anode and cathode.

② Rise time (T_r) :-

→ The time taken by anode current to increase from $0.1 I_a$ to $0.9 I_a$ is called rise time.

→ It is also time taken by the anode voltage to fall from $0.9 V_a$ to $0.1 V_a$.

→ During rise time turn on losses in the thyristor are highest due to high anode voltage and large anode current together.

③ Spread time (T_s): —

→ It is the taken by the anode current to rise from $0.9 I_a$ to I_a . It is also defined as the time for the forward blocking voltage to fall from $0.1 V_a$ to ON-state voltage drop. (1 to 1.5 volt).

→ During spread time conduction spreads over the entire cross-section of the cathode of SCR.

→ Total turn on time = Delay time + Rise time + Spread time

Switching Characteristics during Turn OFF: —

→ Thyristor turn-off means that it has change from ON state ^{to OFF state} and is capable of blocking the forward voltage.

→ This process is also called commutation process.

→ SCR can be turned off by reducing the anode current below holding current.

→ If forward voltage is applied to the SCR at the moment its anode current falls to zero, the device will not be able to block this forward voltage as the carriers (holes and electrons) in the four layers still favourable for condition.

→ So thyristor is reversed biased for a finite period after the anode current as reached zero.

→ The turn off time

$$T_{off} = T_{rr} + T_{gr}$$

∴ T_{rr} = Reverse recovery time

T_{gr} = Gate recovery time.

→ T_{rr} is the time taken for the removal of excess carriers from top and bottom layers of SCR.

→ Gate recovery process is the removal excessive carriers from junction J_a by application of reverse voltage.

→ T_{gr} is the time taken for removal of trapped charges from junction J_a .

$t_1 - t_3 \rightarrow$ Reverse recovery period.

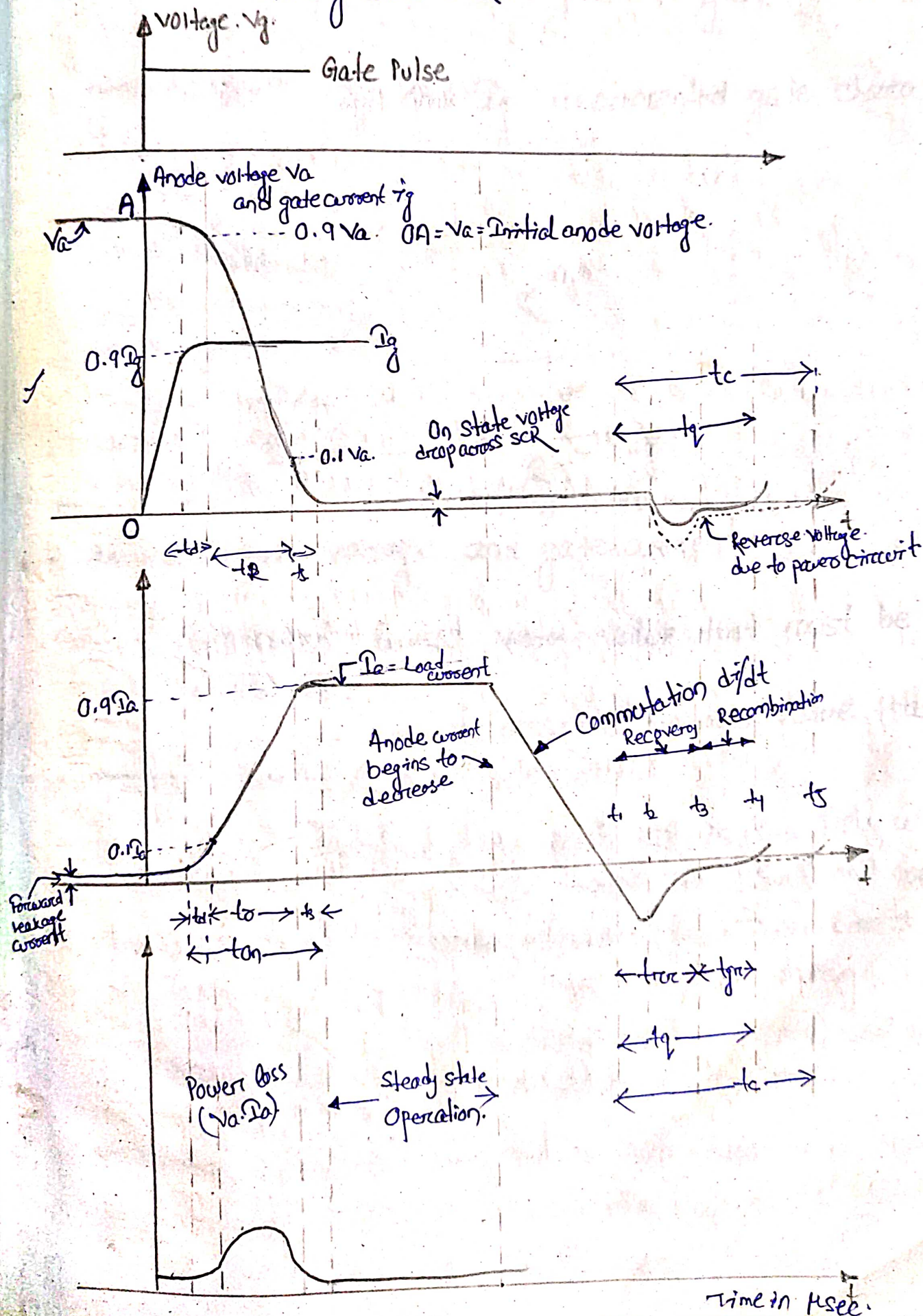
$t_3 - t_1 \rightarrow$ Gate recovery time.

→ Thyristor turn off time taken for removal of is the range of 3-100ms

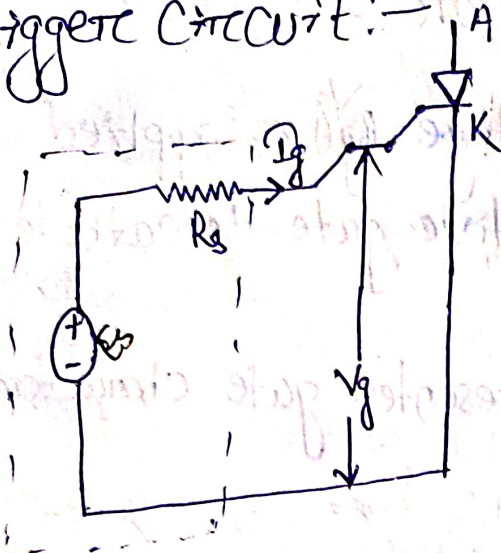
→ Turn off time depends on magnitude of forward current, $\frac{di}{dt}$ at the time of commutation, junction temp.

↳ Thyristors with slow turn off time (50-100ms) are called converter grade SCR.

↳ Thyristors with fast turn on time (3-50ms) are called inverter grade SCR.



Trigger Circuit:-



$$E_s - I_g R_s - V_g = 0$$

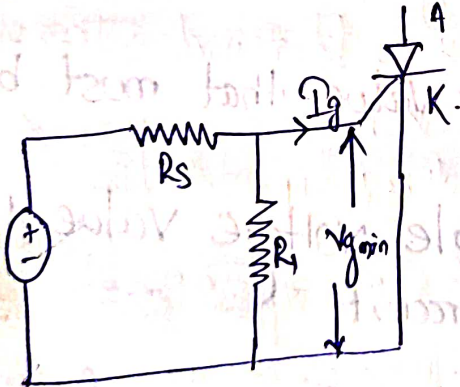
$$\Rightarrow E_s = V_g + I_g R_s$$

where, E_s = Gate source voltage

V_g = Gate cathode voltage

I_g = Gate current

R_s = Gate source resistance



$$E_s = V_g + I_g R_s$$

$$= V_{gmin} + \left(I_{gmin} + \frac{V_{gmin}}{R_1} \right) R_s$$

* Resistance R_1 is connected across gate cathode terminals as to provide an easy path to flow of leakage current between the SCR terminals.

Protection of Thyristor :-

- ① Over voltage protection.
- ② Over current protection.
- ③ Gate protection.

① Over voltage protection :-

- * Over voltage across thyristor may lead to thyristor failure.
- * A thyristor may be subjected to internal over voltage or external over voltage.

↳ Internal over voltage :-

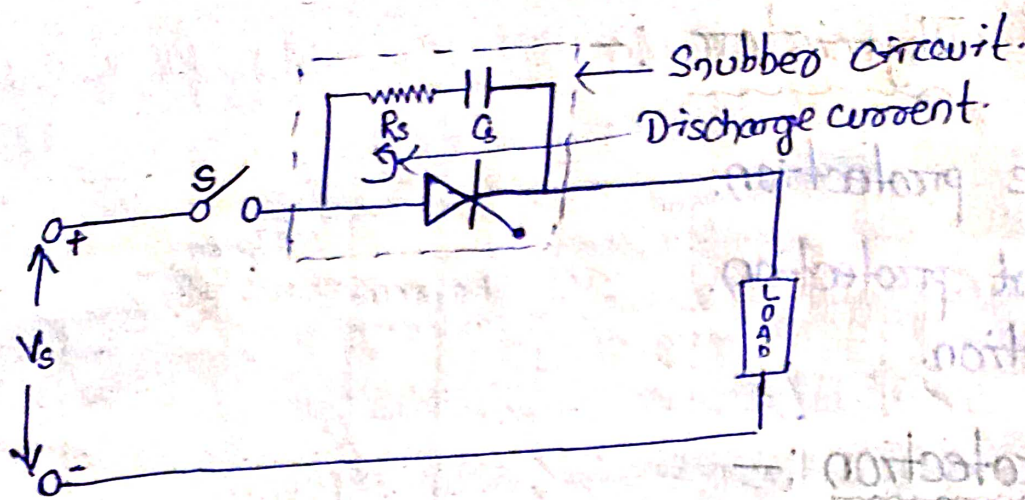
- * It is caused by thyristor operation large voltage may be generated internally during turn off of a thyristor. As this internal over voltage may be several times the break over voltage of the device, the thyristor may be destroyed permanently.

↳ External over voltage :-

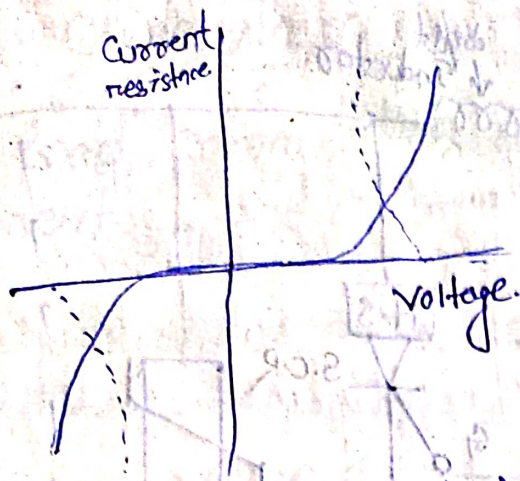
- * It is caused due to interruption of current flow in an inductive circuit and also due to lightning stroke on the lines feeding the thyristor system.

↳ Suppression of overvoltages :-

- * The effect of over voltage is usually minimised by using snubber circuit and non linear resistor called voltage clamping device (V_c).



- * The R.C circuit called snubber circuit is connected across the device to be protected.
- * It is helpful in minimise the over voltage transient ^{s.i} spike and for limiting $\frac{dv}{dt}$ across the thyristor.
- * When the SCR is turned ON capacitor discharges through the SCR and the resistance R_s show that initial discharge current and turn on $\frac{di}{dt}$ is reduced.
- * The voltage clamping device is a non-linear resistor connected across SCR. under normal working condition of voltage the device has high resistance and draws only a small leakage current.
- * When voltage surge appears, the device operates in low resistance region and produces a virtual short circuit across the SCR.
- * As a result voltage across SCR is clamped to a ~~shape~~ safe value.
- Ex:- Selenium, ^{diode} rectifier, metal oxide varistor are generally used against over voltage.



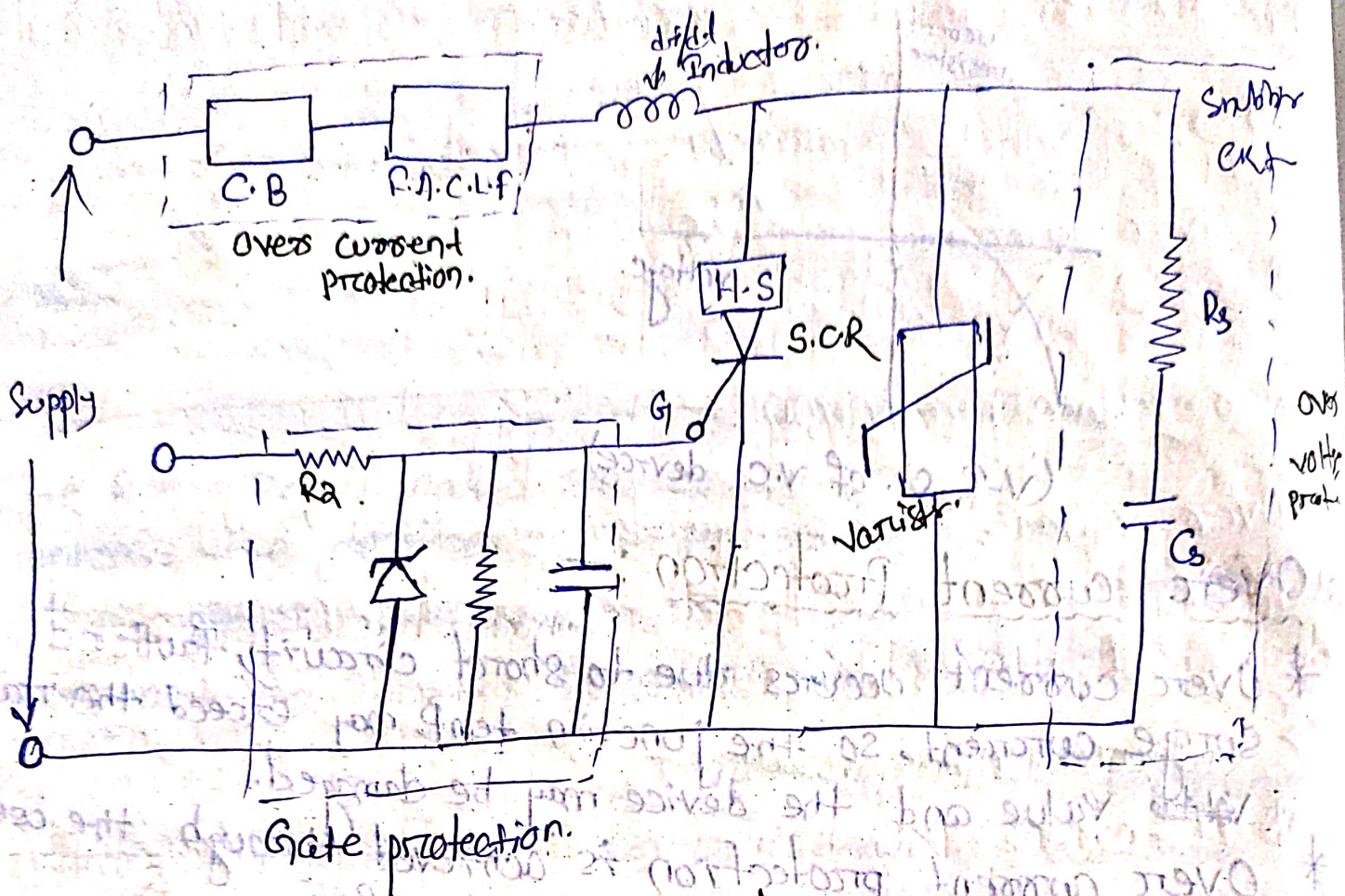
(V-I ch. of V.C device)

② Over Current Protection :-

- * Over current occurs due to short circuit, faults and surge current, so the junction temp. may exceed the rated value and the device may be damaged.
- * Over current protection is achieved through the use of circuit breakers and fast acting fuse.
- * proper co-ordination betn the fast acting fuse and thyristor is required.

③ Gate Protection :-

- * Gate circuit should be protected against over voltage and over current. protection against over voltage is achieved by connecting a zener diode across the gate circuit.
- * A resistor R_a connected in series with the gate circuit which provides protection against over current.
- * A capacitor and a resistor are also connected across gate to cathode to by pass the noise signals.
- * ~~Un~~ wanted signal may turn ON the SCR leading to mal-operation of SCR. Gate protection against such signals is obtain by using shielded cable.



R.A.C.L.F. - Fast acting current limiting fuse

Turn-off method of Thyristor:-

↳ A thyristor can be turned off when.

