Prity

Unit 1 Power Semiconductor Devices

* Introduction

→ Power Electronics is a combination of electrical power and semiconductor switches.

→ It convert and control and conditioning the flow of electrical power (energy) using switches that switches are power semiconductor devices.
Example - Diode, BJT, MOSFET, IGBT (insulated gate Bipolar transistor), *SCR (Silicon controlled Rectifier) (Thyrister) TRIAC, DIAC.

→ The word Power Electronics combines three terms namely Power, Electronics and control

* **Power** - It relates with the generation, transmission and distribution of electrical power.

* **Electronics** - It deals with solid state devices or semiconductor devices and circuits.

* **Control** - It deals with the steady state and dynamic characteristics of a closed loop control system.

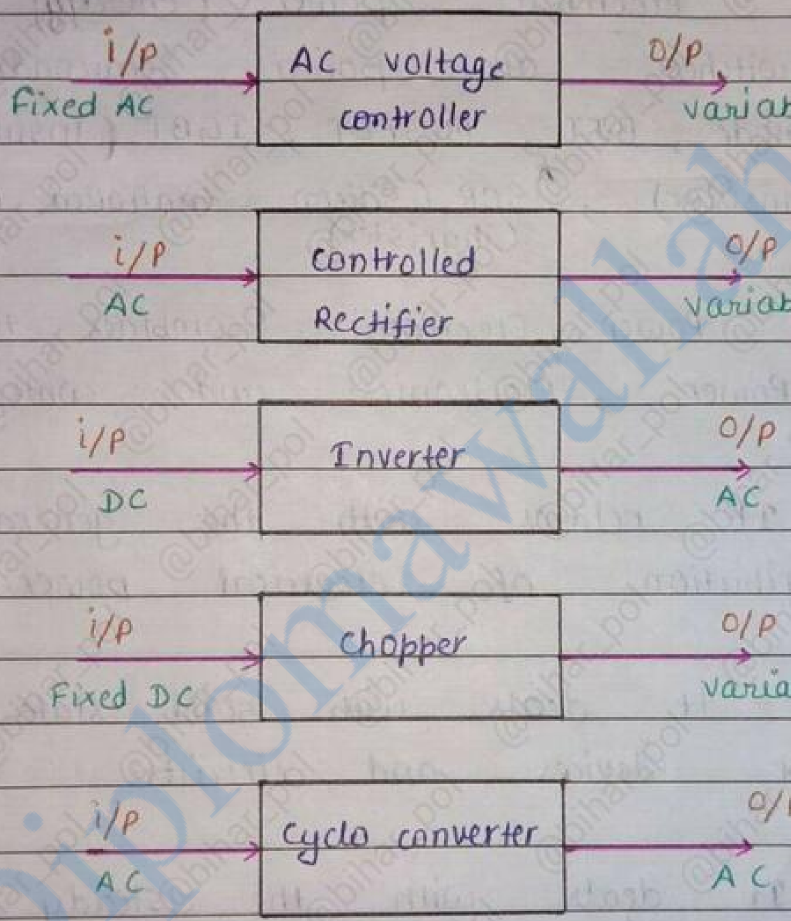
★ Power electronics is based on the principle of switching of the power semiconductor devices.

→ Semiconductor devices related very low power level of the order of few watt or milli watt.

→ *Power semiconductor devices relateos at high power level, power handling capacity and speed of switching are two most important criteria related to power devices.

→ A consumer need electric power according to their requirement. This requirement vary from time to time and consumer to consumer.

Example - AC to AC, AC to DC, DC to AC, Fixed DC to variable DC etc.



$$f_{input} \neq f_{output}$$

Application of Power Electronics

1. Battery charging system
2. Electric Drive control
3. Speed control of AC and DC motor
4. Power supply in Aircraft (Standby or emergency)
5. SMPS - Switch mode Power Supply

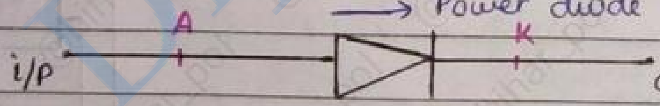
6. UPS - Uninterrupted Power Supply
7. HVDC → controlled converter - sending end.
→ Inverter (Receiving end)
8. AC & DC CB
9. Blower and fans.

NOTE:-

→ The device should be either fully ON or fully OFF operation as a switch will reduce the power dissipation in this switches.
→ Now, ACR rating is 10 KV and RMS current rating of 3000 Amphers and power handling capacity is about to 30 MV.
→ very low resistance in forward conduction and very high resistance in reverse conduction that means its on/OFF condition

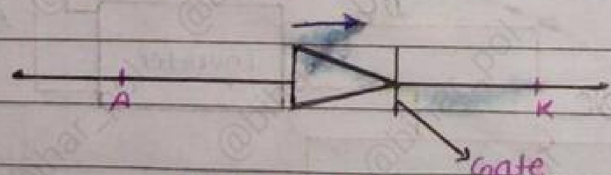
Sparking, $P_{Loss}\uparrow$

Mechanical switch

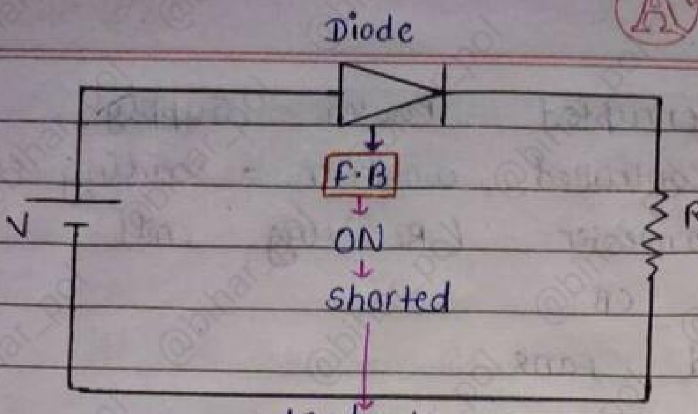


Diode → ON → F.B
→ OFF → R.B

Power Semiconductor Device



Switch → DC switch
→ either fully ON
→ completely OFF



Load to source connected

$$I = V/R = \text{Finite}$$

R·B Mode → OFF

ideal → $I = 0$

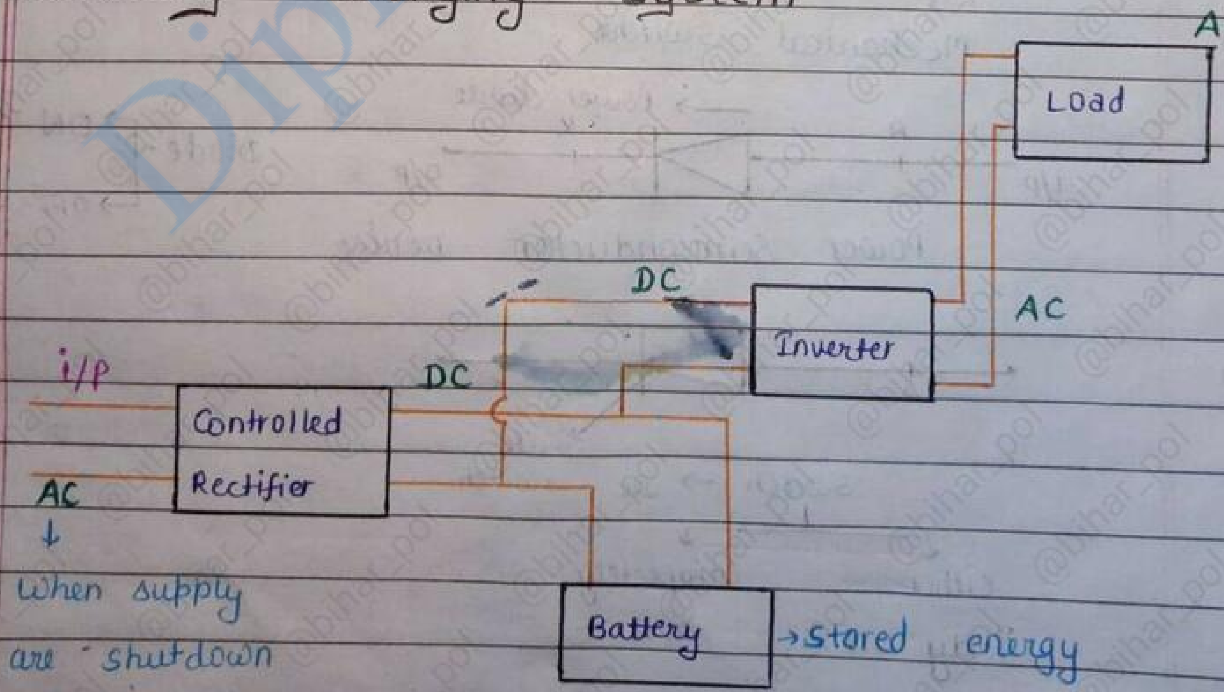
Load to source disconnected

→ Open circuit

$$I = \frac{V}{R}$$

$$R = \frac{V}{I} = \frac{V}{0} = \infty$$

- Battery charging System



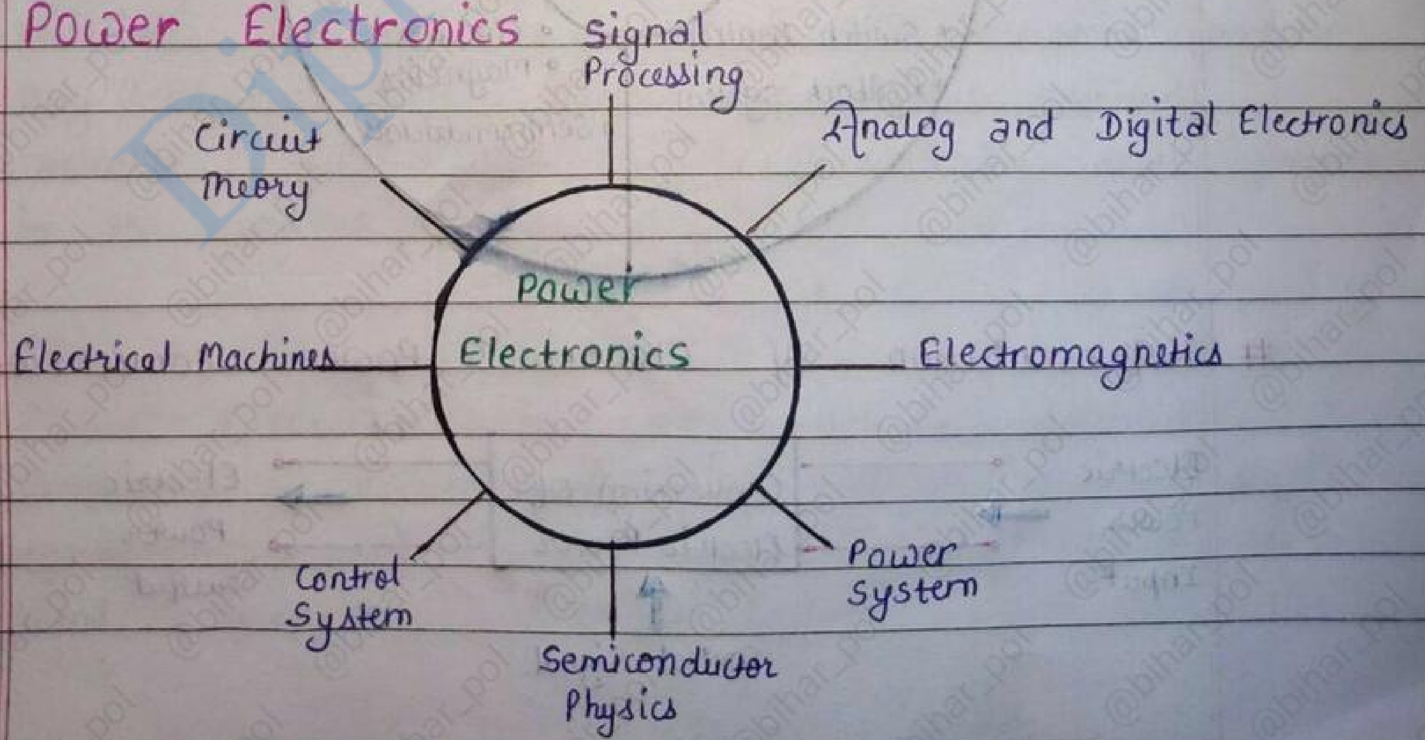
General Requirement of Power Devices

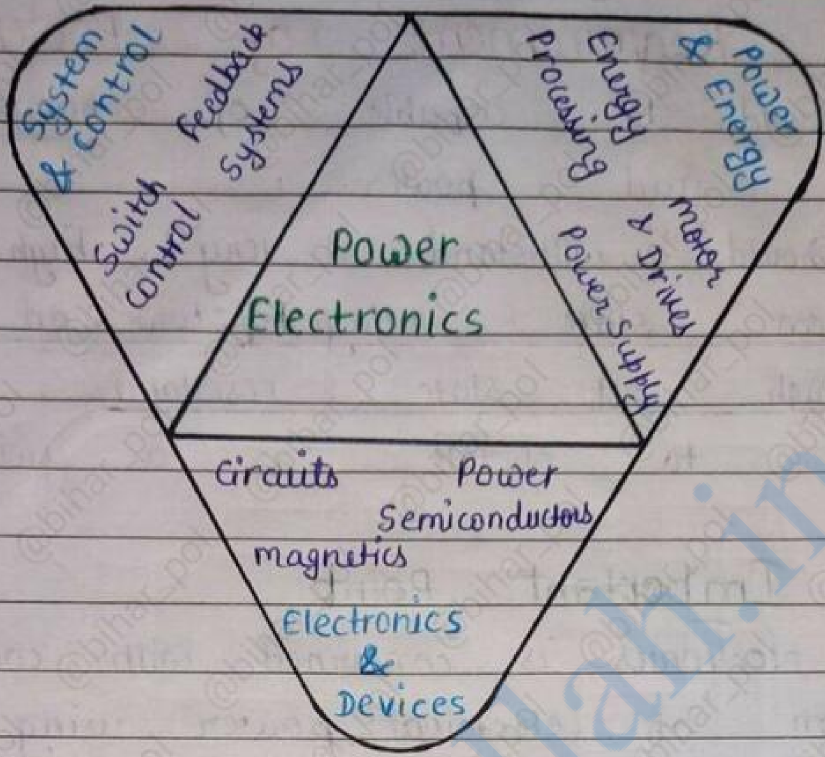
- → This should be capable of handling large current and power.
- → They should withstand very high voltage.
- Imp obj → ★ Low on state voltage drop; low on state resistance very high off state resistance.
- → Capability to operate as a switch.

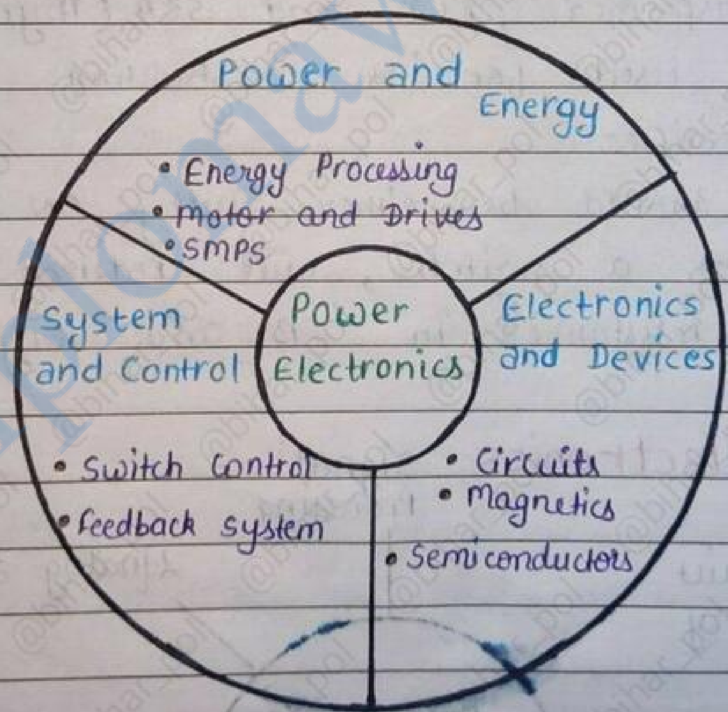
Some Important Point

- → Power electronics is concerned with controlled and conversion of electrical power using electronics devices.
- → Power electronics circuit uses semiconductor devices like diode, Transformer, FET and SCR (Thyristor).
- → Silicon is used for its construction and its operation as on rectifier.
- → The device should be either fully ON or fully OFF operation as a switch, will reduced power dissipation.
- → Very low resistance in FB and very high in RB.

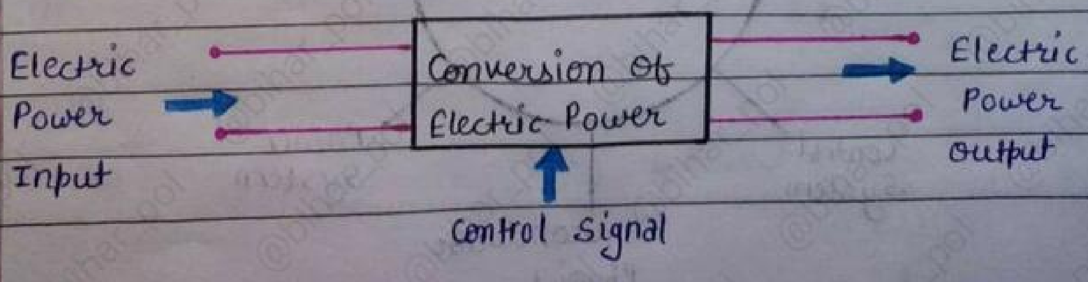
* Power Electronics







Representation of Electric Power conversion

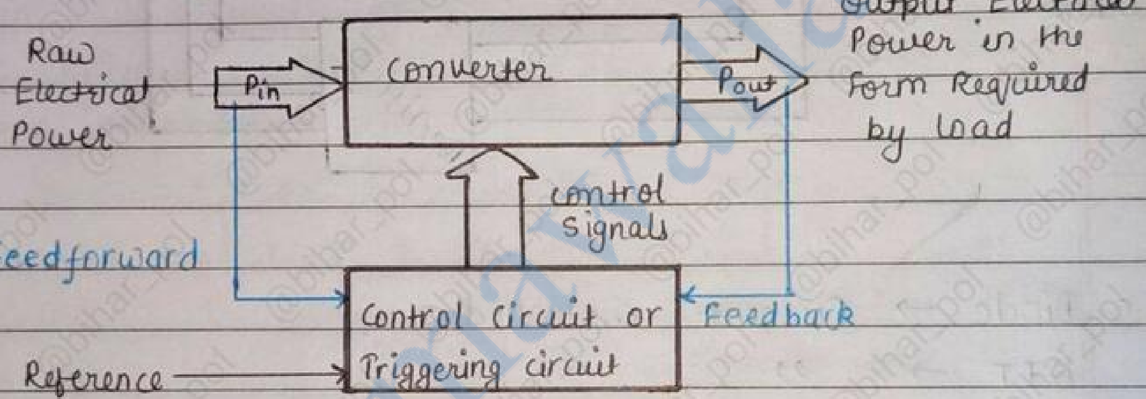


• Power Diode

→ Power semiconductor diode is the "Power level" counter part of the "low power signal diodes".

→ The symbol of the power diode is same as signal level diode. However, the construction and packaging is different.

* Block Diagram of a Power Processor



→ Converter has power switching semiconductor devices and energy storing elements like inductors and capacitors.

→ Resistive elements are avoided in converters because they cause power loss and reduce efficiency.

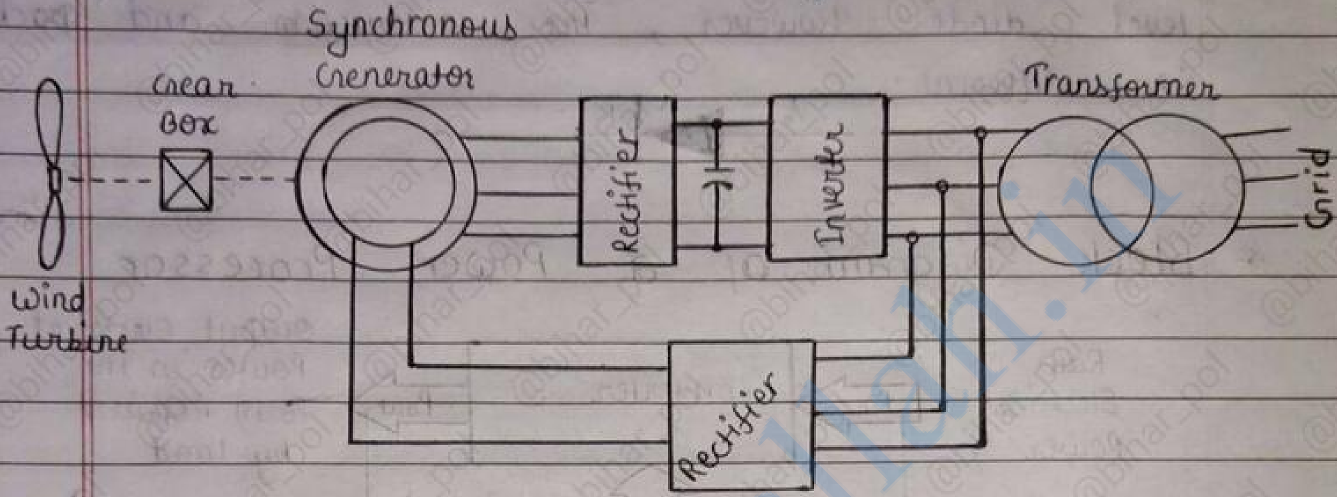
→ controller switches on/off the switching devices present in the converter.

* ~~Block~~

* Power Electronics in Wind Energy Systems

→ Frequency and magnitude of voltage generated by synchronous generator varies due to changes in wind speed.

→ The grid supply is rectified to supply D.C to the field coils on the rotor of the alternator.
→ The inverter produces A.C from D.C link voltage and feeds to the grid through a step-up transformer.



Diode → Current controlled
BJT → ,,
MOSFET → voltage
FET → ,,
UJT → ,,
OP-Amp → Voltage controlled device
SCR → current
Thyristor → Current controlled device
IGBT → voltage controlled device
Oscillator → ,,
JFET → ,,
Amplifier → ,,
Transistor → current controlled device

* P-Type Semiconductor

→ Trivalent impurities are added to Si or Ge to create a deficiency of electrons or holes charges.
→ The holes created by doping process.
→ The no. of holes can be controlled by the no. of trivalent impurity atoms.
→ The trivalent atom can take an electron-acceptor atom.
→ Current carries in p-type are holes – majority carries. electrons – minority carries.

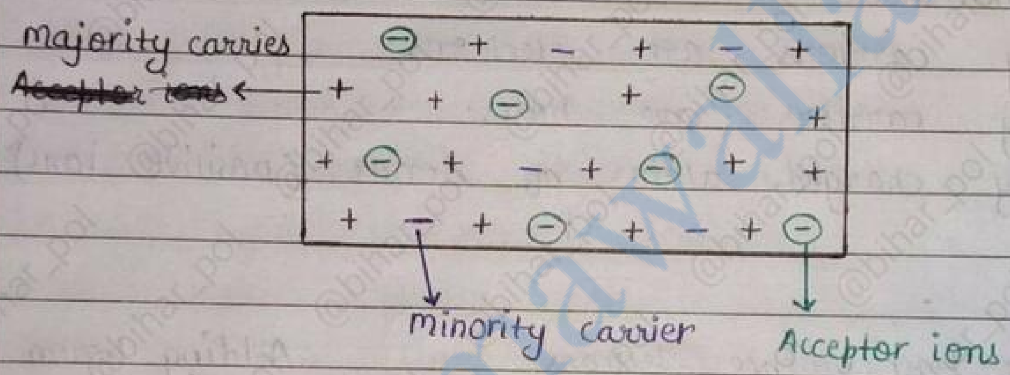


Fig :- P-type

→ Majority carriers are holes.
→ minority carriers are electrons
→ Negatively - charged atoms of acceptor (negative ions).

* N-Type Semiconductor

→ Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the centre. The extra electron from the Sb atom becomes a free electron.
→ It is made by adding an impurity to a pure semi-conductor such as silicon or germanium. The impurities used may be phosphorous, arsenic, antimony, bismuth or some other chemical element.

→ They are called donor impurities.
The impurity is called a donor because it gives a free electron to a semiconductor.

~~The purpose~~

→ When a small amount of Pentavalent impurity is added to a pure semiconductor providing a large number of free electrons in it, the extrinsic semiconductor thus formed is known as n-Type semiconductor.

→ Majority carriers are electrons.

→ Minority carriers are holes.

→ Positively charged atoms of donor (positive ions).

- Si

Silicon :- Four valence electrons

B

Boron :- Three valence electrons

⇒ Adding boron to pure silicon crystal results in lack of an electron. And it becomes a hole.

Thyristor

Thyristor Family

* SCR – Silicon controlled Rectifier
* GTO – Gate turn off SCR
* RCT – Reverse conducting SCR
* SITH – Static Induction Thyristor
* GATT – Gate Associated turn off SCR
* LASCR – Light activated SCR
* TRIAC – Bidirectional Triode Thyristor
* DIAC – Bidirectional Diode Thyristor
* LASCS – Light Activated SCS
* LAS – Light activated switch
* SUS – Silicon Unilateral Switch
* SBS – Silicon Bilateral Switch
* SCS – Silicon controlled switch

* SCR (Silicon Controlled Rectifier)

→ SCR is a synonym of Thyristor.

• Introduction

The silicon controlled rectifier (SCR) which is a power electronic device is unquestionable of the greatest intrest today. It was first introduced in 1956 by Bell Telephone laboratories. It can convert alternating current into direct current and at the same time can control the amount of power fed to the load. Thus it combines the features of a rectifier and

SCR

→ In off state, it has a very high resistance.

→ In on state, there is a small on (forward) resistance.

a transistor.

→ It is a three terminal four layer semi-conductor device.

→ Its three terminal is Anode, Cathode and Gate.

→ Its four layer is P-N-P-N.

→ Its three junctions are J_1, J_2 and J_3.

→ G - Controlling Terminal (Only turn ON the SCR)

A, K - Power Terminal

obj → * It is current or charge controlled device, semi-controlled device, unidirectional current flow device and bipolar (It blocks both +ve and -ve polarity).

→ The width of the junction is * 50 μm to 100 μm.

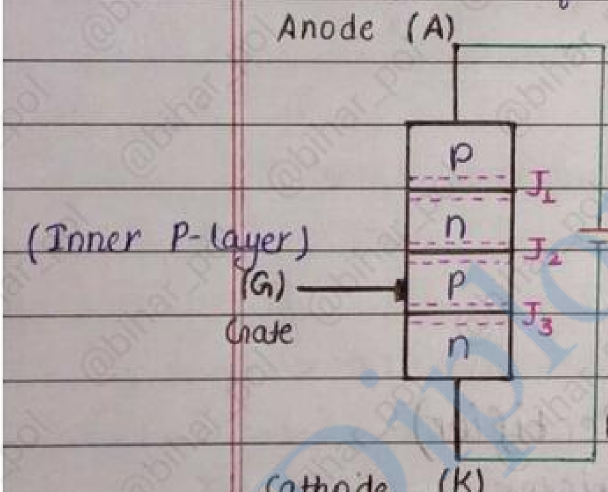


Fig:- Basic construction

Fig:- Schematic Symbol

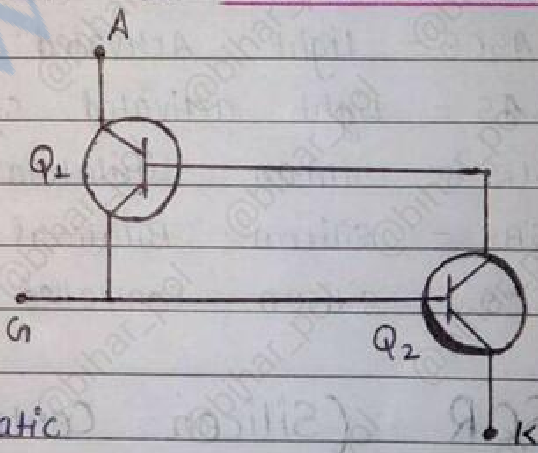


Fig:- Equivalent Circuit

- Anode → (A) → +ve
- Cathode → (C) → -ve

- Applications

→ Motor controls, Time-delay circuits, heaters controls, phase controls etc.

→ ~~SCR has~~

• Working of SCR

The working of SCR can be discussed in three modes:-

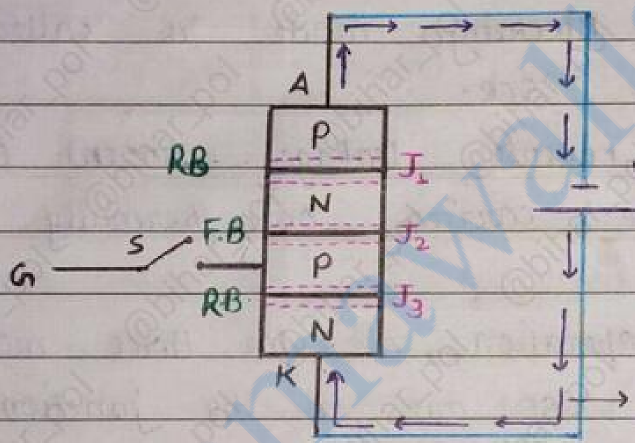
1. RBM (Reverse Blocking mode) → OFF → Open → switch
2. FBM (Forward Blocking mode) → OFF → open → switch
3. F.C.M (Forward conduction mode) → ON → closed → switch

1. Reverse Blocking Mode

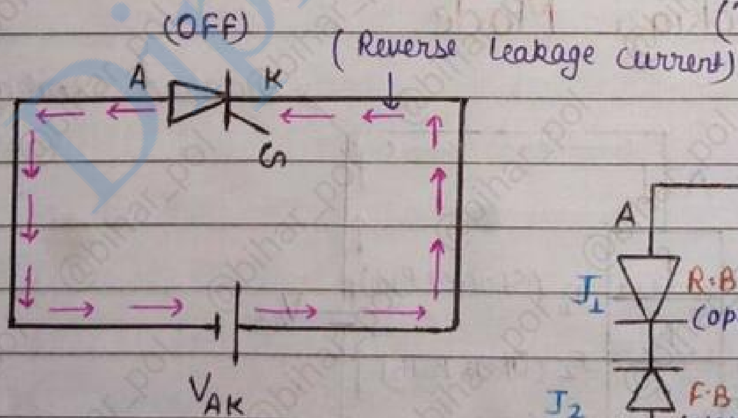
Anode (A) → -ve

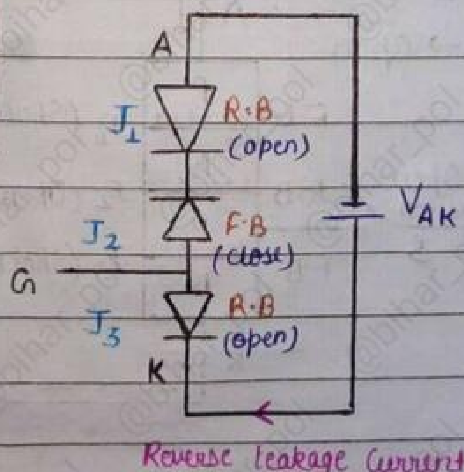
Cathode (K) → +ve

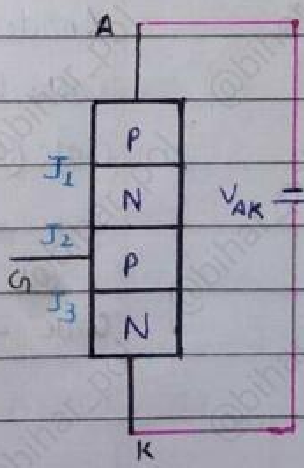
Gate (G) → open

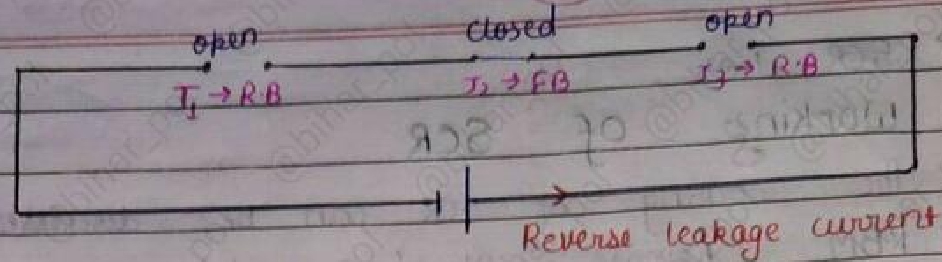


→ Reverse leakage current
↓
Due to minority charge carrier
(Thermally generated electron)









→ When cathode is made +ve w.r.t anode and switch S is open or gate circuit is open.

→ Junctions J_1 and J_3 are seen to be R.B where Junction J_2 is F.B.

→ A small leakage current of the order of few milli amps or micro amps depending upon the SCR rating flow in the circuit.

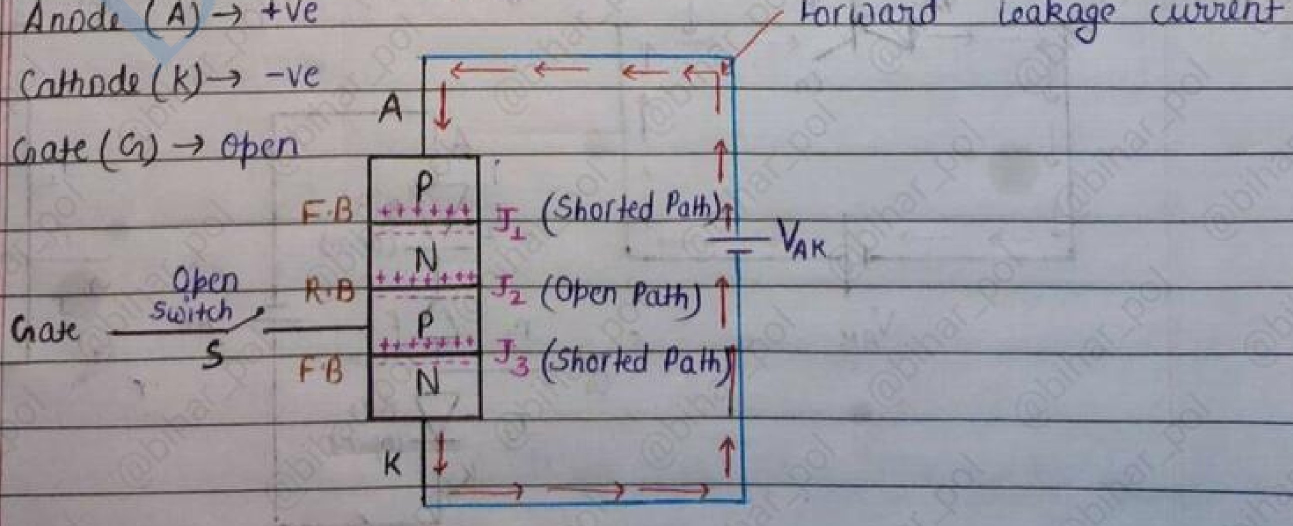
→ The Reverse Blocking mode is called the OFF state of the SCR.

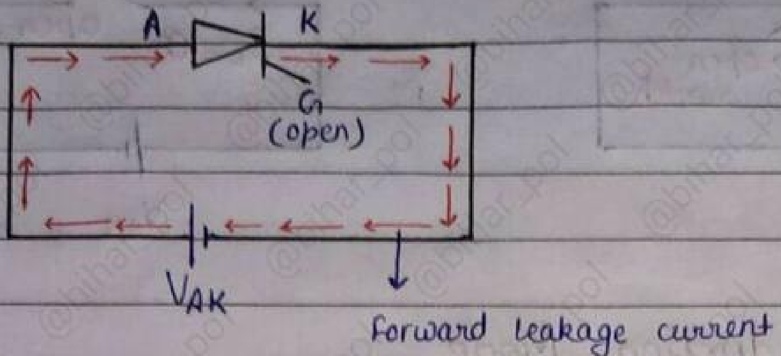
obj → Here, ★ V.V.I. small reverse leakage current flows due to minority charge carrier or thermally generated electrons.

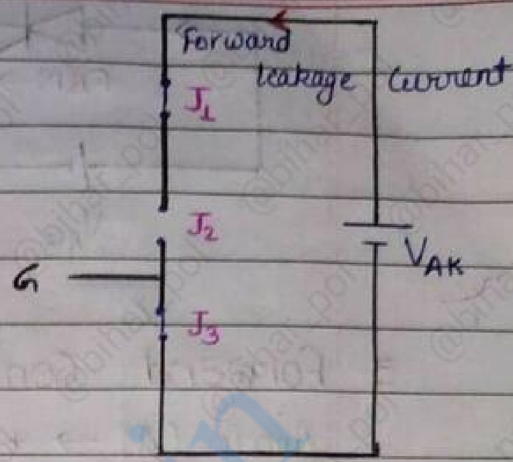
→ For proper operation, all the three modes are in forward biased or one of the junction is in breakdown condition.

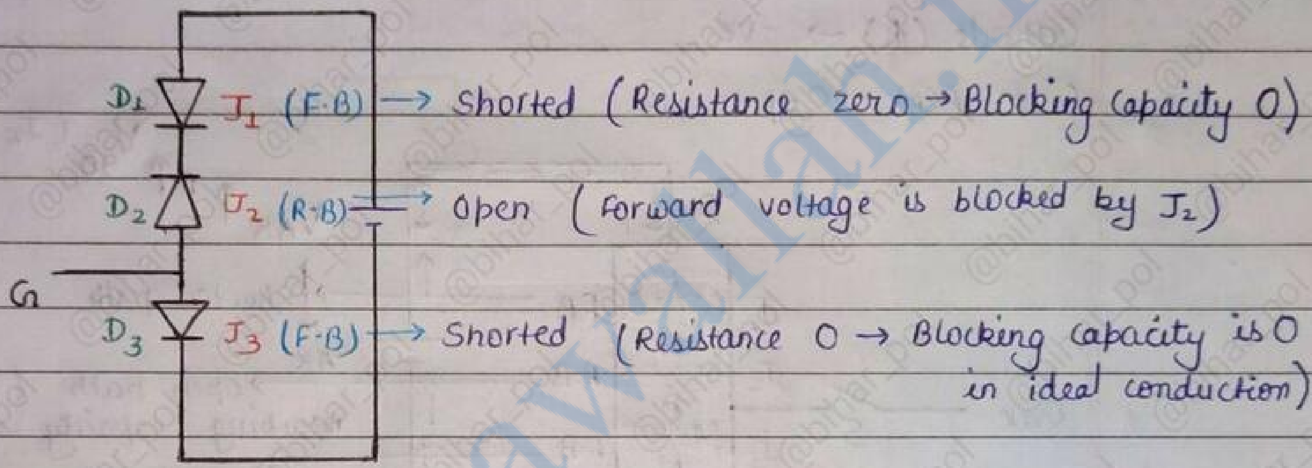
2. Forward Blocking Mode

Anode (A) → +ve
Cathode (K) → -ve
Gate (G) → open









→ When anode terminal is connected with +ve terminal of the supply and cathode is connected with -ve terminal of the supply with gate supply zero, then the mode is called forward blocking mode.

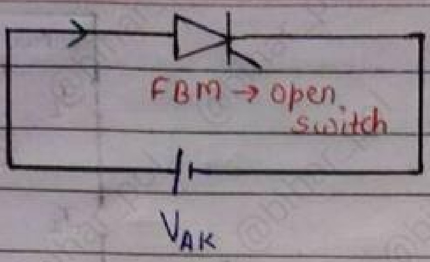
→ The junctions J_1 and J_3 are forward biased but the junction J_2 is reverse biased.

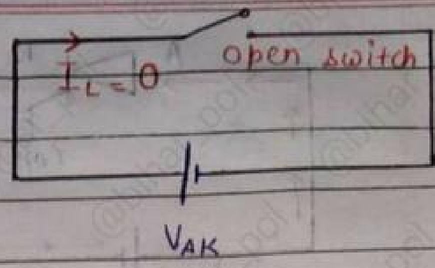
→ Junctions J_1 and J_3 break due to forward V_{AK} voltage, but junction J_2 doesn't break because it is in R.B mode. So, the SCR doesn't come in conduction mode.

→ A very small leakage current flows at J_2 junction, it is called forward leakage current.

→ In a forward blocking mode, SCR is treated as open switch.

Forward leakage current



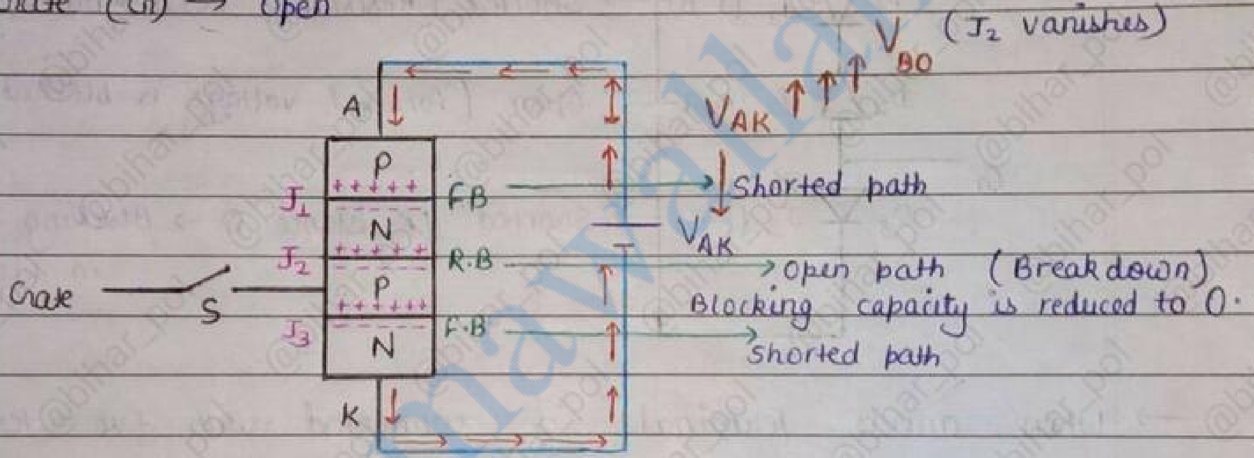


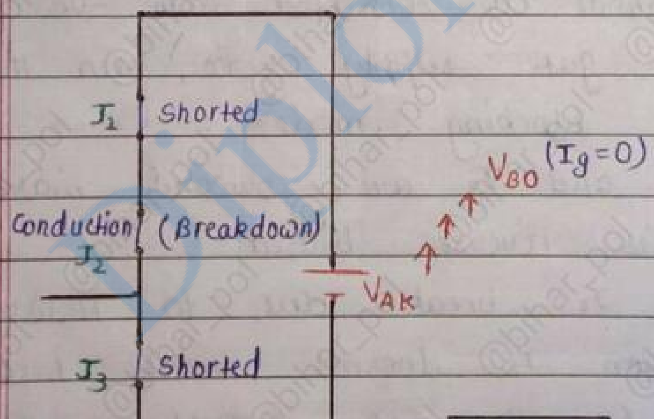
3. Forward Conduction Mode

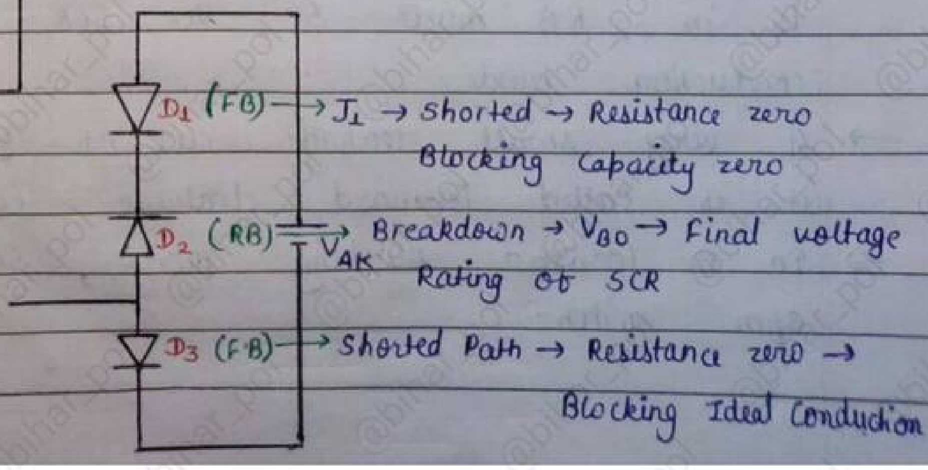
Anode (A) → +ve

Cathode (K) → -ve

Gate (G) → open

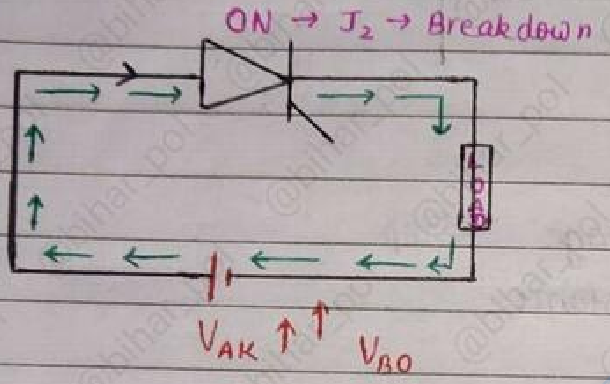


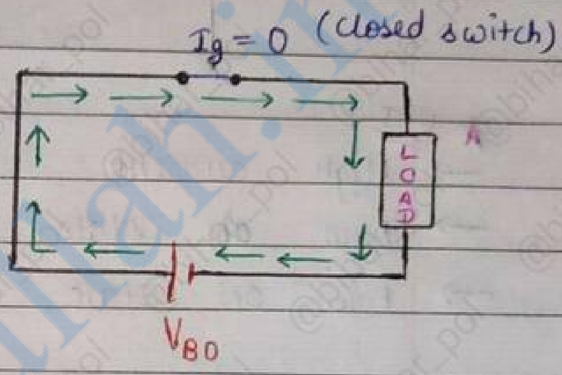




→ When anode to cathode forward voltage is increased with gate circuit is open ($I_G = 0$), a reverse biased junction 'J_2' is vanished and the voltage called Forward Breakover voltage (V_{BO}). after that, thyristor (SCR) turned ON.

→ In forward conduction mode, thyristor is treated as closed switch.





SCR as a Switch

→ The SCR has only two states of operation i.e, it can be either fully ON or completely.

→ There is no active region of operation like transistor. Therefore, it is equivalent to a switch.

→ As it cannot operate in the active region, it cannot be used as an amplifier.

BJT	SCR
Active → amp	RBM → open
Saturation → switch	FBM → open
Cut-off → open	FCM → closed

obj ★ V_{BO} is the final forward voltage rating of the SCR.

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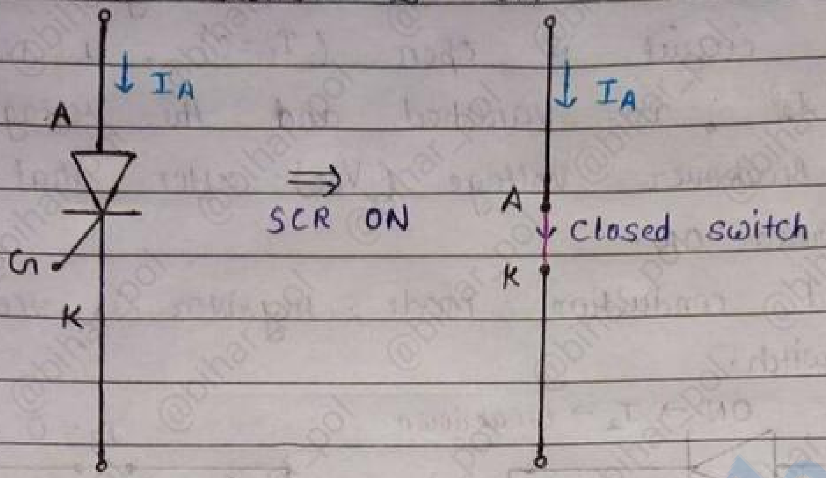
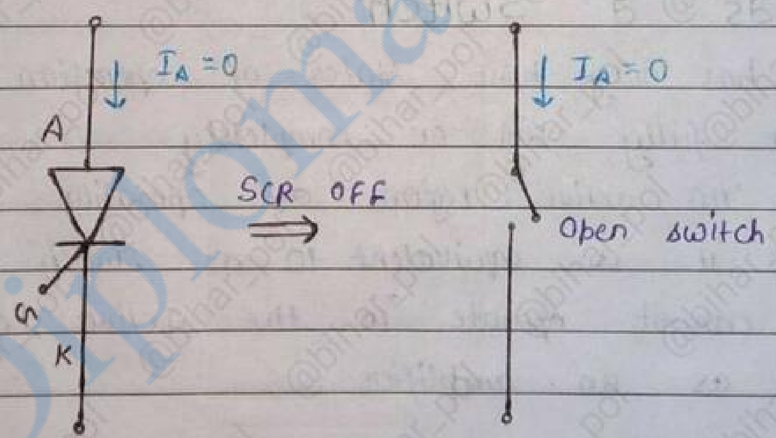
- When SCR switch is ON.



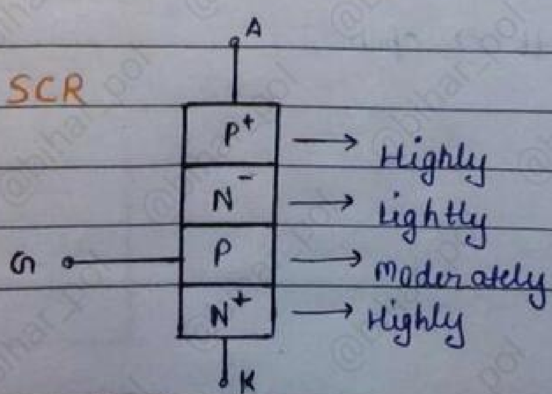
★ V.I
→ High current
→ Low ON state voltage drop
→ Low ON state resistance.

- When SCR switch is OFF.

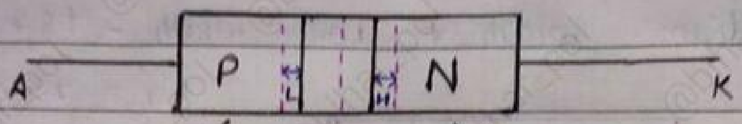


★ V.V.I
→ Zero current
→ High OFF state voltage drop.
→ High OFF state resistance.

* Doping level of SCR



$P^+ \rightarrow$ highly dropped $\rightarrow 10^{19}/cm^3$
$N^- \rightarrow$ lightly dropped $\rightarrow 10^{14}/cm^3$
$P \rightarrow$ moderately dropped $\rightarrow 10^{17}/cm^3$
$N^+ \rightarrow$ Highly dropped $\rightarrow 10^{19}/cm^3$



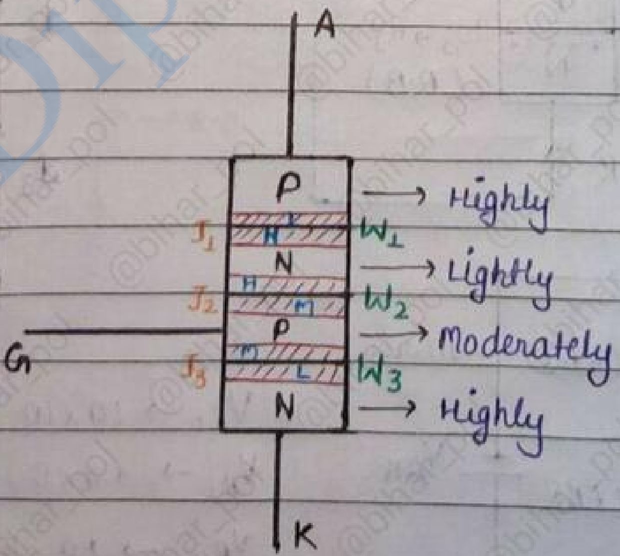
Highly dopped $\downarrow$ less involved in making depletion width (L → Low)

Lightly doped $\downarrow$ More involved in making depletion width (H → High)

* Width ∝ its resistance Value

$$\text{Doping} \propto \frac{1}{\text{Depletion width}}$$

L → Lightly dopped → Low
H → Highly dopped → High
M → moderately dopped → Medium



W_1 = ~~Low~~ width + High width

L = 5m H = 10m M = 8m

ω_1 = Low width + High width = 5m + 10m

ω_1 = 15 m ↑

ω_2 = High width + Medium width = (10 + 8) m

ω_2 = 18 m ↑

ω_3 = Medium width + Low width = (8 + 5) m

ω_3 = 13 m ↑

$$\omega_2 > \omega_1 > \omega_3$$

$$R_2 > R_1 > R_3$$

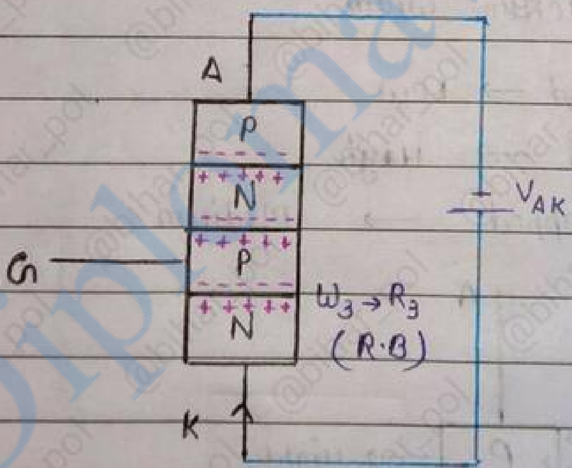
more width, more voltage blocking capacity

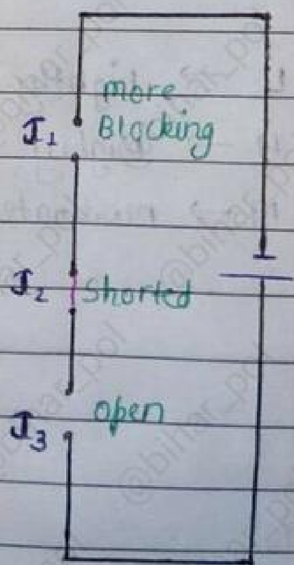
- RBM

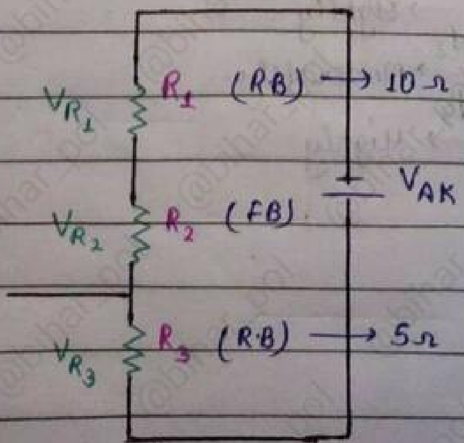
A → -ve

K → +ve

G → open







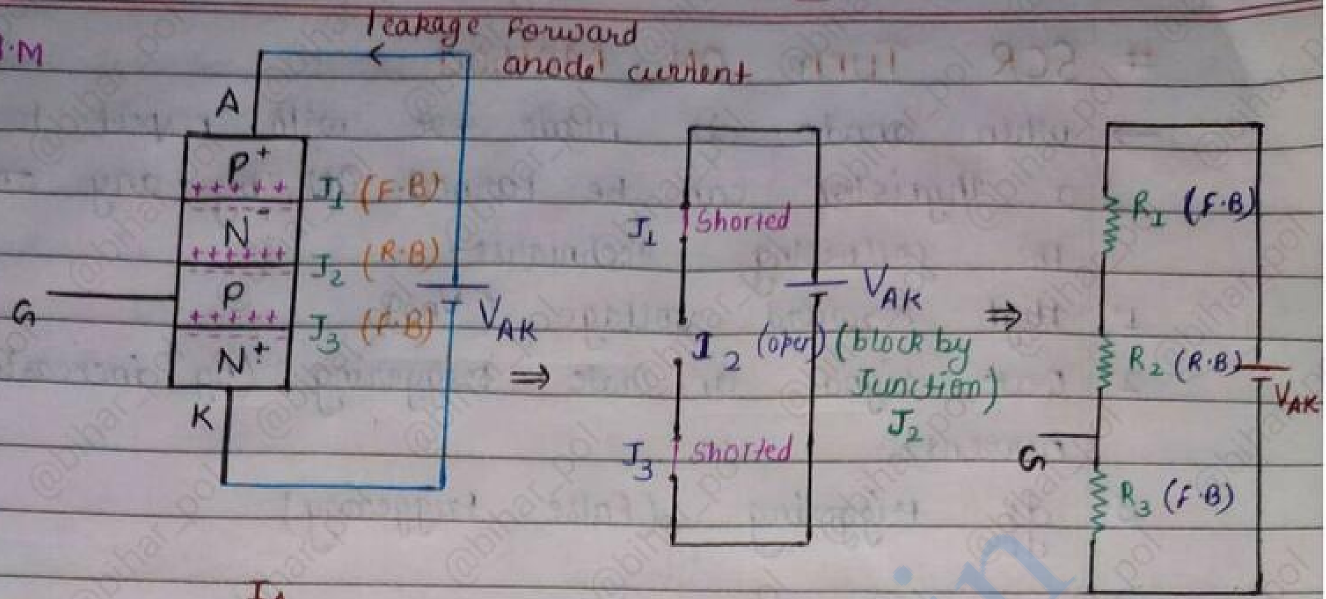
$V_{R_1} \rightarrow 10 \times 10 = 100V$

$V_{R_2} \rightarrow 10 \times 0 = 0V$

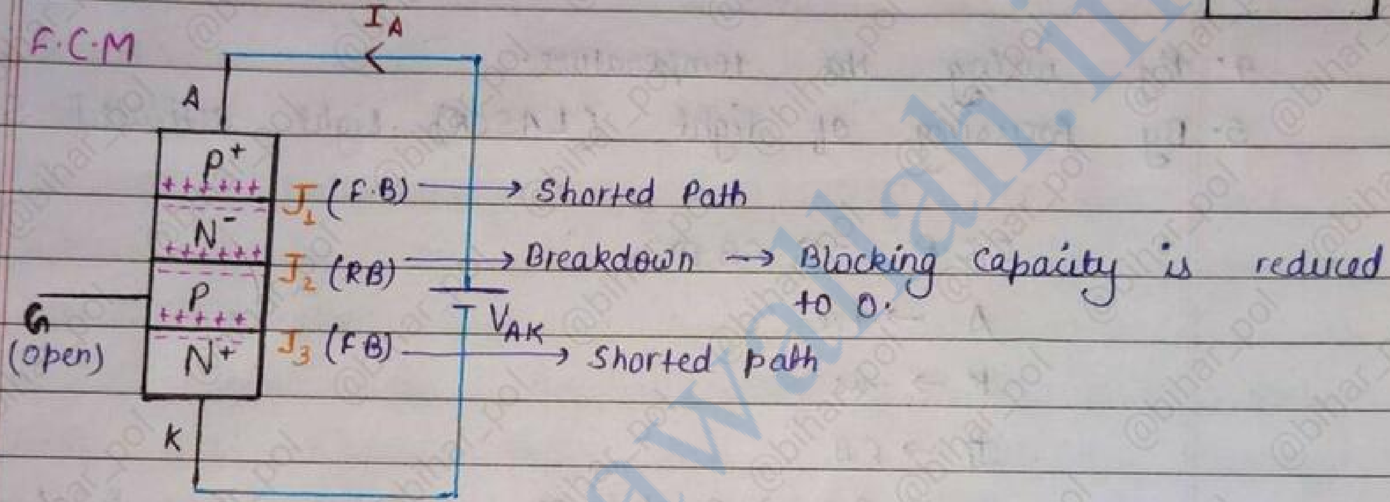
$V_{R_3} \rightarrow 10 \times 5 = 10V$

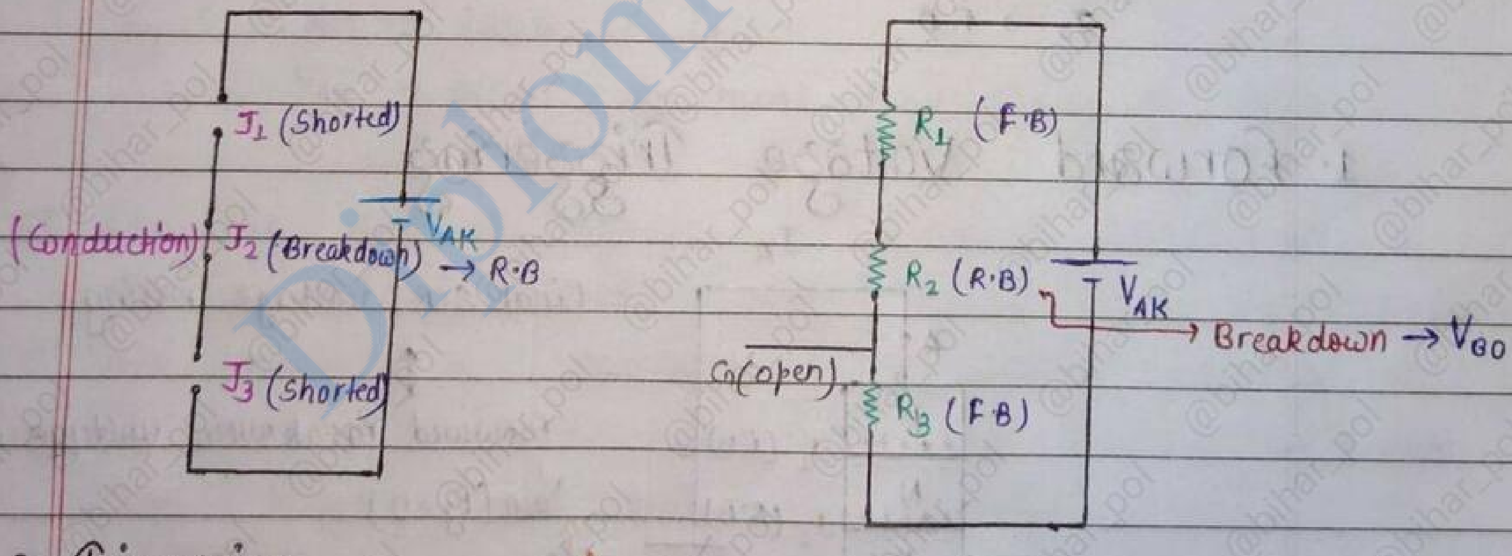
$V_{R_1} > V_{R_2}$

- F.B.M



- F.C.M





- Triggering

→ The turning on process of the SCR is known as triggering.

→ In other words, turning the SCR from forward-Blocking state to forward-conduction state is known as triggering.

SCR Turn ON - Method

→ when anode is made +ve with respect to cathode a Thyristor can be turned ON by any one of the following technique:

1. High forward voltage (V_{BO})
2. Gate signal or Gate triggering (By increasing gate current).
3. $\frac{dv}{dt}$ triggering (False triggering)
4. By rising the temperature.
5. By focusing of light (LASCR) Light activated SCR.

S.C.R → F.B.M

A → +ve

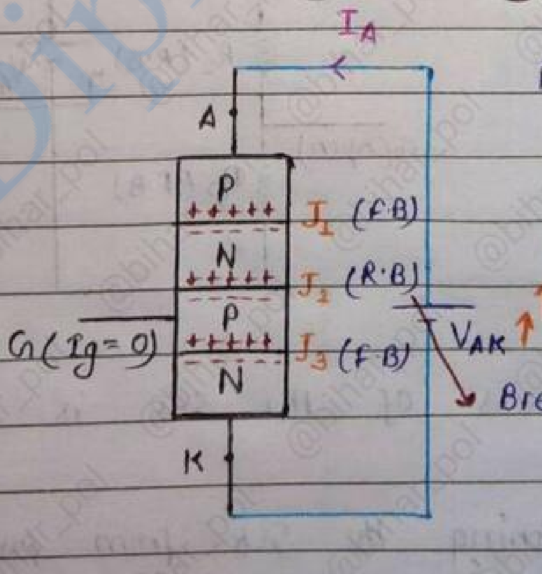
K → -ve

J_1 → F.B

J_2 → R.B → Breakdown condition (conductive)

J_3 → F.B

1. Forward Voltage Triggering



Final SCR voltage rating

↑

Forward Breakover voltage

V_{BO} (I_g = 0)

Breakdown (V_{BO}) ← Excess heating device can be damaged conductive

↓

Blocking capacity is reduced to minimum (zero)

→ When forward voltage is applied between anode and cathode with gate circuit is open.

→ The Juntion 'J₂' is in Reverse bias and Depletion layer is formed across junction 'J₂'.

→ With increase in anode to cathode voltage (V_{AK} ↑↑↑ V_{BO}) the width of the layer (Junction J_2) is decreases and a stage comes when the depletion layer across J_2 junction vanishes.

→ At the voltage when J_2 is vanished is called forward breakover voltage (V_{BO}) and this voltage are temp. dependent.

→ Forward breakover voltage is taken as the final voltage rating of the device during the design of SCR application.

→ A thyristor with forward ~~breakdown~~ breakover voltage 800v is higher than the normal working voltage 400v.

$V_{BO} \rightarrow 800\,V \rightarrow I_g = 0$

$V_{AK} \rightarrow 400\,V \rightarrow I_g$ must have some +ve value.

→ If the forward voltage is gradually increased a stage comes thyristor may destroy due to overheating.

→ This method is generally not prefered because the SCR may damaged due to high power dissipation when triggered at high voltage (V_{BO})

SCR Turn ON - Method

→ When anode is made +ve with respect to cathode a Thyristor can be turned ON by any one of the following technique.

1. High forward voltage (V_{BO})
2. Gate signal or Gate triggering (By increasing gate current).
3. $\frac{dv}{dt}$ triggering (False triggering)
4. By rising the temperature.
5. By focusing of light (LASCR) Light activated SCR.

S.C.R → F.B.M

A → +ve

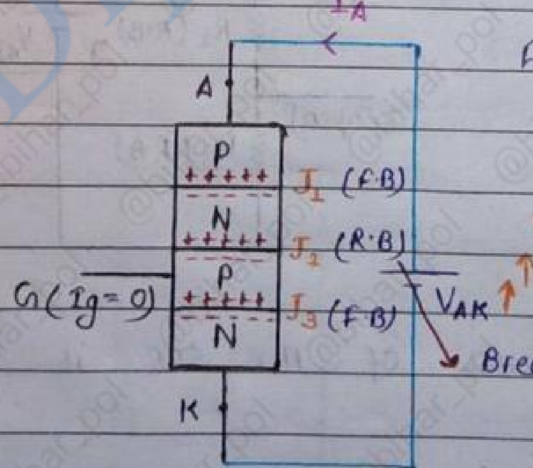
K → −ve

J_1 → F.B

J_2 → R.B → Breakdown condition (conductive)

J_3 → F.B

1. Forward Voltage Triggering



Final SCR voltage rating

↑

Forward Breakover voltage

V_{BO} (I_g = 0)

Breakdown (V_{BO}) ← Excess heating device can be damaged conductive

↓

Blocking capacity is reduced to minimum (zero)

→ When forward voltage is applied between anode and cathode with gate circuit is open.
→ The Juntion 'J_2' is in Reverse bias and Depletion layer is formed across junction 'J_2'.
→ With increase in anode to cathode voltage ($V_{AK}\uparrow\uparrow\uparrow V_{BO}$), the width of the layer (Junction J_2) is decreases and a stage comes when the depletion layer across J_2 junction vanishes.
→ At the voltage when J_2 is vanished is called forward breakover voltage (V_{BO}) and this voltage are temp. dependent.
→ Forward breakover voltage is taken as the final voltage rating of the device during the design of SCR application.
→ A thyristor with forward ~~breakdown~~ breakover voltage 800v is higher than the normal working voltage 400v.

$V_{BO} \rightarrow 800\text{ v} \rightarrow I_g = 0$

$V_{AK} \rightarrow 400\text{v} \rightarrow I_g$ must have some +ve value.

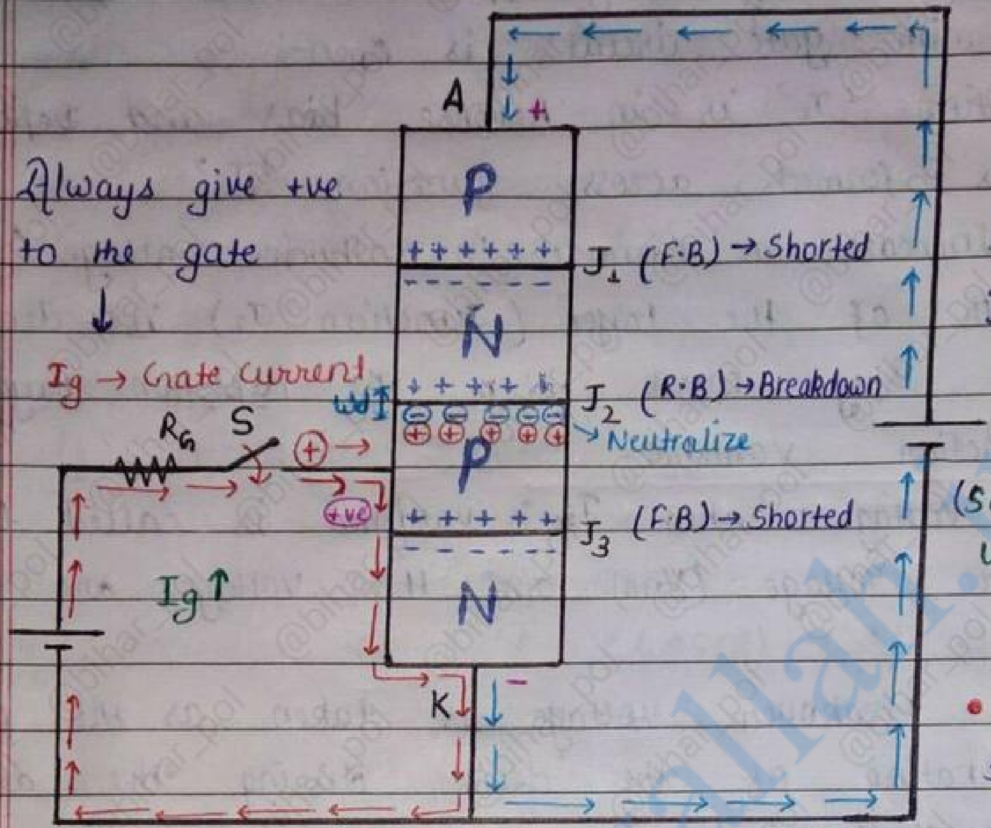
→ If the forward voltage is gradually increased a stage comes thyristor may destroy due to overheating.
→ This method is generally not prefered because the SCR may damaged due to high power dissipation when triggered at high voltage (V_{BO})

L-10

Imp. 2. Gate Triggering

★ → This is most widely used SCR triggering ~~used~~ method.
→ Turning ON of SCR by gate triggering is simple and reliable.

To keep away from unecessary power loss



- Condition 1
  - A → +ve
  - K → -ve
  - G → S → open
  - SCR Not comes in conduction at V_{AK}.
  - (SCR ON at very low voltage)

- Condition 2
  - S → closed

$I_g \uparrow\uparrow \quad V_{AK} \downarrow\downarrow$

* We can't increase voltage upto V_{BO} because it is voltage rating of SCR. So, we can't turn ON SCR on this voltage ~~we can do with decrease value of~~ we can turn ON at the value less than V_{BO}.

$I_g \uparrow$ → More charge → V_{AK}]
$I_g \downarrow$ → less charge → V_{AK}] →

SCR → half controlled ; charge controlled or current controlled

- Gate → involved to only to turn ON process of the SCR.

$V_{BO} = 800V$ → S → open → $I_g = 0$

$I_g \propto \frac{1}{\text{Breakdown voltage required to } J_2}$

→ A Thyristor with forward breakover voltage 800v is higher than normal working voltage 400v that means the SCR will remain in forward blocking state with normal working voltage across the anode and cathode with gate circuit is open.

→ In this mode anode is connected with positive terminal of the cell and cathode is connected with -ve terminal of the cell, Here +ve gate is used, In this case junction J_1 and J_3 are F.B mode and J_2 are in R.B mode.

→ A Positive gate supply is given at the inner part of the SCR, this +ve gate supply increases the speed of electron and makes the avalanche breakdown at junction J_2, after this breakdown SCR is turned ON and comes in conductive.

→ If the magnitude of gate current is increased more electron would reach junction J_2, so SCR gets turned ON at much lower forward applied voltage.

→ The gate terminal is injecting positive charge in the inner P-layer, then this ~~injecting~~ injected +ve charge will neutralize the -ve charge present the J_2 junction width will reduced hence it require less voltage to goes into breakdown condition.

→ Typical value of gate current magnitude are of the order of 20 to 200mA or directly proportional to the rating of the SCR.

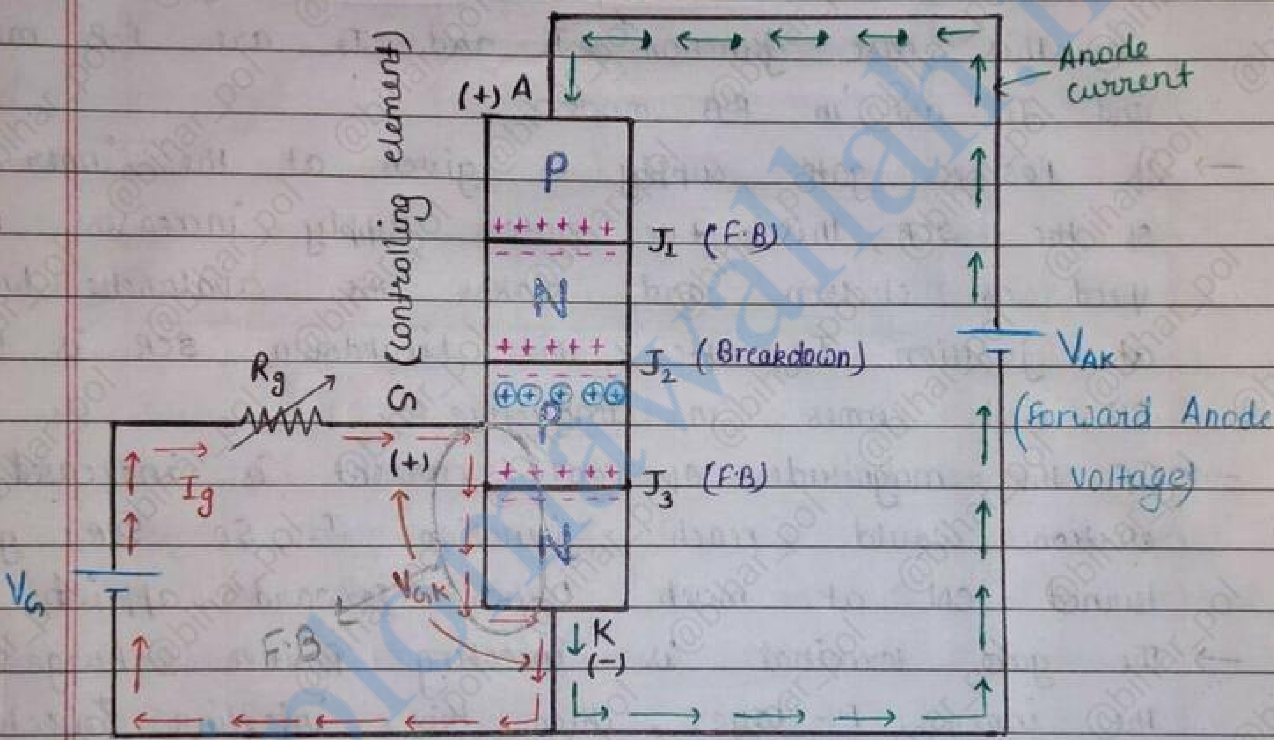
⇒ There are three types of signals are used for gate triggering.

(a) DC Gate Triggering (Continuous Gate Triggering)

(b) AC Gate Triggering

(c) Pulse Gate Triggering

(a) DC Gate Triggering



I^2R_g → Gate Power loss

A, K → Power terminal , G → controlling terminal.

→ A DC voltage of adequate magnitude and correct polarity is applied between the gate and cathode terminals.

→ So, that gate to cathode junction will always be forward biased and continuous gate current is allowed to flow.

★→ If the gate current is sufficiently high, then SCR will turn ON. Even after turning ON of the SCR, the gate current continues to flow.

→ The continuous gate current causes large gate power loss. There is no isolation between the gate circuit and anode circuit.

- Application of a d.c gate signal causes the flow of gate current which triggers the SCR.
- Disadvantage is that the gate signal has to be continuously applied resulting in power loss.
- Gate control circuit is also not isolated from the main power circuit.

Imp★

(b) Pulse Gate Triggering

→ The continuous DC operation increases the gate power dissipation, therefore a pulsed triggering of SCR is generally used.

→ In the pulsed triggering technique, a gate current pulsed is used for triggering of SCR

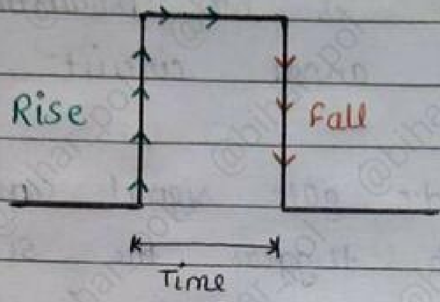
★→ Once SCR is turned ON the gate current is reduced to zero, most of the times, a turn of high frequency pulses, instead of only one pulse applied to the gate of SCR. This is called multiple pulsed triggering. The pulse frequency of the order of 5 to 10 KHz.

- Train of Pulses

Frequency → 10 KHz

The triggering pulse is rectangular in shape.

- **Magnified Gate Pulse**



→ Width of the pulse must be equal to the TURN ON time of the SCR.

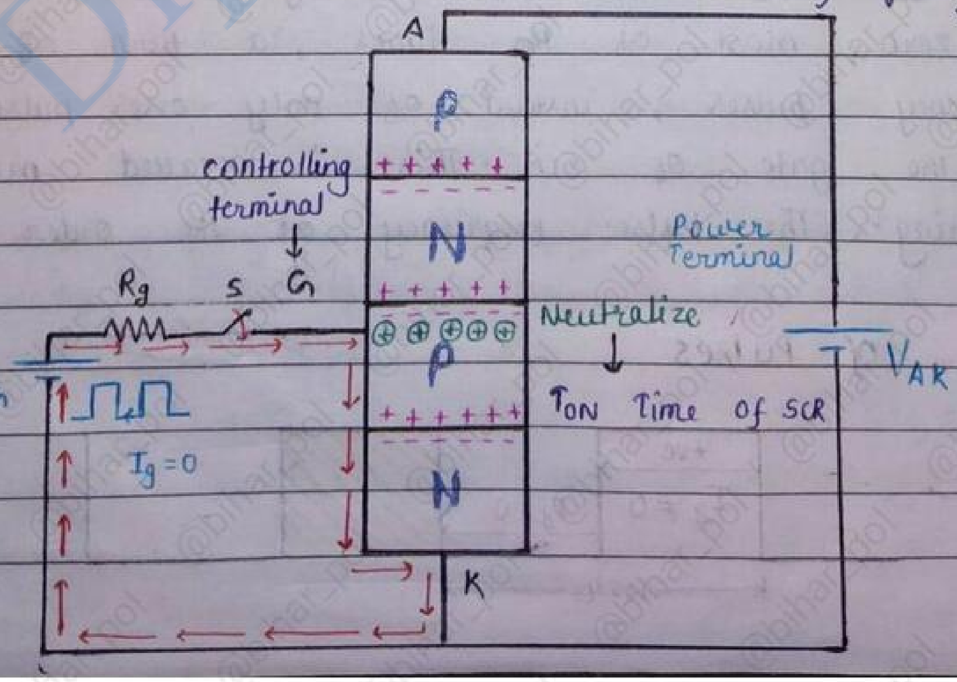
→ A train of identical pulses should be applied to the gate for the entire conduction period of SCR.

→ This multiple pulse triggering will help triggering of SCR if it turn off due to load fluctuation. Gate power dissipation is reduced as the Gate current for short duration.

Example – Pulsed TRF, UJT,

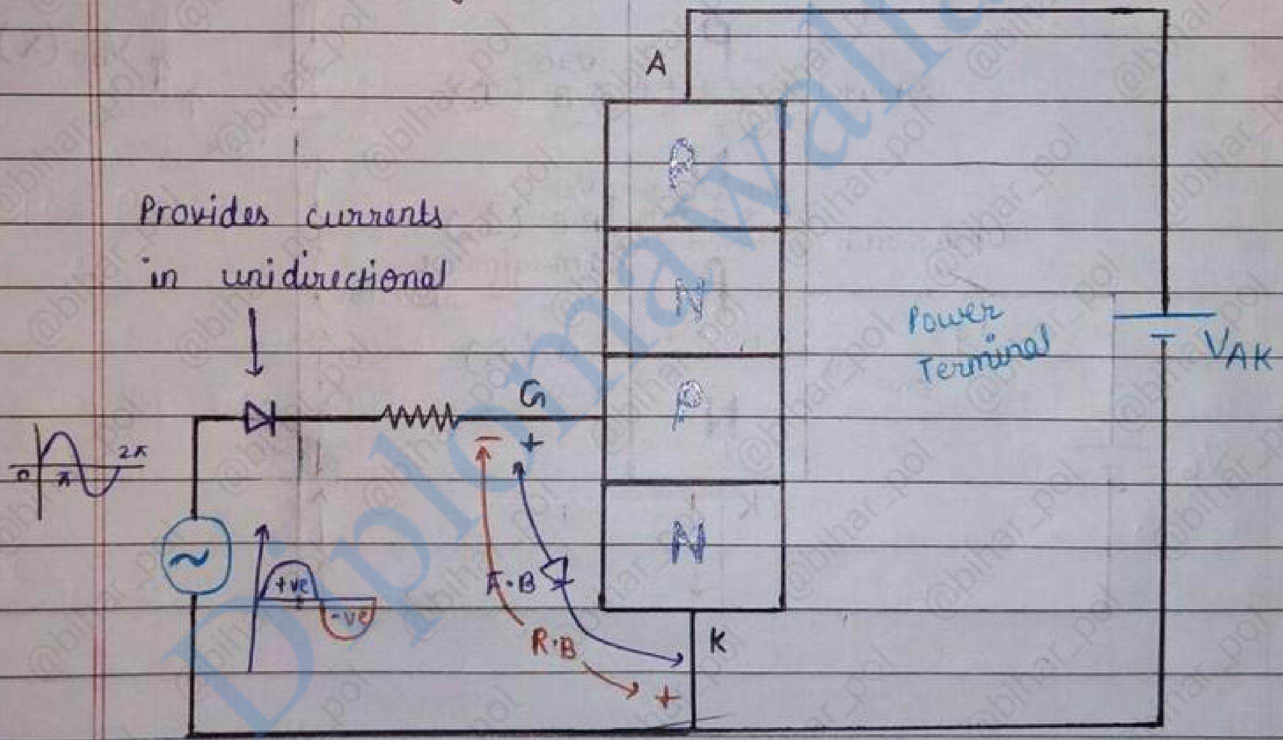
* Optocoupler also provides electrical isolation between the main circuit and low power frequency ckt.

Width of the Pulse $\geq T_{ON}$ time of the SCR



* Here the SCR is triggered by the application of a positive pulse or correct magnitude.
* For thyristors it is important to switched ON at proper instants in a certain sequence.
* This can be done by train of the high frequency pulses at proper instants through a logic circuit.
* A pulse transformer is used for circuit isolation. Here, the gate looses are very low because the drive is discontinuous.

(c) AC Gate Triggering



G-K Junction → F·B

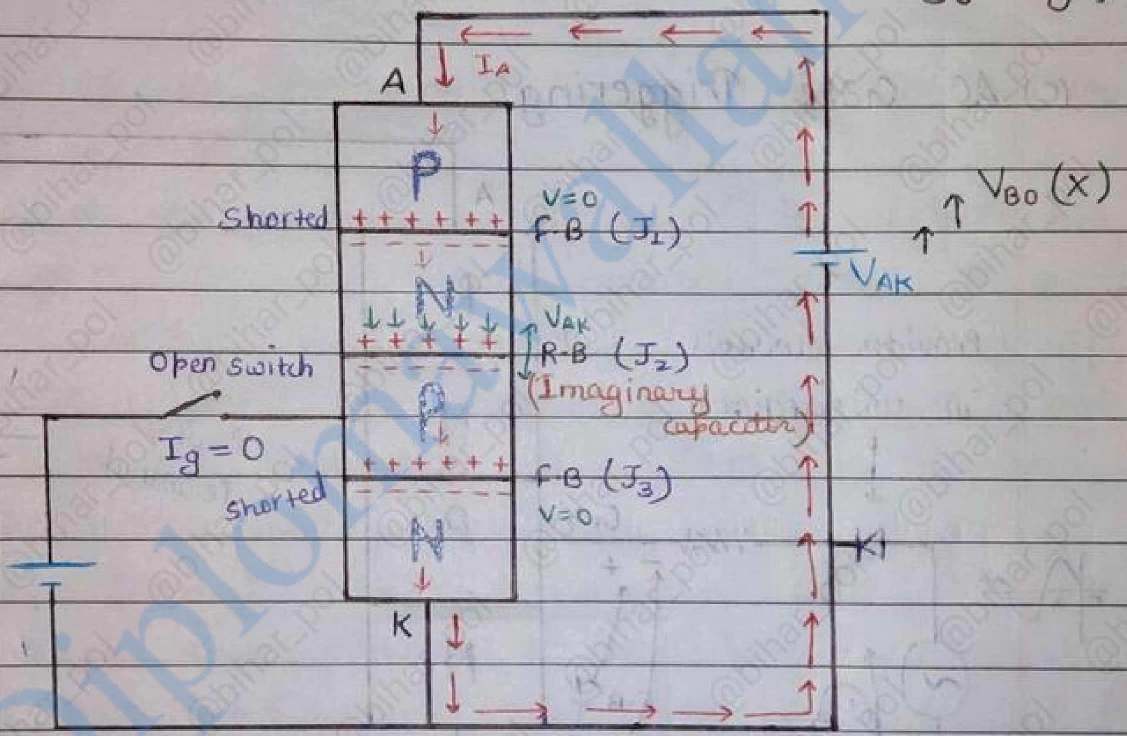
→ In this method, a phase-shifted A.C voltage derived from the mains supplies the gate signal.

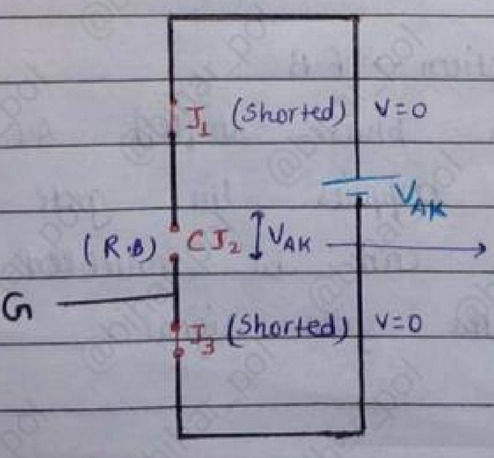
→ Instant of firing can be controlled by phase angle control of the gate signal.

* Here AC source is used for gate signals.
* This scheme provides proper isolation between power and control circuit.
* Drawback of this scheme is that a separate transformer is required to step down AC supply.

L-12 •

3. $\frac{dv}{dt}$ Triggering (False Triggering & Unwanted Triggering)





$V \rightarrow I_c$(flow) → charging turn and then SCR ON with any gate current

→ Due to forward voltage the junction J_2 is reversed biased. This reversed biased junction J_2 behaves as a capacitor due to charges existing across the junction CJ_2.

→ If forward voltage is applied, a charging current through the junction capacitance C_J may turn ON the SCR. This junction capacitance (CJ_2).

→ Therefore if the rate of change of voltage across the device is large the device may turn ON ~~the~~ SCR. even through the voltage appearing across the device is small.

→ This I_C current plays the role of gate current and turn ON the SCR even through gate signal is zero.

$$Q = CV \qquad \{\because i = dQ/dt\}$$

$$Q_{J2} = C_{J2} \cdot V_{AK}$$

$$\frac{dQ_{J2}}{dt} = C_{J2} \cdot \frac{dV_{AK}}{dt} \uparrow\uparrow$$

$$\uparrow\uparrow I_{CJ2} = C_{J2} \frac{dV_{AK}}{dt} \uparrow\uparrow$$

C_{J2} ↓ Almost constant

If I_{CJ2} charging $> I_{Latching}$

↓ SCR turn ON

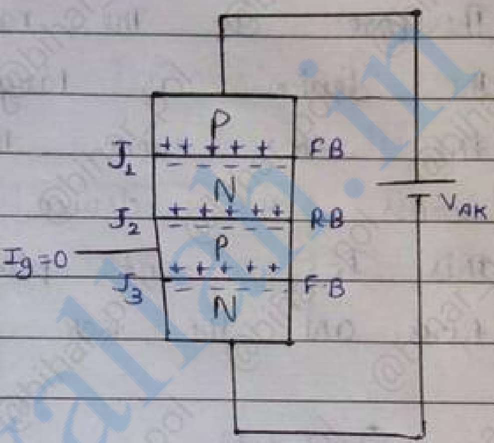
$$\left(\frac{dv}{dt}\right)_{operated} < \left(\frac{dV}{dt}\right)_{specified}$$

★★ In this method of triggering SCR are not damaged. Only SCR turn ON.

Q. The Junction capacitance of the SCR can be assumed to be independent of off state voltage, The limiting value of charging current to turn on the SCR is 12 μA. If the critical value of $\frac{dv}{dt}$ is 800 v/μs determine the junction capacitance.

