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JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR

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B. Tech III-I Sem. (EEE)	3	1	0	3

15A02503 POWER ELECTRONICS

Course **Objectives:**

The objectives of the course are to make the student learn about

- the basic power semiconductor switching devices and their principles of operation.
- the various power conversion methods, controlling and designing of power converters.
- the applications of Power electronic conversion to domestic, industrial, aerospace, commercial and utility systems etc.
- the equipment used for DC to AC, AC to DC, DC to Variable DC, and AC to Variable frequency AC conversions.

UNIT I
POWER SEMI CONDUCTOR DEVICES

Semiconductor Power Diodes, Thyristors – Silicon Controlled Rectifiers (SCR's) – TRIACs, GTOs - Characteristics and Principles of Operation and other Thyristors – Classification of Switching Devices Based on Frequency and Power Handling Capacity- BJT – Power Transistor - Power MOSFET – Power IGBT — Basic Theory of Operation of SCR – Static Characteristics – Turn On and Turn Off Methods- Dynamic Characteristics of SCR - Two Transistor Analogy – Triggering Circuits— Series and Parallel Connections of SCR's – Snubber Circuits – Specifications and Ratings of SCR's, BJT, IGBT.

UNIT II
PHASE CONTROLLED CONVERTERS

Phase Control Technique – Single Phase Line Commutated Converters – Mid Point and Bridge Connections – Half Controlled Converters, Fully Controlled Converters with Resistive, RL Loads and RLE Load– Derivation of Average Load Voltage and Current – Line Commutated Inverters -Active and Reactive Power Inputs to the Converters without and with Free Wheeling Diode, Effect of Source Inductance – Numerical Problems. Three Phase Line Commutated Converters – Three Pulse and Six Pulse Converters – Mid Point and Bridge Connections - Average Load Voltage with R and RL Loads – Effect of Source Inductance–Dual **Converters (Both Single Phase and Three Phase) - Waveforms –Numerical Problems.**

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UNIT III

CHOPPERS AND REGULATORS

Commutation Circuits – Time Ratio Control and Current Limit Control Strategies – Step Down and Step up Choppers Derivation of Load Voltage and Currents with R, RL and RLE Loads- Step Up Chopper – Load Voltage Expression– Problems. Study of Buck, Boost and Buck-Boost regulators, buck regulator. e.g. TPS54160, hysteretic buck regulator e.g.LM3475, Switching Regulator and characteristics of standard regulator ICs – TPS40200, TPS40210, TPS 7A4901, TPS7A8300

UNIT IV

INVERTERS

Inverters – Single Phase Inverter – Basic Series Inverter – Basic Parallel Capacitor Inverter Bridge Inverter – Waveforms – Simple Forced Commutation Circuits for Bridge Inverters – Single Phase Half and Full Bridge Inverters-Pulse Width Modulation Control-Harmonic Reduction Techniques-Voltage Control Techniques for Inverters – Numerical Problems, Three Phase VSI in 120^0 And 180^0 Modes of Conduction.

UNIT V

AC VOLTAGE CONTROLLERS & CYCLO CONVERTERS

AC Voltage Controllers – Single Phase Two SCR's in Anti Parallel – With R and RL Loads – Modes of Operation of TRIAC – TRIAC with R and RL Loads – Derivation of RMS Load Voltage, Current and Power Factor Wave Forms – Firing Circuits -Numerical Problems - Thyristor Controlled Reactors; Switched Capacitor Networks.

Cyclo Converters – Single Phase Mid Point Cycloconverters with Resistive and Inductive Load (Principle of Operation only) – Bridge Configuration of Single Phase Cycloconverter (Principle of Operation only) – Waveforms

Course **Outcomes:**

After going through this course, the student acquires knowledge about:

- Basic operating principles of power semiconductor switching devices.
- the operation of power electronic converters, choppers, inverters, AC voltage controllers, and cycloconverters, and their control.
- How to apply the learnt principles and methods to practical applications.

TEXT BOOKS:

1. Power Electronics, M. D. Singh and K. B. Khanchandani, Mc Graw Hill Education (India) Pvt. Ltd., 2nd Edition, 2007, 23rd Reprint 2015.
2. Power Electronics: Circuits, Devices and Applications, Muhammad H. Rashid, Pearson, 3rd Edition, 2014, 2nd Impression 2015.

Power Electronics :-

→ The Study of Electronic circuits to control and convert the Electric power.

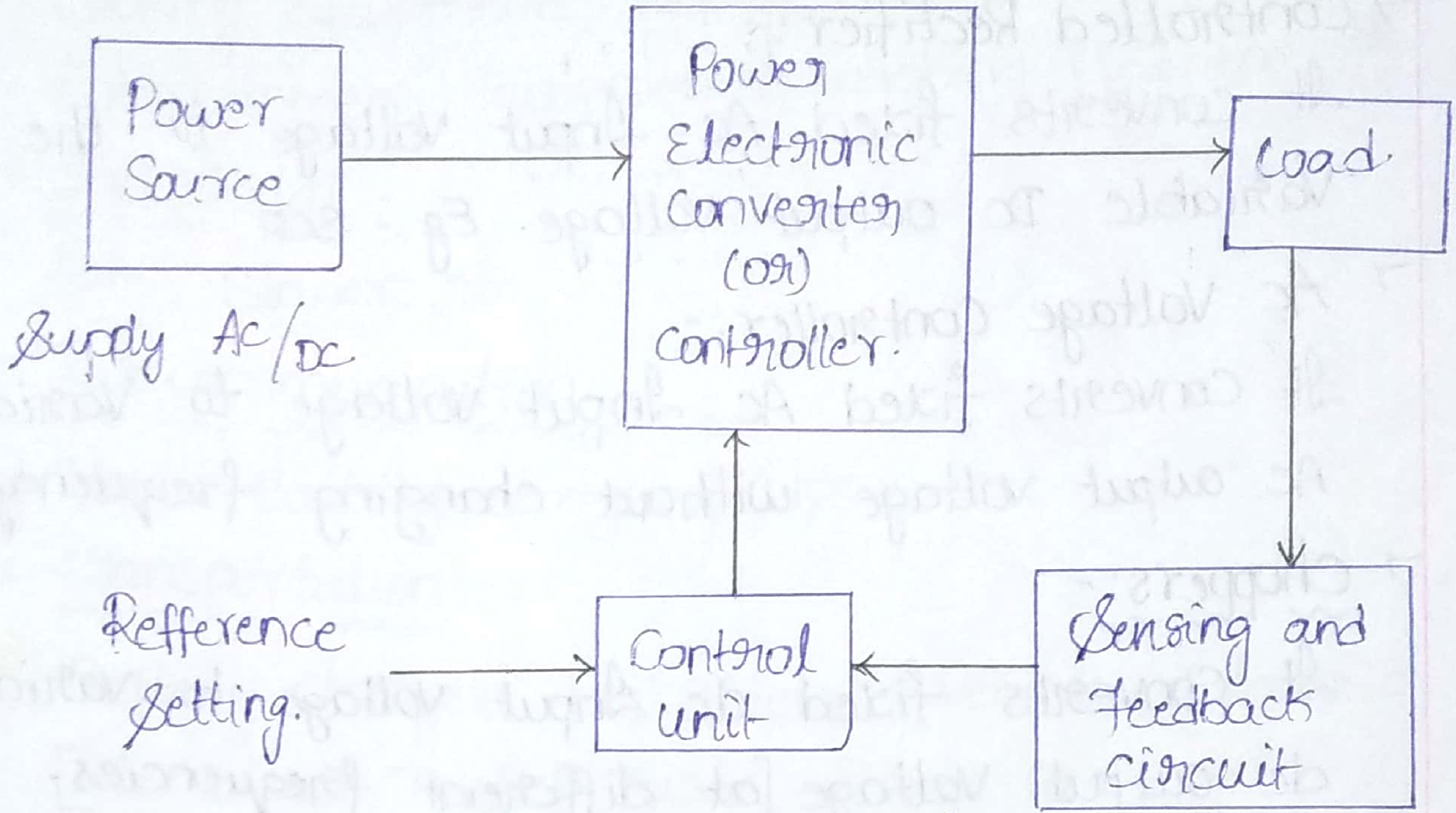


fig:- Power Electronic System.

Types of power Electronic Converters:-

→ Ac - Dc Converter.
  - → uncontrolled Rectifier.
  - → Controlled Rectifier.

→ Ac - Ac converter
  - → Ac Voltage controllers.
  - → Cycloconverters.

→ Dc- Dc Converter - chopper.

→ Dc- Ac Converter - Inverter.

→ Uncontrolled Rectifier:-

→ Uncontrolled Rectifier Converts fixed Ac Input Voltage to fixed DC output Voltage Eg:- Diode

→ Controlled Rectifier:-

It converts fixed Ac Input Voltage to the Variable Dc output Voltage. Eg:- SCR.

→ Ac Voltage Controller:-

It Converts fixed Ac Input Voltage to Variable Ac output Voltage without changing frequency.

→ Choppers:-

It Converts fixed dc Input Voltage to Variable dc output Voltage [at different frequencies]

→ Inverters:-

It Converts fixed DC Input Voltage to the Variable ac output voltage.

→ CycloConverters:-

It converts fixed Ac Input Voltage to the Variable Ac output voltage at different frequencies.

→ Advantages:-

(1) High Efficiency due to low losses.

(2) Installation cost due to small size

(3) Long Life & less maintenance due to the absence of Rotating parts.

(4) High Reliability & flexibility in operation.

→ Applications of power Electronics:-

→ Domestic Applications:-

Cooking Equipments, Refrigerators, Cooking equipments, Entertainment Equipments, washing Machine, etc...

→ Industrial:-

fans, Blowers, etc..,

→ Telecommunication:-

Mobile Battery chargers, UPS.

→ Transportation:-

Battery chargers for Electric vehicles, Electric locomotives, Trolley Buses, Street cars, etc...

→ Utility System Applications:-

HVDC Systems, Solar and wind plants, etc....

→ Commercial:-

Personal Laptops, Mobiles, etc...

→ Disadvantages:-

(1) Thyristor Controlled converters have low overloading capacity.

(2) power semiconductor devices have tendency to generate harmonics in supply system as well as in Load circuit.

Power Semi Conductor Devices.

- Power Semiconductor Devices.
  - Power Diode
  - Power Transistor
    - Power BJT'S
    - Power MOSFET'S
    - Power IGBT'S.
  - Thyristors
    - SCR.
    - TRIAC
    - DIAC
    - RCT.
    - GTO.
    - SCS.
    - SUS.
    - PUT
    - LASCR, etc...

→ Power Diode is an uncontrolled device, because their Turn on and Turn off are not under the Control.

→ Power Transistor is a controlled device, because their Turn and Turn off are under the control. Transistor is turned on by applying a current signal to it's base terminal and it will remains into on State untill current Signal is present. Transistor is turned off by removing current Signal from base terminal.

→ Thyristor is a control device, because it is turned on by applying (Gate pulse between) low Voltage Short duration between

once Thyristor Turned on, Gate looses its Control and Thyristor will remains into ON state. Thyristor will turn off, when the anode current flowing through the thyristor reduced to zero, f or certain current level called Holding current, force to th by means of External circuit (commutation circuit).

→ Thyristor is the name given to family of the power semiconductor devices having common p-n-p-n structure.

→ The Name thyristor is derived from the capital letters of THYRotron and tranSISTOR.

→ Because, in characteristics point of view, it is similar to Thyroton and in construction point of view it is similar to Transistor.

→ SCR :-

→ Construction :-

→ SCR is the first silicon based Power Semi-Conductor switching device developed by the Bell Laboratories in 1957.

→ SCR is the most popularly used device, mostly in industries because of following advantages compared to other family devices :-

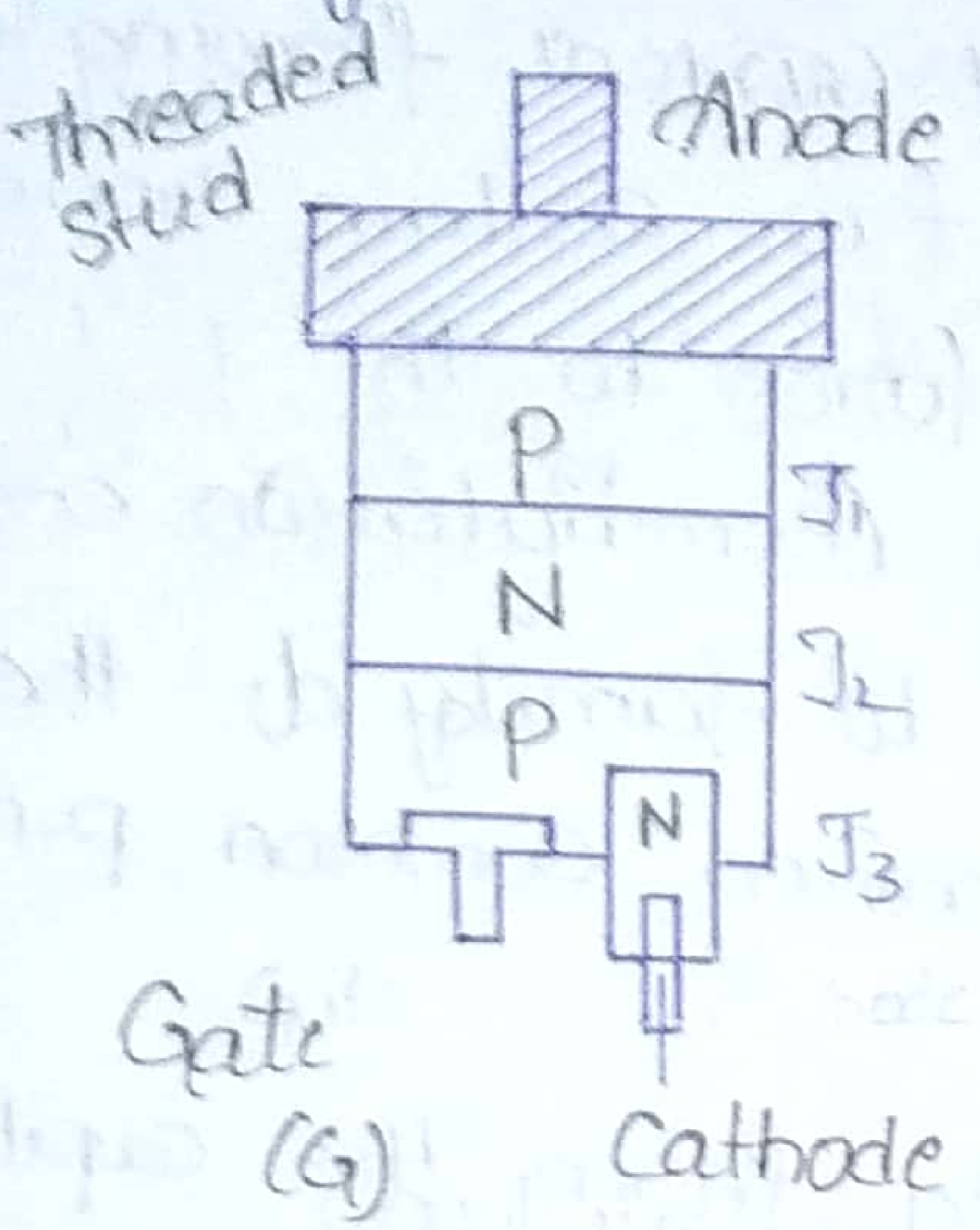
(1) Compact in size.

(2) High Reliability

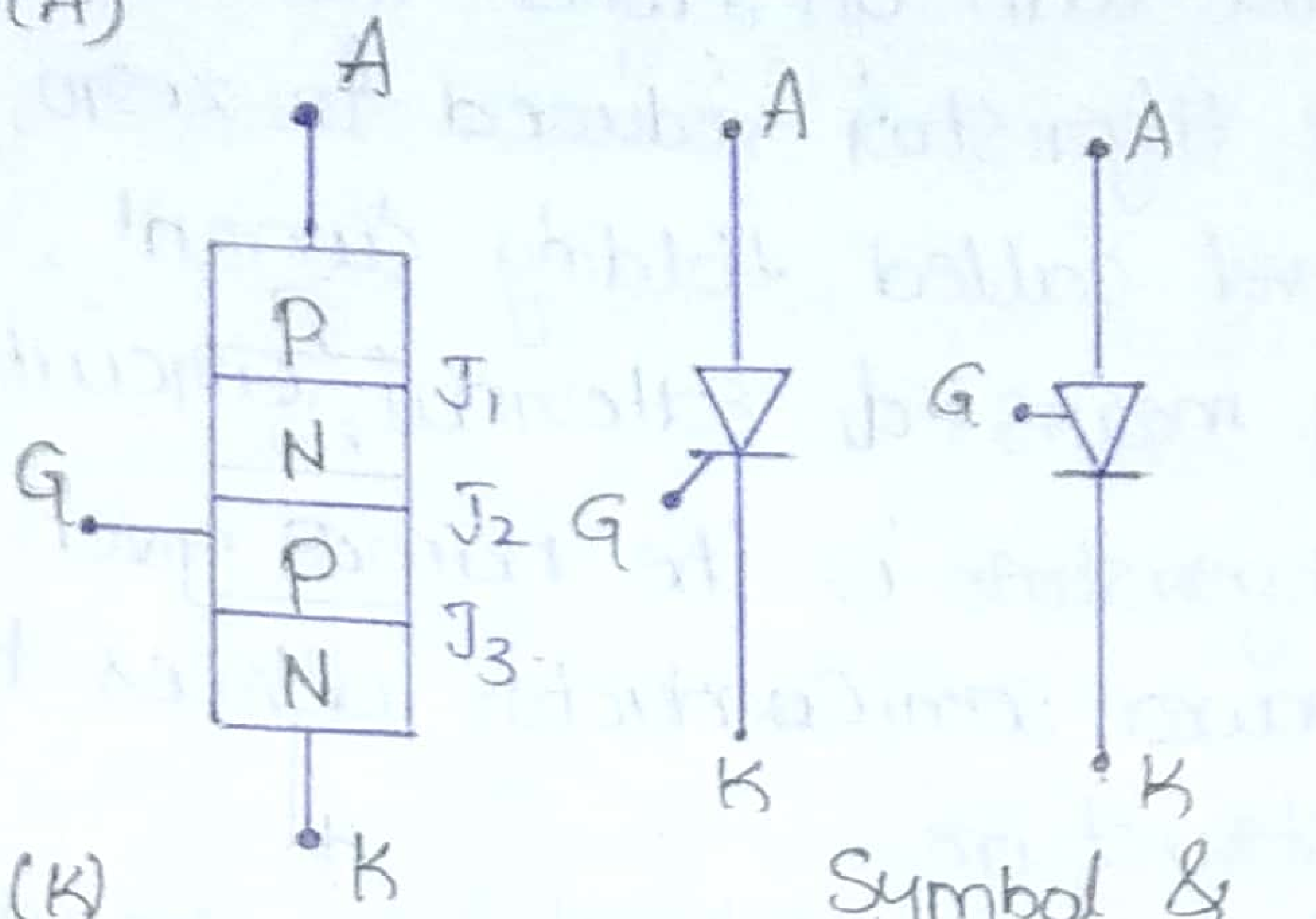
(3) Low losses.

(4) They can handle large amount of V & I ratings.

→ Now a days, the available voltage and current ratings of SCR is 7KV, 5KA.



(a) Construction of SCR



Symbol & Schematic diagram of SCR.

→ SCR is a four layer, 3 Junctions & 3 terminal Power Semiconductor Switching Device. It has 3 terminals i.e., Anode, (A) Cathode (K) and Gate (G).

→ for SCR Gate acts as a control terminal that means the current flowing through SCR can be controlled by varying applied electrical signal to Gate (signal) Terminal.

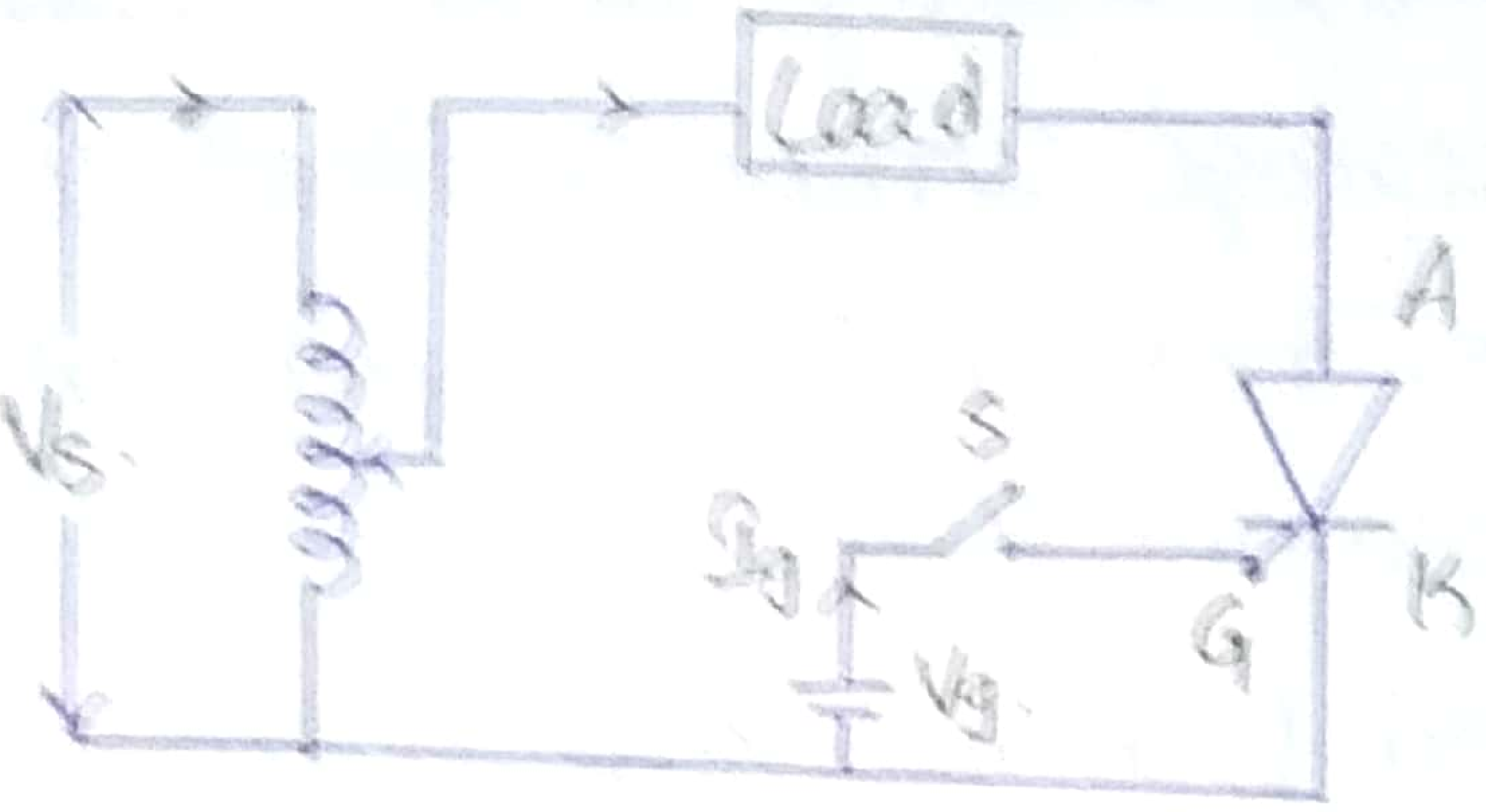
→ Anode and cathode are power Terminals i.e., they can handle large amount of voltage and allows major current through the device.

→ The function of threaded stud is tightening the SCR's on the frame of heat sinks with help of nuts.

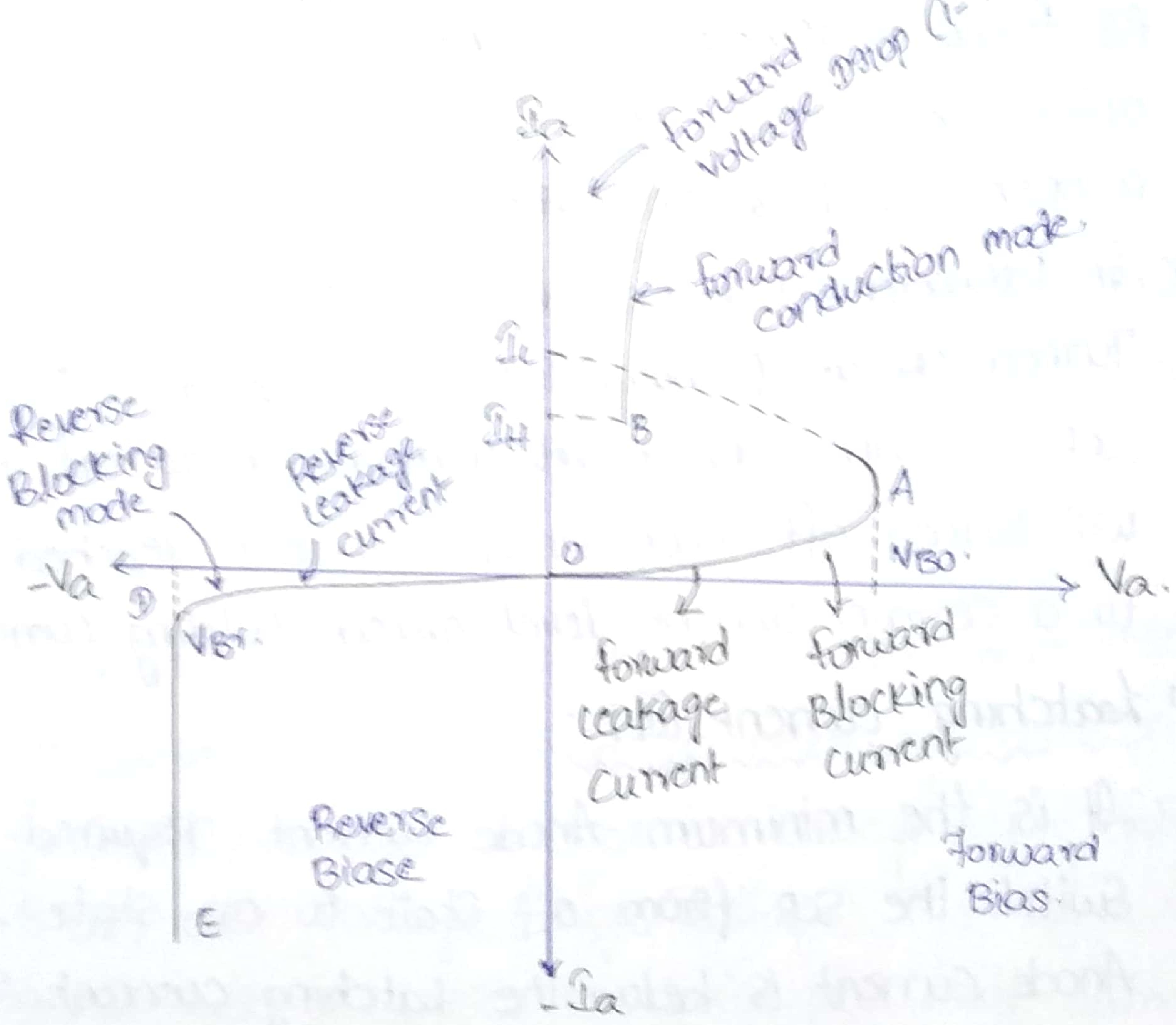
→ Like Diode, SCR is a unilateral (unidirectional) device. It blocks current from cathode to Anode

→ unlike Diode, it can also blocks the current from Anode to cathode, until if it is triggered by proper Gate pulse between Gate & cathode.

→ Operation & Static characteristics of SCR:-



Circuit, obtain SCR characteristics.



I_L - Latching current

I_H - Holding current.

VBO - Forward Breakover voltage.

V_{Br} - Reverse Breakdown voltage.

Va - Anode voltage.

I_a - Anode current.

μA - Ge } In
nA - Si } RBias.

$I_L = 25\,mA$

$I_H = 10\,mA$

/ $I_L = 2.5 I_H$ /

/ $I_H = 0.4\, I_L$ /.

→ In Reverse Blocking Mode, a small leakage current called Reverse leakage current flows through SCR. As Reverse Leakage current is Small, a SCR offers High Impedance. Therefore, SCR acts as open switch in Reverse Blocking Mode.

→ In forward Blocking Mode, a small leakage current called forward leakage current flows through SCR. As forward leakage current is very small, SCR offers Very High Impedance. Therefore, SCR acts as a open switch in this mode.

→ In forward Conduction mode, SCR is triggered or Turned ON at forward Break over Voltage (V_{BO}). once SCR is turned ON it will remains in to ON State. it will turned off when anode current reached below to a certain current level called Holding current (I_H).

→ Latching current (I_L):-

→ It is the minimum Anode current required to Switch the SCR from off State to on State. If Anode current is below the Latching current, SCR does not turned on.

→ Typical value of Latching current, $I_L = 25$ mA.

→ It is associated with Turn on process.

→ Holding current:-

→ It is the minimum anode current required to hold the SCR into ON State. If Anode current is below the Holding current, SCR will not Turned off.

→ Typical value of Holding current is $I_H = 10$ mA.

→ Latching current is always greater than Holding Current and it's ratio is given by,

$$I_H = 0.4\ I_L.$$

$$I_L = 2.5\ I_H.$$

→ Forward Breakover voltage (V_{BO}):-

→ The voltage at which SCR is switched ~~of~~ from off state to ON state without applying any Gate signal is called forward Breakover voltage.

→ Reverse Breakdown Voltage:- (V_{Br})

→ The Voltage at which a large current flows through SCR in reverse bias condition, is called Reverse Breakdown voltage.

→ Turn-ON Methods of SCR:-

→ forward voltage Triggering is undesirable Method. Because, in this method in order to Turn on SCR, forward voltage will be increased upto forward Break over voltage (large voltage). This large voltage gives raise to losses in device and may damage the SCR permanantly.

→ dv/dt Triggering:-

→ when Anode is made positive with respect to cathode SCR can be triggered by using following five Method

(1) forward voltage Triggering.

(2) Gate voltage Triggering

(3) dv/dt Triggering.

(4) Temperature Triggering.

(5) Light Triggering. (LASCR)

→ In this method, the reverse bias junction acts as a capacitor due to charges existing across Reverse bias junction j_2. charging current flowing through the junction capacitance is given by.

$$I_c = C_J \cdot \frac{dV_a}{dt}$$

→ If rate of change of forward voltage (dv/dt) is large, current flowing through Junction capacitance is also large. This current plays the role of Gate current i.e., SCR is turned on eventhough Gate Signal is not applied.

→ Typical value of dv/dt is 20-500V/μs.

i.e., per μs the voltage rise should be 20-500V, otherwise malfunctioning of SCR's takes place & False Turn on of SCR takes place.

(3) Temperature Triggering:-

→ In this method SCR is triggered at High Temperature. This High Temperature may gives rise to losses and may damage the SCR permanantly. So, this is undesirable Method.

(4) Light Triggering:-

→ In this method, a Special terminal is called Niche is made inside the p-layer instead of Gate terminal. whenever light is allowed to strike on this terminal free charge carriers are generated, when the Intensity of the light is more than normal Value, generated charge carriers moves freely across the three junctions. As a result current flaws through device and device gets turned on.

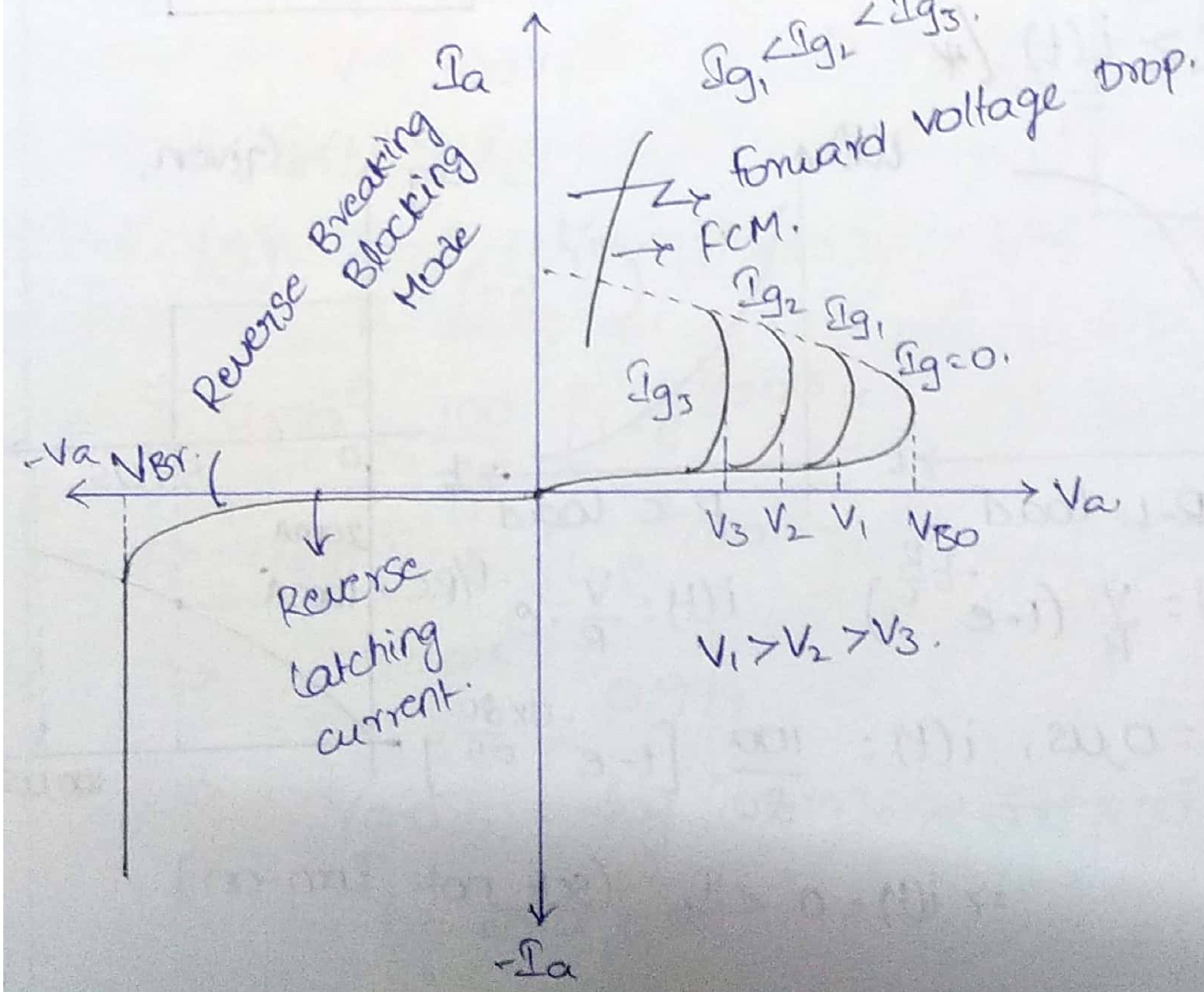
→ It is also known as LASCR i.e. Light Activated Silicon Control Rectifier.

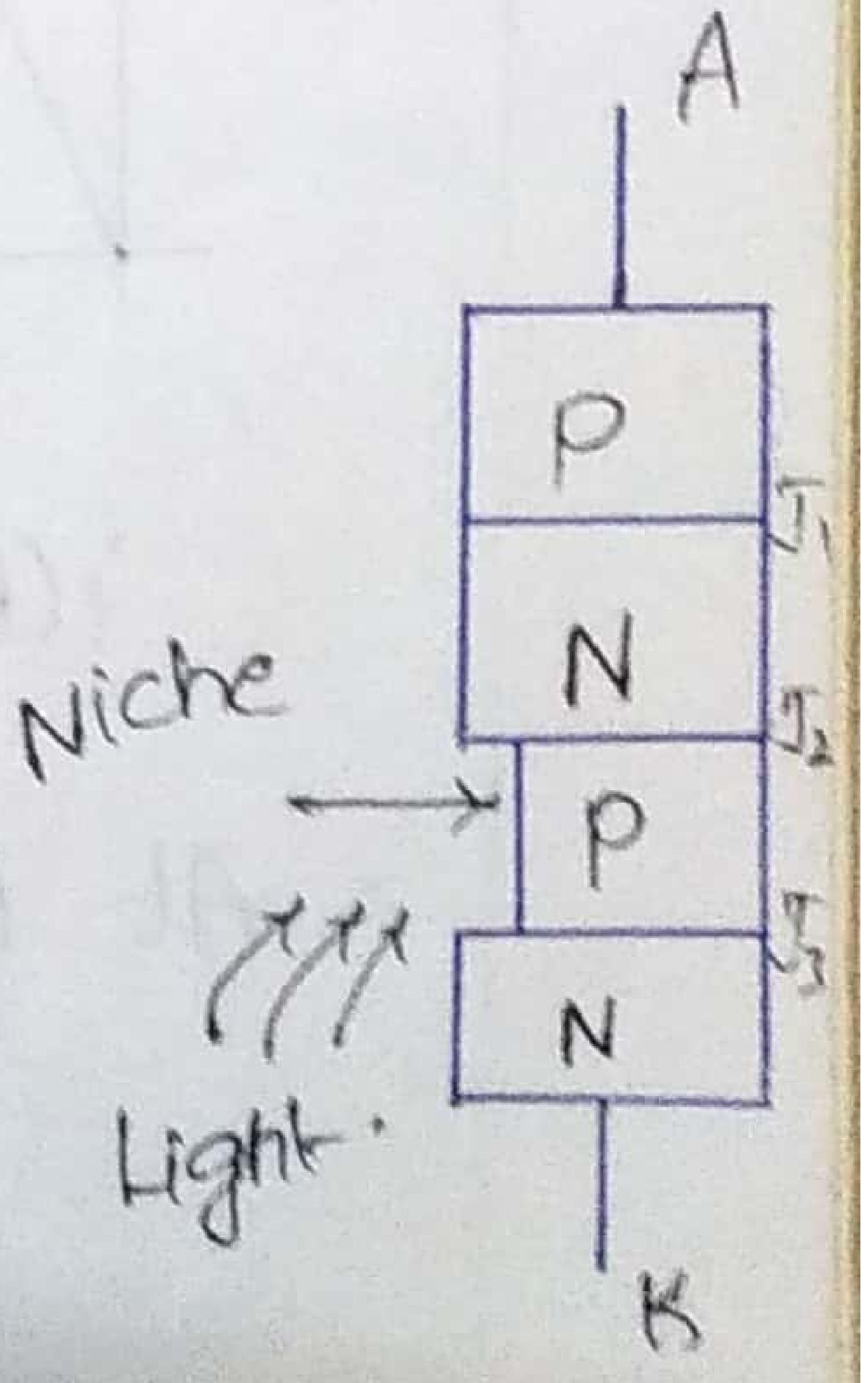
→ This method is mainly used in HVDC Transmission.

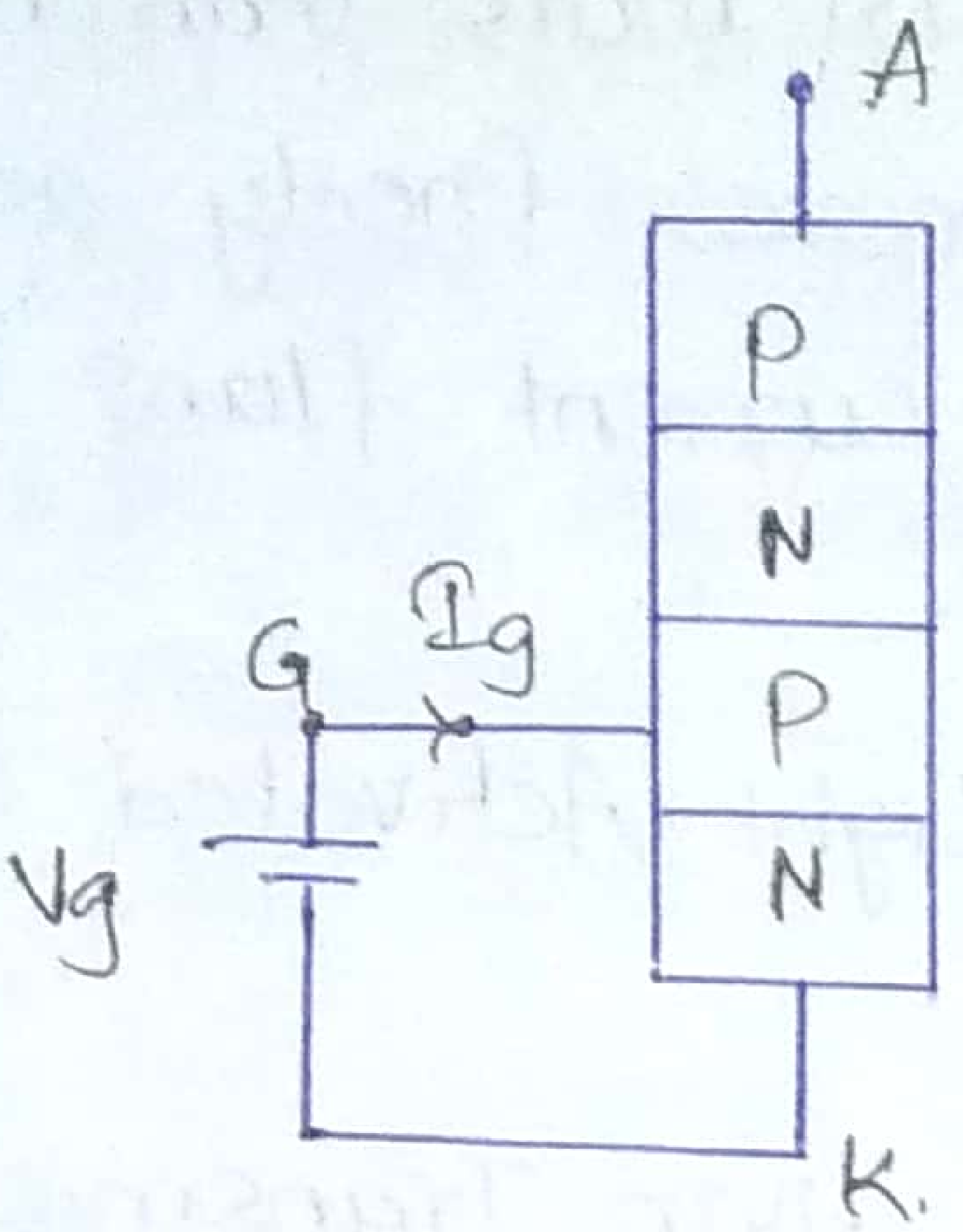
→ Gate Triggering:-

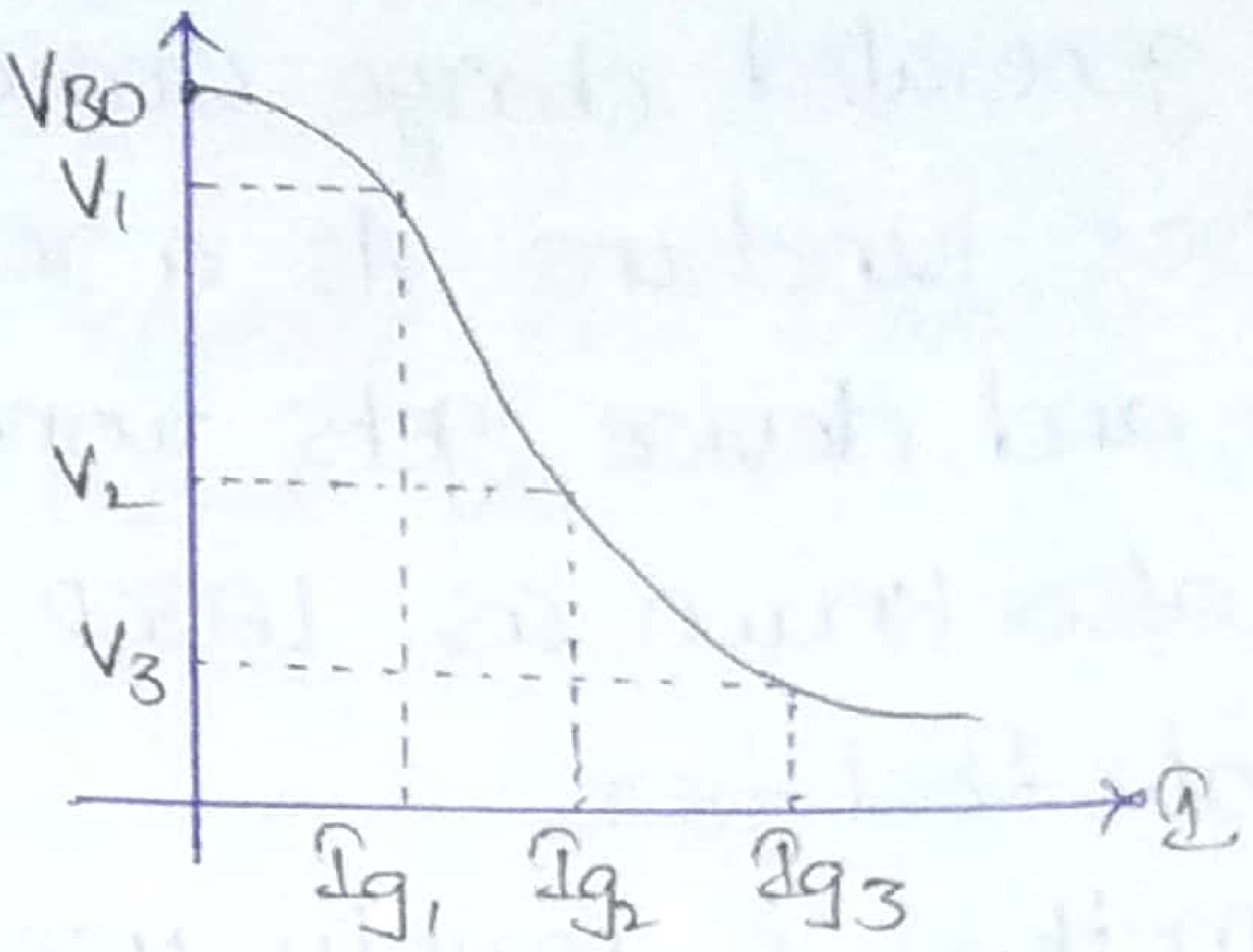
→ In this method, no need to increase the forward Voltage upto forward Breakover voltage (V_{BO}), unlike as forward voltage Triggering Method, SCR is turned on at a voltage which is lower than forward Break over Voltage by applying a Gate pulse between Gate and cathode.

→ If the magnitude of Gate current increases, forward V_{BO} decreases.



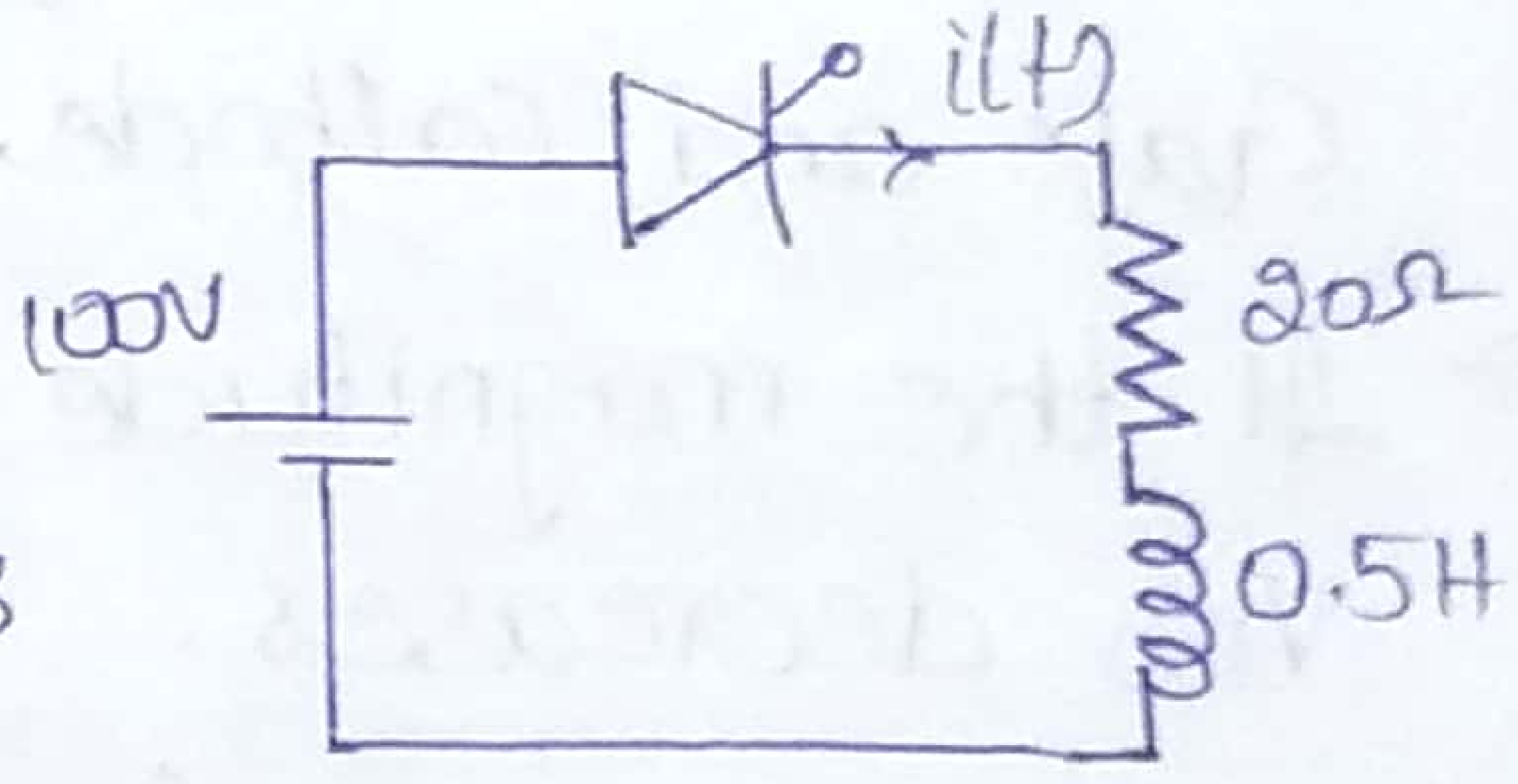






→ In these five methods, Gate Triggering Method is Commonly used method to turn on SCR when Anode is made positive with respect to cathode

* The SCR shown in figure has latching current of 20mA and is fired by pulse of width 50μsec. Determine whether the SCR is triggered or not.

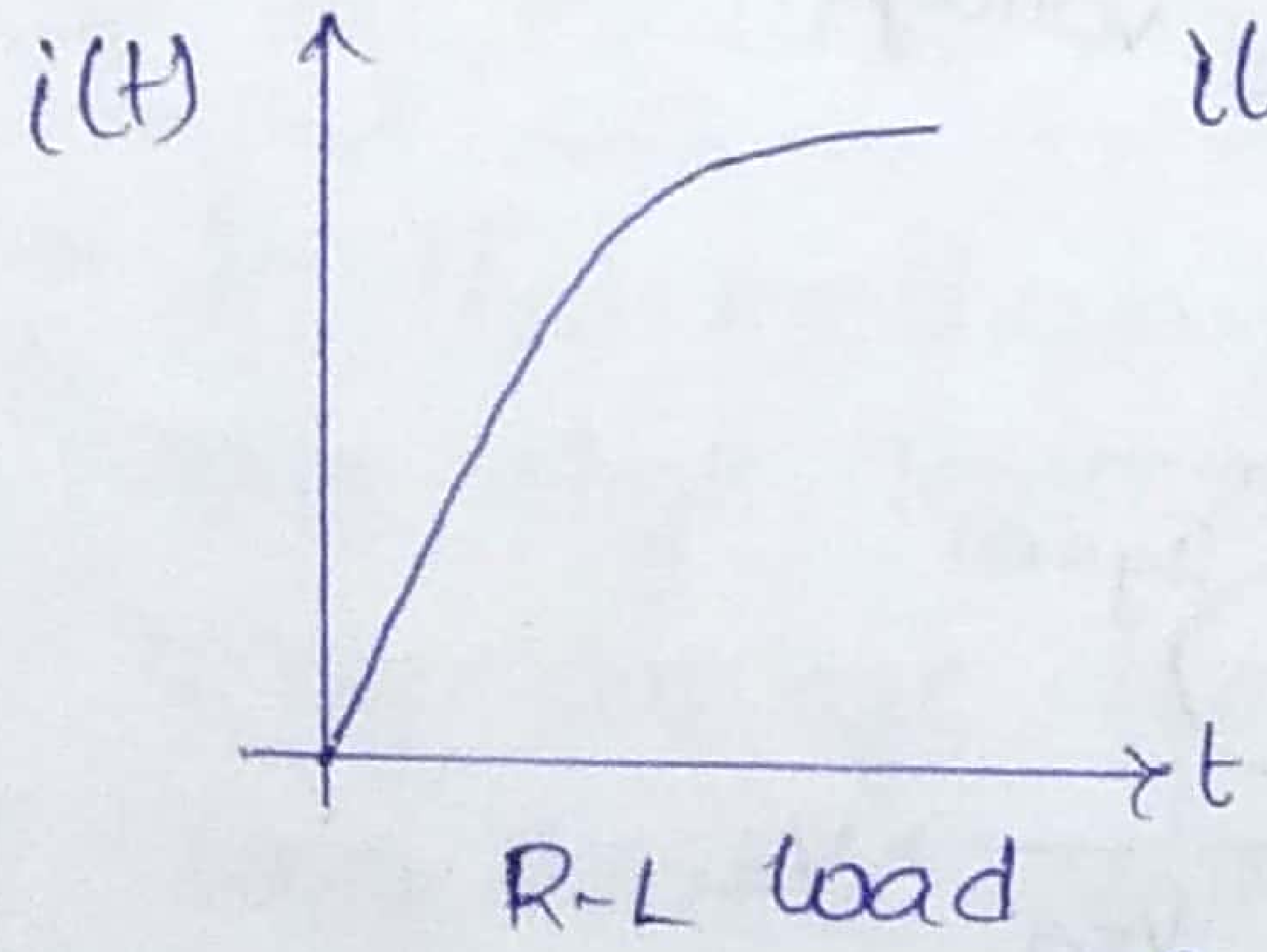


Sol:- Given, $I_L = 20mA$

Gate pulse = 50μsec.

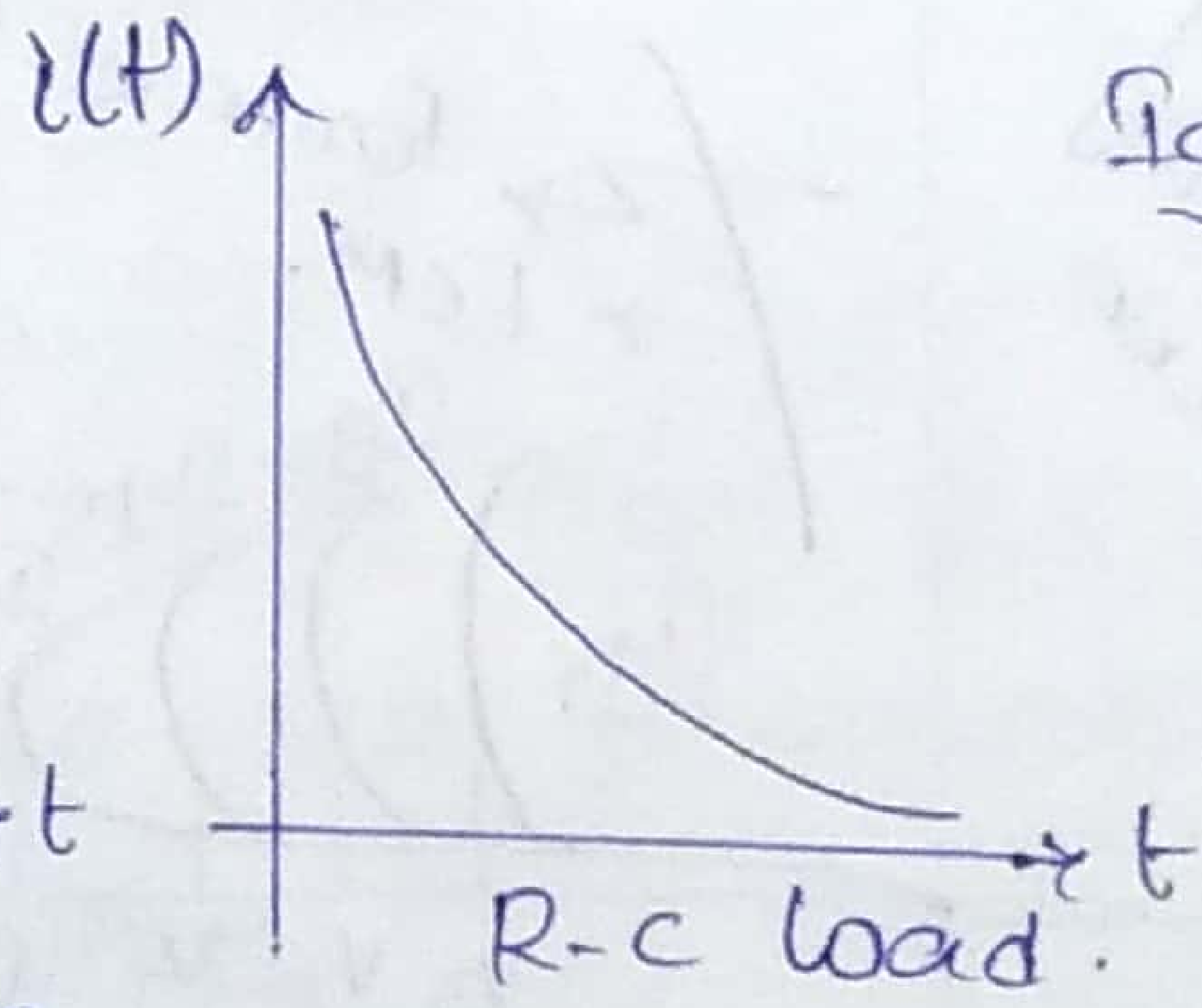
*/ Turn on SCR, Condition is

$I_L \geq i(t)$. /*



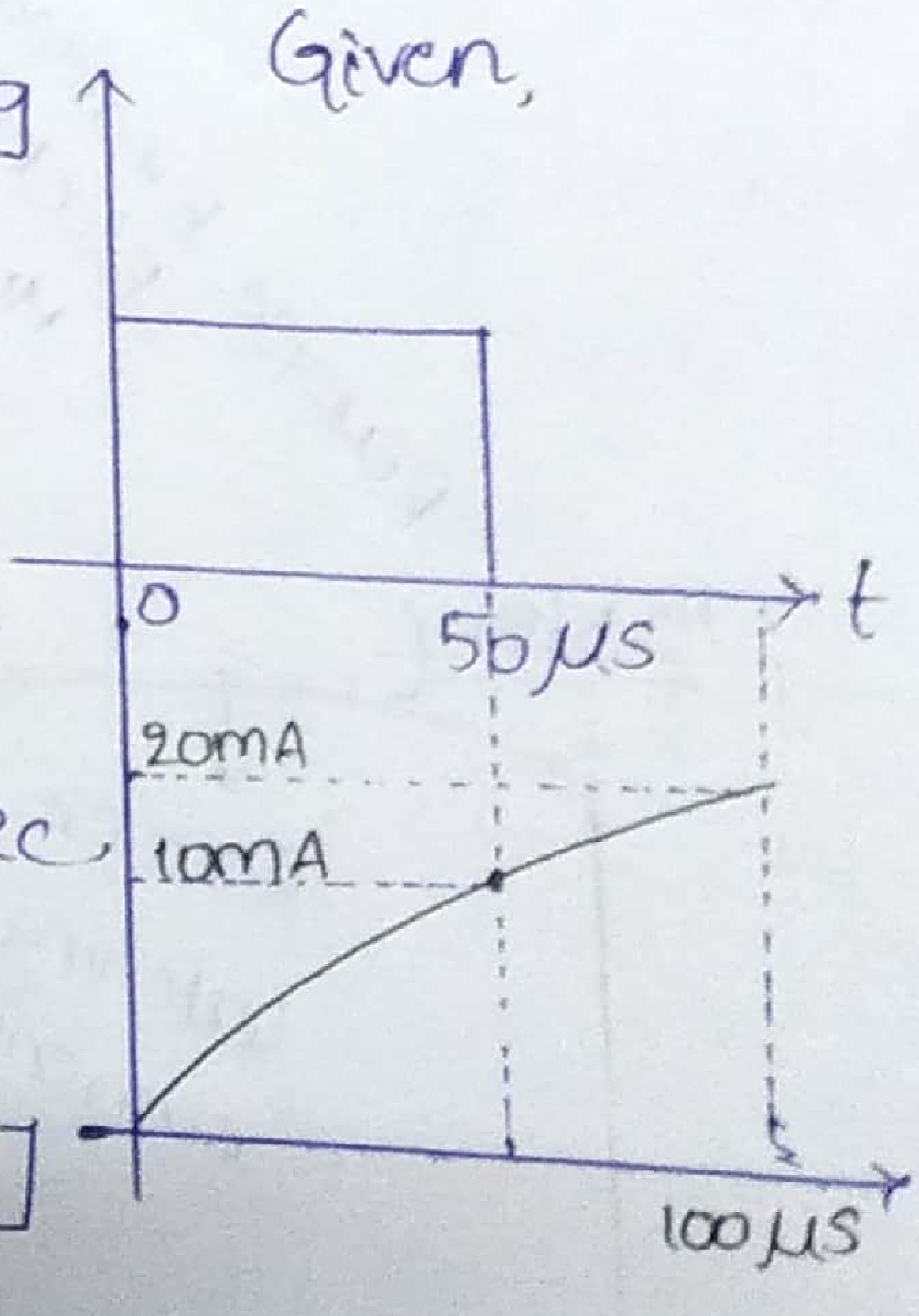
R-L Load

$i(t) = \frac{V}{R}(1-e^{-t\frac{R}{L}})$



R-C Load.

$i(t) = \frac{V}{R} \cdot e^{-t/RC}$



∴ At $t = 0\mu s$, $i(t) = \frac{100}{20}\left[1-e^{\frac{-0\times20}{0.5}}\right]$

$\Rightarrow i(t) = 0 < I_L$ (SCR not Turn-on)

→ At $t = 50\,\mu s$

$$\Rightarrow i(t) = \frac{100}{20}\left[1 - e^{-50\times10^{-6} \times \frac{20}{0.5}}\right]$$

$= 10mA < I_L$ (SCR not turn-on)

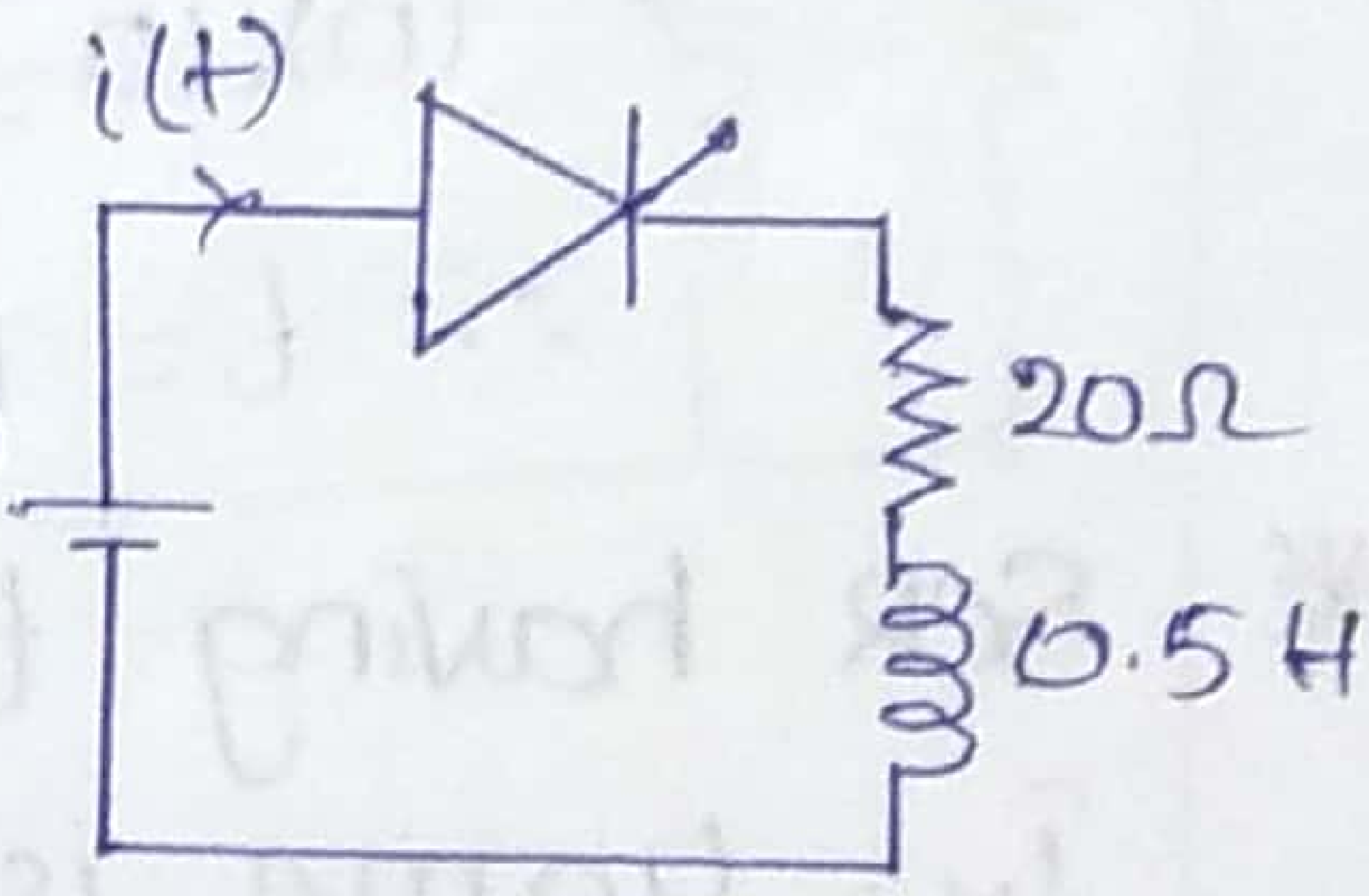
→ At $t = 100\,\mu s$

$$\Rightarrow i(t) = \frac{100}{20}\left[1 - e^{-100\times10^{-6} \times \frac{20}{0.5}}\right]$$

$\approx 20mA$ [SCR will turn-on]

→ In Gate Triggering, the width of Gate signal is proper i.e., it will ensure that the current flowing through the SCR raises above the latching current.

SCR is connected in series $L = 0.5\,H$ and $R = 20\Omega$. A 100V DC voltage applied to circuit. If the $I_L = 4mA$ find minimum width of Gate pulse required to proper to turn on SCR.



Given, $I_L = 4mA$.

$V = 100V$.

$I(t) \geq I_L$.

$$i(t) = \frac{V}{R}\left(1 - e^{-t/\tau}\right)$$

$$\Rightarrow 4\times10^{-3} = \frac{100}{20}\left[1 - e^{-t/0.025}\right]$$

$$\Rightarrow 4\times10^{-3} = 5\left[1 - e^{-t/0.025}\right]$$

$$\Rightarrow e^{-t/0.025} = 0.999.$$

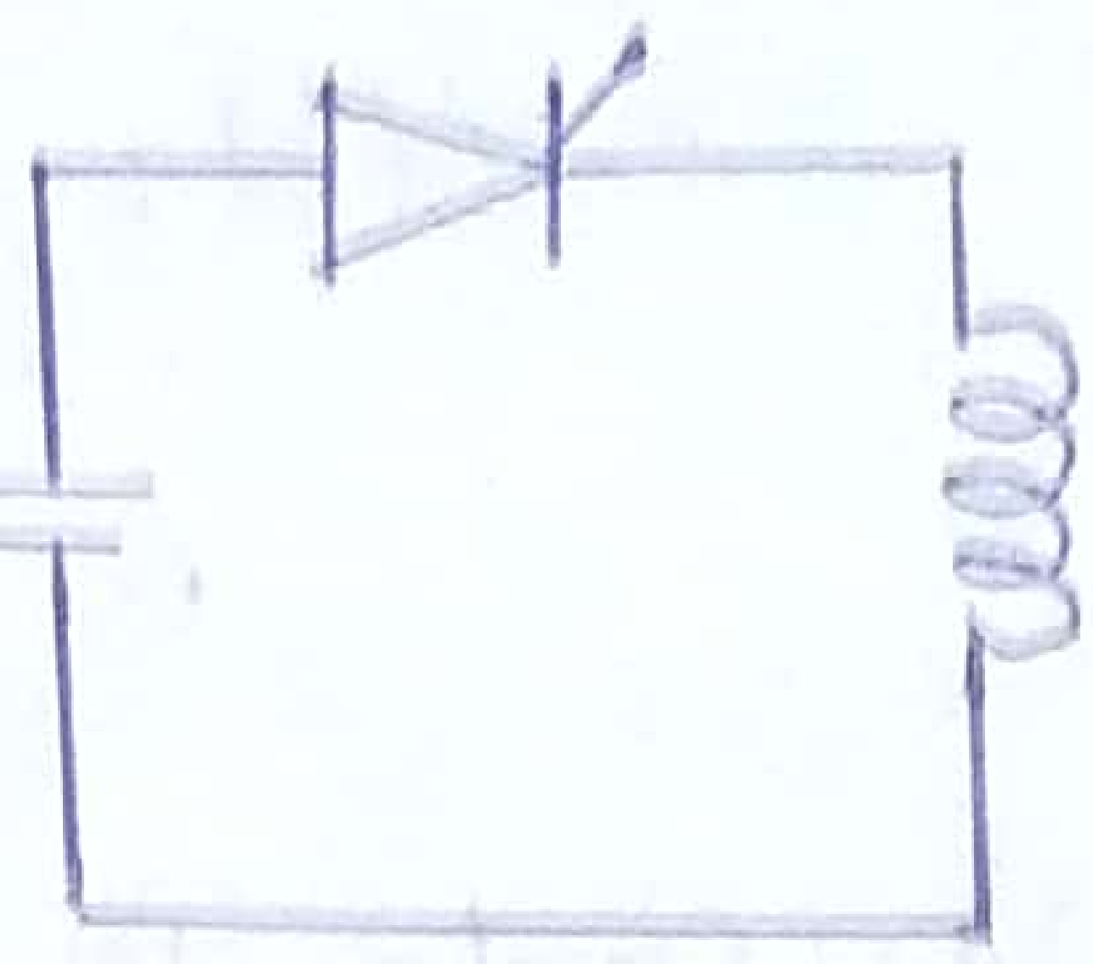
$$\Rightarrow -t/0.025 = \log(0.999) = -1.000\times10^{-3}$$

$$\therefore t = 25.01\,\mu sec$$

* Latching current for SCR inserted between 200 dc Source at a load is 10mA. Compute minimum Gate pulse width required to turn on SCR in case of Load is

(1) $L=0.2H$ (2) 20Ω (3) in series of R&L

Sol:- (1) $i(t) \geq I_L \Rightarrow I_L = 100\times10^{-4}A$



$$V(t) = L\cdot\frac{di(t)}{dt}$$

$$\Rightarrow Vdt = L\,di$$

$$\Rightarrow Vt = Li$$

$$\Rightarrow t = \frac{Li}{V} = \frac{0.2\times10\times10^{-3}}{200} = 100\,\mu s.$$

(2) $$100mA = \frac{V}{R}(1-e^{-t/\tau})$$

$$\Rightarrow 100\times10^{-3} = \frac{200}{20}(1-e^{-t/0.01})$$

$$\Rightarrow 10\times10^{-3} = 1-e^{-t/0.01}$$

$$\therefore t = 100.50\,\mu s.$$

* SCR having turn on time 5μs and I_L of 50mA and $I_H = 40mA$ is triggered by a short duration pulse as shown in circuit. The minimum pulse required to turn on SCR will be.

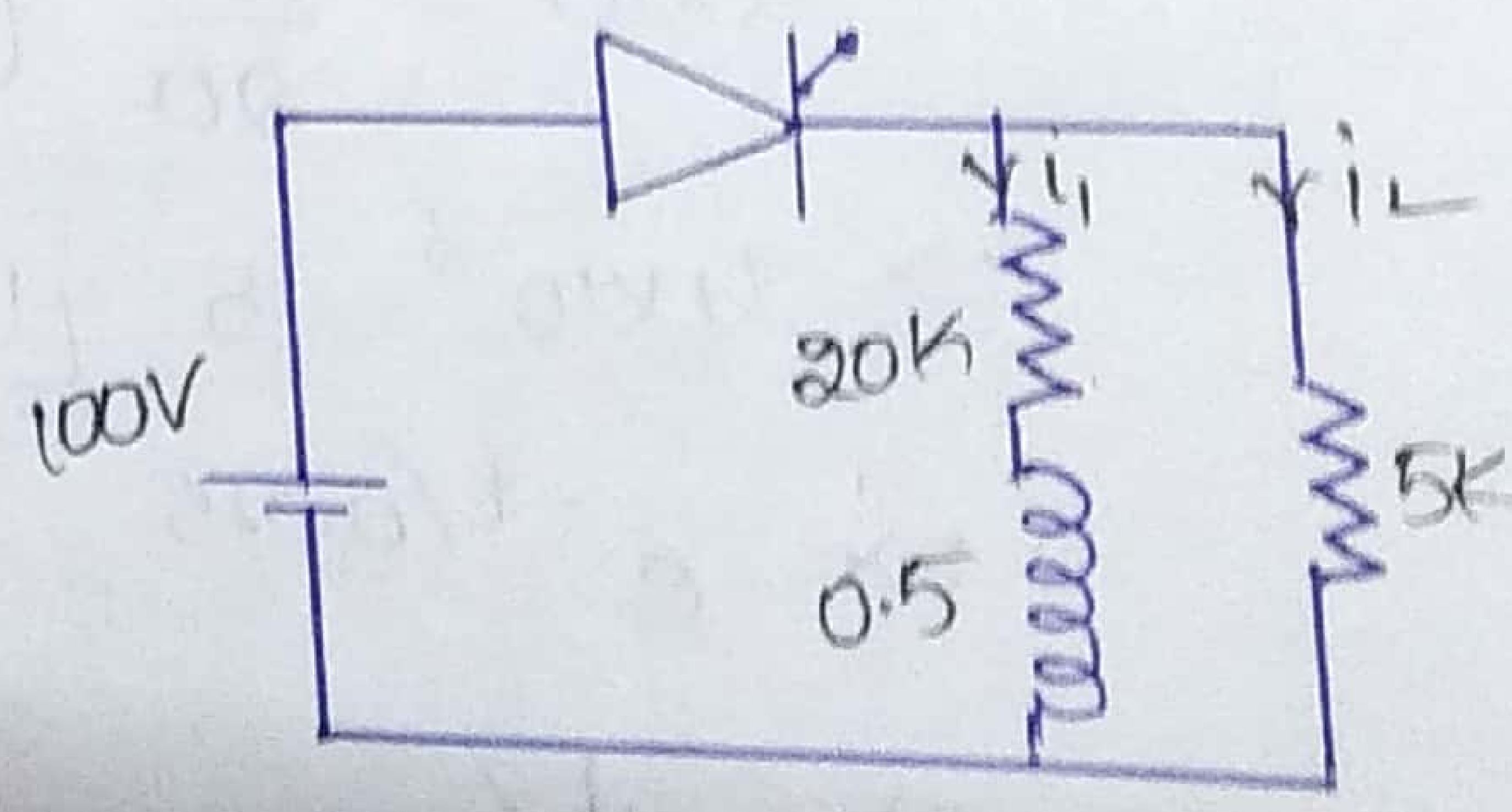
Sol:- $T_{ON} = 5\mu s$.

$I_L = 50mA$, $I_H = 40mA$

$I(t) \geq I_L$

$I = I_L = 50mA$

$\therefore I = I_1 + I_2$



$I_2 = \frac{V}{R} = 20mA$

$\Rightarrow I_1 = \frac{V}{R}(1-e^{-t/\tau})$

$\Rightarrow I_1 = 5(1-e^{-t/0.025})$

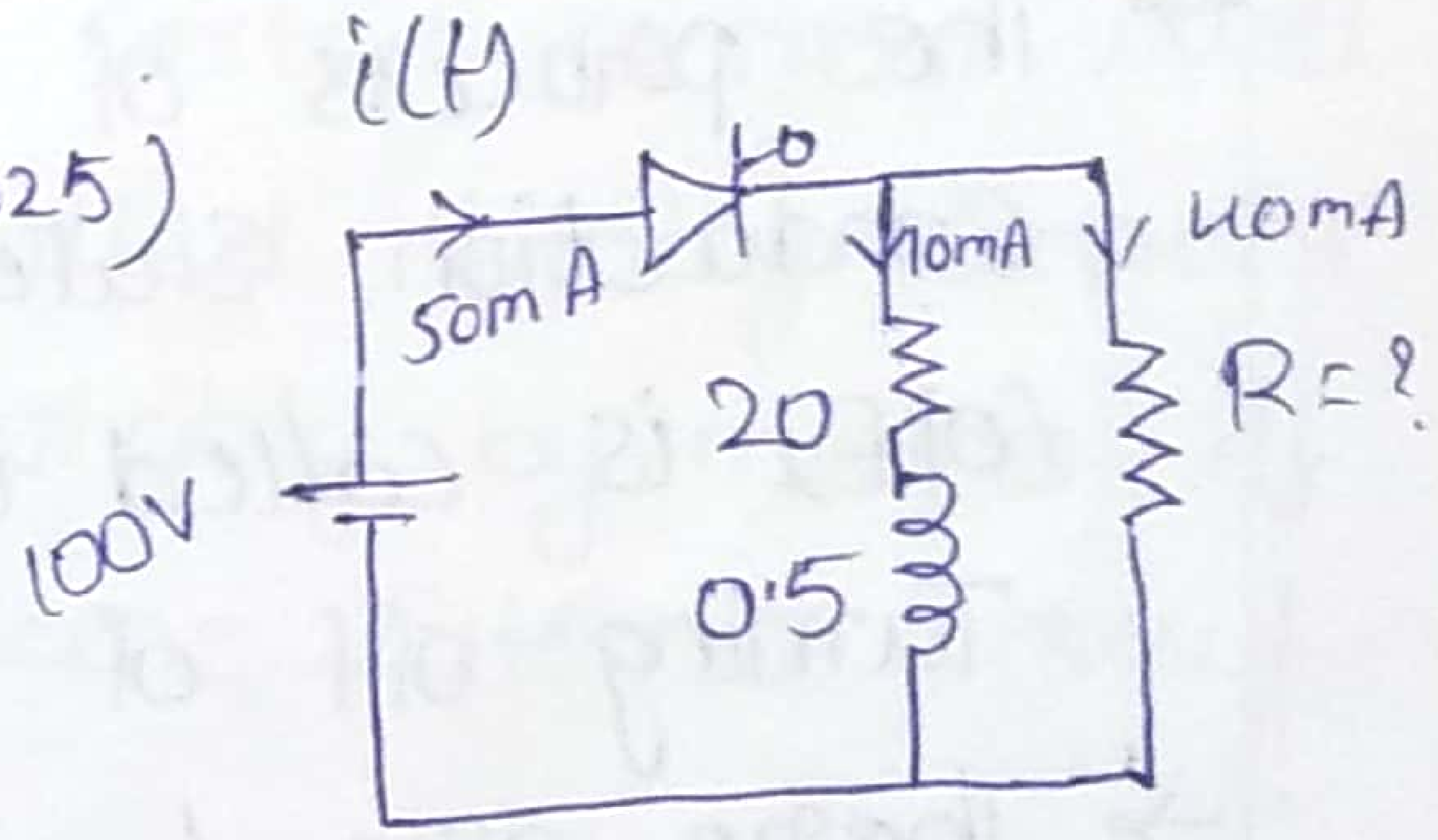
$\therefore I = I_1 + I_2$

$\Rightarrow 50mA = 5(1-e^{-t/0.025}) + 20mA$

$\Rightarrow e^{-t/0.025} = 0.994.$

$\therefore t = 150.45\ \mu s.$

* In the SCR circuit shown in figure the SCR has a Latching current of 50mA is fired by pulse of 50μS. Show that without Resistance the SCR will fail remain ON, when firing ends and max value of R to ensurely find.



Sol:- $I(t) = \frac{V}{R}(1-e^{-t\frac{R}{L}})$.

(1) $I(t) = \frac{100}{20}(1-e^{-50\times10^{-6}/0.025})$

$= 9.99mA.$

$I(t) < I_L$. (SCR fails to turn ON with out 'R').

(2) $\boxed{I(t) \geq I_L}$ → condition to turn ON SCR

$\Rightarrow I_1 = 9.99mA \cong 10mA$

$I(t) = 50mA = I_L$

$I(t) = I_1 + I_2. \Rightarrow 50mA = 10mA + 40mA.$

$\Rightarrow I_2 = 40mA$

$\therefore \frac{V}{R} = 40mA.$

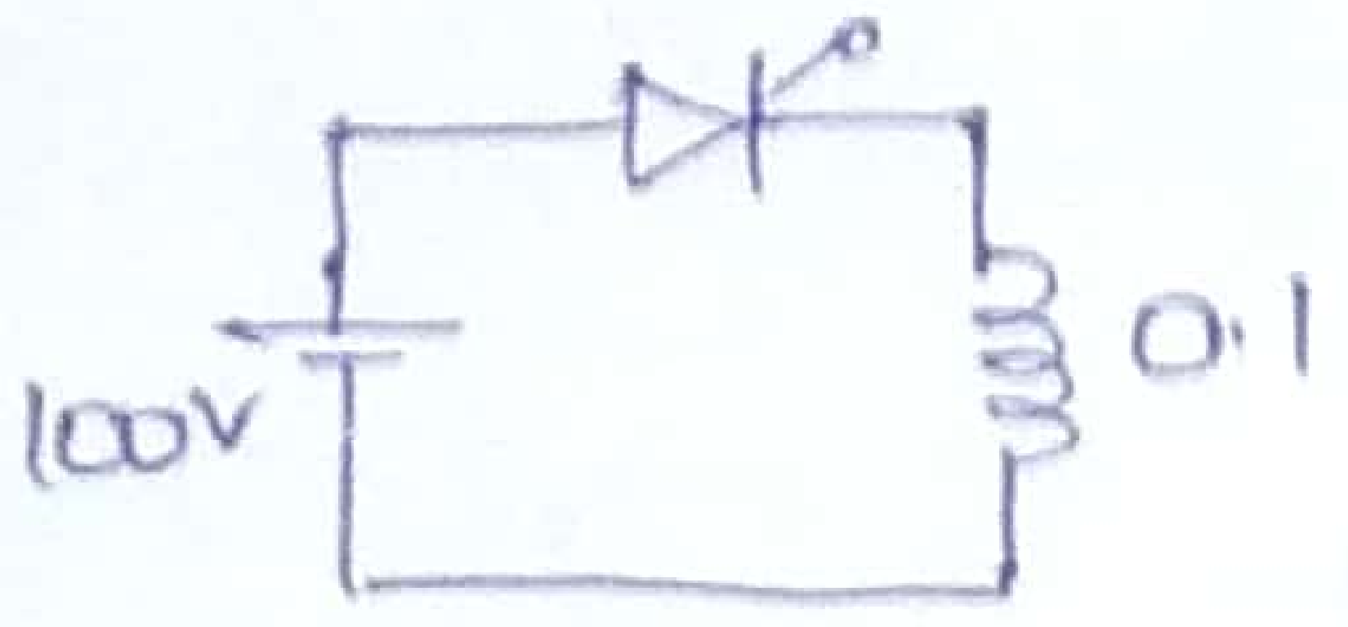
$\therefore R = \frac{V}{40\times10^{-3}} = \frac{100}{40\times10^{-3}} = 2.5k\Omega$

$\therefore R = 2.5k\Omega$

To
→ The Turn-on SCR the R-value must be 2.5kΩ

* A I_L of below circuit is 4mA. The minimum width of Gate pulse required to turn on SCR, L=0.1H.

Sol:-



$V t = i L.$

$\Rightarrow \cancel{V} t = \frac{iL}{V} = \frac{0.1 \times 4m}{100} = 4\mu sec.$

→ Turn off Methods of SCR:-

→ Conditions required to Turn-off SCR:-

(1) $I_a < I_H$. i.e., if current flowing through SCR is less than Holding current.

(2) when a reverse voltage applied across SCR for sufficient time, recover it's Blocking Capabilities.

→ The process of bringing SCR from forward Conduction State (ON) to forward Blocking state (OFF) is called Commutation i.e., the process of Turning off of SCR is called commutation.

→ There are two types of Commutation:-

(1) Natural Commutation.

(2) Forced Commutation.

Note:-

→ Turn off Time of SCR (3m 3-100)μs

→ Turn on Time of SCR (1-4μs).

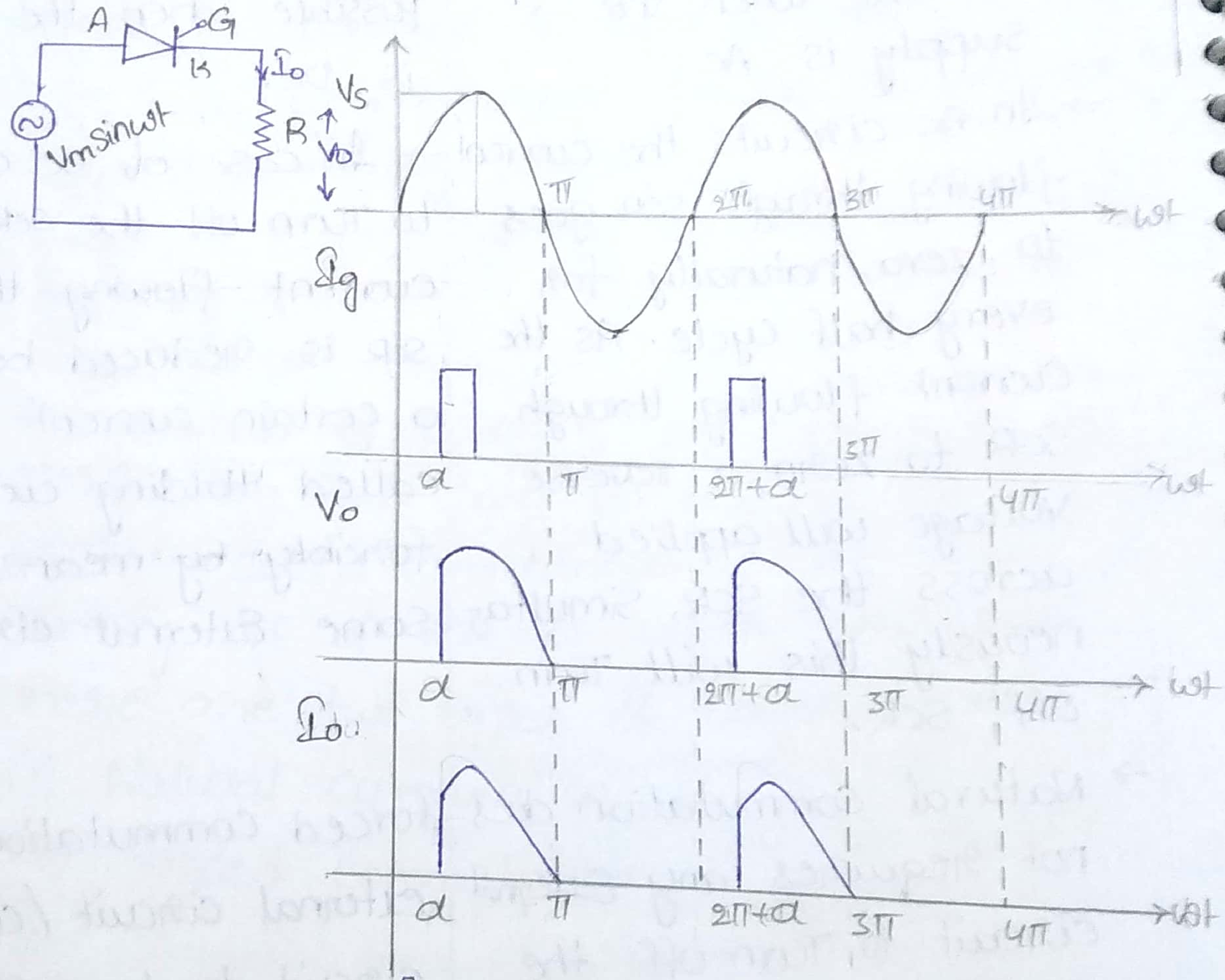
→ Converter Grade SCR's have slow Turn-off Time

→ Inverter Grade SCR's have ~~High~~ fast Turn-off Time.

Natural Commutation	Forced Commutation.
→ The process of Turning off SCR without using any external circuit is called Natural Commutation.	The process of Turning off SCR by using the external circuit is called forced Commutation.
→ Natural commutation is Possible when the supply is Ac.	forced commutation is possible when the supply is DC
→ In AC circuits, the current flowing through SCR goes to zero, naturally for every half cycle. As the current flowing through SCR to zero, a reverse Voltage will applied across the SCR, Simultaneously this will Turn off SCR.	→ In case of DC circuits, to Turn off the SCR, the current flowing through SCR is reduced below to a certain current level called Holding current forcibly by means of some External circuit.
→ Natural commutation does not requires any External circuit to Turn off the SCR. It uses Supply Voltage or Main voltage to turn off SCR. So, It is also called as Line Commutation.	forced Commutation requires external circuit / commutation circuit to turn off the SCR. Commutation circuit having Inductors, Capacitors, one or more Thyristors & Diodes... The commutation circuit stores energy during on period of SCR, this energy used to Turn off SCR.

→ Phase Control Rectifiers, Ac voltage controllers & Step down cyclo-converters require Natural Commutation to Turn off SCR.	→ Dc CHOPPERS, Inverters and Step-up cyclo-converters requires forced Commutation to turn off the SCR.

→ **Principle of Natural Commutation :-**



→ During +ve HC :- [(0-π) (2π-3π) ....]

SCR - FB.

At, ωt = α, SCR = ON, $V_o = V_S$, $I_o = \frac{V_o}{R}$.

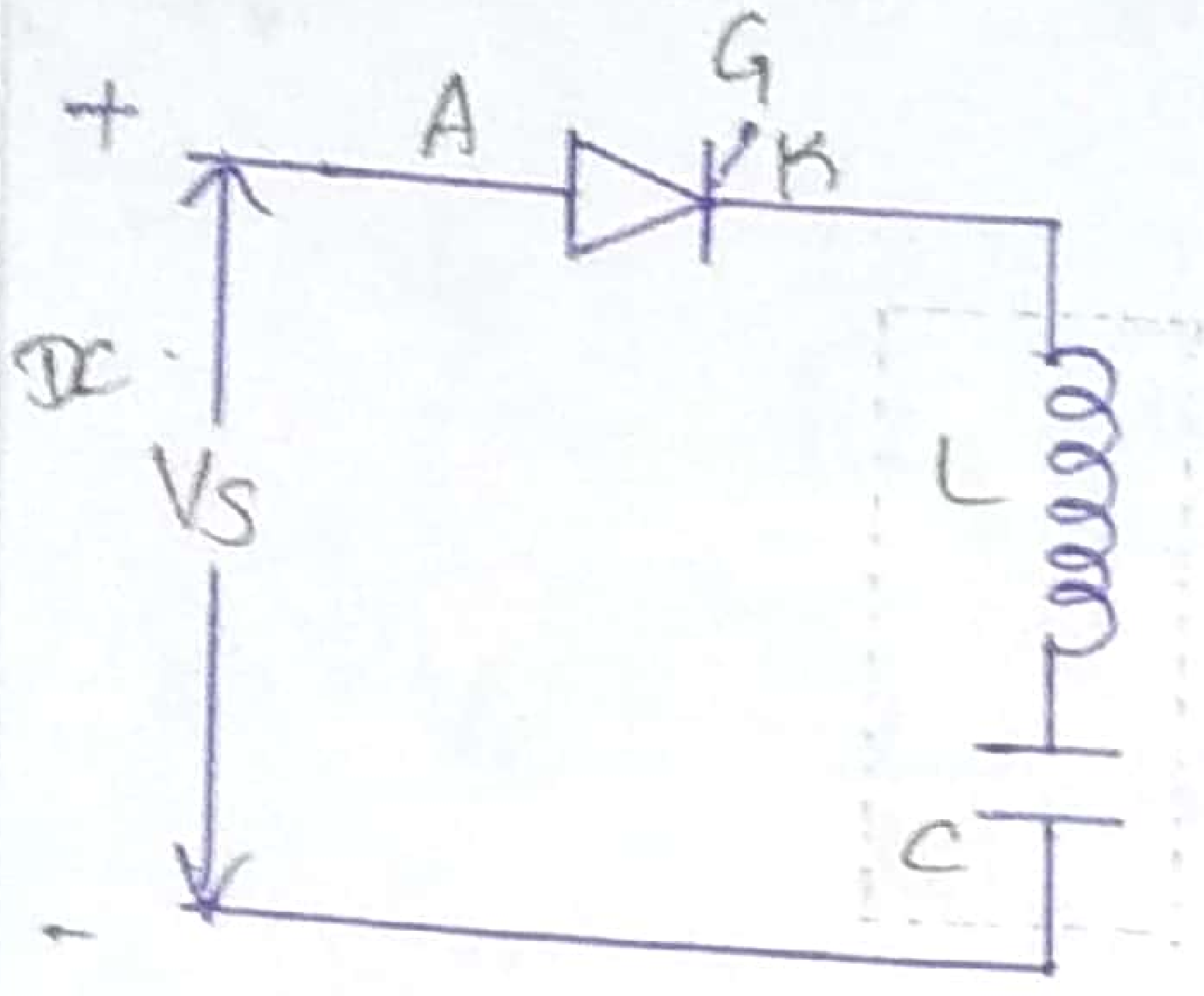
At, ωt = π, $V_S = 0$, $V_o = 0$, $I_o = 0$.

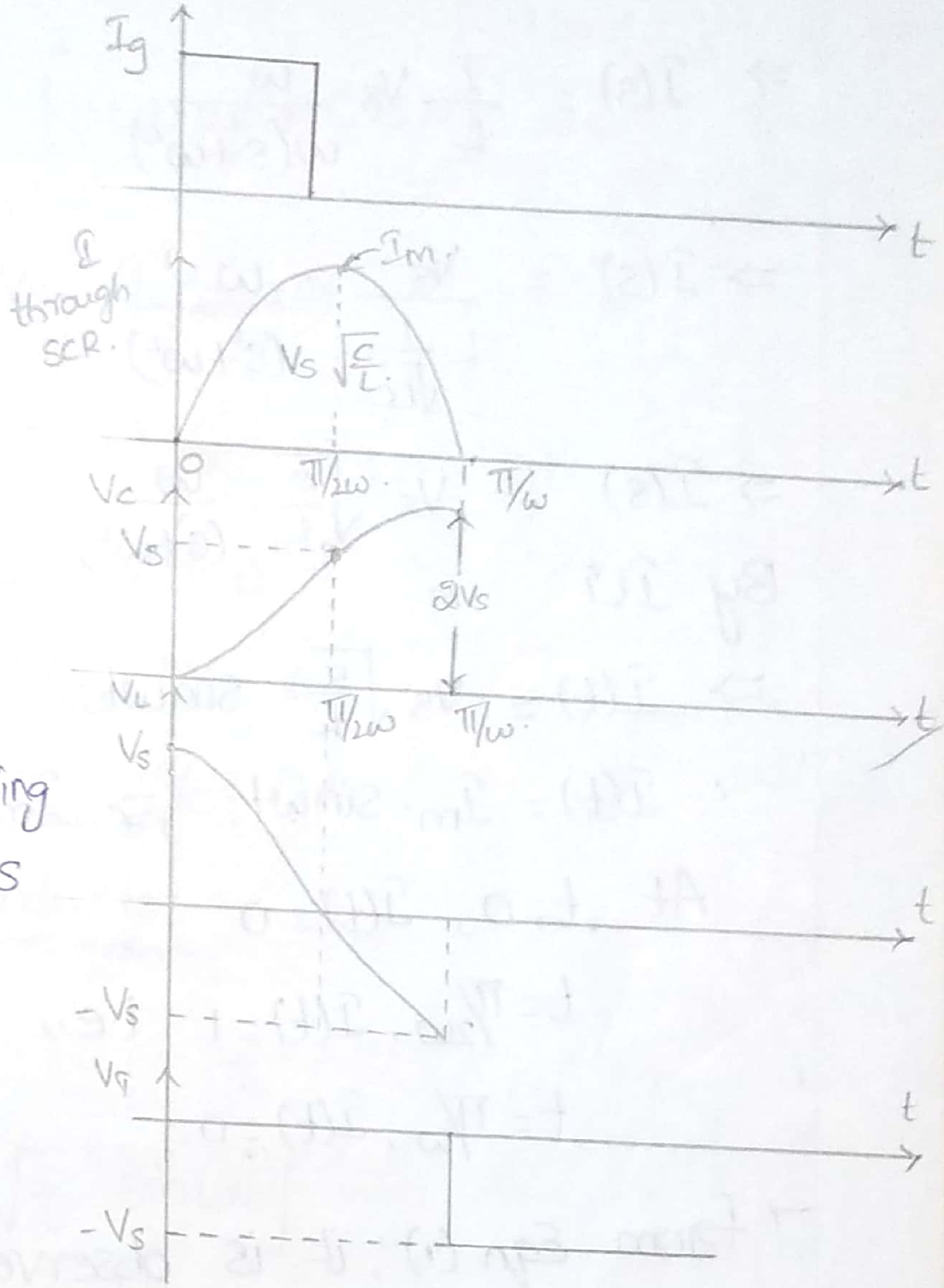
→ During -ve HC [(π-2π), (3π-4π), ...]

SCR → R.B.

SCR = OFF, $V_o = 0$, $I_o = 0$.

→ Principle of forced Commutation :-





→ Assume, SCR is triggered at the instant t=0.

→ Now, current flowing through the SCR is By appling the KVL to above circuit, then

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

Applying Laplace Transforms.

$$\Rightarrow \frac{V_s(S)}{S} = LS\cdot I(S) + \frac{1}{SC}\cdot I(s).$$

$$\Rightarrow \frac{V_s}{S} = \left(LS + \frac{1}{SC}\right) I(S).$$

$$\Rightarrow \frac{V_s}{S} = \left[\frac{LCS^2+1}{SC}\right]\cdot I(S)$$

$$\Rightarrow I(S) = \frac{C\cancel{S}}{S^2CL+1} \times \frac{V_s}{\cancel{S}}$$

$$\Rightarrow I(S) = \frac{V_s}{1} \times \frac{C}{LC(S^2 + \frac{1}{LC})}$$

$$\Rightarrow I(s) = \frac{1}{L(s^2+\omega^2)} \cdot V_s \qquad \left[\because \omega^2 = \frac{1}{LC} \ \& \ \omega = \frac{1}{\sqrt{LC}}\right]$$

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

$$\Rightarrow I(s) = \frac{V_s}{L \cdot \frac{1}{\sqrt{LC}}} \cdot \frac{\omega}{(s^2+\omega^2)}$$

$$\Rightarrow I(s) = V_s \cdot \sqrt{\frac{C}{L}} \cdot \frac{\omega}{(s^2+\omega^2)}$$

By ILT:

$$\Rightarrow I(t) = V_s \sqrt{\frac{C}{L}} \cdot \sin\omega t$$

$$\therefore I(t) = I_m \cdot \sin\omega t \qquad \Rightarrow I_m = V_s \cdot \sqrt{\frac{C}{L}}$$

At $t = 0$, $I(t) = 0$

$t = \pi/2\omega$, $I(t) = 1$ i.e., $I(t) = V_s \cdot \sqrt{\frac{C}{L}}$

$t = \pi/\omega$, $I(t) = 0$.

→ from Eqn (1), it is observed that current flowing through SCR is reduced to zero it instant $t = \pi/\omega$ and SCR gets turned off i.e., Here SCR is turned off by using commutation circuit consists of Inductor & Capacitor.

→ Voltage through capacitor (across) V_c:-

$$V_c = \frac{1}{C} \int_0^t i(t) \cdot dt$$

$$= \frac{1}{C} \int_0^t V_s \cdot \sqrt{\frac{C}{L}} \cdot \sin\omega t \cdot dt$$

$$= \frac{1}{C} \cdot V_s \sqrt{\frac{C}{L}} \cdot \int_0^t \sin\omega t \cdot dt$$

$$\Rightarrow V_c = \frac{1}{c} \cdot V_S \frac{\sqrt{c}}{\sqrt{L}} \cdot \left(\frac{-\cos\omega t}{\omega}\right)_0^t$$

$$\Rightarrow V_c = \frac{V_s}{\sqrt{Lc}} \cdot \frac{1}{\omega} \cdot \left[-\cos\omega t + \cos 0\right]$$

$$\Rightarrow V_c = \frac{1}{\omega} \cdot \omega \cdot V_S \cdot (1 - \cos\omega t)$$

$$*/ \; V_c = V_S (1 - \cos\omega t) \; /*$$

→ At Instant, $t = 0$, $V_c = 0$

$t = \pi/2\omega$, $V_c = V_S$

$t = \pi/\omega$, $V_c = 2V_S$.

→ Voltage across Inductor:-

$$V_L = L \cdot \frac{di(t)}{dt}$$

$$\Rightarrow V_L = L \cdot \frac{d}{dt}\left[V_S \cdot \sqrt{\frac{c}{L}} \cdot \sin\omega t\right]$$

$$\Rightarrow V_L = L \cdot V_S \cdot \sqrt{\frac{c}{L}} \cdot \frac{d}{dt}(\sin\omega t)$$

$$\Rightarrow V_L = V_S \cdot \sqrt{Lc} \cdot (\omega \cdot \cos\omega t)$$

$$\Rightarrow V_L = V_S \cdot \sqrt{Lc} \cdot \frac{1}{\sqrt{Lc}} \cdot (\cos\omega t)$$

$$*/ \; \therefore V_L = V_S \cdot (\cos\omega t) \; /*$$

At $t = 0$, $V_L = 1 (V_S) = V_S$

$t = \pi/2\omega$, $V_L = 0$.

$t = \pi/\omega$, $V_L = -V_S$.

→ Voltage across Thyristor:-

→ During conduction period of SCR, Voltage across SCR is zero. i.e., $V_T = 0$

→ During off period of SCR, Voltage across SCR is $V_T = -V_S$. It shows that SCR is subjected to the Reverse voltage at instant $\pi/\omega = t$, to recover its Blocking Capabilities.

→ By applying KVL to ckt during off period,

$\Rightarrow -V_S + V_T + V_L + V_C = 0$

$\Rightarrow V_T = V_S - V_L - V_C$.

$\Rightarrow V_T = V_S - (2V_S) + (+V_S - V_S)$

$\therefore$ */ $V_T = -V_S$ /* (off period).

→ Dynamic characteristics of SCR (or)

→ Switching characteristics of SCR:-

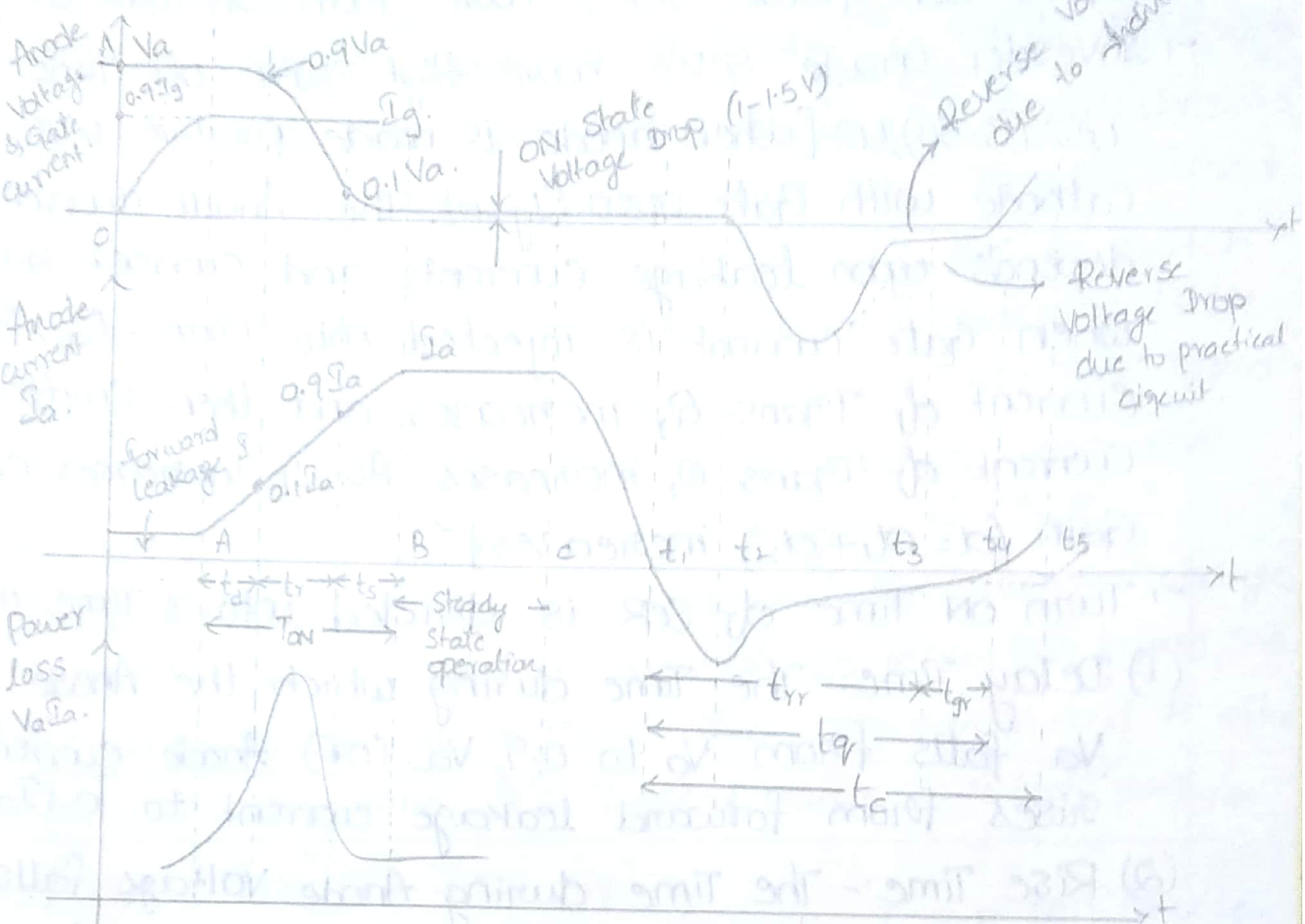
→ Static characteristics gives operation of SCR.