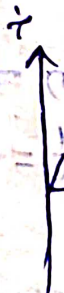
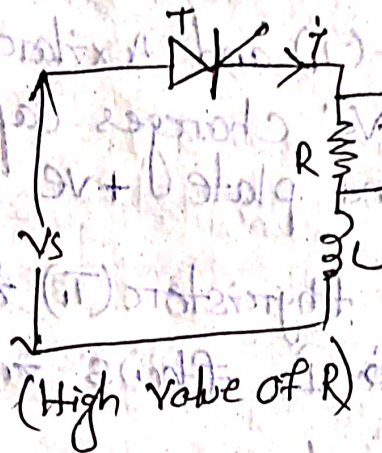
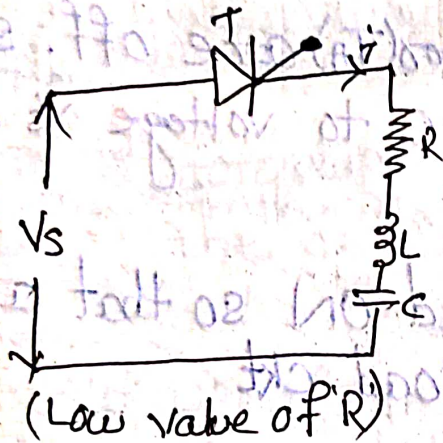
- ① its anode current falls below holding current
- ② A reverse voltage is applied to thyristor for a sufficient time to enable it to recover to blocking state.

↳ Thyristor can be turned off by

- ① Load commutation.
- ② Resonant Pulse Commutation. (Class-B)

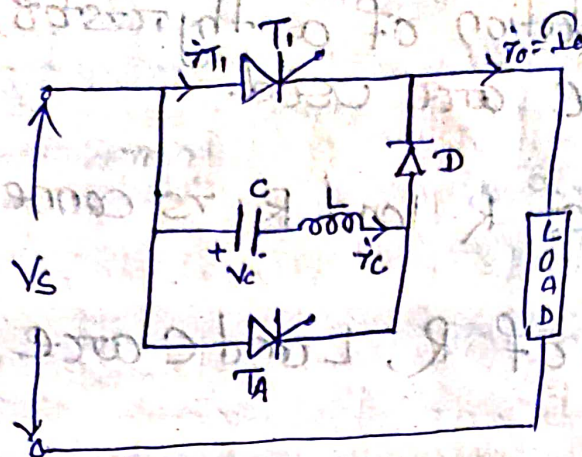
① Load Commutation : — (Class-A Commutation)

- For load commutation of a thyristor, commutating components L and C are used.
- For high value of R load R is connected across C .
- For low value of R , L and C are connected in series



- The nature of ckt should be such that the current must have tendency to decay to zero.
- When these ckt are energized from D.C. source i first rises to max^m value and then begins to fall. When current decays to zero and tends to reverse, thyristor (T) is turned off on its own.
- Load commutation is possible only in D.C ckt.

Class-B Commutation (Resonant pulse commutation)



- ↳ Thyristor (T_1) and Auxiliary thyristor (T_A) are off. Source voltage V_s charges capacitor C to voltage V_s with left hand plate +ve
 - ↳ At $t=0$, thyristor (T_1) is turned ON so that a constant current I_o flows in the load ckt
 - ↳ Till time t_1 , $V_c = V_s$, $I_c = 0$, $i_{T_1} = I_o$
 - ↳ For initiating the commutation of main thyristor (T_1), Auxiliary thyristor (T_A) is ON at $t = t_1$
 - ↳ With (T_A) ON a resonant current i_c begins to flow from C through T_A , L and back to C .
- $$i_c = -I_p \sin \omega t$$
- ↳ Capacitor voltage $V_c = \frac{1}{C} \int i_c dt$

$$= V_s \cos \omega t$$
 - ↳ After a half cycle of i_c from t_1 , $i_c = 0$,
 $V_c = -V_s$ and $i_{T_1} = i_o$

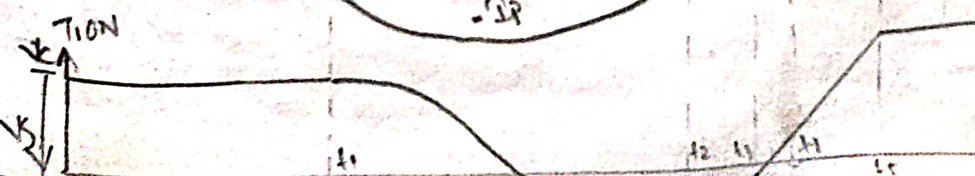
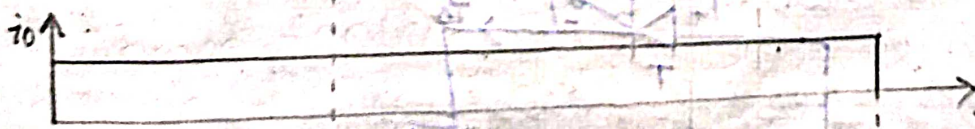
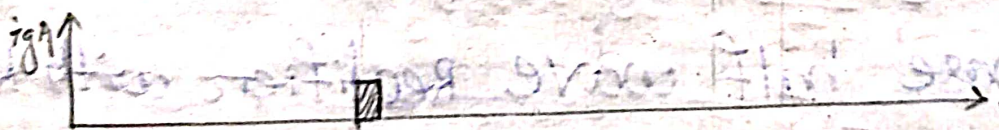
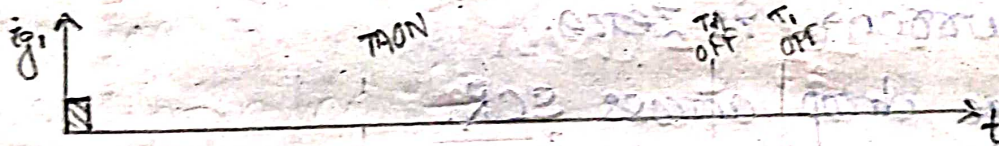
→ with $V_c = -V_s$, Right hand plate has +ve polarity
As i_c tends to reverse at t_2 . T_A will be off.

→ Resonant current i_c now flows through C, L, D, T_1 and back to C.

$$\rightarrow i_{T_1} + i_c = I_0$$

$$\Rightarrow i_{T_1} = I_0 - i_c$$

→ when i_c in the reverse direction reaches the value I_0 forward current in T_1 is reduced to zero. and the device T_1 is turned off. As Thyristor is turned off gradually by resonant pulse commutation build up of resonant current it is called resonant pulse commutation.



Phase-Controlled Rectifier Dt-22.08.19

↳ In phase-controlled Rectifier AC is converted to D.C using thyristor or SCR.

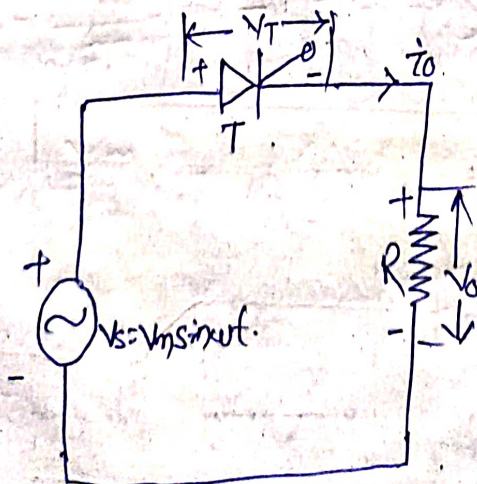
↳ In phase controlled rectifier a thyristor is turned OFF as A.C supply voltage reverse biases it provided anode current has fallen to a level below holding current.

↳ The turning off by supply voltage itself is called Natural or Line commutation.

Assumption :-

- ① All the switches are ideal.
- ② Holding current is zero.
- ③ No voltage drop across SCR.

Single phase half wave Rectifier with R-Load



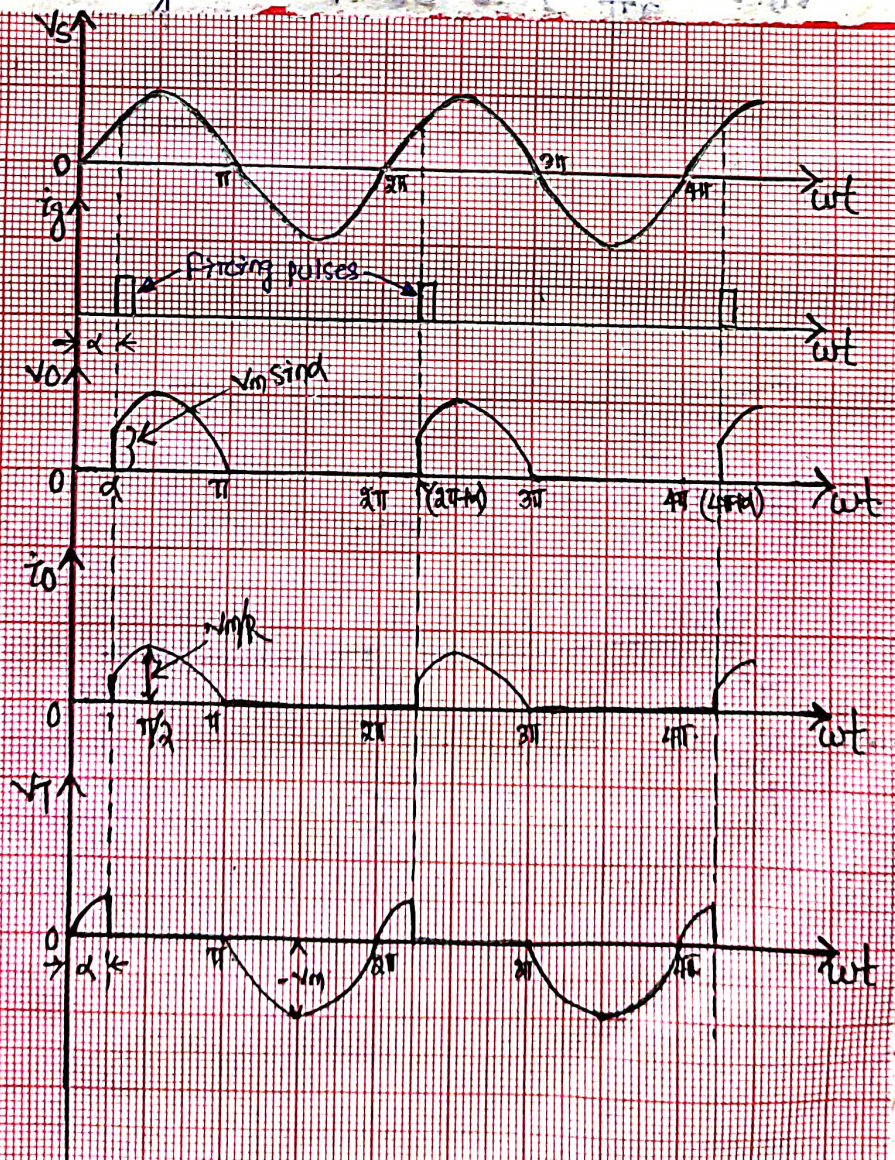
* The circuit consists of a single thyristor feeding DC power to a resistive load 'R'

* The source voltage $V_s = V_m \sin \omega t$ is applied.

* SCR will conduct when +ve voltage and gate signal is applied across anode, cathode and gate cathode terminal respectively

* Thyristor blocks the flow of load current until it is triggered.

* At some delay angle α a positive gate signal is applied betn gate and cathode.



Single-phase half wave Rectifier with 'R' Load (Voltage and current wave form)

* Thyristor conducts from $\omega t = \alpha$ to π , $2\pi + \alpha$ to 3π and so on, so, during this period $V_o = V_s$, $V_T = 0$.

* Over the firing angle delay α , Load voltage $V_o = 0$,

* From $\omega t = \pi$ to 2π SCR will be OFF. So $V_o = 0$, $V_T = V_s$

* As firing angle is increased. From 0 to π average load voltage decreases from largest value to '0'

* Thyristor is reverse biased for π radian. The circuit then OFF time. $t_c = \pi/\omega$ sec.
 $\omega t = \pi$
 $\Rightarrow t = \pi/\omega$

* Average voltage V_o across load 'R' is.

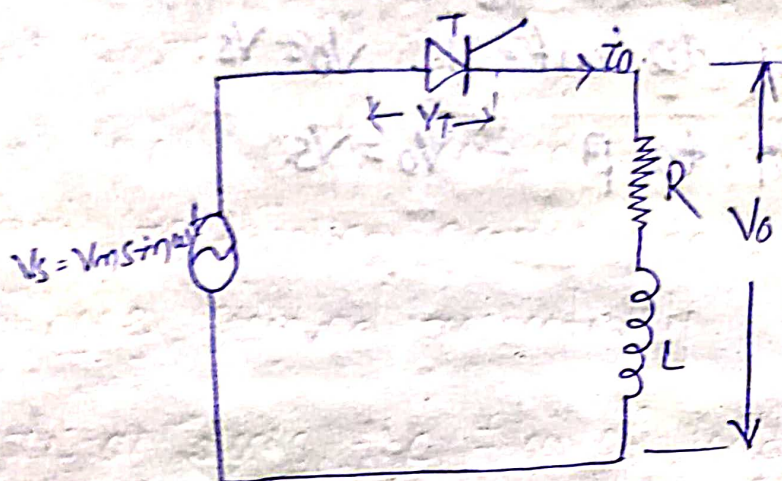
$$\begin{aligned} V_o &= \frac{1}{2\pi} \int_{\alpha}^{\pi} V_s d(\omega t) \\ &= \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t) \\ &= \frac{V_m}{2\pi} [-\cos \omega t]_{\alpha}^{\pi} \\ &= \frac{-V_m}{2\pi} [\cos \pi - \cos \alpha] \\ &= \frac{-V_m}{2\pi} [-1 - \cos \alpha] \\ &= \frac{V_m}{2\pi} [1 + \cos \alpha] \end{aligned}$$

* Average load current $i_o = \frac{V_o}{R}$

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

Firing angle: It is measured from the angle that gives largest output voltage to the instant it is triggered

Single-phase Half-wave circuit with R-L Load :-



- Circuit diagram shows a single phase supply feeding a R-L load through a thyristor.
- At $\omega t = \alpha$ thyristor is turned ON by gate signal so load voltage $V_o = V_s$
- load current i_o rises gradually due to inductance. After some time i_o reaches max^m value and then begins to decrease.
- At $\omega t = \pi$, $V_o = 0$, but i_o is not zero because of load inductance 'L'. At some angle β , $\beta > \pi$, i_o reduces to zero and SCR is turned OFF which is already reversed biased.
- At $\omega t = \beta$, $V_o = 0$, $i_o = 0$.
At $\omega t = 2\pi + \alpha$ SCR is triggered again and V_o is applied to the load and load current develops as before.

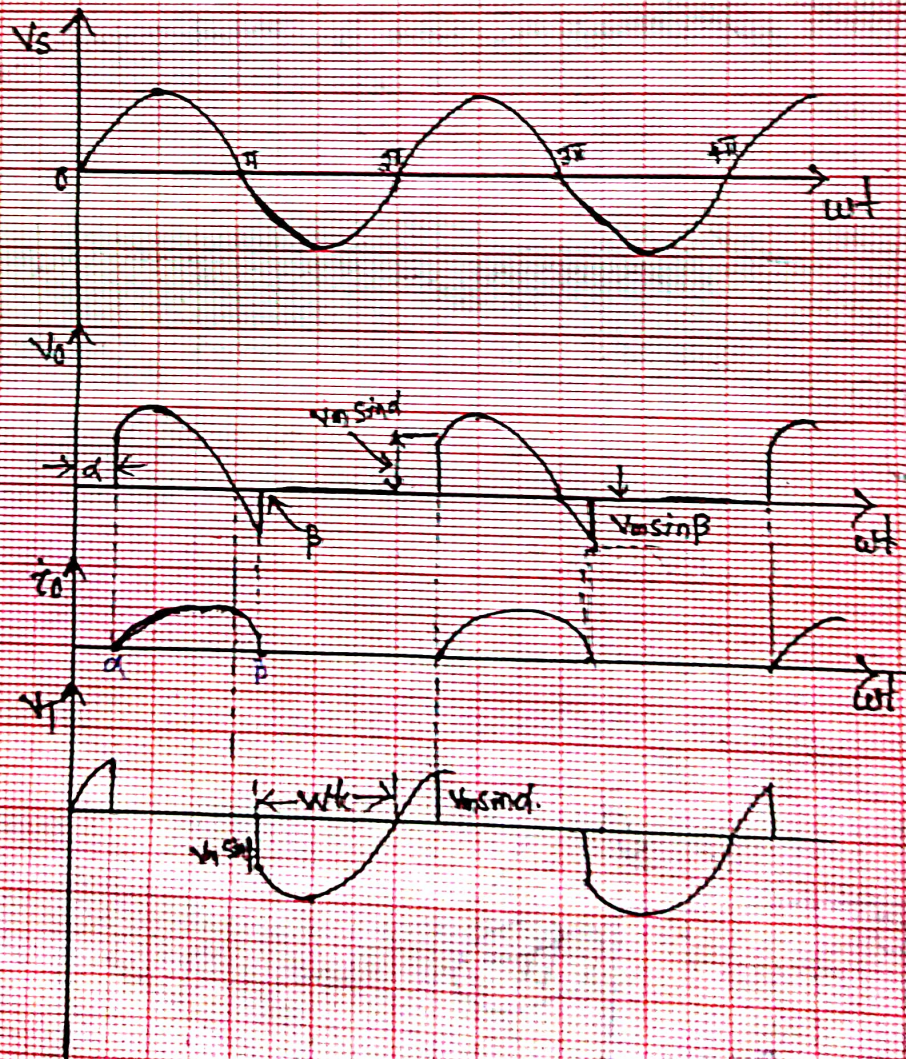
→ β is called extinction angle ($\beta - \alpha$). it's called conduction angle.