⇒ $I_{CJ2} = 12\ \mu A$

$\frac{dV_{AK}}{dt} = 800\ V/\mu s$



$I_{CJ2} = C_{J2}\frac{dV_{AK}}{dt}$

$12\,\mu A = C_{J2} \cdot 800\,v/\mu s$

$\frac{12\,\mu A \cdot \mu s}{800\,V} = C_{J2}$

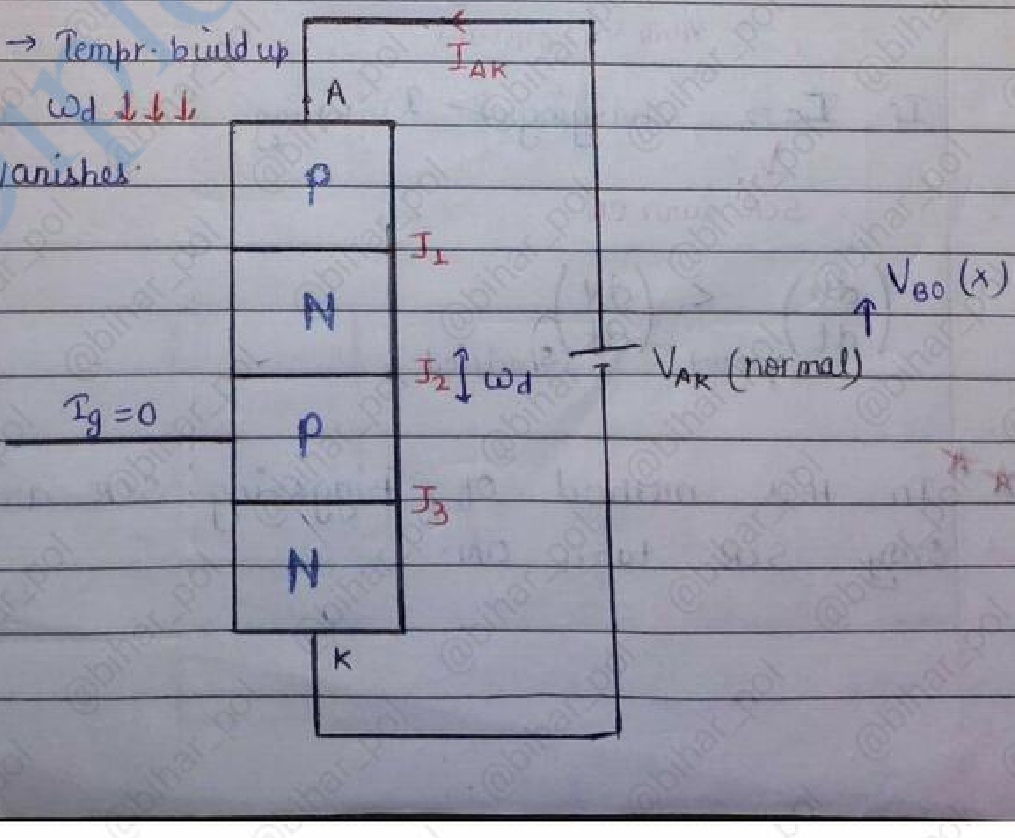
$C_{J2} = 0.015\ pF$

4. Thermal Triggering or Temperature Triggering

$I_2 \rightarrow J_2 \rightarrow$ Tempr. build up

Temp ↑↑ ω_d ↓↓↓

$\omega_d \rightarrow$ vanishes



→ During forward blocking, most of the applied voltage appears reverse biased junction J_2.

→ This voltage across junction J_2 associated with leakage current may raise the temperature of this junction. With increase in temperature, leakage current through junction J_2 further increases.

→ This cumulative process may turn ON the SCR at some high temperature.

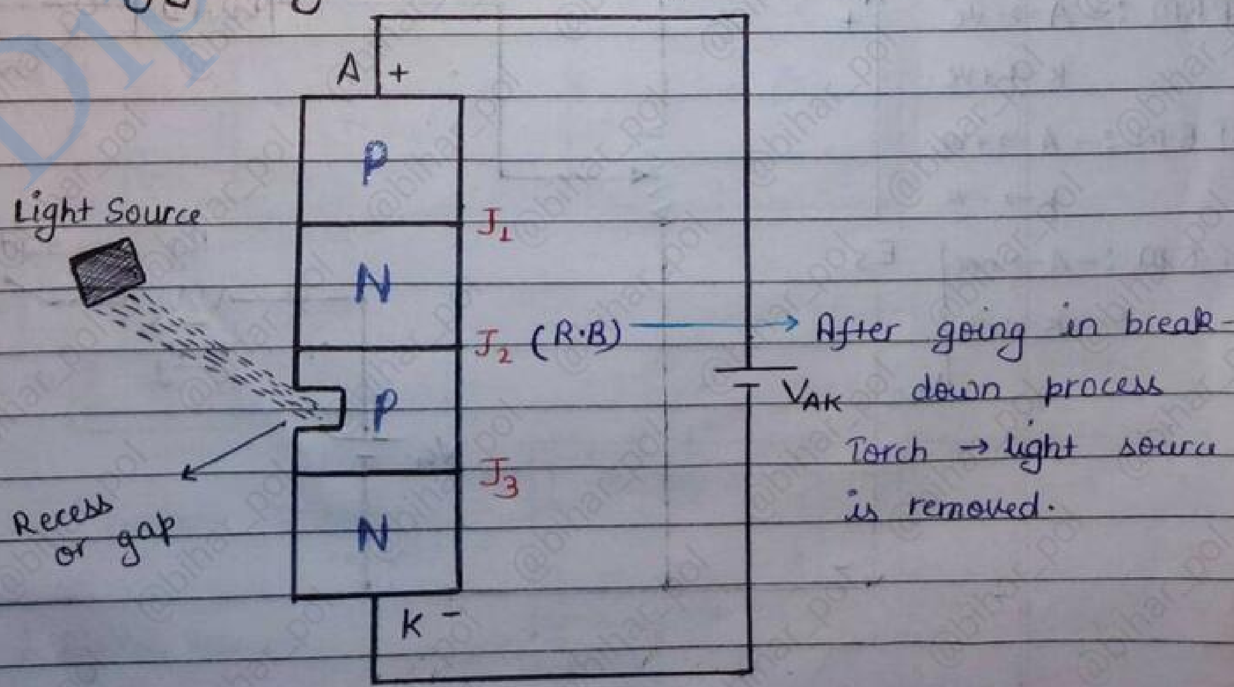
→ High temperature triggering may cause Thermal runaway and is generally avoided.

→ The width of depletion layer of SCR decreases with inc. in junction temp.

→ Therefore, in SCR, when V_{AK} is very near its breakdown voltage, the device is triggered by increasing the junction temperature.

→ By increasing the junction temperature, the reverse biased junction, J_2 collapses. Thus, the SCR starts to conduct.

5. Light Triggering (LASCR) Light activated SCR.



Uses :-

- Series parallel combination of SCR.
- HVDC

→ For light triggering of SCR a Recess or Gap is made in inner P-layer of SCR.

→ When light ray falls on this recesses, free charge carrier electrons and holes are generated. If we increases the intensity of light, then ~~for~~ forward biased SCR breakes reverse biased junction J_2, and the SCR is turned ON.

→ As the SCR is turned ON light source is removed.

→ This type of SCR is called light source is removed.

L-23

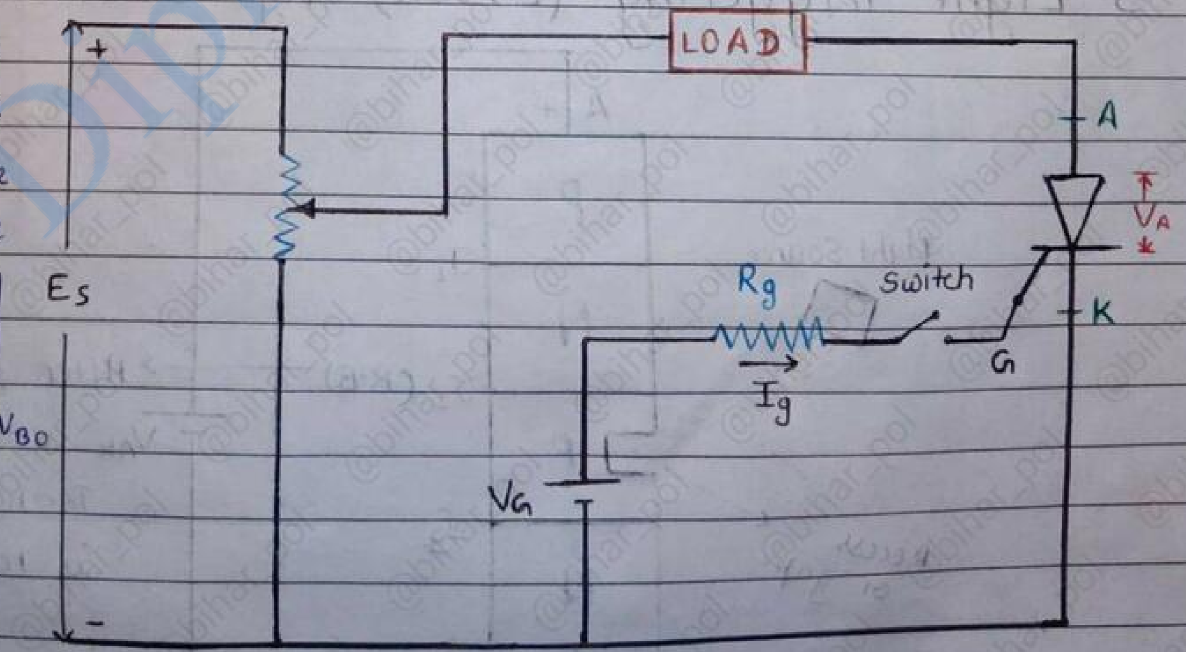
* V-I Characteristics of Thyristor

- SCR circuit

RBM :- A → -ve
K → +ve

F.B.M :- A → +ve
K → -ve

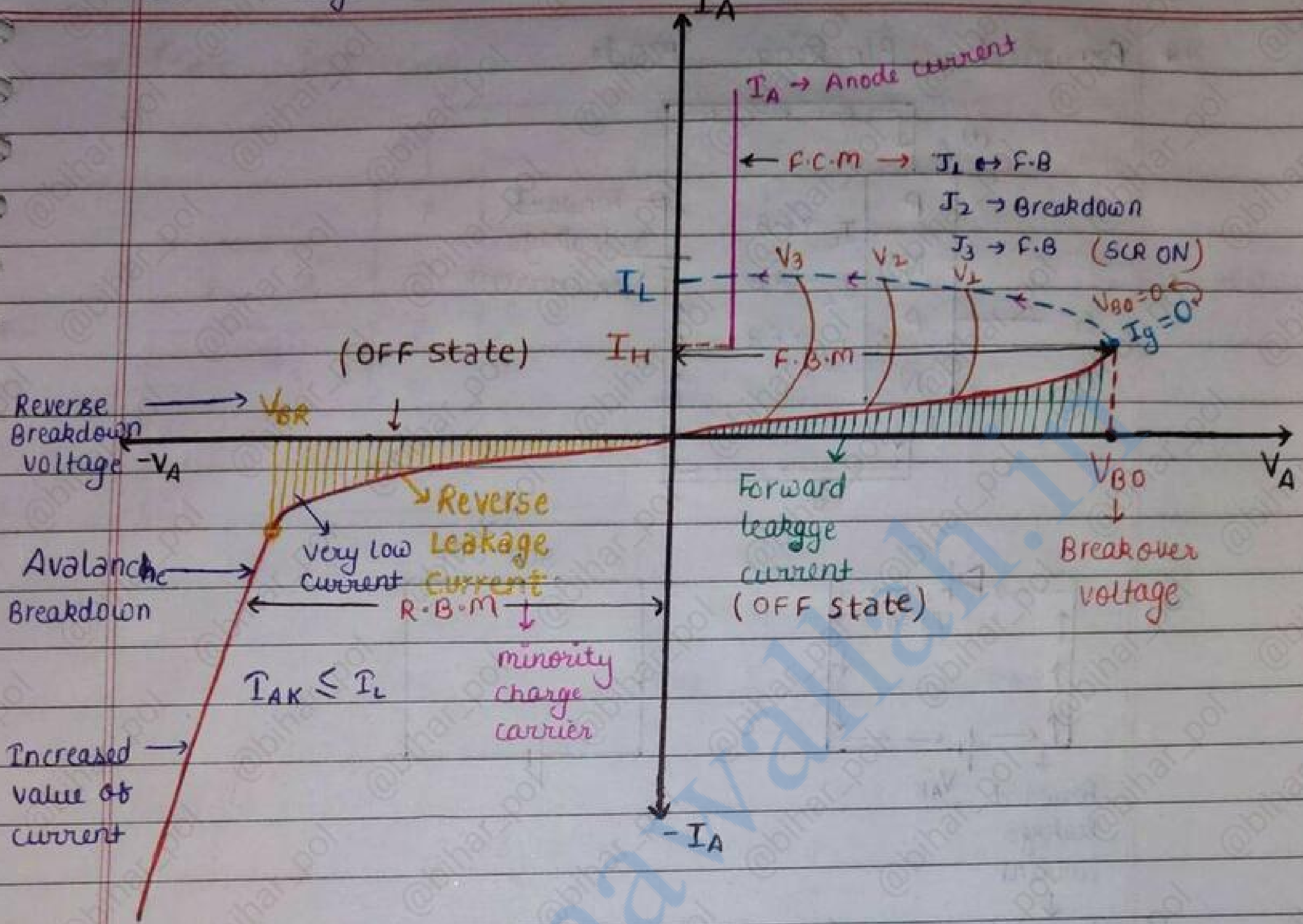
F.C.M :- A → +ve
K → -ve



V_{BO} = ~~Final~~ Forward final voltage rating of the SCR.

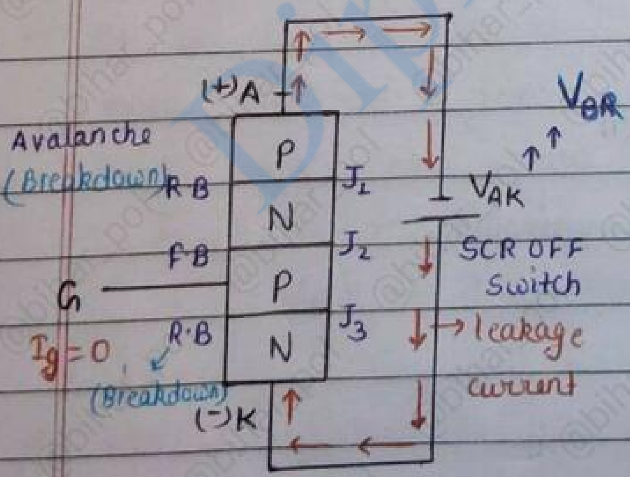
Device can never be operate on V_{BO}.

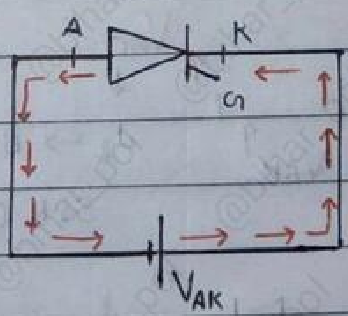
- Both leakage current are temperature dependent.



* Reverse Blocking mode

SCR OFF state





Reverse current > leakage current

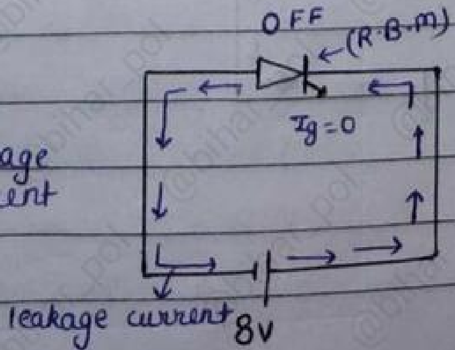


Fig (a)

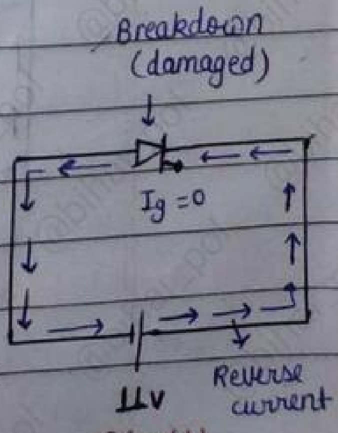
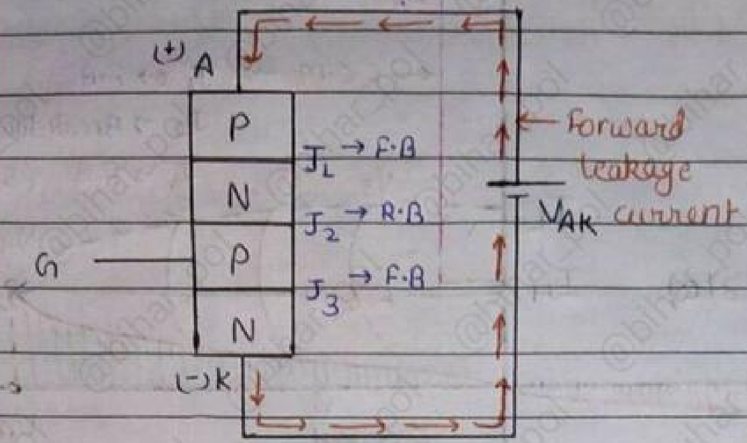
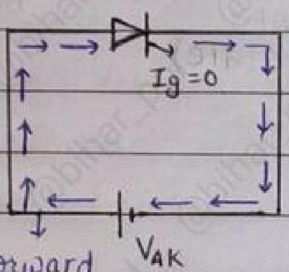


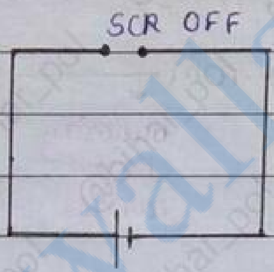
Fig (b)

Fig (a) & Fig (b) represent R.B.M mode.

* Forward Blocking mode





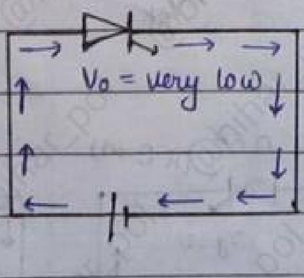


forward leakage current
↓
minority charge carrier

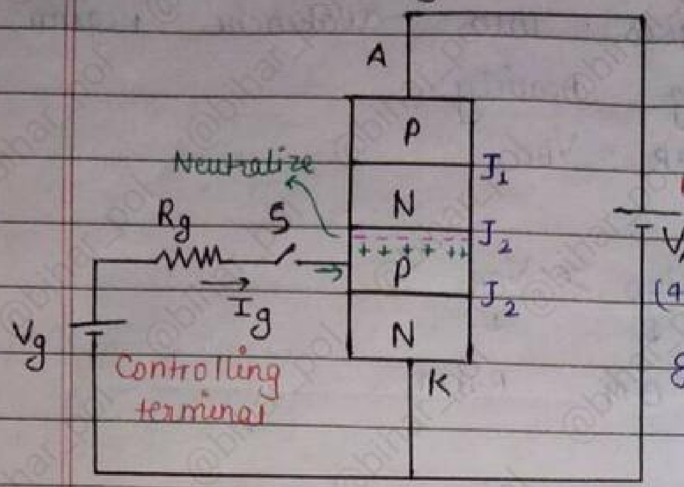
* Forward conduction mode

$V_{AK} \uparrow \uparrow \uparrow V_{BO}$
↓
$J_2 \to$ Breakdown

SCR ON



* Gate Triggering



SCR does not ON
↓
$V_{BO} \leftarrow I_g = 0$
(800V) ↘ Biggest value

Power terminal

V_{AK} ← Normal Anode to cathode voltage
(400V)
↓
gate supply (+ve gate supply)

V_{BO} (800V)	V_1 (700V)	V_2 (600V)	V_3 (500V)	V_{AK} (400V)
↓	↓	↓	↓	↓
$I_g = 0$	$I_g = 2\,mA$	$I_g = 4\,mA$	$I_g = 6\,mA$	$I_g = 10\,mA$
↓ does not ON				

$$V_3 < V_2 < V_1 < V_{BO} \quad (I_g = 0)$$

$$I_{g_3} > I_{g_2} > I_{g_1} > 0$$

L-15

- **Forward Breakover Voltage (V_{BO})**

→ It is the maximum voltage when gate is open, i.e, there is no gate supply given at which SCR turns ON or comes in conduction mode.

$J_2 \rightarrow V_{AK} \rightarrow$ Blocking $\rightarrow I_g = 0$
↓ $\rightarrow V_{BO} \rightarrow$ Breakdown $\rightarrow I_g = 0$

- **Reverse Breakdown Voltage (V_{BR})**

→ It is the minimum reverse voltage that can be applied on SCR without conducting in reverse direction.

→ It is the value of reverse voltage from the

Anode Current

I_L (Latching current) $I_L > I_H$ I_H (Holding current)

cathode to anode at reverse blocking mode at which the device goes into avalanche region and starts conducting heavily.

Symmetrical SCR → $V_{BR} = V_{BO}$

Unsymmetrical SCR → $V_{BO} > V_{BR}$

(V_{BO} ↓ F.B.M, V_{BR} ↓ R.B.M)

- **Forward Leakage Current**

→ The small current flowing in the forward direction in the OFF state of the device.

→ This current is generated due to the minority charge carrier and therefore it depends on the operating temperature.

- **Reverse Leakage Current**

→ It is the small current in reverse mode when SCR not comes in conduction.

A → −ve
K → +ve
G → open

- **Latching Current** → Relates to turn ON the SCR

→ It is defined as the minimum value of anode current required to maintain the thyristor in ON state immediately after a thyristor has been turned ON and the gate signal is removed.

→ Latching current is usually greater than the holding current. (Page NO - 42)

- **Holding Current** → SCR turn OFF Process

→ It is defined as the minimum current that can

$I_{AK} \geq I_L$ (to remains it in ON state after triggering)

SCR to be ON → Gate = I_g (+ve value)

$I_{AK} < I_H$ → SCR off state

flow through SCR and still hold it in ON state.

→ If the forward anode current is reduced below holding current, SCR will be turned OFF.

Difference between Latching Current and Holding

Latching Current (I_L = I_g +ve value)	($I_H = I_g \to 0$) → Gate ckt is removed. Holding Current
1. Latching current is associated with turn-ON process of SCR.	Holding current is associated with turn-OFF process of SCR.
2. It is the minimum value of anode current which it must attain during turn-ON process to maintain conduction when gate is removed.	Thyristor can be turned OFF or returned to forward current falls below a low level current called the holding current.
3. Latching current is 2 to 3 times of holding current. (I_L/I_H = 2 to 3)	Holding current is less than the latching current. (I_L = 2 to 3 I_H)

→ Latching current is always higher than holding current ($I_L > I_H$)

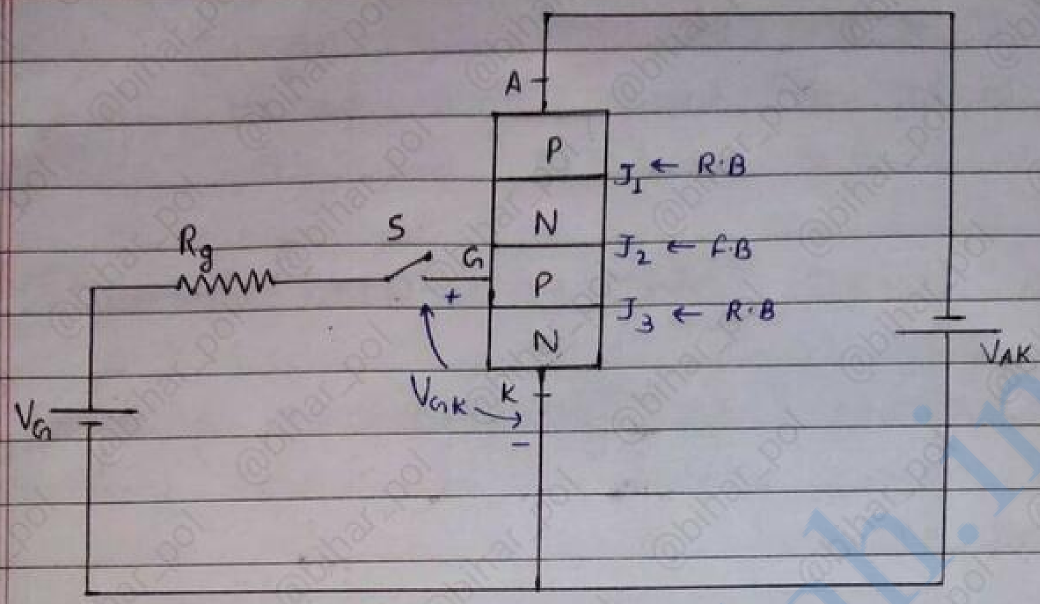
Q. What happens if +ve gate signal is given to an RB SCR?

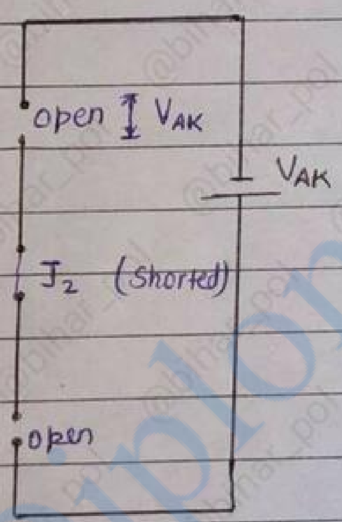
→ When +ve supply is given to the R.B SCR, then the complete reverse voltage is applied across J_1.

→ This commulatively increases the power loss, temperature, leakage current and the SCR is thermally destroyed at J_1.

→ This phenomenon is known as thermal runaway of the SCR.

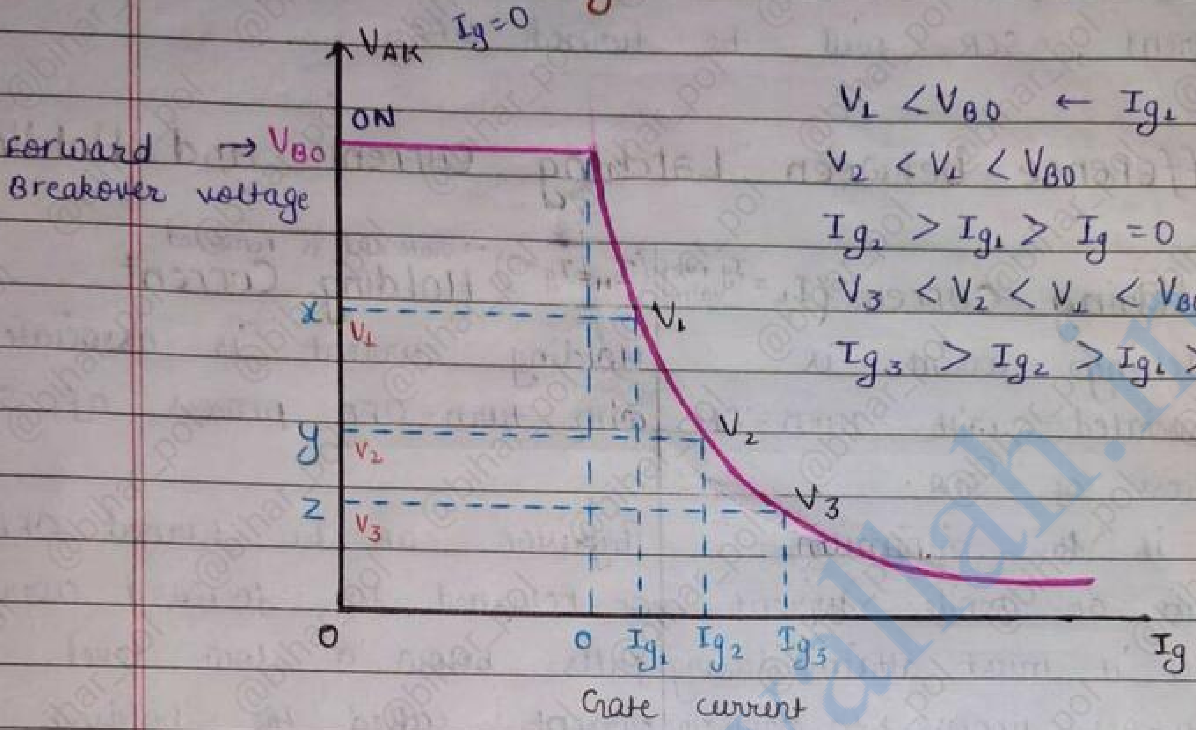
★ Gate terminal is located near kathode.
★ Gate terminal is located far from anode.





★ Always +ve supply is given to Gate terminal.
Gate → controlling terminal
A, K → power terminal

Effect of Gate Current on Forward Breakover Voltage.



$V_1 < V_{BO} \leftarrow I_{g_1} > I_{g_0}$

$V_2 < V_1 < V_{BO}$

$I_{g_2} > I_{g_1} > I_g = 0$

$V_3 < V_2 < V_1 < V_{BO}$

$I_{g_3} > I_{g_2} > I_{g_1} > I_g = 0$

⇒ From the above fig
for gate current
$I_g = 0$
Forward Breakover is V_{BO}

⇒ for Gate current
I_{g_1}, Forward Breakover voltage is V_1
$V_1 < V_{BO}$

⇒ for gate current I_{g_2}
Forward Breakover voltage V_2.

→ magnitude of forward breakover voltage (V_{BO}) and reverse breakdown voltage (V_{BR}) are nearly the same and both are temperature dependent.

$V_{BR} > V_{BO}$

→ It is dangerous to operate SCR in the reverse break-down state because it may get damaged due to overheating.

→ Forward Breakover Voltage (V_{BO}) ← $I_g = 0$

- It is the maximum voltage when gate terminal is open that is there is no gate supply is given at which SCR is turn ON to conduction mode.

→ Reverse Breakdown Voltage (V_{BR}) ← $I_g = 0$

- It is maximum Reverse voltage that can be applied on the SCR without conducting in reverse direction.
- It is the value of reverse blocking mode at which the device goes into avalanche region and start conducting heavily.

- **Latching Current (I_L)**

→ Consider that the SCR is in forward blocking state then the SCR can be turned ON by applying a gate signal.

→ Then the SCR goes into forward conduction mode.

→ Latching current is the minimum forward current that flows through the SCR to keep it in forward conduction mode that is ON mode at the time of triggering.

→ If forward current is less than latching current then the SCR is not comes in conduction mode.

→ The latching current is of the order of ★10 to 15 mA.

→ I_A reduced to went into Holding current.

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Normal Operation of SCR

→ Anode to cathode voltage must be less than the forward breakover voltage (V_{BO}).

$V_{AK} < V_{BO}$

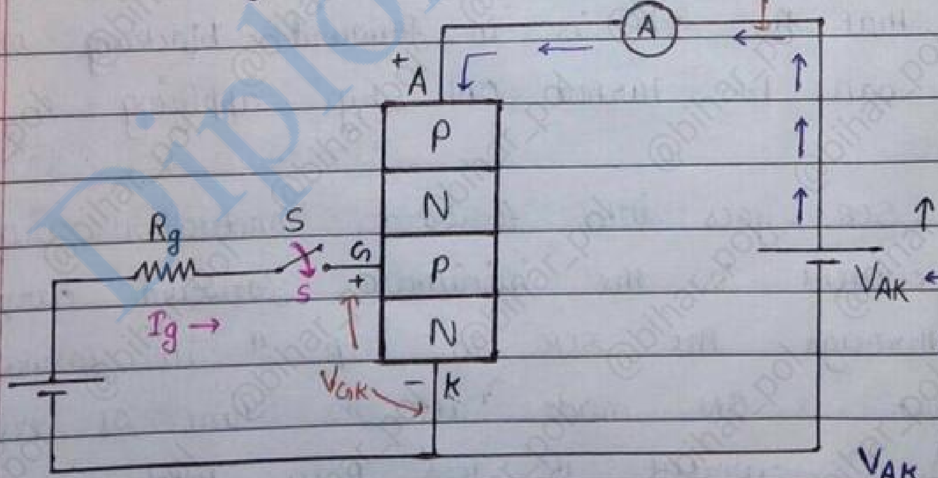
↓ $I_g = +ve$ ↓ $I_g = 0$

→ Applying an appropriate gate signal +ve gate voltage w.r.t to cathode.

→ when the device is to be turned off from ON state, forward Anode current (I_{AK}) must go below the holding current (I_H).

→ Magnitude of gate current must be less than maximum gate current allowed otherwise gate circuit may be damaged.

→ Anode to cathode voltage must be more than finger voltage. A finger voltage is that voltage below which an SCR cannot be turned ON with a gate signal. (Leakage current)



$I_g = 0$

$V_{BO} = 600\,V$ (X)

$V_{AK} \leftarrow 200\,V$

↓

SCR does not turn ON

$V_{AK} \leftarrow$ 205 V → Finger voltage

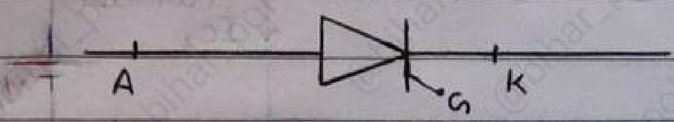
$I_g \rightarrow +ve$

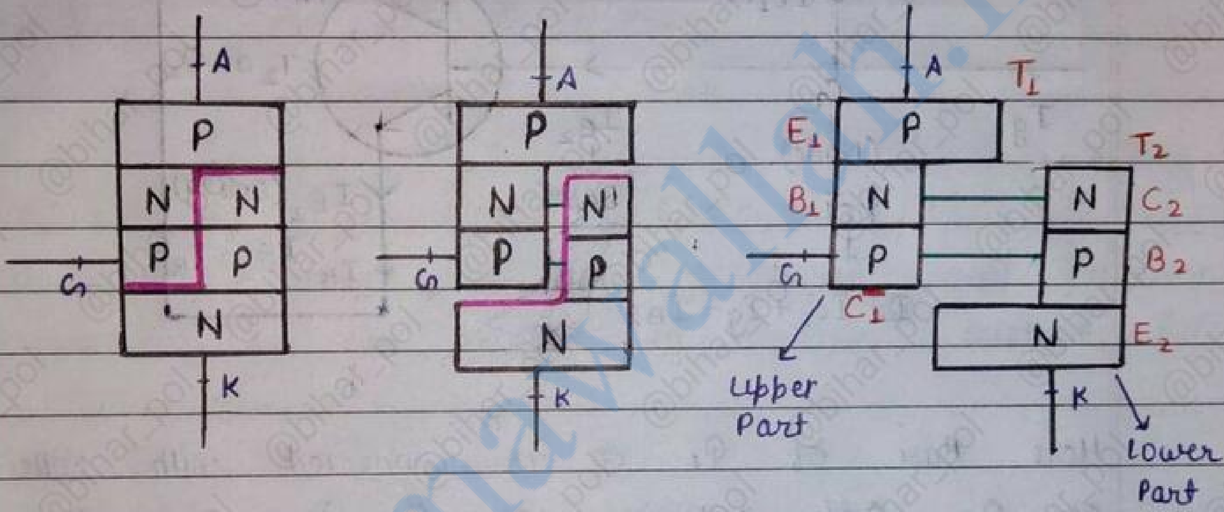
SCR turn ON

V.V.I ★★

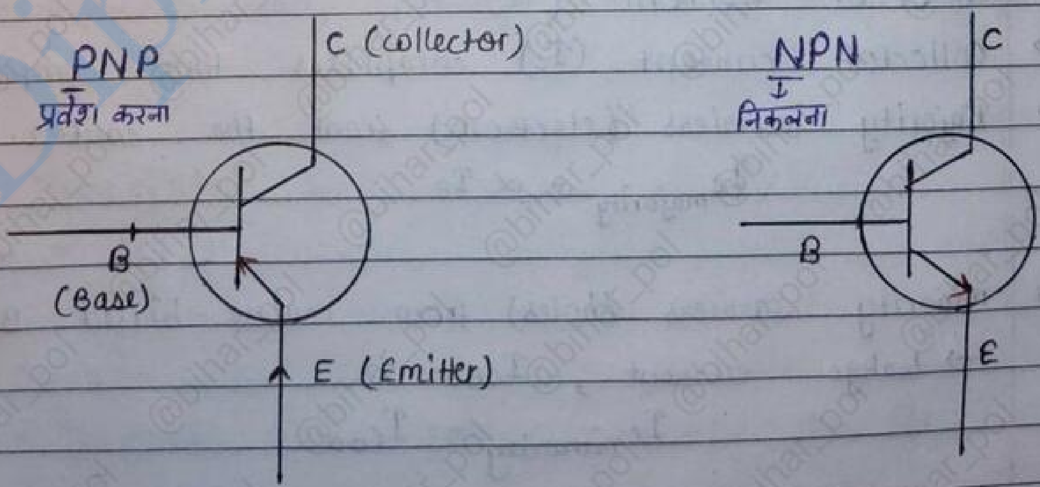
Two Transistor Analogy of SCR

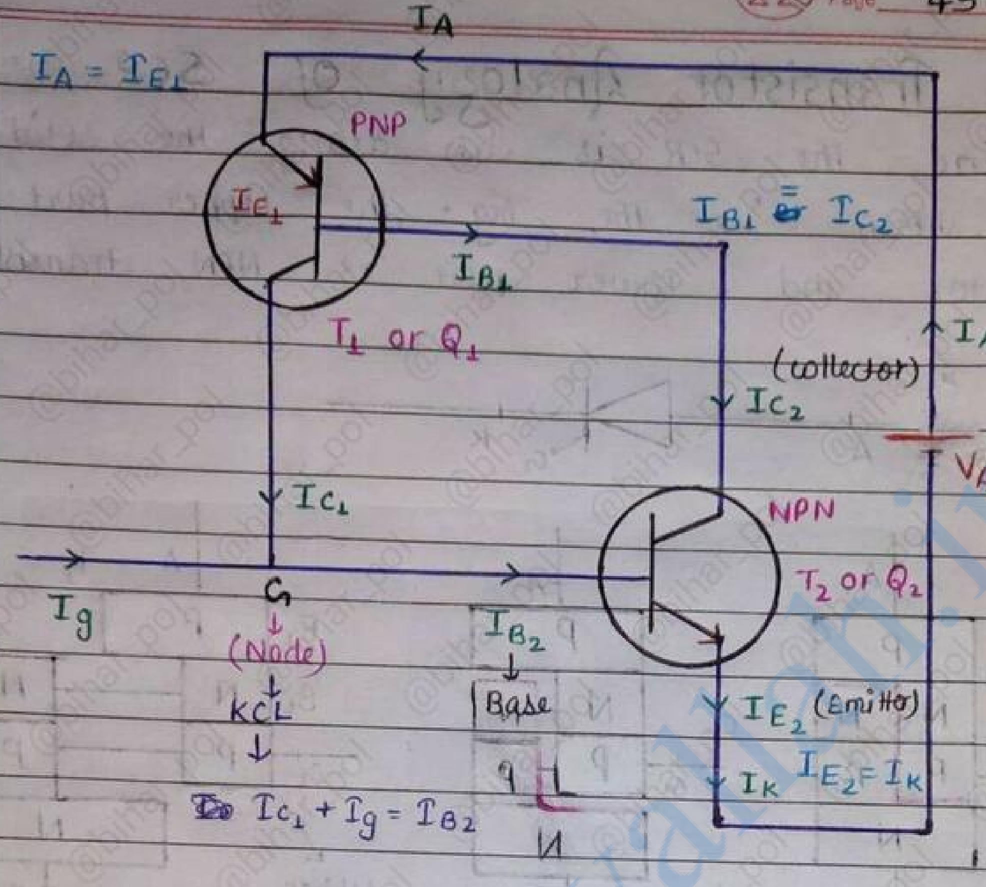
→ Imagine the SCR is cut along the solid dark line shown in the fig. The upper part is PNP transistor and lower part is NPN transistor.





- PNP and NPN Transistor





Here Base of Q_1 is connected with collector of Q_2 and collector of Q_1 is connected with Base of Q_2 which is shown in the above fig.

L-17

- **Collector Current (I_c)**

→ Collector current (I_c) comprises two components;

- Majority carriers (electrons) from the emitter.

$$I_{c_{majority}} = \alpha I_E$$

- Minority carriers (holes) from reverse-biased BC junction → leakge current, I_{CBO}

$$I_{c_{minority}} = I_{CBO}$$

→ Total collector current (I_c);

$$\boxed{I_c = \alpha I_E + I_{CBO}}$$

→ Since leakage current I_{CBO} is usually so small that it can be ignored.

- Transistor Equations

→ Alpha Factor :-

$$\alpha = \frac{I_c}{I_E}$$

→ Current Gain :-

$$\beta = \frac{I_c}{I_B}$$

→ Kirchhoff's Current Rule :-

$$I_E = I_C + I_B$$

V.V.I**

* Derivation of Anode Current (I_A)

→ We know that in any transistor total collector current I_C is related to emitter current I_E.

- For Transistor

$I_C = \alpha I_E + I_{CBO}$ (BJT eq.)

where,

α = common Base current gain

I_{CBO} = common Base leakage current with emitter terminal is open.

- For Transistor Q_1

$I_{C_1} = \alpha I_{E_1} + I_{CBO1}$

where,

α_1 = common Base current gain of Q_1

I_{CBO1} = common Base leakage current of Q_1

$I_{E_1} = I_A$ (According to fig.)

$$\boxed{I_{C_1} = \alpha_1 I_A + I_{CBO1}} \quad \text{—— (1)}$$

For any transistor we can write :-

$$I_E = I_B + I_C$$

- For Transistor Q_2

$I_{C_2} = \alpha_2 I_{E2} + I_{CBO2}$

Where,

α_2 = common base current gain of Q_2

I_{CBO2} = Common base leakage current of Q_2

Again

$I_{E_2} = I_K$

$$I_{C_2} = \alpha_2 I_K + I_{CBO_2} \quad — (2)$$

For Transistor Q_1

$I_A = I_{B1} + I_{C1}$ (From transistor equation)

$\therefore I_{B_1} = I_{C_2}$ (From fig.)

$I_A = I_{C_1} + I_{C_2}$

Now,

Putting the value of equation 1 and equation 2

$$I_A = \alpha_1 I_A + I_{CBO_1} + \alpha_2 I_K + I_{CBO_2} \quad — (3)$$

Apply KVL equation at Node G :-

$I_{B2} = I_g + I_{C_1}$

Now from whole ckt →

$I_A + I_g = I_K$

Put the value of I_K in equation (3)

$I_A = \alpha_1 I_A + I_{CBO_1} + \alpha_2 (I_A + I_g) + I_{CBO_2}$

$I_A = \alpha_1 I_A + \alpha_2 I_A + \alpha_2 I_g + I_{CBO_2} + I_{CBO_1}$

$I_A - \alpha_1 I_A - \alpha_2 I_A = \alpha_2 I_g + I_{CBO_2} + I_{CBO_1}$

$I_A [1 - (\alpha_1 + \alpha_2)] = \alpha_2 I_g + I_{CBO_2} + I_{CBO_1}$

$$I_A = \frac{\alpha_2 I_g + I_{CBO_2} + I_{CBO_1}}{1 - (\alpha_1 + \alpha_2)}$$

★ For proper operation value of $(\alpha_1 + \alpha_2)$ is less than 1.

Comparison between SCR and BJT

	SCR	BJT
1.	Four layer P-N-P-N device.	Three layer PNP or NPN device.
2.	It is current controller or charge controller.	It is current controller.
3.	Gate has no ~~current~~ control once SCR is turned ON.	Base has full control over operation of BJT.
4.	External circuit are required to turn OFF the SCR.	No external circuit is required. BJT is turned off if base drive is removed.
5.	Switching frequency is low.	Switching frequency are high.
6.	False triggering takes place if $\frac{dv}{dt}$ is high. (SCR turn ON)	BJT is damaged if $\frac{dv}{dt}$ is exceeded.

* Avalanche Breakdown

→ The minority charge carrier under reverse biased junction flowing through the junction. Acquire a kinetic energy which increases with the increase in reverse voltage.

→ At a sufficient high reverse voltage, the kinetic energy of minority charge carrier becomes so large, that they knock out electron from covalent bond of the semiconductor material.

→ As a result of collision, the liberated electron in turn to librated more electron and a current becomes very large leading to the breakdown of

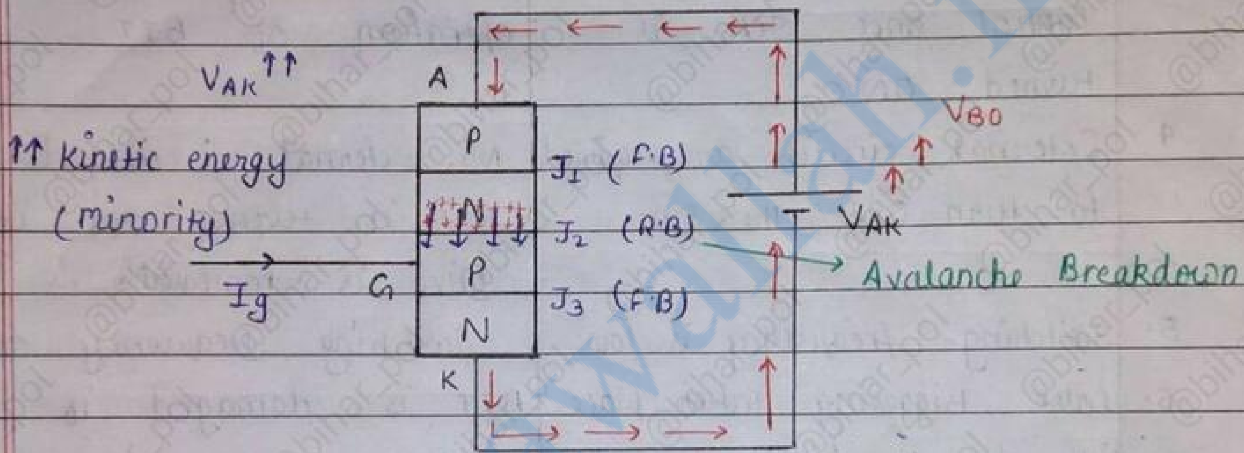
- The ~~only~~ work of I_g is only to turn ON the SCR. ($I_g \neq 0$ +ve value)
- SCR ON ; $I_g = 0$
- When SCR is to be OFF = $I_g = 0$
- ★★ Gate involve only to turn ON the SCR, not involve to turn OFF.

the crystal structure.

→ This Phenomenon is called the avalanche breakdown.

obj★ → It exist in lightly doped junction.

★ Avalanche Breakdown occurs due to ~~KE~~ Kinetic energy or kinetic energy of minority charge carrier.



L-18

Q. What is thyristor commutation?

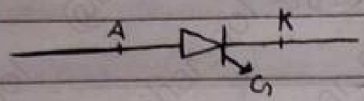
→ The process used for turning off a thyristor is called as commutation. By the commutation process, the thyristor operating mode is changed from forward conducting mode to forward blocking mode. So, the thyristor commutation methods or thyristor commutation techniques are used to turn off.

Introduction to Commutation

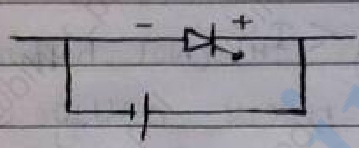
→ The process of turning off of a conducting SCR is known as ~~comut~~ commutation, once the SCR is fired turned ON the gate losses control over it.

- The process of technique in SCR in which SCR moves to F.B.M (R.B.M) from F.C.M, this process is called commutation.

→ The thyristor turned OFF required, Anode current to fall below the holding current a reverse voltage is applied to SCR for sufficient time to enable it to recover the blocking state.



$I_A < I_H$ ← SCR OFF



Reverse voltage is applied SCR OFF.

*→ Commutation depends upon the nature of the source AC or DC, the commutation can be natural or forced.

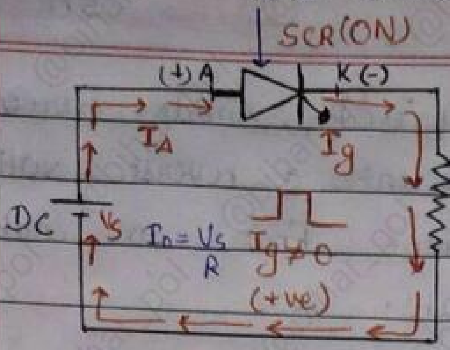
⇒ Object Point

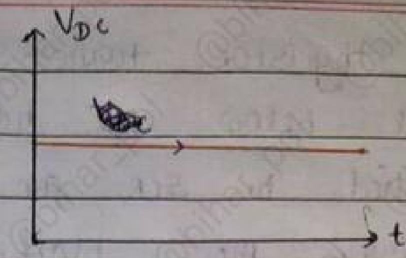
1. Uncontrolled switch — diode
2. Fully controlled switch — GTO, TRIAC, BJT
3. Semicontrolled switch — SCR

Types of commutation

- AC → Natural commutation or Line commutation
  - Current commutation
  - voltage commutation
- DC → Forced commutation (obj. Imp)
  - Class A (load commutation)
  - Class B (current commutation)
  - Class C (Impulse or complimentary commutation)
  - * Class D (voltage commutation)

Forced commutation technique





$I_A < I_H$ (Not happend naturally)

- Apply reverse voltage ON SCR.

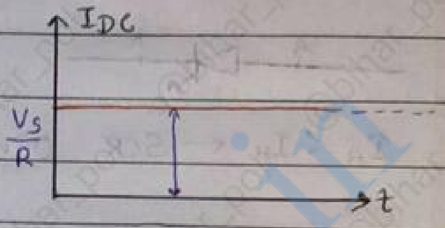
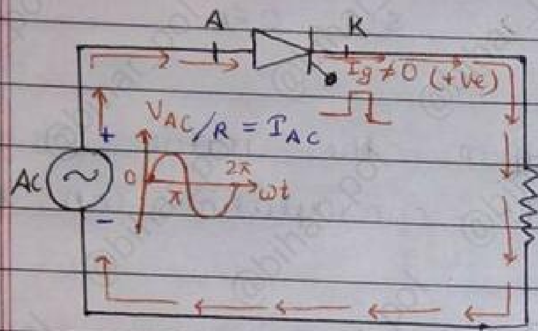
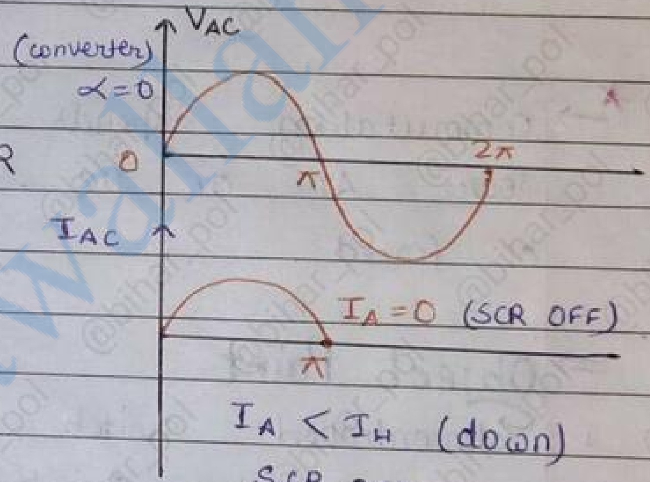


Fig :- (a)





A → + K → -ve (0 to π)

A → - K → +ve (π to 2π)

- In AC natural commutation exist.

Fig (b)

→ Commutation technique are broadly classified into two categories namely natural commutation and forced commutation depending upon the nature of source voltage AC or DC.

AC → Natural , DC → forced.

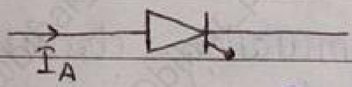
★ → Forced commutation circuit are further classified into two categories namely current commutation and voltage commutation.

1. Natural Commutation

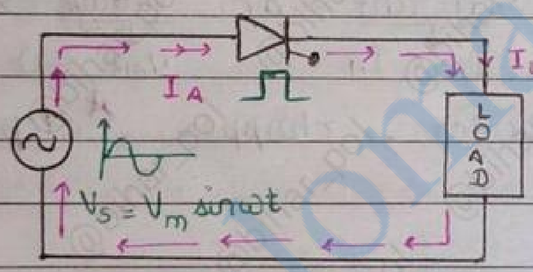
→ It is applied to AC circuits.
When SCR is turned off due to its forward anode current going below the holding current naturally. It is said to be naturally commutated circuit.

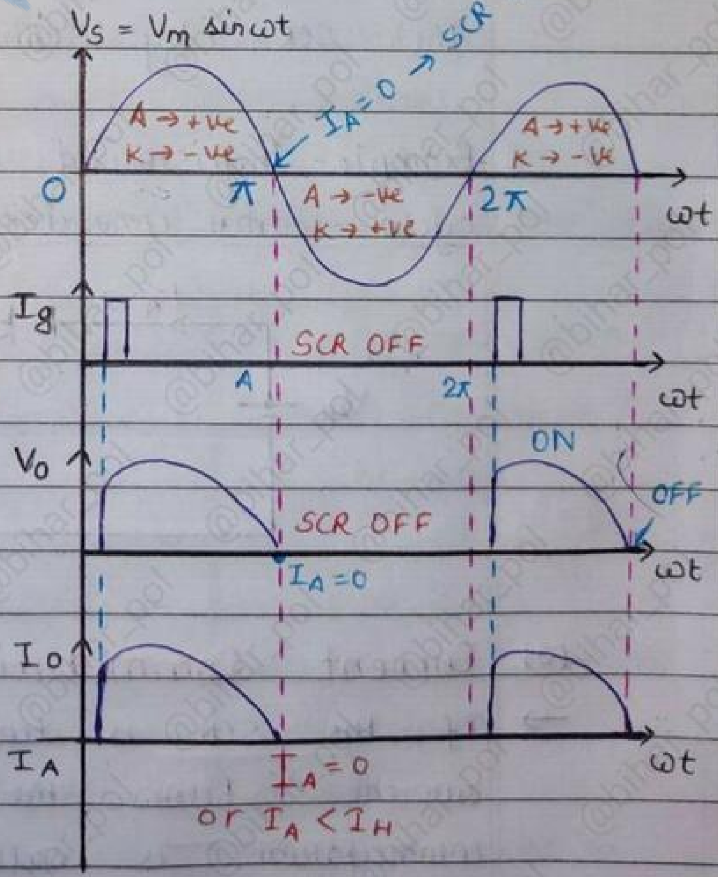
→ In this commutation SCR gets turned off only at -ve half cycle of the supply.

Example -
- Phase controlled Rectifier
- AC voltage Regulation
- V.V.I ★ Step- down cyclo converter



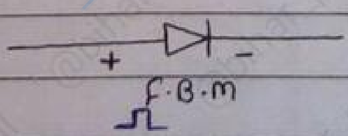
$I_A < I_H$; $V_{AK} < 0$



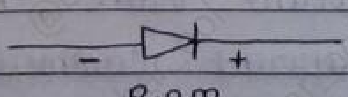


$V_{BO} \uparrow$ ON → $I_g = 0$

$\downarrow V_{AK}$ → ON → $I_g \neq 0$ (+ve)



F.B.M mode gate supply is given



2. Forced Commutation

→ It is applied to DC circuits.

→ Forced commutation is achieved by reverse biasing SCR device or by reducing SCR ~~circuit~~ current below the holding current value.

→ Commutating elements such as inductance and capacitance are used here.

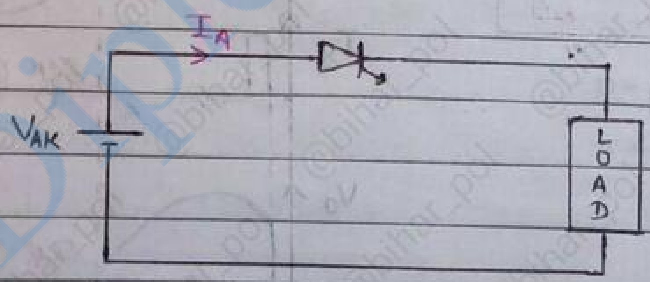
→ When the SCR operates on pure DC input voltage, there forward current cannot be reduced below holding current naturally.

→ Therefore, the thyristor must be commutated forcely by using additional commutating circuit.

→ The external commutating circuit will turn OFF the SCR by either current or voltage commutation.

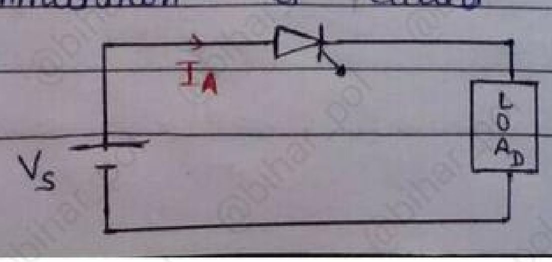
current ↓ $I_A < I_H$; voltage ↓ $V_{AK} < 0$

Example – Thyristorised inverter, chopper, * step up cyclo-~~conv~~ converter.



(a) Current Commutation

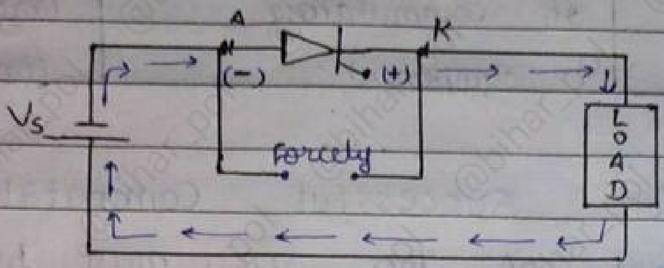
→ If the SCR is turned OFF by reducing its anode current below the holding current value, then the commutation is called as current commutation.



$I_A < I_H$
↓
Forcely (SCR turn ON)

(b) Voltage Commutation

→ If the conducting SCR is turned OFF by applying a large reverse voltage across it, then the commutation is called voltage commutation.



$V_{AK} < 0$

Different Types of Forced Commutation Technique

~~Class~~ -A

1. Class-A commutation (Load commutation)
2. class-B commutation (current commutation)
3. class-C commutation (Impulse commutation)
4. Class-D commutation (Voltage commutation)

* Difference between Natural and Forced commutation.

	Parameters	Natural Commutation	Forced Commutation
1.	Need of external commutating components.	Not Necessary	External components are necessary.
2.	Types of supply	AC	DC
3.	Power loss in commutation component	No power loss	Some power loss takes place.
4.	Types of commutation	$I_{AK} < I_H$ $V_{AK} < 0$	Voltage commutation Current commutation

R — dissipating element

Commutating component:
- L — charging & discharging element
- C — ✓

5.	Cost of commutating circuit	Not costly	Commutating circuit is costly.
6.	Size of the circuit	Small due to absence of commutating component.	Big size due to large commutating components.

* Conditions for Successful Commutation

→ Forward current of the SCR must be reduced to zero, $I_{AK} = 0$.

→ Reverse voltage must be applied across the SCR for a duration more than the turn off time of the device.

→ Critical rate of rise of voltage of the device should never be exceeded to avoid re-triggering of the SCR.

L-20

* Class-A Commutation

→ It is also called resonant commutation or self commutation or load commutation.

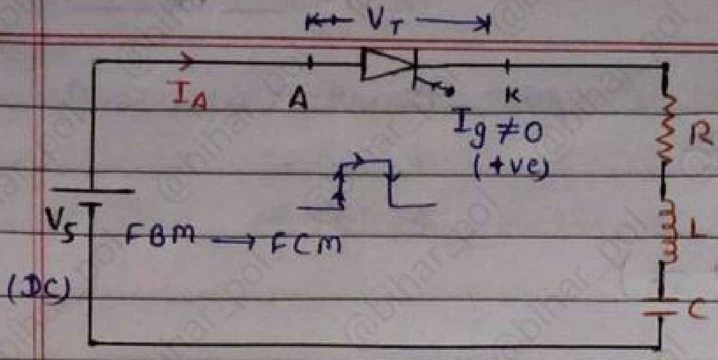
→ In this commutation of SCR, the commutating components L and C are connected in series or parallel.

V.V.I → Load commutation is possible in DC circuit and not in AC circuit.

→ The essential requirement is that the overall circuit must be underdamped circuit.

$$\boxed{R^2 < \frac{4L}{C}}$$ ← underdamped condition.

or, $R < 2\sqrt{L/C}$



R → LOAD

L, C → commutating component

Fig (a)

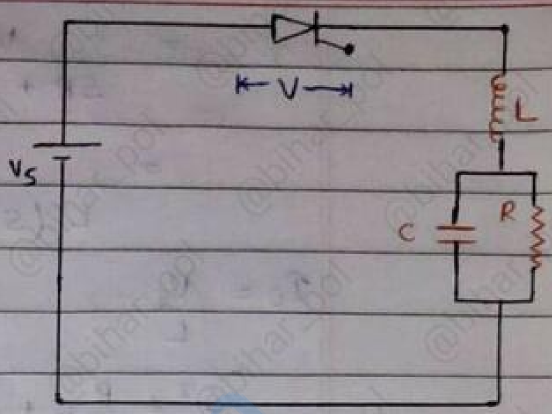


Fig (b)

V.V.I ★★★★★

NOTE :-

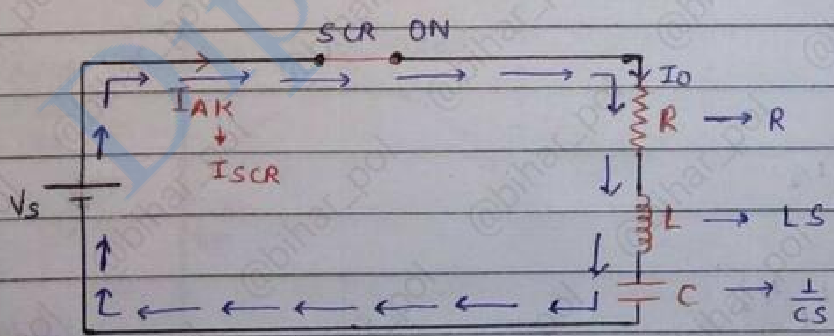
→ R is the load resistance.

→ For low value of "R", L and C are connected in series. (Fig a).

→ For high value of "R", load R is connected across C or parallel C (fig b).

- Circuit operation

→ Now, I_g will turn ON the SCR. SCR behaves as closed switch.



$I_O = I_A = I_{SCR}$

From the laplace transform, output current is

$$I_O = \frac{V_S}{Z} = \frac{\frac{V_S}{S}}{R + SL + \frac{1}{CS}}$$

$$= \frac{V_s}{SR + S^2L + \frac{1}{C}}$$

$$= \frac{V_s}{L\left(S^2 + \frac{R}{L}S + \frac{1}{LC}\right)}$$

$$I_0 = \frac{\frac{V_s}{L}}{S^2 + \frac{R}{L}S + \frac{1}{LC}}$$

So, the characteristics equation will be

$$S^2 + \frac{R}{L}S + \frac{1}{LC} = 0 \quad \text{—— (1)}$$

We know that for standard characteristics, equation will be -

$$S^2 + 2\varepsilon\omega_n S + \omega_n^2 = 0 \quad \text{—— (2)}$$

Now equating equations (1) & (2)

$$\omega_n^2 = \frac{1}{LC}, \quad \omega_n = \frac{1}{\sqrt{LC}} \quad \text{—— (3)}$$

$$2\varepsilon\omega_n = \frac{R}{L}$$

$$\Rightarrow 2\varepsilon\frac{1}{\sqrt{LC}} = \frac{R}{L} \quad (\text{using (3)})$$

$$\varepsilon = \frac{R\sqrt{LC}}{2L}$$

$$\varepsilon = \frac{R L^{1/2} C^{1/2}}{2L}$$

$$\varepsilon = \frac{R}{2} L^{1/2 - 1} C^{1/2}$$

$$\varepsilon = \frac{R}{2} \frac{C^{1/2}}{L^{1/2}}$$

$$\varepsilon = \frac{R}{2}\sqrt{\frac{C}{L}}$$

Now, we know that in underdamped case

$$\varepsilon < 1$$

$$\frac{R}{2}\sqrt{\frac{C}{L}} < 1$$

$$\frac{R}{2} < \sqrt{\frac{L}{C}}$$

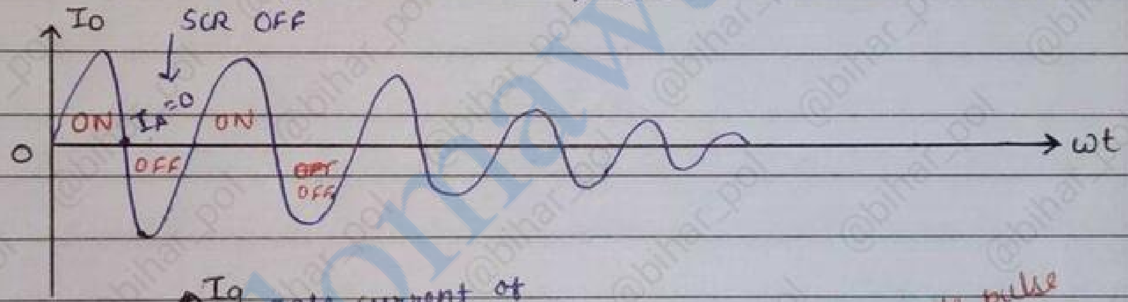
$$R < 2\sqrt{\frac{L}{C}}$$

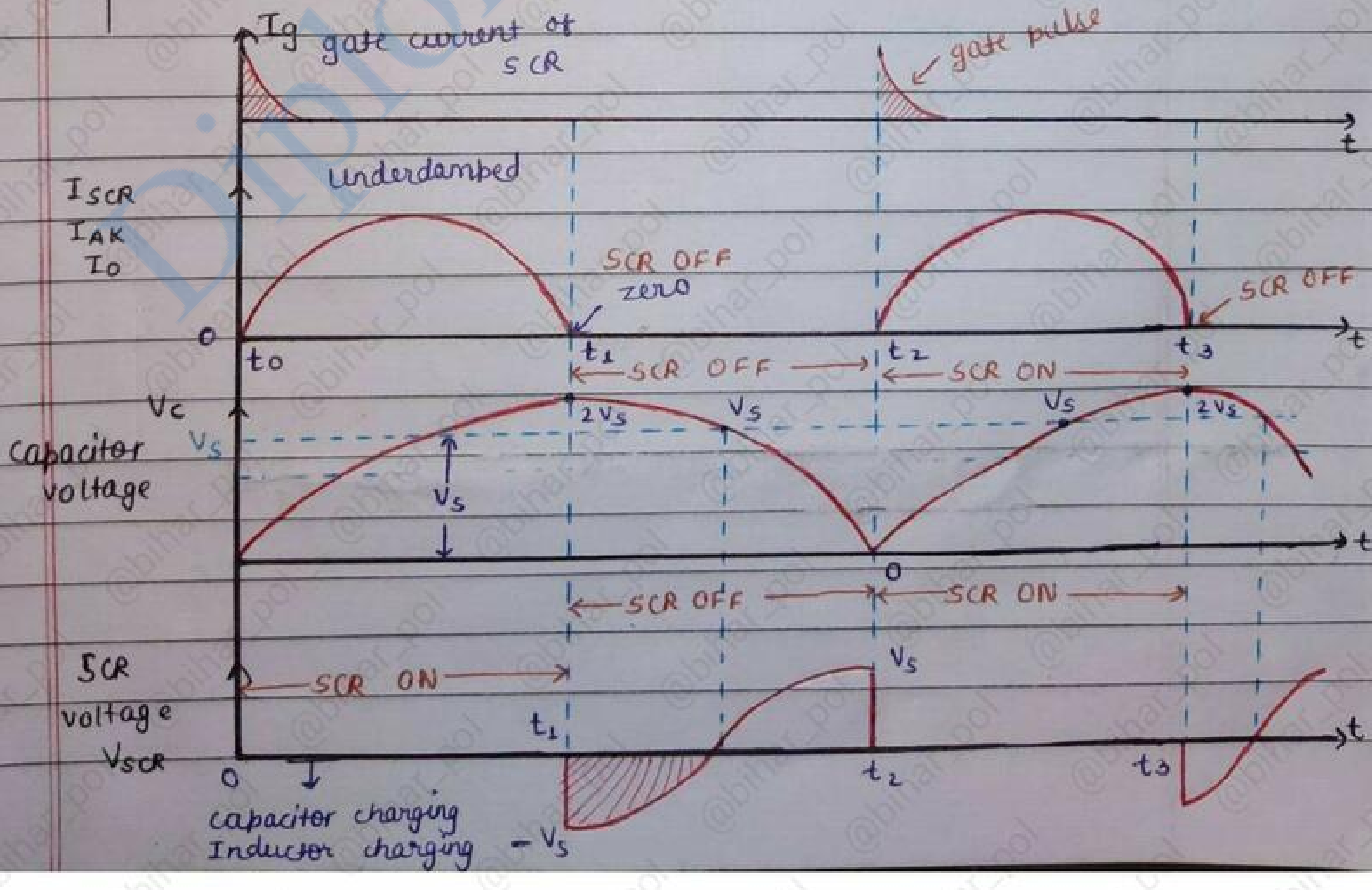
$$R^2 < \frac{4L}{C}$$ ← for underdamped circuit

Here, resonant frequency is

$$\omega_r = \omega_n\sqrt{1-\varepsilon^2}$$

To turn off the SCR, anode current must be zero (I_H)





SCR can stay ON during 0 to π

$\omega_r t = \pi$

$t = \frac{\pi}{\omega_r}$ = maximum conduction time of SCR.

α → firing angle → converter

$\omega_r t = \pi - \alpha$

$t = \frac{\pi - \alpha}{\omega_r}$ ← conduction time of SCR.

Series connection → To meet high voltage requirement

Parallel connection → To meet high current requirement

SCR can stay ON during 0 to π

$$\omega_r t = \pi$$

$$t = \frac{\pi}{\omega_r} = \text{maximum conduction time of SCR.}$$

α → firing angle → converter

$$\omega_r t = \pi - \alpha$$

$$t = \frac{\pi - \alpha}{\omega_r} \leftarrow \text{conduction time of SCR.}$$

L-21

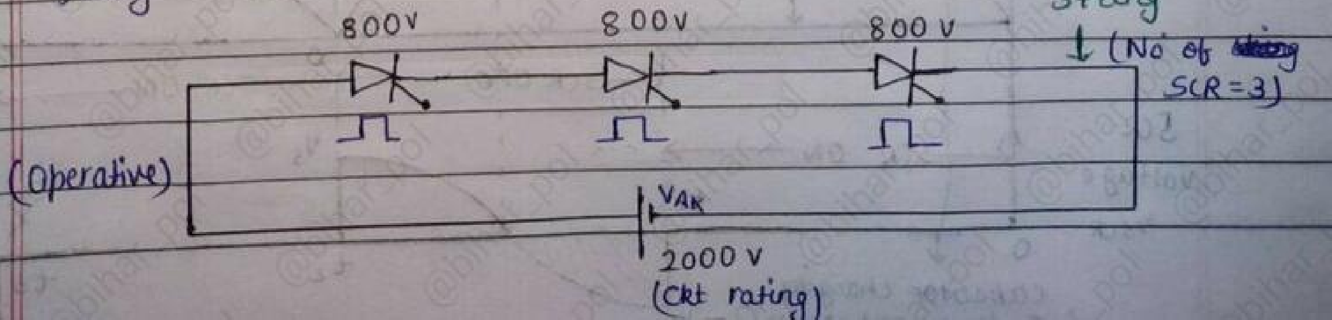
* Series and Parallel Operation of SCR

→ For some industrial application the demand of voltage and current rating is very high that a single SCR can't handle to fulfill such a requirement.

→ In such cases, SCRs are connected in series in order to achieve high voltage demand, and those SCRs are connected in parallel for fulfill the high current demand.

→ Nowadays, SCRs are available of ratings upto 10 KV and 3KA. But sometimes we face demand, more than these ratings. In this case combination of more than one SCRs is used. Series connection of SCRs meets high voltage demand and parallel connection ~~combination~~ of SCRs meets high current demand.

• These series and parallel connection of SCR or Thyristor will work efficiently if all SCRs are fully utilized.

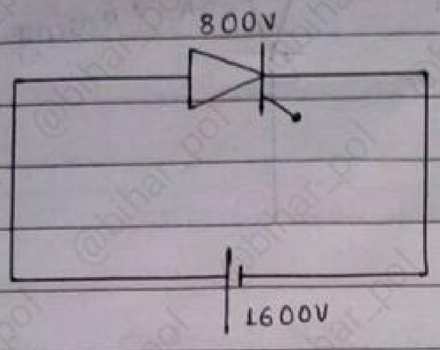


Let,

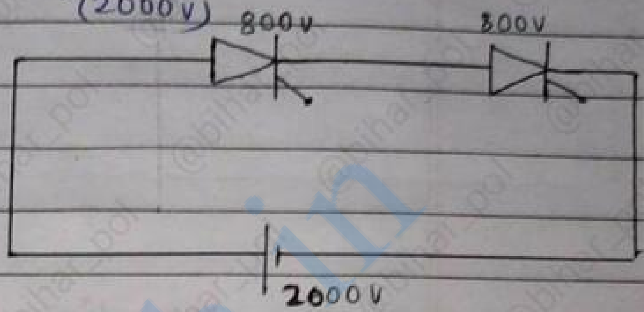
ckt → SCR Rating → 800V → (five SCR)

(Rating of 1 SCR)

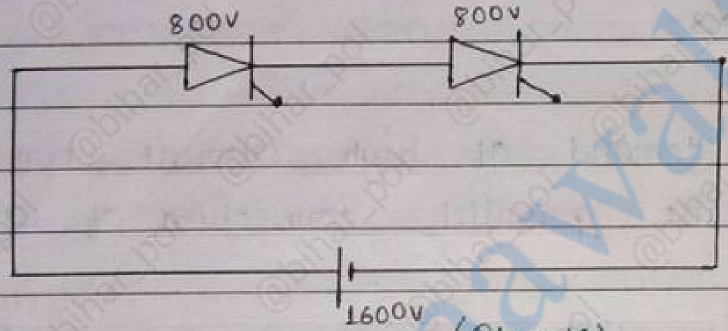
ckt design → our requirement → 1600V ↘ (2000V)



(cannot operate)



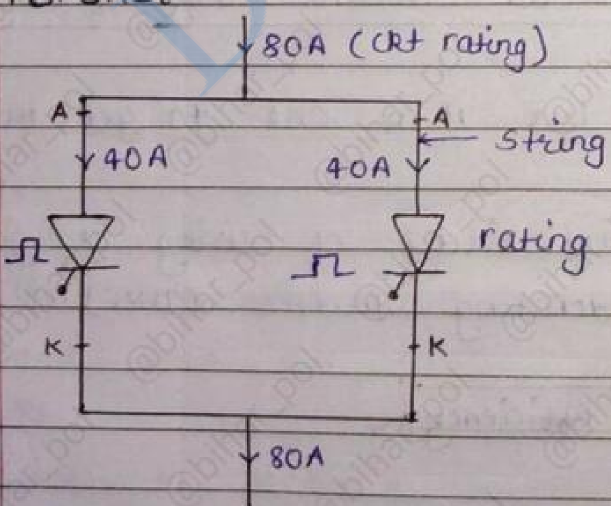
(cannot operate)



(Operate)

*** To meet the requirement of high voltage demand we have to use series connection of SCR.

- Parallel



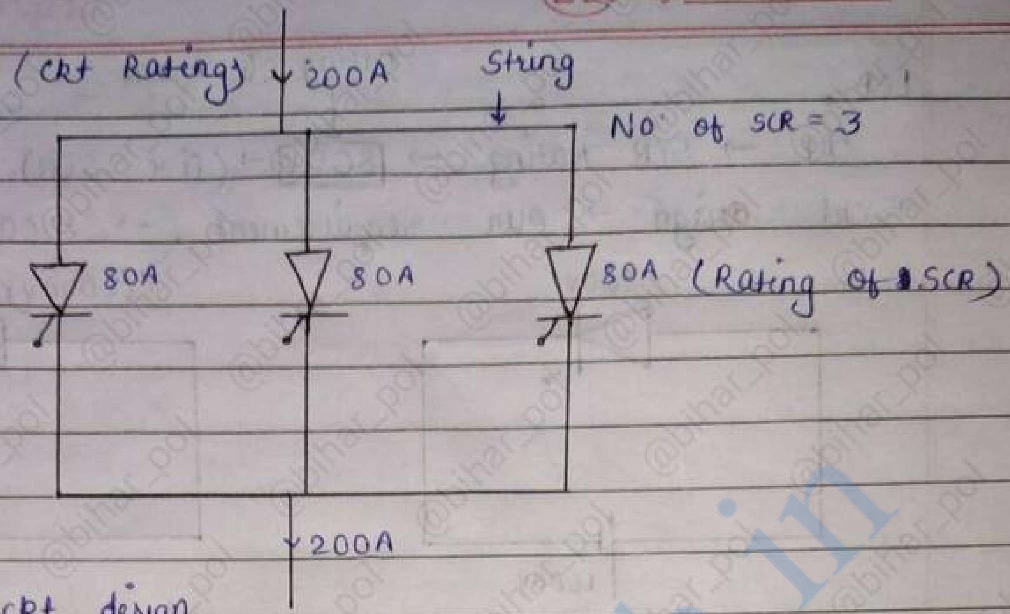
No. of SCR → 2

rating of SCR → 40 A

SCR → 40A → current Rating

× 2 → SCR

80 A



200A → ckt design
80A → SCR → Available
No of SCR → 3

★ * To meet the demand of high current requirement we have to use parallel connection of SCR.

⇒ In series or parallel connection of SCR, a term string efficiency is defined as —

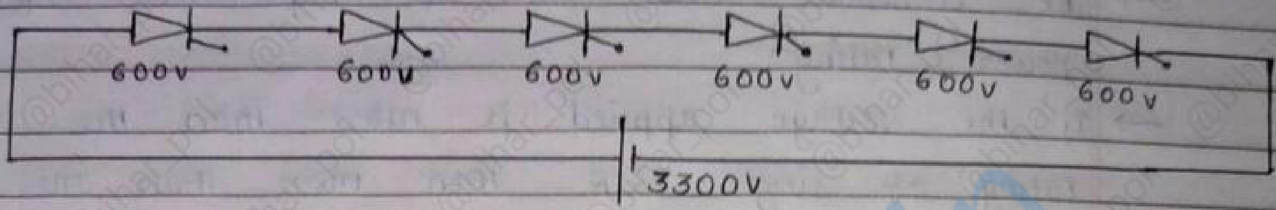
$$\text{String Efficiency} = \frac{\text{Actual voltage / current rating of whole string (ckt)}}{\text{No of thyristors} \times \text{Individual voltage or current rating of on SCR}}$$

→ String efficiency being less than one to get best result.

→ A measure of the reliability of string is given by a factor called derating factor (DRF):

$$\text{DRF} = 1 - \text{String efficiency}$$

Q. For a string voltage of 3300V, there be six series connected SCR, each SCR rating 600V. Find String efficiency and DRF.



⇒ Given,

Voltage rating of each SCR = 600V

No. of SCR = 6

String voltage = 3300 V

$$\therefore \text{String efficiency} = \frac{\text{Actual voltage rating of whole string}}{\text{No. of SCR} \times \text{Individual voltage rating of SCR}}$$

$$\eta = \frac{3300\ V}{6 \times 600 V}$$

$$= \frac{3300}{3600} = 0.917$$

$$= 91.7\ \%\ Ans.$$

$$DRF = 1 - \eta$$

$$= 1 - 0.917$$

$$= 0.083$$

$$= 8.3\ \%\ Ans.$$

L-22
V.V.I
Q. Why series and Parallel operation of SCR is used?

⇒ The SCR with voltage and current rating of 10 KV and 3KA are easily available todays.

It is necessary to operate SCR in series or parallel due to following reasons :—

→ The SCR with high power rating is not easily available so low power SCR may be operated in series or parallel to obtained the required high ratings.

→ Use of low power device in series or parallel may be economical than use of single device of high power rating.

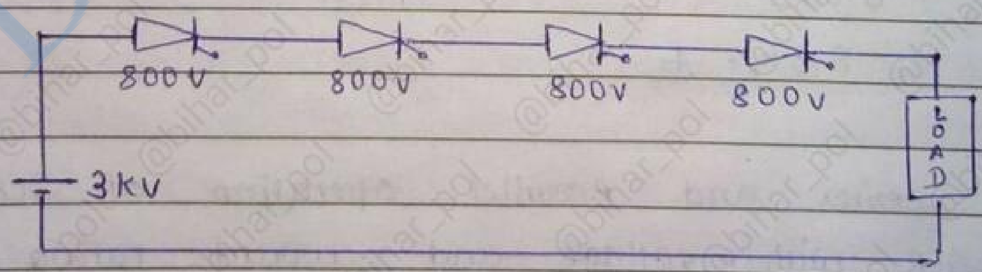
→ If the voltage applied is more than the voltage rating of single SCR then more than one SCR of same class is connected in series like a string which will suit to the applied voltage.

→ If the applied current is more than total current rating of SCR then more than one SCR of same class is connected in parallel which will suit the total current.

Q. In a power circuit of 3KV, four SCR each of rating 800V are connected in series what is the percentage of series derating factor (DRF)

(a) 50 (b) 25 (c) 12.5 (d) 6.25

$$\text{String efficiency} = \frac{\text{Actual voltage rating of whole string}}{\text{No. of SCR} \times \text{Individual voltage rating of one SCR}}$$



Given,

No. of SCR = 4

~~Supply~~ = String voltage = 3KV = 3 × 1000 = 3000V

Individual voltage rating of one SCR = 800V

$\frac{dv}{dt} \rightarrow$ False Turn ON
↓
(Not damaged)

Q. What happen on SCR because of dv/dt ?
(a) False turn ON (b) damaged (c) No effect (d) None.

$$\eta = \frac{3000V}{4 \times 800V} = \frac{3000}{3200} = 0.9375 = 93.75\%$$

$\therefore$ DRF $= 1 - \eta$
$= 1 - 0.9375$
$= 0.0625 \times 100$
$= 6.25\%$ Ans.

Q. A thyristor string is made up of a no. of SCRs connected in series and parallel. The string has voltage and current rating of 11 KV and 4 KA respectively. The voltage and current rating of available SCRs are 1800 V and 1000 A respectively, for a string of 90%. Calculate the no. of series and parallel connected SCRs.

⇒ Given,
Actual voltage = 11 KV = 11000 V
Actual current = 4 KA = 4000 A
Voltage rating of each SCR = 1800 V
Current rating of each SCR = 1000 A
String efficiency = 90%
Let the no. of series connected SCRs be n_1.
Let the no. of parallel connected SCRs be n_2.
For series connected SCRs,
String efficiency, $\eta = 90\%$

$$\therefore \frac{11000V}{n_1 \times 1800V} = \frac{90}{100}$$

$$n_1 = \frac{1100}{162} = 6.79 \simeq 7$$

$\therefore$ No. of series connected SCRs = 7 Ans.

For parallel connected SCRs,
string efficiency, $\eta = 90\%$.

$$\therefore \frac{4000\ A}{n_2 \times 1000 A} = \frac{90}{100}$$

$$\Rightarrow n_2 = \frac{40}{9} = 4.44 \simeq 4$$

$\therefore$ No. of parallel connected SCRs $\simeq 4$ Ans.

V.V.I.

Applications of SCR

1. It is used for phase control. (AC voltage controller).
2. It is used for power control.
3. It is used for light dimming control. (light intensity)
4. It is used for temperature control.
5. It is used for motor speed control. (AC motor, DC motor)
6. It is used for static switch.
7. It is used for controlled rectifier. (converter)
8. It is used for inverter and chopper.
9. It is used for relay control.
10. It is used for automatic alarm system.

Causes of damage of SCR

1. Exceeding the voltage and current rating.
2. Exceeding the di/dt and dv/dt rating. (★ False turn ON)
3. Exceeding the specified reverse voltage.
4. Excessive reverse power dissipation.
5. Repeated low energy transient causing local heating of the device.

SCR Ratings

→ SCR rating indicates voltage, power, current and temperature limit which a SCR uses without getting damaged.

→ Rating and specification serve as a link between the designer and the user of SCR system. For reliable operation, it is to ensure that current and voltage rating do not exceed during its working.

1. Current Rating
2. Surge current Rating
3. RMS current Rating
4. I^2t Rating
5. di/dt rating
6. dv/dt rating
7. Anode voltage Rating

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1. Average Current Rating

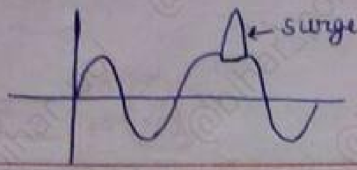
→ This is the average current of SCR that can safely carry without exceeding the junction temperature limit.

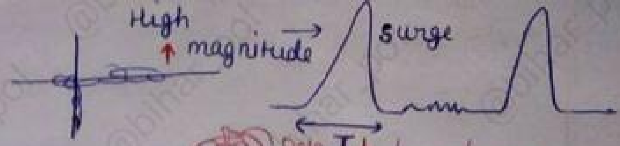
→ The average current ~~during~~ rating depends on the temperature and the time for which a device operates per cycle.

Imp. → The average value of SCR current also depends on the shape of the current flowing through it.

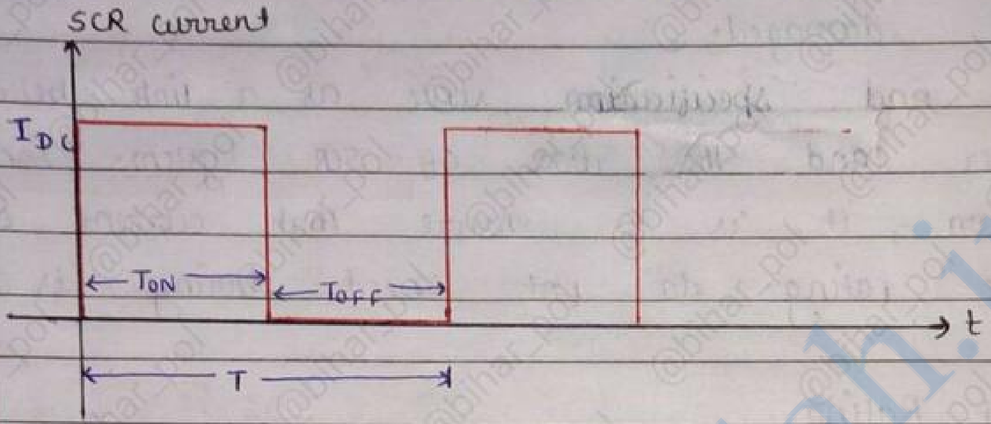
→ If the SCR current is rectangular in shape, then the average current is proportional to the ~~ratio~~ duty cycle of the waveform which is the ratio of on-time to the total time.

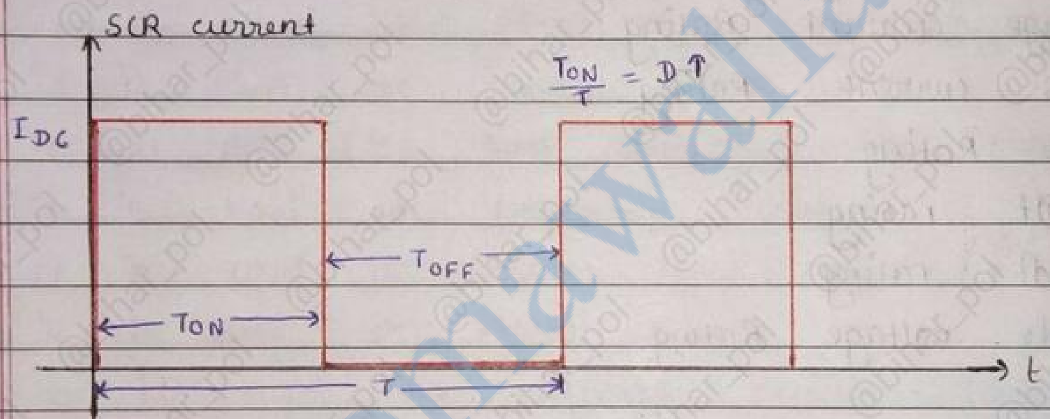
Surge caused due to
i) Naturally
ii) Switching action





→ With increase in the duty cycle, the average current value increases even though the peak value of current is same (I_{DC}).





- Duty cycle – $D = \frac{T_{ON}}{T}$

D ↑ Avg. current ↑

2. Surge Current Rating

→ The surge current rating indicates the maximum possible non repetitive or surge current which the device can withstand without damaging itself.

→ The surge current is assumed to be sinusoidal at 50 Hz. It is specified in terms of number of number of surge cycle with a specific peak value.

obj → As the duration of the surge increases, the surge rating decreases.

3. RMS Current Rating

→ The power loss and ~~healthy~~ heating of an SCR depends on the R.M.S value of SCR current. The RMS and average value are identical for a direct current.

→ The RMS current rating is shown on the specification sheet. For individual SCR, it is necessary to prevent excessive heating in the resistive ~~current~~ element of SCR such as joints, leads etc.

→ The R.M.S current rating is repetitive type of current rating and if proper cooling methods are used, this rating can be increased.

4. I^2t Rating (Temperature Rating)

→ This rating gives an idea about the maximum energy, a power device can absorb or dissipate without getting damaged.

→ The current, I is the RMS value of device current for an interval, t. The I^2t rating of the device is used for selection of I^2t rating of a fuse or protecting device.

→ The I^2t rating of a fuse should be less than that of the device, otherwise it will not be successful in protecting the device against over current.

→ Typical value of $\frac{di}{dt}$ is 20 to 500 A/μsec.

* dI/dt rating

$\left(\frac{dI}{dt}\right)_{specified} > \left(\frac{dI}{dt}\right)_{Actual\ ckt\ existence}$

↳ 150 A/μsec ↳ 120 A/sec
↳ 150 A/μsec < ↳ 160 A/μsec

• SCR is good operating condition
• SCR local hotspot damaged.

5. dI/dt Rating

→ This rating of a thyristor indicates the maximum rate of rise of current from anode to cathode without any harm to the device when a thyristor is turned ON, conduction starts at a place near the gate. This small area of conduction is spread to the whole area of junction.

→ If the rate of rise of anode current (di/dt) is large as compared to the spreading velocity of carriers across the cathode junction, local hotspots will be formed near the gate connection on account of high current density. This causes the junction temperature to rise above the safe limit ~~of~~ and as a consequence, SCR may be damaged permanently.

→ Therefore, a limit on the value of di/dt at turn on is specified in amperes per micro-seconds for all SCRs.

obj → Typical value of di/dt is 20 to 500 A/μ sec.

6. Forward dv/dt Rating (False turn ON)

→ If the rate of rise of forward anode to cathode voltage is high thyristor may turn ON even when there is no gate signal and anode to cathode voltage is less than forward breakover voltage.

→ When a SCR in the forward blocking mode the applied voltage appears across junction J_2, junction J_1 and J_3 are forward biased. The reverse biased junction behaves like a capacitor.

→ When forward voltage is suddenly applied to the device a charging current $C_J \frac{dV_{AK}}{dt}$ begains to flow

* Forward dv/dt rating

Rating $\left(\frac{dv}{dt}\right)_{specified} > \left(\frac{dv}{dt}\right)_{actual}$

↳ 20V/µsec ↳ 10V/µsec — SCR false turn ON will not happen

↳ 20V/µsec ↳ 21V/µsec — SCR may false turn ON

which may turn ON the SCR.

→ The forward dv/dt rating depends on the junction temperature, higher the junction temperature lower the forward dv/dt rating of the device.

→ In practice, dv/dt triggering is never employed as it gives random turn ON of a SCR this type of triggering also leads to destructions of the device through high junction temperature.

7. Anode Voltage Rating

→ The thyristor is made up of four layer and three junction, the middle junction J_2 block the forward voltage whereas the two end junction J_1, J_3 block the reversed voltage.

→ The anode voltage rating indicate the value of maximum voltage that a SCR can withstand without a breakdown of junction area J_2 with gate ckt is open.

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Protection Of SCR

1. Overcurrent Protection

→ In an SCR due to over-current, the junction temperature exceeds the rate value and the device gets damaged.

→ Over current is interrupted by conventional fuses and circuit breakers.

→ The fault current must be interrupted before the SCR gets damaged and only the faulty branches of the network should be isolated.

→ Circuit breaker has long tripping time. So it is used for protecting SCR against continuous over loads (or) against surge currents of long duration.