→ During ON & OFF Period of SCR, it is subjected to different voltages across it and different currents through it. The Time Variations of Voltage across SCR and current through SCR during ON & OFF period gives Dynamic characteristics of SCR.

→ Dynamic characteristics also tells about switching losses and Device velocity in changing from the forward conduction state (ON) to forward Blocking state (OFF) or viceversa.

→ Losses that occur in SCR will changing from the forward conduction state to forward Blocking state or viceversa are called switching losses.

→ Static characteristics & Dynamic characteristics in that Switching losses is major factor while designing the device.



→ t_d - Delay Time

→ t_r - Raise Time.

→ t_s - Spread Time.

→ T_{ON} - Turn on time Of SCR.

→ t_{rr} - Reverse Recovery Time.

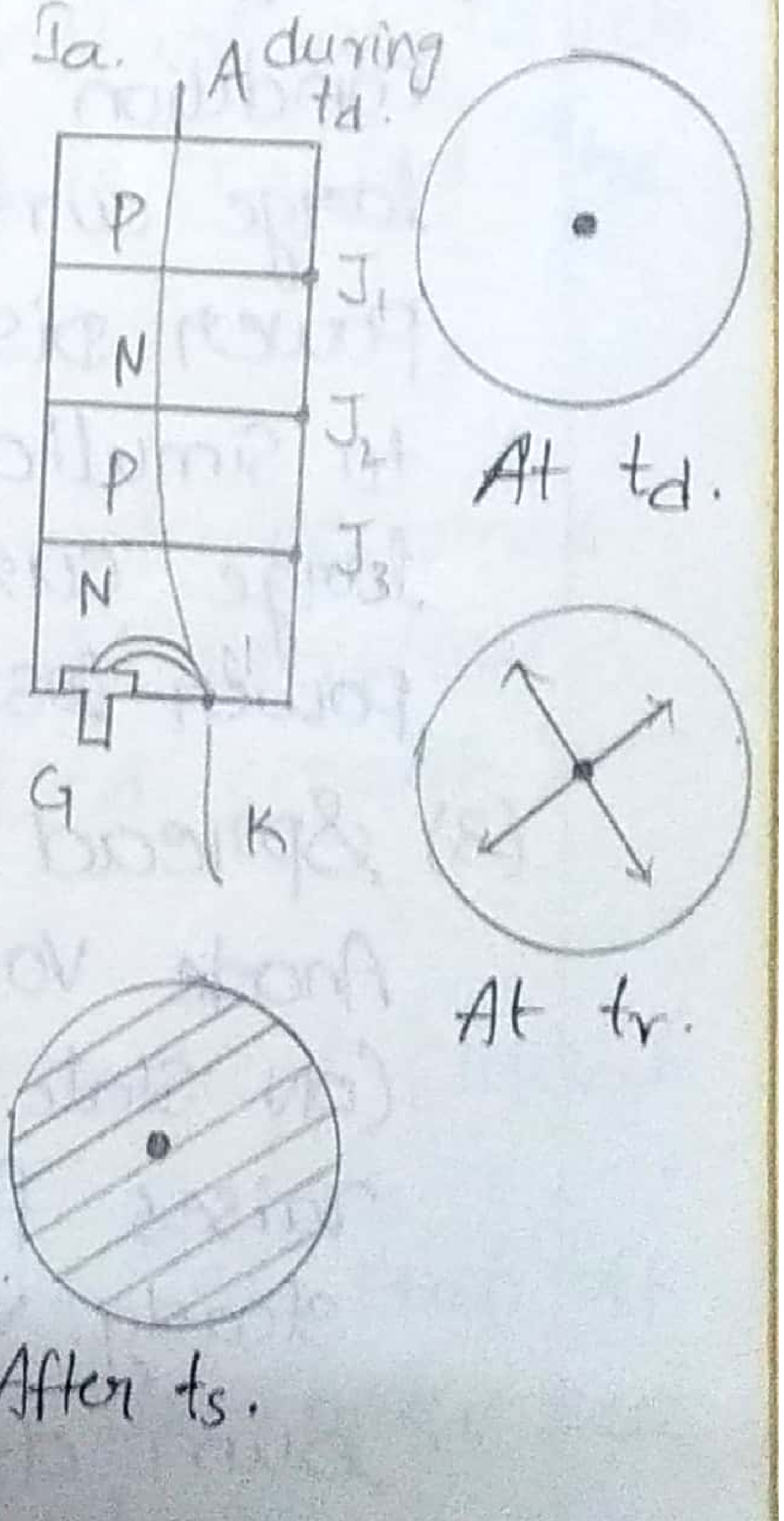
→ t_{gr} - Gate Recovery Time

→ t_q - Device Turn on Time.

→ t_c - circuit Turn on Time.

→ Magnitude of Turn on Time of SCR depends upon Gate current and also load circuit parameters.

fig:- Distribution of Ia during td.



→ Turn-on Time of SCR:-

→ The Time taken by SCR to switch from forward Blocking state to forward conduction state.

→ Converter Grade SCR's have Turn off time (50-100)μs

→ Inverter Grade SCR's have High Turn off Time i.e, (3-50)μs [when anode is made positive w.r.to cathode with Gate open ($I_g=0$). The Anode current depends upon leakage currents and current Gains. when Gate current is injected into Trans. Q_2, Base current of Trans. Q_2 increases and then Emitter current of Trans Q_2 increases. As I_E increases current Gain ($\alpha = \alpha_1+\alpha_2$) increases]"

→ Turn ON Time of SCR is divided into 3 Time intervals

(1) Delay Time:- The Time during which the Anode voltage V_a falls from V_a to $0.9\,V_a$. (or) Anode current rises from forward leakage current to $0.1\,I_a$.

(2) Rise Time:- The Time during Anode Voltage falls from $0.9\,V_a$ to $0.1\,V_a$ (or) Anode current rises from $0.1\,I_a$ to $0.9\,I_a$ is called Rise Time. During Rise Time condition loss is more due to large Voltage and large currents simultaneously present in SCR i.e, power Dissipation during Rise Time is large due to simultaneously application of large Voltage & large current. These power Dissipation is called power loss or switching loss in SCR.

(3) Spread Time:- The Time during which the Anode Voltage falls $0.1\,V_a$ to its lower Value (ON State Voltage Drop 1-1.5V) or Anode current raises from $0.9\,I_a$ to it's max Value or steady value.

∴ Sum of $t_r+t_d+t_s = T_{ON}$ Time of SCR.

→ Typical Value of T_{ON} Time of SCR is (1-4)μs

→ Turn on Time depends upon magnitude of Gate current and Load circuit parameters. If the magnitude of Gate current is increases and Turn off Time dec

→ If Load circuit Consists of series RL, di/dt is slow & then Turn on Time Increases. If Load circuit Consists series RC then di/dt is fast and then Turn on Time ↓

→ Turn off Time of SCR:- Time taken by SCR to switch from forward conduction to forward Blocking Mode is called Turn off Time & is divided into two types:-

→ Reverse Recovery Time:- It is removal of excessive charges from top and bottom layers of SCR.

→ Gate Recovery Time:- It is removal of excessive charge carriers across middle Junction or inner two layers SCR

/ forward voltage can be applied(or) between A and K after Gate Recovery Time It's Typical value is (3-100)μs. /

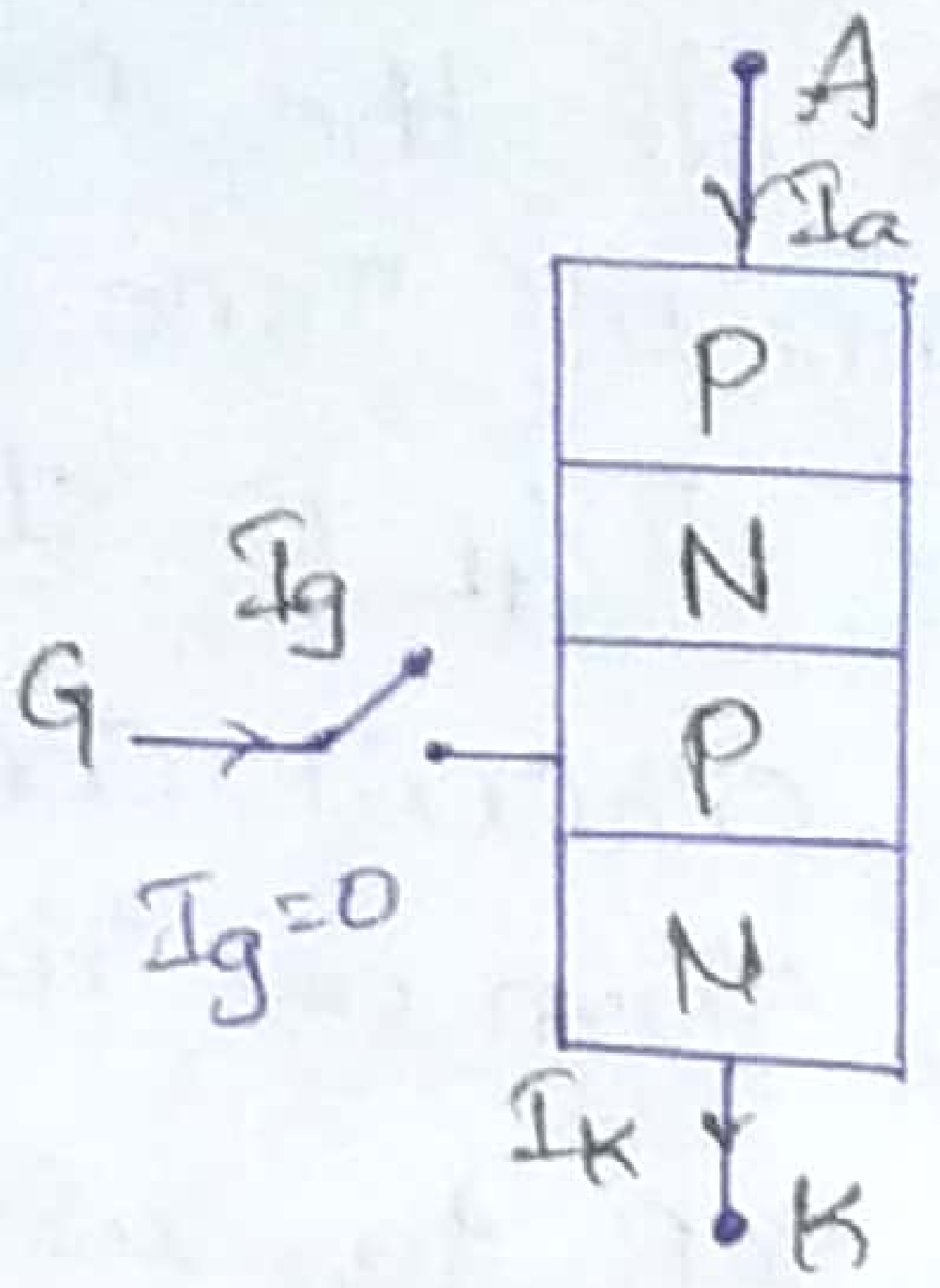
→ Device Turn off Time (T_q):-
Turn off Time provided to Individual SCR (or) Device
It is the time during the instant at which Anode current becomes zero (t_1) and the instant at which Reverse Voltage reaches to zero (t_4) is called the Device Turn off Time

→ Circuit Turn off Time:-
The Time during which Anode current becomes zero (t_1) and reverse voltage due to practical circuit reaches to zero (t_5) is called circuit Turn off Time, (or)

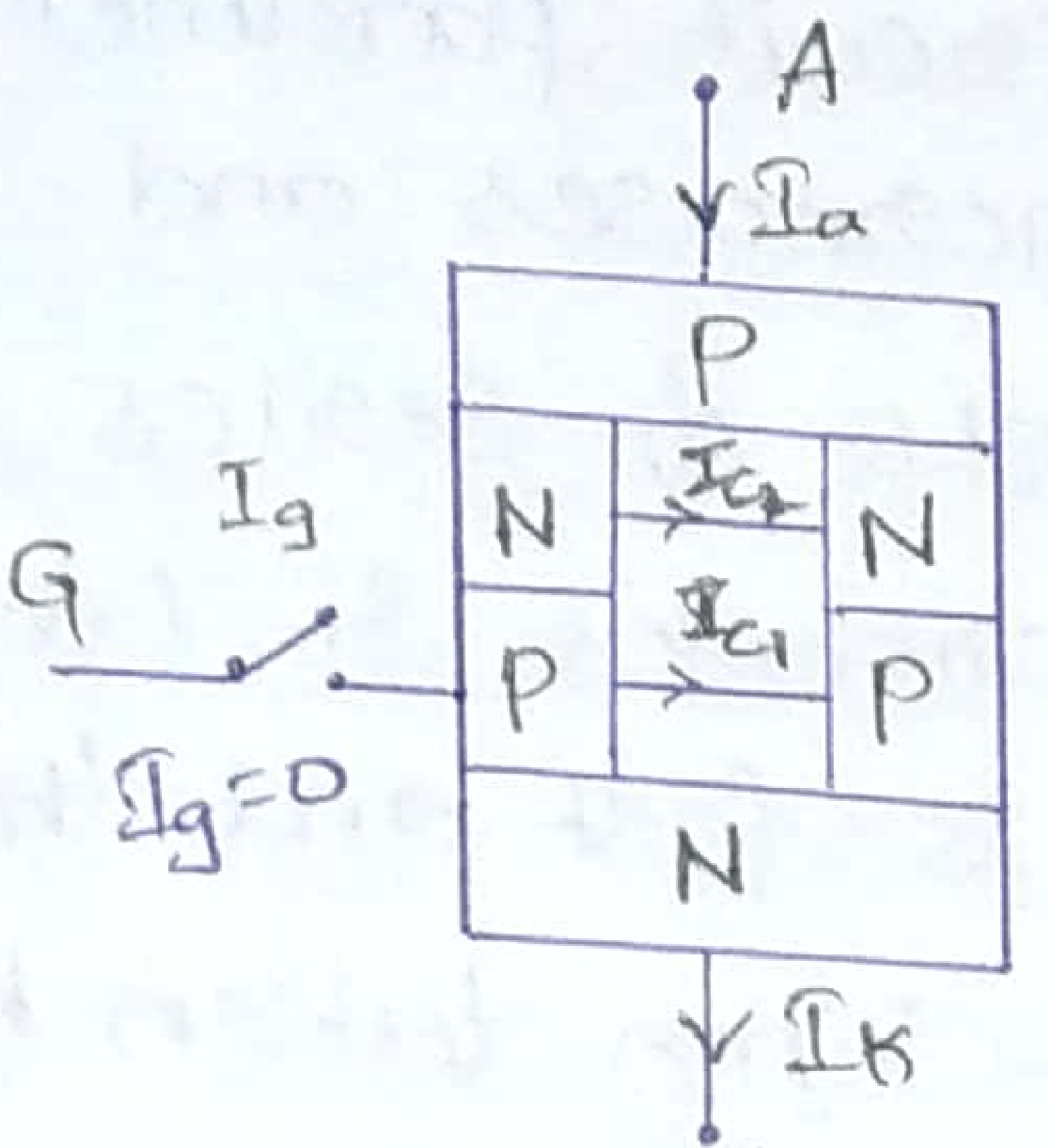
→ The T_{off} Time provided to SCR by practical circuit is called Turn off Time

→ Circuit T_{off} Time is (far) greater than Device Turn off Time for reliable operation of SCR. otherwise SCR will Turn on at any undesirable Instant.

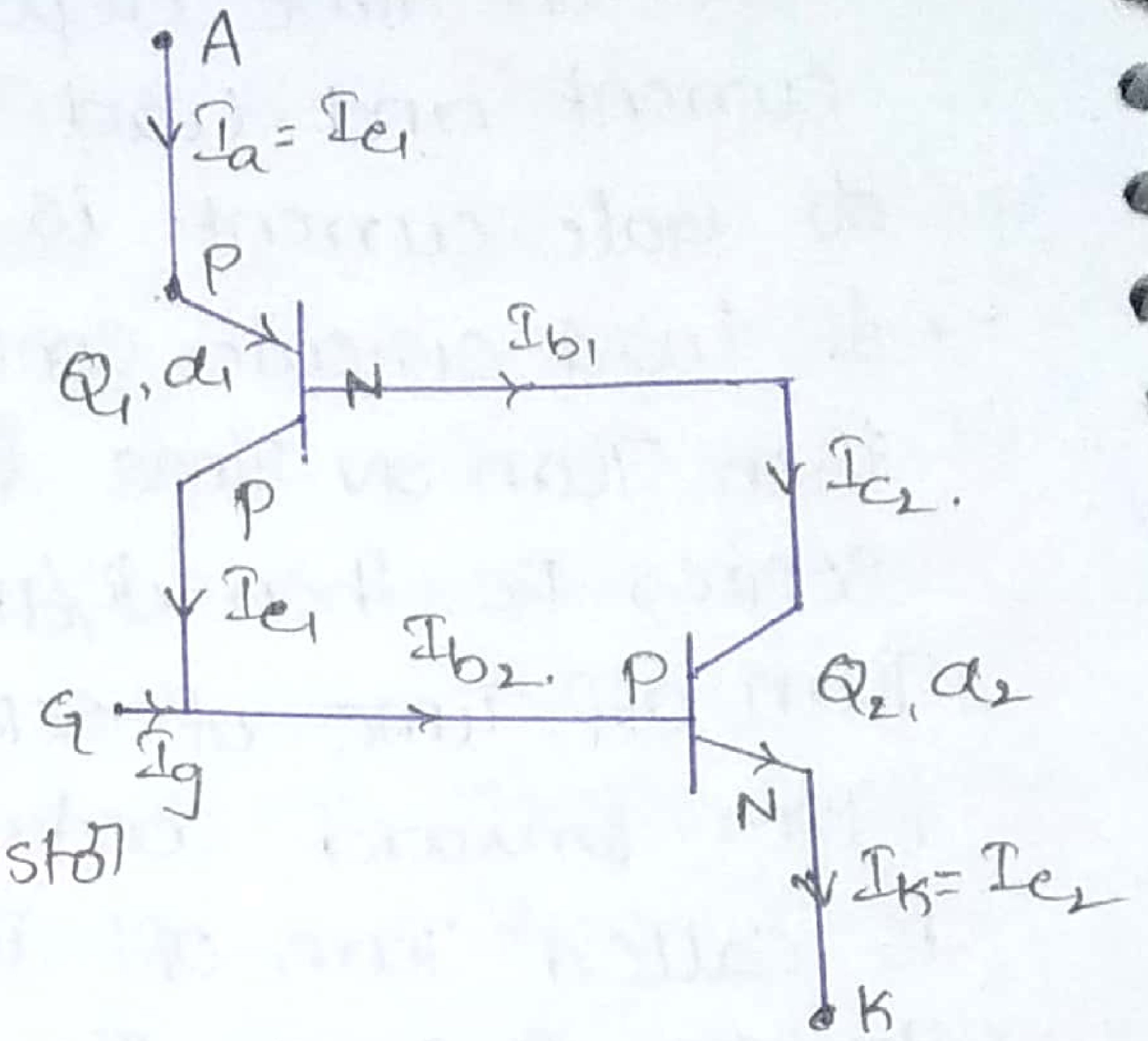
Two Transistor Analogy:-



(a) SCR



(b) Two-Transistor Model.



(c) Circuit Configuration.

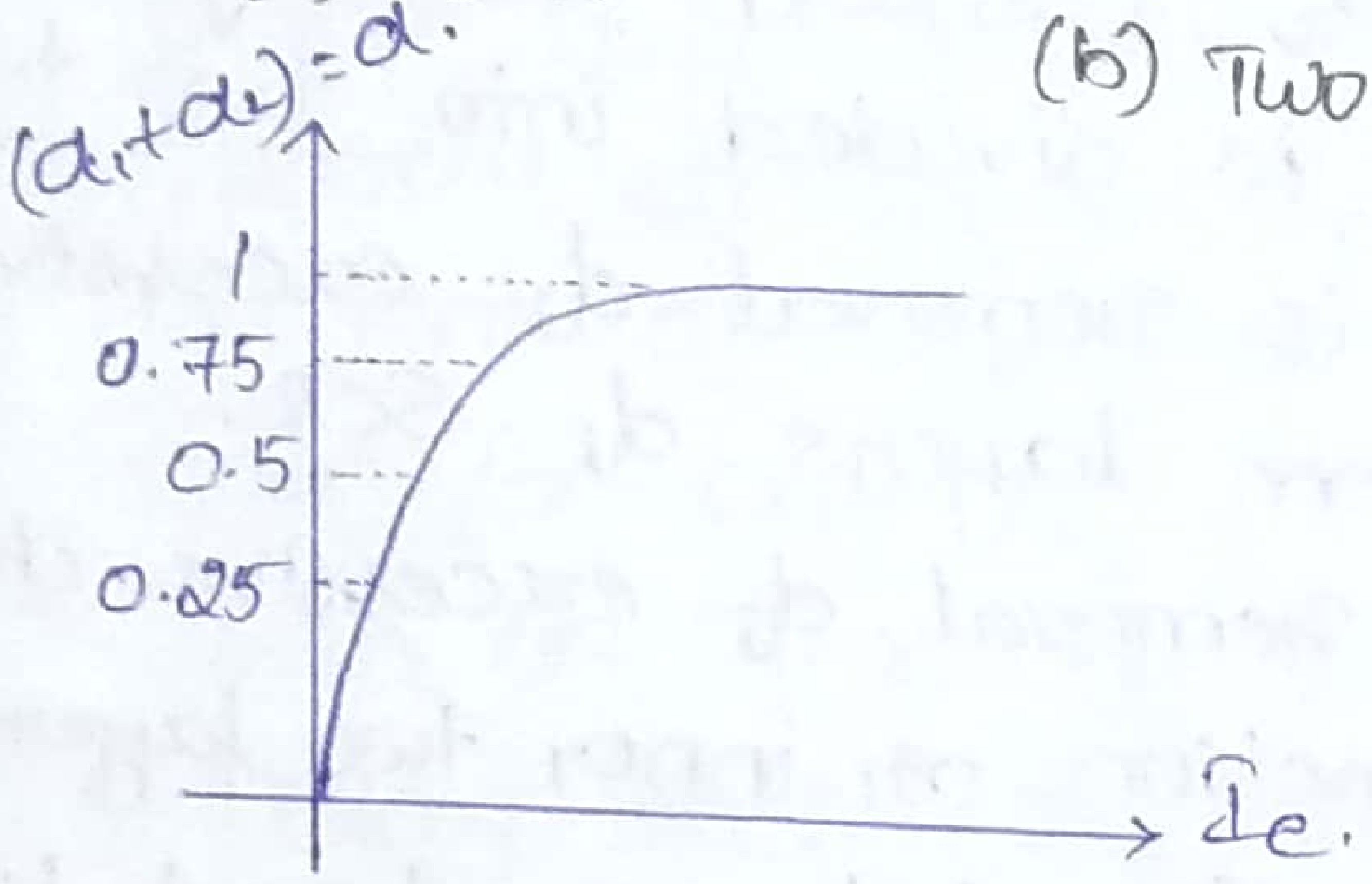


fig:- Typical Variation b/w Emitter current & Current Gain (d) (α) for Silicon Transistor.

- $\alpha_1 = \frac{I_{C_1}}{I_{e_1}}$

- In Two Transistor Analogy, the operation of four layer SCR can be explained by Considering two Transistors.

- A Two Transistor Model can be obtained by bisecting the inner middle layers into two (parts) half's as shown in fig.

- α_1 & α_2 are the Common Base current Gains of Transistor-Q_1 and Transistor-Q_2. It is measure of how closely the collector current and Emitter currents are related and is defined as the ratio of Collector current to Emitter current.

$\Rightarrow \alpha_1 = \frac{I_{c_1}}{I_{e_1}}$; $\alpha_2 = \frac{I_{c_2}}{I_{e_2}}$

$\Rightarrow I_{c_1} = \alpha_1 \cdot I_{e_1}$ & $I_{c_2} = \alpha_2 \cdot I_{e_2}$.

$\Rightarrow I_{c_1} = \alpha_1 I_{e_1} + I_{CBO1}$. $\rightarrow (1)$; $I_{c_2} = \alpha_2 I_{e_2} + I_{CBO2} \rightarrow (2)$

(By considering leakage current)

from fig (c) :-

$I_{b_1} = I_{c_2} \rightarrow (3)$

$I_{c_1} = I_{b_2} \rightarrow (4)$

Apply KCL at Q_1 & Q_2

$\Rightarrow I_{e_1} = I_{b_1} + I_{c_1} \rightarrow (5)$

$\Rightarrow I_{e_2} = I_{c_2} + I_{b_2} \rightarrow (6)$

→ Sub Eqn (1) in Eqn (5).

$\Rightarrow I_{e_1} = I_{b_1} + \alpha_1 I_{e_1} + I_{CBO1}$.

$\Rightarrow I_a = I_{b_1} + \alpha_1 I_a + I_{CBO1}$ ($\because I_a = I_{e_1}$)

$\Rightarrow I_a (1-\alpha_1) = I_{b_1} + I_{CBO1}$.

$\Rightarrow I_{b_1} = I_a (1-\alpha_1) - I_{CBO1} \rightarrow (7)$

from Eqn. (3)

$I_{b_1} = I_{c_2}$.

$\Rightarrow I_a (1-\alpha_1) - I_{CBO1} = \alpha_2 I_{e_2} + I_{CBO2}$.

$\Rightarrow I_a (1-\alpha_1) - I_{CBO1} = \alpha_2 I_K + I_{CBO2}$ [$\because I_{e_2} = I_K$ & $I_K = I_a + I_g$].

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

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

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

$$\therefore * \Big/ I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1-(\alpha_1+\alpha_2)} \Big/ * \rightarrow (8)$$

→ If Leakage currents are neglected.

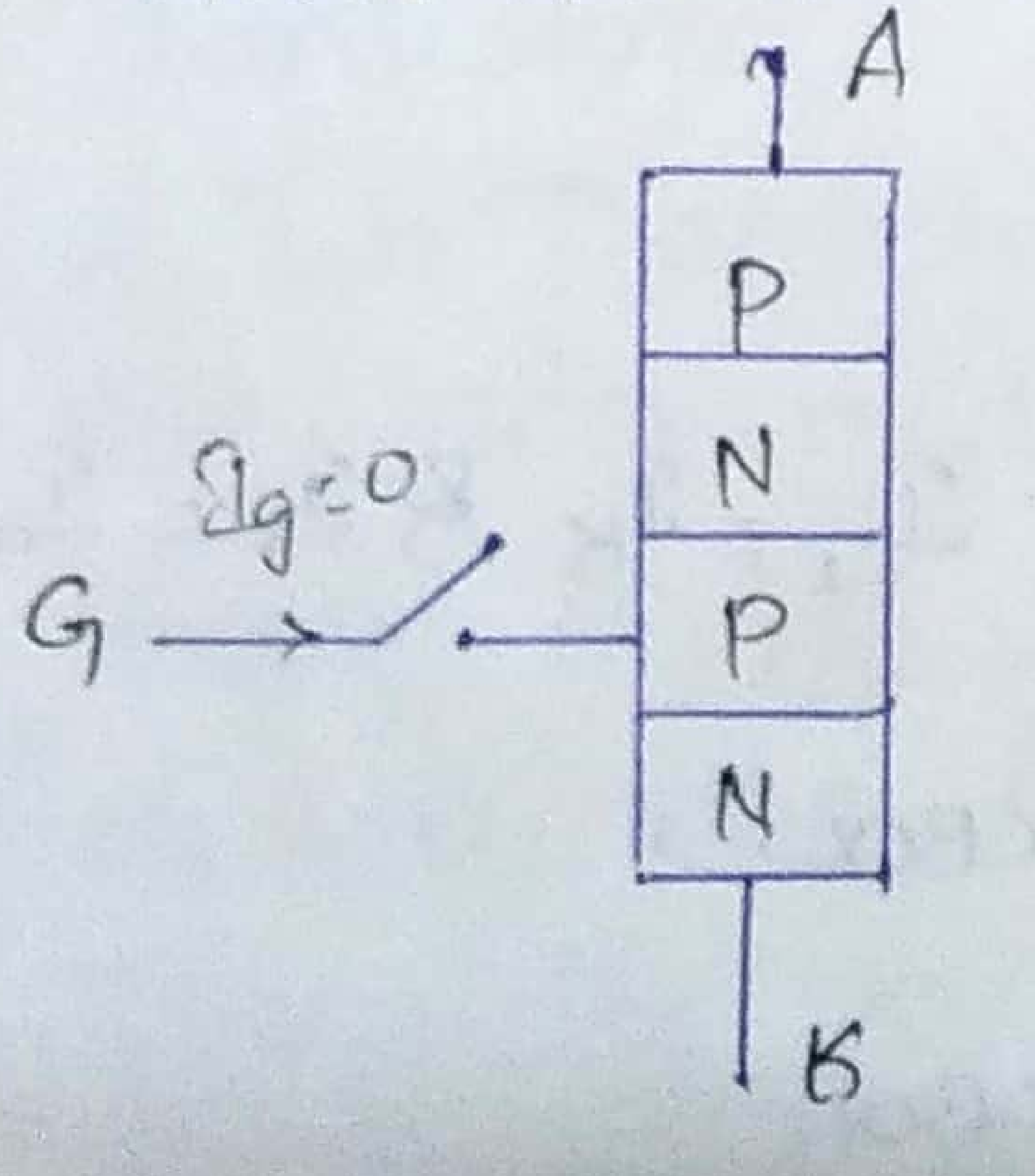
$$\therefore\ I_a = \frac{\alpha_2 I_g}{1-(\alpha_1+\alpha_2)} \quad \rightarrow (8+1)$$

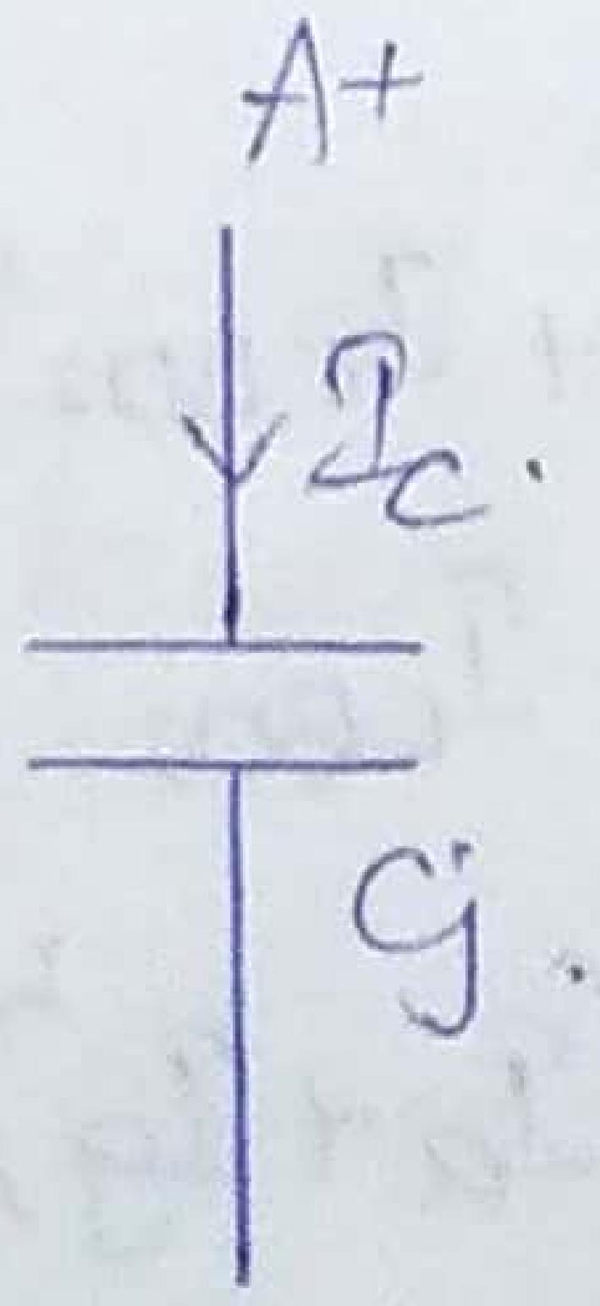
→ from Eqn (8) it is observed that Anode current mainly depends on Gate current I_g and current Gains α_1 & α_2.

→ for Silicon Transistor, Emitter current is low, for low values of current Gain. As Emitter current increases current Gain also increases rapidly & reached to its Steady Value, as shown in fig (d).

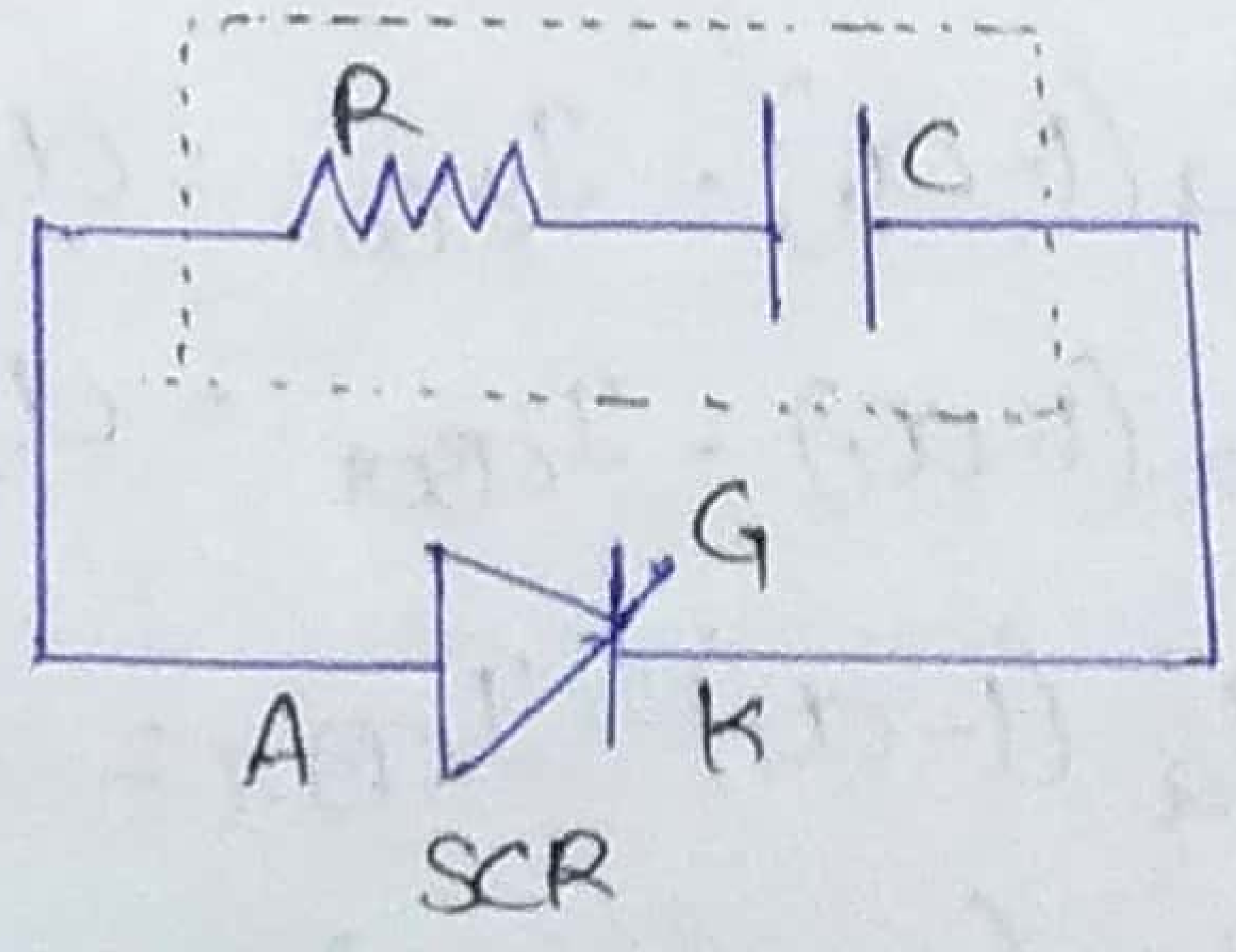
→ when Anode is made positive with respect to Cathode with Gate open ($I_g = 0$). The Gate current depends upon leakage currents and current Gains. When Gate current is injected into the Trans. Q_2. When Base current of Trans- Q_2 increases and then Emitter current of Trans- Q_2 increases. As I_E increases current Gain ($\alpha = \alpha_1 + \alpha_2$). increases at $\alpha = 1$, Anode current becomes Infinity and SCR is turn on.

→ Snubber circuit :-





Snubber ckt.



→ Refer dv/dt triggering :-

$$I_c = \frac{dQ}{dt} = \frac{d\,(C_j V_a)}{dt}$$

$$\Rightarrow I_c = c_j \frac{dV_a}{dt} + V_a \cdot \frac{dc_j}{dt}$$

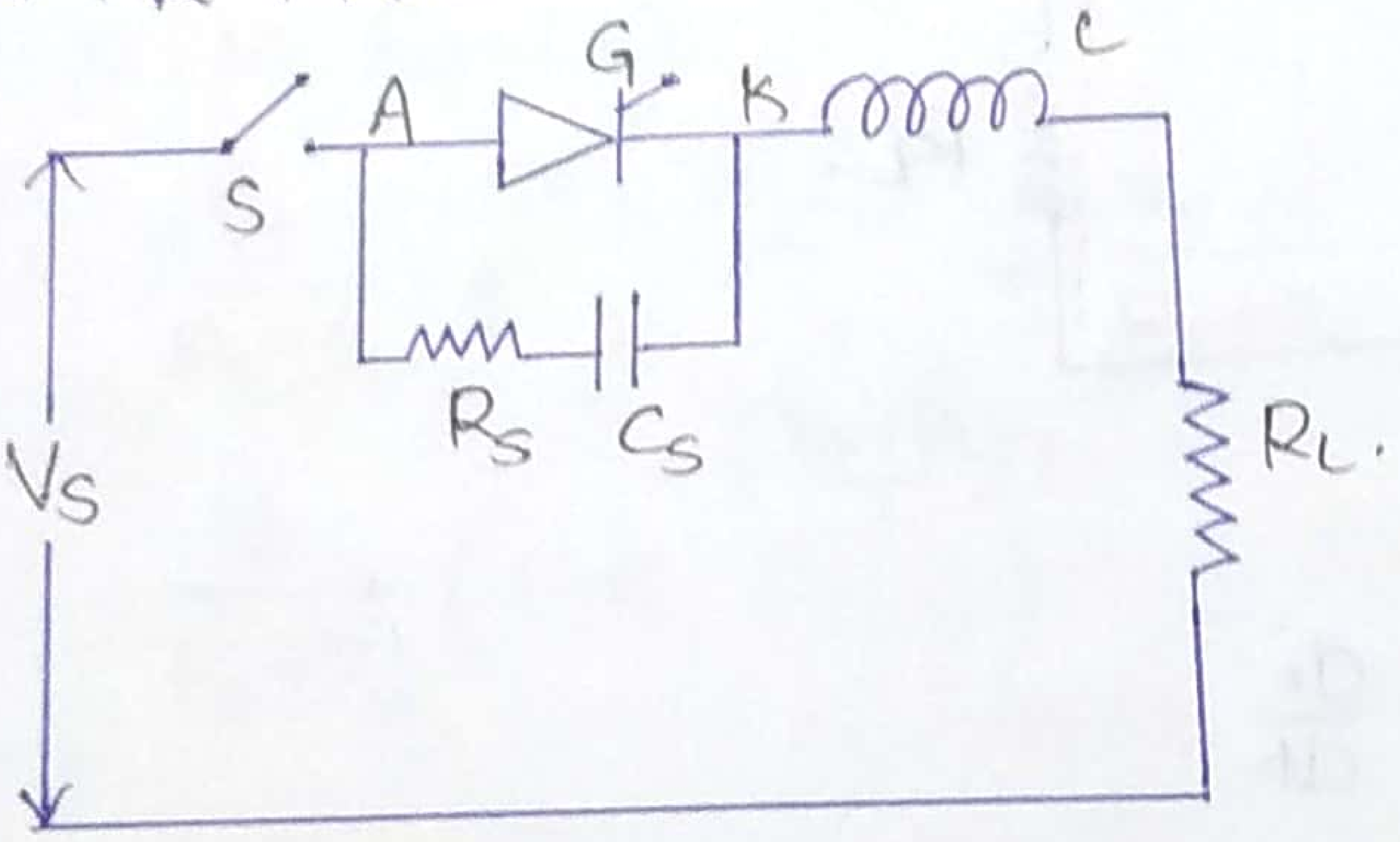
$$\therefore \frac{dc_j}{dt} = 0$$

$$\therefore I_c = c_j \frac{dV_a}{dt}$$

→ To avoid malfunctioning (or) false Turn on of SCR, high dv/dt be limited. The High dv/dt is limited by Snubber circuit in parallel to device.

→ Snubber circuit is a series combination of the Resistance and Capacitance, connected in parallel to the device in order to limit high dv/dt.

→ Design of Snubber circuit:-



→ when Switch S is closed a sudden voltage applied across the SCR and Capacitor behaves as short circuit. As a Result voltage across capacitor and SCR is zero at the instant of closing the switch because both are connected in parallel.

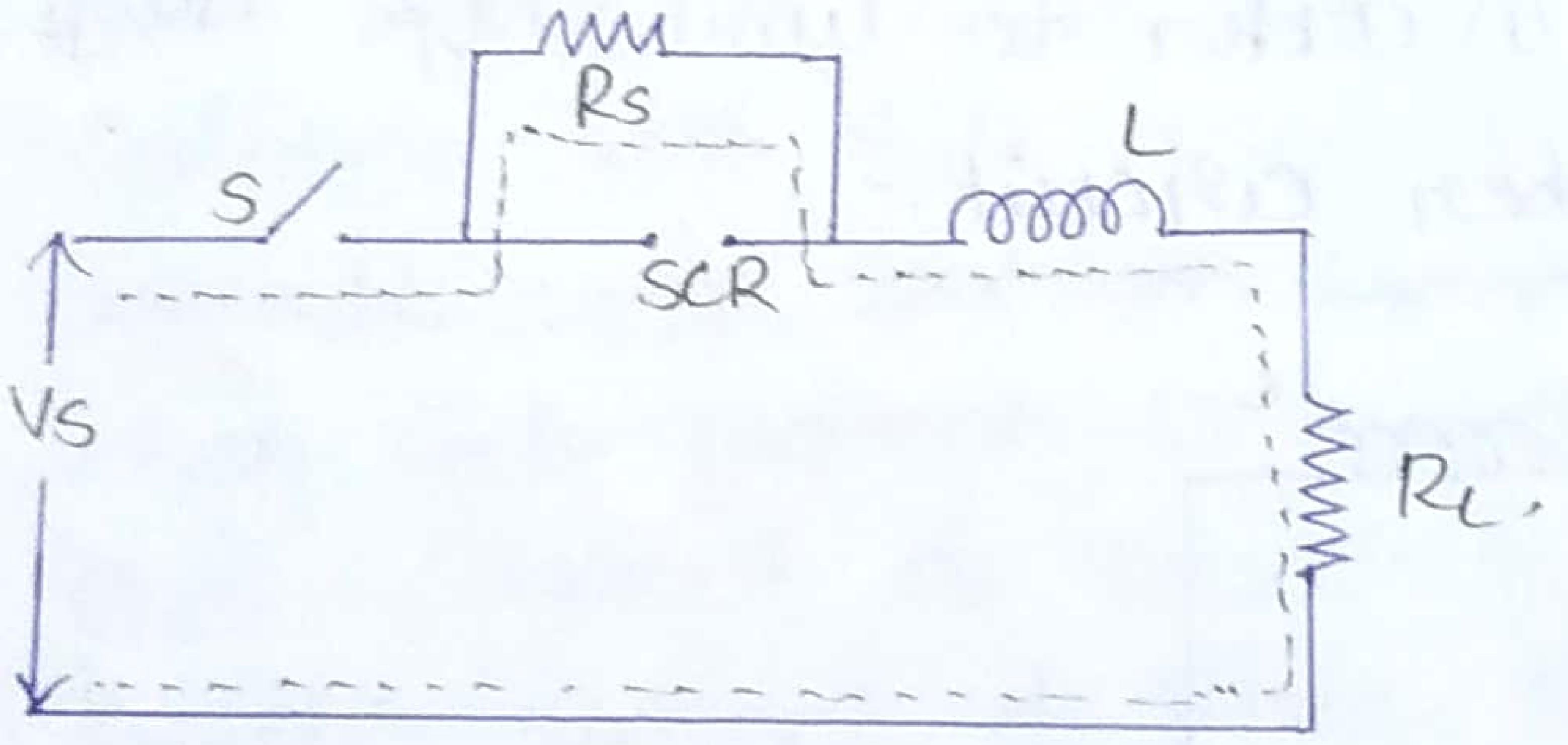
→ As time goes on capacitor build ups voltage and charged to full voltage V_s. i.e., before the SCR is turned on capacitor is charged to full voltage when SCR is turned on by applying a proper Gate pulse the capacitor discharges current $(I = \frac{V_s}{R_t})$. through SCR, where R_t = local Resistance path.

formed by SCR and capacitor.

→ As Local Resistance path is very low; discharging current is High. These large discharging current may damage SCR permanently.

→ To avoid magnitude of discharging current, a Resistance Rs is connected in series with Capacitor C_s.

→ (To find Resistance) when Switch is closed, Capacitor behaves as short circuit and SCR is in forward Blocking Mode. The Equivalent circuit after closing Switch is shown in figure.



→ Applying KVL,

$$V_s = (R_s+R_L)i + L\cdot\frac{di}{dt}$$

$$\Rightarrow L\frac{di}{dt} + (R_s+R_L)i = V_s$$

$$\Rightarrow \frac{di}{dt} + \left(\frac{R_s+R_L}{L}\right)i = \frac{V_s}{L}. \rightarrow (1)$$

This is the Linear first Order DE, compare it with Non-Homogenous Eqn.

$$\Rightarrow \frac{dx}{dt} + px = K \rightarrow (2)$$

whose Solution is,

$$x = ce^{-pt} + e^{-pt}\int Ke^{+pt}\,dt$$

$$x = i;\ p = \frac{R_s+R_L}{L};\ K = \frac{V_s}{L}$$

Now, $i = Ce^{-\left(\frac{R_s+R_L}{L}\right)t} + e^{-\left(\frac{R_s+R_L}{L}\right).t} \int \frac{V_s}{L} \cdot e^{\left(\frac{R_s+R_L}{L}\right).t} dt.$

$$\Rightarrow i = Ce^{-\left(\frac{R_s+R_L}{L}\right)t} + \cancel{e^{-\left(\frac{R_s+R_L}{L}\right)t}} \cdot \frac{\frac{V_s}{\cancel{L}} \cdot \cancel{e^{+\left(\frac{R_s+R_L}{L}\right).t}}}{\frac{R_s+R_L}{\cancel{L}}}$$

$$\Rightarrow i = Ce^{-\left(\frac{R_s+R_L}{L}\right)t} + V_s/R_s+R_L \rightarrow (3)$$

At $t=0,\ i=0$

i.e., $t^-=0;\ i=0$

$t^+=0;\ i=0.$

$$\Rightarrow 0 = Ce^{-\left(\frac{R_s+R_L}{L}\right)0} + \frac{V_s}{R_s+R_L}.$$

$$\Rightarrow 0 = C + \frac{V_s}{R_s+R_L}.$$

$V \rightarrow 230$

$I \rightarrow 1.5, 2, 2.5, 3, 3.5, 4$

$\omega \rightarrow$ ~~162, 210~~
176, 220, 280, 330, 380, 440

$T \rightarrow 16.2, 12.45, 9.81, 8.58, 7.26, 6.54.$

Sub c. in Eqn (3).

$$\Rightarrow i = \frac{-V_s}{R_s+R_L} \cdot e^{-\left(\frac{R_s+R_L}{L}\right).t} + \frac{V_s}{R_s+R_L}$$

$$= \frac{V_s}{R_s+R_L}\left(1-e^{-\left(\frac{R_s+R_L}{L}\right)t}\right)$$

$$\Rightarrow i = I\left(1-e^{-t/\tau}\right) \rightarrow (4)$$

τ = Time constant $= \frac{L}{R_s+R_L}$; $I = \frac{V_s}{R_s+R_L}.$

diff. Eqn (4) w.r. to t.

$$\Rightarrow \frac{di}{dt} = 0 - I \cdot e^{-t/\tau}\left(-1/\tau\right).$$

$$= \frac{V_s}{R_s+R_L} \cdot e^{-t/\tau}\left(1/\frac{L}{R_s+R_L}\right)$$

$$= \frac{V_s}{L} \cdot e^{-t/\left(\frac{L}{R_s+R_L}\right)}$$

$\Rightarrow \frac{di}{dt} = \frac{V_s}{L} \cdot e^{-\left(\frac{R_s+R_L}{L}\right)t}$, At $t=0$, $\frac{di}{dt}$ is max

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

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

→ from fig (2). The voltage across the Thyristor is given by. $V_a = iR_s$.

$$\Rightarrow \frac{dV_a}{dt} = \frac{di}{dt} R_s.$$

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

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

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

→ As circuit Consists of 3 parameters R, L, C. Apply KVL

$$\Rightarrow \quad V_s = Ri + L\cdot\frac{di}{dt} + \frac{1}{C}\int i\cdot dt$$

$$\Rightarrow \quad \frac{dV_s}{dt} = R\cdot\frac{di}{dt} + L\cdot\frac{d^2i}{dt^2} + \frac{i}{C} \qquad (\text{since in dc } \frac{dV_s}{dt} = 0)$$

$$\Rightarrow \quad L\cdot\frac{di^2}{dt^2} + R\cdot\frac{di}{dt} + \frac{i}{C} = 0.$$

$$\Rightarrow \quad \frac{d^2i}{dt^2} + \frac{R}{L}\cdot\frac{di}{dt} + \frac{i}{LC} = 0$$

Let, $\frac{di}{dt} = D$

$$\Rightarrow \quad D^2 i + \frac{R}{L}\cdot Di + \frac{i}{LC} = 0$$

$$\Rightarrow \quad D^2 + \frac{R}{L}\cdot D + \frac{1}{LC} = 0.$$

$$\Rightarrow D^2 + \frac{R}{L}D + \frac{1}{LC} = 0.$$

Characteristics Eqn of Second order System.

$$\Rightarrow s^2 + 2\xi\omega_n s + \omega_n^2 = 0$$

$$\therefore \omega_n^2 = \frac{1}{LC} \Rightarrow \omega_n = \frac{1}{\sqrt{LC}}$$

$$2\xi\omega_n = \frac{R}{L} \Rightarrow 2\xi\frac{1}{\sqrt{LC}} = \frac{R}{L}.$$

$$\Rightarrow 2\xi\frac{1}{\sqrt{C}} = \frac{R}{\sqrt{L}}.$$

$$\Rightarrow 2\xi\sqrt{\frac{L}{C}} = R.$$

$$\Rightarrow 4\xi^2\sqrt{\frac{L}{C}} = R^2.$$

/ $C = \left(\frac{2\xi}{R}\right)^2 \cdot L$ /

*/ $R = \left(\frac{dv_a}{dt}\right)_{max} \cdot \frac{L}{V_s}$.

$L = \frac{V_s}{\left(\frac{di}{dt}\right)_{max}}$ & $C = \left(\frac{2\xi}{R}\right)^2 \cdot L.$ /*

* A SCR is controlling the power in Load Resistance R_L, Supply Voltage is 230V DC and specified limits for $\frac{di}{dt}$ and $\frac{dV}{dt}$ are 60A/μ sec. and 350V/μ sec. Design Snubber circuit.

Sol:- Given, $\frac{di}{dt} = 60A/\mu sec$; $\frac{dV}{dt} = 350V/\mu sec$; $V_s = 230$.

$$\therefore R = \left(\frac{dV}{dt}\right)_m \frac{L}{V_s}.$$

$$\therefore L = \frac{V_s}{\left(di/dt\right)} = \frac{230}{60} = 3.83\ H$$

$\therefore R = \frac{dv}{dt} \times \frac{L}{V_S}$

$= 350 \times \frac{3.83}{230}$

$\therefore R = 5.83 \Omega$

$\therefore C = \left(\frac{2\xi}{R}\right)^2 \cdot L$ (Under Damped System)

$= \left[\frac{2 \times 0.5}{5.83}\right]^2 \times 3.833$

$\therefore C = 0.113$ f.

* An SCR can be triggered with 220V/μsec, with charging current flows through the junction is 5mA. Calculate Equivalent Capacitance of the Depletion layer.

Sol:- Given, $\frac{dv}{dt} = 220 \, V/\mu sec$

$I_C = 5mA$

we have, $I_C = C_j \frac{dv}{dt}$

$\Rightarrow C_j = \frac{5m}{220} = 22.7 \mu F$

$\therefore C_j = 22.7 \mu F$

* The capacitance of Reverse Biased Junction J_2 in SCR is 25 pf and can be assumed to be independent of off state Voltage. The limiting value of charging current to turn on SCR is 160mA. Determine value of $\frac{dv}{dt}$

IES

Sol:- Given, $C_j = 25 \times 10^{-12}$; $I_C = 16m$.

$\therefore \frac{dv}{dt} = \frac{16m}{25p} = 640 \times 10^6 \, V/sec$

$= 640 \, V/\mu sec.$

→ Series & Parallel operation of SCR :-

→ Now-a-days the available voltage and current rating of SCR is 10 KV, 3KA. In sometimes we face more load demand than these ratings, in such a case we need to connect two or more SCR's in series or parallel in order to meet high voltage & high current demand.

→ Series connection of SCR's meet High voltage demand.

→ Parallel connection of SCR meet High current dem.

→ These is the necessity of series & parallel op. of SCR

→ String Efficiency :-

→ It is the measure of utilisation of SCR Rating.

$$\text{String } \eta = \frac{\text{Actual V/I Rating of whole String}}{\text{Individual V/I Rating of SCR} \times n}$$

n = No. of SCR's connected in series or parallel in a string.

→ Ideally, String $\eta = 1$. ie., all the SCR connected in string will utilise their rating fully.

→ Practically, String η always < 1, because even though we are using same rating SCR's due to having difference in there V-I characteristics, they share unequal voltages.

→ Derating factor (D) :-

→ It is measure of Reliability of the string and it is given by,

/ $D = 1 - \eta$ /

→ with increase of No. of SCR's in a string, Voltage or current shared by each SCR reduces, reliability of string increases but utilisation of SCR rating decreases.

∴ String Efficiency decreases.

→ Series Operation of SCR:-

→ (pro) when System voltage is greater than Voltage rating of single SCR, in Such a case two or more SCR's Should be connected in Series in order to meet High Voltage Demand.

→ Problems arise in Series operation:-

(1) Unequal Sharing of voltage due to having the difference in forward blocking characteristics.

(2) Unequal sharing of Voltage in the Reverse Recovery characteristics.

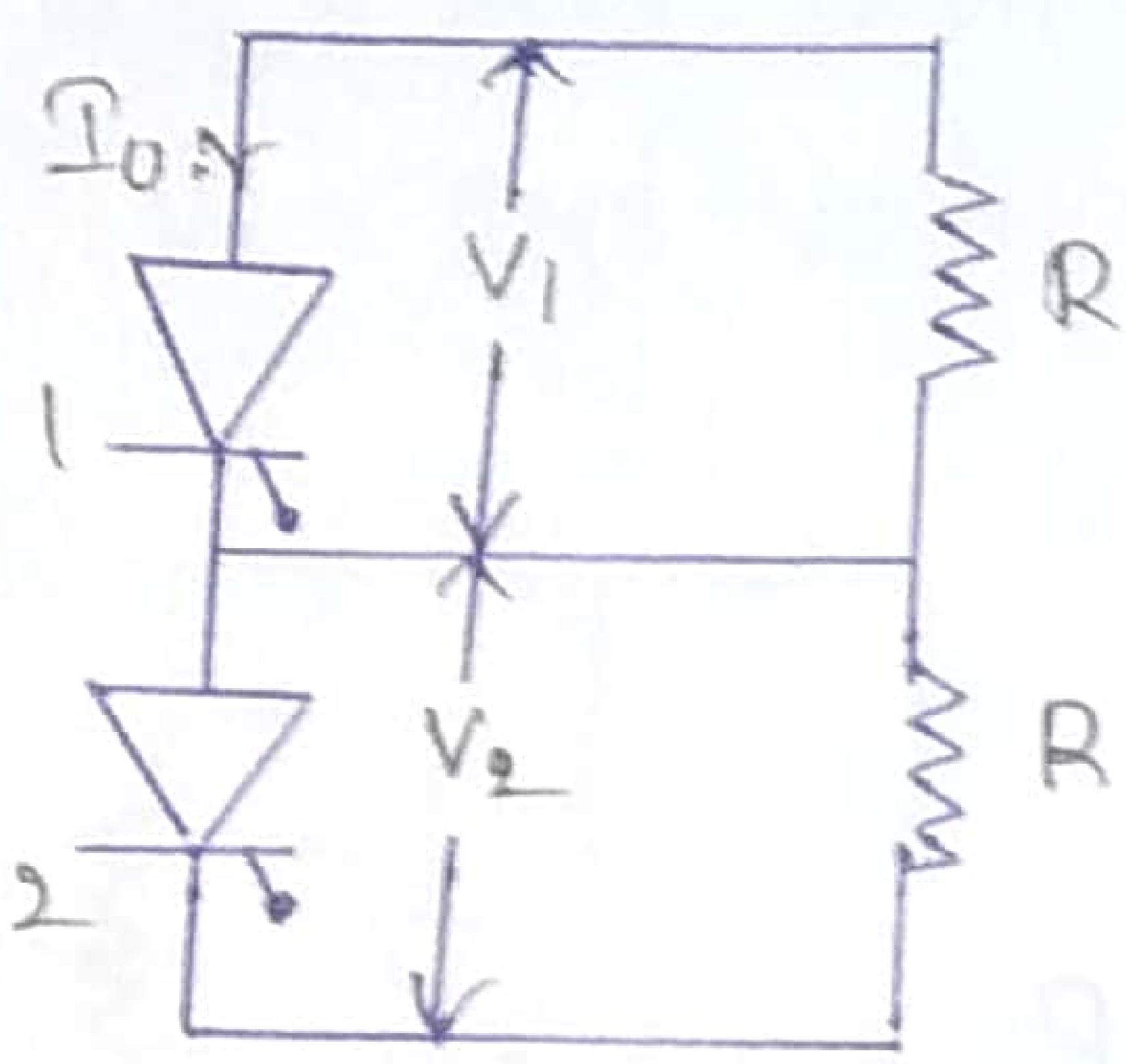
→ Problm 1:-

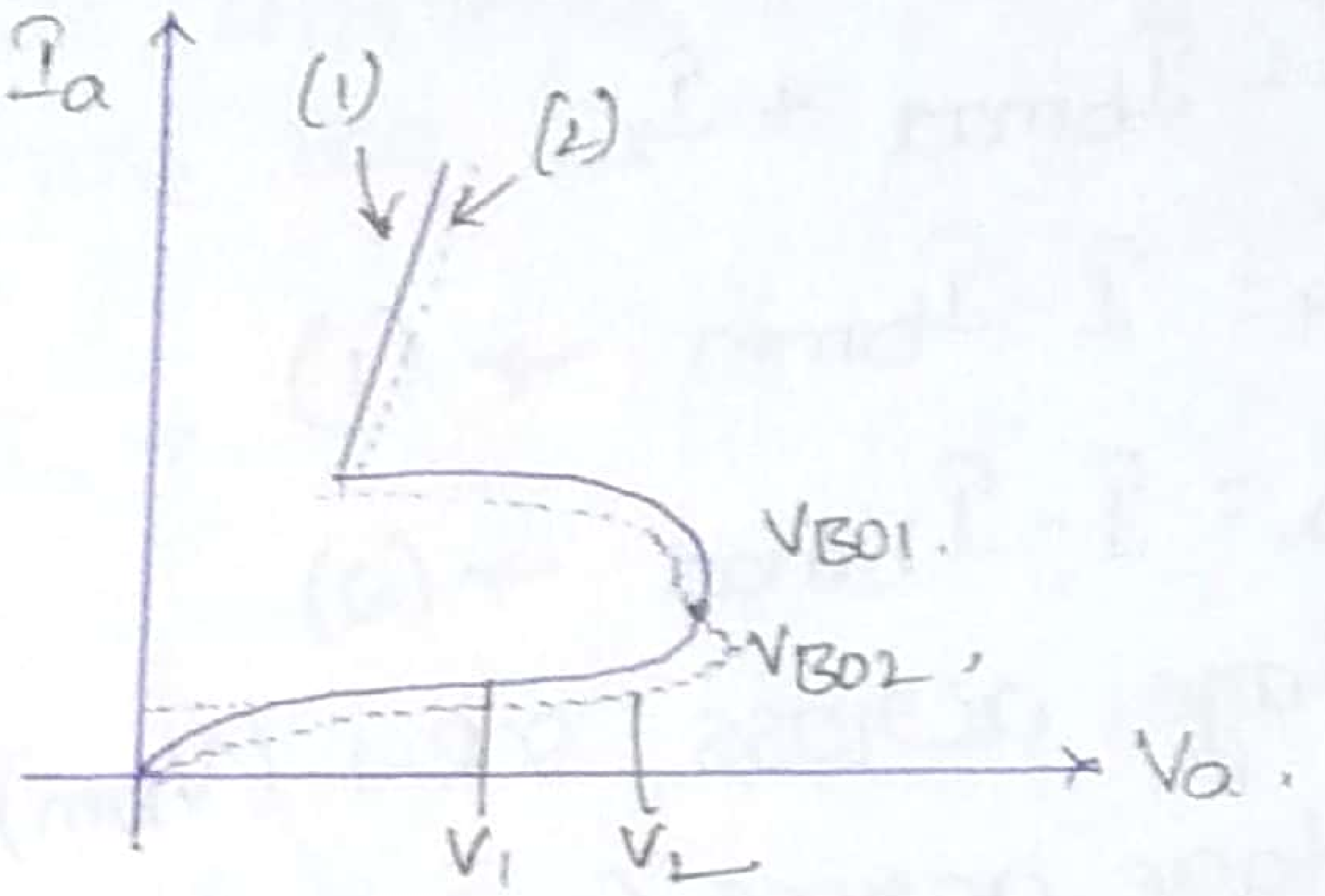
→ from fig (2). it is observed that due to having difference in their forward blocking characteristics, for same leakage current I_0, SCR's Connected in String shares unequal Voltage i.e., SCR$_1$ blocks V_1 and SCR$_2$ blocks V_2 which is greater than

→ The Internal Reason to share unequal Voltage is due to having diff in their internal Resistance)

→ The unequal Sharing of voltage across each SCR

Can be avoided by using same value of shunt Resistance (R) across each SCR.



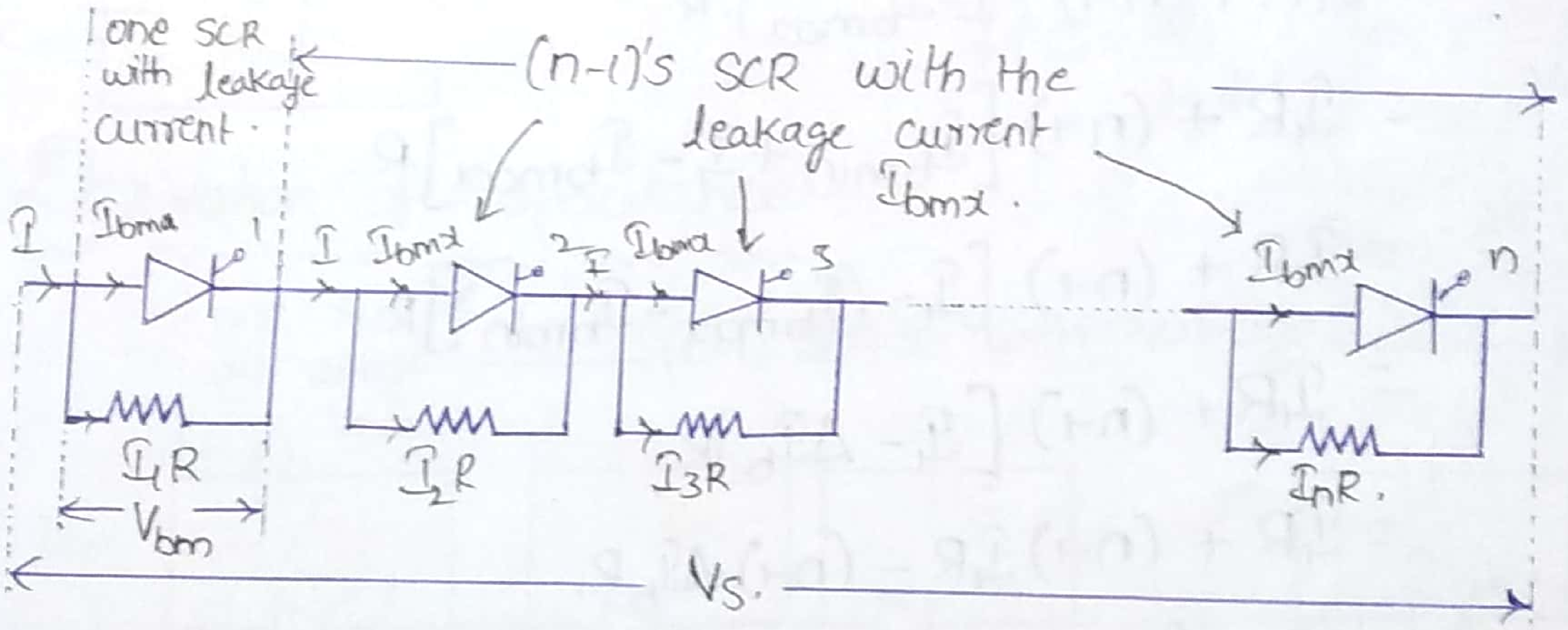


fig(1):-

fig(2):- $r_1 = \frac{V_1}{I_0}$ & $r_2 = \frac{V_2}{I_0}$.

$$\eta = \frac{V_1+V_2}{V_1 \times 2} = \frac{1}{2}\left(1+\frac{V_2}{V_1}\right).$$

→ Derivation of Resistance (r_1):-



→ Consider n No. of SCR's are connected in series, across each SCR same value of Resistance R are connected shown in figure

→ Let SCR, has minimum leakage current (I_{bm}) and remaining (n-1) SCR's has maximum leakage current (I_{bms}). As SCR-1 has minimum leakage current it blocks maximum voltage (V_{bm}) which is greater than voltage blocked by (n-1) SCR's.

from fig(3)

$\Rightarrow I = I_{bmin} + I_1$;

$I = I_{bmax} + I_2$.

& $I_1 = I - I_{bmin} \rightarrow (1)$

$I_2 = I - I_{bmax} \rightarrow (2)$.

→ Voltage across SCR-1 $(V_{bm}) = I_1 R$.

→ Voltage across (n-1) SCR's $= (n-1) I_2 R$.

Total String Voltage, V_s

$$\Rightarrow V_s = I_1 R + (n-1) I_2 R.$$

$$= I_1 R + (n-1)(I - I_{bmax}) \cdot R.$$

$$= I_1 R + (n-1)\left[I_{bmin} + I_1 - I_{bmax}\right] R.$$

$$= I_1 R + (n-1)\left[I_1 - (I_{bmax} - I_{bmin})\right] R$$

$$= I_1 R + (n-1) \cdot \left[I_1 - \Delta I_b\right] R.$$

$$= I_1 R + (n-1) I_1 R - (n-1) \Delta I_b R.$$

$$= I_1 R\left[1 + (n-1)\right] - (n-1) \Delta I_b R$$

$$= I_1 R(n) - (n-1) \Delta I_b R.$$

$$= I_1 R n - (n-1) \Delta I_b R$$

$$\Rightarrow (n-1) \Delta I_b R = I_1 R n - V_s.$$

$$\Rightarrow (n-1) \Delta I_b R = V_{bm} n - V_S.$$

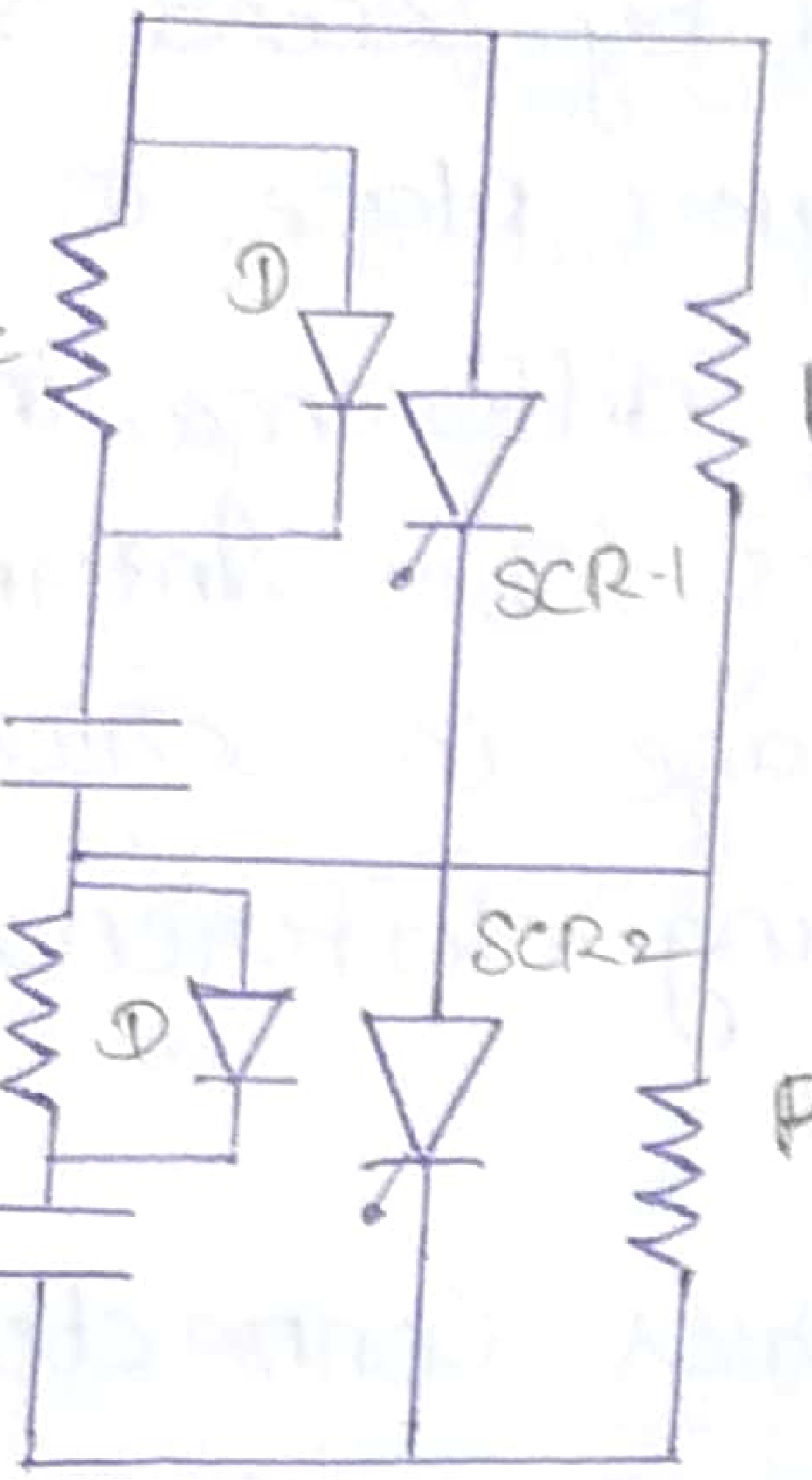
$$*/ \therefore R = \frac{n V_{bm} - V_s}{(n-1) \Delta I_b} /*$$

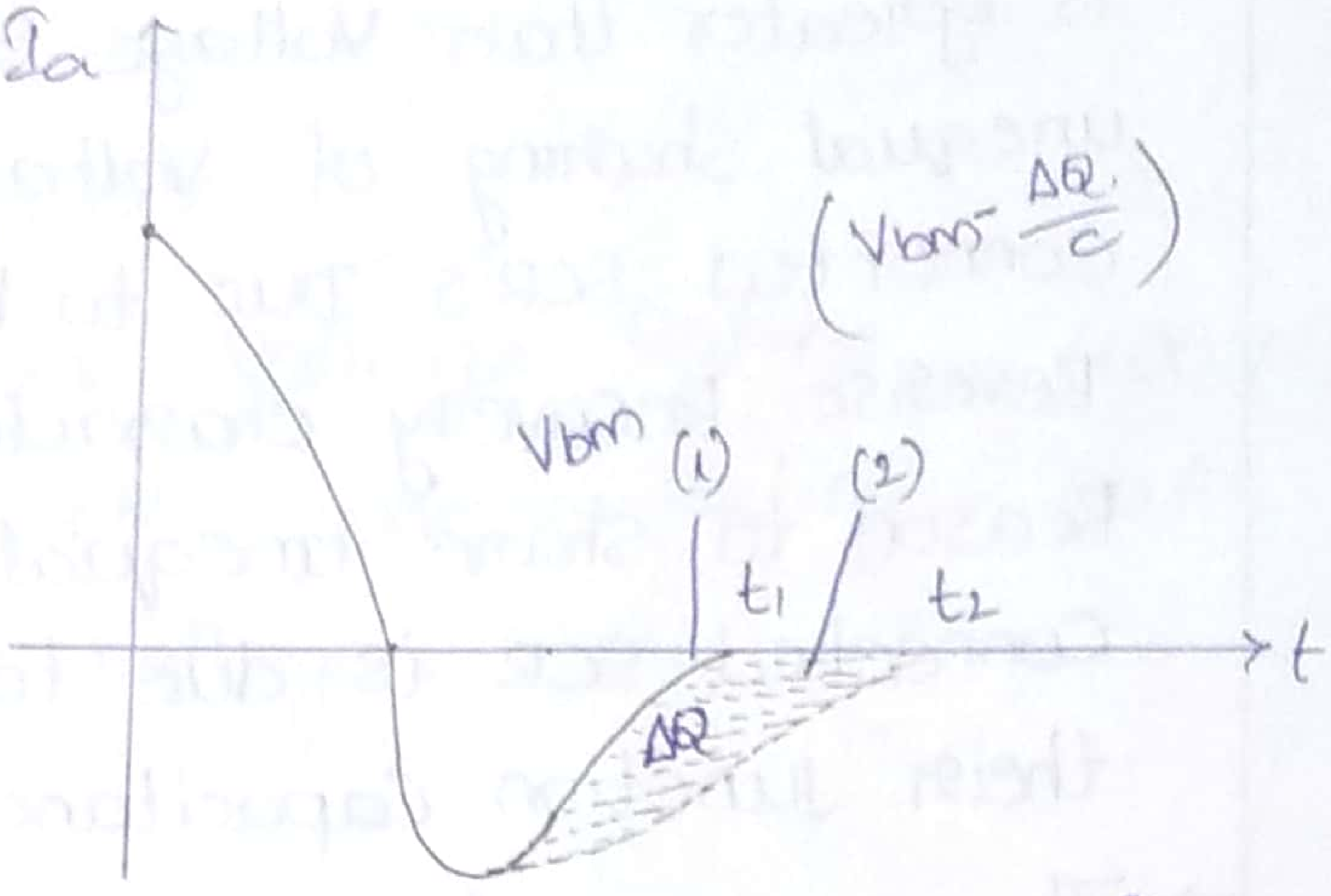
→ once value of R is ~~ca~~ known power can be calculated by using, */ $P_R = \frac{V_r^2}{R}$ /*

where V_{bm}: max. permissible voltage blocked by SCR.

ΔI_b = Max. permissible Difference in leakage currents.

V_r = RMS Voltage across SCR.





$\downarrow\uparrow C_1 = \frac{Q_1}{V_1 \downarrow\uparrow}$; $\uparrow C_2 = \frac{Q_2}{V_2 \downarrow}$

→ Derivation of Capacitance:-

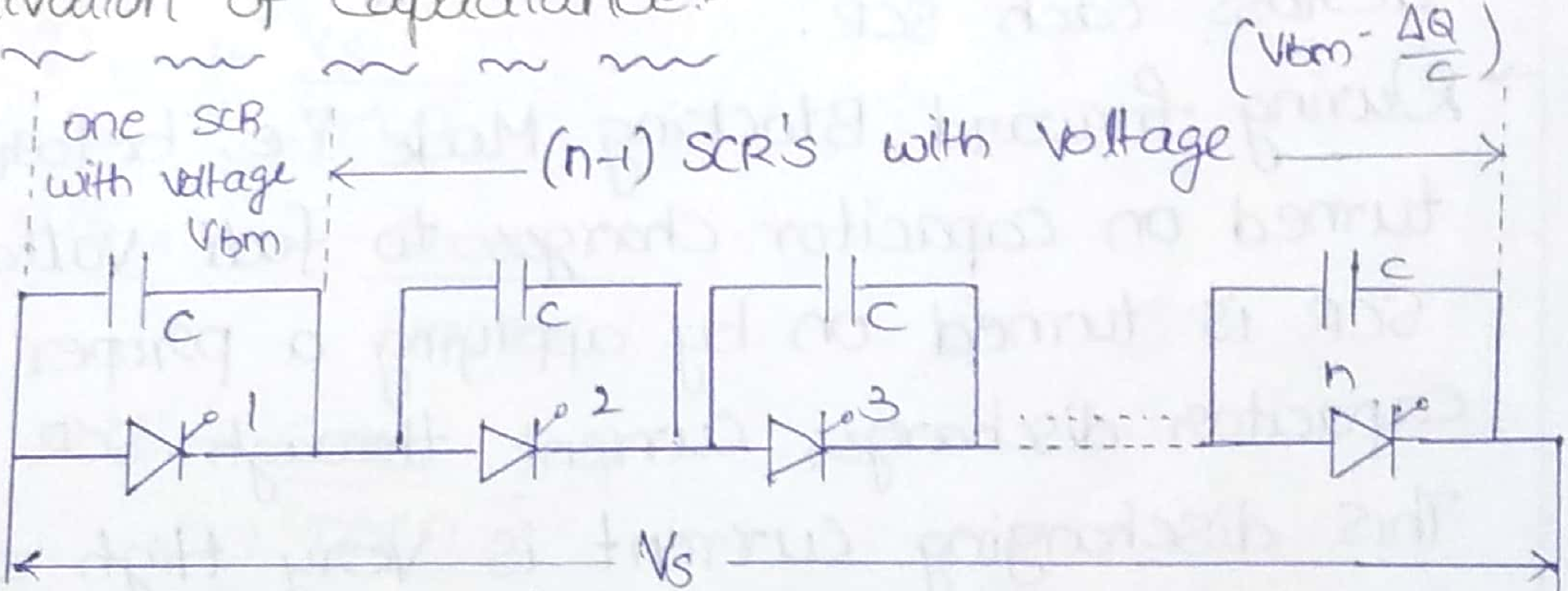


fig (3) String voltage.

→ Total String voltage; $V_s = V_{bm} + \left(V_{bm} - \frac{\Delta Q}{C}\right)(n-1)$

$\Rightarrow V_s = V_{bm} + (n-1)V_{bm} - (n-1)\frac{\Delta Q}{C}$

$\Rightarrow V_s = V_{bm}n - (n-1)\frac{\Delta Q}{C}$

$\Rightarrow (n-1)\frac{\Delta Q}{C} = nV_{bm} - V_s$

/ $C = \frac{(n-1)\Delta Q}{nV_{bm} - V_s}$ /

→ from fig (ii) it is observed that due to having difference in reverse recovery characteristics, SCR-1 has less Reverse Recovery Time and SCR-2 has more Reverse Recovery Time. As SCR-1 has less recovery time, it blocks maximum Voltage which is greater than Voltage blocked by second SCR. i.e., unequal sharing of Voltage takes place in Series connected SCR's; Due to having difference in their Reverse Recovery characteristics. (The Internal Reason to share unequal Voltage in series connected SCR is due to having difference in their junction Capacitances).

→ The unequal Sharing in the series connected SCR can be avoided by connecting capacitance, c across each SCR.

→ During forward Blocking Mode i.e., before SCR is turned on capacitor charges to full voltage. when SCR is turned on by applying a proper Gate pulse, capacitor discharges current through SCR ($i = \frac{V_s}{R_f}$). This discharging current is very High as Local Resistance path is very low, and may damage SCR permanently. To limit this high discharging current a Resistor R_c is connected in series with the capacitor 'c'.

→ Diode D across Resistor makes fast charging of capacitor. As SCR-1 has low junction capacitance ($C_{j_1} = \frac{Q_1}{V_1}$), it blocks max. Voltage (V_{bf}). As SCR_2 has High Junction Capacitance, It blocks voltage which ($V_{bm} - \frac{\Delta Q}{C}$)

is less than V_{bm}.

* Calculate No. of SCR'S each with rating of 400V. 50A in series string with a total voltage of 6KV. Take the Derating factor as 15%

A) Given, 400V, 50A

$V_{Tot} = 6KV.$

Derating factor = 15%

V_T = Individual SCR Voltage Rating = 400V

I_T = Individual SCR Current Rating = 50A

V_S = Total String voltage = 6KV.

$D = 15\% = 0.15.$

$$\therefore \eta = \frac{V_S}{V_T \times n} \text{ (or) } \frac{I_S}{I_T \times n}.$$

$$\Rightarrow D = 1 - \frac{V_S}{V_T \times n}$$

$$\Rightarrow 0.15 = 1 - \frac{6000}{400 \times n}$$

$$\Rightarrow 0.15 + \frac{6000}{400 \times n} = 1.$$

$$\Rightarrow \frac{6000}{400 \times n} = 1 - 0.15$$

$$\Rightarrow \frac{6000}{400 \times n} = 0.85 \Rightarrow \frac{1}{400 \times n} = \frac{0.85}{6000}$$

$$\Rightarrow \frac{1}{n} = \frac{0.85 \times 400}{6000}$$

$$\Rightarrow \frac{1}{n} = 0.0566.$$

$$\therefore n = 17.64 \approx 18.$$

* SCR's with rating of 1200V and 250A are used in string to handle 5KV and 2KA. Calculate no. of series and parallel SCR's required incase Derating factor is (i) 0.2 (ii) 0.4

Sol:- Given, $V_T = 1200V$; $I_T = 250A$

$V_S = 5KV$; $I_S = 2KA$

$D = 0.2$ & 0.4

(1) $0.2 = D$

$$\Rightarrow 1 - \frac{V_S}{V_T \times n_S} = 0.2 \quad \text{(series)}$$

$$\Rightarrow 1 - 0.2 = \frac{V_S}{V_T \times n_S}$$

$$\Rightarrow \frac{5000}{1200 \times n_S} = 0.8$$

$$\Rightarrow \frac{1}{n_S} = \frac{0.8 \times 1200}{5000} = 0.192$$

$\therefore n_S = 5.2 = 5$ SCR's

(2) $0.4 = D$

$$\Rightarrow 1 - \frac{I_S}{I_T \times n_P} = 0.4$$

$$\Rightarrow 1 - \frac{2K}{250 \times n_P} = 0.4$$

$$\Rightarrow \frac{1}{n_P} = \frac{0.6}{2K} \times 250 = 13.33$$

$\therefore n_P = 14$ SCR's.

* In a power circuit of 3KΩV, 4 Thyristors each of rating 800V are Connected in Series. what is the percentage Series Derating factor.

S) Given, $V_S = 3KV$

$n = 4$.

$V_T = 800\ V$.

$\therefore \eta = \frac{V_S}{V_T \times n} = \frac{3000}{4 \times 800} = 0.9375$

$\therefore \eta = 93.75\ \%$

$D = 1 - \eta = 1 - 0.9375 = 0.0625$

$\therefore D = 6.25\ \%$

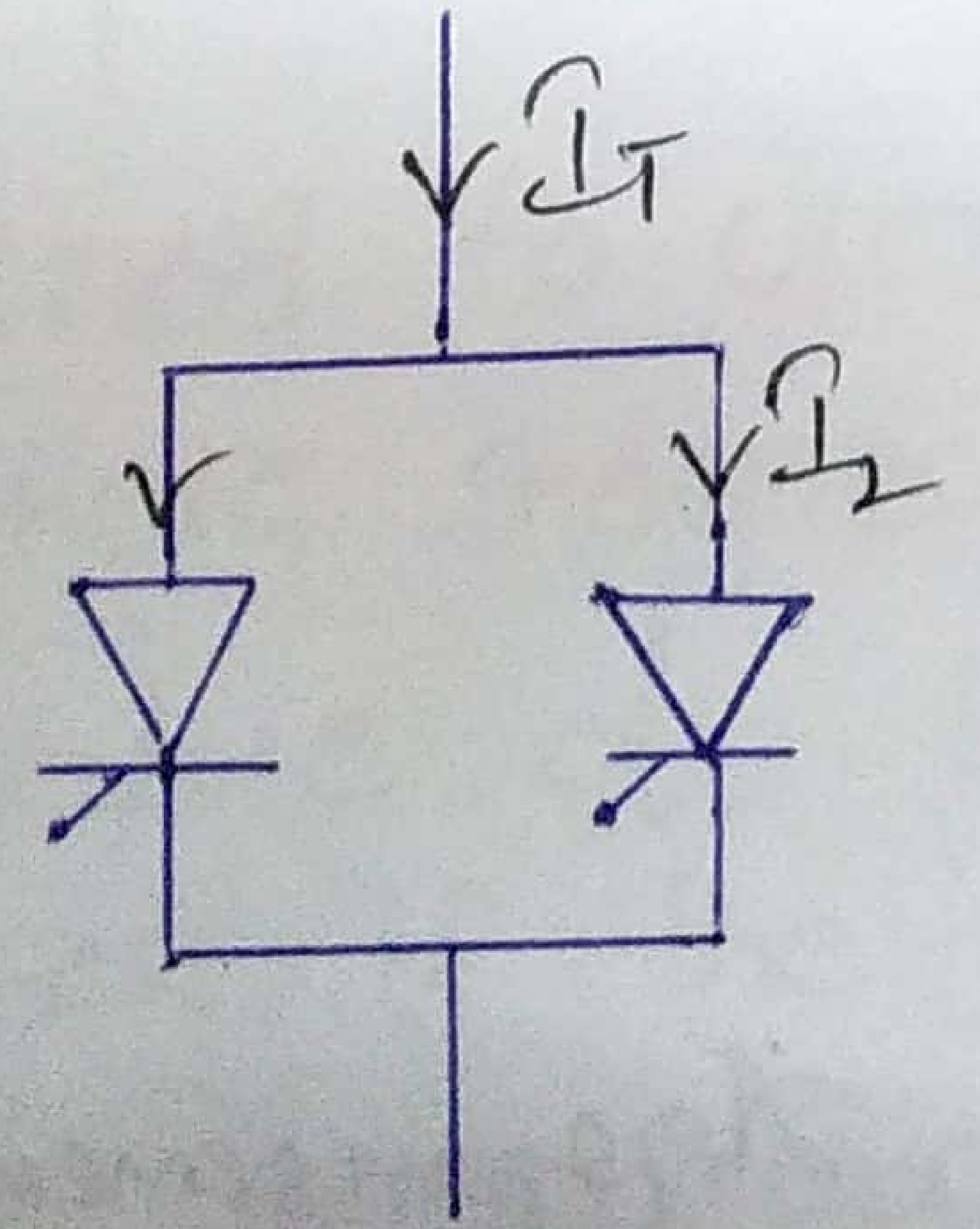
* No. of Thyristors each with rating of 500V, 75A requir in each branch of series parallel combination for a circuit with Total Voltage and current is 7.5 kV, 1KA. If device Derating factor is 14% what is no. of

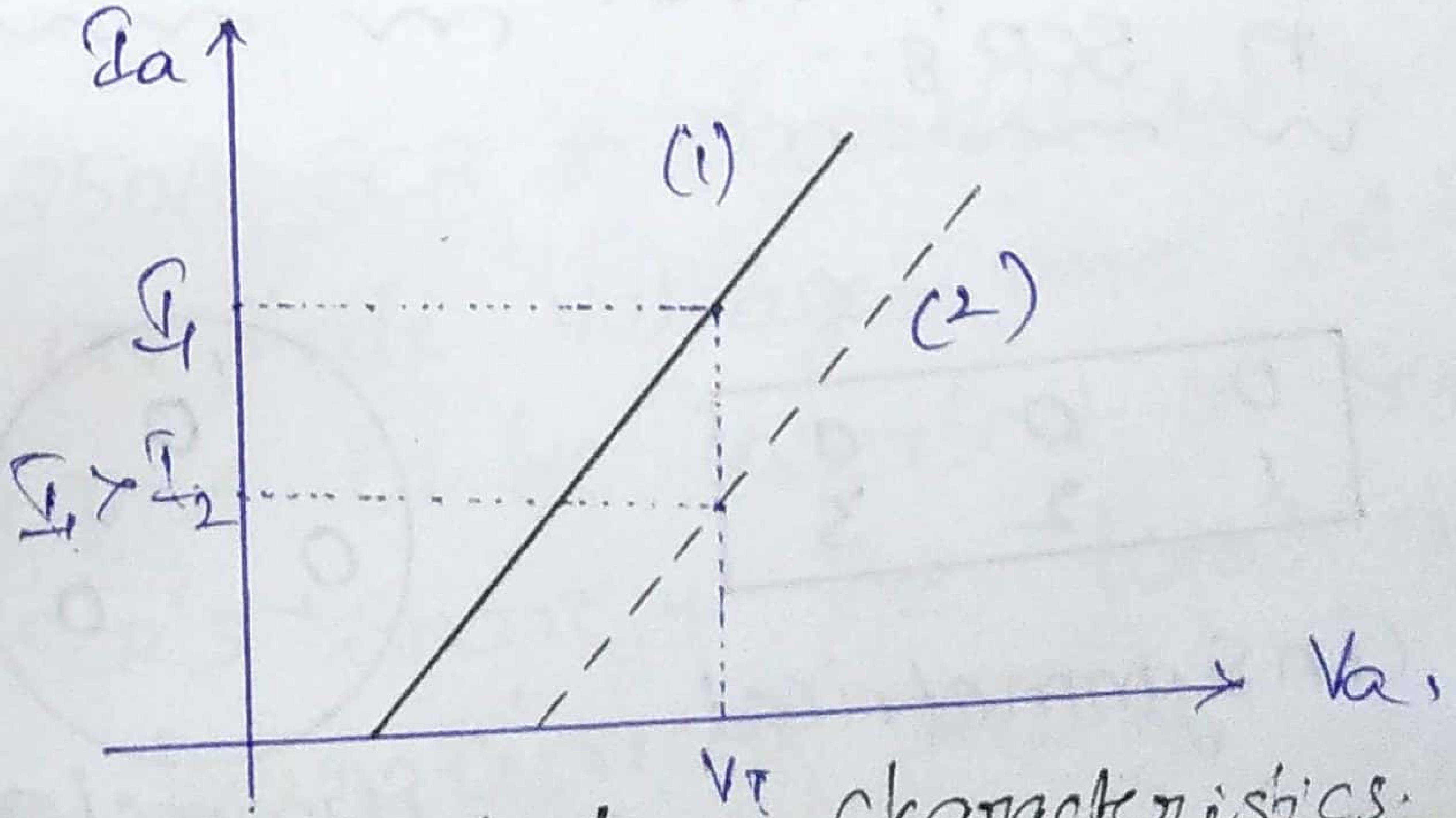
→ Parallel operation of SCR's-

→ when the current required by the load is greater than single SCR current rating. In such a case two or more SCR's should be connected in parallel. In order to meet High current Demand.

→ Problems arising in parallel operation:-

→ unequal sharing of currents in the parallel connected SCR's due to having diff. in their forward conduction characteristics.





forward Conduction characteristics.

→ SCR-1 :-

$I_1^2 R_{j1} \rightarrow$ Jun Temp ↑ → R_{j1} → I_1 ↑ → $I_1^2 R_{j1}$

SCR-2 :-

$I_2^2 R_2 \downarrow \rightarrow$ Jun. Temp ↓ → R_{j1} ↑ → I_2 ↓ → $I_2^2 R_2$

→ from fig (2) it is observed that due to having diff in the forward conduction characteristics of two parallel connected SCR's, for same voltage Drop SCR-1 shares current I_1 and SCR-2 shares current I_2 which is less than I_1 i.e., unequal current sharing takes place in the parallel connected SCR's due to having diff in their forward conduction characteristics. (Internal Reason to share unequal currents in parallel connected SCR's is due to having diff in their Junction Temp.)

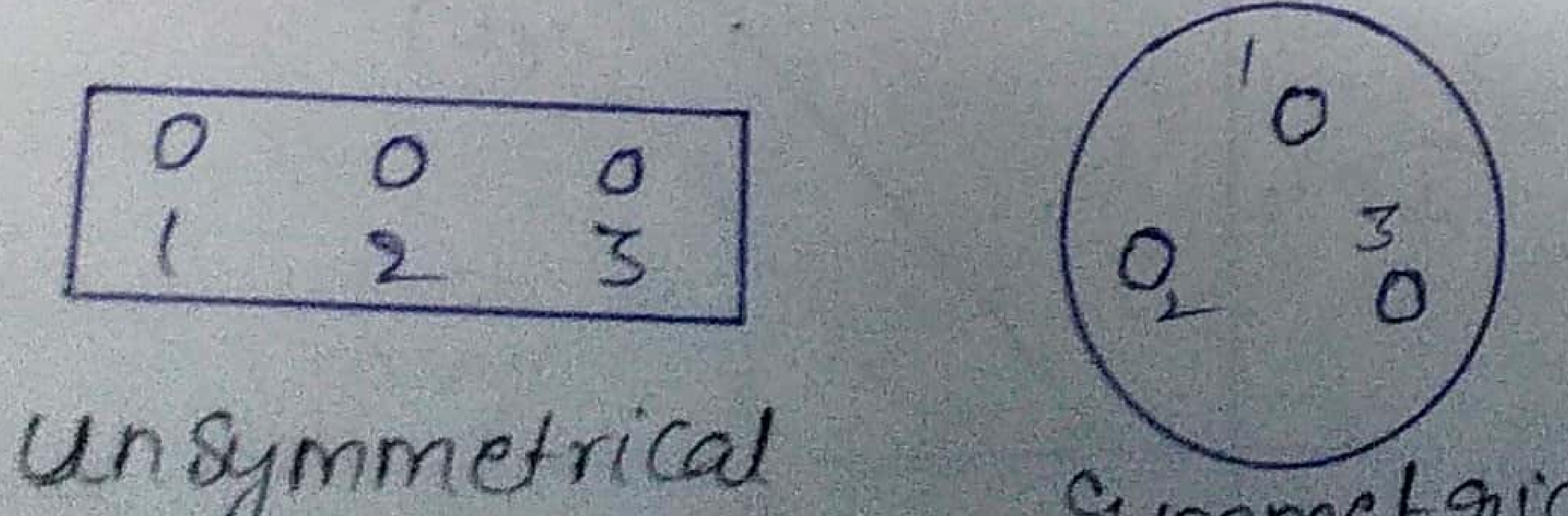
→ String Efficiency $\eta = \dfrac{I_1 + I_2}{I_1 \times 2}$

$$\therefore \eta = \frac{1}{2}\left(1 + \frac{I_2}{I_1}\right).$$

$$\therefore \eta < 1.$$

→ It shows that eventhough we are using same SCR's they share unequal currents due to having in their forward conduction characteristics. Thus, String Efficiency is less than 1.

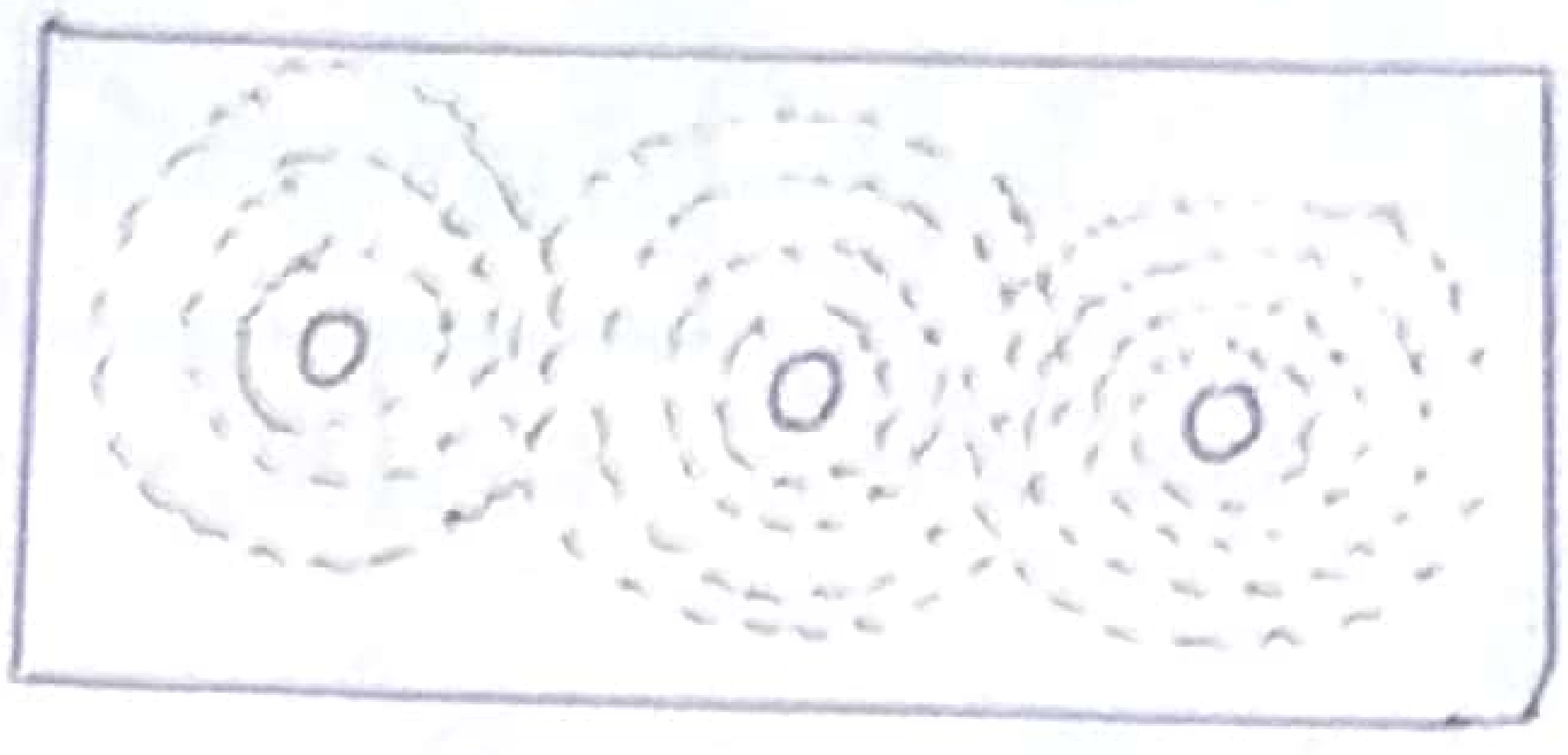
→ Methods to ensure/avoid proper current sharing in SCR's :-

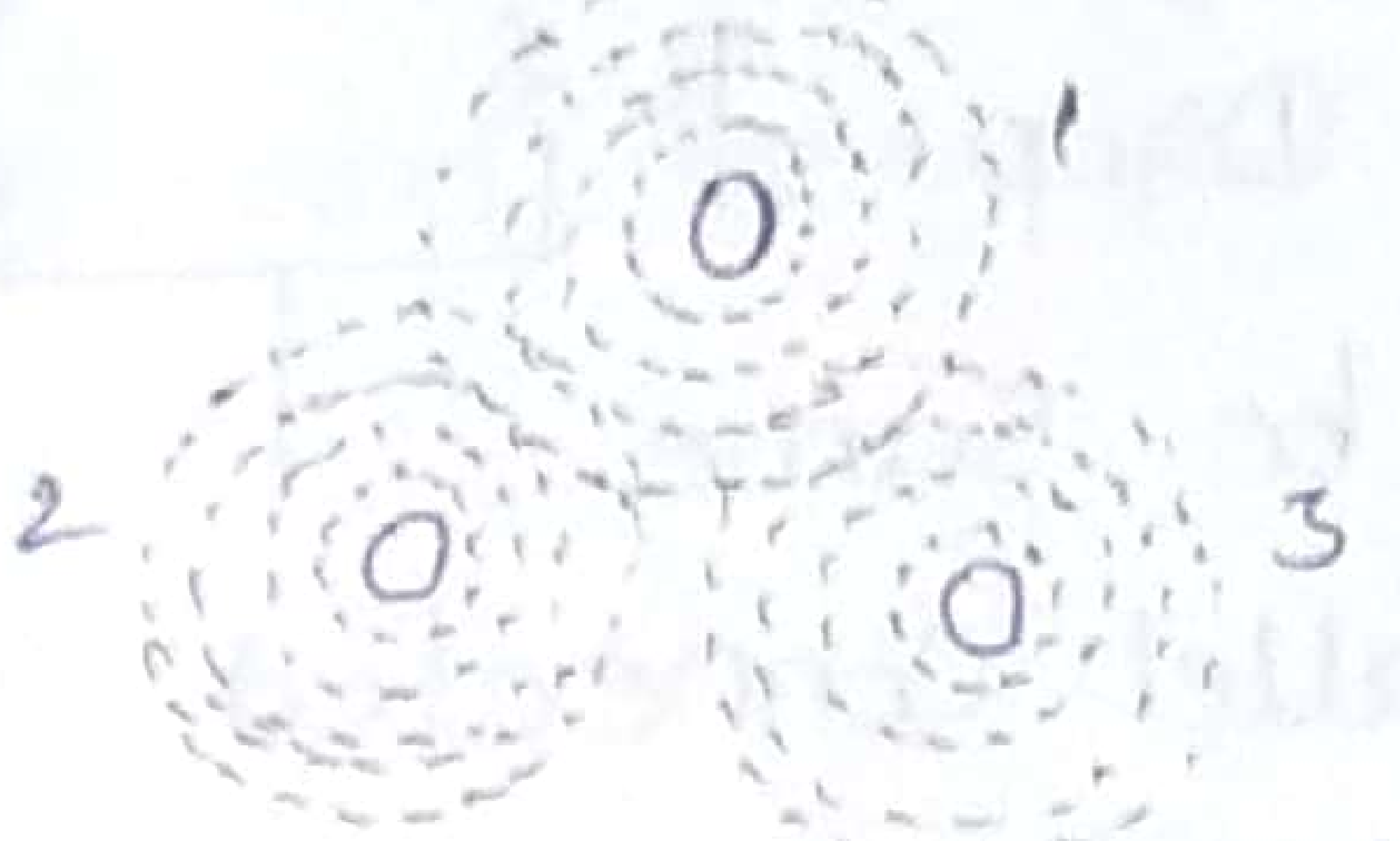


Unsymmetrical

Symmetrical Arrangement

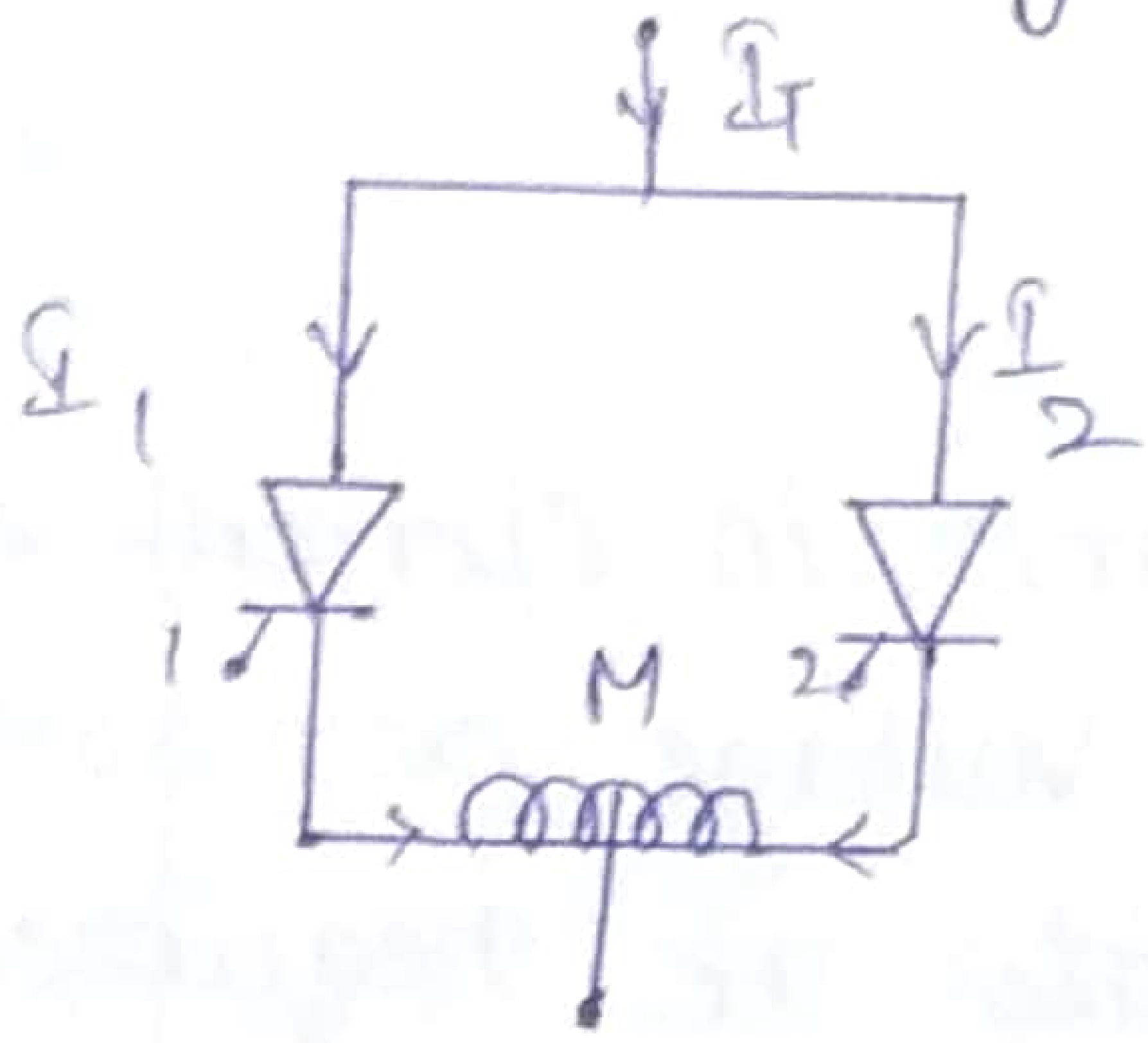
(1) The unequal current sharing can be avoided by mounting all the SCR's on common Heat sinks symmetrically.


un symmetrical



symmetrical

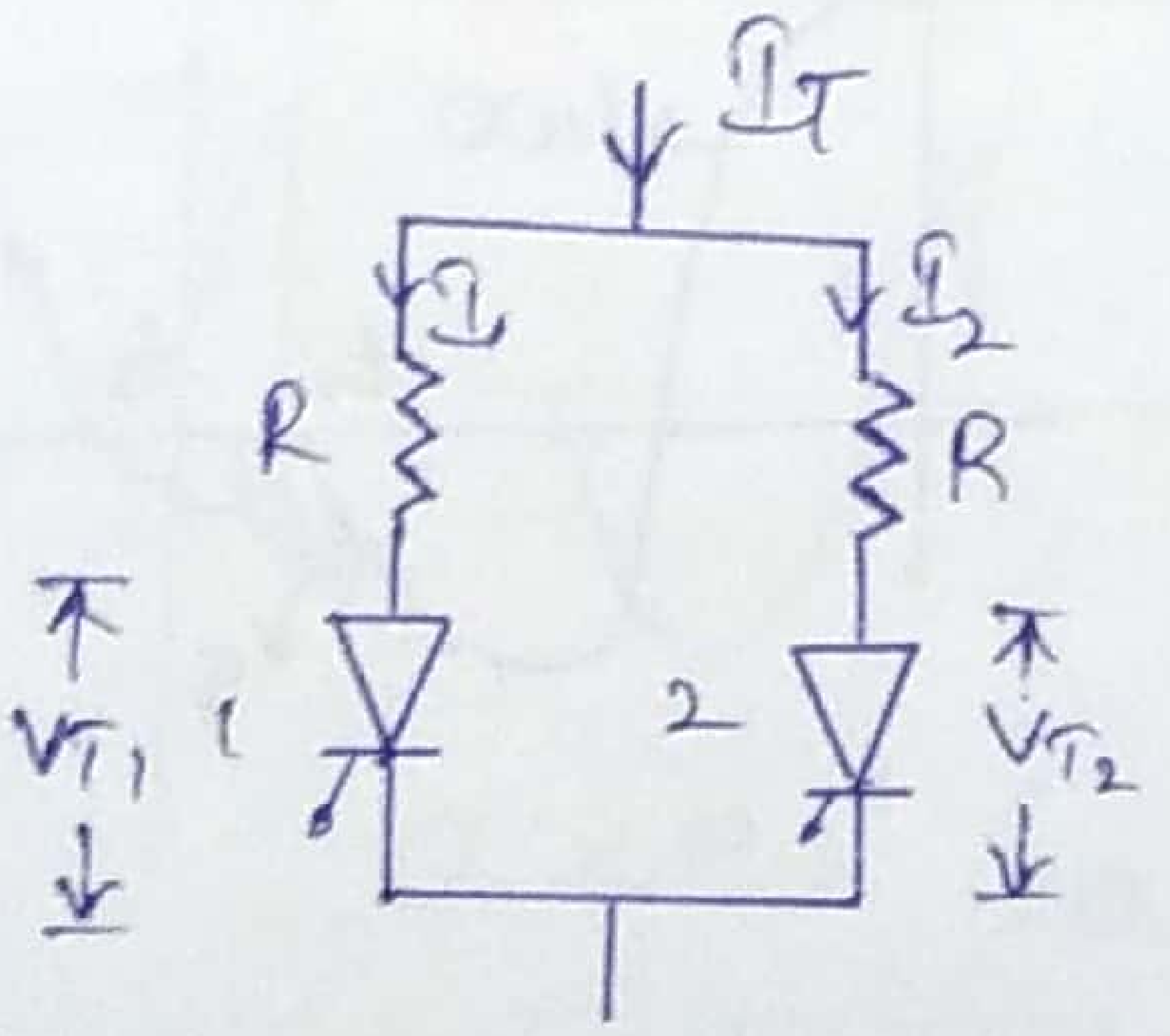
(2) The unequal current sharing can be avoided by connecting the Reactor shown in figure.