→ From $\omega t = \alpha$ to $\omega t = \pi$, $V_o = V_s$.

From $\omega t = \pi$ to β $\Rightarrow V_o = V_s$

$$t_c = \frac{2\pi - \beta}{\omega}$$

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Single-phase half wave rectifier with R-L load (voltage and current waveform)

Average output voltage,

$$V_o = \frac{1}{2\pi} \int_{\alpha}^{\beta} V_s d(\omega t)$$

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

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

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

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

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

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

Average

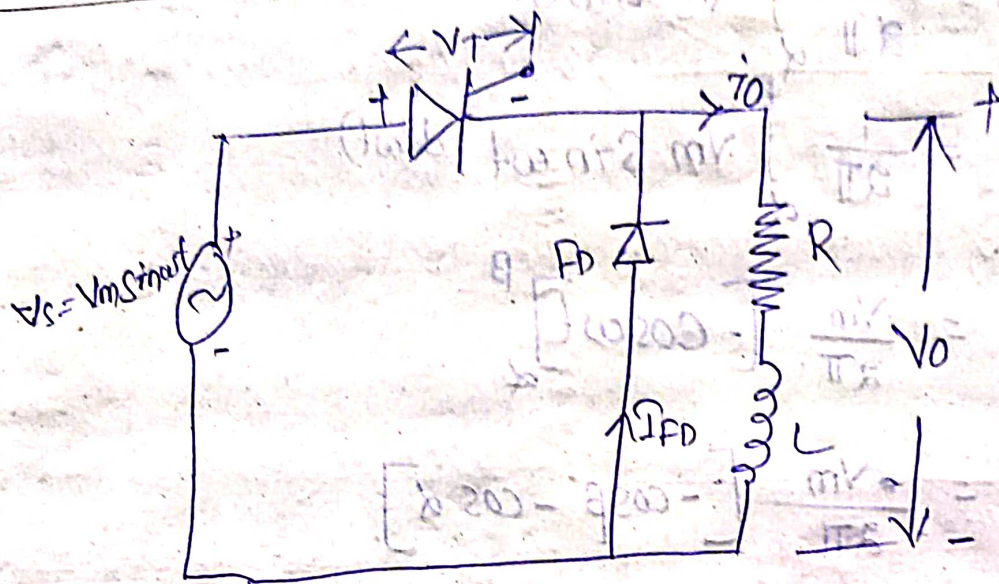
load

current

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

$$= \frac{V_m}{2\pi R} \left[\cos \alpha - \cos \beta \right]$$

Single-phase half wave rectifier with R-L load and free wheeling diode :-



- A free wheeling diode is also called by pass diode or commutating diode used to improve the load current wave form.
- At $\omega t = 0$, source voltage is +ve but at some delay angle α , forward biased SCR is triggered and source voltage (V_s) appears across load as V_o .
- At $\omega t = \pi$ source voltage V_s is zero and V_s tends to reverse free wheeling diode (FWD) is forward biased through the conducting SCR.
- As a result I_o is transfer immediately from SCR to FWD.
- At the same time SCR is having reverse voltage and zero current, so it is turned OFF at $\omega t = \pi$.

↳ During free wheeling period load current does not decay to zero until the SCR is triggered again at $(2\pi + \alpha)$. Here load is taken as highly inductive.

↳ Circuit turn off time $t_c = \frac{\pi}{\omega}$ sec.

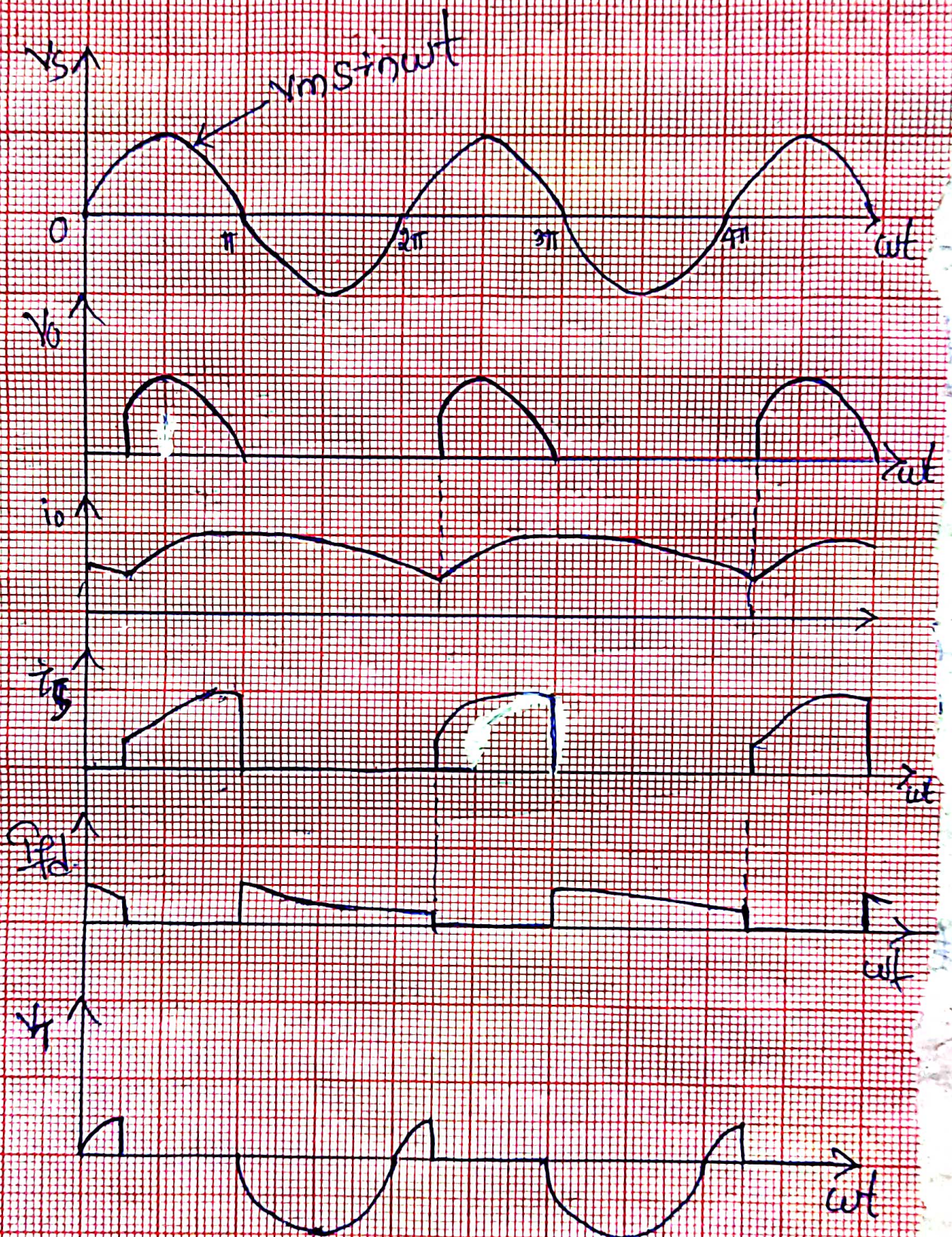
Operation of the circuit may be explained in two mode - conduction mode, free wheeling mode.

Conduction mode :-

SCR conducts from α to π , $2\pi + \alpha$ to $3\pi + \alpha$ and so on and F.D is reverse biased.

Free wheeling mode :-

F.D conducts from π to $2\pi + \alpha$, 3π to $4\pi + \alpha$ and so on. and thyristor is reverse biased and ~~thyristor is~~ ~~reverse biased~~ from π to 2π and 3π to 4π .



Single-phase half-wave rectified with
 R-L load and free wheeling diode.
 (Voltage current wave form).

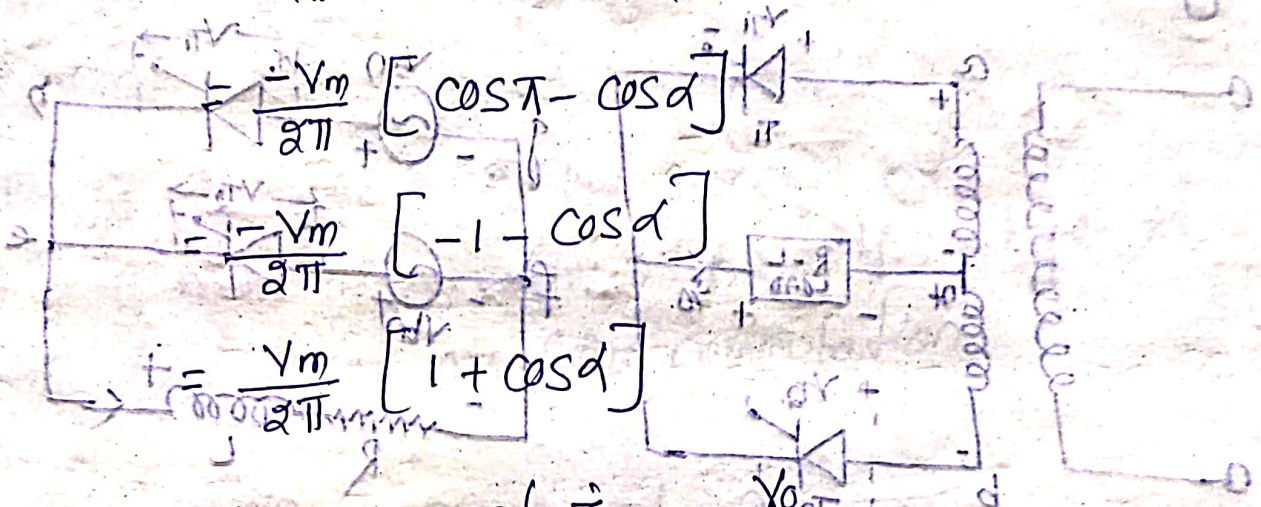
Average output Voltage :-

$$V_o = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_s d(\omega t)$$

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

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

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



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

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

Advantage of using F.D. :-

- (i) Input power factor is improve.
- (ii) load current wave form is improve.
- (iii) load performance is better.
- (iv) Overall converter efficiency improves.

Disadvantage :-

Supply current is unidirectional and in form of D.C pulses single phases half wave

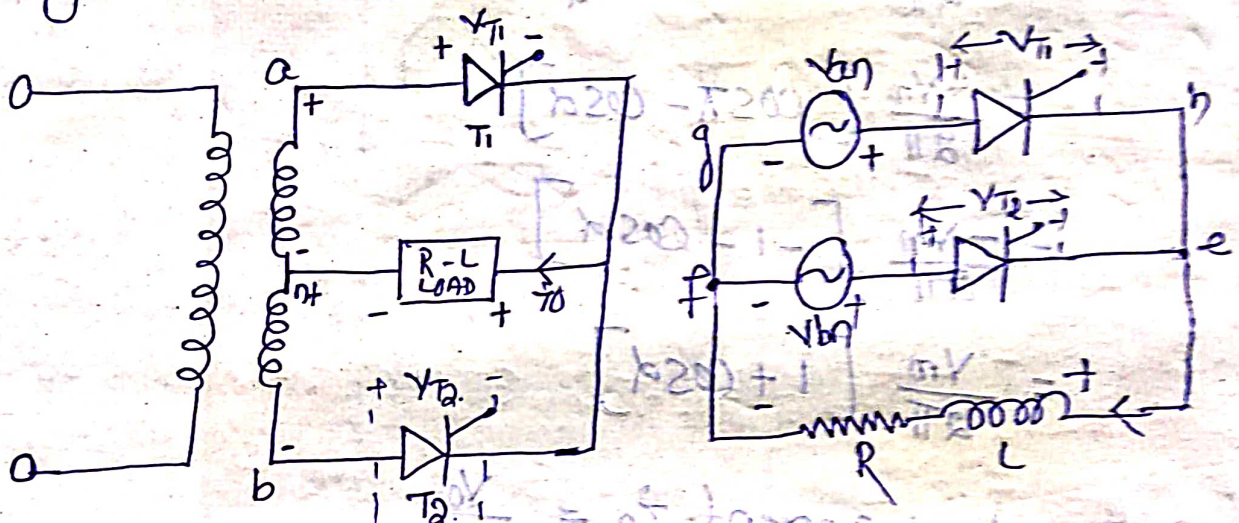
Full wave controlled converter :-

→ There are two basic configuration for full wave converter.

(i) Mid point converter (center taped)

(ii) Bridge converter

Single phase full wave mid point converter



- The ckt diagram using a centre tapped transformer and two thyristors and a R-L load is shown.
- It uses an I/p transformer with two winding for each I/p phase winding.
- when terminals positive with respect to n and n terminal is positive with respect to b.
- when a terminal 'A' is positive with respect to N and N terminal is positive with respect to b.

i.e. $V_{an} = V_{nb}$
 $V_{an} = -V_{bn}$

↳ It is assumed here that load or output current is continuous and ratio for primary to each secondary is unity.

↳ During +ve half cycle thyristor T_1 is forward biased and in -ve half cycle thyristor T_2 is forward biased.

↳ At delay angle α Thyristor T_1 gets turned on.

↳ At this angle α SCR T_2 is subjected to reverse voltage.

↳ T_2 is turned off the process of SCR turned off by natural reverse off supply voltage is called natural or line commutation.

↳ Apply in KVL in ckt.

$$V_{an} - V_{T_1} + V_{T_2} - V_{bn} = 0$$

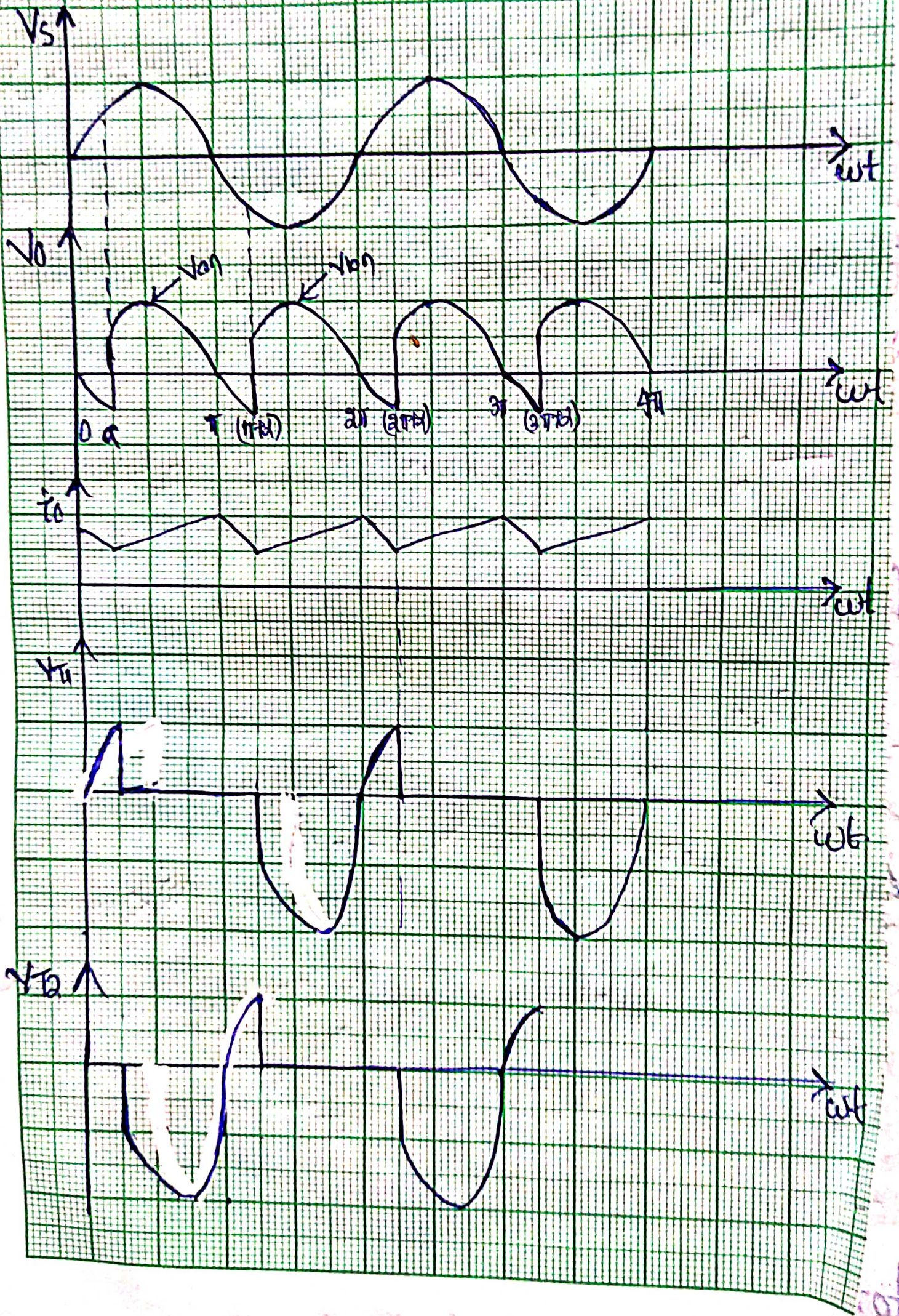
$$\Rightarrow V_{T_1} = V_{an} + V_{nb} \quad [V_{T_2} = 0]$$

$$= -V_m \sin \omega t - V_m \sin \omega t$$

$$= -2V_m \sin \omega t$$

↳ Thyristor T_1 conduct from α to $\pi + \alpha$ after $\omega t = \pi$, T_1 is reverse biased, but then conduct due to R-L load till SCR T_2 is not gated.