→ Fast acting current limiting fuse is used to protect SCR against large surge currents of very short duration.

→ For overcurrent protection we have to connect either fuse or circuit breaker in series with the SCR.

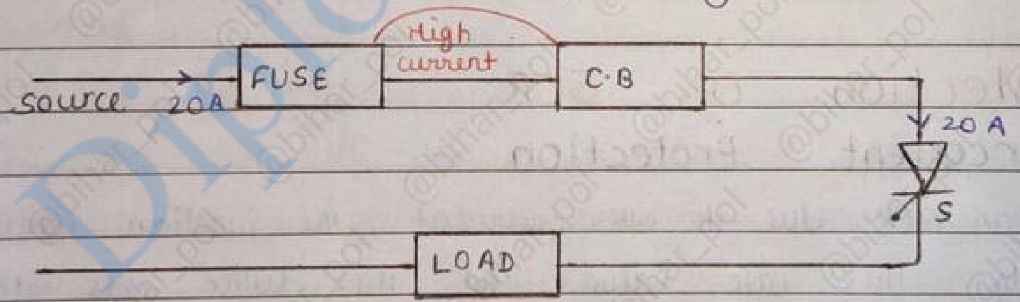
Imp. → Fast acting, fuses are normally used to protect the semi-conductor devices.

Imp. → $$(I^2t)_{fuse} < (I^2t)_{SCR}$$

I^2t rating of fuse will less than the I^2t rating of device (SCR)

NOTE :-

→ The overcurrent capability of SCR is better than that of a transistor. So protecting transistors mosfet, IGBT is more difficult than protecting the SCR.



2. Over Voltage Protection

Overvoltage may result in false turn-ON of the device (or) damage the device.

SCR is subjected to internal and external over voltage.

(a) Internal Overvoltage

→ The reverse recovery current of the SCR decays at

Internal voltage → $L\, di/dt$

External voltage → Thundering

a very fast rate i.e, high di/dt.

→ so, a voltage is produced whose magnitude is $L(di/dt)$

(b) External Overvoltage

→ These are caused by the interruption of current flow in the inductive circuit and also due to lightning strokes on the lines feeding the SCR systems.

→ The effect of overvoltage is reduced by using snubber circuits and non-linear resistors called voltage clamping devices.

→ Varistors are connected across (parallel) the SCR for overvoltage protection.

→ Varistors is non-linear resistor. All metal oxides behave as non-linear resistors.

Example :- ZnO → It is also called voltage clamping device.

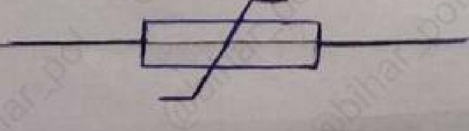
→ Metal oxide varistor (MOV) is a device, the resistance of which increases if voltage applied across it. Varistor are non-linear device. They consist of metal oxide particle seperated by an oxide film of insulation.

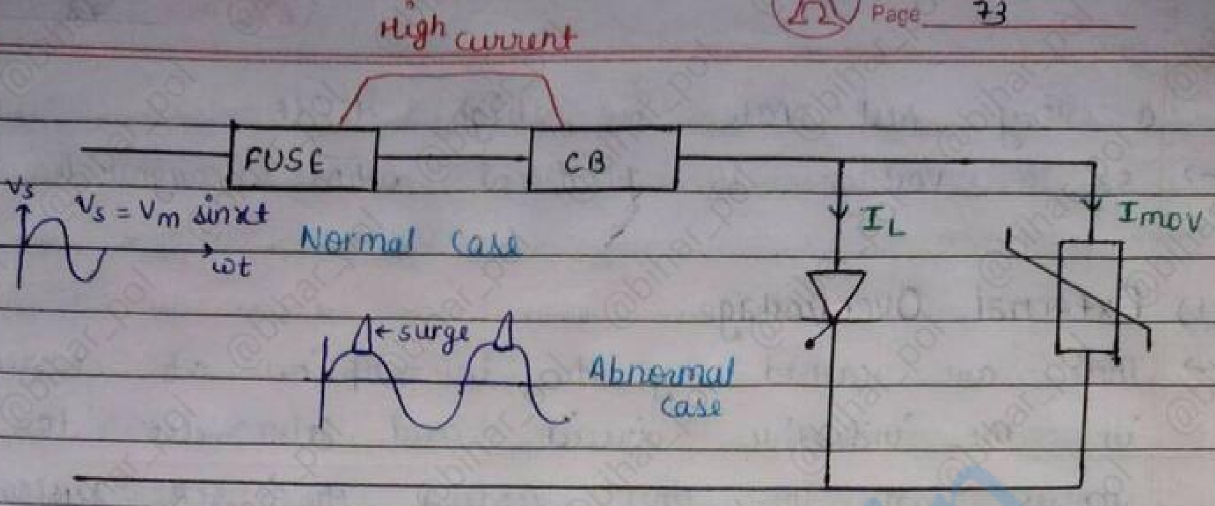
→ As the applied voltage is increased the film becomes conductive and the current flow is increased.

→ High voltage appears across MOV, its resistance decreases. so, it draws heavy current to load the AC supply.

→ This will reduced the supply voltage and the surge suppression is achieved.
↓
(bypass)

• Symbol of metal oxide varistor (MOV)

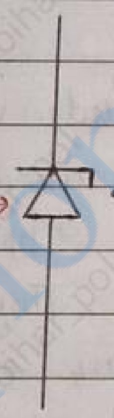




MOV
↓
High voltage
↓
Non-linear resistor

* MOV or Non-linear resistor
- Abnormal case → Surge bypassed
  V↑ R↓ I↑
- Normal case
  V↓ R↑ I↓

Selenium diode →
↓
Non linear



← Voltage clamping device
Voltage clamping ability is poor, so, it is generally not used.

→ Non-linear graph (varistor, MOV) or voltage dependent resistor ohm's law is not applied.

→ Rating of SCR depends upon type of cooling method, better the cooling method provided higher rating of the SCR.

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3. dv/dt Protection of SCR

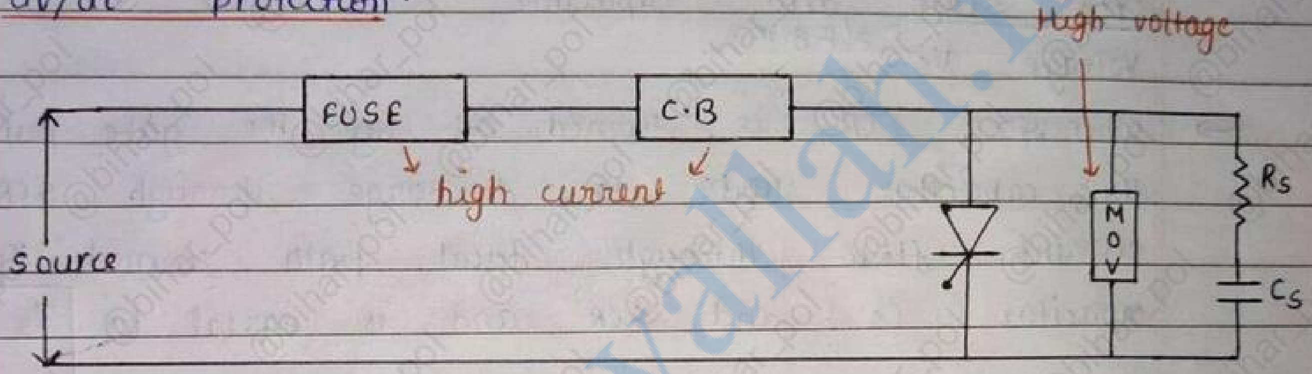
→ $\uparrow I_c = C_J \frac{dV_{AK}}{dt} \downarrow$

- Only to turn on the SCR.
- SCR cannot be damaged.

→ For controllable operation of SCR, the rate of rise of forward anode to cathode voltage dV_{AK}/dt must be kept below specified limit.

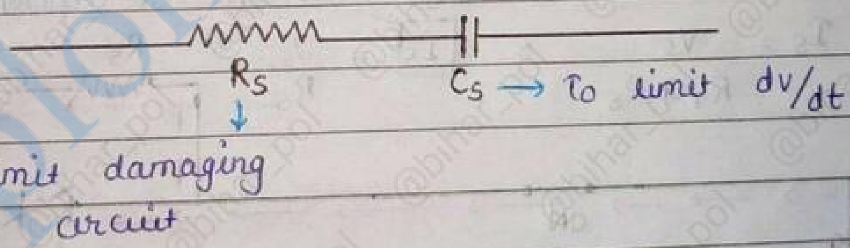
→ Typical value of dv/dt = 20 - 500 v/μs

obj → Snubber circuit is connected across the SCR for dv/dt protection.

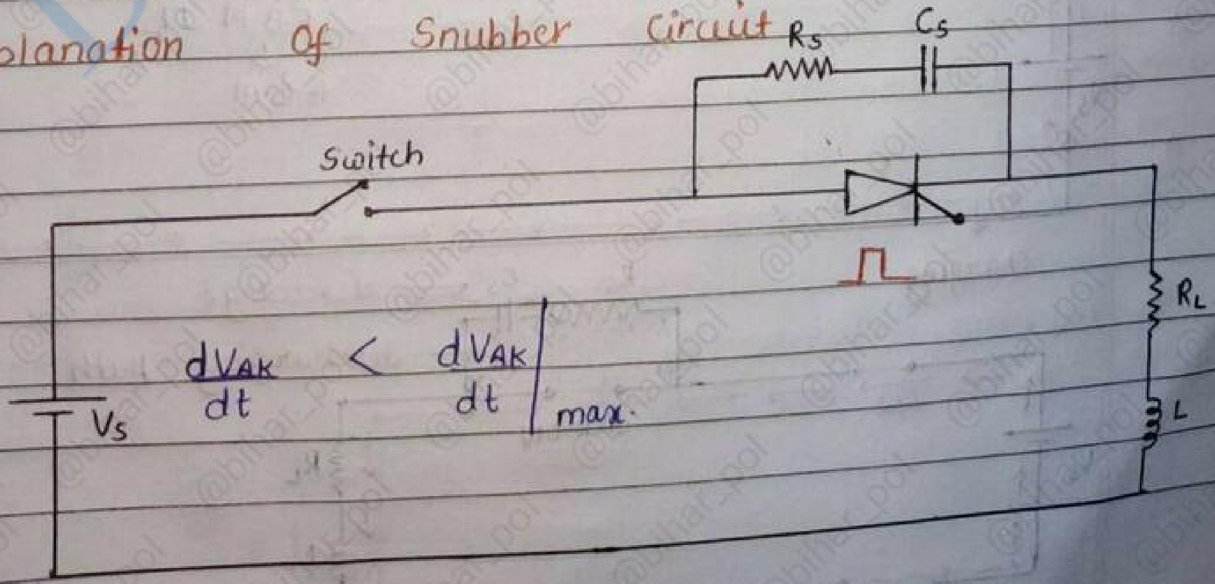


R_S - Snubber resistance

C_S - snubber capacitance



• Explanation Of Snubber Circuit



$$\frac{dV_{AK}}{dt} < \left.\frac{dV_{AK}}{dt}\right|_{max}$$

→ A snubber circuit consists of a series combination of a resistance R_S and a capacitance C_S and it is connected in parallel with SCR.

→ The capacitance C_S itself is sufficient to protect from unwanted abnormal triggering of the SCR.

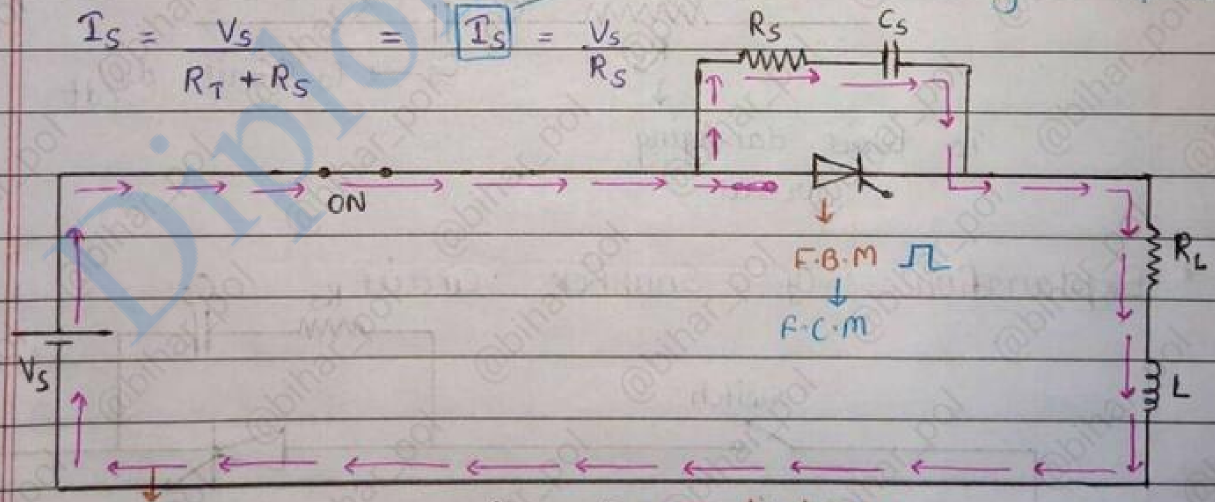
→ When gate pulse is not applied and dv/dt is less that is maximum limit, SCR will be in off state (F.B.M) and capacitor is charged to supply voltage V_S.

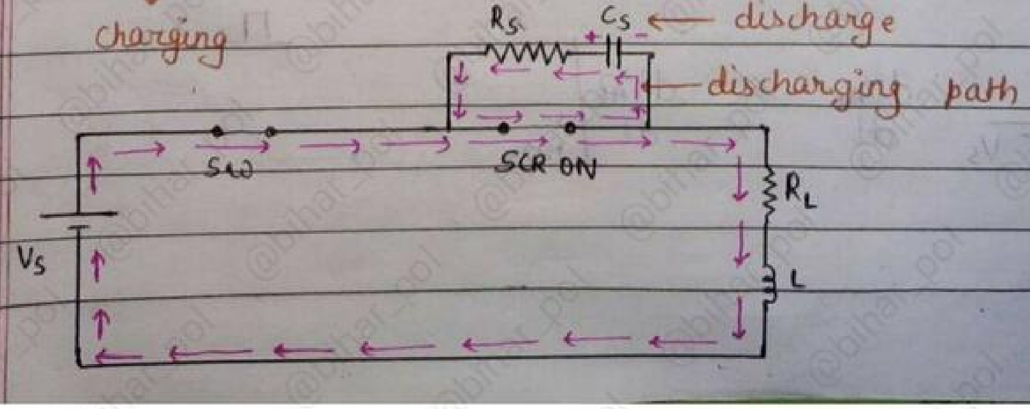
→ Whenever SCR is turned ON by the gate pulse, the capacitor starts to discharge through SCR and current flow through local path formed by capacitor C_S and SCR and is equal to $I_S = \frac{V_S}{R_T}$,

R_T is quite low, I_S is high.

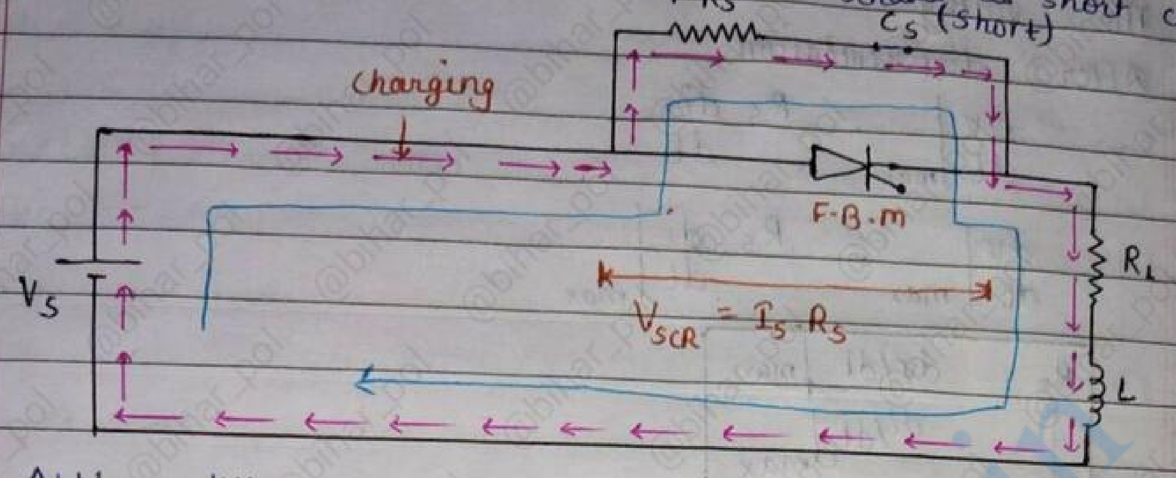
→ So, for the safe value, we have to connect the series resistance R_S. → In SCR current rating is specified.

$$I_S = \frac{V_S}{R_T + R_S} = I_S = \frac{V_S}{R_S}$$





When switch is closed the capacitor behaves as short ckt.



Apply KVL,

$$V_S = I_S(R_S + R_L) + L\frac{dI_S}{dt}$$

Taking LT on both sides.

Now, solution of the above equation.

$$I_S = \frac{V_S}{R_S + R_L}\left(1 - e^{-t/\tau}\right)$$

$$= I\left(1 - e^{-t/\tau}\right)$$

where,

$$I = \frac{V_S}{R_S + R_L}$$

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

After differentiation above eqⁿ

$$\frac{dI}{dT} = I e^{-t/\tau} \cdot \frac{1}{\tau}$$ $\left\{\because \text{At } t=0, \frac{di}{dt} \text{ is maximum}\right\}$

$$\frac{dI}{dt} = \frac{V_S}{(R_S + R_L)} \cdot \frac{R_S + R_L}{L} \cdot e^{-t/\tau}$$ $\{e^{-0} = 1\}$

$$\left.\frac{di}{dt}\right|_{max} = \frac{V_S}{L}$$

$$\therefore L = \frac{V_S}{\left.di/dt\right|_{max}}$$

The voltage across SCR is $V = i_s R_s$

After differentiation

$$\left.\frac{dv}{dt}\right|_{max} = R_s \frac{di_s}{dt}$$

$$\left.\frac{dv}{dt}\right|_{max} = R_s \left.\frac{di}{dt}\right|_{max}$$

$$R_s = \frac{dv/dt|_{max}}{di/dt|_{max}}$$

→ Snubber resistance

→ Snubber capacitance

$$C_s = \frac{4 \varepsilon^2 L}{(R_L + R_s)^2}$$

where,

ε = 0.4 to 0.7 underdamped condition

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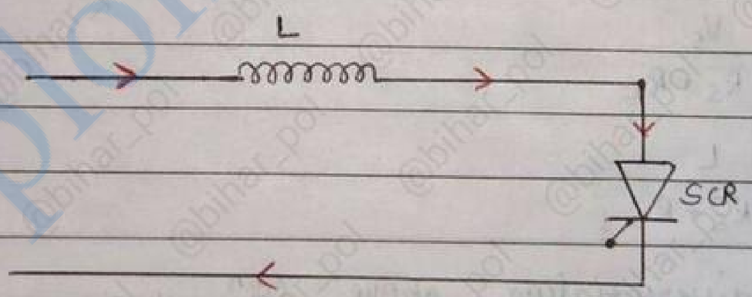
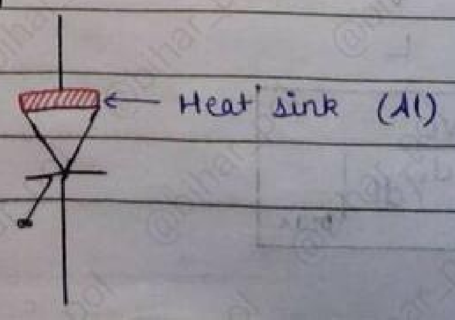
4. dI/dt Protection



★ → Connect the inductor in series with SCR to protect against dI/dt.

★ → Typical value of $\frac{dI}{dt}$ = 20-500 A/μs

5. Thermal Protection



→ For thermal protection or internal power loss heat sink is used.

6. Gate Protection

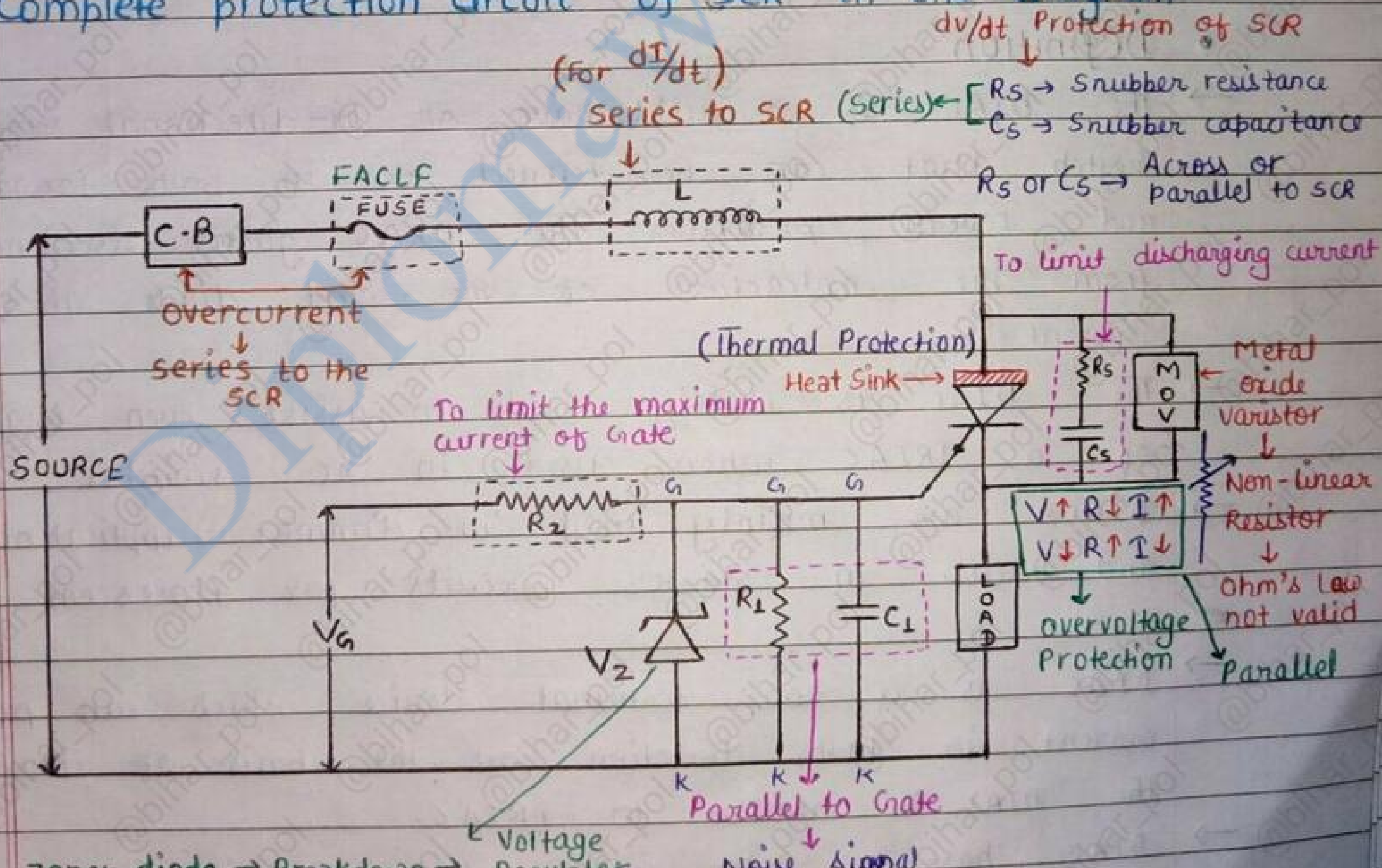
→ For overcurrent protection, resistor is used in series with SCR.

→ For overvoltage protection, zener diode is used in parallel with SCR.

★★★★★ V.V.I. A capacitor or resistor is also connected across the gate to cathode, to bypass the noise signal.

→ The capacitor value should be less than 0.1 μF.

* Complete protection Circuit of SCR in One diagram



zener diode → Breakdown → Voltage Regulator
↓
Over Voltage protection of gate terminal

→ R → dissipating element
→ L, C → charging, discharging element.
→ L cannot accept sudden change in current (di/dt)
→ C cannot accept sudden change in voltage (dv/dt)

- FACLF :- Fast acting current limiting fuse
  ↓ overcurrent Protection

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DIAC

- Definition

→ The DIAC is a full-wave or bi-directional semiconductor switch that can be turned on in both forward and reverse polarities. The DIAC gains its name from the contraction of the word diode alternating current.

→ The DIAC is widely used to assist even triggering of a TRIAC when used in AC switches.

→ DIACs are mainly used in dimmer applications and also in starter circuits for florescent lamps.

→ DIAC is a two terminal device which can pass current in both direction on the basis of construction The DIAC is similar to TRIAC.

→ DIAC has no any gate supply. It is four layer semi-conductor device in which there are two SCR in antiparallel mode.

→ The terminal DIAC means (DI + AC) DI means two and AC means AC phase controller so DIAC is a two terminal device which control ac phase.

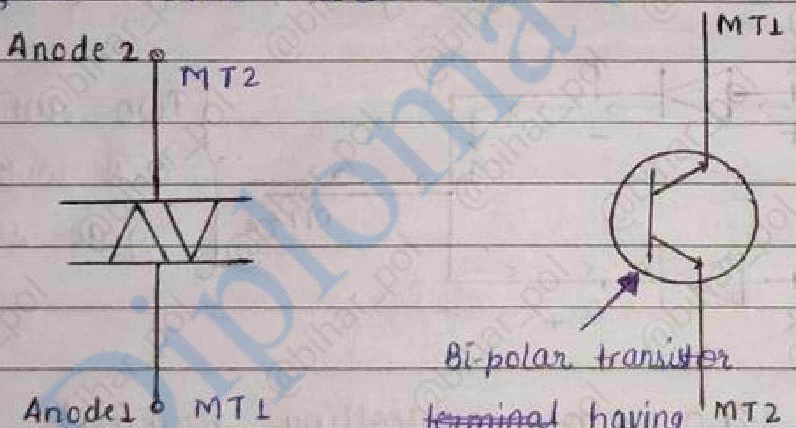
DIAC ⟶ DI + AC
DI ↓ Two
AC ↓ Alternating current.

→ The terminal are not named it can be used in any direction, it is low power triggering device and no control terminal.

- Circuit Symbol

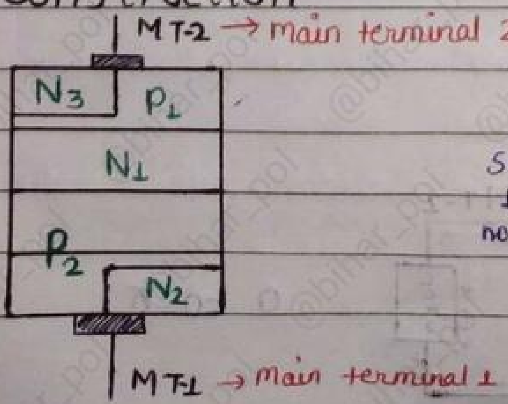
→ This demonstrates the structure of the device which can be considered also as two junctions.

→ The two terminals of the device are normally designated either Anode 1 and Anode 2 or main terminal 1 and 2, i.e MT1 and MT2



* It is also known as TRIAC having no Gate signal.

- Construction



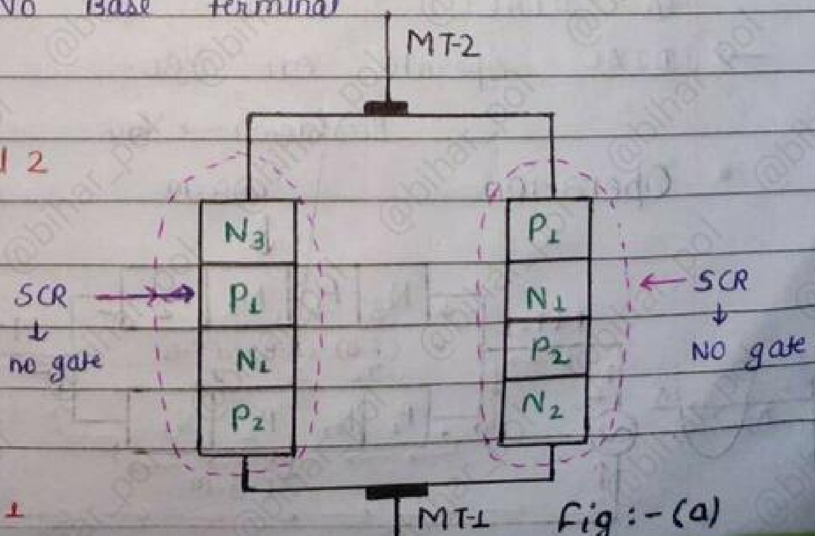
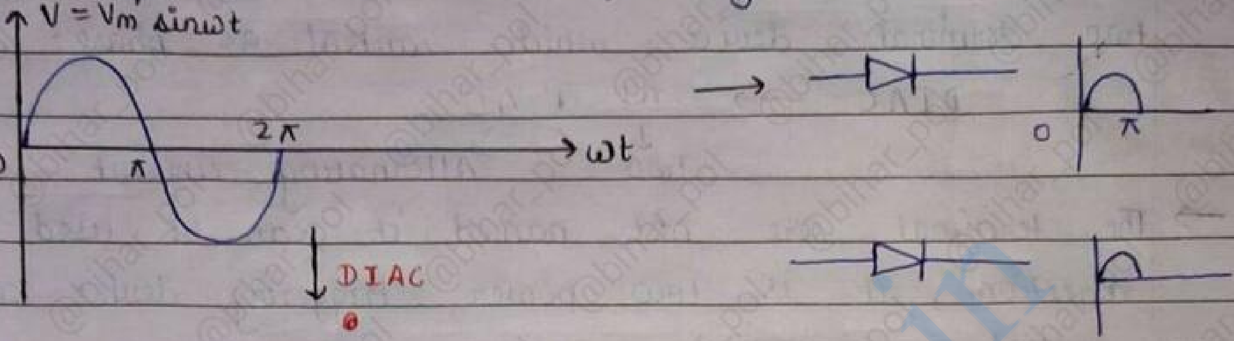
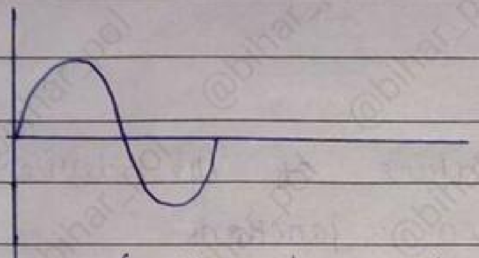


Fig :- (a)

• DIAC
→ Two SCR antiparallel.
→ Bidirectional AC switch Two terminal
→ uncontrolled device.

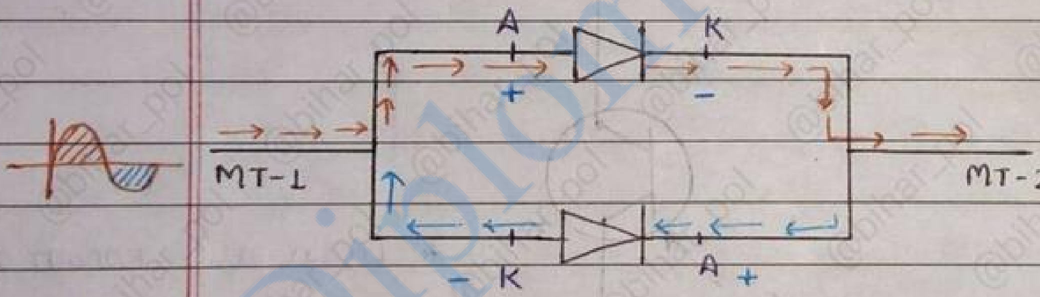
- DIAC only works on AC only.
- It operates on both polarity of AC.





(output is same)

Symbol Representation of fig:-(a)



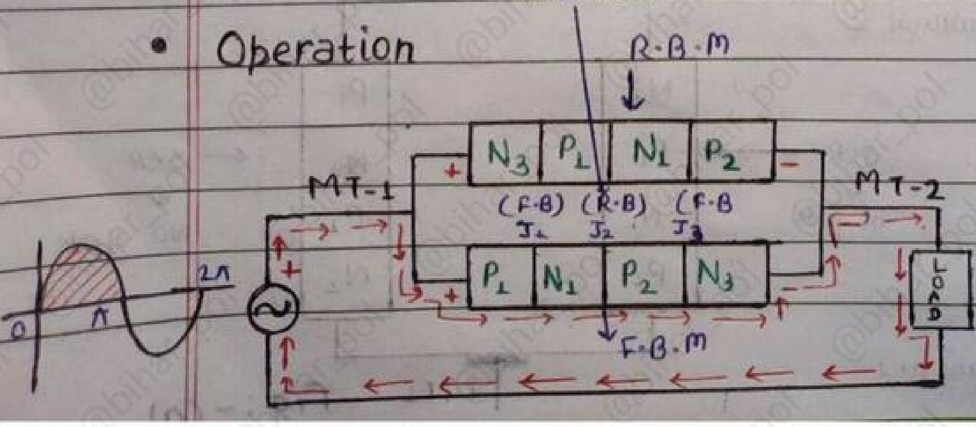
{Two antiparallel SCR with no any gate supply.}

→ There is no any controlling terminal present in DIAC.

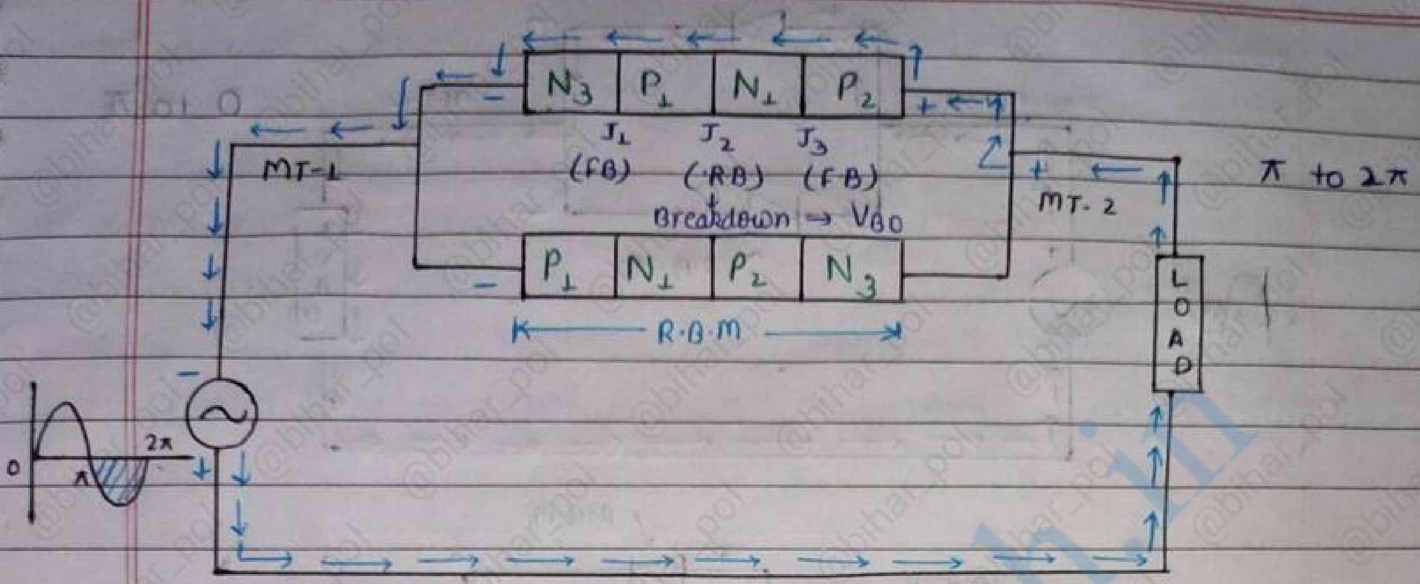
→ DIAC operate on V_{BO}.

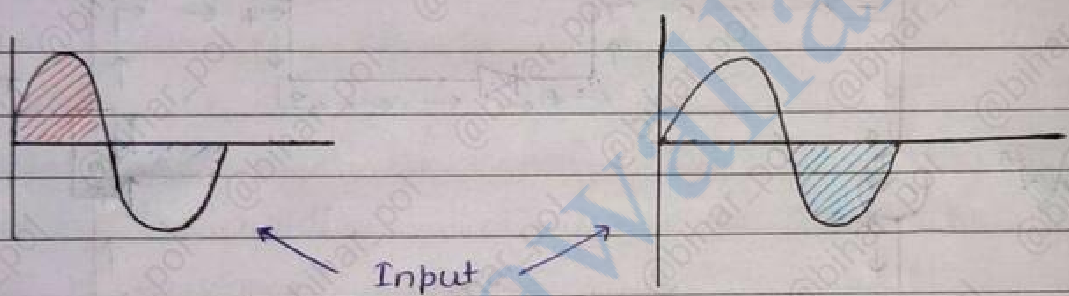
Breakdown → V_{BO}

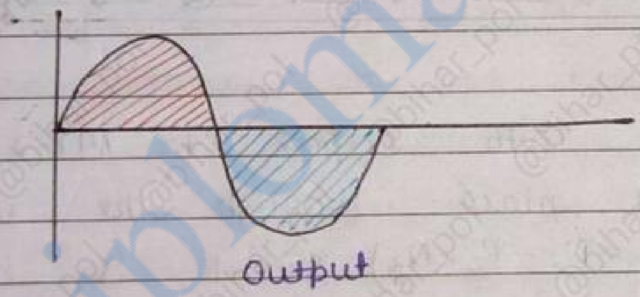
- Operation

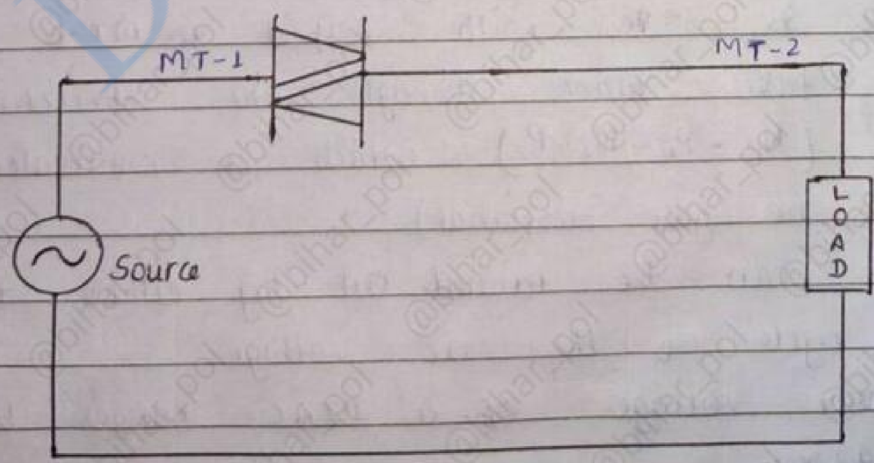


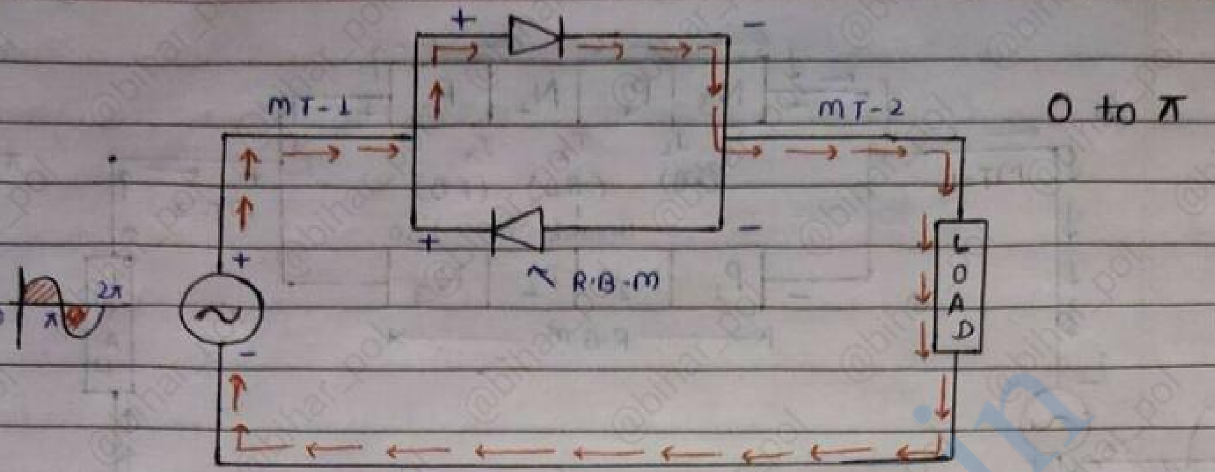
0 to π

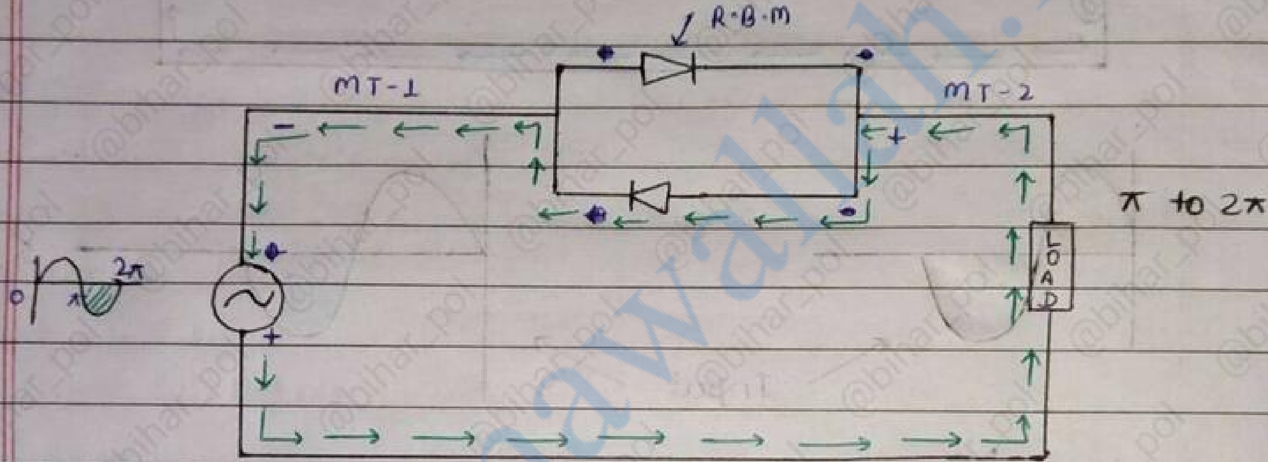

N3 P1 N1 P2
J1 J2 J3
(FB) (RB) (FB)
Breakdown → VBO
MT-1
MT-2
P1 N1 P2 N3
R·B·M
LOAD
0
π
2π
π to 2π


Input


Output


MT-1
MT-2
LOAD
Source





→ When MT-1 is +ve with respect to MT-2, the conduction takes place through the structure formed by ($P_1 - N_1 - P_2 - N_3$) which is equivalent to SCR (with no gate terminal).

→ When MT-2 is +ve with respect to MT-1, the conduction takes place through the structure formed by ($N_3 - P_1 - N_1 - P_2$) which is equivalent to SCR (with no gate terminal)

→ The device can be turned on by either +ve or -ve half cycle of the ac voltage.

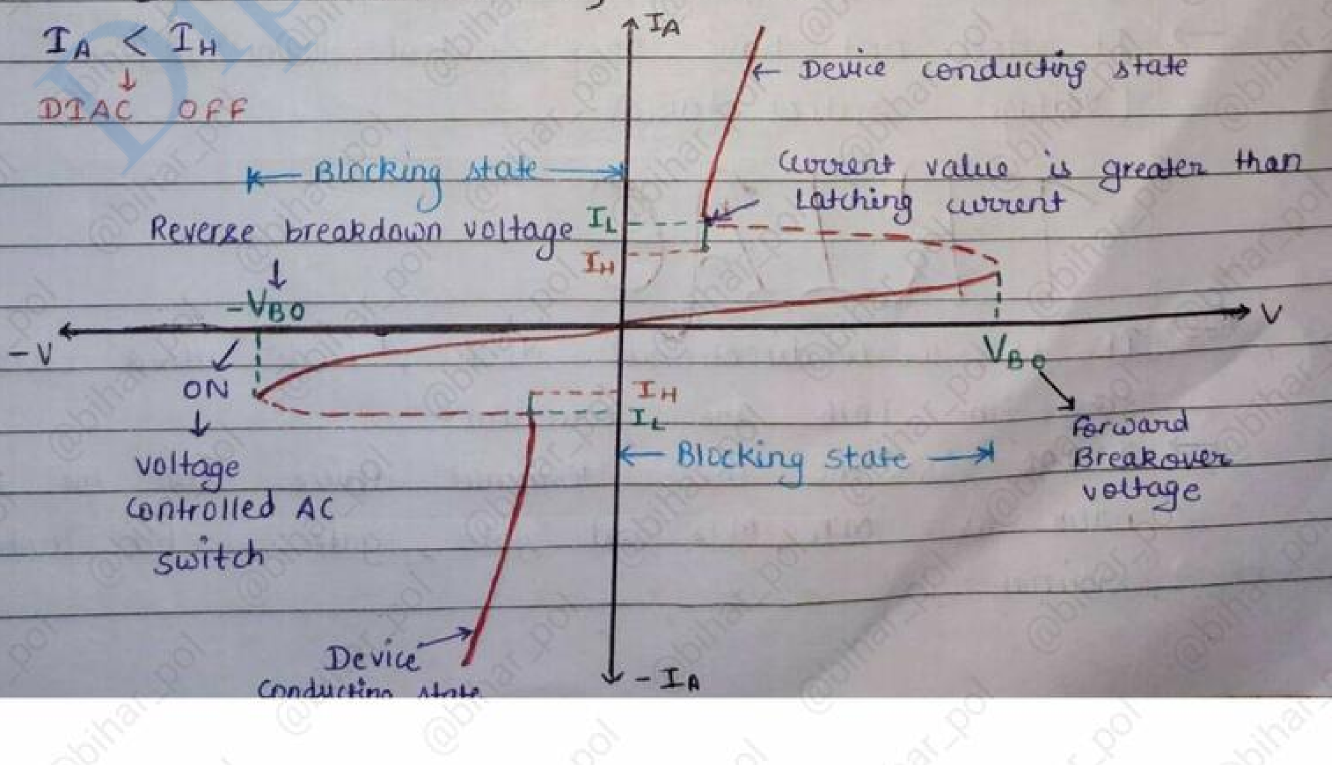
→ The breakover voltage of a DIAC ranges between 20V to 42V.

- Operation

→ The DIAC is essentially a diode that conducts after a 'break-over' voltage, designated V_{BO} is exceeded.
→ when the device exceeds this break-over voltage, it enters the region of negative dynamic resistance.
→ This results in a decrease in the voltage drop across the diode with increasing voltage. Accordingly, there is a sharp increase in the level of current that is conducted by the device.
→ The diode remains in its conduction state until the current through it drops below what is termed the holding current, which is normally designated by the letters I_H.
→ Below the holding current, the DIAC reverts to its high-resistance state.
→ Its behaviour is bi-directional and therefore its operation occurs on both halves of an alternating cycle.

L-28

- V-I Characteristics of DIAC



★ TRIAC can be turned on both +ve and -ve supply of gate.

→ When the forward voltage is less than the breakover voltage, then the DIAC is off and the small current flows. $(V_F < V_{BO})$

→ When the applied forward voltage becomes more than V_{BO} then DIAC becomes ON and conducts so that large current flows through it. $(V_F > V_{BO})$

→ The DIAC remains ON as long the current through it is greater than the holding current. $(I < I_H)$

⇒ The break over voltage of DIAC ranges in between 28 volt to 42 volt.

- Application

→ Lamp dimmer

→ Fan speed Regulation

→ Temperature controller

→ AC switches

- Disadvantage

→ It is a low power device

→ It does not have any control terminal. (voltage control device).

TRIAC

→ It is a bi-directional device, that allow current flow in both the direction.

→ TRIAC is the three terminal device with the terminal name as MT_1, MT_2 and gate, gate is the controlling terminal.

• TRIAC two SCR antiparallel Gate present.

→ It's operation is similar to two SCR in antiparallel.
→ The gate terminal is near to MT_1.
→ TRIAC can be turned ON by applying either +ve or -ve voltage to the gate w.r.t terminal MT_1, whereas SCR can be turned on by only +ve gate signal.
→ The current flow from MT-1 to MT-2, when MT-1 is FB with respect to MT-2, similarly current flow from MT-2 to MT-1 when MT-2 is FB with respect to MT-1, the current flow, whenever the gate source is applied.

Current controlled ← V_{BO} → damaged

Bi-directional device → AC switch

TRIAC → Three — MT-1 → main terminal-1 ⎤ Power
MT-2 → main terminal-2 ⎦ terminal.
Gate → controlling terminal

Near about MT-1

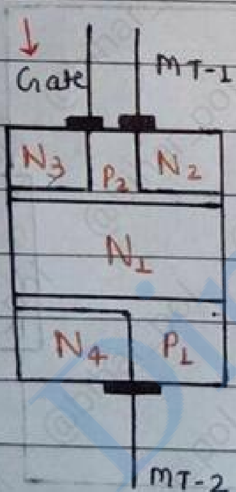


Fig:-(a)

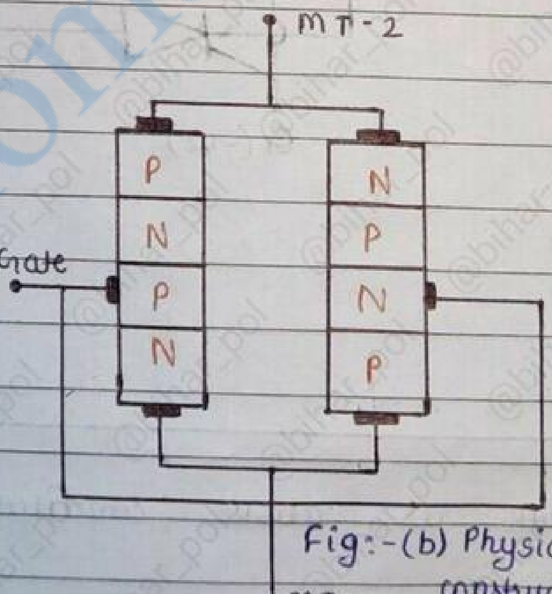


Fig:-(b) Physical construction

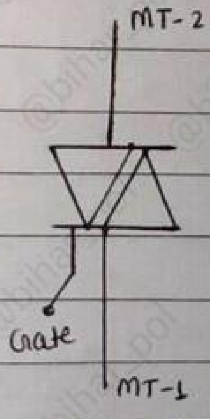


Fig:-(c) Circuit Symbol

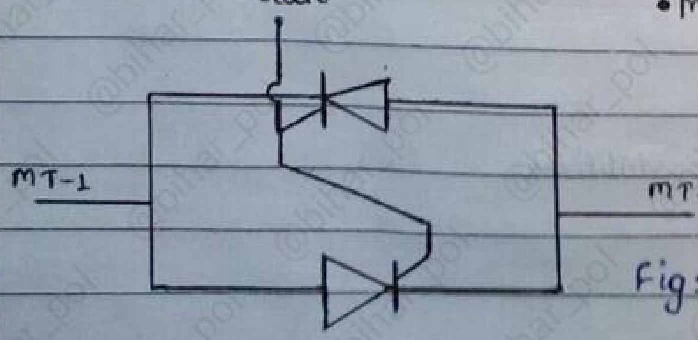
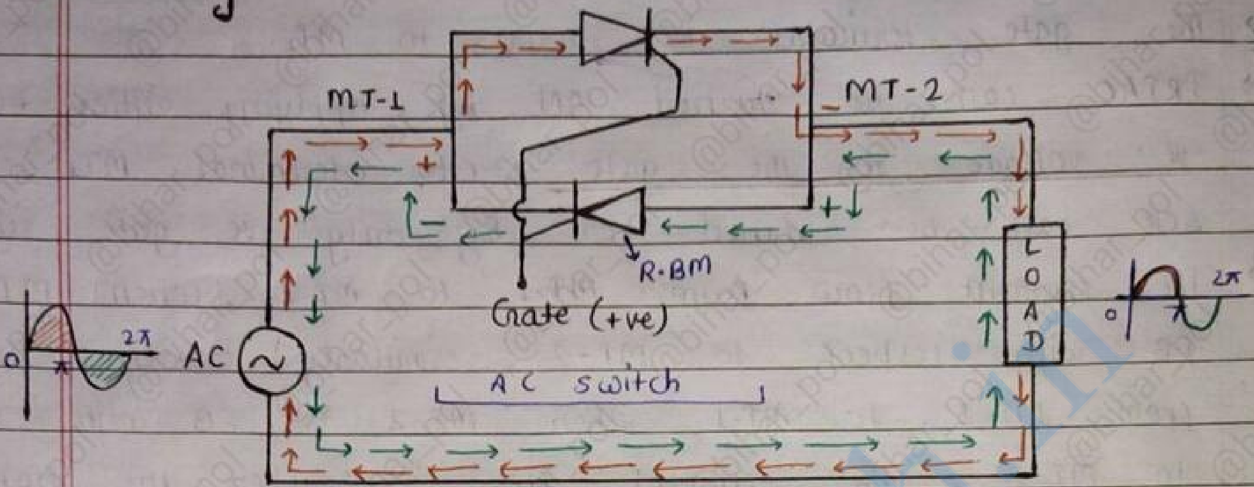


Fig:-(d) Two thyristor anology

- Working

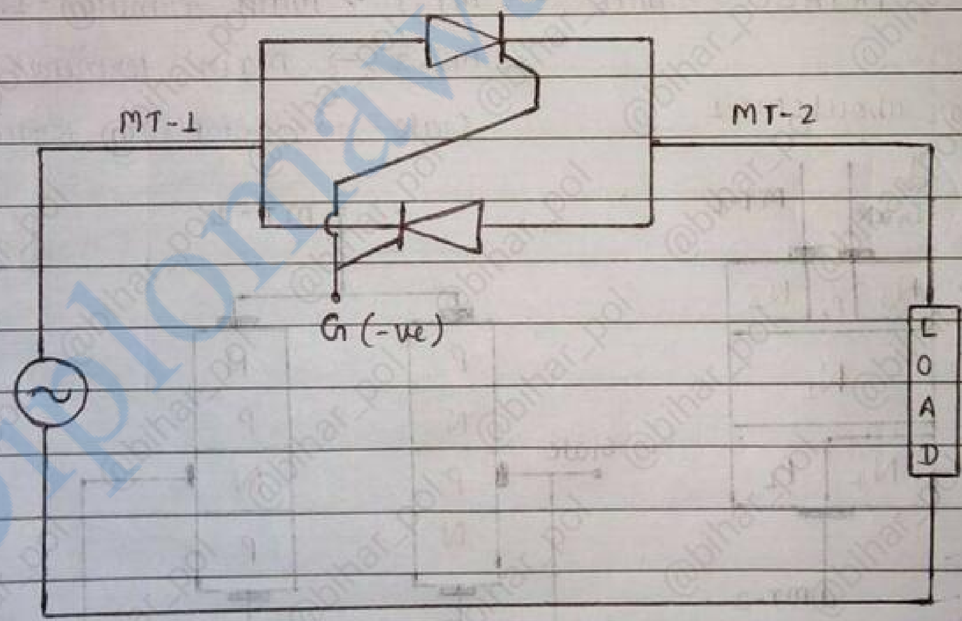


0 to π → Gate (+ve supply)

MT-1 → +ve] ON
MT-2 → -ve] MT-1 to MT-2

0 to 2π → Gate (+ve)

MT-1 → -ve] MT-2 to
MT-2 → +ve] MT-1



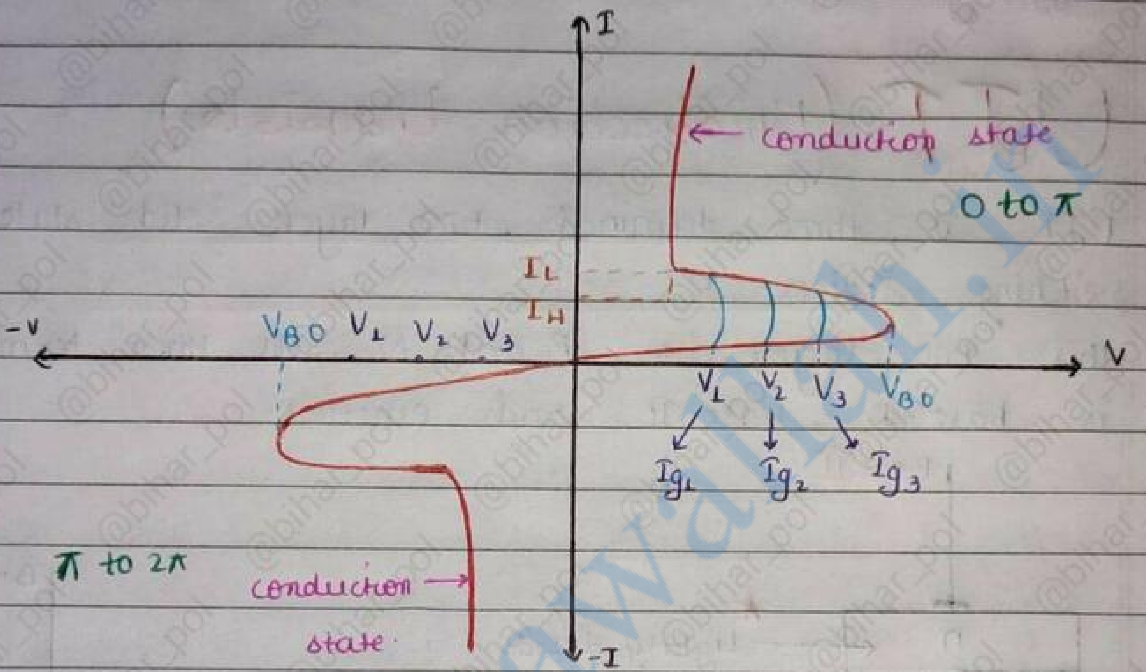
Same as above condition.

- Application

→ As a static switch
→ In the AC voltage stablizer
→ Fan speed regulator
→ lamp dimmer

→ Temperature controller
→ AC voltage controller

- V-I characteristics



- Advantage of TRIAC

1. It is a bi-directional switch, so we control the power delivered to load in both half cycle of the SCR.
2. It is equivalent to two SCR connected back to back.
3. It can be turned ON by +ve as well as -ve gate current.
4. It is more suitable for resistive load.
5. It can control power delivered to the AC load such as fan, motor.
6. It can be used single heat sink.

- Disadvantage

1. Cannot be used as controlled rectifier

2. Low dv/dt rating compare to SCR.
3. Low di/dt rating.
4. It's power rating is lower than SCR.
5. Triggering circuit is complicated.

L-29

UJT (Unidirection transistor)

→ UJT is three terminal, two layer solid state switching devices.

→ This two layer is P and N, its three terminal is base I, base II and emitter.

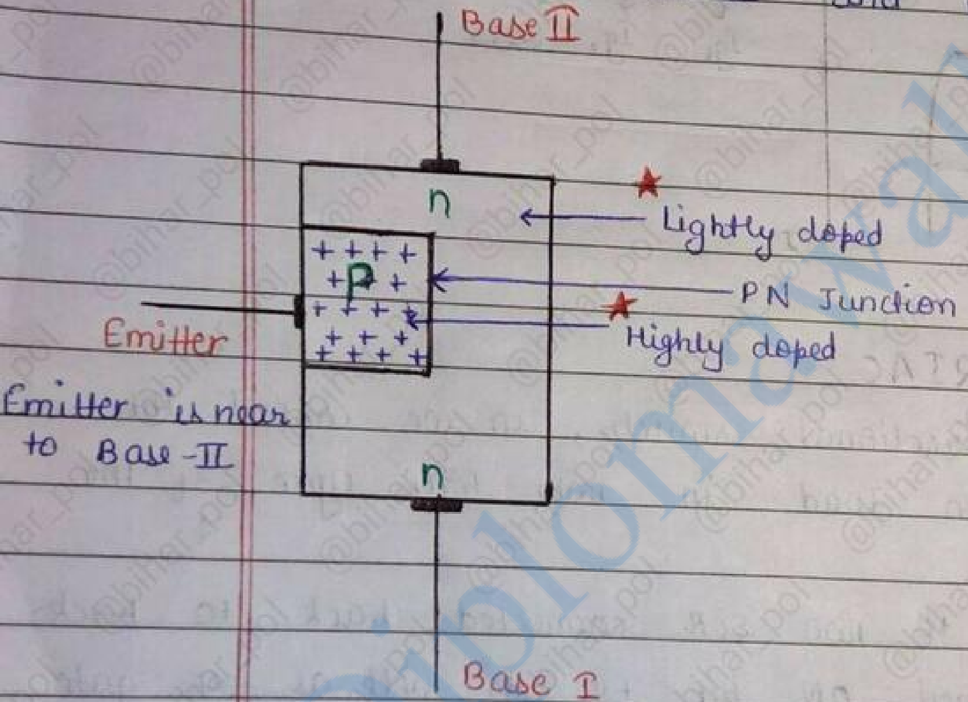


Fig (a) :- Constructional Symbol

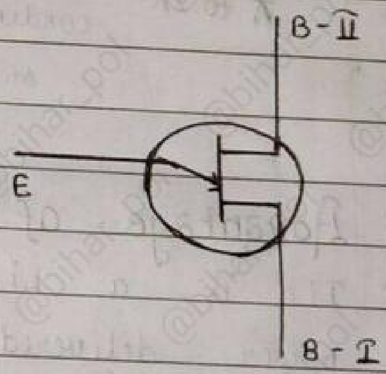


Fig (b) :- Symbol

- Construction

→ The basic structure of a UJT is shown below it consist of a lightly doped big N-type Si-material with a small piece of heavily doped P-type material alloyed with in which produced single P-N junction.

→ The N-type material consist of two terminal base-I and base - II and P- type material consist of emitter terminal.

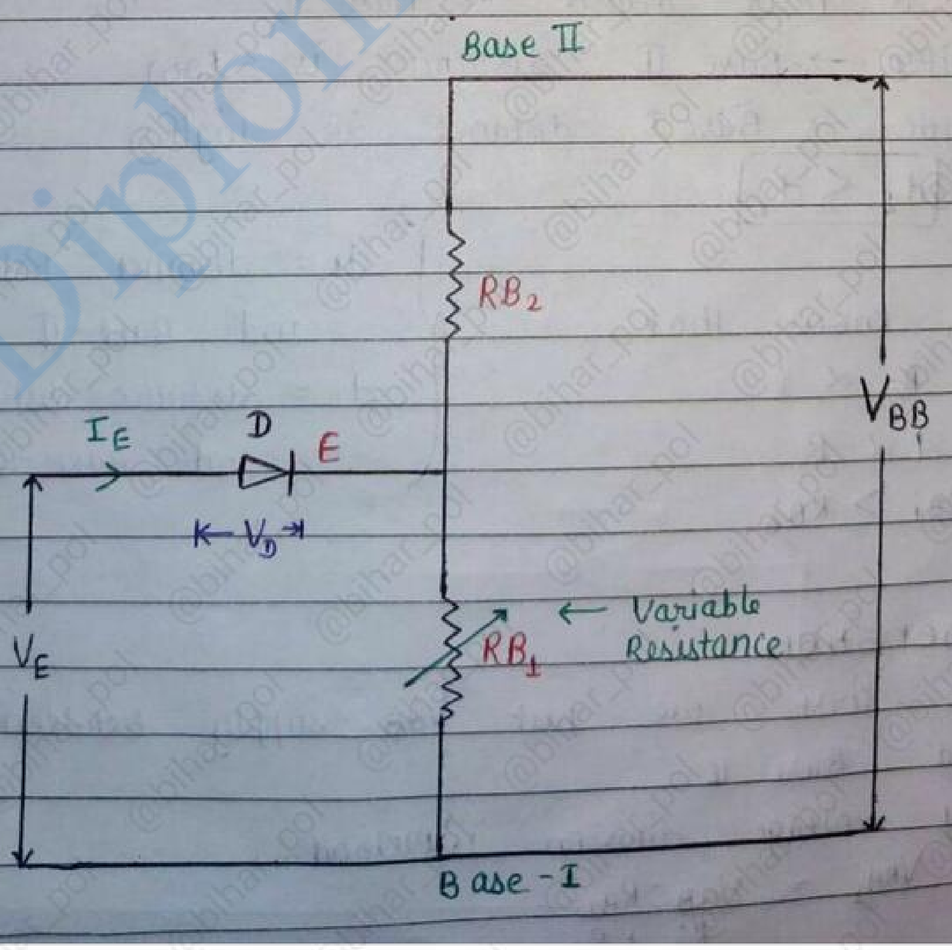
→ The emitter junction is usually located closer to base - II due to which it becomes unsymmetrical, a symmetrical system does not provide optimum electrical characteristics.

→ A P-N Junction is formed by emitter terminal.

→ The N- type Si- material being lightly doped has a high resistance and can be represented as two resistance connected in series, i.e, RB_1 and RB_2 from base - 1 to base - 2 respectively.

→ The resistance RB_1 acts as variable resistance because its value varies with variation of the emitter current

• Equivalent circuit of UJT



★ → R_{B_1} is variable because its value depends upon the basis voltage across the P-N junction.

→ The typical value of R_{B_1} may vary from 5kΩ down to 50Ω for the change in emitter current 0 to 50μA.

→ The total resistance of UJT is called inner-base resistance and it is denoted by R_{BB}

i.e,

$$R_{BB} = R_{B1} + R_{B2} \quad \text{(emitter is open)}$$

R_{BB} ↓ Inner Base resistance.

→ The value of R_{BB} lies from 4kΩ - 10kΩ. The R_{B1} is greater than R_{B2}.

$$R_{B1} > R_{B2}$$

R_{B1} = 60% of R_{BB}

* E is near about → Base II

Emitter → Base II distance is low

Emitter → Base I distance is high.

$$d_1 < d_2$$

We know that

$R \propto l$

$\therefore d \propto R$

$R_{B1} > R_{B2}$

d_1 = distance between Emitter and Base-II

d_2 = distance between Emitter and Base - I

- Operation

At first we put V_{BB} supply between Base-I and Base II.

By voltage division method

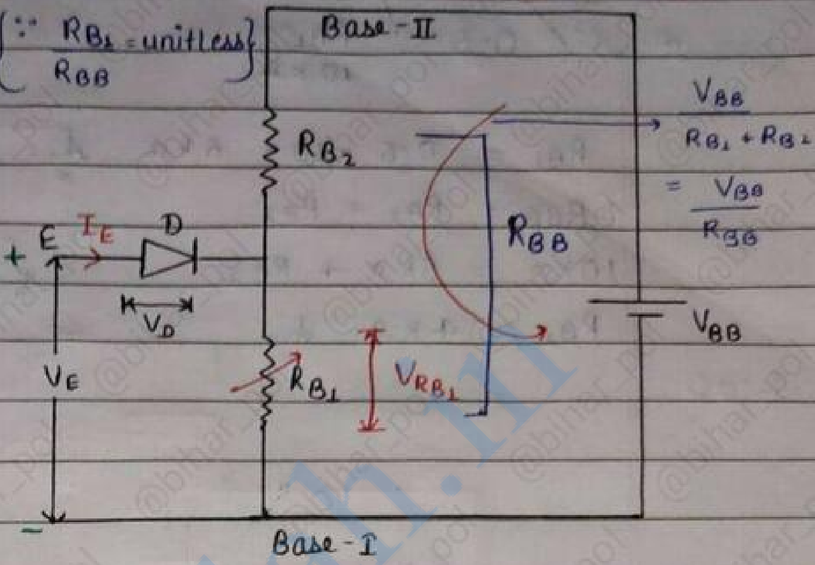
$$V_{RB_1} = \frac{V_{BB} \cdot R_{B1}}{R_{B1} + R_{B2}}$$

$$V_{RB_1} = \frac{V_{BB} \cdot R_{B1}}{R_{BB}}$$ $\left\{ \because \frac{R_{B1}}{R_{BB}} = \text{unitless} \right\}$

$$\boxed{V_{RB_1} = V_{BB} \cdot \eta}$$

Here,

★★ η = Intrinsic Stand off Ratio



- Intrinsic Stand off ratio is the internal property of the UJT, It's value lies between 0 and 1.
- Typical value of η lies in between ★ 0.5 to 0.8.

Q. $\eta = 0.6$, $R_{BB} = 10\,k\Omega$ $R_{B_2}, R_{B_1} = ?$

$\Rightarrow \eta = \frac{R_{B1}}{R_{BB}}$

$0.6 = \frac{R_{B1}}{10\,k\Omega}$

$R_{B1} = 0.6 \times 10 = 6\,k\Omega$ Ans

$\because R_{BB} = R_{B1} + R_{B2}$

$10\,k\Omega = 6\,k\Omega + R_{B2}$ $\{\because R_{B1} > R_{B2}\}$

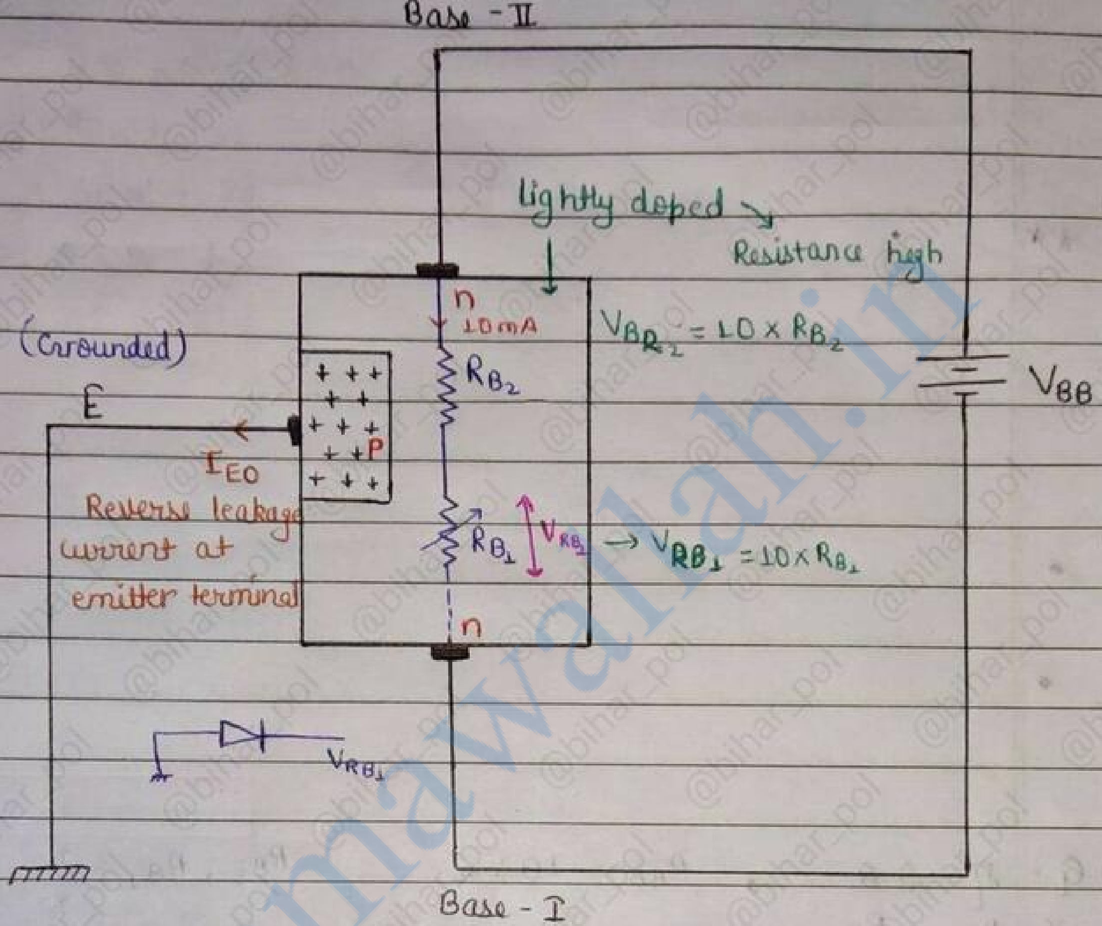
$\therefore R_{B2} = 10\,k\Omega - 6\,k\Omega$

$= 4\,k\Omega$ Ans

$\therefore R_{B1} > R_{B2}$

$\Rightarrow 6\,k\Omega > 4\,k\Omega$

* At first Emitter terminal is Grounded



→ Device does not turn ON.

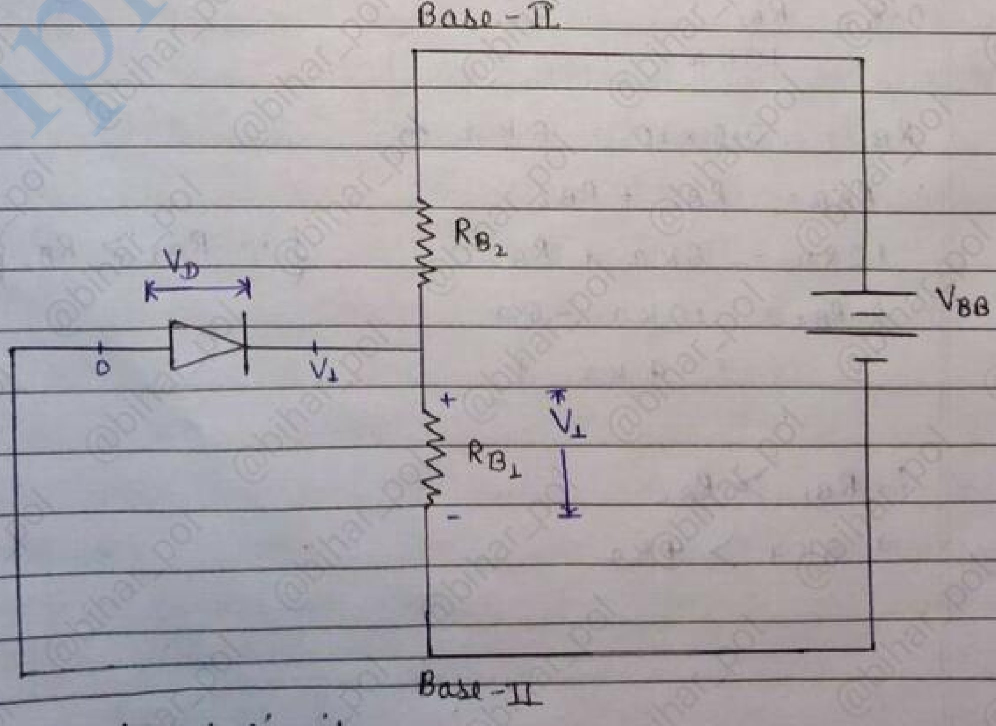
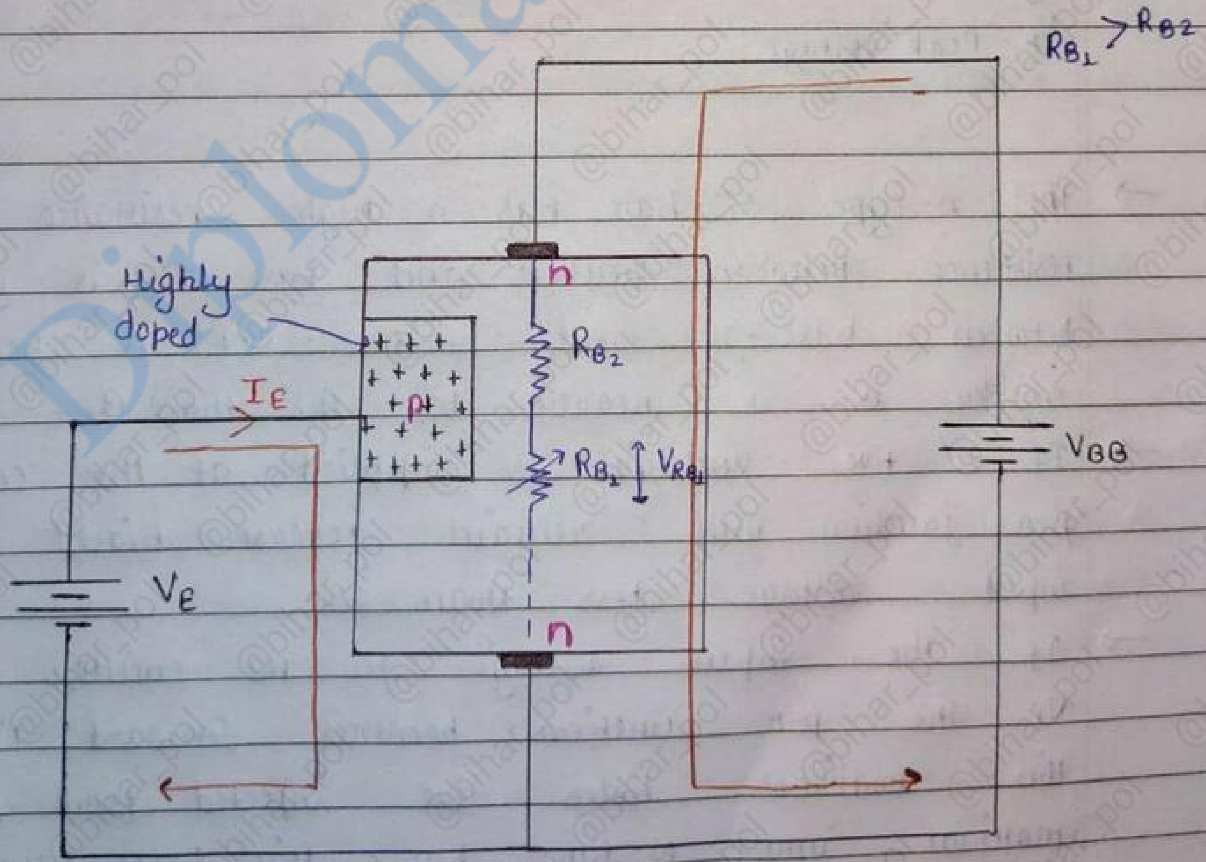


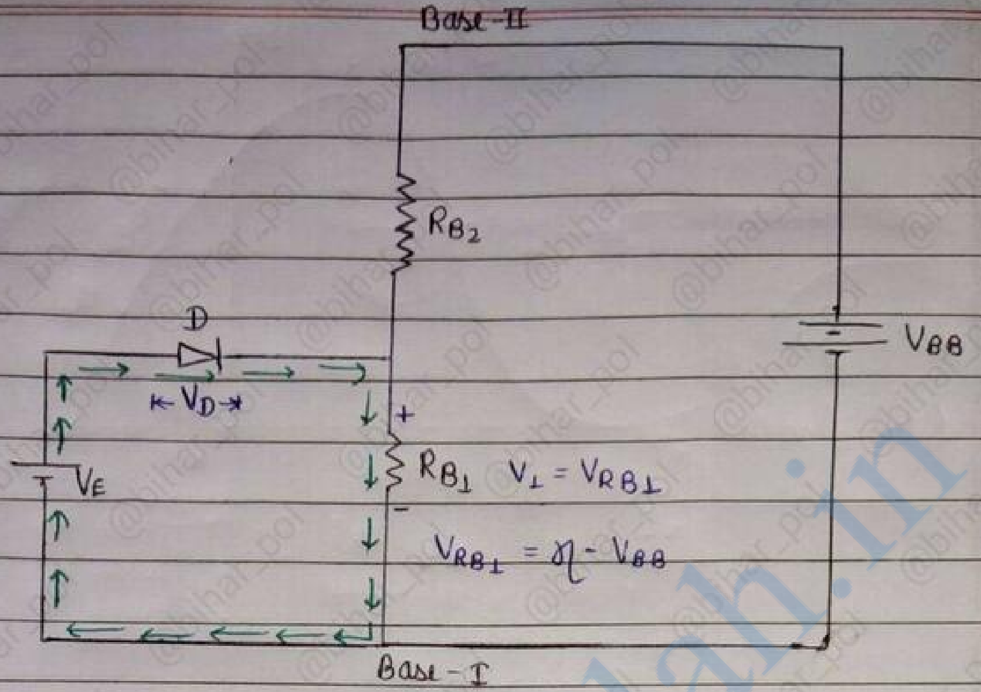
Fig :- Equivalent circuit.

→ At first emitter terminal is grounded the P-N Junction is reversed biased and I_{EO} (leakage current) flow in the circuit.

→ If voltage V_{BB} is applied between B_2 and B_1 with emitter is open, a voltage gradient is established along the n-type bar since the emitter is located near to B_2 more than half of V_{BB} appear between the emitter and B_1 the voltage V_{B_1} between emitter and B_1 is established a reverse biased on the P-N junction and the emitter current is cutt off but some leakage current flow from B_2 to emitter due to minority charge carrier.

* Connect the V_E at Emitter terminal





By KVL, $V_E > V_1 \rightarrow$ UJT turn ON

$V_E - V_D - V_{RB_1}$

$V_E - V_D - \eta V_{BB}$

$$V_E = V_D + \eta V_{BB}$$

↓

V_P = Peak voltage

→ The n-type Si bar has a high resistance, the resistance between emitter and base-I is greater than between base-II and emitter. It is because emitter ~~is~~ is nearer to B_2 than B_1.

→ If a +ve voltage is applied at the emitter the p-n junction will remain reverse biased as the input voltage less than V_1.

→ If the input voltage to the emitter exceed the V_1 the p-n junction becomes forward biased under this conditions holes are injected from p-type material into N-type bar, this holes are ~~repeated~~ repeled by +ve B_2 terminal and they are attracted towards the B_1 terminal of the si-bar.

→ This accumulation of holes in the emitter to B_1 region results in the decreases of resistance in this section of bar as a result internal voltage drop from emitter to B_1 is decreases and hence the emitter current I_E increases and the device is turn ON.

- V-I characteristic

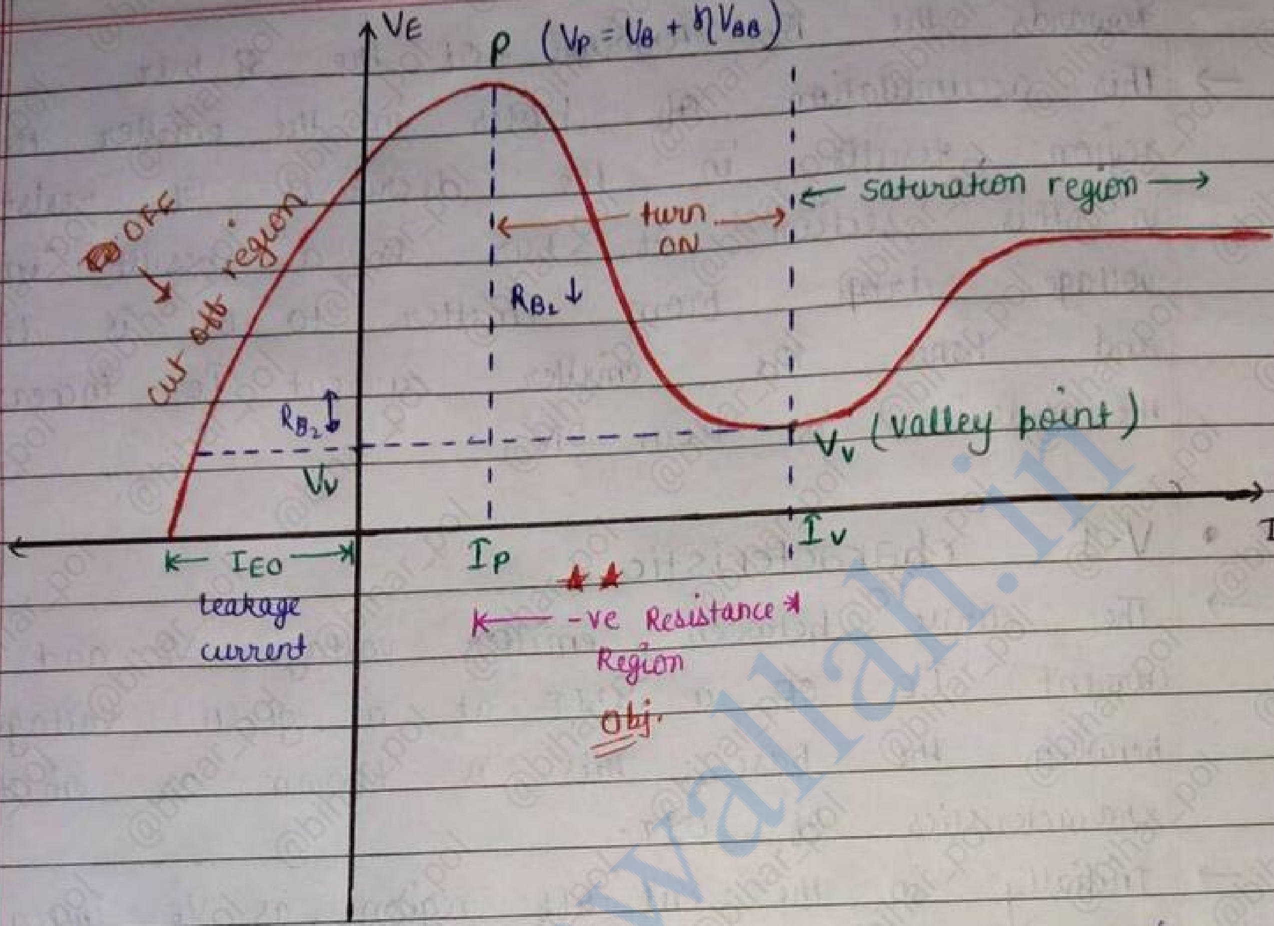
→ The curve between emitter voltage V_E and emitter current I_E of a UJT at a given voltage V_B between the base, this is known as emitter characteristics of UJT.

→ Initially in the cut-off region, as V_E increases from zero, slight leakage current flow from terminal B_2 to the emitter.

→ This current is due to the minority carrier in the reverse biased ~~curre~~ diode.

NOTE :- As the emitter potential increases and reaches * $V_P = V_D + \eta V_{BB}$ the UJT starts conducting

then with increase in emitter current I_E the emitter voltage decreases, the reduction in voltage across UJT is due to the drop in resistance R_{B1} with increase the value of I_E.



→ Peak point to valley point -ve ~~regio~~ resistance region.

→ After valley point the device is driven to saturation region.

- Advantage of UJT

→ low cost

→ low power absorbing device under normal operating condition.

- Application

→ As a triggering device for SCR and TRIAC.

→ In the relaxation oscillator.

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UJT as a Relaxation Oscillator

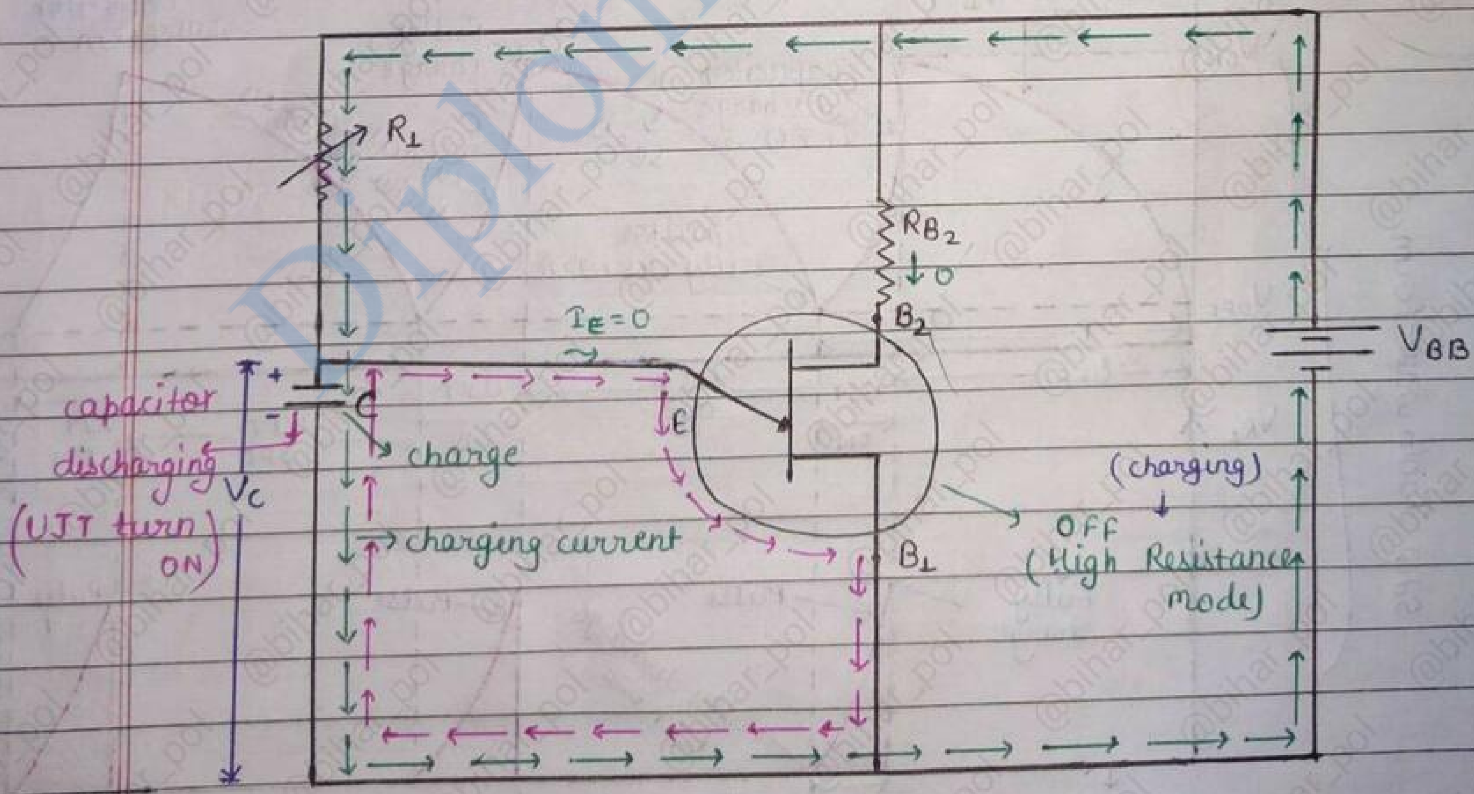
→ When a battery V_{BB} is turned ON the UJT the capacitor charges through the resistor R_1.

→ During the charging period the voltage across the capacitor rises in an exponential manner until it reaches the peak point voltage.