(1) $I_1 = I_2$
Net $\phi = 0$
Net $e = 0$
Reactor acts as (ϕ) SC

(2) $I_1 > I_2$ (unequal)
Net $\phi = +ve$
Net $e = +ve$
Reactor acts as voltage source

(3) The unequal current sharing can be avoided by Connecting Resistance-R in series with each SCR. In parallel connected SCR's forward voltage Drop should be same. The Resistance R tries to equalise the unequal currents.

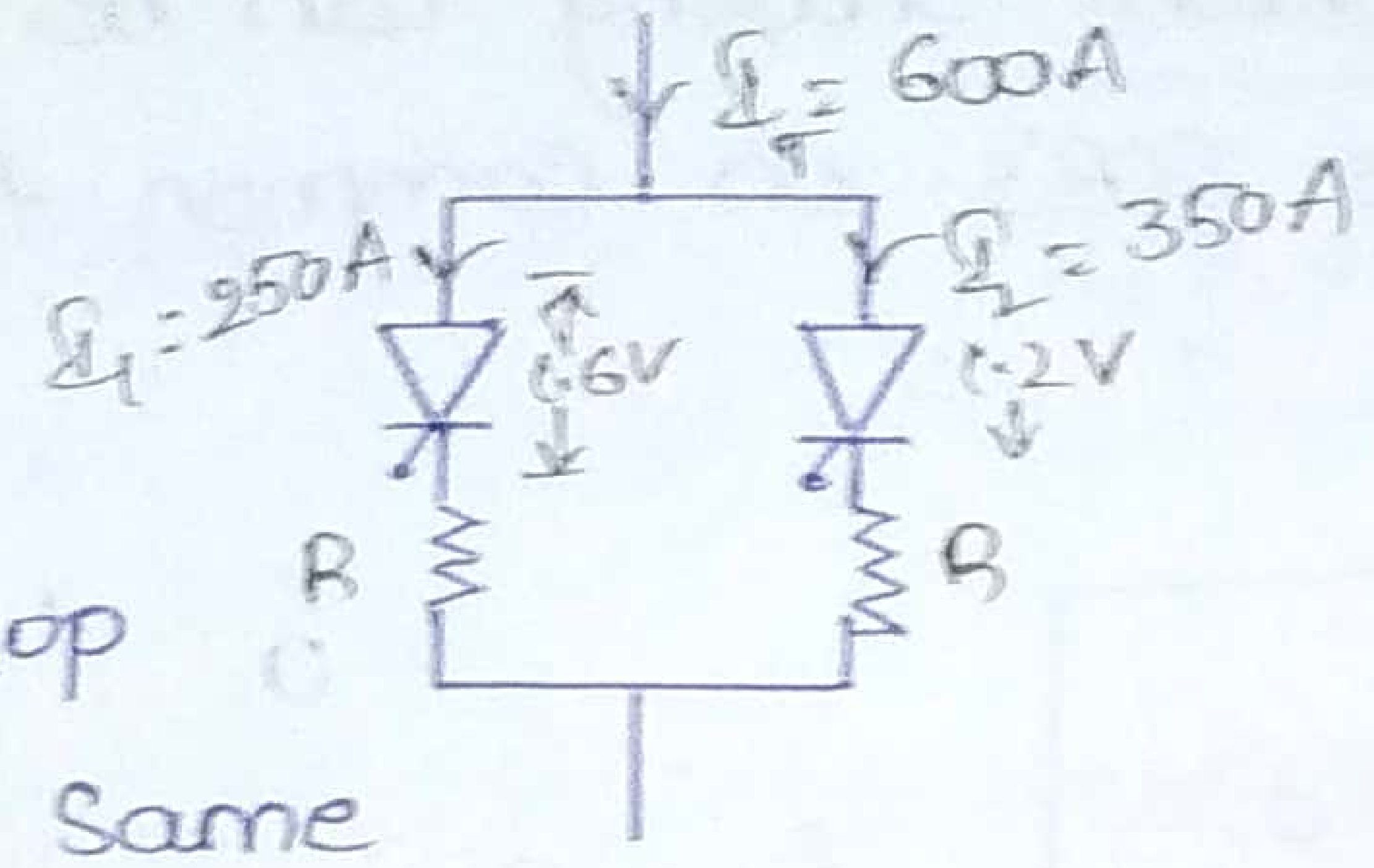


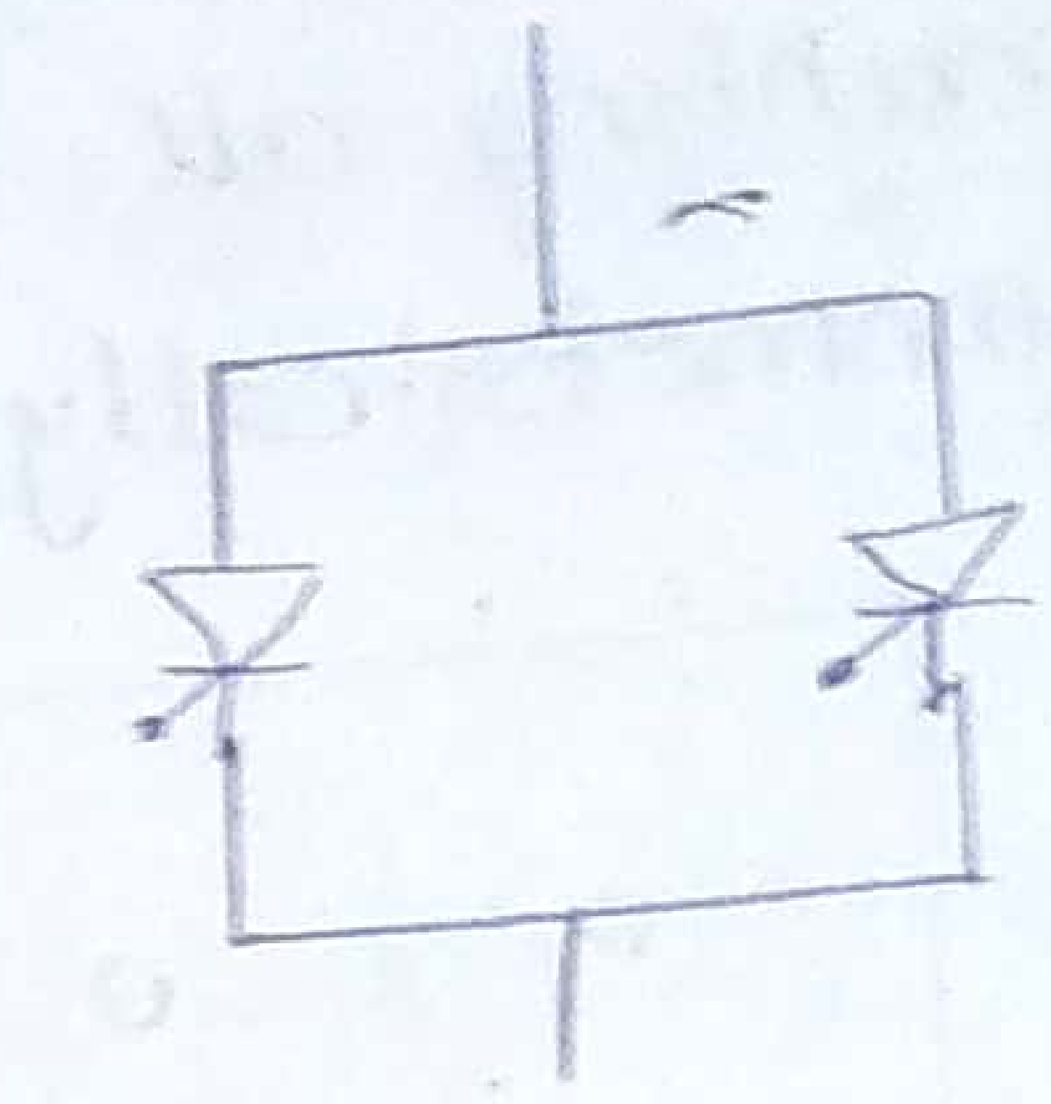
Forward Voltage Drop

$$V_{T_1} + I_1 R = V_{T_2} + I_2 R$$

* It is required to operate 250A SCR in parallel with 350A SCR with there respective ON State voltages are 1.2 V & 1.6 V Calculate value of Resistance to be inserted in series with each SCR, if the two SCR's shared the total current of 600A in proportional to their current rating.

Sol:- Given,





forward
Voltage Drop
should be same
in parallel connected SCR's.

$$\Rightarrow V_{T_1} + I_1 R \neq V_{T_2} + I_2 R$$

$$\Rightarrow 1.6 + 250R = 1.2 + 350R$$

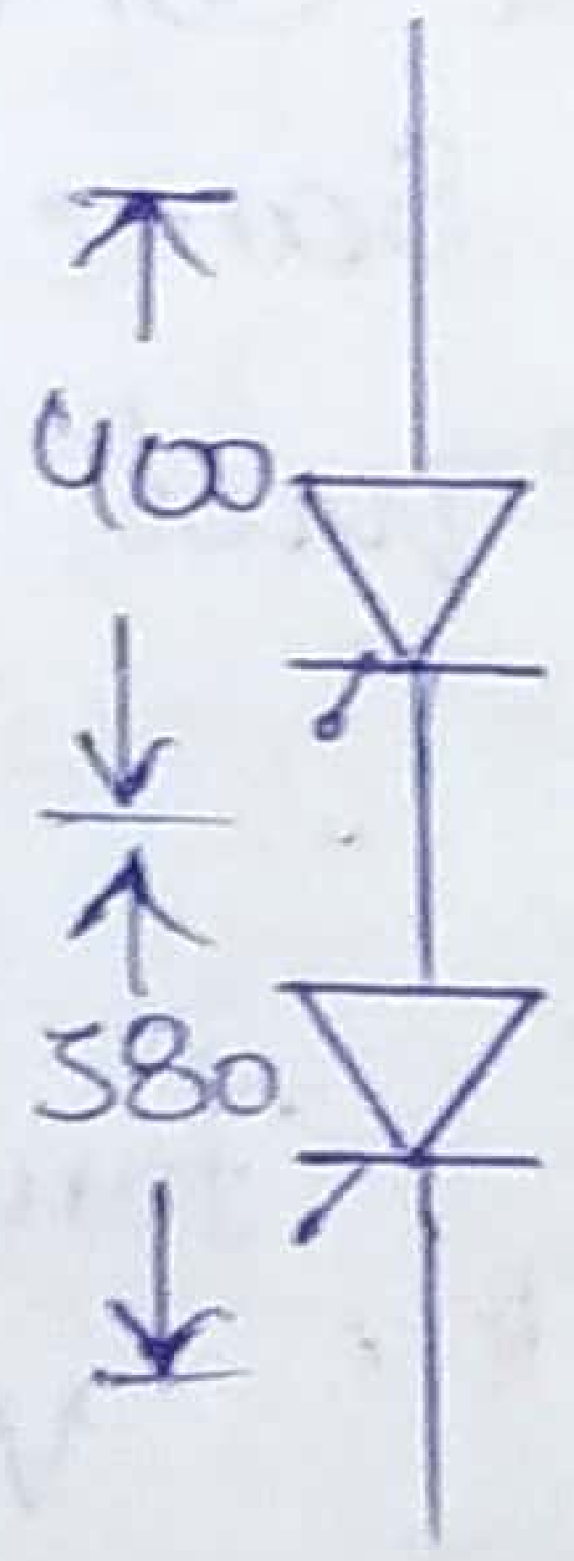
$$\Rightarrow R = \frac{0.4}{100} = 4m\Omega$$

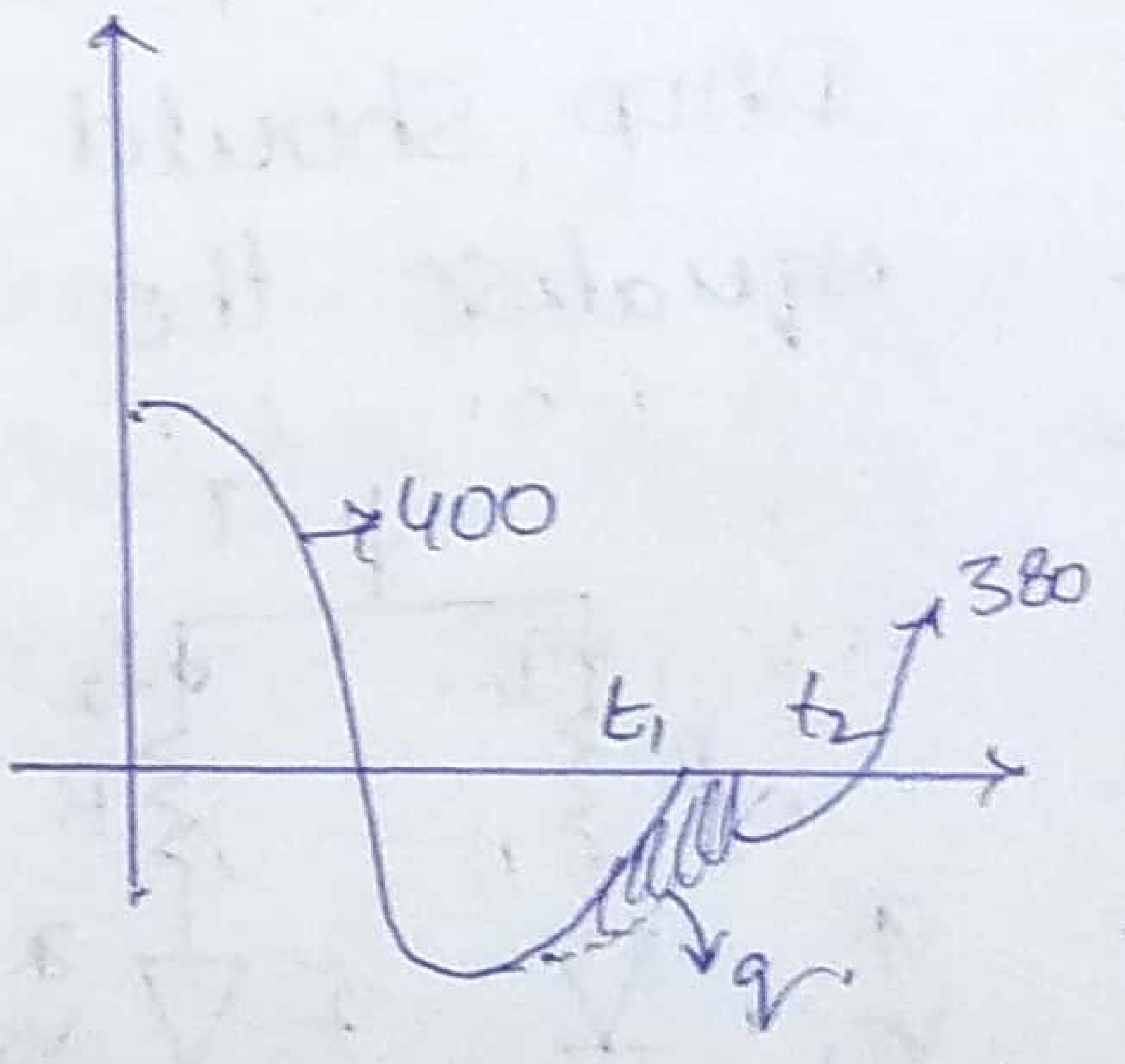
$$\therefore R = 4m\Omega$$

* Two SCR's have difference of 2mA in current are Connected in series in circuit. Voltage across the devices are 400V & 380V. Calculate the required Equalising Resistance and also design suitable circuit for Thyristor, if the permissible diff in blocking Voltage is 20V and diff in recovery charge is 33µC.

Sol:-

$$R = \frac{nV_{bm} - V_s}{(n-1)\Delta I_b}$$





$$C = \frac{(n-1)\Delta Q}{nV_{bm} - V_s}$$

Given, $\Delta Q = 33\mu$

$\Delta I_b = 2mA$

$$\therefore R = \frac{2 \times 400 - 780}{(2-1) \times 2m} = \frac{20}{2m} = 10K\Omega$$

$$C = \frac{(2-1) \times 33\mu}{(2)(400) - 780} = \frac{33\mu}{20} = 16.5 \times 10^{-5} F$$

$$= 1.65 \mu F.$$

→ Firing circuits (or) Triggering circuits for SCR:-

→ Firing circuit produces Gate signals for the SCR.

→ To Turn on the SCR there are 3 firing circuits

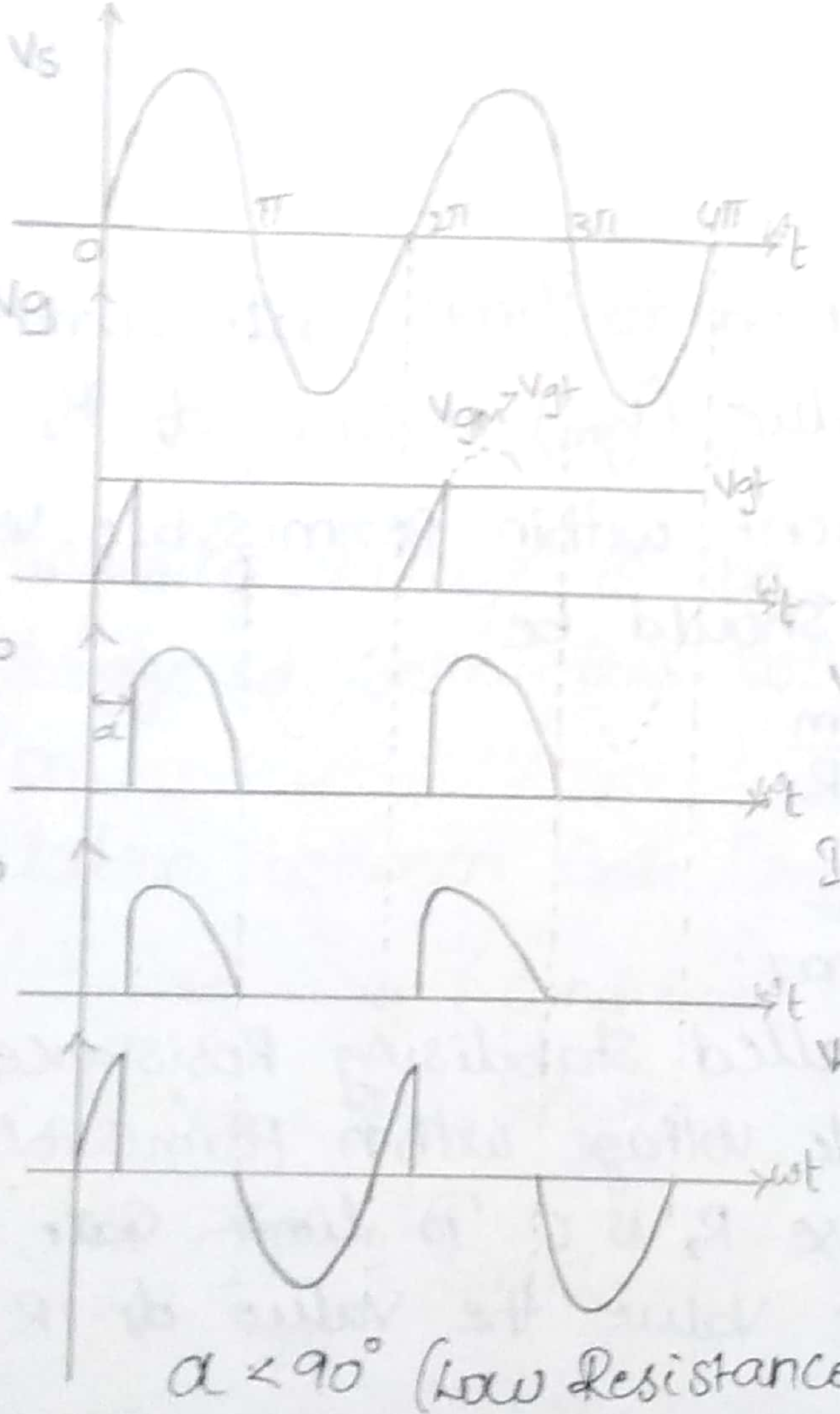
↳ To Generate Gate signals and then,

(i) R-firing circuit:-

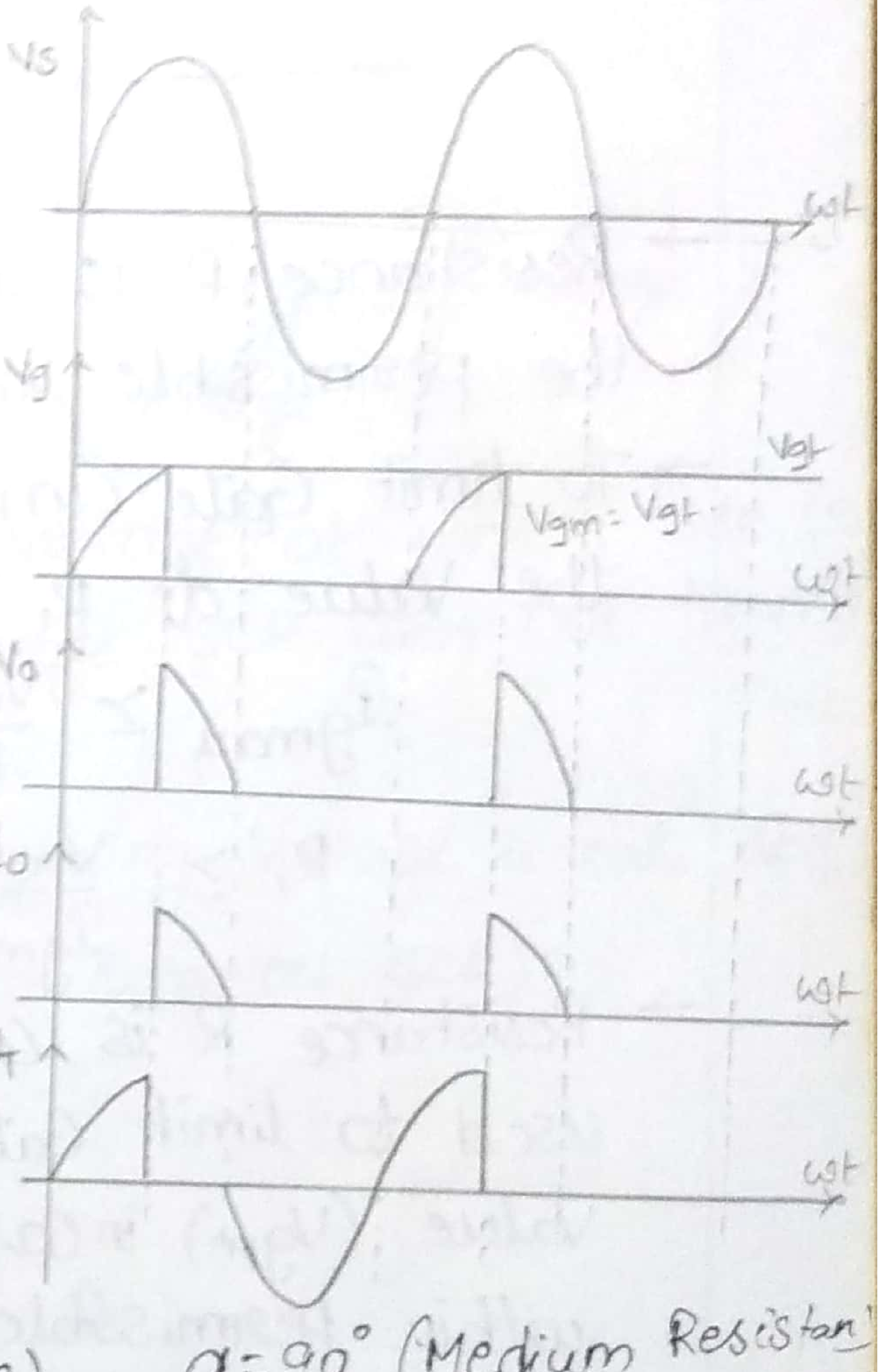
(ii) RC- firing circuit.

(iii) UJT firing circuit.

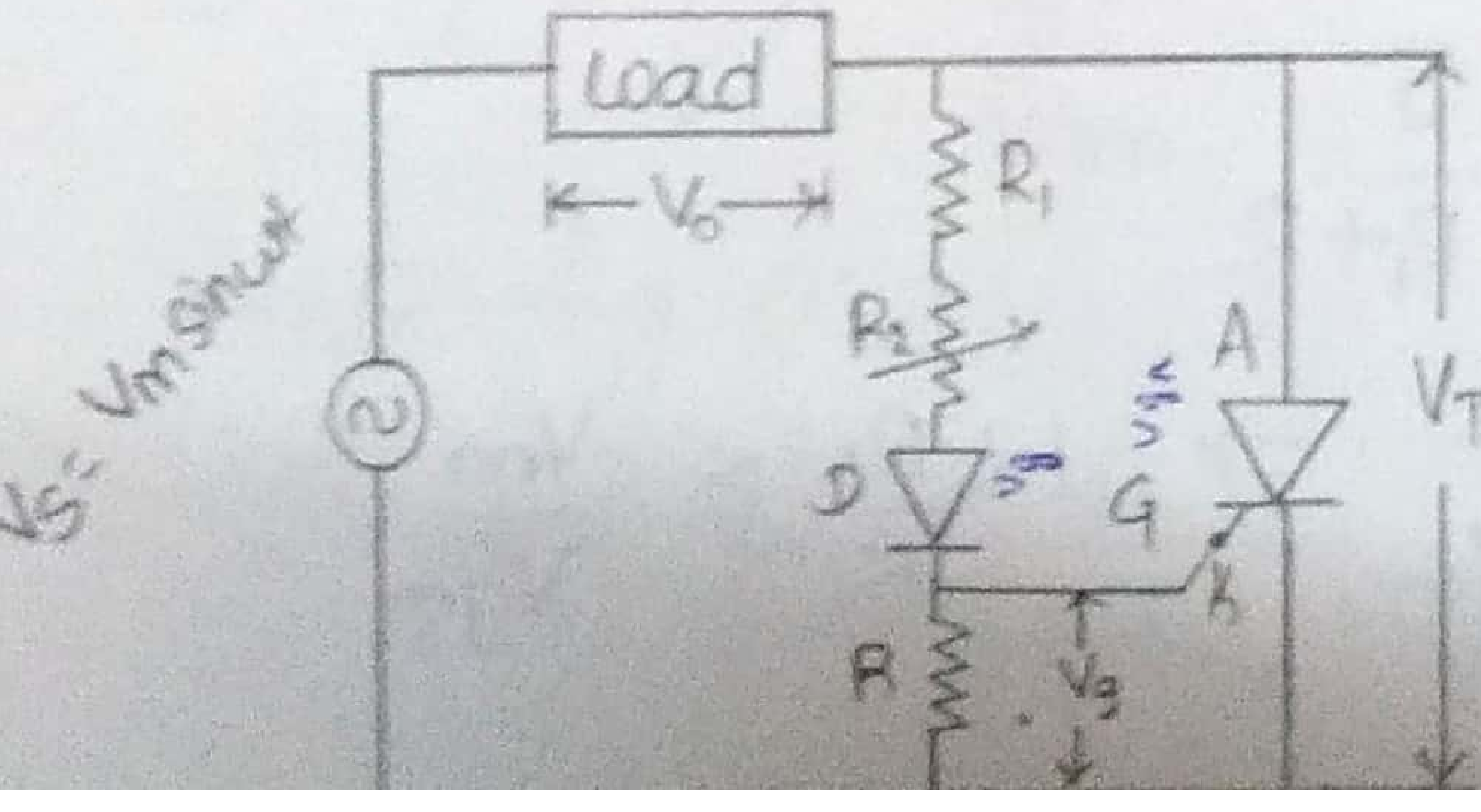
→ R-firing circuit:-



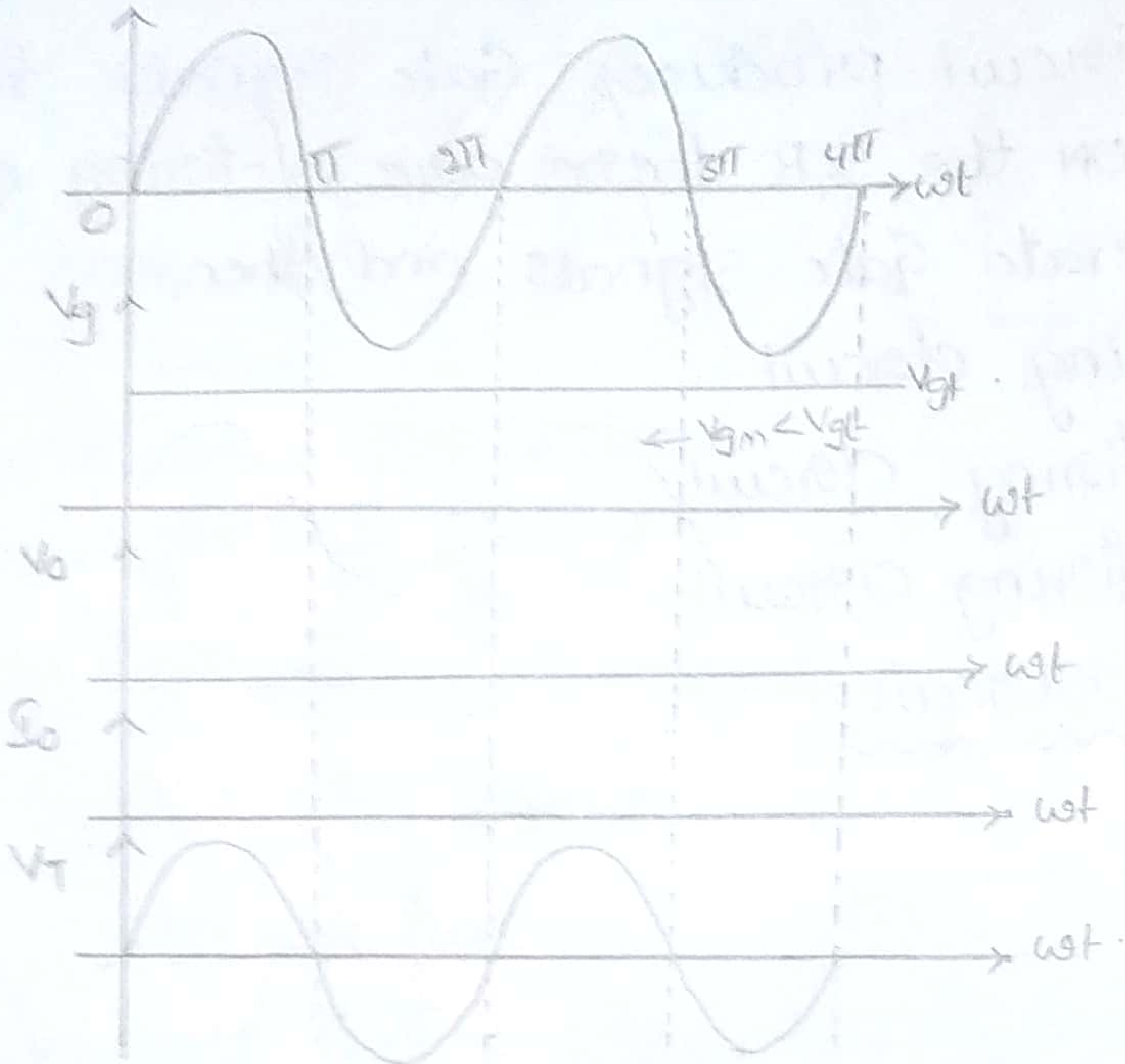
$\alpha < 90°$ (Low Resistance)



$\alpha = 90°$ (Medium Resistan



For α > 90° (High Resistance)



→ Resistance R_1 is used to limit Gate current within the permissible value (I_{gm}) in case of $R_2 = 0$.

→ To limit Gate current within permissible Value the Value of R_1 should be

$$I_{gmax} \geq \frac{V_m}{R_1}.$$

$$R_1 \geq \frac{V_m}{I_{gmax}}.$$

→ Resistance R is called Stabilising Resistance, it is used to limit Gate voltage within Permissible Value (V_{gm}) in Case R_2 is 0. To limit Gate voltage within permissible Value, the value of R Should be

$$V_{gm} \geq V_m \times \frac{R}{R_1 + R}.$$

$$\frac{V_{gm}}{V_m} \geq \frac{1}{1+\frac{R_1}{R}} \Rightarrow 1+\frac{R_1}{R} \geq \frac{V_m}{V_{gm}}$$

$$\Rightarrow \frac{R_1}{R} \geq \frac{V_m}{V_{gm}} - 1.$$

$$\Rightarrow \frac{R_1}{R} \geq \frac{V_m - V_{gm}}{V_{gm}}.$$

$$\Rightarrow R. \leq \frac{V_{gm}R_1}{(V_m - V_{gm})}.$$

→ Diode D blocks flow of current in negative ½ cycle and allows current in positive Half cycle.

→*/ firing Angle in SCR is less than 180°/*

→ Let, V_{gm} = Max. Gate Voltage (or)
peak Gate voltage

V_{gt} = Gate Triggering or Fingering voltage
(or) Gate Turn ON Voltage.

→ fingering voltage is the voltage at which SCR is triggered. Below this voltage SCR does not turned on.

Relation between Gate Triggering Voltage & Gate volt.

$V_{gt} = V_g$ (Condition to Turn ON SCR).

$V_{gt} = V_{gm} \sin\omega t.$

$$\Rightarrow \frac{V_{gt}}{V_{gm}} = \sin\alpha.$$

$$\Rightarrow \alpha = \sin^{-1}\frac{V_{gt}}{V_{gm}}.$$

from fig (i),

$$V_{gm} = V_m \times \frac{R}{R_1 + R_2 + R}.$$

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

$\Rightarrow \boxed{\alpha = \sin^{-1} R_2}$ (V_{gt}, V_m, R_1, R are constants)

$\therefore \alpha \propto R_2$)

→ Thus in R firing circuits α is controlled by varying R_2. But, the firing angle never be more than 90° i.e., Range of firing angle in R-firing circuit is (0-90°)

→ for low value of Resistance R_2, the maximum Gate Voltage is V_{gm} is High and is greater than Gate triggering Voltage ($V_{gm} > V_{gt}$). In this case Gate Voltage reaches to Gate triggering Voltage ($V_g = V_{gt}$) at an firing angle $\alpha < 90°$ as shown in figure and SCR gets Turned ON.

→ As Resistance R_2 increases, the maximum Gate Voltage decreases and becomes equals to the Gate triggering Voltage ($V_{gm} = V_{gt}$). In this case the Gate Voltage reaches to Gate triggering Voltage (V_{gt}) exactly at $\alpha = 90°$ and SCR gets turned on.

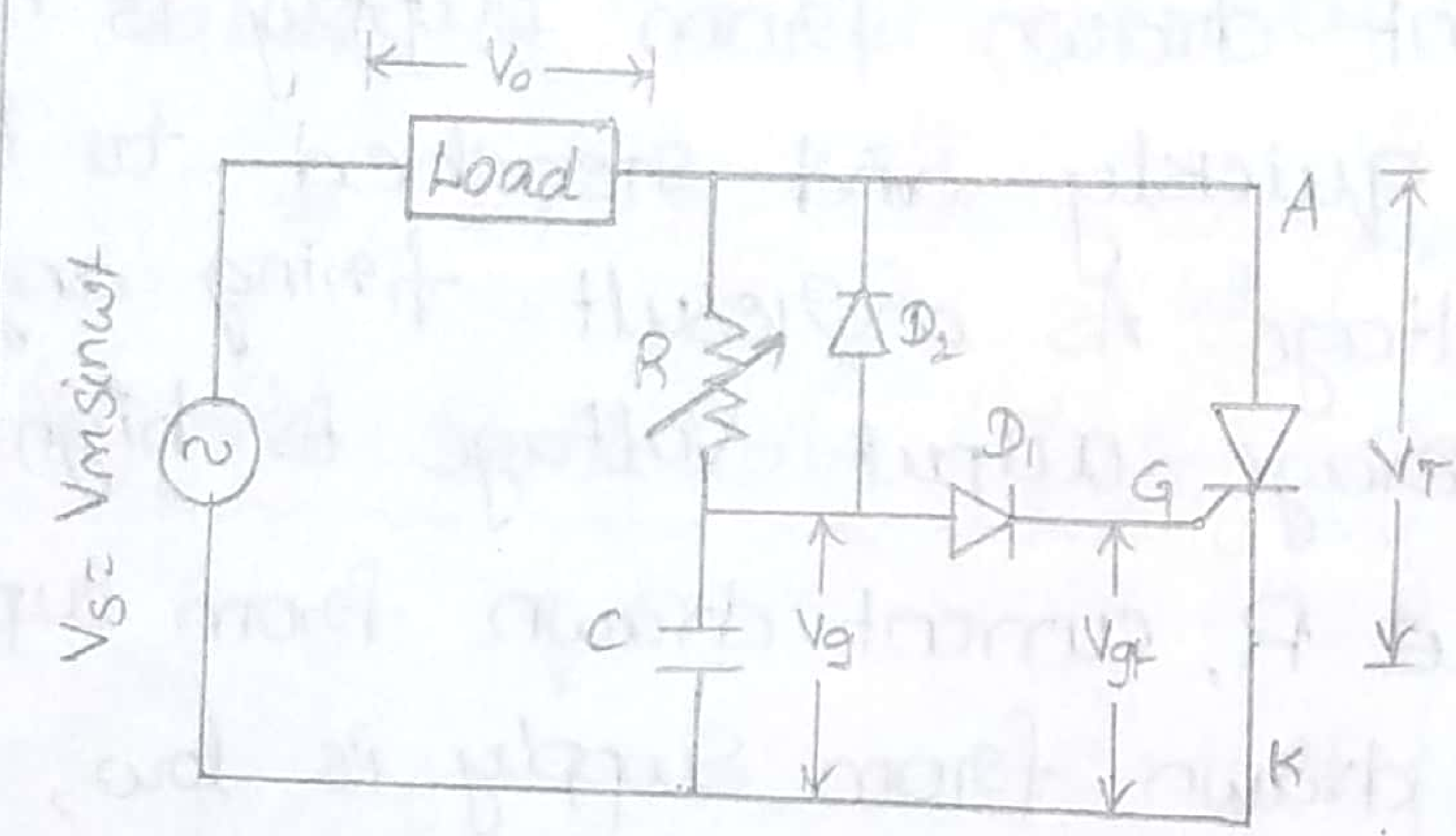
→ As Resistance R_2 further increased to large value, a maximum Gate Voltage further decreases and becomes less than Gate Triggering Voltage ($V_{gm} < V_{gt}$). In this case, Gate Voltage never reaches to Gate Triggering Voltage ($V_g \neq V_{gt}$) and SCR do not turned on then $V_o = I_o = 0$ and $V_T = V_S$ as shown in figure

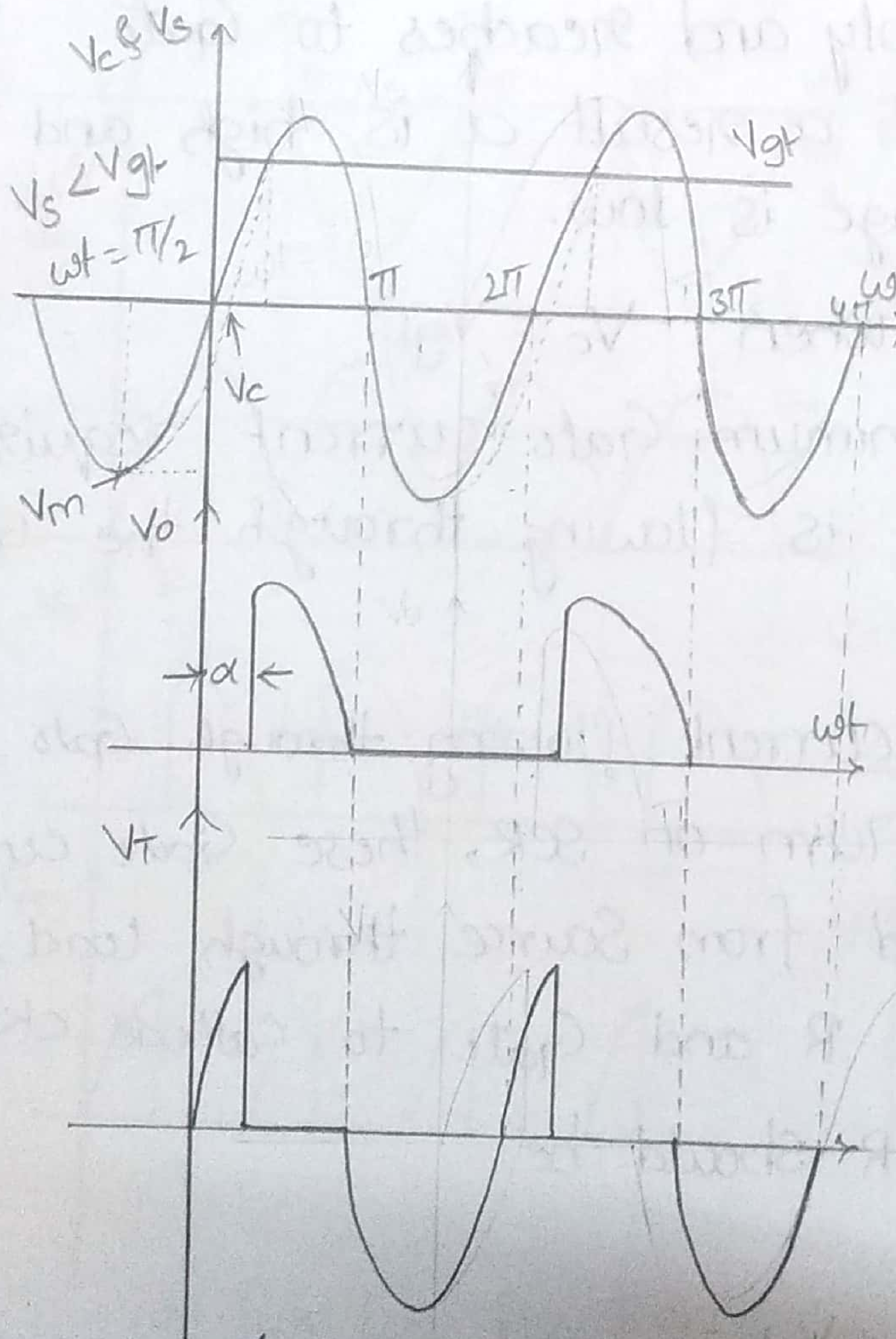
→ Limitation :-

→ In R-firing circuit, the firing angle never be more than 90° because for $\alpha > 90°$ max Gate Voltage (V_{gm}) is less than Gate Triggering Voltage (V_{gt}) and Gate Voltage never reaches to Gate Triggering Voltage then SCR does not turned ON.

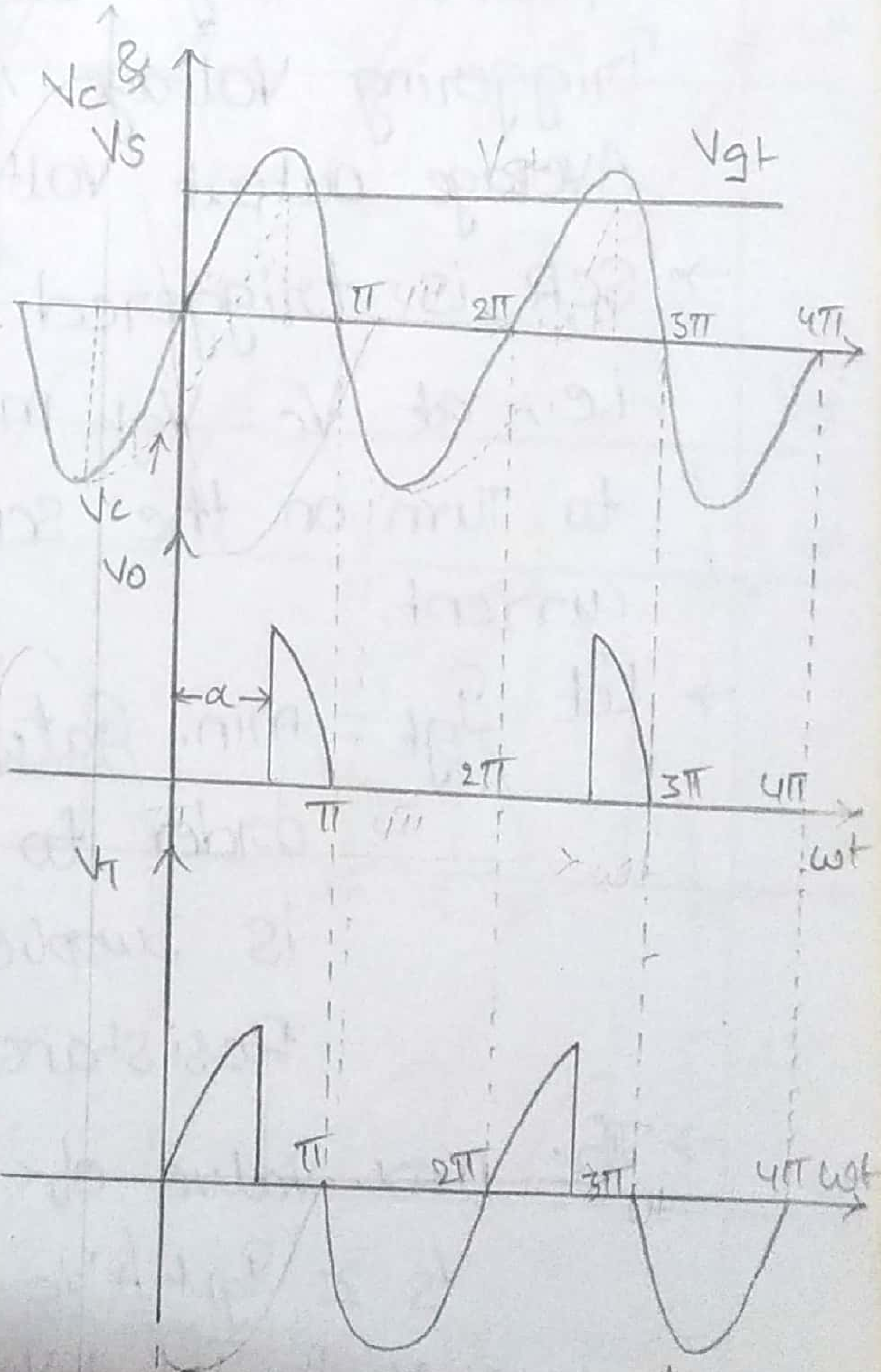
→ RC Firing circuit :-

(i) RC Half wave Firing circuit :-





For Low Value of R.



For High Values of R

→ The limited range of R-firing angle can be overcome by using RC firing circuit.

→ In RC firing circuit, we use RC circuit in order to increase the range of firing angle.

→ In RC firing circuit, the firing angle is controlled from 0 to 180° by varying Resistance R i.e, in RC firing circuit range of firing angle is (0-180°)

→ for low Resistance, current drawn from supply is high. As current drawn from supply is high, capacitor charges quickly and reached to the Gate Triggering voltage As a result firing angle α is low and average output voltage is high.

→ for High Resistance R, current drawn from supply is low. As current drawn from supply is low, capacitor charges slowly and reaches to Gate Triggering voltage. As a result α is high and the Average output voltage is low.

→ SCR is triggered when $V_c = V_{gt}$.
i.e., at $V_c = V_{gt}$ minimum Gate current required to Turn on the SCR is flowing through the Gate current.

→ Let I_{gt} = min. Gate current flowing through Gate, in order to Turn on SCR, these Gate current is supplied from Source through Load, Resistance R and Gate to cathode ckt.

→ The max. Value of R should be

$$V_s \geq I_{gt} R + V_c$$

$$\Rightarrow V_s \geq I_{gt} + V_{gt} + V_d$$

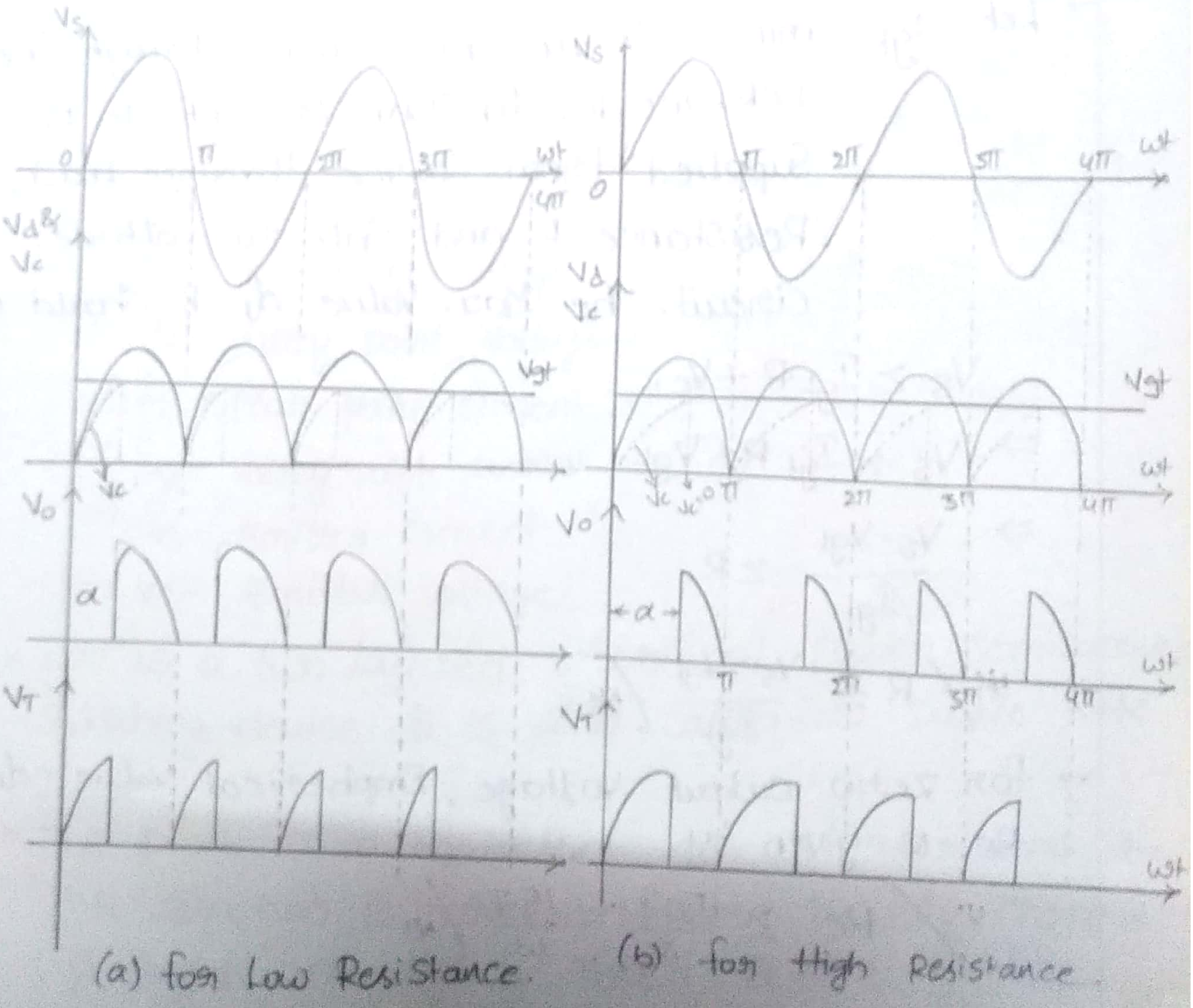
$$\Rightarrow V_s - V_{gt} - V_d \geq I_{gt} \cdot R$$

$$\Rightarrow */ R \leq \frac{V_s - V_{gt} - V_d}{I_{gt}} /*$$

- In RC firing circuit, minimum firing angle required to turn on SCR is α_1 & max. firing angle required is α_2. Before α_1 and after α_2 condition $V_c = V_{gt}$ never satisfies.
- for zero output voltage, the Empherical (formula) value of RC is given by,

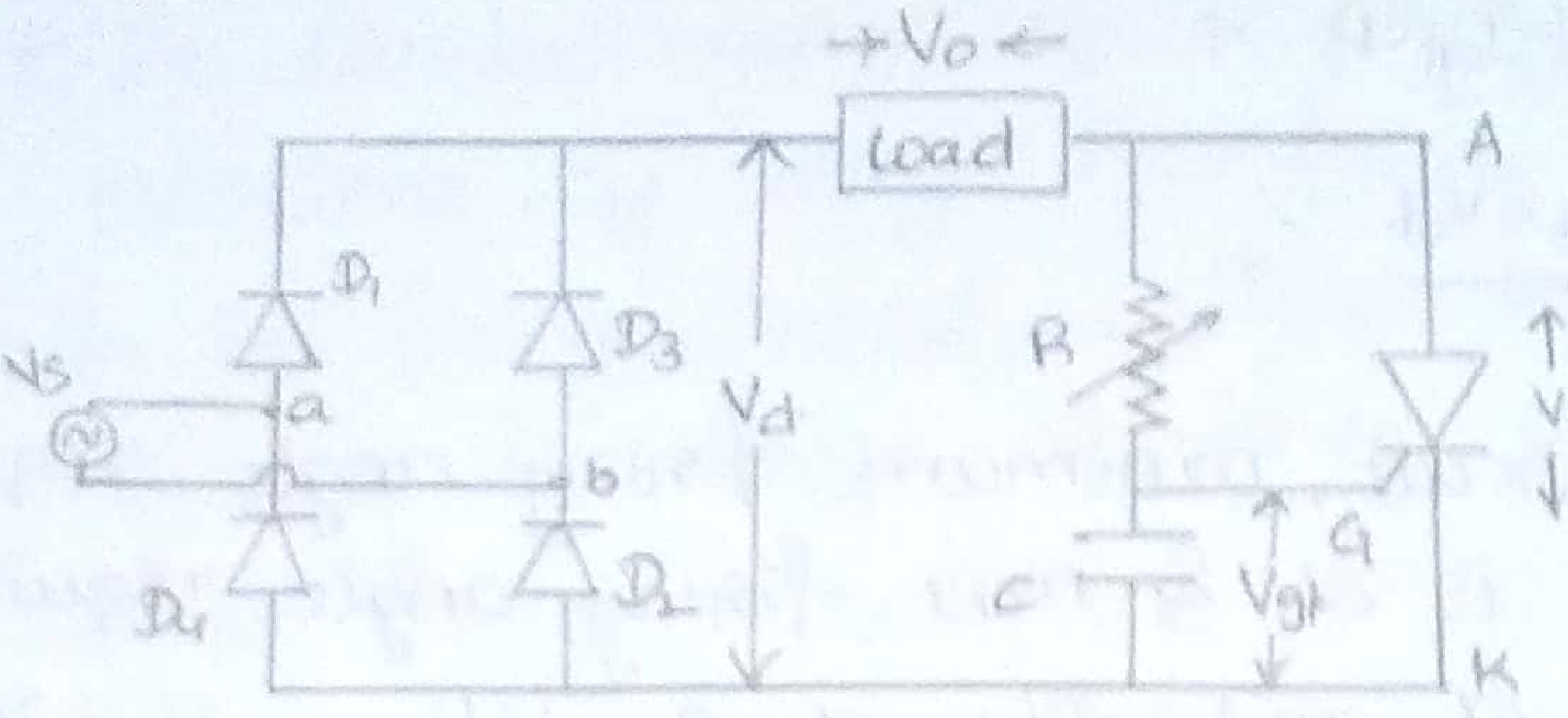
$$*/ RC \geq \frac{1.3T}{2} \approx \frac{4}{\omega} /*.$$

(b) RC Full-wave firing circuit:-



(a) for Low Resistance.

(b) for High Resistance



Rc full wave firing circuit.

- Rc full wave firing circuit uses fw Diode Bridge Rectifier. The Diodes D_1, D_2, D_3 & D_4 forms Diode Bridge Rectifier.
- SCR is turned on when $V_c = V_{gt}$ i.e., at $V_c = V_{gt}$ minimum Gate current required to Turn on the SCR is flowing in the Gate terminal.
- Let, I_{gt} = min. Gate current flowing through the SCR, inorder to Turn on SCR, it is Supplied from Source through Load, Resistance R and Gate to cathode circuit. The Max. Value of R should be,

$$V_s \geq I_{gt} \cdot R + V_c.$$

$$\Rightarrow V_s \geq I_{gt} R + V_{gt}.$$

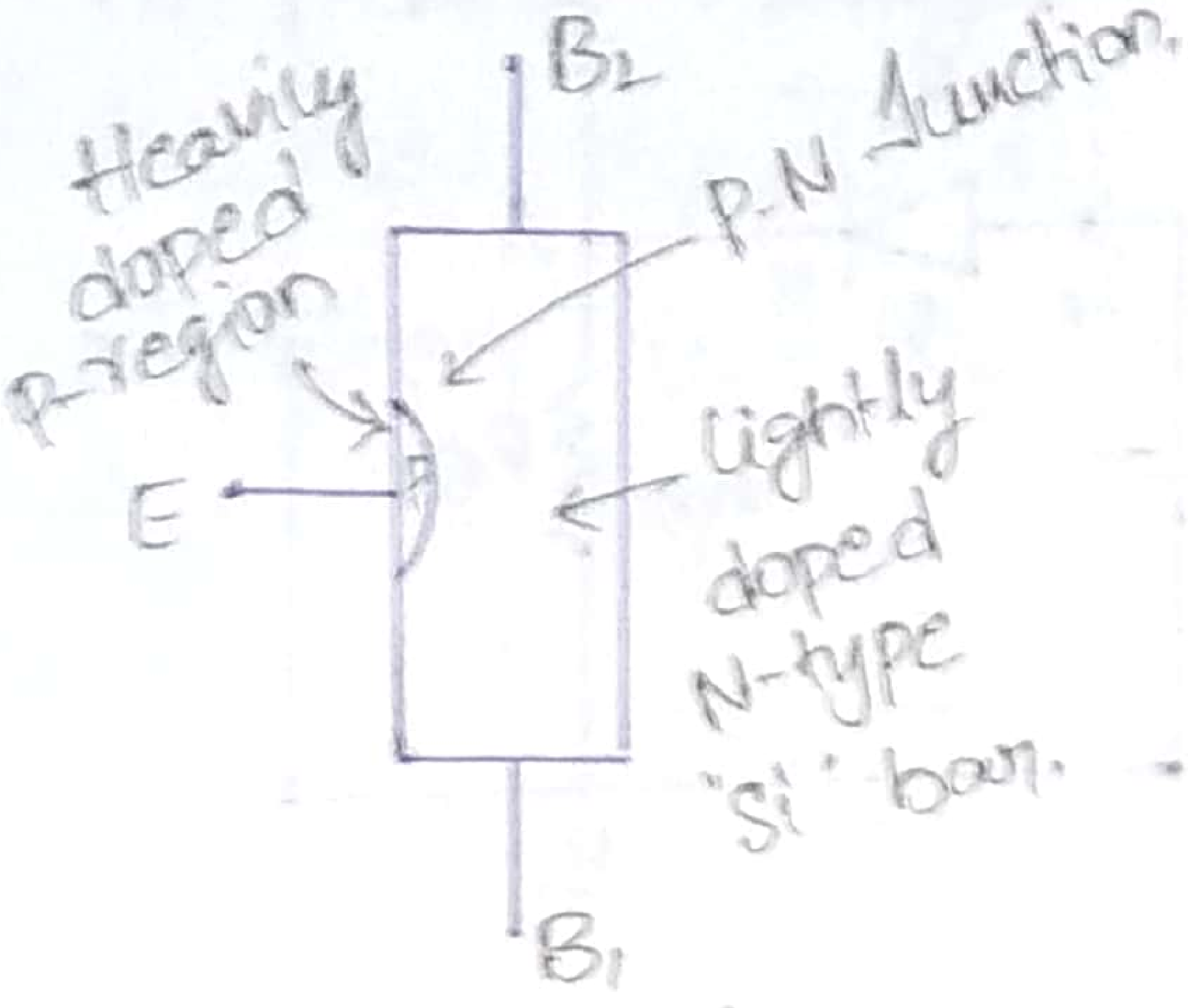
$$\Rightarrow \frac{V_s - V_{gt}}{I_{gt}} \geq R.$$

$$*/ \; R \leq \frac{V_s - V_{gt}}{I_{gt}} \; /*$$

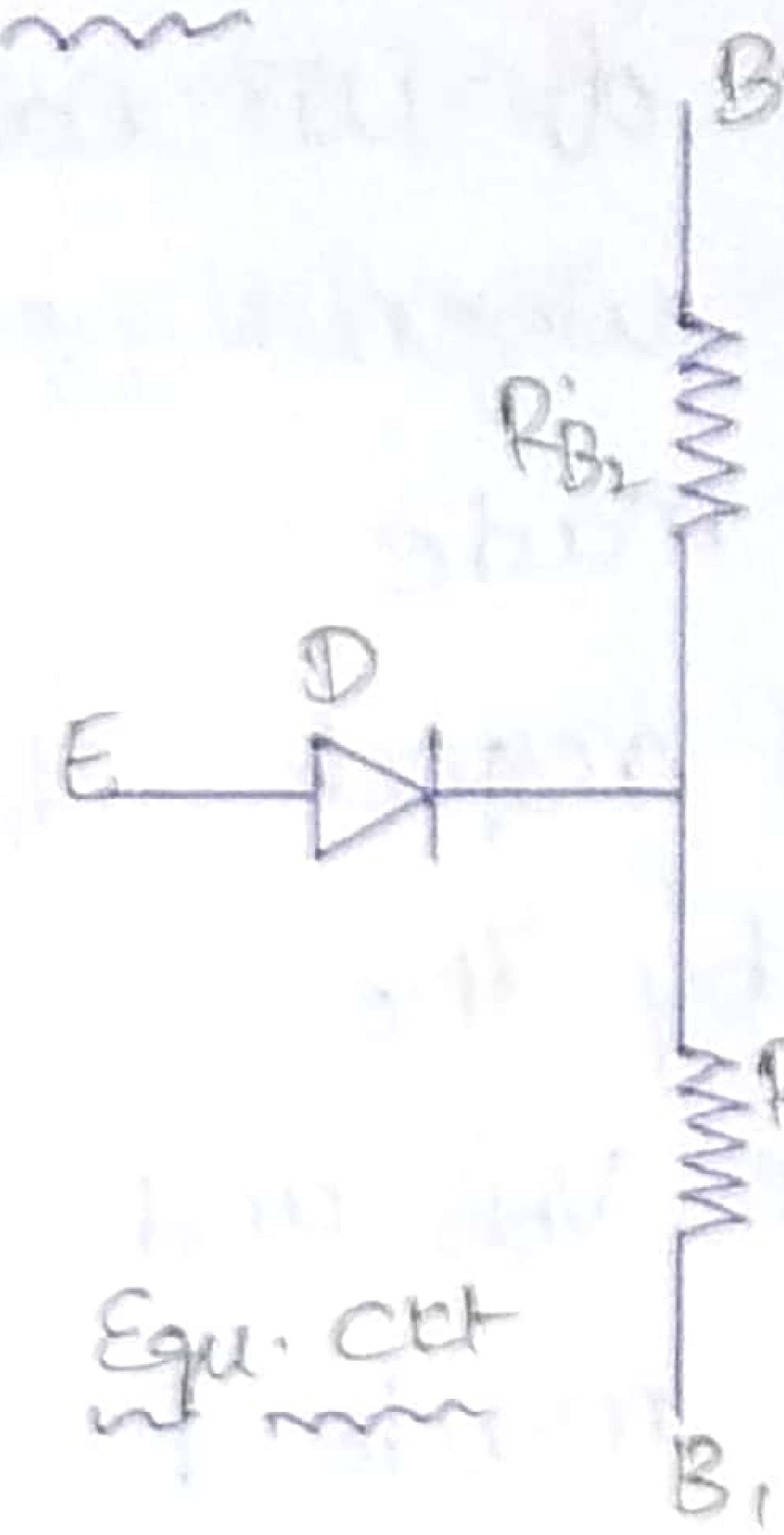
- for zero output Voltage, Empherical Value of Rc is given by,

$$*/ \; Rc \geq \frac{50T}{8} \approx \frac{15.7}{\omega} \; /*$$

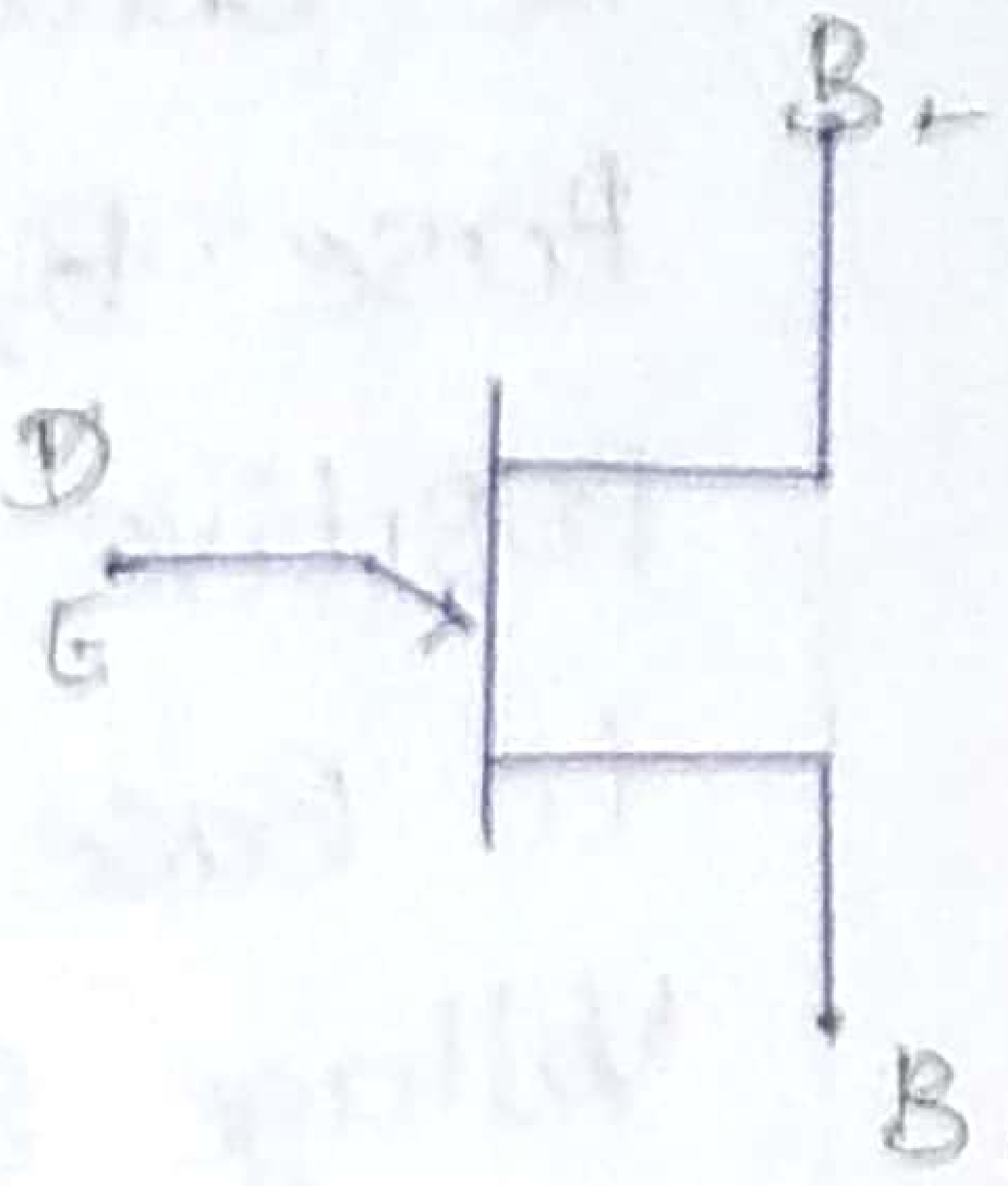
Uni Junction Transistor:-



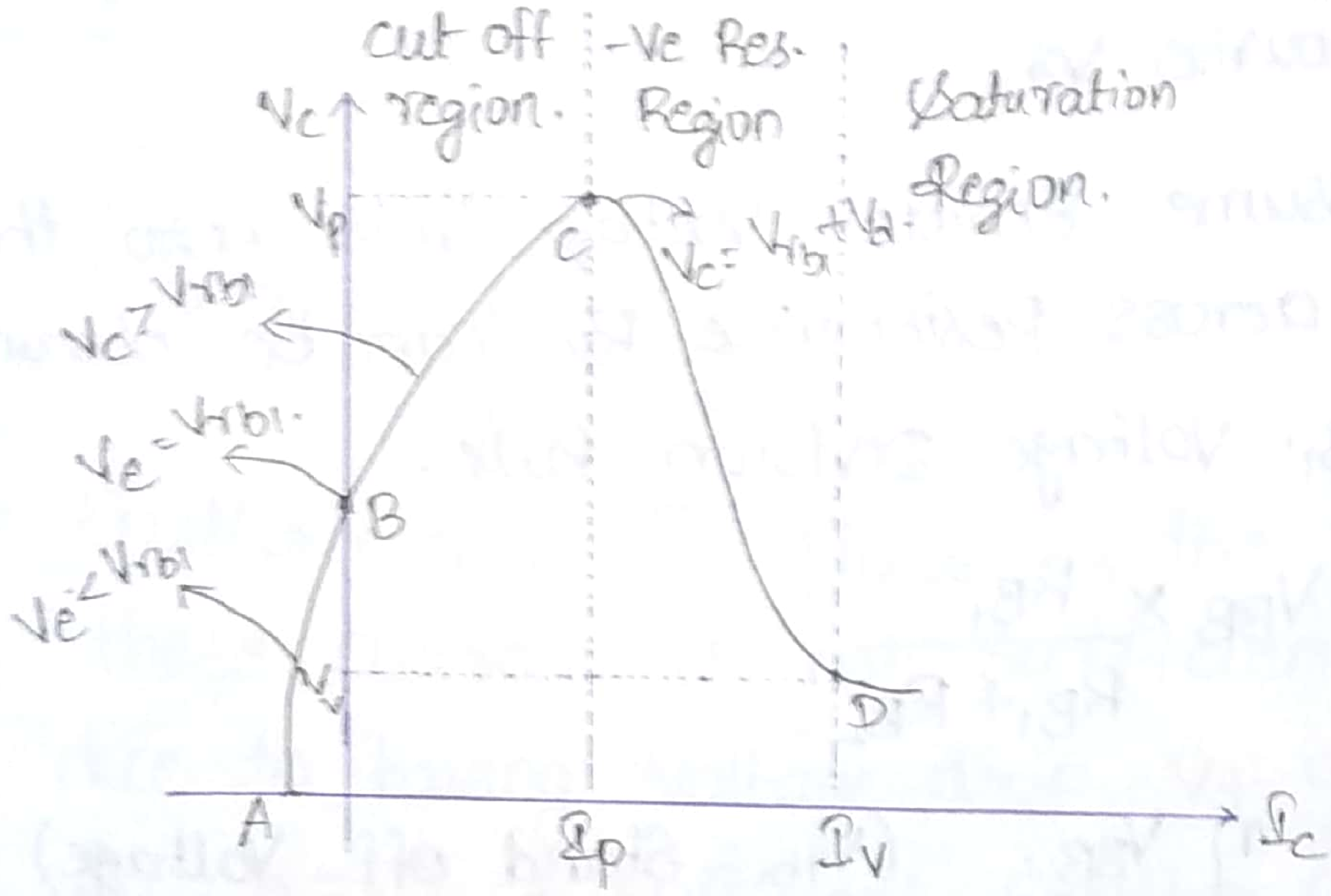
Basic Structure



Equ. ckt



Symbol



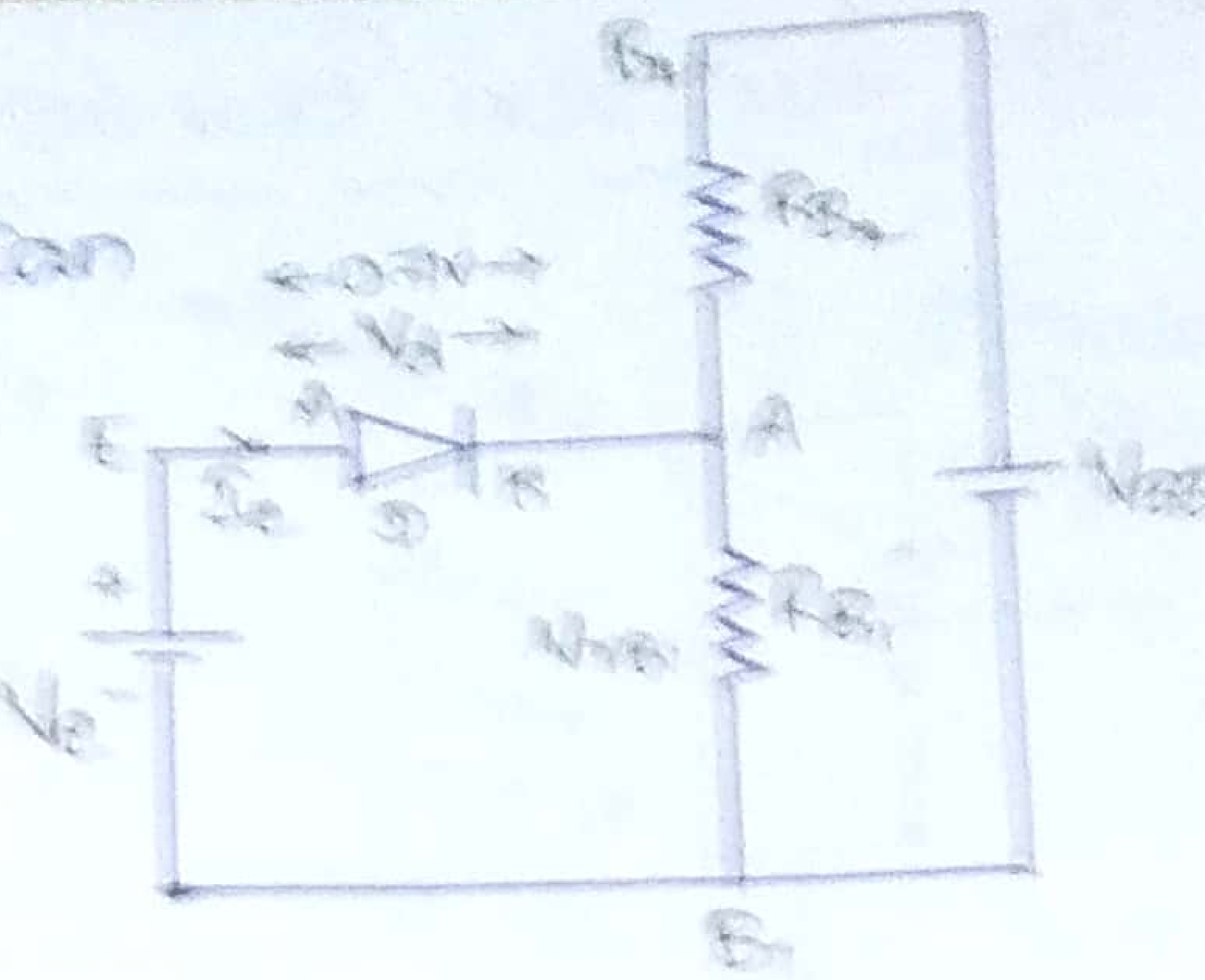
- → V_P - Peak point Voltage.
- → V_V - Valley point Voltage.
- → I_P - Peak point current.
- → I_V - Valley point current.
- → I_e - Emitter current
- → V_e - Emitter Voltage.

→ UJT is a two layered, 3 terminal power Semiconductor Switching device. It is also called as Double Base Diode.

→ The Diode D in Equivalent circuit represents the P-N Junction is formed between heavily Doped P region and lightly Doped Entire Si-bar.

→ Operation of UJT:-

→ The operation of UJT can be obtained when Base B_2 is made positive with respect to Base B_1 by the Voltage Source V_{bb} and Emitter E is made positive with respect to B_1 by Voltage Source V_E.



→ Initially assume Emitter Voltage V_E is zero, then the Voltage across Resistance R_{B_1} can be obtained by using R_{B_1} Voltage Division Rule.

$$V_{rB_1} = V_{BB} \times \frac{R_{B_1}}{R_{B_1}+R_{B_2}}.$$

$$\Rightarrow V_{rB_1} = \eta V_{BB}. \quad (V_{rB_1} = \text{Stand off Voltage})$$

$$\Rightarrow \eta = \frac{R_{B_1}}{R_{B_1}+R_{B_2}} = \frac{R_{B_1}}{R_{BB}}$$

→ $R_{BB} = R_{B_1} + R_{B_2}$ = Inter base Resistance

→ η = Intrinsic Stand off Ratio (0.4 – 0.8)

Case (i):-

when, $V_e < V_{rB_1}$ $(V_e \neq 0)$

D = RB = OFF

$I_e = 0$.

UJT = not turn on = off

→ But due to minority charge carriers, Small reverse leakage current flows through Emitter circuit

Case (2) :-

→ As Emitter Voltage increases, at one instant it becomes equals to V_{rB_1} Voltage i.e.,

when $V_e = V_{rB_1}$.

$I_e = 0$.

D = RB = OC.

UJT = not turn on = Off.

Case (3) :-

→ As Emitter voltages increases again, it becomes greater than V_{rB_1}. i.e.,

when $V_e > V_{rB_1}$

D = FB = SC.

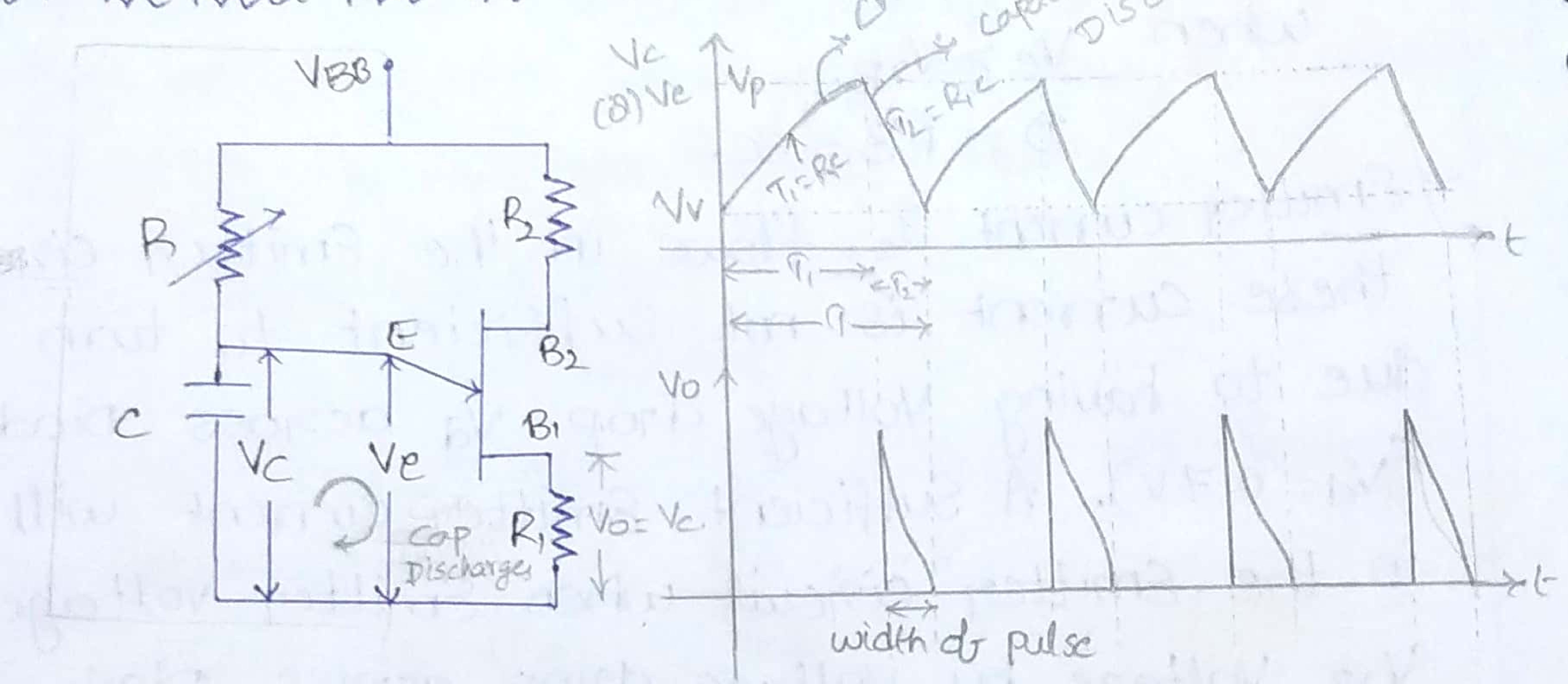
→ Emitter current I_e, flows in the Emitter circuit but these current is not sufficient to turn on UJT due to having Voltage drop V_d across Diode - D ($V_d = 0.7V$). A Sufficient Emitter current will flow in the Emitter circuit when Emitter voltage exceeds V_{rB_1} Voltage by voltage drop across Diode V_d i.e.,

/ $V_e \geq V_{rB_1} + V_d$. /

and then UJT turned on.

→ At Peak point C, UJT is turned on. when UJT is turned on, the Emitter terminal injects holes from p-layer into N-layer. The injected holes are repelled by base - b_2 & attracted by Base - B_1. As a result the region between ~~B~~ E and B_1 is additionally filled up with charge carriers. As a result Conductivity increases → $I_e \uparrow$ $R_{B_1} \downarrow$ $\eta \downarrow$ $V_{B_1} \downarrow$ $V_e \downarrow$.

- As Emitter to current I_e increases, Emitter voltage V_e decreases (-ve Res. characteristics) and reaches to valley point D. Beyond this valley point, UJT is saturated.
- The increase in I_e causes decrease in Resistance and then Emitter voltage. It shows that UJT has Negative Resistance characteristics.
- Because of having Negative Resistance characteristics UJT is popularly employed in Relaxation oscillator.
- UJT Relaxation oscillator:-



- Relaxation oscillator is non linear electronic ckt that produces non-sinusiodal output signal. The o/p signals may be Sawtooth, Triangular & square or Rectangular signals.
- The Resistances R_1 and R_2 are current limiting Resistors which are very small compared to the internal Resistance of UJT Base (R_{B_1} & R_{B_2}).
- The Resistance R & capacitor C are used to determine frequency of oscillations.

from fig. $T = T_1 + T_2$ ($\because T_1 >> T_2$)

$T = T_1$; At $t = T = T_1$.

$\Rightarrow V_C = V_P$.

$\Rightarrow V_{BB}(1 - e^{-t/RC}) = \eta V_{BB} + V_d$

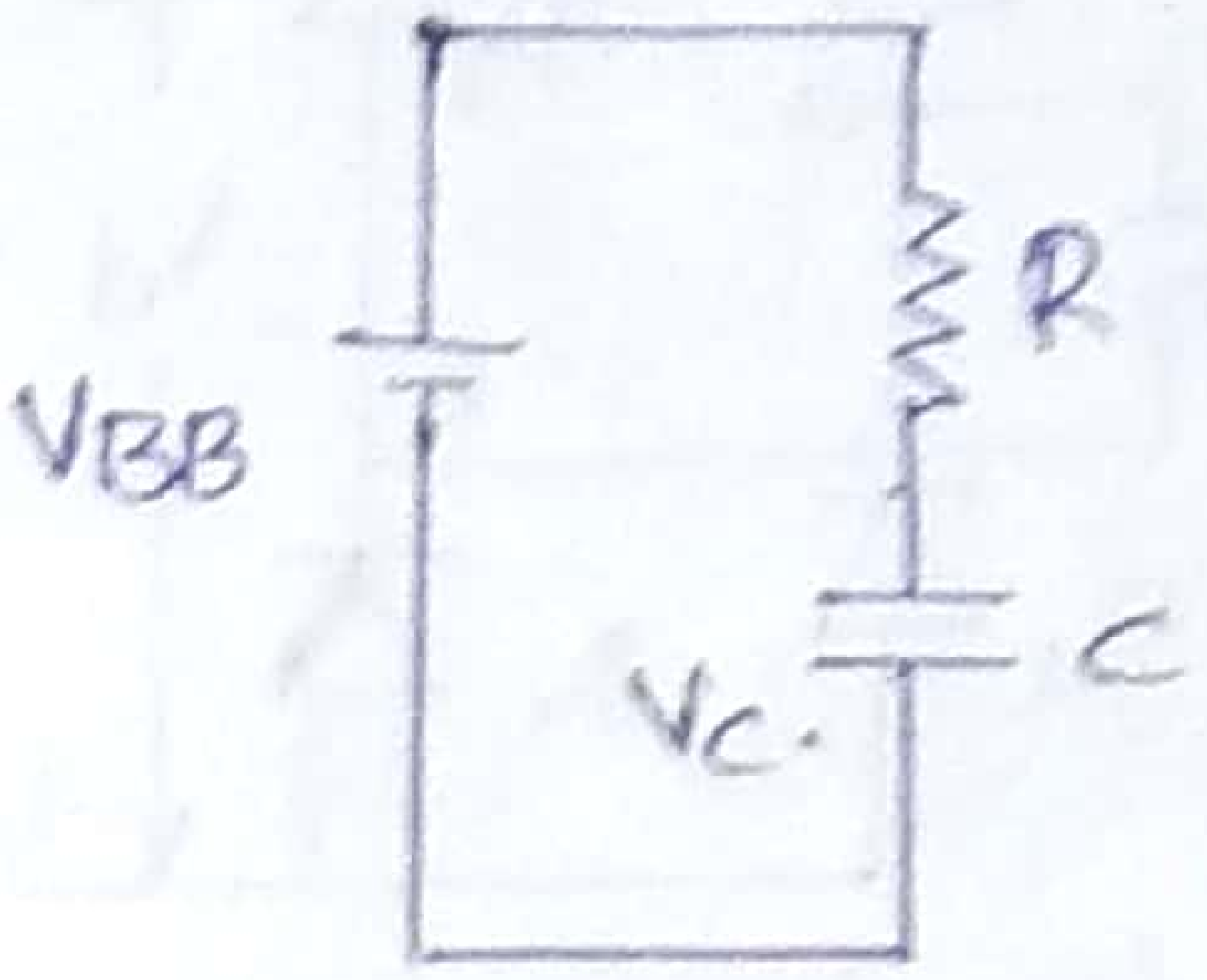
$\Rightarrow \cancel{V_{BB}}(1 - e^{-T/RC}) = \eta \cancel{V_{BB}}$

$\Rightarrow e^{-T/RC} = 1 - \eta$.

$\Rightarrow T/RC = \ln\left(\frac{1}{1-\eta}\right)$

$\therefore T = RC. \ln\left(\frac{1}{1-\eta}\right)$

$\therefore f = 1/T$.



$$*/ \ f = \frac{1}{RC \ln\left(\frac{1}{1-\eta}\right)} \ /*$$

→ when Resistance R is minimum, freq of oscillations are maximum, when R is max, freq of oscillations are minimum. i.e.,

/ $R \to R_{min}$; $f \to f_{max}$ & $R \to R_{max}$; $f \to f_{min}$ /

* Si UJT have 20V between the bases. If η is 0.6. find Values of Stand of voltage & peak point voltage

Sol:- Given, $V_{BB} = 20V$

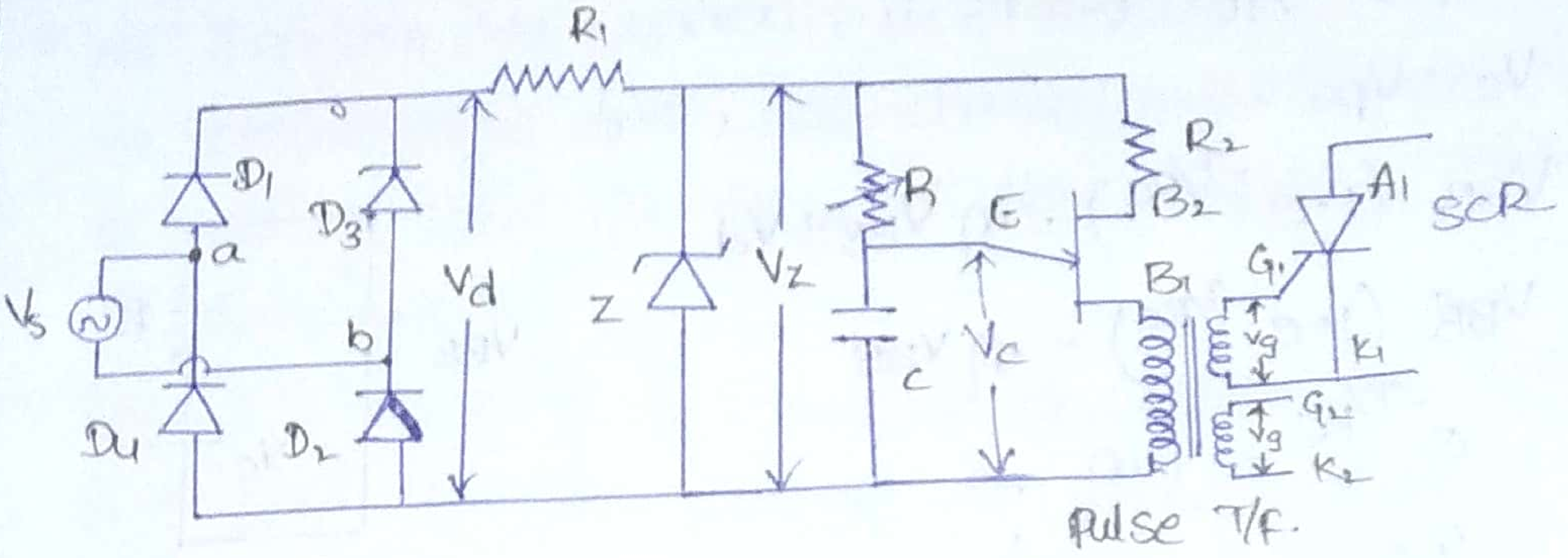
$\eta = 0.6$.

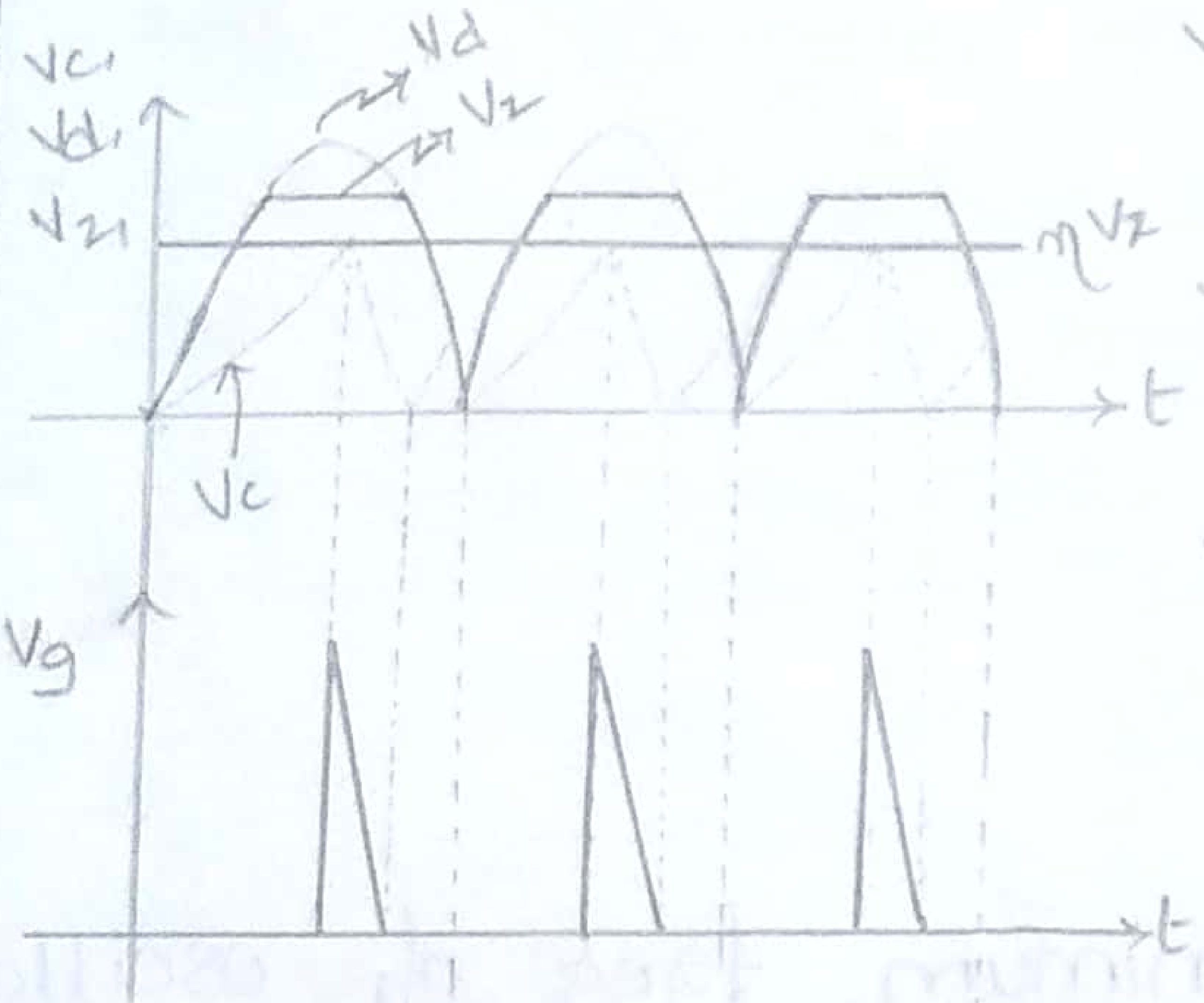
$V_{rB_1} = \eta V_{BB} = 0.6 \times 20 = 12V$ //

$V_p = V_{rB_1} + V_d = 12 + 0.7 = 12.7V$ //

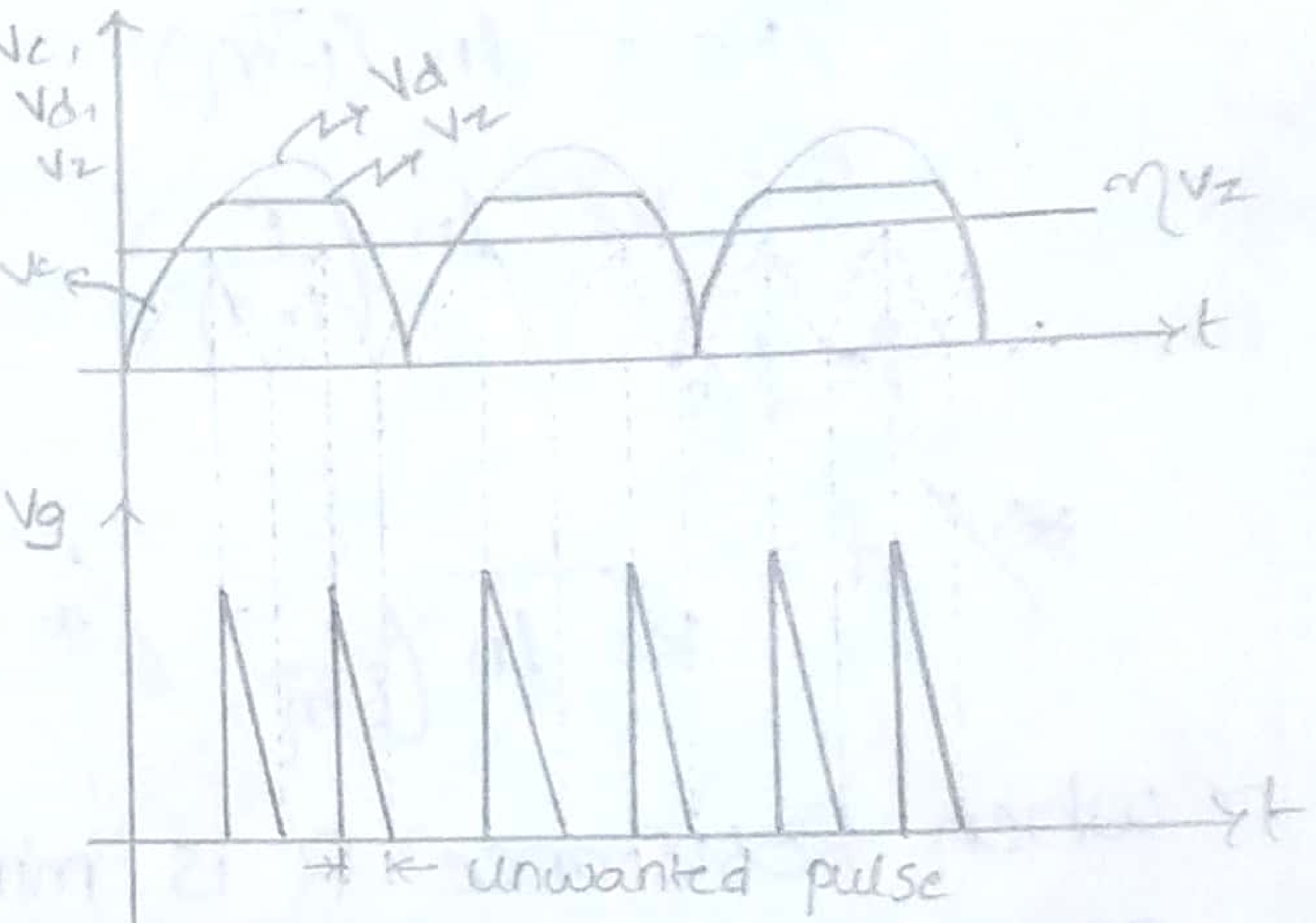
→ Synchronised (Triggering) UJT (or)

RAMP Triggering:-





(i) For High Resistance



(ii) for Low Resistance

- It uses full wave Diode Bridge Rectifier, here D_1, D_2, D_3, D_4 forms Diode Bridge Rectifier. It converts ac to pulsating dc.
- Resistance R_1 lowers the Rectified output Voltage V_d to a Suitable Value for Zener Diode and UJT.
- Zener Diode clips the Rectified output Voltage (V_d) to constant Voltage (V_z). this Voltage is
- when applied as input to RC circuit.
- when Voltage V_z is applied to RC circuit, the capacitor charges through Resistance R. when capacitor Voltage reaches to UJT triggering Voltage, UJT gets turned on.
- once UJT is turned on capacitor Voltage discharges through primary winding of pulse Transformer.

- According to Mutual Inductance principle, Gate voltages are generated in Secondaries of pulse Tr. when Anode is made positive w.r.to cathode SCR gets turned on.