↳ At $\omega t = \pi + \alpha$ T_2 is triggered T_1 is reverse biased with voltage $2V_m \sin \alpha$.



Average output voltage is

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

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

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

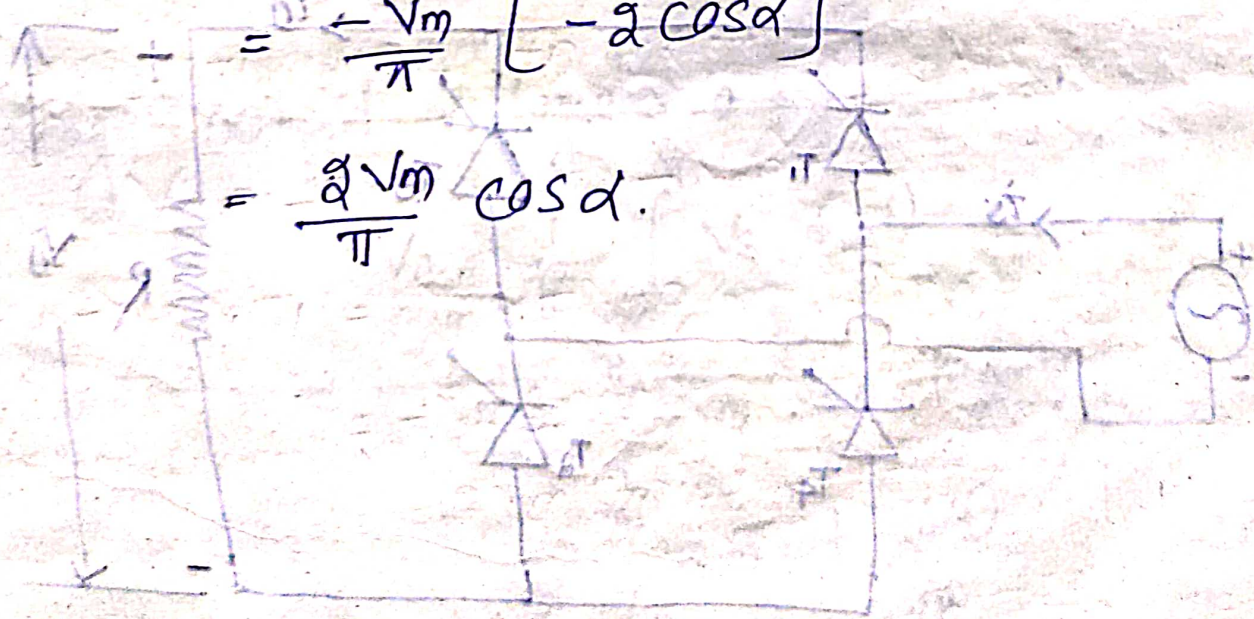
$$= \frac{V_m}{\pi} [-\cos \omega t]_{\alpha}^{\pi+\alpha}$$

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

$$= \frac{-V_m}{\pi} [-\cos \alpha - \cos \alpha] \quad [\cos(180^\circ + \alpha) = -\cos \alpha]$$

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

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

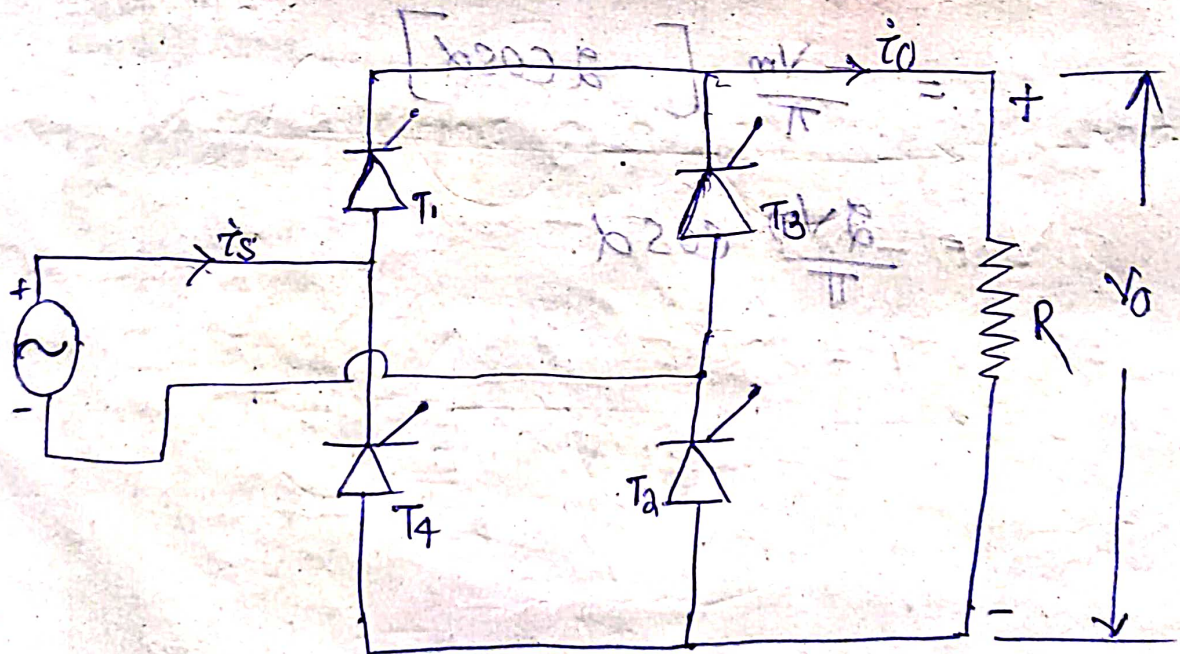


Single-phase full wave bridge converters:- Dt-30.08.2019

→ Single phase full wave ^{bridge converters} controllers are basically of 3-types

- ① uncontrolled converters (only diodes)
- ② Semi-converter/half controlled converter (SCR, diode)
- ③ fully controlled converters (only SCR)

Single-phase full converters:-

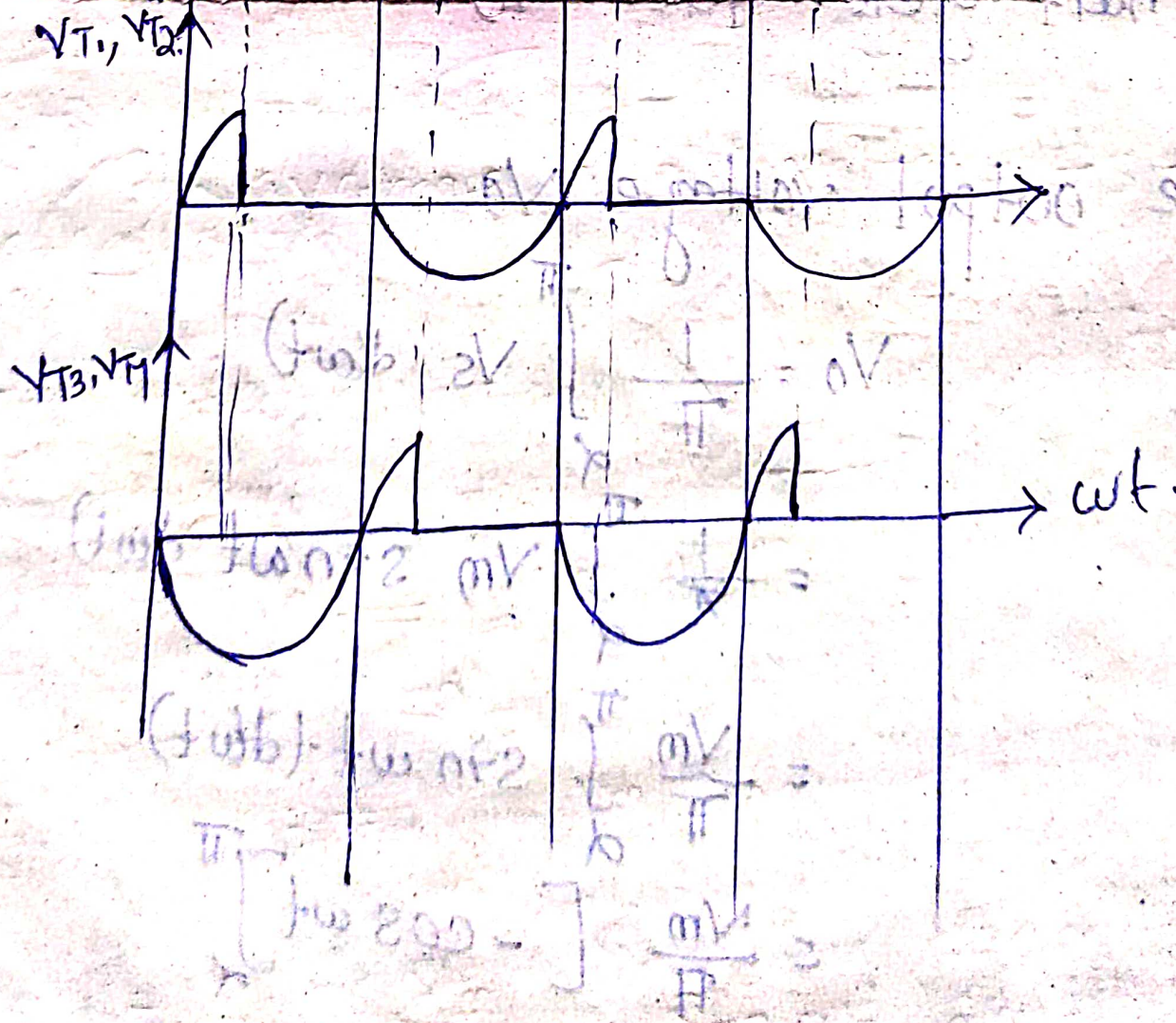
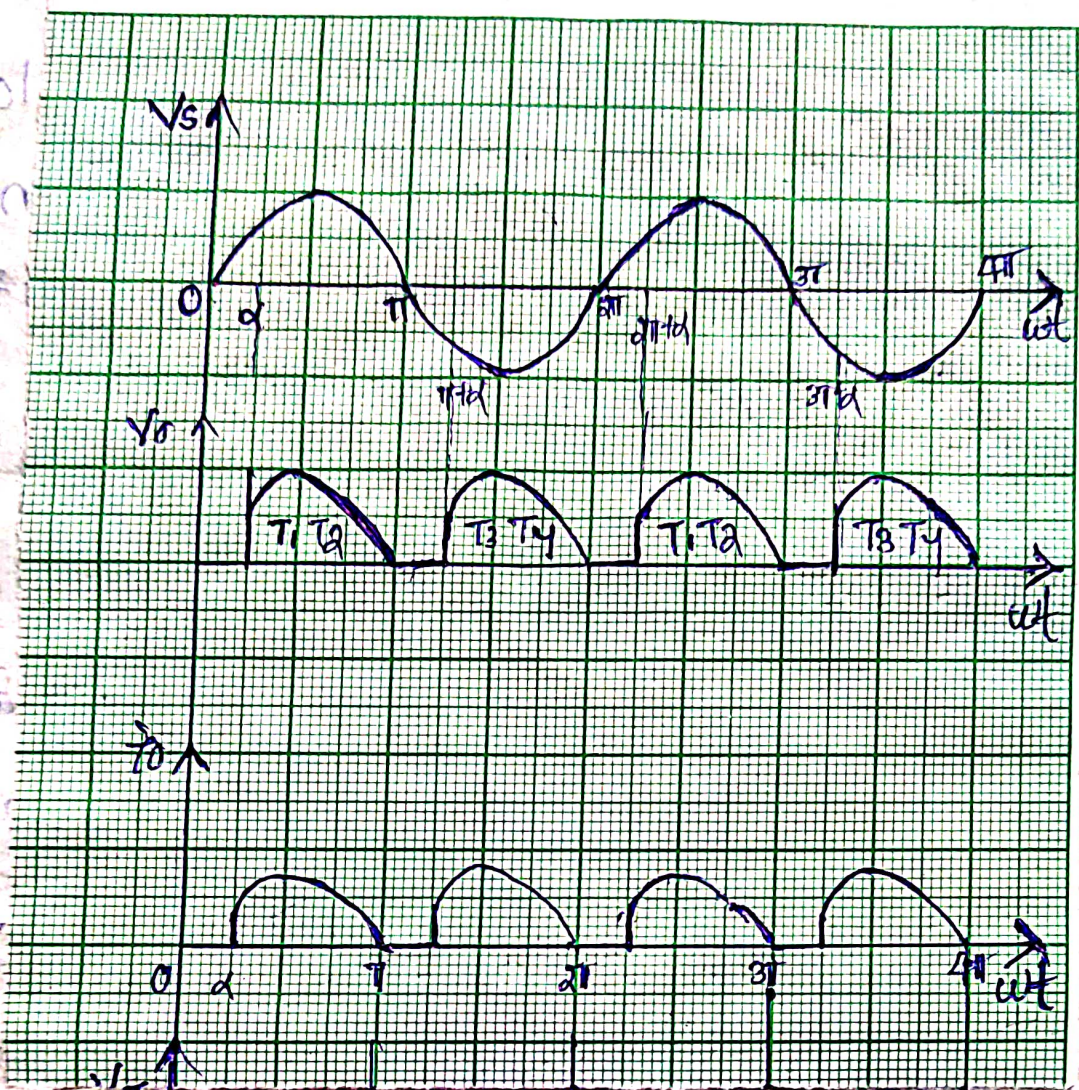


→ A single phase full bridge converter uses four SCR. The load is resistive feeding from a single phase AC supply.

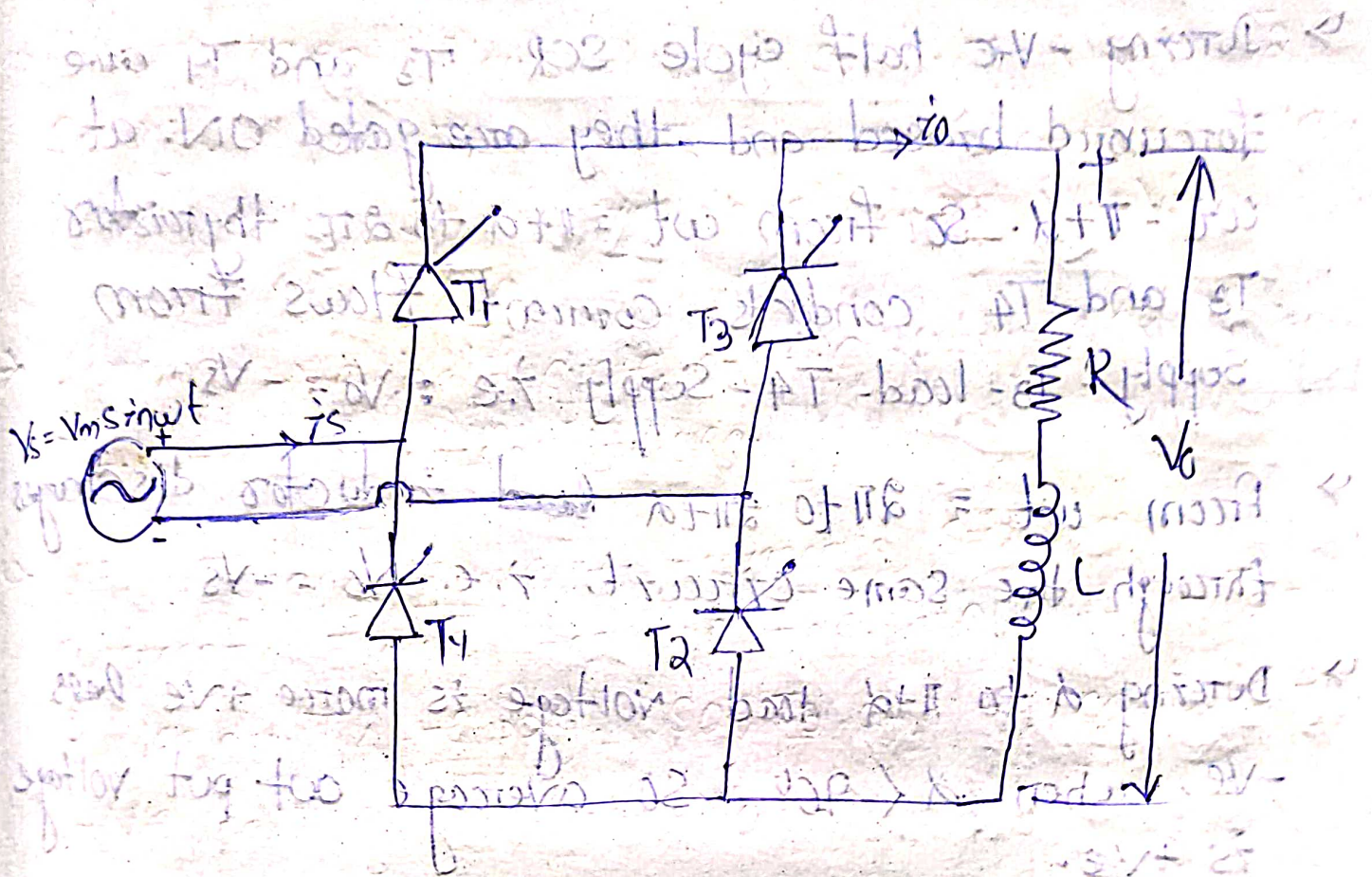
- During first +ve half cycle SCR T_1 and T_2 are forward biased.
- If T_1 and T_2 are given gate signal simultaneously then current flows through supply - T_1 - R load - T_2 - Supply. Hence T_1 and T_2 are conduction in +ve half cycle, so during this period $V_o = V_s$
- During -ve half cycle of A.C supply SCR T_3 and T_4 are forward biased.
- If T_3 and T_4 are triggered simultaneously current flows through the path supply - T_3 - R load - T_4 - Supply. So T_3 and T_4 conducts in -ve half cycle. Hence $V_o = -V_s$