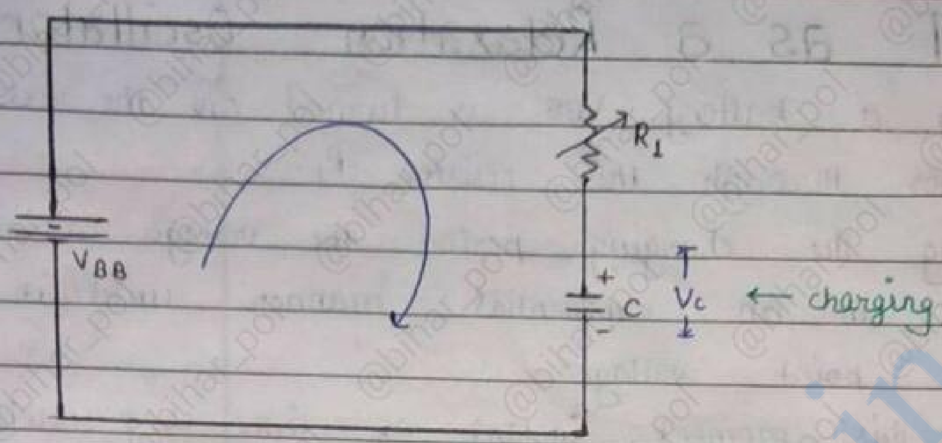
→ At this ~~moment~~ instant of time UJT switches to its low resistance conducting mode and the capacitor is discharges between emitter and Base - I.

→ As the capacitor voltage is zero then UJT is switch OFF and the next cycle begins allow the capacitor C charge again. The frequency of the output saw tooth wave can be varied by charging the value of R_1.

→ Since this control the time constant R_1C of the capacitor charging circuit.



$V_{BB} - R_1 I - \frac{1}{C}\int I\,dt = 0$



Qa By applying KVL:—

$V_c = V_{BB}\left(1 - e^{-t/R_1C}\right)$

Case I

UJT → OFF

C → charge

Full charge

Case II

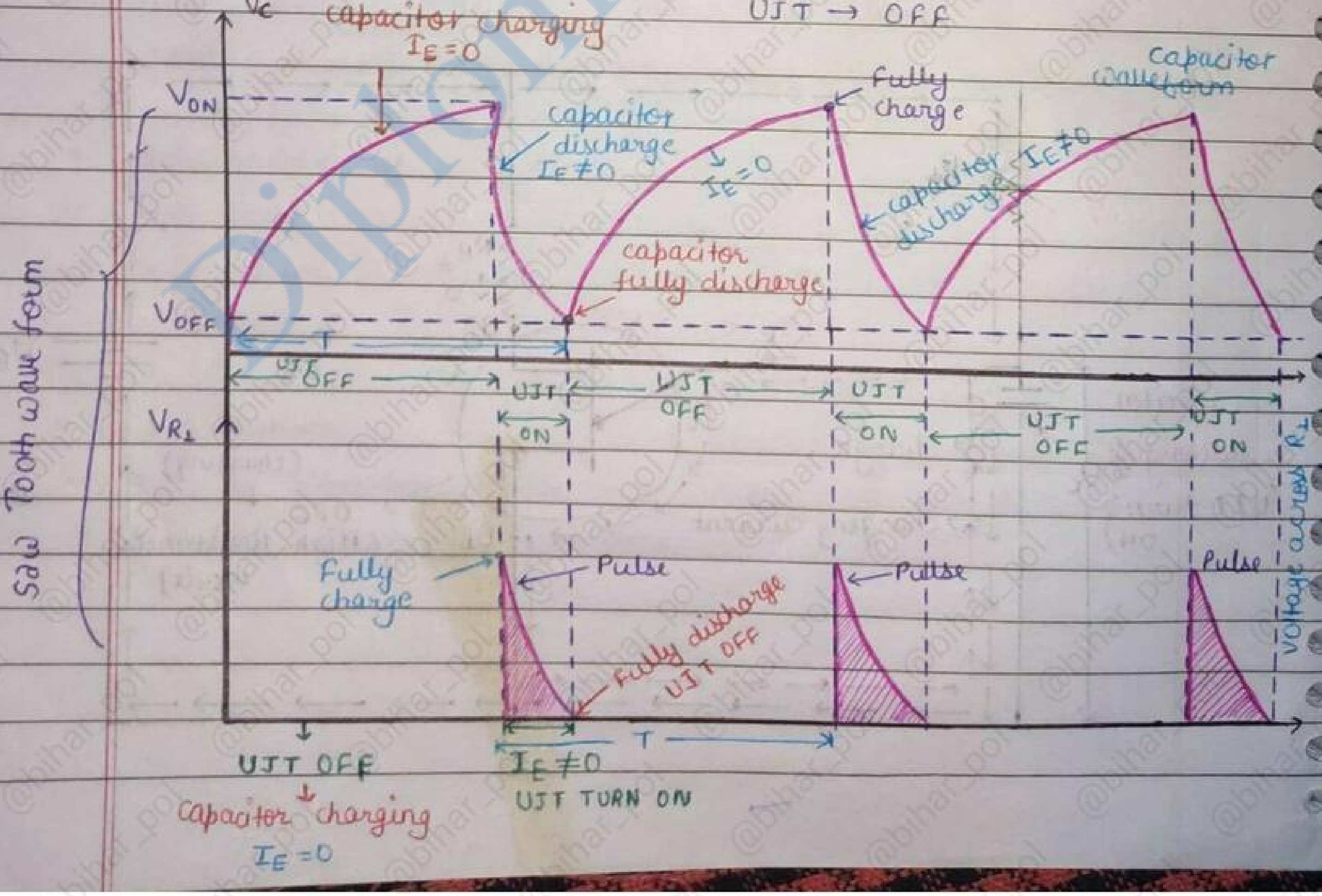
UJT → ON

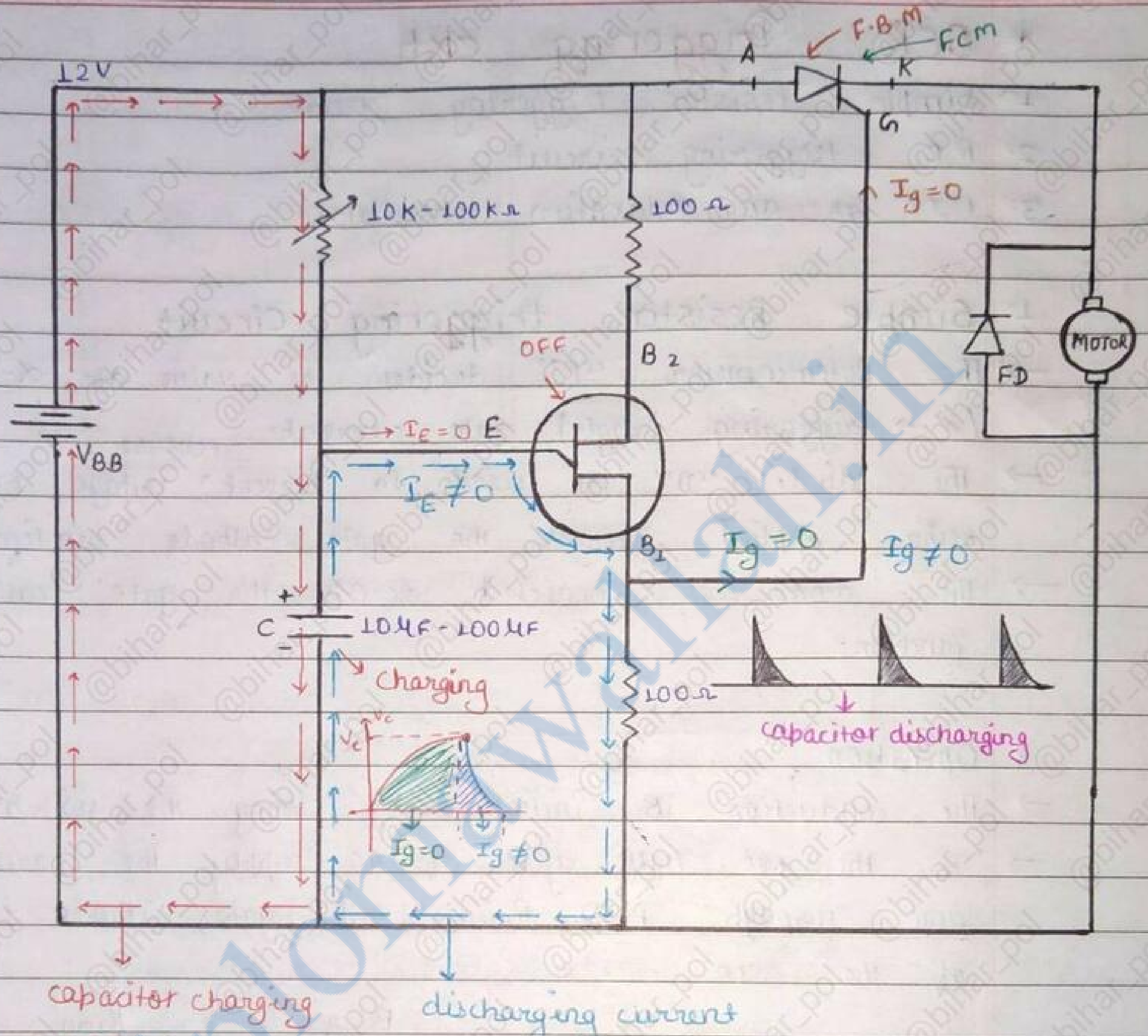
$I_E \neq 0$

C → discharging

Fully discharge

UJT → OFF



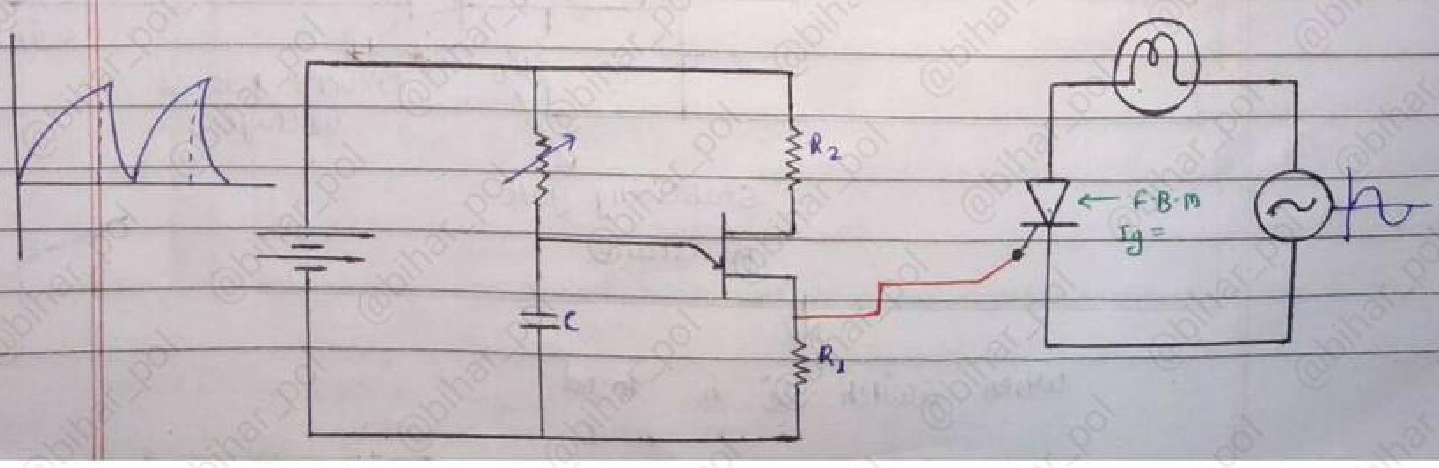


UJT → OFF

$I_E = 0$

$I_g = 0$ → capacitor charging

$I_g \neq 0$ → capacitor discharging (UJT → ON) → Fully discharge



* SCR Triggering ckt

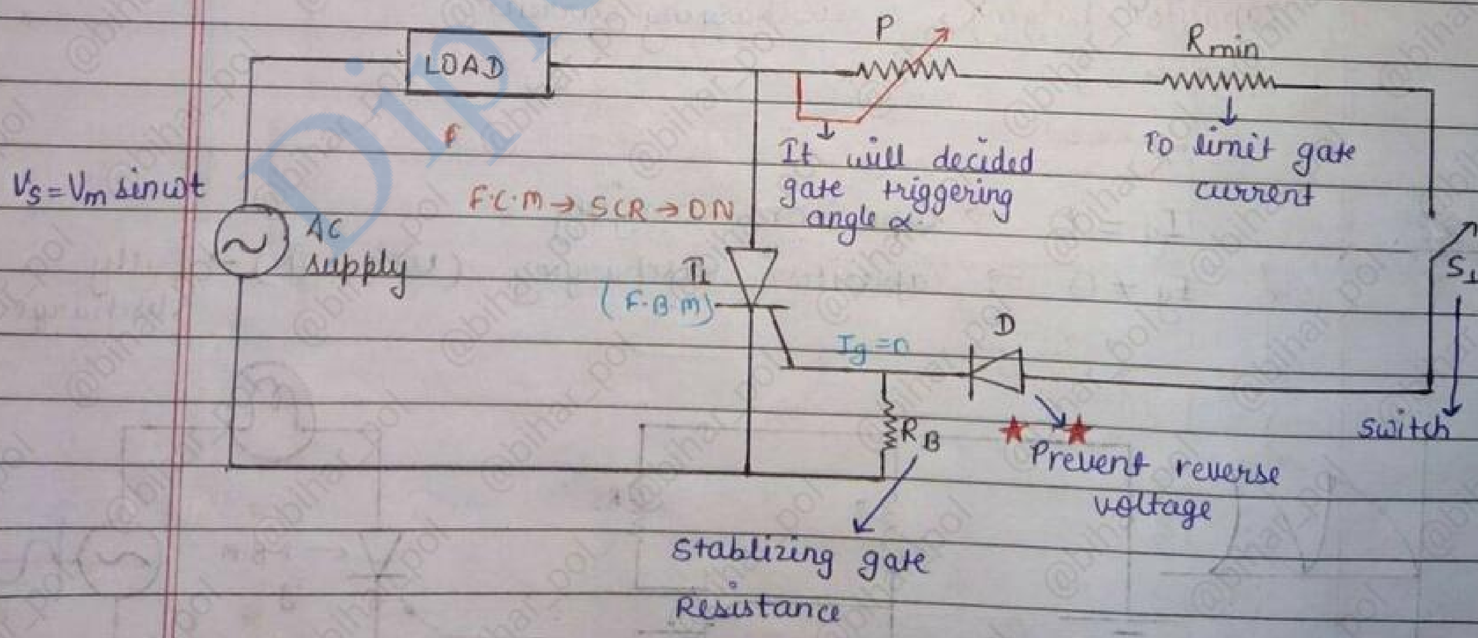
1. Simple resistor triggering circuit
2. R.C triggering circuit
3. UJT as an relaxation oscillator.

1. Simple Resistor triggering Circuit

→ The Potentiometer "P" decides the value of α. (α → triggering angle) gate current.
→ The diode "D" is used to prevent reverse voltage from being applied across the gate cathode junction.
→ The diode is connected across the gate cathode junction.

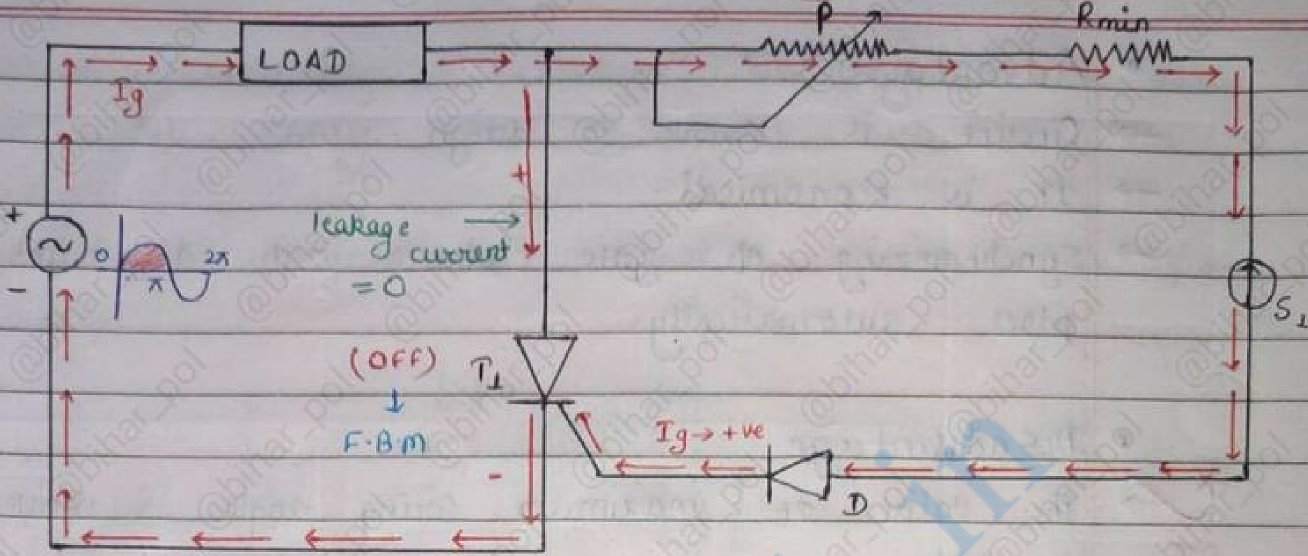
- **Operation**

→ The conduction is initiated by closing the switch S_1.
→ In the +ve half cycle of AC supply the current flow through P, D, R_{min} and gate cathode junction of the SCR.



⇓

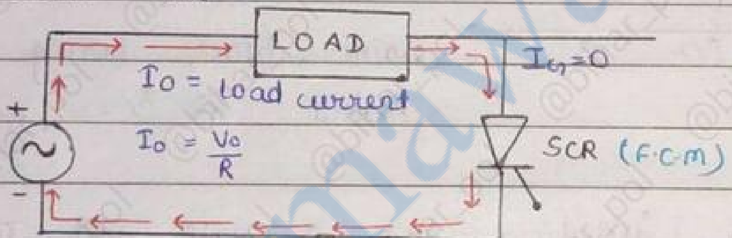
When switch S_1 is closed



$R_{min} \geq \frac{V_m}{I_{gm}}$

$I_{gm} \longrightarrow$ max^m gate current

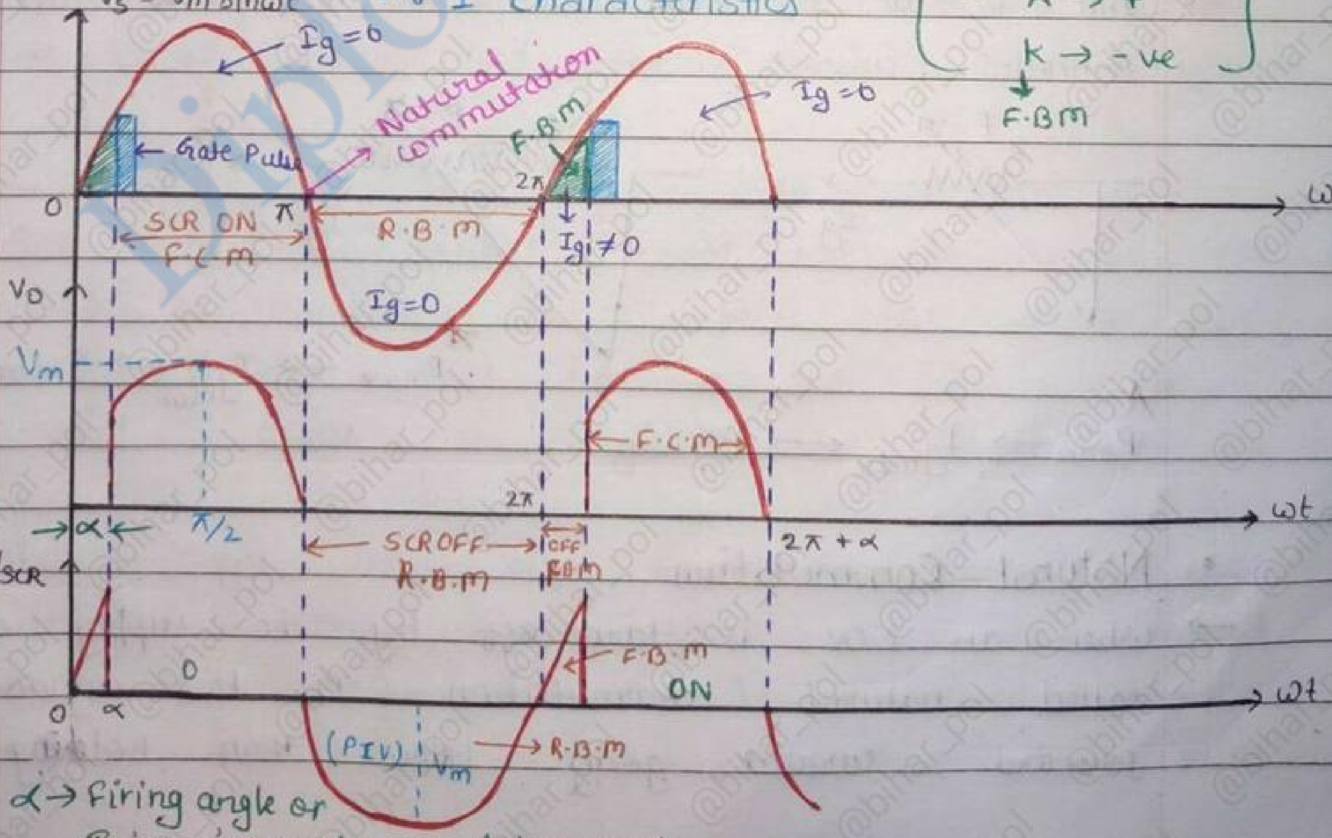
SCR turn ON



{ + → − α to π
− → + π to 2π }

{ 2π to 2π + α
⇒ A → +
K → −ve
↓
F.B.M }

• V·I characteristics



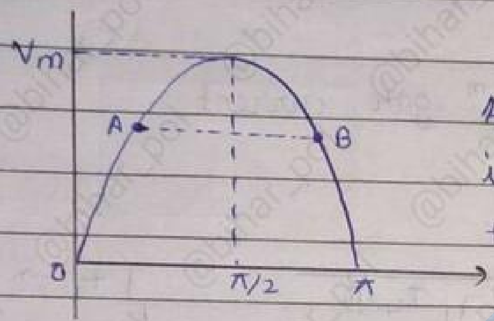
α → Firing angle or Triggering angle or delay angle

- **Advantage**

→ Circuit is simple to design.
→ It is economical.
→ Synchronizing of gate current with AC mains takes place automatically.

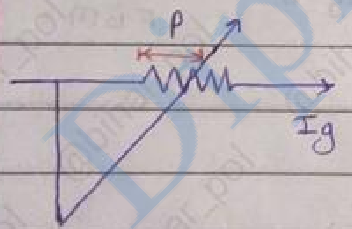
- **Disadvantage**

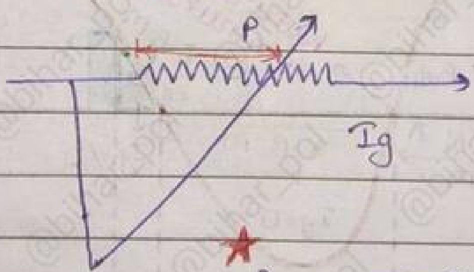
★ → The value of maximum firing angle is limited α_{max} is 90°. (obj.)



Anode voltage at point A and B is same, therefore gate current required to turn ON SCR at (A) and (B) is same, hence firing angle is limited to $\pi/2$.

→ No electrical isolation between gate and anode circuit.
→ Due to use of only one SCR, this is a half wave controlled circuit.





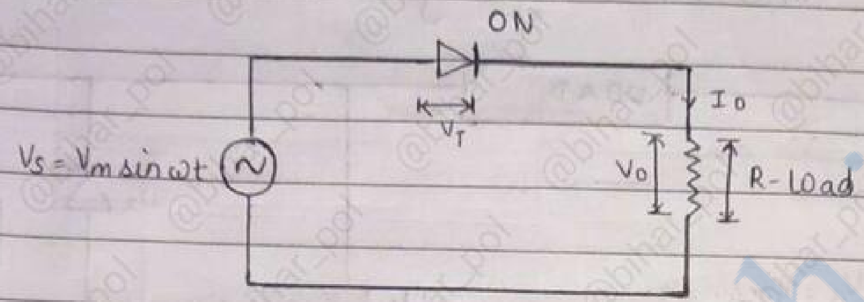
★ $P_{max} \rightarrow I_{g_{min}} \rightarrow \alpha_{max}$

★ $P_{min} \rightarrow I_{g_{max}} \leftarrow \alpha_{min}$

- **Natural Commutation**

→ When an SCR is turn off by ac supply is called natural commutation. In this commutation forward current going below than holding current naturally, in this commutation SCR gets turn off only at -ve half cycle of the supply.

→ The circuit diagram of natural commutation is given below -



→ During -ve half cycle SCR anode current get reduces and goes below than the holding current due to this SCR gets turn off.

- **Firing Angle**

⇒ Definition

Firing angle of SCR is defined as the angle between the instant SCR would conduct if it were a diode and the instant it is triggered.

⇒ Conditions to be ~~SCR~~ TURN ON SCR :-

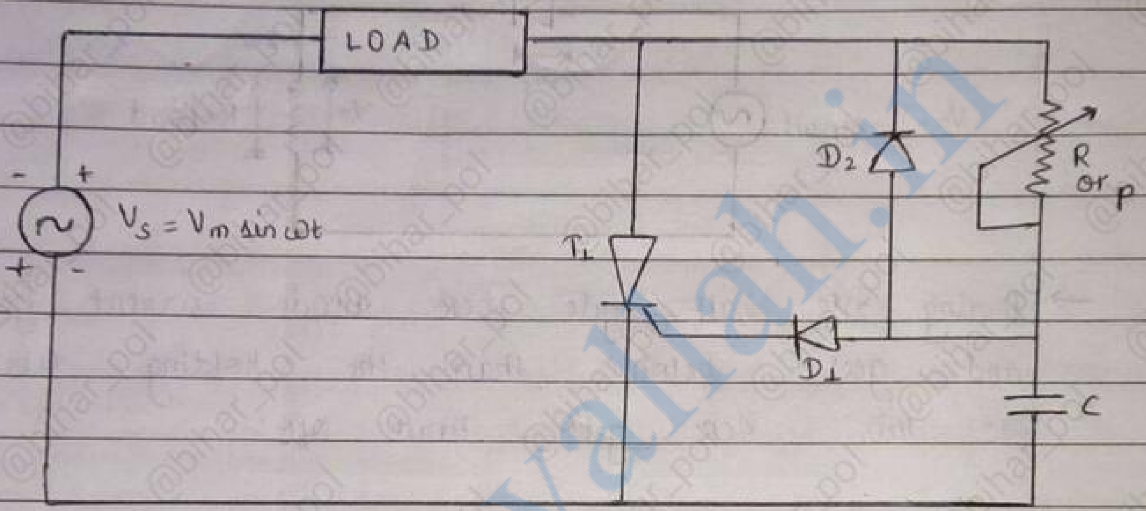
- SCR must be forward biased i.e its anode voltage must be positive with respect to cathode voltage.
- SCR must be gated i.e a gate signal must be applied across the gate and cathode terminal.

→ Firing angle may also be defined as the angle measured from the instant SCR gets forward biased to the instant it is triggered. From this definition, the firing angle for our example is α.

2. R-C Triggering Circuit

→ The variation of α is between $0°$ to $180°$.

→ The value of α_{max} is not restricted to $90°$, this has becomes possible because of use of a capacitor in the triggering circuit.



- Operation

→ In the negative half cycle of the AC supply, diode D_2 is in forward biased.

→ It will short circuit the potentiometer 'R' and the capacitor C is charged to negative peak voltage through D_2 with its upper plate is negative with to its lower plate.

→ In the positive half cycle Diode D_2 is in reversed biased. The capacitor 'C' will charge through R to the trigger point of the SCR, In a time determined by the RC time constant and the rising anode voltage.

→ The Diode D_1 will isolate and protect the gate cathode junction against reverse (negative) voltage.

→ As soon as the capacitor voltage becomes sufficient positive to forward biased the Diode D_1, and gate, junction of SCR, the SCR will be turned ON.

★ Imp → The firing angle α can be changed from 0° to 180° by varrying the potentiometer R or P.

→ As soon as the SCR turned ON, the voltage across it reduces to very low value (V) and the gate current goes to zero.

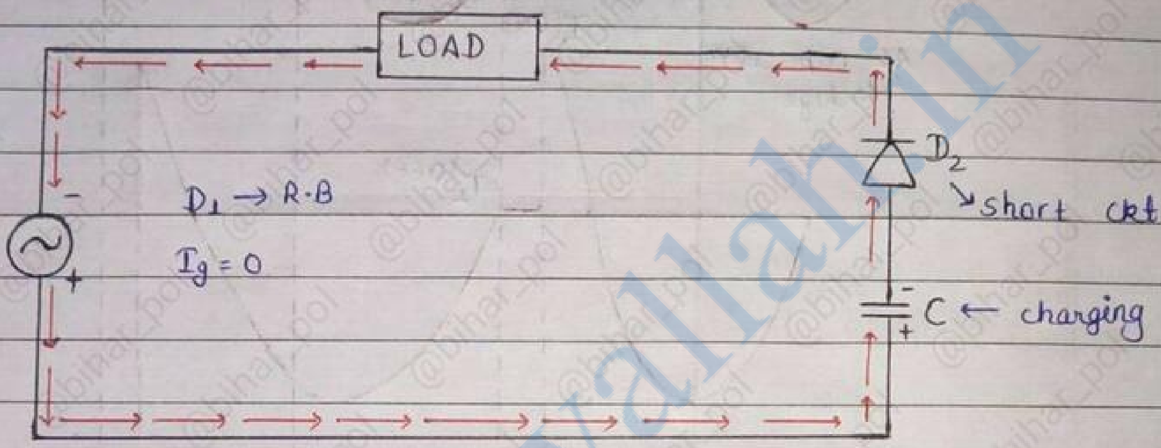


Fig :- Operation of negative Half cycle

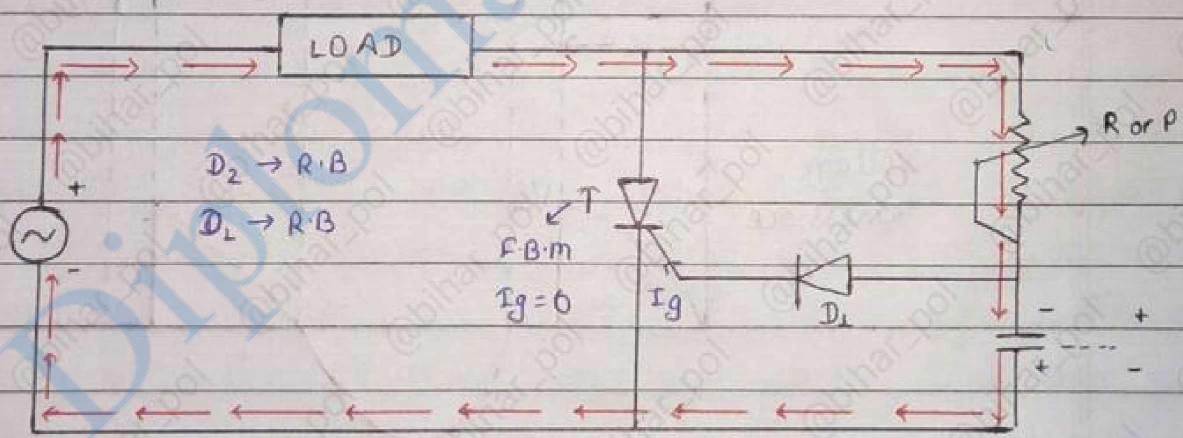


Fig :- Operation of positive Half cycle.

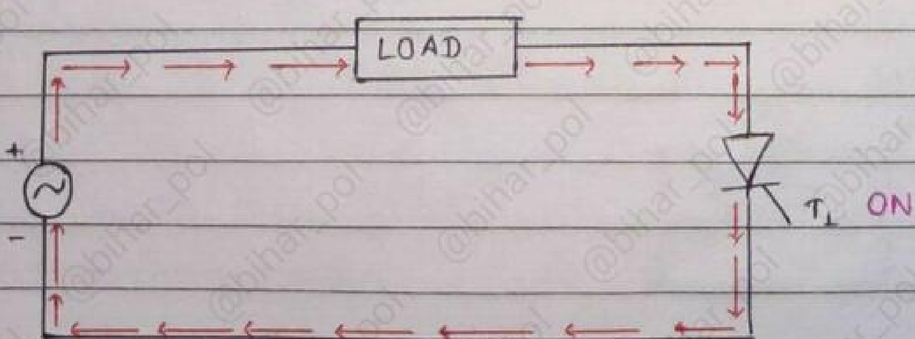
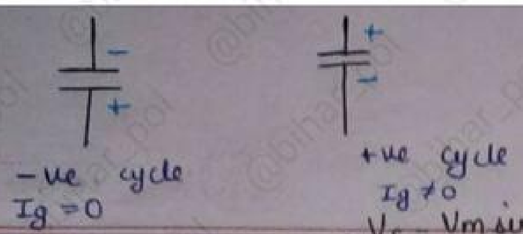
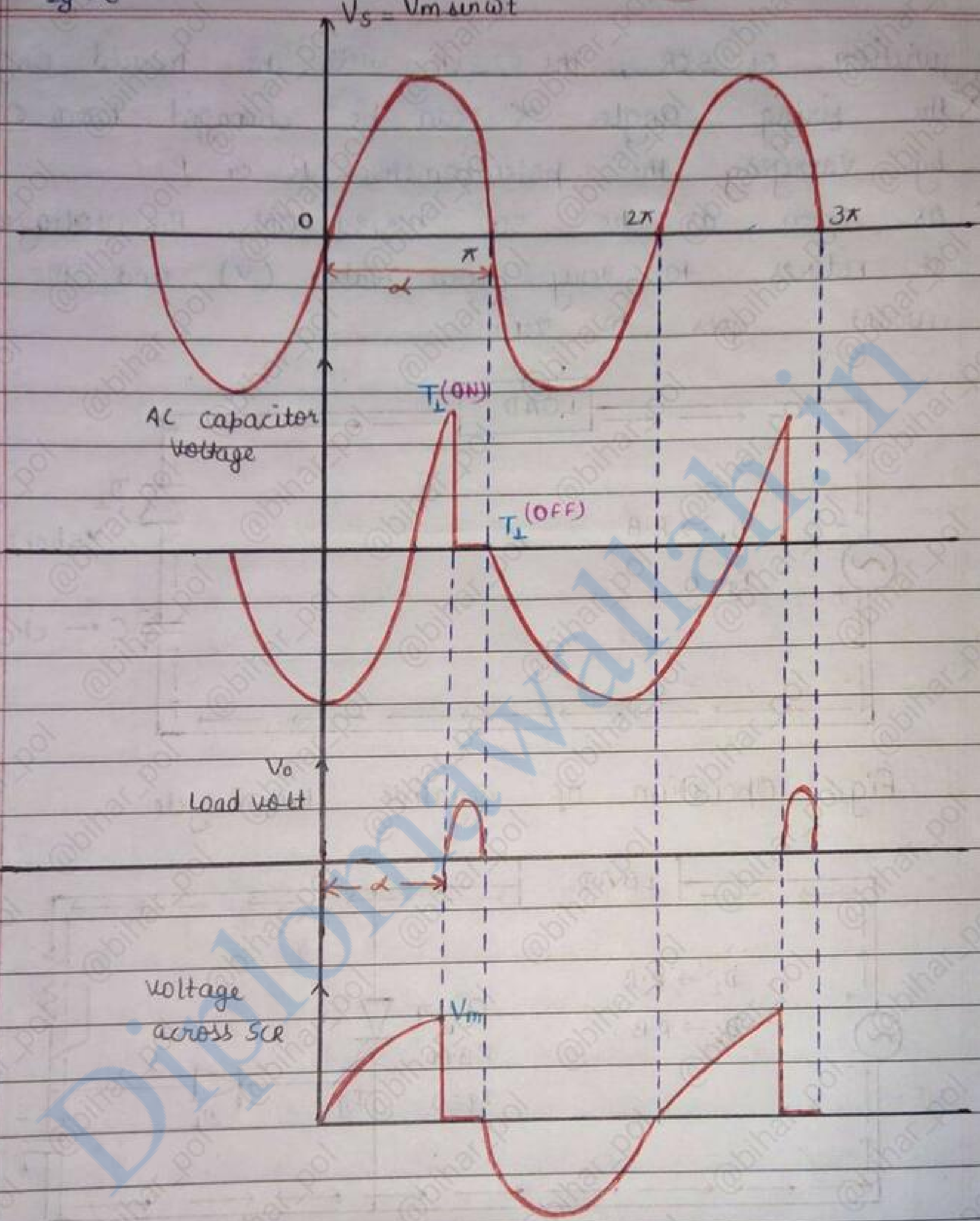


Fig :- +ve Half cycle SCR ON

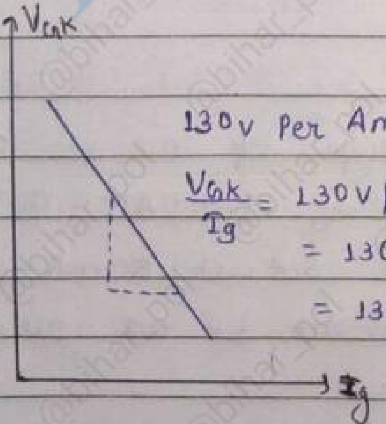

-ve cycle
Ig = 0
+ve cycle
Ig ≠ 0


Vs = Vm sinωt
0
π
2π
3π
α
AC capacitor voltage
T1 (ON)
T1 (OFF)
V0
Load volt
α
voltage across SCR
Vm

	Parameter	R-Triggering	R-C Triggering	UJT Triggering
1.	Range of firing angle	0 to 90°	0 to 180°	0 to 180°
2.	Isolation of control circuit and power circuit.	Not Possible	Not Possible	Possible
3.	Firing of multiple CR ~~supply fluctuation~~ (Triggering)	Not Possible	Not Possible	Possible
4.	Effect of supply fluctuation.	α changes	α changes	α remain constant
5.	Rating of triggering circuit component	very high	very high	Low
6.	Cost	Low	cheap	costlier than RC ckt
7.	Types of triggering	AC gate triggering	AC gate triggering	Pulsed gate triggering
8.	Synchronization with AC mains	Automatic	Automatic	Automatic

L-34

Q. For SCR the gate cathode characteristics has a straight line slope of 130 volt per amps for a trigger voltage source of 15 volts and allowable gate power dissipation of 0.5 watt. Calculate the gate source resistance.

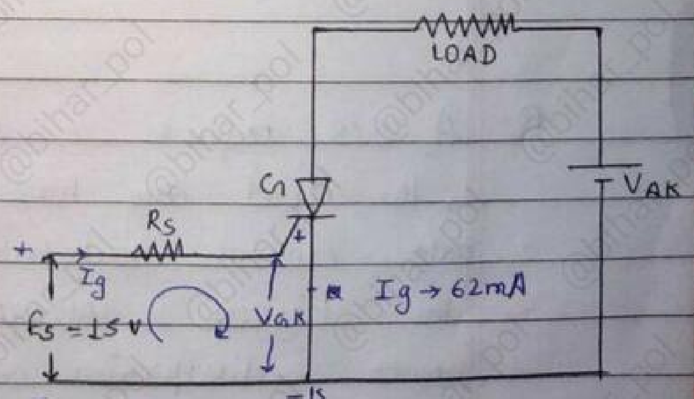


130V Per Amps

$\frac{V_{GK}}{I_g} = 130\text{V per Amps}$

$= 130 \frac{V}{A}$

$= 130\ VA^{-1}$



By KVL

$E_s - I_g R_s - V_{GK} = 0$

$E_s = V_{GK} + I_g R_s \rightarrow$ Gate source resistance — (i)

E_s ↓ Gate source voltage, V_{GK} ↓ Gate cathode voltage, I_g ↓ Gate current

Given,

$\frac{V_{GK}}{I_g} = 130\ VA^{-1}$

$V_{GK}\, I_g = 0.5\ \omega$

$V_{GK} = 130\ VA^{-1}\, I_g$

$130\, I_g \cdot I_g = 0.5\ \omega$

$I_g^2 = \frac{0.5}{130} = 0.062\ A = 62\ mA$

$V_{GK} = 130 \cdot I_g$

$V_{GK} = 130 \cdot 62\ mA \quad \{62 \times 10^{-3}\}$

$\therefore V_{GK} = 8.06$ volt

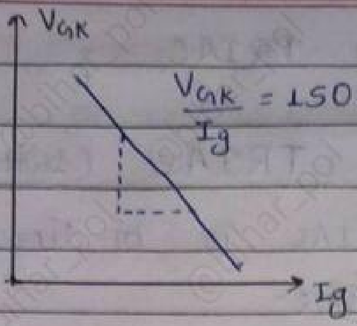
Now from equation (i)

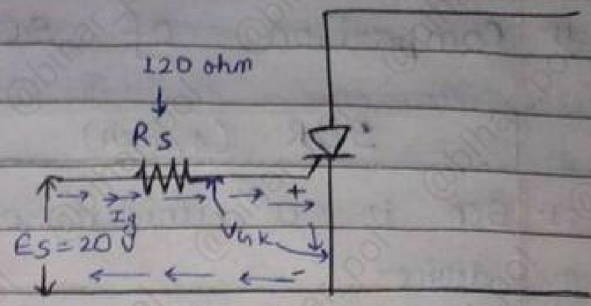
$E_s = V_{GK} + I_g R_s$

$15\ V = 8.06 + 0.062 \cdot R_s$

$R_s = \frac{15 - 8.06}{0.062} = 111.94\ \Omega$ Ans

Q. A SCR requires a source voltage of 20V for triggering, the load line has a slope of $150\ VA^{-1}$. The minimum gate current to turn on the SCR is 80mA. calculate the trigger voltage and current for an average power dissipation of 200mW.





Given,

$I_{g_{min}} = 80\,mA$

$V_{GK} \cdot I_g = 200\,m\omega$ $\Rightarrow V_{GK} = \frac{200 \times 10^{-3}}{I_g}$ — (i)

$= 200 \times 10^{-3}\,\omega$

By KVL,

$E_s = - I_g R_s - V_{GK}$

$E_s = I_g R_s + V_{GK}$

$20 = I_g \cdot 120 + \frac{200 \times 10^{-3}}{I_g}$

$20 I_g = 120 I_g^2 + 200 \times 10^{-3}$

$120 I_g^2 - 20 I_g + 200 \times 10^{-3} = 0$

$I_{g_1} = 0.1559\,A$

$I_{g_2} = 0.0108\,A$

Now,

From eqn (i)

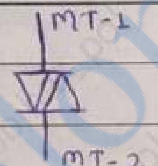
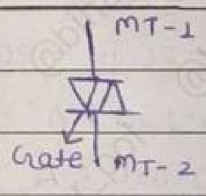
$V_{GK_1} = \frac{200 \times 10^{-3}}{0.1559} = 128\,V$

$V_{GK_2} = \frac{200 \times 10^{-3}\,\omega}{0.0106} = 18.86\,V$

Comparison of SCR and TRIAC

	SCR (switch)	TRIAC (switch)
1.	SCR is a unidirectional device.	TRIAC is bi-directional device.
★ 2.	The gate current can only be positive (only +ve supply)	The gate current can be +ve or -ve
3.	SCR can operate (ON) only one quadrant.	TRIAC can operate both the quadrant.
4.	UJT is used for triggering the SCR.	DIAC is used for triggering the TRIAC.

Comparison between DIAC and TRIAC

	DIAC	TRIAC
1.	 AC → AC O/P	 $I_g \uparrow V_{BO} \downarrow$
2.	It is two terminal device.	It is a three terminal device.
3.	Breakover voltage cannot be controlled (V_{BO})	Breakover voltage can be controlled by adjusting the gate current.
4.	DIAC is low power device.	TRIAC is high power device.
5.	It is used as triggering device for the TRIAC	It is used in appliances like fan speed control, light dimmer etc.

* Heat Sink

→ Some power loss occurs in a SCR during its working. The various composed of this power loss in the junction region of a SCR are under —

(i) Forward conduction loss
(ii) Loss due to leakage current during forward are reverse blocking.
(iii) Switching losses at turn ON and turn OFF.
(iv) Gate triggering loss.

→ At industrial power frequencies between zero and 400Hz, the forward conduction loss or on state conduction loss is usually two major components.

→ These electrical losses produced thermal heat which must be removed from the junction region. The thermal losses and hence temperature rise of the device, increases with the SCR ratings. The cooling of SCR becomes more difficult as the SCR rating increases.

→ The heat produced in a SCR by electrical loss is dissipated to ambient fluid (Air or water) by mounting the device on a heat sink, when heat due to losses is equal to that dissipated by the heat sink steady junction temperature is reached.

→ Device failure occurs if this heat is not removed from the junction at a sufficient rate, for this purpose heat sink is used.

→ The process or technique by which heat sink is fitted in the SCR body is called mounting.

The effectiveness of heat sink depends on following factors :—

1. Thermal conductivity of metal.
2. It's surface area
3. Thickness of the metal.
4. It's orientation and situation.

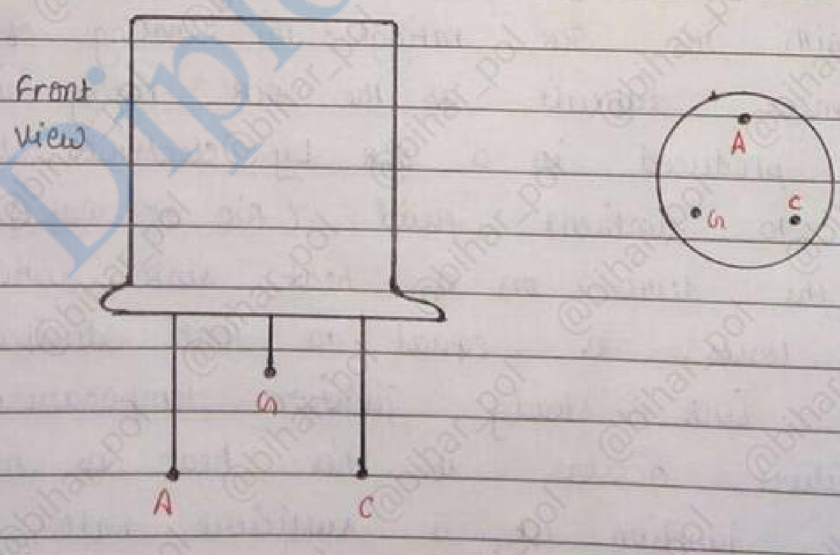
- The heat generated in a junction due to power loss takes the following path.

Junction Temp. ⟶ SCR case ⟶ Heat sink ⟶ Surrounding medium

Mounting

1. Lead Mounting

→ For load current rating of about one Amps, lead mounted SCRs are used. Such SCR donot required any additional cooling or heat sink. Their housing dissipate sufficient heat by radiation or convection.



2. Bolt Mounting

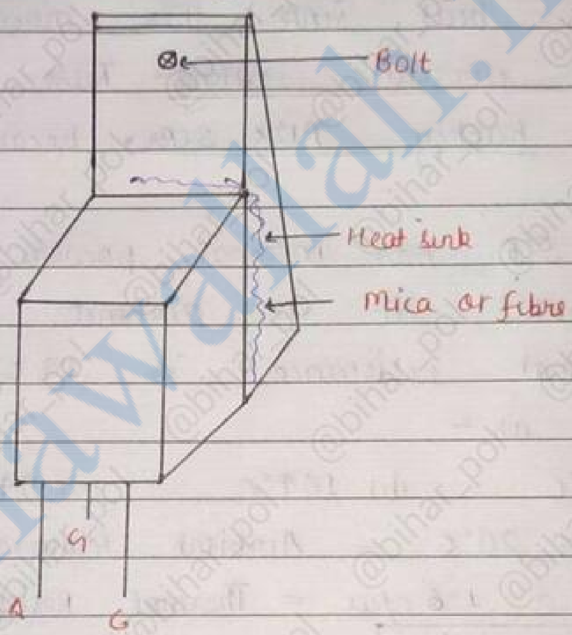
→ It is also called flat pack mounting. It is commonly used for small and medium rating SCR.

→ The device has flanges or tabs which contains holes using bolts these SCR are mounted on heat sinks.

obj Bolt is made of Nylon.

→ The mica or fibre insulation is kept in ~~for~~ between the heat sink and SCR.

→ Small and medium rating SCR:



3. Stud Mounting

→ This type of construction is very widely used due to its flexibility and ruggedness, the threaded stud forms the anode.

→ The SCR is attatched to a heat sink by means of threaded stud and Nut, thus anode gets electrically connected to the heat sink.

→ Both mica and fibrous material conduct heat easily but acts as insulators to electricity.

4. Press Fit Mounting

→ It is used for large rating SCR. It is designed for normal insertion into a slightly larger heat sink.

5. Pressure Mounting

→ The SCR is clamped under a very large external size heat sink. This mounting is used very ~~large~~ high current rating. These SCR are also called as huckey PUK SCRs, because of their shape.

Q. A SCR has internal power dissipation of 40W and operated at an ambient temperature of 20°C. If thermal resistance is 1.6 C/W, the junction temperature is as –

(a) 114°C (b) 164°C (c) 94°C (d) 84°C ✓

⇒ $T_A = 20°C$ = Ambient temperature

$Q_{JA} = 1.6\ C/W$ = Thermal Resistance

$$\boxed{P = \frac{T_J - T_A}{Q_{JA}}}$$

$$40 = \frac{T_J - 20}{1.6\ C/W}$$

$$40 \times 1.6 = T_J - 20$$

$T_J = 84°C$ Ans

↓

Junction temperature

Unit-2 Converter or Phase Controlled Converter or Rectifier

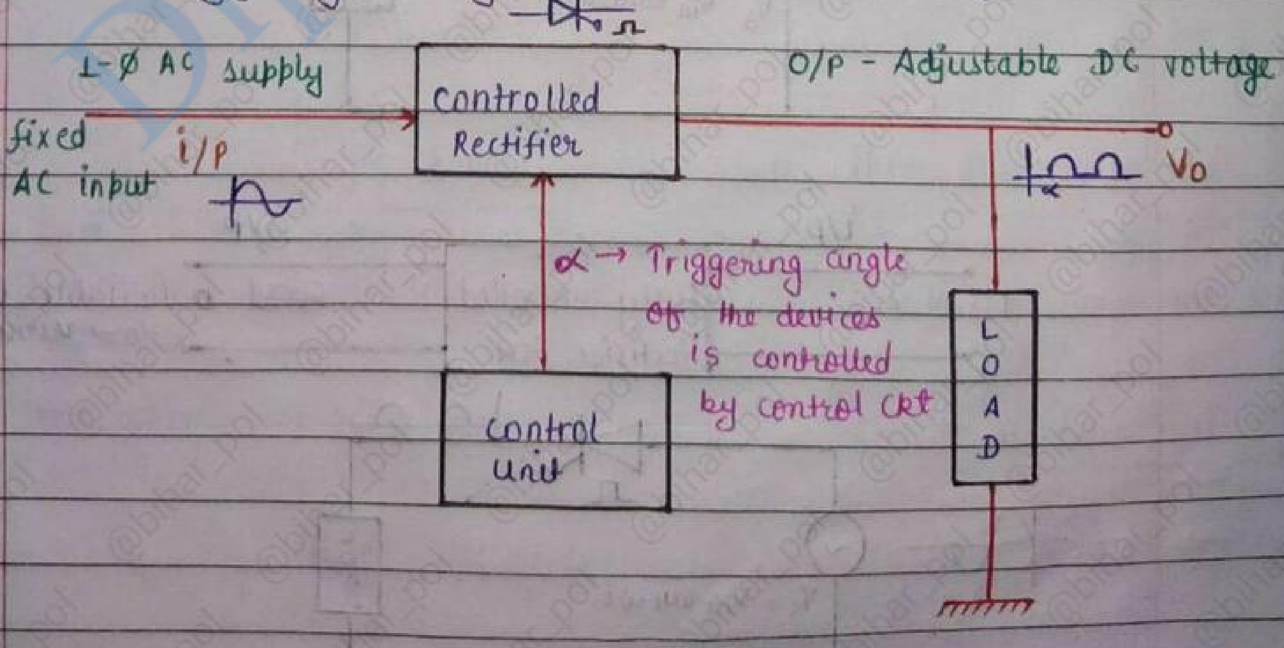
L-36

→ The Rectifier circuit using diodes operates on AC supply voltage. They convert AC voltage into a fixed DC voltage. Therefore the diodes rectifier are known as uncontrolled rectifier.

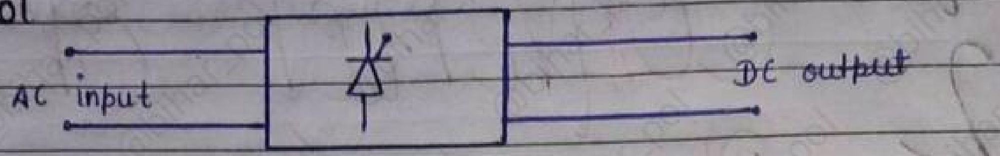
→ If we use SCRs in place of diode then the output DC voltage can be controlled by varrying the firing angle (α) of the SCR.

→ Therefore rectifier circuit using SCRs are known as controlled rectifier.

→ It is basically AC to DC converter. The power transferred to the load is controlled by controlling the triggering angle of the devices (α).



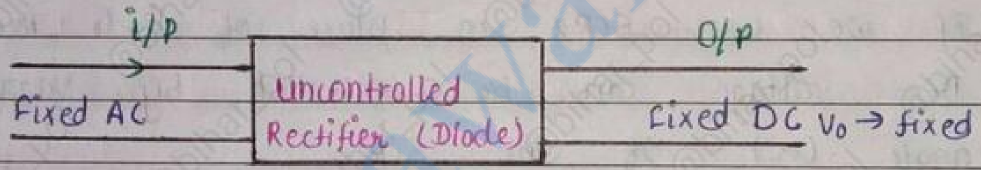
- Symbol

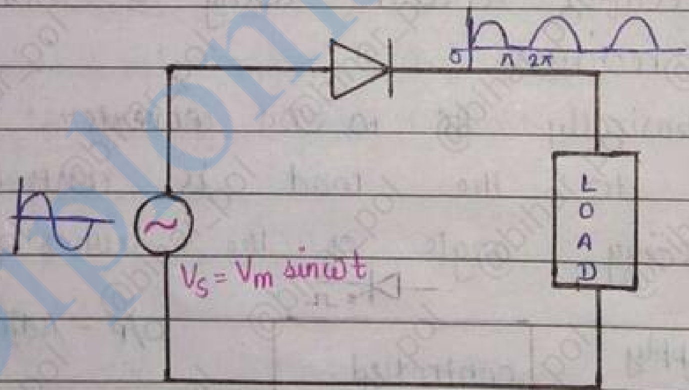


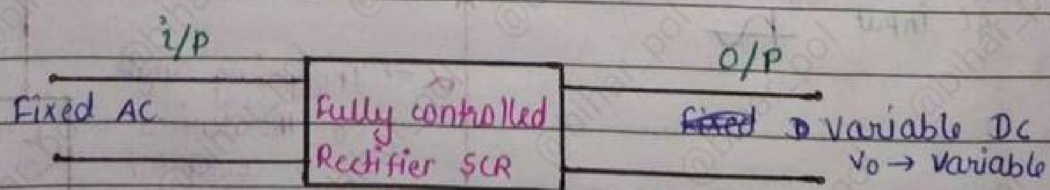
→ A conducting thyristor is turned off due to natural or line commutation.

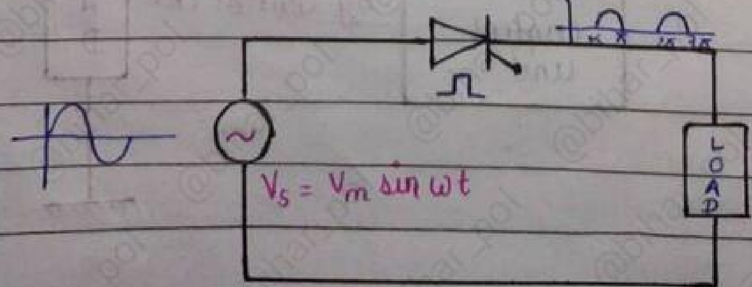
→ The AC mains voltage itself is used for commutating the SCR, therefore these converter are known as line commutated converter (LCC).

→ These converter are simple and less expensive and the efficiency of rectification in general is above 95%.







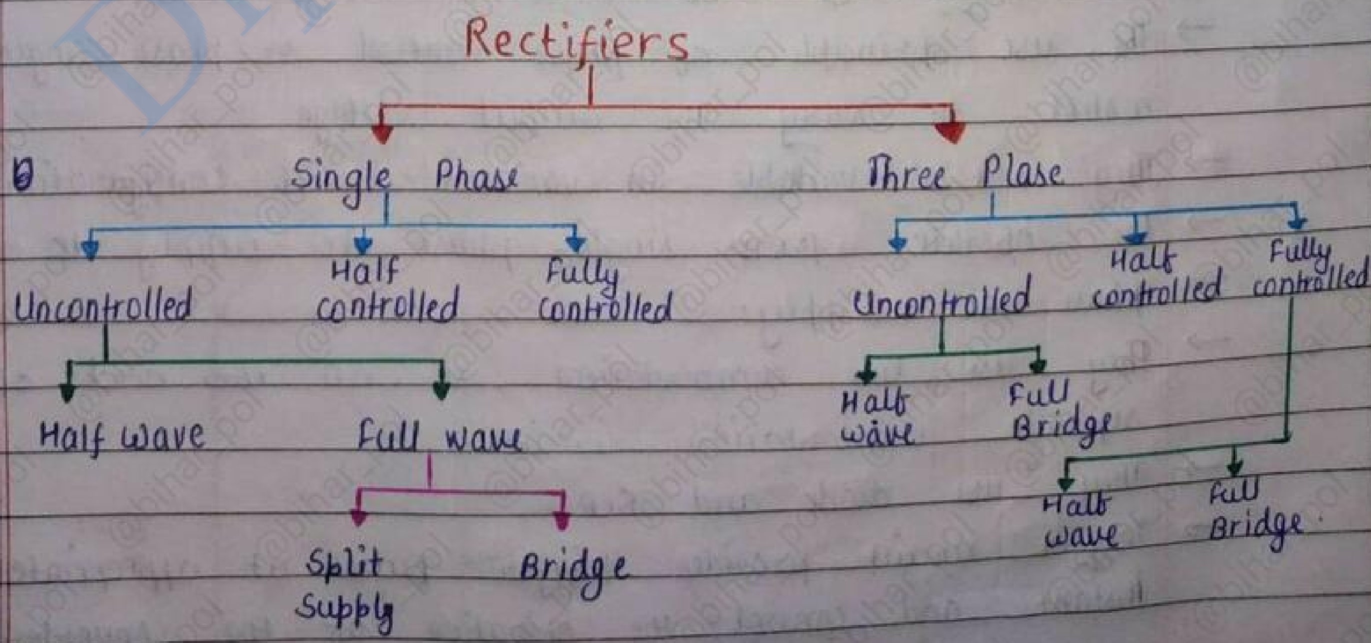


A Phase controlled rectifier need no commutating circuit.

Comparison between Uncontrolled and Controlled Rectifier

	Uncontrolled Rectifier	Controlled Rectifier
1.	Only diodes are used.	Only SCR or SCR and diodes are used.
2.	Fixed AC —▷|— Fixed DC V_0 = constant	Fixed AC —▷|— Variable DC $\downarrow \alpha \uparrow$ $\downarrow V_0 \uparrow$
3.	Trigger circuit is not required.	Trigger circuit is required.
4.	Firing angle is fixed and always zero.	Variable firing angle.
5.	It is used at low power rating.	It is used at medium and high power rating.
6.	Application - DC Power supply. for constant DC supply requirement.	Application - DC motor speed control, DC traction system, heating control.

L-37



Types of Power Electronic Converter

- AC to DC converters
  - Diode Rectifier
  - Phase controlled Rectifier
- DC to DC converters
- DC to AC converters
- AC to AC converters
  - Cycloconverters
  - AC voltage Regulators

* To simplify the study of Phase controlled rectifier assumption are as follows:—

→ SCR and diodes are ideal switches that is there is no voltage drop across them.

→ No reverse current exists under reverse voltage condition.

→ Holding current is zero.

→ Trigger circuits are not shown.

* Necessity of Converter

→ The use principle of phase control or phase angle control to vary the output voltage.

→ They are available in various circuit configuration.

→ The operate from single phase AC supply to three phase AC supply.

→ They use line commutation, so no ~~me~~ need of seperate commutation circuit.

→ They use diode and SCR.

→ Trigger circuit provides trigger pulses at appropriate instant and control the operation of the converter.

→ Converter circuit performance changes according to type of load and source impedance.

* Application

→ Steel rolling mills, Paper mills, Printing presses and textile mills employing DC motor drives.

→ Traction system working on DC.

→ Electrochemical and electrometallergical Process.

→ magnet Power supplied.

→ Portable hand tool drives.

→ HVDC - High voltage DC.

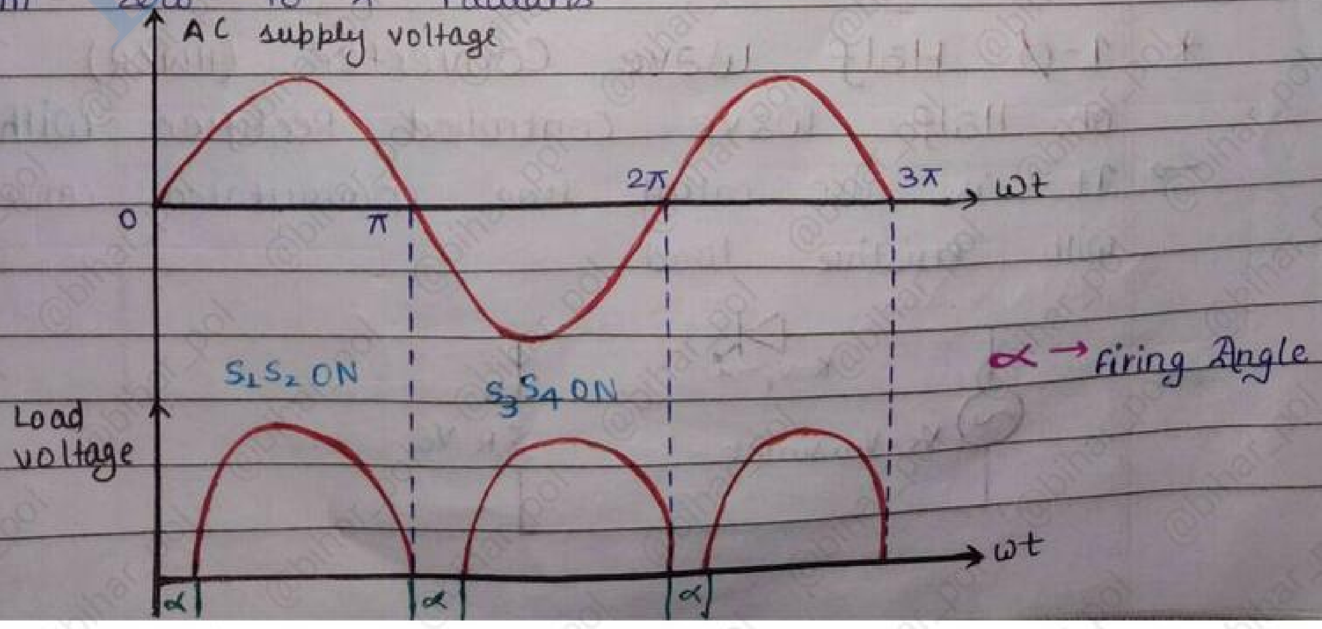
* Delay Angle or Firing Angle (α) or Triggering Angle

→ It is defined as angle measured from the instant SCR gets forward biased to the instant it is triggered.

→ The delay angle or firing angle is the value of "ωt" at which a SCR or pair of SCR is turned ON.

→ It is denoted by α and measured with respect to the zero crossing instant of the AC supply voltage.

→ The value of delay angle α varies from 0° to 180° or from zero to π radians.

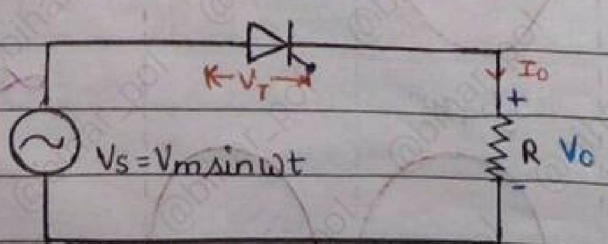


Controlled Rectifier or Converter or Line Commutated Converter

- 1-ϕ
  - HWCR — Half wave controlled Rectifier
    - R- Load
    - R-L Load
    - R-L Load with F.D (Freewheeling diode)
  - FWCR — Full wave controlled Rectifier
    - Centre tapped controlled Rectifier converter (M2 - configuration)
      - R- Load
      - R-L Load
      - R-L Load with F.D
    - Bridge controlled converter (Rectifier)
      - R- Load
      - R-L Load
      - R-L Load with F.D
- 3-ϕ

* 1-ϕ Half Wave Converter (HWCR) or, Half Wave Controlled Rectifier with R-Load

→ It is also called line commutated converter with Resistive load.



In AC +ve half cycle, Pulse is given.

obj $0 < \omega t < \alpha$

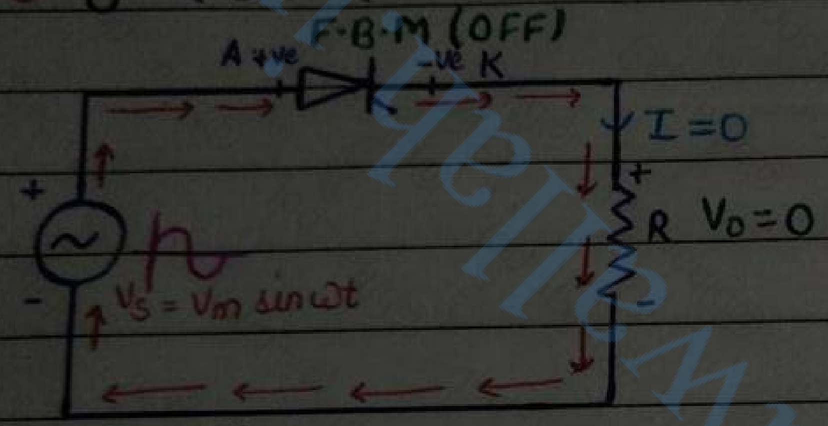


Fig – 1

obj $\alpha < \omega t < \pi$

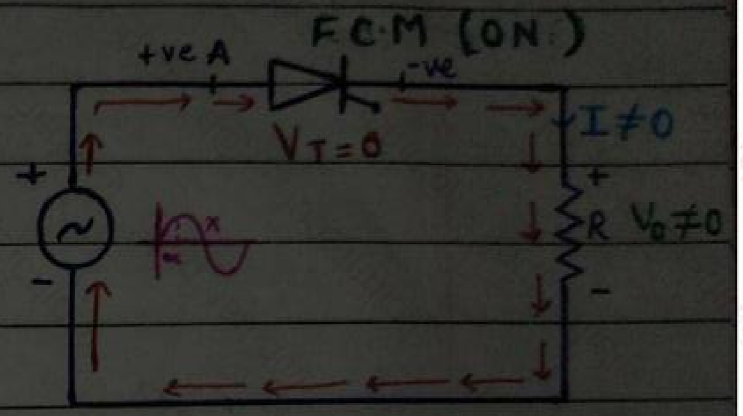


Fig – 2

obj $\pi < \omega t < 2\pi$

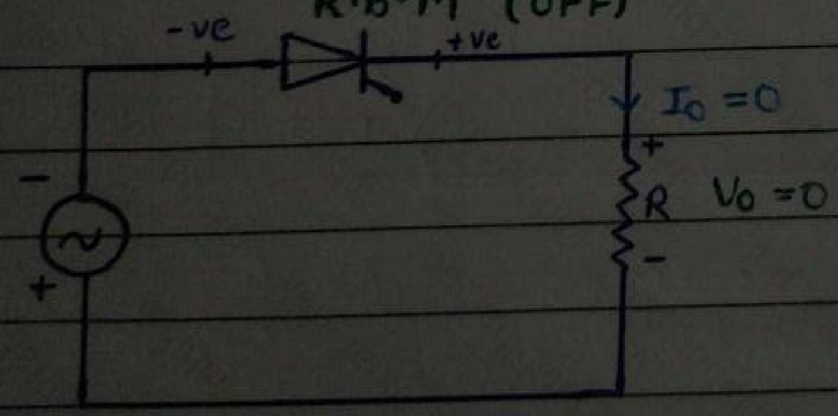
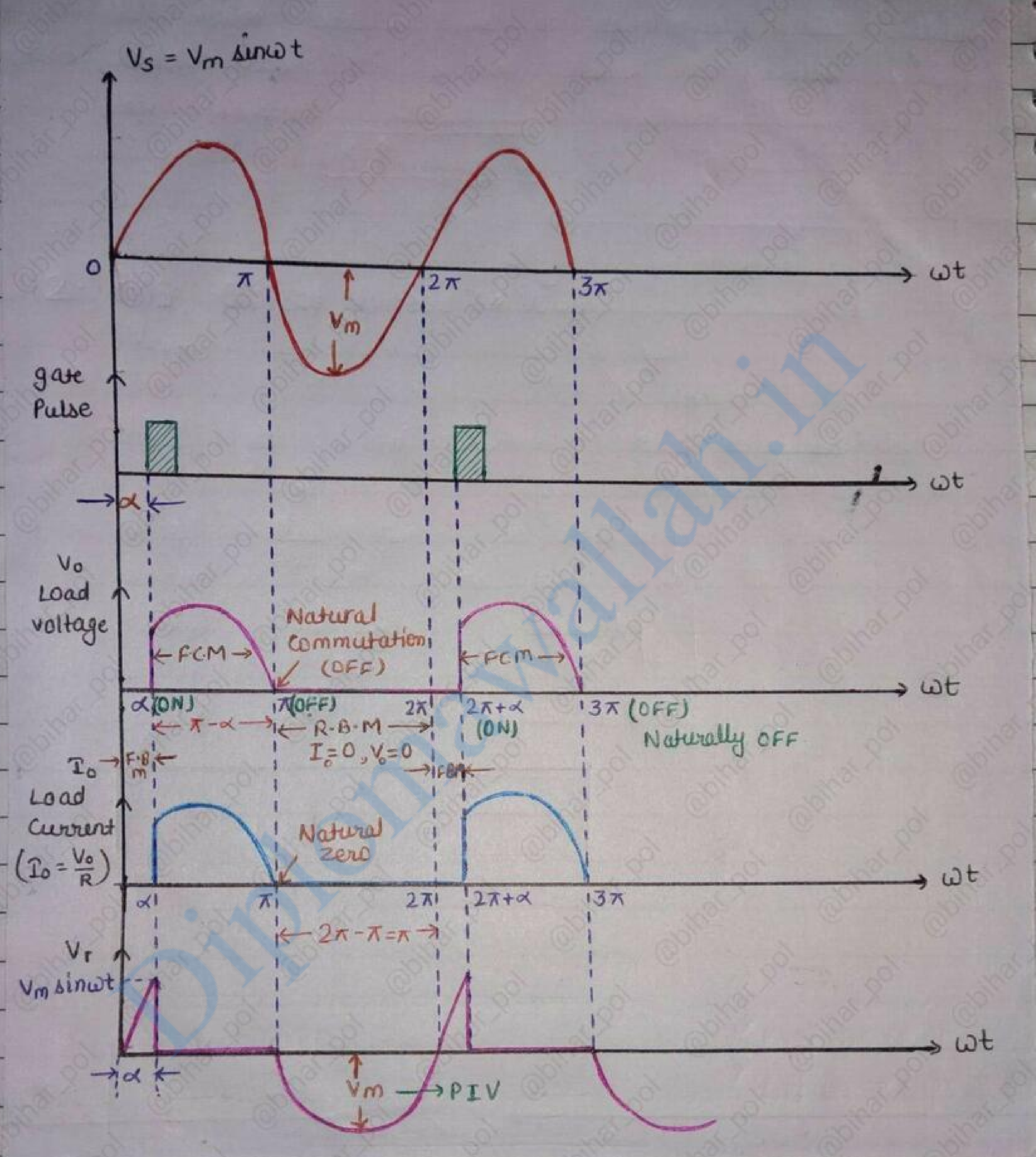


Fig – 3

$V_S - V_T + V_0 = 0$

$V_S - V_T = 0$

$V_T = V_S = V_m \sin\omega t$



PIV = V_m (obj)

$I_A \sim 0$, $I_H = 0$, π

π to 2π SCR → R.B.M

SCR → π → OFF, 2π तक

2π पर → F.B.M → Pulse

2π+α → SCR ON

3π → OFF, 4π

4π+α → conduction.

- **Circuit Turn off Time**

→ Circuit turn off time is decided for the R.B.M mode of SCR.

$$\omega t_c = 2\pi - \pi \qquad \{\omega t_c = \text{circuit turn off time}\}$$

$$\omega t_c = \pi$$

$$\boxed{t_c = \frac{\pi}{\omega}} \rightarrow \text{Circuit off.}$$

- **Conduction Time**

→ Conduction time is decided for the F.C.M mode of S.C.R.

→ It is represented by γ (gamma).

$$\boxed{\gamma = \pi - \alpha}$$

↓ conduction Angle

$$\omega t = \pi - \alpha$$

$$\boxed{t = \frac{\pi - \alpha}{\omega}} \leftarrow \text{conduction Time}$$

L-39

1. **Output Average Voltage** → $V_{o\,Avg}$ or $V_{o\,DC}$

$$V_{o\,Avg} = \frac{1}{T}\int_0^T V_s \, d\omega t = \frac{1}{T}\int_0^T V_m \sin\omega t \, d\omega t \qquad \{T \rightarrow 2\pi\}$$

$$V_{o\,Avg} = \frac{1}{2\pi}\int_0^{2\pi} V_m \sin\omega t \cdot d\omega t$$

$$= \frac{1}{2\pi}\left[\underbrace{\int_0^{\alpha} V_m \sin\omega t \cdot d\omega t}_{F.B.M = 0} + \underbrace{\int_{\alpha}^{\pi} V_m \sin\omega t \cdot d\omega t}_{F.C.M} + \underbrace{\int_{\pi}^{2\pi} V_m \sin\omega t \cdot d\omega t}_{R.B.M = 0}\right]$$

$$V_{o\,Avg} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \cdot d\omega t = \frac{V_m}{2\pi}\Big|-\cos\omega t\Big|_{\alpha}^{\pi}$$

$$\boxed{V_{o\,Avg}\Big|_{\alpha=0} = \frac{V_m}{2\pi}\Big|1 + \cos\alpha\Big| = \frac{V_m}{2\pi}\Big|\cos\alpha \uparrow + 1\Big|_{0,\,15^\circ,\,30^\circ,\,45^\circ,\,90^\circ}}$$

$$V_{o\,Avg.max}\Big|_{\alpha=0} = \frac{V_m}{\pi}$$

The above equation we can see that output voltage varies with 'α' if we change the value of α then output voltage is changed.

$\alpha \uparrow \; V_{0\,Avg} \downarrow$

2. RMS Output Voltage → $V_{0\,RMS}^2$

$$V_{0\,RMS}^2 = \frac{1}{T}\int_0^T V_s^2\, d\omega t = \frac{1}{2\pi}\int_0^{2\pi} V_s^2 \cdot d\omega t$$

$V_s \to V_m \sin\omega t$

$$V_{0\,RMS}^2 = \frac{1}{2\pi}\int_\alpha^\pi V_m^2 \sin^2\omega t \cdot d\omega t = \frac{V_m^2}{2\pi}\int_\alpha^\pi \frac{(1-\cos 2\omega t)}{2}\, d\omega t$$

$$V_{0\,RMS}^2 = \frac{V_m^2}{4\pi}\left[\int_\alpha^\pi d\omega t - \int_\alpha^\pi \cos 2\omega t\, d\omega t\right]$$

$$V_{0\,RMS}^2 = \frac{V_m^2}{4\pi}\left[|\omega t|_\alpha^\pi - \left|\frac{\sin 2\omega t}{2}\right|_\alpha^\pi\right]$$

$$V_{0\,RMS}^2 = \frac{V_m^2}{4\pi}\left[\pi - \alpha - \frac{\sin 2\pi}{2} + \frac{\sin 2\alpha}{2}\right]$$

($\frac{\sin 2\pi}{2} = 0$)

$$V_{0\,RMS}^2 = \sqrt{\frac{V_m^2}{4\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

$$V_{0\,RMS}^2 = \frac{V_m}{2\sqrt{\pi}}\sqrt{\pi - \alpha + \frac{\sin 2\alpha}{2}}$$

α → Firing Angle → Radian

3. Form Factor

* Pure DC → 1
* Impure → Near to 1.

$$\frac{V_{0\,RMS}}{V_{0\,Avg}} = \frac{\frac{V_m}{2\sqrt{\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}{\frac{V_m}{2\pi}(1+\cos\alpha)}$$

$$\text{Form factor} = \frac{\frac{1}{\sqrt{\pi}}\left(\pi - \alpha + \frac{\sin 2\alpha}{\alpha}\right)}{\frac{1}{\pi}(1+\cos\alpha)}$$

4. Voltage Ripple Factor → VRF

$$R.F = (FF^2 - 1)^{1/2} = \sqrt{(\text{Form Factor})^2 - 1}$$

→ Ideally ripple factor should be zero and practically it should be as small as possible.

→ Pure DC ripple factor = 0

5. DC Power Output → $P = VI_L = \frac{V^2}{R}$

→ The DC power output for a resistive load is given by

$$P_{L_{DC}} = V_{L_{DC}} \cdot I_{L_{DC}} = V_{L_{DC}} \cdot \frac{V_{L_{DC}}}{R}$$

$$P_{L_{DC}} = \frac{V_{L_{DC}}^2}{R} \quad \text{or} \quad P_{o_{DC}} = \frac{V_{o\,DC}^2}{R} = \frac{V_{o\,Avg}^2}{R}$$

($V_{L_{DC}}$ → V_o Avg.; $P_{o_{DC}}$ → O/P DC power)

$$\boxed{P_{L_{DC}} = \frac{V_{o\,Avg}^2}{R}}$$

6. AC Power Output → $P_{LAC} = P_{oAC}$

→ The AC output for a resistive load is given by

$$P_{LAC} = V_{L\,RMS} \cdot I_{L\,RMS} = V_{L\,RMS} \cdot \frac{V_{L\,RMS}}{R}$$

$$P_{LAC} = \frac{V_{L\,RMS}^2}{R} = \frac{V_{o\,RMS}^2}{R} = \frac{V_{L\,AC}^2}{R}$$

7. Rectification Efficiency → η

→ The Rectification efficiency or rectification ratio of a rectifier

$$\eta = \frac{P_{LDC}}{P_{LAC}} = \frac{P_{oDC}}{P_{LAC}} = \frac{V_{L\,DC}^2/R}{V_{o\,AC}^2/R} = \frac{V_{o\,Avg}^2}{V_{o\,RMS}^2}$$

Now, substituting the expression for $V_{o_{Avg}}$ or $V_{o_{RMS}}$:

$$\eta = \frac{\left(\frac{V_m}{2\pi}\right)^2 (1+\cos\alpha)^2}{\frac{V_m^2}{4\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)} = \frac{\frac{(1+\cos\alpha)^2}{\pi}}{\pi - \alpha + \frac{\sin 2\alpha}{2}}$$

$$\boxed{\eta = \frac{(1+\cos\alpha)^2}{\pi\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}}$$

8. Peak Inverse Voltage (PIV) ⟶ SCR → R·B·M

$PIV = V_m = \sqrt{2}\,V_s$ ← Source RMS value.

9. Input Volt Amps

Input V_A = (RMS source voltage) × (RMS line current) $= V_s \cdot I_{oR}$

10. Input Power Factor (IPF)

$$IPF = \frac{\text{Power delivered to load (AC)}}{\text{Input } V_A}$$

$$= \frac{V_{oR}\cdot I_{oR}}{V_s \cdot I_{oR}} = \frac{V_{oR}}{V_s} = \frac{\frac{V_m}{2\sqrt{\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}{\frac{V_m}{\sqrt{2}}}$$

$$\boxed{IPF = \frac{\sqrt{2}\times\sqrt{2}}{\sqrt{2}\times 2\sqrt{\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

$$\boxed{IPF = \frac{1}{\sqrt{2\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

~~Q. A single phase trans~~

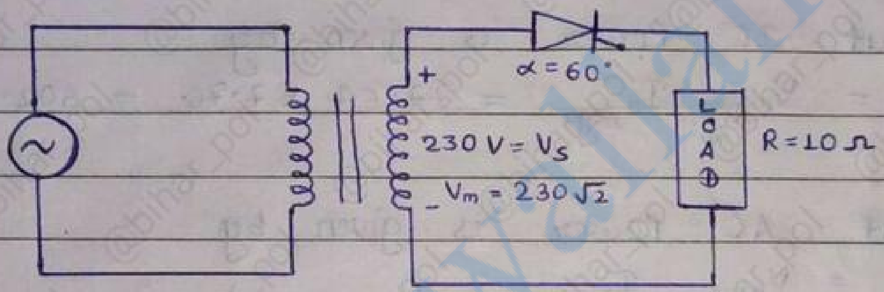
11. Transformer Utilisation Factor ⟶ (TUF)

$$TUF = \frac{P_{AC}}{I_{Rms}\cdot V_{Rms}} = \frac{V_o I_o}{V_s \cdot I_s} = \frac{V_o I_o}{V_s \cdot I_{Rms}}$$

V_s ↓ Source R·MS; I_{Rms} ↓ Load RMS

Q- A single Phase transformer with Secondary voltage 230 V, 50 Hz deliver power to load $R = 10\Omega$ through a half wave controlled rectifier circuit. For a firing angle, delay of 60° determine.

(i) The rectification efficiency
(ii) Form Factor
(iii) Voltage Ripple Factor
(iv) Transformer Utilization factor
(v) PIV of SCR.



Given data,

$V_s = 230$ V (RMS value)

$R = 10\Omega$, $\alpha = 60°$

Now, $V_m = V_s \cdot \sqrt{2} = 230\sqrt{2}$

- Average Load voltage $(V_0)_{Avg.} = \frac{V_m}{2\pi}(1 + \cos\alpha)$

$V_s = 230$ V
$V_m = 230\sqrt{2}$, $V_{0_{Avg.}} = \frac{230\sqrt{2}}{2\pi}(1 + \cos 60°)$

$(V_0)_{Avg.} = 77.64$ V

- Average load current is given by $(I_0)_{Avg.} \rightarrow$

$$(I_0)_{Avg} = \frac{V_{0_{Avg}}}{R} = \frac{77.64}{10} = 7.76 \text{ A}$$

- The RMS value of output voltage is given by $\rightarrow$

$$(V_0)_{RMS} = \frac{V_m}{2\sqrt{\pi}}\left[\pi - \alpha + \frac{1}{2}\sin 2\alpha\right]^{1/2}$$

$$= \frac{230\sqrt{2}}{2\sqrt{\pi}}\left[\pi - \frac{\pi}{3} + \frac{1}{2}\sin 120^\circ\right]$$

$V_{o_{RMS}} = 145.875\ V$

- The RMS value of output current is given by

$I_{o_{RMS}} = \frac{V_{o_{RMS}}}{R} = \frac{145.875}{10}$

$I_{o_{RMS}} = 14.87\ A$

- Output DC Power is given by

$P_{o_{DC}} = V_{o_{Avg.}} \cdot I_{o_{Avg.}} = 77.64 \times 7.76 = 602.8\,W$

- Output AC Power is given by

$P_{o_{AC}} = V_{o_{Rms}} \cdot I_{o_{Rms}}$

$= 145.87 \times 14.87 = 2169.08$

- Rectification efficiency

$\eta = \frac{P_{o\,dc}}{P_{o\,AC}} = \frac{602.8\,W}{2169.08} = 0.2779 = 27.79\%$

- Form factor =

$F.F = \frac{V_{o_{RMS}}}{V_{o_{Avg.}}} = \frac{145.87}{77.64} = 1.879$

- Voltage Ripple factor

$VRF = \sqrt{FF^2 - 1} = \sqrt{1.879^2 - 1} = 1.5908$

- The transformer utilisation Factor $= \frac{V_o I_o}{V_s I_s} = \frac{V_{o\,Avg.} \cdot I_{o\,Avg}}{V_s \cdot I_{o_{RMS}}}$

$TUF = \frac{77.64 \times 7.764}{230 \times 14.58} = 0.1796$

- $PIV = V_m = \sqrt{2}\, V_s$

$= \sqrt{2} \times 230 = 325.27\ V$

Q. A 1-Ø half wave rectifier is used to supply power to a load of impedance 10Ω from 230V, 50Hz AC supply at the firing angle of 30°. Calculate the load current.

⇒ $R_L = 10\Omega$, $\alpha = 30°$

Average load voltage $V_{o_{Avg.}} = V_{Ldc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$

$V_{o_{Avg.}} = \frac{230 \cdot \sqrt{2}}{2\pi}(1 + \cos 30°)$

$= 96.6\ V$

(ii) Average load current $I_{Ldc} = I_{o_{Avg.}} = \frac{V_{o_{Avg.}}}{R} = \frac{V_{Ldc}}{R}$

$I_{o_{Avg.}} = 9.66\ A$

Q. A Resistive load of 10Ω is connected through a half wave circuit to 220V, 50 Hz single Phase source. Calculate the power delivered to load for a firing angle of 60°. Find also the value of input power factor.

⇒ $R = 10\Omega$, $V_S = 220\ V$, $\alpha = 60°$

RMS output voltage is given by

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

$$= \frac{220 \cdot \sqrt{2}}{2\sqrt{\pi}}\left[(\pi - \pi/3) + \frac{1}{2}\sin 120°\right]^{1/2}$$

$= 139.53\ V$

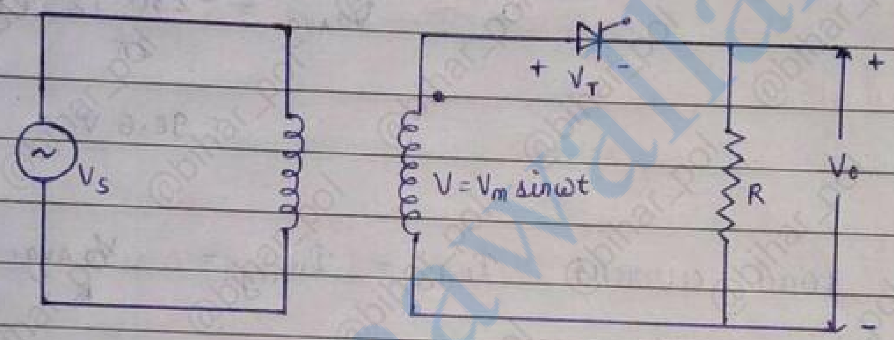
Power delivered to load $P_{AC} = \frac{V_{Rms}^2}{R} = \frac{139.53^2}{10} = 194720$

Input Power factor $IPF = \frac{V_{Rms}}{V_s} = \frac{139.53}{220} = 0.634$ lag.

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

Q. A thyristor is used to control the power of 1 kW, 230 V, 50 Hz heater. Determine the heater power for firing angles of 45° and 90°.

⇒



$V_s = 230V$, $f = 50 Hz$, $P = 1 kW$, $\alpha = 45°$, $90°$
$\alpha = 45° \to \pi/4$, $90° \to \pi/2$

$V_m = 230\sqrt{2}$

The resistance of load will be

$$R = \frac{V_s^2}{P} = \frac{230^2}{1\times10^3} = 52.90\,\Omega$$

$$R = 52.90\,\Omega$$

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

$$= \frac{230\sqrt{2}}{2\sqrt{\pi}}\left[\pi - \pi/4 + 1/2 \sin 90°\right]^{1/2}$$

$$= 91.75\left[3\pi/4 + 1/2\right]^{1/2}$$

$$= 91.75\,[2.85]^{1/2}$$

$$V_{Rms} = 155\,V.$$

→ Inductor cannot accept sudden change in current.
→ Capacitor cannot accept sudden change in voltage.
→ When switch ON, Internal drop value = 0

The value of power is given by.

$$P_{heater} = \frac{V_{Rms}^2}{R} = \frac{155^2}{52.90} = 454.15 \text{ watt}$$

at $\alpha = \pi/2$

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

$$= \frac{230\sqrt{2}}{2\sqrt{\pi}}\left[\pi - \pi/2 + \frac{1}{2}\sin 2\pi/2\right]^{1/2}$$

$$= 91.75\left[\pi/2\right]^{1/2}$$

$$= 114.99$$

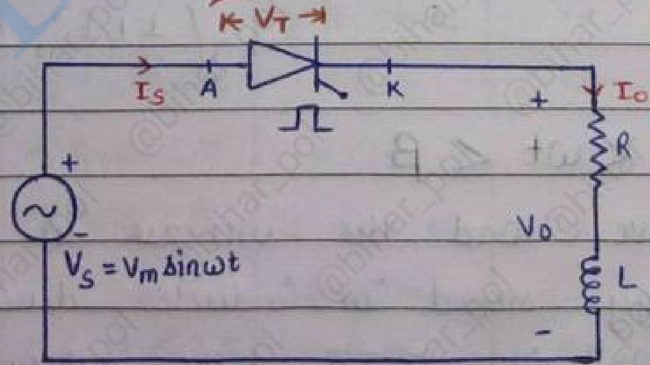
$$V_{oRMS} = 115 \text{ V}$$

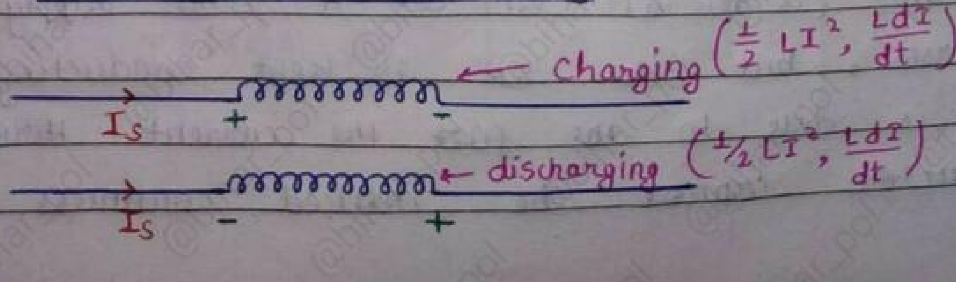
The value of power is given by $P_{heater} = \frac{V_{Rms}^2}{R} = \frac{115^2}{52.90}$

$$P_{heater} = 250 \text{ W}$$

$$IPF = \frac{V_{RMS}}{V_S} = \frac{115}{230} = 0.5 \text{ lag}$$

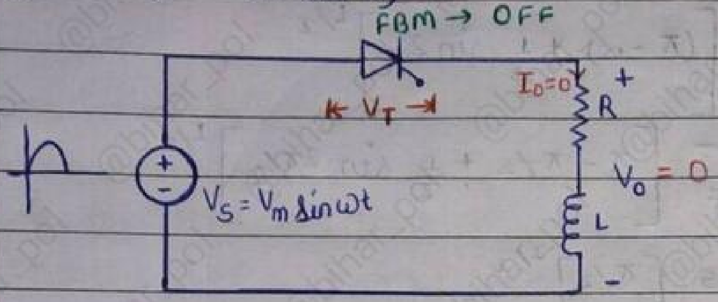
* 1-Ø HWCR with R-L Load
Or, Operation of HWCR with R-L Load





Mode 1 :- $0 < \omega t < \alpha$

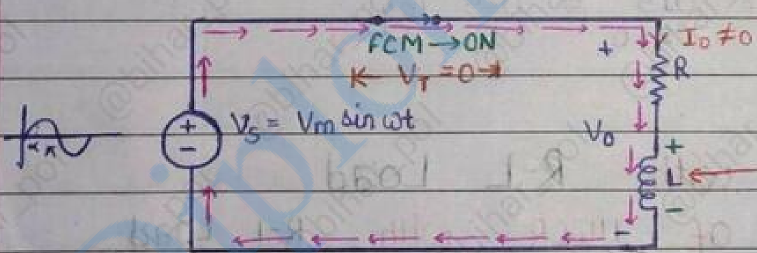
→ In this mode SCR is in forward blocking mode (OFF state) such that the voltage across SCR. ($V_t = V_s = V_m \sin\alpha$)



$V_o = 0$, $I_o = 0$
Load to source is disconnected.