Pulse Transformer:-

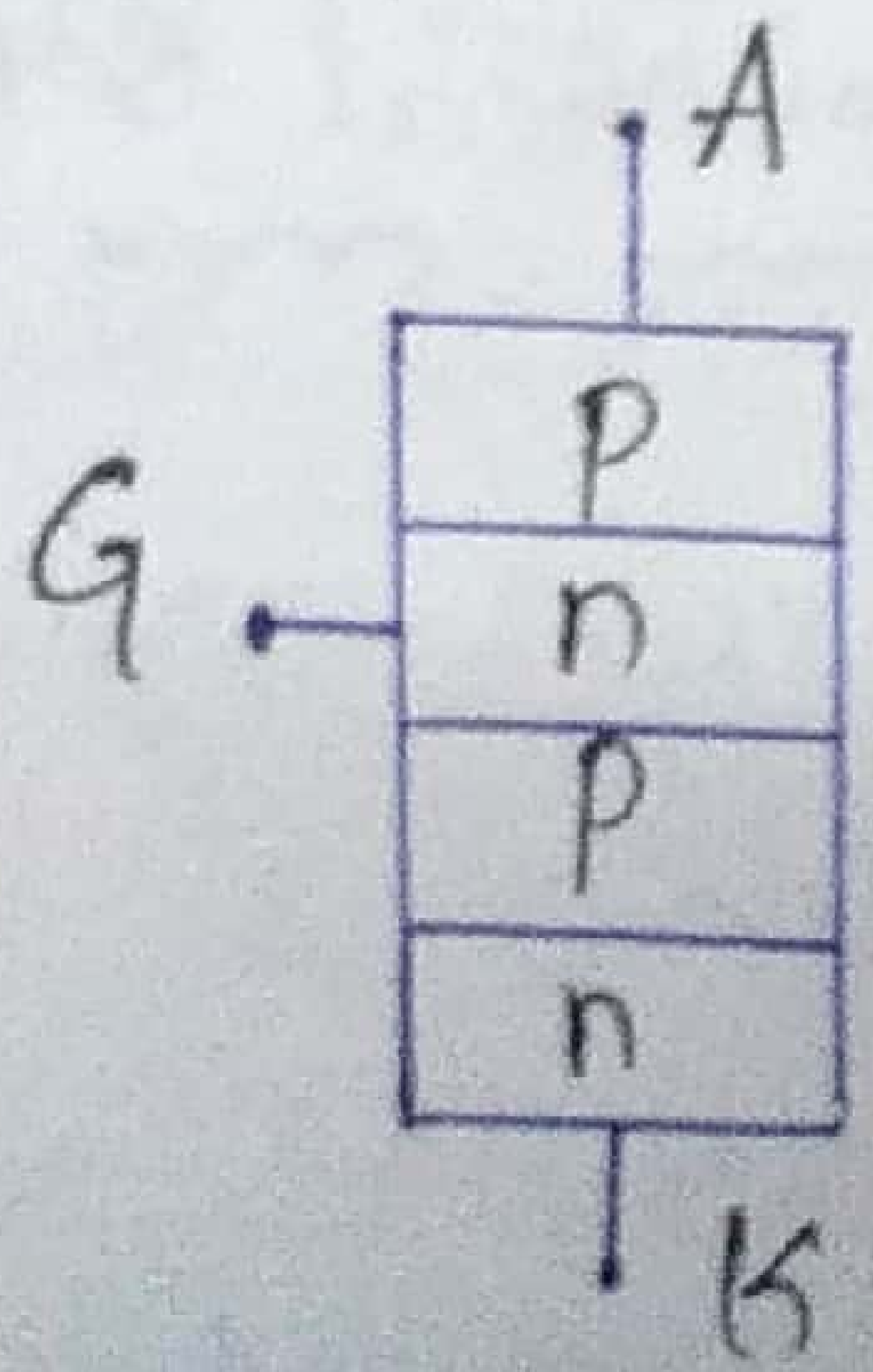
- firing circuits are operated at low voltages (5-20) where as Thyristor circuits are operated at High Voltage levels (>250V). (Hence, electrical isolation) their must be electrical isolation between low voltage firing circuits and High voltage Thyristor ckts. Hence these electrical isolation is provided by pulse T/F
- It has only one primary winding and multiple secondary windings. Multiple secondary windings allows simultaneous Gate signals to one or more devices.

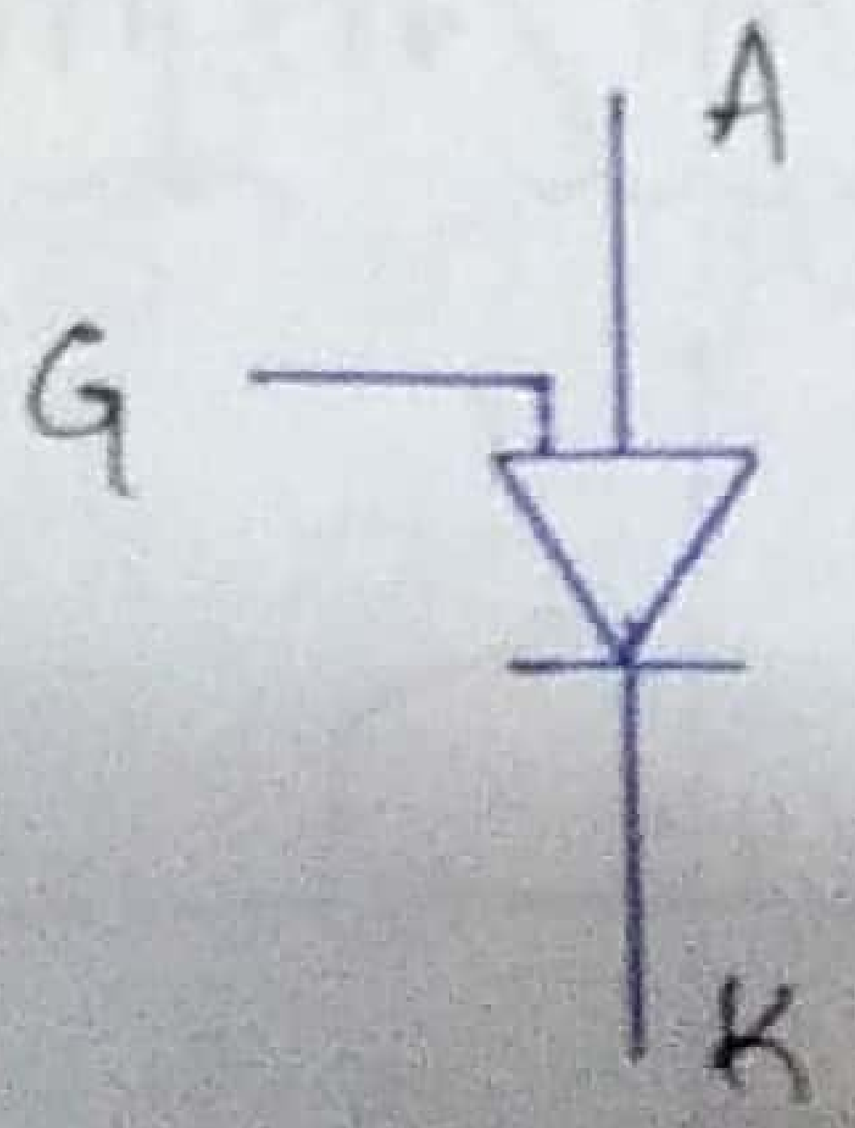
Advantages of pulse T/F:-

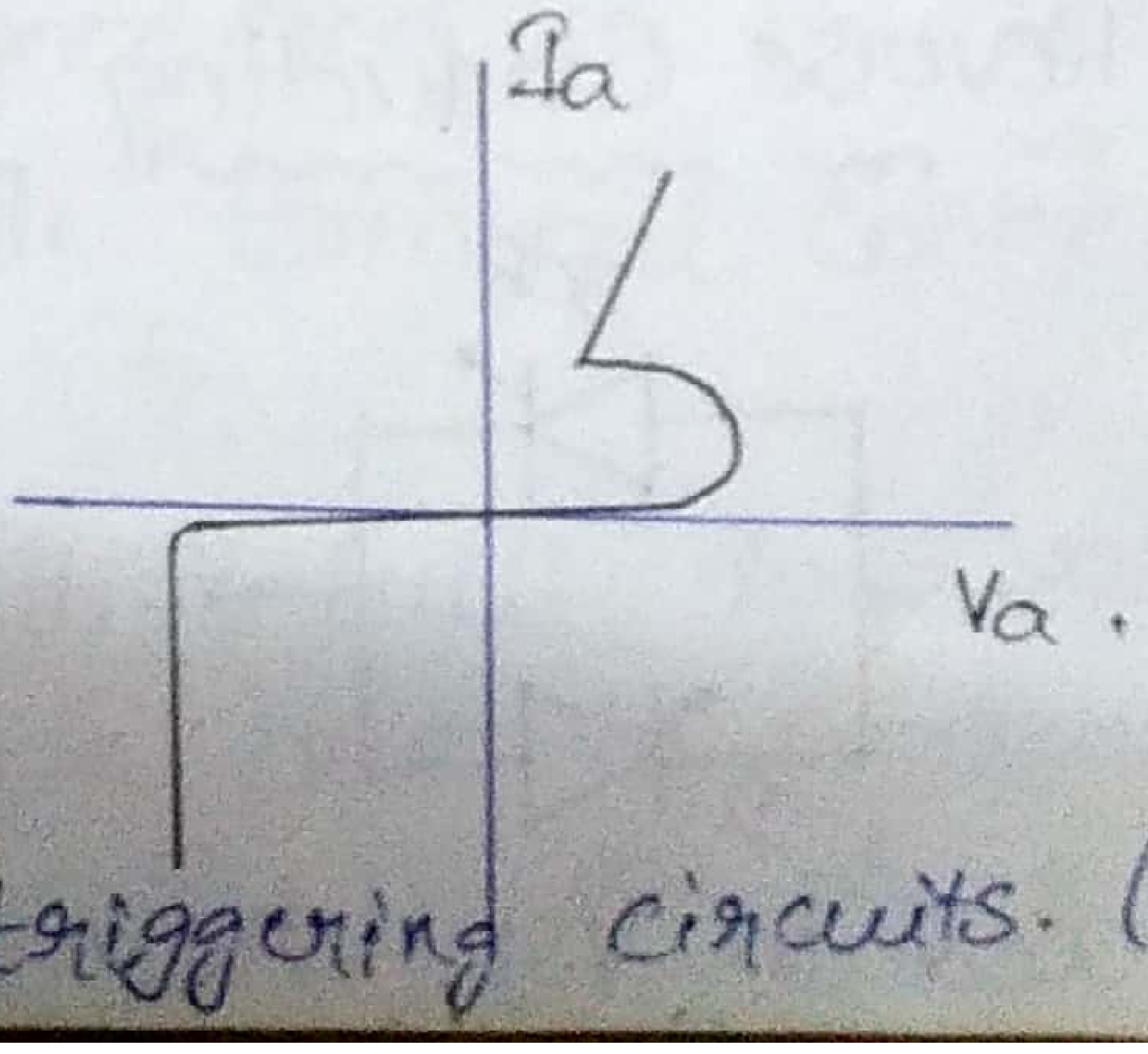
- It provides electrical isolation between low V firing circuit and HV Thyristor circuits.
- from the same firing circuit Triggering of one or more SCR's is possible.

Thyristor Family Devices:-

(1) PUT (programmable Unijunction Transistor):-

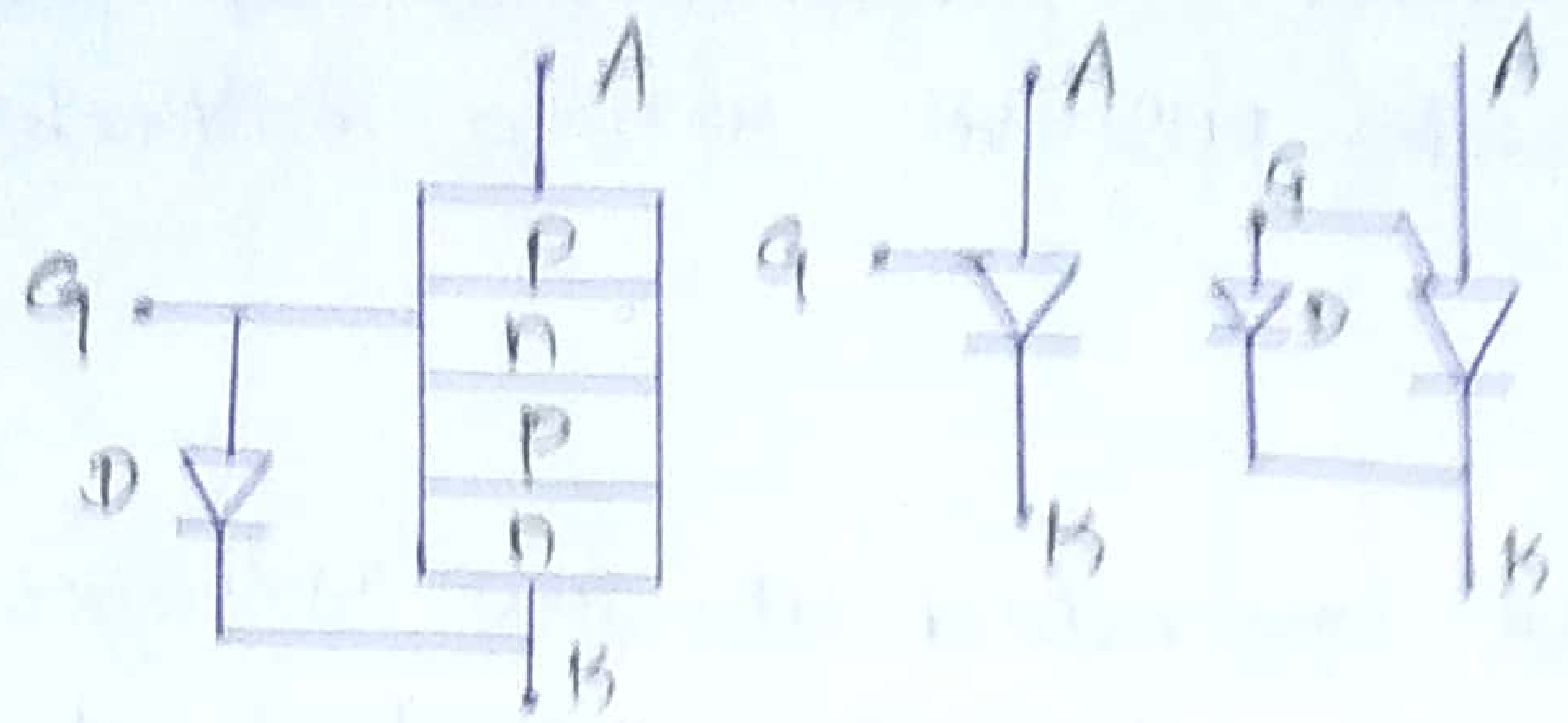


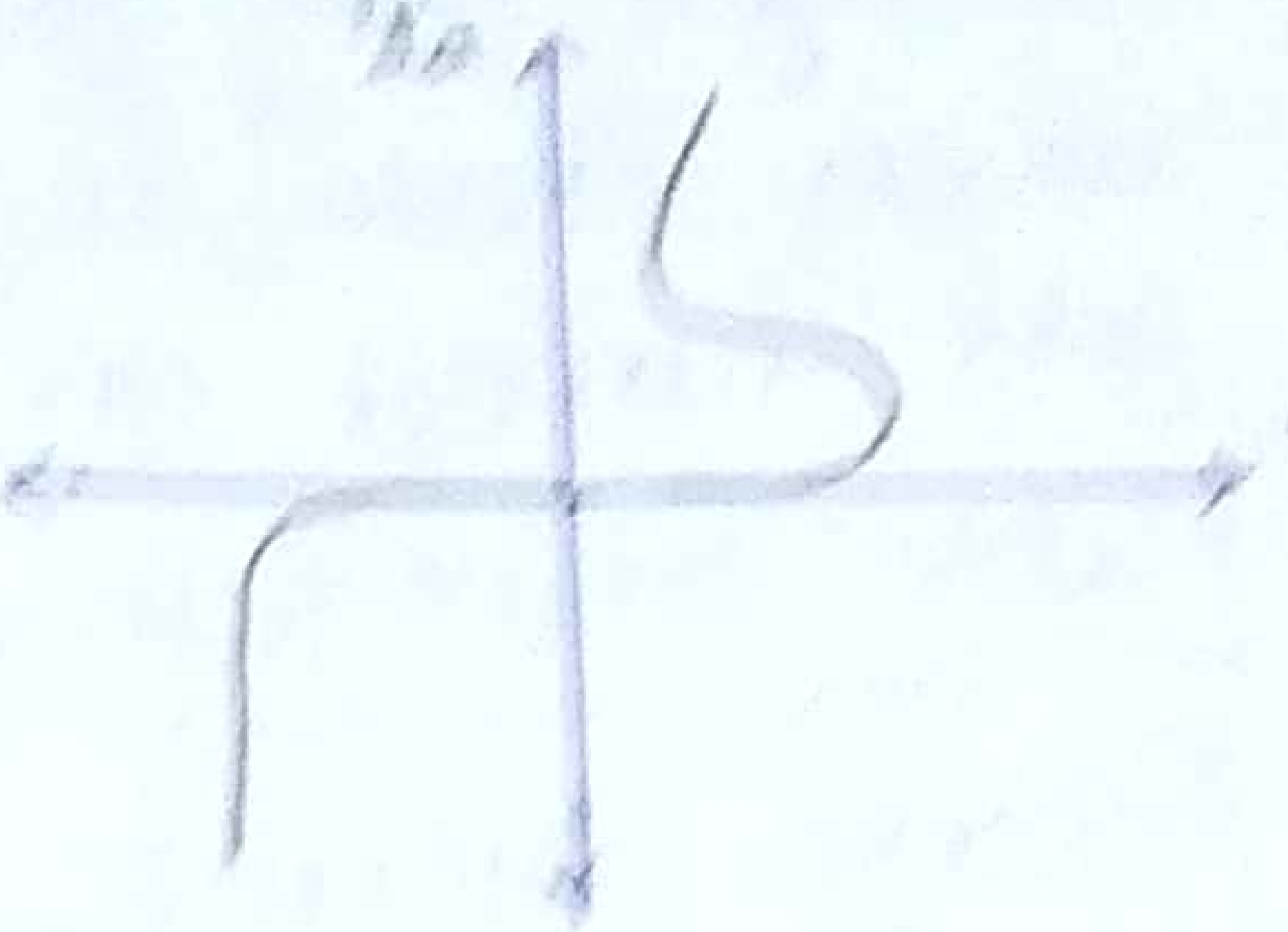




- used in logic, timing and triggering circuits. (200V, 1A)

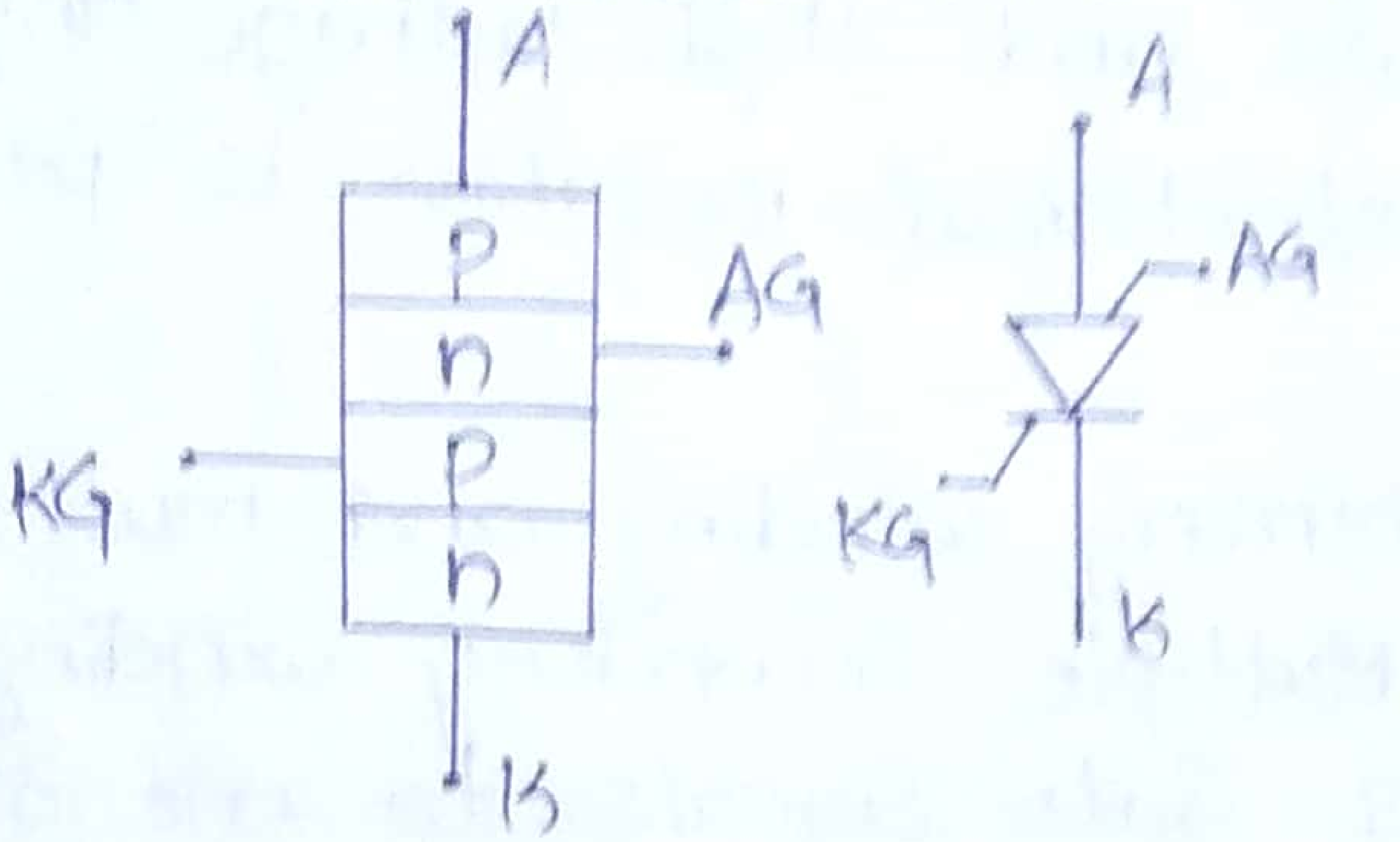
→ SUS (Silicon Unilateral Switch):-

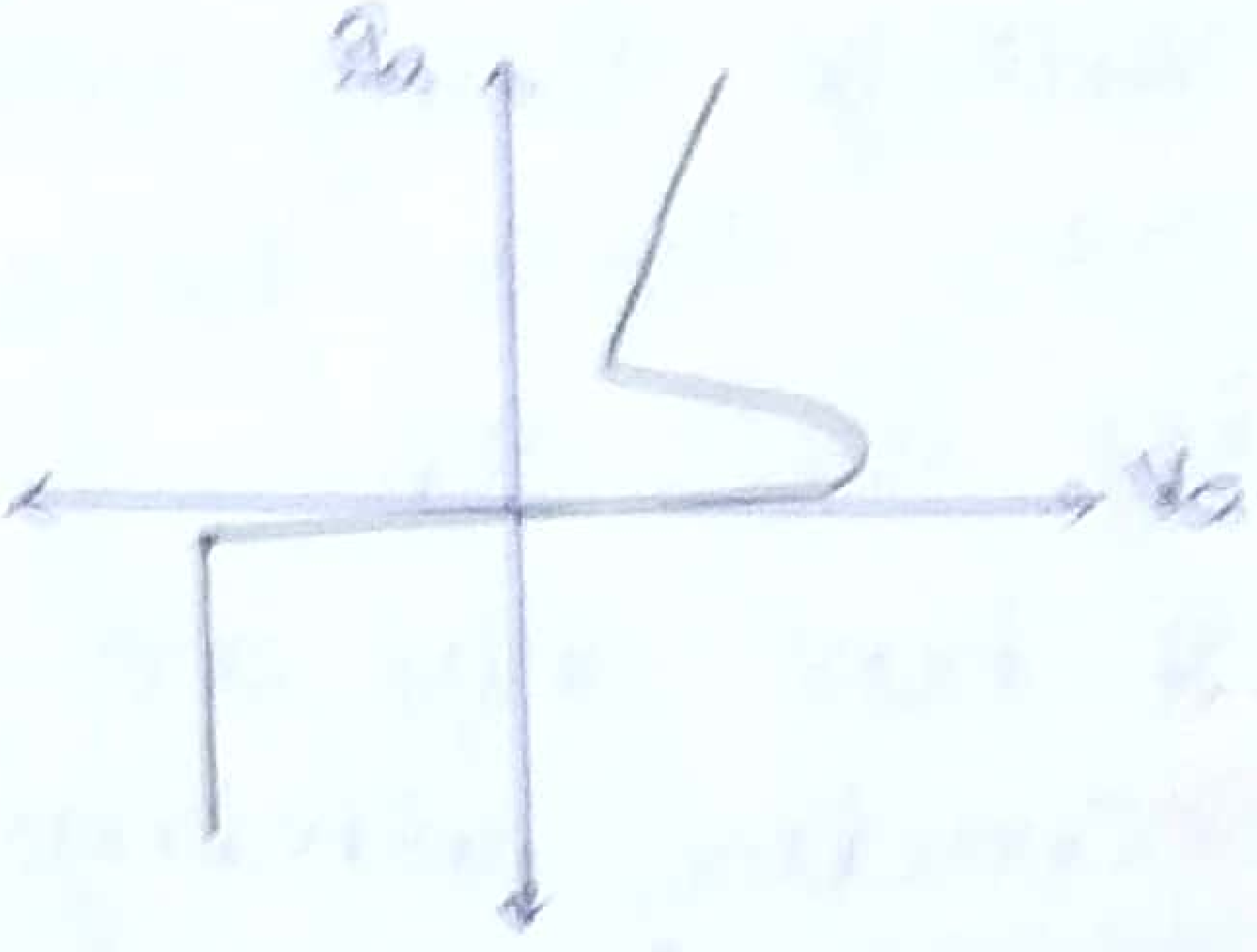




→ used in logic, timing and triggering circuit. (20V, 5A)

→ Silicon Controlled Switch SCS:-

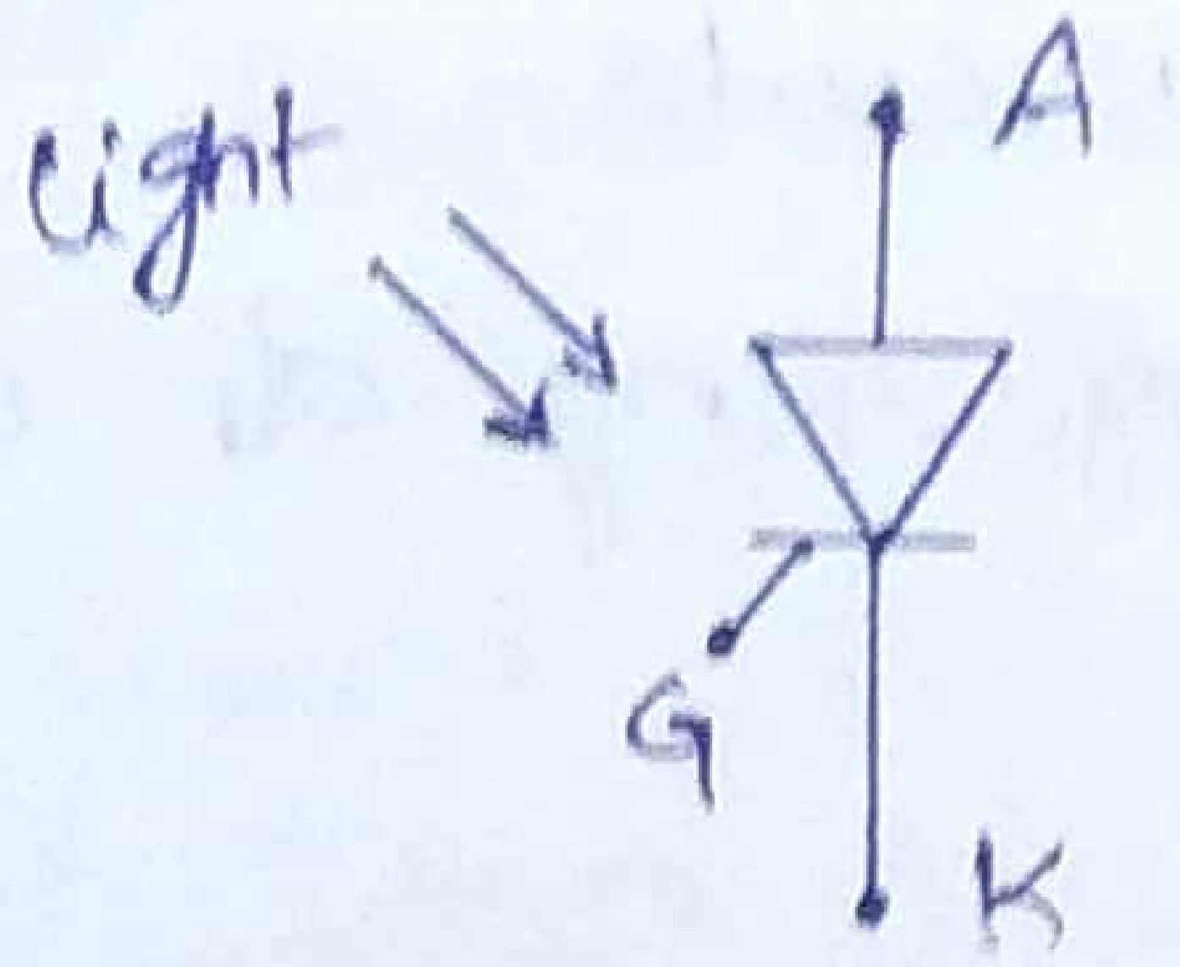


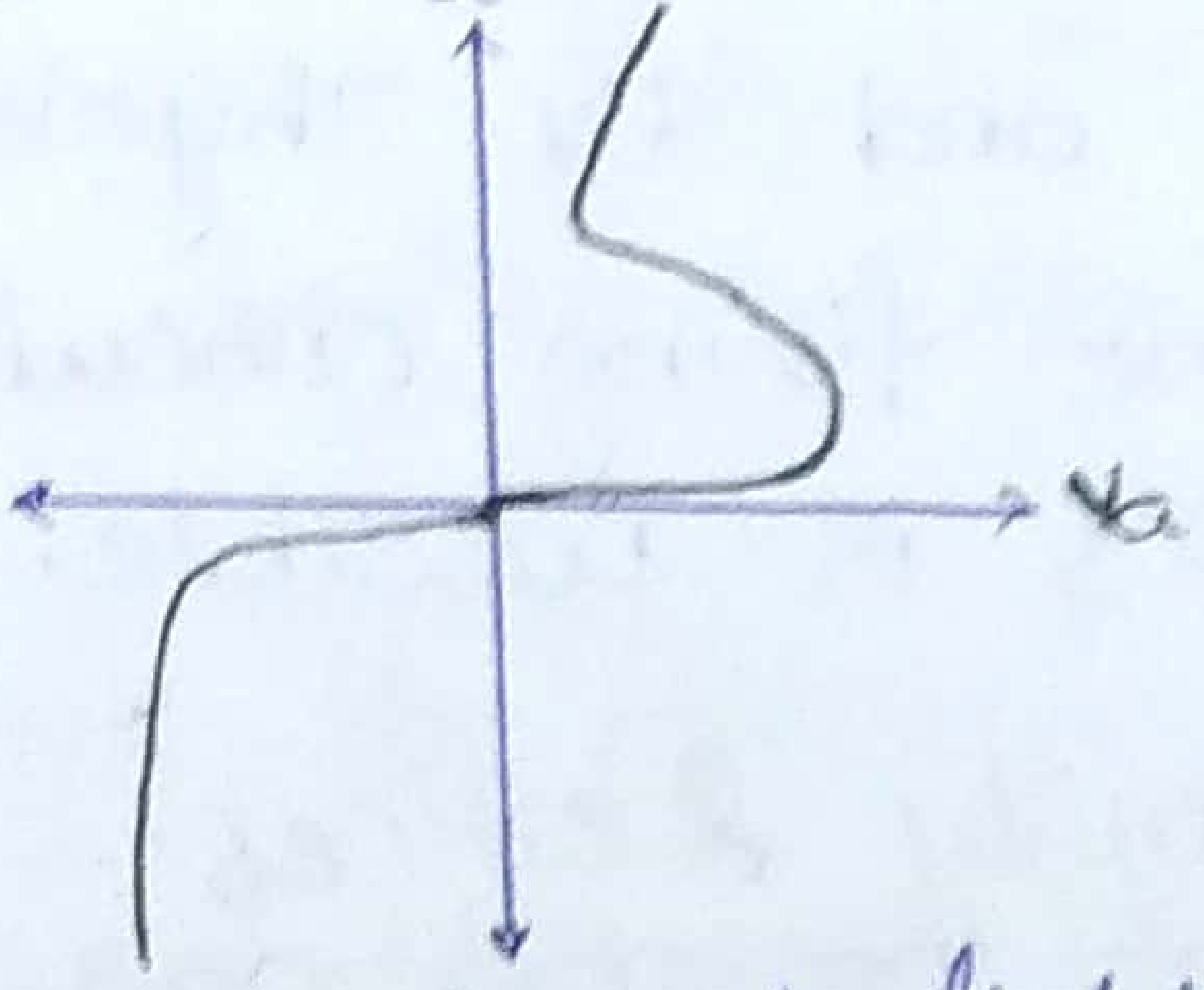


→ used in logic, timing and triggering circuits.

→ (100V, 200mA.), Voltage sensors and also in oscillators.

→ Light Activated SCR:-

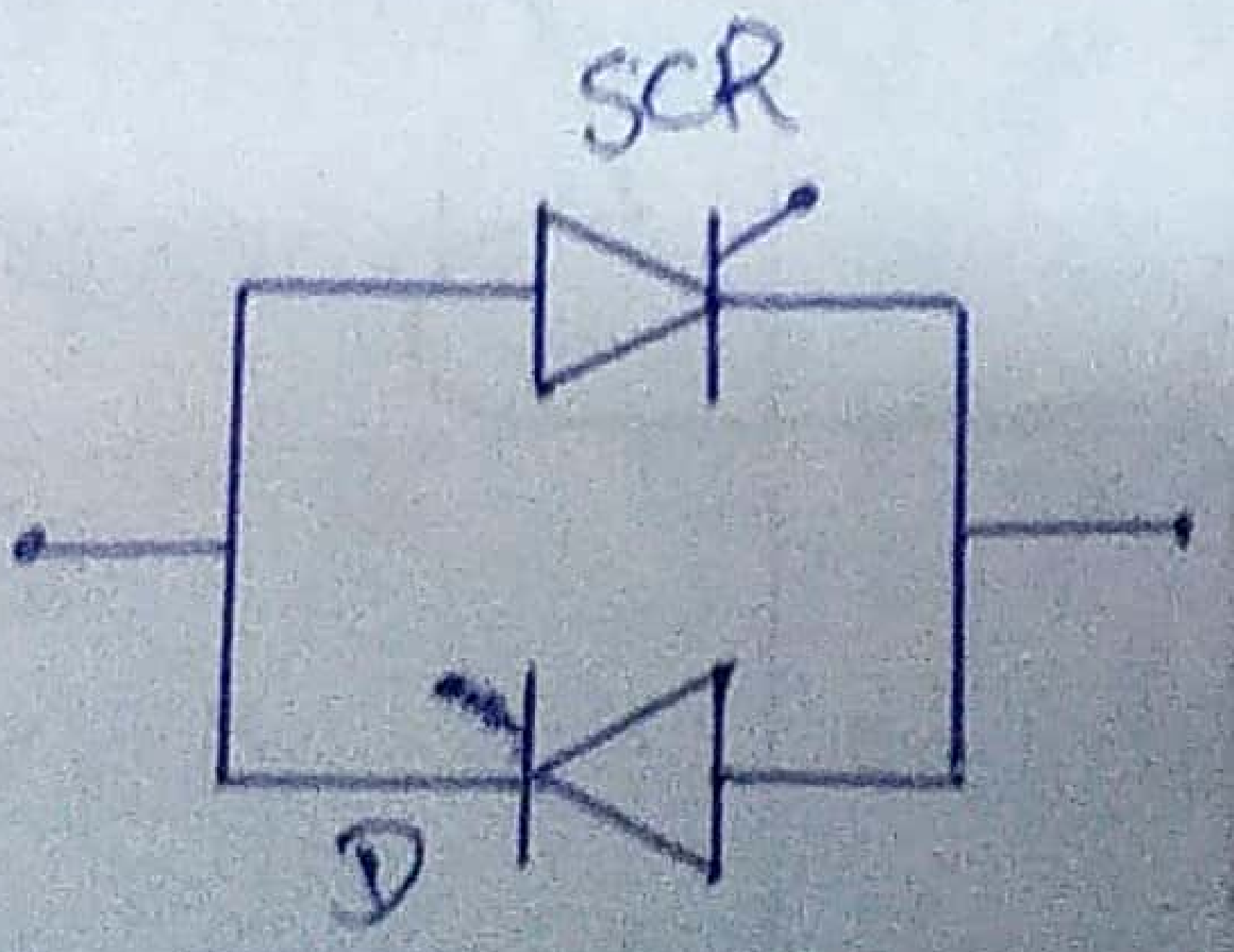


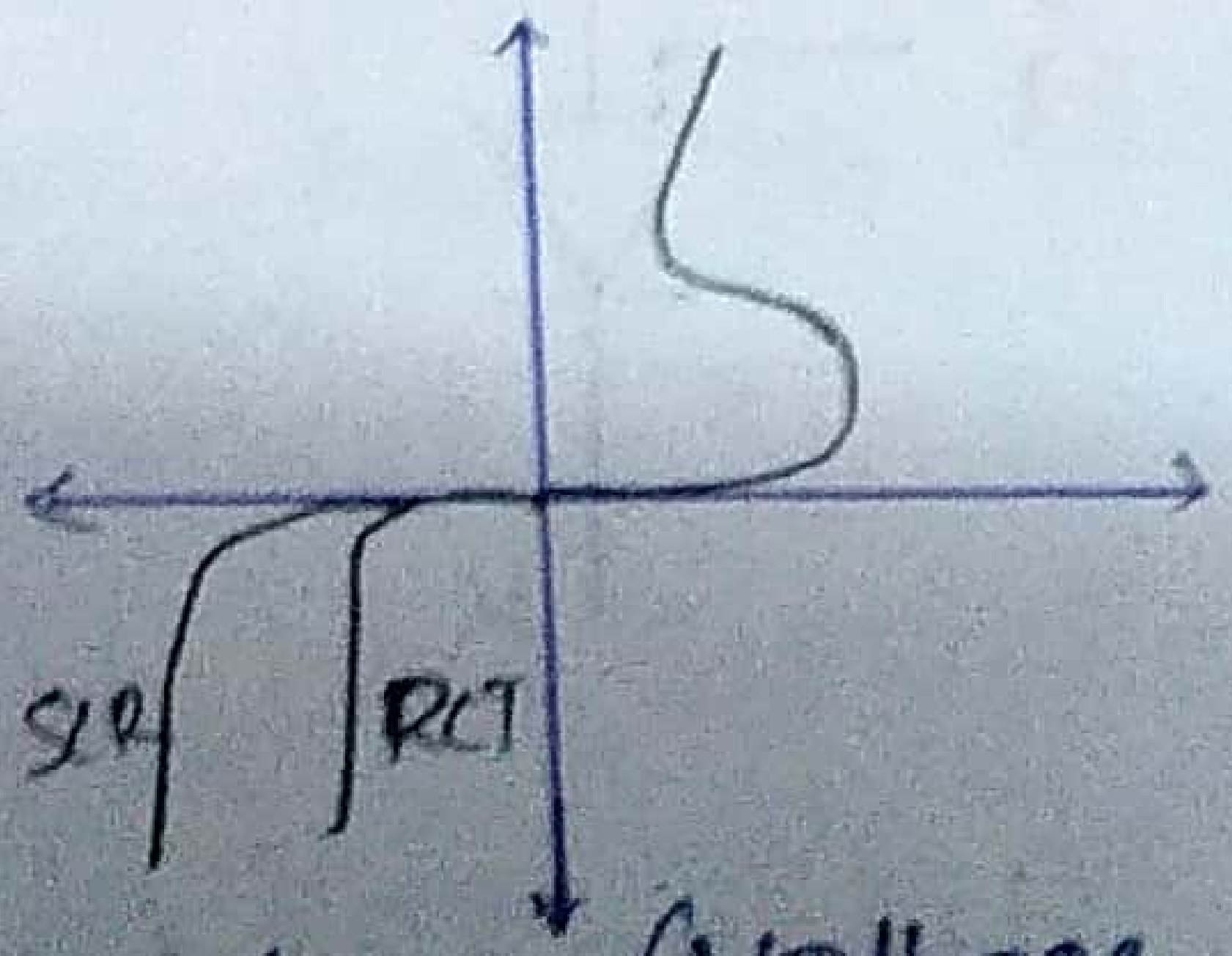


→ Used in HVDC, Trans, Street lights. G is used to turn

→ (600V, 300A.) on the device at low light intensity Cond.

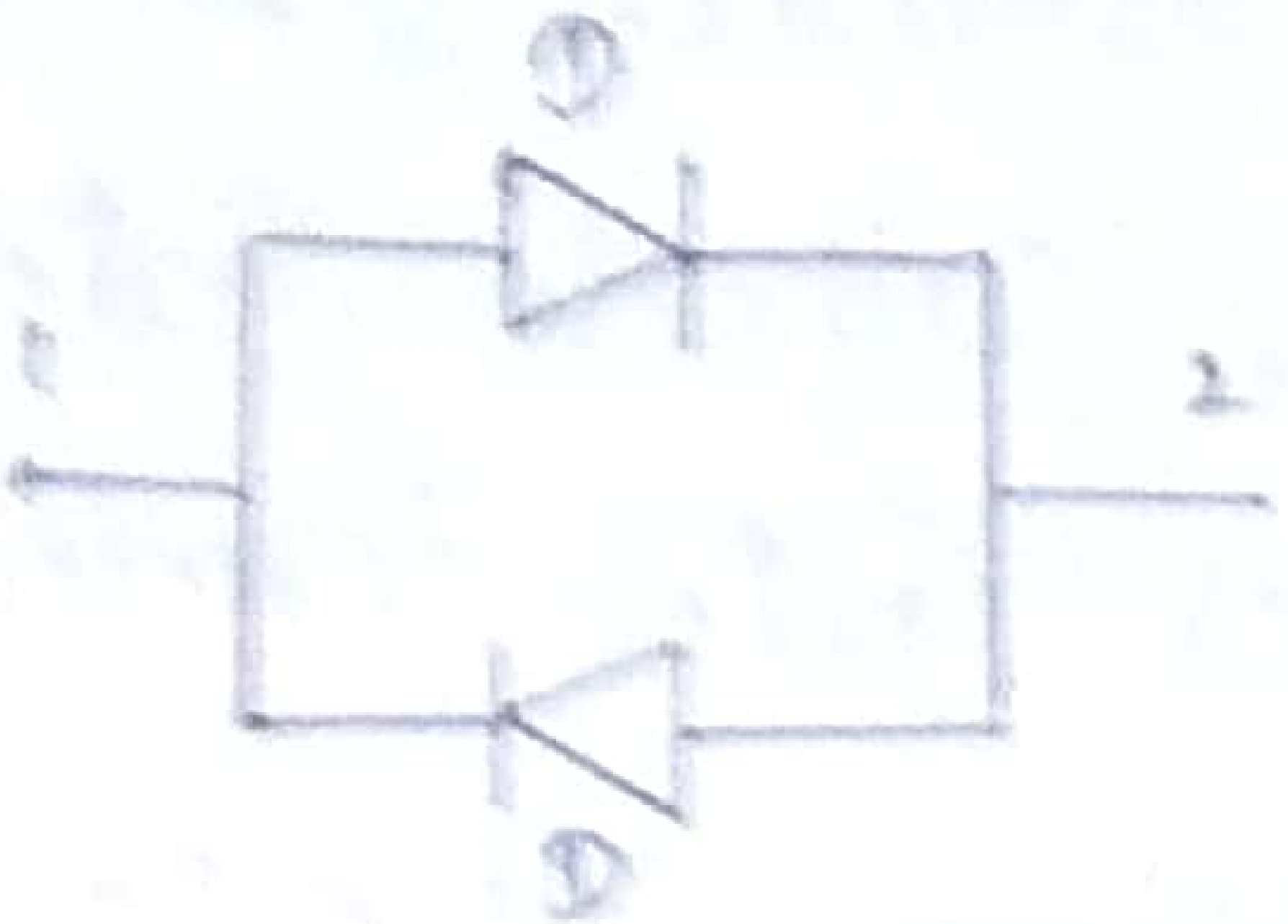
→ Reverse Conducting Thyristor / Asymmetrical SCR:-

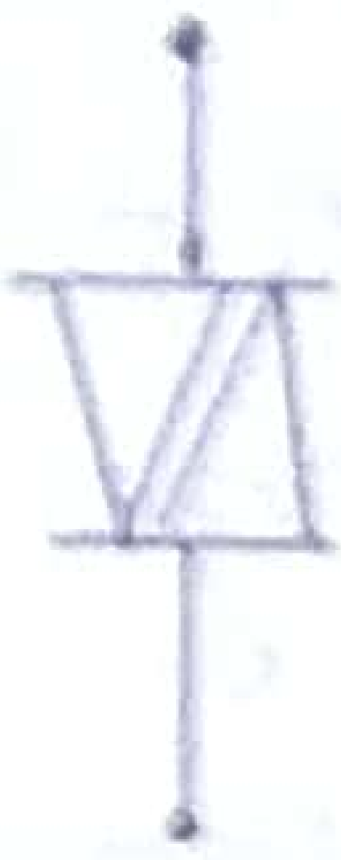


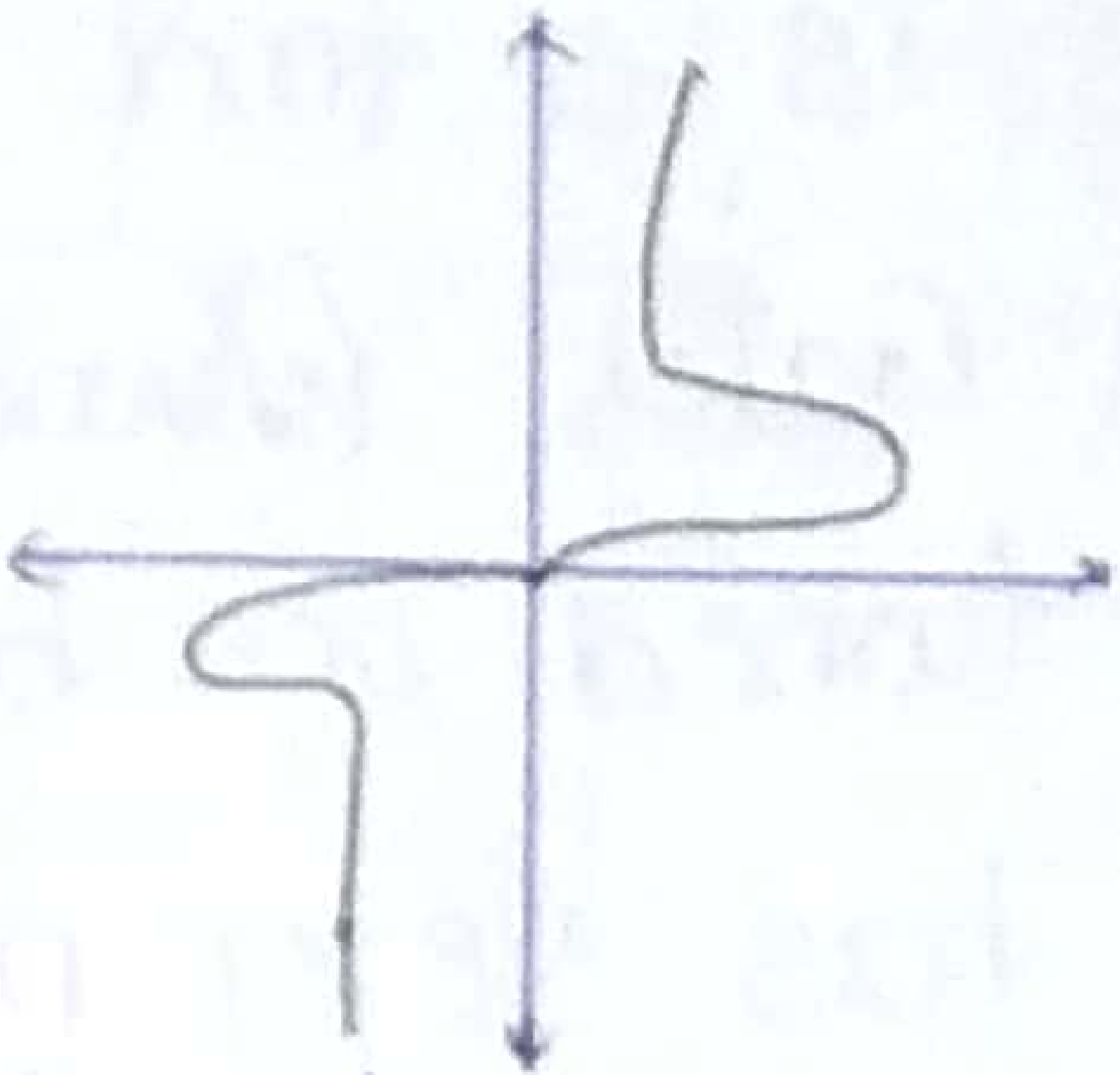


→ Used in VSI, 2500V, 400A. (Voltage Source Inverters).

→ Bire Bidirectional Diode - DIAC:-

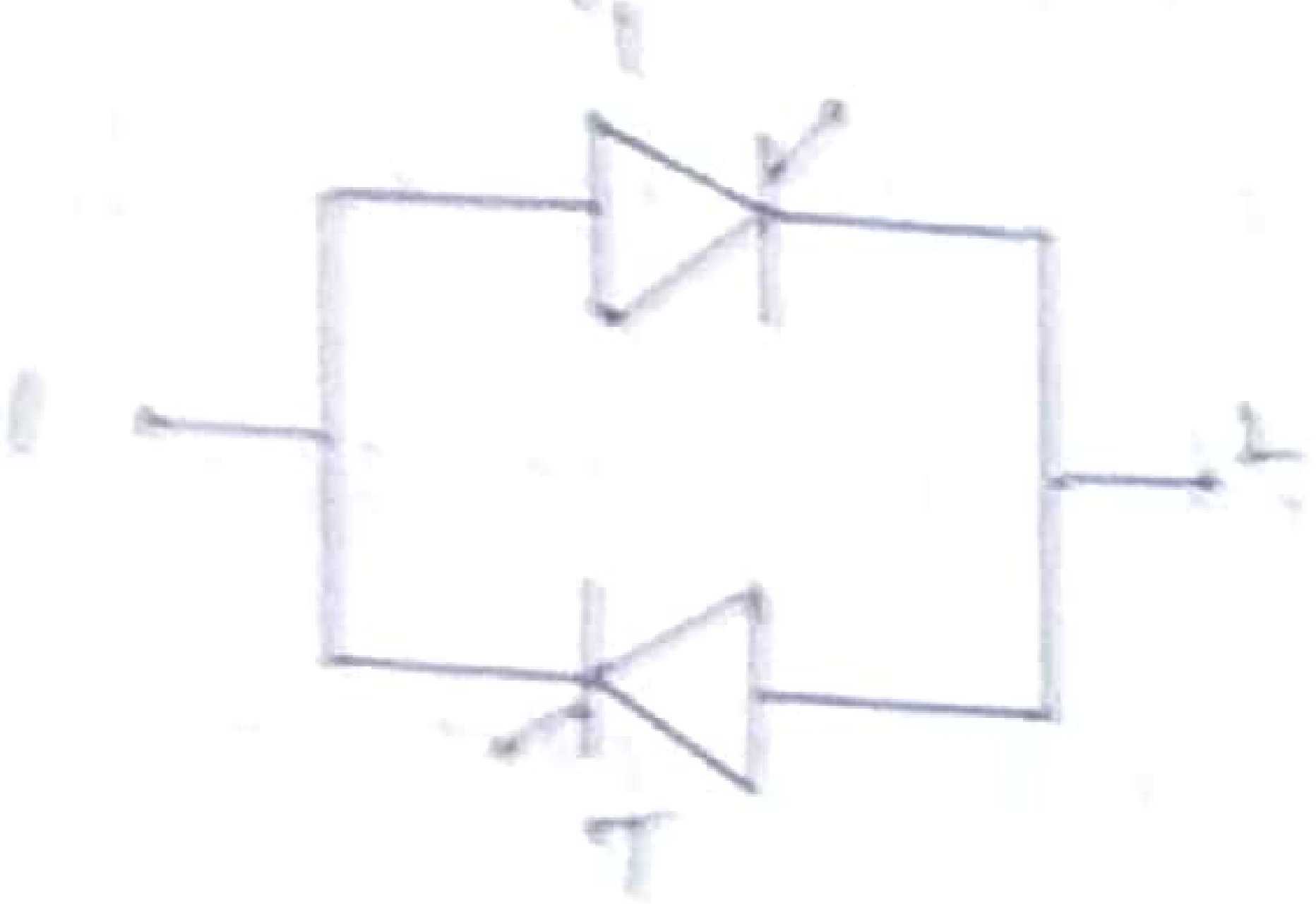


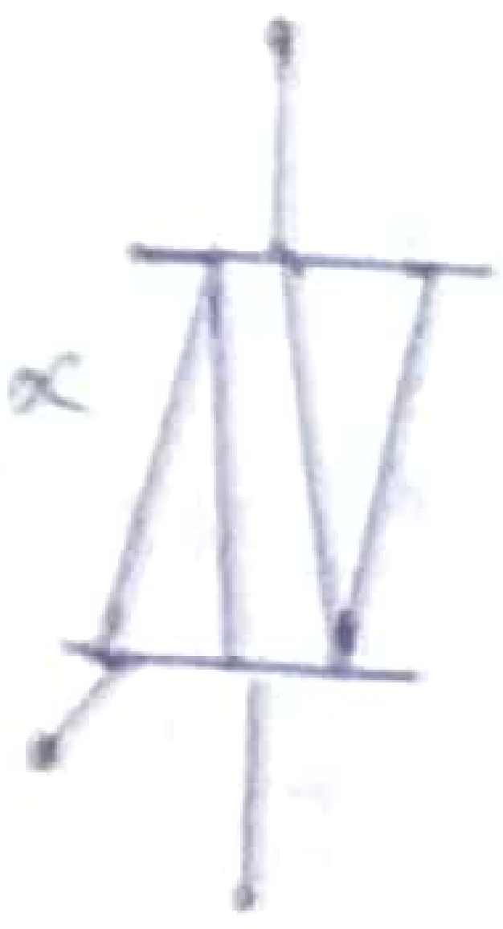


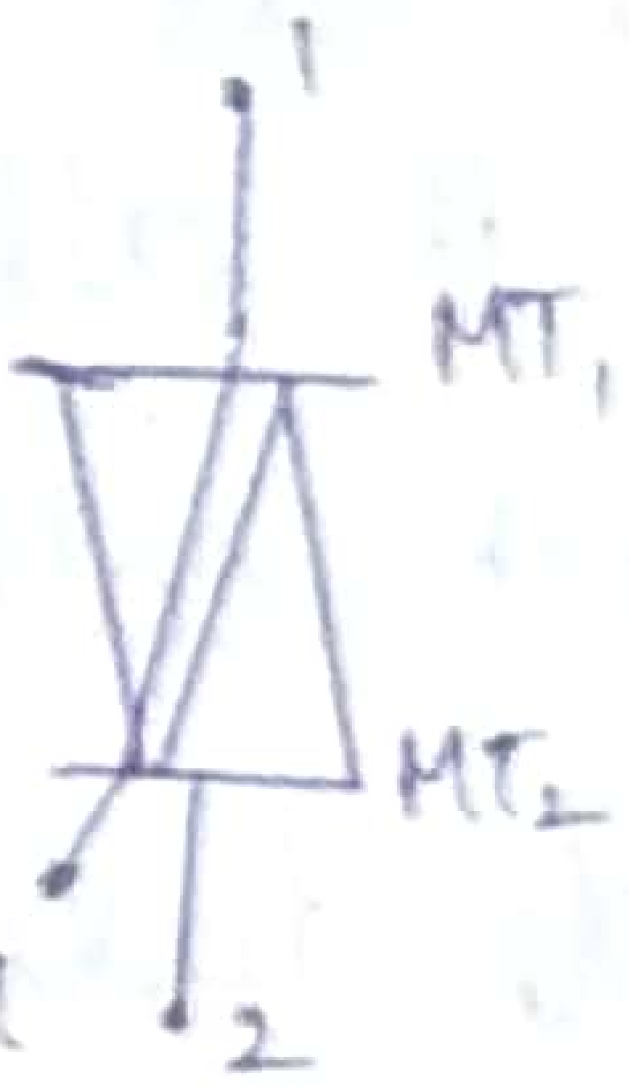


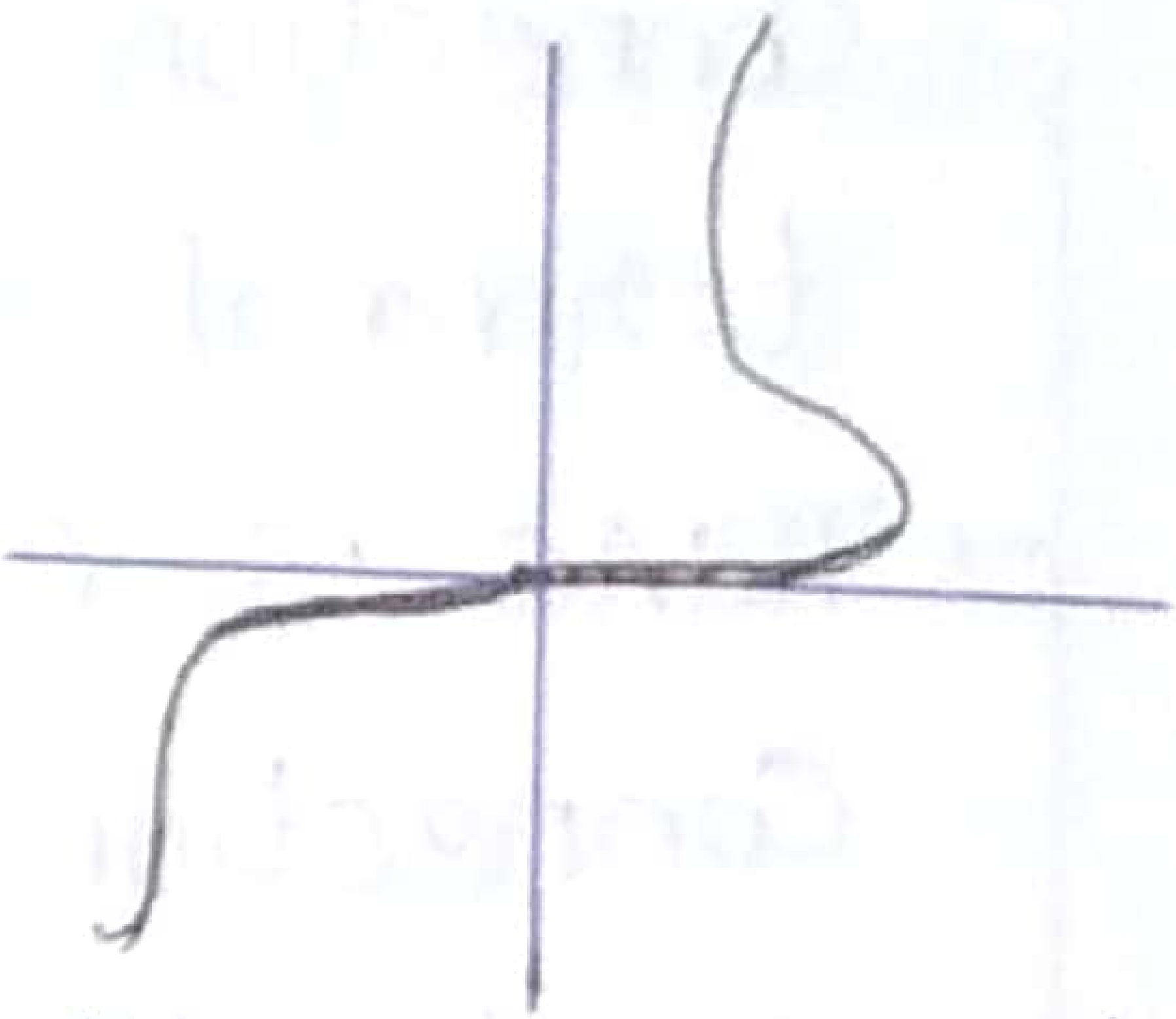
→ Used as firing circuit for TRIAC. It has no control.

→ Bidirectional Thyristor - TRIAC:-





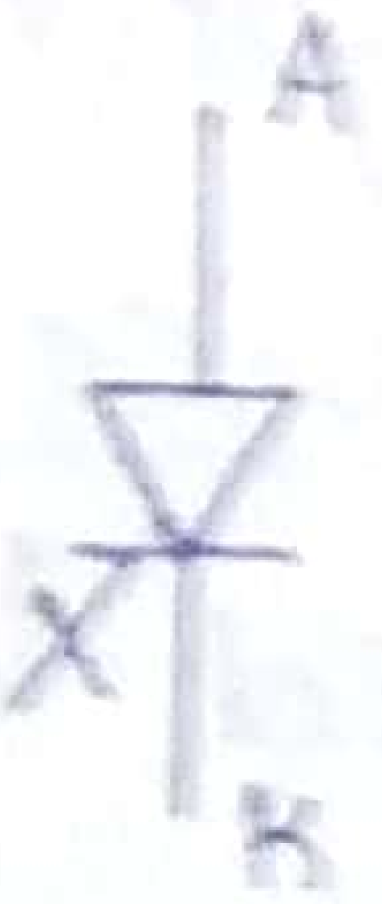


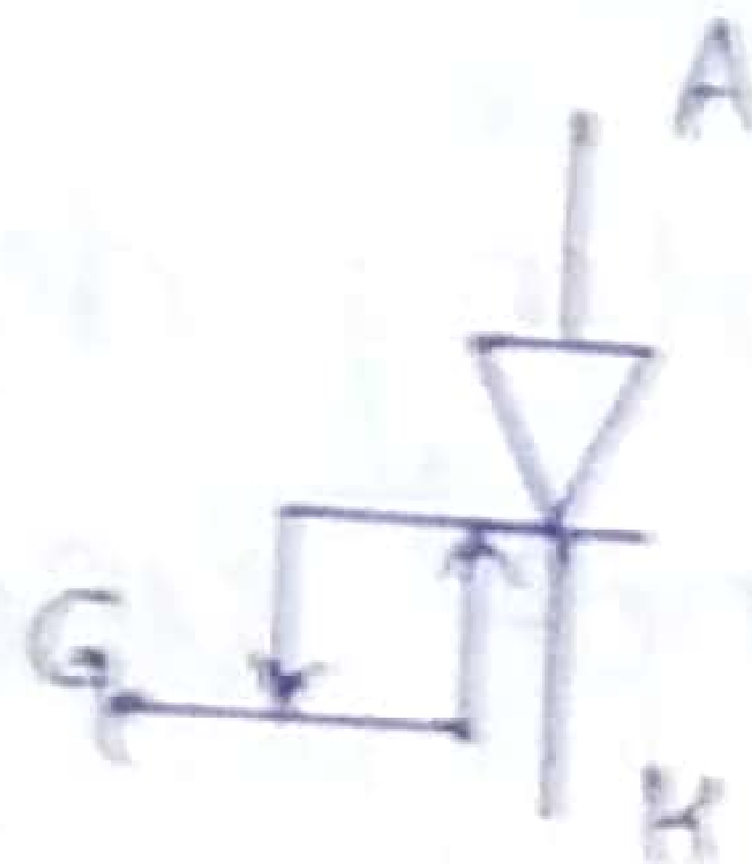


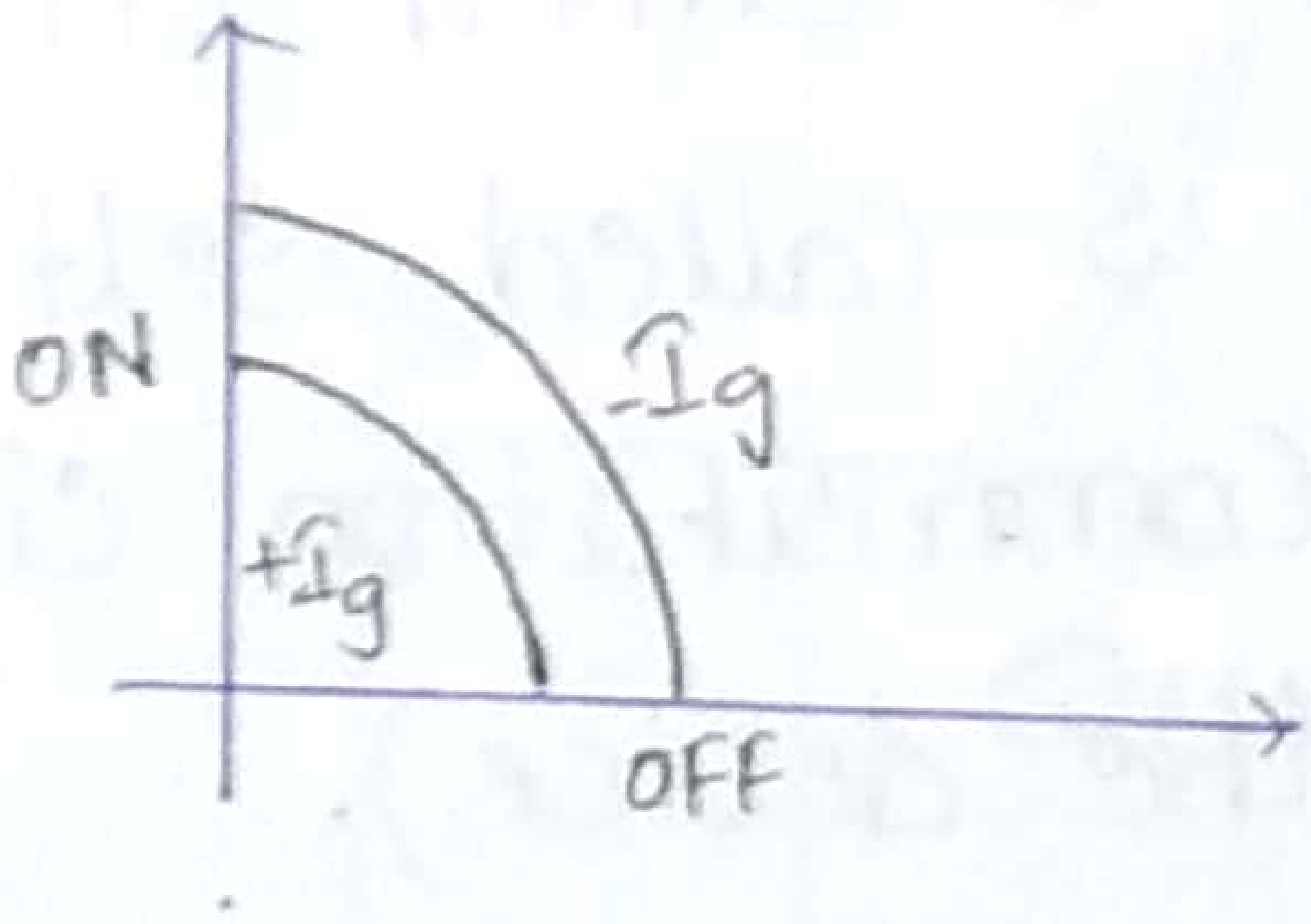
→ used in Speed Control of Machines. It has control.

→ 1200V, 100A.

→ Gate Turn off Thyristor - GTO:-







→ It is also called as Self Commutating Device.

→ 500V, 3000A & It has low current Gain.

→ It is used in ups, Inverters, DC-DC Converters...

→ PUT is a four layer, 3 terminal, power Semiconductor device like SCR. But diff between SCR and PUT is in SCR Gate terminal is connected to P-layer near Cathode, where as in PUT Gate terminal connected to N-layer near Anode.

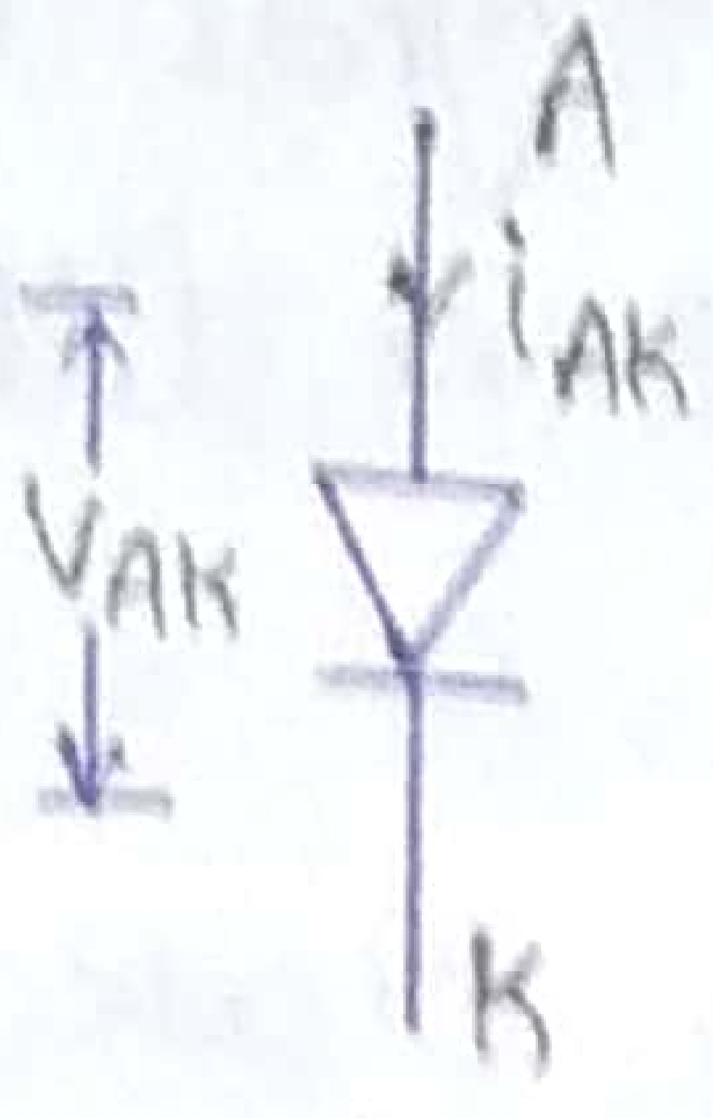
→ SUS is similar to PUT with inbuilt low Voltage diode between Gate & Cathode, due to presence of Diode it is turned on at a fixed Cat Anode to

Cathode Voltage.

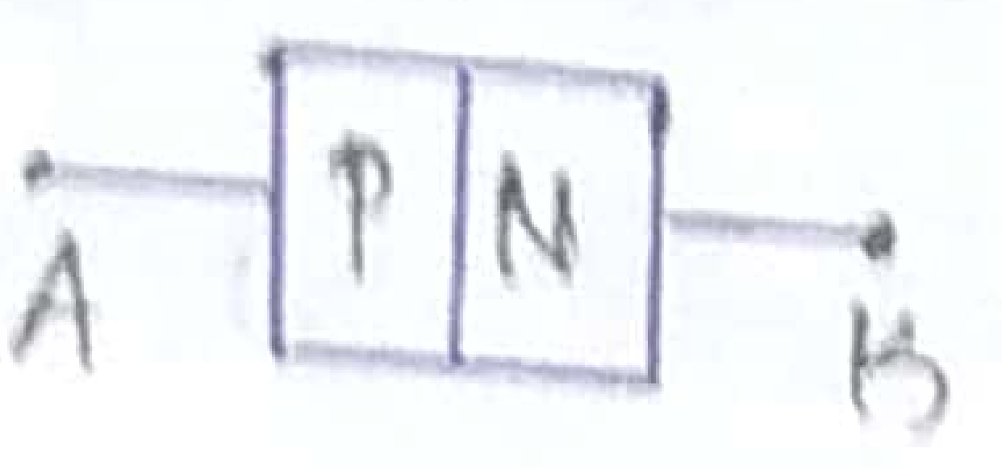
- SCS is a four layered, four terminal device. It has two Gates (Anode Gate - AG & cathode Gate - KG). It is turned on by using either Gate terminal.
- RCT has very poor Reverse voltage capacity, compared to SCR.
- DIAC is electrically equivalent to antiparallel Connection of two diodes. It has no controlled terminal, & it allows current in both directions.
- TRIAC is electrically equivalent to antiparallel connection of two SCR's. It has Control terminal. So, it allows controlled conduction in the both directions.
- GTO is turned on by applying positive Gate current and it is turned off by applying Negative I_g. So, it is called Self-Commutating device (In GTO commutation circuit is not used, to turn off the device).
- The Gate current required to turn off GTO is very High (20%-30%) of Anode current. The Gate current required to turn on GTO is also high compared to SCR.
- The current Gain of GTO is low as it requires more Gate current to turn off device.

  $\therefore$ Current Gain $= \frac{I_A}{I_g}$.
- Latching & Holding currents of GTO is high compared to SCR.

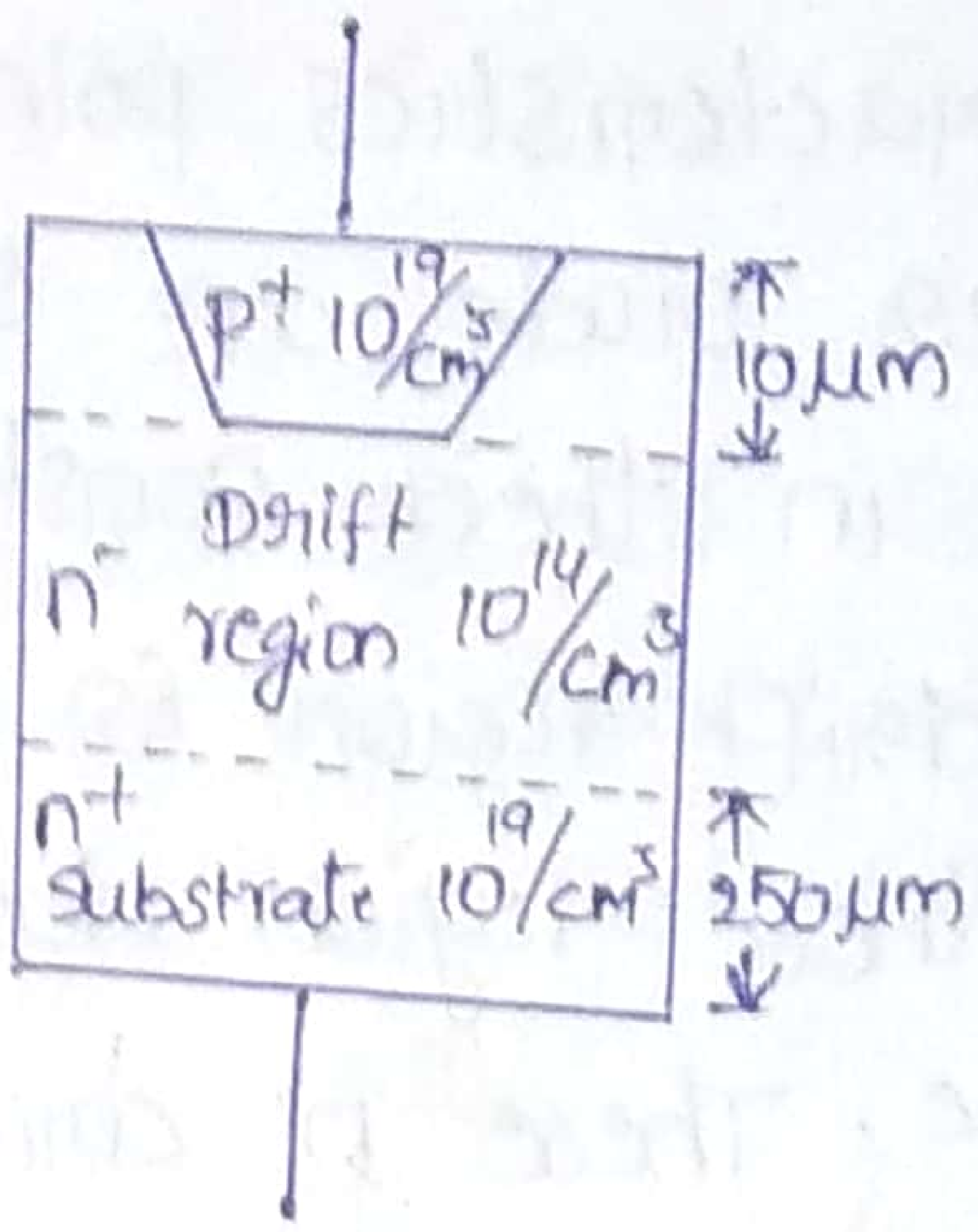
Power Diodes:-



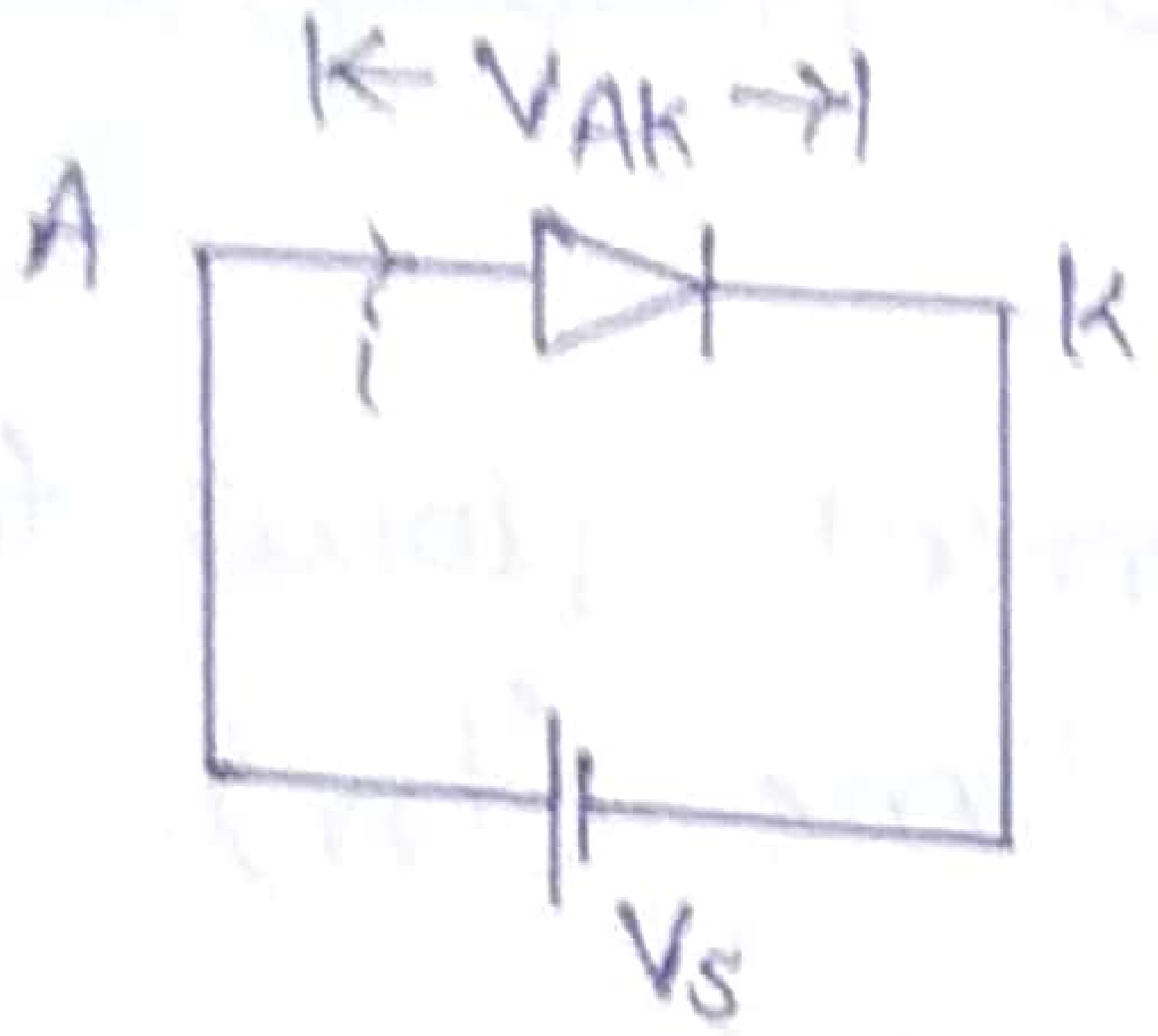
Symbol

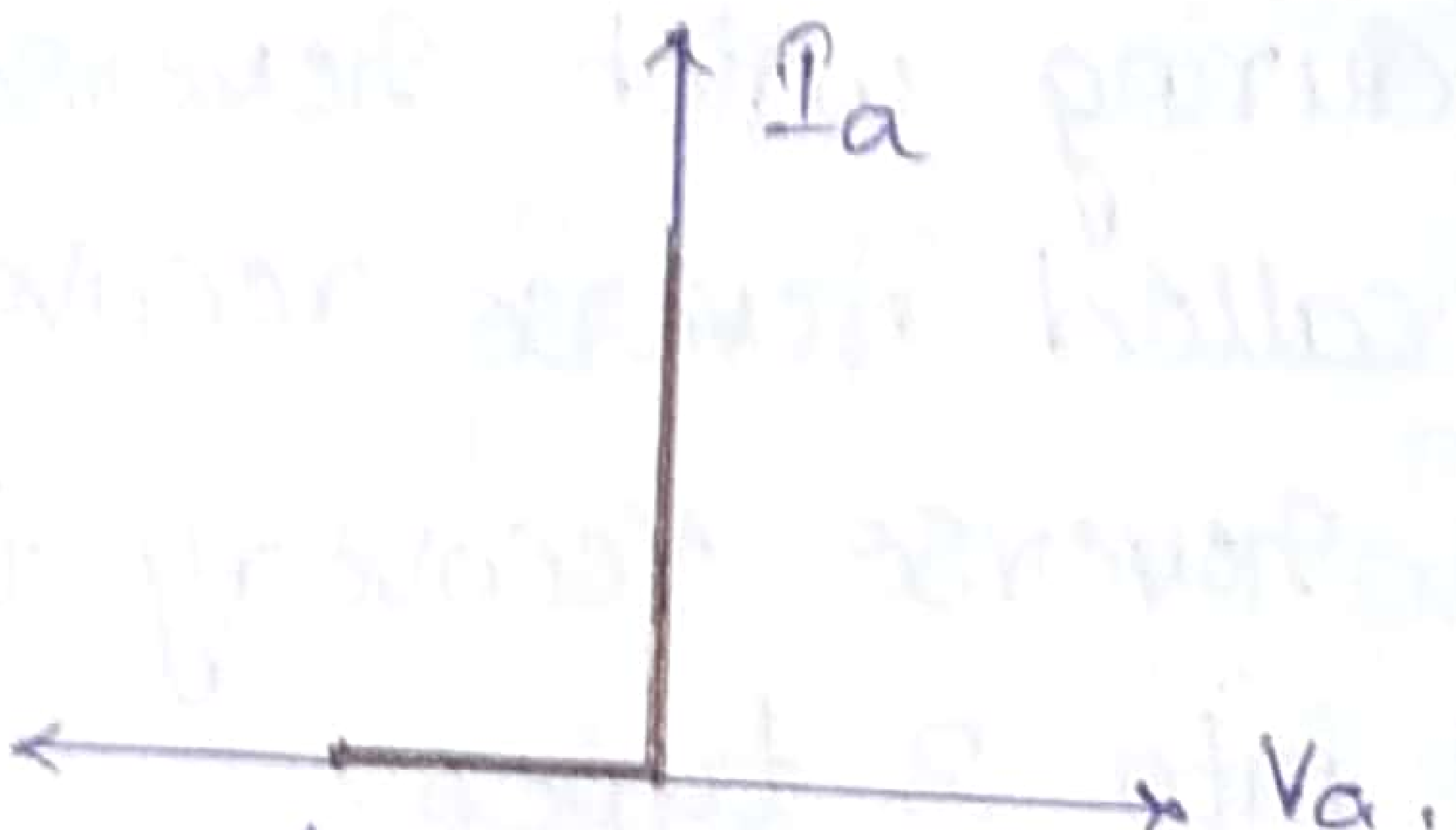


Structure of Signal diode.

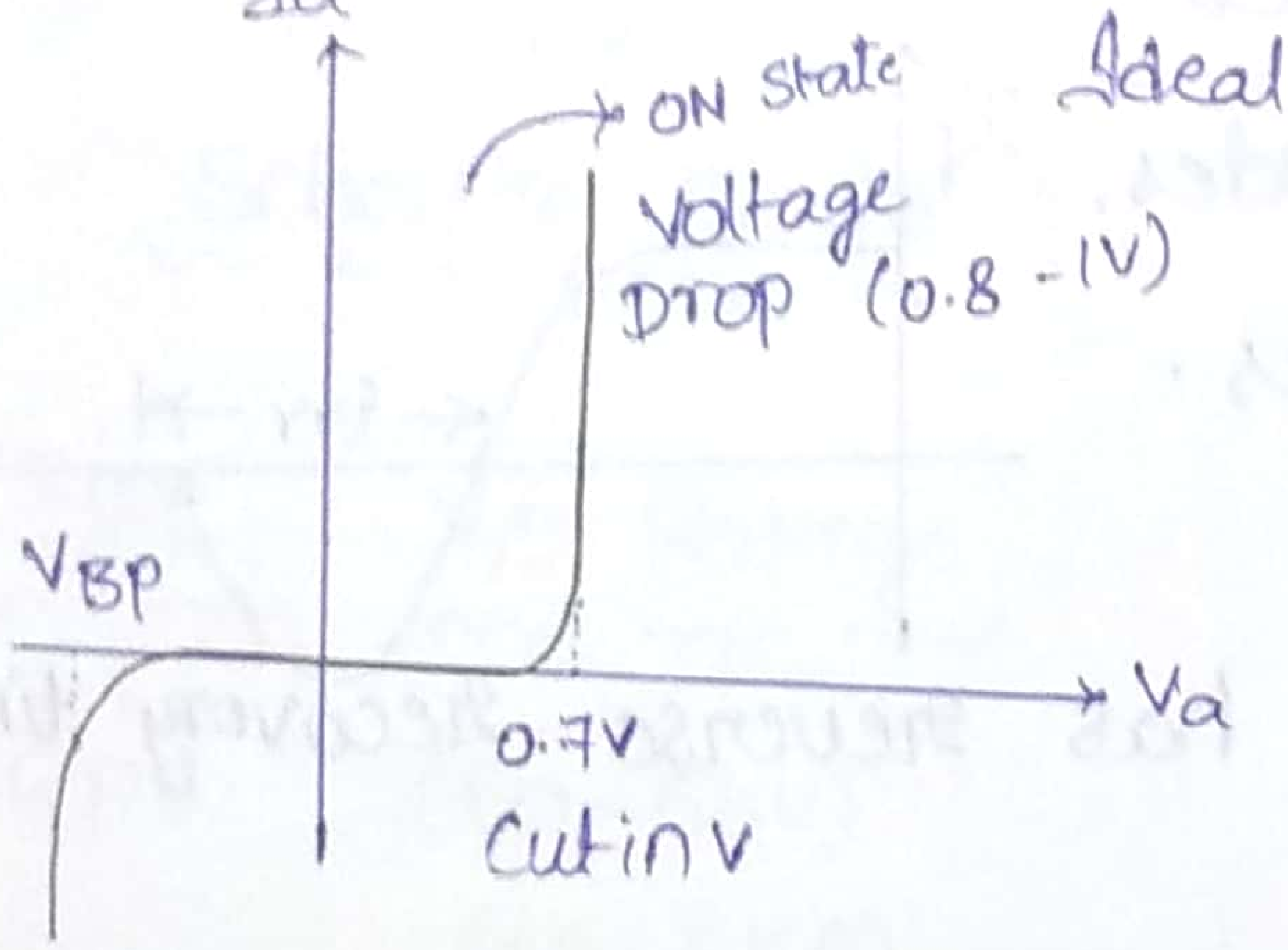


Structure of power Diode.

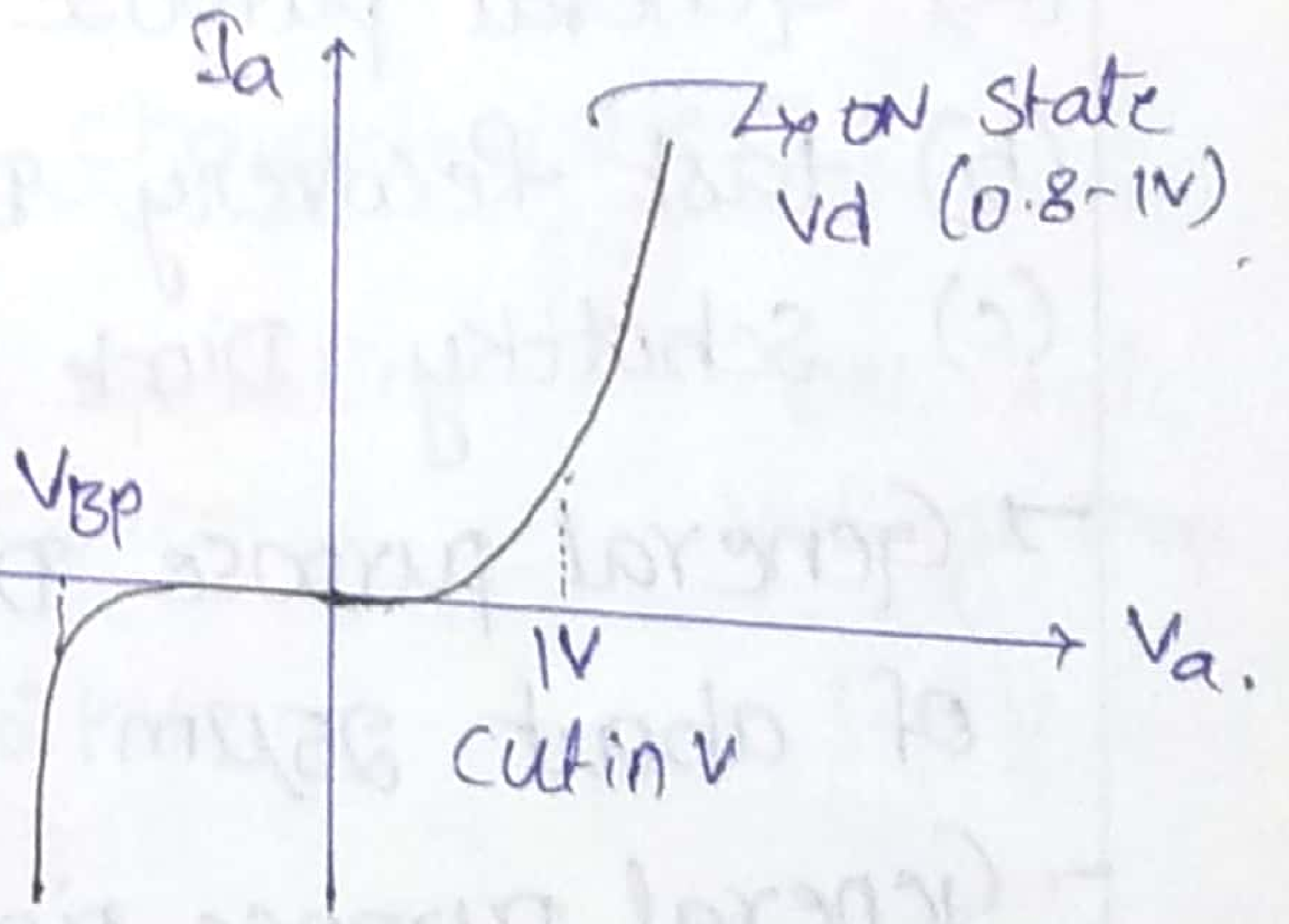




Ideal characteristics of Diode.



VI-char. of Signal Diode



VI-char. of power diode.

- → A Diode is a 2 layer, 2 terminal Semiconductor device. The two terminals are Anode & Cathode.
- → power Diode is uncontrolled device, because their turn on & turn off are not under Control.
- → power Diode is a unidirectional device, it allows current from Anode to cathode, it doesn't allows current from Cathode to Anode.
- → Signal Diodes are designed to operate at low voltage and current ratings (low power ratings). where as power Diodes design to operate at high

Voltage and current ratings (High power rating)

→ Characteristics point of view both Signal Diode & Power Diode are same, but their is a little diff. in their construction.

→ n^- drift region is present in power Diode, thickness of these region depends on Breakdown Voltage of Diode. These n^- drift region is not present in Signal Diode.

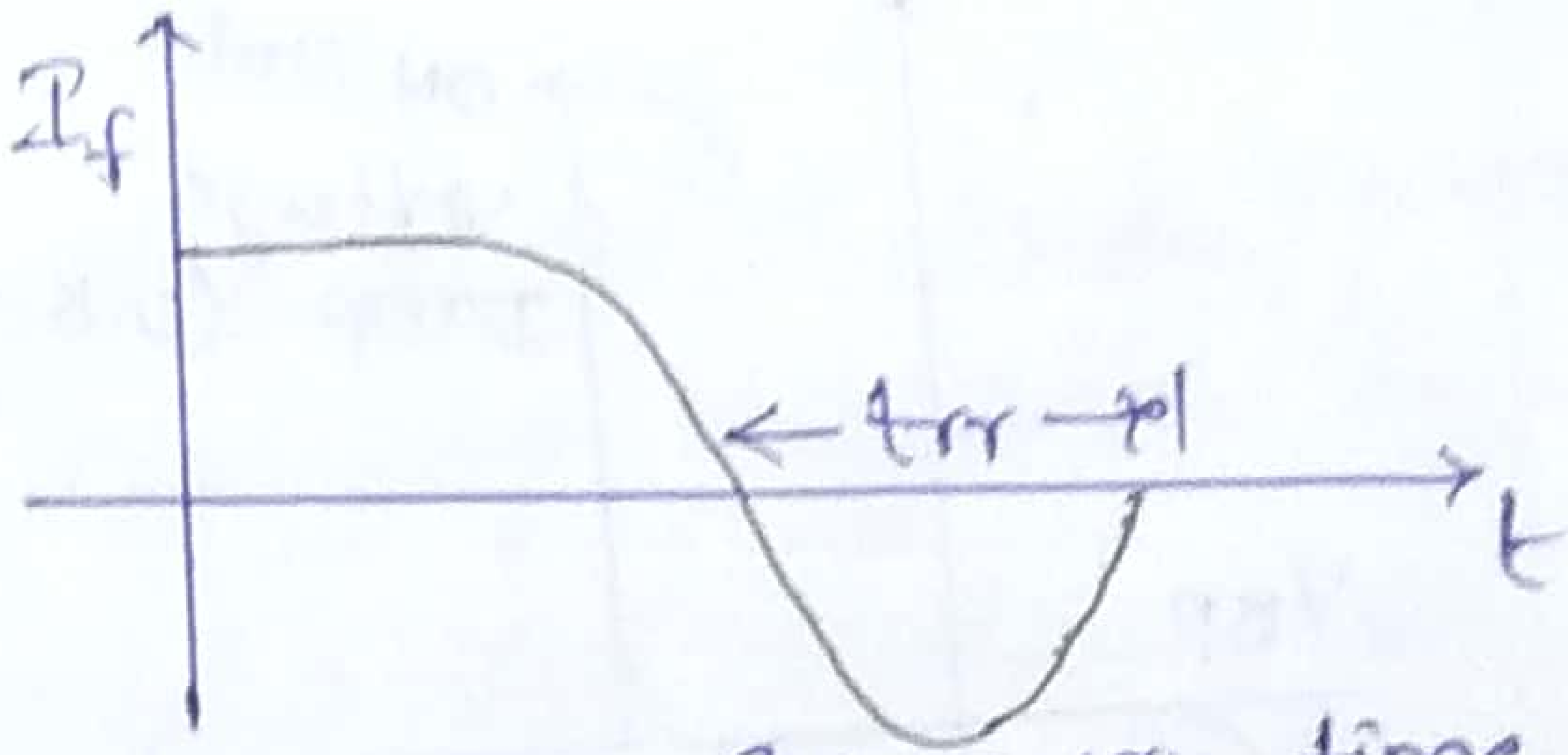
→ The time during which reverse current flows through diode is called reverse recovery time (trr).

→ Based on reverse recovery time, Diodes are classified into 3 types:-

(a) General purpose Diodes.

(b) fast Recovery Diodes.

(c) Schottky Diode.



→ General purpose Diode has reverse recovery time of about 25μm.

→ General purpose diode is used in Battery charging, Electric Traction, welding & UPS, etc....

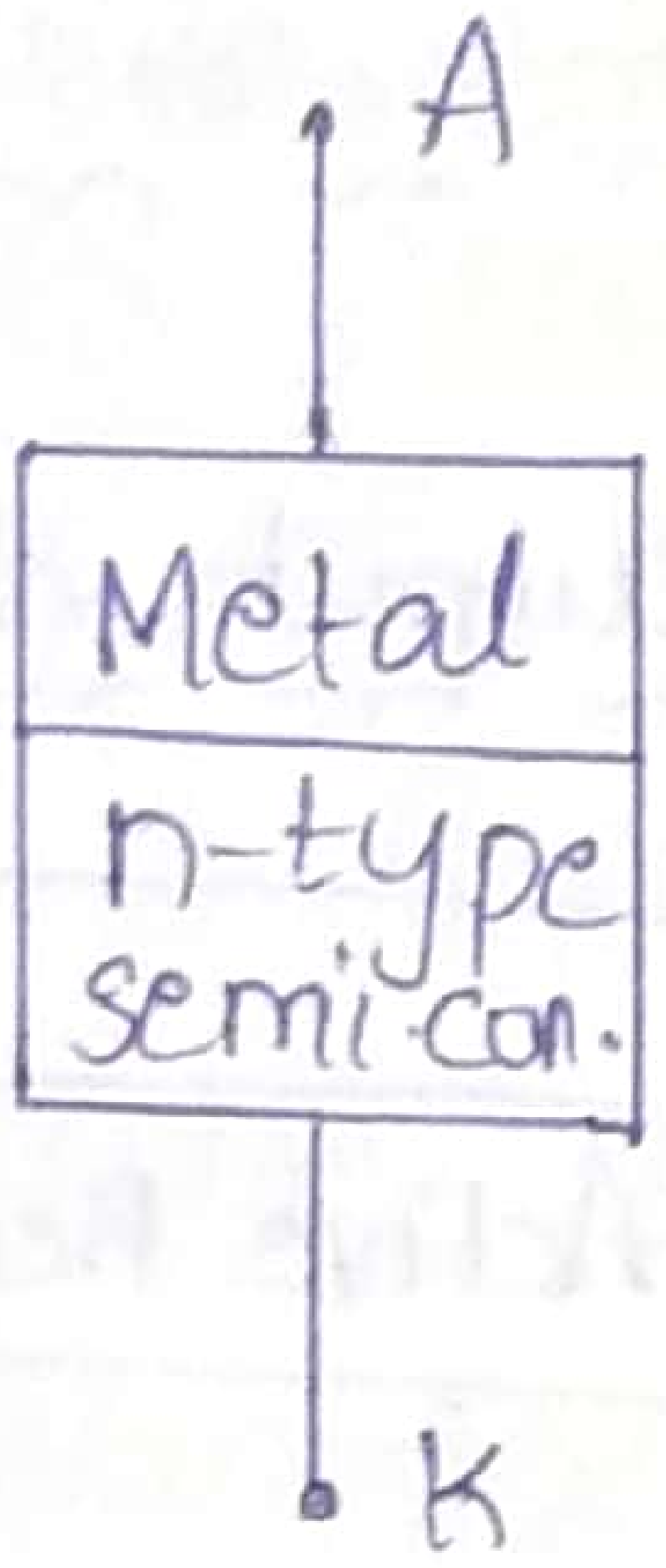
→ fast Recovery Diode has Reverse Recovery Time of about 5μm or less. These are used in choppers, commutation circuits, Inverters and UPS.

→ Schottky Diode uses metal to semiconductor junction instead of PN junction. Metal is Made with Aluminium and Semiconductor is made with Silicon So SchotKKy has Aluminium Silicon junction.

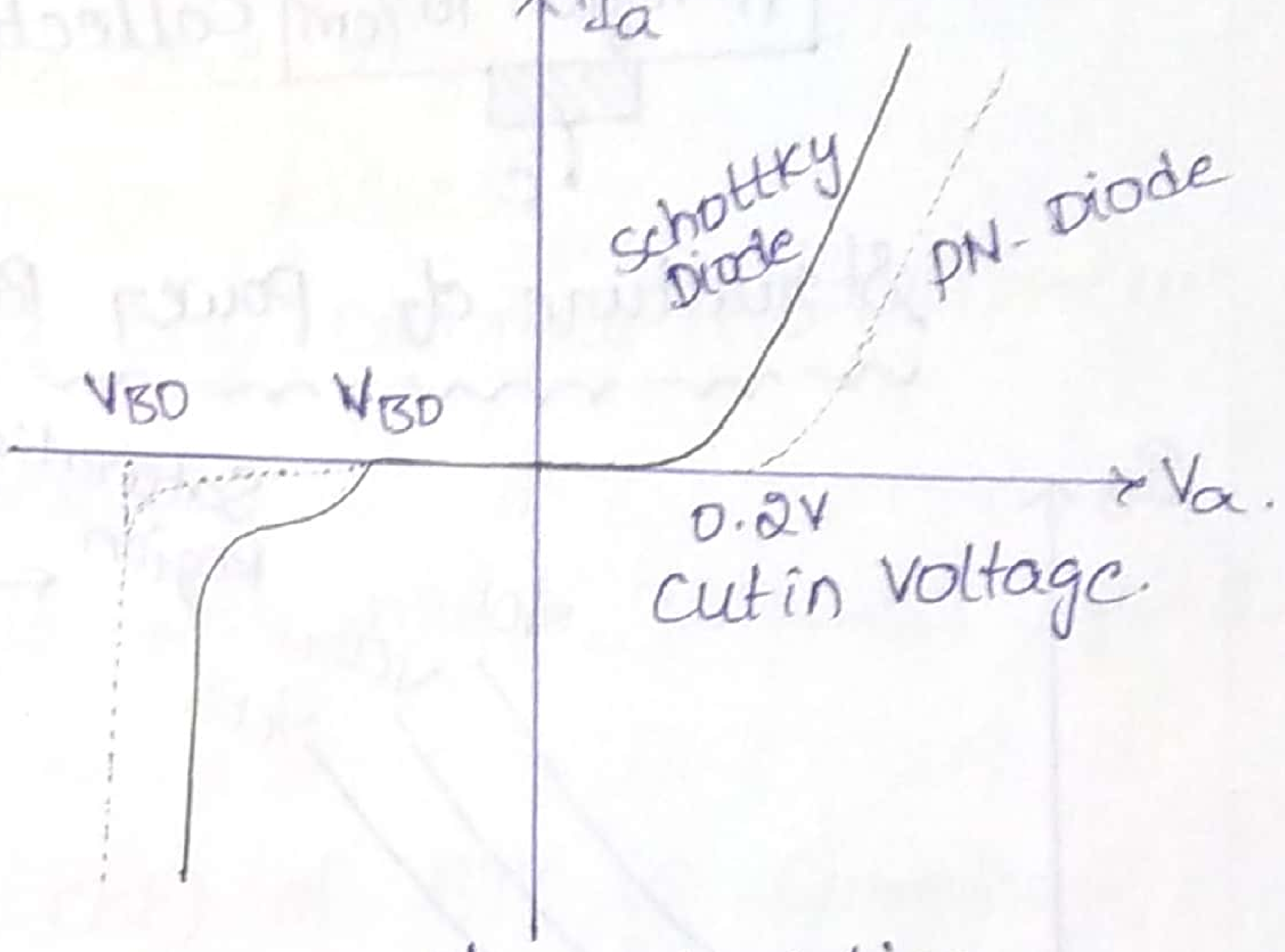
→ Due to absence of pn Junction, Storage time is less, then turn off time is less. Hence Schottky Diode has less turn off time and high operating frequency.

→ Due to absence of n^- drift region, the ON State Voltage Drop in Schottky Diode is less, Compared to PN Junction Diode.

→ The Reverse Breakdown Voltage of Schottky Diode is less compared to PN Junction Diode. But it has high reverse leakage current compared to PN Junction Diode.



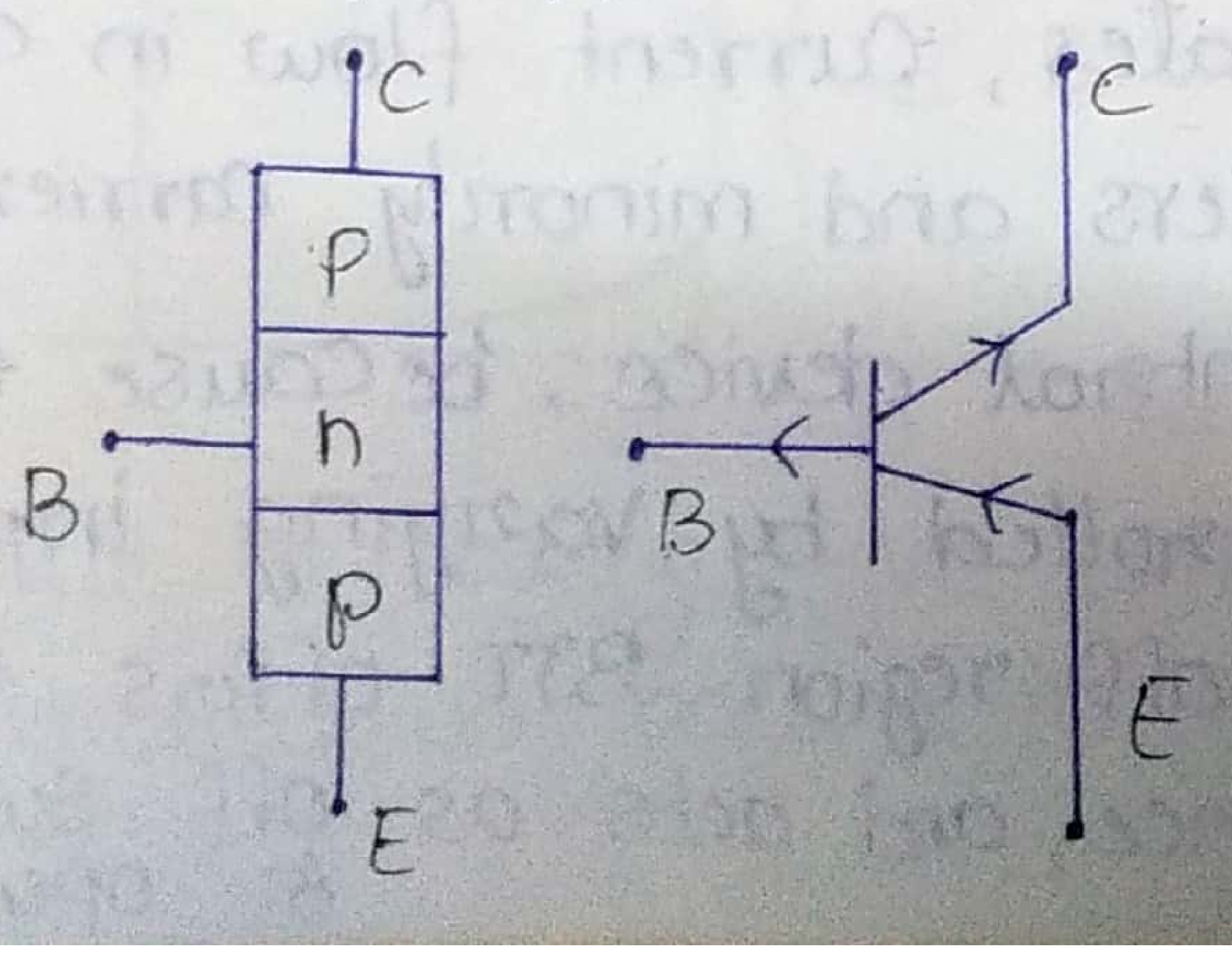
Schottky Diode.