Average output voltage V_o

$$\begin{aligned}
 V_o &= \frac{1}{\pi} \int_{\alpha}^{\pi} V_s \, d(\omega t) \\
 &= \frac{1}{\pi} \int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t) \\
 &= \frac{V_m}{\pi} \int_{\alpha}^{\pi} \sin \omega t \, d(\omega t) \\
 &= \frac{V_m}{\pi} \left[-\cos \omega t \right]_{\alpha}^{\pi} \\
 &= -\frac{V_m}{\pi} [\cos \pi - \cos \alpha] \\
 &= -\frac{V_m}{\pi} [-1 - \cos \alpha] \\
 &= \frac{V_m}{\pi} [1 + \cos \alpha]
 \end{aligned}$$



Single phase full bridge converter with R-L Load :-



- The circuit diagram shows a single phase A.C supply feeding a R.L load through 4 thyristors T_1, T_2, T_3 and T_4 .
- During +ve half supply thyristors T_1 and T_2 are forward biased and at $\omega t = \alpha$ T_1 and T_2 are triggered.
- From $\omega t = \alpha$ to π current flows from supply - T_1 - load - T_2 - supply i.e. $V_o = V_s$

→ From $\omega t = \pi$ to $\pi + \alpha$ Inductor discharges through the same circuit, so $V_o = V_s$

→ During -ve half cycle SCR T_3 and T_4 are forward biased and they are gated ON. at $\omega t = \pi + \alpha$. So from $\omega t = \pi + \alpha$ to 2π thyristors T_3 and T_4 conduct. Current flows from Supply - T_3 - load - T_4 - Supply i.e. $V_o = -V_s$.

→ From $\omega t = 2\pi$ to $2\pi + \alpha$ ~~load~~ inductor discharges through the same circuit. i.e. $V_o = -V_s$.

→ During α to $\pi + \alpha$ load voltage is more +ve less -ve, when $\alpha < 90^\circ$. So average out put voltage is +ve.

→ when $\alpha > 90^\circ$ average output voltage is -ve.

Average output voltage V_o

$$V_o = \frac{1}{\pi} \int_{\pi+\alpha}^{2\pi} V_s d(\omega t)$$

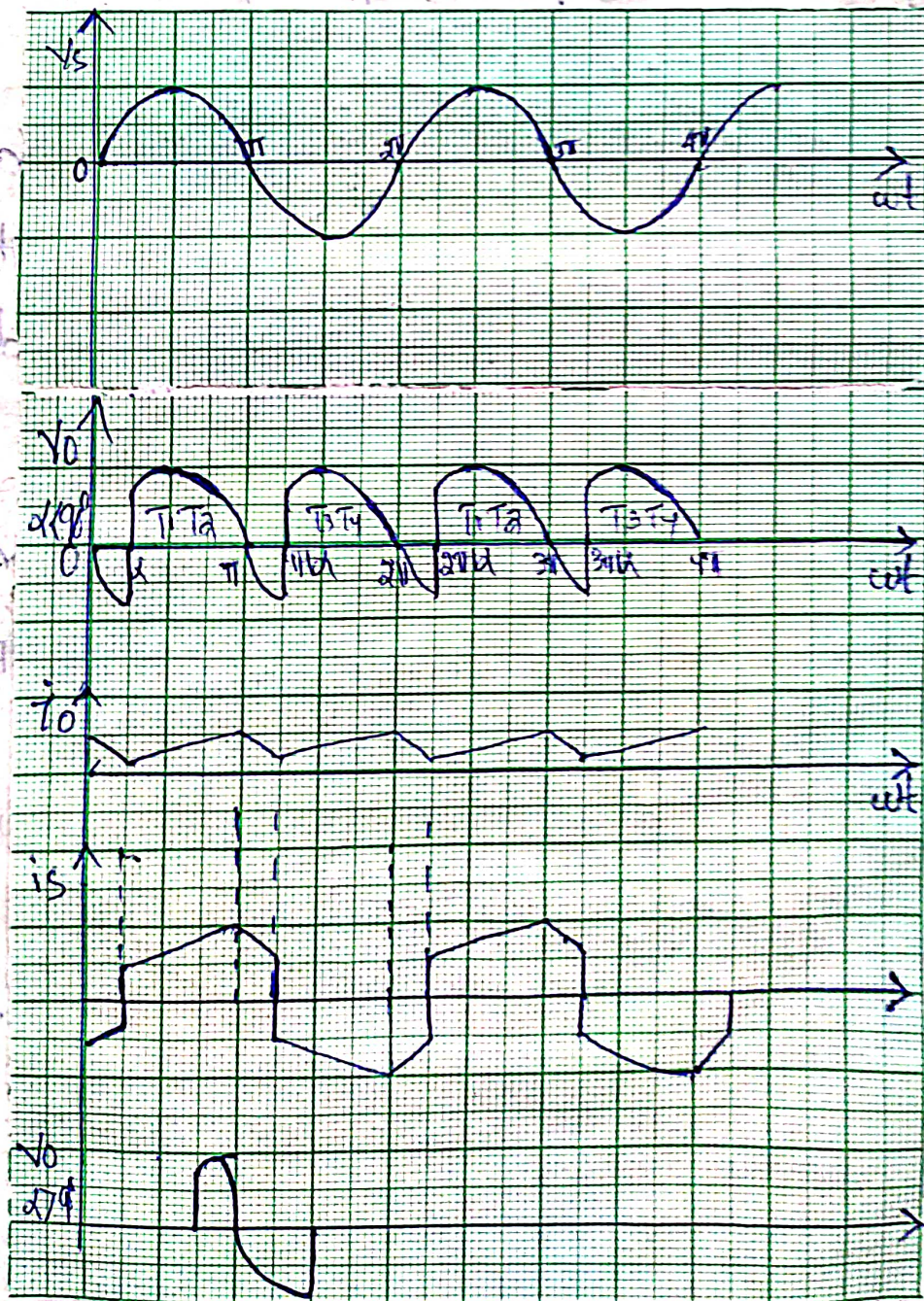
$$= \frac{1}{\pi} \int_{\pi+\alpha}^{2\pi} V_m \sin \omega t d(\omega t)$$

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

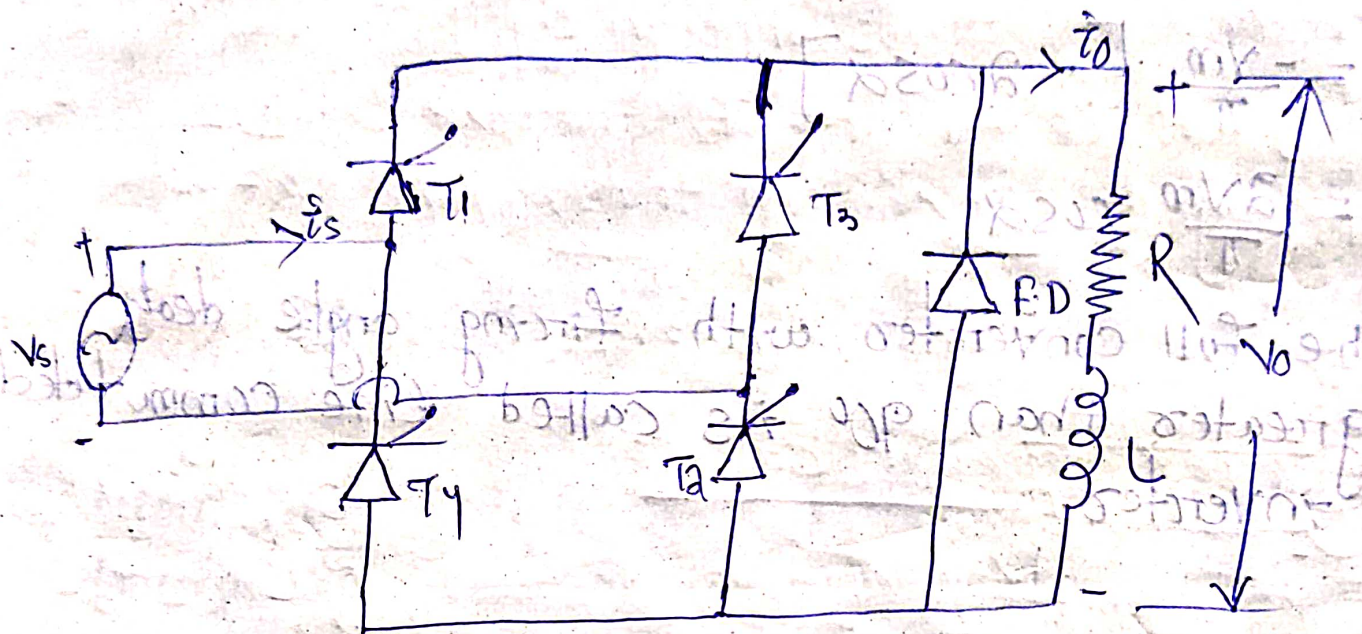
$$= \frac{V_m}{\pi} [-\cos \omega t]_{\pi+\alpha}^{2\pi}$$

$$\begin{aligned}
 &= -\frac{V_m}{\pi} [\cos \pi + \alpha - \cos \alpha] \\
 &= -\frac{V_m}{\pi} [-\cos \alpha - \cos \alpha] \\
 &= -\frac{V_m}{\pi} [-2\cos \alpha] \\
 &= \frac{2V_m}{\pi} \cos \alpha
 \end{aligned}$$

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



Single phase full bridge converter with R-L load and free wheeling diode:-



- The circuit diagram shows a single phase AC Supply feeding a R-L load through 4 thyristors T_1, T_2, T_3 and T_4 and a free wheeling diode connected across the load.
- During +ve half supply thyristors T_1 and T_2 are forward biased and at $\omega t = \alpha$, T_1, T_2 are triggered.
- From $\omega t = \alpha$ to π current flows from supply $\rightarrow$ load $\rightarrow T_2$ $\rightarrow$ Supply i.e. $V_o = V_s$
- From $\omega t = \pi$ to $\pi + \alpha$ Inductor discharges through free wheeling diode to load.. So $V_o = 0$.

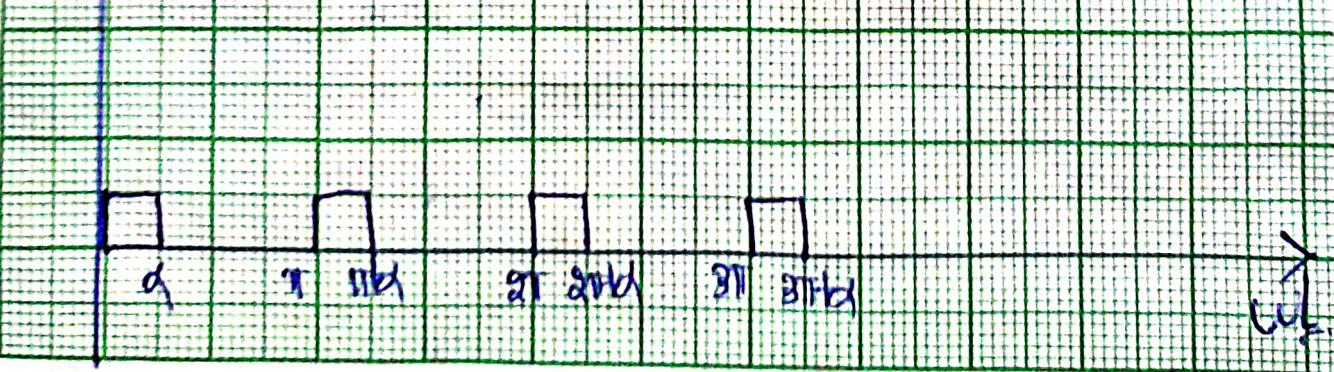
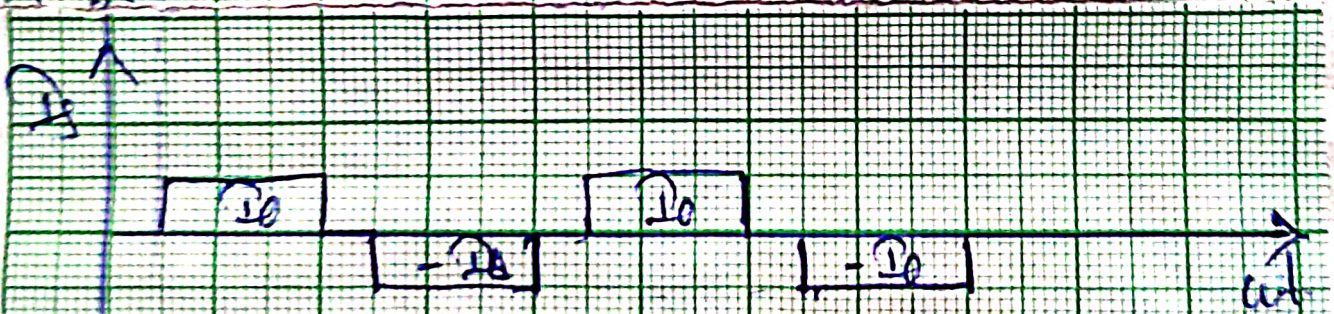
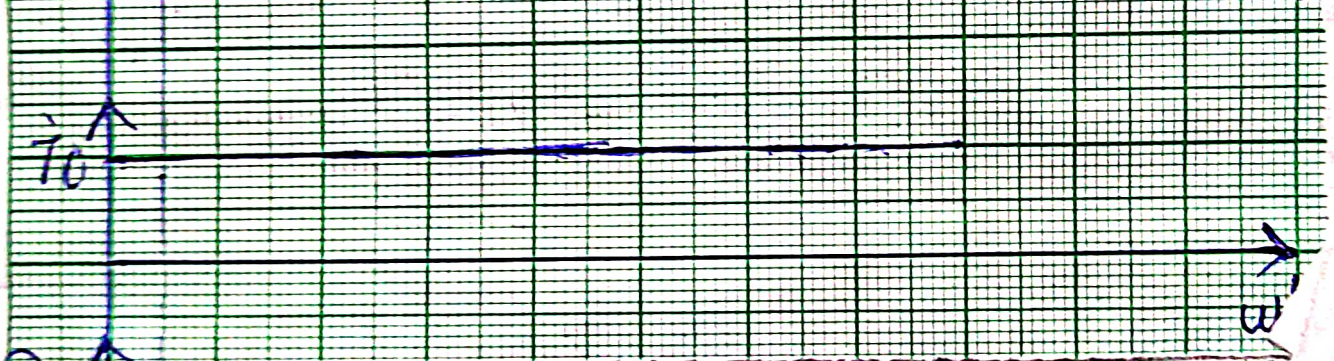
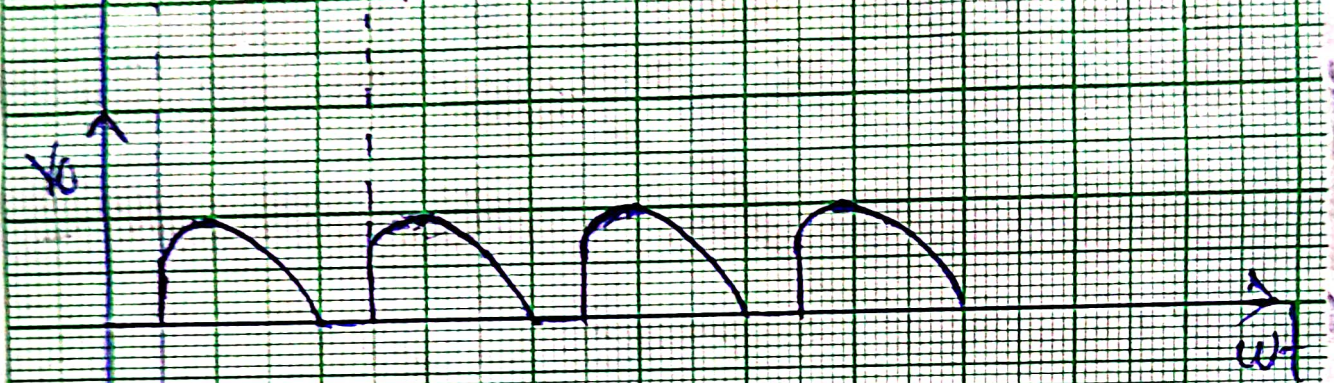
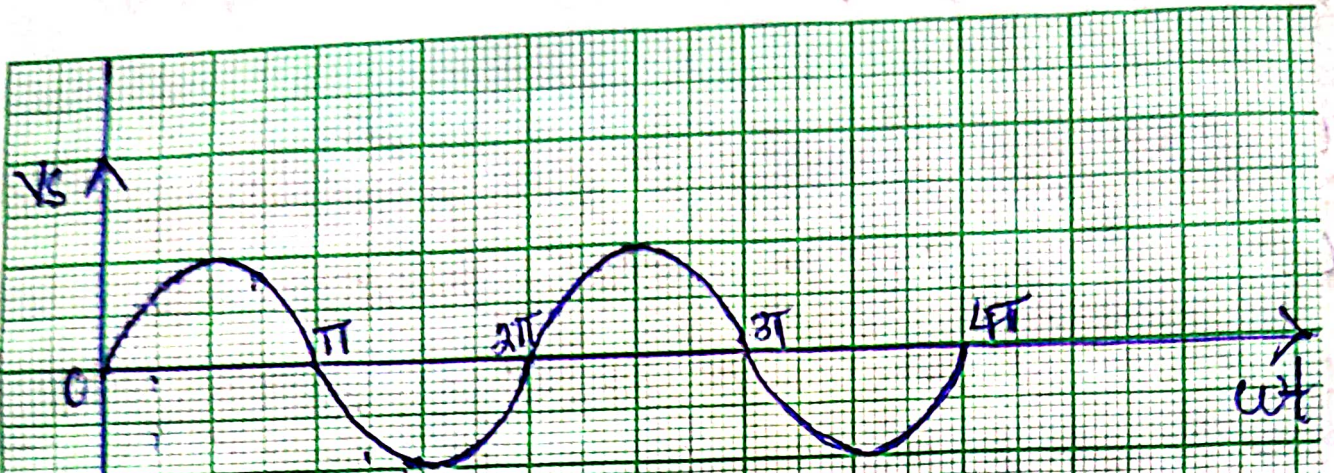
During -ve half cycle thyristors T_3 and T_4 are forward biased they get ON. at $\omega t = \pi + \alpha$ so from $\omega t = \pi + \alpha$ to 2π Thyristor T_3 and T_4 conducts. current flows from supply - T_3 - load - T_4 - supply. i.e. $V_o = -V_s$.