Mode 2 :- $\alpha < \omega t < \pi$

→ Here the SCR is in forward conduction mode, so the voltage across the SCR is zero, At some delay angle α forward biased (blocking) is triggered and source voltage V_s is appears across the load as V_o.



$\left(\frac{1}{2} L I^2, \frac{L dI}{dt}\right)$

Mode 3 :- $\pi < \omega t < \beta$

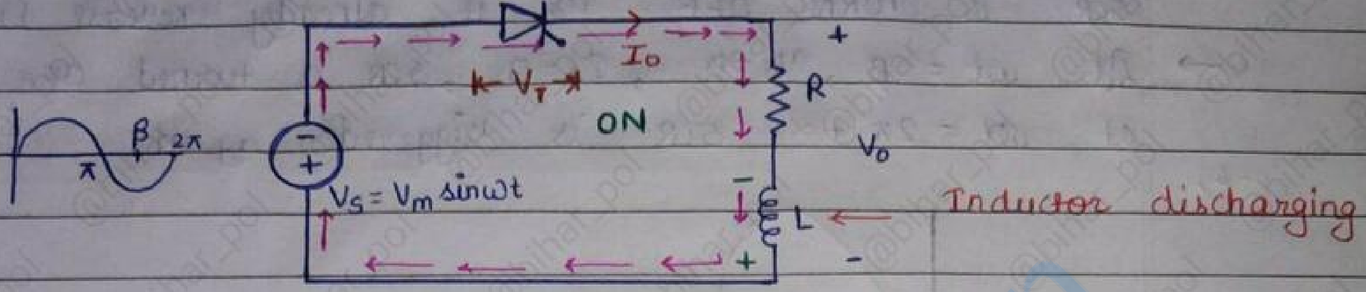
→ Due to inductive load the increase in current gradually, energy stored in inductor during the instant (α to π). - At $\omega t = \pi$, the supply voltage is reverses, but the SCR is kept conducting.

→ It is due to the fact the current through the inductor cannot be reduced continues to flow

$\alpha \rightarrow \pi$ = Inductor charging

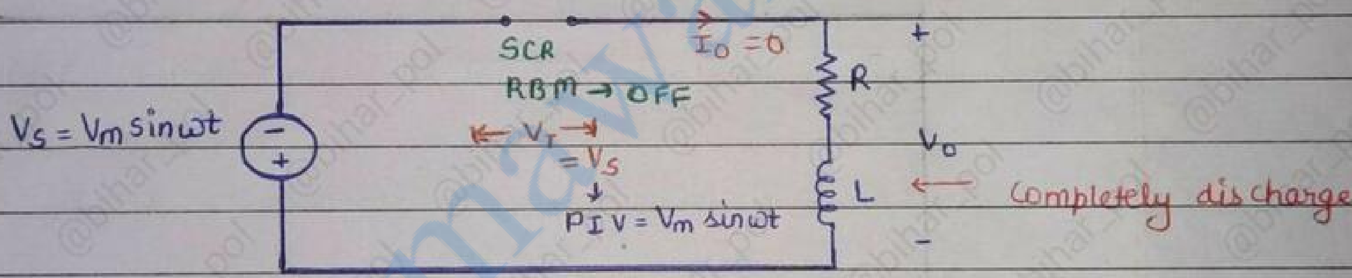
β = completely inductor discharge

upto $\beta \cdot \rightarrow$ (extinction Angle).



Mode 4 :- $\beta < \omega t < 2\pi$

→ At $\omega t = \beta$ the load current I_0 is zero and due to -ve supply voltage thyristor turn off, here SCR is in RBM mode and voltage across the SCR $V_T = V_S$.



Mode 5 :- $2\pi < \omega t < 2\pi + \alpha$

→ In this mode SCR is in forward blocking mode and is similar to mode 1.

	SCR state	V_0	V_T
$0 < \omega t < \alpha$	F.B	0	$V_S = V_m \sin\alpha$
$\alpha < \omega t < \pi$	F.C	V_S	0
$\pi < \omega t < \beta$	F.C due to inductor energy	V_S	0
$\beta < \omega t < 2\pi$	R.B	0	V_S
$2\pi < \omega t < 2\pi + \alpha$	F.B	0	$V_S = V_m \sin\alpha$

+ve Inductor charging ($\alpha < \omega t < \pi$); -ve RBM ($\pi < \omega t < \beta$)

conduction Angle / discharging ($V_T = 0$ rows)

ckt turn OFF time or PIV ($\beta < \omega t < 2\pi$, V_S)

→ At some angle $\beta > \pi$, I_0 reduces to zero and SCR is TURN OFF as it already reverse biased.
→ At $\omega t = \beta$, $V_0 = 0$, $I_0 = 0$, SCR is turned OFF and at $\omega t = 2\pi + \alpha$ SCR is triggered again.

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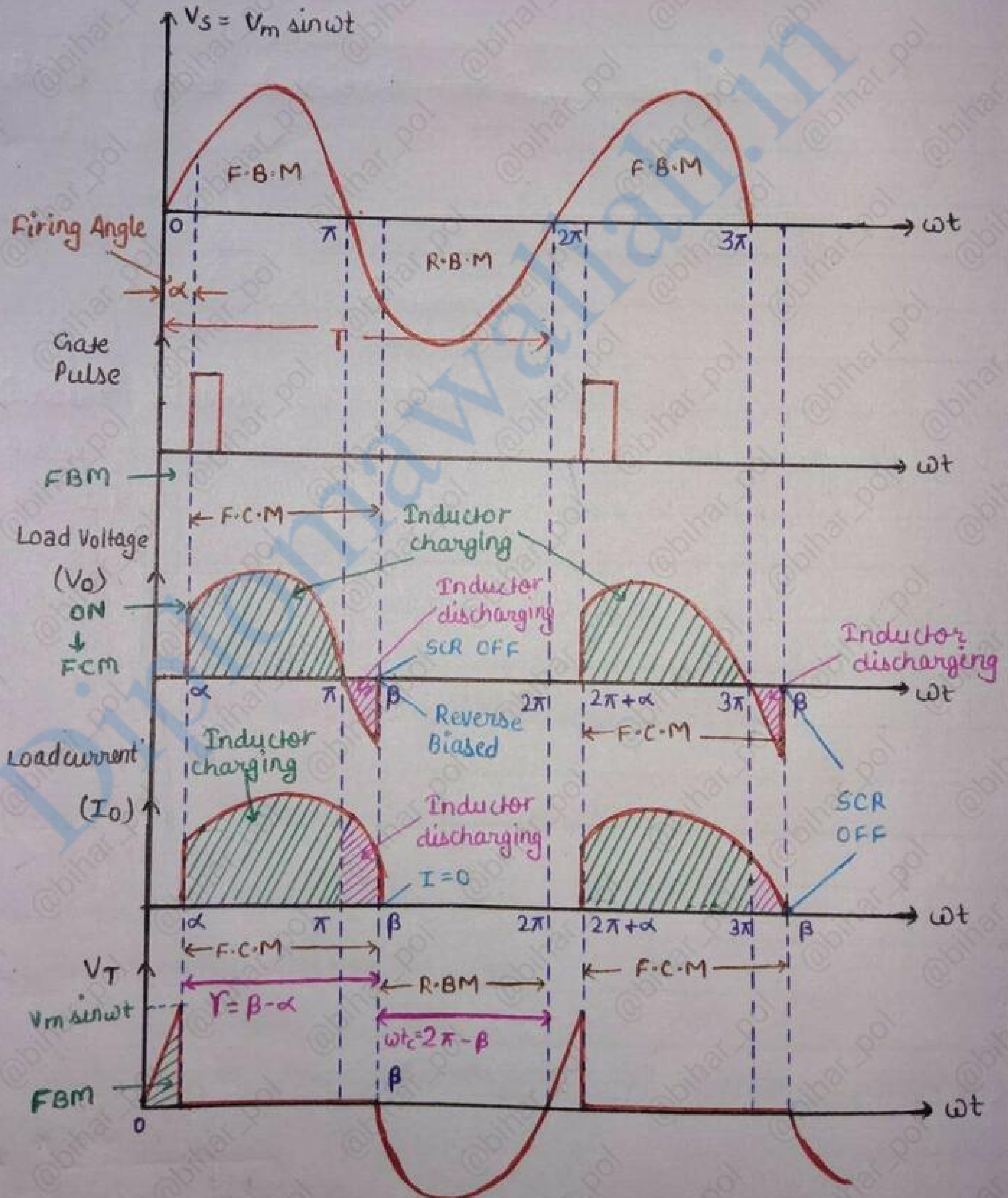


Q. Why SCR does not OFF on π ?

⇒ π पर SCR के पास Reverse voltage तो apply हो जाता है लेकिन Anode current का value zero नहीं होता है। ($I_A \downarrow I_H$) इसके कारण हमारा SCR π पर Turn OFF नहीं होता है, जो की β तक चला जाता है।

★ γ = conduction Angle = SCR conducting

$= \beta - \alpha$

★ ωt_c = Circuit turn off time

= SCR is in RBM mode

$= 2\pi - \beta$

1. Average Load Voltage $(V_0)_{Avg}$ or $V_{o_{DC}}$

$$V_{o_{Avg}} = \frac{1}{T}\int_0^T V_s\,dt = \frac{1}{2\pi}\int_0^{2\pi} V_s \sin\omega t\, d\omega t = \frac{1}{2\pi}\int_0^{\beta} V_m \sin\omega t\, d\omega t$$

$$V_{o_{Avg}} = \frac{V_m}{2\pi}\Big|-\cos\omega t\Big|_{\alpha}^{\beta} = \frac{V_m}{2\pi}\left|-\cos\beta + \cos\alpha\right|$$

$$\boxed{V_{o_{Avg}} = \frac{V_m}{2\pi}\left|\cos\alpha - \cos\beta\right|}$$

$\alpha \rightarrow$ Firing Angle

$\beta \rightarrow$ Extinction Angle

2. Average Load Current → $I_{o_{Avg}}$ or $I_{o_{DC}}$

$$I_{o_{DC}} = \frac{V_{o_{Avg}}}{R} = \frac{V_{o_{DC}}}{R}$$

$$I_{o_{Avg}} = \frac{V_m}{2\pi R}\left|\cos\alpha - \cos\beta\right|$$

3. RMS Load Voltage → $V_{o_{RMS}}$ or $V_{o_{AC}}$

$$V_{o_{AC}} = \sqrt{\frac{1}{T}\int_0^T V_s^2\,dt}$$

$$V_{o_{RMS}}^2 = \frac{1}{2\pi}\int_0^{2\pi}(V_m \sin\omega t)^2 d\omega t = \frac{1}{2\pi}\int_\alpha^\beta V_m^2 \sin^2\omega t \cdot d\omega t$$

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

$$= \frac{V_m}{2\sqrt{\pi}}\sqrt{(\beta-\alpha) - \frac{1}{2}\{(\sin 2\beta - \sin 2\alpha)\}}$$

4. RMS Load Current → $I_{o_{RMS}}$ or $I_{o_{AC}}$

$$I_{o_{AC}} = \frac{V_{o_{RMS}}}{R}$$

$$= \frac{V_m}{2\sqrt{\pi}R}\sqrt{(\beta-\alpha) - \frac{1}{2}\{(\sin 2\beta - \sin 2\alpha)\}}$$

5. Circuit turn Off Time

→ Circuit turn off time is always determined by when the SCR is in RBM.

$$\omega t_c = 2\pi - \beta$$

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

↓ Circuit turn off time

6. Conduction Angle

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

7. Input Power Factor $= \frac{P_{out}}{V_A} = \frac{P_{out}}{V_S \cdot I_S}$

P_{out} ↓ → -ve clip present in o/p voltage waveform.

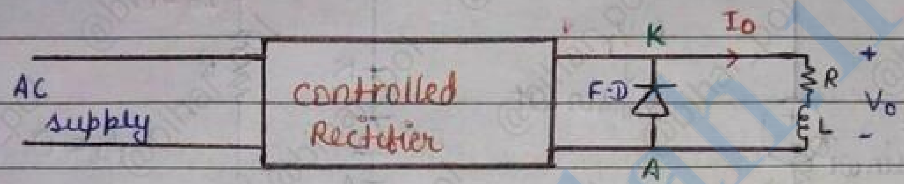
★ ★ obj

$\boxed{P_{out}\downarrow \quad IPF \downarrow}$

★ By using freewheeling diode input P.F ~~increased~~ improved.

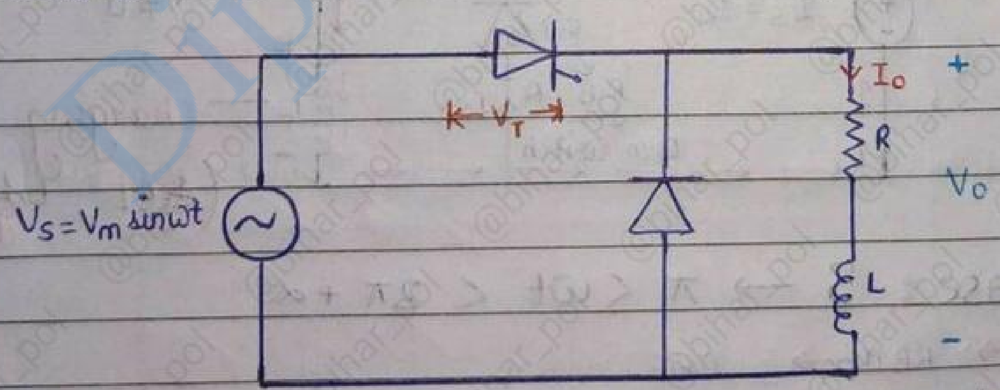
* # Advantage of freewheeling diode (FD) in controlled Rectifier

Input power factor is improved.
Load current wave form is improved.
As the energy stored in inductance is transferred to resistance during the freewheeling period overall converter efficiency is improved.



→ It helps to maintained load current continuous such as in speed controls on DC motor. A continuous armature current improves the performance of DC motor.

→ FD is known as ~~sn~~ snubber diode, supressor diode clamp diode, this is a diode used to eliminate flyback which is nothing but a sudden voltage spike seen across an inductive load when its supply voltage is suddenly removed or reversed biased. → Define.



HWCR R-L Load with freewheeling diode

FD → Freewheeling diode
↓
Basic Diode

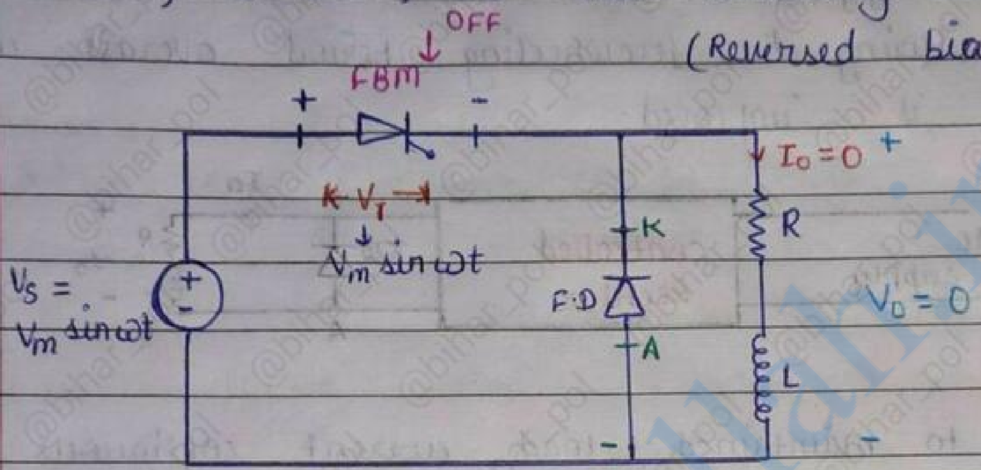
Mode Case:-1 → $0 < \omega t < \alpha$

↓ getting Pulse SCR

SCR → F.B.M → OFF

Load to source → disconnected.

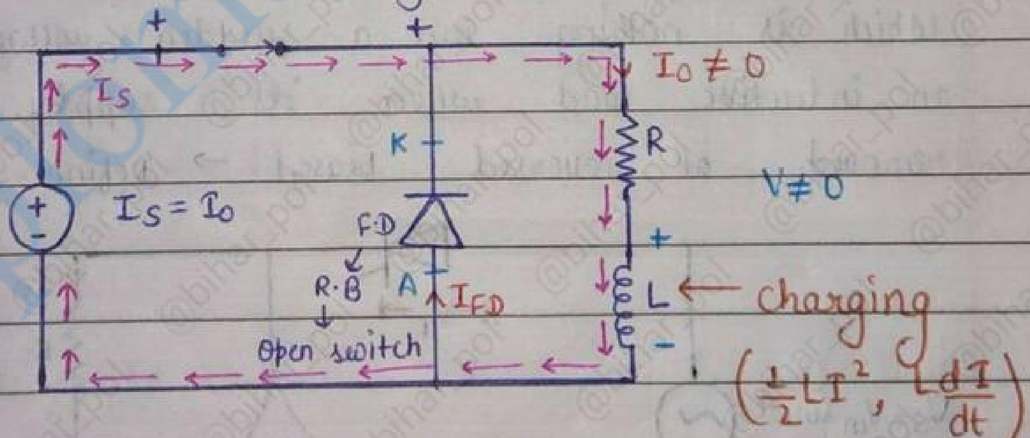
$V_0 = 0$, $I_0 = 0$, F.D → Non conducting mode (Reversed biased)



Case:-2 → $\alpha < \omega t < \pi$

SCR → FCM → $V_T = 0$, Load to source is disconnected.

FD → R.B → Non conducting mode open ckt.

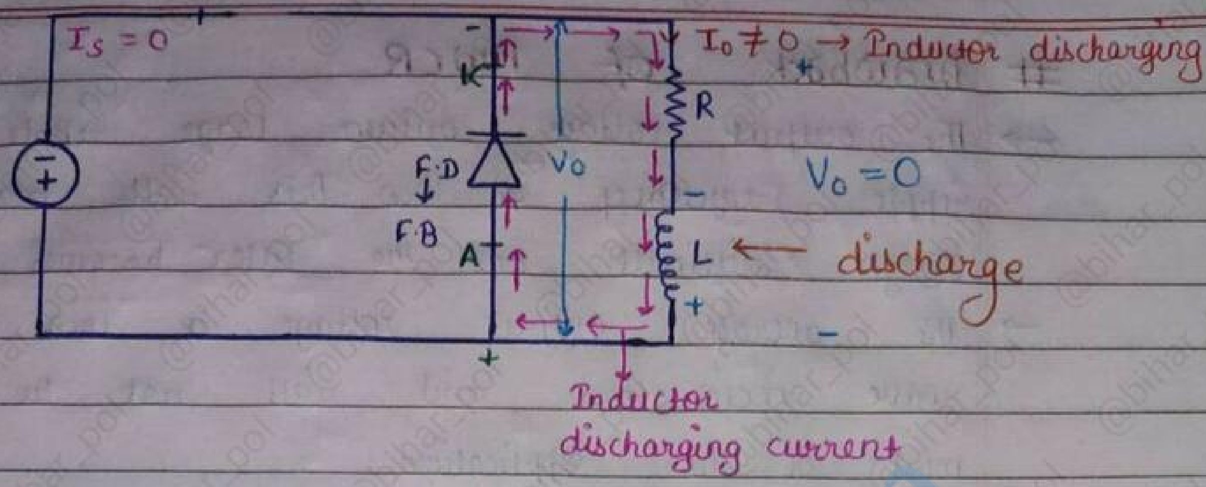


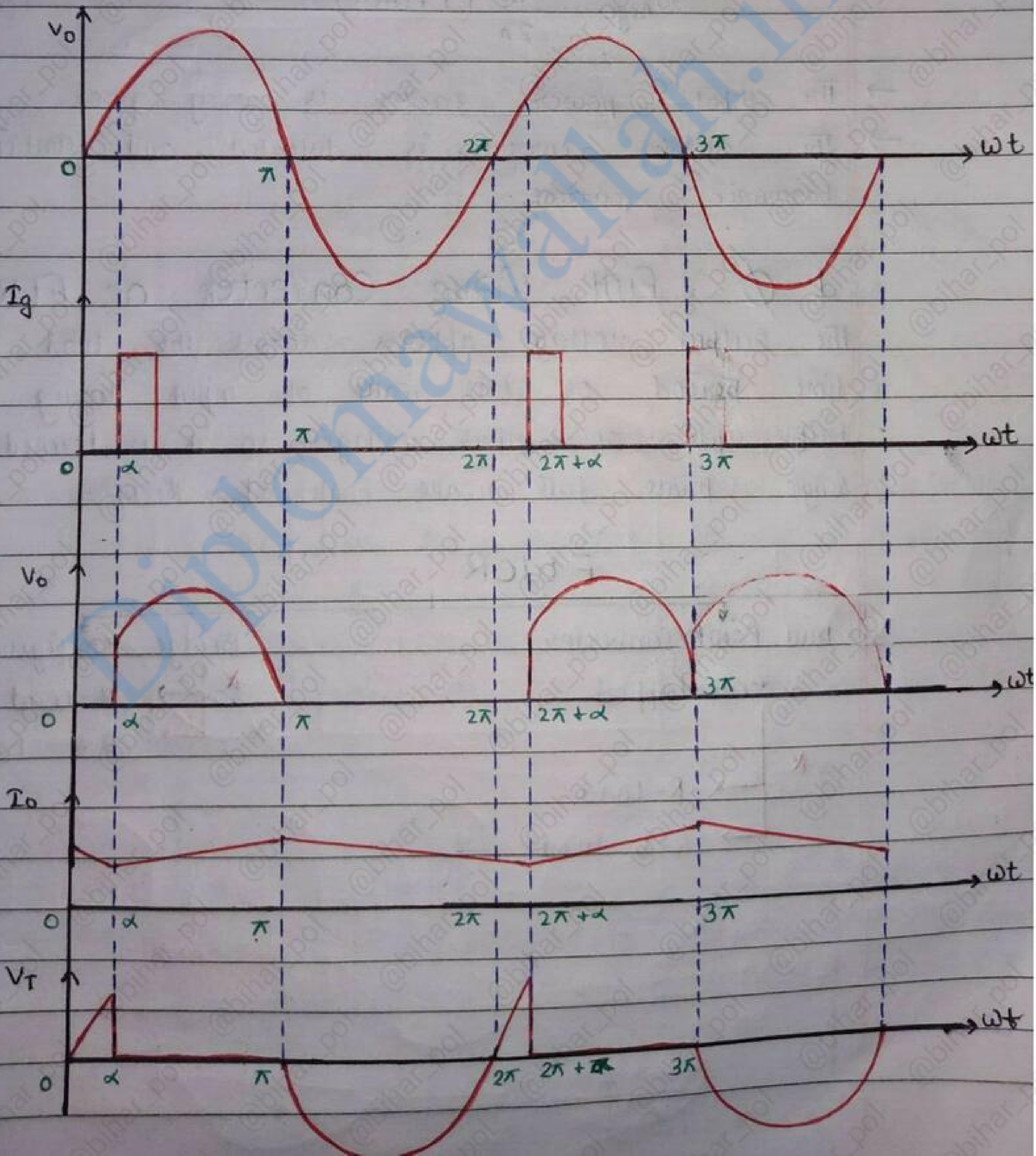
Case:-3 → $\pi < \omega t < 2\pi + \alpha$

SCR → RBM → OFF

F.D → conduct → idea → 0 V

Practical → 0.7 V


$I_s = 0$
K
F.D
F.B
A
V_0
R
L
$I_0 \neq 0$ → Inductor discharging
$V_0 = 0$
← discharge
Inductor discharging current


V_0
ωt
0
π
2π
3π
I_g
α
2π+α
V_0
I_0
V_T

Drawback of HWCR

→ The output voltage contain large ripple and the ripple frequency is low. This will make the filter design difficult and the filter becomes bulky.

→ The average output voltage is low due to half wave rectification and will not be useful in most of the application.

$$V_{O_{Avg.}} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

→ The input power factor is very poor.

→ The supply current is distorted and contain harmonic current.

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1-Ø Full Wave Converter or FWCR

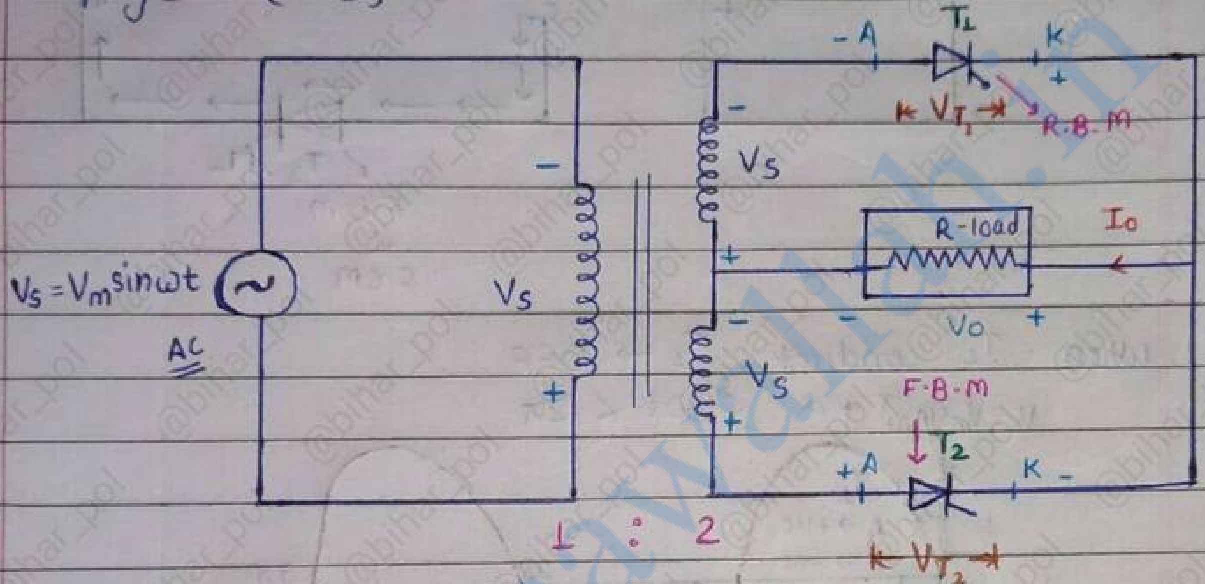
The output voltage appears across the load for a time period of full wave of input during both the half cycle of input voltage so it is termed as single phase full wave controlled Rectifier.

FWCR

- Mid Point converter / centertapped
  - * R- Load
  - R-L Load
- Bridge configuration
  - * R-load
  - * R-L Load

* 1-Ø Mid-Point Full Wave Converter
or, 1-Ø centretapped Full wave Converter

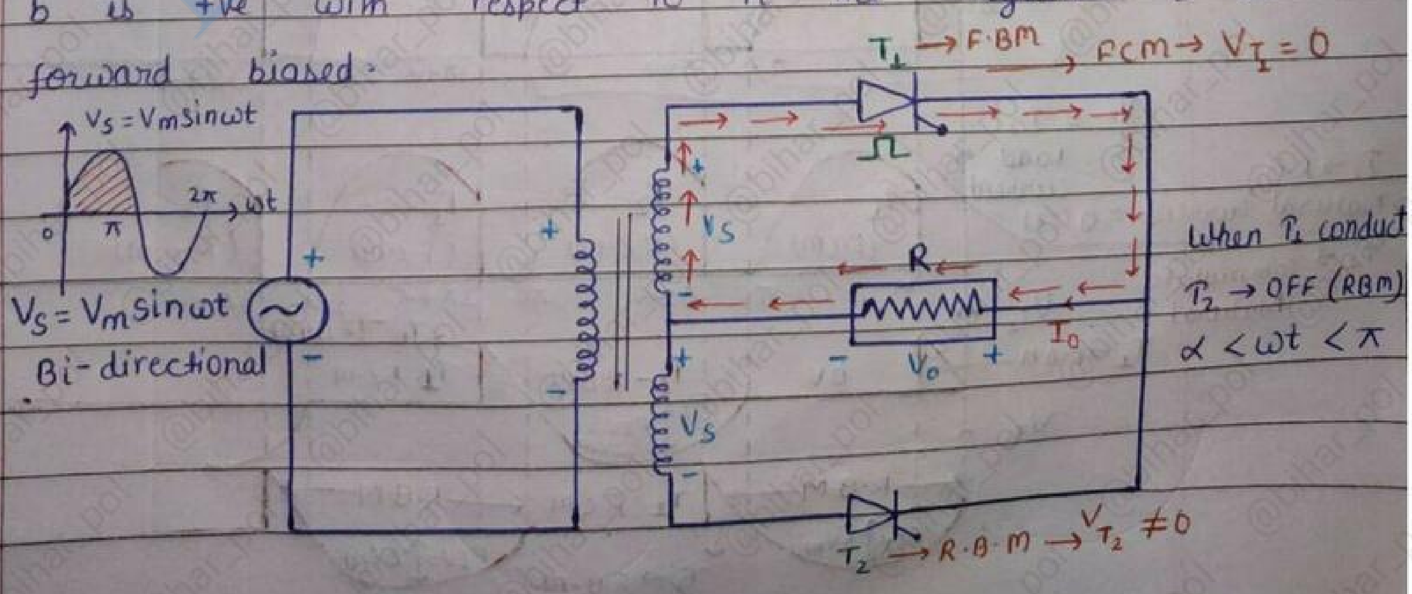
In a 1-Ø full wave controlled rectifier circuit with mid-point configuration, two SCR and a single phase transformer with a centretapped secondary winding are employed (used).

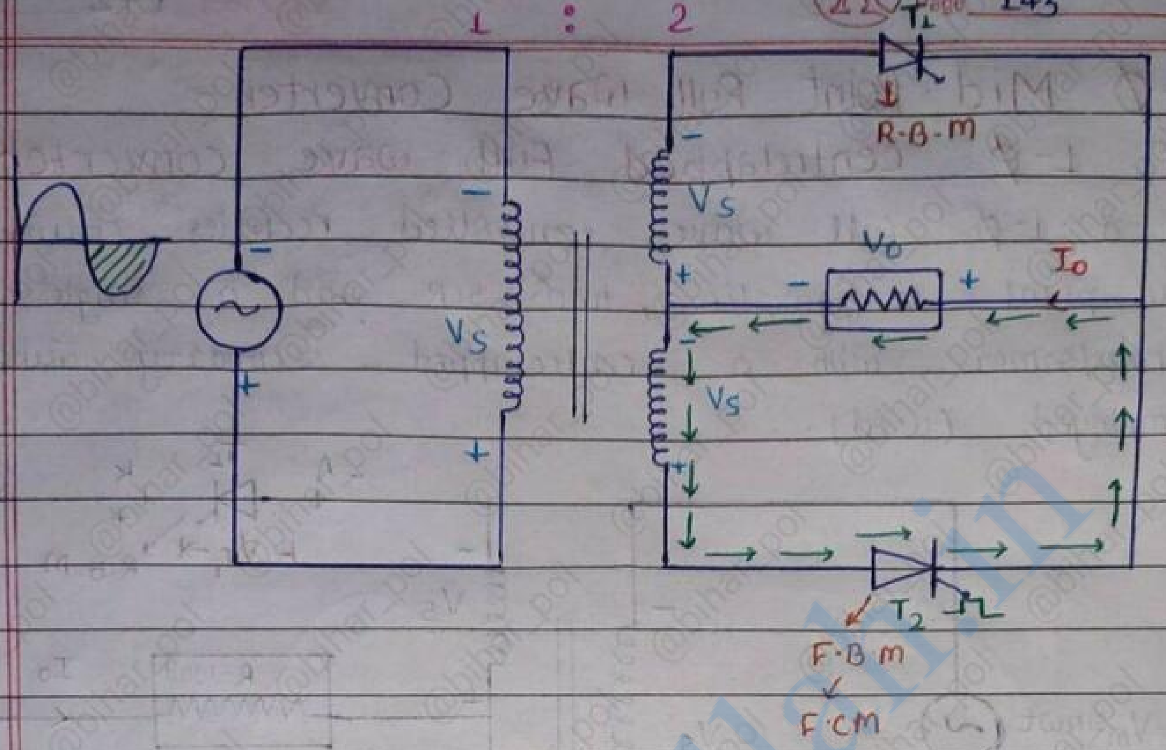


→ This is mainly used in rectifier for low rating.

→ During the +ve half cycle of the AC supply where terminal a is +ve w.r.t to n, thyristor T_1 is forward biased.

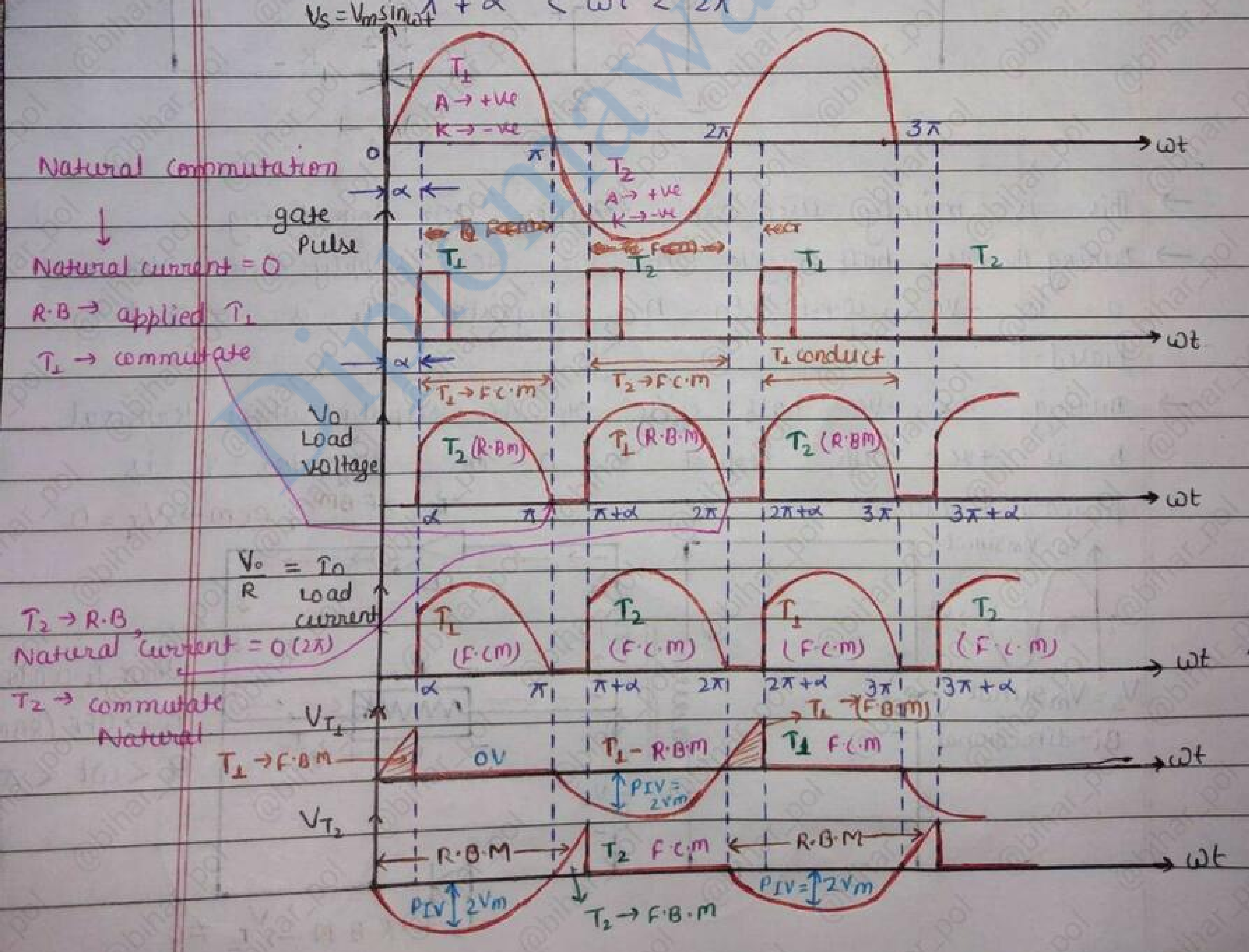
→ During the -ve half cycle of AC supply where terminal b is +ve with respect to n the thyristor T_2 is forward biased.





When T_2 conduct $T_1 \rightarrow$ OFF

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



Unit 3 Inverter

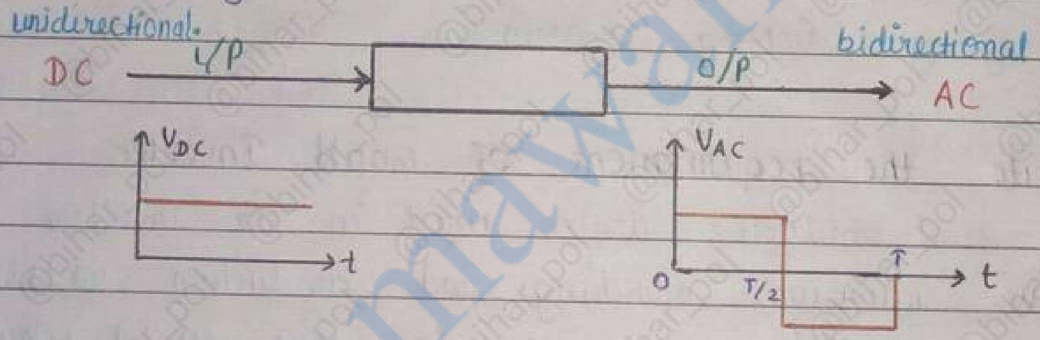
→ A device that convert DC power into AC power at desired output voltage and frequency is called an inverter.

or,

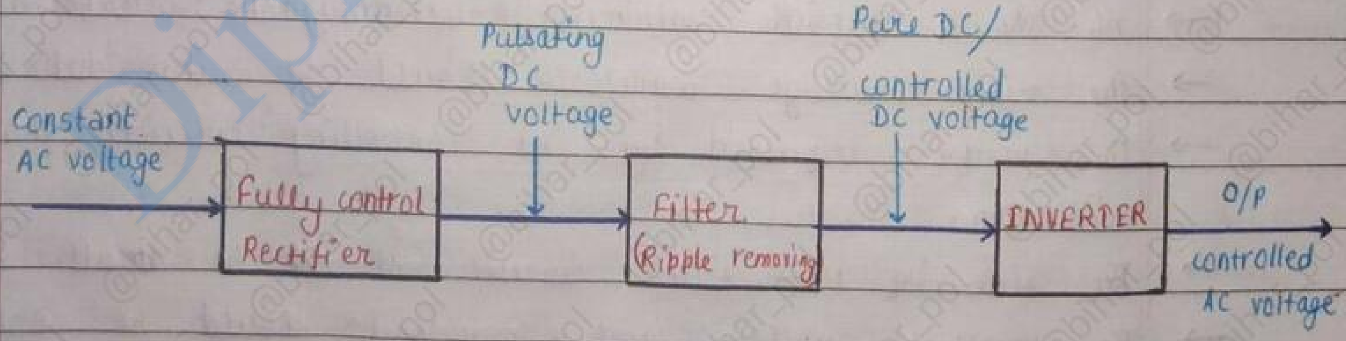
→ Circuit that performs the opposite function of rectifiers is known as inverter.

or,

→ Inverter is device that converts direct current (DC) input to alternating current (AC) output.



Imp Block diagram of Inverter



* When AC mains present :-

→ Inverter unit converts AC mains supply into DC and stores DC power in the battery.

→ The input AC power is directly passes to output load through changeover relay.

* • When AC mains Absence :-

→ DC power stored in the battery is converted into AC by the use of electronic circuits, inverter transformer, etc. and is supplied to the load.

* Application of Inverter :—

1. Adjustable speed of AC drive.
2. Induction heating and Induction motor speed control.
3. Stand by Air-craft power supply.
4. UPS for computers.
5. HVDC Tr line.
6. Synchronous drive
7. Emergency lighting system.

* Write the requirement of Good Inverter

→ The semi-conductor device used in the inverter should have minimum switching and conduction losses.

→ It's gain (AC output voltage / DC input voltage) should be high.

→ It should provide minimum electromagnetic interference.

→ The output voltage waveform should be sinusoidal.

→ The power required by its controlling circuit should be minimum.

→ The size of the filter circuit should be small.

→ The output voltage and frequency should be ~~controlled~~ controllable in the desired uses.

For example- Inverter must be capable of keeping voltage and frequency constant for some application.

→ It's working must be long.

Classification of Inverter

- **Nature**
  - VSI / VFI → Voltage Source Inverter (Voltage fed Inverter)
  - CSI / CFI → Current Source Inverter (Current fed Inverter)
- **Type of communication**
  - Line commutated Inverter
  - Forced commutated Inverter
- **Configuration of ckt**
  - * Series Inverter
  - * Parallel Inverter
  - * Bridge Inverter
    - Half Bridge (R-load) *Imp.
    - Full Bridge (R-load) *Imp.

* Voltage Source Inverter / VFI

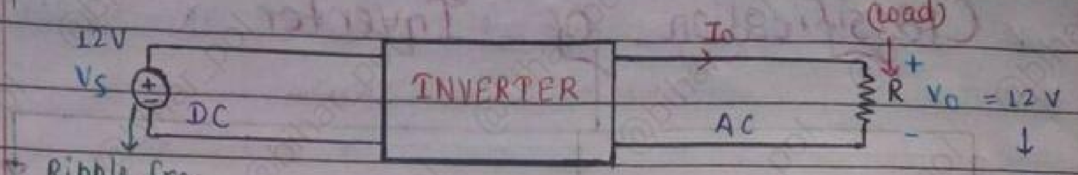
→ A voltage source inverter also known as voltage fed inverter is one in which the DC source has small or negligible internal impedance. In case of VSI the input to the inverter are ~~parallel~~ provided by a ripple free DC source.

→ For such inverter the amplitude of load voltage is equal to DC input voltage, The current wave form depends upon load.

$I_0 = \frac{V_0}{R}$ ↓R↑ (load) ↓I_0↑

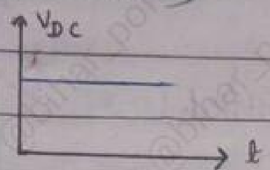
Example :- $I_0 = \frac{12}{4\Omega} = 3A$

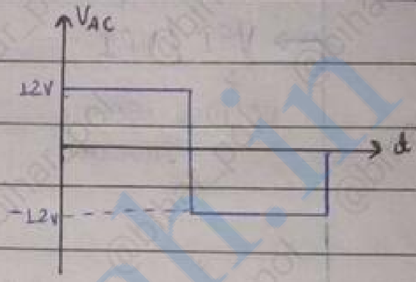
$I_0 = \frac{12}{6\Omega} = 2A$



→ Ripple free
↓
Pure DC
(unidirectional)

$V_o = V_s$
↓
Bidirectional
+ve , -ve





* Current Source Inverter / CSI

→ In current source inverter, voltage source is first converted in current source and then supply the power to the inverter.

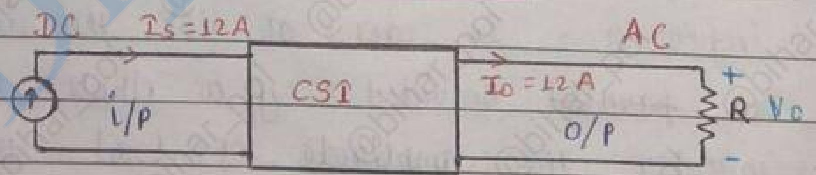
→ In this case the input current is maintained constant.

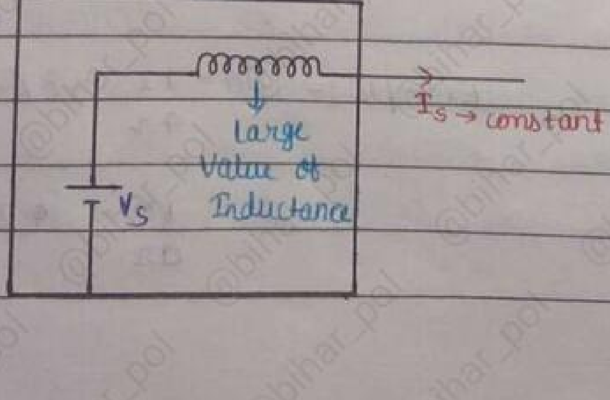
★ Imp (obj) → The constant current source can be obtained by connecting large inductance in series with the uncontrolled or controlled rectifier.

→ The load current is equal to source current but load voltage depends upon load.

$V_o = I_o R$

$V_o = I_S R$



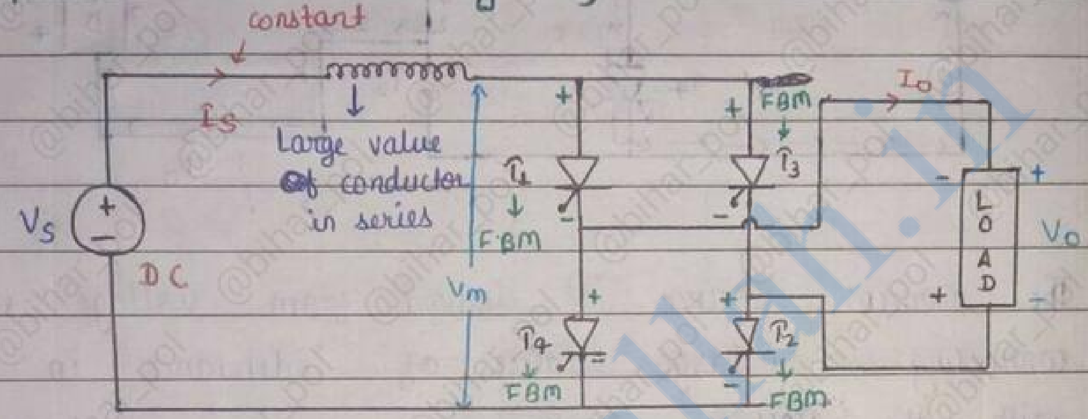


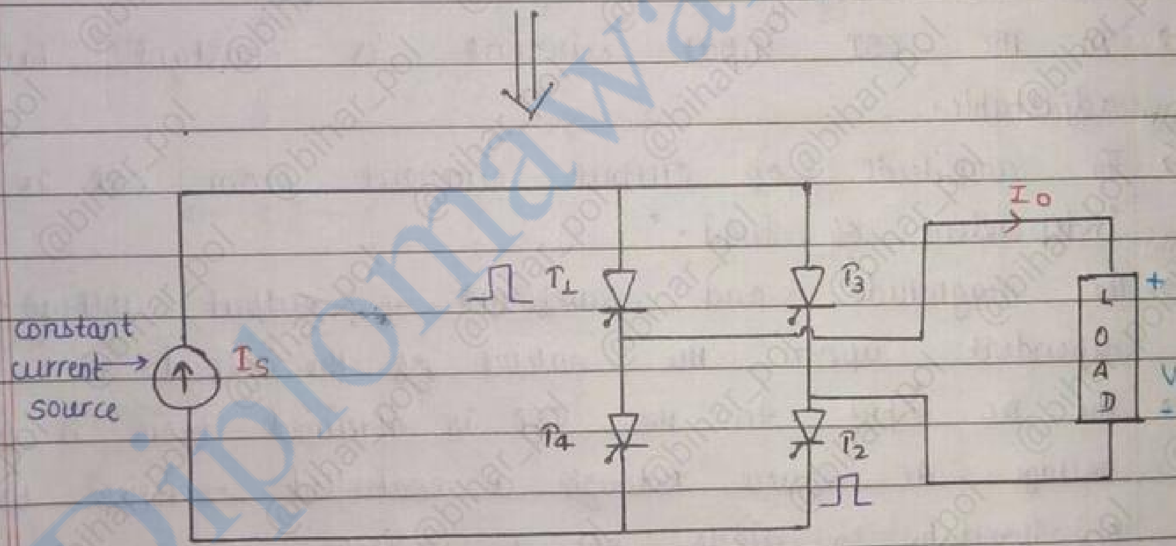
→ It supplies a constant output current due to the presence of the series connected inductance.

→ If the output current is varies then we have to varied the source voltage.

L-52

Explain the working Of Current Source Inverter

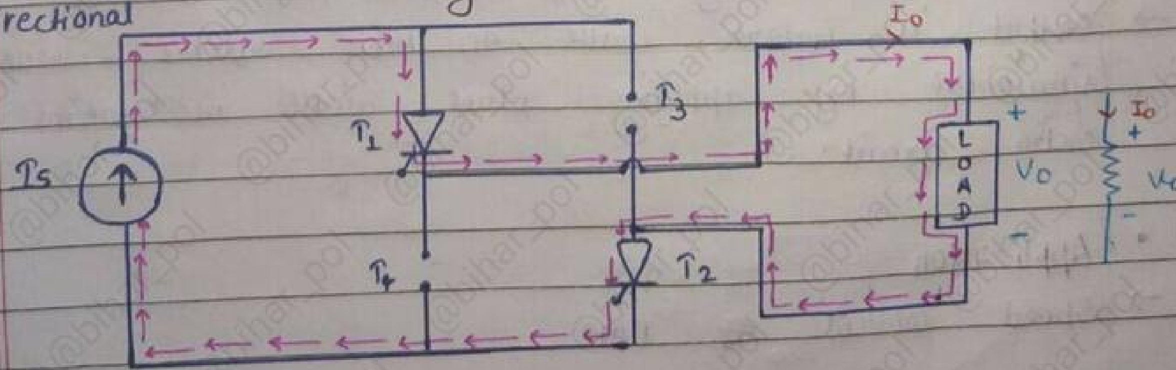




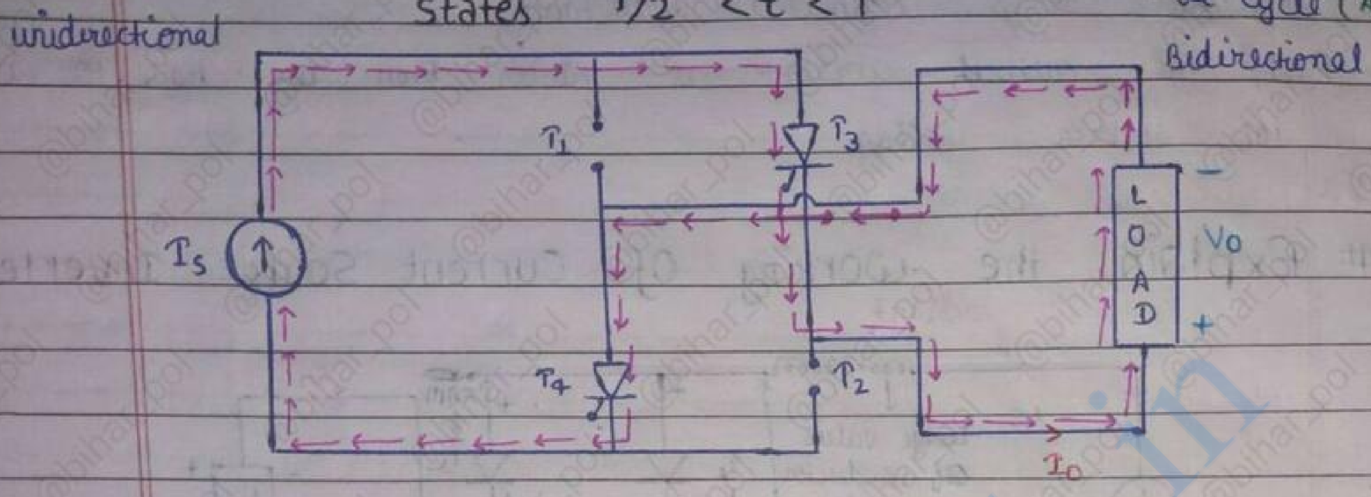
Mode - 1 → when $T_1 T_2$ conduct $0 < t < T/2$ & $T_3 T_4$ Non conducting state

+ve cycle (AC)

unidirectional



Mode-2 → When T_3, T_4 conduct $T_1 T_2$ → Non Conducting states $T/2 < t < T$ -ve cycle (AC)



→ The current source is derived from voltage source by connecting a large value of inductance in series with the voltage source.

→ In the CSI input current is constant but adjustable.

★ V.V.I obj → The amplitude of output current from CSI is independent of load.

★ V.V.I obj → The magnitude and waveform of output voltage is dependent upon the nature of the load.

→ The DC input to the CSI is obtained from a fixed voltage AC source through a controlled rectifier bridge or through a diode as a switch.

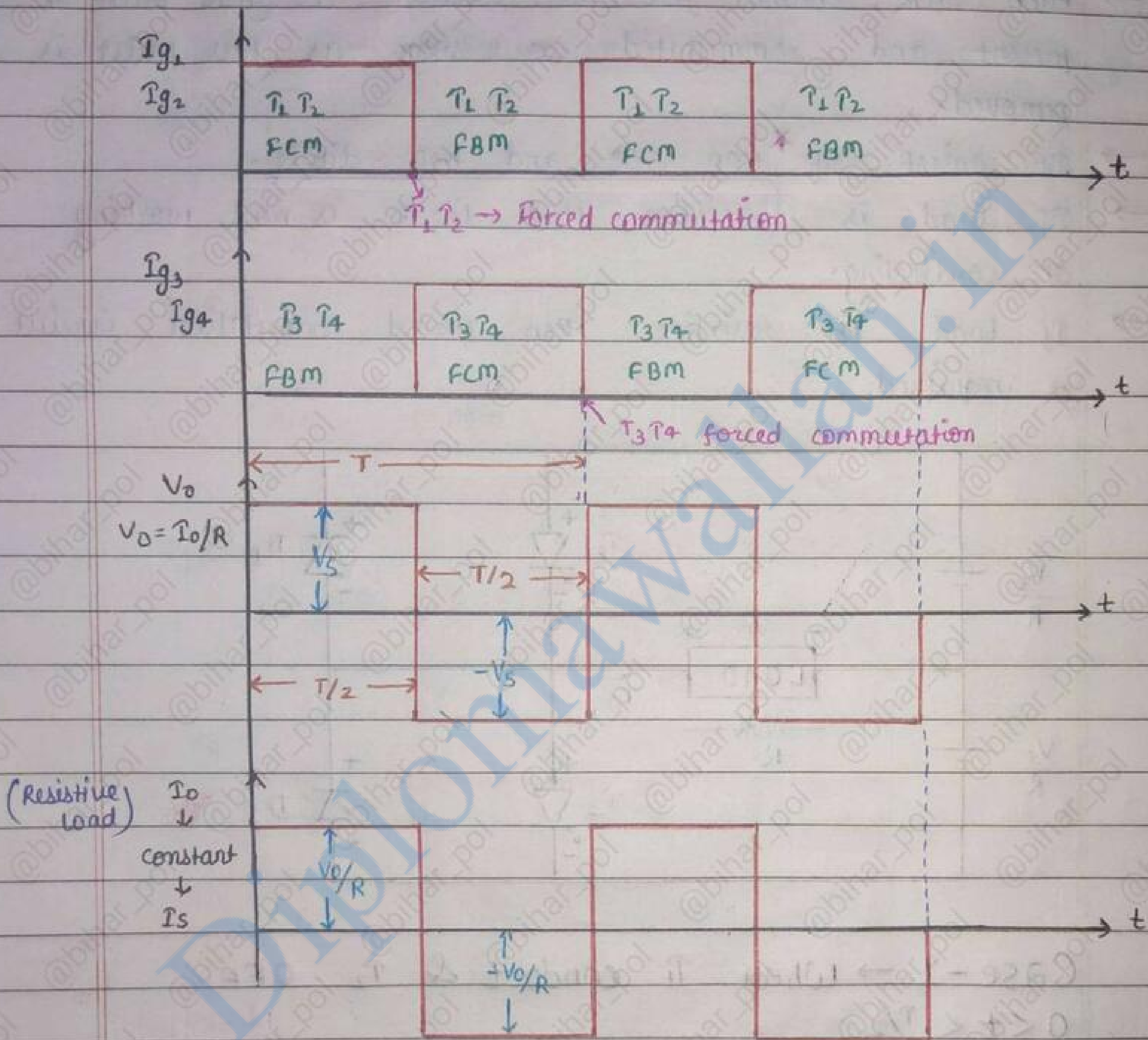
→ In order that i/p to CSI is almost ripple free and constant using large value of inductor.

→ Output is square wave AC then square wave to sinusoidal by applying pluse width modulation using extra circuit.

- Application

→ Speed control of IM

→ Induction heating
→ Synchronous motor starting.
→ lagging VAR



* **Voltage Source Inverter**

1. 1-Ø half bridge inverter
2. 1-Ø full bridge inverter

Freewheeling diode is working but when load is inductive.

1. 1-Ø Half Bridge Inverter (VSI)

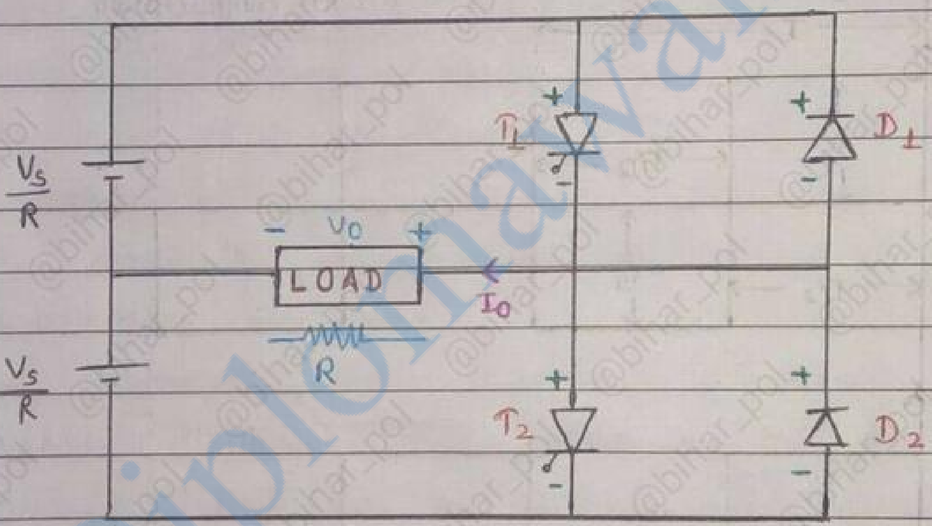
- Assumption →

→ Each SCR conduct for the duration its gate pulse is present and commutated as soon as this pulse is removed.

→ It consist of * two SCR and two - diode.

→ If load is resistive then diode is not working or conducting.

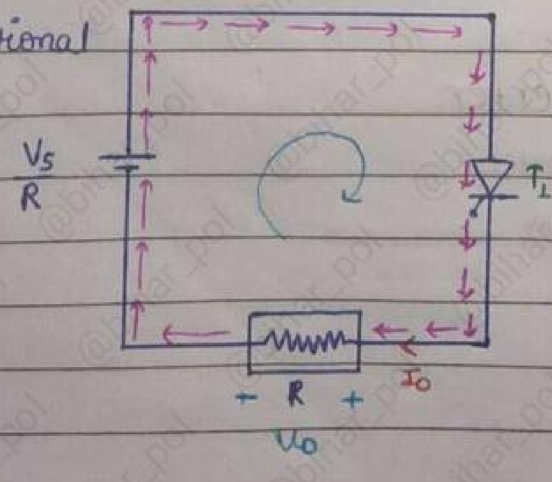
→ If load is resistive then forced commutation circuit is required.



Case-1 → When T_1 conduct & T_2 OFF

$0 < t < T/2$

unidirectional



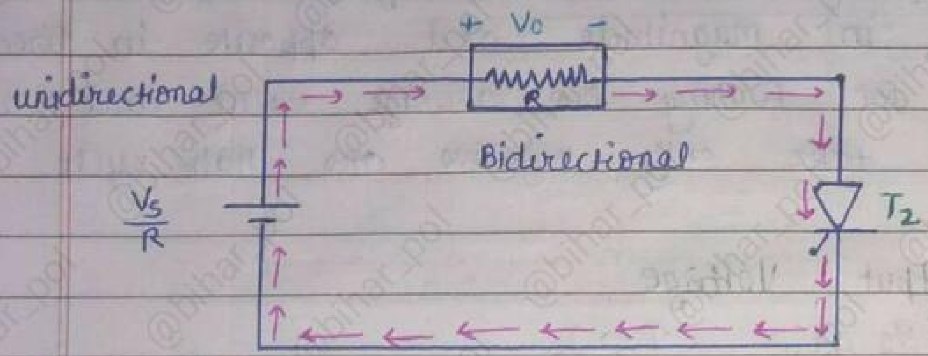
Here load is resistive then diode not conduct

$\frac{V_s}{2} - V_0 = 0 \quad \therefore V_0 = \frac{V_s}{2}$

$I_0 = \frac{V_0}{R} = \frac{V_s}{2R}$

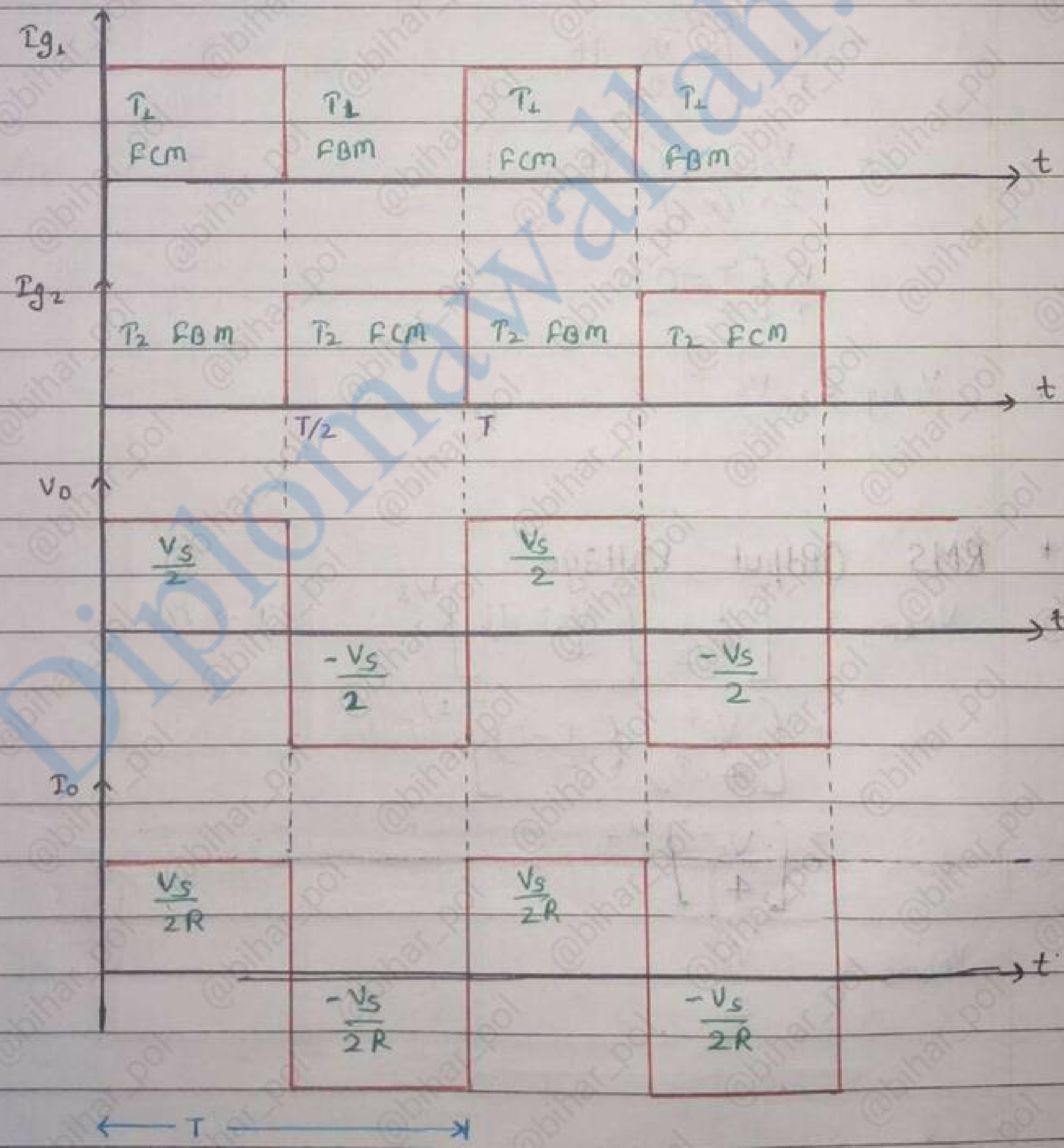
Case-2 → When T_2 conduct T_1 OFF

$T/2 < t < T$



$$\frac{V_s}{2} - V_0 = 0 \quad \therefore V_0 = \frac{V_s}{R}$$

$$I_0 = \frac{V_0}{R} = \frac{V_s}{2R}$$



★ Square wave → RMS value, Average Value are same.

NOTE:-
Here average value of full cycle is zero due to equal in magnitude and opposite in direction so ~~avera~~ for finding the average value and RMS value we take only ~~negative~~ one half cycle.

* Average Output Voltage

$$V_{O_{Avg}} = \frac{1}{T}\int_0^T \frac{V_s}{2}\,dt = \quad T \to \frac{T}{2}$$

$$= \frac{1}{T/2}\int_0^{T/2} \frac{V_s}{2}\,dt$$

$$= \frac{V_s}{2 \times T/2}\int_0^{T/2} 1\,dt$$

$$= \frac{V_s}{T}\left[\frac{T}{2} - 0\right]$$

$$V_{O_{Avg}} = \frac{V_s}{2}$$

* RMS Output Voltage

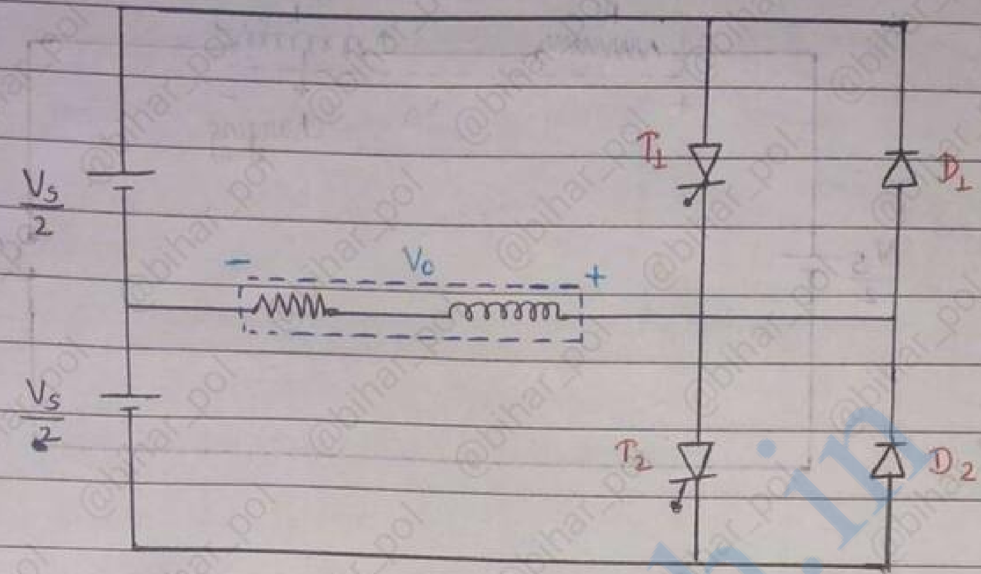
$$V_{O_{RMS}} = \left[\frac{1}{T/2}\int_0^{T/2} \frac{V_s^2}{4}\,dt\right]^{1/2} \qquad T \to T/2$$

$$= \left[\frac{V_s^2}{2 \cdot T/2}\left(\frac{T}{2} - 0\right)\right]^{1/2}$$

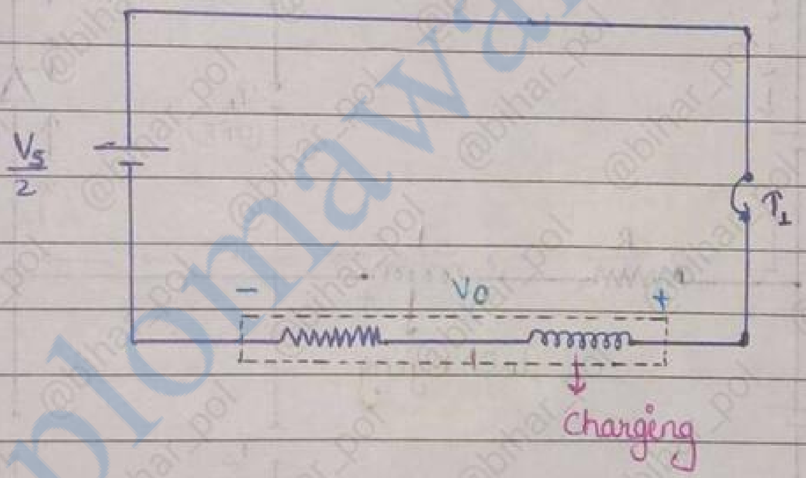
$$= \left[\frac{V_s^2}{4}\right]^{1/2}$$

$$V_{O_{RMS}} = \frac{V_s}{2}$$

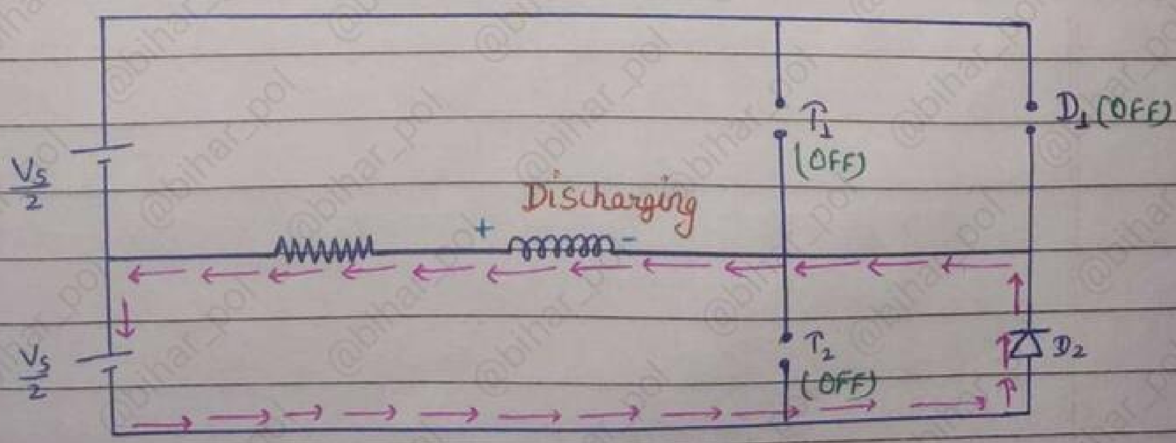
1-Ø Half bridge inverter with R-L load



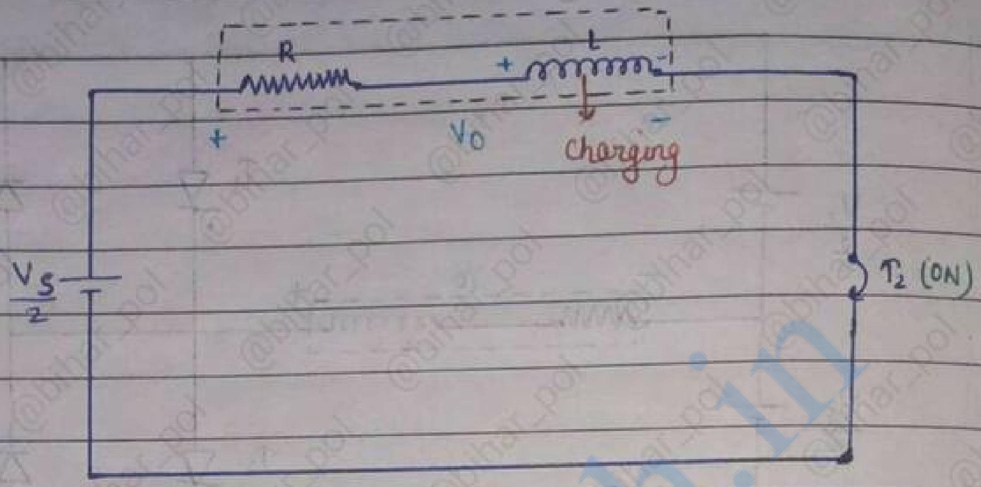
- When T_1 ON



- When T_2 OFF and T_1 OFF

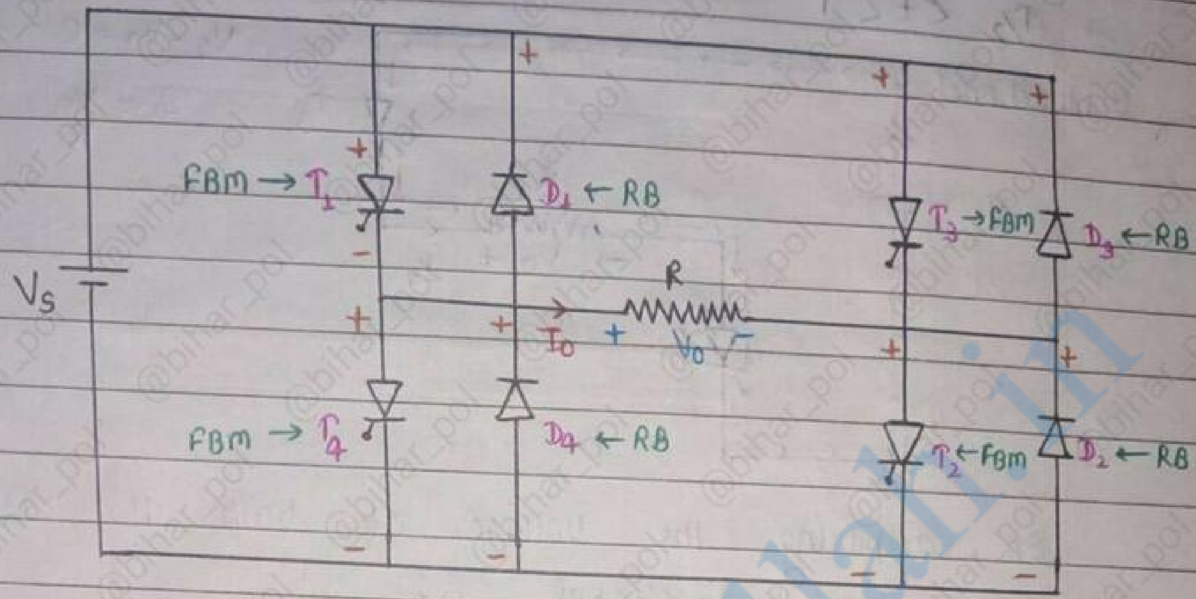


- When T_2 ON



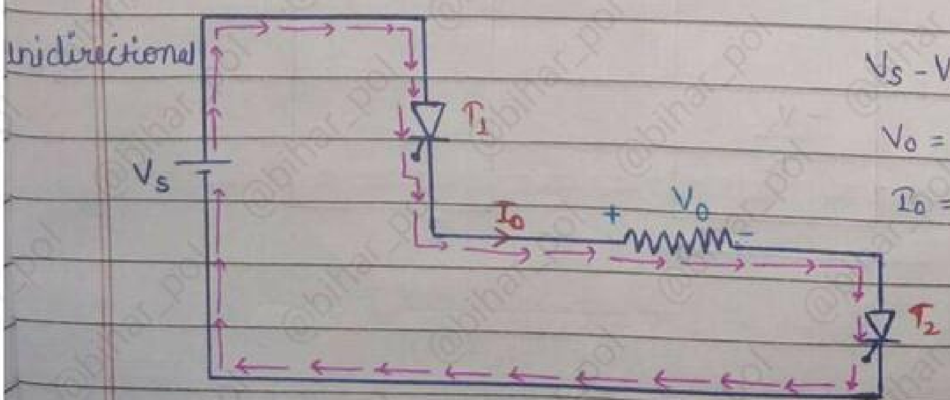
- When T_2 Off , T_1 OFF

2. 1-ϕ Full bridge Inverter



→ It consist of four SCR and four diode.
→ In this inverter the no. of SCR and diode is twice of that of half bridge inverter.
→ The amplitude of output voltage is double where as output power is four times in the inverter as compared to their half bridge.
→ In this inverter the T_1 and T_2 conduct load voltage V_s and when T_3 T_4 conduct load voltage is $-V_s$.
→ When load is resistive then diode not conduct.

Case-I → When T_1 T_2 conduct (F.C.M) T_3 T_4 Off (FBM)
$0 < t < T/2$

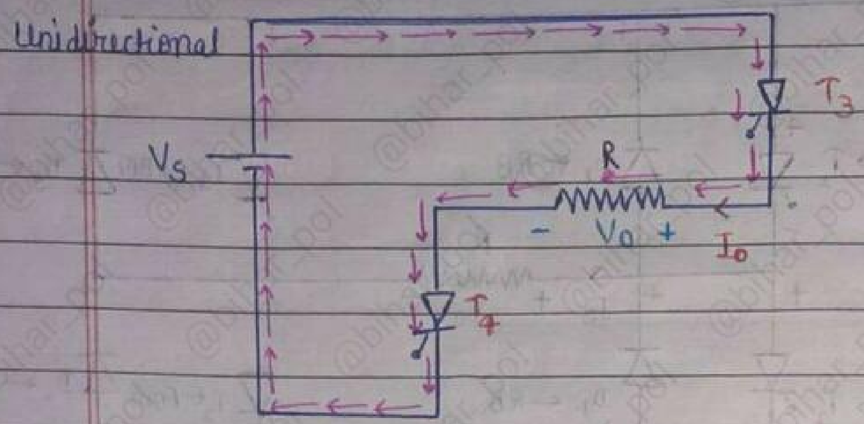


$V_s - V_0 = 0$

$V_0 = V_s$

$I_0 = \frac{V_0}{R} = \frac{V_s}{R}$

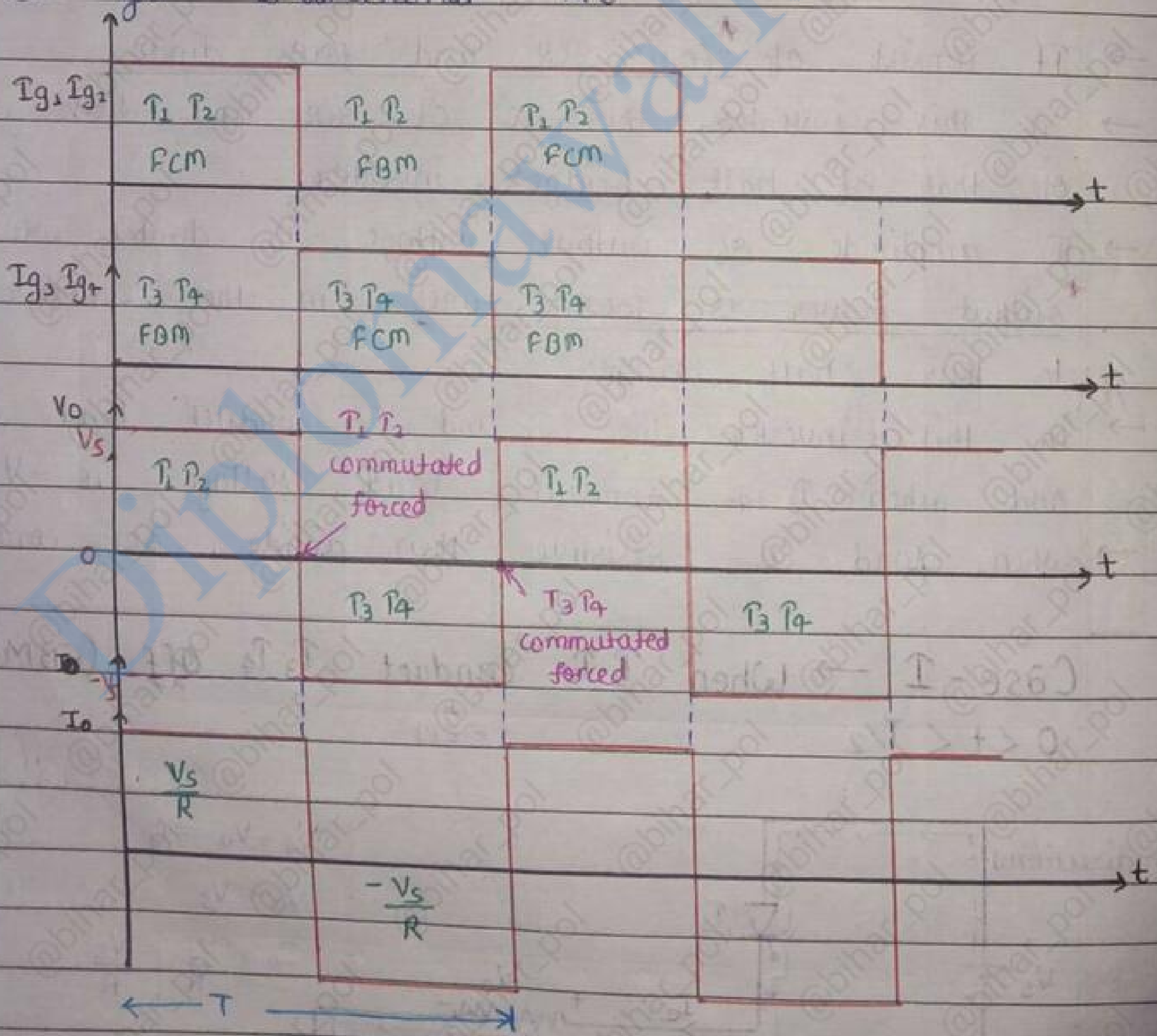
Case – II → When $T_3 T_4$ conduct $T_1 T_2$ off (FBM)
$T/2 < t < T$



$V_s - V_0 = 0 \quad \therefore V_0 = V_s$

$I_0 = \frac{V_s}{R}$

On comparing the voltage of both the cases then we get bi-directional AC



* Average Output Voltage

$$V_{O_{Avg}} = \frac{1}{T}\int_0^T V_s\,dt \qquad T \to T/2$$

$$= \frac{1}{T/2}\int_0^{T/2} V_s\,dt$$

$$= \frac{2}{T} \cdot V_s \cdot \frac{T}{2}$$

$$= V_s$$

* RMS Output Voltage

$$V_{O_{RMS}}^2 = \frac{1}{T}\int_0^T V_s^2\,dt = \frac{1}{T/2}\int_0^{T/2} V_s^2\,dt \qquad T \to T/2$$

$$= \frac{2}{T} \cdot V_s^2 \cdot \frac{T}{2}$$

$$V_{O_{RMS}} = V_s$$

Comparison of Half bridge and Full bridge Inverter

	Parameter	Half Bridge Inverter	Full Bridge Inverter
1.	No. of thyristor required to be used.	2	4
2.	Output voltage waveform	Square	Square
3.	Current rating of power devices	Equal to load current	Equal to load current
4.	No. of devices conducting simultaneously	1	2
5.	Voltage across the non-conducting thyristor	V_s volt	V_s volt
6.	Efficiency	High	High

underdamped → $R < \frac{4L}{C}$

Imp.*

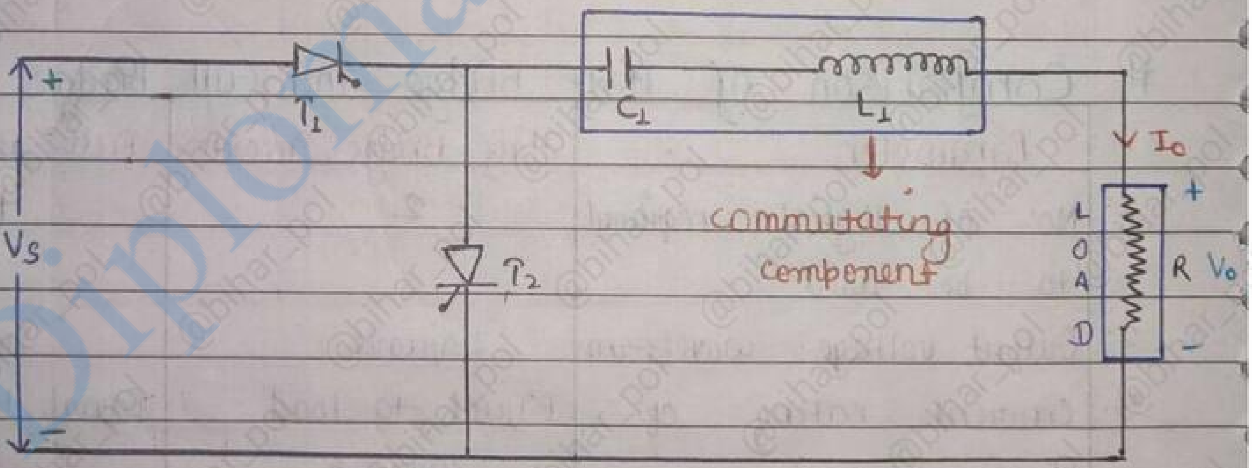
Series Inverter

→ The series inverter uses class A type commutation, the commutating component L_1, C_1 are connected in series with the load and to formed the underdamped tuned circuit.

→ Since the SCR turn ~~ON~~ OFF themself, this ckt is known as ★★ self commutated inverter ckt.

→ Inverter is called series inverter because the commutating component permanently connected in series with the load, the series circuit must be under-damped and current attains zero value due to nature of series circuit.

→ It is also classified as self commutated inverter and load commutated inverter. It operate at high frequencies 200 Hz to 1000 Hz.



• Operation

* When T_1 conduct

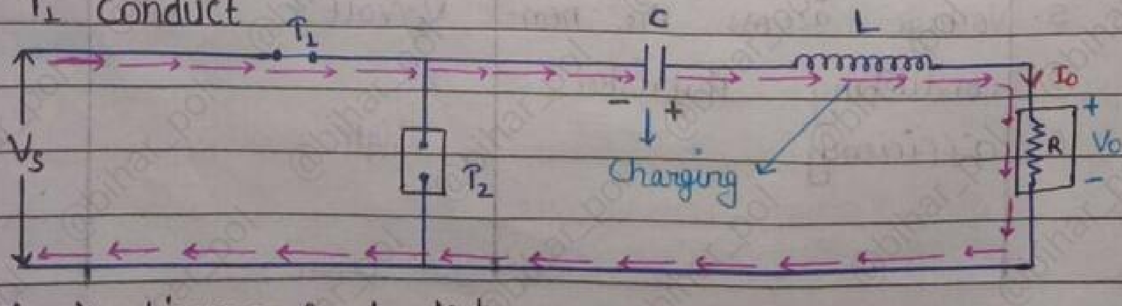


Fig :- Circuit diagram for t_0 to t_1

* When T_2 conduct

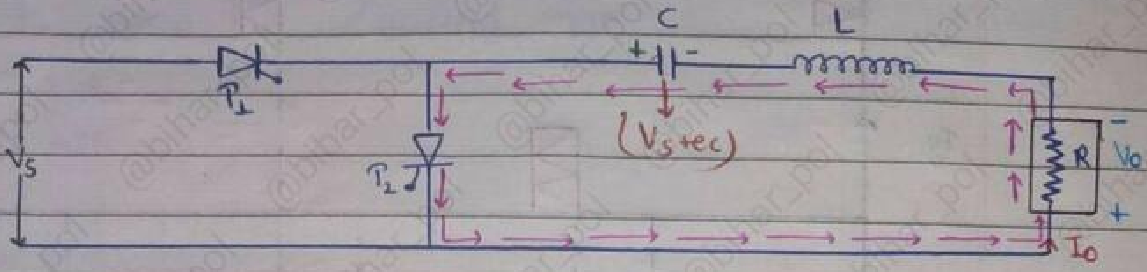
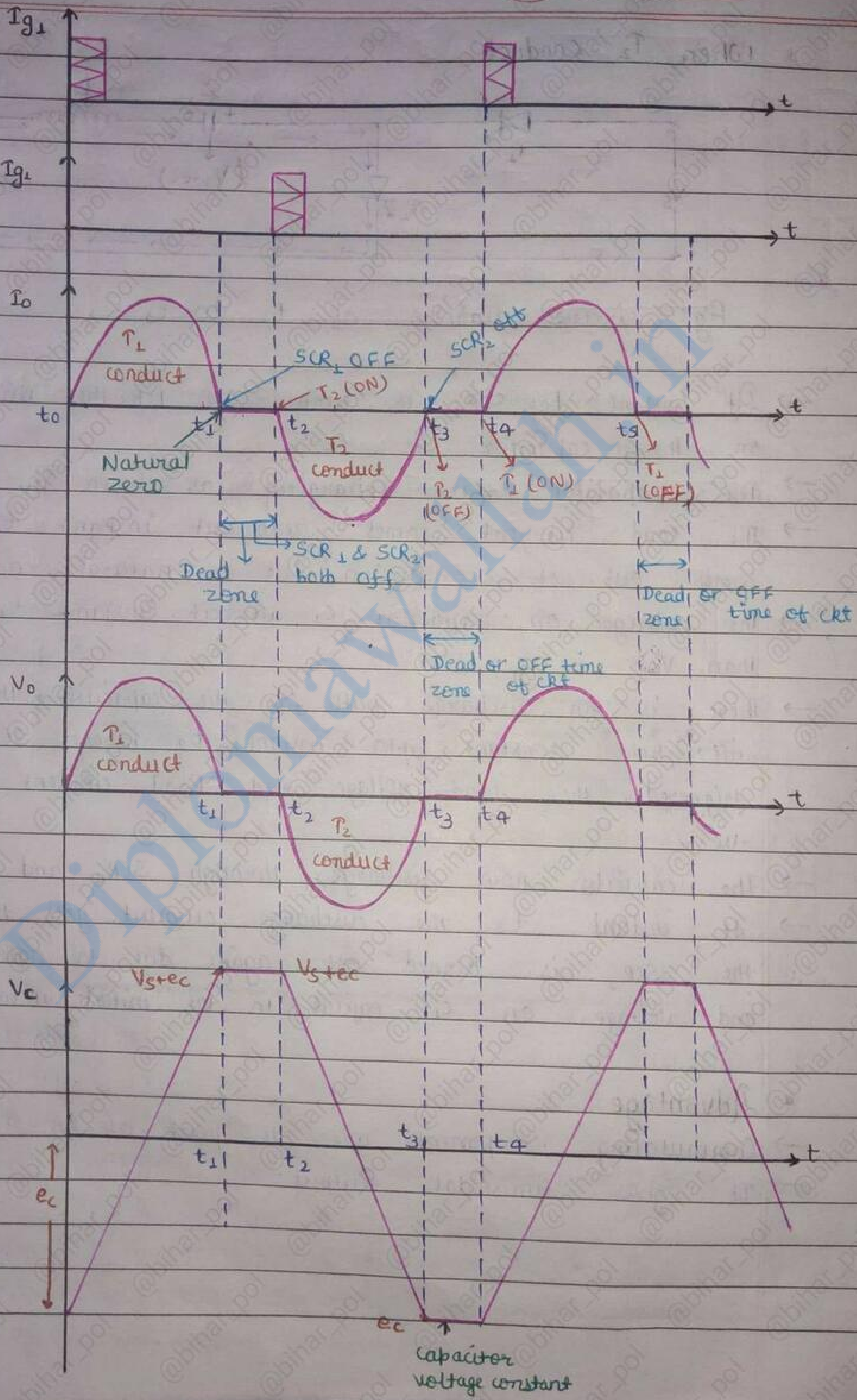


Fig:- circuit diagram of t_2 to t_3

→ At instant t_0 SCR_1 is turned ON let the initial voltage on the capacitor be e_c.
→ The capacitor start charging as shown in above ckt.
→ The load current comes zero at instant t_1 and SCR_1 comes out of conduction due to natural commutation.
→ The voltage on capacitor C_1 ~~as~~ at instant t_1 is greater than V_s.
→ There is no discharge path for the capacitor. This voltage will held constant upto instant t_2 where SCR_2 is triggered, the load voltage and load current both becomes -ve.
→ The capacitor now discharge through SCR_2 and load.
→ At instant t_3 the discharge current goes to zero and the SCR_2 is turned off again due to natural commutation and voltage on C_1 equal to the initial voltage e_c.