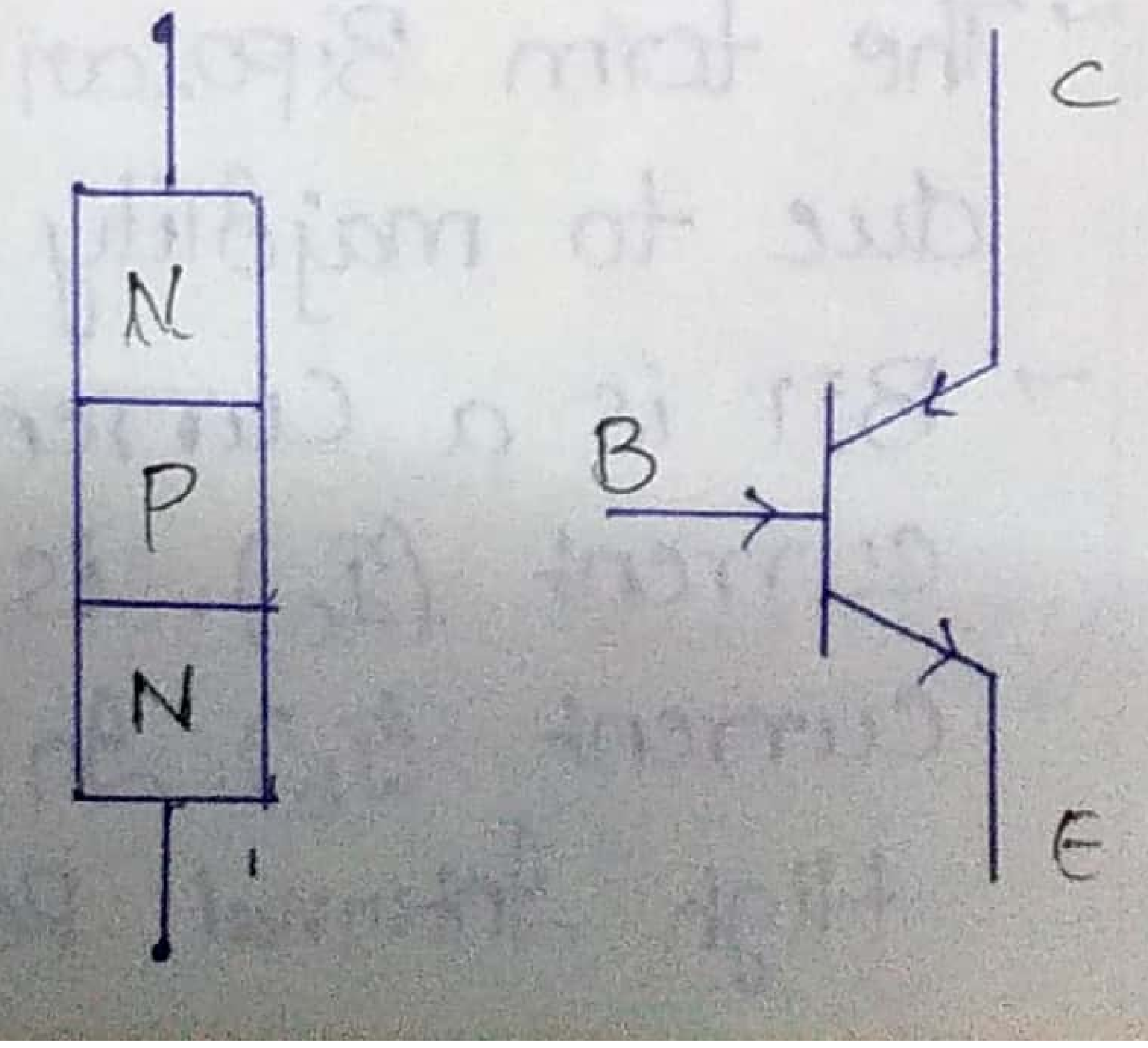


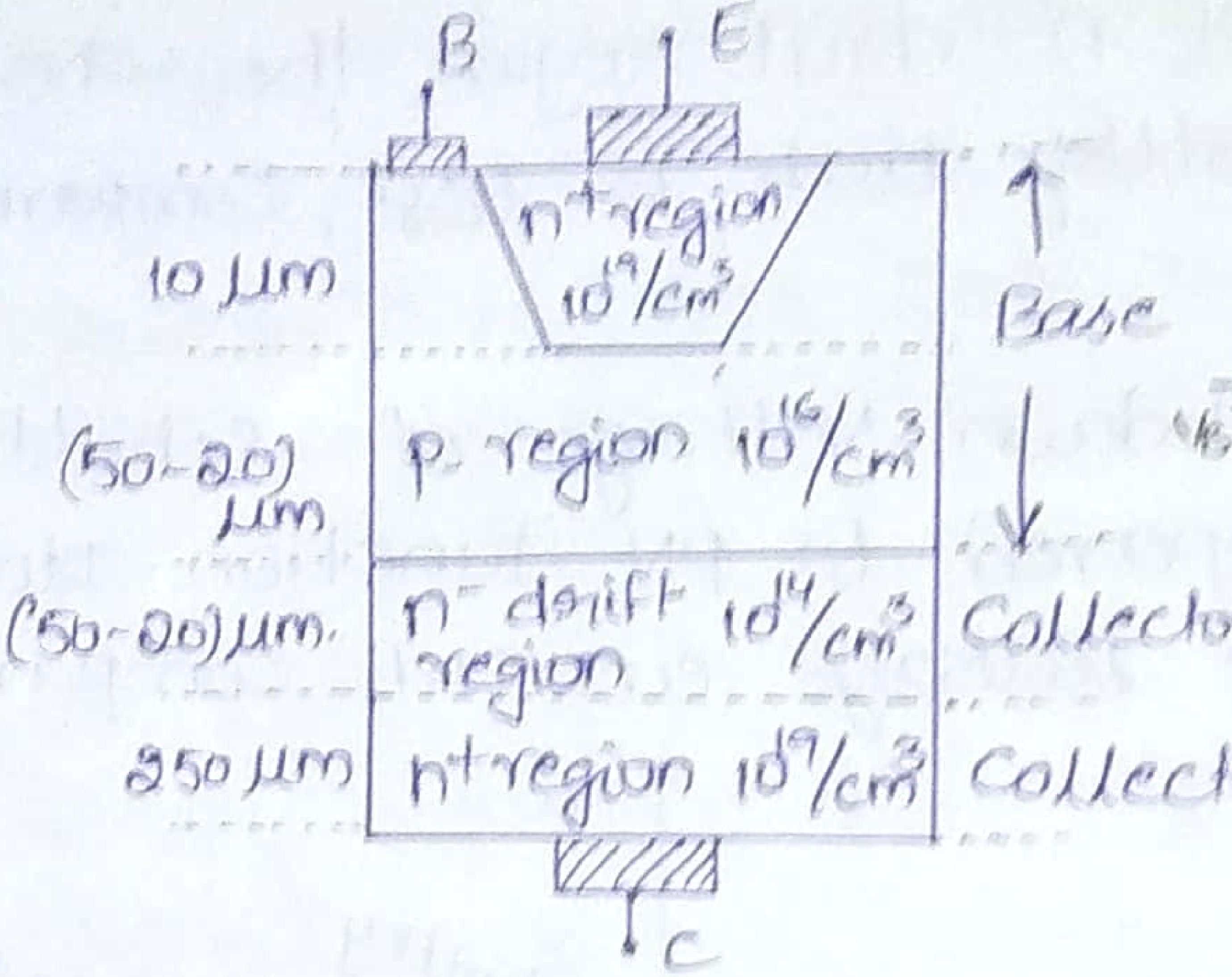
Characteristics.

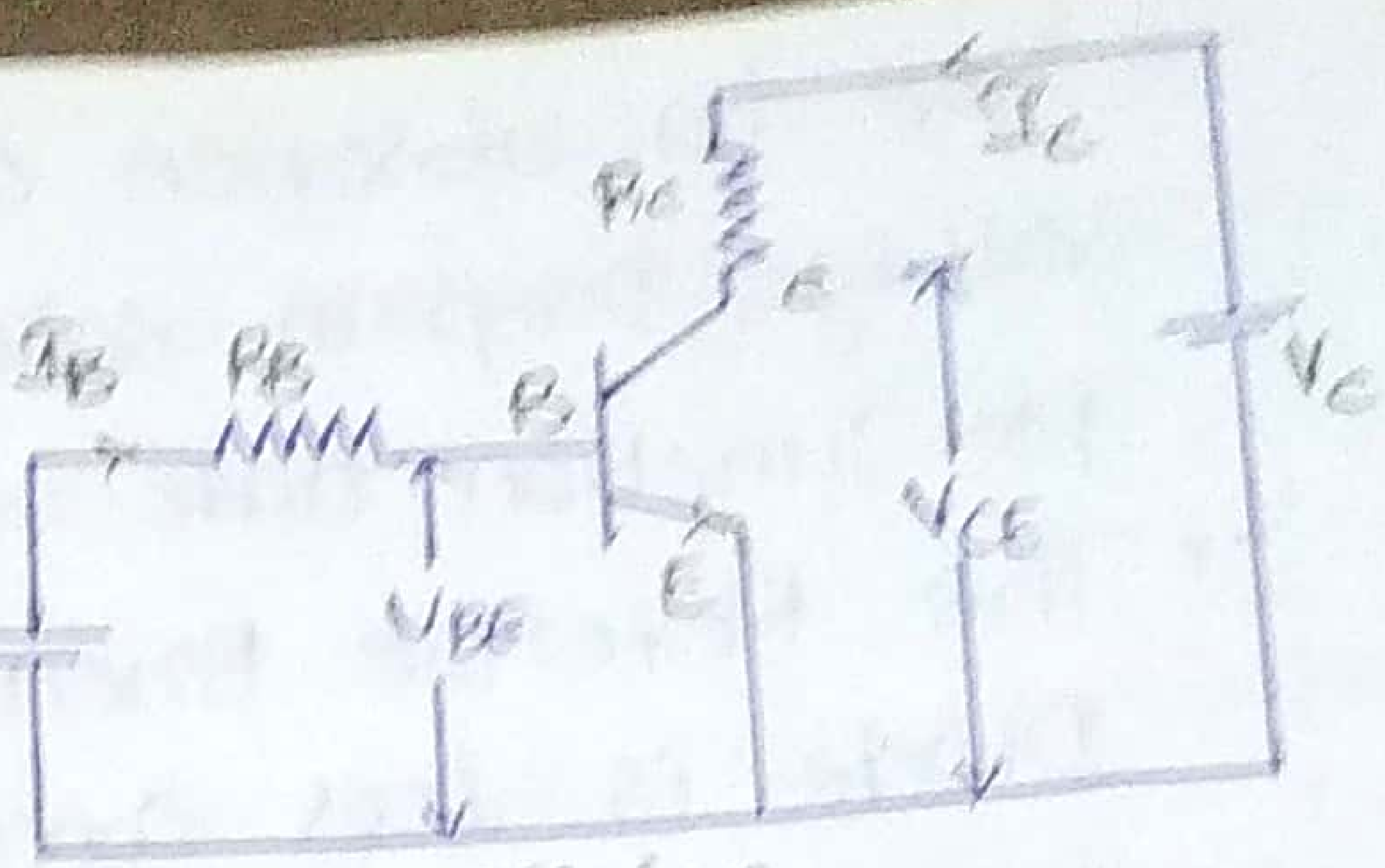
Type.	V/I Ratings	Max. operating frequency.	ON State Voltage Drop.
GPD.	(50-5KV) (1A-5KA)	2KHz.	1-2V.
FRD	(50V-3KV) (1A-1KA)	12KHz	1-1.5V
Schottky	100V/(1A-300A)	20KHz	0.5V-1V.

→ Power BJT's:-





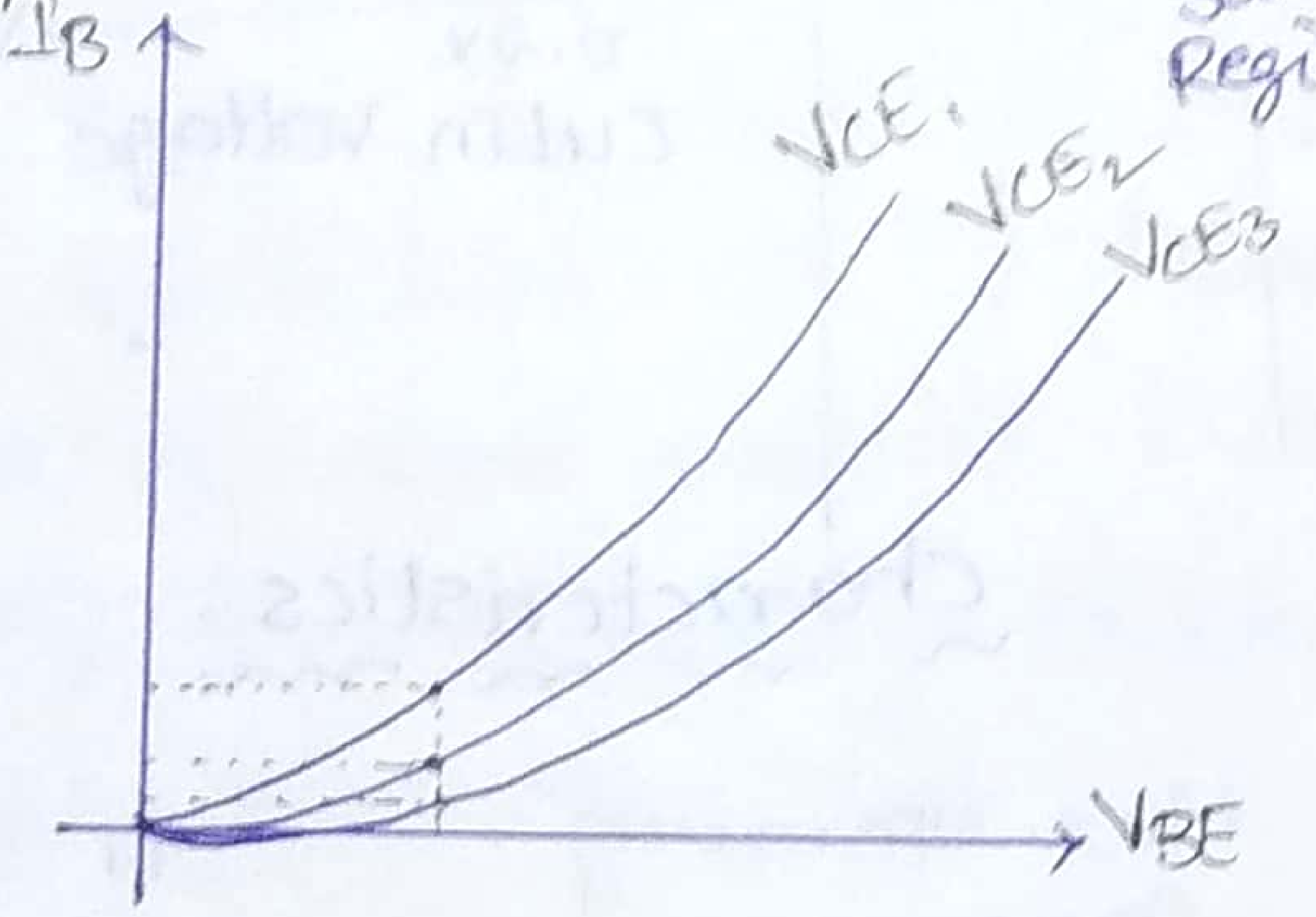


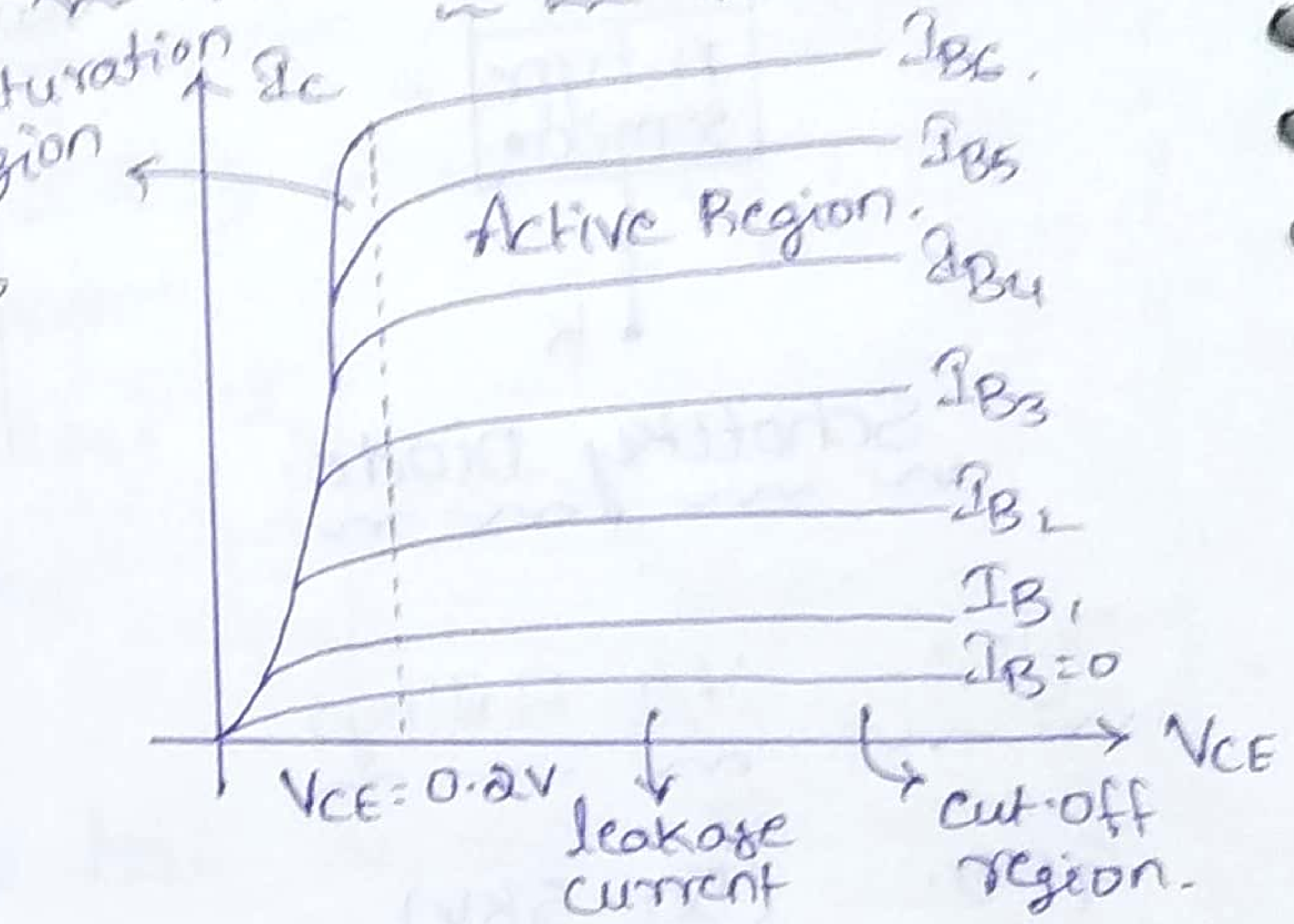


Circuit to obtain characteristics of BJT

Structure of power BJT

output characteristics.





Input characteristics.

- BJT is a 3 layer, 3 terminal, 2 junction power Semiconductor switching device. power BJT may be pnp or npn Transistor.
- npn Transistors are commonly used in High Voltage and High currents applications, since it is easy to manufacture & low cost
- The term Bipolar indicates, current flow in device due to majority carriers and minority carriers.
- BJT is a current control device, because output current (I_c). is controlled by varying input current (I_b). In cut-off region BJT offers very High Internal Resistance, and acts as off switch or open switch.

→ (Advantages :-)

→ In Saturation region, BJT offers very small internal Resistance and it acts as ON Switch or closed switch

→ In active region, BJT acts as Amplifier.

→ Advantages:-

→ It has Small turn on & turn off time. Hence their Switching frequencies are High.

→ BJT has Small turn on losses.

→ It does not requires any commutation circuit.

→ BJT is a Bipolar Device.

→ BJT'S are available with much reduced costs.

→ Disadvantages:-

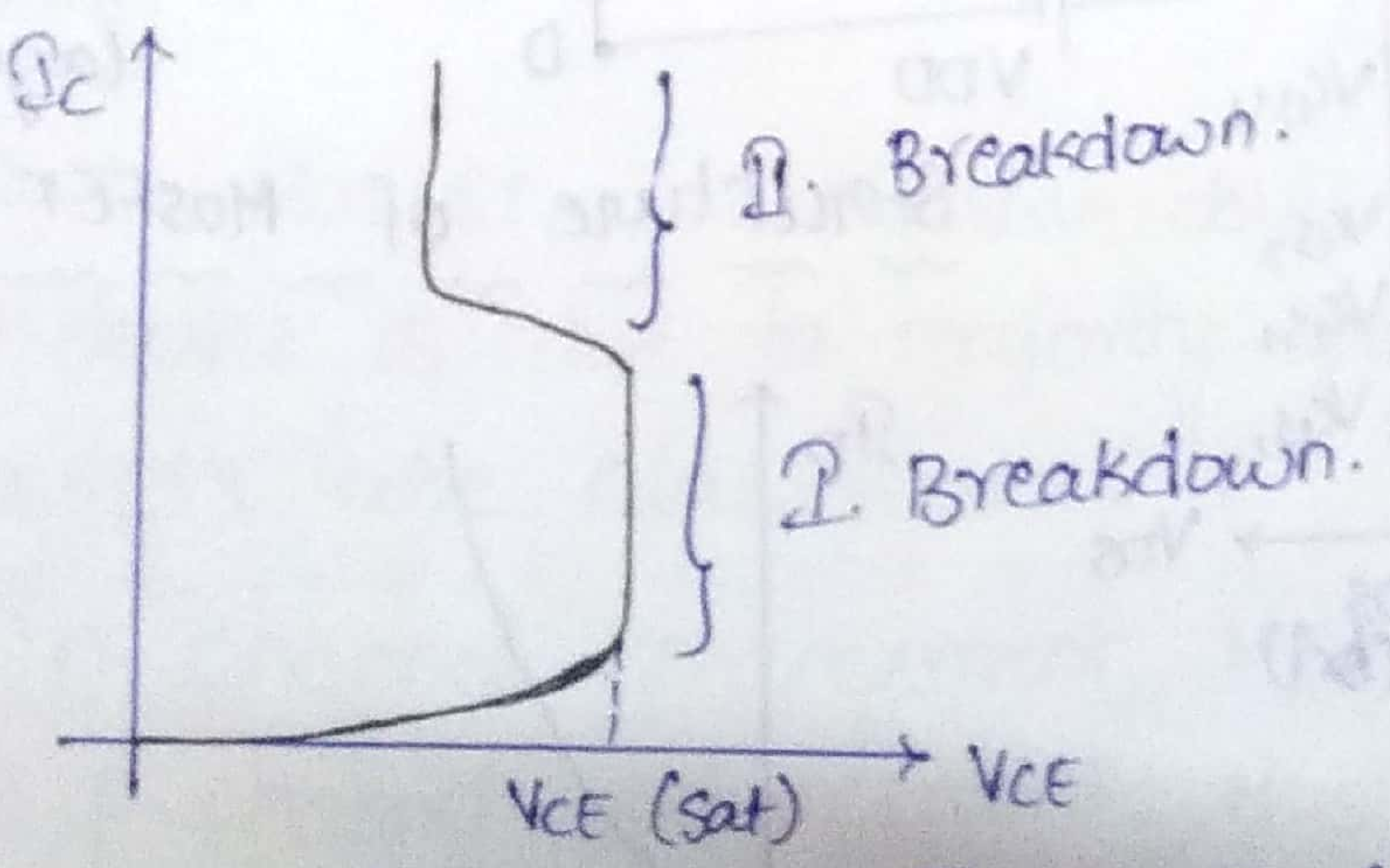
→ Drive circuit (ctrl ckt) of BJT is Complex.

→ Paralleling of BJT is not possible because d/ having Negative Temperature co-efficient.

→ Applications:-

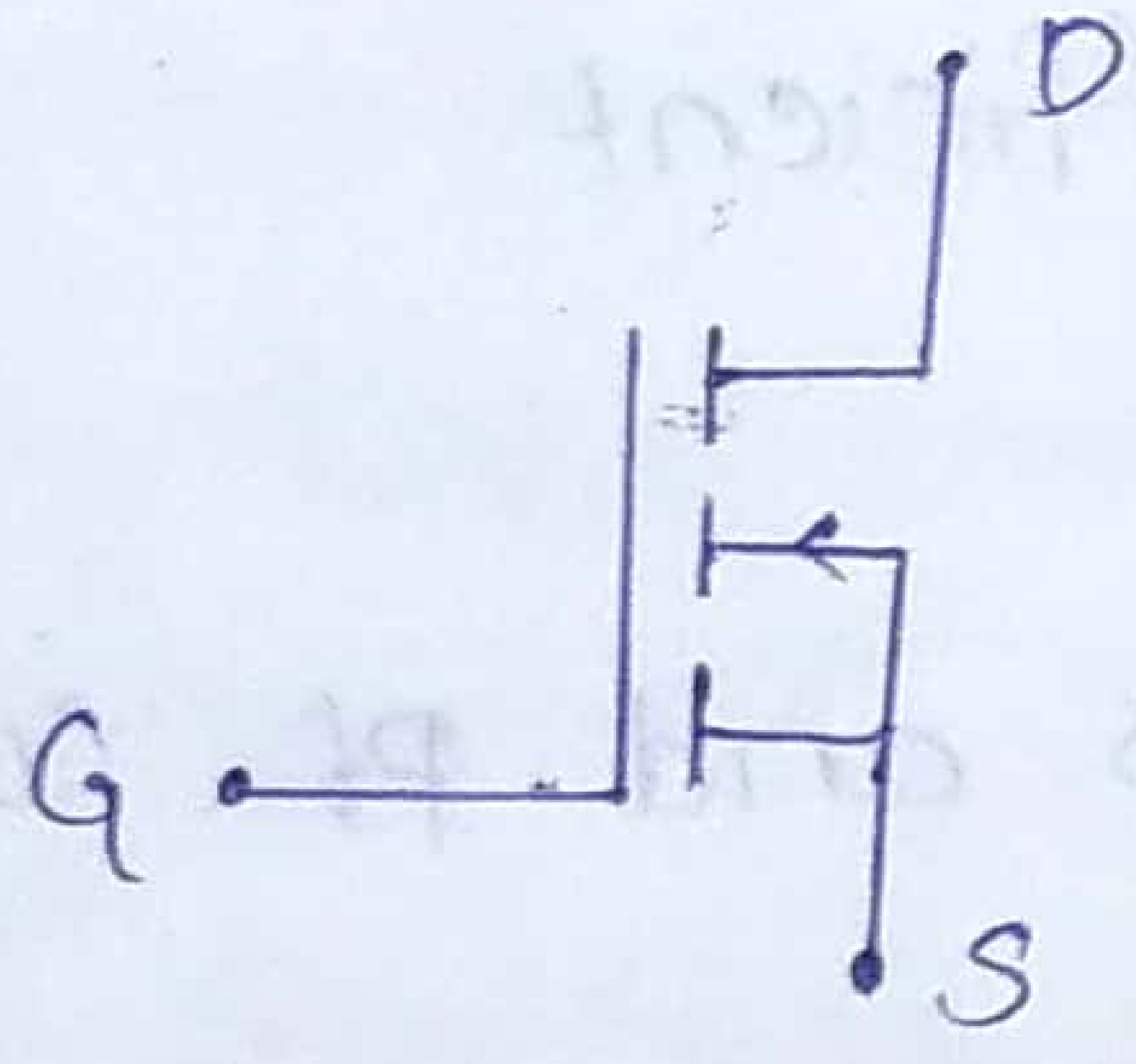
→ Used in Bridge Inverters, choppers and pf correction Techniques.

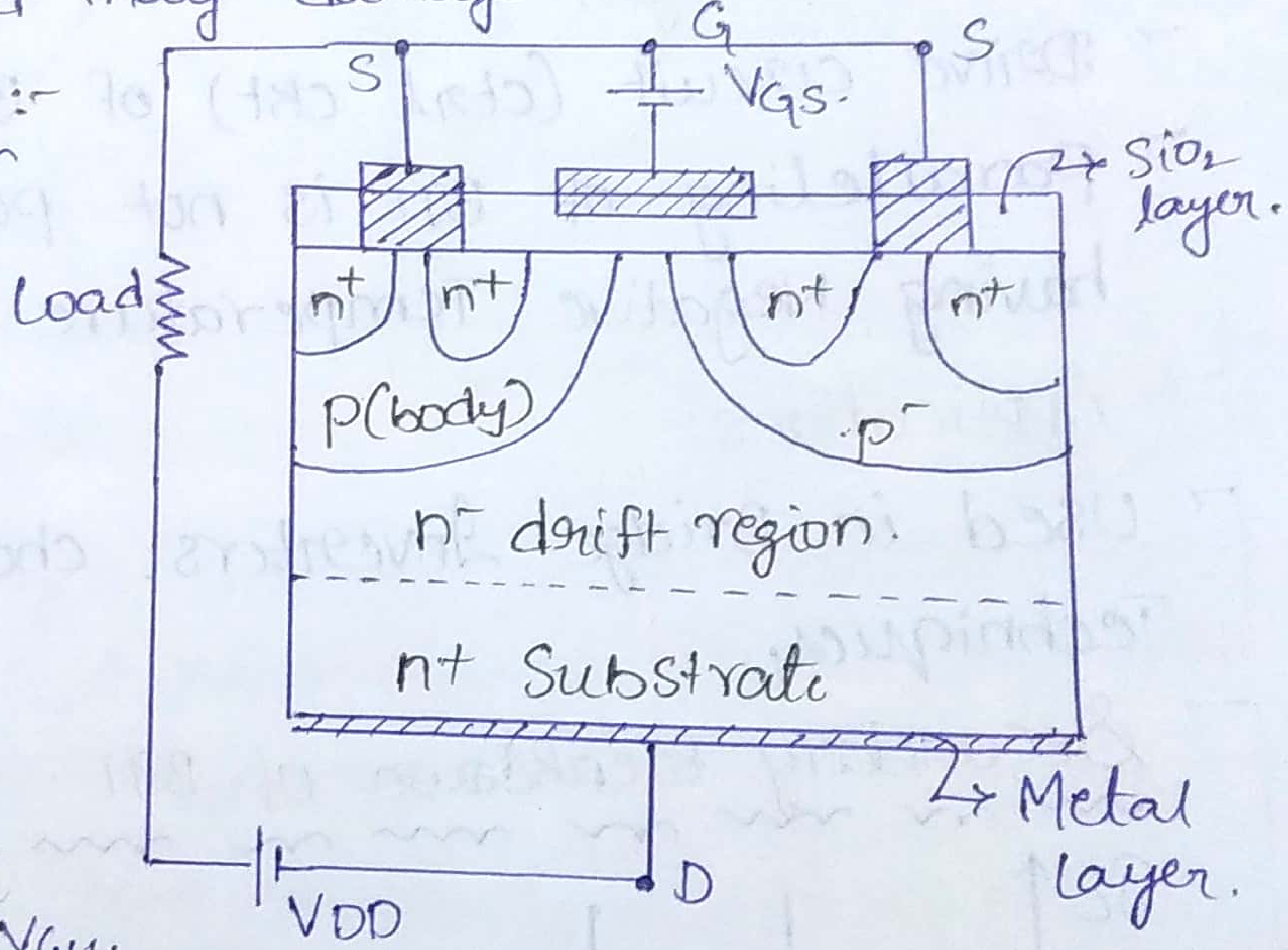
→ Secondary Breakdown of BJT :-



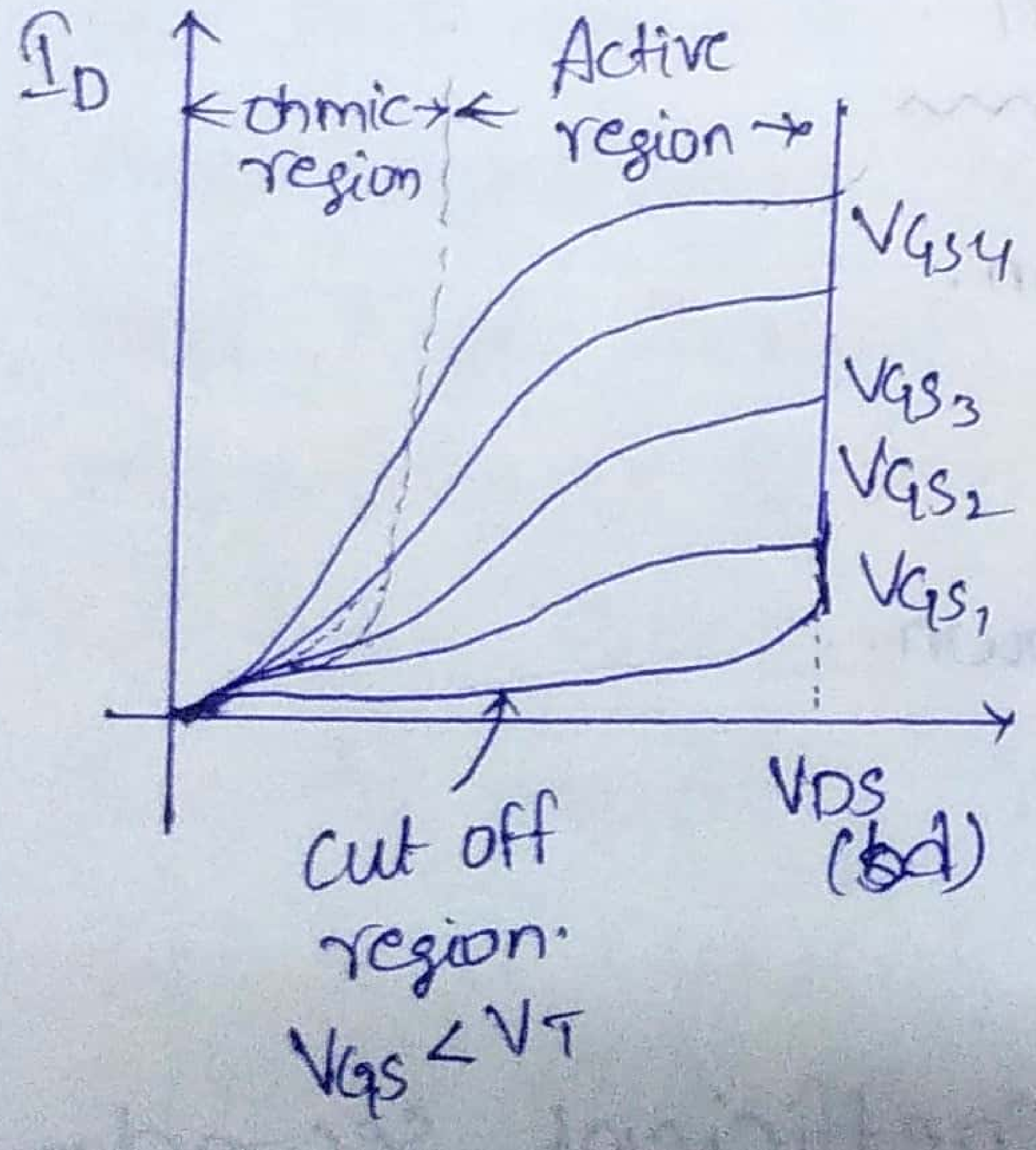
→ Due to having -ve Temp. Coefficient secondary Breakdown occurs in BJT.

- Primary Breakdown occurs at VCE Saturated region across reverse biased junction. As result Collector current increases rapidly.
- The increased collector current would raises the Temperature at reverse biased junction. The raised temp. decreases the junction resistance, since BJT has Negative (Resi) Temperature co-efficient. As a result collector to emitter voltage decreases and Collector current increases rapidly. This large collector currents creates hotspots in the highly concentrated regions, (In this) and then increases the temperature. The increased temperature leads to power loss and may damage BJT.
- Power MOSFET :-

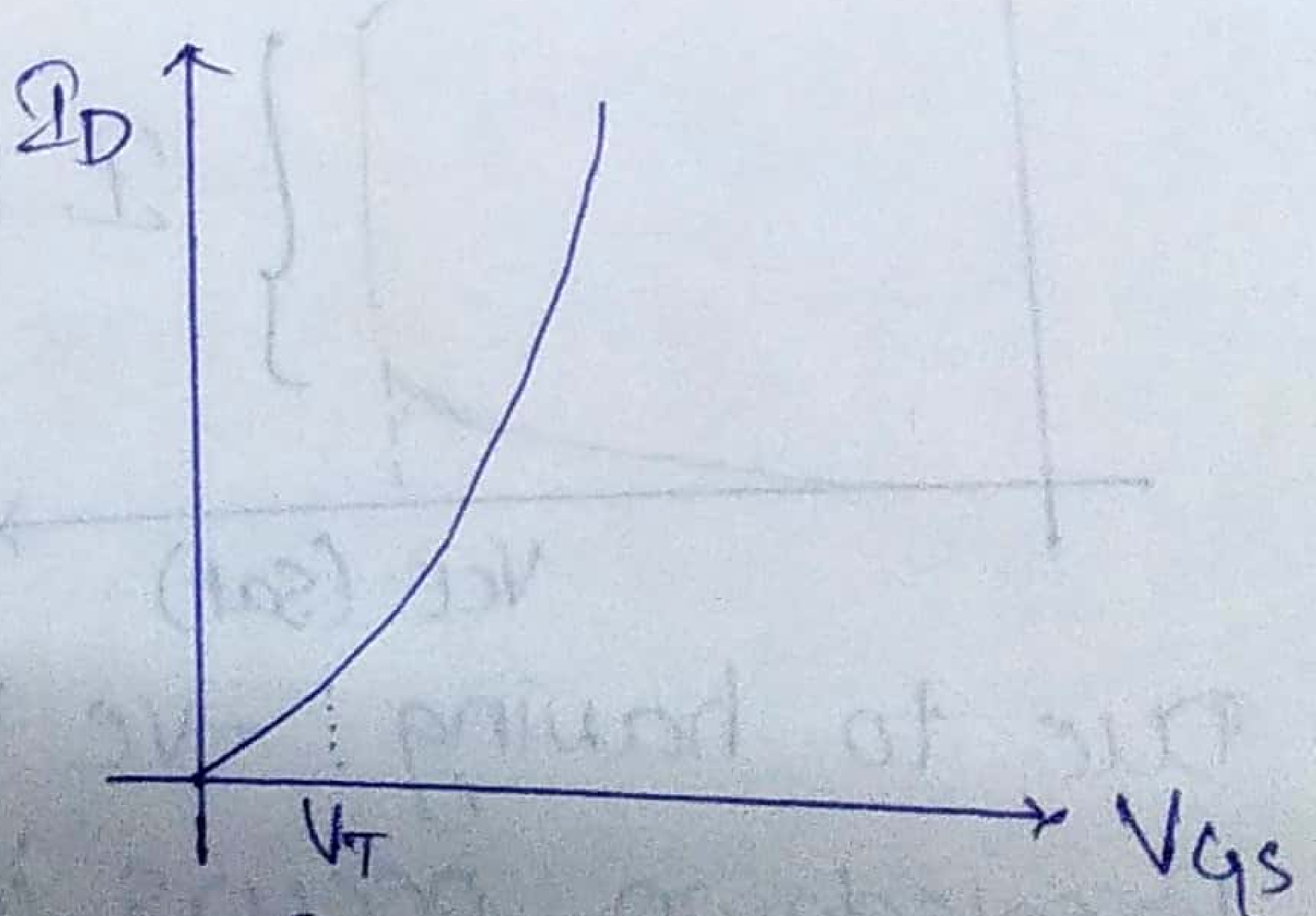




Structure of MOSFET.

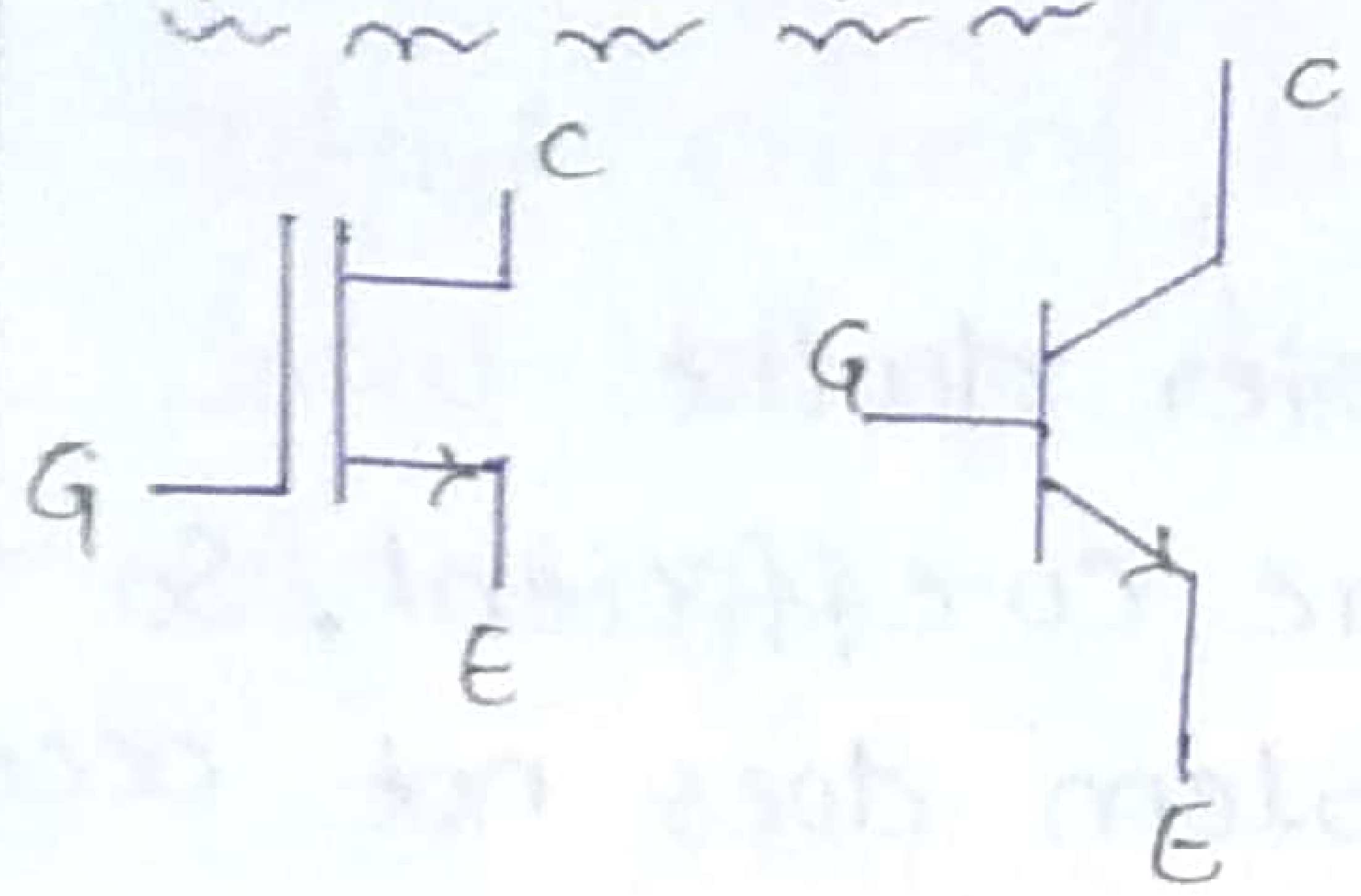


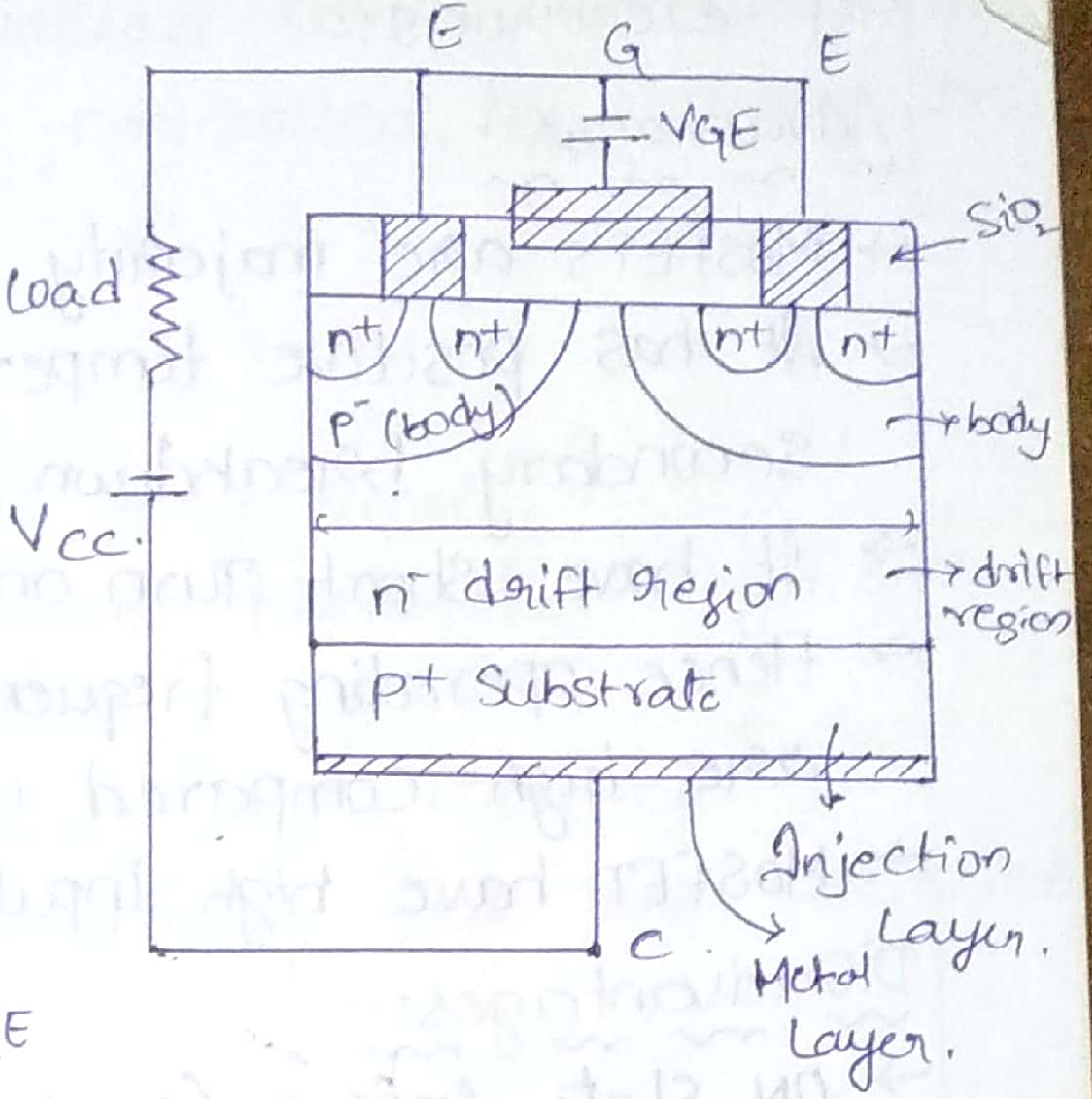
Output characteristics

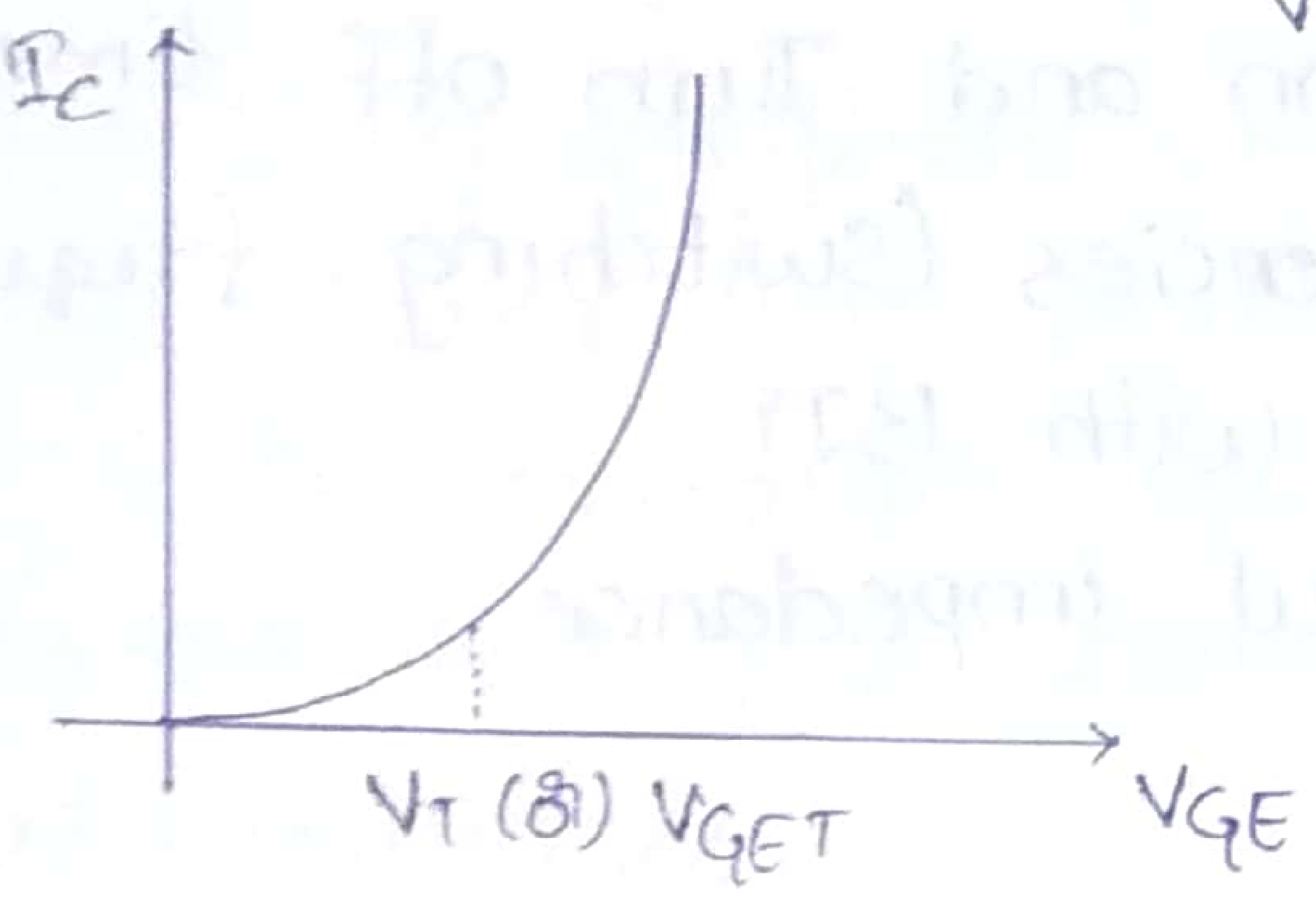


Transfer characteristics

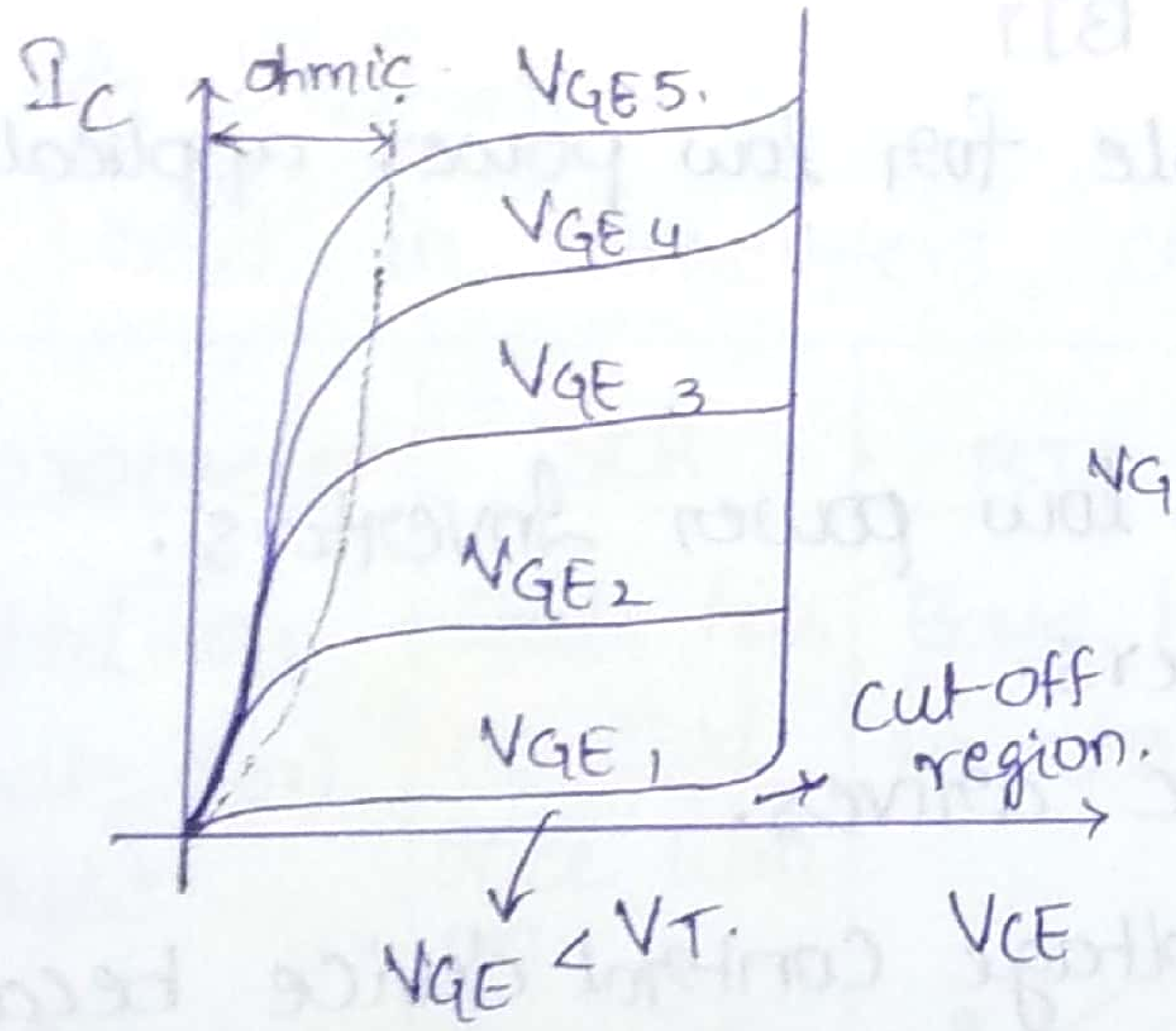
→ Power IGBT :-



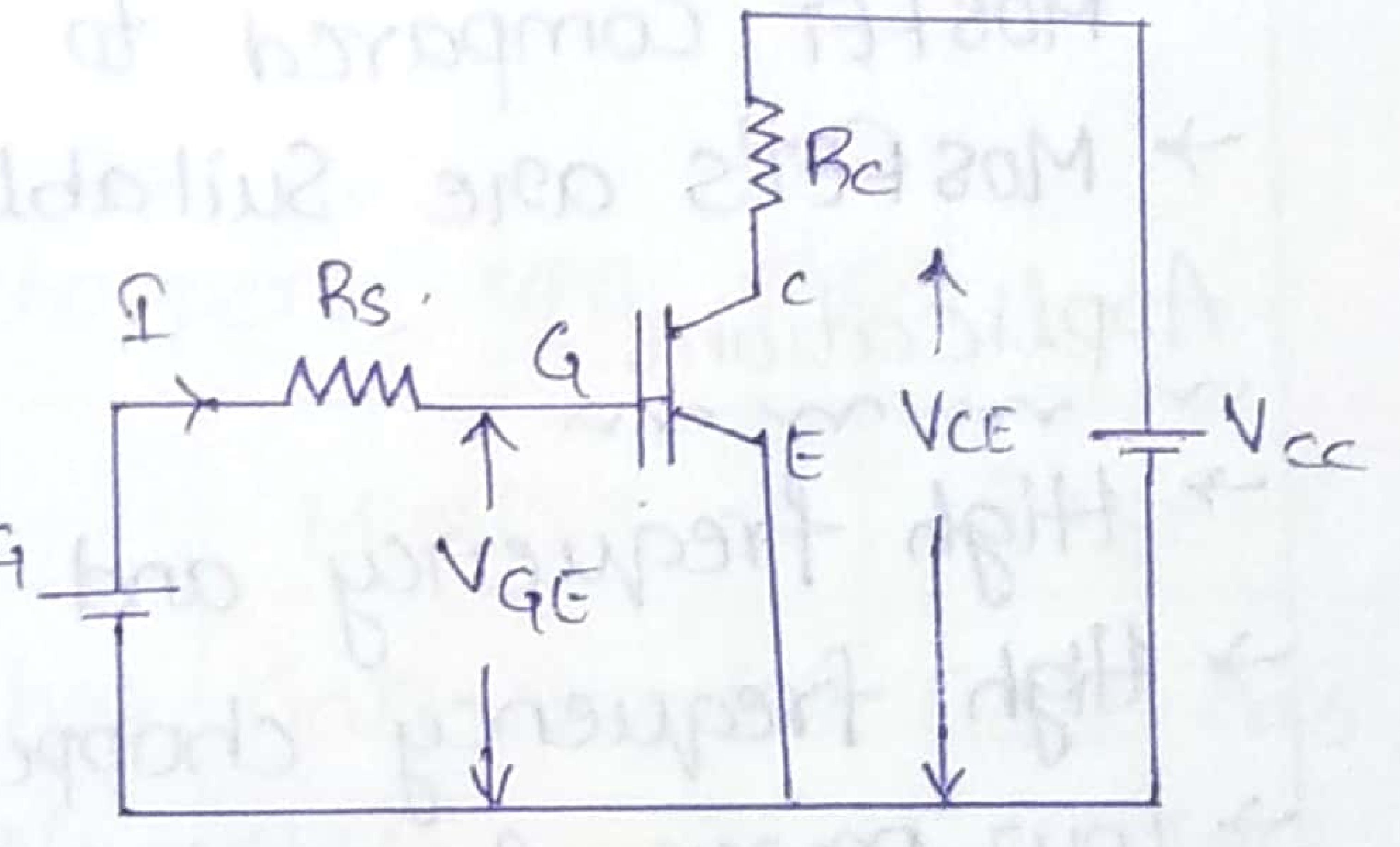




Transfer characteristics.



output characteristics.



Circuit to obtain characteristics of power IGBT.

MOSFET :-

Power MOSFET is unipolar device, the current flow in device is due to majority charge carriers only. Power MOSFET's are classified into:-

(a) n-channel enhancement MOSFET.

(b) p-channel enhancement MOSFET.

→ In these two n-channel enhancement power MOSFET is commonly used due to having higher mobility of electrons:-

Advantages:-

→ MOSFET's are majority carrier device.

→ It has positive temperature co-efficient, So secondary breakdown problem does not occurs.

→ It have short Turn on and Turn off times.

→ Hence operating frequencies (switching frequencies) are high compared with BJT.

→ MOSFET have high input impedance.

Disadvantages:-

→ ON State losses (conduction losses) are high in MOSFET Compared to BJT.

→ MOSFET'S are suitable for low power applications.

Applications:-

→ High frequency and low power Inverters.

→ High frequency choppers.

→ Low power AC and DC drives.

→ power MOSFET is a voltage control device because output current (I_d) is controlled by varying the Input Voltage (V_{GS}).

→ Power IGBT Theory:-

→ IGBT is formed by Combining Gate Circuit of MOSFET and Emitter to collector circuits of BJT. It has advantages of both BJT and MOSFET. It has high Input Impedance like MOSFET and low ON State conduction losses like BJT. Secondary Breakdown problem does not occurs in IGBT. Because of these advantages it is Popular device in Power Electronics.

→ It is a Voltage controlled Device. Because it's output current (I_C) is controlled by varying the Input Voltage (V_{GE}).

→ Advantages:-

→ Drive (ctrl) circuit is very simple.

→ Switching frequencies are higher than Thyristor, but lower than MOSFET.

→ Low commutation circuits are required.

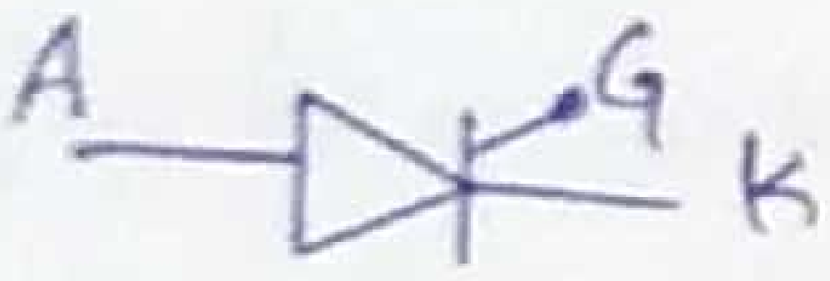
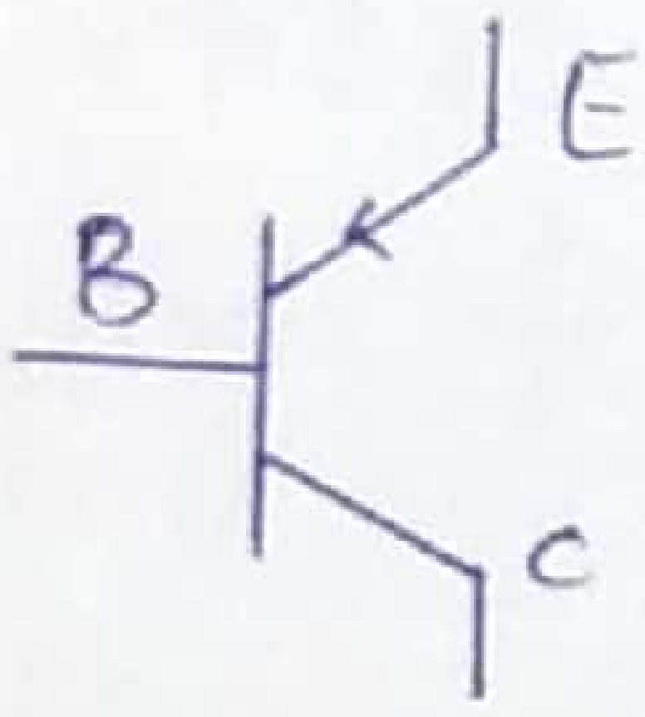
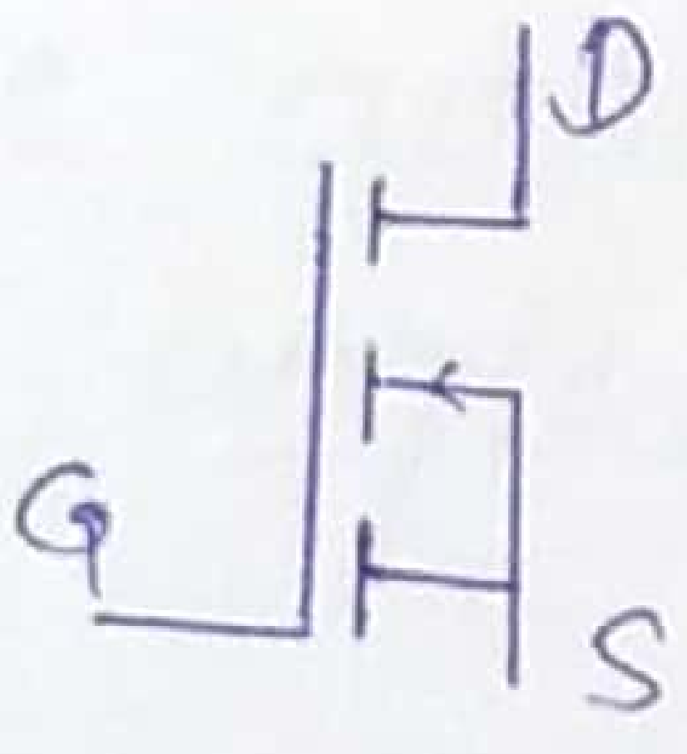
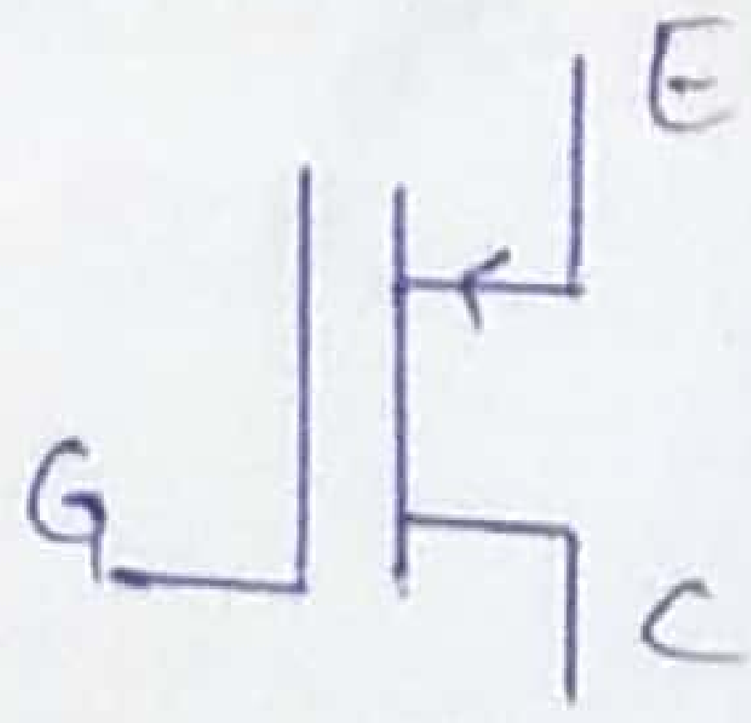
→ IGBT's has flat approximately flat Temp. coefficient

→ Disadvantages:-

→ IGBT's are costlier a than BJT's and MOSFET's.

→ Applications:-

→ Used in Inverters, choppers, ups, etc...

Parameter	SCR	BJT	MOSFET	IGBT.
→ ctrl of Gate (or) Base.	Gate has no ctrl once turn on.	Base has to ctrl.	Gate has full ctrl.	Gate has full ctrl.
→ Symbol.				
→ ON State Voltage Drop	less than 2V	<2V	(4-6)V.	3.3V.
→ Voltage / Current ctrl device	current ctrl device	current ctrl.	voltage ctrl device	Voltage ctrl device.
→ Switching frequency	500 Hz	10 KHz	upto 100KHz	20KHZ.
→ Temperature Co-efficient	Negative	Negative	positive.	Approximately Flat but positive at High currents

Parameter	SCR	BJT	MOSFET	IGBT
→ Voltage Rating.	7KV.	1.4 KV	1KV	1.2KV.
→ current Rating.	5KA	400A	50A.	500A.
→ Type of Carrier in device	Bipolar Device	Bipolar Device	unipolar Device	unipolar Device

unit - II

13-08-18

Phase Controlled Converters

→ Rectification :-

→ The process of converting alternating voltage or current into direct current or voltage. The conversion from ac to dc can be obtained by using power semiconductor devices such as Diodes, SCR's power BJT's, etc.., Here power semiconductor devices acts as a switches.

→ Rectifiers are classified into two
(a) uncontrolled Rectifiers.
(b) controlled Rectifiers.

→ Uncontrolled Rectifier converts fixed ac input voltage to fixed dc output voltage. Eg :- Diode.

→ Controlled Rectifier converts fixed ac input voltage to variable dc output voltage. Eg :- SCR.
In controlled Rectifiers the output voltage is controlled by varying firing angles of SCR

→ Phase Angle Control :-

→ The processing of controlling output voltage of converter by varying firing angles of SCR is called phase angle control.

→ Types of controlled Rectifiers :-
(a) Based on input supply
  → 1-ϕ controlled Rectifier.
  → 3-ϕ controlled Rectifier.

(b) Based on Quadrant Operation.

- one quadrant converter (1-ϕ, Semiconductor converter).
- Two quadrant converter (1-ϕ, full converter).
- four quadrant converter (Dual converter)

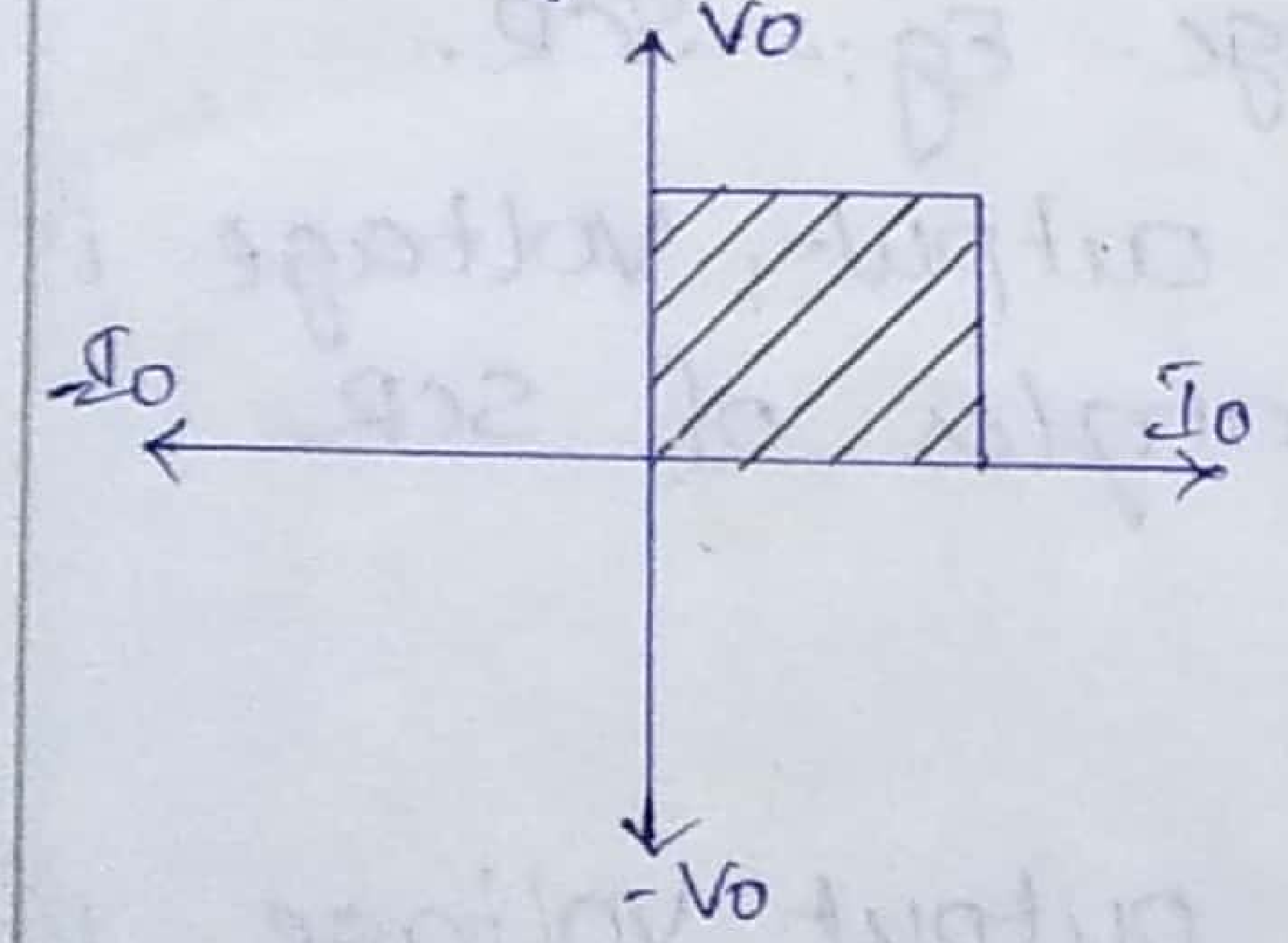
(c) Based on number of pulses.

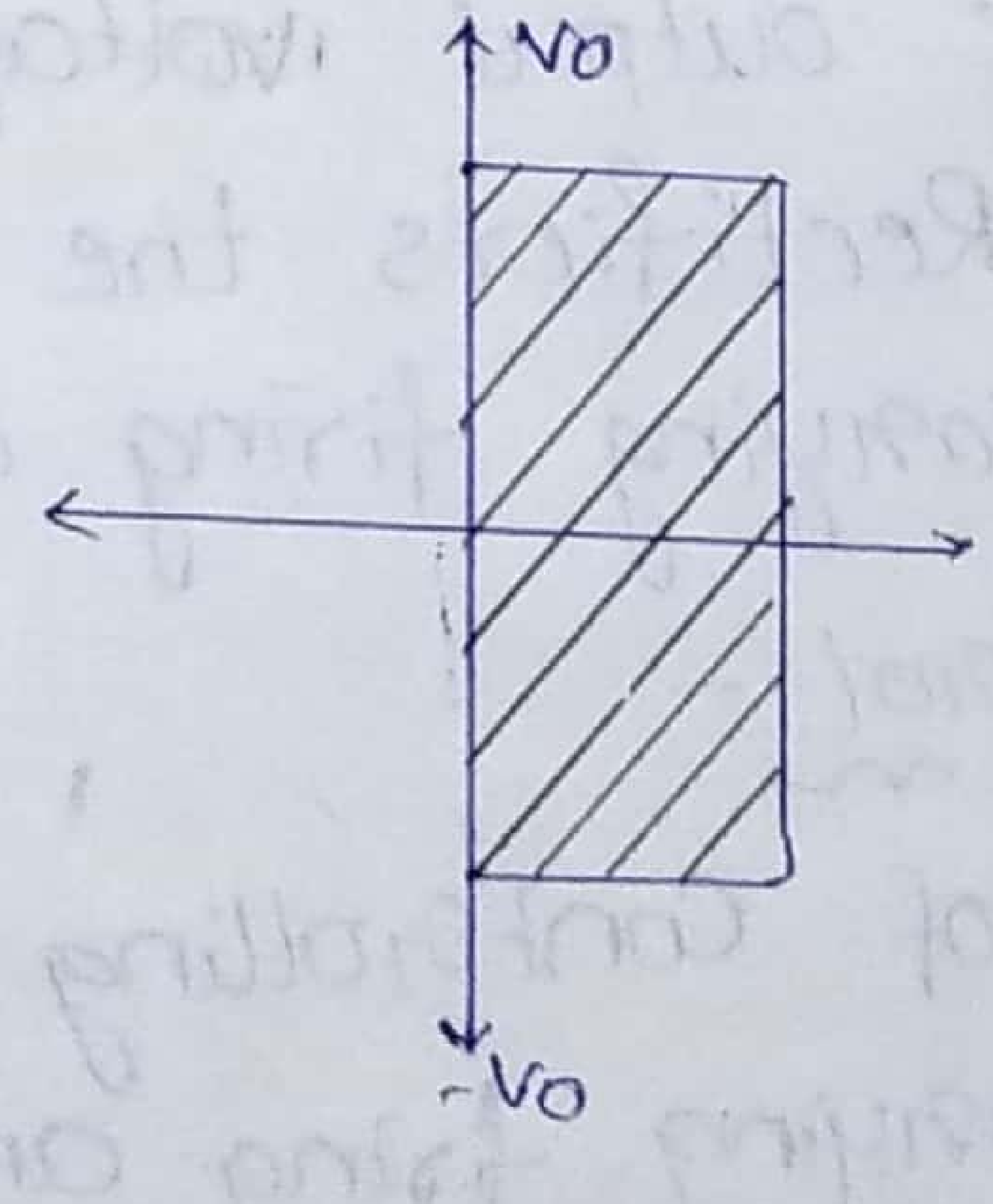
- one pulse converter. (1-ϕ HWCR)
- Two pulse converter. (1-ϕ FWCR औ 1-ϕ semi converter)
- Three pulse converter. (3-ϕ HWCR)
- Six pulse converter. (3-ϕ FWCR)

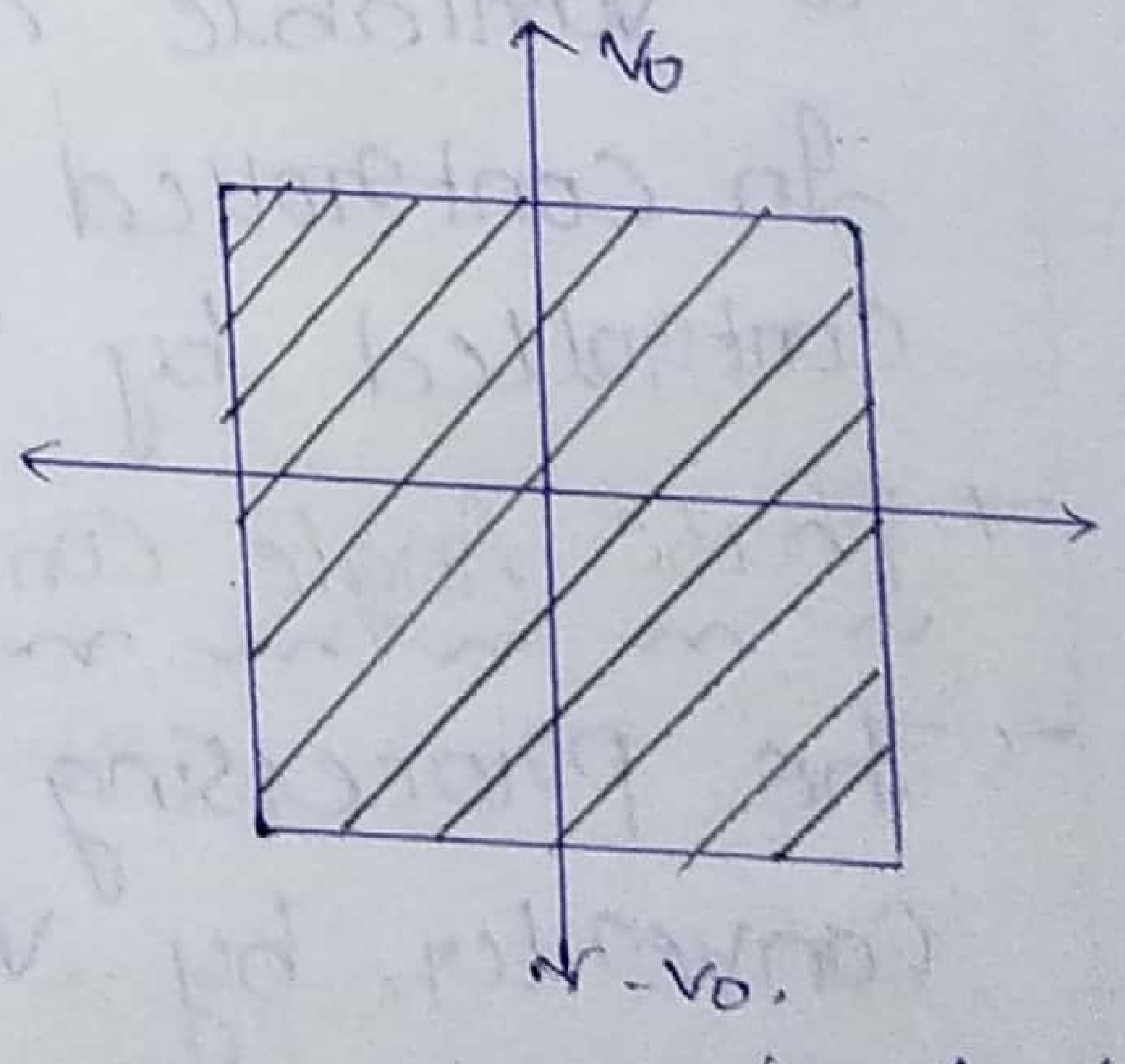
→ one quadrant converter means avg. output voltage and avg. output current is always +ve.

→ Two quadrant converter means avg. output voltage is either +ve or -ve, but avg. output current is always positive.

→ four quadrant converter means the avg. output voltage or current are either +ve औ -ve.







→ one pulse converter means only one pulse is to be generated during every supply cycle to trigger SCR.

→ Two pulse converter means two pulses are to be generated during every supply cycle to turn on various SCR's.

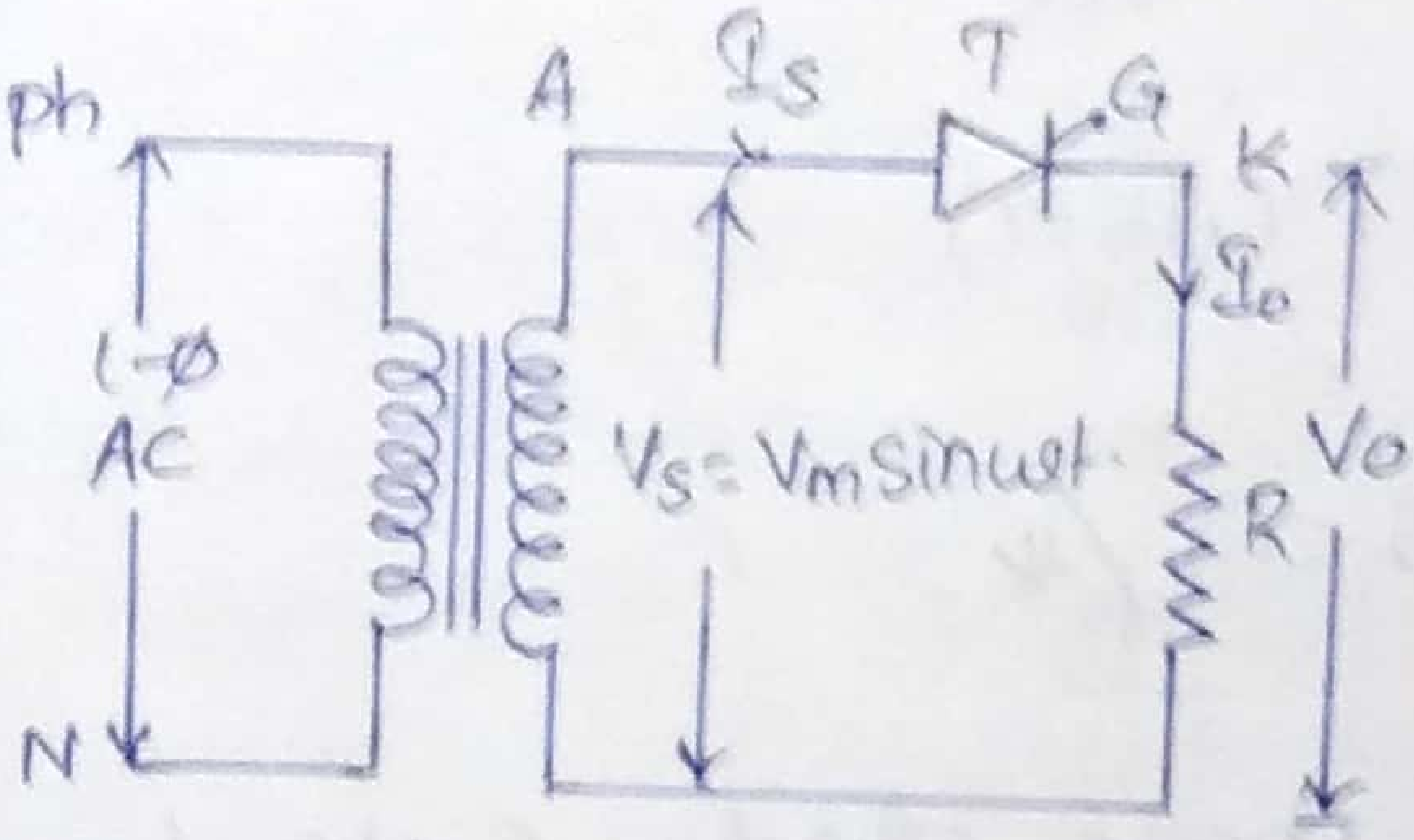
→ Three pulse converter means three triggering pulses are to generated for every supply cycle to turn on SCRs.

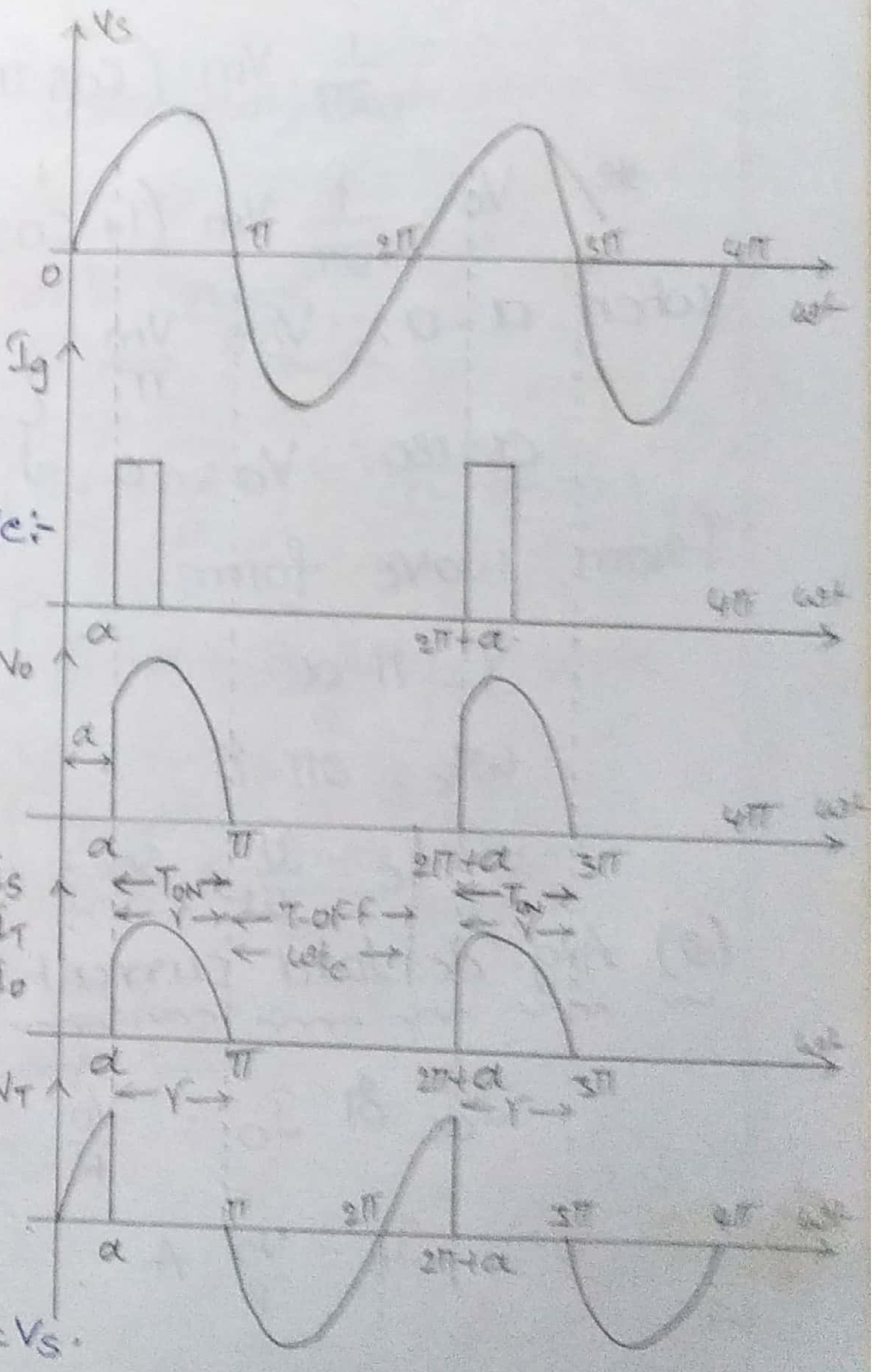
→ Six pulse converter means, six pulses are to be generated for every supply cycle to turn on various SCR's.

→ Applications:-

- → Speed Control of DC Motors.
- → Used to supply DC power for Inverter.
- → Provides DC supply for Machines Excitation.
- → DC Traction, HVDC Transmission System.

→ 1-ϕ Half wave Controlled Rectifier with R-Load:-





→ operation:-

→ During positive Half cycle:-
(0-π, 2π-3π, ...)

Thyristor = FB.

At, $\omega t = \alpha$

T-ON ; $V_o = V_s$; $I_o = \frac{V_o}{R}$; $V_T = 0$.

At, $\omega t = \pi$:

$V_s = 0$; $V_o = 0$; $I_o = 0$.

→ During Negative Half cycle:- (π-2π, 3π-4π, ...)

Thyristor = RB.

T = OFF ; $V_o = 0$; $I_o = 0$; $V_T = V_s$.

(1) Avg. dc load Voltage (V_{dc} or V_o) :-

$$V_{avg} = \frac{1}{T}\int_0^T V.dt$$

$$\Rightarrow V_{dc} \text{ ও } V_o = \frac{1}{2\pi}\int_0^{2\pi} V_o \cdot d\omega t$$

$$\Rightarrow V_o = \frac{1}{2\pi}\left[\int_0^{\alpha} 0.d\omega t + \int_{\alpha}^{\pi} V_m \sin\omega t \cdot d\omega t + \int_{2\pi}^{2\pi} 0.d\omega t\right]$$

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

$$= \frac{1}{2\pi}\Big[V_m(-\cos\omega t)\Big]_{\alpha}^{\pi}$$

$$= \frac{1}{2\pi} V_m (\cos\pi + \cos\alpha)$$

$$*/ \; V_o = \frac{1}{2\pi} V_m (1+\cos\alpha) \; /*$$

when $\alpha = 0$; $V_o = \frac{V_m}{\pi}$ } phase Angle Control Technique.

$\alpha = 180$; $V_o = 0$

from, wave forms

$$\gamma = \pi - \alpha$$

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

$$\Rightarrow t_c = \frac{\pi}{\omega} \text{ sec.}$$

(2) Avg. dc load current (I_{dc} ও I_o):-

$$I_{dc} \text{ ও } I_o = \frac{V_o}{R}.$$

$$\Rightarrow I_o = \frac{V_o}{R} \text{ A}$$

(3) RMS Dc Load Voltage (V_{dc} & $V_o)_{rms}$:-

$$\rightarrow \quad V_{orms} = \sqrt{\frac{1}{T}\int_0^T V^2 \cdot dt}$$

$$\rightarrow \quad V_{orms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V^2 \cdot d\omega t}$$

$$\Rightarrow \quad V_{orms}^2 = \frac{1}{2\pi}\left[\int_0^{\alpha} 0 \cdot d\omega t + \int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d\omega t + \int_{\pi}^{2\pi} 0 \cdot d\omega t\right]$$

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

$$= \frac{V_m^2}{4\pi}\int_{\alpha}^{\pi} (1-\cos 2\omega t) \cdot d\omega t$$

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

$$= \frac{V_m^2}{4\pi}\left[\left(\pi - \frac{\sin 2\pi}{2}\right) - \left(\alpha - \frac{\sin 2\alpha}{\alpha}\right)\right]$$

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

$$*/ \quad V_{orms} = V_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2} \quad /*$$

(4) RMS Dc Load Current (I_{orms}):-

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

(5) Dc Load power [P_{dc} or P_0] :-

→ It is the product of dc load voltage and dc load current.

$$\therefore \quad P_0 = V_0 I_0 \text{ or } I_0^2 R \; ; \; \frac{V_0^2}{R} \text{ W.}$$

(6) Power delivered to load (P_{ac}):-

→ $P_{ac} = V_{orms} \cdot I_{orms}$.

$$P_{ac} = \frac{V_{orms}^2}{R} \text{ (or) } I_{o\,rms}^2 R .$$

→ It is product of RMS load Voltage and RMS load current

(7) Input volt Ampere Rating:-

→ It is product of Source Voltage & Source current

I/p VA rating = $V_S \cdot I_S$.

VA rating = $V_S \cdot I_{orms}$ $(I_S = I_{orms})$.

(8) Input power factor:-

→ It is the ratio of power delivered to load to input VA rating

$$\therefore \text{Input pf} = \frac{\text{Power delivered to load}}{\text{I/p VA}}$$

$$= \frac{V_{orms} \cdot I_{orms}}{V_S I_S}$$

$$= \frac{V_{orms} \cdot \cancel{I_{orms}}}{V_S \cancel{I_{orms}}}$$

$$*/ \text{ I/p Pf} = \frac{V_{orms}}{V_S} . /*$$

(9) Transformer Utilisation Factor:-

→ It is ratio of dc output power to VA rating of secondary winding of Transformer.

$$\therefore TUF = \frac{\text{Dc o/p Power}}{\text{VA rating of Secondary wdg of T/F.}}$$

$$\therefore TUF = \frac{P_{dc}}{V_s I_s} = \frac{V_o I_o}{V_s I_{orms}} \quad (\because I_o = I_{orms})$$

(10) Rectifier Efficiency:-

→ It is the ratio of dc output power to power delivered to load.

$$\eta = \frac{P_{dc}}{P_{ac}}.$$

(11) Form Factor:-

→ It is the ratio of RMS voltage to Avg. voltage.

$$FF = \frac{V_{orms}}{V_o}.$$

(12) Ripple factor:-

→ It is ratio of RMS Value of ac component to

$$RF = \frac{\text{RMS Value of AC Component}}{\text{DC Component.}}$$

$$RF = \frac{(V_{ac})_{rms}}{V_o}.$$

$$(V_{ac})_{rms} = (V_{orms}^2 - V_o^2)^{1/2}$$

$$\Rightarrow RF = \frac{(V_{orms}^2 - V_o^2)^{1/2}}{V_o} = \left[\frac{V_{orms}^2 - V_o^2}{V_o^2}\right]^{1/2}$$

$$\Rightarrow RF = \sqrt{\left(\frac{V_{orms}}{V_0}\right)^2 - 1}.$$

$$*/\ RF = \sqrt{FF^2 - 1}.\ /*$$

→ Rectifier output = Ac comp + Dc comp.

$$V = V_{ac} + V_0.$$

$$V_{ac} = V - V_0$$

$$(V_{ac})_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_{ac}^2 \cdot d\omega t}$$

$$\Rightarrow (V_{ac})^2_{rms} = \frac{1}{2\pi}\int_0^{2\pi} (V - V_0)^2 \cdot d\omega t$$

$$= \frac{1}{2\pi}\int_0^{2\pi} (V^2 + V_0^2 - 2VV_0) \cdot d\omega t$$

$$= \frac{1}{2\pi}\left[\int_0^{2\pi} V^2 d\omega t + \frac{1}{2\pi}\int_0^{2\pi} V_0^2 d\omega t - \frac{1}{2\pi}\int_0^{2\pi} 2V \cdot V_0 d\omega t\right]$$

$$\therefore (V_{ac})^2_{rms} = \frac{1}{2\pi}\int_0^{2\pi} V^2 \cdot d\omega t + \frac{1}{2\pi} V_0^2 \cdot (2\pi) - 2V_0 \int_0^{2\pi} V \cdot d\omega t \frac{1}{2\pi}$$

$$(V_{ac})^2_{rms} = V_{orms}^2 + V_0^2 - 2V \cdot V_0$$

$$= V_{orms}^2 - V_0^2$$

$$\therefore (V_{ac})_{rms} = (V_{orms}^2 - V_0^2)^{1/2}$$

(13) Peak Inverse Voltage (PIV):-

→ The Max Voltage that appears across SCR during Reverse Bias Condition.

$$*/\ PIV = V_m\ /*$$

(14) circuit Turn off Time:-

→ Time between the instant at which Anode current falls to zero after that how much time

SCR is in reverse bias condition.

$$*/ \; t_c = \frac{\pi}{\omega} \; /*$$

→ (15) Firing Angle:-

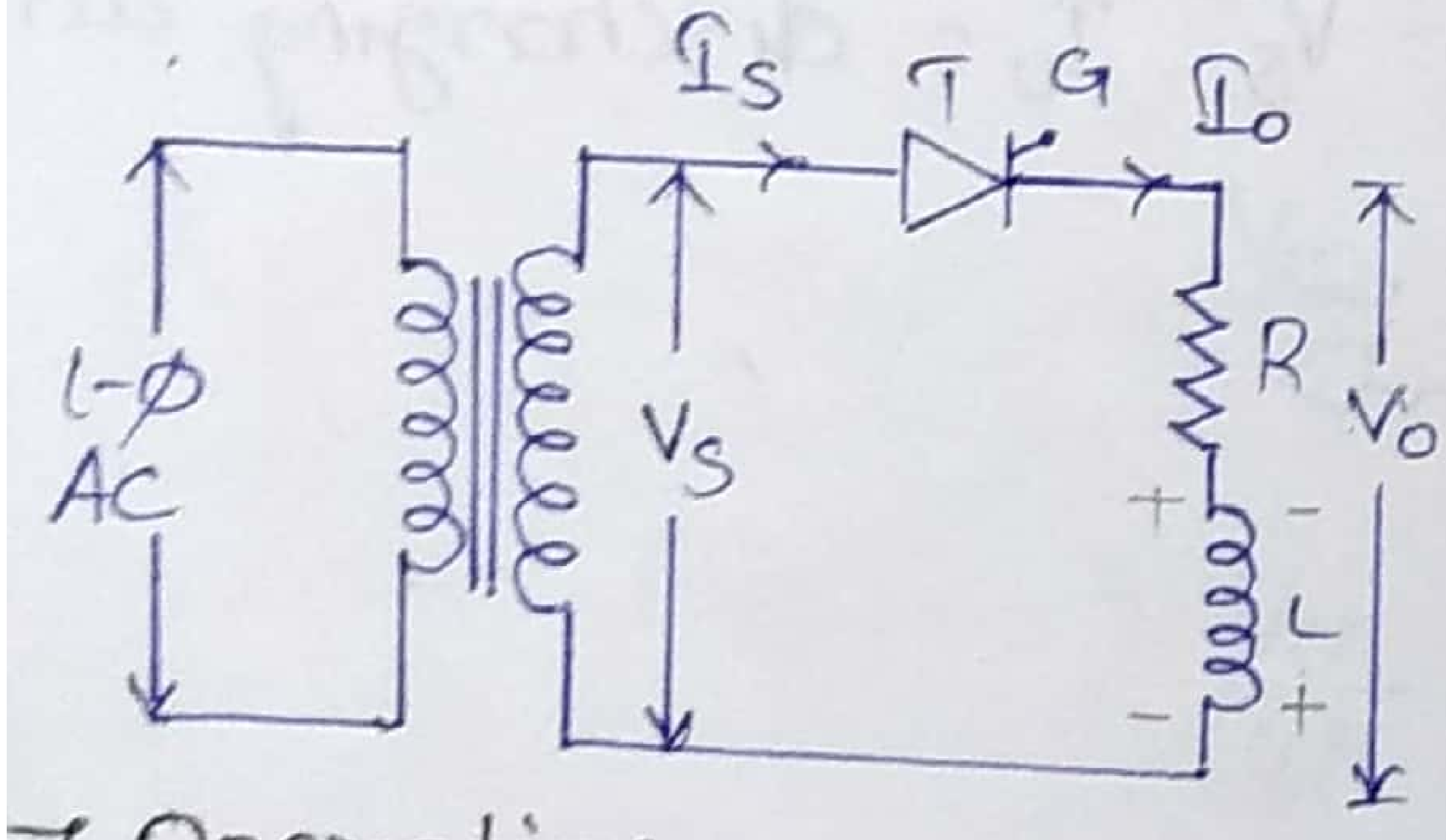
→ The Angle between zero crossing of input supply Voltage and the instant at which SCR is triggered is called firing Angle. It is denoted by "α".

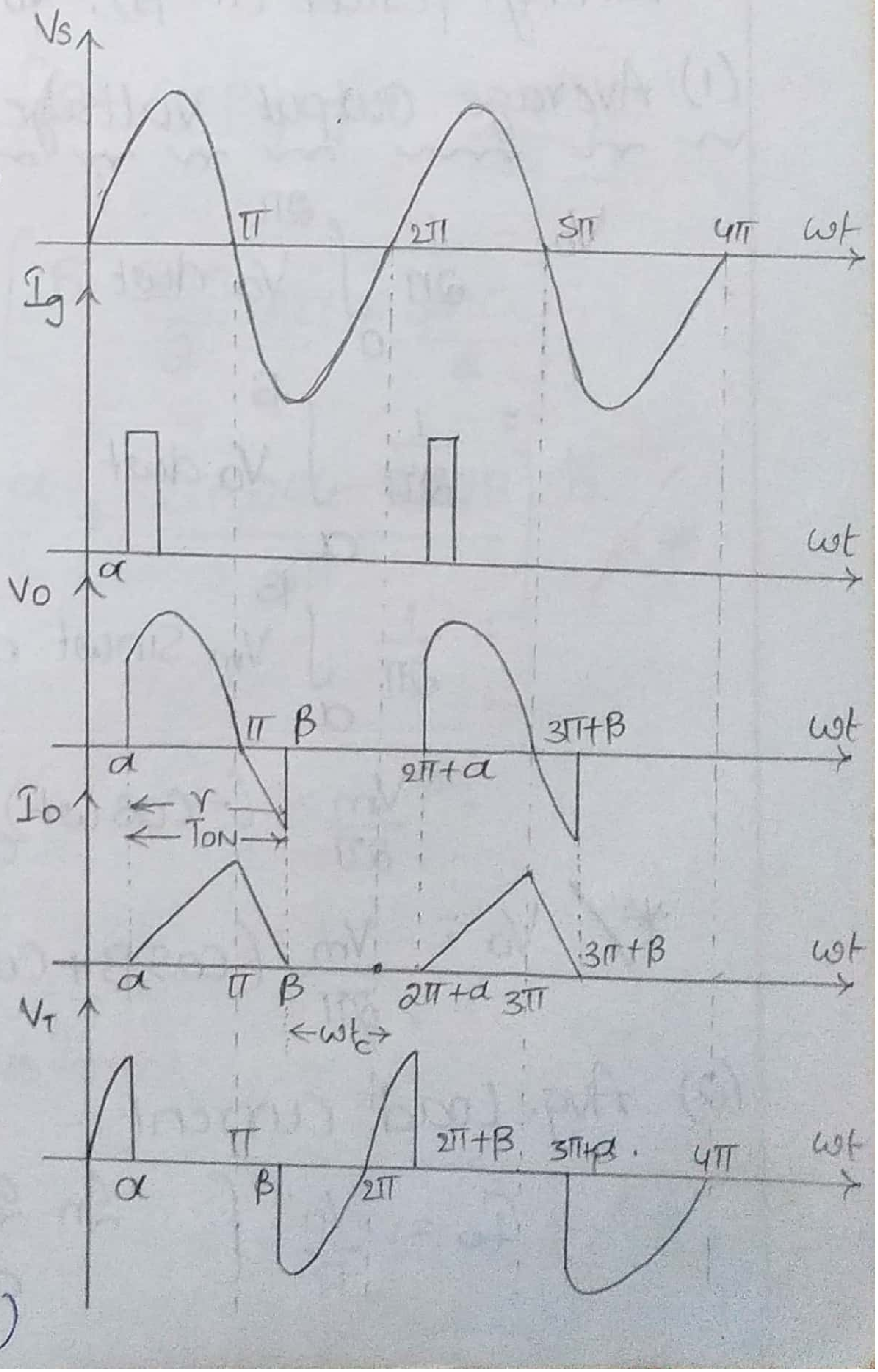
(16) Conduction Angle:-

→ The Angle during which SCR is in Conduction, is called Conduction Angle. It is denoted by γ.

$$\gamma = \pi - \alpha.$$

→ 1-Φ HWCR with R-L Load:-





→ Operation:-

→ During positive Half cycle (0-π, 2π-3π, ...)

Thyristor- F.B.

At ωt = α;

T = ON ; $V_o = V_s$;

I_o: Increases Slowly (because Series R-L Load) reached to its Peak Value.

→ At the Same time, during period (α to π)

→ Inductor - L stores energy with polarity "+" & "-".

→ At $\omega t = \pi$, $V_S = 0$; $V_0 = 0$; but $I_0 \neq 0$ (due to the Inductance, it does not allow suddern changes in current).

→ During Negative Half cycle :-

Thyristor - R.B.

→ In RB Condition, SCR should be off, but it conducts forcely due to Inductance, until Inductor dissipates its stored energy. i.e., during the period $(\pi - \beta)$, inductor dissipates its stored energy by reversing it's polarities. and allowed to SCR conducts forcely.