From $\omega t = 2\pi$ to $2\pi + \alpha$ Inductor discharges through freewheeling diode to load. So, $V_o = 0$.

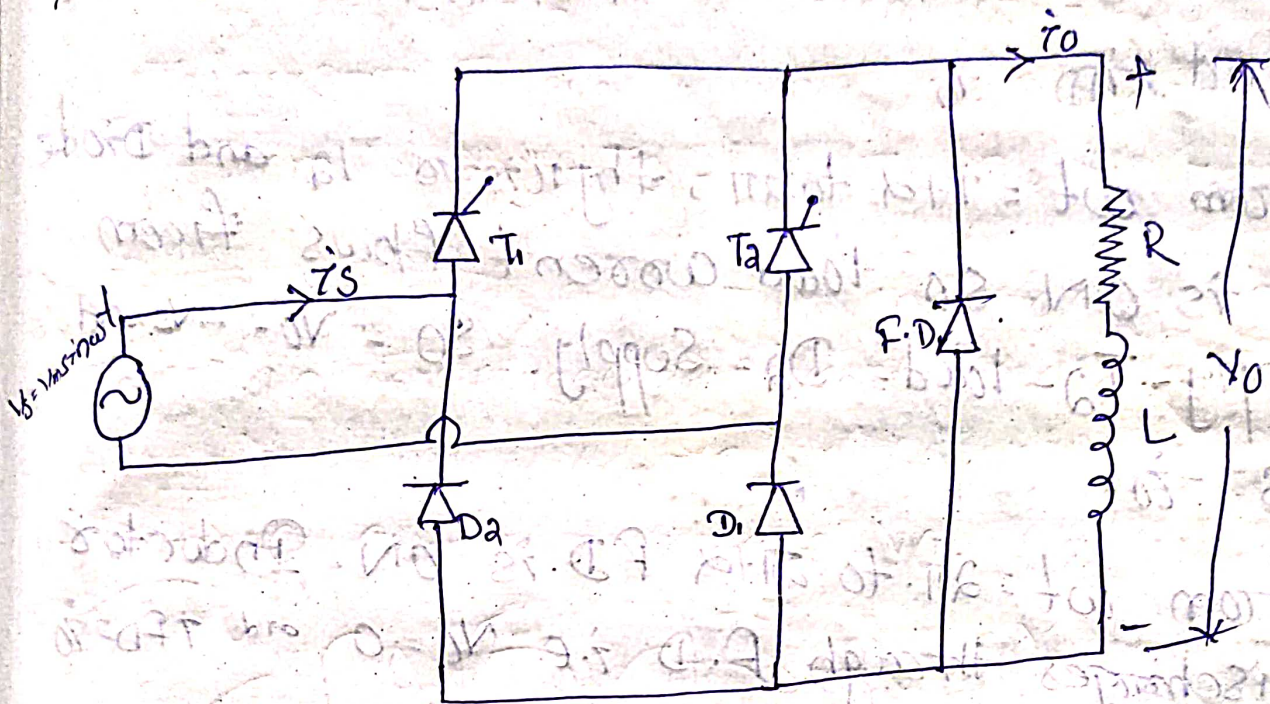
Average output voltage V_o .

$$\begin{aligned} V_o &= \frac{1}{\pi} \int_{\alpha}^{\pi} V_s d(\omega t) \\ &= \frac{1}{\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t) \\ &= \frac{V_m}{\pi} \left[-\cos \omega t \right]_{\alpha}^{\pi} \\ &= \frac{-V_m}{\pi} \left[\cos \pi - \cos \alpha \right] \\ &= \frac{-V_m}{\pi} \left[-1 - \cos \alpha \right] \\ &= \frac{V_m}{\pi} \left[1 + \cos \alpha \right]. \end{aligned}$$

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Single phase semiconverter (Half controlled rectifier) :-

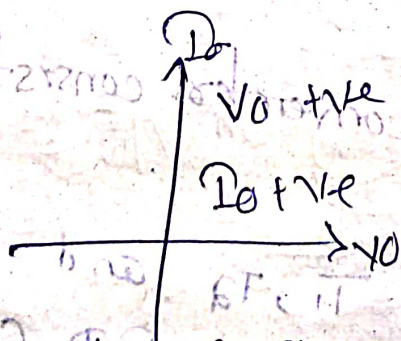


- A single phase semiconverter consists of two thyristors and three diodes.
- The two thyristors T_1, T_2 and diodes D_1, D_2 and free wheeling diode F.D. connected across the load.
- During +ve half cycle of A.C supply thyristor T_1 and Diode D_1 are forward biased. T_1 is triggered at a firing angle delay α .
- With T_1 ON load gets connected to source through T_1 and D_1 .
- For the period $\omega t = \alpha$ to π load current i_o flows from supply T_1 - load - D_1 - supply.
So $V_s = V_o$ and $i_s = i_o$ +ve i.e. $i_s = i_o$

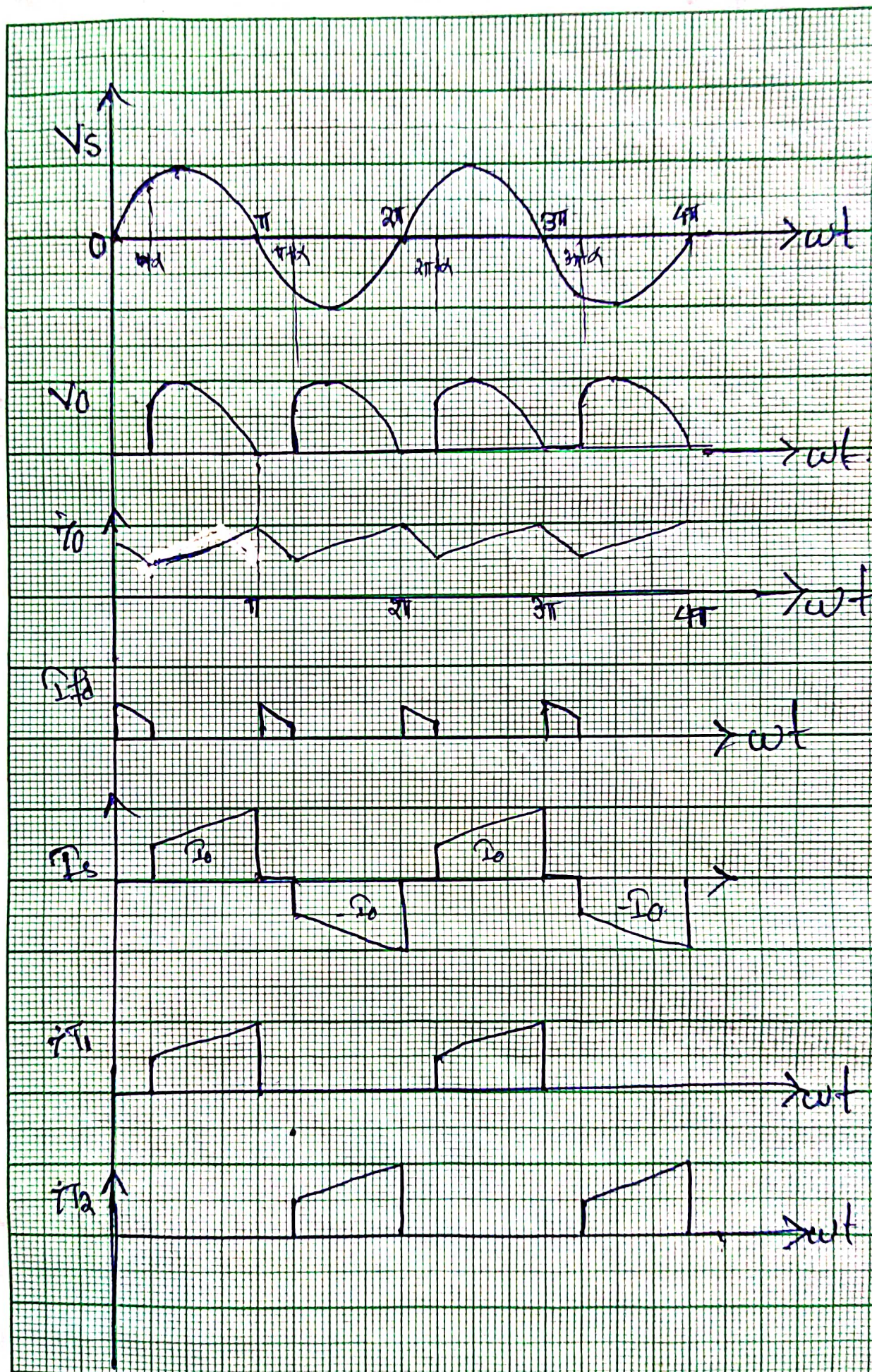
(vi) From $\omega t = \pi$ to $\pi + \alpha$ F.D. gates forward biased and starts conducting. load current is transferred from T₁ D₁ to F.D. So, $V_o = 0$ and $i_{FD} = i_o$

(vii) From $\omega t = \pi + \alpha$ to 2π , thyristor T₂ and Diode D₂ is ON. So load current flows from Supply - T₂ - load - D₂ - Supply. So $V_o = -V_s$ and $i_s = -i_o$

(viii) From $\omega t = 2\pi$ to $2\pi + \alpha$ F.D. is ON. Inductor discharges through F.D. i.e. $V_o = 0$ and $i_{FD} = i_o$



Semi-converter always operate in first quadrant.



Power factor correction :-

- The supply power factor in phase-controlled converters is low, when the output voltage is less than ^{the} V_{max} . i.e. when the firing angle is large.
- The poor power factor operation is a major problem in variable speed drives and in high power application.
- The various technique to improve power factor in phase controlled converters are
 - ① phase angle controll (P.A.C)
 - ② Semi-converter operation of full converter
 - ③ Asymmetrical firing

D.C Chopper

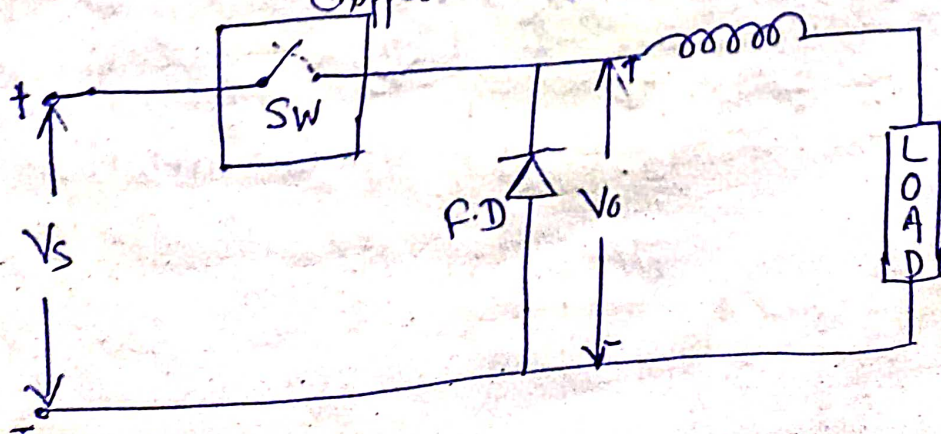
- ↳ A D.C Chopper is a static device that converts fixed D.C to variable D.C.
- ↳ Choppers are used in battery operated vehicles, fork lift trucks, trolley buses, tram bus or cars, Battery charging, speed control and breaking of D.C motors.
- ↳ The power semiconductor devices used for a Chopper can be forced commutated thyristors, power BJT, power MOSFET, GTO, or IGBT.

D.C chopper can be

- ① Stepdown chopper
- ② Step up chopper.

① Stepdown chopper

- ② In step down chopper average output voltage V_o is less than the input voltage V_s .
- i.e. $V_o < V_s$

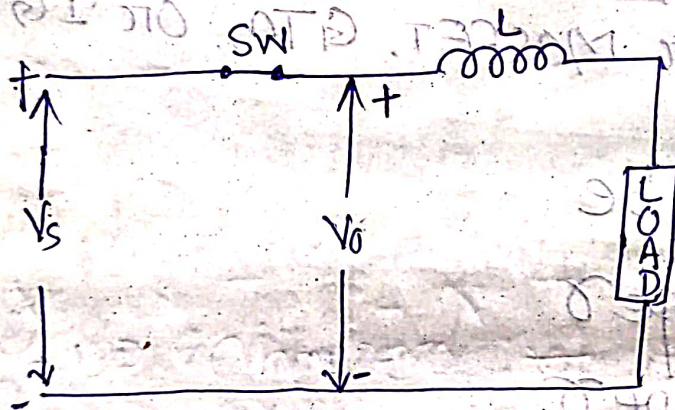


(*) Chopper is high speed ON/OFF semiconductor switch.

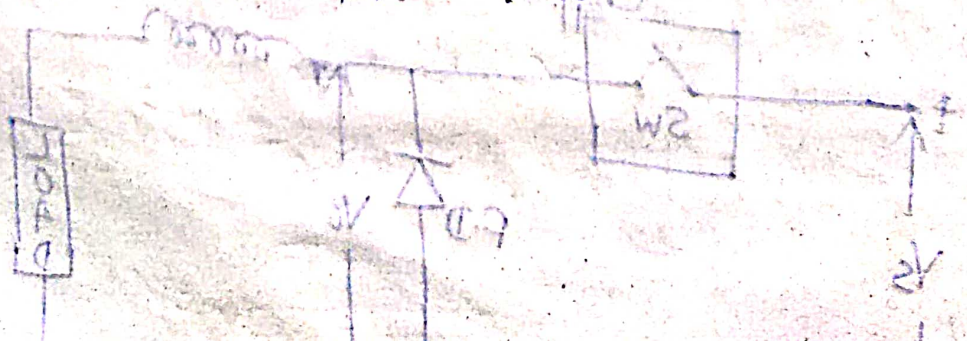
(iii) It connects source to load and disconnect the load from source at a fast speed.

(iv) The ckt consists of a D.C source, a switch, a freewheeling diode, Inductor L and load.