- Advantage

→ Commutating component are the part of the load.
→ It gives sinusoidal output.


Ig1
t
Ig2
t
Io
T1 conduct
SCR1 OFF
T2 (ON)
SCR2 off
t0
t1
t2
t3
t4
t5
Natural zero
T2 conduct
T2 (OFF)
T1 (ON)
T1 (OFF)
Dead zone
SCR1 & SCR2 both off
Dead or OFF time of ckt
Dead zone
Dead or OFF time of ckt
zone
Vo
T1 conduct
T2 conduct
Vc
Vs+ec
Vs+ec
ec
ec
Capacitor voltage constant

- t_0 to t_1

Load to source is connected via T_1

$V_0 \rightarrow +ve$

$I_0 \rightarrow +ve$

- t_2 to t_3

Load to source is disconnected capacitor discharging. R-Load.

$V_0 \rightarrow -ve$

$I_0 \rightarrow -ve$

- Disadvantage

→ Load current flow through commutating inductance and capacitance.

→ They must have high current rating.

→ There is a distortion in the output current and voltage waveform.

- Application

→ Induction heating.

→ Ultrasonic equipment

→ To provide supply to the cycloconverter.

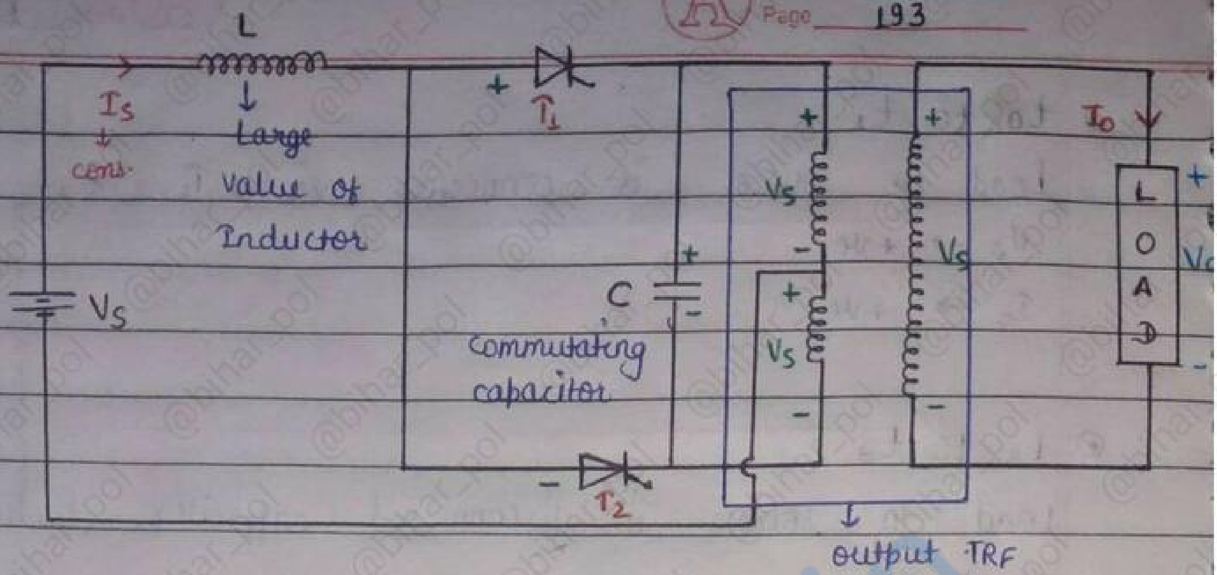
L-54

* Parallel Inverter

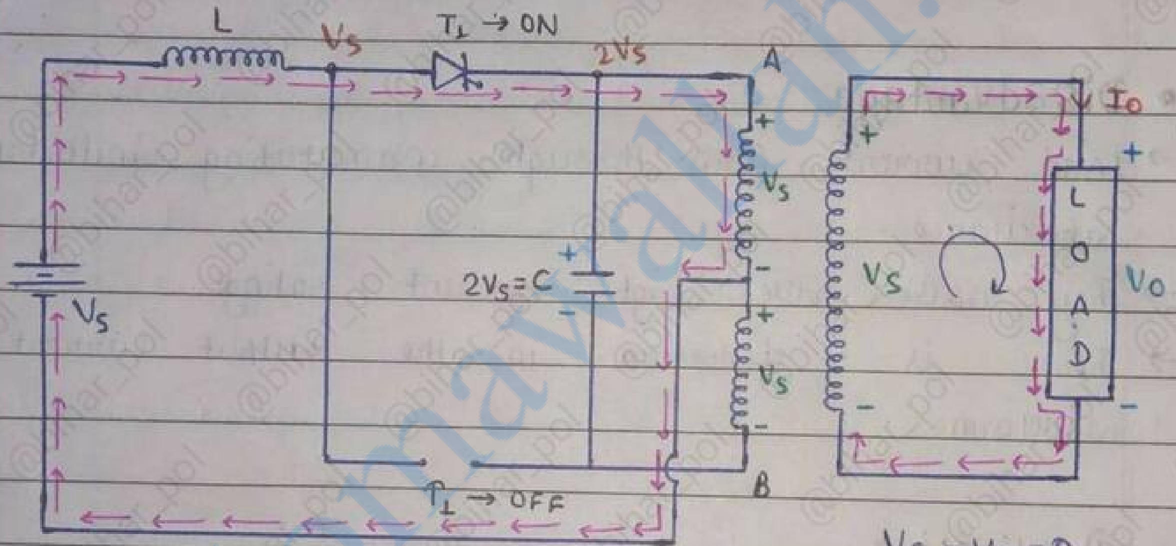
→ The basic 1-Ø parallel inverter circuit consist of 2 SCR. T_1 and T_2, an output TRF, and commutating capacitor C.

→ The function of L to make source current is constant.

→ During the working of this inverter capacitor C comes parallel with the load via TRF. So it is called parallel inverter.



Mode-1 → T_1 ON (F.CM), T_2 OFF (FBM)



$$V_S - V_O = 0$$

$$V_S = V_O$$

$$I_O = \frac{V_O}{R}$$

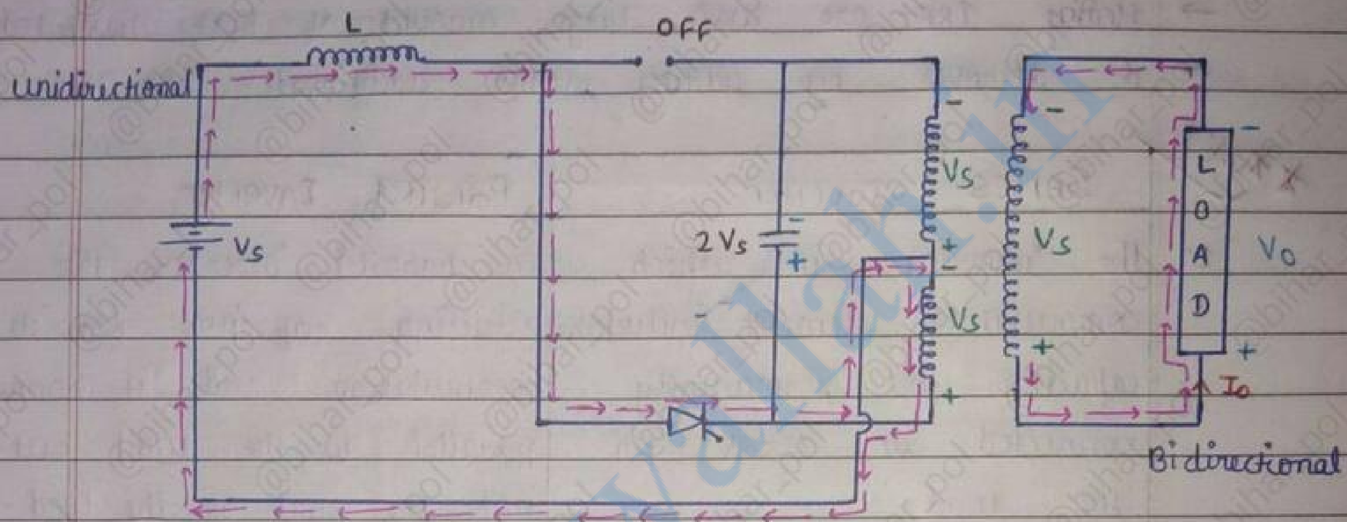
→ At thyristor T_1 is triggered the current flow path is given in above circuit here supply voltage V_S appears across the half of the primary winding hence the voltage $2V_S$ is induced across upper as well as lower half of the primary winding.

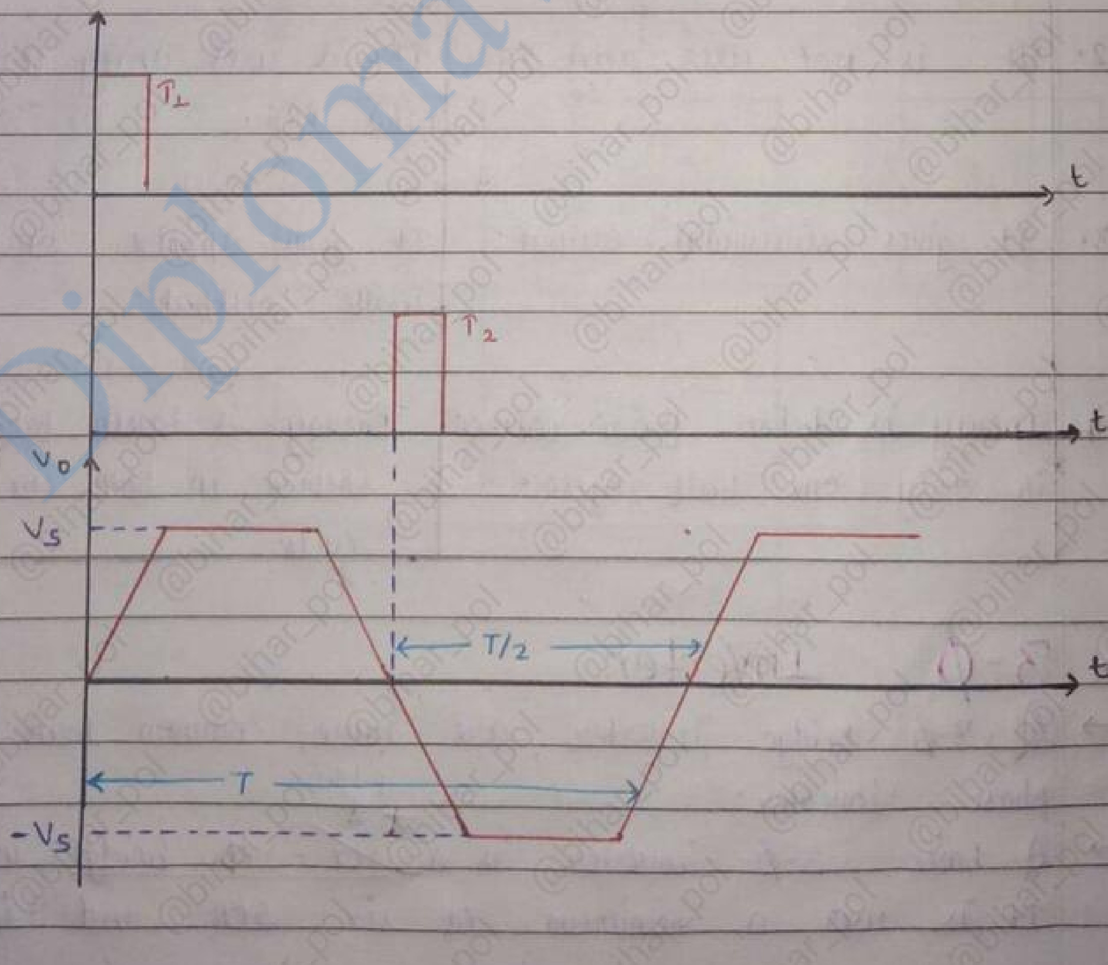
→ Here capacitor is connected parallel to the load so is charged upto $2V_S$.

→ Now T_2 is triggered as soon as t_2 is triggered a capacitor voltage of $2V_S$ is applied across T_1. Hence

T_1 immediately turn OFF, the load current start flowing through other half of the primary winding and the current flow path is given in above ckt.

Mode - 2 T_2 ON , T_1 OFF





- **Advantage**

→ Output voltage waveform is better than series inverter
→ switching frequency is higher.

- **Disadvantage**

→ Heavy TRF are used, large amount of heat dissipated,
→ it removes by adding some additional ckt.

★★V.V.I

	Series Inverter	Parallel Inverter
1.	The inverter in which commutating element inductor, capacitor are permanently connected in series with the load.	In parallel inverter the utilising capacitor for its commutation and it connect parallel to the load but not the part of the load.
2.	It is not uses any TRF.	It is uses unity transformation ratio TRF.
3.	It gives sinusoidal output.	It gives approx square wave output.
4.	Energy is taken from source in only one half cycle.	Energy is taken from the source in both the half cycle.

* 3-ϕ Inverter

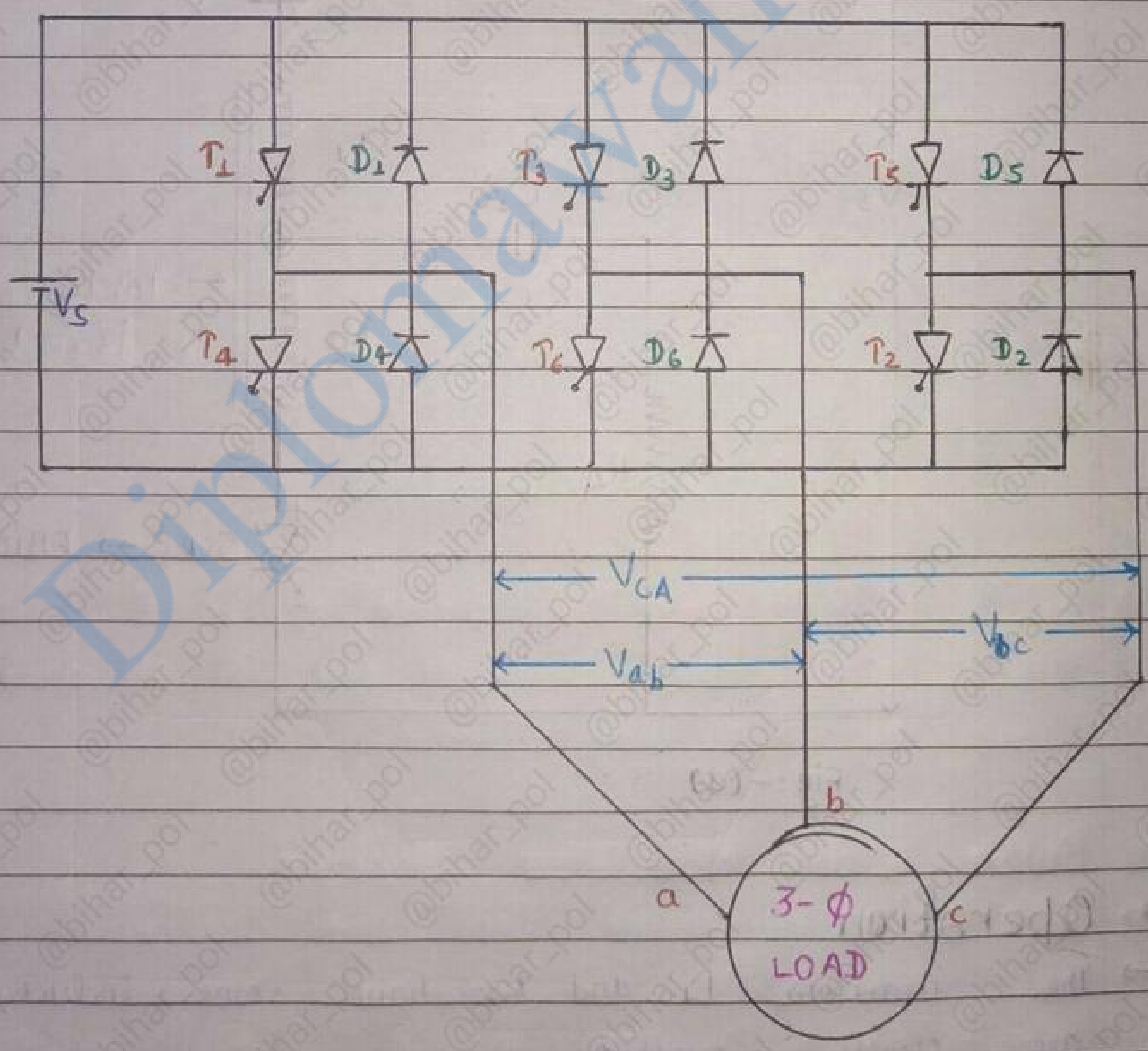
→ A 3-ϕ bridge inverter are more common than single phase inverter.
→ A basic 3-ϕ inverter is a ★★(V.V.I.) six-step bridge inverter, It is uses a minimum of six SCR and six-diode.

→ For one cycle of 360°, each step would be of 60° interval for a six-step interval this means that thyristor would be gated at regular interval of 60° in proper sequence so that a 3-ϕ AC voltage is synthesised at the output terminal of a six-step bridge inverter.

→ 3-ϕ bridge inverter consist of three half bridge inverter arranged side by side. The 3-ϕ load is assumed to be star connected.

→ There are two modes of operation.

(i) 180° mode (ii) 120° mode



* Modified Series Inverter

→ One of the major disadvantage of basics series-inverter circuit is the limitation on its maximum output frequency.

→ This can be overcome by the improved series circuit, the output frequency can be increased by turning on SCR2 even before SCR1 is turned OFF.

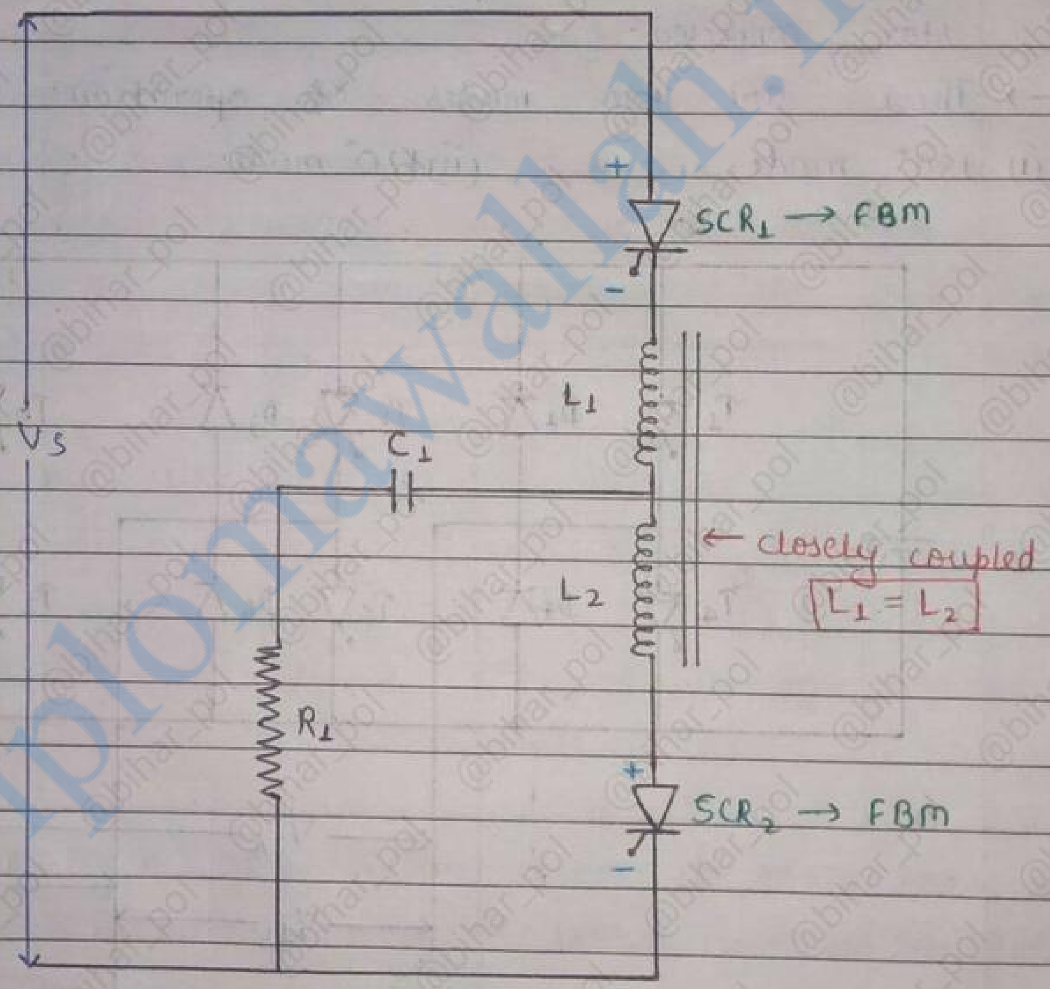


Fig:- (a)

• Operation

→ The inductor L_1 and L_2 have same inductance and are closely coupled.

→ Therefore when SCR_1 is fired and current I_1 starts flowing the , the potential across L_1 will be +ve with a polarity as shown in fig (b) capacitor C_1 charges with polarity as shown in fig (b).

→ The inductance voltage in inductance L_2 will reverse biased the SCR_2.

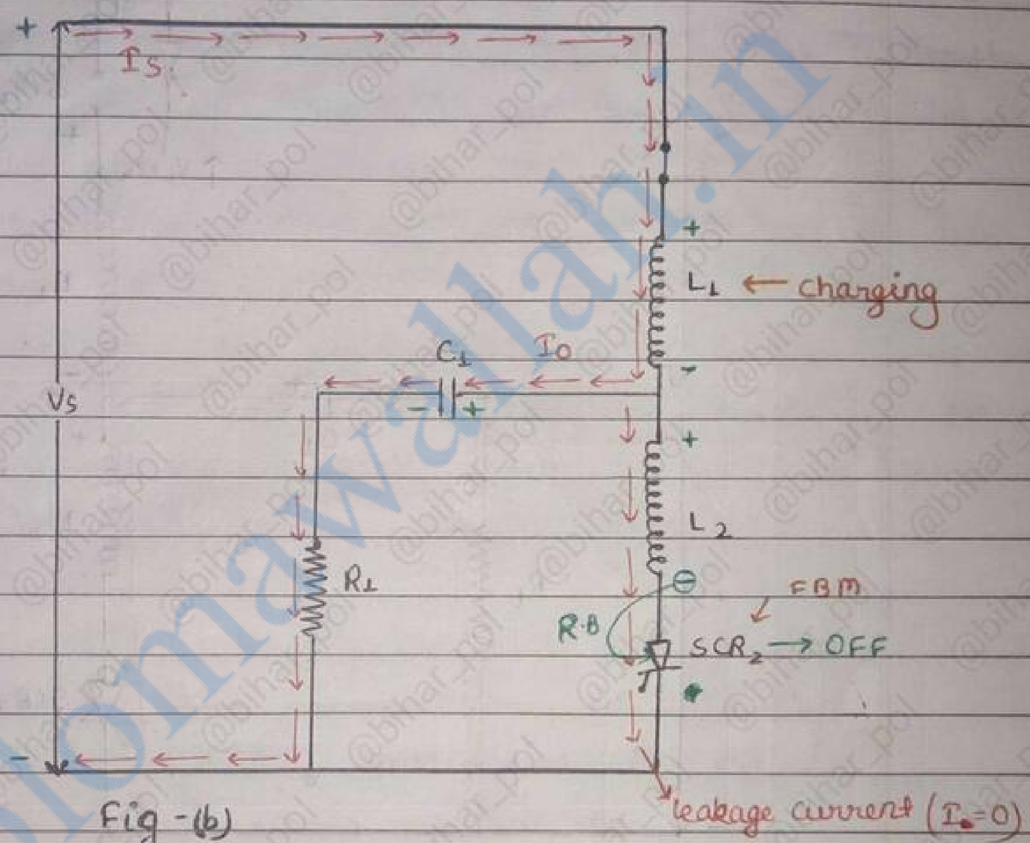


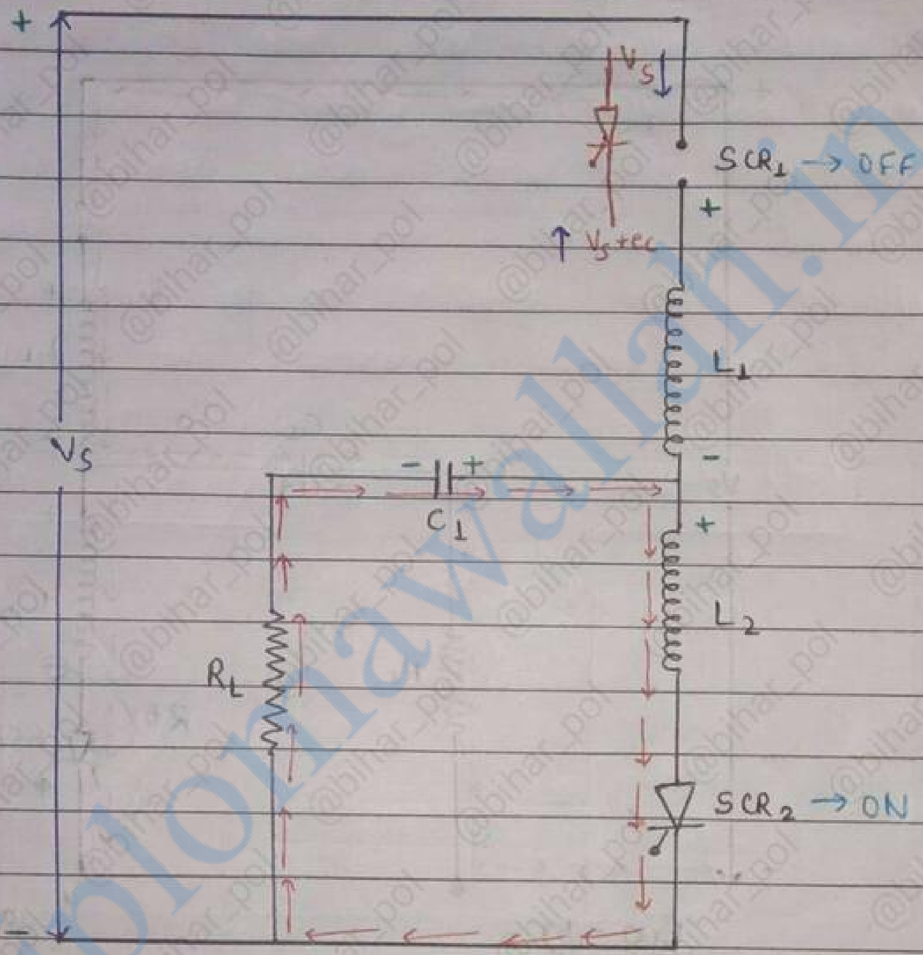
Fig - (b)

→ Suppose that SCR_2 is turned ON before SCR_1 is turned off, At the instant of firing SCR_2 the voltage on C_1 will be slightly less than this (V_S+e_c) with the polarity as shown in fig the load voltage and current will be close to zero.

→ Thus the cathode potential of SCR_1 is raised to a higher level than its anode voltage and therefore SCR_1 will be turned off due to the application of reverse voltage across it, as similar operation will take place if

SCR_1 is triggered before SCR_2 is turned off.

→ Thus there is no danger of short ckt on input power supply due to the inclusion of the closely coupled reactors L_1 and L_2 in the circuit.



→ The only the first disadvantage of basics series inverter has been eliminated but all the other drawback remains as they are.

* Pulse Width Modulated Scheme.

→ In the pulse width modulation technique a fixed DC input voltage is ~~gio~~ given to the inverter and a controlled AC output voltage is obtained by adjusting the ON and OFF periods of the inverter.

→ This method of controlling the output voltage and is termed as pulse width modulation.

→ The output voltage control with this method can be obtained without any additional components.

→ The lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirement are minimized. 3rd & 5th harmonics reduced and 7th, 9th and 11th are filter out easily.

→ PWM techniques are characterised by constant amplitude pulses the width of these pulses is however modulated to obtain inverter output voltage control and to reduce its harmonics content.

Different PWM techniques are as under

1. Single Pulse width modulation (SPWM)
2. Multiple Pulse width modulation (MPWM)
3. Sinusoidal Pulse width modulation

1. Single Pulse width Modulation (SPWM)

→ The constant DC input voltage is applied at the input of the inverter and output voltage is controlled by switching semi-conductor device of the inverter.

→ As the semi-conductor devices receives only one pulse during one half cycles, one semi-conductor device is switched ON.

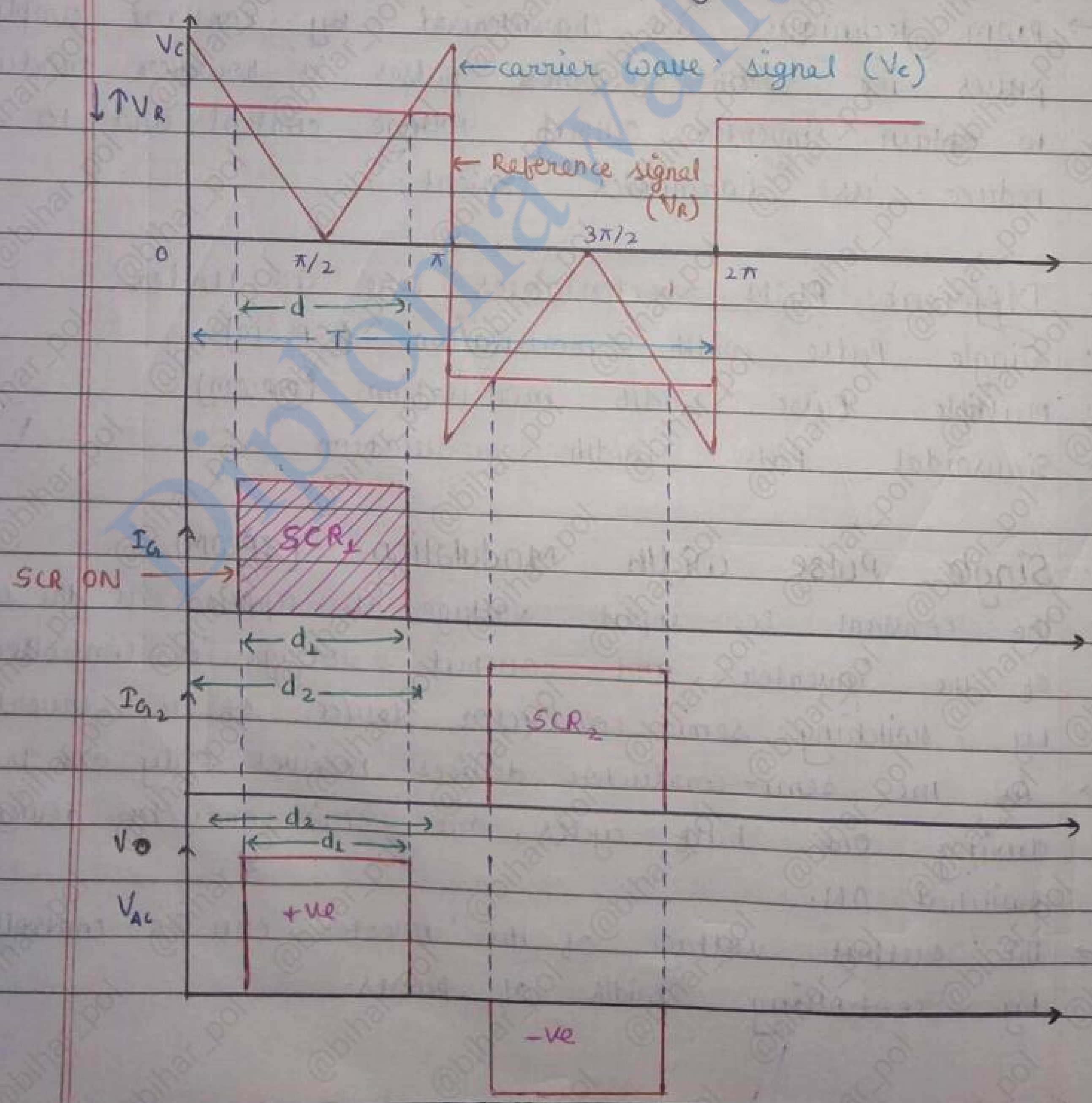
→ The output voltage of the inverter can be controlled by controlling width of pulses.

→ The figure shows the gate signal and output voltage waveform for 1-ϕ, full bridge inverter.

→ The gate signal is generated by compairing (V_R) amplitude reference signal and V_c amplitude control signal.

→ The width of gate pulse can be varied from 0° to 180° by controlling the reference signal from 0 to V_R, this will control the O/P voltage of the inverter.

→ The frequency of the output voltage depends upon frequency of reference signal.



2. Multiple Pulse Width modulation Technique (MPWM)

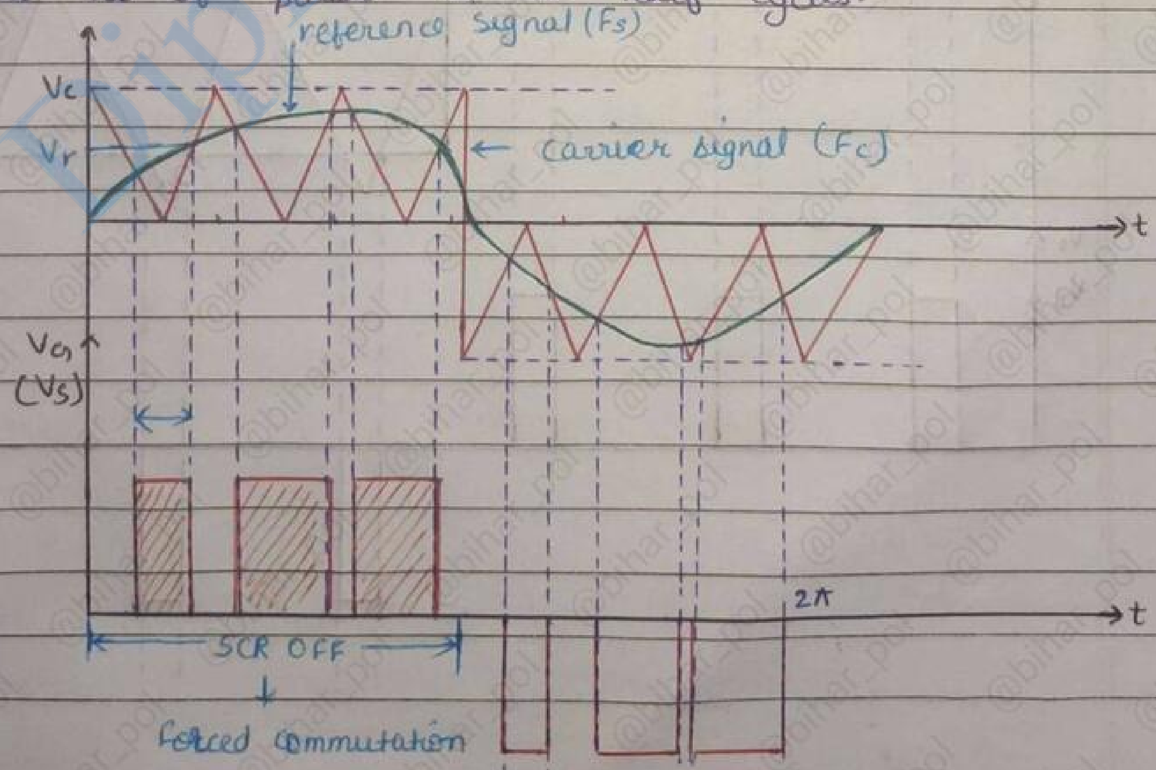
→ In this modulation technique the harmonics content is reduced by using several pulses in each half cycle of the output voltage.

→ The thyristor are turned ON and OFF many in a half cycle to obtain pulses in the half cycles. The gateing signal for turning ON the SCR are generated by comparing the reference signal with a triangular carrier wave.

→ The thyristor are turned off by forced commutation to obtain the trigger pulses, the comparison of reference signal and triangular carrier signal is done in comparator.

→ when magnitude of carrier signal falls to that of the reference signal, the SCR is turned off by forced commutation.

→ The output frequency depends on the frequency of reference signal and the carrier frequency determines the no. of pulses in the half cycles.



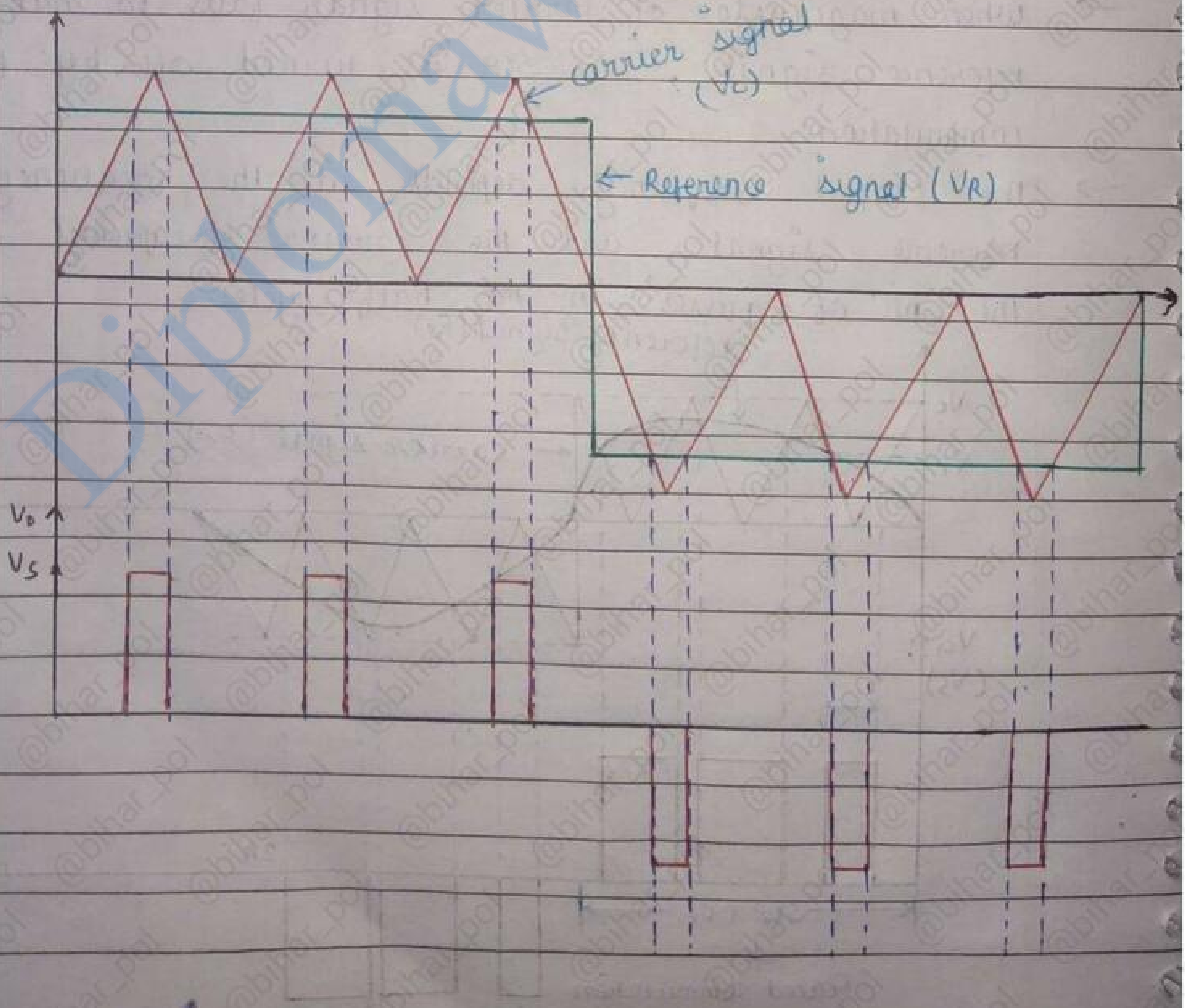
3. Sinusoidal Pulse Width Modulation Technique

→ In this method of modulation several pulse per half cycle are used as in the case of multiple pulse modulation.

→ In MPWM the pulse width is equal for all the pulses, but in sinusoidal PWM, the pulse width is sinusoidal function of the angular position of the pulse in a cycle.

→ For ~~reta~~ realizing sinusoidal PWM, a high frequency triangular carrier wave V_c is compared with a sinusoidal reference wave V_R of the desired frequency.

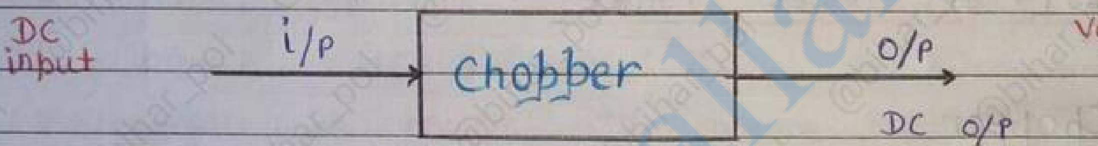
→ The intersection of V_c and V_R wave determine the switching instant and commutation of the modulated pulses, V_c is the peak value of triangular carrier wave and V_r ~~of~~ the reference or modulating signal.

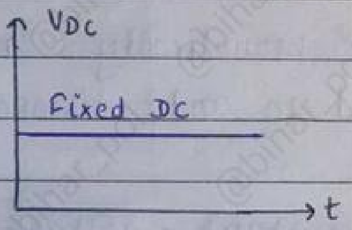


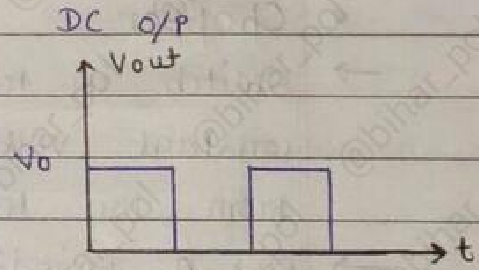
Unit - 4 Chopper

* Chopper

→ Chopper is a power electronics device, which convert fixed DC into variable DC ~~that~~ i.e; it increases or decreases the input voltage.





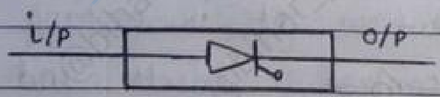


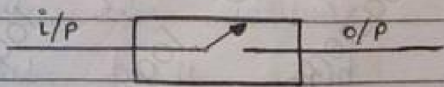
$V_0 > V_S$ → Step up chopper

$V_0 < V_S$ → Step down chopper

→ Like a transformer a chopper can be used to step down or step-up the DC voltage.

→ Generally chopper is represented as a switch in a square box.





→ When switch is off no current can flow and when the switch is ON current flows in the direction of arrow head only.

→ It is basically a static power electronic device.

→ It is high speed switch which connect or disconnects the load from source at high rate to get variable or chopped voltage at the output.

→ On state voltage drop is 0.5V to 2.5V and it can be low hence it is to be neglected.

→ Here chopper is nothing but a power semiconductor device like power mosfet, Power BJT, SCR, IGBT and GTO etc.

★ → For high speed application we use SCR in the chopper ckt and low power we use GTO, IGBT, Power BJT or Power Mosfet.

- Chopper

→ Switch is turned on and off periodically. In this way constant voltage can be connected to and disconnected from the load.

→ By a periodic application of constant voltage at a particular frequency across the load, variable voltage can be achieved by controlling the on period of the switch.

or,

→ Chopper is a basically static power electronics device which converts fixed dc voltage / power to variable DC voltage or power. It is nothing but a high speed switch which ~~control~~ connects and disconnects the load from source at a high rate to get variable or chopped voltage at the output.

→ DC to DC converter is very much needed nowa days as many industrial applications are dependent upon DC voltage source. The performance of these applications will be improved if we use a variable DC supply.

It will help to improve controllability of the equipment also.

Basic Principle of DC chopper

→ A chopper is a static device that converts fixed dc input voltage to a variable dc output voltage directly.

→ A chopper may be through of as dc equivalent of an dc transformer since they behave in an identical manner. as chopper involve one stage conversion these are more efficient.

→ The power semiconductor devices ~~the~~ used for a chopper circuit can be power BJT, power MOSFET, GTO or force commutated thyristor. These devices, in general, can be represented by a switch SW with an arrow. ~~as shown in~~

Principle of chopper operation

→ There are basically two time periods in chopper operation, one is the "on" time denoted as TON and other is the "off" time denoted as TOFF.

→ During TON we get the constant source voltage VS across the load and during TOFF we get zero voltage across the load.

→ In this way we obtain a chopped dc voltage at the load terminals.

Application of Chopper

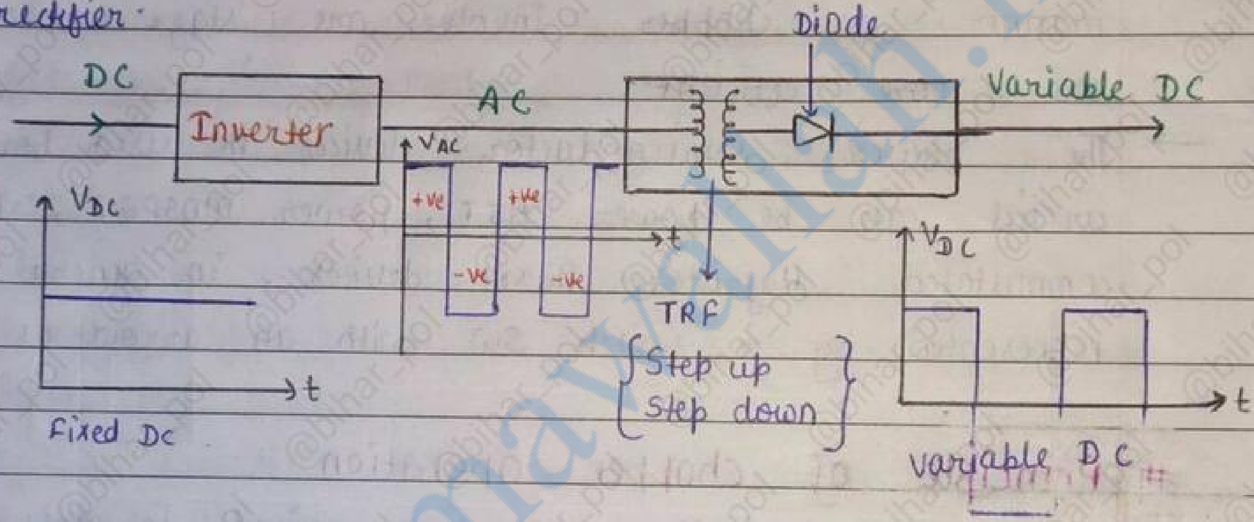
1. Chopper is used in subway cars.
2. Chopper is used in marine lifts.
3. Chopper is used in trolley cars.
4. Electric Automobile.
5. Mine holders.

Classification of chopper

1. AC link chopper
2. DC chopper

1. AC link chopper

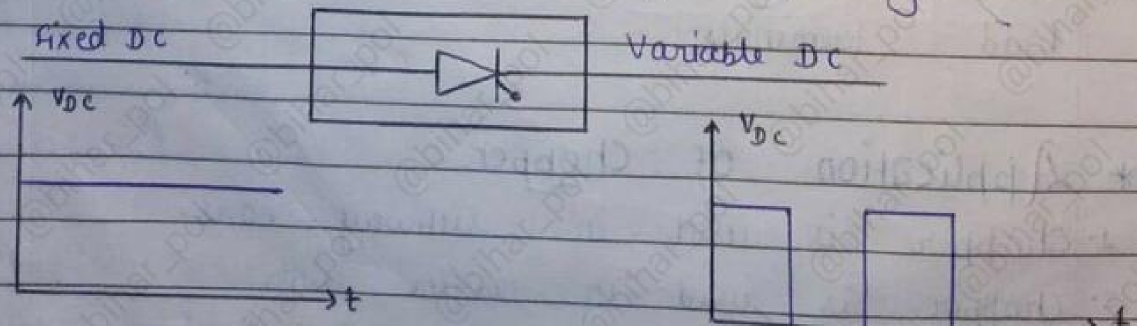
→ DC is first converted into AC by an inverter. AC is then stepped-down or step up by transformer which is then converted back to DC by a diode rectifier.



DC → AC, AC → DC } Two stage conversion hence it is costly, bulky and less efficient.

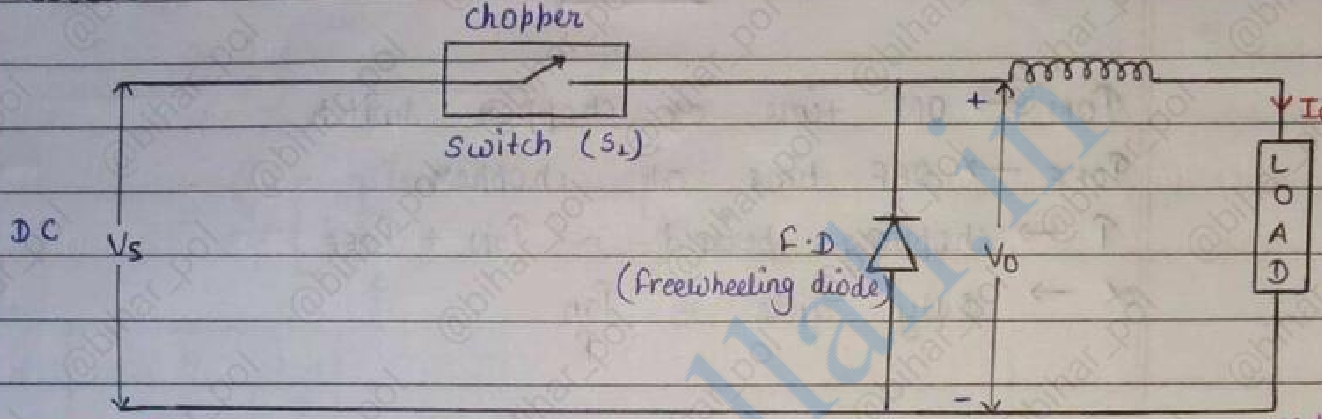
2. DC Chopper

→ It convert power directly from DC to DC. It provide smooth control and possess high efficiency.



Step-down chopper

Q. Explain the working of chopper with waveform and also find average output voltage, RMS output.
or,
Show that the load voltage is independent of load current.



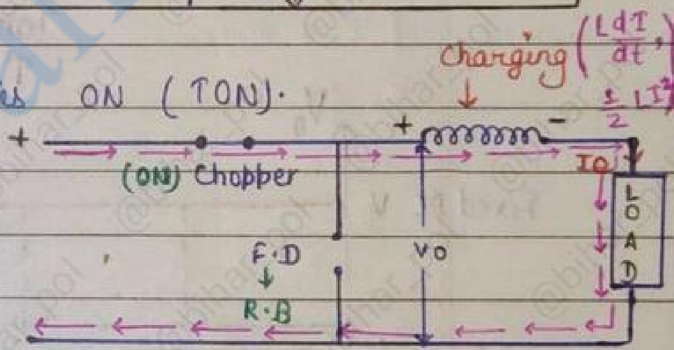
Case I

When S_1 is closed or chopper is ON (T_{ON}).

Apply KVL in closed loop.

$$V_s - V_0 = 0$$

$$\therefore V_s = V_0$$

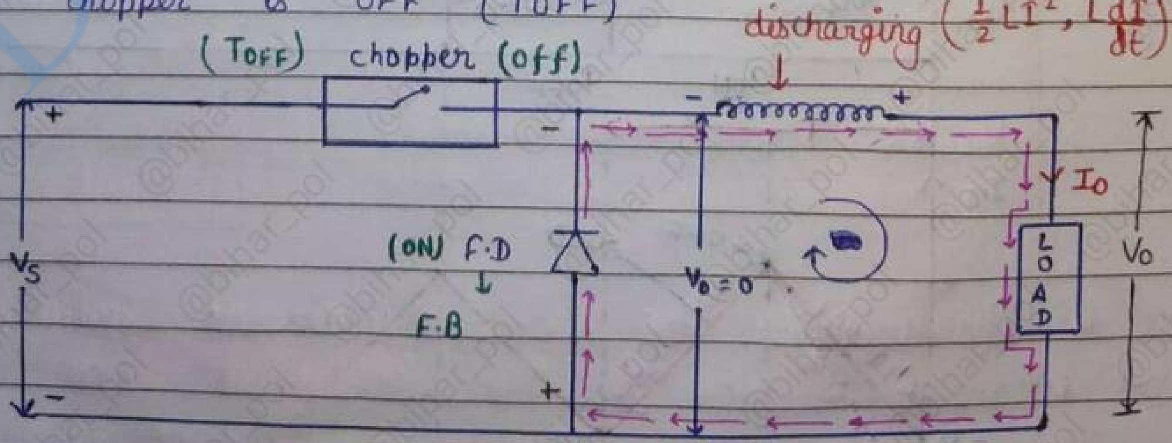


FD ⟶ R.B ⟶ OFF

During the period T_{ON} chopper is ON and load voltage.

Case II

When chopper is OFF (T_{OFF})



→ During the interval T_{OFF} chopper is OFF load current flows through FD and hence the load voltage V_0 is zero due to short ckt of FD.

→ During T_{ON} load current rises (inductor is charging) whereas during T_{OFF} load current decays (inductor is discharging) and in this manner a chopped DC voltage is produced at the load terminal.

$\boxed{V_0 = 0}$ → due to short ckt of FD.

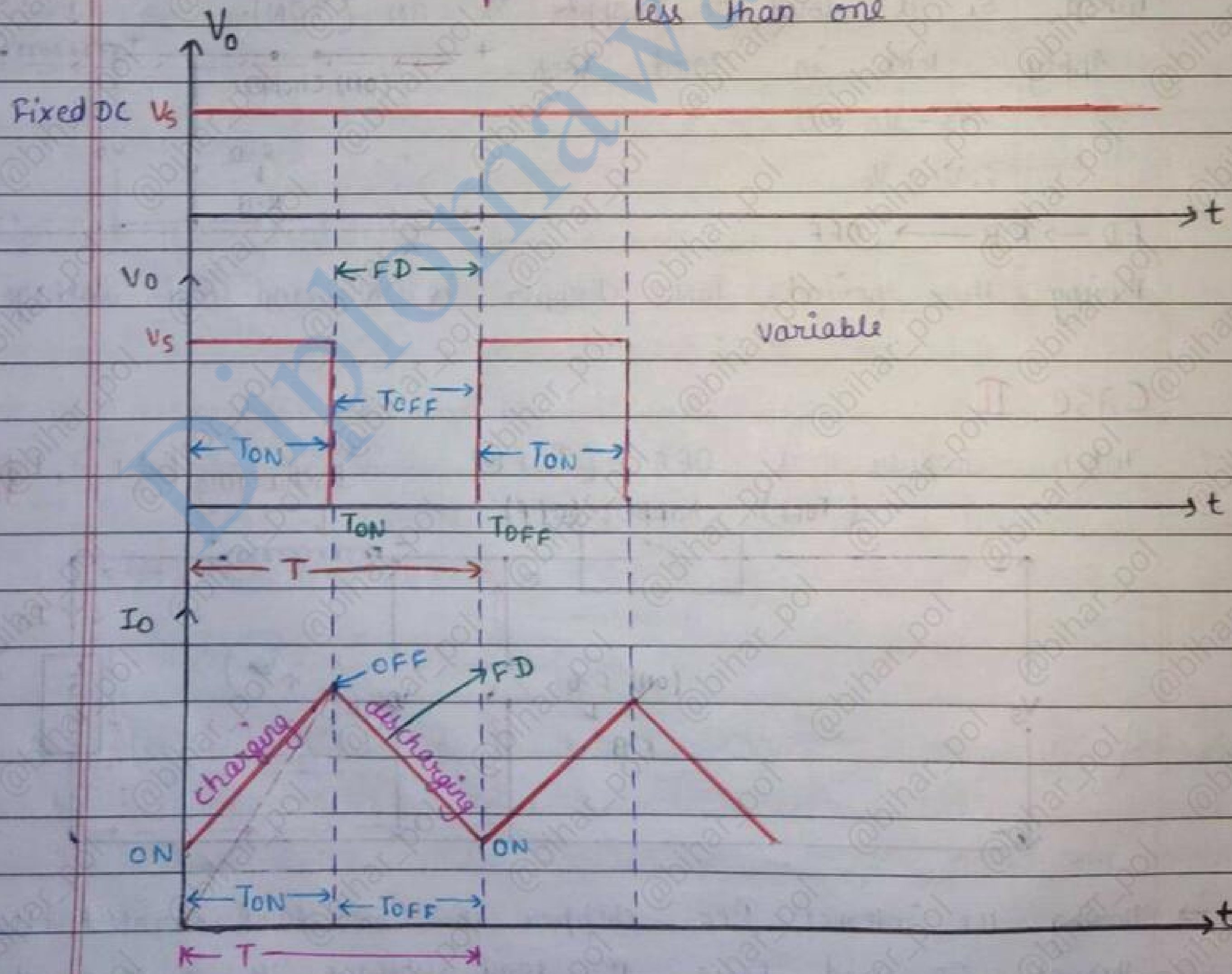
T_{ON} → ON time of chopper switch

T_{OFF} → OFF time of chopper

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

α → Duty cycle $= \frac{T_{on}}{T}$

$\frac{T_{on}}{T}$ → unit less, less than one



* The Output Voltage or Average DC Load Voltage

$$V_0 = \frac{1}{T}\int_0^T V_s\,dt$$

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

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

$$= \frac{V_s}{T}\left[t\right]_0^{T_{ON}} = V_s \cdot \frac{T_{on}}{T}$$

$$\boxed{V_0 = V_s \cdot \frac{T_{ON}}{T}}$$

$$\boxed{V_0 = V_s \cdot \alpha} \quad (\alpha = 0.5)$$

$V_0 = 10 \times 0.5$

$5 \rightarrow$ step down

* RMS O/P voltage V_{RMS}

$$V_{o_{RMS}}^2 = \frac{1}{T}\int_0^T V_s^2\,dt$$

$$V_{o_{RMS}}^2 = \frac{1}{T}\int_0^{T_{on}} V_s^2\,dt$$

$$V_{o_{RMS}}^2 = \frac{V_s^2}{T}\left|t\right|_0^{T_{on}}$$

$$V_{o_{RMS}} = \sqrt{V_s^2\,\frac{T_{on}}{T}}$$

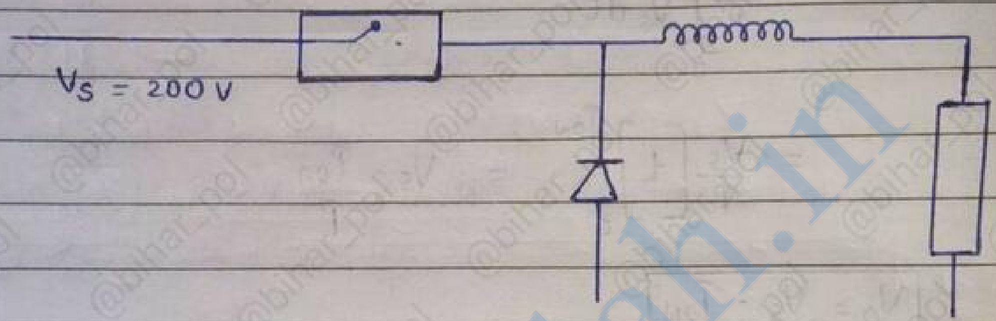
★ obj

$$\boxed{V_{o_{RMS}} = V_s\sqrt{\alpha}}$$

→ Here T_{on} is always less than 1 hence $V_0 < V_s$ that means the above ckt diagram are also called step down chopper ckt.

Q. A chopper having a supply voltage of 200V DC and operating at a frequency of 1 KHz find out (a) duty cycle (b) average load voltage (c) RMS load voltage. If the ON time of the chopper is 500 μ sec.

⇒



$f = 1\ KHz$, $V_s = 200V$

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

$\therefore T = \frac{1}{F} = \frac{1}{1KHz} = \frac{1}{1000} = 10^{-3}$ sec.

$T_{ON} = 500 \times 10^{-6}$ sec $= 500 \mu$ sec.

(a) duty cycle $(\alpha) = \frac{T_{on}}{T} = \frac{500 \times 10^{-6} sec}{10^{-3} sec} = 0.5$ Ans.

(b) Average load voltage $(V_{0\,Avg}) = V_S \cdot \alpha$
$= 200 \times 0.5$
$= 100V$ Ans.

(c) $V_{0RMS} = V_S\sqrt{\alpha} = 200\sqrt{0.5}$
$= 140\ V$ Ans.

* Advantages of chopper circuits.

1. Ripple content in the output is small.
2. Peak / average and rms / average current ratios are small.
3. The chopper is supplied from a constant dc voltage using batteries.

4. current drawn by the chopper is smaller than in phase controlled converters.

5. chopper circuit is simple and can be modified to provide regeneration and the control is also simple.

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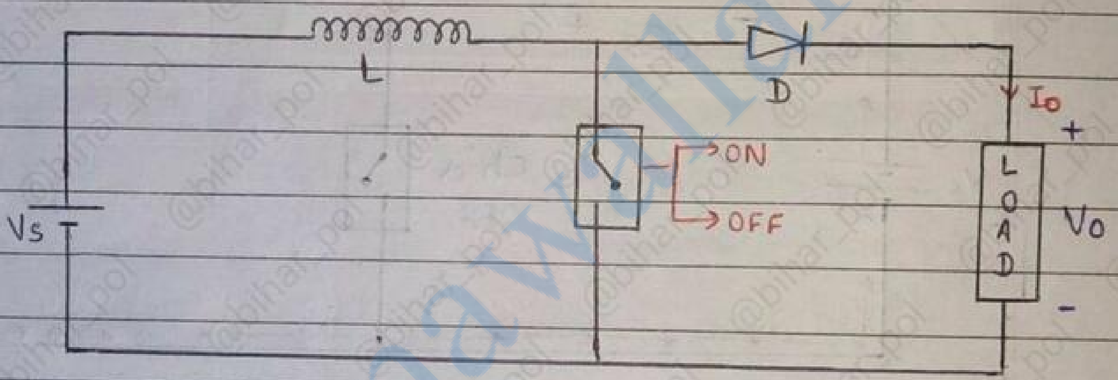
Step-up chopper
($V_0 > V_s$)

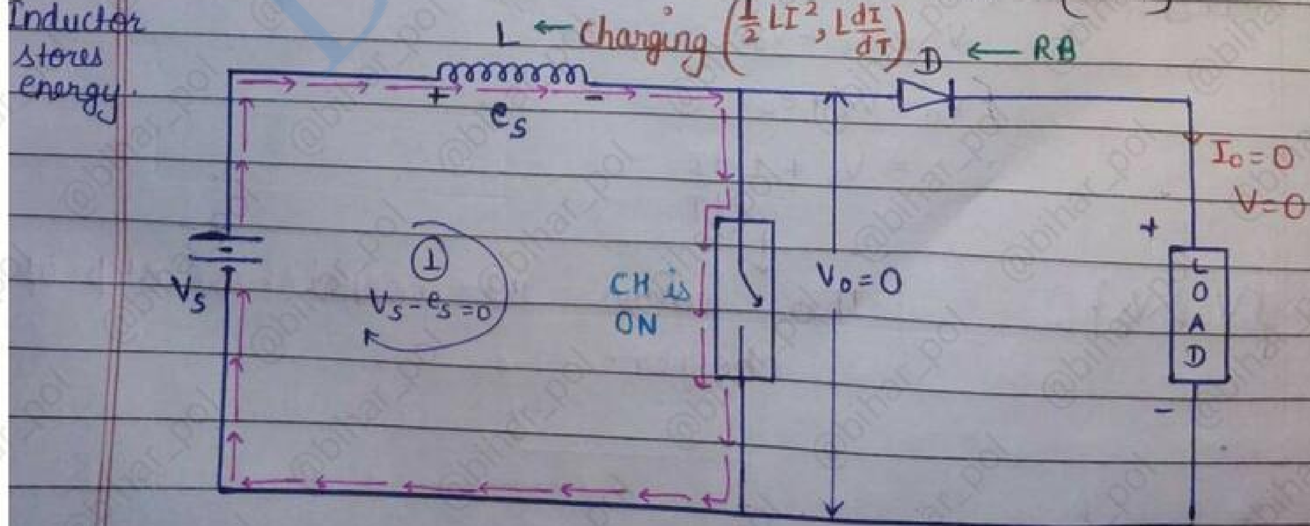
→ Average output voltage V_0 is greater than input voltage V_s can be obtained by a chopper called step-up chopper.



→ In this chopper a large inductor L in series with source voltage V_s is essential.

Case I :-

When chopper switch is ON (T_{ON})



Apply KVL in loop ①:

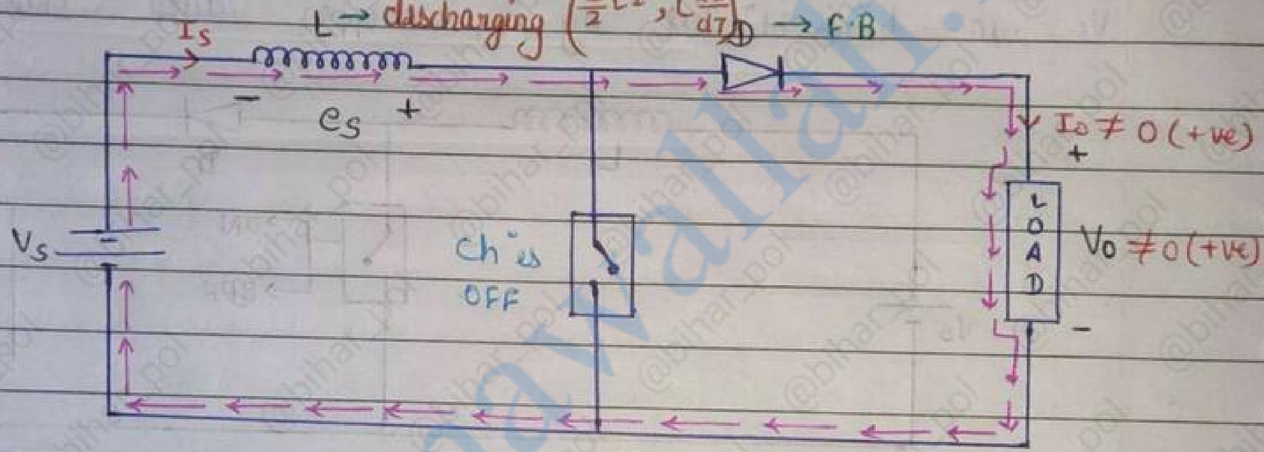
$$V_S - e_S = 0$$

$$V_S = e_S$$

when chopper is ON the closed current path is as shown in fig. and inductor stores energy during T_{ON}.

Case II :-

When chopper is OFF (T_{OFF})



when chopper is off as the inductor current cannot die down instantaneously, this current is forced to flow through the diode and load for a time of T_{OFF}.

Apply KVL,

$$V_S + e_S - V_0' = 0$$

$$V_0 = V_S + e_S$$

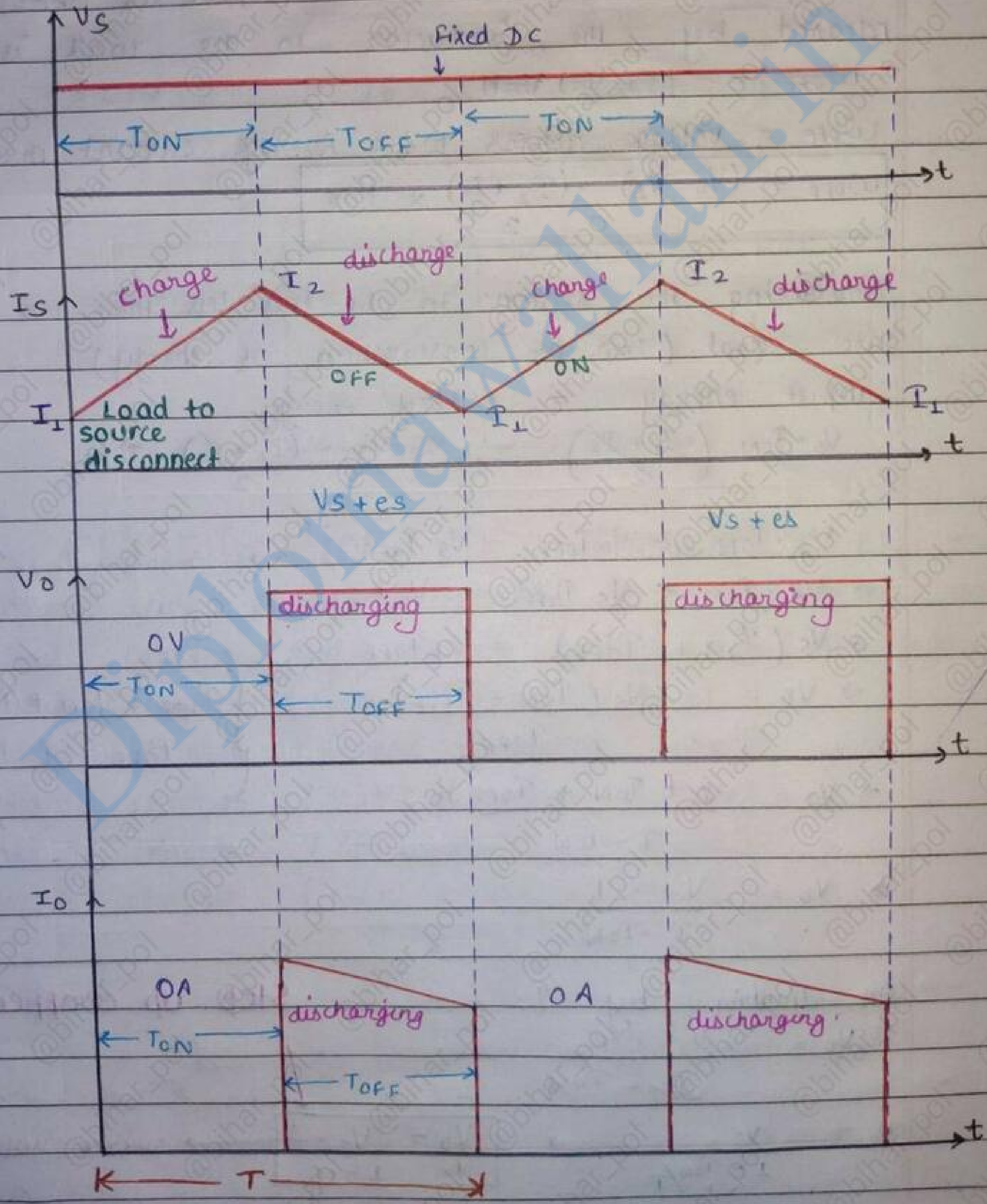
$$= V_S + L\frac{dI}{dT}$$

$\{V_0 > V_S\}$

↓ This causes the copper is step-up chopper.

Also Prove that, $V_0 = \frac{V_s}{1-\alpha}$

where, V_0 = output voltage
V_s = source voltage
α = duty cycle.



During ON period energy input to the inductor from the source is.

W_{in} = (voltage across L) (Average current through L) × T_{ON}

$$W_{in} = V_S \times \frac{I_1 + I_2}{2} \times T_{ON}$$

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

~~W_{OFF} = ($V_0 - V_S$) Voll~~

W_{OFF} = voltage across L × Average current through L × T_{OFF}

$$W_{OFF} = (V_0 - V_S) \cdot \frac{(I_2 + I_1)}{2} \times T_{OFF}$$

Considering the system to be loss less these two energies are equal (low of conservation of energy)

input energy = output energy

$$V_S \cdot T_{ON} \left(\frac{I_1 + I_2}{2}\right) = V_0 - V_S \cdot \frac{(I_1 + I_2)}{2} \cdot T_{OFF}$$

$$V_S \cdot T_{ON} = V_0 T_{OFF} - V_S \cdot T_{OFF}$$

$$\Rightarrow V_S \cdot T_{ON} + V_S T_{OFF} = V_0 T_{OFF}$$

$$\Rightarrow V_S (T_{ON} + T_{OFF}) = V_0 T_{OFF}$$

$$\Rightarrow V_0 = \frac{V_S (T_{ON} + T_{OFF})}{T_{OFF}}$$

$$\left\{ \begin{aligned} T &= T_{ON} + T_{OFF} \\ T_{OFF} &= T - T_{ON} \end{aligned} \right\}$$

$$\Rightarrow V_0 = \frac{V_S (T_{ON} + T_{OFF})}{T - T_{ON}}$$

$$\Rightarrow V_0 = \frac{V_S \cdot T}{T - T_{ON}}$$

On dividing by T.

$$V_0 = \frac{V_S \cdot T/T}{T/T - T_{ON}/T}$$

$$V_0 = \frac{V_S}{1 - T_{ON}/T} \Rightarrow \boxed{V_0 = \frac{V_S}{1 - \alpha}}$$

Step up chopper

V_0 → load voltage

V_S → source voltage

α → duty cycle

If,

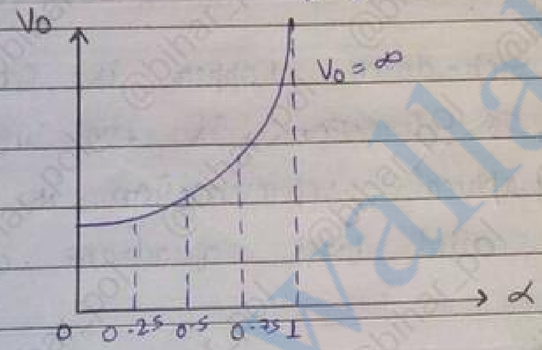
$\alpha = 0$, $V_0 = \frac{V_s}{1-0} = V_s$

$\alpha = 0.25$, $V_0 = \frac{V_s}{1-0.25} = \frac{4}{3} V_s$

$\alpha = 0.5$, $V_0 = \frac{V_s}{1-0.5} = 2V_s$

$\alpha = 0.75$, $V_0 = 4V_s$

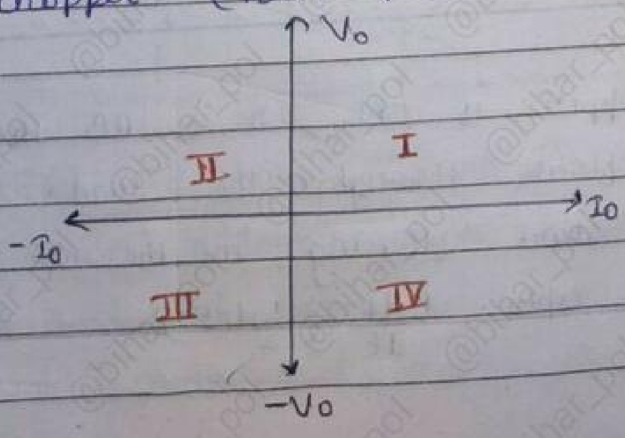
$\alpha = 1$, $V_0 = \frac{V_s}{1-1} = \infty$



Classification of chopper

→ Chopper are classified according to the direction of output current and output voltage into five types

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



Flow of Power from load to source then V_0, I_0 (-ve) (+ve)

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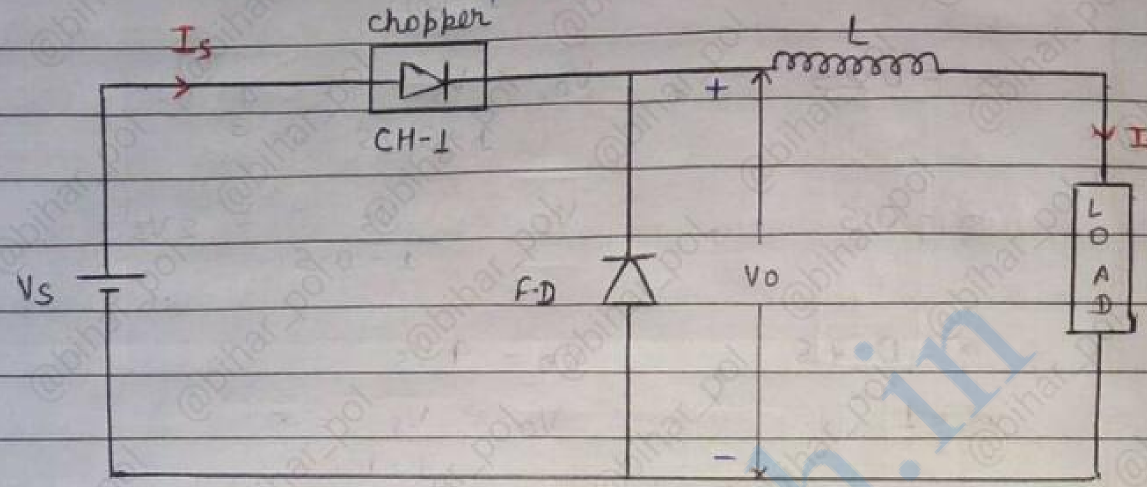
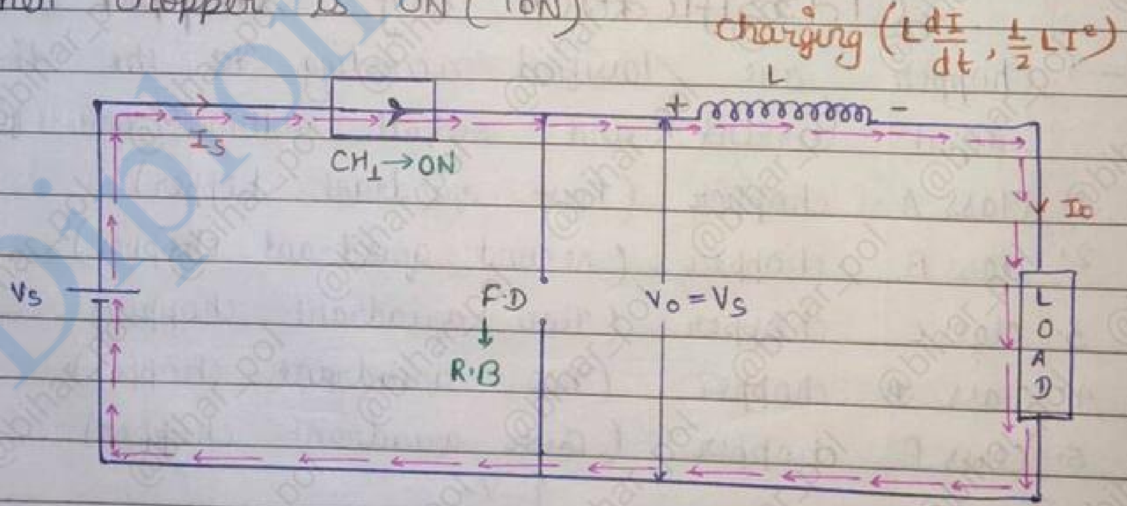
1. First quadrant chopper or Type A chopper or Class A chopper



Generally step-down chopper is called A chopper. Here, V_0, I_0 direction is +ve in chopper is ON and OFF and its graphical representation is in first quadrant so it is called first quadrant chopper.

Case I :-

When chopper is ON (T_{ON})



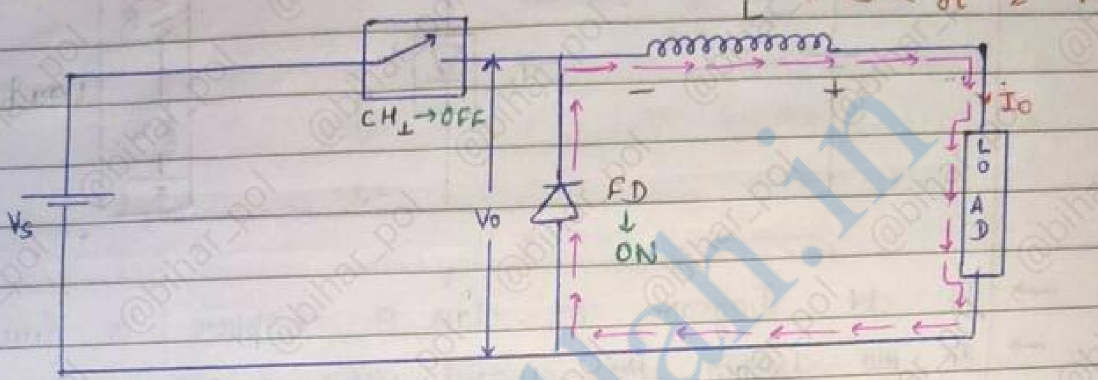
→ When CH_1 chopper is ON, FD is RB then $V_0 = V_s$, and I_0 current flows through the load.

→ Here current start flowing in the ckt through V_s, inductor start charging upto $L\frac{di}{dt}$ ($\frac{1}{2}LI^2$)

$V_0 = V_s$
$I_0 = +ve$ → I^{st} Quadrant

Case II :- When CH_1 is OFF (T_{OFF})

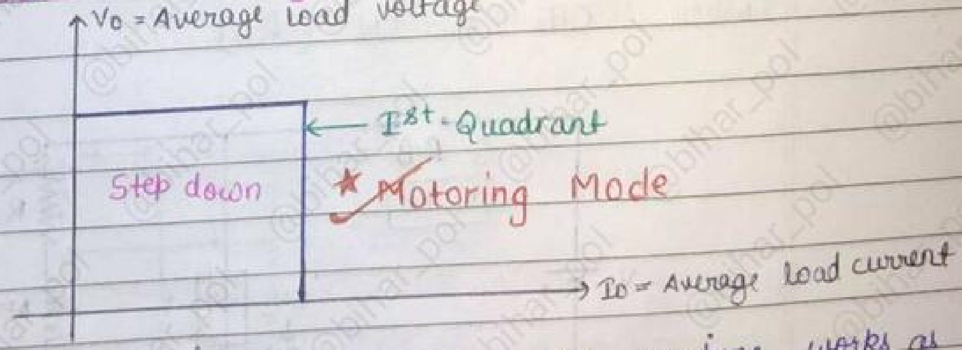
discharging ($L\frac{dI}{dt}$, $\frac{1}{2}LI^2$)



→ If CH_1 is OFF then diode gets forward biased due to inductor $L\frac{di}{dt}$, where inductor polarity charged ~~from~~ and current flow in same direction as in case I.

→ Power flow in type A chopper is always from source to load. This chopper is also called step-down chopper because average output voltage V_0 is always less than the input DC voltage V_s.

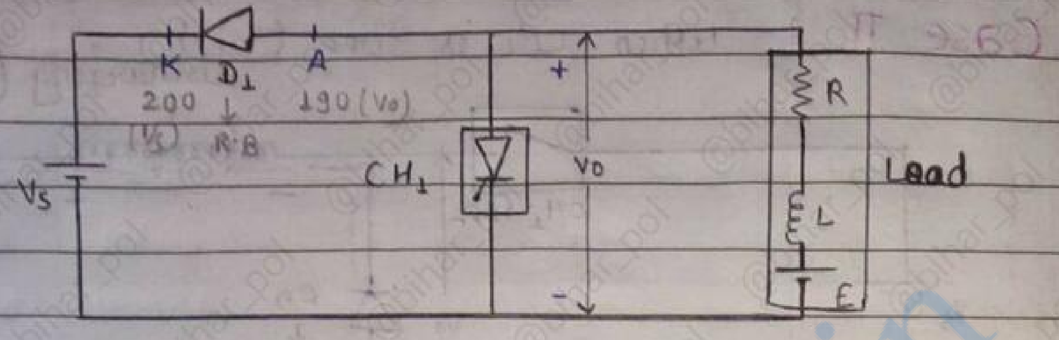
V-I characteristics of Class A chopper



NOTE :- • If the load current is a DC machine works as a motor, as it always receives electrical energy and convert it into mechanical energy.

• This type of chopper is suitable for motoring operation.

2. Second Quadrant or Type B chopper or Class B chopper



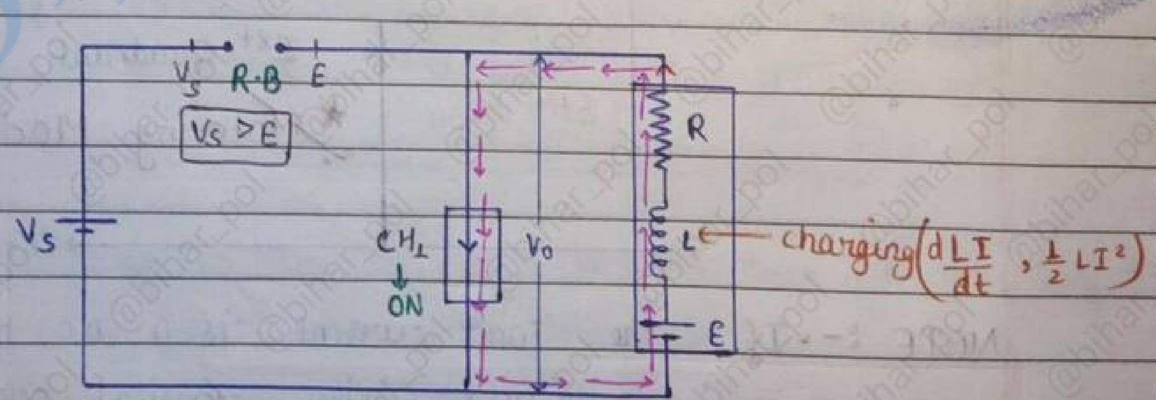
→ The ckt diagram of class B chopper is given above.
→ In this chopper the current flow in opposite direction that is load to source so the V-I characteristics of class B chopper is in second quadrant so it is called second quadrant chopper.

NOTE:- The load must contains a DC source E like a battery in this chopper.

- Operation

Class I :-

when CH_1 is ON (T_{ON})



→ If CH_1 is ON then diode D_1 gets R·B, here current flow in the circuit by voltage E through R and L, here inductor

Start charging. The current flow diagram is given below.

CH_1 is ON → $V_0 = 0$ ← chopper 1 short to load

I_0 → −ve → current is outgoing from load.

L → stores energy durin T_{ON}

Case II :-

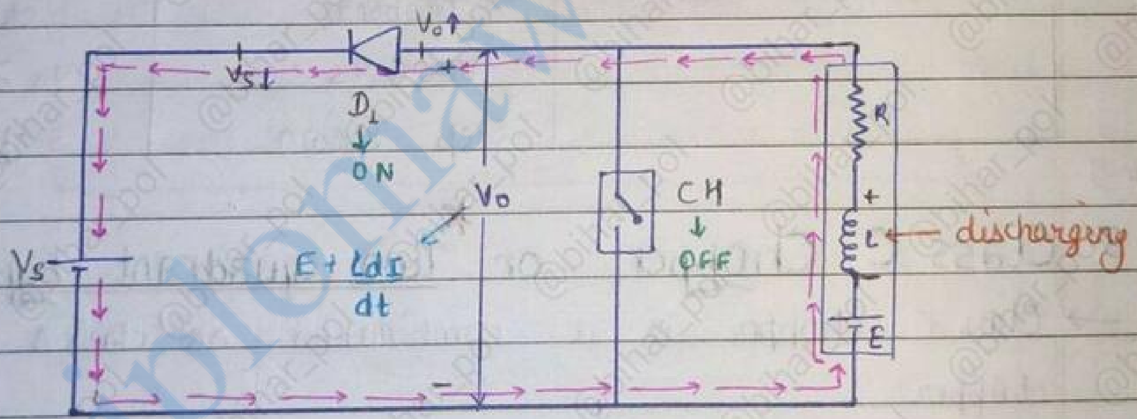
When CH_1 is OFF (T_{OFF})

→ when CH_1 is off, then diode gets turn ON and $V_0 = E + L\frac{dI}{dt}$, exceeds the source voltage V_s. F.B ↓V_s ⊲ V_0↑

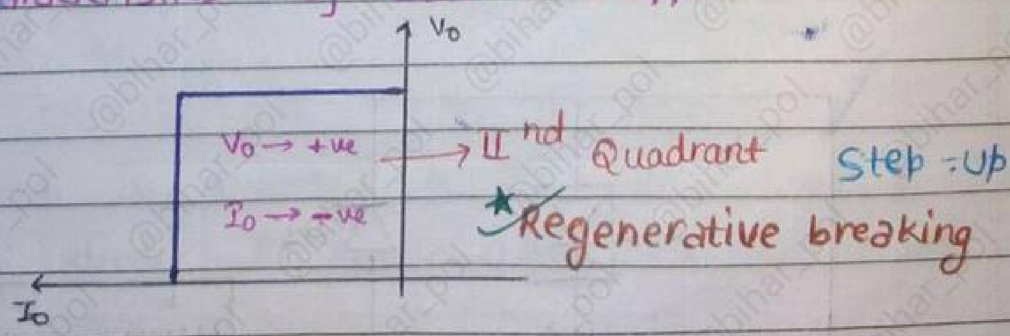
→ Thus the total voltage E + inductor voltage is greater than V_s.

→ This will forward biased the diode D_1 and stored energy is returned back to source.