→ During period $(\pi = \beta)$; $V_0 = V_S$; I_0 = discharging current

(1) Average output voltage :-

$$V_0 = \frac{1}{2\pi}\int_0^{2\pi} V_0 . d\omega t.$$

$$= \frac{1}{2\pi}\int_\alpha^{\beta} V_0 . d\omega t$$

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

$$= \frac{V_m}{2\pi}(-\cos\omega t)_\alpha^\beta$$

$$*/ \; V_0 = \frac{V_m}{2\pi}(-\cos\beta + \cos\alpha) /*$$

(2) Avg. Load Current :- (V_L - V across Inductor)

$$I_0 = \frac{V_0}{R} \left[\begin{array}{l} \because \text{In Inductor during } +H.C = +V_L \\ \quad \text{during } -HC = -V_L. \\ \quad \therefore \text{Avg. } V = +V_L - V_L = 0 \end{array} \right]$$

(3) RMS Load Voltage :-

$$V_{orms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_o^2 . d\omega t}$$

$$\Rightarrow V_{orms}^2 = \frac{1}{2\pi}\int_0^{2\pi} V_m^2 \sin^2\omega t . d\omega t$$

$$= \frac{V_m^2}{2\pi}\int_0^{2\pi}\left(\frac{1-\cos 2\omega t}{2}\right). d\omega t$$

$$= \frac{V_m}{2\pi}\times\frac{1}{2}\left[\omega t - \frac{\sin\omega t}{2}\right]_0^{2\pi}$$

$$= \frac{V_m}{4\pi}\left[\omega t - \frac{\sin\omega t}{2}\right]_\alpha^\beta$$

$$= \frac{V_m}{4\pi}\left[\left(\beta - \frac{\sin\beta}{2}\right) - \left(\alpha - \frac{\sin\alpha}{2}\right)\right]$$

$$= \frac{V_m}{4\pi}\left[\beta - \frac{\sin\beta}{2} + \alpha + \frac{\sin\alpha}{2}\right]$$

$$*/ \quad V_{orms} = V_m\left[\frac{\beta-\alpha}{4\pi} + \frac{\sin 2\alpha - \sin 2\beta}{8\pi}\right]^{1/2} \quad /*$$

(4) $I_{orms} = \frac{V_{orms}}{R}$,

(5) $P_{dc} = V_o . I_o$.

(6) $P_{ac} = V_{orms} . I_{orms}$.

(7) Input VA = $V_s . I_s = V_s I_{orms}$.

(8) Input pf = $\frac{V_{orms}}{V_s}$.

(9) TUF = $\frac{V_o I_o}{V_s I_{orms}}$

(10) $\eta = \frac{P_{dc}}{P_{ac}}$; (11) $FF = \frac{V_{orms}}{V_0}$.

(12) $RF = \sqrt{FF^2-1}$; (13) $PIV = V_m$.

(14) $\omega t_c = 2\pi - \beta$; (15) $\gamma = \beta - \alpha$.

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

→ Calculation of Extension Angle (β):-

→ During ON period of SCR.

Apply KVL

$\Rightarrow V_m \sin\omega t = I_0 R + L\cdot\frac{dI_0}{dt}$

$\Rightarrow \frac{dI_0}{dt} + \frac{R}{L}\cdot I_0 = \frac{V_m \sin\omega t}{L} \rightarrow (1)$

This is first order non-linear diff. Eqn, Solution is

$I_0 = \frac{V_m}{Z}\sin(\omega t-\phi) + A e^{-t/\tau} \rightarrow (2)$

where, $Z = \sqrt{R^2+X_L^2}$

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

At $\omega t = \alpha, I_0 = 0$; $t = \alpha/\omega$.

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

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

Sub A in Eqn. (2)

$\Rightarrow I_0 = \frac{V_m}{Z}\sin(\omega t-\phi) - \frac{V_m}{Z}\sin(\alpha-\phi)\, e^{\frac{\alpha}{\omega}\frac{R}{L} - t\cdot\frac{R}{L}}$.

$\Rightarrow I_0 = \frac{V_m}{Z}\left[\sin(\omega t-\phi) - \sin(\alpha-\phi)\cdot e^{-\frac{R}{\omega L}\cdot(\omega t-\alpha)}\right]$

At, $\omega t = \beta$, $I_0 = 0$. ; $0 = \frac{V_m}{Z}\left[\sin(\beta-\phi) - \sin(\alpha-\phi)\cdot e^{-\frac{R}{\omega L}(\beta-\alpha)}\right]$

$\Rightarrow t = \beta/\omega$

$$*/ \sin(\beta-\phi) = \sin(\alpha-\phi)\, e^{\frac{-R}{\omega L}(\beta-\alpha)} /*$$

→ Drawbacks of RL Load:-

→ Avg. output Voltage is reduced due to Negative Spikes from $\omega t = \pi - \beta$ in output Voltage. This Drawback can be overcome by connecting free wheeling Diode across the load.

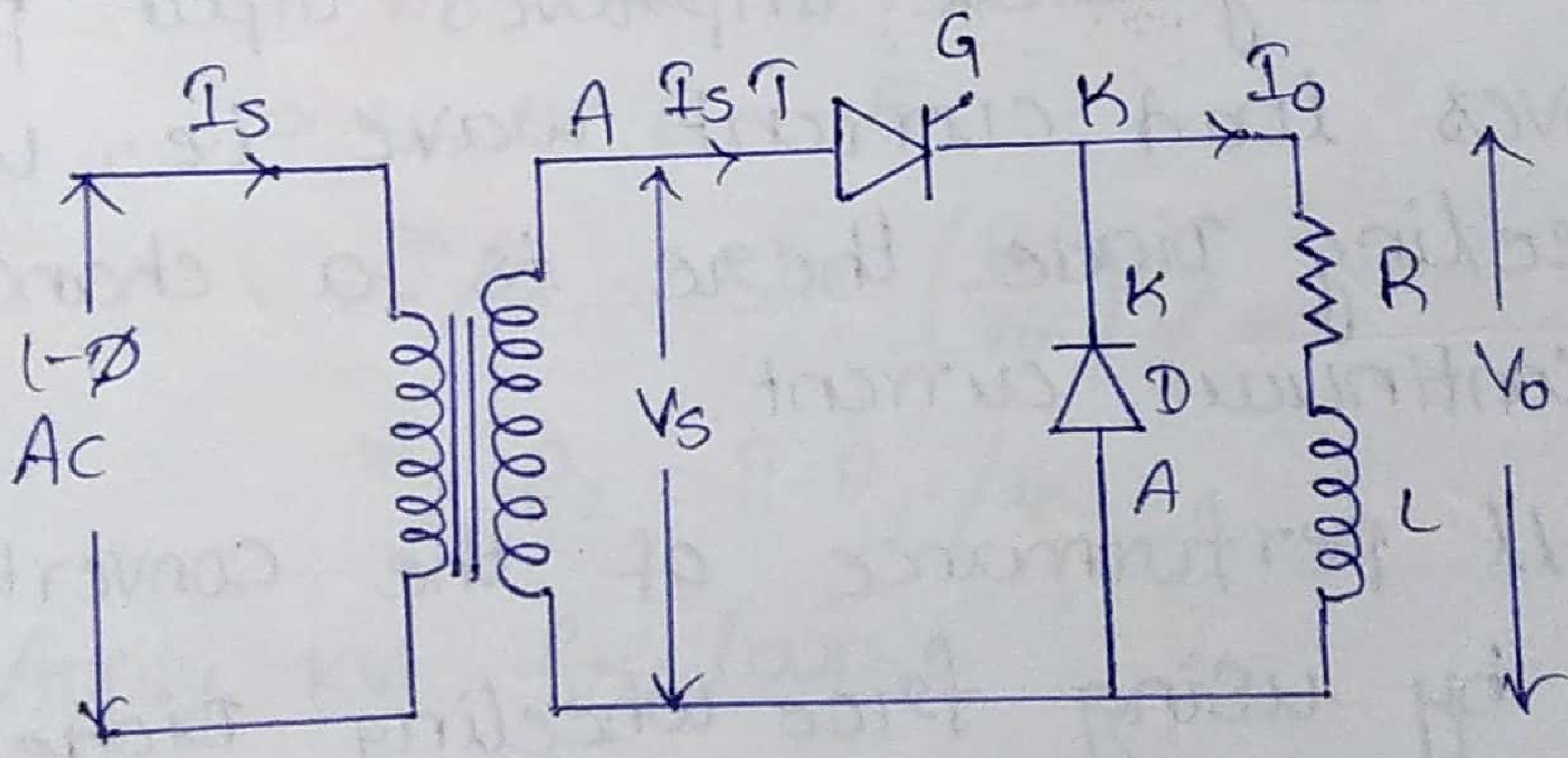
→ $1-\phi$ HWCR with RL Load with free wheeling Diode

→ free wheeling Diode is always connected across the load. It is also called as Bypass Diode or commutating Diode.

→ functions:-

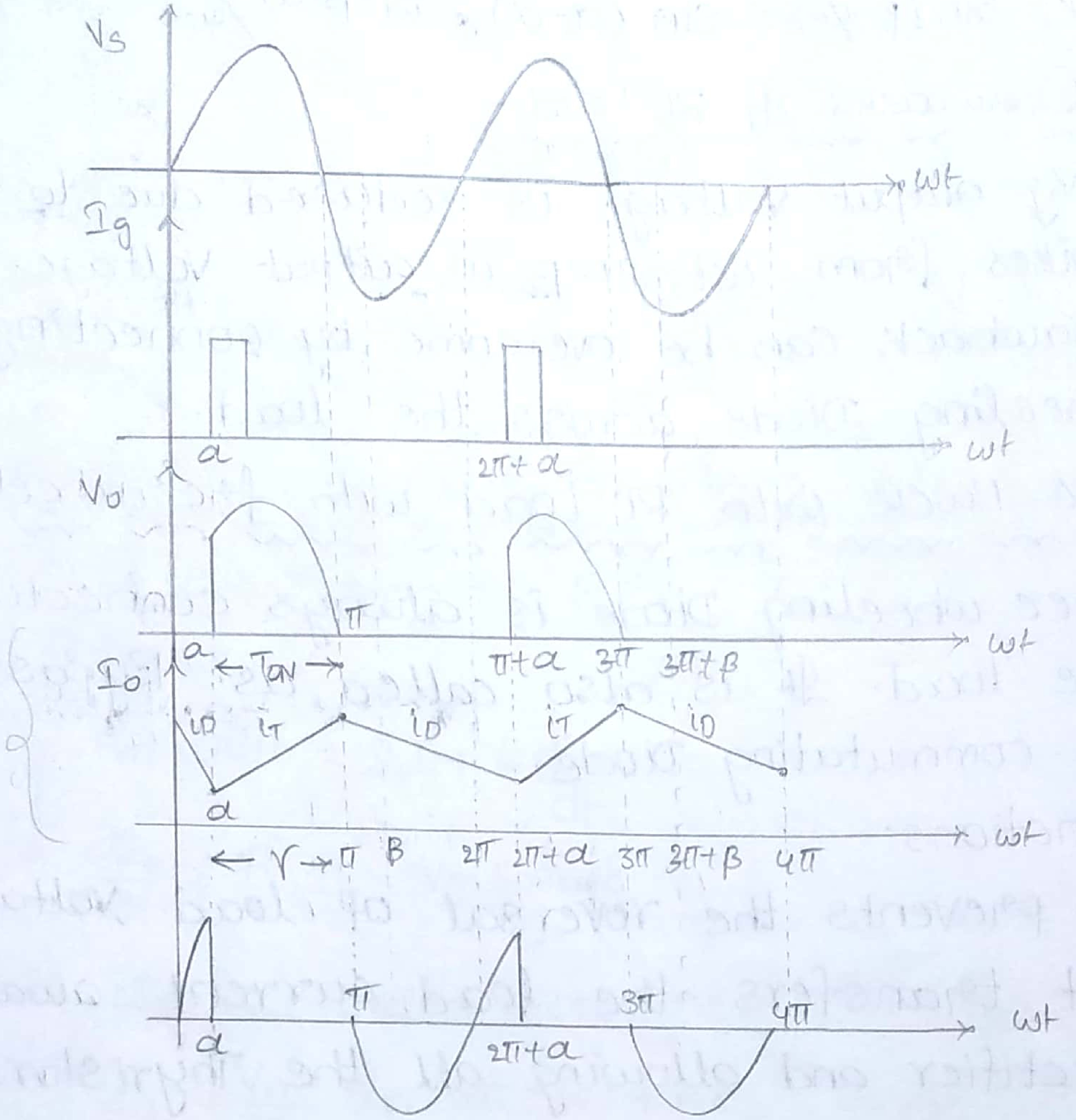
(1) It prevents the reversal of load voltage

(2) It transfers the load current away from rectifier and allowing all the Thyristors to recover its reverse blocking characteristics.



(1) Free wheeling Diode remove negative Spike from $\omega t = \pi - \beta$ in output Voltage.

(2) As Negative Spikes are removed, average output Voltage increases and then output power increases.



(3) free wheeling Diode improves input pf

(4) It improves load current wave i.e., using free wheeling Diode there is a chance of getting continuous current.

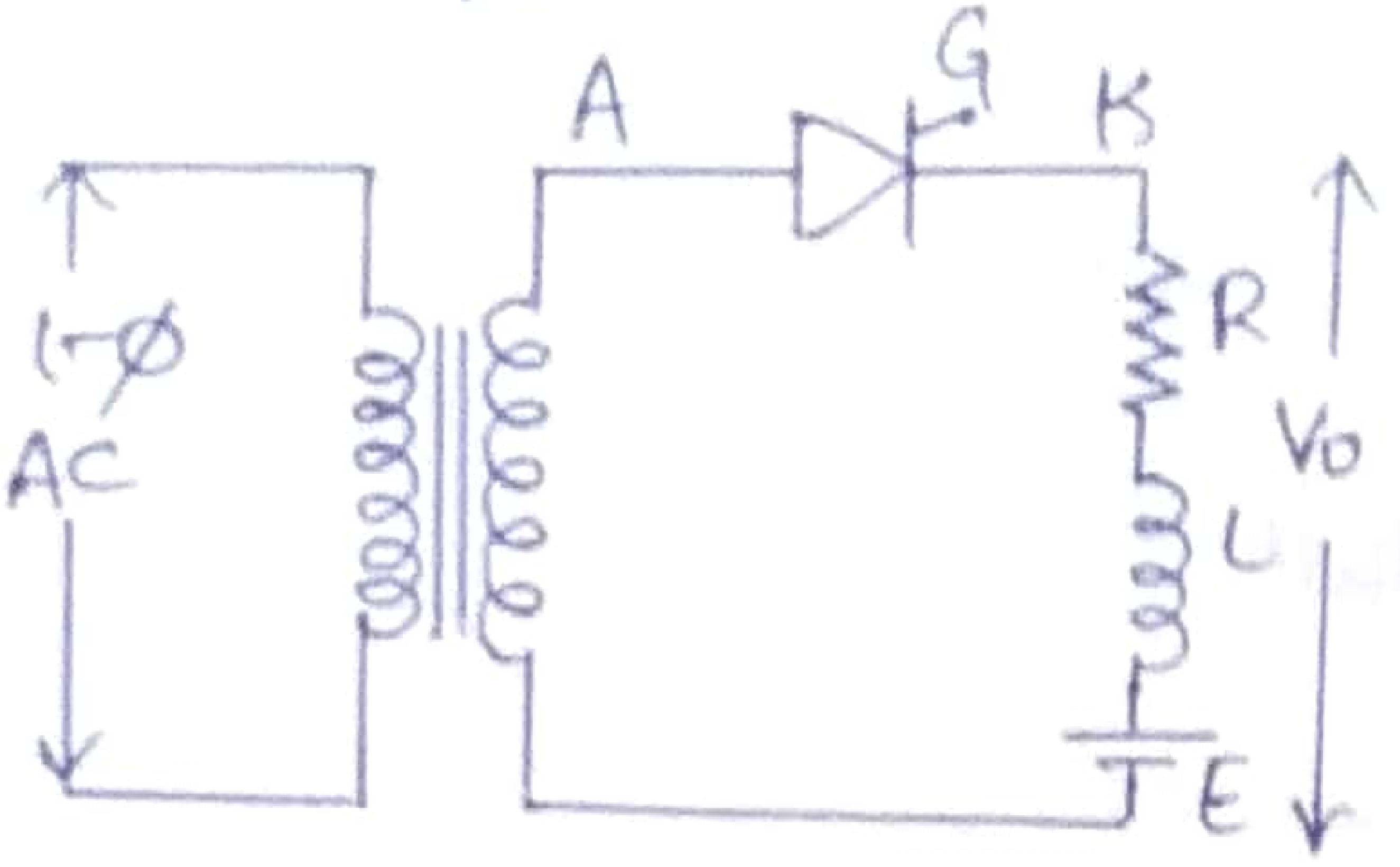
(5) The overall performance of the converter is improved by using free wheeling Diode.

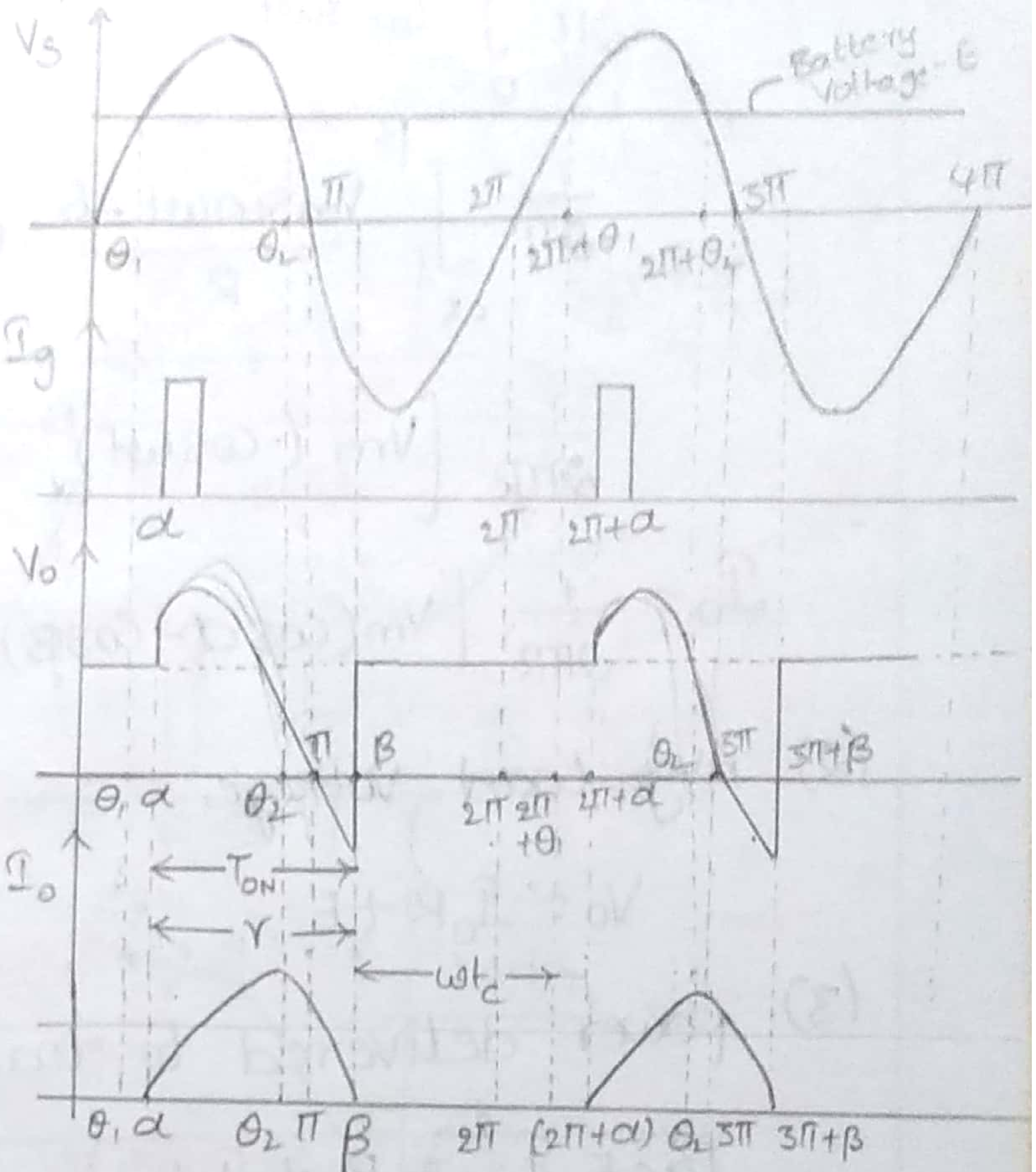
Note:-

→ (1) Single phase HWCR with RL Load with free wheeling Diode is identically same as 1-Ø HWCR with R-Load.

(2) formulae are same for 1-Ø HWCR with R-load and 1-Ø HWCR with RL load with FWD.

→ 1-ϕ HWCR with RLE Load:-





→ $(\alpha - \theta_2)$ = Inductor stores energy

→ $(\theta_2 - \beta)$: Inductor discharges it's stored energy & there by allowing thyristor to the conductor forcely.

At, $\omega t = \theta_1$, $V_s = E$

$\Rightarrow V_m \sin \omega t = E$

$\Rightarrow V_m \sin \theta_1 = E$

$\Rightarrow */ \theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right). /*$

$*/ \theta_2 = \pi - \theta_1. /*$

→ Apply KVL for loop

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

Avg. voltage across L is zero. ↳ Since during charing $+V_o$; discharging $-V_o$.

$\Rightarrow V_m \sin \omega t = i_o R + E$

$$\Rightarrow i_o = \frac{V_m \sin \omega t - E}{R}.$$

(1) Avg. load current:-

$$I_0 = \frac{1}{2\pi}\int_0^{2\pi} i_0 \cdot d\omega t$$

$$= \frac{1}{2\pi}\int_\alpha^\beta \frac{V_m \sin\omega t - E}{R} \cdot d\omega t$$

$$= \frac{1}{2\pi R}\left[V_m(-\cos\omega t)_\alpha^\beta - E(\omega t)_\alpha^\beta\right]$$

$$I_0 = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos\beta) - E(\beta - \alpha)\right] \rightarrow (1)$$

(2) Avg. load voltage:-

$$V_0 = I_0 R + E$$

(3) power delivered to load:-

$$P_{ac} = I_{orms}^2 R + I_0 E$$

(power dissipation in R) + (power delivered to Battery)

(4) Input VA:-

$$I/p\ VA = V_s I_s = V_s I_{orms}$$

(5). I/p PF:-

$$i/p\ Pf = \frac{I_{orms}^2 R + I_0 E}{V_s I_{orms}}$$

(6) $\gamma = \beta - \alpha$

(7) $\omega t_c = 2\pi + \theta_1 - \beta$

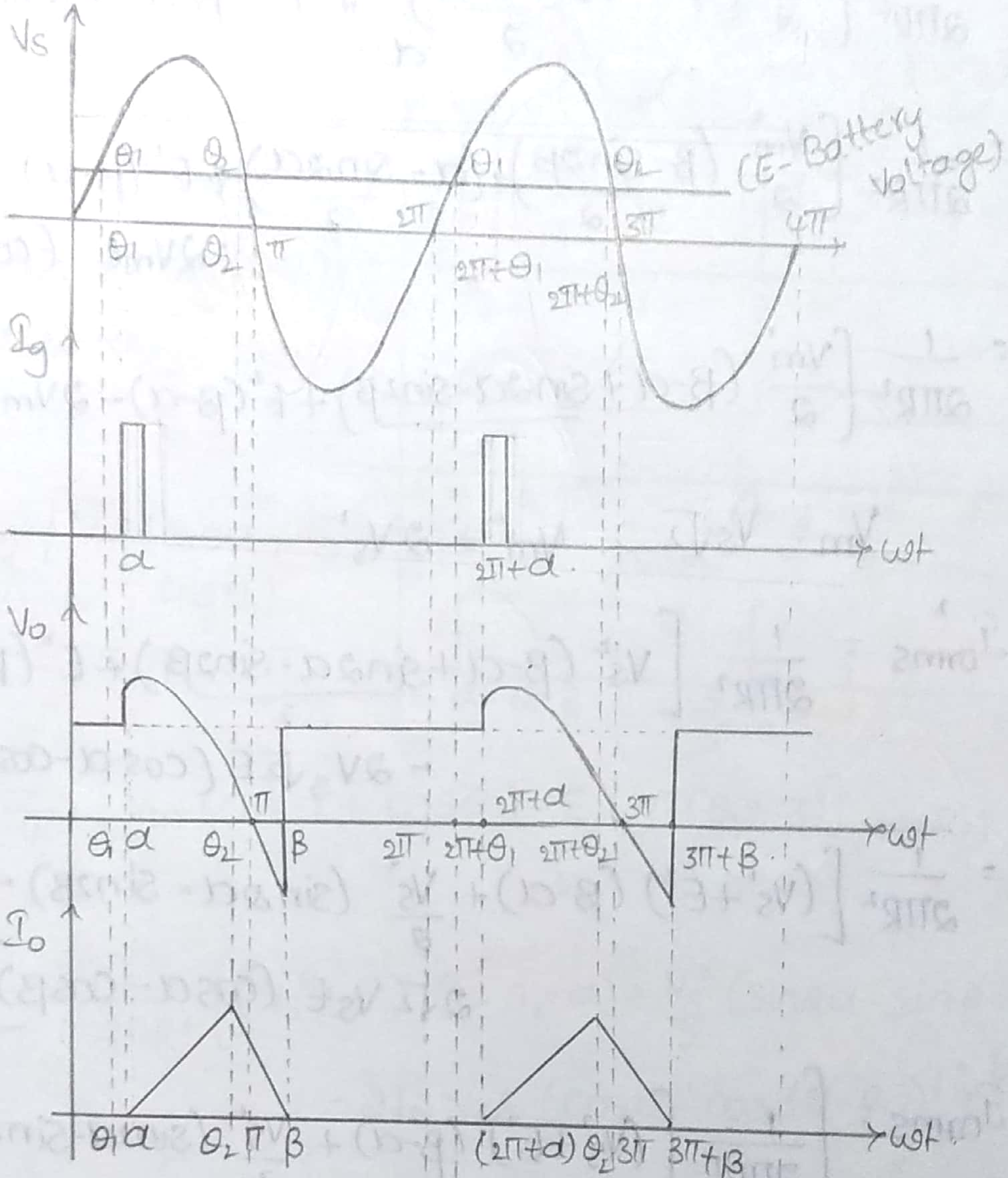
$$*/\ t_c = \frac{2\pi + \theta_1 - \beta}{\omega} /* \rightarrow (3)$$

(8) PIV :- Apply KVL

$$V_s + V_T + E = 0 \Rightarrow V_T = -V_s - E$$

$$V_T = -(V_m \sin\omega t + E)$$

$$|V_T|_{max} = V_m + E$$



→ RMS Load current:-

$$I_{orms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_0^2 \, d\omega t}$$

$$\Rightarrow I_{orms}^2 = \frac{1}{2\pi}\int_\alpha^\beta \left(\frac{V_m \sin\omega t - E}{R}\right)^2 \cdot d\omega t$$

$$\Rightarrow I_{orms}^2 = \frac{1}{2\pi R^2}\int_\alpha^\beta (V_m \sin\omega t - E)^2 \cdot d\omega t$$

$$= \frac{1}{2\pi R^2}\int_\alpha^\beta (V_m^2 \sin^2\omega t + E^2 - 2V_mE\sin\omega t) \cdot d\omega t$$

$$= \frac{1}{2\pi R^2}\left[\frac{V_m^2}{R^2}\left(1-\cos\omega t\right)_{\alpha}^{\beta} + \int_{\alpha}^{\beta} E^2 \cdot d\omega t - 2V_mE\int_{\alpha}^{\beta}\sin\omega t \cdot d\omega t\right]$$

$$= \frac{1}{2\pi R^2}\left[\frac{V_m^2}{2}\left(\omega t - \frac{\cancel{co}\sin 2\omega t}{2}\right)_{\alpha}^{\beta} + E^2(\beta-\alpha) - 2V_mE\left(-\cos\omega t\right)_{\alpha}^{\beta}\right]$$

$$= \frac{1}{2\pi R^2}\left[\frac{V_m^2}{2}\left(\beta - \frac{\sin 2\beta}{2}\right) - \left(\alpha - \frac{\sin 2\alpha}{2}\right) + E^2(\beta-\alpha) - 2V_mE\left(-\cos\beta + \cos\alpha\right)\right]$$

$$= \frac{1}{2\pi R^2}\left[\frac{V_m^2}{2}\left(\beta-\alpha + \frac{\sin 2\alpha - \sin 2\beta}{2}\right) + E^2(\beta-\alpha) - 2V_mE\left(\cos\alpha - \cos\beta\right)\right]$$

$$V_m = V_s\sqrt{2} \; ; \quad V_m^2 = 2V_s^2$$

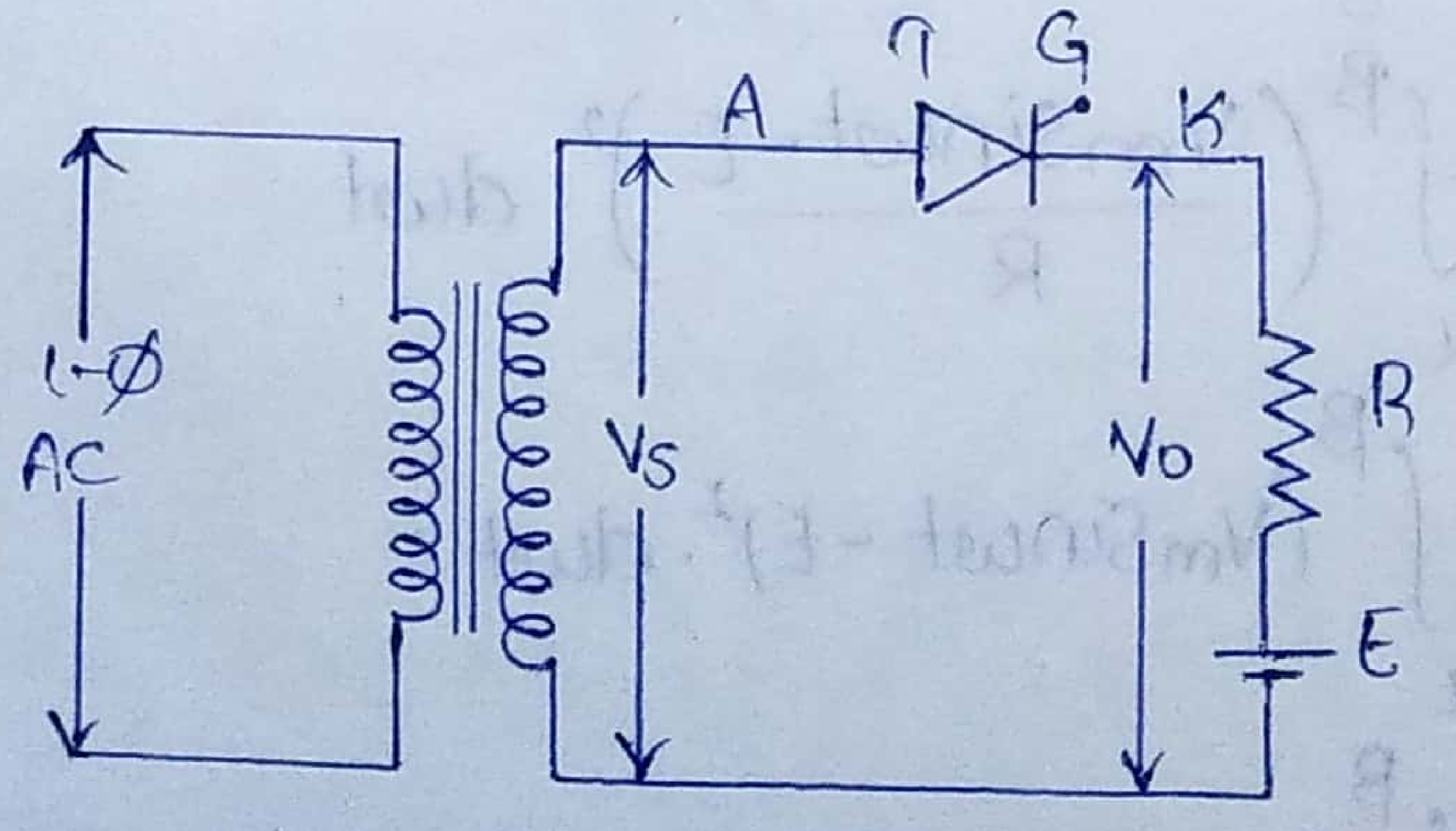
$$\Rightarrow I_{orms}^2 = \frac{1}{2\pi R^2}\left[V_s^2\left(\beta-\alpha + \frac{\sin 2\alpha - \sin 2\beta}{2}\right) + E^2(\beta-\alpha) - 2V_s\sqrt{2}E\left(\cos\alpha - \cos\beta\right)\right]$$

$$= \frac{1}{2\pi R^2}\left[\left(V_s^2+E^2\right)(\beta-\alpha) + \frac{V_s^2}{2}\left(\sin 2\alpha - \sin 2\beta\right) - \cancel{I_0}\; 2\sqrt{2}V_sE\left(\cos\alpha - \cos\beta\right)\right]$$

$$\therefore I_{orms} = \left[\frac{1}{2\pi R^2}\left[\left(V_s^2+E^2\right)(\beta-\alpha) + \frac{V_s^2}{2}\left(\sin 2\alpha - \sin 2\beta\right) - 2\sqrt{2}V_sE\left(\cos\alpha - \cos\beta\right)\right]\right]^{1/2} . \quad \rightarrow (2)$$

→ Case 1:-

→ When Inductor is not present:-



$V_s = V_m \sin\omega t$

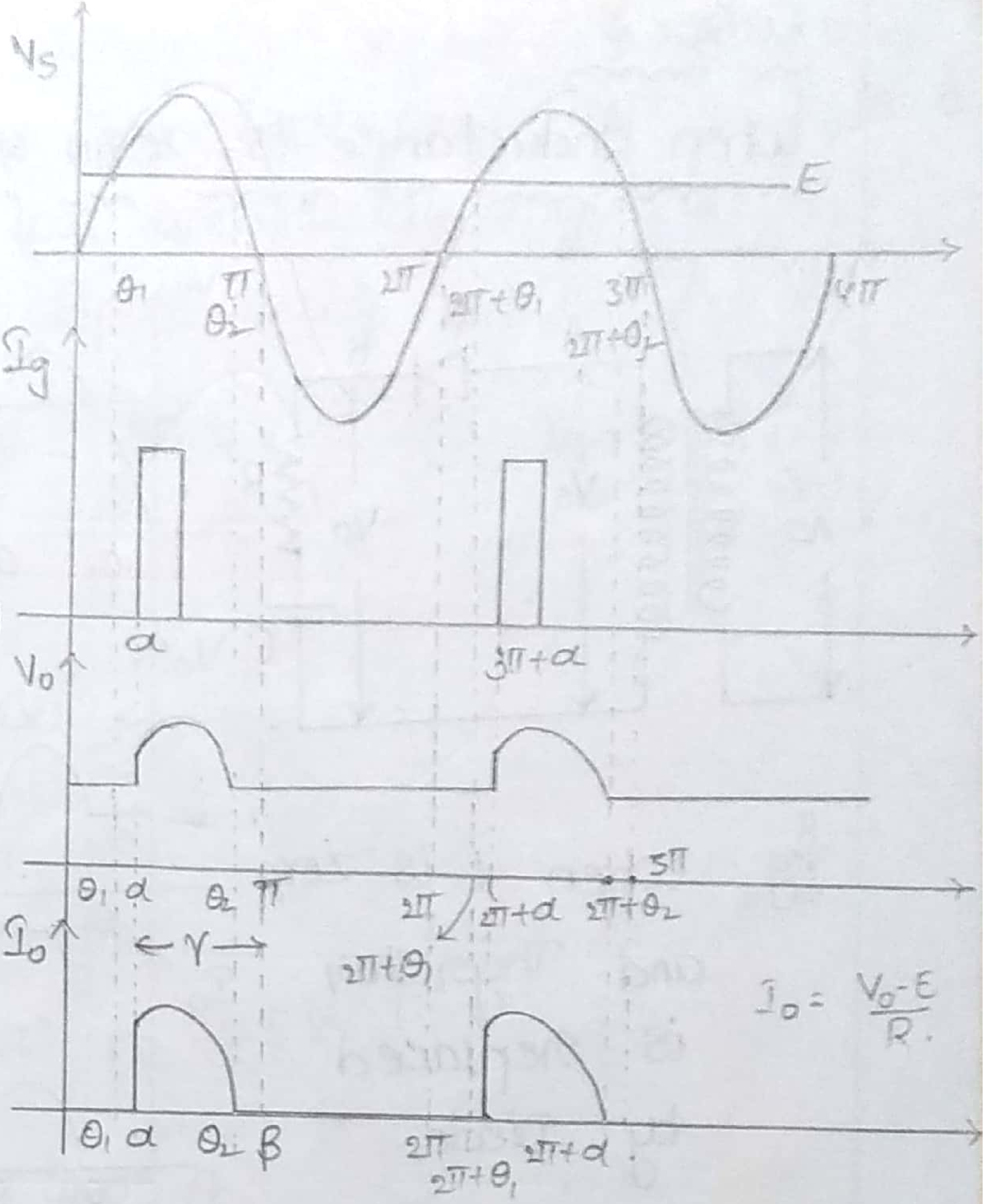
→ when L is not present i.e., L=0

$$\Rightarrow \beta = \theta_2 = \pi - \theta_1 .$$

Eqn. (1)

$$\Rightarrow I_0 = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos(\pi-\theta_1)) - E(\pi-\theta_1-\alpha)\right]$$

$$\Rightarrow I_0 = \frac{1}{2\pi R}\left[V_m(\cos\alpha + \cos\theta_1) - E(\pi-(\theta_1+\alpha)\right]$$



$$\therefore I_0 = \frac{1}{2\pi R}\left[V_m(\cos\alpha + \cos\theta_1) - E(\pi-(\theta_1+\alpha)\right] \rightarrow (4)$$

Eqn (2).

$$\Rightarrow I_{orms} = \left\{\frac{1}{2\pi R^2}\left[(V_s^2+E^2)(\pi-\theta_1-\alpha) + \frac{V_s^2}{2}(\sin2\alpha - \sin2(\pi-\theta_1)) - 2\sqrt{2}V_sE(\cos\alpha - \cos(\pi-\theta_1))\right]\right\}^{1/2}$$

$$\therefore I_{orms} = \left\{\frac{1}{2\pi R^2}\left[(V_s^2+E^2)(\pi-\theta_1-\alpha) + \frac{V_s^2}{2}(\sin2\alpha + \sin2\theta_1) - 2\sqrt{2}V_sE(\cos\alpha + \cos\theta_1)\right]\right\}^{1/2} \rightarrow (5).$$

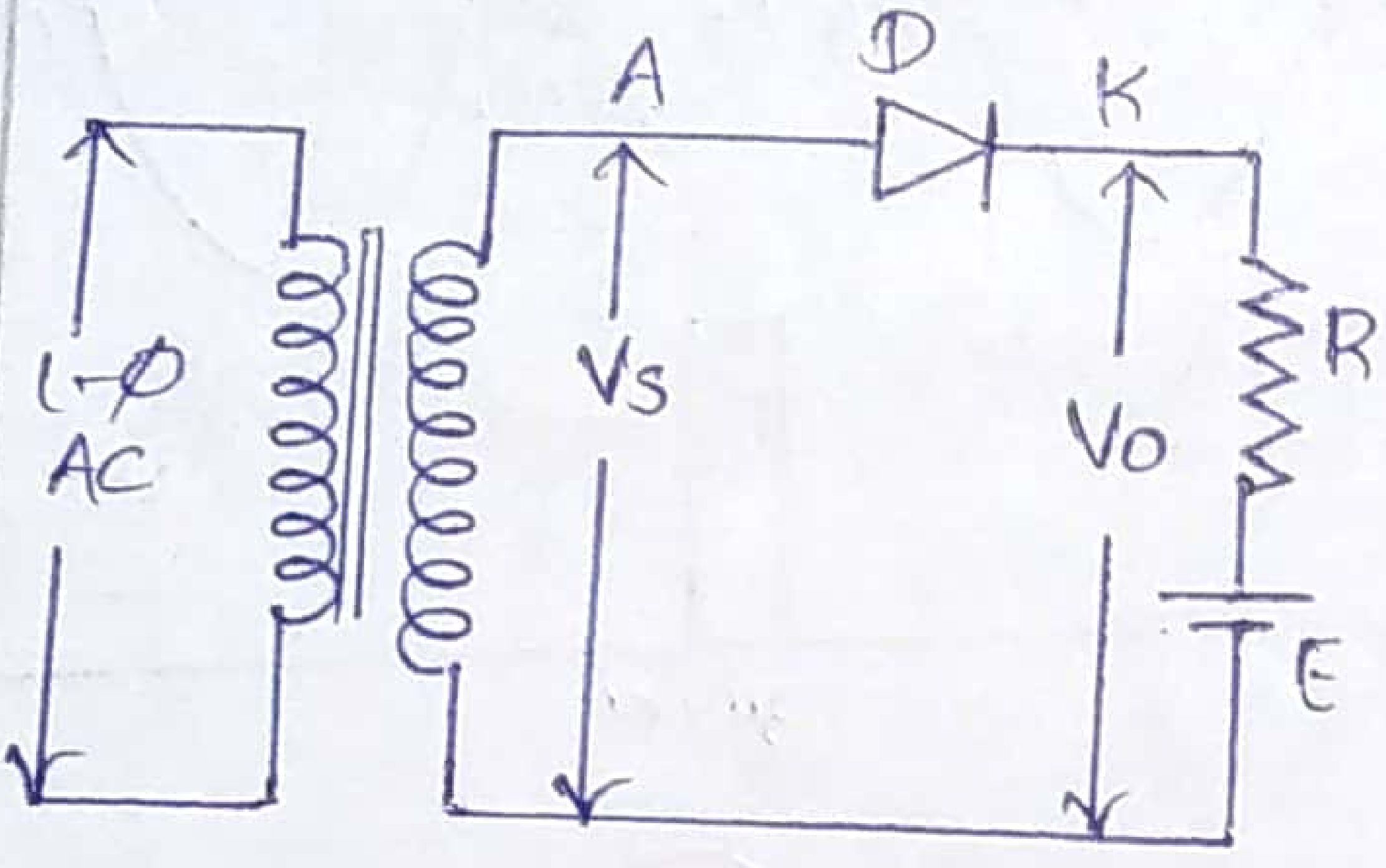
Eqn. (3).

$$\Rightarrow t_c = \frac{2\pi+\theta_1-(\pi-\theta_1)}{\omega} = \frac{\pi+2\theta_1}{\omega} \rightarrow (6)$$

$$\therefore t_c = \frac{\pi+2\theta_1}{\omega} \text{ Sec.} \rightarrow (6)$$

→ Case - ३ :-

→ when Inductance is zero & Diode is ON continuosly :-



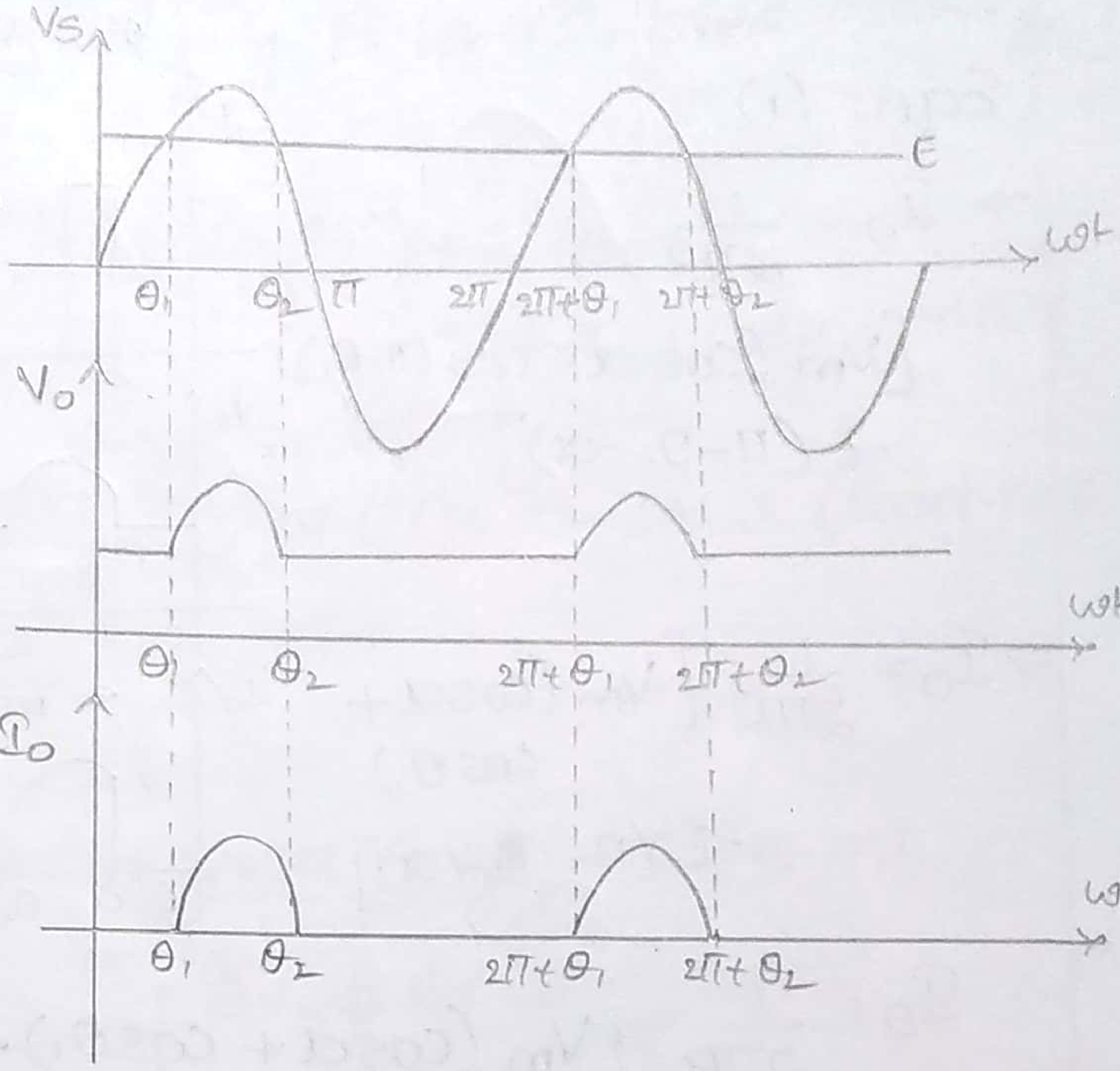


fig:- when L is zero and Thyristor is replaced by Diode.

In this case, $\theta_1 = \alpha$; $\beta = \theta_2$

$\Rightarrow 2\pi + \theta_1 = 2\pi + \alpha$; $2\pi + \beta = 2\pi + \theta_2$.

Eqn (4) :-

$$\Rightarrow I_0 = \frac{1}{2\pi R}\left[V_m(\cos\theta_1 + \cos\theta_1) - E(\pi - (\theta_1 + \theta_1)\right]$$

$$\therefore I_0 = \frac{1}{2\pi R}\left[2V_m\cos\theta_1 - E(\pi - 2\theta_1)\right] \rightarrow (7)$$

Eqn (6) :-

$$\therefore t_c = \frac{\pi + 2\theta_1}{\omega} \text{ sec} \rightarrow (9)$$

Eqn (5) :-

$$\Rightarrow I_{orms} = \left\{\frac{1}{2\pi R^2}\left[(V_s^2 + E^2)(\pi - \theta_1 - \theta_1) + \frac{V_s^2}{2}(\sin 2\theta_1 + \sin 2\theta_1) - 2\sqrt{2}V_sE(\cos\theta_1 + \cos\theta_1)\right]\right\}^{1/2}$$

$$= \left\{\frac{1}{2\pi R^2}\left[(V_s^2 + E^2)(\pi - 2\theta_1) + V_s^2\sin 2\theta_1 - 4\sqrt{2}V_sE\cos\theta_1\right]\right\}^{1/2}$$

→ Problems:-

* 1-ϕ HWR is operated from 120V, 60Hz Supply, if load is Resistive of Value 10Ω and Delay angle $\alpha = \pi/3$. find (i) η. (ii) FF (iii) Ripple factor (iv) TUF (v) PIV.

Sol:- Given, $V_s = 120V \times \sqrt{2} = 169.7V$ $(\because V_m = V_s\sqrt{2})$

$f = 60 Hz$

$R = 10\Omega$

$\alpha = \pi/3 = 60°$.

(i) $\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_o I_o}{V_{orms} \cdot I_{orms}}$

$\Rightarrow V_o = \frac{V_m}{2\pi}(1 + \cos\alpha) = 40.5V$.

$\Rightarrow I_o = \frac{V_o}{R} = \frac{40.5}{10} = 4.05 A$

$\Rightarrow V_{orms} = V_m \left[\frac{\pi - \alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2}$

$= 76.105 V$

$\Rightarrow I_{orms} = \frac{V_{orms}}{R} = \frac{76.105}{10} = 7.61 A$.

$\therefore \eta = \frac{40.5 \times 4.5}{76.1 \times 7.61} = 28.01\%$

(ii) form factor = $\frac{\text{RMS Value}}{\text{Max. Value}} = \frac{76.10}{40.5} = 1.87$.

(iii) Ripple factor = $\sqrt{FF^2 - 1} = \sqrt{1.87^2 - 1} = 1.58$.

(iv) TUF = $\frac{P_{dc}}{V_s \cdot I_s} = \frac{V_o I_o}{V_o I_{orms}} = 0.179$.

(v) PIV = $V_m = 169.7 V$

* 1-ϕ HW Converter is operated from 120V, 50Hz Supply and load R = 10Ω. If the avg. output voltage is 25% of max. possible avg. output voltage. find (i) Delay angle (ii) RMS & Avg. output currents. (iii) Input pf. (iv) RMS and Avg. Thyristor current.

Sol:- Given, $V_S = 120V$,

$f = 50Hz$.

$R = 10\Omega$; $V_m = 120 \times \sqrt{2} = 169.7V$

$V_0 = 25\%$ of V_{omax}.

→ for R-Load:-

$$V_0 = \frac{V_m}{2\pi}(1+\cos\alpha)$$

for $\alpha = 0$; $V_0 = \frac{V_m}{\pi}$; $\alpha = 180°$; $V_0 = 0$.

∴ At $\alpha = 0$, we get max. output voltage.

$$\Rightarrow V_{omax} = \frac{V_m}{2\pi}(1+\cos 0) = \frac{V_m}{2\pi}(2) = \frac{V_m}{\pi}$$

$$= \frac{169.7}{\pi} = 54.01V$$

$$\therefore V_0 = \frac{V_m}{\pi} \leq 25\% \text{ of } V_{max}$$

$$\therefore V_0 = .25 \times 54.01 = 13.5V.$$

(1) $$V_0 = \frac{V_m}{2\pi}(1+\cos\alpha)$$

$$\Rightarrow 13.5 = \frac{169.7}{2\pi}(1+\cos\alpha)$$

$$\therefore \alpha = 120°$$

(2) $$I_0 = \frac{V_0}{R} = \frac{13.5}{10} = 1.35 A.$$

(3). $$I_{orms} = \frac{V_{orms}}{R}.$$

$$\therefore V_{orms} = V_m\left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2}$$

$\Rightarrow V_{orms} = 169.7\left[\frac{\pi - (120\times\frac{\pi}{180})}{4\pi} + \frac{\sin 2(120)}{8\pi}\right]^{1/2}$

$\Rightarrow V_{orms} = 37.51V.$

$\therefore I_{orms} = \frac{37.51}{10} = 3.75A$

(3) $I_{TA} = I_0 = 1.35A$; $I_{rmsT} = I_{orms} = 3.75A$

(4) Input pf $= \frac{V_{orms}}{V_S} = \frac{37.51}{20} = 0.312$ lags.

* Design circuit produce an avg. output voltage of 40V across 100Ω load resistor, from a 120V rms, 60Hz. find power absorbed by Resistor by, pf.

Sol:- Given, Avg. o/p Voltage, $V_o = 40V$.

$R = 100\Omega$; $V_S = 120V \Rightarrow V_m = 169.7V$

Power absorbed, $P_{dc} = V_{orms} \cdot I_{orms}$

$\Rightarrow P_{ac} = V_{orms} \cdot I_{orms}$.

$\Rightarrow V_{orms} = V_m\left[\frac{\pi - a}{4\pi} + \frac{\sin 2a}{8\pi}\right]^{1/2}$

$\therefore V_o = \frac{V_m}{2\pi}(1+\cos a) \Rightarrow \alpha = 61.2°$

$\Rightarrow V_{orms} = 75.62V$; $P_{dc} = 75.62 \times \frac{75.62}{100}$

$\therefore P = 57.1W$

(ii) Input pf $= \frac{V_{orms}}{V_o} = 0.63$ lags

* A 230V, 50Hz, 1-φ one pulse SCR Controlled Converter is triggered at a firing angle of 40° and load current extinguisher at angle of 210°. Find the circuit Turn off Time, Avg. o/p Voltage and avg. load current for

(i) $R = 5\Omega$; $L = 2mH$ (2) $R = 5\Omega$; $L = 2mH$: $E = 110V$.

Sol:- Given, $\alpha = 40°$

$V_S = 230V$, $f = 50Hz$

$\beta = 210°$

(i) $R = 2+3\,\Omega$; $L = 2\,mH$

$$t_c = \frac{2\pi - \beta}{\omega} = \frac{2\pi - \left[210 \times \frac{\pi}{180^\circ}\right]}{2\pi(50)} = 8.33\,ms$$

(ii) $$V_0 = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$

$$= \frac{250 \times \sqrt{2}}{2\pi}\left[\cos 40^\circ - \cos 120^\circ\right] = 484.4\,V$$

(iii) $$I_0 = \frac{V_0}{R} = \frac{84.48}{5} = 16.89\,A.$$

→ RLE load:-

(i) $$t_c = \frac{2\pi + \theta_1 - \beta}{\omega}$$

$$\Rightarrow \theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right) = \sin^{-1}\left[\frac{110}{250\sqrt{2}}\right] : 19.76^\circ$$

$$\Rightarrow t_c = \frac{2\pi + (19.76 - 210) \times \frac{\pi}{180}}{2\pi(50)} = 9.43\,ms$$

(ii) $V_0 = I_0 R + E$

$$\Rightarrow I_0 = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos\beta) - E(\beta - \alpha)\right]$$

$$= \frac{1}{2\pi(5)}\left[250\sqrt{2}(\cos 40 - \cos 210) - 110(210 - 40)\right]$$

$$= 6.506\,A$$

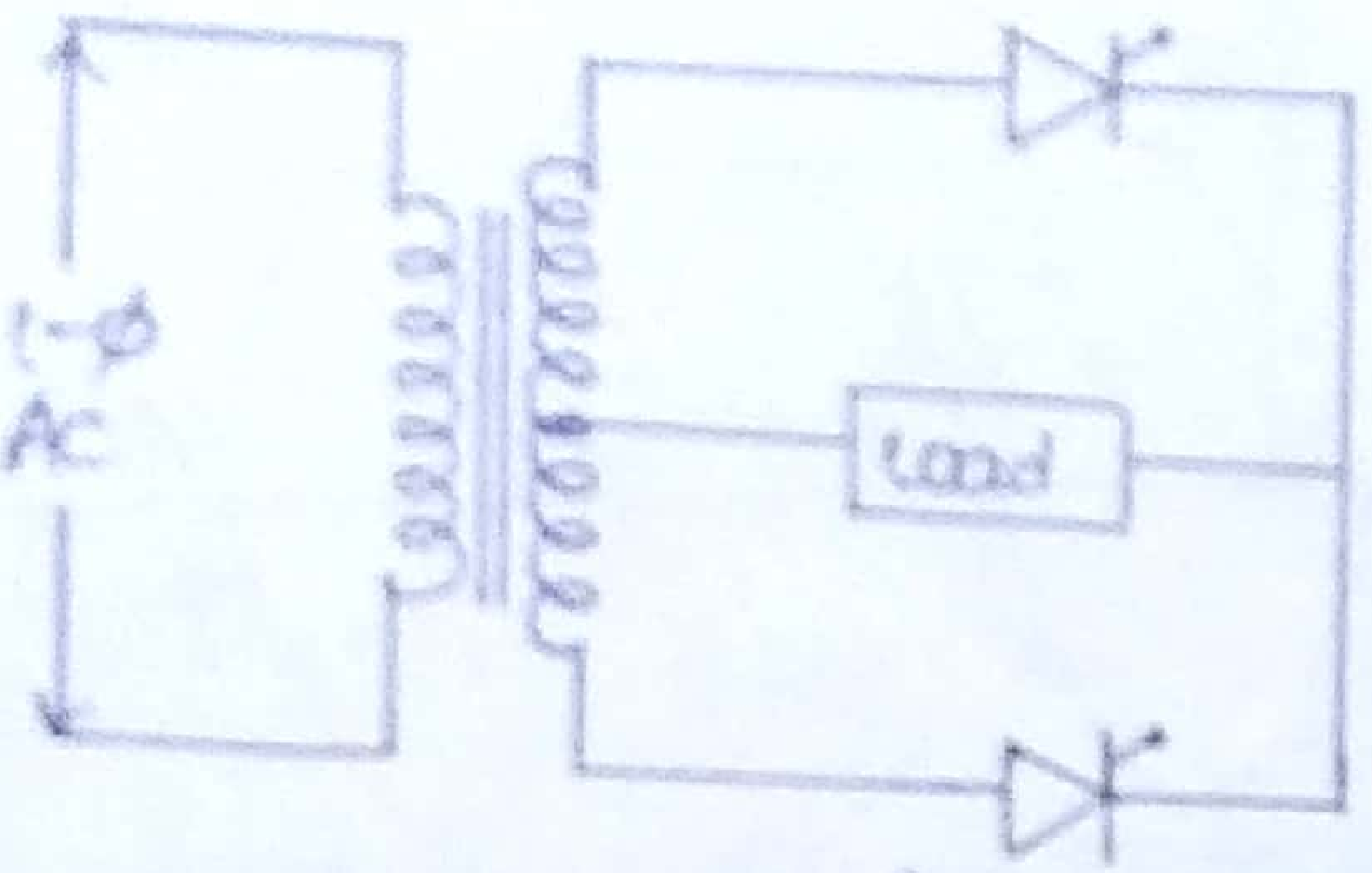
$$\therefore V_0 = (6.506)(5) + 110$$

$$\therefore V_0 = 142.53\,V //$$

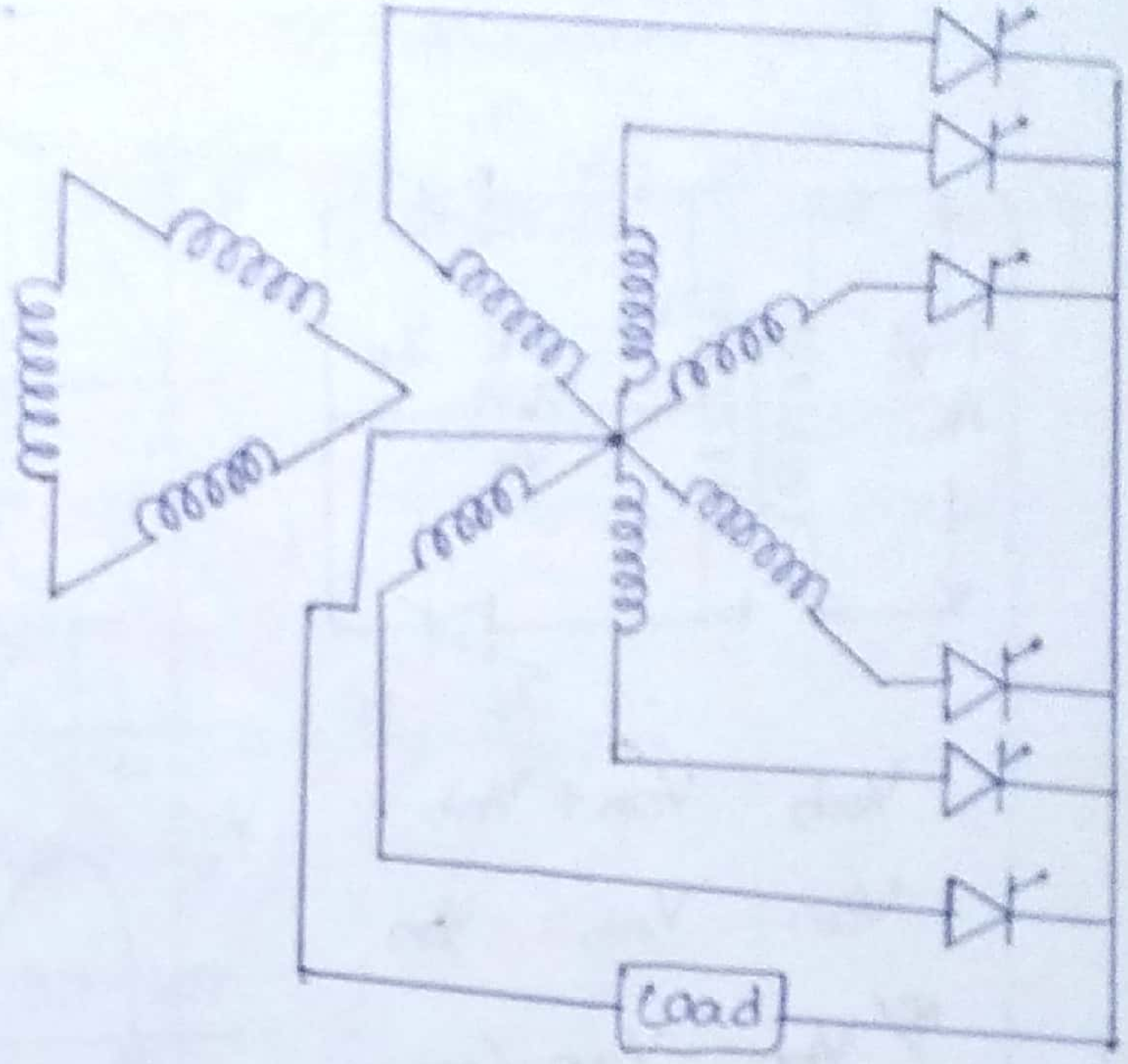
→ 1-ϕ FW controlled converters :-

(1) Mid point configuration.

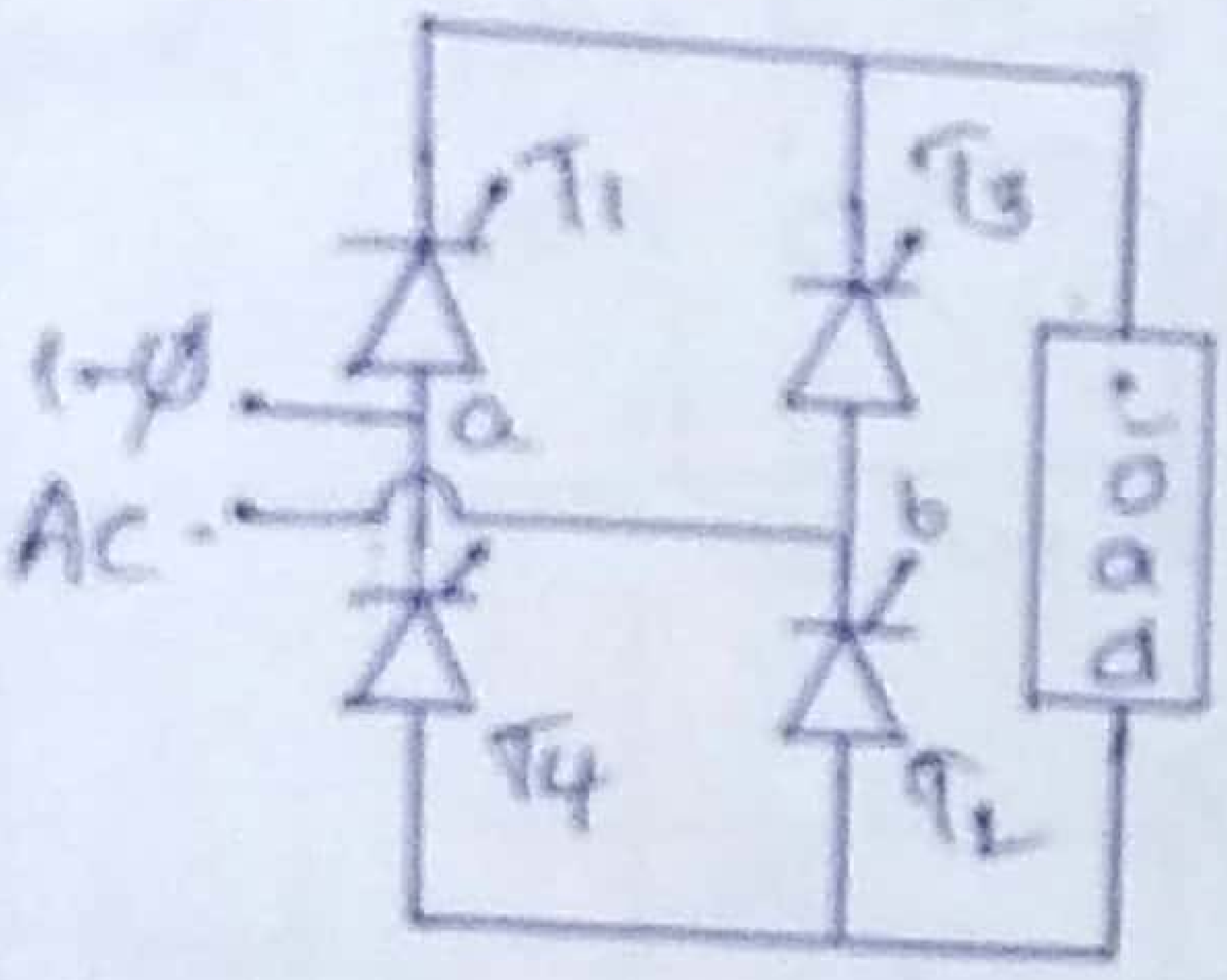
(2) Bridge configuration.



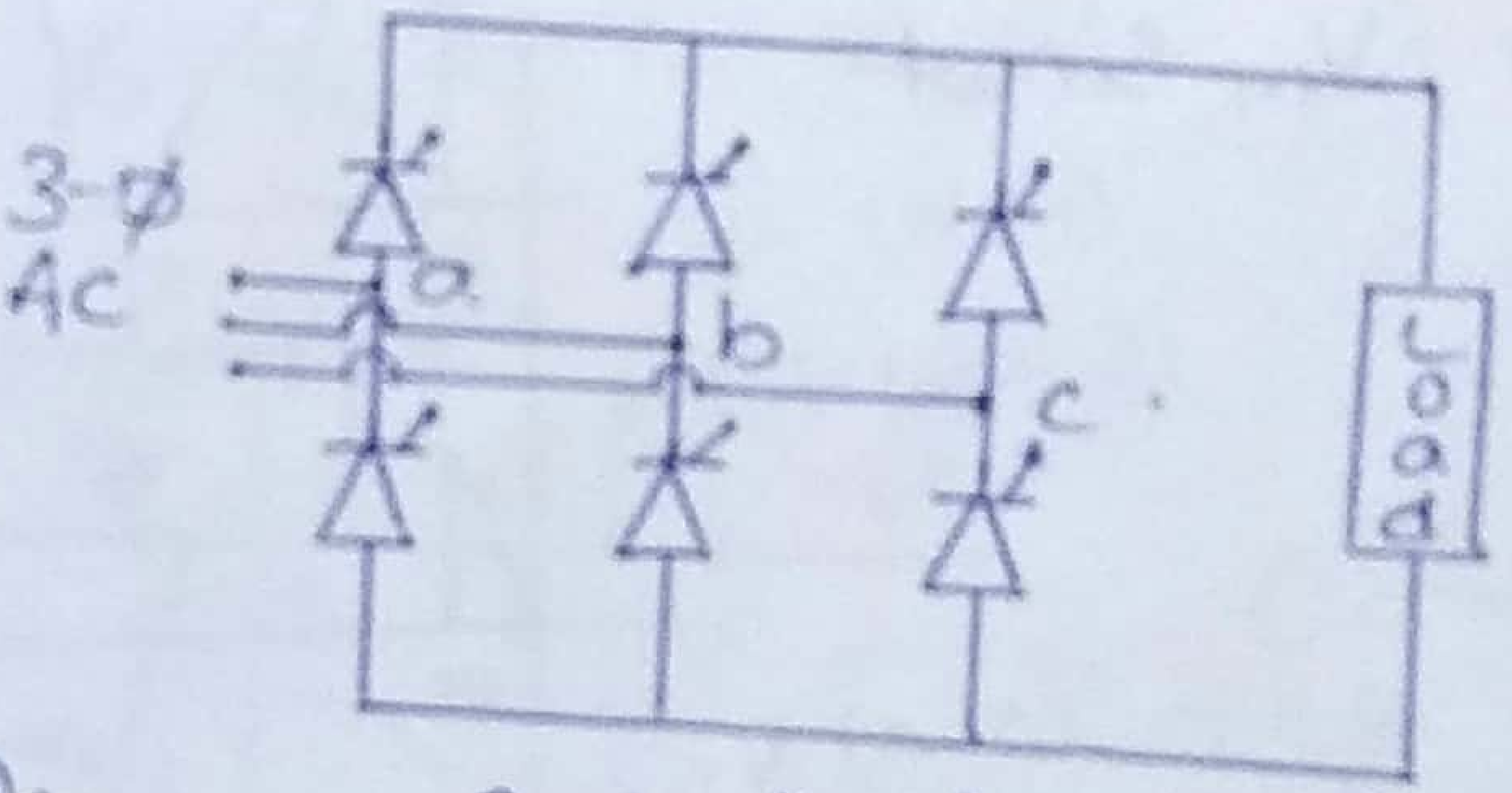
Mid point Configuration.



3-ϕ Mid point Conf



Bridge Configuration.



3-ϕ - Bridge Configuration

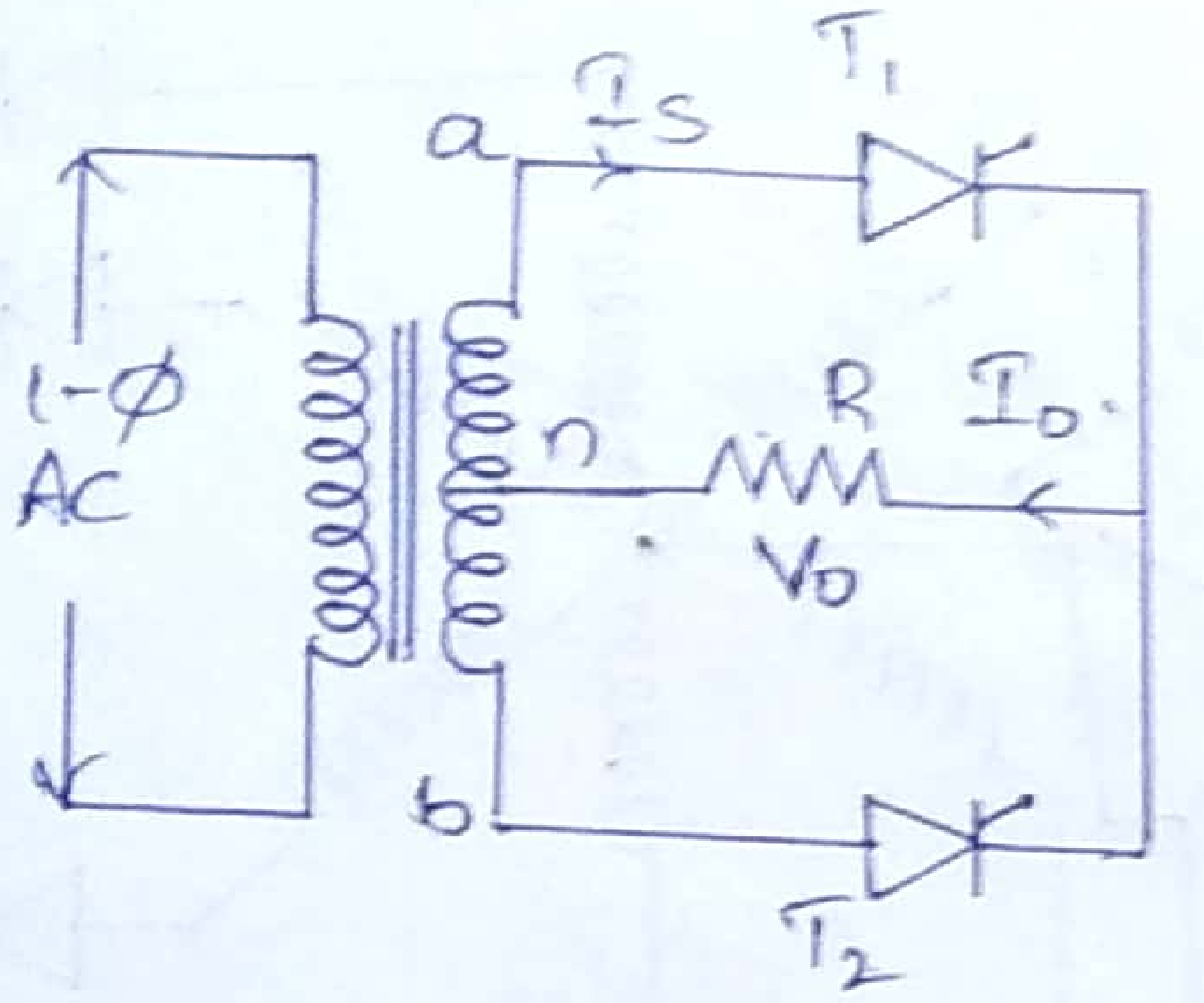
→ A Single phase full wave controlled converter is also known as 2-pulse converter. Since two triggering pulses are to be generated during complete supply cycle inorder to turn on various SCR's.

→ There are two configurations in 1-ϕ FWCC
(1) Mid point configuration.
(2) Bridge Configuration.

→ Mid point configuration uses T/F as input with the centre tapped secondary winding.

→ In Bridge config. SCR's are connected in form of Bridge.

→ $1-\phi$ FWCR with R-Load:-



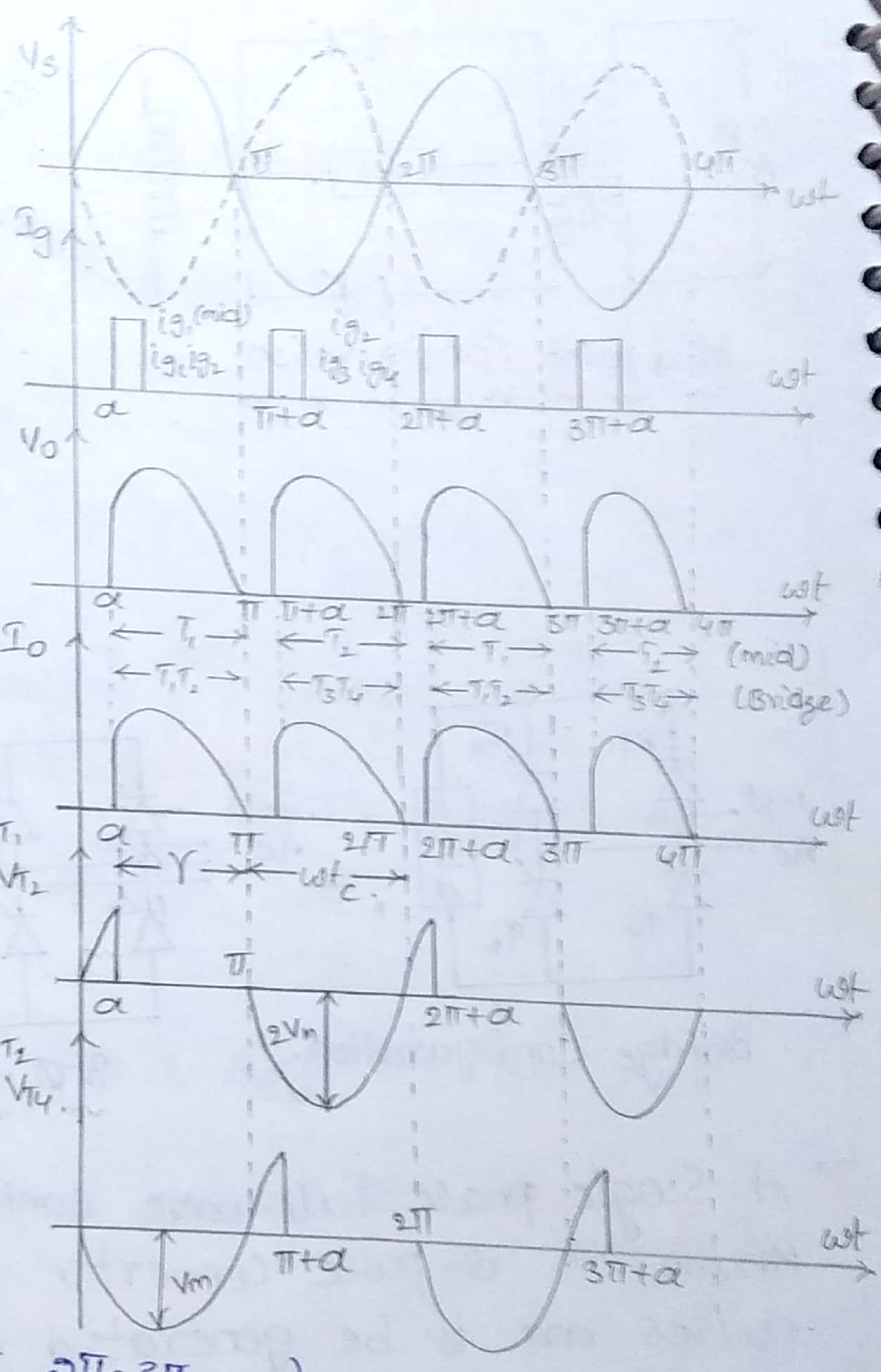
$V_{ab} = V_{an} + V_{nb}$

$V_{an} = V_{nb} = -V_{bn}$

/ $V_{bn} = -V_{an}$ /

→ $V_{an} = V_m \sin\omega t$

→ $V_{bn} = -V_m \sin\omega t$



Operation:-

→ During +HC $(0-\pi, 2\pi-3\pi, \ldots)$

$T_1 \rightarrow FB$; $T_2 \rightarrow RB$.

At $\omega t = \alpha$, $T_1 = ON$; $V_0 = V_{an}$, $I_0 = \frac{V_0}{R}$

At $\omega t = \pi$, $V_s = 0$; $V_0 = 0$; $I_0 = 0$

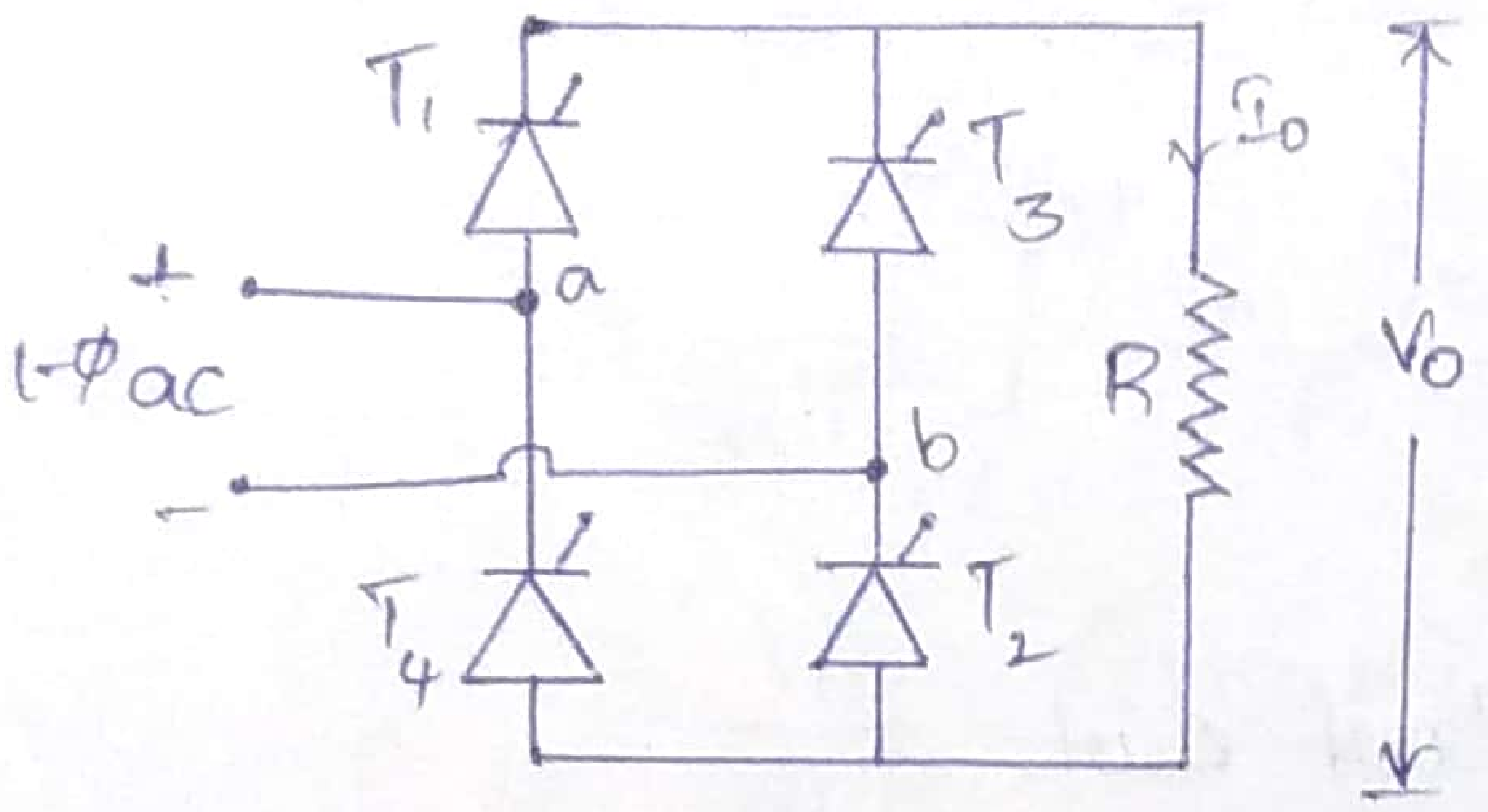
→ During -HC $(\pi-2\pi, 3\pi-4\pi \ldots)$

$T_1 \rightarrow RB$; $T_2 \rightarrow FB$.

At $\omega t = \pi+\alpha$; $T_2 = ON$; $V_0 = V_{bn}$; $I_0 = \frac{V_0}{R}$

At $\omega t = 2\pi$; $V_s = 0$; $V_0 = 0$; $I_0 = 0$.

→ Bridge configuration:-



when 'a' is +ve w.r.t b.

$\Rightarrow V_S = \underset{+\,-}{V_{ab}}$

when 'b' is +ve w.r.to a

$\Rightarrow V_S = V_{ba} = -V_{ab}$

$\therefore V_{ab} = V_m \sin\omega t$

$V_{ba} = -V_m \sin\omega t$.

→ During +Hc (0-π, 2π-3π, ...)

$T_1 T_2 = FB$; $T_3 T_4 = RB$

At $\omega t = \alpha$; $T_1 T_2 = ON$; $V_0 = V_{ab}$; $I_0 = \frac{V_0}{R}$.

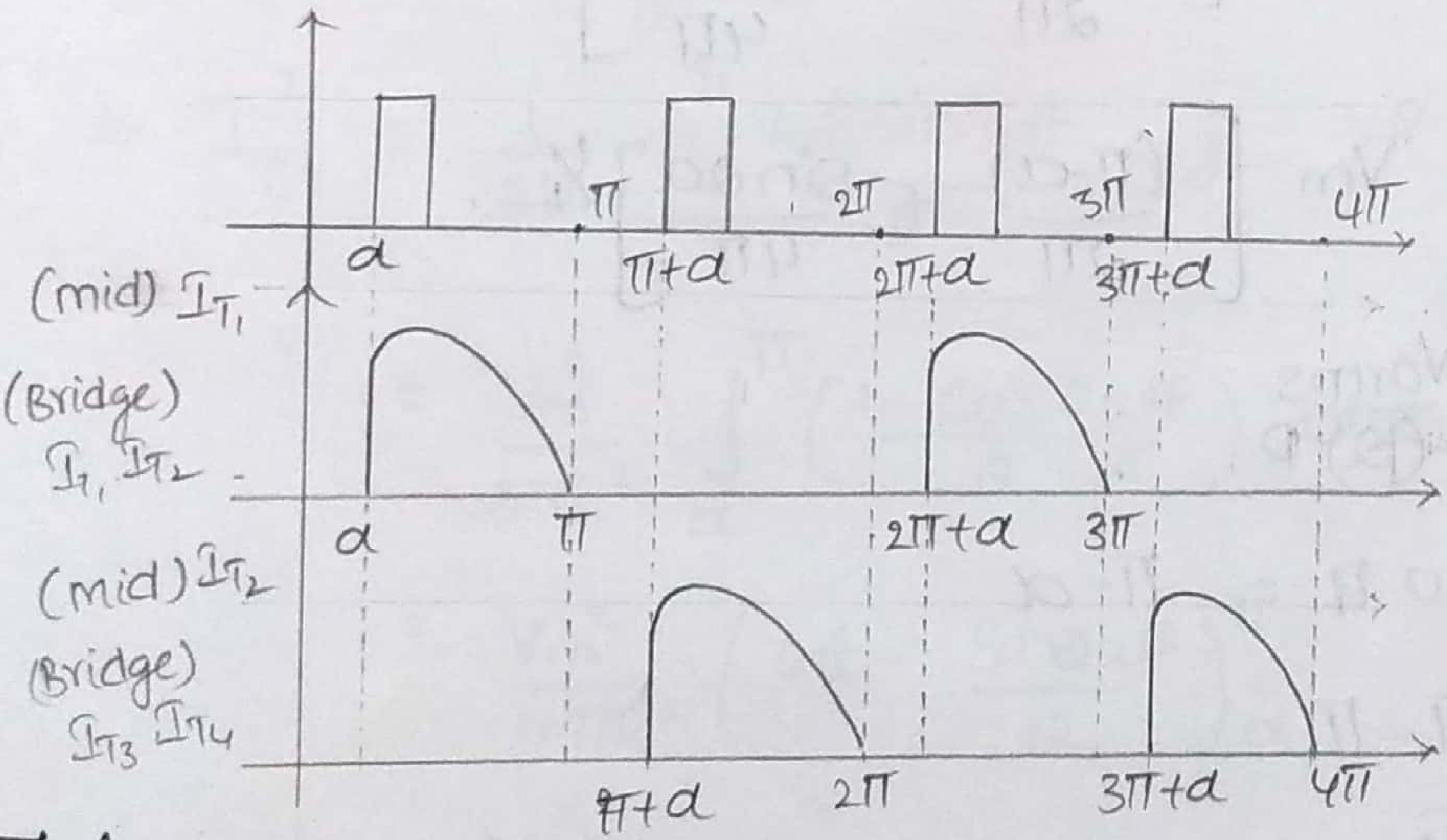
At $\omega t = \pi$; $V_0 = 0$; $V_S = 0$; $I_0 = 0$.

→ During -Hc (π-2π, 3π-4π. ...)

$T_1 T_2 = RB$; $T_3 T_4 = FB$

At $\omega t = \pi + \alpha$; $T_3 T_4 = ON$: $V_0 = V_{ba}$, $I_0 = \frac{V_0}{R}$

$\omega t = 2\pi$, $V_S = 0$; $V_0 = 0$; $I_0 = 0$



(continuation for mid & waveforms) Bridge.

→ Avg. Load Voltage:-

(1) $V_0 = \frac{1}{\pi}\int_0^{\pi} V_0 \cdot d\omega t$

$= \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \cdot d\omega t = \frac{V_m}{\pi}(-\cos\omega t)_{\alpha}^{\pi}$

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

$= \frac{V_m}{\pi}(1 + \cos\alpha)$.

/ $V_0 = \frac{V_m}{\pi}(1 + \cos\alpha)$ /

/. $V_{oHWCR} = \frac{1}{2} V_{oFWCR}$ (

(2) $I_o = \frac{V_o}{R}$. A.

(3) $V_{orms} = \sqrt{\frac{1}{\pi} \int_0^{\pi} v^2 \cdot d\omega t}$

$$\Rightarrow V_{orms}^2 = \frac{1}{\pi} \int_\alpha^{\pi} V_m^2 \sin^2 \omega t \; d\omega t$$

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

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

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

$$= V_m^2 \left[\frac{(\pi-\alpha)}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]$$

$$\therefore V_{orms} = V_m \left[\frac{(\pi-\alpha)}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2}.$$

(4) $I_{orms} = \frac{V_{orms}}{(\cancel{R}) R}$.

(5) $\gamma = \alpha$ to $\pi = \pi - \alpha$

(6) $\omega t_c = 2\pi - \pi$

$\therefore t_c = \frac{\pi}{\omega}$,

(7) $I_s = I_{orms}$.

(8) Input pf $= \frac{P_{ac}}{V_s I_s} = \frac{V_{orms} \cdot I_{orms}}{V_s I_{orms}}$.

$\therefore$ Input pf $= \frac{V_{orms}}{V_s}$,

(9) Avg. Thyristor current.

$$I_{TA} = \frac{1}{2\pi}\int_0^{2\pi} I_T \cdot d\omega t \qquad \left[\because I_T = I_0 = \frac{V_0}{R} = \frac{V_s}{R} = \frac{V_m \sin\omega t}{R}\right]$$

$$= \frac{1}{2\pi}\int_\alpha^\pi \frac{V_m \sin\omega t}{R}\, d\omega t.$$

$$= \frac{V_m}{2\pi R}\left(-\cos\omega t\right)_\alpha^\pi$$

$$= \frac{V_m}{2\pi R}\left(1+\cos\alpha\right)$$

$$= \frac{V_0}{2R}. \qquad \left(\because V_0 = \frac{V_m}{\pi}(1+\cos\alpha) \quad I_0 = \frac{V_0}{R}\right)$$

$$\therefore I_{TA} = \frac{I_0}{2}.$$

(10) RMS Thyristor current:-

$$I_{TR} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_T^2 \cdot d\omega t}.$$

$$\Rightarrow I_{TR}^2 = \frac{1}{2\pi}\int_\alpha^\pi \frac{V_m^2 \sin^2\omega t}{R^2}\cdot d\omega t$$

$$= \frac{V_m^2}{2\pi R^2}\int_\alpha^\pi \left(\frac{1-\cos 2\omega t}{2}\right)\cdot d\omega t.$$

$$= \frac{V_m^2}{4\pi R^2}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_\alpha^\pi$$

$$\Rightarrow I_{TR}^2 = \frac{V_m^2}{4\pi R^2}\left[\pi - \alpha + \frac{\sin 2\alpha}{2}\right]$$

$$= \frac{V_m^2}{2R^2}\left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]$$

$$\Rightarrow I_{TR} = \frac{V_m}{\sqrt{2}R}\left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2}. \qquad \left[\because V_{orms} = V_m\left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2} \quad I_{orms} = \frac{V_{orms}}{R}\right]$$

$$\therefore I_{TR} = \frac{I_{orms}}{\sqrt{2}}$$

(ii) Peak Inverse Voltage:-

PIV = $2V_m$ for mid point configuration.

PIV = V_m for Bridge configuration

for mid point Configuration:-

$V_{ab} = V_{an} + V_{nb}$.

$\Rightarrow V_{ab} = V_m \sin\omega t + V_m \sin\omega t$.

$\Rightarrow V_{ab} = 2V_m \sin\omega t$.

when T_1- conducts

$V_{T_2} - V_{T_1} + V_{ab} = 0$. $(\because V_{T_1} = 0)$

$\Rightarrow V_{T_2} = -V_{ab} = -2V_m \sin\omega t$.

$|V_{T_2}|_{max} = 2V_m$ //.

when T_2- Conducts:-

$V_{T_2} + (-V_{T_1}) - V_{ab} = 0$

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

$(\because V_{T_2} = 0)$

$\Rightarrow |V_{T_1 max}| = 2V_m$.

for Bridge Configuration:-

when $T_1 T_2$ conducts:-

$-V_{T_4} + V_{T_2} - V_{ab} = 0$.

$(\because V_{T_2} = 0)$

$\Rightarrow V_{T_4} = -V_{ab} = -V_m \sin\omega t$.

$\Rightarrow -V_{T_1} + V_{ab} + V_{T_3} = 0$. $(\because V_{T_1} = 0)$

$\Rightarrow V_{T_3} = -V_{ab} = -V_m \sin\omega t$

$V_{T_3} = V_{T_4} = -V_m \sin\omega t$

$|V_{T_3}|_{max} = |V_{T_4}|_{max} = |-V_m \sin\omega t|$

$\therefore |V_{T_3}|_{max} = |V_{T_4}|_{max} = V_m$ //

→ 1-∅ FWCR with RL-Load:-

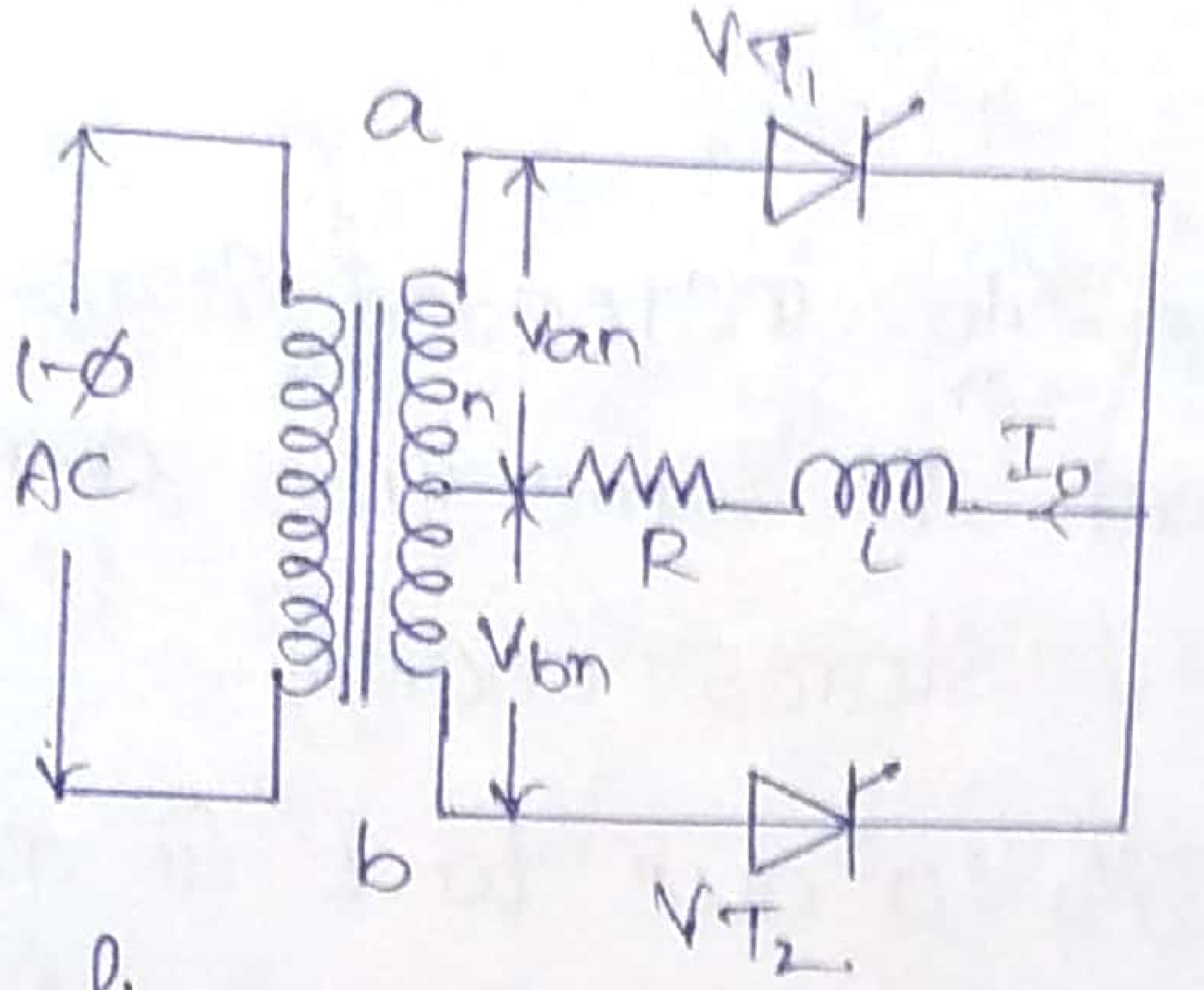
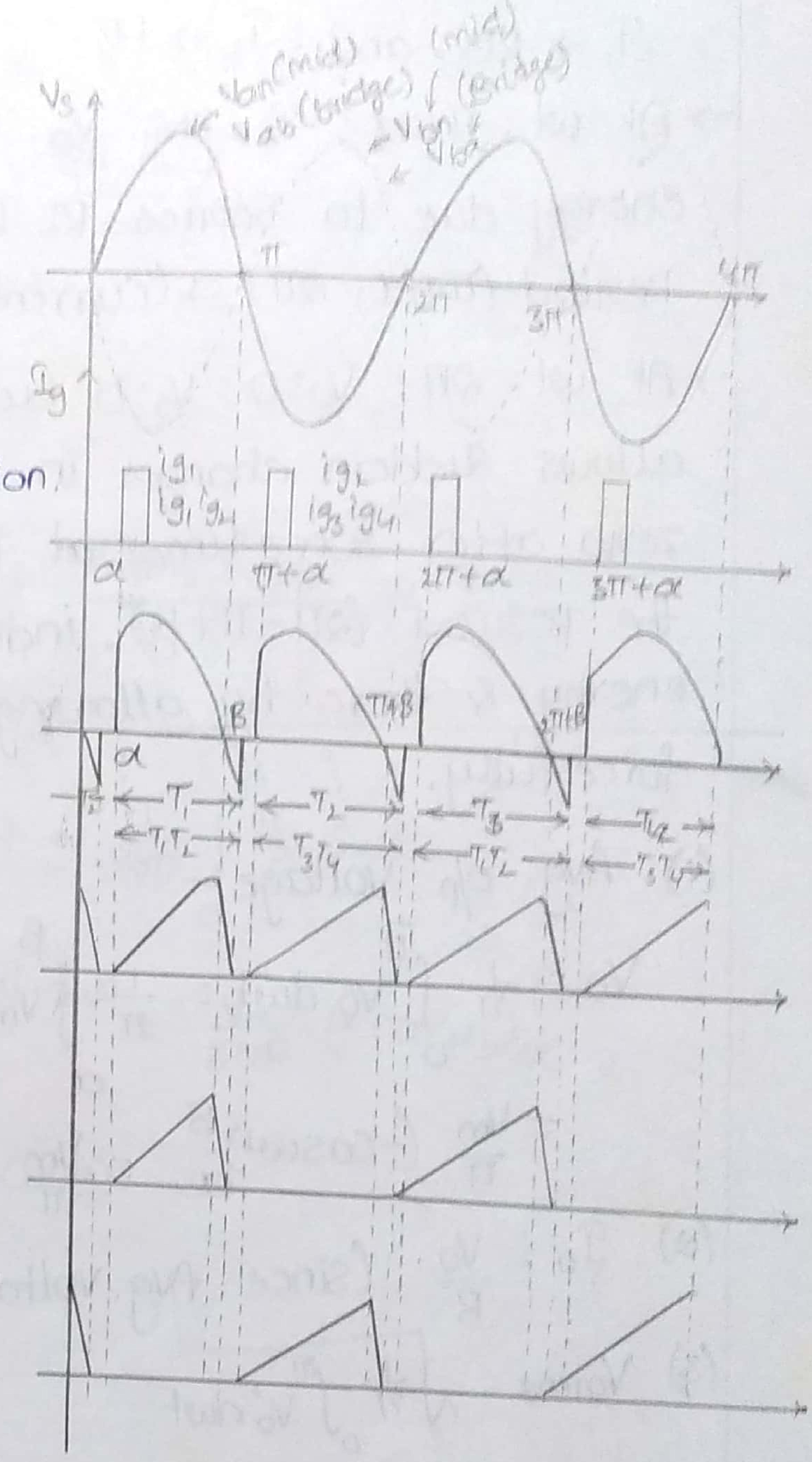


fig:- Mid point configuration.



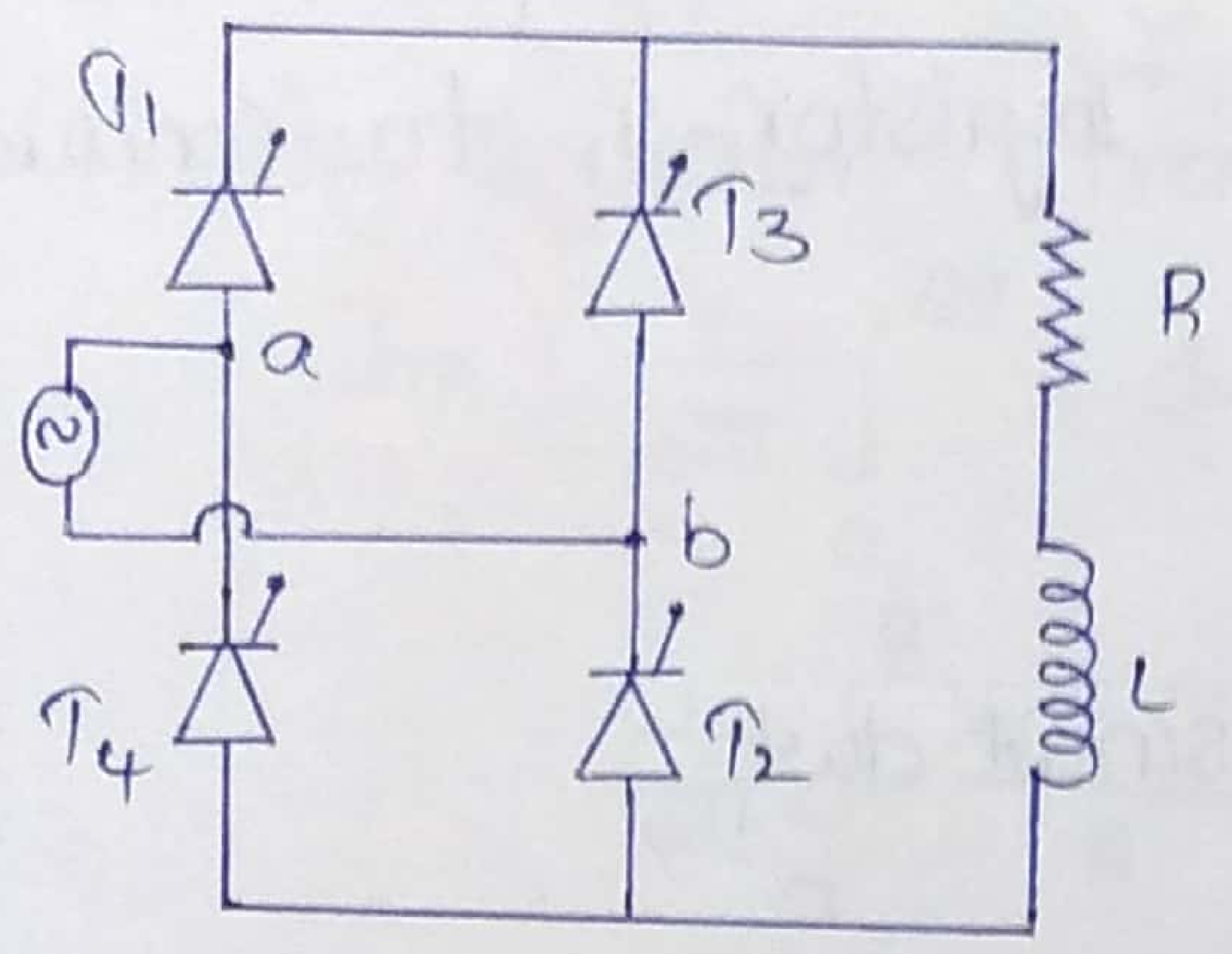


fig :- Bridge configuration.

→ operation:-

(a) mid point:-

→ During positive halfcycle (0-π, 2π-3π, ----)

$T_1 \rightarrow FB$; $T_2 \rightarrow RB$.

At $\omega t = \alpha$; $T_1 = ON$; $V_o = V_{an}$; $I_o = \frac{V_o}{R}$ due to RL Load (serie

At Same time during period (α-π) - L starts charging.

At $\omega t = \pi$; $V_s = 0$; $V_o = 0$; $I_o \neq 0$; due to L is doesn't allows sudden changes in current, but I_o falls to zero, after some time at instant $\omega t = \beta$, i.e., During period π-β inductor L dissipates its stored energy & there by allowing thyristor T_1 conducts forcefully.

→ During Negative HC (π-2π, 3π-4π....):

$T_1 \rightarrow$ RB and $T_2 \rightarrow$ FB.

→ At $\omega t = \pi + \alpha$; T_2 = ON; $V_0 = V_{on}$; I_0 = increased stored energy due to series RL Load. At Same time, during period ($\pi+\alpha$ - 2π) → (current) L stores energy.

→ At $\omega t = 2\pi$; $V_0 = 0$; $V_s = 0$ but $I_0 \neq 0$ due to L (it doesn't allows sudden changes in current) but I_0 falls to zero after some time at instant $\omega t = \pi + \beta$ i.e, during the period ($2\pi - \pi + \beta$), inductor L- dissipates its stored energy & there by allowing Thyristor-T_2 to conduct forcefully.

(1) Avg. o/p voltage:-

$$V_0 = \frac{1}{\pi}\int_0^{\pi} V_0 \cdot d\omega t = \frac{1}{\pi}\int_{\alpha}^{\beta} V_m \sin\omega t \cdot d\omega t$$

$$= \frac{V_m}{\pi}\left(-\cos\omega t\right)_{\alpha}^{\beta} = \frac{V_m}{\pi}\left(\cos\alpha - \cos\beta\right) //.$$

(2) $I_0 = \frac{V_0}{R}$ [Since Avg. voltage across L- is zero].