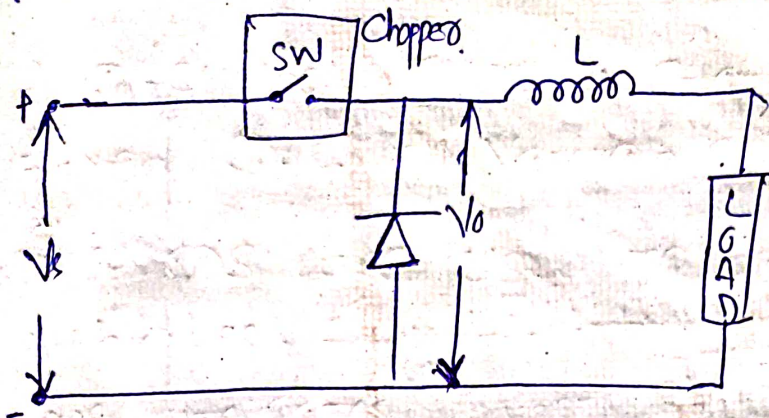
* When SW ^(chopper) is ON



- Diode is reversed biased due to D.C sources.
- Current flows from +ve end of D.C source - Switch - inductor - load - -ve supply so, $V_o = V_s$.
- In this period, Inductor ' L ' stores energy from D.C supply and its current increases gradually from minimum value to max value.



* When Sw (chopper) is OFF :-



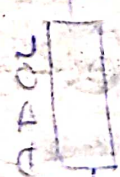
- Free-wheeling diode is forward biased due to inductor.
- Inductor discharges stored energy through load and free-wheeling diode. So, $V_o = 0$.

T_{on} - ON time.

T_{off} - OFF time.

$T = T_{on} + T_{off}$ = chopping period.

Average load voltage $V_o = \frac{T_{on}}{T_{on} + T_{off}} \times V_s$



$$= d \times V_s$$

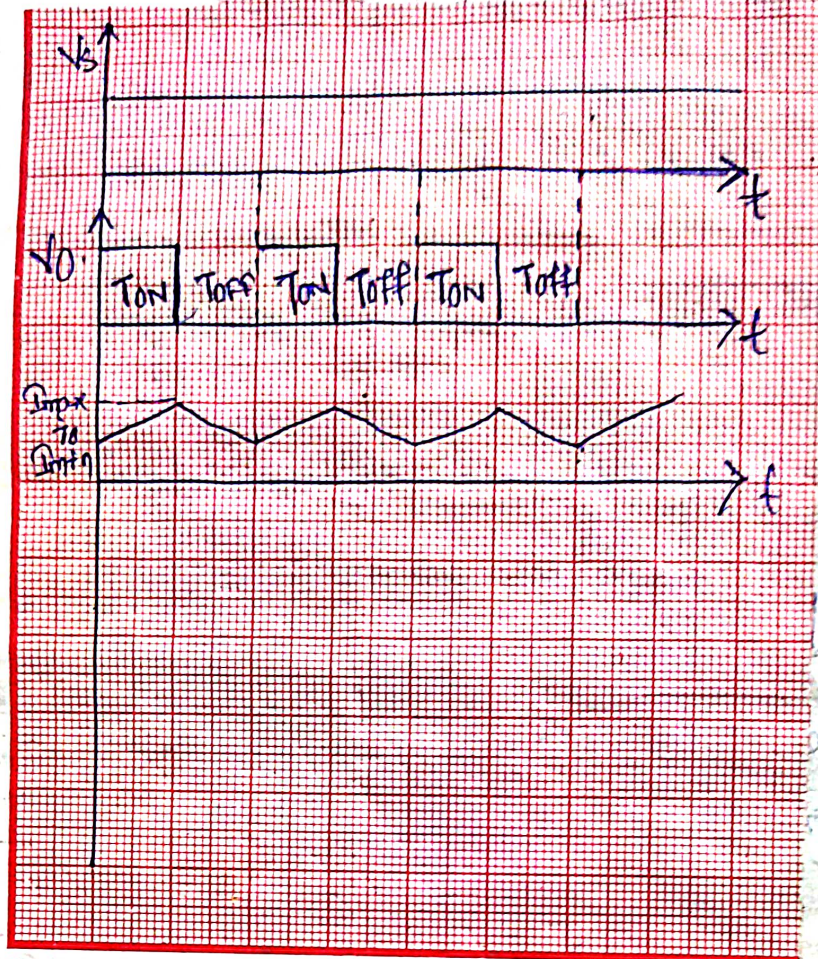
where, $d = \frac{T_{on}}{T}$ (duty cycle)

d is called duty ratio. d value varies from 0 to 1.

$$V_o = \frac{T_{on}}{T} V_s$$

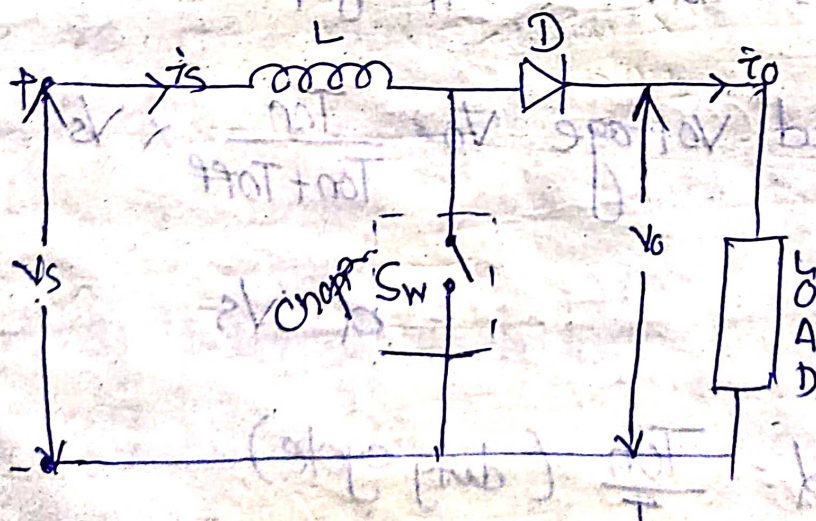
$$V_o = f T_{on} V_s$$

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



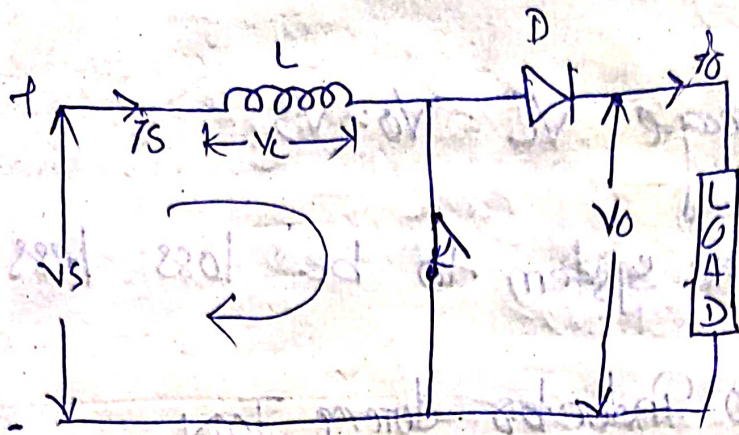
Oxford Paper Products Pvt. Ltd., Kolkata-700 009

Step-up chopper :—



→ In step up chopper average voltage V_o is greater than input voltage V_s

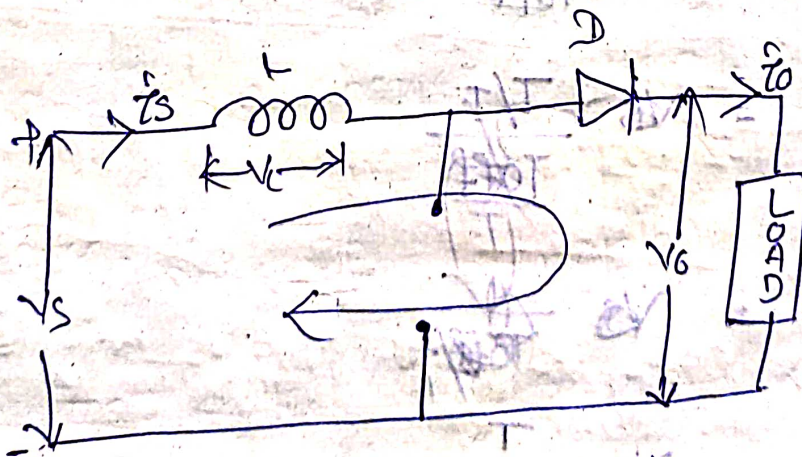
When Sw is ON :-



- During on time current flows through Inductor and Switch only. In this period Inductor store energy from supply.
 - Current through inductor would increase from I_1 to I_2
- $V_0 = 0$, and $V_L = V_S$

When Sw is off :-

- when Sw is off inductor current can't decrease instantaneously, It is forced to flow through the diode and load for a time t_{off} .



- During T_{off} period load gets supply both from Inductor and DC source.
- So load voltage $V_0 = V_S + L \frac{di}{dt}$.

* When sw is off current would fall from I_2 to I_1

* Inductor voltage $V_L = V_o - V_s$

* Considering the system to be loss less energy

Energy input to Inductor during T_{ON}

= Energy released by inductor T_{OFF}

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

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

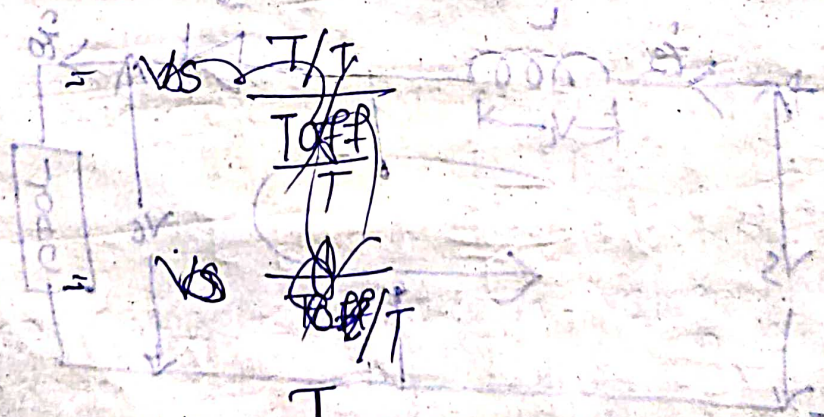
$$\Rightarrow V_s \cdot T_{ON} = V_o \cdot T_{OFF} - V_s \cdot T_{OFF}$$

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

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

$$\Rightarrow V_o = V_s \frac{T}{T_{OFF}}$$

$$\Rightarrow V_o = V_s \frac{T/T}{T_{OFF}/T}$$

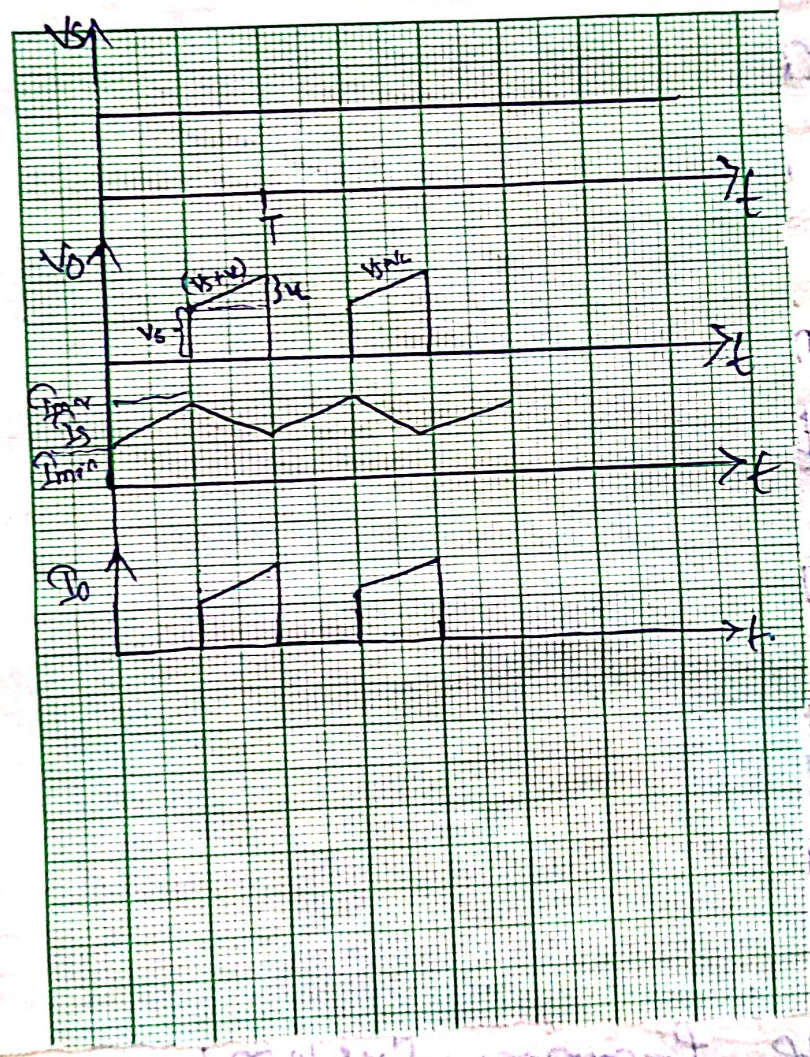


$$V_o = V_s \frac{T}{T - T_{ON}}$$

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

$$\Rightarrow \boxed{V_o = \left(\frac{1}{1-d} \right) V_s}$$

d value varies from 0 to 1, so V_o is always greater than V_s .



Control Strategy of chopper :-

The various control strategies for varying duty cycle d are :-

- (i) Time ratio control
- (ii) Current limit control

(i) Time ratio control :-

↳ In this control scheme, time ratio $\frac{T_{on}}{T}$ is varied. There are 2 different methods for this control.

(a) Constant frequency system :-

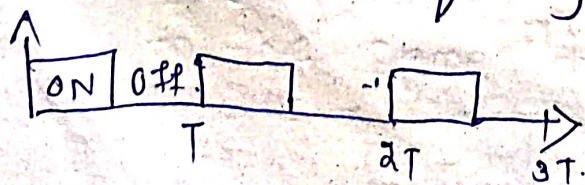
↳ Here ON time T_{on} is varied but chopping frequency (f) or chopping period T is kept constant.

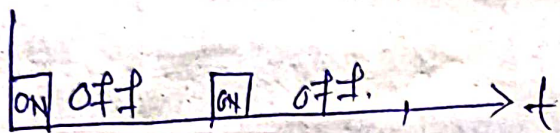
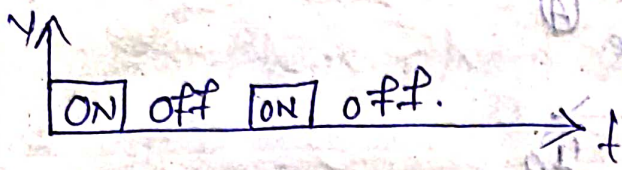
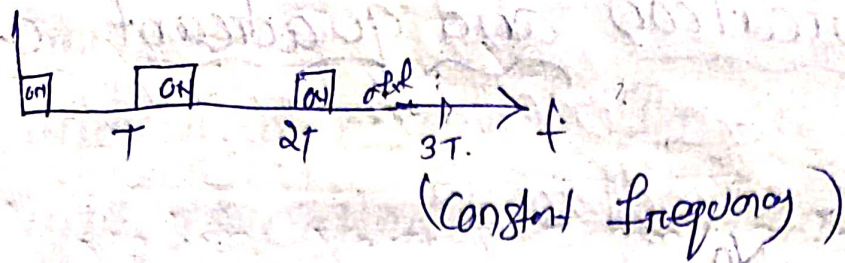
↳ This process is also called pulse width modulation scheme.

(b) Variable frequency system :-

↳ Here chopping frequency (f) or chopping period (T) is varied by either varying T_{on} or varying T_{off} .

↳ This is called frequency modulation scheme.



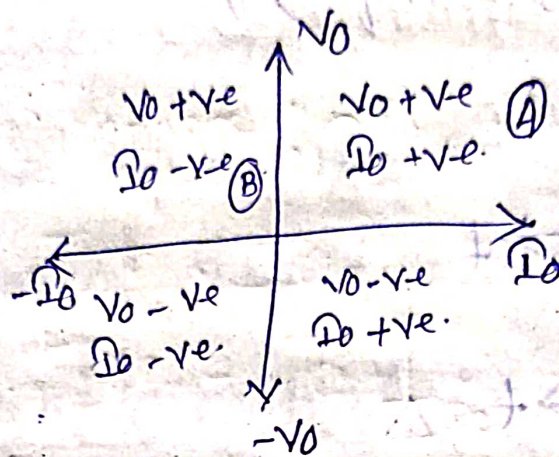


(Variable frequency system)

Current limit control

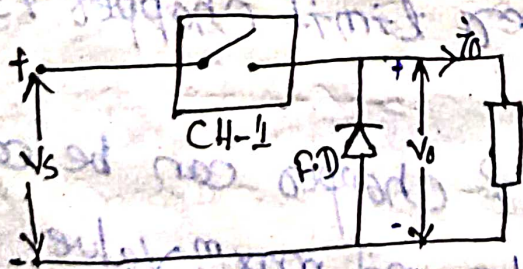
- In this scheme the ON and OFF chopper is guided by previous set value of minimum load current or max^m load current.
- When load current reaches max^m value then switch is off.
- When it falls to lower limit chopper is switched ON.
- Switching frequency of chopper can be control by setting minimum value and max^m value.
- PWM (pulse width modulation) is the common method for power control of chopper.