$V_0 > V_s$, I_0 → −ve

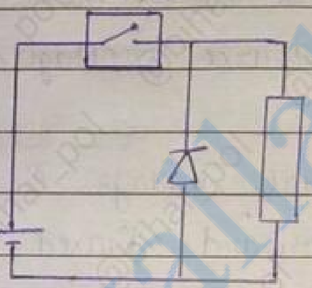
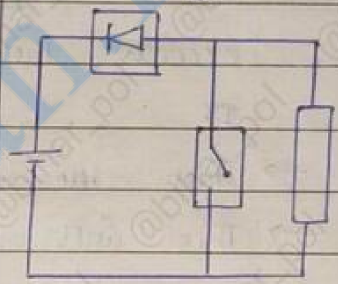


VI characteristics of class B chopper



- Power flow load to source.
- step up chopper.

Comparison of Class A and Class B chopper

	Parameters	Class A	Class B
1.	Quadrant operation	I^{st}	2^{nd}
2.	Power flow	source to load	load to source
3.	Load voltage	+ve	+ve
4.	Load current	+ve	−ve
5.	Configuration		
6.	Application	As a monitoring chopper $V_0 < V_s$ Step down	As a regenerative chopper $V_0 > V_s$ Step up

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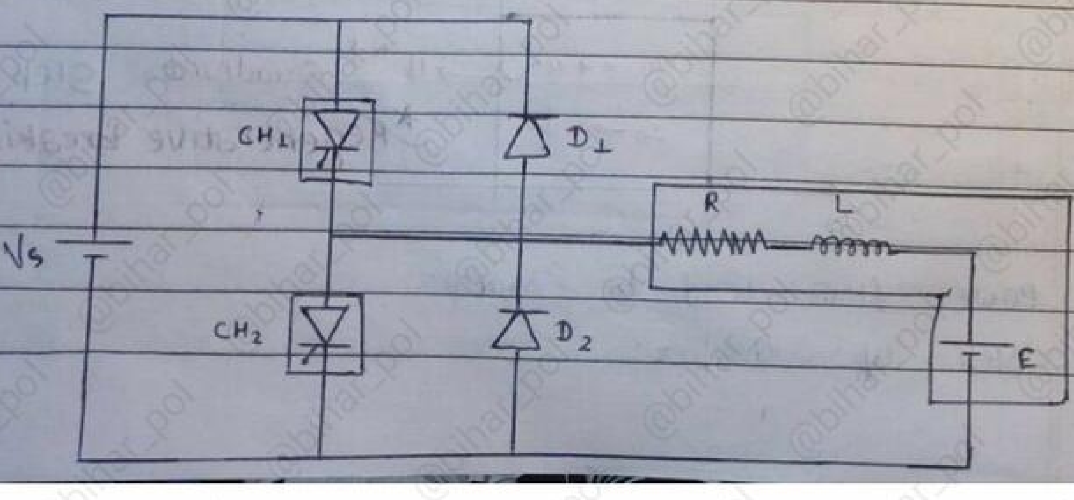
3. Class C Chopper or Two quadrant type A chopper

→ Class C chopper is a combination of class A and class B chopper.

→ It's V-I characteristics is in two quadrant I^{st} and II^{nd}. So it is called two-quadrant chopper.



Q-

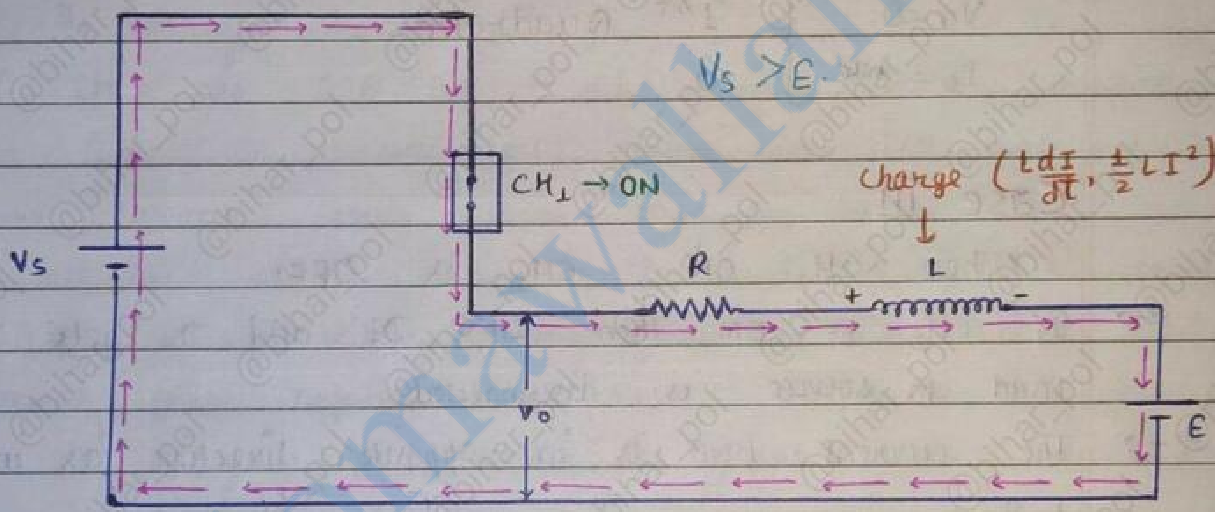
- Operation →

Case I :-

At first CH_1 is ON CH_2 is OFF.

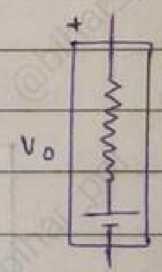
→ If CH_1 is ON then Diode D_1 is OFF, D_2 is OFF and CH_2 is also OFF.

→ The load current flows from the DC supply to the load ~~current flow~~ thus the load voltage and load current both are +ve and load receives power from source.



$V_0 = V_s$ (+ve)
I_0 = +ve

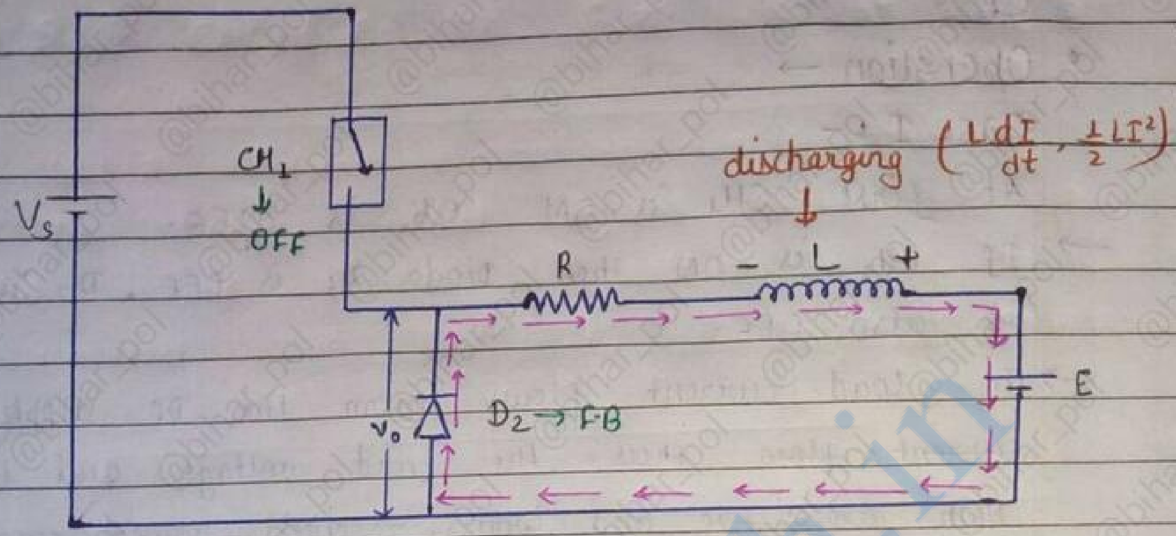
{ I^{st} quadrant.



Case II :-

When CH_1 is OFF CH_2 is OFF.

→ The load is disconnect to the source voltage. In this case the diode D_2 is conducts and the output load voltage is zero.



$V_0 = 0$
$I_0 = +ve$ } I^{st} Quadrant

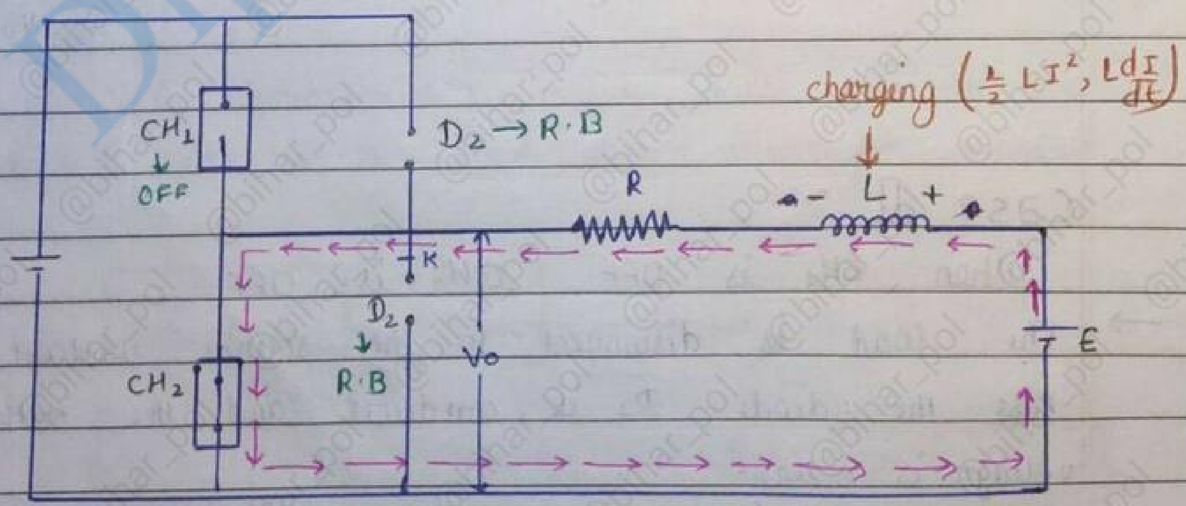
Case III

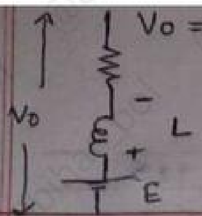
When CH_2 ON CH_1 is OFF.

→ If CH_2 is ON then CH_1, D_1 and D_2 gets off. Load to source is disconnected.

→ The current flow is in opposite direction as in case I & II.

$V_0 = 0$
$I_0 = -ve$



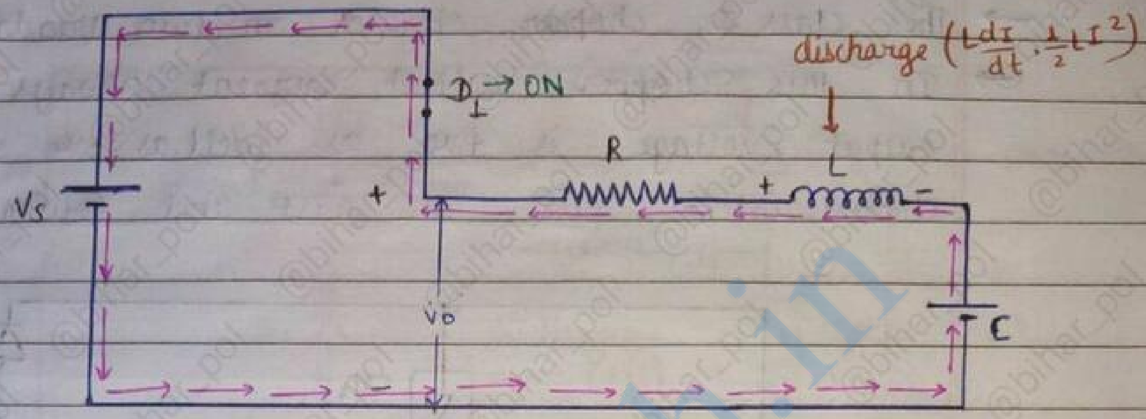


$V_0 = E + L\frac{dI}{dt}$

$V_0 > V_s$
↓
$D_1 A > D_2 K$ $\quad$ $D_1 \to ON$

Case IV

When CH_2 OFF , CH_1 OFF.



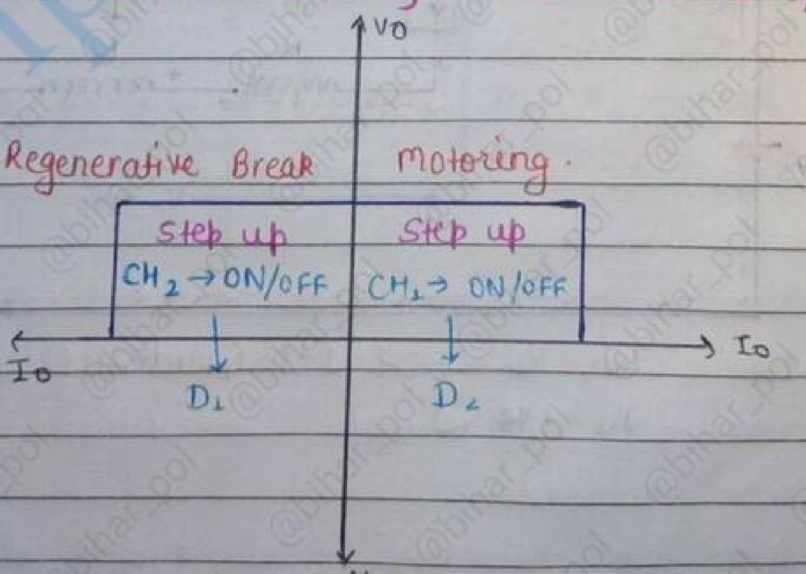
$D_1 \to ON$, $D_2 \to RB$

→ If CH_2 get OFF due to this charged inductor forward biased the diode D_1, and rest devices CH_1, D_2 ~~and~~ are OFF.

→ Here, current flows from load to source.

→ In all the above cases case I and case II load current and voltage gets positive whereas in case III & cas IV load current gets negative and voltage ~~density~~ polarity have positive. Hence, the graph between V_0 and I_0 is lies in two quadrant.

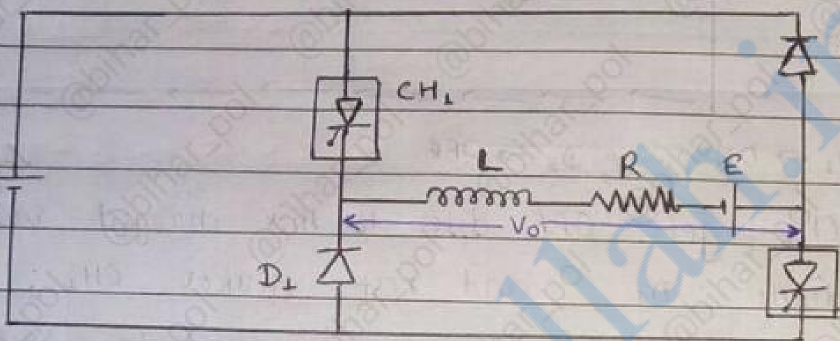
V-I characteristics of Class C chopper



4. Class D chopper or Four Quadrant type B chopper

→ The class D chopper operates on two quadrant.

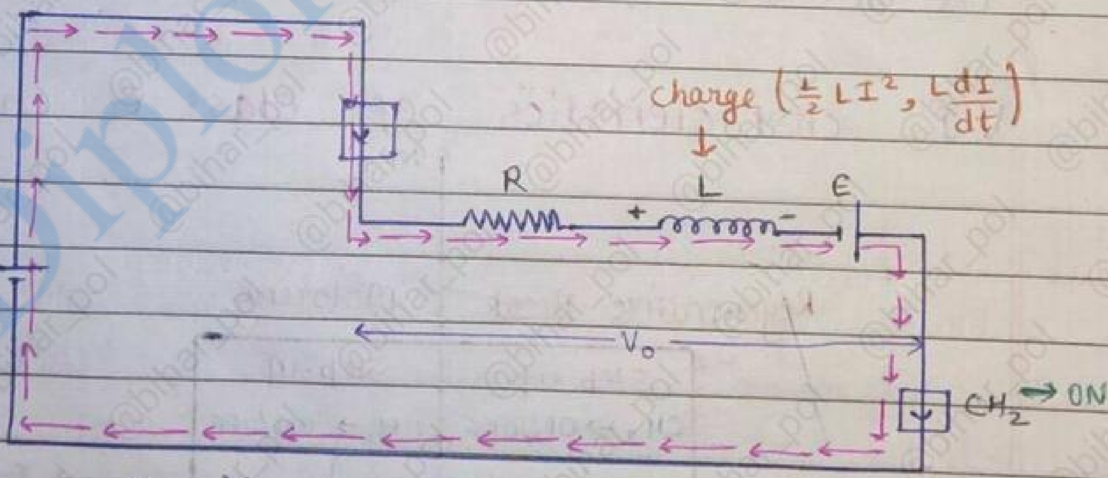
→ In this chopper output current always +ve but output voltage is +ve as well as -ve so, its VI characteristics lies in first and fourth quadrant.



Case I :-

When both chopper is ON CH_1 & CH_2 ON, D_1 & D_2 OFF.

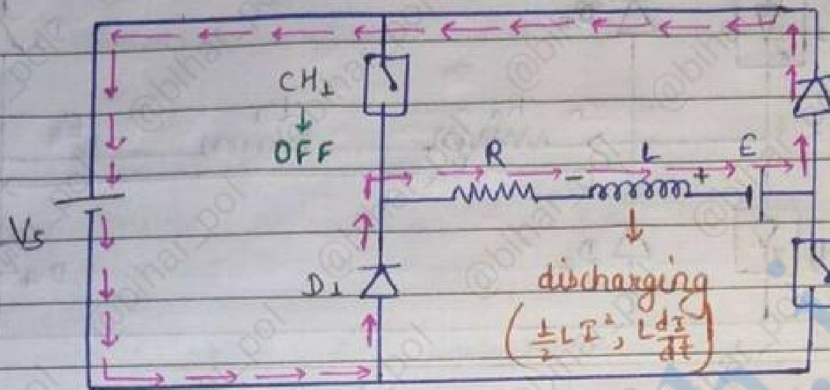
$$V_0 = V_S$$
$$I_0 = +ve$$



$V_0 = V_S$, $I_0 = +ve$ } → I^{st} Quadrant

Case II :-

CH_1 & CH_2 → BOth are OFF D_1, D_2 → ON.

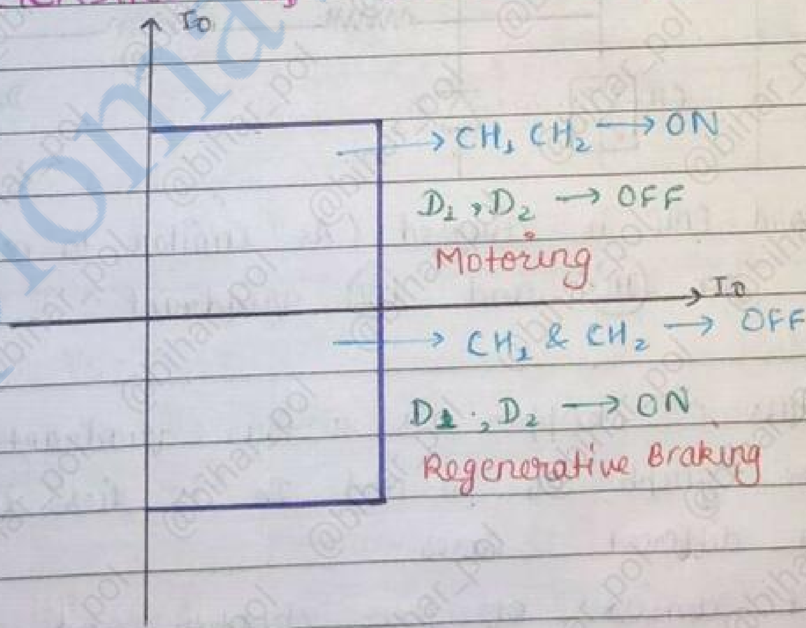


$$V_0 = E + L\frac{dI}{dt}$$

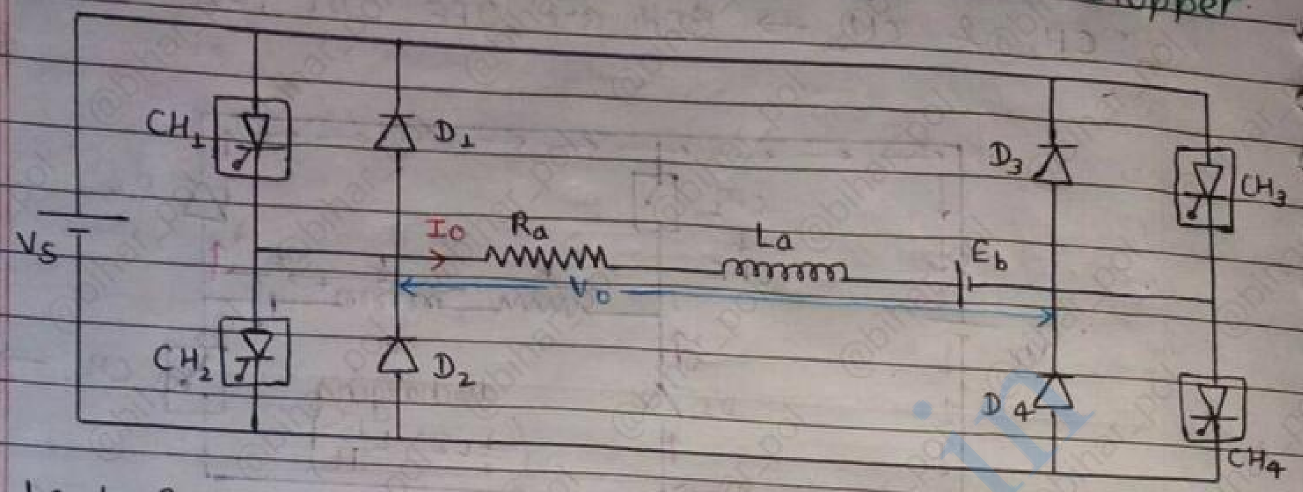
$$I_0 = +ve$$

} Polarity is reverse

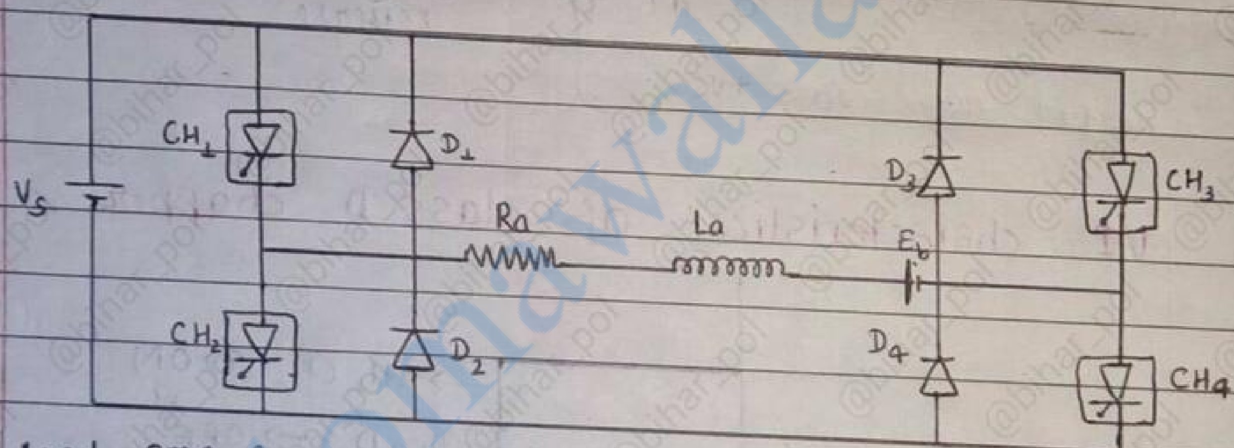
V-I characteristics of class D chopper.



5. Class E chopper or four Quadrant chopper



Load EMF - E → Study for (I) and (II) quadrant.



Load EMF is reversed (As similar to reverse motoring) for (III) and (IV) quadrant.

→ Class E chopper is a four quadrant chopper because the graph of V_0 and I_0 is lies in all quadrant in different cases.

→ It consist of four chopper and four diode in antiparallel CH_1, CH_2, CH_3, CH_4, D_1, D_2, D_3, D_4.

→ The numbering of chopper corresponds to their respective quadrant operation.

First quadrant operation only → CH_1 is operated
Second quadrant operation only → CH_2 is operated

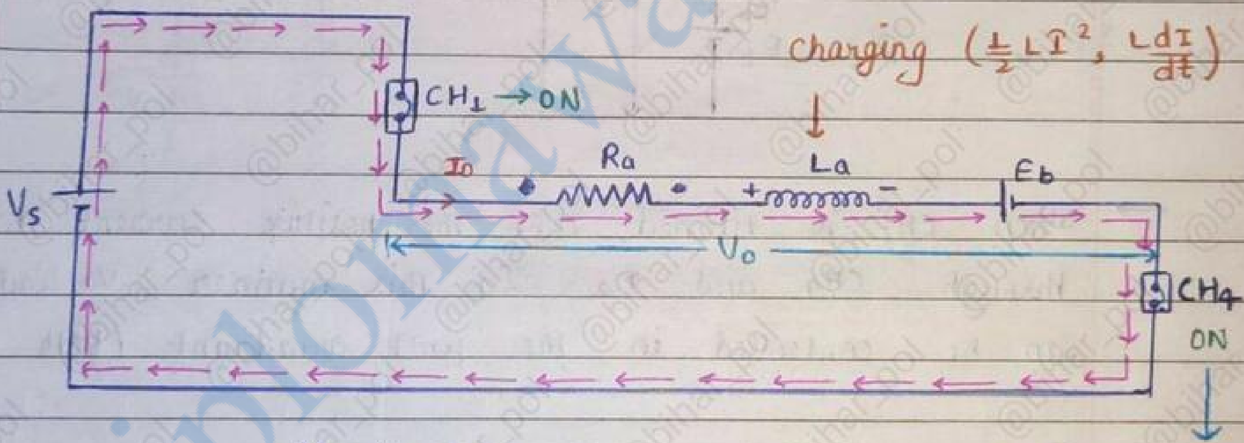
Third quadrant operation only → CH_3 is operated
Fourth quadrant operation only → CH_4 is operated

Operated means ON/OFF.

1. First Quadrant operation

Case I
→ In this mode of chopper CH_4 is kept ON, next CH_1 is triggered, while CH_2 and CH_3 are kept Non-conducting state or OFF.

CH_1 → Triggered → ON / OFF
CH_2 & CH_3 → OFF
CH_4 is ON



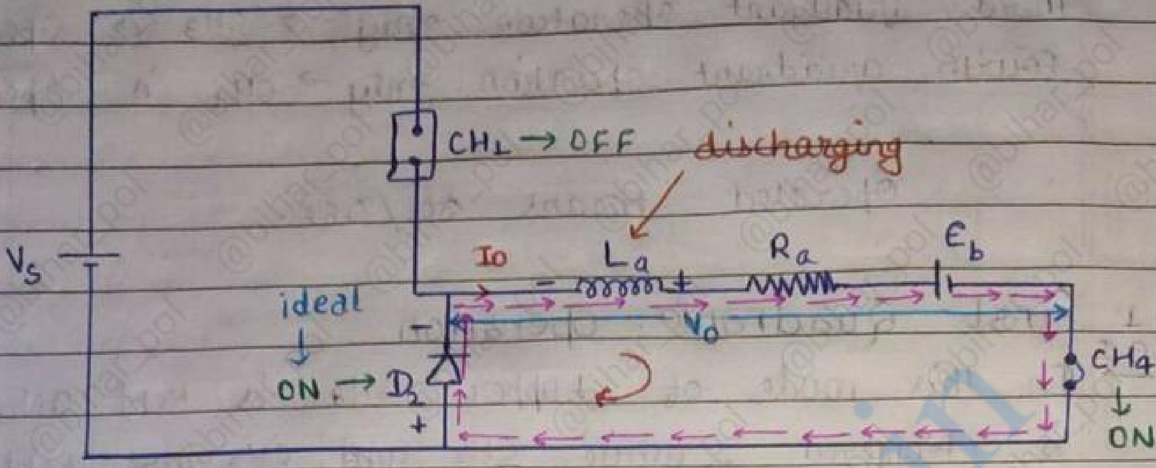
$V_S - V_0 = 0$
$V_0 = V_S \rightarrow +ve$
$I_0 = +ve$

when, CH_1 is ON, CH_2 is OFF

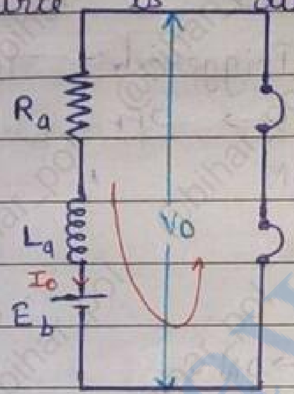
Motoring mode

With CH_1 and CH_4 switch ON current flows through load from the source. In this condition, load voltage V_0 is equal to V_s.

Case II :– CH_1 is OFF, CH_2 & CH_3 OFF, CH_4 ON.
D_2 → is in conducting mode.



Load to source is disconnected



$V_o = 0$, $I_o = +ve$ } → I^{st} quadrant operation

Step-down chopper.

→ When CH_1 is turned OFF the positive current freewheels through CH_4 and D_2. In this manner, V_o and I_o can be controlled in the first quadrant (both positive).

2. Second Quadrant Operation

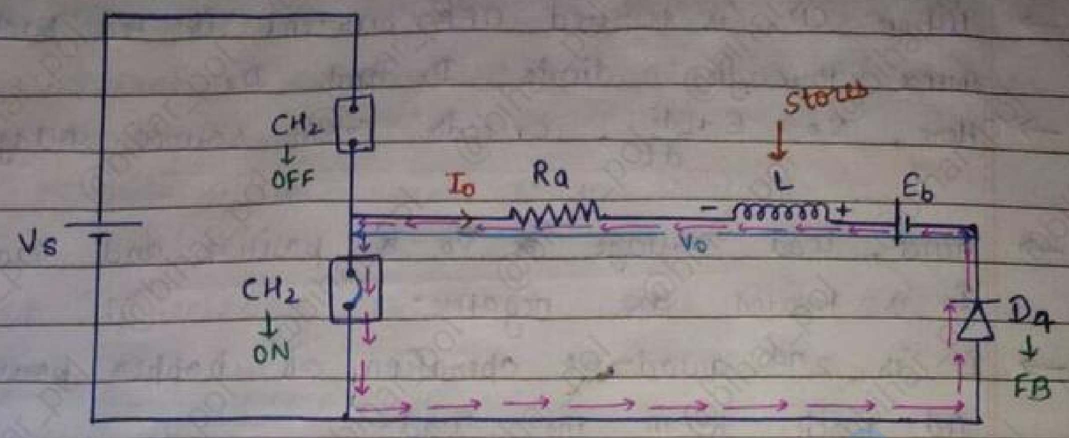
Case I :- CH_2 operated (ON / OFF)

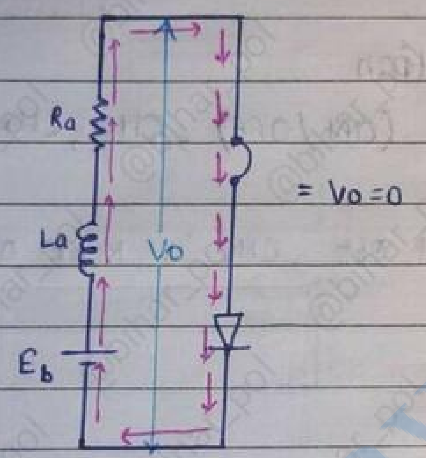
→ In this mode CH_2 is trigged and CH_1, CH_3, CH_4 are kept OFF.

- CH_2 → triggered
- CH_1 → open
- CH_3 → open
- CH_4 → open

→ Inductor stores energy at time CH_2 is ON.

→ When CH_2 is ON reverse current flow through L, CH_2, D_4, E

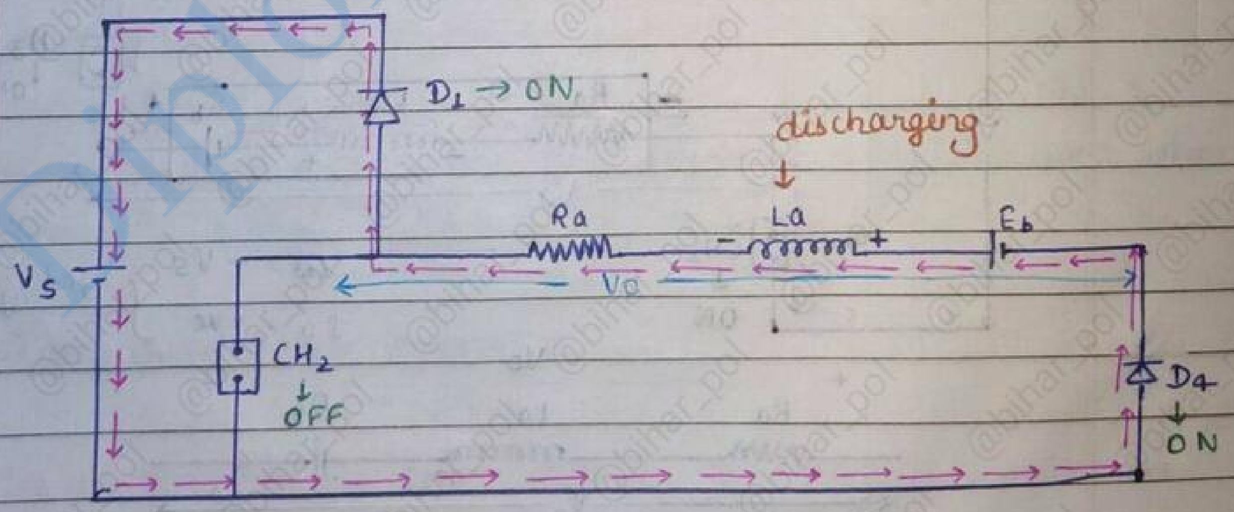




$I_0 = -ve$ } 2^{nd} quadrant
$V_0 = 0$

Inductor charging mode.

Case II :- CH_2 is OFF



$V_0 = E_b + L_a \frac{dI_0}{dt}$

$E_b \rightarrow$ gap

$V_0 > V_S$

$V_0 > V_S (+ve)$, $I_0 = -ve$ (Regenerative breaking)

2^{nd} Quadrant

→ When CH_2 is turned OFF current is fed back to source through diode D_1 and D_2.

→ Here, $V_0 = E + L\frac{di}{dt}$, exceeds from source voltage V_s.

→ Hence, load voltage V_0 is positive and load current I_0 is treated as negative.

→ It is 2nd quadrant operation of chopper power is fed back from the load.

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3. Third Quadrant Operation

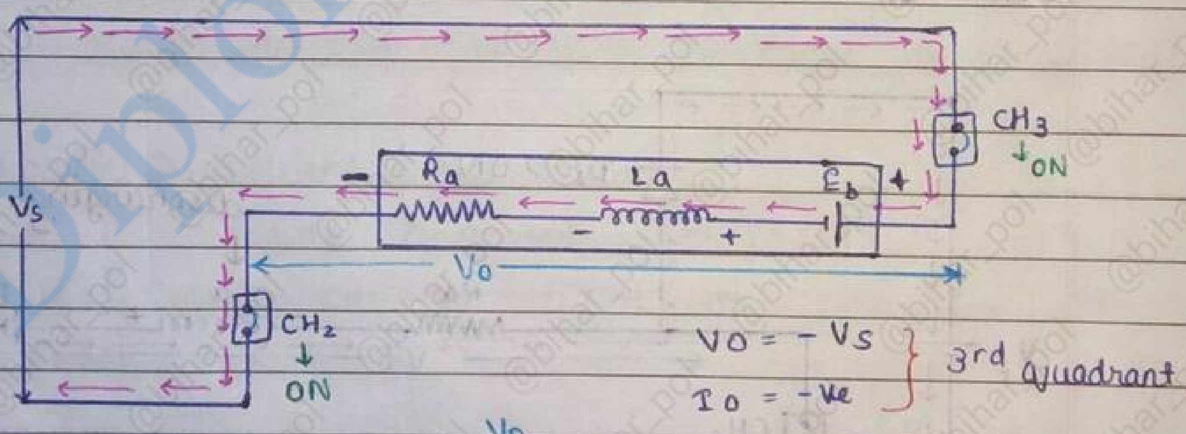
Case I :- CH_3 Operated (ON/OFF), CH_1, CH_4 OFF, CH_2 ON.

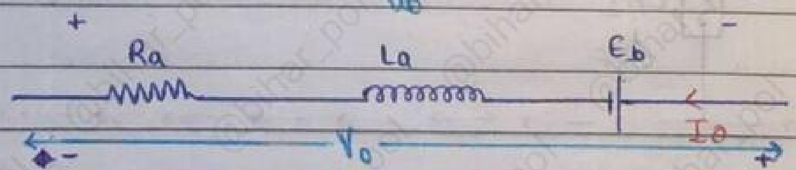
→ In this mode CH_1 is kept off, CH_2 is kept ON and CH_3 is operated.

$CH_2 \rightarrow$ ON

$CH_1 \rightarrow$ OFF

$CH_3 \rightarrow$ ON





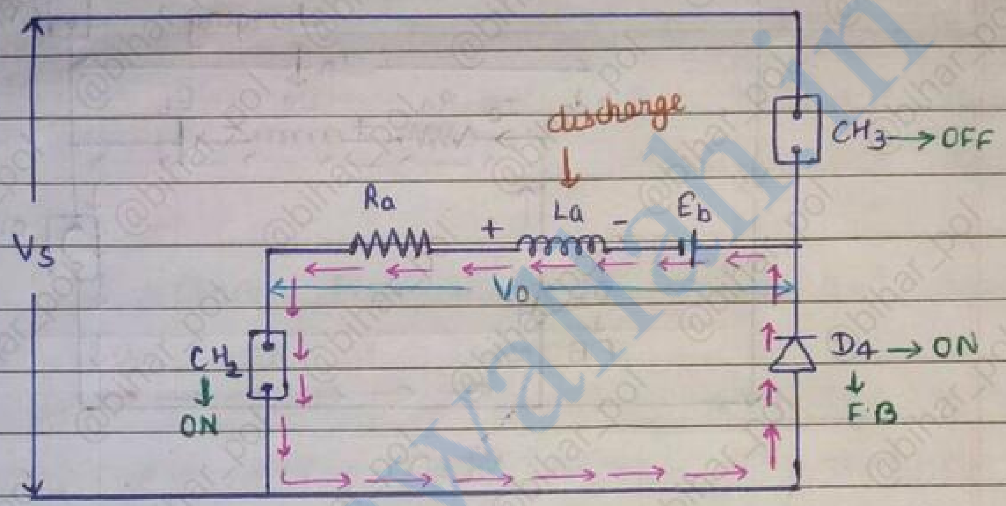
→ When CH_3 is ON the load current gets connected to supply voltage V_s under this condition the V_0 and I_0

both are -ve.

→ The operation lies in third quadrant and inductor is in charging mode.

→ The power flow from source to load.

Case II :- CH_3 is OFF , CH_1, CH_4 OFF , CH_2 ON



$V_0 = 0$, $I_0 = -ve$ } 3rd Quadrant

→ When CH_3 is turned OFF negative current freewheels through diode D_4 and CH_2 and V_0 and I_0 can be controlled.

→ In this condition, $V_0 = 0$

→ Here, chopper operates at stepdown and inductor releases energy through diode D_4 and CH_2.

4. Four Quadrant Operation.

$CH_4 \rightarrow$ Operated.

Case I :- When CH_4 chopper is triggered, while the other devices remains OFF.

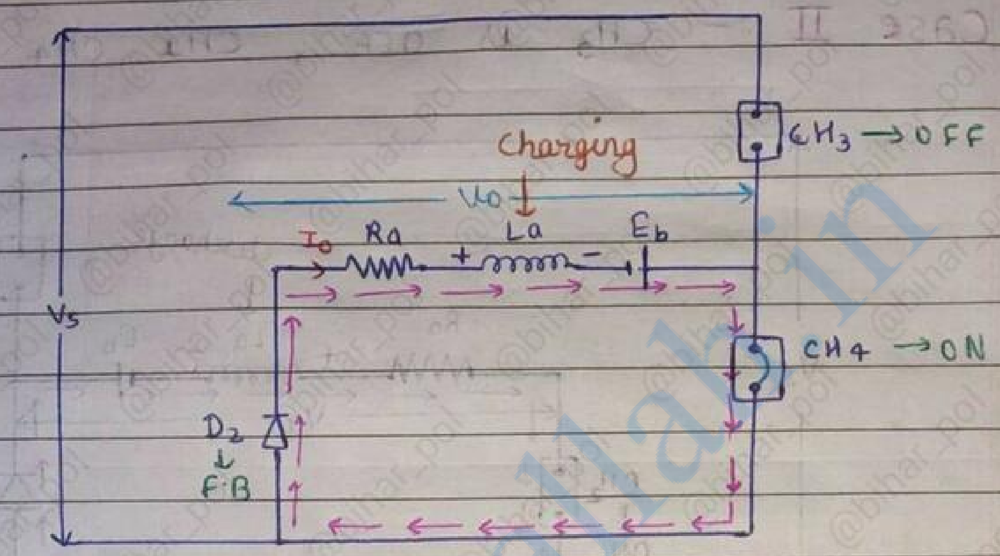
$CH_1 \rightarrow$ OFF

$CH_2 \rightarrow$ OFF

$CH_3 \rightarrow$ OFF

→ The load current I_0 flows through CH_4 and D_2 and R_a and L.

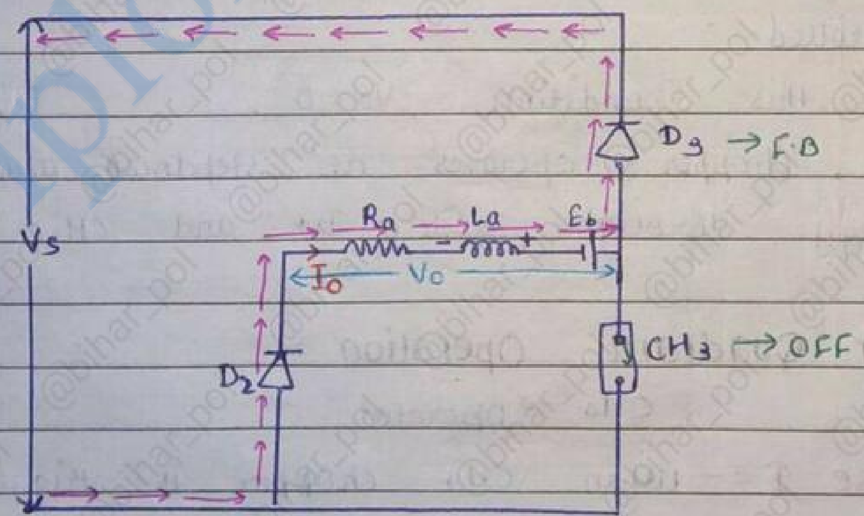
→ In this mode the inductor is in charging mode and I_0 current is +ve and V_0 polarity is -ve.



$V_0 = 0$

$I_0 = +ve$

Case II :- CH4 is OFF



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

Step up.

$V_0 > V_s$ — V_0 is treated as -ve

$V_0 = -ve$

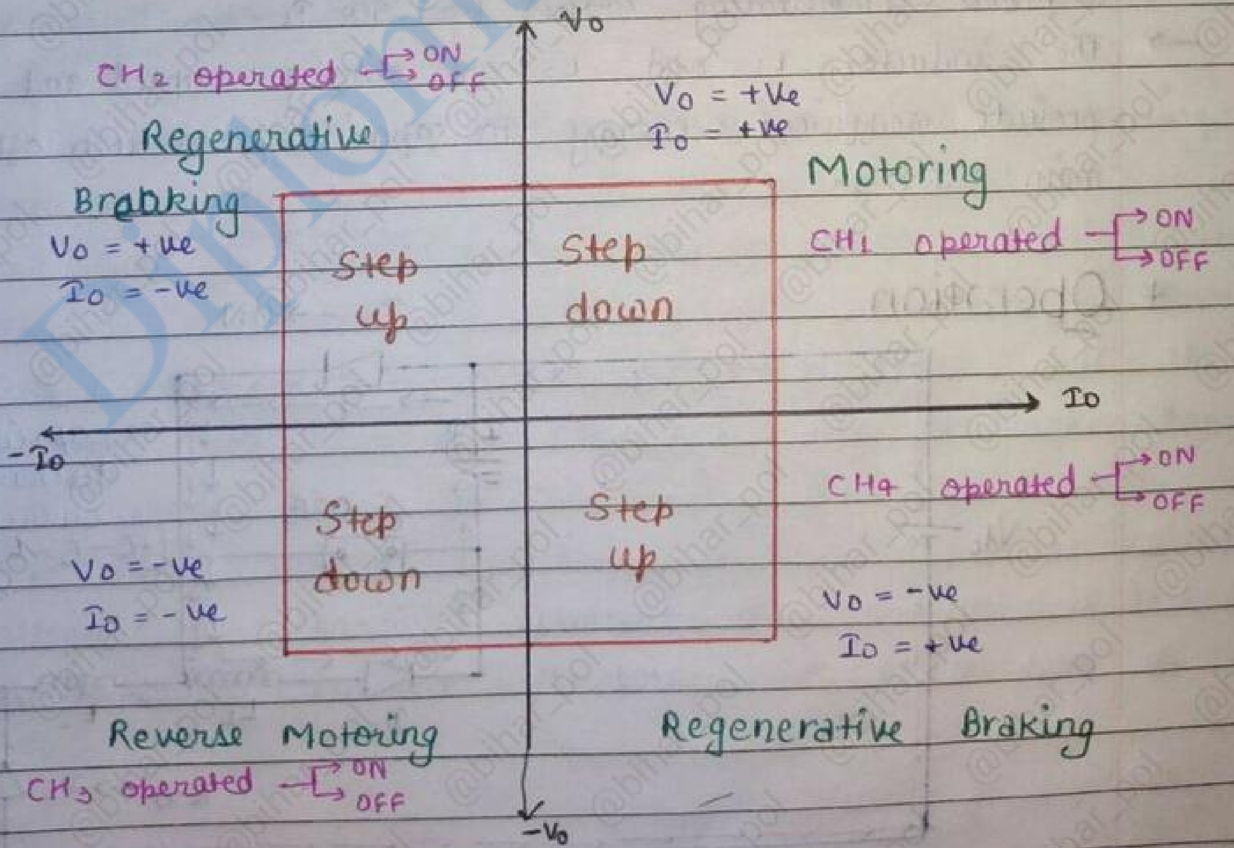
$I_0 = +ve$ — Regenerative braking.

→ When CH_4 is turned OFF the current is fed back to source through diode D_2 and D_3.

Here, load voltage is treated as negative but load current is positive. Hence, the copper operation is in 4th quadrant because output voltage is treated as negative and load current is +ve.

→ Power is fedback from load to source and chopper operates as step up chopper.

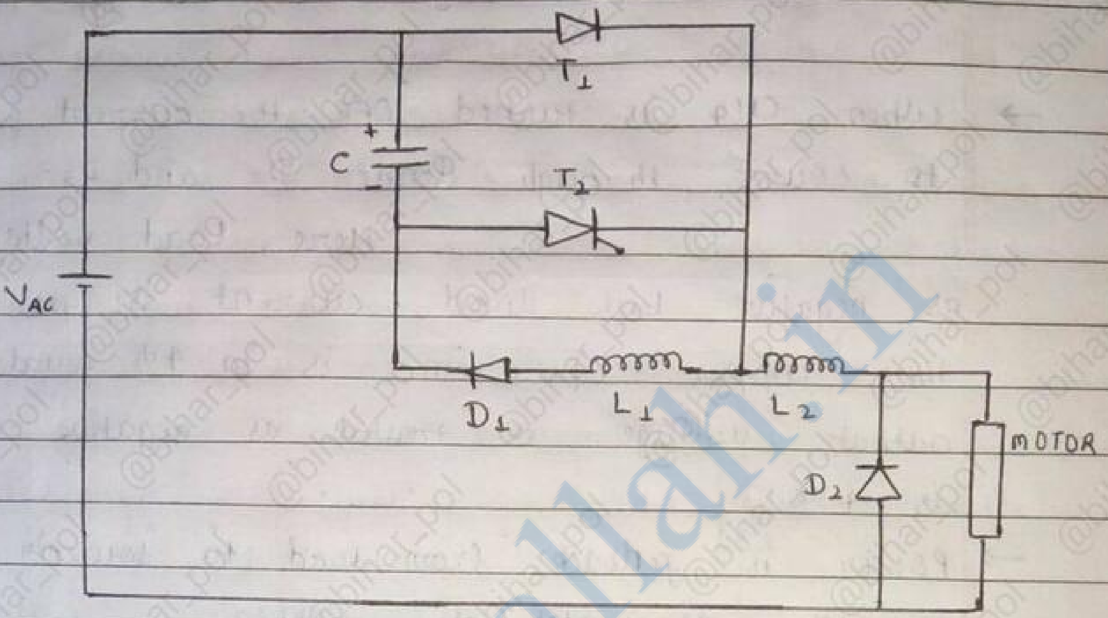
VI characteristics of class E chopper



Jones chopper → Capacitor initially charge.

* Jones chopper

The basics ckt of the jones ~~ckt~~ chopper is shown below:-



→ The class D commutation circuit is used in jones chopper.

→ The SCR T_1 is main SCR whereas SCR T_2, diode D_1, capacitor C makes commutating circuit for SCR T_1.

→ The inductor L_1 and L_2 are closely coupled and they provide sufficient energy to capacitor to turn off the main SCR T_1.

* Operation

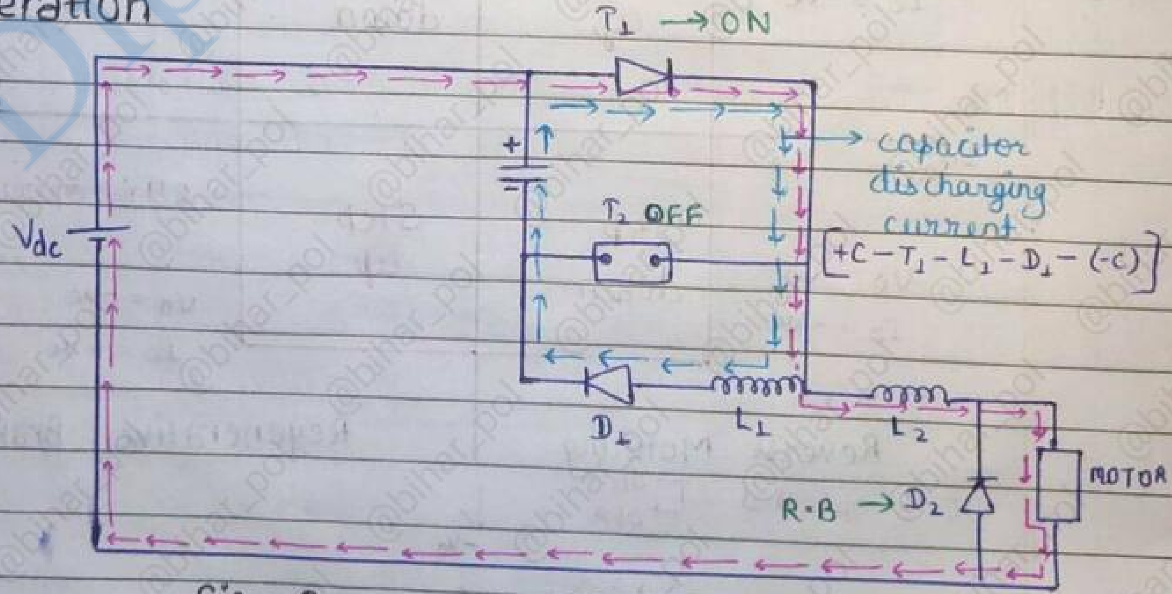


Fig - I

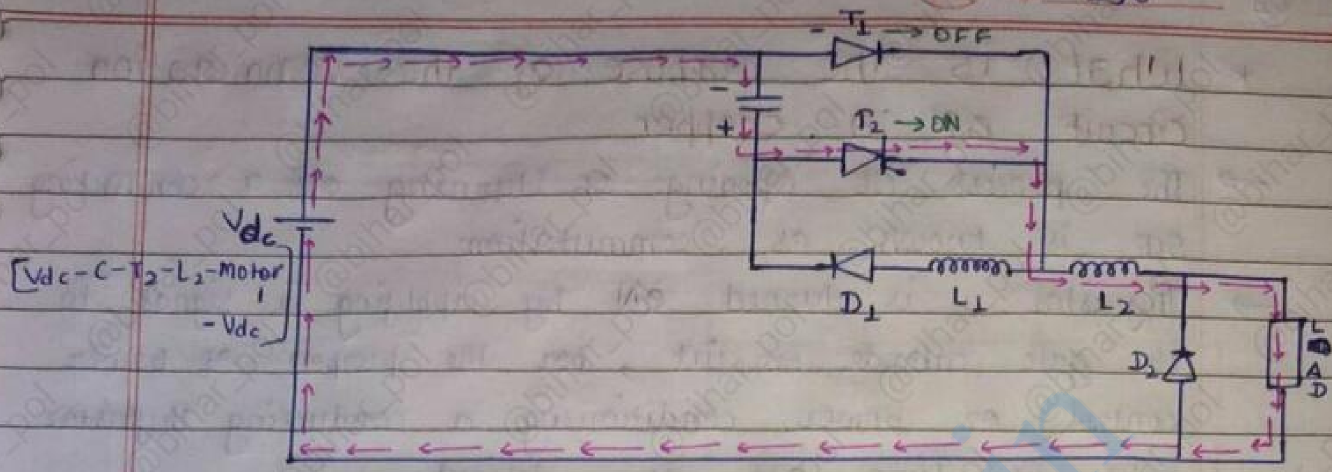


Fig - II

→ The capacitor is initially charged with upper plate +ve and lower plate -ve, when the SCR T_1 is turned ON. The load current flows through path $+V_{dc} - T_1 - L_2 -$ motor $- (-)V_{dc}$.

→ The capacitor discharges through path $+C - T_1 - L_1 - D_1 - (-)C$ once capacitor discharges, it will again charges with reverse ~~pulley~~ polarity with upper plate -ve and lower plate is +ve.

→ The stored energy of load flows through freewheeling diode when SCR T_1 is turned OFF.

→ The SCR T_1 gets reverse voltage and turned off when SCR T_2 is turned ON, the load current flows through path $+V_{dc} - C - T_2 - L_2 -$ motor $- V_{dc}(-)$.

→ As the load current flows the capacitor again charges with upper plate positive and lower plate (-ve).

→ when the voltage across capacitor is equal to supply voltage, the charging current of capacitor is less than the holding current therefore SCR T_2 is turn off.

* What is the purpose of the Commutation circuit of a chopper.

→ The process of opening or turning off a conducting SCR is known as commutation.

→ Thyristor is turned ON by applying a signal to its gate cathode circuit, for the purpose of power control or power conditioning a conducting thyristor must be turn off as desired.

→ The thyristor turn off requires that it anode current falls below the holding current and a reverse voltage is applied to SCR for a sufficient time to enable it to recover the blocking state.

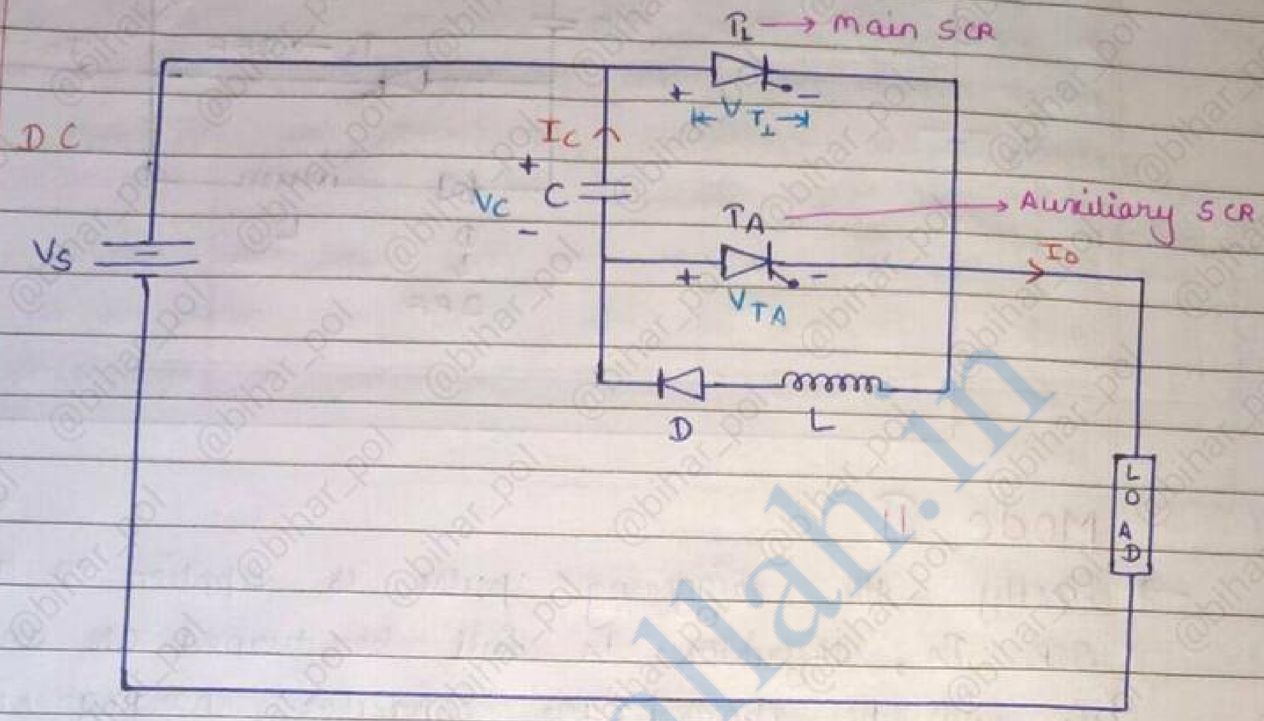
→ Commutation is defined as the process of turning off a SCR, one SCR start conducting gate looses control over the device, therefore external means may have to ~~apodo~~ adopt to commutate the SCR.

→ Thyristor commutation technique use resonant LC or underdamped RLC circuit to force the current and or voltage of a SCR to zero to turn off the device.

The various commutation technique are as follows:

1. Class A commutation
   → Load commutation
2. Class B commutation
   → Resonant Pulse commutation
3. Class C commutation
   → Complementary commutation
4. Class D commutation
   → Impulse commutation or Auxiliary commutation.

4. Class D commutation

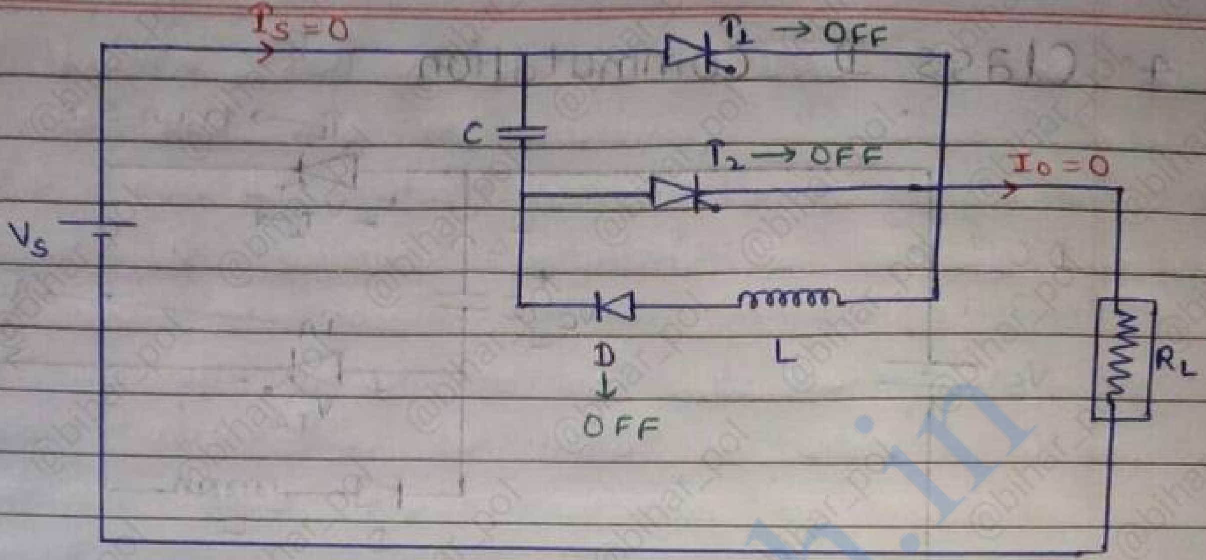


→ The above fig. show the class D commutating circuit which consist of two SCR such as main SCR T_1 and auxiliary SCR T_A, inductor L_1 diode D and a commutating capacitor C.

→ The main SCR T_1 and load resistance R_L acts as a power ckt but inductor L_1, diode D and auxiliary SCR T_A are used to form the commutation circuit.

Mode I

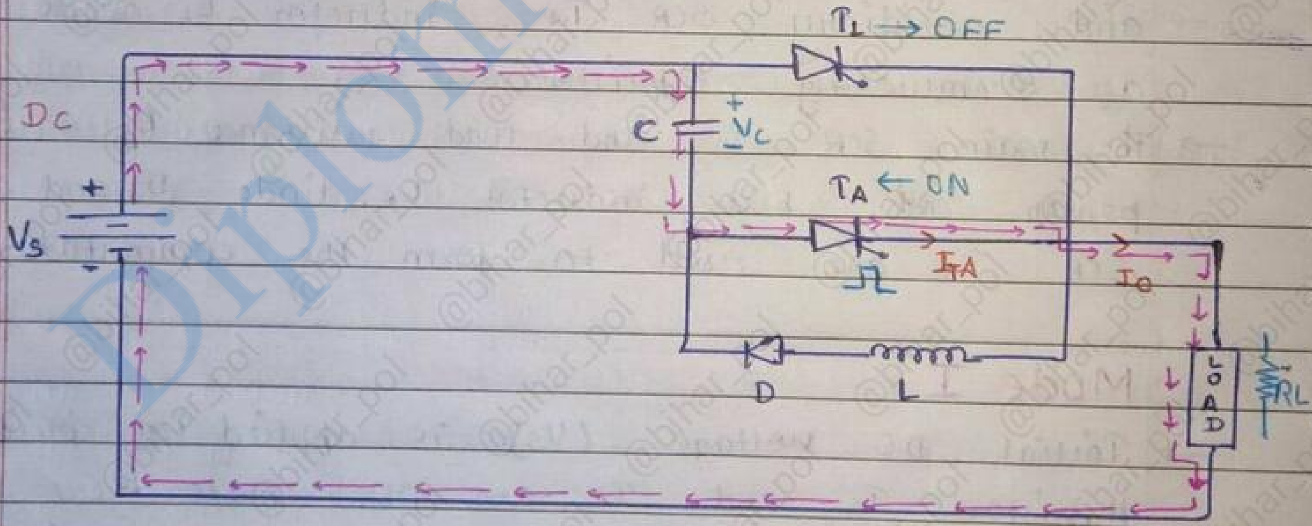
→ Initial DC voltage (V_s) is applied to circuit the thyristor T_1 and T_A are off state there is no current flow through DC supply and commutation circuit, the condition of T_1 and T_A and capacitor may be represented by T_1 is in off state T_A is in off state $V_0 = 0$.



Mode II

→ Firstly the triggering pulse is applied to auxiliary SCR T_A, thyristor T_A will be turned ON and capacitor C will be charged the capacitor charging current flow through the path.

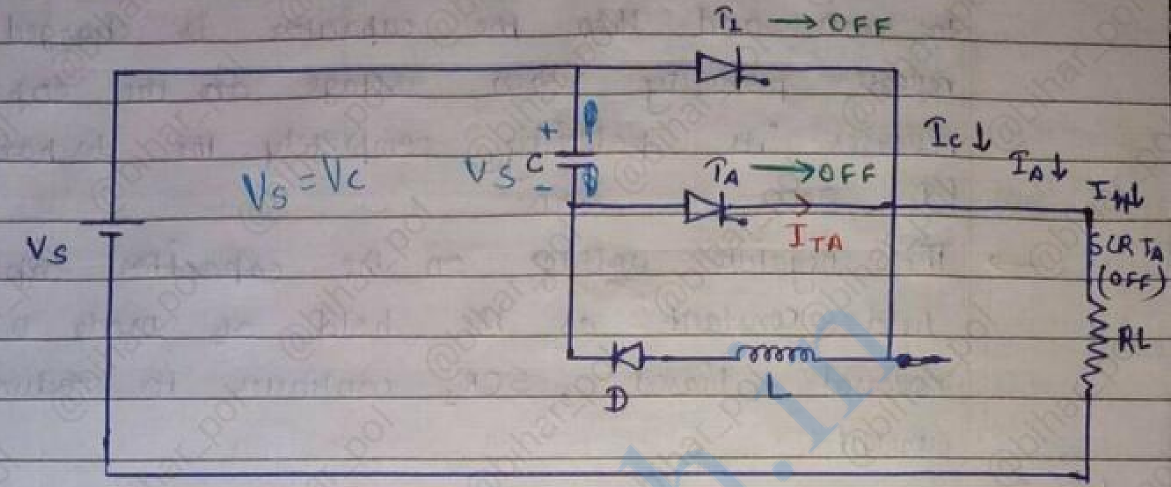
$$V_S^+ - C^+ - C^- - T_A - \text{Load} - V_S^-$$



→ Since the voltage across the capacitor C (V_C) is increases gradually, the current flow through SCR (T_A) decreases slowly.

→ Whenever the capacitor is fully charged to V the auxiliary SCR T_A is turned OFF.

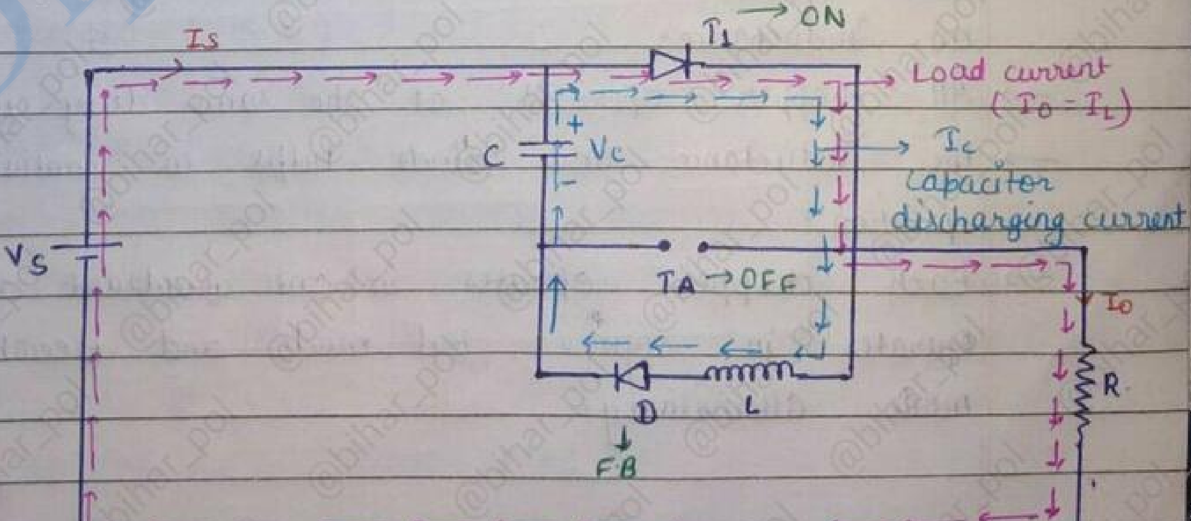
T_1 is OFF, T_A is off and $V_0 = V_S$



Mode III

→ When the triggering pulse is applied to main thyristor T_1 the current flow in two different path the load current I_0 flow through following path $[V_S^+ - T_1 - R_L - V^-]$ and commutating current capacitor discharging current flow through the following path. $[C^+ - T_1 - L - D - C^+]$

→ When the capacitor is fully discharged its polarity will be reversed. The discharging of capacitor C in reverse direction is not possible due to presence of diode D, At the end this mode of operation T_1 is in ON state, T_A is in off state $V_C = -V$



→ The positive voltage ~~on~~ the capacitor decreases first to zero and then the capacitor is charged with a reverse polarity when voltage on the capacitor reverses its polarity completely the discharge current (I_c) goes to zero.

→ The negative voltage on the ~~capacitor~~ capacitor is held constant as the hold of Diode D is now reversed biased, SCR_1 continues to conduct the load current.

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* Multiphase chopper

→ When a chopper is used in a high power ckt (Ex- Railways Traction). The high frequency component of ripple in the source current and voltage can cause undesirable interference with the communication and control circuit.

→ The method to ~~ab~~ avoid this problem is to use a multiphase chopper which consist of a no. of choppers operating in parallel and feeding the motor collectively.

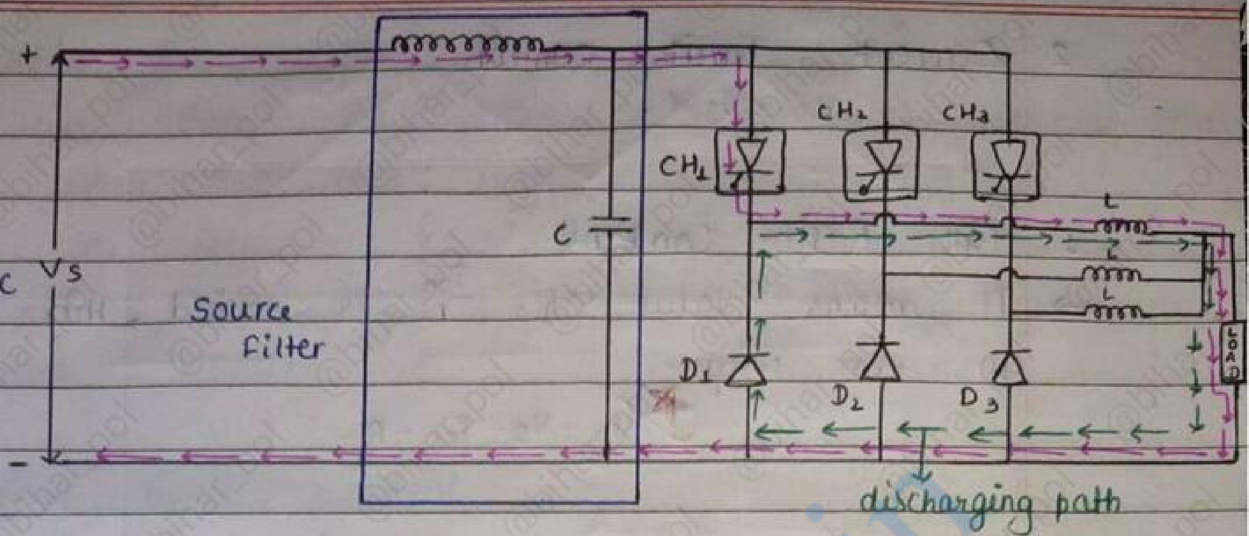
→ Each chopper is connected to the load through an inductance.

→ All chopper operates at the same duty cycle (α).

→ The inductance and diode helps in continuous operation.

→ Each chopper operates in one quadrant only and operates in source fed mode and freewheeling mode alternatively.

converter → α → firing angle



- When CH_1 off L discharge and follow a path for discharge.
- When CH_2 ON same path follows as CH_1. and when CH_2 OFF L discharge ~~and~~ as by D_2 path.
- CH_3 same as CH_1 & CH_2.

Q. Write down the control strategy of chopper or define the duty cycle related to chopper. Name the two technique to control the duty cycle.

- Duty cycle – It is defined as the ratio of ON time to the total time. It is denoted as α.

$$\alpha = \frac{T_{on}}{T} = \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

$$\therefore \alpha < 1$$

- Control Strategy – Since the average value of output voltage V_0 can be controlled through α by opening and closing the semiconductor switch theory are two types of control strategy employed in DC chopper which are as ....

1. Time Ratio Control (TRC
   - → constant frequency operation
   - → variable frequency operation

2. Current limit control

$V_0 = V_s \alpha$

1. Time Ratio Control

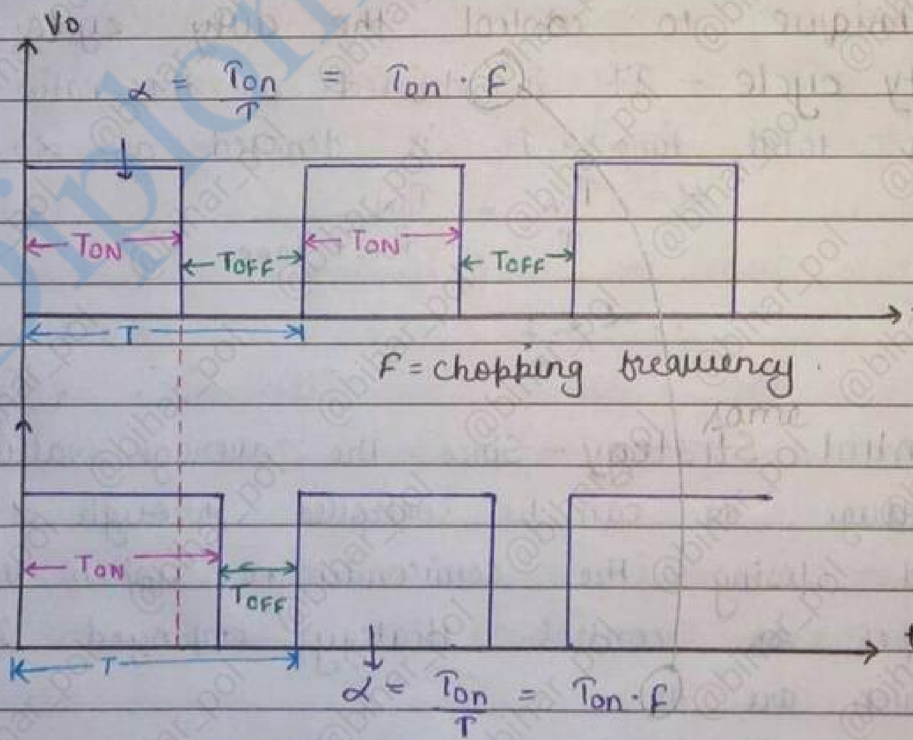
→ It means value of $\frac{T_{on}}{T}$ is varied, this is affected in two ways.

$V_0 = V_s \cdot T_{on} \cdot f$

(a) Constant frequency operation

→ In this scheme the turn ON time T_{on} is varied keeping chopper frequency $(f = \frac{1}{T})$ is constant.

→ The variation of turn ON time (T_{on}) results in pulse width modulation (PWM) control this type of operation is also called pulse width modulation control.



Inverter, chopper } → forced commutation.

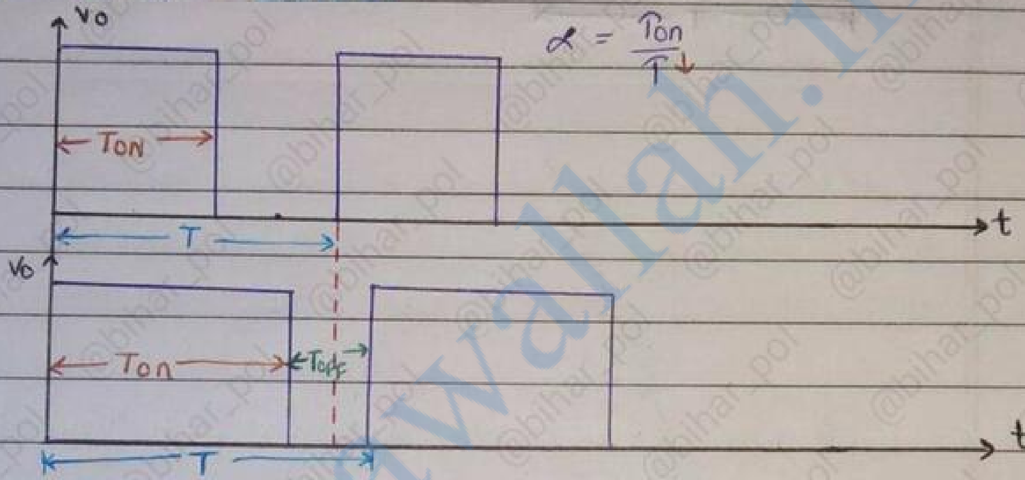
(b) Variable frequency operation.

→ In this scheme the chopping frequency F is varied and here either T_{ON} and T_{OFF} is kept constant.

→ Since the frequency $f = 1/T$ is ~~constant~~ controlled, this method of controlling α is called frequency modulation controlled scheme.

2. ~~Current limit~~ Control

$\alpha = \frac{T_{on}}{T\downarrow}$



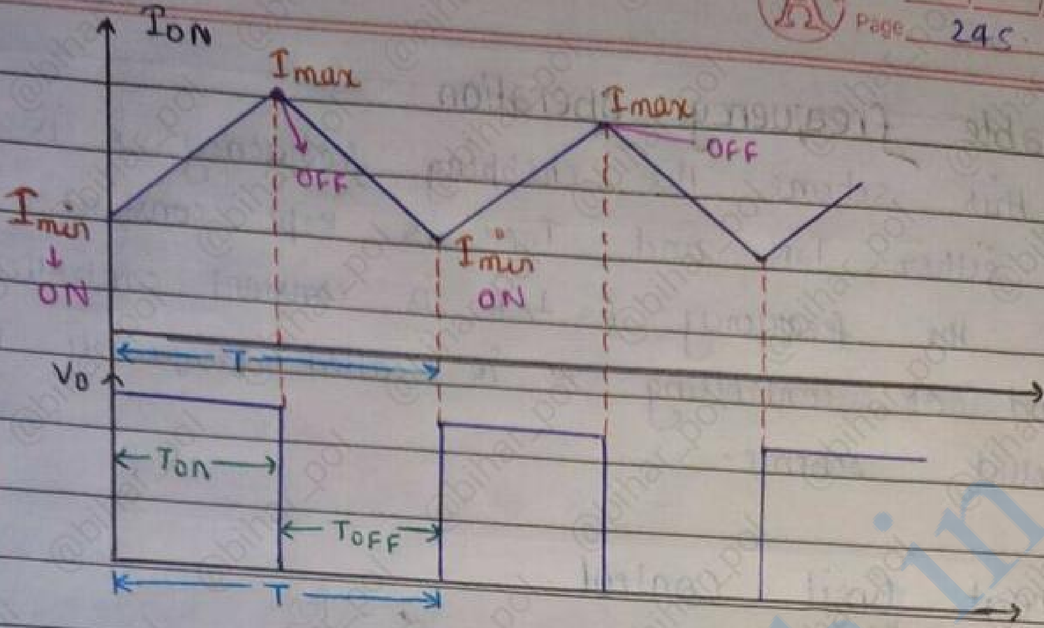
$\alpha = \frac{T_{on}}{T\downarrow}$

2. Current Limit Control

→ Chopper is switched OFF when load current exceeds a certain limit and chopper is switched ON when load current reaches a lower limit in this way chopper is switched ON and OFF. So that current in the load is maintained b/w two limit ($I_{max} \rightarrow I_{min}$)

→ Difference between I_{max} and I_{min} decide the switch frequency this is called current limit control system.

→ Ripple current $I_{max} - I_{min}$ can be lowered and this in ~~two~~ turn necessities higher switching frequency and therefore more switching losses.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Imax
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Unit:- 5 & 6

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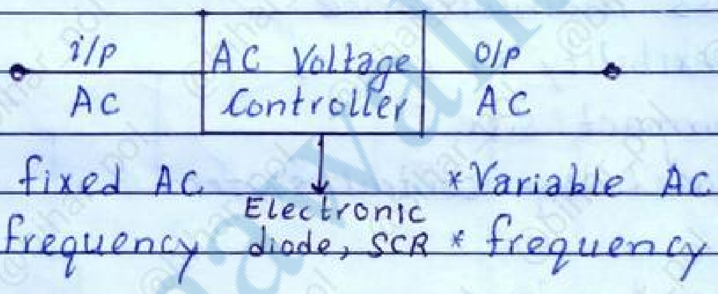
AC Power Control & Speed Motor Control

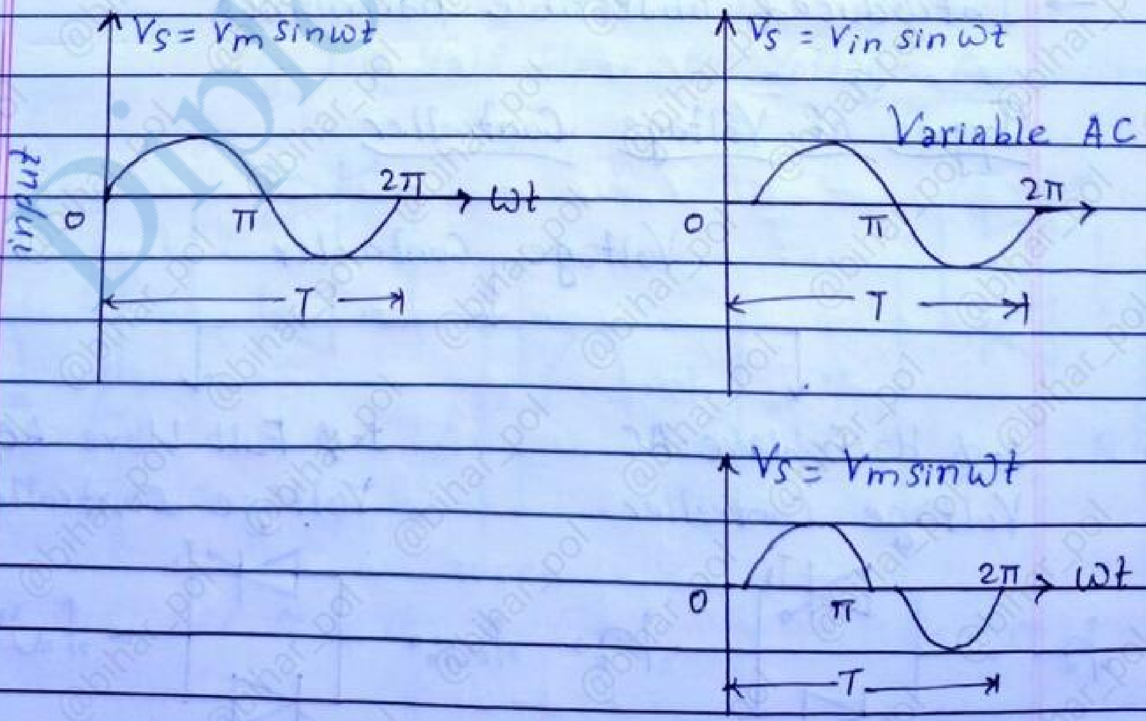
Line Commuted Converters

AC Voltage Controller → Unidir

→ AC voltage controller is thyristor based device which converts fixed alternating voltage directly to a variable alternating voltage without change in frequency. It is also called phase controlled device.



→ Commutation → Natural or Line commutation



Applications

- → Domestic & industrial heating
- → Transformer tap changing
- → Lighting control
- → Speed control of 1-ϕ or & 3-ϕ AC drives
- → Induction motor starting

Advantages

- → High efficiency
- → Less maintainance
- → Flexibility in control
- → Compact size
- → Closed loop control system

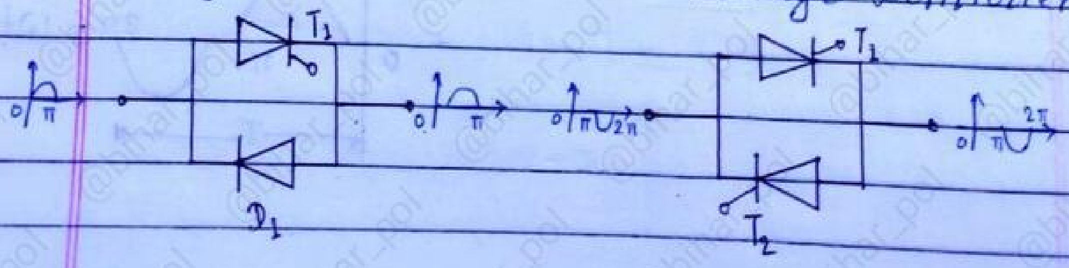
Disadvantage

- → Introduced objectible harmonics

Types of Voltage Controller

Voltage Controller

- 1-ϕ Half Wave AC Voltage Controller
- 1-ϕ Full Wave AC Voltage Controller



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1) 1-ϕ Half Wave AC Voltage Controller → Unidirectional Controller

→ It is also called 1-ϕ unidirectional AC voltage controller.

→ During +ve half cycle, T_1 is triggered at firing angle, α and it conducts $\omega t = \alpha$ to π for R-load.

→ During -ve half cycle, diode D_1 is forward biased. Therefore, it conducts from $\omega t = \pi$ to 2π.

→ Only +ve half cycle can be controlled. -ve half cycle cannot be controlled.