(3) $V_{orms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} V_0^2 \, d\omega t}$.

$$\Rightarrow V_{orms}^2 = \frac{1}{\pi}\int_{\alpha}^{\beta} V_m^2 \sin^2\omega t \cdot d\omega t$$

$$= \frac{V_m^2}{\pi}\int_{\alpha}^{\beta} \frac{1-\cos2\omega t}{2} \cdot d\omega t = \frac{V_m^2}{2\pi}\left[\omega t - \frac{\sin2\omega t}{2}\right]_{\alpha}^{\beta}$$

$$= \frac{V_m^2}{2\pi}\left[\left(\beta - \frac{\sin2\beta}{2}\right) - \left(\alpha - \frac{\sin2\alpha}{2}\right)\right]$$

$$= \frac{V_m^2}{2\pi}\left[(\beta-\alpha)\left(\frac{\sin2\alpha + \sin2\beta}{2}\right)\right]$$

$$*/ \; V_{orms} = V_m\left[\frac{(\beta-\alpha)}{2\pi} + \frac{(\sin2\alpha - \sin2\beta)}{4\pi}\right]^{1/2} \; /*$$

(4) $I_{orms} = \frac{V_{orms}}{R}.$

(5) $\gamma = \beta - \alpha.$

(6) $\omega t_c = 2\pi - \beta \Rightarrow$ */ $t_c = \frac{2\pi - \beta}{\omega}$ /*

(7) $PIV = 2V_m \Rightarrow$ Mid point.

$PIV = V_m \Rightarrow$ Bridge.

(8) $I_s = I_{orms}$

(9) Input pf $= \frac{P_{ac}}{VA\ rating} = \frac{V_{orms} I_{orms}}{V_s I_s} = \frac{V_{orms}}{V_s}.$

(10) Avg. Thyristor current:-

$$I_{TA} = \frac{1}{2\pi}\int_0^{2\pi} I_T . d\omega t = \frac{1}{2\pi}\int_\alpha^\beta \frac{V_o}{R} . d\omega t$$

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

$$= \frac{V_m}{2\pi R}(\cos\alpha - \cos\beta)$$

$$= \frac{V_o}{2R} = \frac{I_o}{2}.$$

$$\therefore I_{TA} = \frac{I_o}{2}$$

(11) RMS Thyristor current:-

$$I_{TR} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_T . d\omega t}.$$

$$\Rightarrow I_{TR}^2 = \frac{1}{2\pi}\int_\alpha^\beta \frac{V_m^2 \sin^2\omega t}{R^2} . d\omega t \quad \left[I_T = I_o = \frac{V_o}{R} = \frac{V_m \sin\omega t}{R}\right]$$

/ $I_{TR} = \frac{I_{orms}}{\sqrt{2}}.$ /

(ii) 1-φ FWCR with RL load continuous current wave form

→ By increasing the value of inductance in load circuit, β increases at one stage β becomes greater than or equal to π+α (i.e, $\beta \geq \pi+\alpha$), we will get continuous current mode operation.

→ for discontinuous current mode of operation

/ $\beta < \pi+\alpha$; $\gamma < \pi$ /

→ for continuous current, mode of operation;

/ $\beta \geq \pi+\alpha$; $\gamma = \pi$ /

(1) $V_o = \frac{V_m}{\pi}(-\cos\beta+\cos\alpha)$

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

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

(2) $I_o = \frac{V_o}{R}$.

(3) V_{orms}

$= V_m\left[\frac{\beta-\alpha}{2\pi} + \frac{\sin2\alpha - \sin2\beta}{4\pi}\right]^{1/2}$

$= V_m\left[\frac{\pi+\alpha-\alpha}{2\pi} + \frac{\sin2\alpha - \sin2(\pi+\alpha)}{4\pi}\right]^{1/2}$

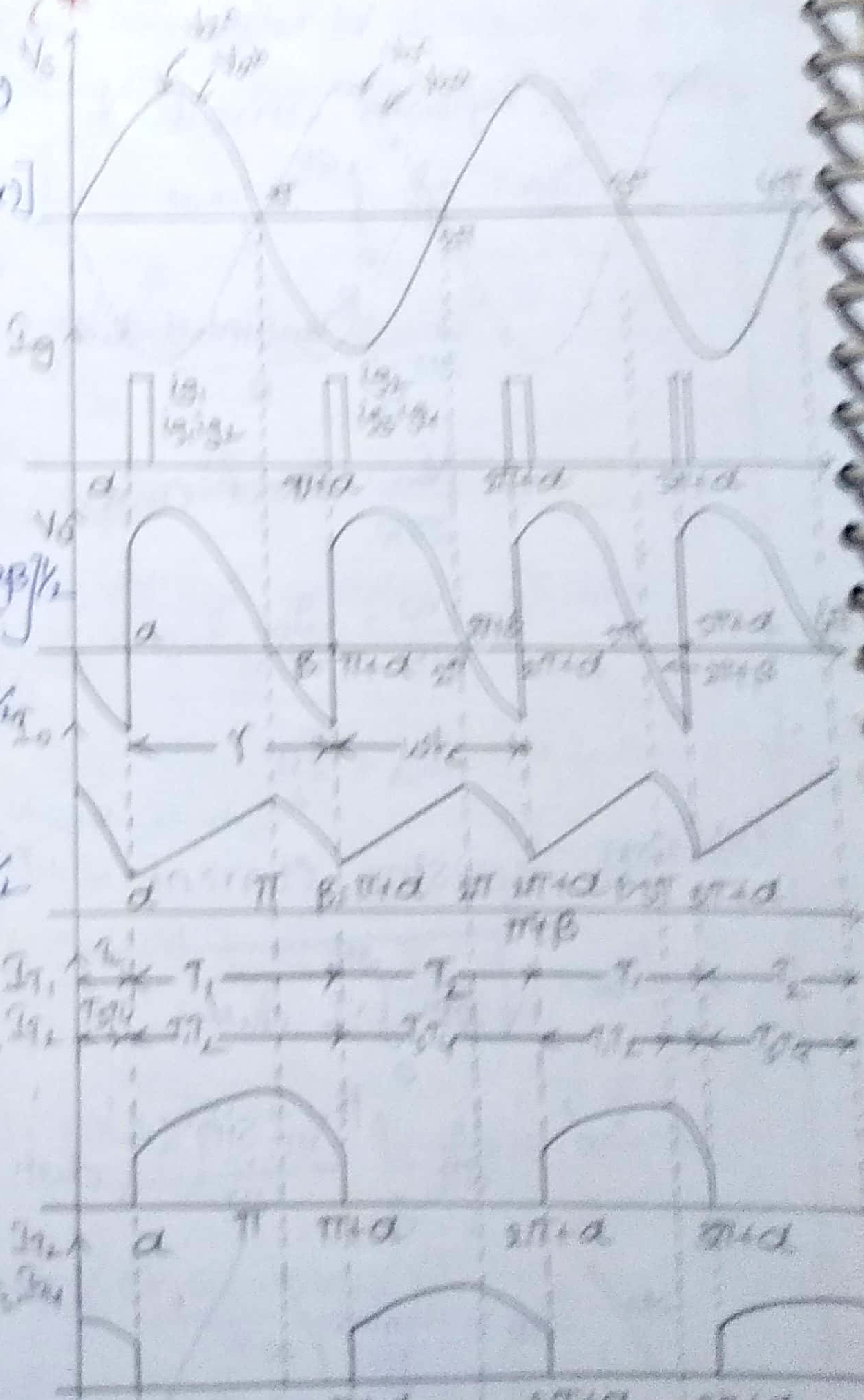
$= V_m\left[\frac{\pi}{2\pi} + \frac{\sin2\alpha - \sin2\alpha}{4\pi}\right]^{1/2}$

$= V_m\left[\frac{1}{2}\right]^{1/2}$

$= \frac{V_m}{\sqrt{2}} = V_s$

$V_{orms} = V_s$

(4) $I_o = \frac{V_{orms}}{R}$



(5) $\gamma = \beta - \alpha.$

$= \pi + \alpha - \alpha = \pi.$

(6) $\omega t_c = 2\pi - \beta$

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

(7) PIV $= 2V_m$ for midpoint.

PIV $= V_m$ for Bridge.

(8) $I_s = I_{orms}.$

(9) Input pf $= \frac{V_{orms}}{V_{0s}}.$

(10) $I_{TA} = \frac{I_o}{2}.$

(11) $I_{TR} = \frac{I\cancel{V}_{orms}}{\sqrt{2}}$ [for $\beta > \pi + \alpha$; $\gamma = \pi$]

(iii) 1-ϕ FWCR RL Load for High Value of L (Continuous current waveforms):-

→ for High Value of L in the load circuit, we will get Ripple free load current. (i.e., Constant)

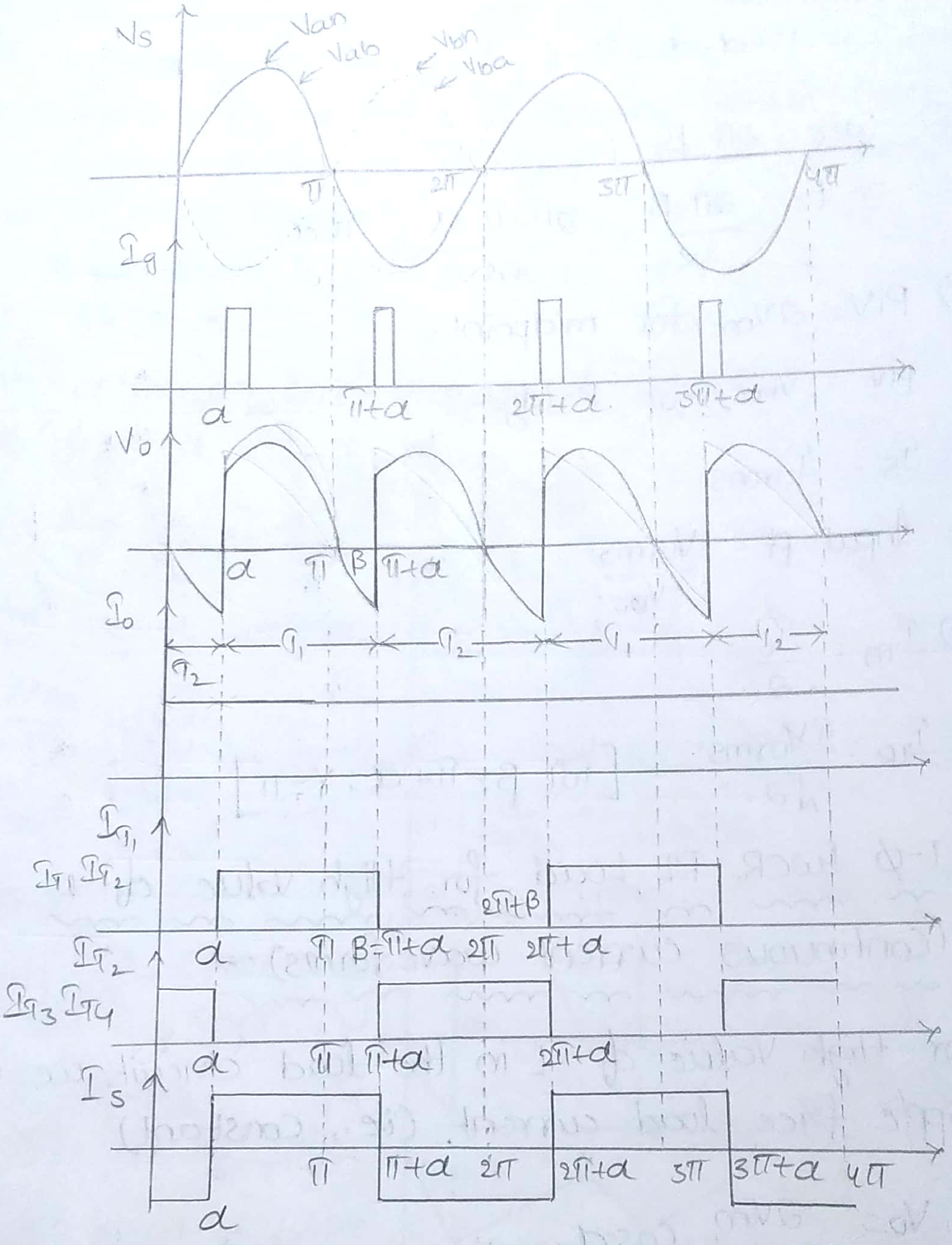
(1) $V_o = \frac{2V_m}{\pi} \cos\alpha.$

(2) $I_o = \frac{V_o}{R}.$

(3) $V_{orms} = \frac{V_m}{\sqrt{2}}$

i.e., $V_{orms} = V_s$

(4) $I_{orms} = \frac{V_{orms}}{R}$



(5) $\gamma = \pi$ (6) $\omega t_c = \pi - \alpha \Rightarrow t_c = \frac{\pi - \alpha}{\omega}$ $\left(\begin{matrix} T_1 \xrightarrow{ON} I_S = I_0 \\ T_2 \rightarrow I_S = -I_0 \end{matrix}\right]$

(~~8~~7) $I_S = I_{orms} = I_0$

$$\Rightarrow I_S = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_s^2 \cdot d\omega t} = \frac{1}{2\pi}\left[\int_\alpha^{\pi+\alpha} I_0^2 d\omega t + \int_{\pi+\alpha}^{2\pi+\alpha} (-I_0)^2 \cdot d\omega t\right]$$

$$= \frac{1}{2\pi}\left[I_0^2(\pi) + I_0^2(\pi)\right] = I_0^2$$

$\therefore I_S = I_0.$

(8) $I_{TA} = \frac{1}{2\pi}\int_0^{2\pi} i_T \, d\omega t = \frac{1}{2\pi}\int_\alpha^{\pi+\alpha} I_0 \, d\omega t = \frac{I_0}{2}$

(9) $I_{TR} = \sqrt{\frac{1}{2\pi}\int_{0}^{2\pi} I_T^2 d\omega t} = \frac{1}{2\pi}\int_{\alpha}^{\pi+\alpha} I_0^2 d\omega t = \frac{I_0}{\sqrt{2}}$.

$\therefore I_{TR} = \frac{I_0}{\sqrt{2}}$.

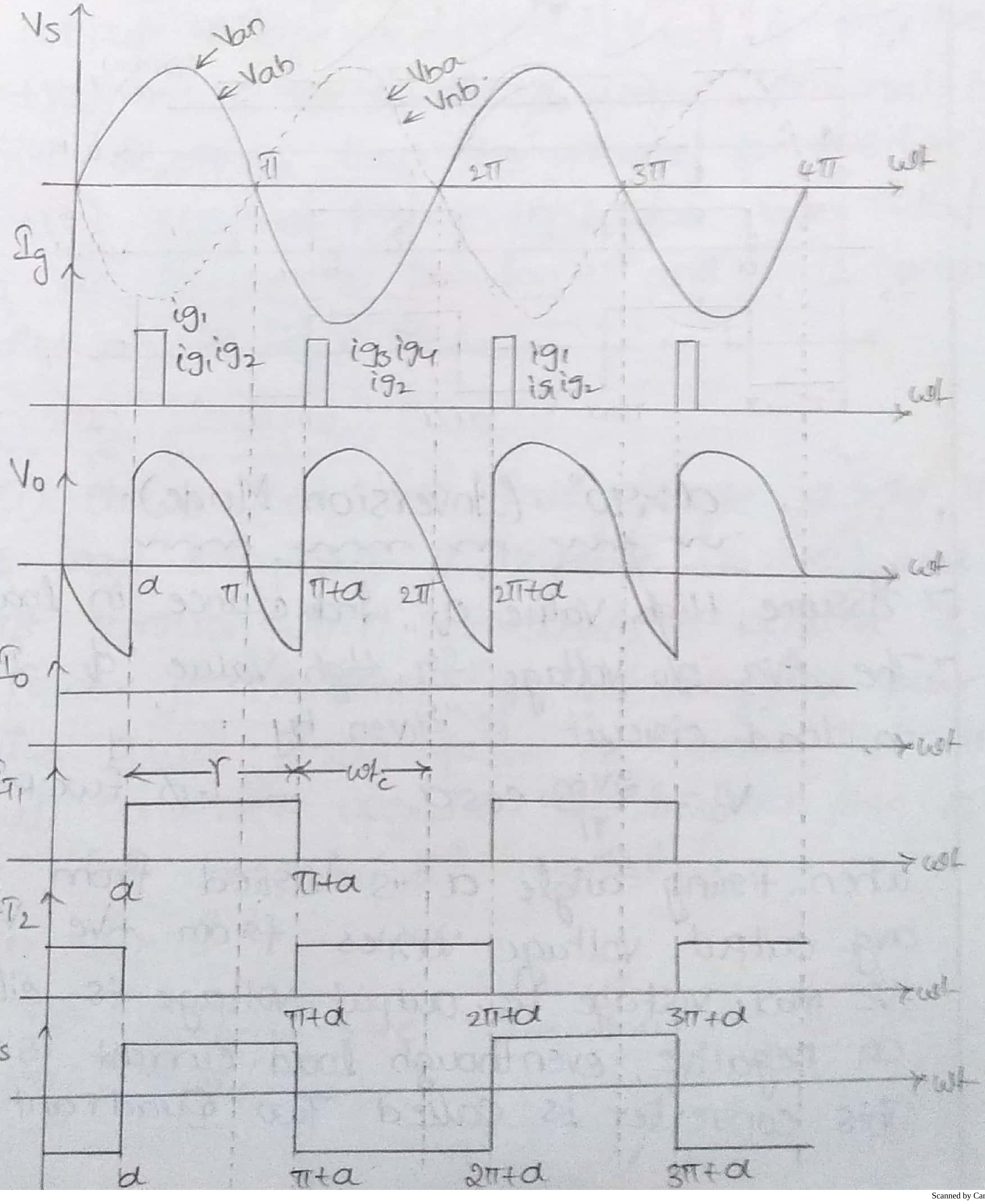
(10) Input pf = $\frac{V_{orms} \cdot I_{orms}}{V_s I_s} = \frac{V_0 I_0}{V_s I_0} = \frac{V_0}{V_s}$.

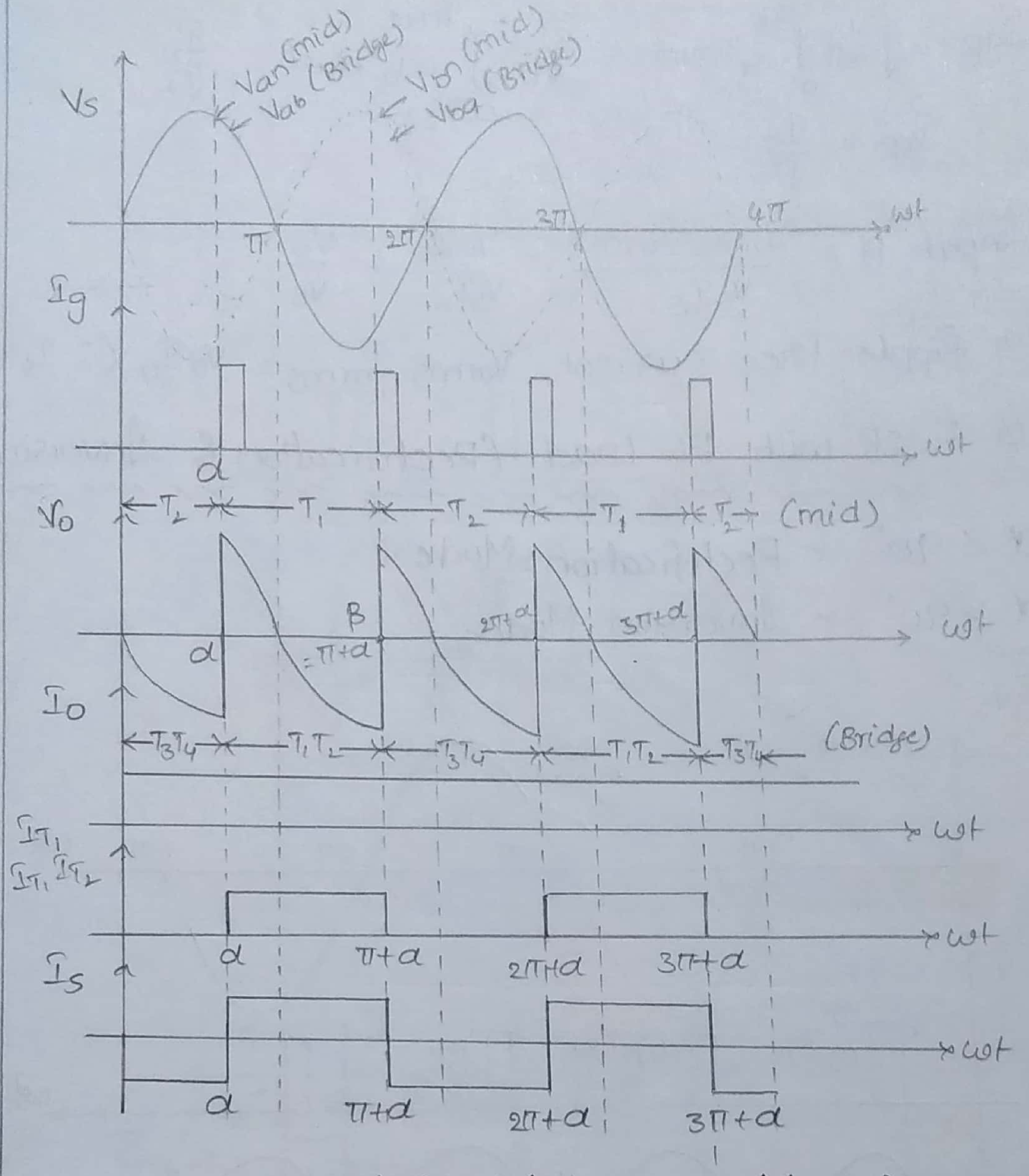
[for Ripple free current, $V_{orms} \cdot I_{orms} = V_0 I_0$ ($\because I_s = I_0$)]

(IV) 1-ϕ FWCR with RL Load (Rectification & Inversion):-

(1) α < 90° → Rectification Mode

(2) α > 90° → Inversion Mode





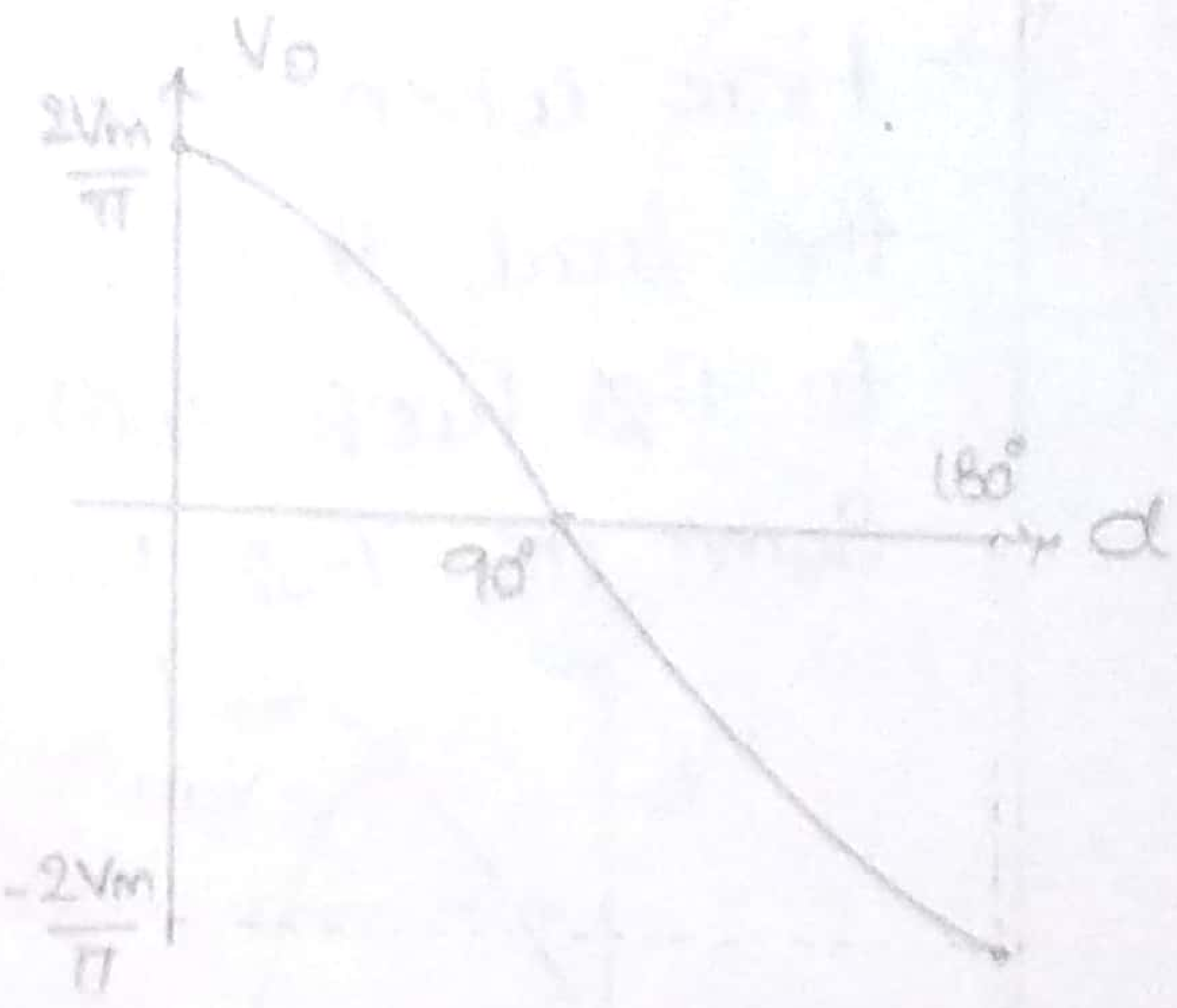
$\alpha > 90°$ (Inversion Mode).

- Assume, High value of Inductance in load circuit.
- The Avg. o/p Voltage for High value of Inductance in load circuit is given by,

$$V_0 = \frac{2V_m}{\pi} \cos\alpha \quad \text{in } 1\text{-}\phi \text{ FWCR}$$

- when firing angle α is varied from 0-180°, the avg. output voltage varies from +ve Vmax to -ve max. voltage i.e., output voltage is either positive or negative, eventhough load current is unidirectional. This converter is called Two Quadrant converter.

→ Rectification Mode:-



→ $V_o = \frac{2V_m}{\pi}\cos\alpha$ →(1)

when $\alpha = 0$, $V_o = +\frac{2V_m}{\pi}$

$\alpha = 90°$, $V_o = 0$.

$\alpha = 180°$, $V_o = -\frac{2V_m}{\pi}$.

when $\alpha < 90°$

$\left.\begin{matrix} V_o = +Ve \\ I_o = -Ve \end{matrix}\right\}$ $P_o = +Ve$
i.e., AC - DC (Rectification Mode).

→ Eqn. (1) shows that, for firing angle $\alpha < 90°$, the avg. output voltage across the load is positive ($V_o = +Ve$) and current through load terminals is positive ($I_o = +Ve$) then the power is positive. ($P_o = +Ve$). positive power indicates power flows from ac source to DC load and full converter operates at Rectifier mode.

→ Inversion Mode:-

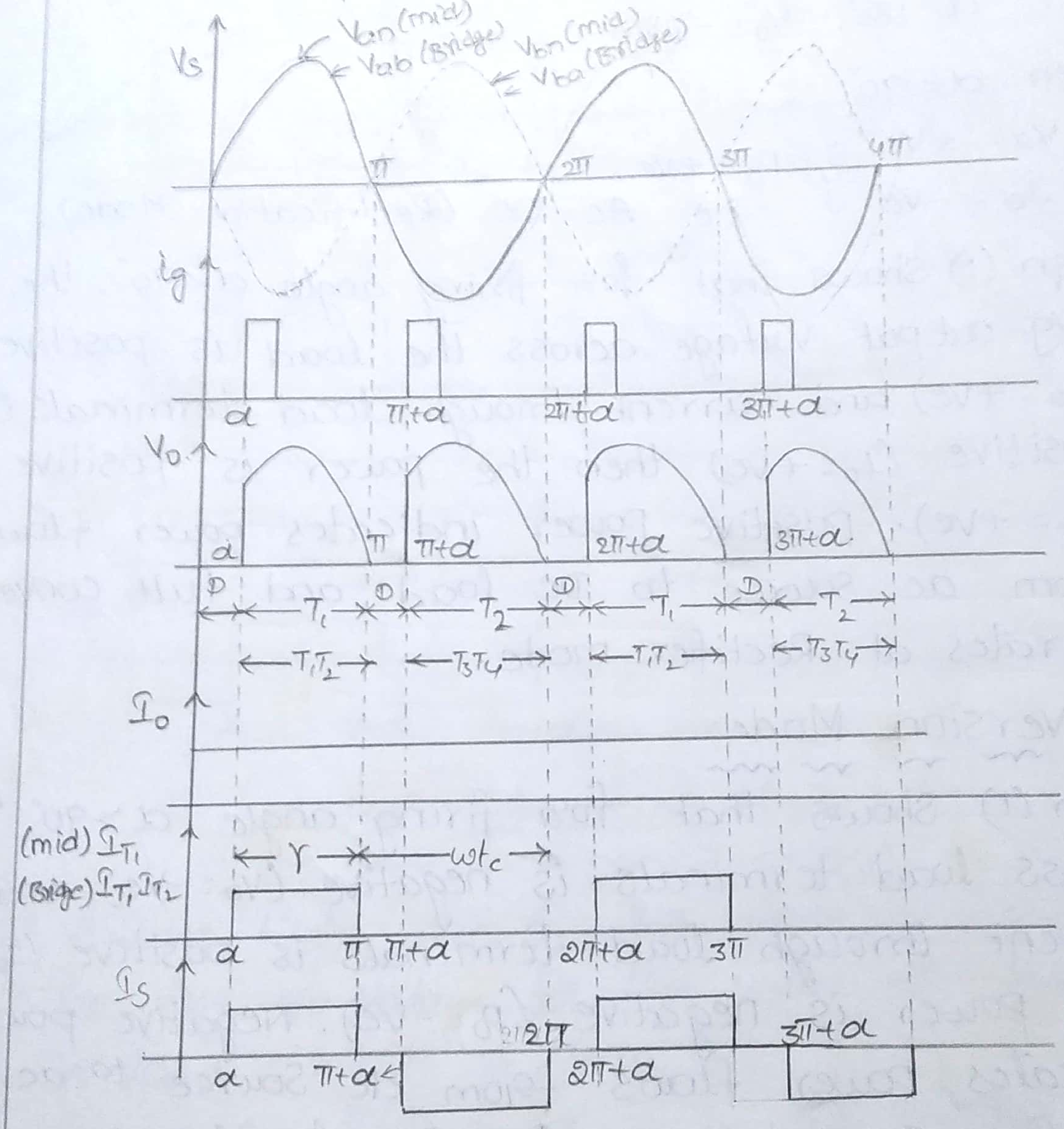
→ Eqn (1) shows that for firing angle $\alpha > 90°$, V across load terminals is negative ($V_o = -Ve$) and current through load terminals is positive ($I_o = +Ve$) then power is negative ($P_o = -Ve$). Negative power indicates power flows from dc source to ac load and full converter operates as Inverter, this is called Line Commutated Inverter.

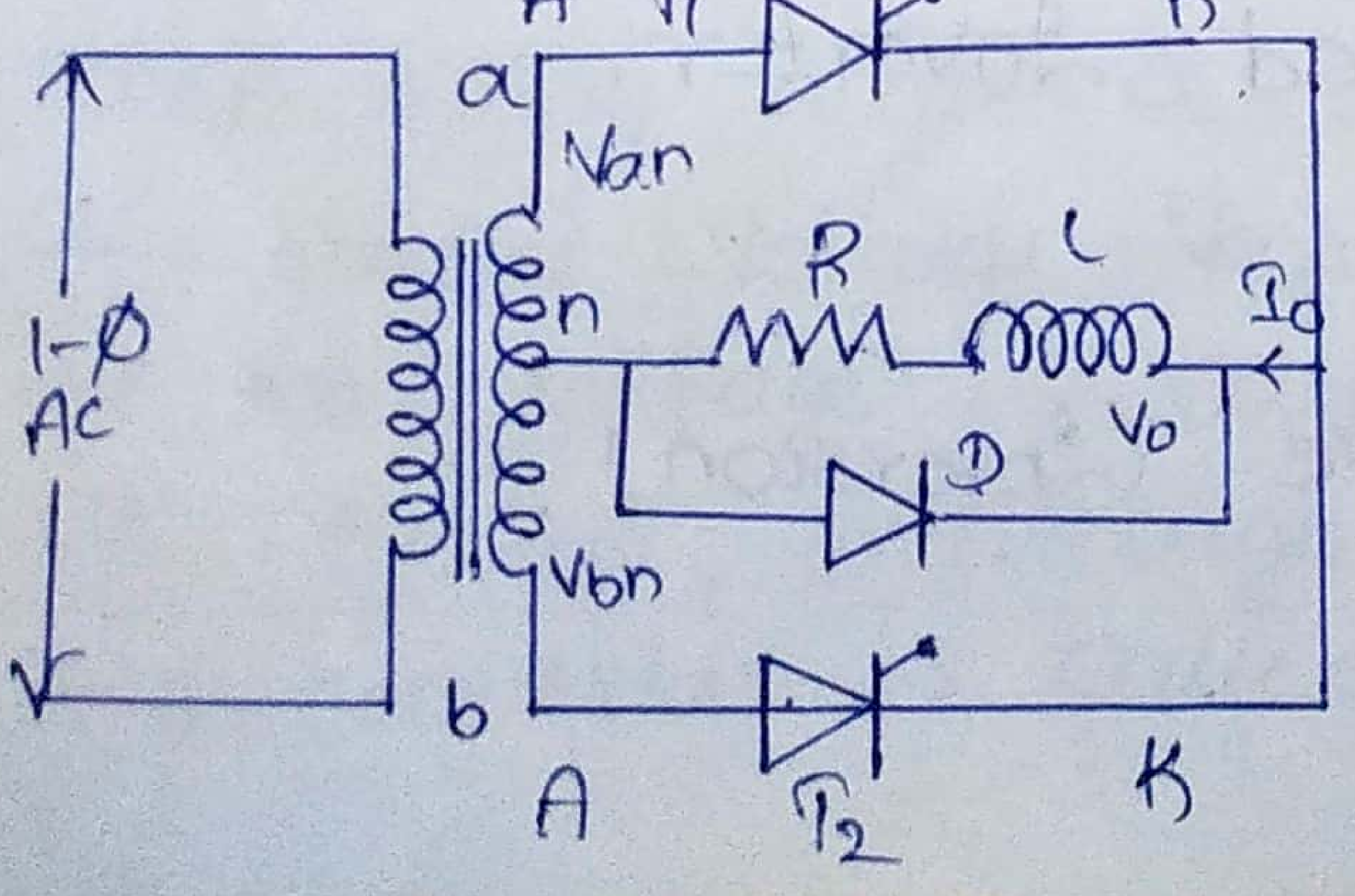
when $\alpha > 90°$,

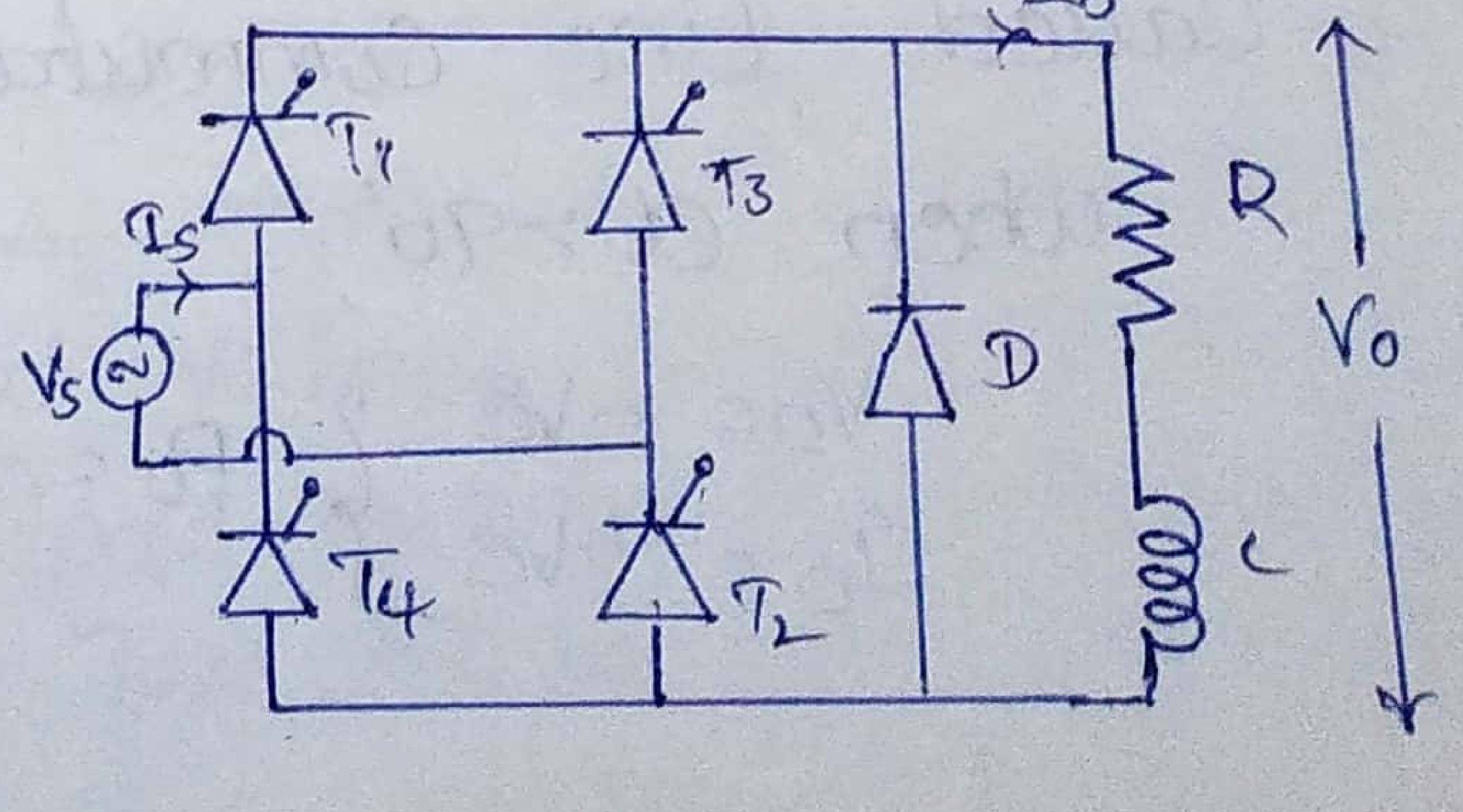
$\left.\begin{matrix} V_o = -Ve \\ I_o = +Ve \end{matrix}\right\}$ $P_o = -Ve$ (Inversion).

1-Ø FwcR with RL-Load with free wheeling Diode:-

→ Here, when free wheeling Diode is connected across the load, the load voltage wave form is similar to 1-Ø FwcR with R-Load. So, all the formulae are Same as 1-Ø FwcR with R-Load.







(1) $V_o = \frac{V_m}{2\pi}(1+\cos\alpha)$.

(2) $I_o = \frac{V_o}{R}$

(3) $V_{orms} = V_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2}$.

(4) $I_{orms} = \frac{V_{orms}}{R}$

(5) $P_o = V_o I_o$.

(6) $P_{ac} = V_{orms} \cdot I_{orms}$

(7) Input pf $= \frac{V_{orms}}{V_s}$.

(8) $I_{TA} = \frac{1}{2\pi}\int_0^{2\pi} I_T \cdot d\omega t$

$= \frac{1}{2\pi}\int_\alpha^{\pi} I_o \cdot d\omega t$

$= \frac{I_o}{2\pi}(\pi-\alpha)$

$\therefore I_{TA} = I_o\left(\frac{\pi-\alpha}{2\pi}\right)$

(9) $I_{TR} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_T^2 \cdot d\omega t}$

$\Rightarrow I_{TR}^2 = \frac{1}{2\pi}\int_\alpha^{\pi} I_o^2 \cdot d\omega t$

$= \frac{I_o^2}{2\pi}(\pi-\alpha)$

$\therefore I_{TR} = I_o\left[\frac{\pi-\alpha}{2\pi}\right]^{1/2}$

(10) $I_s = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_s^2 \cdot d\omega t}$

$\Rightarrow I_s^2 = \frac{1}{2\pi}\left[\int_\alpha^{\pi} I_o^2 \cdot d\omega t + \int_{\pi+\alpha}^{2\pi} (-I_o)^2 \cdot d\omega t\right]$

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

$$\Rightarrow \frac{I_0^2}{2\pi}\left[(\pi-\alpha)+(\pi-\alpha)\right] = I_s^2$$

$$\Rightarrow I_s^2 = I_0^2\left(\frac{\pi-\alpha}{\pi}\right)$$

$$\therefore I_s = I_0\left[\frac{\pi-\alpha}{\pi}\right]^{1/2}$$

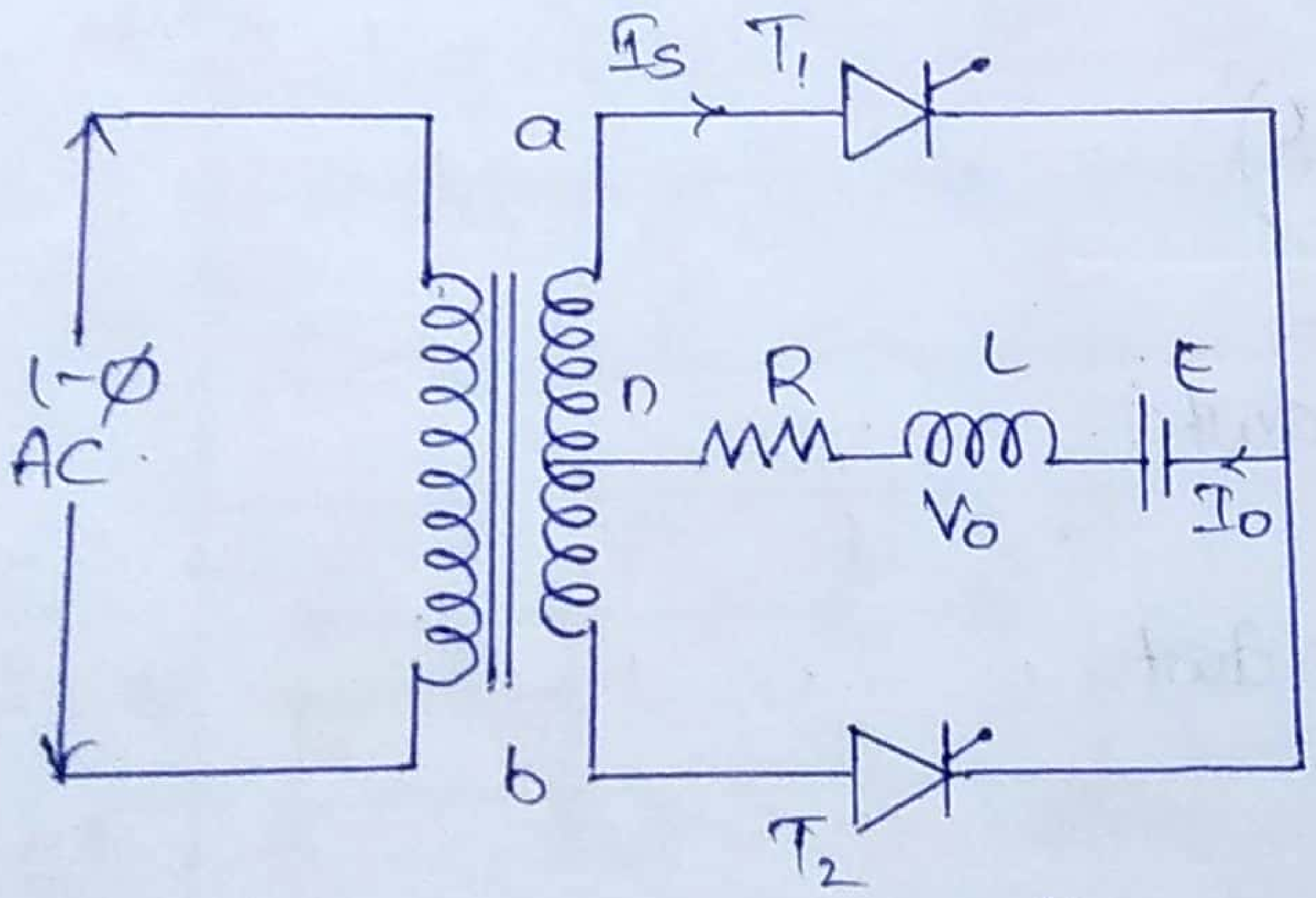
(ii) Input pf $= \frac{V_{orms} \cdot I_{orms}}{V_s I_s}$

$= \frac{V_{orms} I_0}{V_s I_s}$ (∵ High values of L $V_{orms} I_{orms}$)

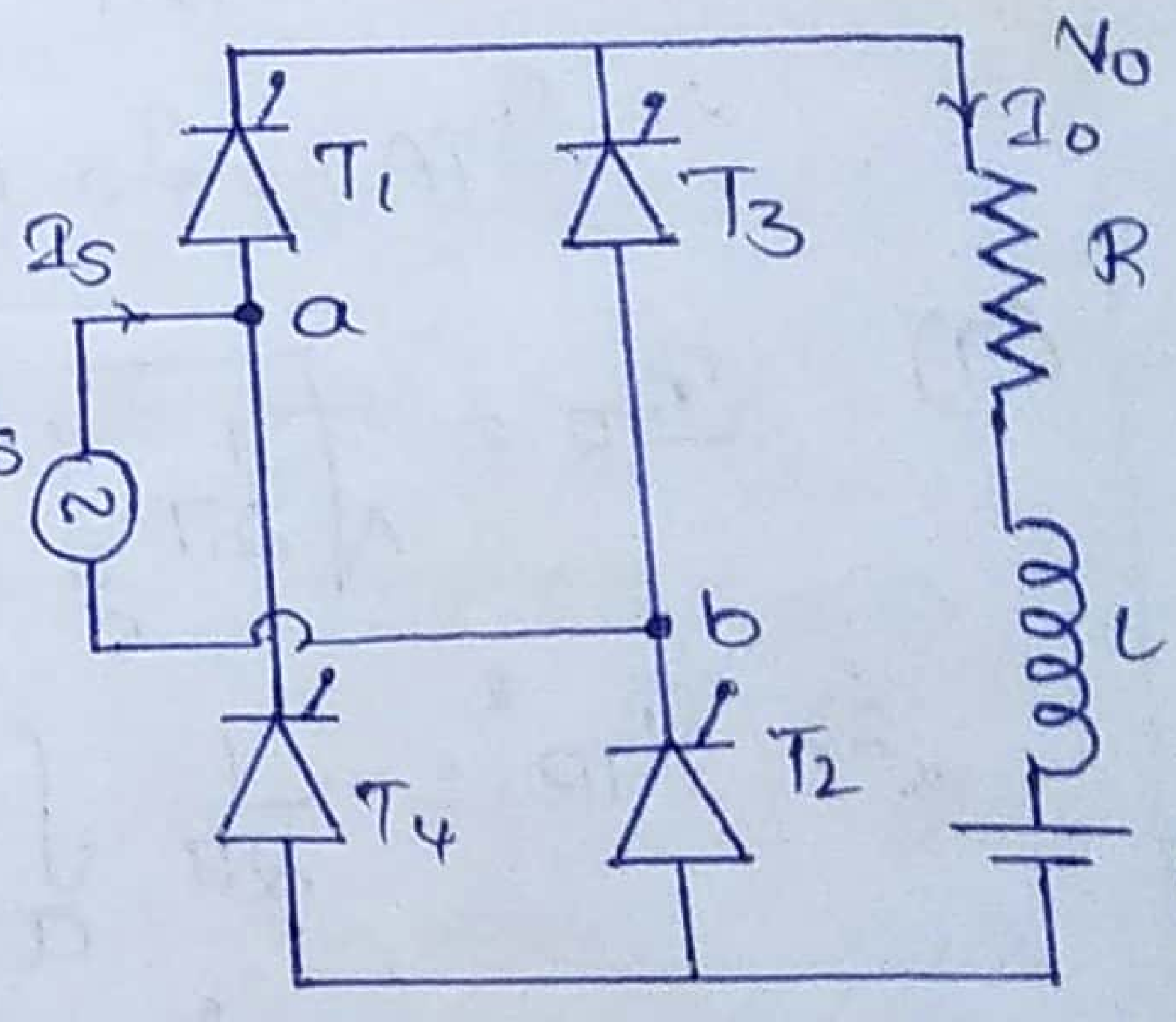
→ Conduction period of free wheeling Diode is 2α during one complete input cycle.

→ During conduction period of free wheeling Diode, Source current is zero.

→ 1-φ FWCR with RLE load:-



Mid point configuration



Bridge Configuration

→ During +HC:-

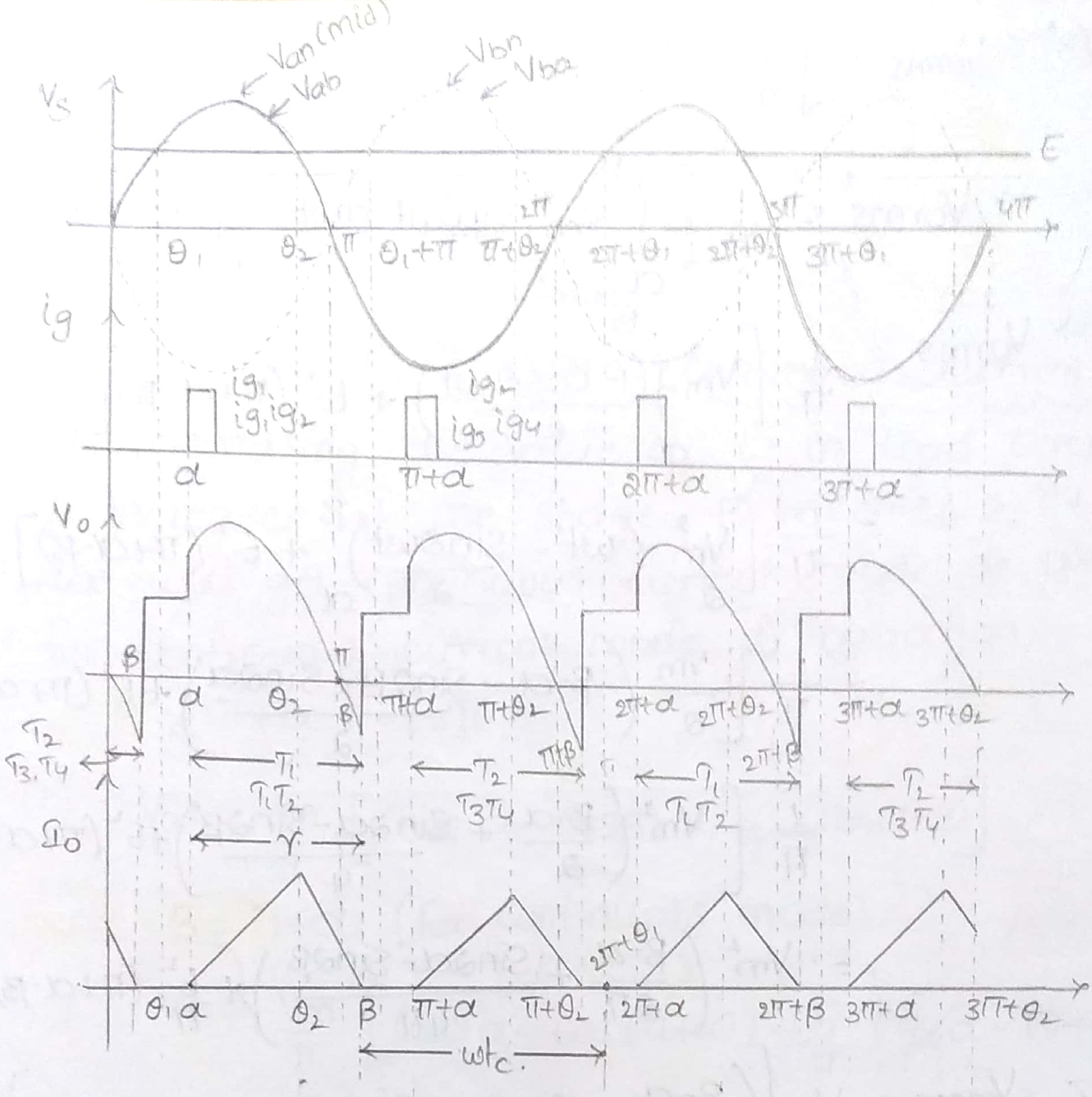
α-θ₂ ⇒ "L" Stores energy.

θ₂-β ⇒ "L" discharges its stored energy & there by allowing Thy "T₁" to conduct forcely.

→ During -HC:-

(π+α) to (π+θ₂) ⇒ L Stores energy.

(π+θ₂) to (π+β) ⇒ L-discharges its stored energy and then T₂ conduct forcefully.



→ $\gamma = \alpha - \beta$; $\omega t_c = \beta$ to $2\pi + \theta_1$.

(1) $V_o = \frac{1}{\pi} \int_0^{\pi} v_o . d\omega t$

$= \frac{1}{\pi} \left[\int_\alpha^\beta V_m \sin\omega t \cdot d\omega t + \int_\beta^{\pi+\alpha} E \, d\omega t \right]$

$= \frac{1}{\pi} \left[V_m (-\cos\omega t)_\alpha^\beta + E(\pi + \alpha - \beta) \right]$

$= \frac{1}{\pi} \left[V_m (-\cos\beta + \cos\alpha) + E(\pi + \alpha - \beta) \right]$

* $V_o = \frac{V_m}{\pi} (\cos\alpha - \cos\beta) + \frac{E}{\pi} (\pi + \alpha - \beta)$ / *

(2) $I_o = \frac{V_o - E}{R}$

(3) $$V_{orms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} V_o^2 \, d\omega t}$$

$$\Rightarrow V_{orms}^2 = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m^2 \sin^2\omega t \, . d\omega t + \int_{\beta}^{\pi+\alpha} E^2 . d\omega t\right]$$

$$\Rightarrow V_{orms}^2 = \frac{1}{\pi}\left[V_m^2 \int_{\alpha}^{\beta}\left(\frac{1-\cos 2\omega t}{2}\right) + E^2(\pi+\alpha-\beta)\right]$$

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

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

$$= \frac{1}{\pi}\left[V_m^2\left(\frac{\beta-\alpha}{2} + \frac{\sin 2\alpha - \sin 2\beta}{4}\right) + E^2(\pi+\alpha-\beta)\right]$$

$$= V_m^2\left(\frac{\beta-\alpha}{2\pi} + \frac{\sin 2\alpha - \sin 2\beta}{4\pi}\right) + \frac{E^2}{\pi}(\pi+\alpha-\beta).$$

$$\therefore V_{orms} = V_m\left[\left(\frac{\beta-\alpha}{2\pi} + \frac{\sin 2\alpha - \sin 2\beta}{4\pi}\right] + \frac{E^2}{\pi}(\pi+\alpha-\beta)\right]^{1/2}$$

(4) $$I_{orms} = \frac{V_{orms} - E}{R}.$$

(5) $\gamma = \beta - \alpha$

(6) $$t_c = \frac{2\pi + \theta_1 - \beta}{\omega}$$

(7) $I_s = I_{orms}.$

(8) $P_{ac} = V_{orms} \cdot I_{orms} + I_o E$

$\Rightarrow P_{ac} = I_{orms}^2 R + I_o E$ – power absorbed to Battery.

↳ power dissipated in R

(9) $$\text{Input pf} = \frac{I_{orms}^2 R + I_o E}{V_s I_s}$$

∴ $\text{Input pf} = \frac{I_{orms}^2 \cdot R + I_o E}{V_s I_{orms}}$

∴ $\text{Input pf.} = \frac{V_{orms} \cdot I_{orms} + I_o E}{V_s I_{orms}}$

→ $1-\phi$ FWCR with RLE Load (continuous current):-

→ By increasing the value of L in load circuit β increases at one stage, β becomes ≥ π+α, we will get continuous current mode of operation

→ for continuous current mode of operation,

$\beta \geq \pi+\alpha$; $\gamma = \pi$.

(1) $V_0 = \frac{V_m}{\pi}\left[(\cos\alpha - \cos\beta) + \frac{E}{\pi}(\pi+\alpha-\beta)\right]$

$\beta = \pi+\alpha$ (for continuous mode)

$\Rightarrow V_0 = \frac{V_m}{\pi}\left[(\cos\alpha - \cos(\pi+\alpha)) + \frac{E}{\pi}(\cancel{\pi+}\alpha - (\cancel{\pi+\alpha}))\right]$

$\Rightarrow V_0 = \frac{V_m}{\pi}\left[\cos\alpha + \cos\alpha\right]$

∴ $V_0 = \frac{2V_m}{\pi}\cos\alpha$.

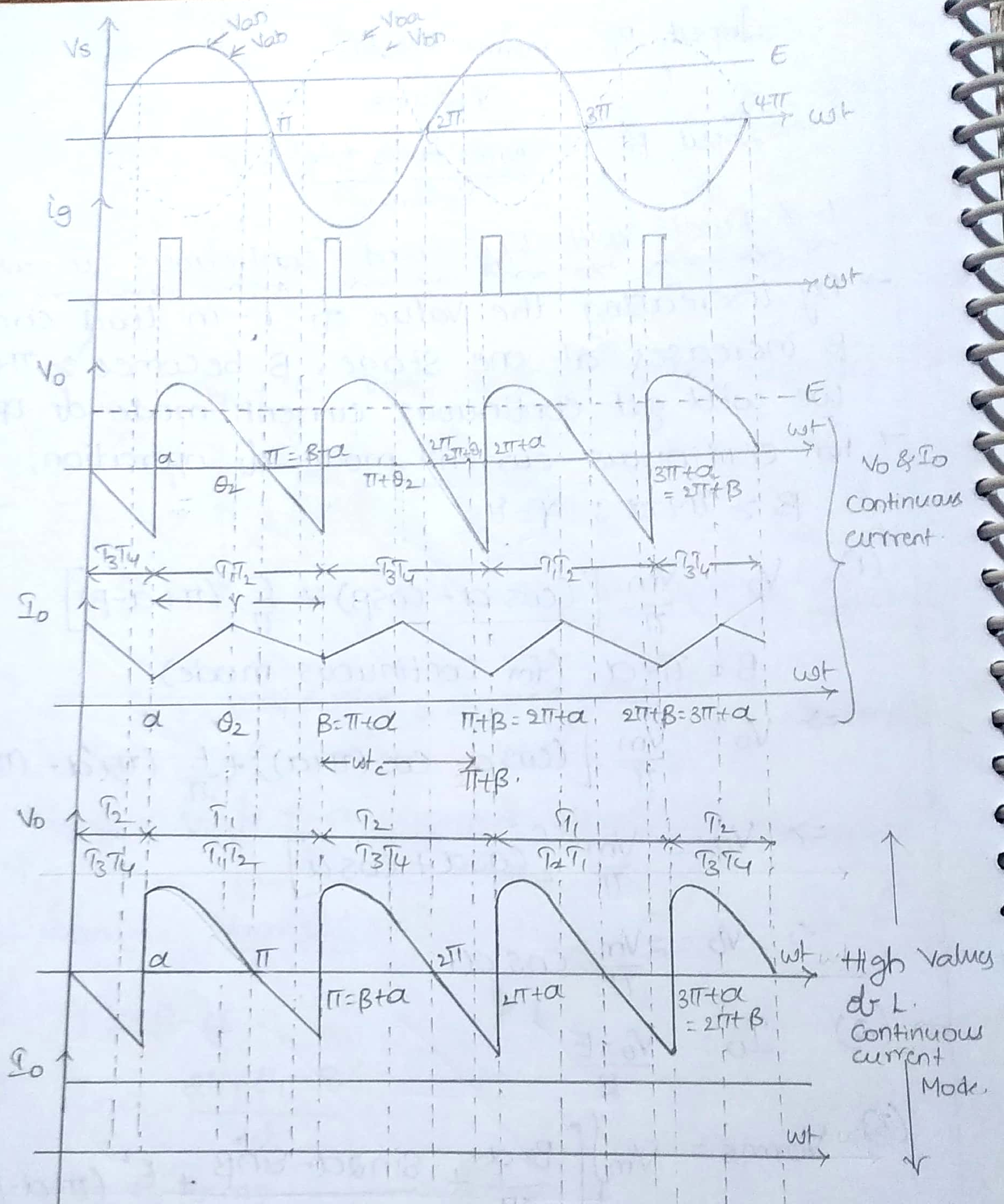
(2) $I_0 = \frac{V_0 - E}{R}$

(3) $V_{orms} = V_m\left\{\left[\frac{\beta-\alpha}{2\pi} + \frac{\sin 2\alpha - \sin^2\beta}{4\pi} + \frac{E^2}{\pi}(\pi+\alpha-\beta)\right]\right\}^{1/2}$

$\beta = \pi+\alpha$

$\Rightarrow V_{orms} = V_m\left\{\left[\frac{\pi+\alpha-\alpha}{2\pi} + \frac{\sin 2\alpha - \sin 2(\pi+\alpha)}{4\pi} + \frac{E^2}{\pi}(\pi+\alpha-(\pi+\alpha)\right]\right\}^{1/2}$

$= V_m\left[\left(\frac{\cancel{\pi}}{2\cancel{\pi}} + 0 + 0\right)\right]^{1/2} = \frac{V_m}{\sqrt{2}} = V_s.$



Vo & Io for Continuous current Mode for High Values of L.

(4) $I_{orms} = \dfrac{V_{orms} - E}{R}$

(5) $\gamma = \beta - \alpha = \pi + \cancel{\alpha} - \cancel{\alpha}$

$\gamma = \pi$.

(6) $t_c = \frac{2\pi + \theta_1 - \beta}{\omega}$; $\beta = \pi + \alpha$

$\Rightarrow t_c = \frac{2\pi + \theta_1 - \pi + \alpha}{\omega}$.

$\therefore t_c = \frac{\cancel{2}\pi + \theta_1 \pm \alpha}{\omega} = \frac{\pi + \theta_1 - \alpha}{\omega}$

(7) $I_s = I_{orms}$

(8) $P_{ac} = V_{orms} I_{orms} + I_o E$

(9) $pf = \frac{V_{orms} I_{orms} + I_o E}{V_s I_{orms}}$.

(3) 1-Ø FWCR with RLE Load Continuous Current Mode for High Values of L :-

→ for High Values of Inductance in Load circuit, we get Constant Load current or Ripple free Load current.

(1) $V_o = \frac{2V_m}{\pi} \cos\alpha$.

(2) $I_o = \frac{V_o - E}{R}$.

(3) $V_{orms} = \frac{V_m}{\sqrt{2}} = V_s$.

(4) $\gamma = \pi$; $t_c = \frac{\pi + \theta_1 - \alpha}{\omega}$

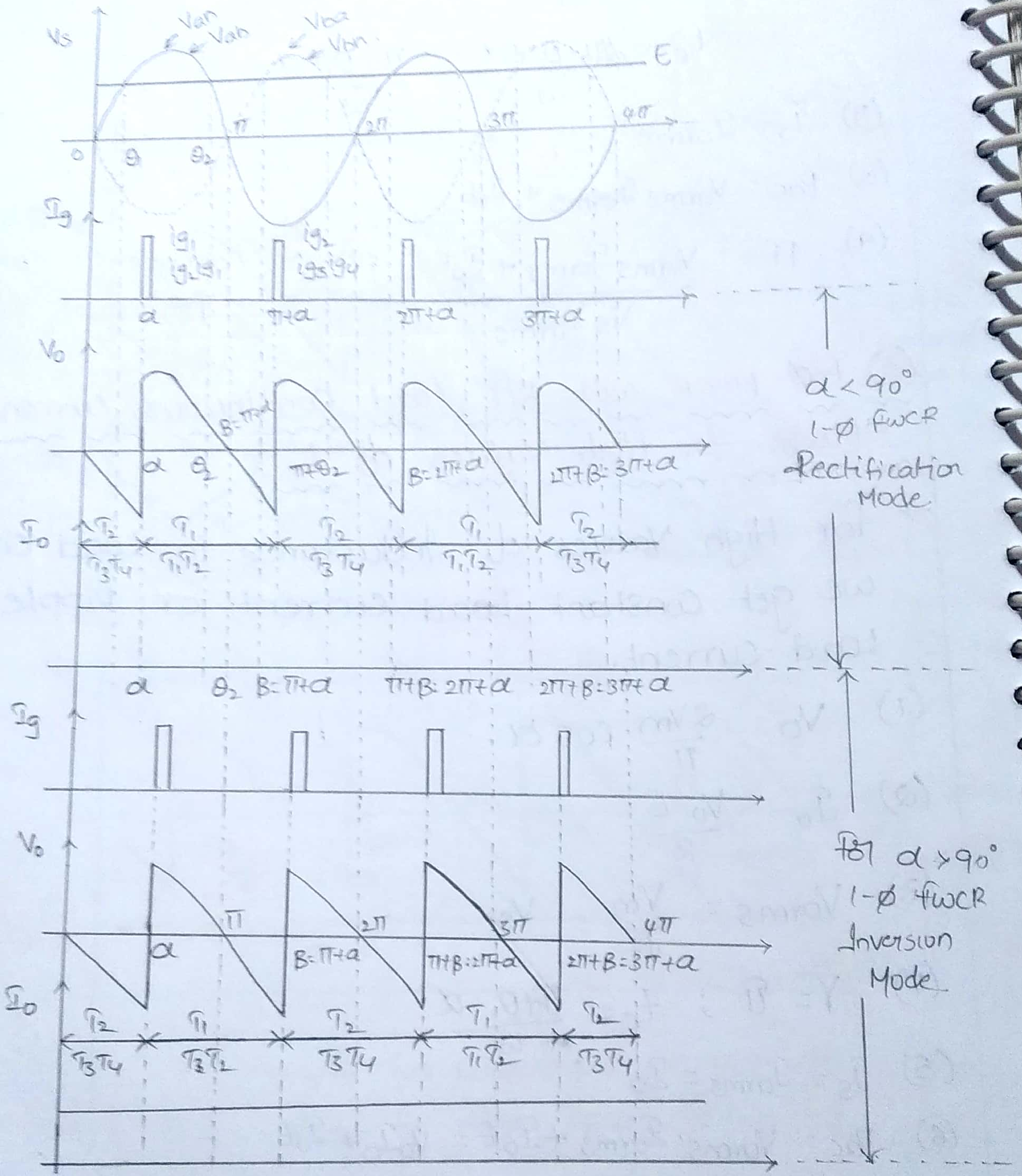
(5) $I_s = I_{orms} = I_o$

(6) $P_{ac} = V_{orms} \cdot I_{orms} + I_o E = V_o I_o + I_o E$.

(7) I/p $pf = \frac{V_o I_o + I_o E}{V_s I_s} = \frac{V_o I_o + I_o E}{V_s I_o}$.

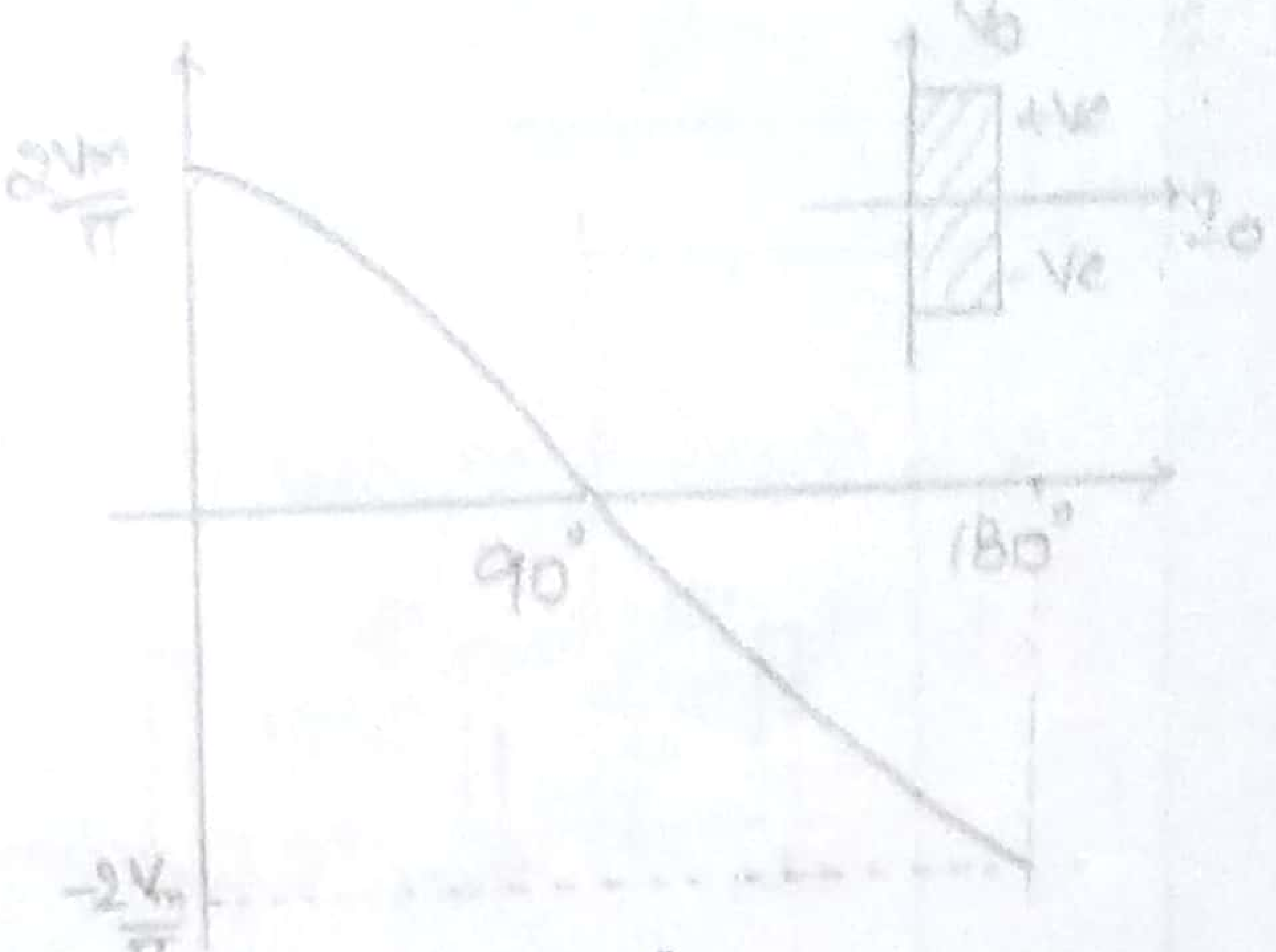
$\therefore$ I/p $pf = \frac{V_o + E}{V_s}$

(4) 1-ϕ FWCR with RLE Load:-
(Rectification & Inversion Modes):-



1-ϕ FHWCR for Inversion and Rectification modes (with RLE Load)

→ Assume High Values of L in load circuit.



⇒ $V_0 = \frac{2V_m}{\pi} \cos\alpha.$

when $\alpha = 0$; $V_0 = \frac{2V_m}{\pi}$

$\alpha = 90°$; $V_0 = 0.$

$\alpha = 180°$; $V_0 = -\frac{2V_m}{\pi}.$

when $\alpha < 90°$

$V_0 = +ve$; $I_0 = +ve$

$P_0 = +ve$

Ac - Dc (Rectification)

when $\alpha > 90°$

$V_0 = -ve$; $I_0 = +ve$

$P_0 = -ve$

Dc Source - Ac load (Inversion)

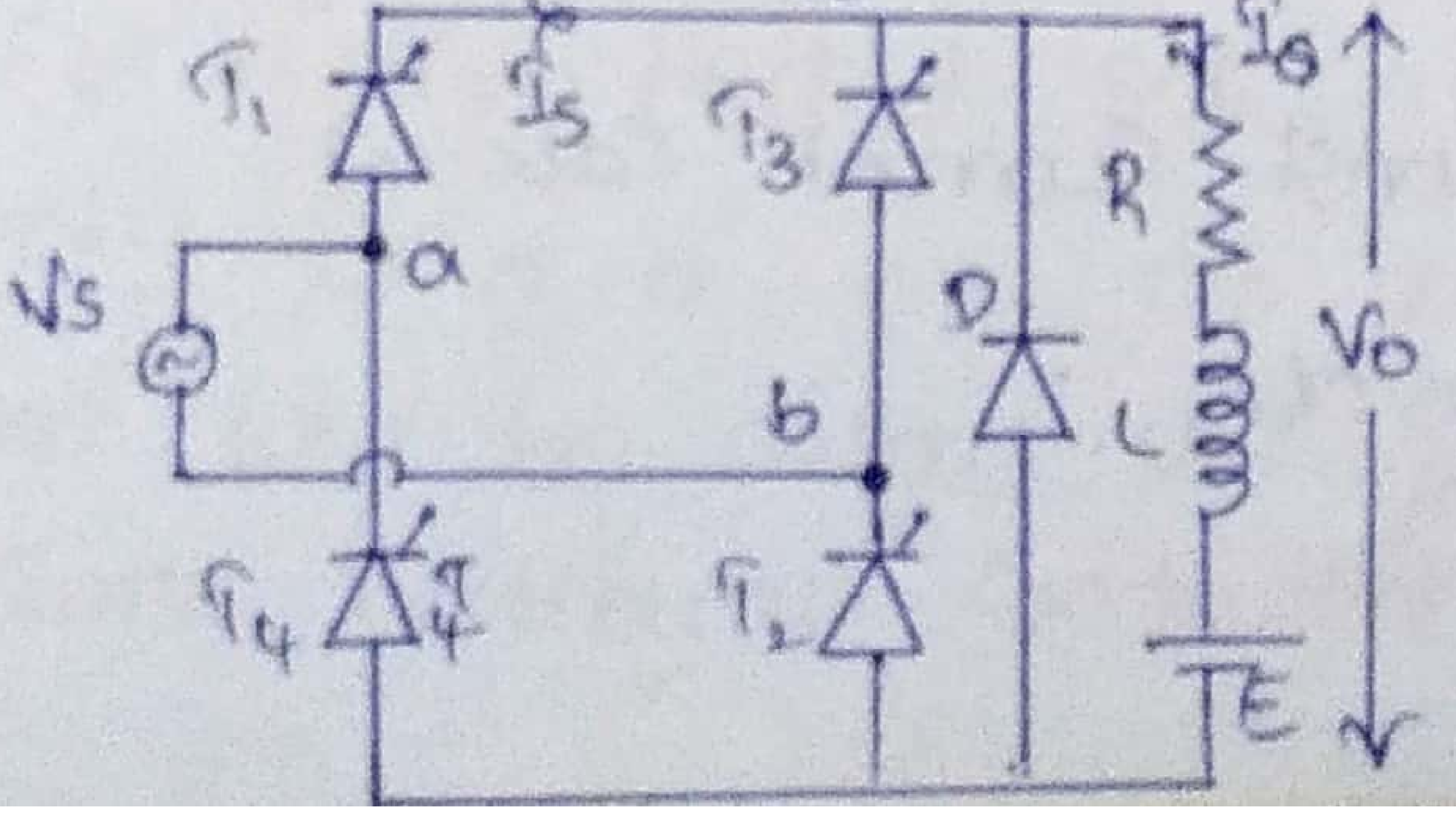
(5) 1-φ FWCR with RLE Load with free wheeling Diode:-

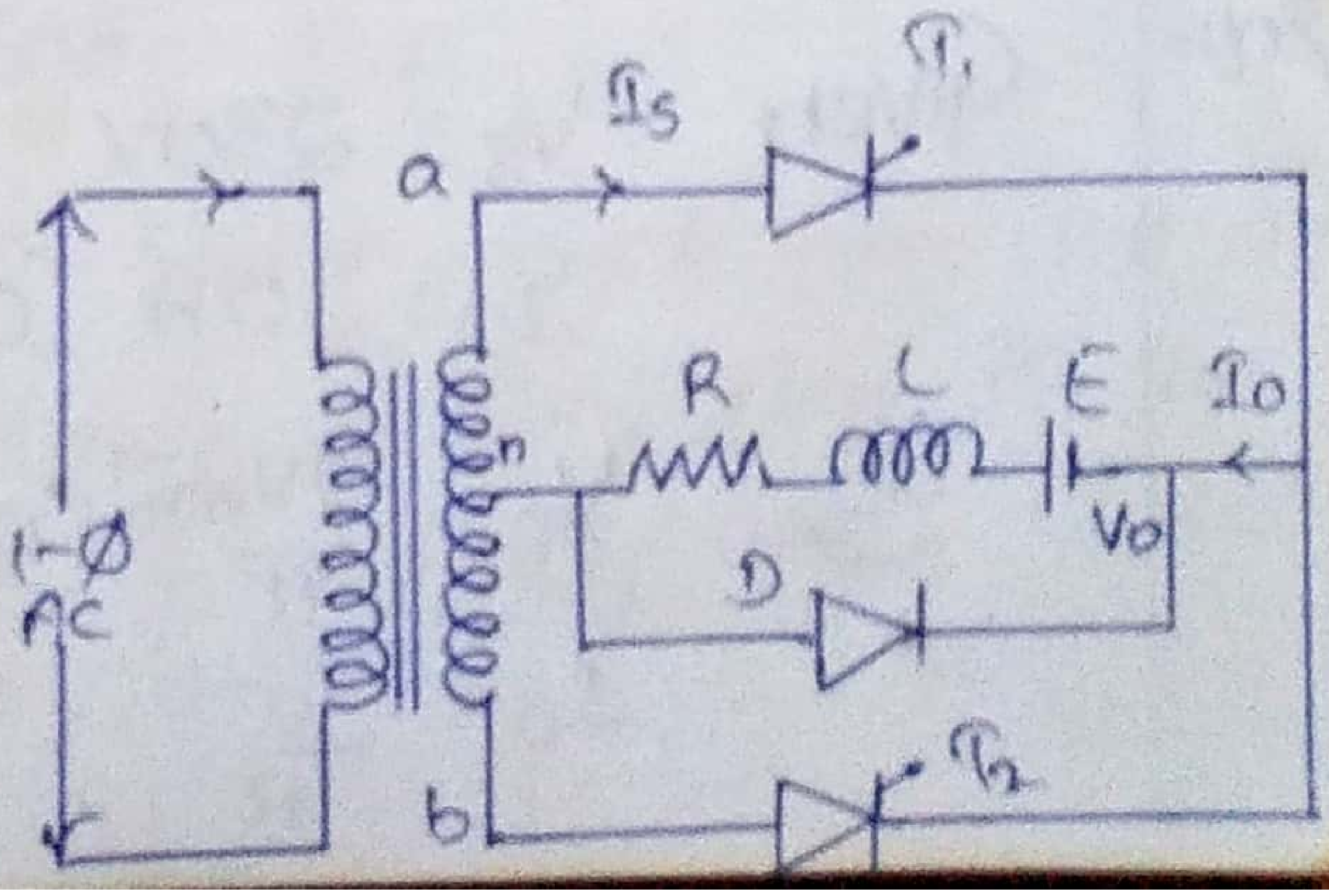
→ In 1-φ FWCR with RLE Load, by connecting the freewheeling Diode across the load, Negative spikes in the output Voltage are eliminated & shown in figure. The load Voltage waveform is exactly Similar to 1-φ FWCR with R-Load. So expressions of V_0, V_{orms}, I_0, I_{orms} are same as 1-φ FWCR with R-Load.

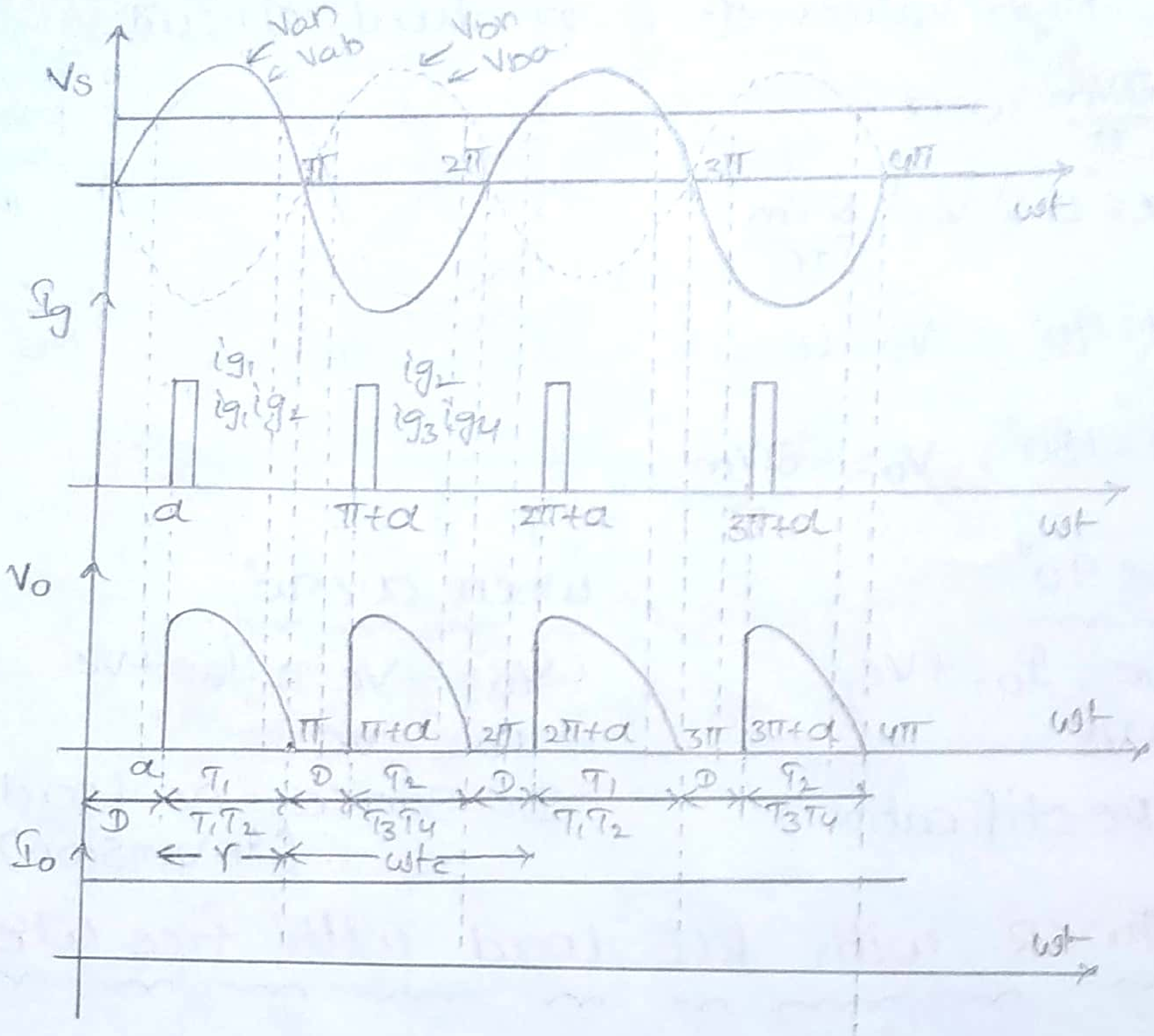
→ $\omega t_c = 2\pi + \theta_1 - \pi$

⇒ $\omega t_c = \pi + \theta_1.$

/ $t_c = \frac{\pi + \theta_1}{\omega}$ /







* 1-ϕ FBC (full Bridge) is connected to RLE load, Source Voltage is 230V, 50Hz, the avg. load current of 10A is constant more the working Range. for R=0.4; L=2mH; Compute

(a) firing Angle Delay for E=120V.

(b) firing Angle Delay for E=-120V.

Indicate (with) Source (which Source) is delivering Power to load in Part a & b and for both sketch Variations of o/p V and load current

(c) In case output current assumed constant, find Input pf for both parts a and b.

Sol:- Given $V_S = 230V$

$I_0 = 10A$ (Const. Current Case-3)

(a) $V_0 = \frac{2V_m}{\pi} \cos\alpha$.

$I_0 = \frac{V_0 - E}{R}$

⇒ $V_o = \frac{2V_m}{\pi}\cos\alpha$.

⇒ $\frac{2\times 230\times\sqrt{2}}{\pi}\cos\alpha = 10\times 0.4+120$

⇒ $\alpha = 53.2^\circ < 90^\circ$ (Rectification Mode)

(b)

⇒ $\frac{2\times 230\times\sqrt{2}}{\pi}\times\cos\alpha = 4-120$

⇒ $\alpha = \cos^{-1}\left[\frac{-116\times\pi}{230\sqrt{2}\times 1.414}\right]$

∴ $\alpha = 124.07 > 90^\circ$ (Inversion Mode)

→ $\alpha > 90^\circ$ indicates power flows from dc source to ac load. Thus, full converter operates as Inverter.

(c) Input pf = $\frac{V_{orms} I_{orms} + E\cdot I_o}{V_s I_s}$.

$= \frac{V_o I_o + I_o E}{V_s I_o}$ (High values of L $V_{orms} I_{orms}$ $V_o I_o$. $I_s = I_o$)

$= \frac{I_o^2 R + I_o E}{V_s I_o}$.

$= \frac{R I_o + E}{V_s}$.

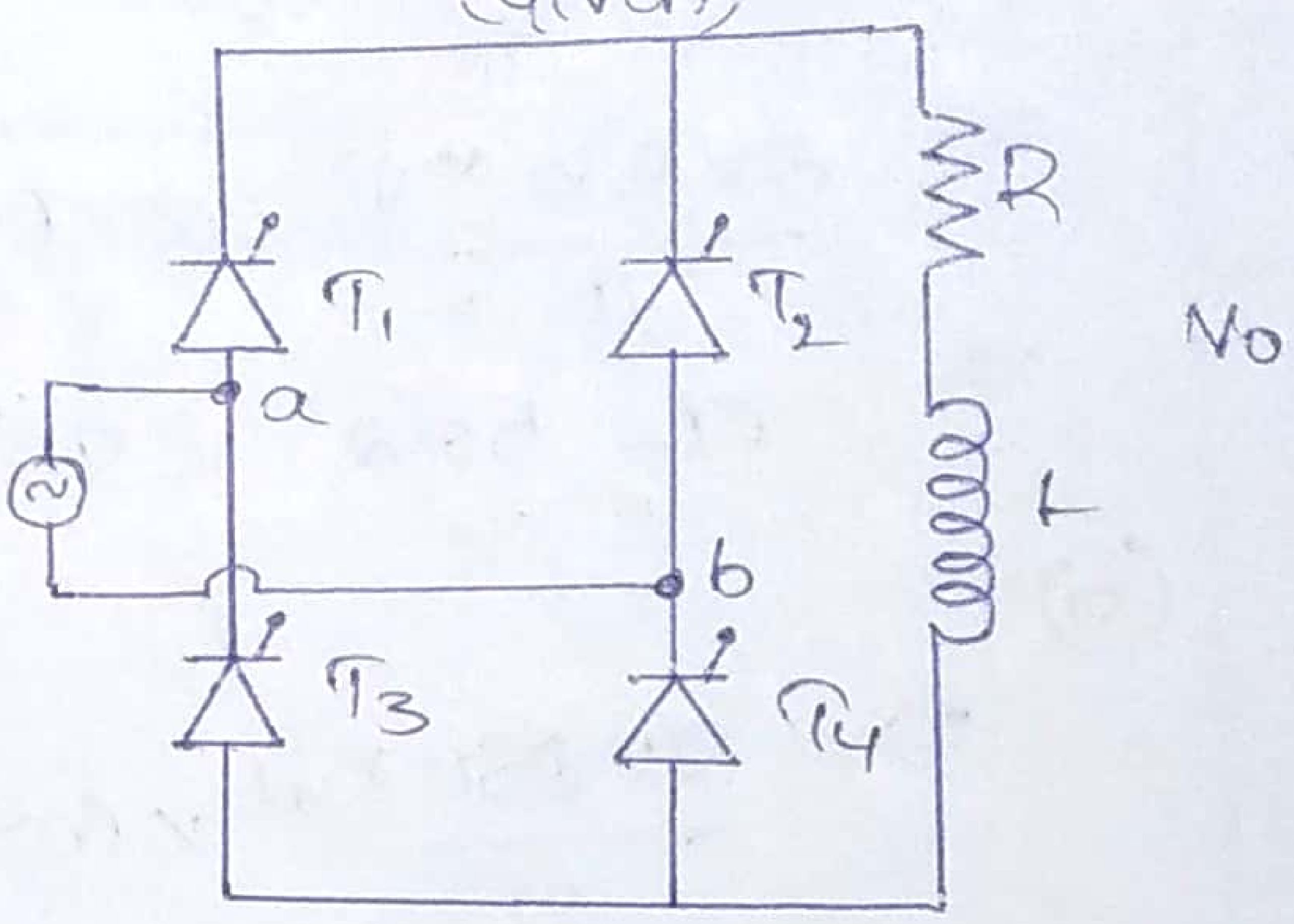
(a) $E = 120$ ⇒ $pf = \frac{10\times 0.4+120}{230} = 0.503$

(b) $E = -120$ ⇒ $pf = -0.503$

* ** A 1-φ fully ctrlled SCR as shown in fet fig. from 1-φ ac supply for $\alpha = 0^\circ$, avg. o/p voltage of converter is 500V. what will be output voltage for firing angle $\alpha = 60^\circ$ Assume continuous conduction.

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

(Given)



At $\alpha = 0°$, $V_o = 300V$

$\Rightarrow 300 = \frac{2V_m}{\pi}\cos\alpha$

$\Rightarrow 300 = \frac{2V_m}{\pi}\cos 0$

$\Rightarrow V_m = \frac{300\pi}{2} = 471.23V$

At $\alpha = 60°$.

$\Rightarrow V_o = \frac{2\times 471.23}{\pi}\cos 60°$

$= \frac{471.23\times\cancel{2}\times\frac{1}{\cancel{2}}}{\pi} = 149.99V$

$\therefore V_o = 150V$

* 1-ø FWCR operated at 120V, 60Hz Supply for R-load of 10Ω. If the avg. output voltage is 25% of maximum possible output voltage. find Delay angle, RMS and avg. output currents, RMS and avg. Thyr. currents.

Sol:- Given $R = 10\Omega$

$V_s = 120V$; $f = 50Hz$.

$V_m = V_s\times\sqrt{2}$

$V_s = \frac{V_m}{\sqrt{2}}$

for FWCR, R-Load

$V_o = \frac{V_m}{\pi}(1+\cos\alpha)$

At $\alpha = 0$; $V_o = V_{omax}$ i.e., $V_o = \frac{2V_m}{\pi}$.

Given, $V_o = 25\%$ of V_{omax}.

$\Rightarrow V_{omax} = \frac{2V_m}{\pi} = \frac{2\times 120\times\sqrt{2}}{\pi} = 108.03V$

$\therefore V_o = 0.25\times 108.03$

$\therefore V_o = 27\ V.$

(1) $V_0 = \frac{V_m}{\pi}(1+\cos\alpha) \Rightarrow (1+\cos\alpha) = \frac{V_m}{\pi} \times \frac{1}{V_0}$

$\Rightarrow \alpha = \cos^{-1}\left[\frac{V_m}{\pi} - 1\right] \Rightarrow \cos\alpha = \frac{V_m}{\pi V_0} - 1.$

$\therefore \alpha = 120^\circ$

(2) $I_0 = \frac{V_0}{R} = \frac{27}{10} = 2.7\,A$

$I_{orms} = \frac{V_{orms}}{R} = 108.$

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

$= 120\times\sqrt{2}\left[\frac{\pi-(\alpha\times\frac{\pi}{180})}{2\pi} + \frac{\sin 2(120)}{4\pi}\right]^{1/2}$

$= 120\times\sqrt{2}\left[\frac{\pi-(120\times\frac{\pi}{180})}{2\pi} + \frac{\sin(120)}{4\pi}\right]^{1/2}$

$\therefore V_{orms} = 53.05\,V.$

$\Rightarrow I_{orms} = \frac{V_{orms}}{R} = \frac{53.05}{10} = 5.3\,A$

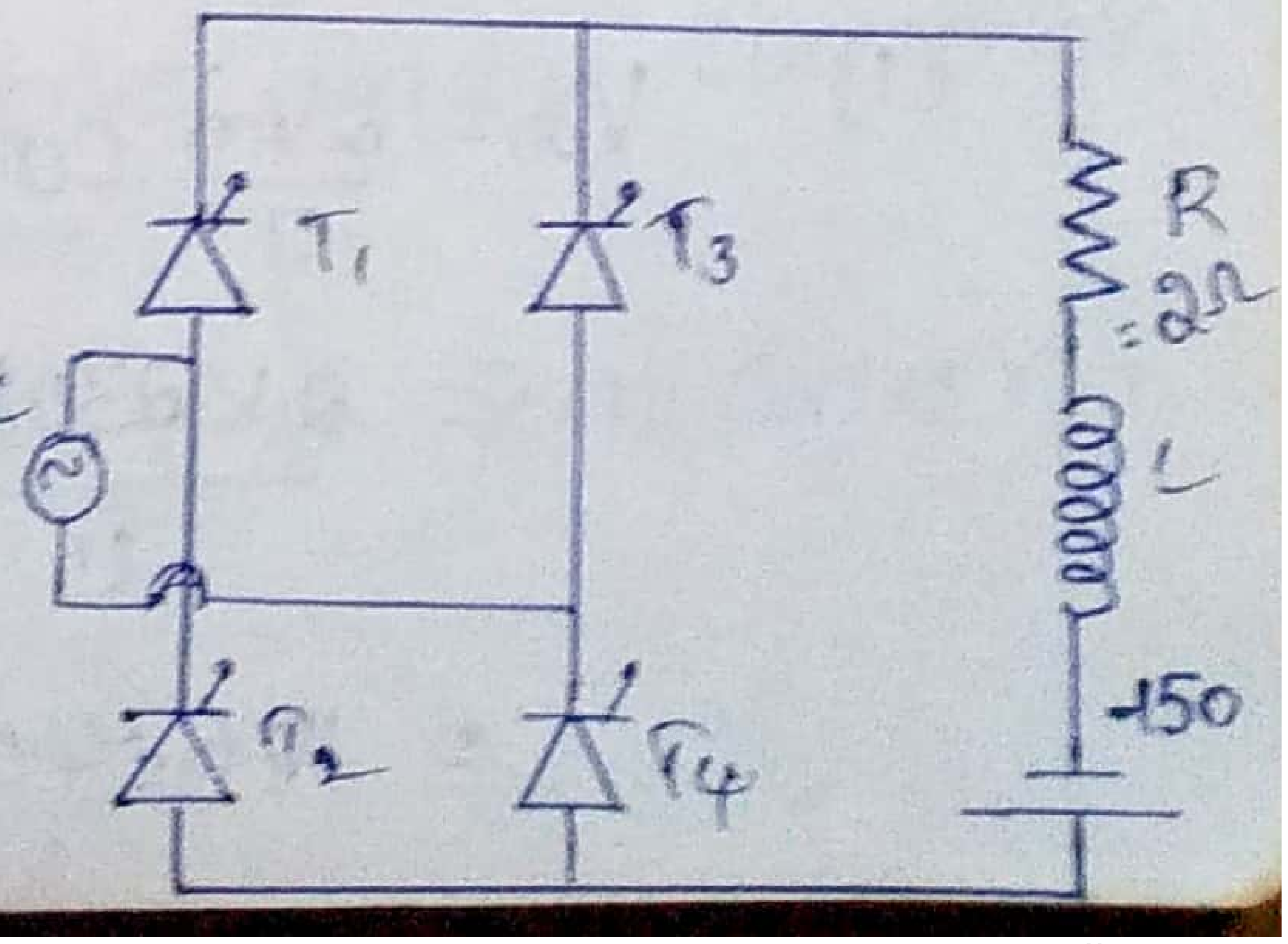
(3) $I_{TA} = \frac{I_0}{2} = \frac{2.7}{2} = 1.35\,A.$

$I_{TR} = \frac{I_{orms}}{\sqrt{2}} = \frac{5.3}{\sqrt{2}} = 3.7\,A$

1-Ø FCBC shown in fig. Assume that the load inductance is sufficient to get continuous and Ripple free load current. Calculate the firing angle of Bridge for the load current of 10A

$\alpha = 128.88^\circ$

Given, $I_0 = 10A.$



* 1-ϕ FWCR Connected to High Inductive load R=2Ω & an emf, $V_s = 250V$, 50Hz. If load current is 10A for $\alpha = 120°$ what should be the emf at load Side.

Sol:- Given, $V_s = 230V$; $\alpha = 120°$; $I_0 = 10A$; $R = 2\Omega$ $\quad E = -123.5V$

$E = ?$

$$\Rightarrow V_0 = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times 230\times\sqrt{2}}{\pi}\cos(120°)$$

$$= -103.53V$$

$$\Rightarrow I_0 = \frac{V_0 - E}{R} \Rightarrow 10 = \frac{-103.53 - E}{2}$$

$$\Rightarrow 20 = -103.53 - E$$

$$\therefore E = 123.5V$$

* 1-ϕ FCBR is fed from 230V, 50Hz Supply. load is Highly Inductive. find avg. load Voltage & current, if $R = 10\Omega$, $\alpha = 45°$. find also Vorms, Ripple factor, FF.

Sol:- Given, $R = 10\Omega$

$V_s = 230V$

$f = 50Hz$

$\alpha = 45°$.

$V_o = 146.42V$

$I_o = 14.64A$

$V_{orms} = 230V$.

$RF = 1.21$

$FF = 1.57$

(i) $$V_0 = \frac{2V_m}{\pi}\cos\alpha.$$

$$= \frac{2\times 230\times\sqrt{2}}{\pi}\times\frac{1}{\sqrt{2}}$$

$$= 146.400V$$

(ii) $I_o = \frac{V_o}{R} = \frac{146.4}{10} = 14.64 A$

(iii) $V_{orms} = \frac{V_m}{\sqrt{2}} = \frac{230 \times \sqrt{2}}{\sqrt{2}} = 230V$

(iv) $RF = \sqrt{ff^2 - 1}$

$\therefore ff = \frac{V_{orms}}{V_o} = \frac{230}{146.4} = 1.5710$

$\Rightarrow RF = \sqrt{ff^2 - 1} = \sqrt{1.57^2 - 1} = 1.2116$

→ 1-φ SemiConverter (or) Half Controlled Converter:-

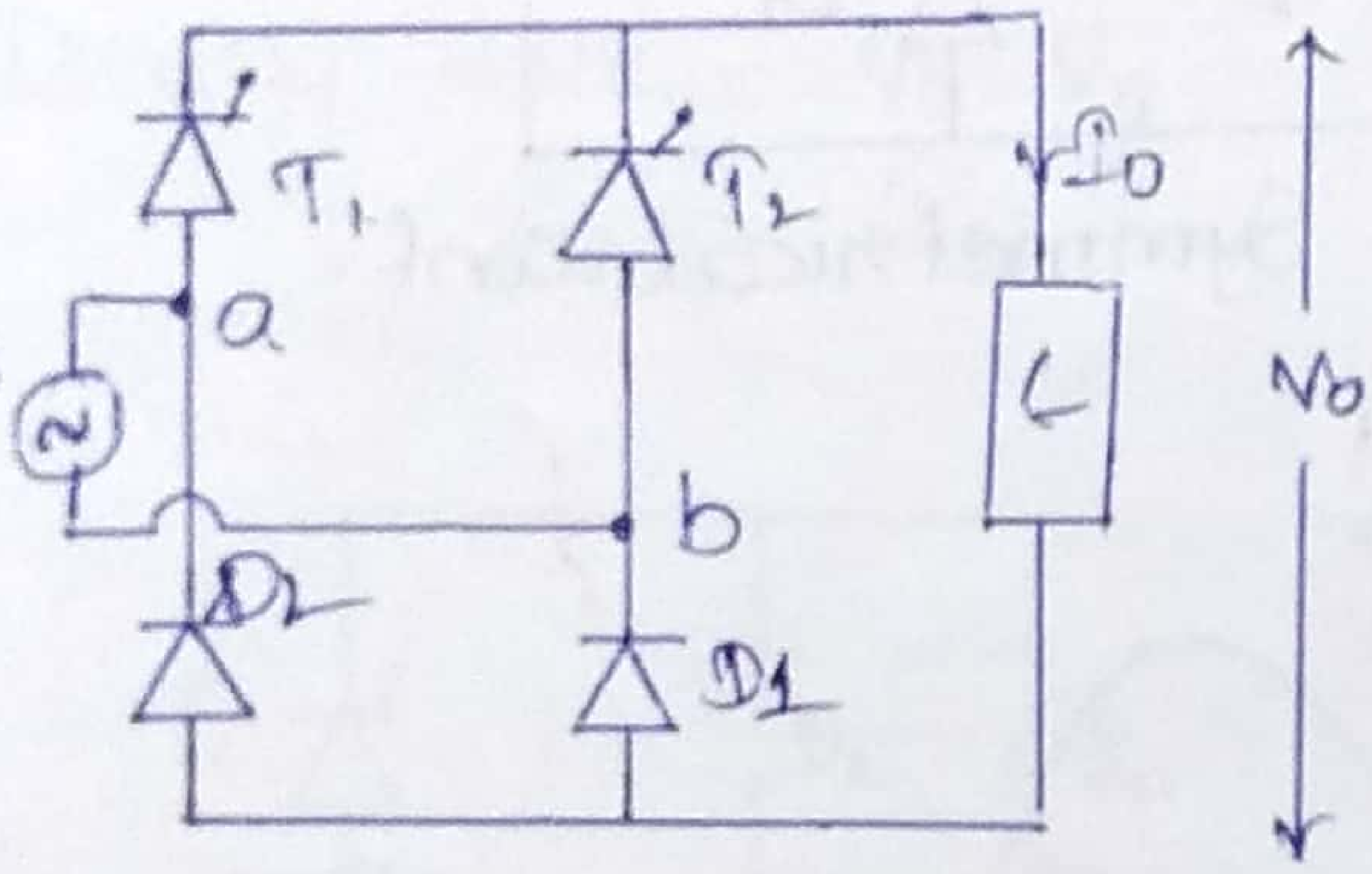
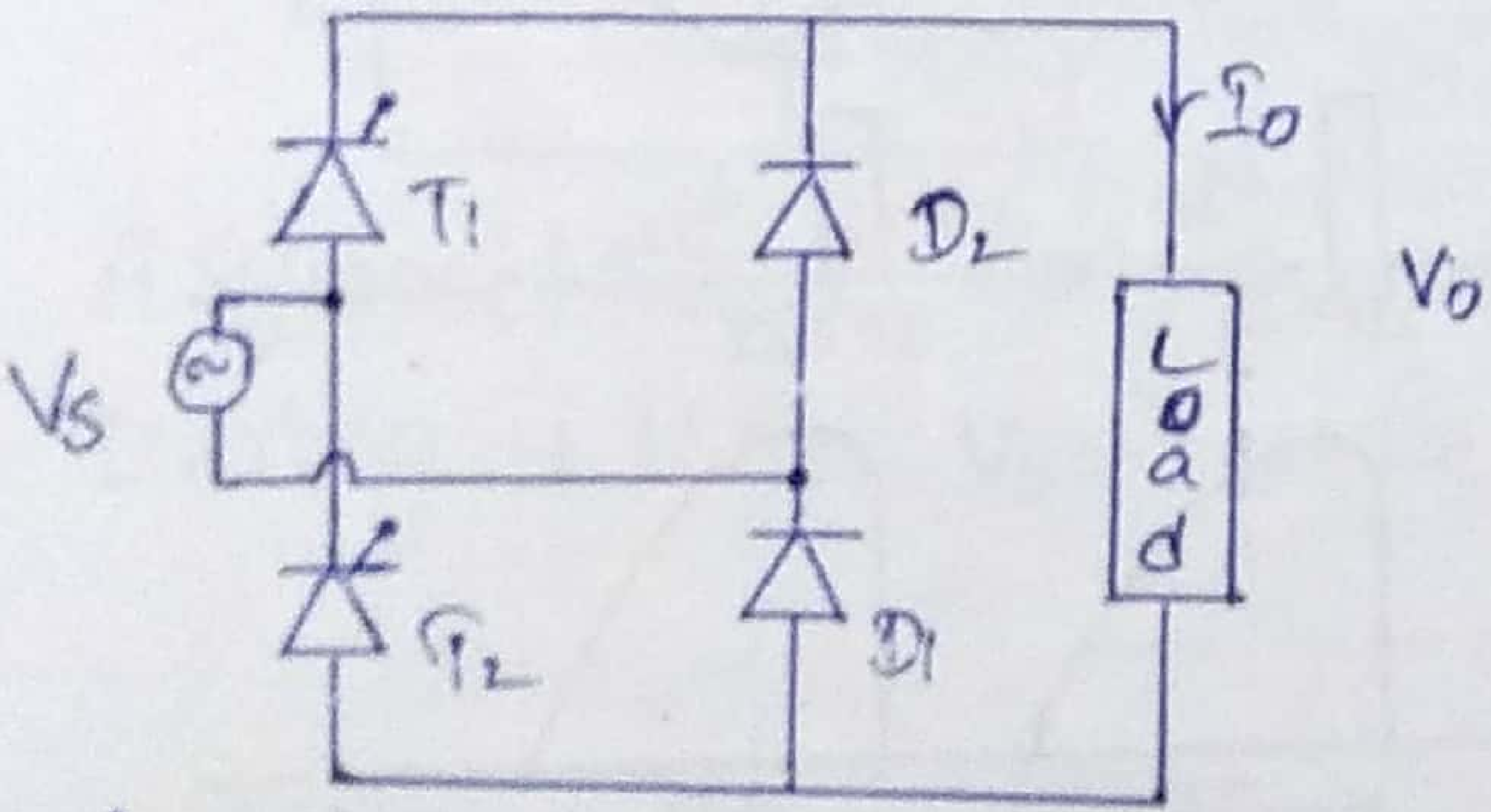


fig:- Symmetrical configuration.



→ A Pair of Thyristors are replaced by uncontrolled devices (Diodes) in 1-φ full wave Bridge converter, a 1-φ Semi converter will form.

→ There are two configurations of 1-φ Semi Converter.