Chopper Configuration and quadrant of operation :-



- ↳ Type-A chopper (1st quadrant operation)
- ↳ Type-B chopper (2nd quadrant operation)
- ↳ Type-C chopper (1st and 2nd quadrant operation)
- ↳ Type-D (1st and 4th quadrant operation)
- ↳ Type-E (4th quadrant operation)

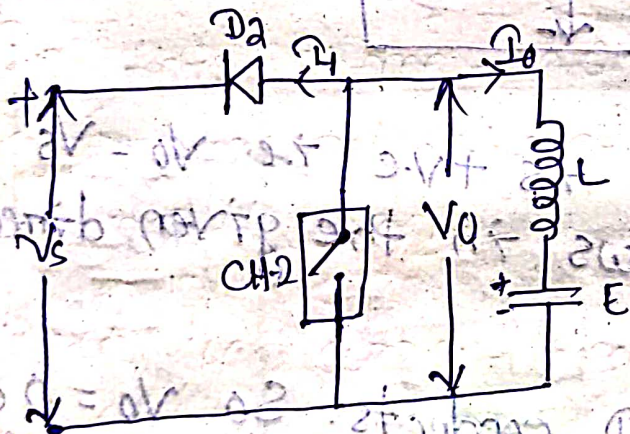
Type-A chopper :-



- ↳ when chopper CH-1 is ON $V_o = V_s$ and I_o flows in the arrow direction
- ↳ When CH-1 is off $V_o = 0$ and I_o continue to flow in the same direction through freewheeling diode F.D.

- So, average value of both load voltage V_o and load current I_o are always +ve.
- This is called 1st quadrant operation of Chopper
- Power flows always from source to load in type A Chopper.
- This Chopper is also called step down chopper as V_o average is always less than I/P Voltage V_s .

Type-B Chopper :-

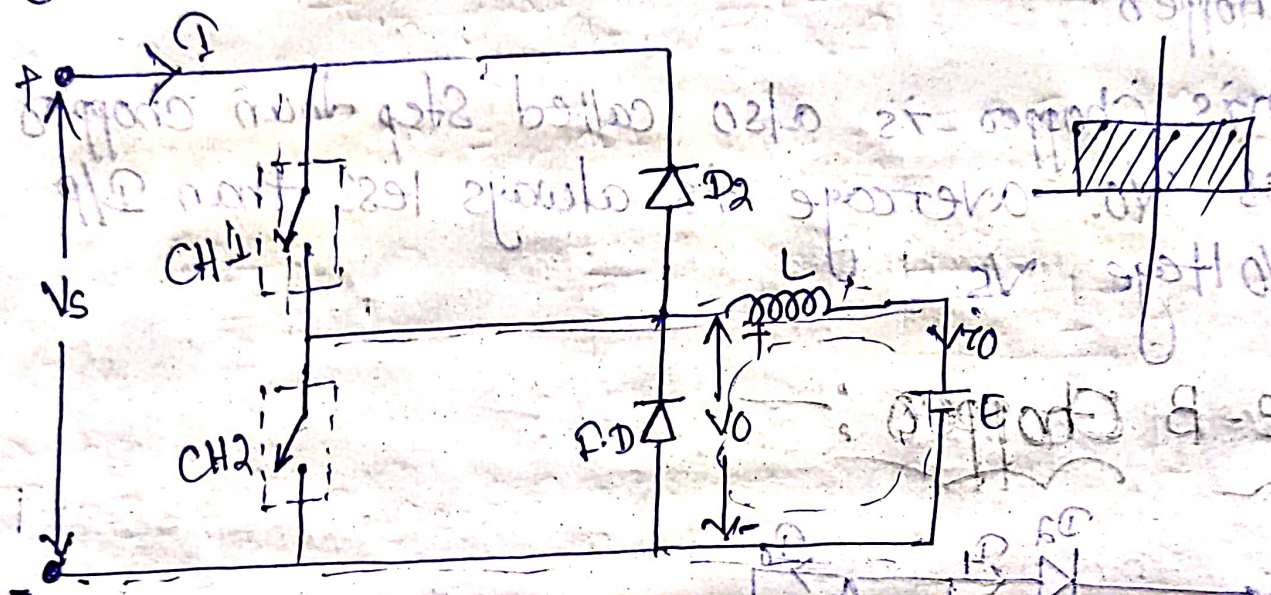


- load must contain a D.C Source E . like a battery or a D.C motor in this chopper.
- when CH-2 is ON, $V_o = 0$ but battery voltage drives current through L and CH-2. Inductor stores energy during ON period of CH-2
- The load current flows opposite to the reference direction so, I_o is negative.
- when CH-2 is OFF diode D_a is forward biased due to $V_o [E + L \frac{di}{dt}]$. V_o exceeds source voltage V_s . So power flows from

load to source

→ Type-B Chopper is used for regenerative braking of D.C motor.

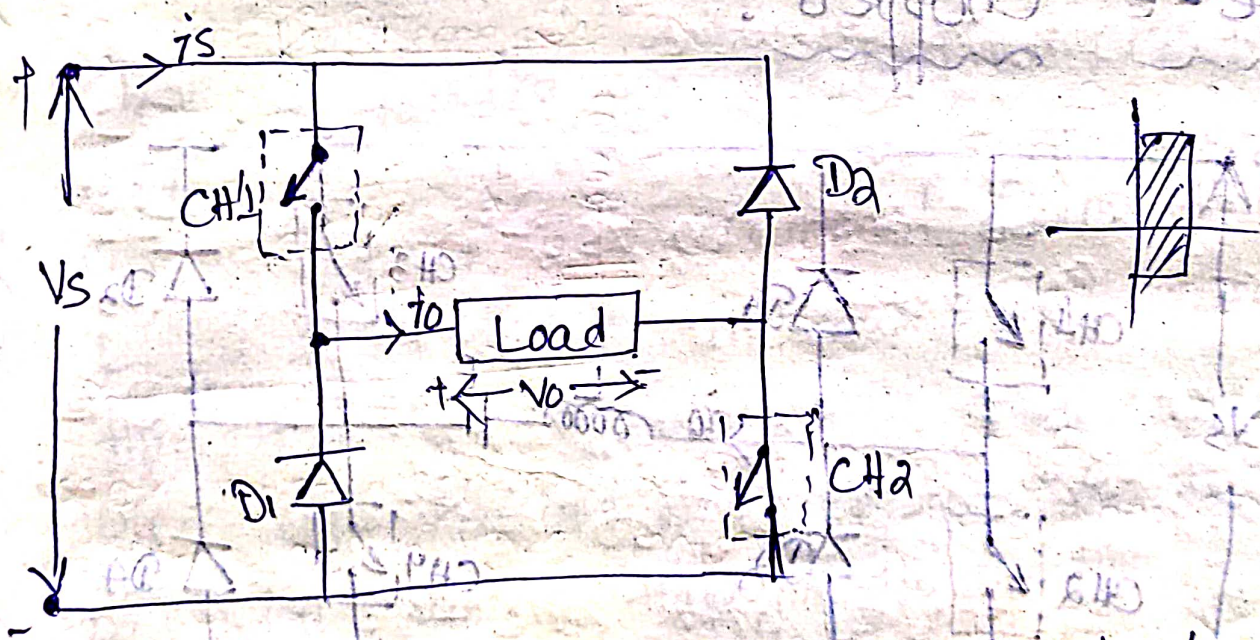
Type-C Chopper : ~



- when CH1 is ON V_o is +ve i.e. $V_o = V_s$ and current I_o flows in the given direction. So, I_o is +ve.
- when CH1 is OFF FD conducts. So $V_o = 0$ and I_o flows in the same direction as before. So, I_o is +ve.
- when Chopper CH2 is ON $V_o = 0$ and I_o flows from battery 'E' through inductor and CH2 to the battery. So, I_o is -ve and $V_o = 0$.
- when CH2 is OFF diode D_2 conducts. Current flows from $E - L - D_2 - V_s - E$. So $V_o = E + L \frac{dI}{dt}$ and I_o is -ve.

- ↳ So output voltage V_o is always +ve but average load current may be +ve or -ve
- ↳ So power flow each from source to load when CH-1 is operated. (First quadrant operation)
power flows from load to source when CH-2 is operated. (2nd quadrant operation)
- ↳ This type of chopper is used for motoring and Regenerative braking of D.C. Motor.

Type-D :-



- ↳ when both CH-1 and CH-2 are ON $V_o = V_s$ and i_o is +ve.
- ↳ when both choppers are off diodes D_1 and D_2 conduct. So $V_o = -V_s$ and i_o is +ve.
- ↳ Average output voltage V_o is +ve when chopper turn on time T_{on} is more than Chopper off time T_{off}

→ Average value of output voltage V_o ,

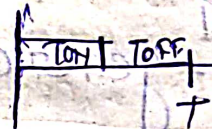
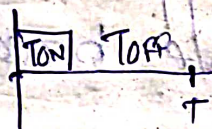
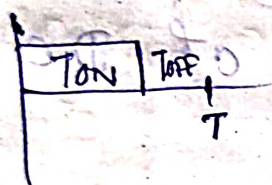
$$V_o = \frac{V_s T_{on} - V_s T_{off}}{T}$$

When,

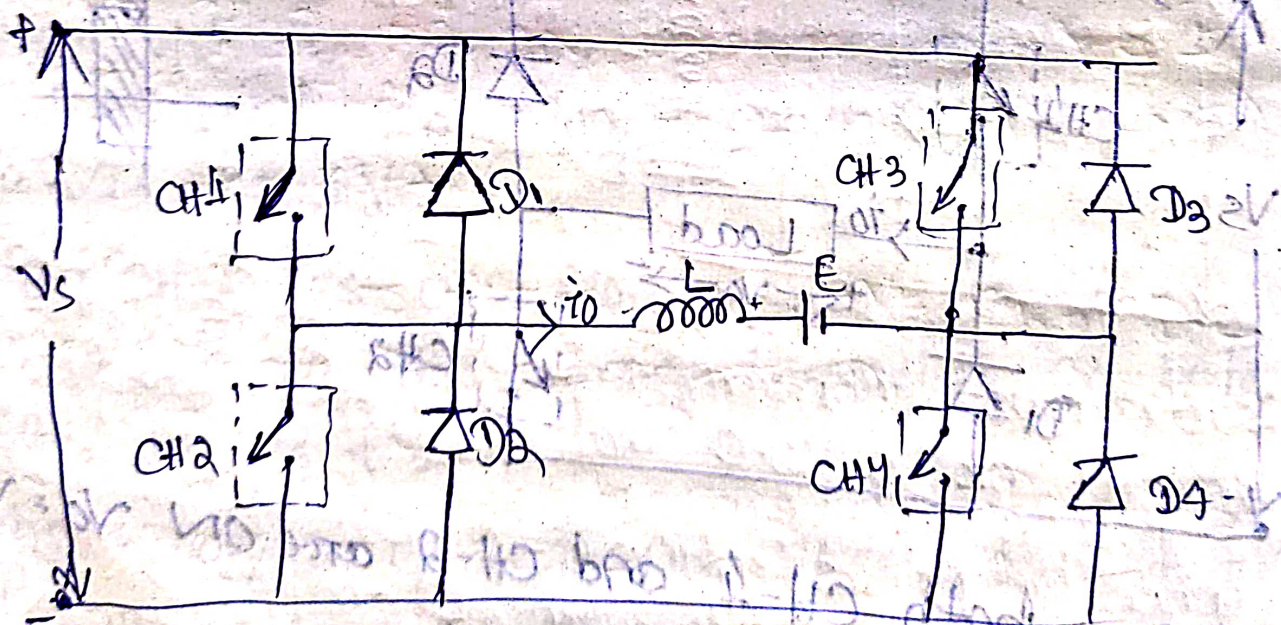
$$T_{on} > T_{off} \text{ or } d > 0.5 \quad (V_o = +V_e)$$

$$T_{on} < T_{off} \text{ or } d < 0.5 \quad (V_o = -V_e)$$

$$T_{on} = T_{off} \text{ or } d = 0.5 \quad (V_o = 0)$$



Type-E Chopper : —



→ It consists of four switches CH-1 to CH-4 and four diodes D_1 to D_4 in anti parallel connection.

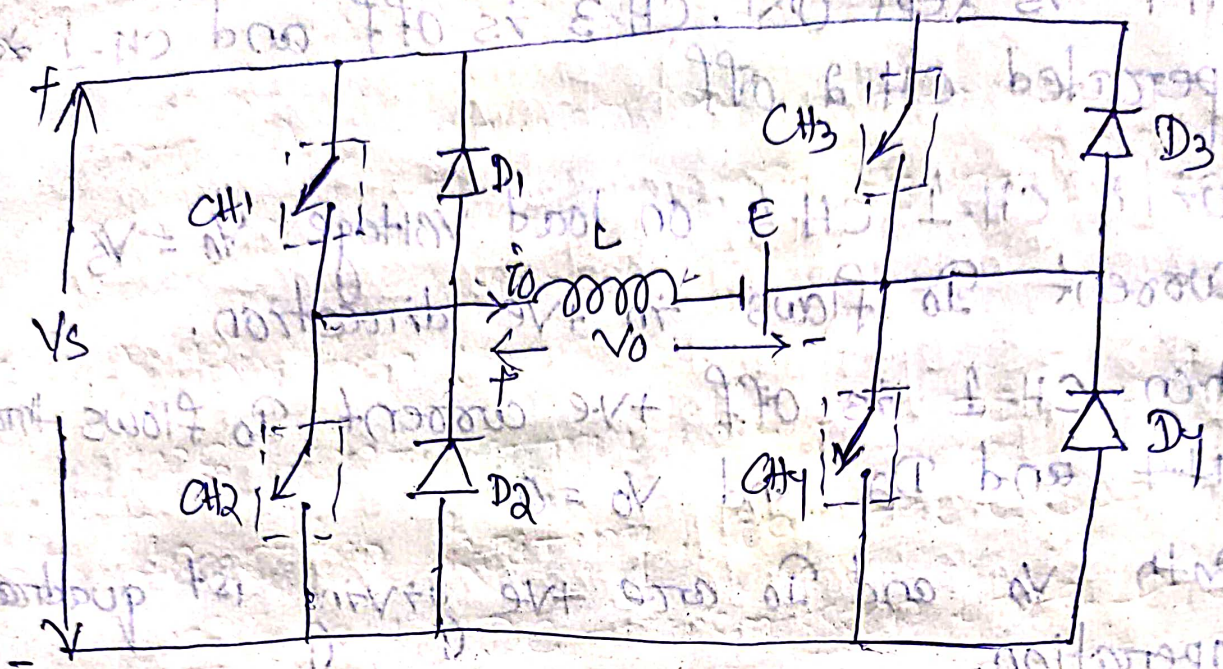
First quadrant operation:

- CH4 is kept ON, CH-3 is off and CH-1 is operated CH-2 off.
- with CH-1, CH-4 on load voltage $V_o = V_s$ current I_o flows in +ve direction.
- when CH-1 is off +ve current I_o flows through CH-4 and D_4 and $V_o = 0$
- Both V_o and I_o are +ve giving 1st quadrant operation.

Second quadrant operation:

- CH2 is operated and CH-1, CH-3, CH-4 are off.
- with CH2 ON - a -ve current flows through L, CH-2, D_4 and E. Inductor stores energy during this time.
- when CH2 is off, current is +ve is fed back to source through D_1 and D_4
- During this period load voltage $V_o = (E + L \frac{di}{dt})$ is more than V_s .
- load voltage V_o is +ve and I_o is -ve giving 2nd quadrant operation of chopper.

3rd quadrant operation :-



→ CH-1 and CH-4 is kept OFF. CH-2 is kept ON and CH-3 is operated.

→ when CH-3 is ON load gets connected to source so that V_o is -ve ($V_o = -V_s$) and I_o is -ve.

→ when CH-3 is turned off -ve current flows through CH-2 and D_1 .

→ So, V_o and I_o both are -ve giving 3rd quadrant operation.

4th quadrant operation :-

→ CH-4 is operated and all other switches are off.

→ when CH-4 ON +ve current flows through CH-4, D_2 , L and E. Inductor stores energy during this time.

- when CH. 4 is off current is fed back to source through D_3 and D_2
- Hence load voltage is -ve and load current is +ve giving 4th quadrant operation.

Chopper Source Filter :-

- A disadvantage of DC to DC chopper is that the DC supply current is pulsating because of the chopping operation
- So the supply current has harmonics that will produce undesirable effects such as source voltage fluctuation, signal interference, supply distortion etc.
- In order to overcome such problems a filter is used between the source and the chopper.