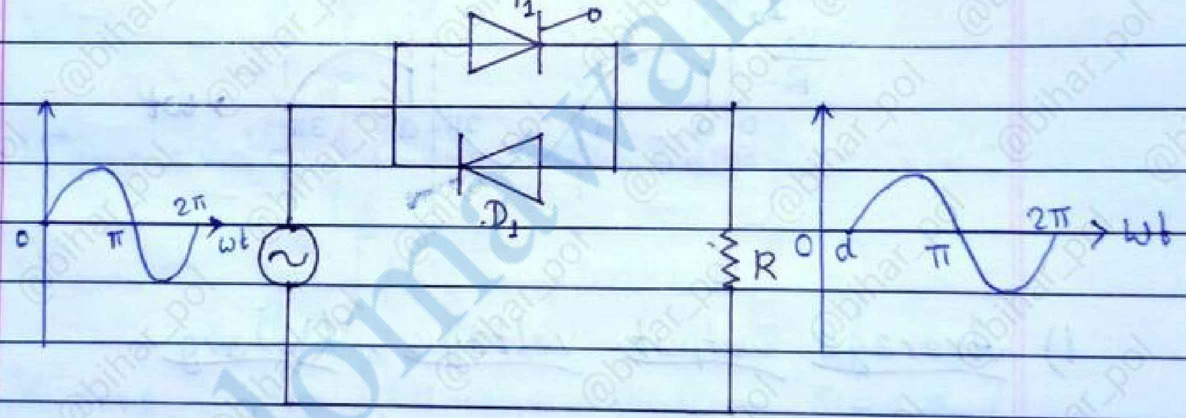
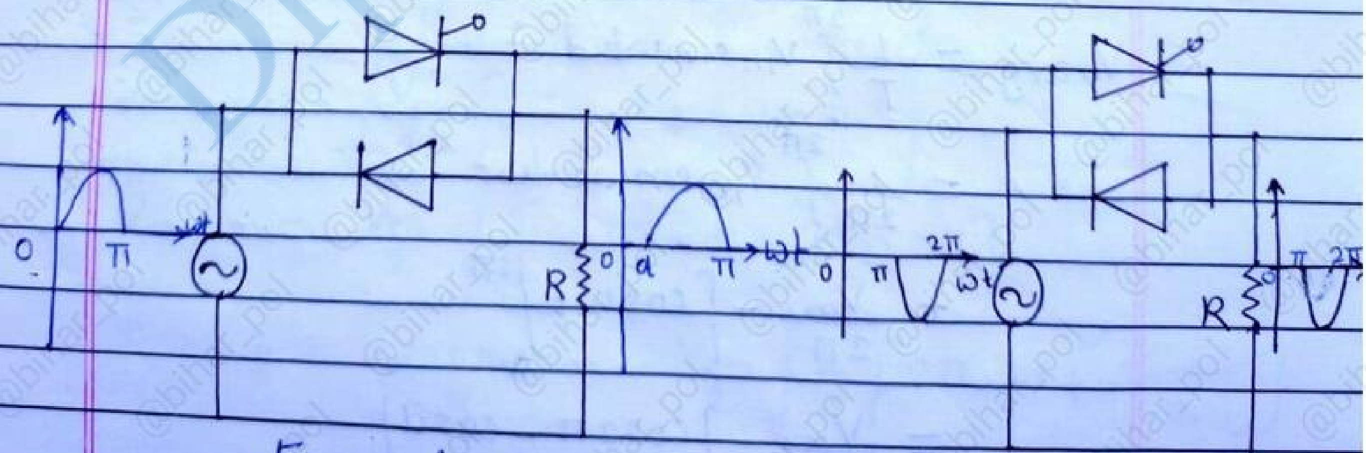


Fig. 1-ϕ Half Wave AC Voltage Controller



For 0 to π For π to 2π

→ Avg. value means dc component

→ α = firing angle, delay angle, triggering angle

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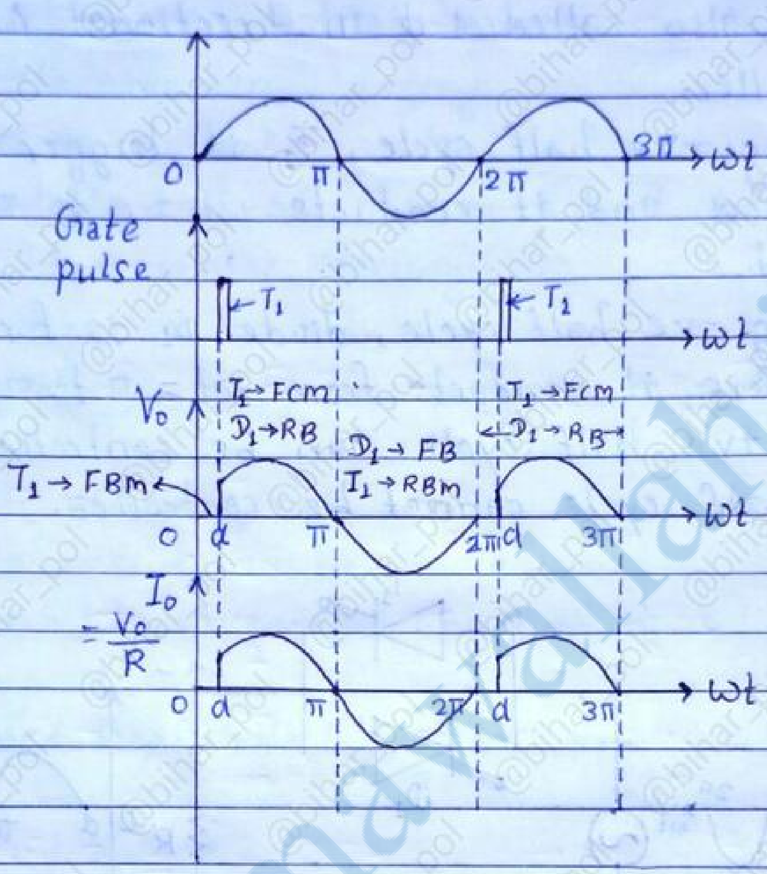
Waveform of 1-ϕ Half-Wave AC Voltage Controller



i) Average output voltage, $(V_0)_{avg}$

$$V_{avg} = \frac{1}{T}\int_0^T V_s\,dt = V_{oDC}$$

$$V_{o\,avg} = \frac{1}{T}\int_0^{2\pi} V_m \sin\omega t\, d\omega t$$

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

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

$$= \frac{V_m}{2\pi} - \left|\cos 2\pi - \cos\alpha\right|$$

$$\boxed{V_{o\,avg} = \frac{V_m}{2\pi}\left|\cos\alpha - 1\right|}$$

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$$I_{oavg} = \frac{V_{oavg}}{R} = \frac{V_m}{2\pi R}|\cos\alpha - 1|$$

Drawback

→ The source current contains DC component and saturated supply transformer core. Therefore, half-controlled regulator is generally not used.

ii) RMS o/p voltage (V_{oRMS})

$$V_{oRMS}^2 = \frac{1}{T}\int_0^T V_s^2 \, dt$$

$$V_{oRMS}^2 = \frac{1}{2\pi}\int_\alpha^{2\pi} V_m^2 \sin^2\omega t \, d\omega t$$

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

$$V_{oRMS}^2 = \frac{V_m^2}{4\pi}\left[|\omega|_\alpha^{2\pi} - \left|\frac{\sin 2\omega t}{2}\right|_\alpha^{2\pi}\right]$$

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

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

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

$$V_{oRMS} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left[2\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}$$

$$I_{oRMS} = \frac{V_{oRMS}}{R} = \frac{\frac{V_m}{2}\sqrt{\frac{1}{\pi}\left[2\pi - \alpha + \frac{\sin 2\alpha}{2}\right]}}{R}$$

$$V_{RMS} = V_s = \frac{V_m}{\sqrt{2}}$$

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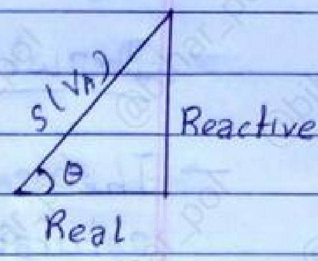
Note: $IPF = \frac{o/p\ power}{VA}$

Power Triangle



$S = P + JQ$

$$KW = KVA \cdot \underset{PF}{\cos\phi}$$

$$\cos\phi = \frac{W}{VA} = \frac{P_o}{V_A}$$

($\cos\phi$ → power factor)

$$\text{Input Power Factor} = \frac{P_o}{VA} = \frac{V_{OR} \cdot I_{OR}}{V_S \cdot I_S}$$

$$I.P.F = \frac{V_{OR} \cdot \cancel{I_{OR}}}{V_S \cdot \cancel{I_{OR}}} = \frac{V_{OR}}{V_S}$$

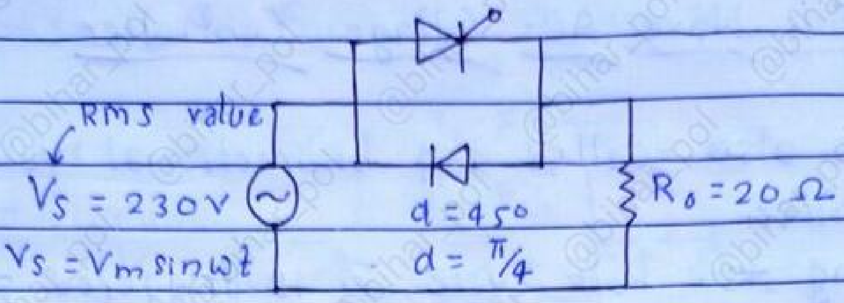
$$= \frac{V_m}{V_S \cdot 2}\left[\frac{1}{\pi}\left(2\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}$$

$$I.P.F = \frac{\cancel{V_m} \cdot \sqrt{2}}{2 \cdot \cancel{V_m}}\left[\frac{1}{\pi}\left(2\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}$$

$$\boxed{I.P.F. = \frac{1}{\sqrt{2}}\left[\frac{1}{\pi}\left(2\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{1/2}}$$

Numerical

Q A 1-ϕ half wave AC voltage controller feeds a load of $R = 20\Omega$ with input voltage of 230V, 50 Hz, firing angle of SCR is 45°. Determine (a) RMS value of output voltage
(b) Power delivered to the load
(c) Average input current



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

$V_{RMS} = 230V$, $V_s = \frac{V_m}{\sqrt{2}}$, $\therefore V_m = V_s\sqrt{2} = 230\sqrt{2}$

$V_{oRMS} = \frac{230\sqrt{2}}{2}\left[\frac{1}{\pi}\left(2\pi - \frac{\pi}{4} + \frac{\sin 90^\circ}{2}\right)\right]^{1/2}$

$V_{oRMS} = 224.68\ V$

ii) $I_{oRMS} = \frac{V_{oRMS}}{R} = \frac{224.68}{20} = 11.234\ A$

$P_{out} = I_{oRMS}^2 R$

$P_{out} = 11.23^2 \cdot 20$

$P_{out} = 2524.1\ W$

$IPF = \frac{P_o}{V_s A} = \frac{P_o}{V_s \cdot I_{oRMS}} = \frac{P_o}{V_s \cdot I_{sRMS}}$

$IPF = \frac{2524.1}{230 \times 11.23} = 0.97$ lagging

iii) $V_{oavg} = \frac{V_m}{2\pi}(\cos\alpha - 1) = \frac{230\sqrt{2}}{2\pi}\left|\cos 45 - 1\right|$

$= -15.17\ V$ ($\because$ area of −ve cycle is more)

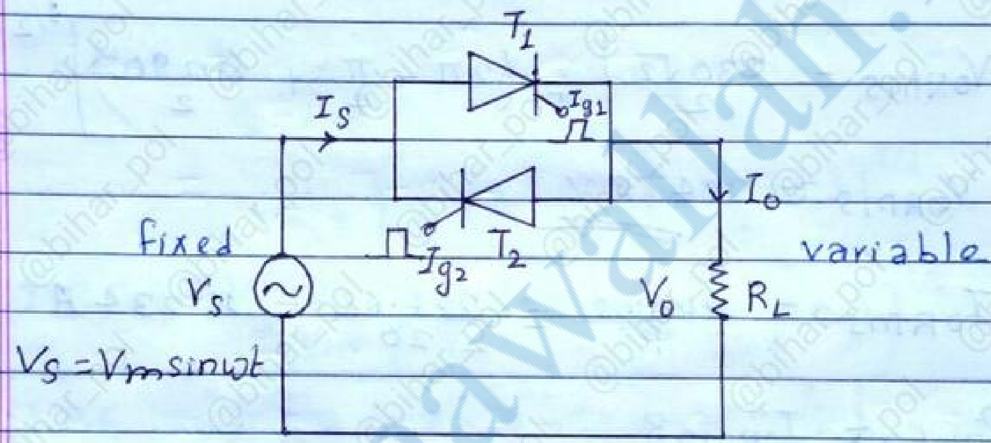
$I_{oavg} = \frac{V_{oavg}}{R} = \frac{15.17}{20}\ A$

1-ϕ Full Wave AC Voltage Controller

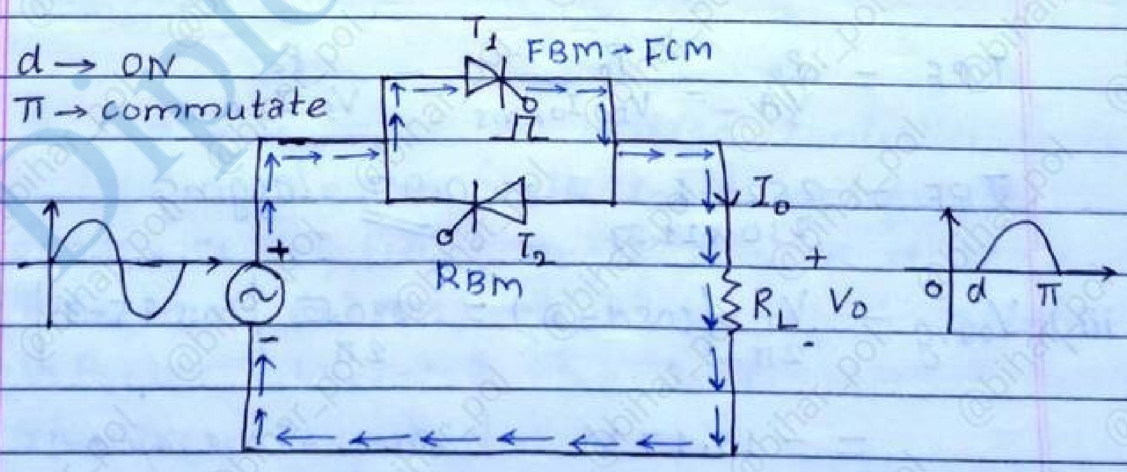
→ It is also called 1-ϕ bidirectional voltage controller.

→ During +ve half cycle, T_1 is triggered at firing angle α, It conducts (T_1) $\omega t \to \alpha$ to π for R-load (Resistive load).

→ During -ve half cycle, T_2 is triggered at $\omega t = \pi + \alpha$ and T_2 conducts at $\omega t = \pi + \alpha$ to 2π.



Mode-I → For α to π



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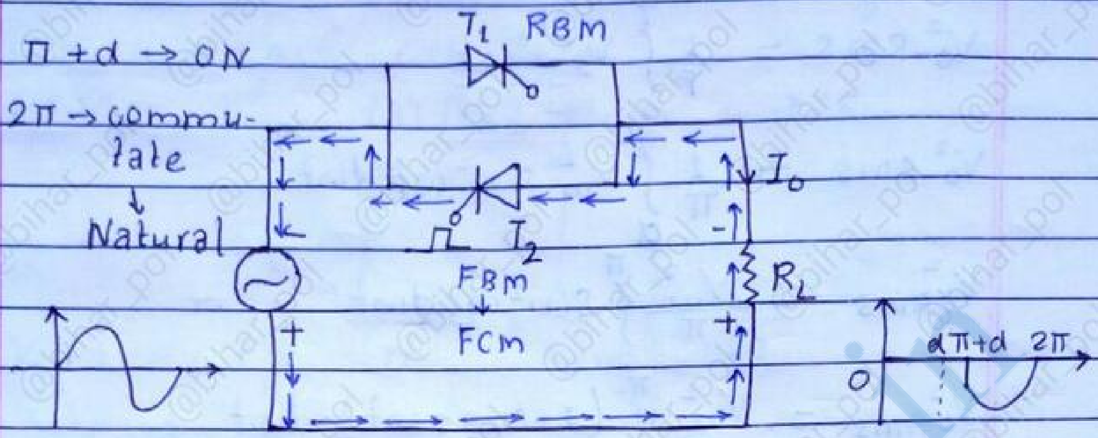
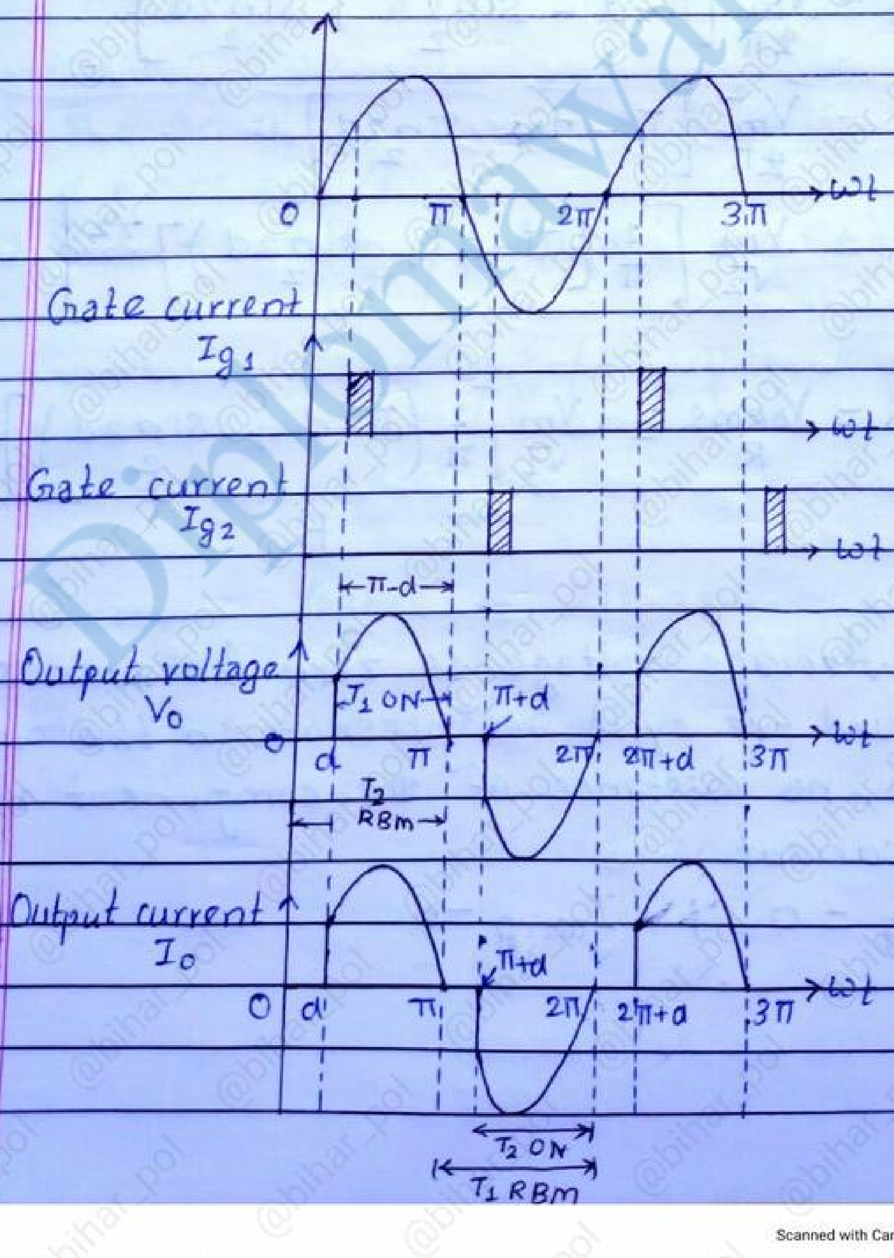
Mode-II → For π+α to 2π

π+α → ON
2π → commutate
↓
Natural



Waveform



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Rms output voltage

$$V_o^2 RMS = \frac{1}{T}\int_0^T V_o^2 \, d\omega t$$

$$V_o^2 RMS = \frac{1}{\pi}\int_\alpha^\pi V_m^2 \sin^2 \omega t \, d\omega t$$

$$V_{oRMS}^2 = \frac{V_m^2}{\pi}\int_\alpha^\pi \sin^2 \omega t \, d\omega t$$

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

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

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

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

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

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

Note: Average voltage is zero because some +ve and -ve cycle are present in the output. Hence, no existance of DC component voltage and current.

$V_{oavg} = 0$; $I_{oavg} = 0$

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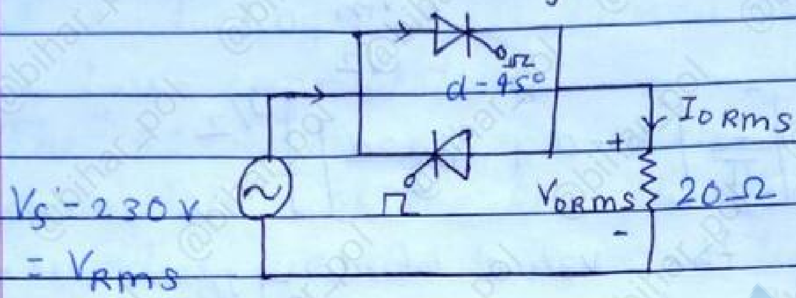
Q A 1-ϕ full wave voltage controller feeds a load of 20 Ω with an input voltage of 230V, 50Hz, $\alpha = 45°$. Calculate
(i) V_{RMS} (ii) load power & IPF

⇒



Given
$V_S = 230V \Rightarrow V_{RMS} = V_S = \frac{V_m}{\sqrt{2}} = 230$

$\Rightarrow V_m = 230\sqrt{2}$
$R = 20\,\Omega$
$\alpha = 45° = \pi/4$

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

$= \frac{230\sqrt{2}}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi - \frac{\pi}{4} + \frac{\sin 90}{2}\right)\right]^{1/2}$

$V_{ORMS} = 219.304V$

(ii) $I_{ORMS} = \frac{V_{ORMS}}{R} = \frac{219.304}{20} = 10.96 A$

Load power, $P_o = I_{ORMS}^2 \cdot R$

$= (10.96)^2 \cdot 20$

$= 2404.71 W$

Scanned with CamScanner

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Now, $IPF = \frac{P_o}{V_A} = \frac{V_{OR} \cdot I_{OR}}{V_S \cdot I_S} = \frac{V_{OR} \cdot I_{OR}}{V_S \cdot I_{OR}}$ $[\because I_S = I_{OR}]$

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

$$I.P.F = \left[\frac{1}{\pi}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]\right]^{1/2}$$

Putting the value of α

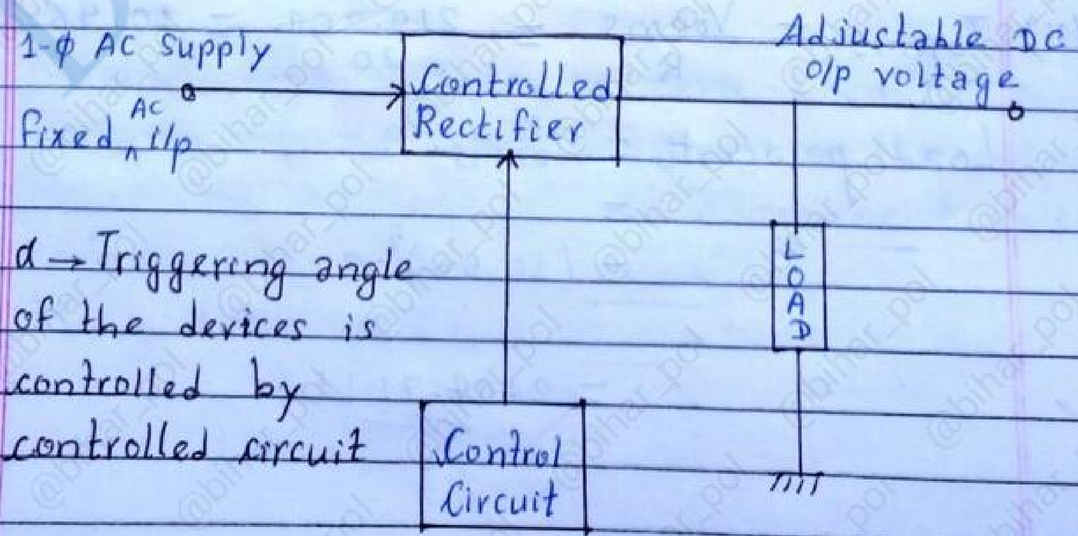
$$I.P.F = \left[\frac{1}{\pi}\left(\pi - \frac{\pi}{4} + \frac{\sin 90}{2}\right)\right]^{1/2}$$

$I.P.F = 0.9535$ lagging

Converter or Phase Controlled Converter or Controlled Rectifier

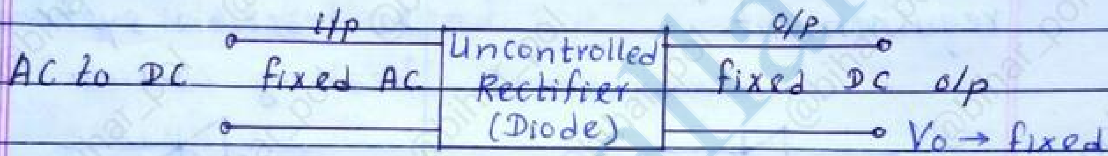
→ The rectifier circuit using SCR is known as controlled rectifier.

→ It is basically an AC to DC converter. The power transferred to the load is controlled by controlling the triggering angle of the devices, α.

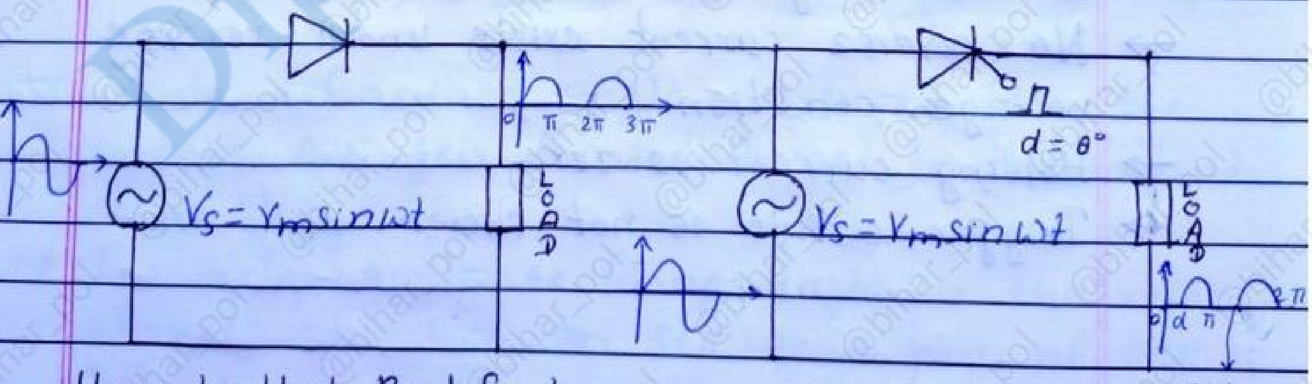


LCC → Line Commutated Converter

- → A conducting SCR is turned off due to natural or line commutation.
- → The AC mains voltage itself is used for commutation of the SCR. Therefore, these converters are also known as line commutated converter. (LCC).

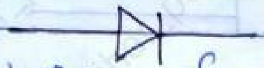
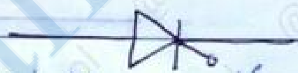


- → In a phase controlled rectifier, there is no need of extra commutation circuit.



Uncontrolled Rectified

Controlled Rectifier

Uncontrolled Rectifier	Controlled Rectifier
→ Only diode is used.	Only SCR or SCR & diode are used.
→ Trigger circuit is not required.	Trigger circuit is required.
→ Firing angle is fixed and always zero.	Variable firing angle.
→ It is used as low power rating.	It is used as medium or high power rating.
→ Constant DC power supply requirement.	DC motor speed control, DC traction system heating control.
 fixed AC fixed DC	 fixed AC Variable DC ↓α↑ ↓V_o↑

<u>To simplify the study of phase controlled rectifier, assumptions are as follows:</u>

→ SCR and diode are ideal switches i.e., there is no voltage across them.
→ No reverse current exists under reverse voltage condition.
→ Holding current is zero.
→ Trigger circuit is not shown.

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Necessity of Converter

→ They use phase control or phase angle control to vary the output voltage.
→ They are available in various circuit configuration.
→ They operate from 1-ϕ AC supply to 3-ϕ AC supply.
→ They use line commutation. So, no need of separate commutating circuit.
→ They use diode and SCR.

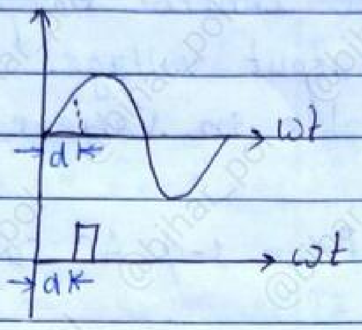
Applications

→ Steel rolling mills, paper mills, printing press and textile mills employing DC motor.
→ Traction system working on DC.
→ Electrochemical and electromettulergical process.
→ HVDC

Delay Angle or Firing Angle or Triggering Angle

→ It is defined as angle measured from the instant SCR gets forward biased to the instant it is triggered.
→ The delay angle or firing angle is the value of "ωt" at which an SCR or a pair of SCR is turned ON.
→ It is denoted by "α" and measured w.r.t. the zero crossing instant of the AC supply voltage.

→ The value of delay angle, α varies from 0° to 180° or from zero to π radians.



Classification

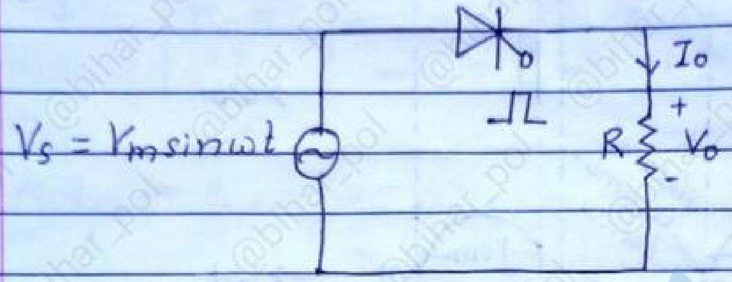
Converter → Controlled Rectifier → Line Commutated Converter

- 1-ϕ
  - HWCR (Half Wave Controlled Rectifier)
    - R-Load ✓
    - R-L Load
    - R-L Load with F.D
  - FWCR (Full Wave Controlled Rectifier)
    - Center tapped controlled rectifier (converter) (M_2-Configuration) numerical
      - R-load ✓
      - R-L Load
      - R-L Load with F.D.
    - Bridge Controller Converter (Rectifier)
      - R-Load
      - R-L Load ✓
      - R-L Load with F.D.
- 3-ϕ

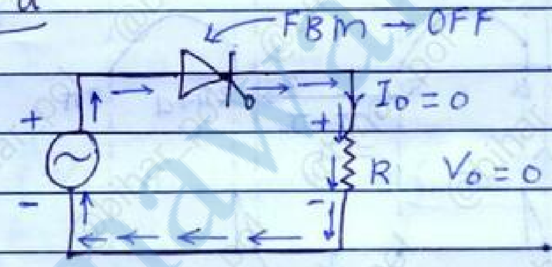
F.D → Freewheeling Diode

1-φ Half-Wave Converter (HWCR)
or
Half-Wave Controlled Rectifier with R-Load

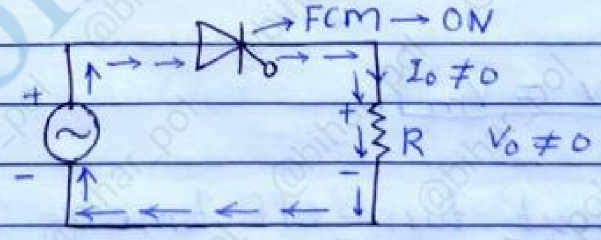
→ It is also called line-commutated converter with resistive load.



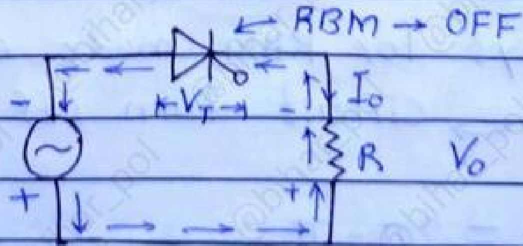
For $0 < \omega t < \alpha$



For $\alpha < \omega t < \pi$



For $\pi < \omega t < 2\pi$



$V_s - V_T + V_o = 0$

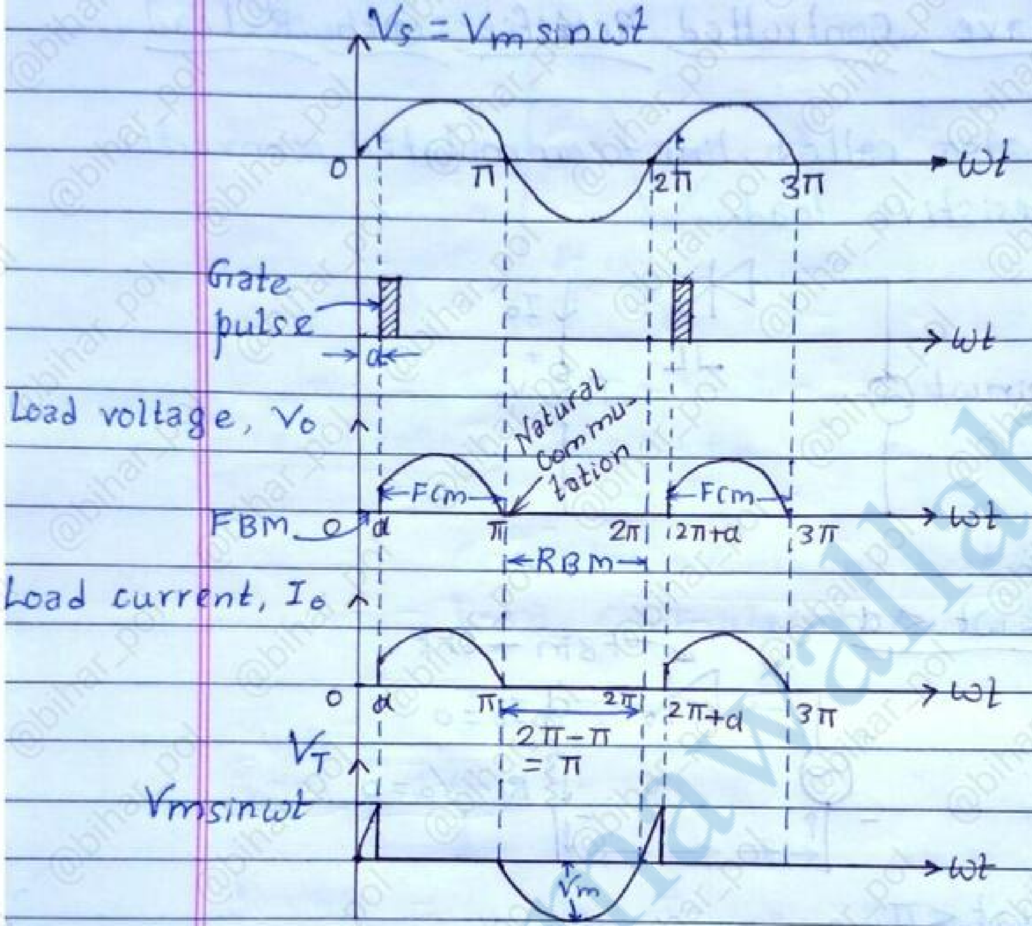
$V_s - V_T = 0$

$V_T = V_s = V_m \sin\omega t$

PIV → Peak Inverse Voltage

VT → Circuit turn-off time

Waveform



$$PIV = V_m$$

Circuit turn-off time

→ Always for RBM mode of SCR

ωt_c → circuit turn off time

$\omega t_c = 2\pi - \pi$

$\omega t_c = \pi$

$$t_c = \frac{\pi}{\omega}$$

Form Factor = 1 (In ideal case)
of pure dc

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Conduction Time

→ Always for ECM mode of SCR

γ = Conduction angle

$= \pi - \alpha$

$\omega t = \pi - \alpha$

$$t = \boxed{\frac{\pi - \alpha}{\omega}} \leftarrow \text{Conduction time}$$

i) **Output Average Voltage** → V_{avg} or V_{oDC}

$$V_{oavg} = \frac{1}{T}\int_0^T V_s \, d\omega t = \frac{1}{T}\int_0^T V_m \sin\omega t \, d\omega t$$

$$V_{oavg} = \frac{1}{2\pi}\int_0^{2\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{1}{2\pi}\left[\int_0^{\alpha} V_m \sin\omega t \, d\omega t + \int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t + \int_{\pi}^{2\pi} V_m \sin\omega t \, d\omega t\right]$$

$$V_{oavg} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t = \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$\boxed{V_{oavg} = \frac{V_m}{2\pi}\left[1 + \cos\alpha\right] = \frac{V_m}{2\pi}\left[\cos\alpha + 1\right]}$$

$$V_{oavg}\Big|_{\alpha = 0} = \frac{V_m}{\pi}$$

→ In the above eq^n, we can see that o/p voltage varies with α. If we change the value of α, then o/p voltage is changed.

$\alpha \uparrow \quad V_{avg} \downarrow$

$\alpha \rightarrow$ Firing angle (radian)

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ii) RMS o/p voltage $\rightarrow V^2_{oRms}$

$$V^2_{oRms} = \frac{1}{T}\int_0^T V_s^2 \, d\omega t = \frac{1}{2\pi}\int_0^{2\pi} V_s^2 \, d\omega t$$

$$V^2_{oRms} = \frac{1}{2\pi}\int_\alpha^\pi V_m^2 \sin^2\omega t \, d\omega t = \frac{V_m^2}{2\pi}\int_\alpha^\pi \frac{(1-\cos 2\omega t)}{2} d\omega t$$

$$= \frac{V_m^2}{4\pi}\left[\int_\alpha^\pi d\omega t - \int_\alpha^\pi \cos 2\omega t \, d\omega t\right]$$

$$V^2_{oRms} = \frac{V_m^2}{4\pi}\left[\left[\omega t\right]_\alpha^\pi - \left[\frac{\sin 2\omega t}{2}\right]_\alpha^\pi\right]$$

$$V^2_{oRms} = \frac{V_m^2}{4\pi}\left[\pi - \alpha - \frac{\sin 2\pi}{2} + \frac{\sin 2\alpha}{2}\right]$$

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

$$\boxed{V_{oRms} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}}$$

Form Factor

$$\frac{V_{oRms}}{V_{oAvg}} = \frac{\frac{V_m}{2\sqrt{\pi}}\left[\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]}{\frac{V_m}{2\pi}(1+\cos\alpha)}$$

$$\text{Form Factor} = \frac{\left[\frac{1}{\sqrt{\pi}}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]}{\frac{1}{\pi}(1+\cos\alpha)}$$

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Voltage Ripple Factor → VRF

$$RF = (FF^2 - 1)^{1/2} = \sqrt{(\text{Form Factor})^2 - 1}$$

→ Ideally, Ripple Factor should be zero and practically, it should be small as possible.

DC Power Output

→ The DC power output for a resistive load is given by

$$P_{LDC} = V_{LDC} \cdot I_{LDC} = V_{LDC} \cdot \frac{V_{LDC}}{R}$$

$$P_{LDC} = \frac{V_{LDC}^2}{R} \text{ or } P_{ODC} = \frac{V_{ODC}^2}{R} = \frac{V_{Oavg}^2}{R}$$

$$P_{LDC} = \frac{V_{Oavg}^2}{R}$$

AC Power Output → $P_{LAC} = P_{OAC}$

The AC output for a resistive load is given by

$$P_{LAC} = V_{LRMS} \cdot I_{LRMS} = V_{LRMS} \cdot \frac{V_{LRMS}}{R}$$

$$P_{LAC} = \frac{V_{LRMS}^2}{R} = \frac{V_{ORMS}^2}{R} = \frac{V_{LAC}^2}{R}$$

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Rectification Efficiency → η

The rectification efficiency or rectification ratio of a rectifier.

$$\eta = \frac{P_{LDC}}{P_{LAC}} = \frac{P_{ODC}}{P_{LAC}} = \frac{V_{LDC}^2/R}{V_{OAC}^2/R} = \frac{V_{0avg}^2}{V_{0Rms}^2}$$

Now, substituting the expression for V_{0avg} or V_{0Rms}.

$$\eta = \frac{\left(\frac{V_m}{2\pi}\right)^2 (1+\cos\alpha)^2}{\frac{V_m^2}{4\pi}\left(\pi-\alpha+\frac{\sin 2\alpha}{2}\right)}$$

$$\eta = \frac{(1+\cos\alpha)^2/\pi}{\pi-\alpha+\frac{\sin 2\alpha}{2}}$$

$$\boxed{\eta = \frac{(1+\cos\alpha)^2}{\pi\left(\pi-\alpha+\frac{\sin 2\alpha}{2}\right)}}$$

Peak Inverse Voltage (PIV) → SCR → R.B.M

$$PIV = V_m = \sqrt{2}\, V_s$$

Input Volt Amps

Input V_A = (Rms source voltage) x (Rms line current)

$$V_A = V_s \cdot I_{OR}$$

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Input Power Factor (IPF)

$$IPF = \frac{\text{Power delivered to load (AC)}}{\text{input } V_A}$$

$$IPF = \frac{V_{OR} \cdot I_{OR}}{V_S \cdot I_{OR}} = \frac{V_{OR}}{V_S} = \frac{\frac{V_m}{2\sqrt{\pi}}\left[\pi - d + \frac{\sin 2d}{2}\right]}{\frac{V_m}{\sqrt{2}}}$$

$$IPF = \frac{\sqrt{2}}{2\sqrt{\pi}}\left[\pi - d + \frac{\sin 2d}{2}\right]$$

$$\boxed{IPF = \frac{1}{\sqrt{2}\,\pi}\left[\pi - d + \frac{\sin 2d}{2}\right]}$$

Numerical

Q A single phase transformer with secondary voltage 230V, 50Hz, delivered power to load 10 Ω through a half wave controlled rectifier circuit for a firing angle delay of 60°. Determine rectification efficiency, form factor, PIV of SCR, voltage ripple factor, input power factor and tuf (Transformer Utilization Factor).

Given

$V_S = 230V$ (RMS value)

$R = 10\Omega$

$d = 60°$

Now, $V_m = V_S\sqrt{2}$

$\Rightarrow V_m = 230\sqrt{2}$

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Average load voltage (V_{oavg}) $= \frac{V_m}{2\pi}(1+\cos 60)$

$V_{oavg} = \frac{230\sqrt{2}}{2\pi}(1+\cos 60)$

$V_{oavg} = 77.64\ V$

The average load current is given by I_{oavg}

$I_{oavg} = \frac{V_{oavg}}{R} = \frac{77.64}{10} = 7.76\ A$

The RMS value of output voltage is given by

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

$= \frac{230\sqrt{2}}{2\sqrt{\pi}}\left[\pi - \frac{\pi}{3} + \frac{1}{2}\sin 120\right]$

$V_{oRMS} = 145.875V$

The RMS value of output current is given by

$I_{oRMS} = \frac{V_{oRMS}}{R} = \frac{145.875}{10}$

$I_{oRMS} = 14.875$

Output DC power is given by

$P_{oDC} = V_{oavg} \cdot I_{oavg} = 77.64 \times 7.76 = 602.8\ W$

Output AC power is given by

$P_{oAC} = V_{RMS} \cdot I_{oRMS} = 145.87 \times 14.87 = 2169.08\ W$

Rectification efficiency

$\eta = \frac{P_{DC}}{P_{oAC}} = \frac{602.8\ W}{2169.08\ W} = 0.2779 = 27.79\%$

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Form Factor, $FF = \frac{V_{oRms}}{V_{oavg}} = \frac{145.87}{77.64} = 1.879$

Voltage Ripple Factor, $VRF = \sqrt{FF^2 - 1} = \sqrt{1.879^2 - 1} = 1.5908$

The transformer utilization factor, TUF

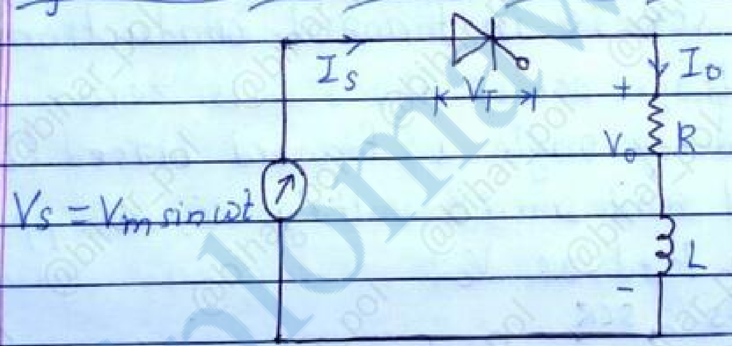
$TUF = \frac{V_o I_o}{V_s I_s} = \frac{V_{oavg}}{V_s I_s} = \frac{V_{oavg} \cdot I_{oavg}}{V_s \cdot I_{oRms}}$

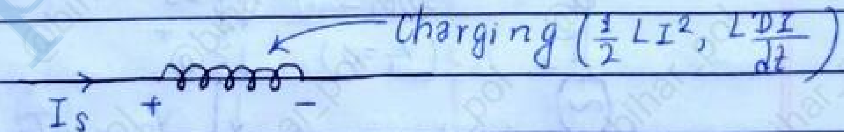
$TUF = \frac{77.64 \times 7.764}{230 \times 14.58} = 0.1796$

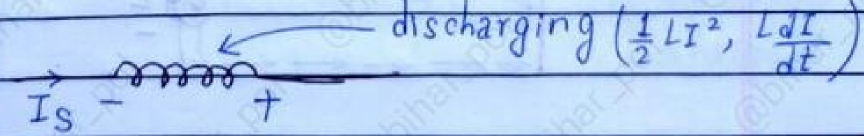
$PIV = V_m = \sqrt{2} V_s = \sqrt{2} \cdot 230 = 325.27 V$

1-φ Half Wave Controlled Rectifier with RL-load

Operation of HWCR with R-L load

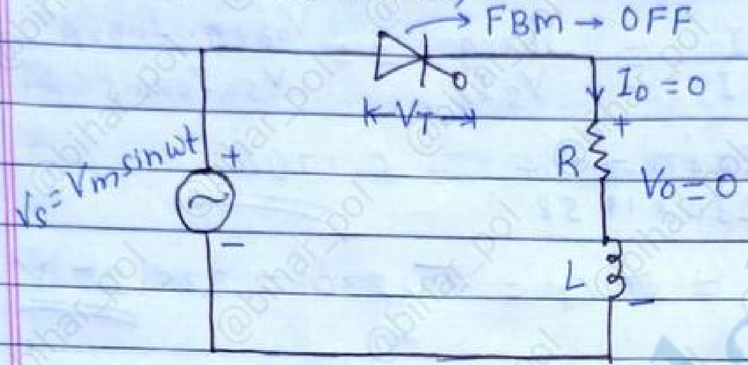






Mode I : $0 < \omega t < \alpha$

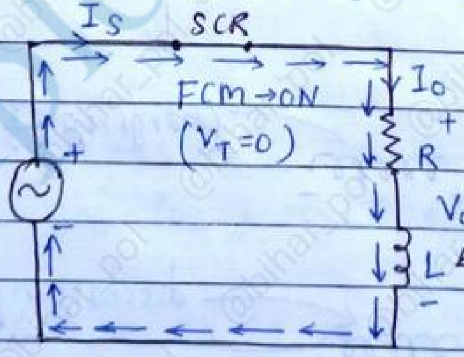
→ In this mode, SCR is in forward blocking mode (OFF state) such that the voltage across SCR ($V_L = V_s = V_m \sin \alpha$)



Load & source are disconnected

Mode II: $\alpha < \omega t < \pi$

→ Here, the SCR is in forward conduction mode, So, the voltage across the SCR is zero. At some delay angle α, forward biased (blocking) is triggered and source voltage V_s is appears across the load as V_0.



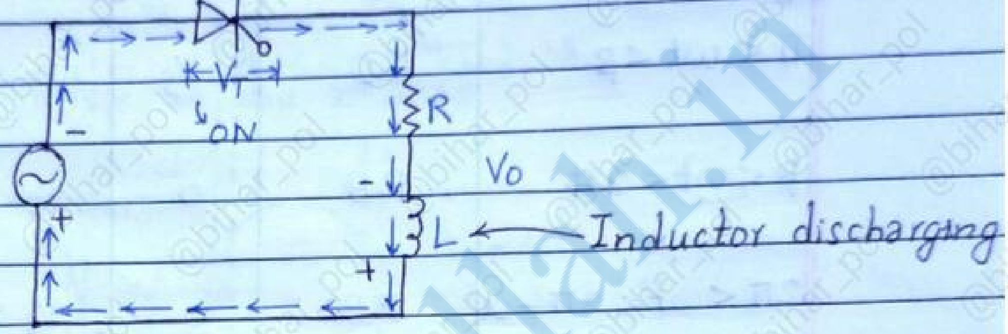
Inductor is in charging mode

Mode III: $\pi < \omega t < \beta$

Due to inductive load, the current increases gradually. Energy is stored in inductor during the instant (α to π).

At $\omega t = \pi$, the supply voltage is reversed, but the SCR keeps conducting.

→ It is due to the fact that the current through the inductor cannot be reduced to zero instantly, hence, due to energy stored in inductor current continues to flow upto β. ← extinction angle.



Mode IV : $\beta < \omega t < 2\pi$

At $\omega t = \beta$, the load current I_0 is zero and due to -ve supply voltage, thyristor turns off.
Here, SCR is in RBM mode and voltage across the SCR is $V_T - V_S$.

Mode V : $2\pi < \omega t < 2\pi + \alpha$

In this mode, SCR is in forward blocking mode and it is similar to mode 1.

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	SCR state	V_0	V_T	
$0 < \omega t < \alpha$	F.B	0	V_S	← Conduction angle
$\alpha < \omega t < \pi$	F.C	V_S	0	→ discharging
$\pi < \omega t < \beta$	F.C	V_S	0	← Ckt turn off time or PIV
$\beta < \omega t < 2\pi$	R.B	0	V_S	
$2\pi < \omega t < 2\pi + \alpha$	F.B.	0	V_S	

→ At some angle $\beta > \pi$, I_0 reduces to zero and SCR is turned off as it is already reverse biased.

→ At $\omega t = \beta$, $V_0 = 0$, $I_0 = 0$, SCR is turned OFF and at $\omega t = 2\pi + \alpha$, SCR is triggered again.

Note: SCR does not turn off at π because reverse voltage is applied at π but the value of anode current is not zero. So, SCR does not turn off and goes to β → extinction angle.

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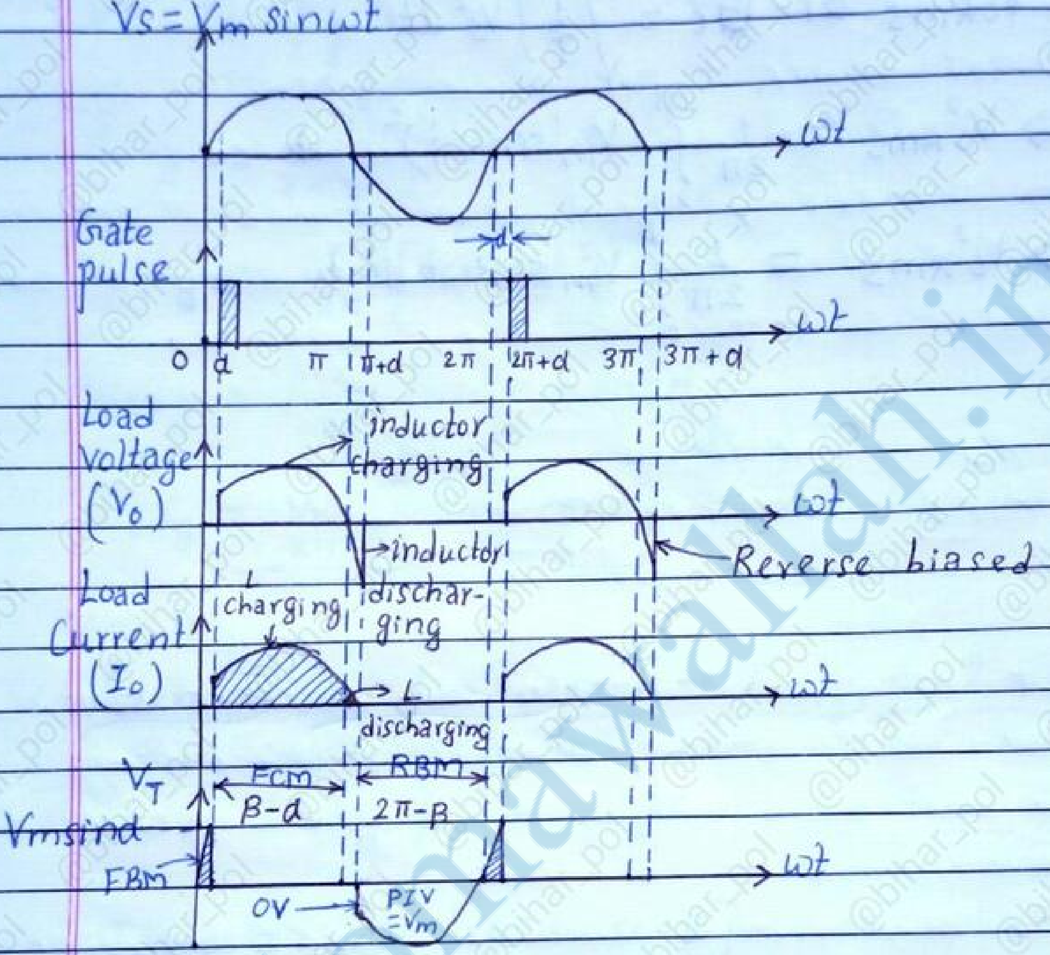
Waveform



$\gamma \rightarrow$ conduction angle $\rightarrow$ SCR conducts

$\gamma = \beta - d$

$\omega t_c \rightarrow$ Circuit Turn-off Time $\rightarrow$ SCR in RBM

$\omega t_c = 2\pi - \beta$

$\Rightarrow t_c = \dfrac{2\pi - \beta}{\omega}$ → Circuit-turn-off Time

→ Circuit turn off time is always determined when the SCR is in RBM.

$\alpha \rightarrow$ Firing angle
$\beta \rightarrow$ Extinction angle

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Average Load Voltage $\rightarrow V_{oavg}$ or V_{oDC}

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

$$V_{oavg} = \frac{1}{2\pi}\int_0^{2\pi} V_s \sin\omega t \, d\omega t$$

$$V_{oavg} = \frac{V_m}{2\pi}\left[-\cos\omega t\right]_0^{2\pi}$$

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

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

Average Load Current $\rightarrow I_{oavg}$ or I_{oDC}

$$I_{oavg} = \frac{V_{oavg}}{R} = \frac{V_{oDC}}{R}$$

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

Note: $\downarrow IPF = \frac{P_{out}\downarrow}{V_A} = \frac{P_{out}}{V_S I_S}$

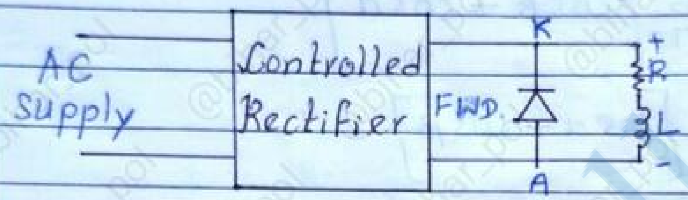
$P_{out}\downarrow \rightarrow$ -ve clip present in o/p voltage waveform

$P_{out}\downarrow$ $IPF\downarrow$

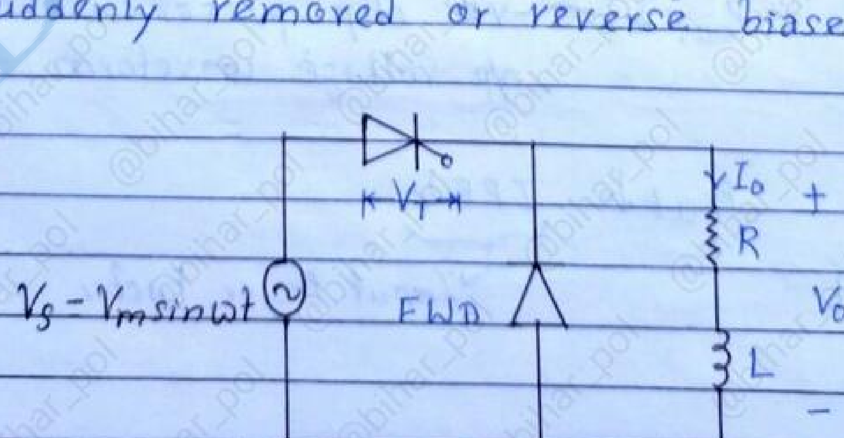
IPF $\rightarrow$ Input Power Factor

Advantages of Freewheeling Diode (FWD) in Controlled Rectifier

→ Input power factor is improved.
→ Load current waveform is improved.
→ As the energy stored in inductance is transferred to resistance during the freewheeling period, overall converter efficiency is improved.



→ It helps to maintain load current continuous such as in speed control of DC motor.
A continuous armature current improves the performance of DC motor.
→ FWD is known as Snubber diode, supressor diode, Clamp diode. This is a diode used to eliminate flyback which is nothing but a sudden voltage spike seen across an inductive load when its supply voltage is suddenly removed or reverse biased.



HWCR R-L Load with Freewheeling Diode

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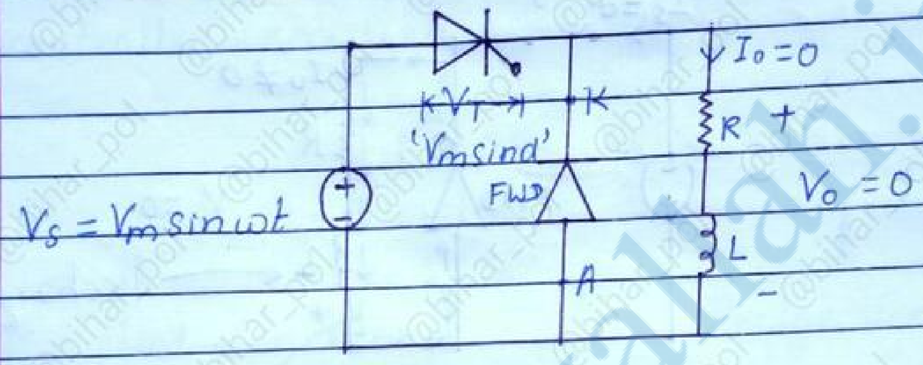
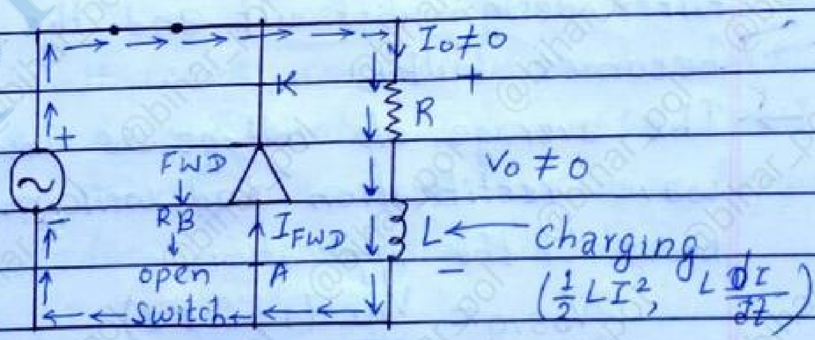
Case - I → $0 < \omega t < \alpha$ → getting pulse SCR

SCR → FBM → OFF
Load to source → disconnected
$V_0 = 0$, $I_0 = 0$
FWD → non-conducting mode



Case - II → $\alpha < \omega t < \pi$

SCR → FCM → $V_T = 0$, Load to source is connected
FWD → R.B → non-conducting mode → open ckt
$I_{FWD} = 0$



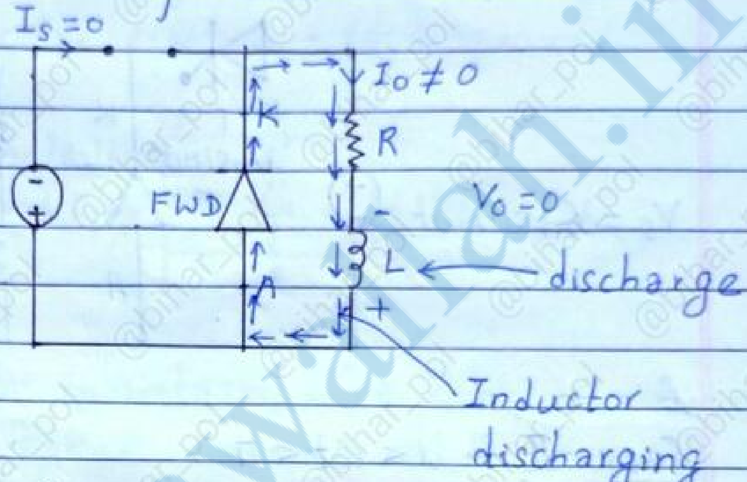
Scanned with CamScanner

Case-III → SCR → RBM → OFF

Case-III → $\pi < \omega t < 2\pi + \alpha$

SCR → RBM → OFF

FWD → conduct ← ideal → 0V
practical → 0.7V



Drawbacks of HWCR

→ The o/p voltage contains large ripple and the ripple frequency is low. This will make the filter design difficult and the filter becomes becomes bulky.

→ The average o/p voltage is low due to half wave rectification and will not be useful in most of the application.

$$V_{oavg} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

→ The input power factor is very poor.

→ The supply current is distorted and contains harmonic current.

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1-ϕ Full Wave Converter or FWCR

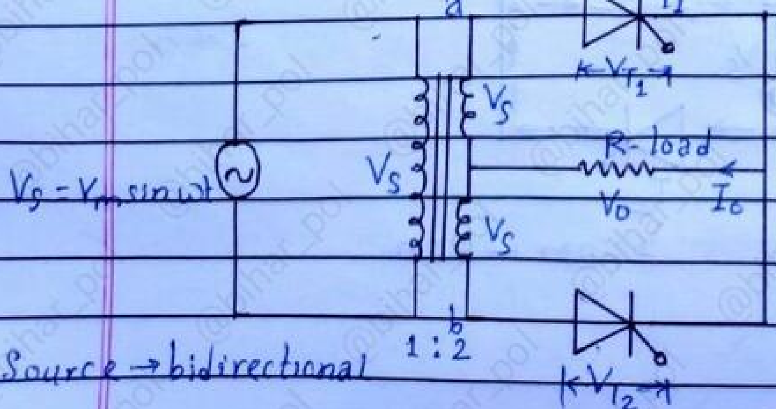
→ The output voltage appears across the load for a time period of full wave of input during both of the half cycle of input voltage. So, it is termed as single phase full wave controlled rectifier.

FWCR

- Mid-point Converter / Centertapped
  - → R - Load
  - → R-L Load
- Bridge Configuration
  - * R - Load
  - * R-L Load

1-ϕ Mid-point Full Wave Rectifier (Center-tapped)

→ In a 1-ϕ full wave controlled rectifier circuit with mid-point configuration, two SCRs and a single phase transformer with a center tapped secondary winding is employed (used).



Source → bidirectional

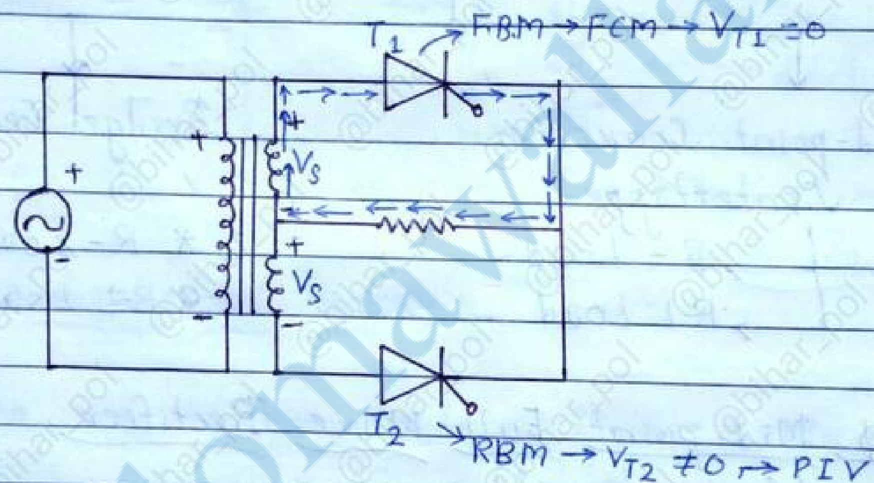
Load → unidirectional

→ This is mainly used in rectifier for low rating.

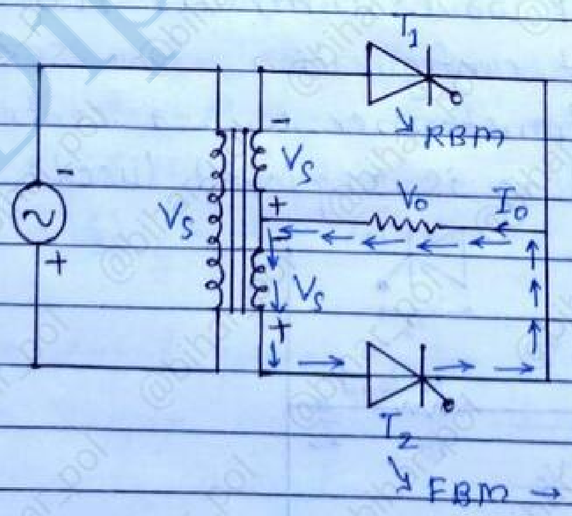
→ During the +ve half cycle of the AC supply where terminal (a) is +ve w.r.t. to n, thyristor T_1 is forward biased.

→ During the -ve half cycle of AC supply where terminal (b) is +ve with respect to (n) the thyristor T_2 is forward biased.

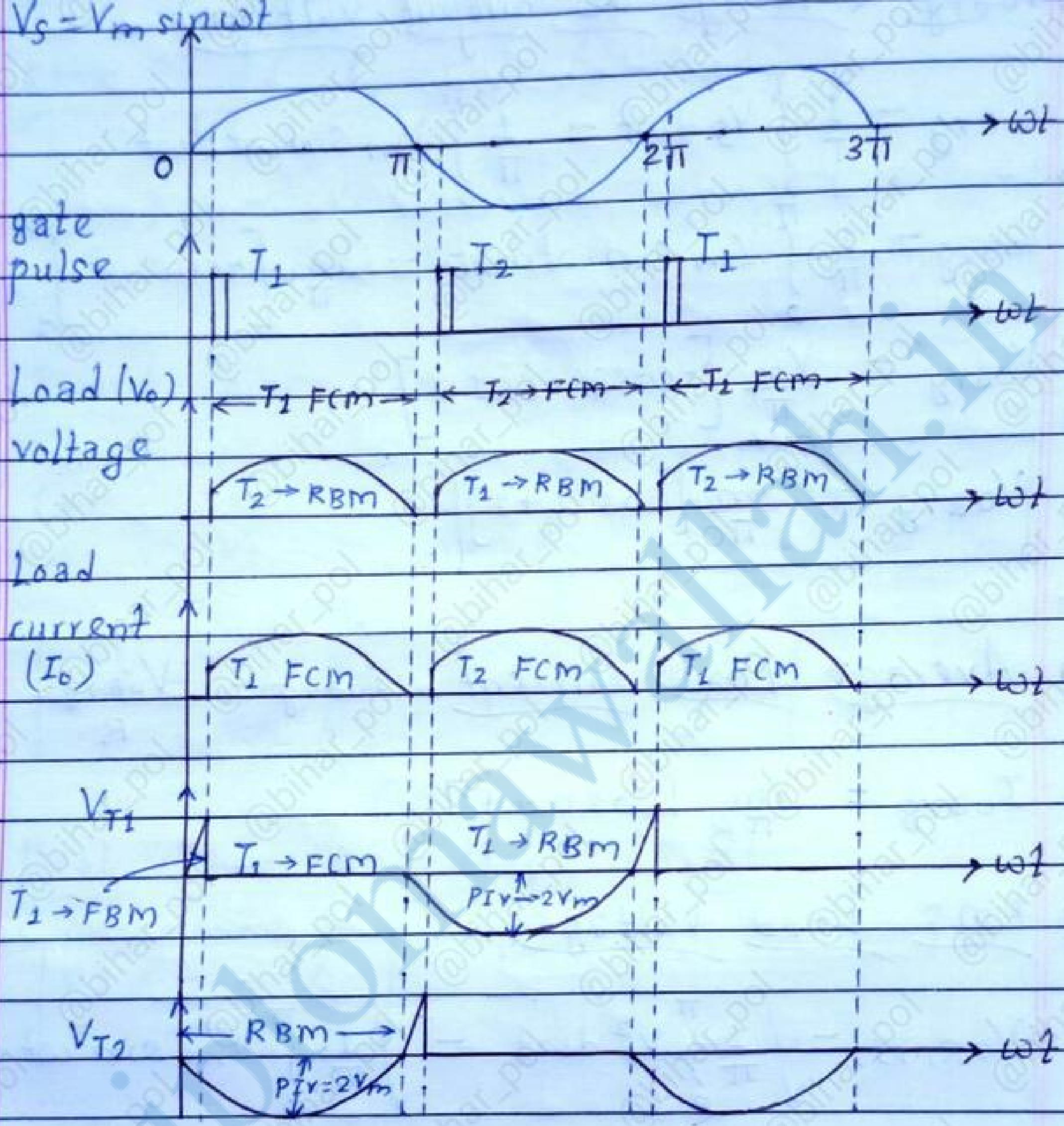
For +ve half cycle



For -ve half cycle



Waveform



Vs = Vm sinωt
0
π
2π
3π
ωt
gate pulse
T1
T2
T1
Load (V0) voltage
T1 FCM
T2 → FCM
T1 FCM
T2 → RBM
T1 → RBM
T2 → RBM
Load current (I0)
T1 FCM
T2 FCM
T1 FCM
VT1
T1 → FCM
T1 → RBM
PIV → 2Vm
T1 → FBM
VT2
RBM
PIV = 2Vm

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Performance Parameters

1) V_{oavg} (Average DC output voltage)

$$V_{oavg} = \frac{1}{T}\int_0^T V_s \, d\omega t = \frac{1}{\pi}\int_0^\pi V_m \sin\omega t \, d\omega t$$

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

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

$$\boxed{V_{oavg} = \frac{V_m}{\pi}\left[\cos\alpha + 1\right]}$$

2) Average Load Current; $I_{oavg} = \frac{V_{oavg}}{R}$

$$I_{oavg} = \frac{V_m}{\pi R}\left[\cos\alpha + 1\right]$$

3) RMS Load Voltage

$$V_{oRMS} = \sqrt{\frac{1}{\pi}\int_0^\pi V_s^2 \, d\omega t} = \sqrt{\frac{1}{\pi}\int_\alpha^\pi V_m^2 \sin^2\omega t \, d\omega t}$$

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$$V_{o\,RMS} = \frac{V_m}{\sqrt{2\pi}}\left[\pi - d + \frac{1}{2}\sin 2d\right]^{1/2}$$

4) RMS Load Current (I_{oRMS})

$$I_{oRMS} = \frac{V_{oRMS}}{R} = \frac{\frac{V_m}{\sqrt{2\pi}}\left[\pi - d + \frac{1}{2}\sin 2d\right]^{1/2}}{R}$$

5) Input Power Factor (IPF)

$$IPF = \frac{V_{oR}}{V_s} = \frac{\frac{V_m}{\sqrt{2\pi}}\left[\pi - d + \frac{\sin 2d}{2}\right]^{1/2}}{V_m/\sqrt{2}}$$

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

6) Peak Inverse Voltage (PIV)

$$PIV = 2V_m$$

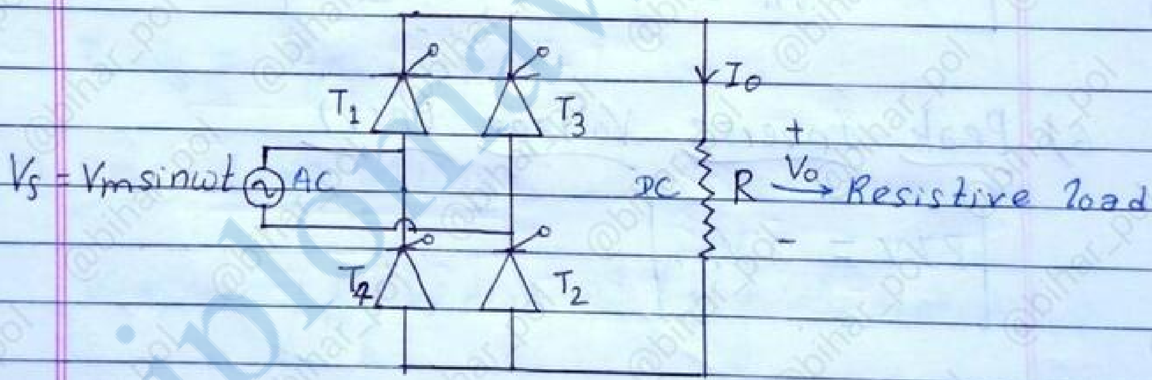
1-φ Full Wave Controlled Bridge Rectifier

or, Operation of full wave bridge with resistive load (R-Load)

→ A 1-φ full bridge converter consists of four SCR T_1, T_2, T_3, T_4 connected in a bridge configuration driving a resistive load.

→ These four SCRs can be divided into into two group each consisting of two SCRs.

→ The full converter circuit being operated on 1-φ AC mains as shown in fig. below.



It can be operated in following modes:

Mode I → $0 < \omega t < \alpha$

→ In this mode, the SCRs T_1 & T_2 are in forward blocking mode or o/p voltage $V_0 = 0V$.

T_3, T_4 → RBM

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Mode II → $\alpha < \omega t < \pi$

→ Here, SCRs T_1 & T_2 are in conduction mode such that $V_0 = V_S$.

$T_3, T_4 \rightarrow$ RBM

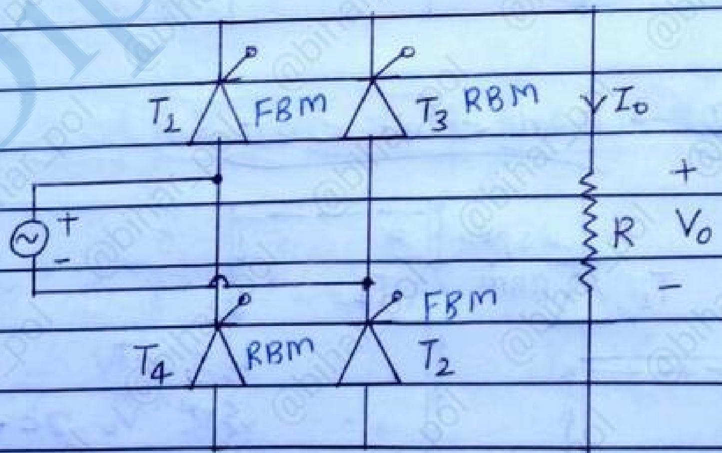
Mode III → $\pi < \omega t < \pi + \alpha$

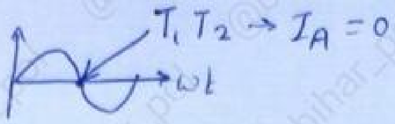
→ The thyristors T_3 & T_4 are in FBM mode and the remaining two SCRs (T_1 & T_2) are in RBM mode. So, o/p voltage = $V_0 = 0V$.

Mode IV → $\pi + \alpha < \omega t < 2\pi$

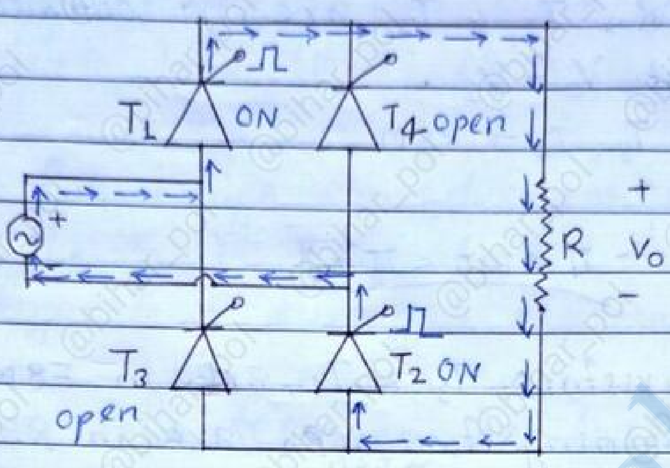
→ During this interval, thyristors T_1 & T_2 remains (RBM) off. Thyristors T_3 & T_4 are in forward conduction mode. So, o/p voltage $V_0 = V_S$.

Mode I → $0 < \omega t < \alpha$

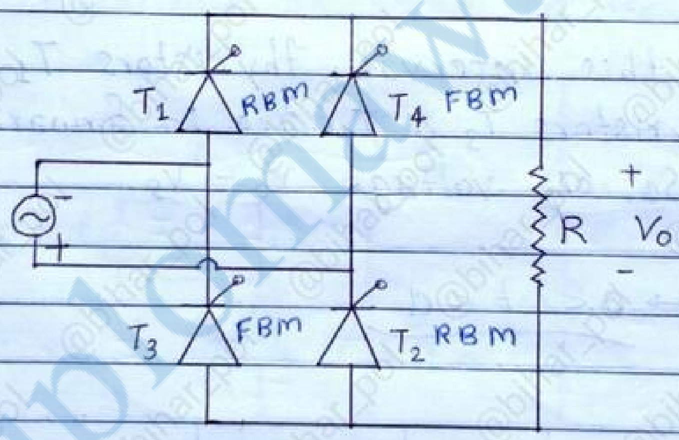




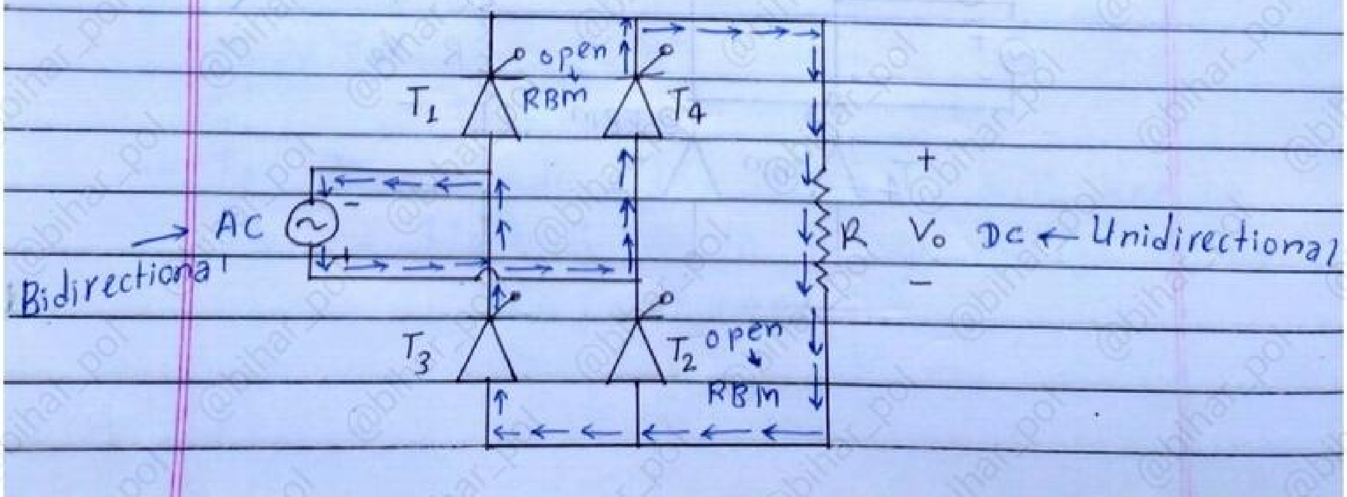
Mode II → $\alpha < \omega t < \pi$



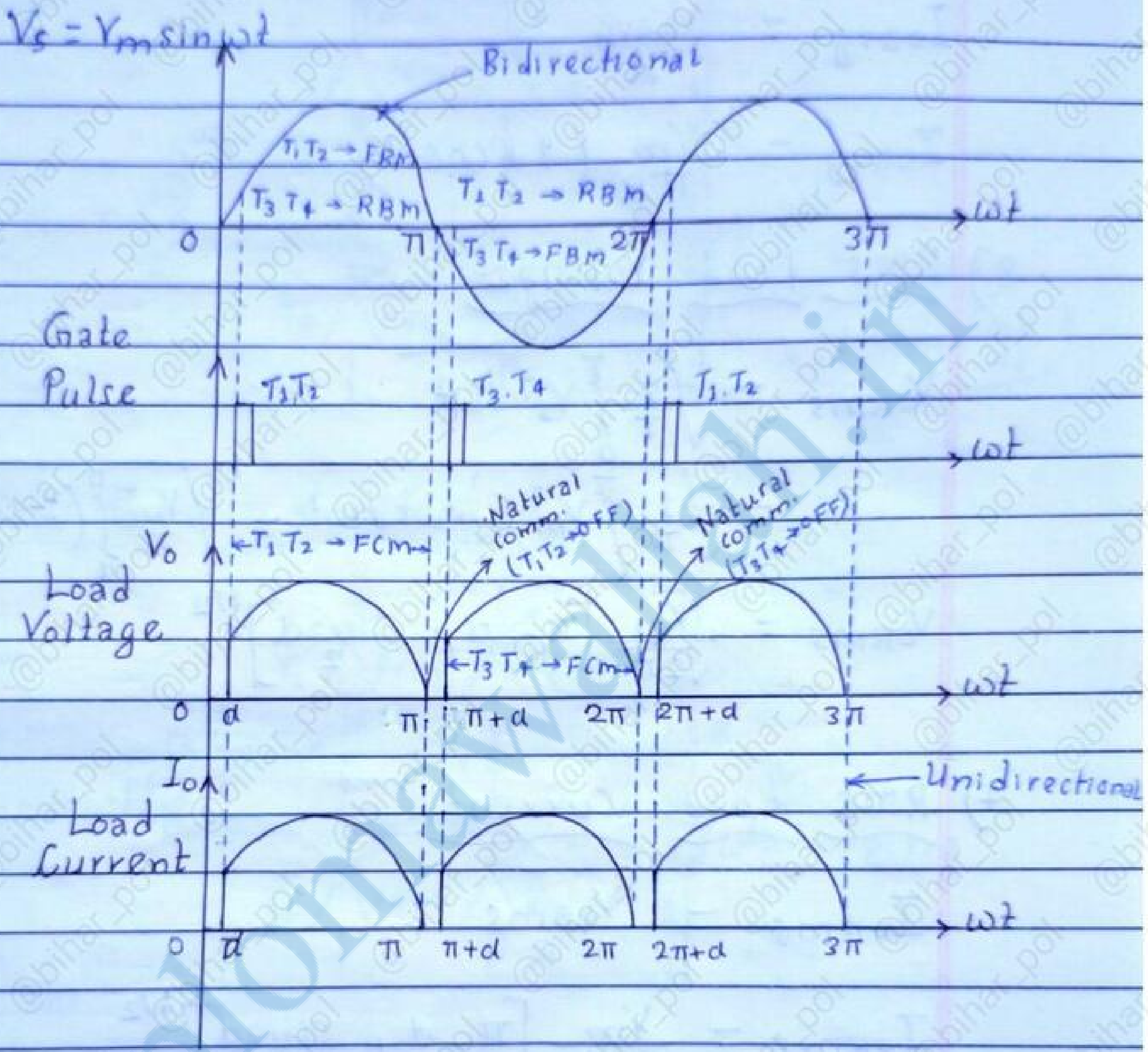
Mode III → $\pi < \omega t < \pi + \alpha$



Mode IV → $\pi + \alpha < \omega t < 2\pi$



Waveform



1) V_{0avg} or V_{DC}

$$V_{0avg} = \frac{1}{T}\int_0^T V_s \, d\omega t = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$$

$$V_{0avg} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

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

$$\boxed{V_{0avg} = \frac{V_m}{\pi}(1+\cos\alpha)}$$

$\downarrow\uparrow V_{0avg} \propto \alpha \downarrow\uparrow$

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2) Average Load Current

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

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

3) RMS Load Voltage

$$V_{oRMS} = \sqrt{\frac{1}{T}\int_0^T V_s^2 \, d\omega t}$$

$$= \sqrt{\frac{1}{\pi}\int_\alpha^\pi V_m^2 \sin^2\omega t \, d\omega t} = \sqrt{\frac{V_m^2}{\pi}\int_\alpha^\pi \left(\frac{1-\cos 2\omega t}{2}\right) d\omega t}$$

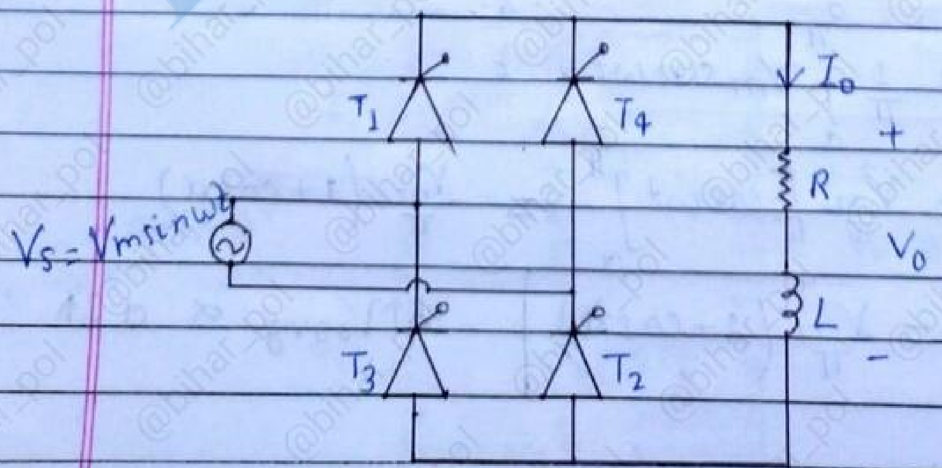
$$V_{oRMS} = \frac{V_m}{\sqrt{2\pi}}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]^{1/2}$$

4) RMS Load Current

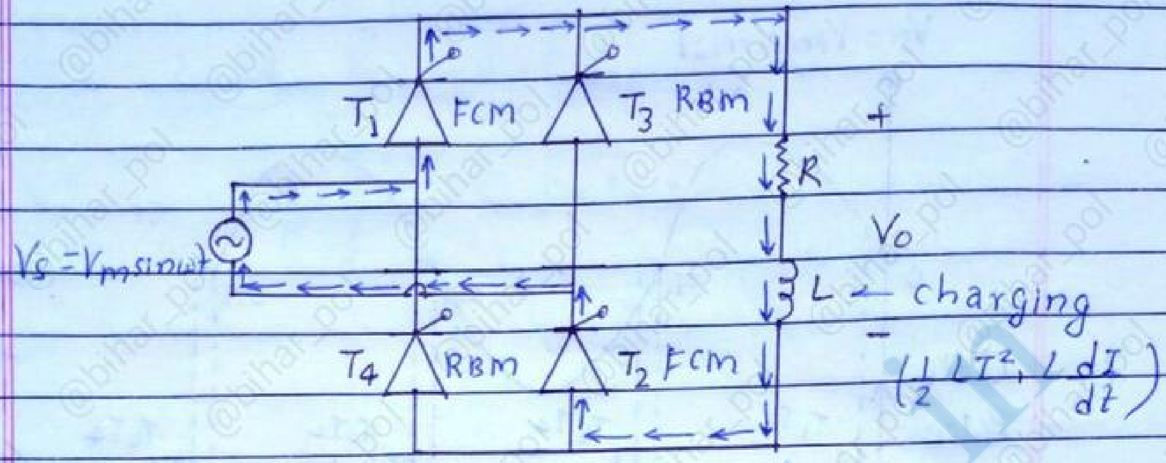
$$I_{oRMS} = \frac{V_{oRMS}}{R}$$

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

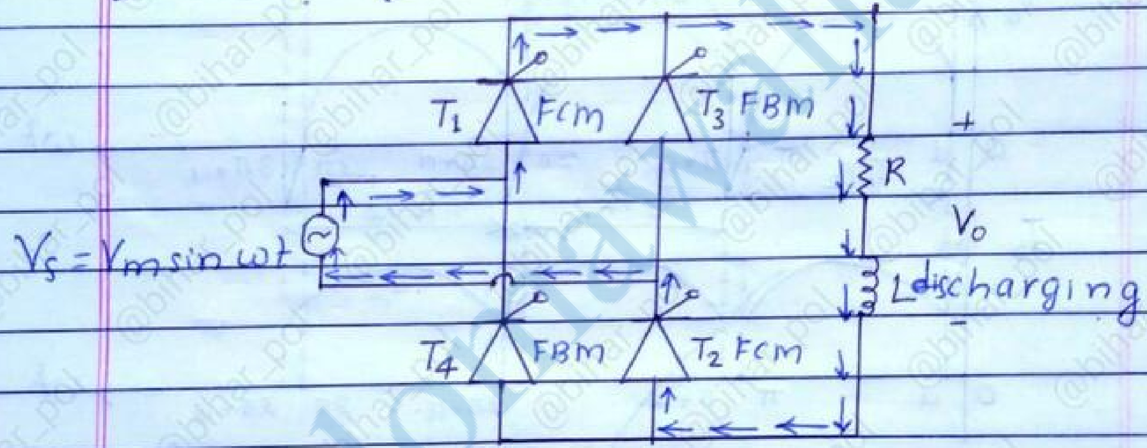
Fully Controlled Bridge with R-L Load



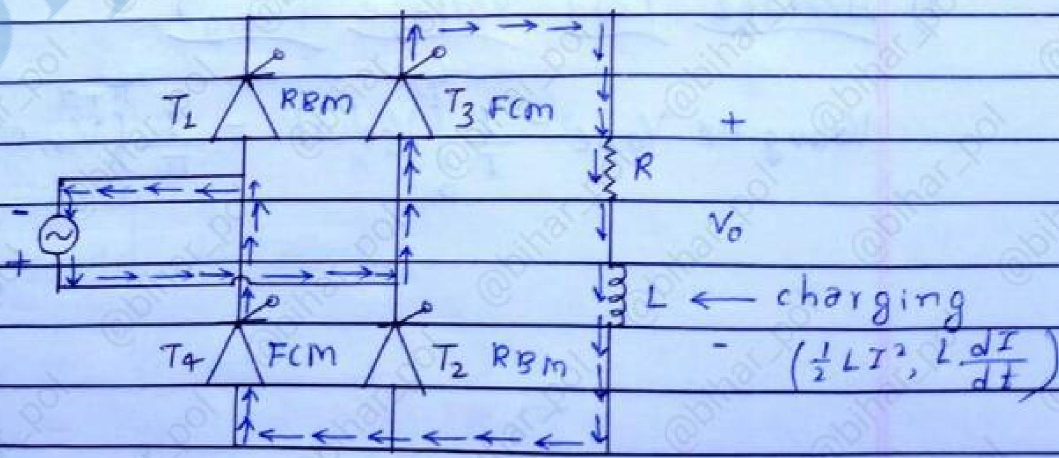
Mode I → $\alpha < \omega t < \pi$



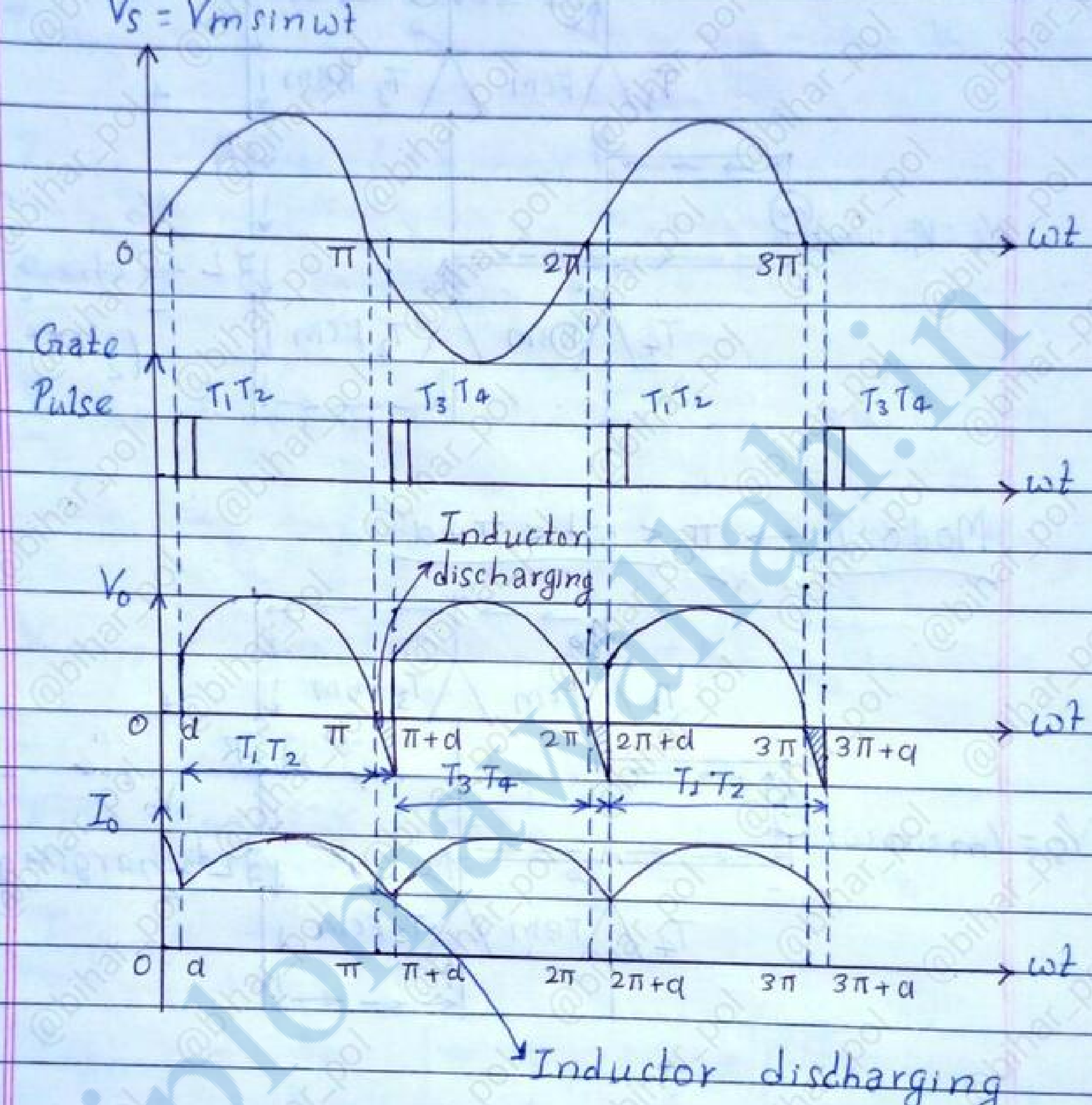
Mode II → $\pi < \omega t < \pi + \alpha$



Mode III → $\pi + \alpha < \omega t < 2\pi$



Waveform



1) Average Load Voltage (V_{oavg})

$$V_{oavg} \text{ or } V_{oDC} = \frac{1}{T}\int_0^T V_s \, d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d\omega t$$

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

$$V_{oRMS} = \frac{V_m}{\sqrt{2}}$$

3) Average Load Current

$$I_{oavg} = \frac{V_{oavg}}{R} = \frac{2V_m}{R\pi}\cos\alpha$$

4) Rms Load Current

$$I_{oRMS} = \frac{V_{oRMS}}{R} = \frac{V_m}{R\sqrt{2}}$$

Low freq. → high ripple → big filter

High freq. → low ripple → small filter

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1-ϕ Converter	3-ϕ Converter
→ These are mainly used low power DC load.	3-ϕ AC to DC converters are preferred to high power DC load.
→ Center-tapped converter requires two SCRs and bridge converter requires 4 SCRs.	Center-tapped converter requires 6 SCRs and bridge converter also requires 6-SCRs.
→ It is less expensive.	It is more expensive.
→ It requires simple triggering circuit.	It requires complex triggering circuit.

	1-ϕ Half Wave	1-ϕ Center-tapped	1-ϕ Bridge type
No. of SCR	1	2	4
TRF necessary	Not	Necessary	Not
PIV	V_m	$2V_m$	V_m
η	40.6%	81.2 %	81.2 %