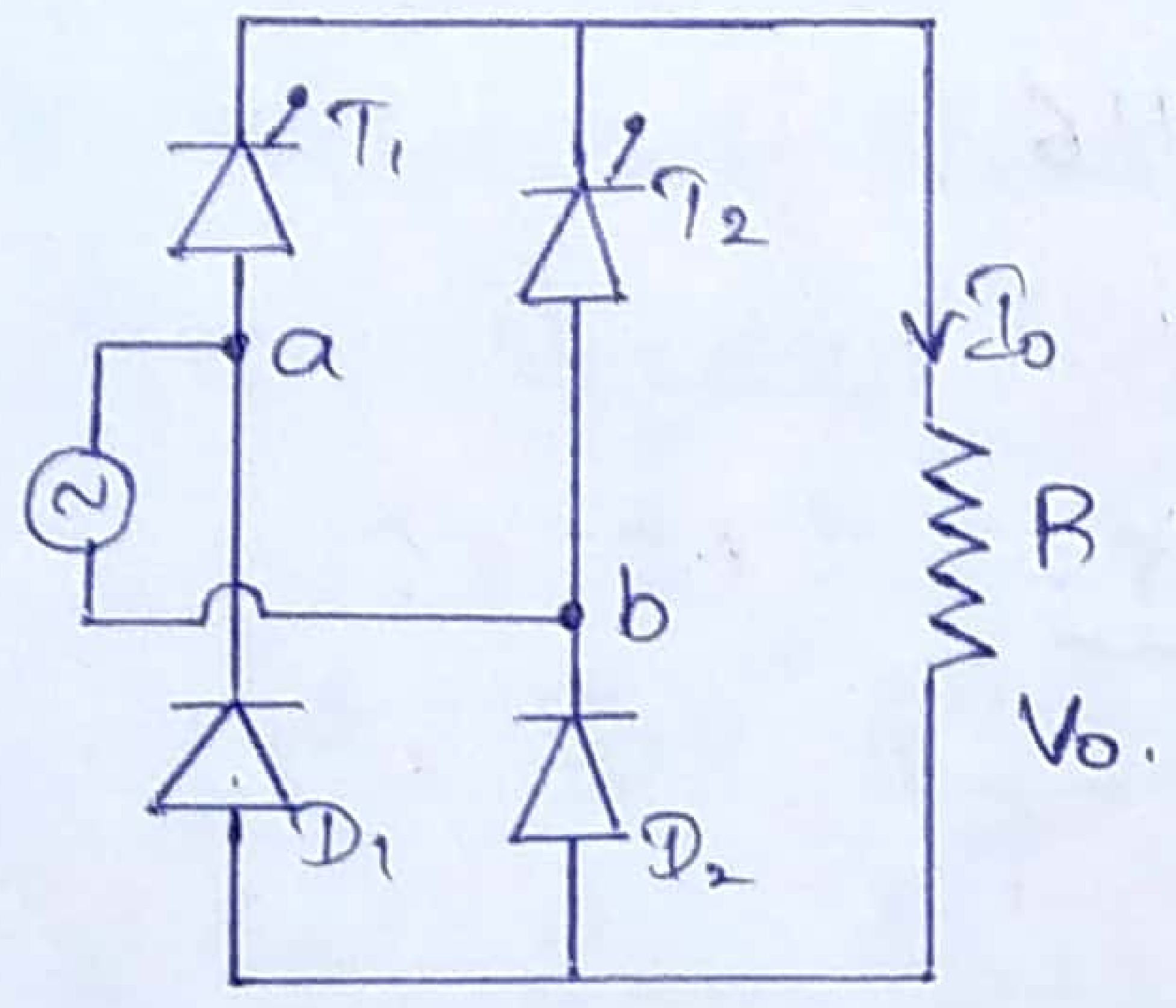
(a) Symmetrical

(b) Asymmetrical.

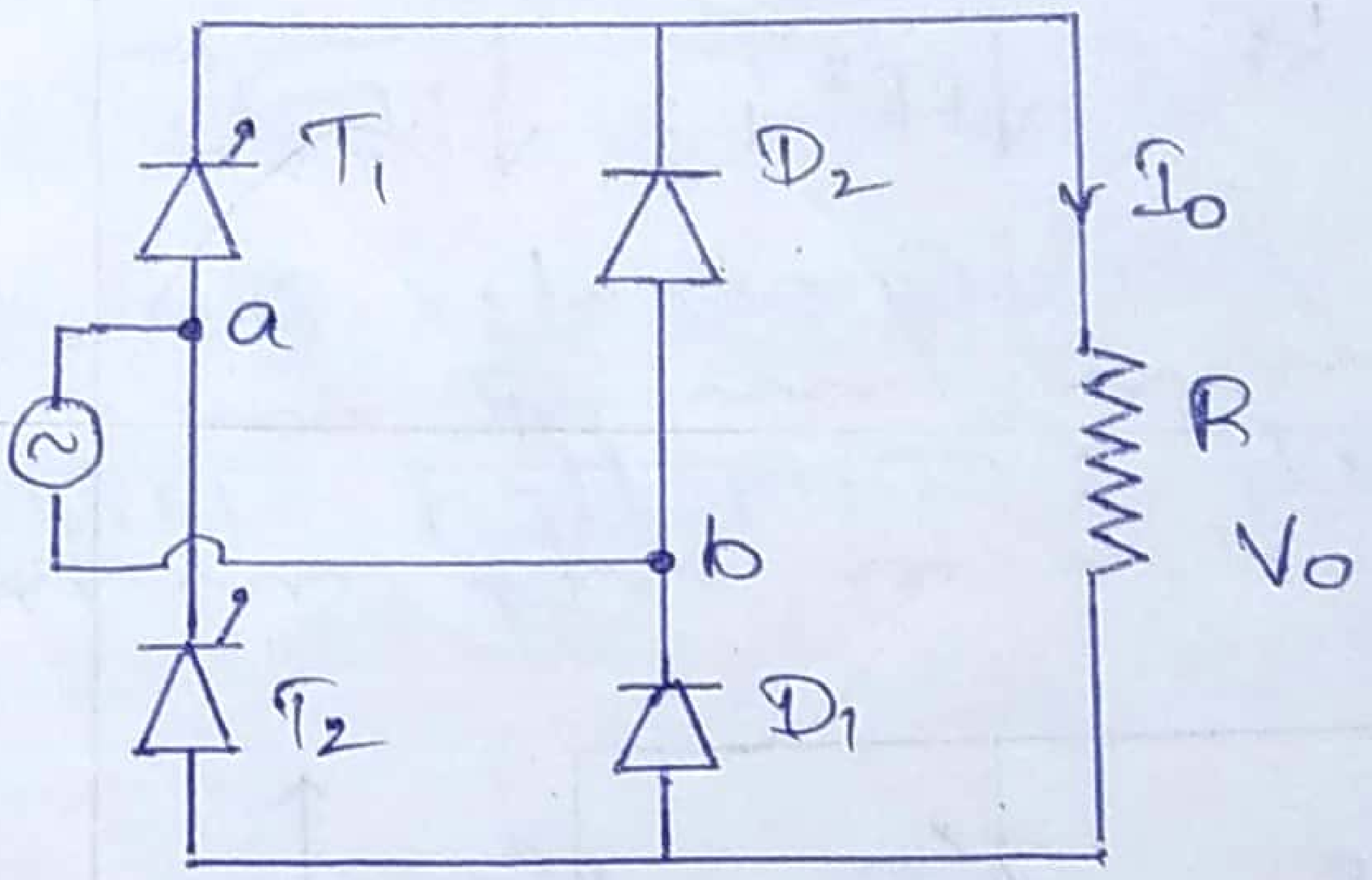
→ Symmetrical configuration of 1-ø Semi Converter employs one SCR and one Diode in each leg.

→ Asymmetrical configuration of 1-ø semiconverter employs two SCR's in one leg and two Diodes in another leg.

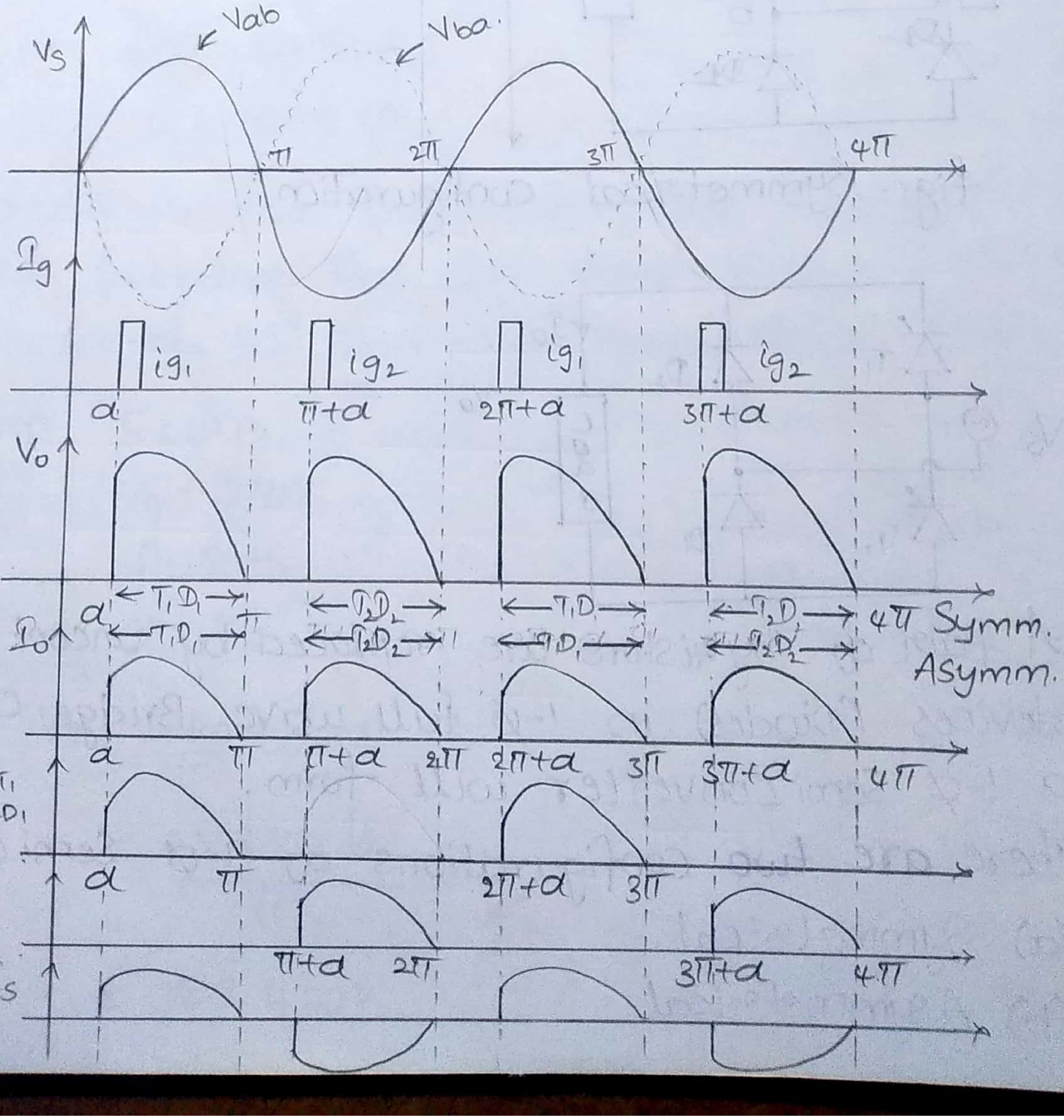
*** → 1-ø Semi Converter with R-Load:-



Asymmetrical conf.

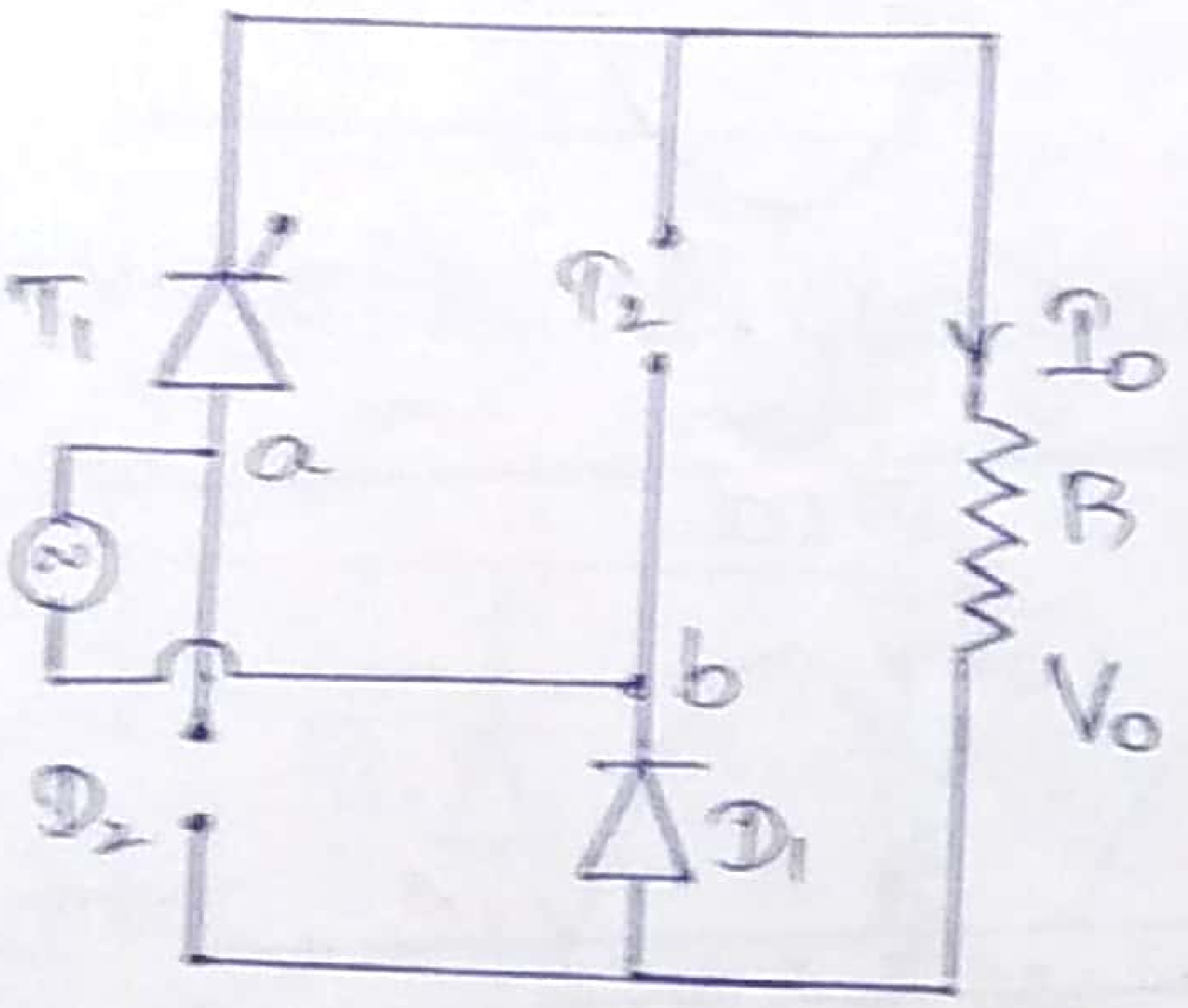


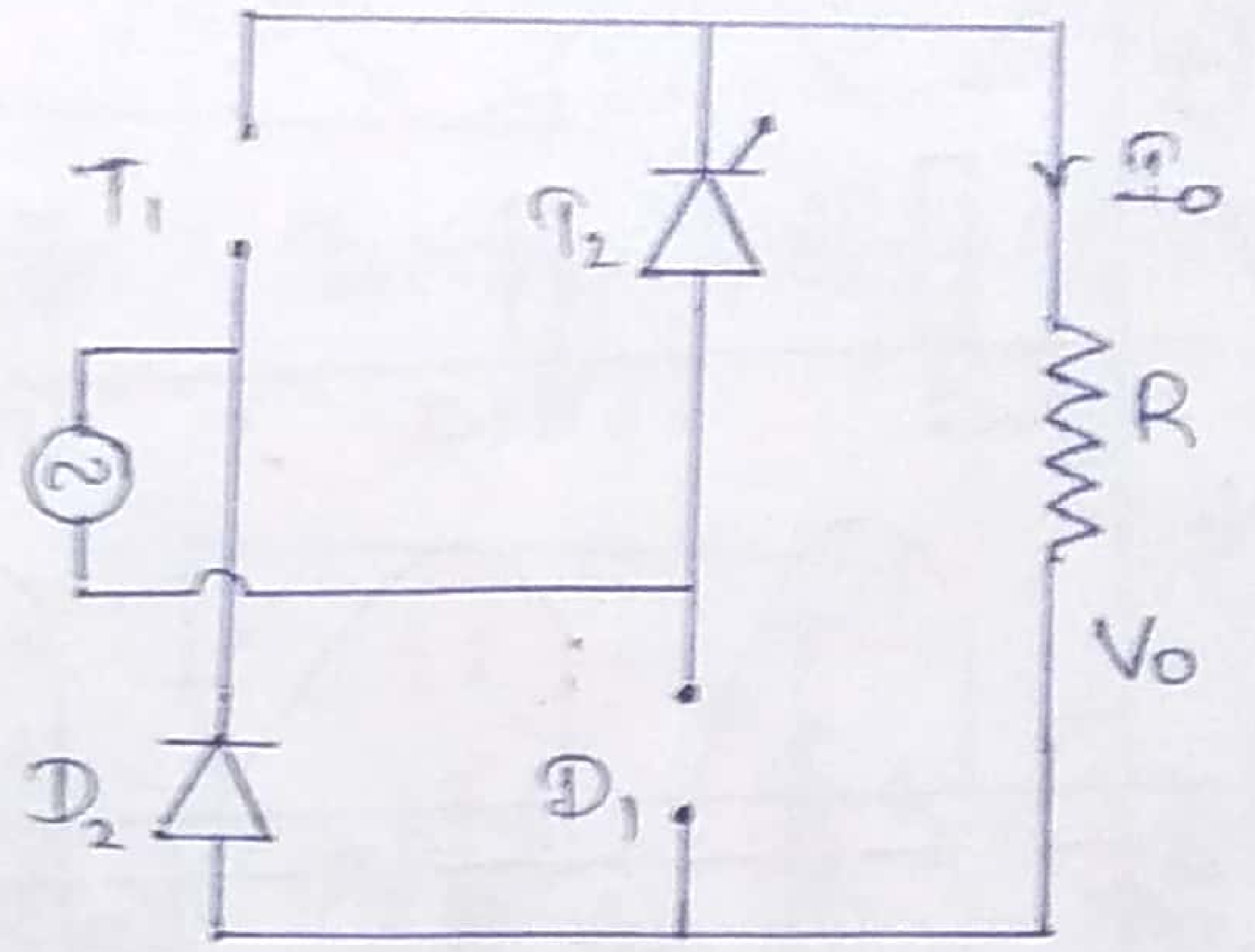
Symmetrical conf.



→ The load voltage wave form is exactly similar to 1-ø FWCR with R-Load. So, the formulaes for V_o, I_o, V_{orms}, I_{orms} are same as 1-ø FWCR with R-load.

→ operation:-

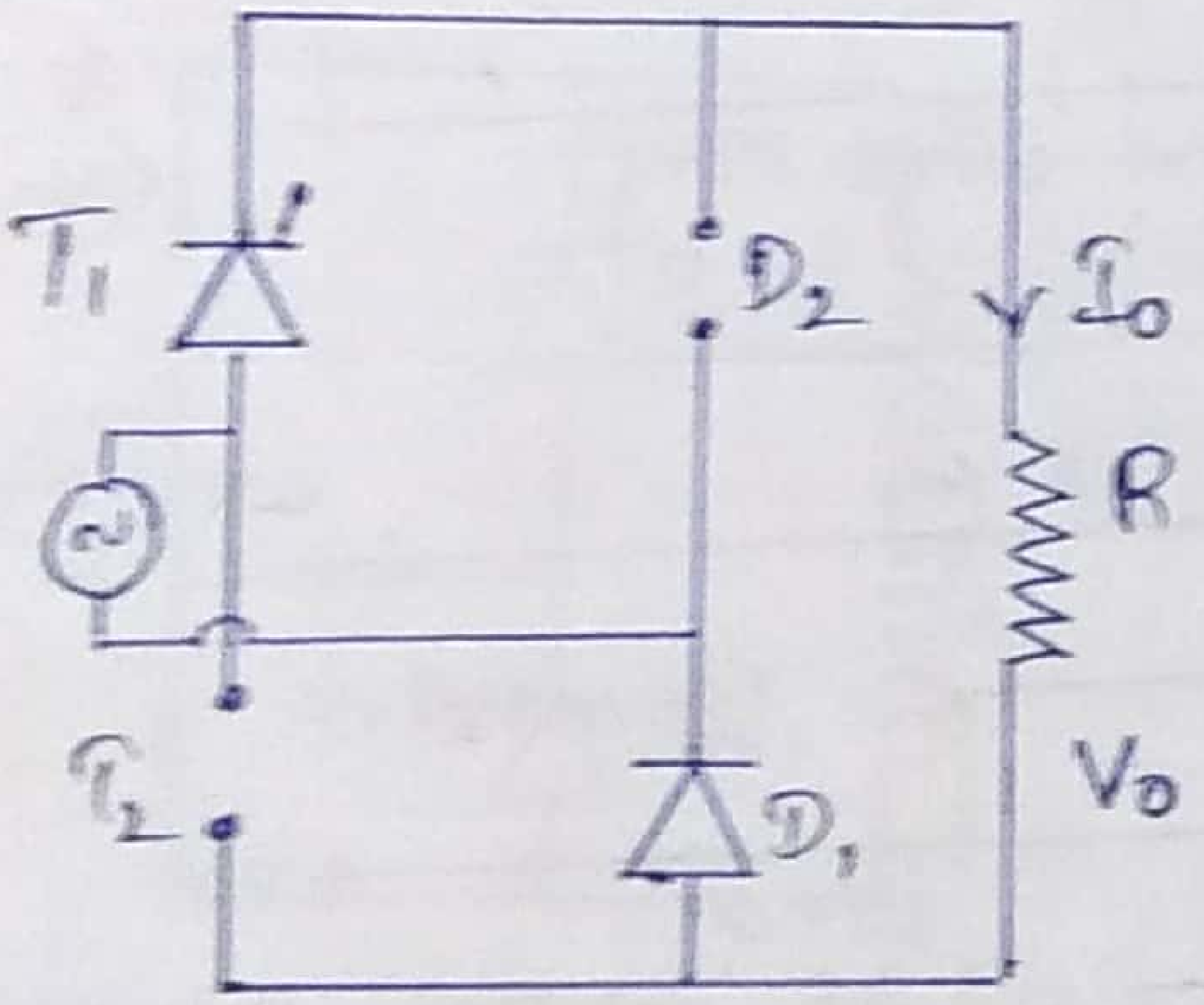


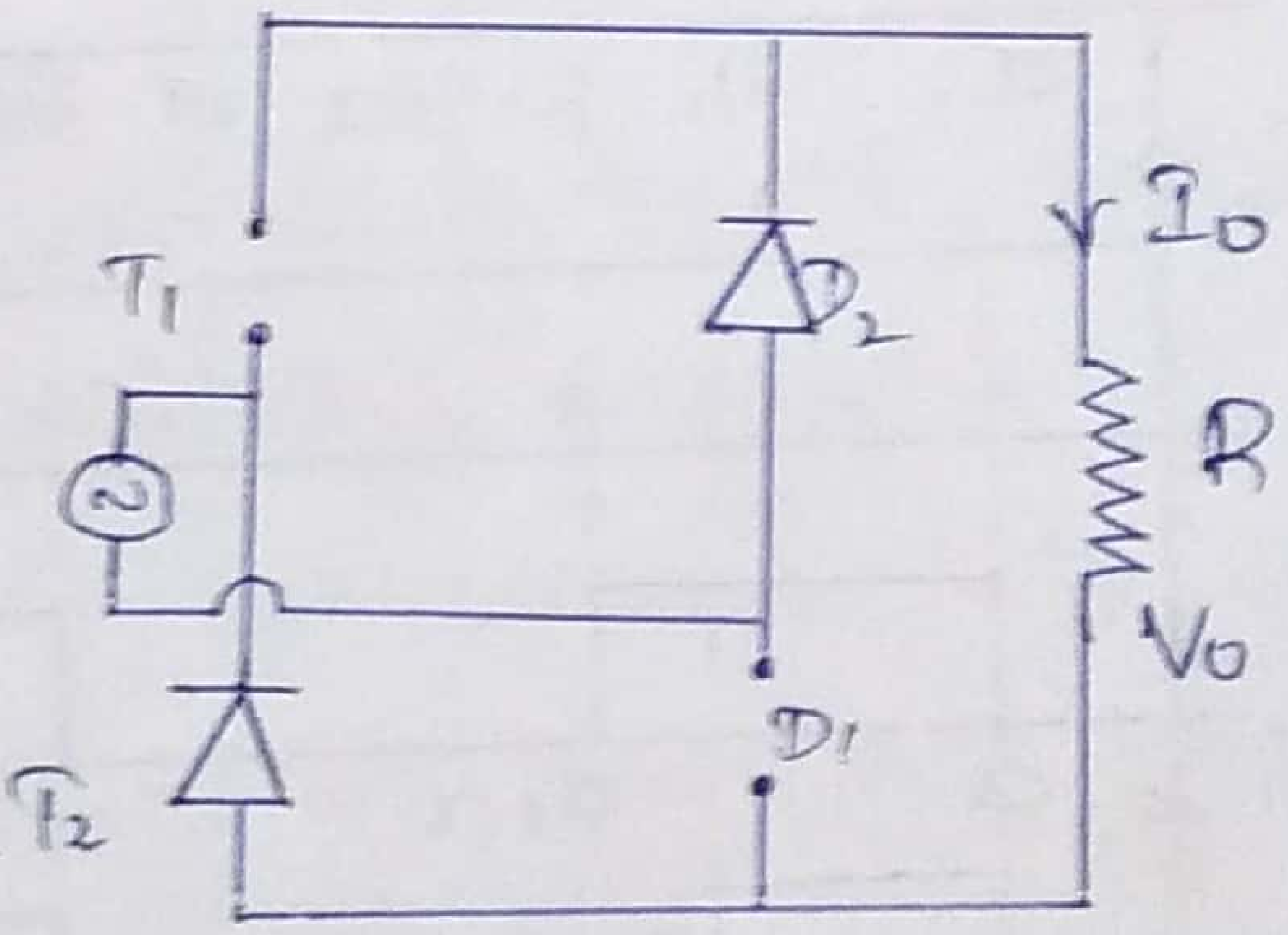


Symmetrical Configuration:-

During +HC:- $V_o = V_s$.
(V_{ab}). $I_s = I_o$.

During -HC:- $V_o = V_s$;
(V_{ba}) $I_s = -I_o$.



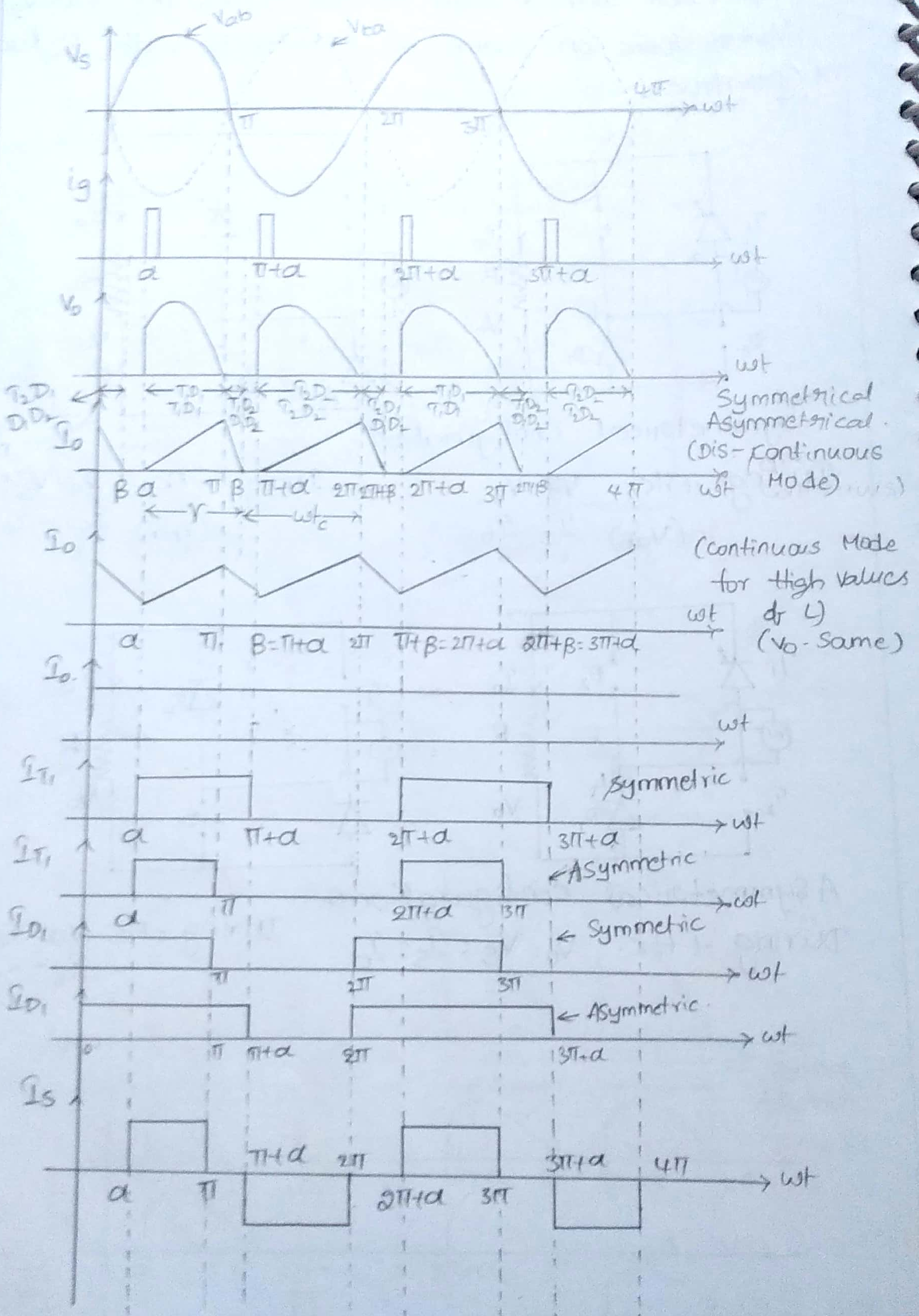


Asymmetrical configuration:-

During +H.C. $V_o = V_s$; $I_s = I_o$

During -HC $V_o = V_s$;
$I_s = -I_o$.

→ 1-ϕ Semiconverter with RL-Load :-



Symmetrical
Asymmetrical
(Dis-continuous Mode)

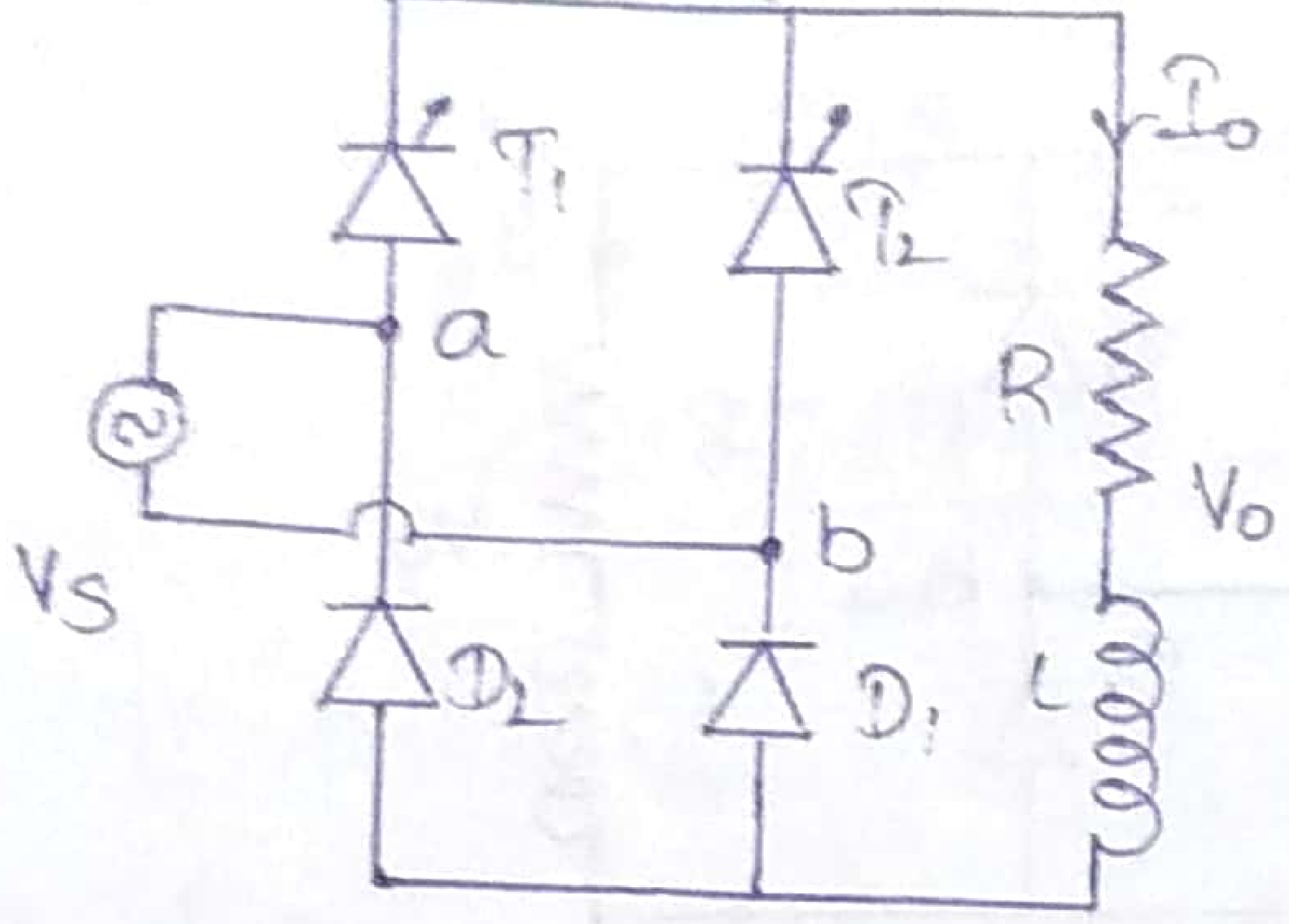
(continuous Mode for High values of L)
(V0 - Same)

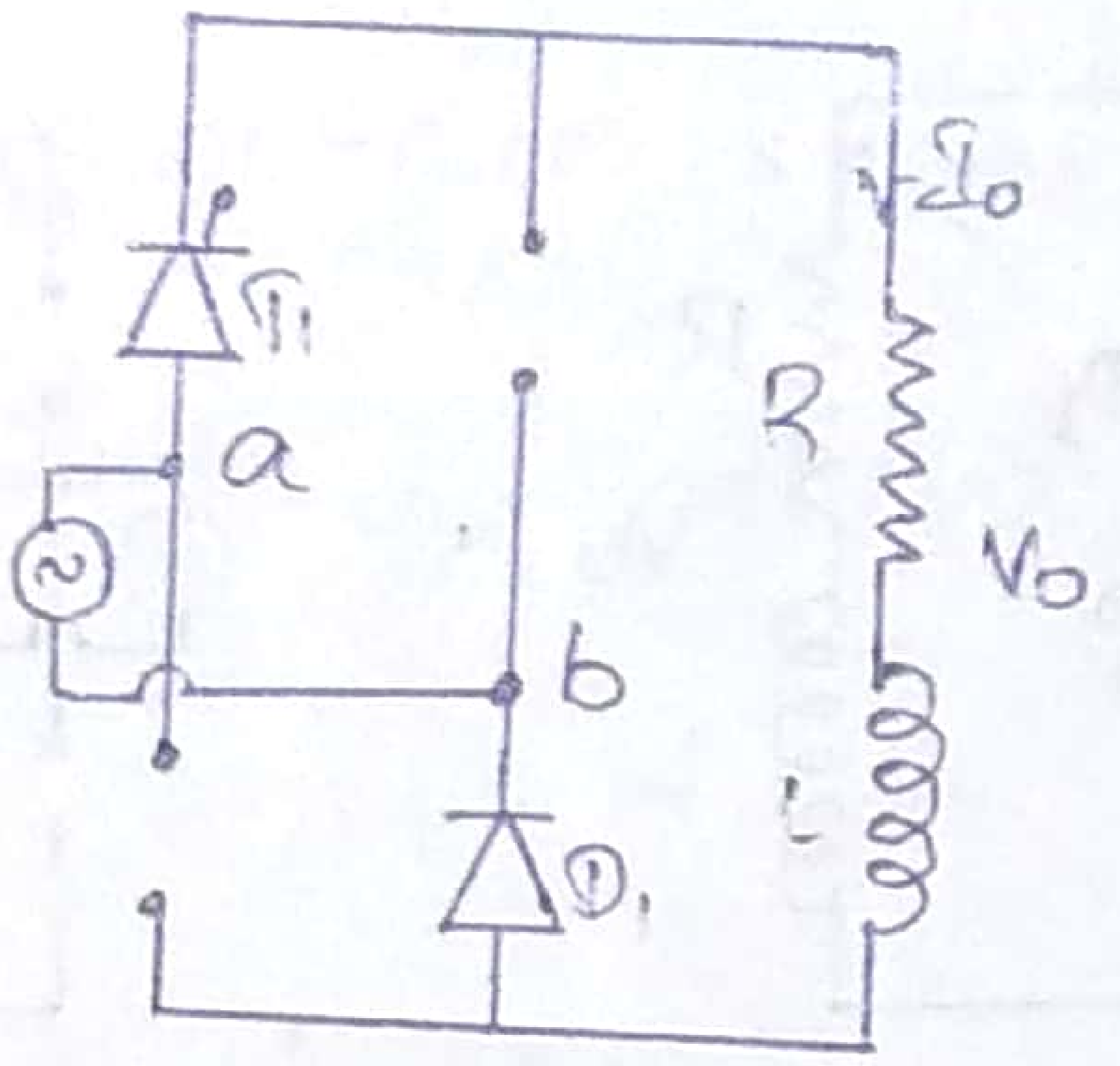
Symmetric

← Asymmetric

← Symmetric

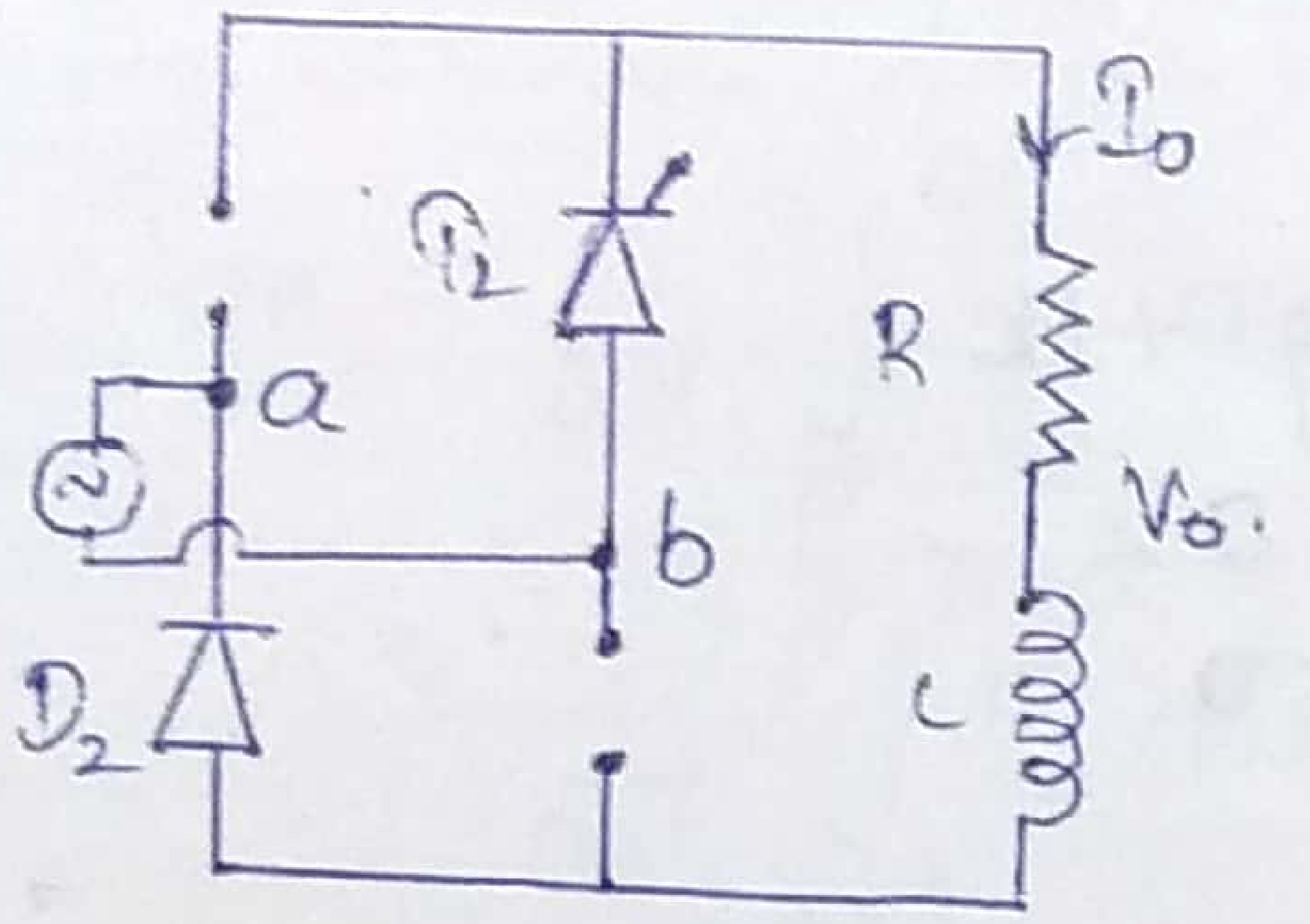
← Asymmetric

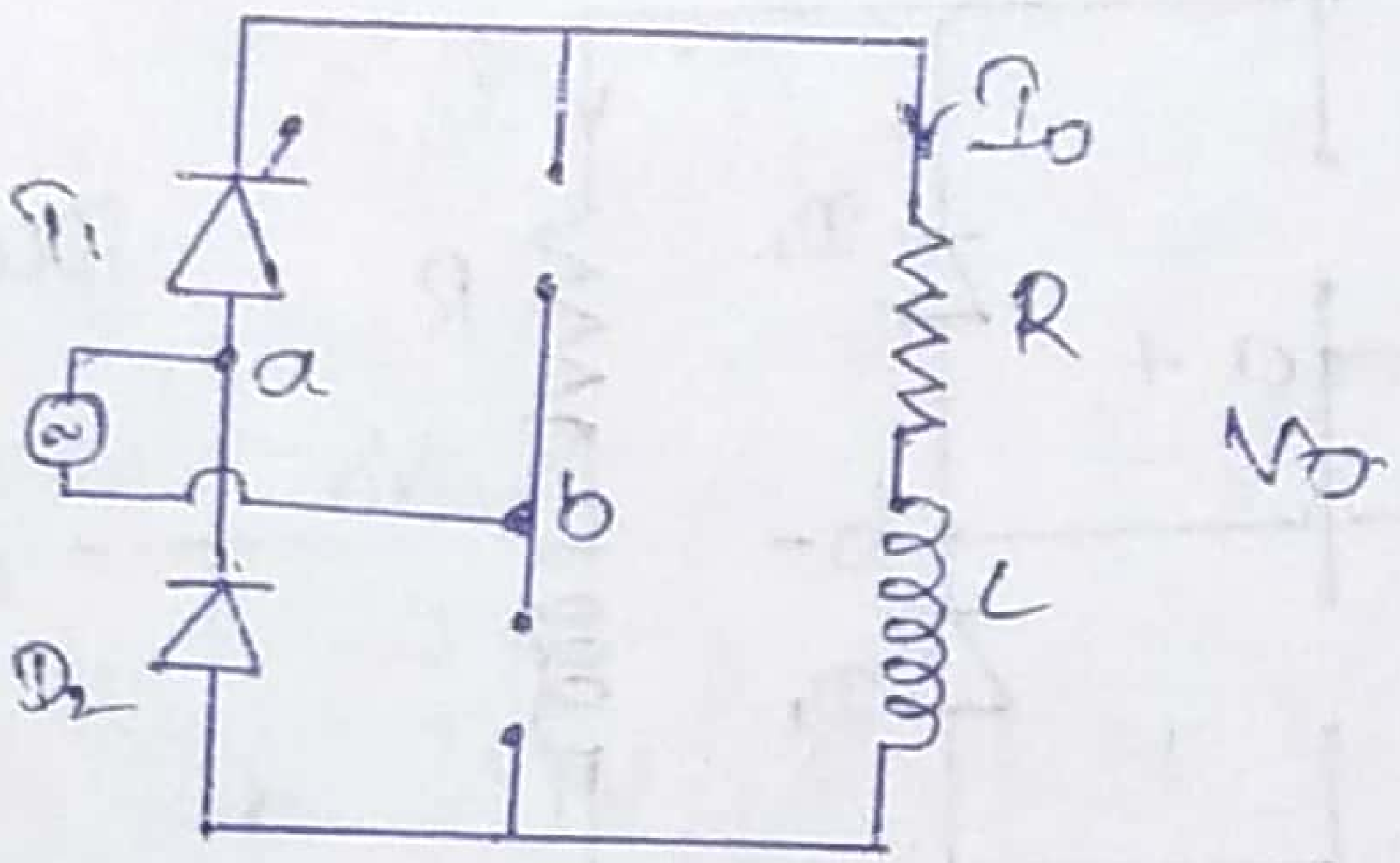




Symmetrical configuration. During +Hc; $V_0 = V_s$

$I_s = I_0$

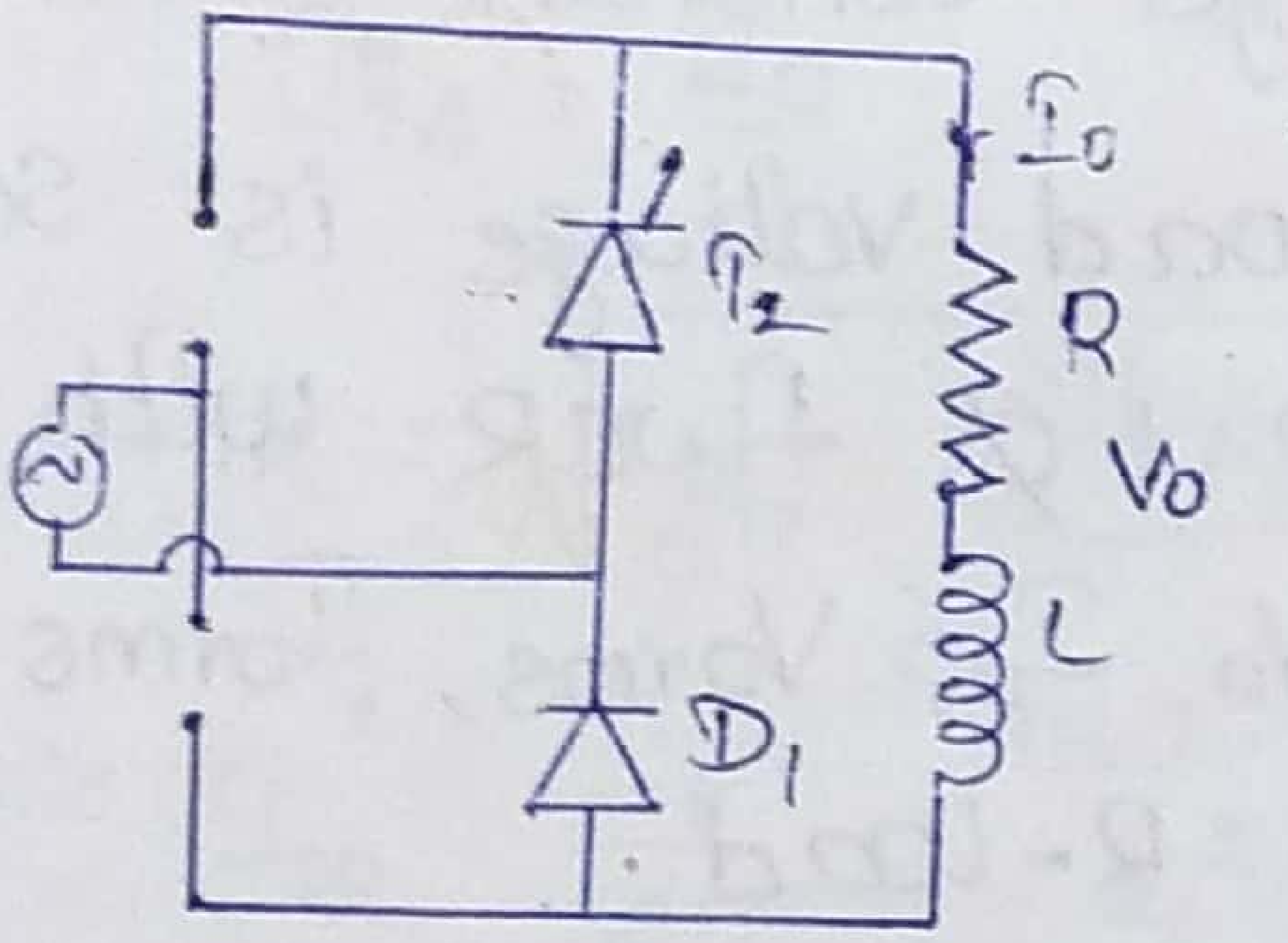




During -Hc:- $I_s = -I_0$.

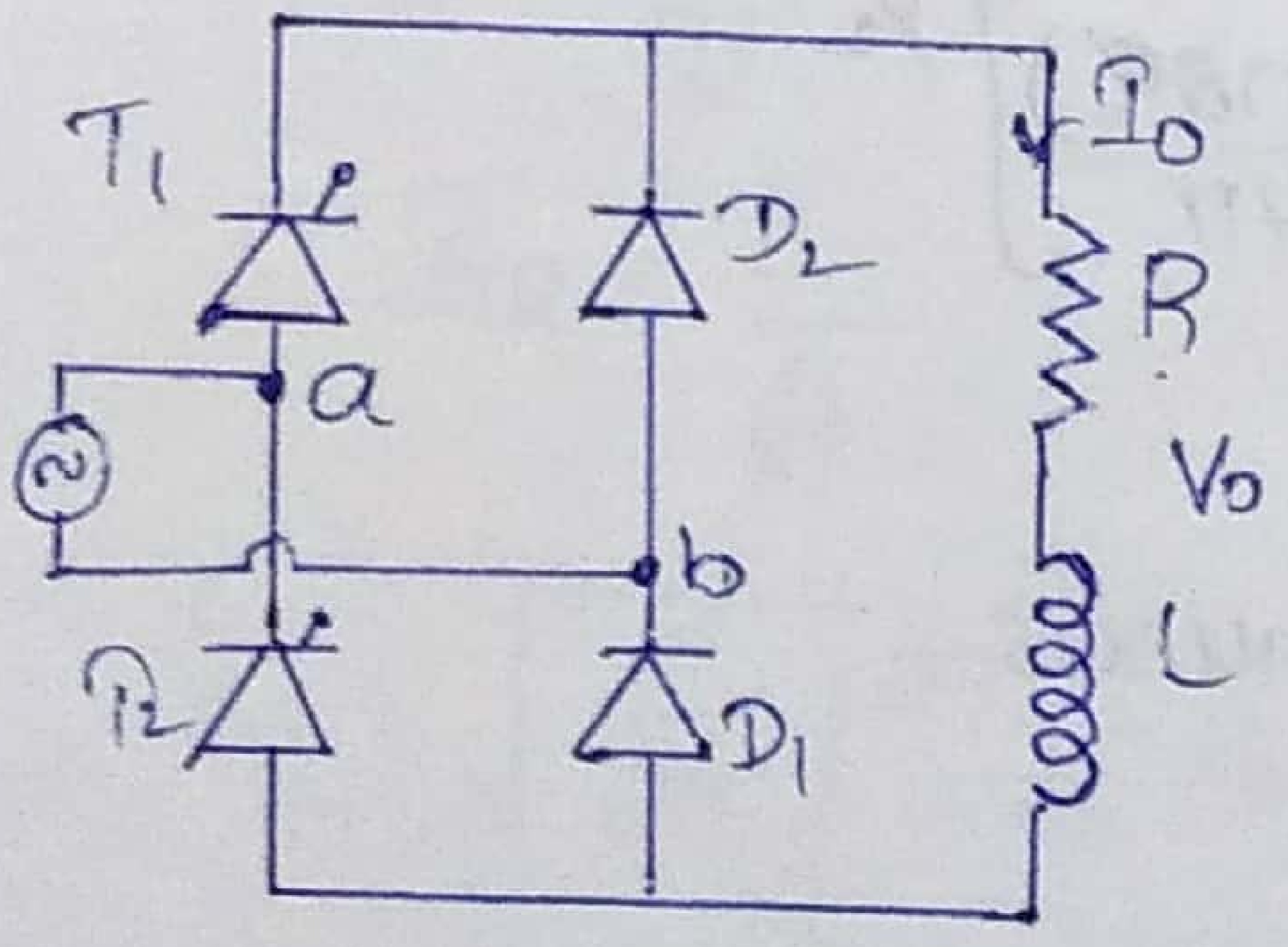
$V_0 = V_s$.

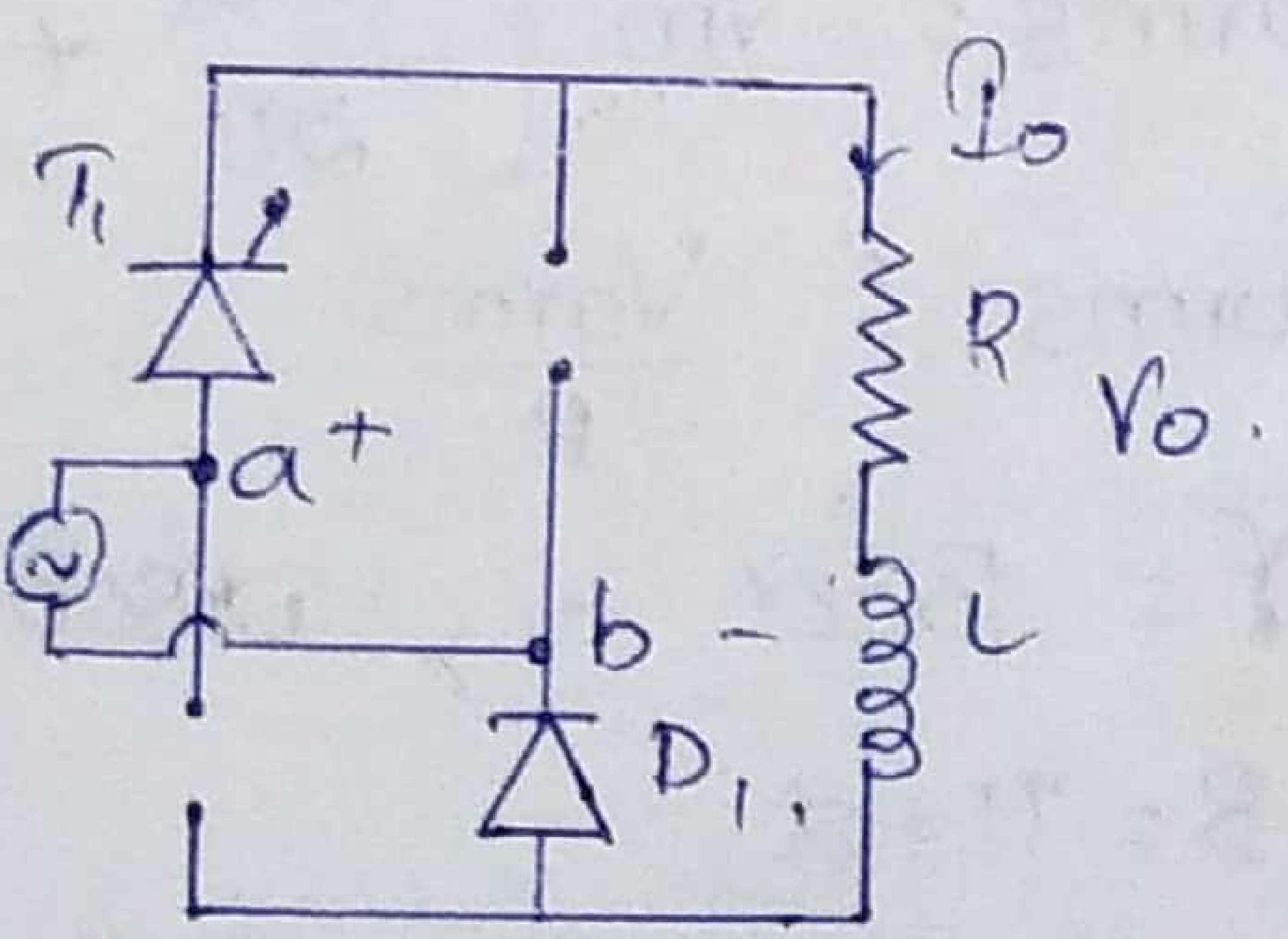
During -Hc $V_0 = 0$; $I_s = 0$.



During +Hc :- $V_s = 0$; $I_s = 0$.

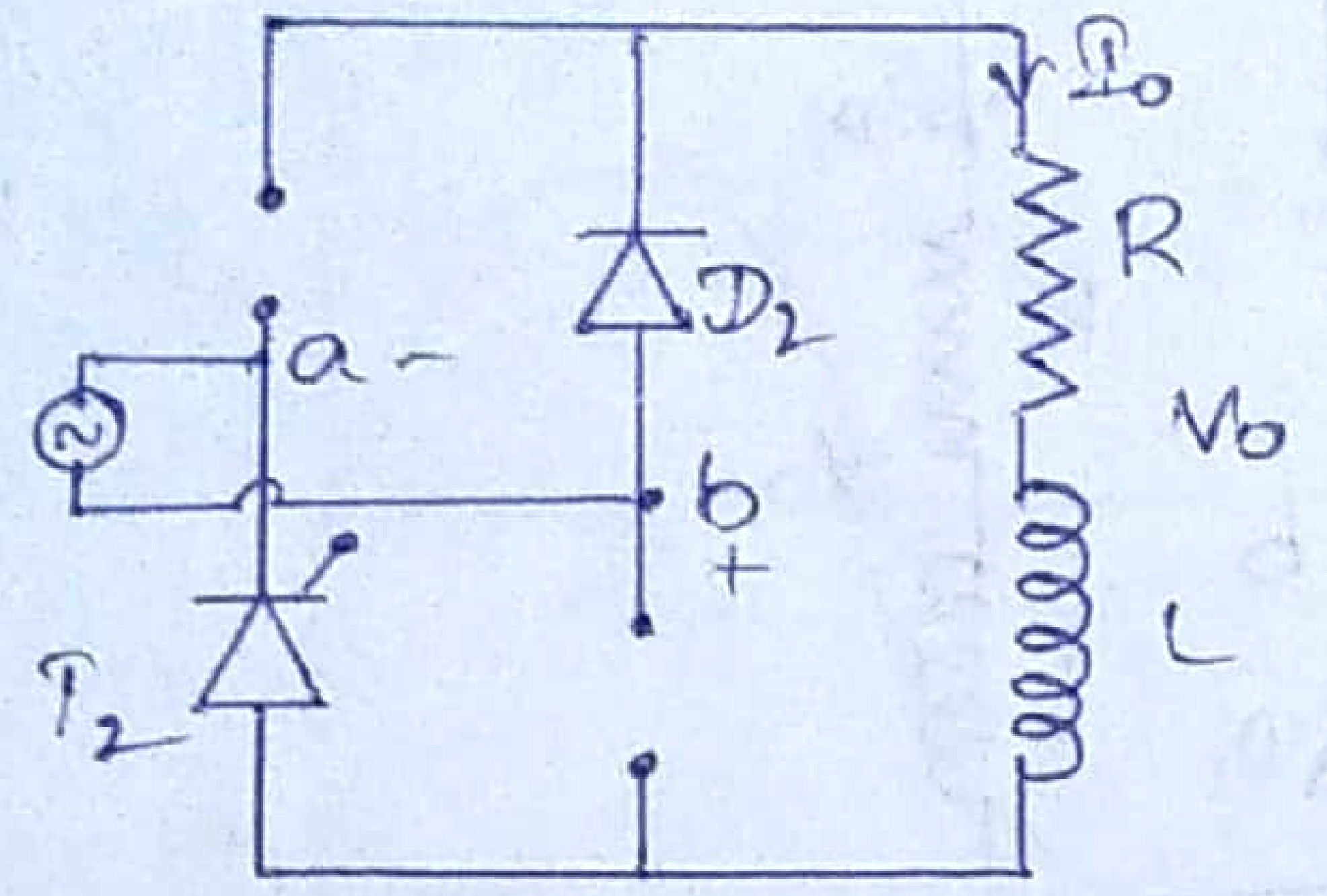
→ A Symmetrical configuration :-



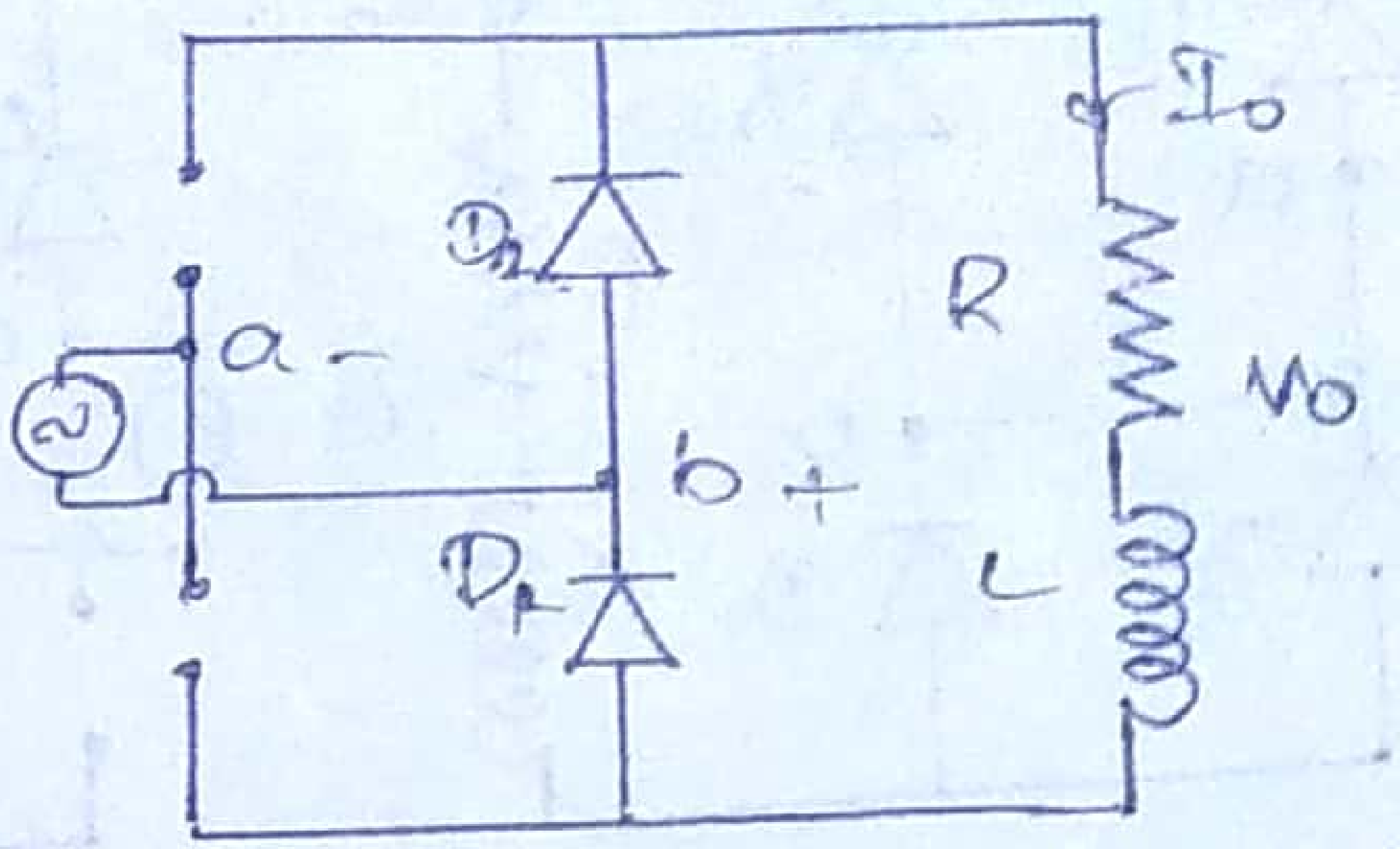


During +Hc :- $V_0 = V_s$; $I_s = I_0$

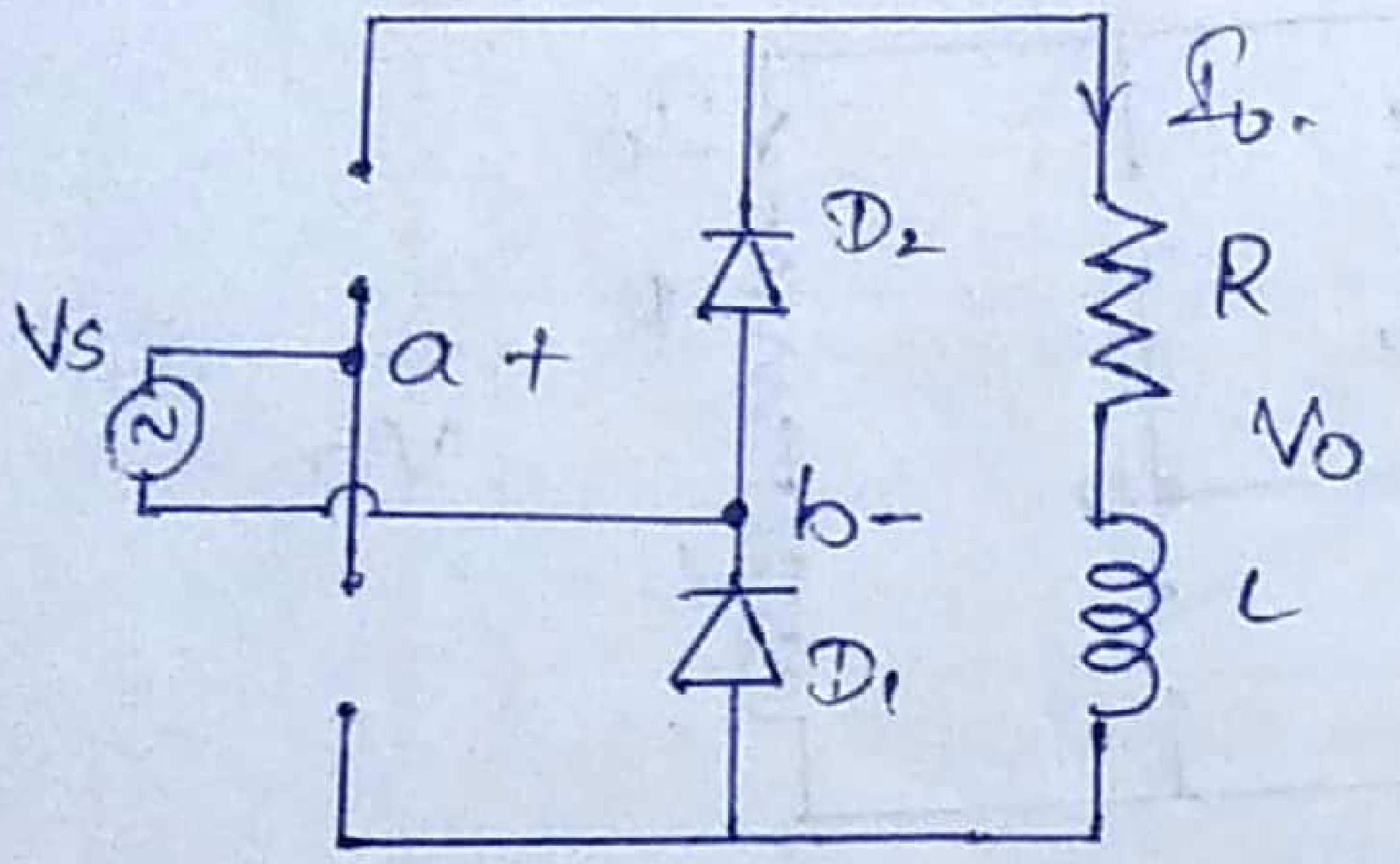
Vab



During -ve ;
$V_0 = V_s$; $I_s = I_0$



During -ve :- $V_0 = 0$; $I_s = 0$.



During +ve.
$V_0 = 0$;
$I_s = 0$.

→ By increasing Inductance value, charging & discharge periods increases and we get constant load current.

→ In the three cases the load voltage is same & it is exactly similar to 1-ø FWCR with R-load. So, the formulaes for V_0, I_0, V_{orms}, I_{orms} are same as 1-ø FWCR with R-load.

(1) $V_0 = \frac{V_m}{\pi}(1+\cos\alpha)$

(2) $I_0 = \frac{V_0}{R}$

(3) $V_{orms} = V_m\left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha)}{4\pi}\right]^{1/2}$

(4) $I_{orms} = \frac{V_{orms}}{R}$

(5) $\gamma = \beta - \alpha$ → Discontinuous

$\beta = \pi + \alpha$

⇒ $\gamma = \pi$ → Continuous.

$$\Rightarrow I_S^2 = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} I_0^2 \cdot d\omega t + \int_{\pi+\alpha}^{2\pi} I_0^2 \cdot d\omega t\right]$$

$$= \frac{I_0^2}{2\pi}\left[(\pi-\alpha) + (2\pi-\pi-\alpha)\right]$$

$$= \frac{I_0^2}{2\pi}\left[(\pi-\alpha)+(\pi-\alpha)\right]$$

$$= \frac{2I_0^2}{2\pi}(\pi-\alpha)$$

$$*/ I_S = I_0\left(\frac{\pi-\alpha}{\pi}\right)^{1/2} \cdot /*$$

(11) Input pf $= \frac{V_{orms} \cdot I_{orms}}{V_S \cdot I_S}$

for High Values of L.

$V_{orms} \cdot I_{orms} = V_0 I_0.$

$$*/ I_p \text{ pf} = \frac{V_0 I_0}{V_S I_S} /*$$

→ Asymmetrical Configuration:-

(8)+(4) $I_{TA} = \frac{1}{2\pi}\int_0^{2\pi} I_T \cdot d\omega t$

$$= \frac{1}{2\pi}\int_{\alpha}^{\pi} I_0 \cdot d\omega t$$

$$= \frac{I_0}{2\pi}(\pi-\alpha)$$

$$\therefore I_{TA} = I_0\left(\frac{\pi-\alpha}{2\pi}\right)$$

(13) $I_{TR} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_T^2 \cdot d\omega t}$

$$\Rightarrow I_{TR}^2 = \frac{1}{2\pi}\int_{\alpha}^{\pi} I_0^2 \cdot d\omega t$$

$$= \frac{I_0^2}{2\pi}(\pi-\alpha)$$

$$\therefore I_{TR} = I_0\left(\frac{\pi-\alpha}{2\pi}\right)^{1/2}$$

(10) $I_S = I_0\left(\frac{\pi-\alpha}{\pi}\right)^{1/2}$; $pf = \frac{V_0 I_0}{V_S \cdot I_S}$

→ Note:-

→ If free wheeling Diode-D is connected across the load, the load current freewheels through free wheeling Diode-D instead of D_1D_2 and T_2D_1. (Symmet) and D_1D_2 and D_1D_2 (Asymmetrical)

→ Diff b/w Symmetrical and Asymmetrical Configurat

Symmetrical.	Asymmetrical.
→ one SCR and one Diode is present in each leg.	→ Two SCR's are present in one leg and two Diodes are present in another leg.
→ SCR's and Diodes conduct for equal duration (π).	→ SCR conducts for shorter duration ($\pi-\alpha$) than Diodes ($\pi+\alpha$).
→ Inherent free wheeling Action takes place through one SCR and one Diode	→ Inherent freewheeling Action takes place through two Diodes.
→ SCR's are driven with common cathode.	→ SCR's must have isolated cathode.

1-Ø Semiconverter feeds an RL-Load, R=7.5Ω and L= very large provides ripple free load current, the converter is supplied by 120V, 50 Hz. find V_0, I_0, Pf, α=60°.

Given, L= Very large

R=7.5Ω

V=120V

$\alpha = 60^\circ$: $f = 50\,Hz$

(1) $V_0 = \frac{V_m}{\pi}(1+\cos\alpha)$

$= \frac{120\times\sqrt{2}}{\pi}(1+\cos 60^\circ)$

$= 81.02V$

(2) $I_0 = \frac{V_0}{R} = \frac{81.02}{7.5} = 10.8\,A$

(3) $pf = \frac{V_0 I_0}{V_S I_S}$.

$\therefore I_S = I_0\left[\frac{\pi-\alpha}{\pi}\right]^{1/2}$

$= 10.8\left[\frac{\pi - 60\left(\frac{\pi}{180}\right)}{\pi}\right]^{1/2} = 8.81A$

$\Rightarrow pf = \frac{V_0 I_0}{V_S I_S} = \frac{81.02\times10.8}{120\times8.81} = 0.827$ lags.

* Repeat the above prblm with same data for 1-φ FWCR.

Sol:- (1) $V_0 = \frac{2V_m}{\pi}(\cos\alpha)$

$= \frac{2\times\sqrt{2}\times120}{\pi}\times0.5 = 54.01\,V$

(2) $I_0 = \frac{V_0}{R} = \frac{54.01}{7.5} = 7.202\,A$

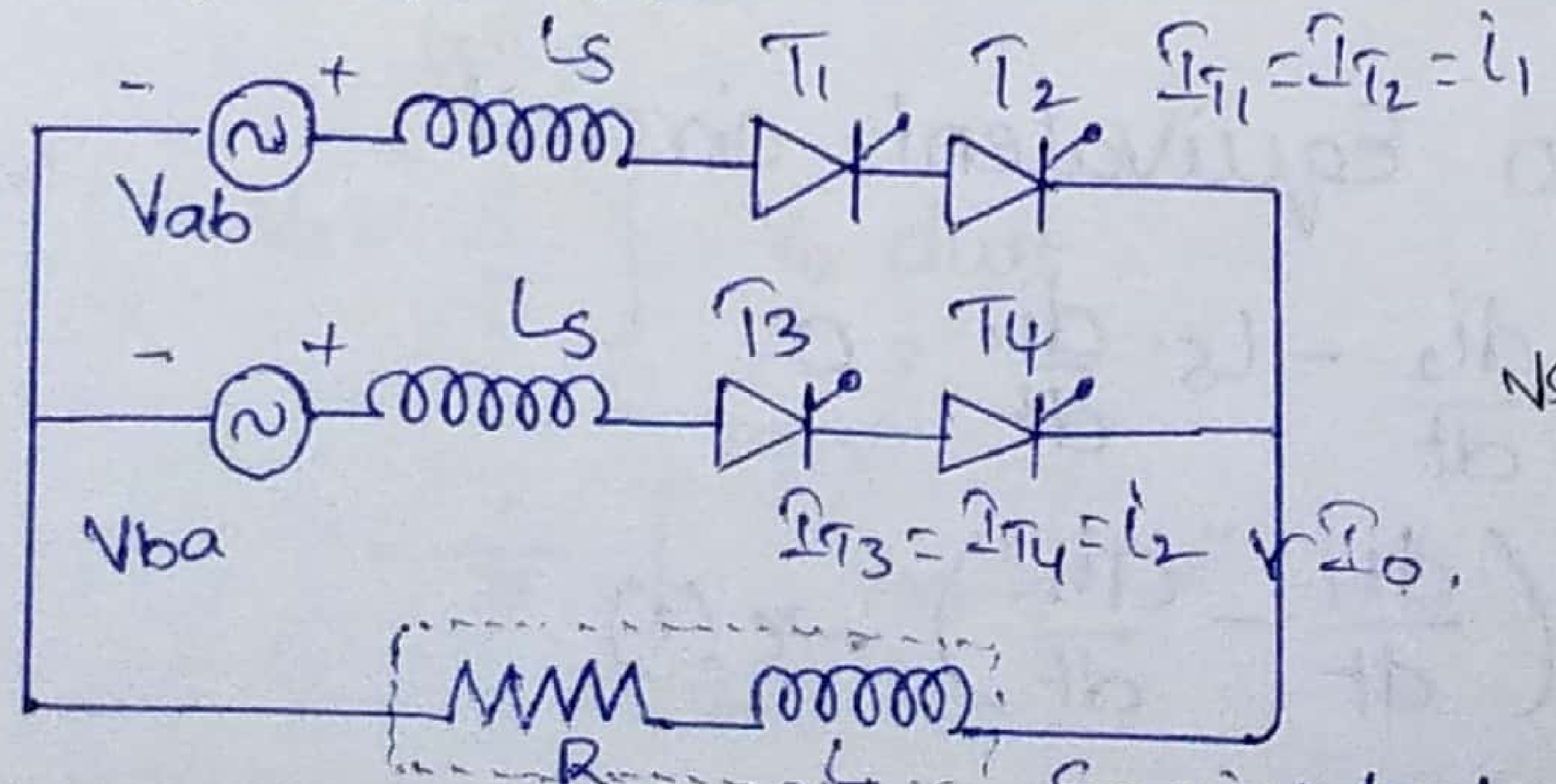
(3) $pf = \frac{V_0 I_0}{V_S I_S}$ $(I_S = I_0)$

$= \frac{54.01}{120} = 0.45$ lags.

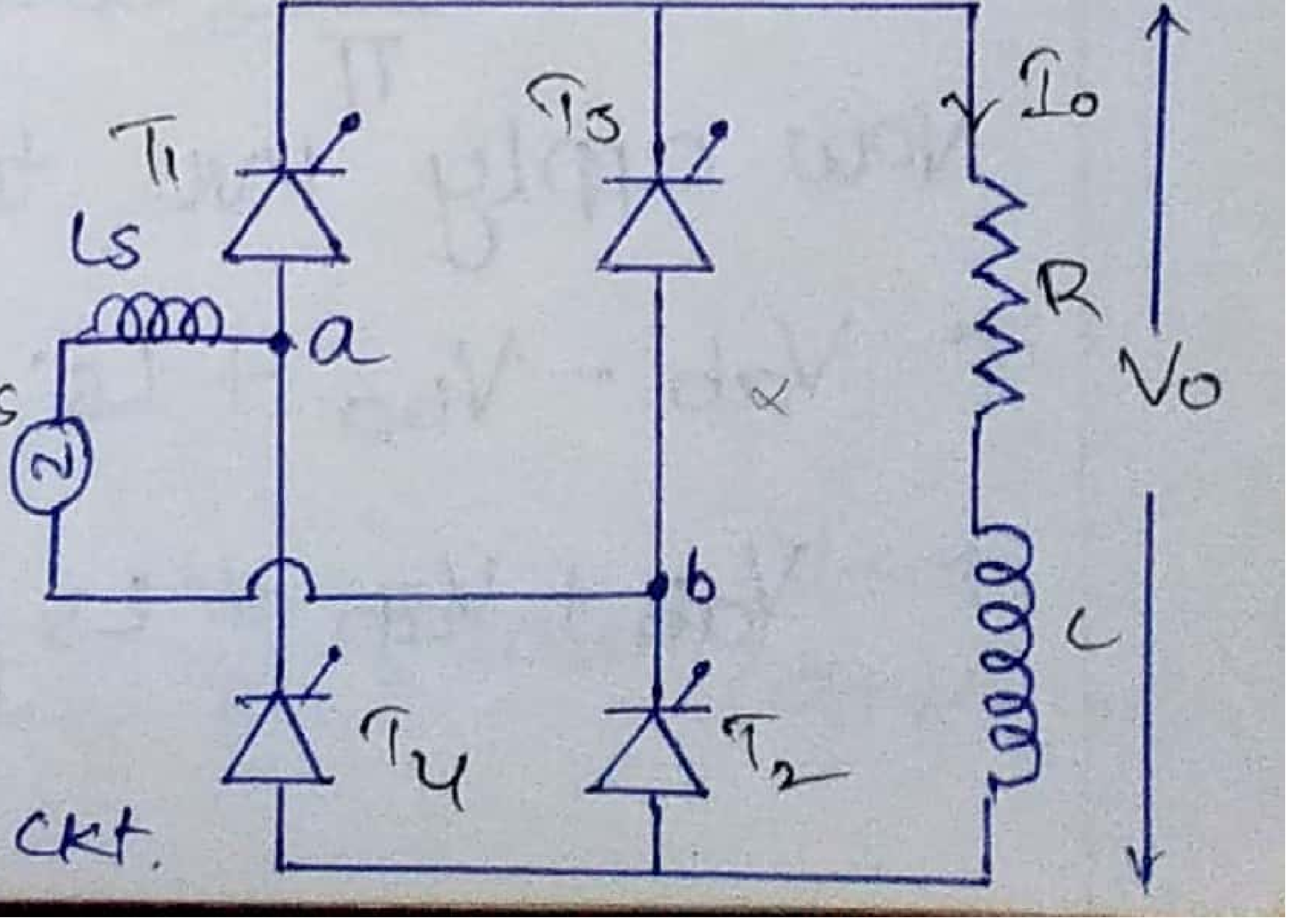
*** Diff b/w Half controlled converter & Full converter:-

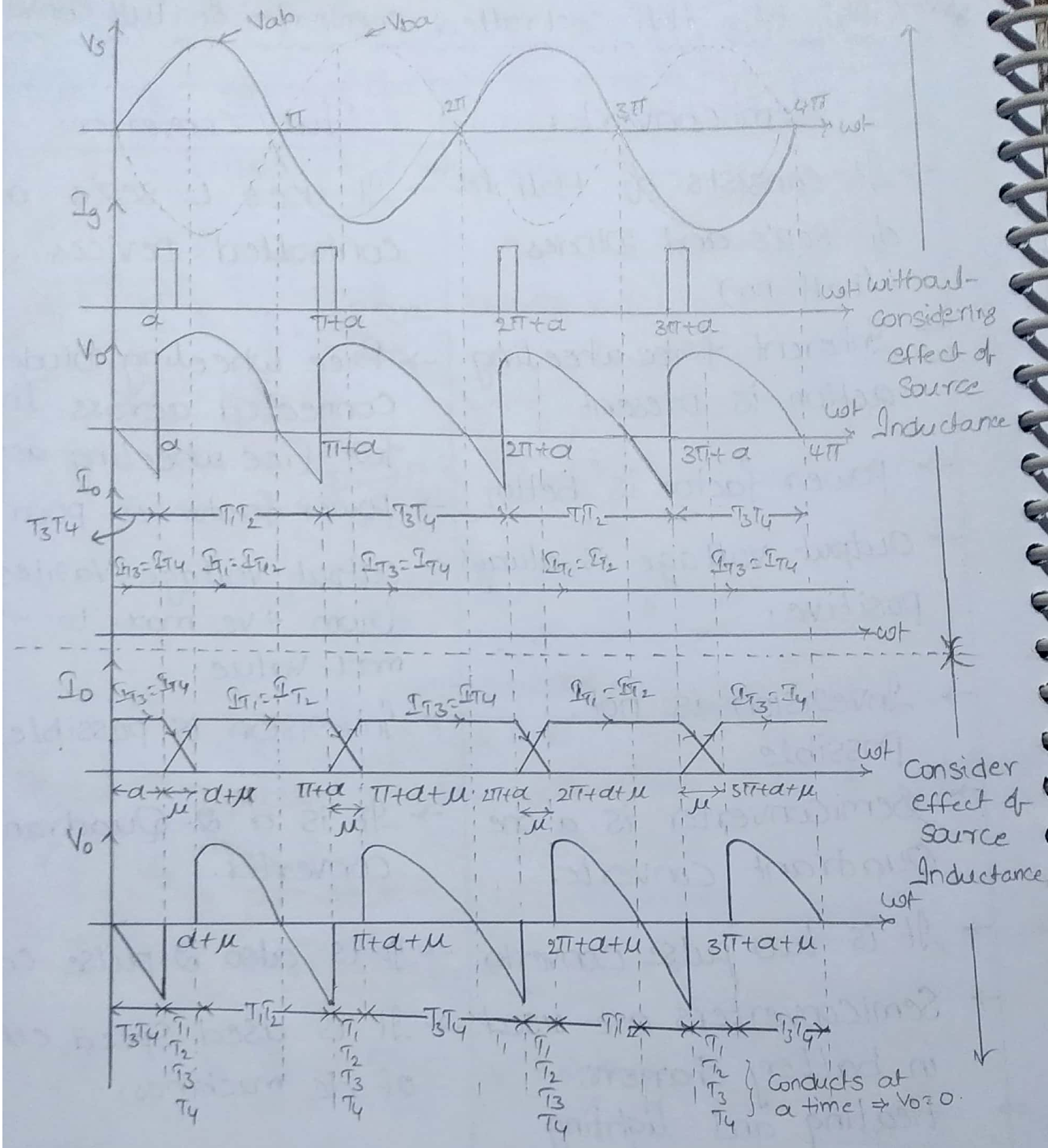
Semi converter	Full Converter.
→ It consists of Half no. of SCR's and Diodes. (half no.)	→ It uses 4 SCR's as controlled Devices.
→ Inherent free wheeling action is present.	→ free wheeling Diode is connected across load for free wheeling action.
→ Power factor is bettor	→ Power factor is poor.
→ Output voltage is always positive.	→ output voltage varies from +ve max. to -ve max. value.
→ Inversion is not possible	→ Inversion is possible.
→ Semiconverter is a one Quadrant converter.	→ It is a 2-Quadrant converter.
→ It is two pulse converter.	→ It is also 2 pulse conv.
→ Semiconverters are used in battery chargers, Heating and lighting control.	→ It is used speed control of dc machines.

*** Effect of Source Inductance:-



Equivalent ckt.





→ Assume High value of Inductance in Load.

$$V_o = \frac{2V_m}{\pi}\cos\alpha$$ → without Source Inductance

Now apply KVL to Equivalent circuit,

$$\Rightarrow V_{ab} - V_{ba} + L_s\cdot\frac{di_2}{dt} - L_s\cdot\frac{di_1}{dt} = 0$$

$$\Rightarrow V_{ab} + V_{ab} = L_s\left(\frac{di_1}{dt} - \frac{di_2}{dt}\right) \rightarrow (1)$$

from fig(2)

$i_1 + i_2 = I_0$.

$\Rightarrow \frac{di_1}{dt} + \frac{di_2}{dt} = 0$.

$\Rightarrow \frac{di_2}{dt} = -\frac{di_1}{dt} \rightarrow (2)$.

Put (2) in (1)

$\Rightarrow \cancel{2}V_{ab} = L_s \cdot \cancel{2}\frac{di_1}{dt}$

$\Rightarrow V_m \sin\omega t = L_s \cdot \frac{di_1}{dt}$

$\Rightarrow di_1 = \frac{V_m}{L} \sin\omega t \cdot dt$

At $\omega t = \alpha$; $i_1 = 0$.

$t = \frac{\alpha}{\omega}$

At $\omega t = \alpha + \mu$; $i_1 = I_0$; $t = \frac{\alpha+\mu}{\omega}$

$$\Rightarrow \int_0^{I_0} di_1 = \int_{\alpha/\omega}^{\frac{\alpha+\mu}{\omega}} \frac{V_m}{L_s} \cdot \sin\omega t \cdot dt$$

$$\Rightarrow I_0 = \frac{V_m}{L_s}\left(\frac{-\cos\omega t}{\omega}\right)_{\alpha/\omega}^{\frac{\alpha+\mu}{\omega}}.$$

$$\Rightarrow I_0 = \frac{V_m}{\omega L_s}\left[-\cos(\alpha+\mu) + \cos\alpha\right]$$

$$\Rightarrow I_0 = \frac{V_m}{\omega L_s}\left[\cos\alpha - \cos(\alpha+\mu)\right] \rightarrow (3)$$

Now, $V_0 = \frac{1}{\pi}\int_0^{\pi} V_0 \cdot d\omega t$.

$$= \frac{1}{\pi}\int_{\alpha+\mu}^{\pi+\alpha} V_m \sin\omega t \cdot d\omega t = \frac{V_m}{\pi}(-\cos\omega t)_{\alpha+\mu}^{\pi+\alpha}$$

⇒ $V_0 = \frac{V_m}{\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right] \rightarrow (4)$

∴ $V_0 = \frac{V_m}{\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right] \rightarrow (4)$

from Eqn. (3), $\cos\alpha = \frac{I_0\omega L_s}{V_m} + \cos(\alpha+\mu) \rightarrow (5)$

put Eqn. (5) in (4)

$$V_0 = \frac{V_m}{\pi}\left[2\cos(\alpha+\mu) + \frac{I_0\omega L_s}{V_m}\right]$$

∴ $V_0 = \frac{2V_m}{\pi}\cos(\mu+\alpha) + \frac{I_0\omega L_s}{\pi} \rightarrow (6)$

from Eqn. (3)

$$\cos(\alpha+\mu) = \cos\alpha - \frac{I_0\omega L_s}{V_m} \rightarrow (7)$$

put Eqn. (7) in Eqn. (4)

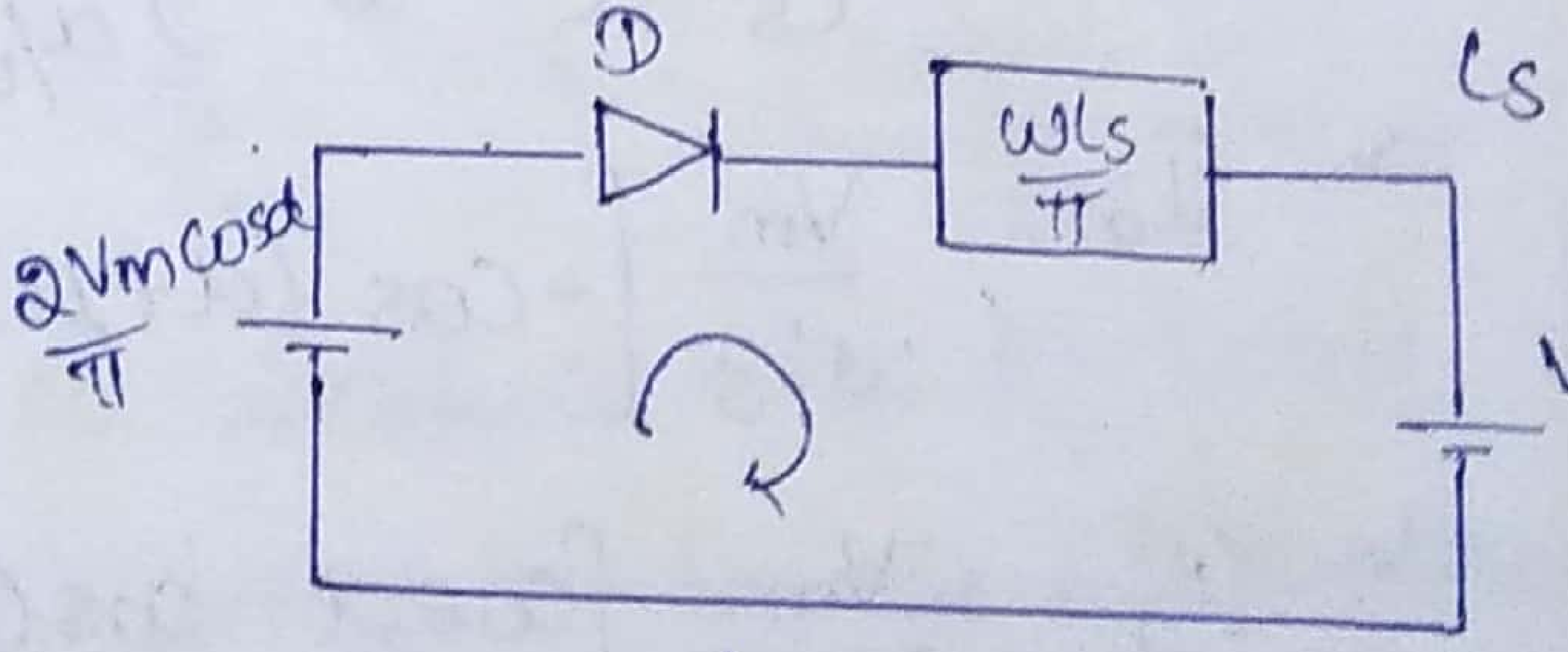
∴ $V_0 = \frac{V_m}{\pi}\left[2\cos\alpha - \frac{I_0\omega L_s}{V_m}\right]$

$$V_0 = \frac{2V_m}{\pi}\cos\alpha - \frac{I_0\omega L_s}{\pi} \rightarrow (8)$$

/ $V_0 = \frac{2V_m}{\pi}\cos\alpha - V_0$ (reduced) /

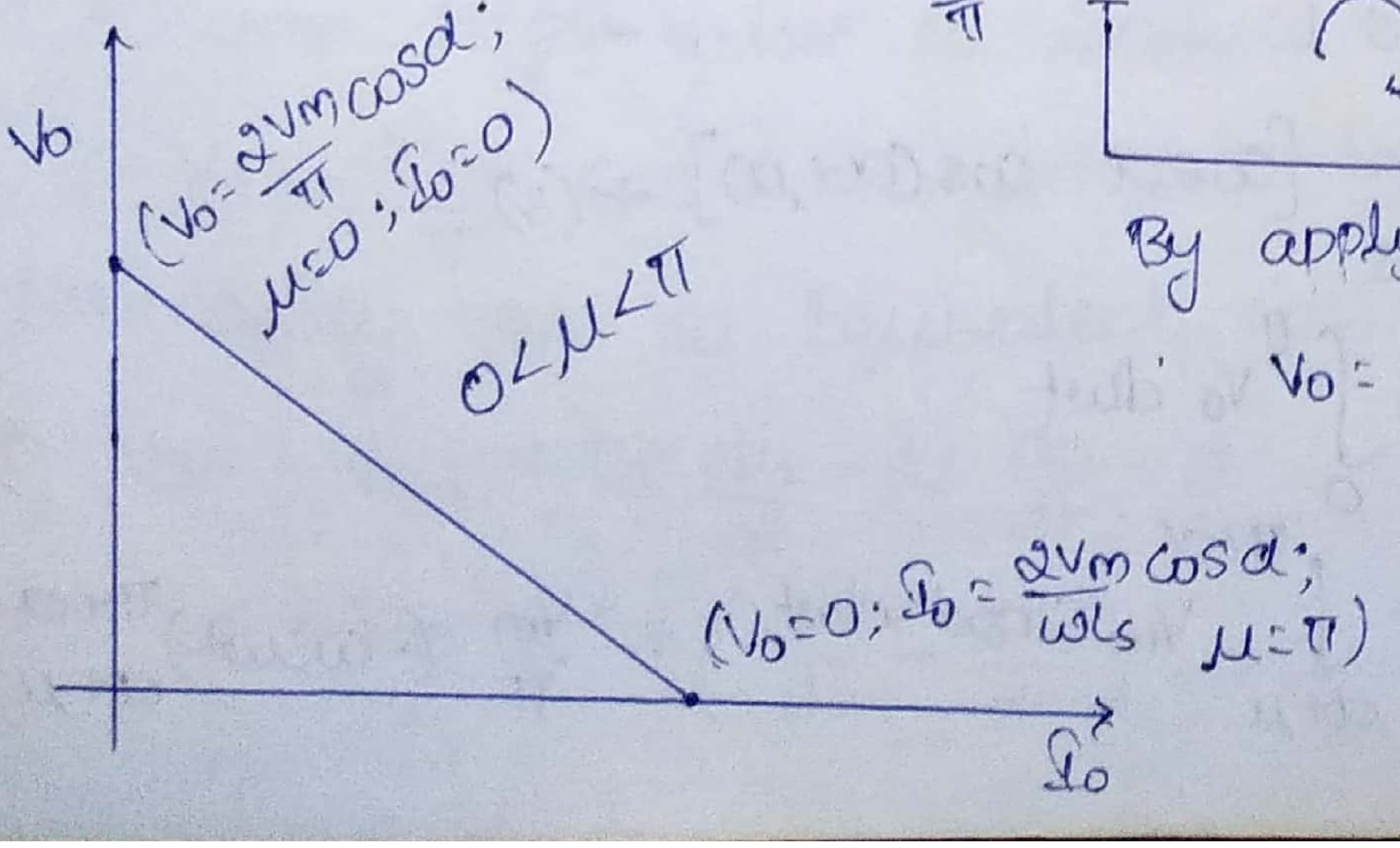
/ V_0 reduced $= \frac{\omega I_0 L_s}{\pi}$ /

DC Equivalent ckt of 1-ϕ FWBC with L_s



By applying KVL

$V_0 = \frac{2V_m}{\pi}\cos\alpha - V_0$ red



→ Source Inductance causes both incoming and outgoing SCR's conducts together. The period when both incoming and outgoing SCR's conducts together is called commutating period (or) overlapping period.

→ The Angle during which both incoming and outgoing SCR's conducts together is called commutating angle (or) overlapping angle

→ During commutating period, output voltage is zero, since all the SCR's are in conduction.

→ As I_o (or) Source Inductance L_s increases, V_o V_o (reduced) decreases as a result V_o decreases as shown in figure (Graph). As V_o decreases μ increases and V_o become zero when $\mu = \pi$, as shown in graph.

→ The DC Equivalent circuit for 1-ϕ FW Bridge Converter with Source Inductance - L_s is shown in figure (4). Here Diode - D represents the load current is unidirectional.

→ Conclusions:-

→ Due to Source Inductance, V_o gets reduced. The Voltage reduced due to Source Inductance is given by $V_o(red) = \frac{\omega 2 I_o L_s}{\pi}$.

→ Due to Source Inductance, the range of firing angle reduces i.e.,

$$* / \; 0 < \alpha < (180-\mu) \; / *$$

→ $V_o = \frac{2V_m}{\pi} \cos\alpha \; ; \; \mu = 0$

/ $V_o = \frac{2V_m}{\pi} \cos\alpha \; ; \; 0 < \mu < \pi$ /
- V_o reduced

$V_o = 0 \; ; \; \mu = \pi$

* 1-ϕ full converter connected ac supply of $330 \sin 314t$ It operates with firing angle $\alpha = \frac{\pi}{4}$, the load current is maintained constant at 5A at load Voltage is 140V. Calcaluate L_s, μ, R.

Sol:- Given, $\alpha = \frac{\pi}{4} = 45^\circ$

$V_s = 330 \sin 314t$.

$V_m = 330$

$\omega = 314$

$I_o = 5A$.

$V_o = 140V$

→ $R = \frac{V_o}{I_o} = \frac{140}{5} = 28\,\Omega$

→ $V_o = \frac{V_m}{\pi}\left(\cos\alpha + \cos(\alpha+\mu)\right)$

$\Rightarrow 140 = \frac{330}{\pi}\left[\cos 45 + \cos(45+\mu)\right]$

$\Rightarrow \frac{140\times\pi}{330} = \cos 45 + \cos(45+\mu)$

$\Rightarrow \cos(45+\mu) = \frac{140\times\pi}{330} - \frac{1}{\sqrt{2}}$

$\Rightarrow \cos 45 \cdot \cos\mu - \sin 45 \cdot \sin\mu = \frac{140\pi}{330} - \frac{1}{\sqrt{2}}$

$\Rightarrow \frac{1}{\sqrt{2}}(\cos\mu - \sin\mu) = \left(\frac{140\pi}{330} - \frac{1}{\sqrt{2}}\right)$

$\Rightarrow \cos\mu - \sin\mu =$

(3) $V_0 = \frac{2V_m}{\pi}\cos\alpha - \frac{I_0 \omega L_s}{\pi}$

$\Rightarrow 140 = \frac{2\times 330}{\pi}\cos(45) - \frac{5\times 314\times L_s}{\pi}$

$\Rightarrow \frac{5\times 314\times L_s}{\pi} = \frac{2\times 330}{\sqrt{2}} - 140$

$\Rightarrow L_s = \left[\frac{2\times 330}{\sqrt{2}} - 140\right]\times\frac{\pi}{314\times 5}$

$\therefore L_s = 17.11\,mH$

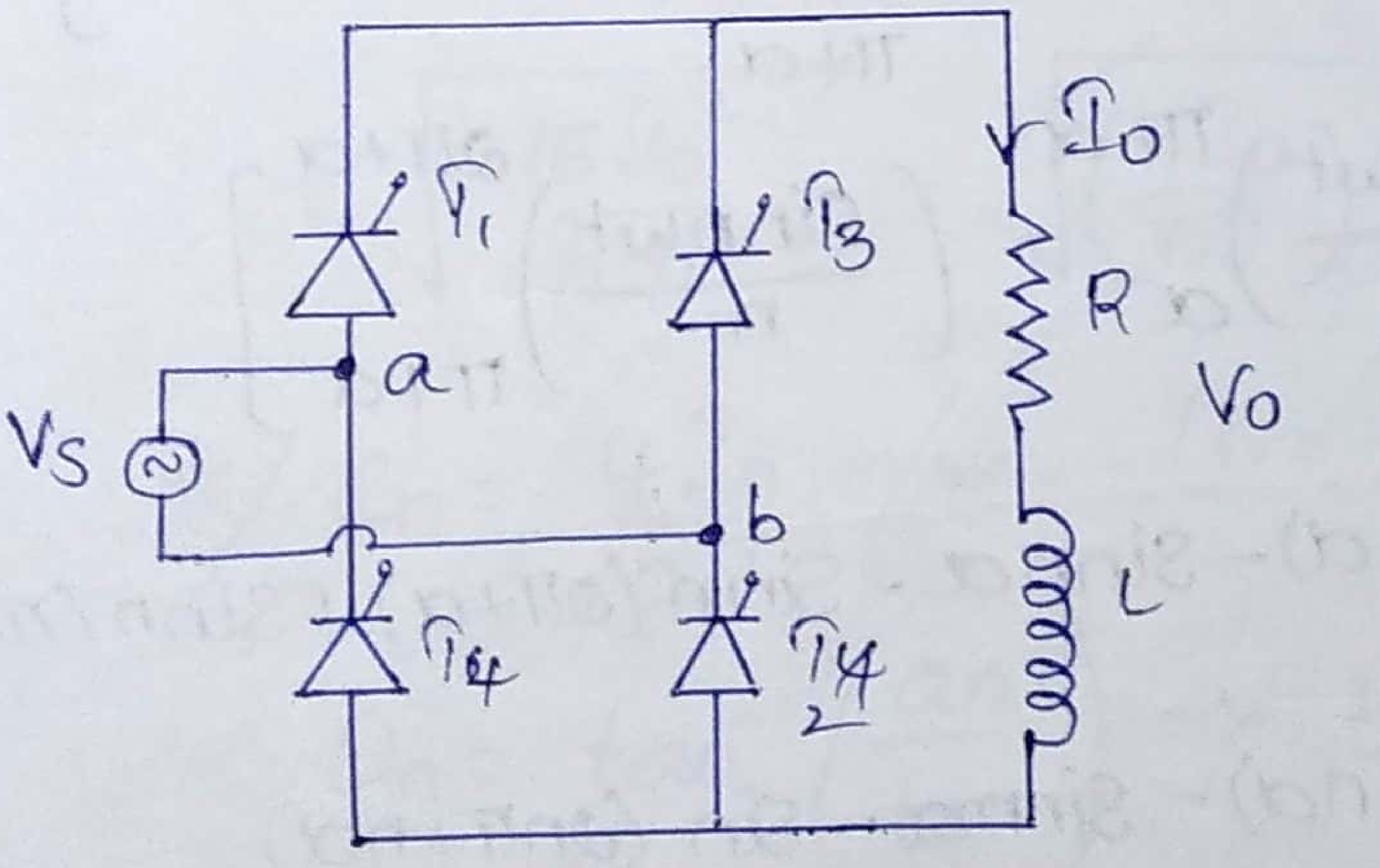
→ Performance of Two pulse Converters:-

→ There are two Two pulse converters

(1) 1-ϕ Full converter.

(2) 1-ϕ Semi Converter.

→ 1-ϕ full Converter:-



→ Wave forms is Same as that of 1-ϕ FWCR-RL Load high Value of Inductance

→ By observing Vs - Sine wave, I_s - Non-sinusiodal wave. It is converted by using fourier Series.

∴ $I_s = a_0 + \sum_{n=1}^{\infty} C_n \sin(\omega t + \theta_n)$

$C_n = \sqrt{b_n^2 + a_n^2}$; $\theta_n = \tan^{-1}\left(\frac{a_n}{b_n}\right)$

∴ $a_0 = \frac{1}{2\pi}\int_0^{2\pi} i_s \cdot d\omega t$

$a_n = \frac{1}{\pi}\int_0^{\pi} i_s \cdot \cos n\omega t \cdot d\omega t$

$b_n = \frac{1}{\pi}\int_0^{\pi} i_s \cdot \sin n\omega t \cdot d\omega t$.

→ $a_0 = \frac{1}{2\pi}\left[\int_\alpha^{\pi+\alpha} I_0 \cdot d\omega t + \int_{\pi+\alpha}^{2\pi+\alpha} -I_0 \cdot d\omega t\right]$

⇒ $\alpha_0 = \frac{I_0}{2\pi}\left[(\pi+\alpha-\alpha) - [(2\pi+\alpha) - (\pi+\alpha)\right]$

⇒ $\alpha_0 = 0$.

→ $a_n = \frac{1}{\pi}\left[\int_\alpha^{\pi+\alpha} I_0 \cdot \cos n\omega t \cdot d\omega t + \int_{\pi+\alpha}^{2\pi+\alpha} -I_0 \cdot \cos n\omega t \cdot d\omega t\right]$

$= \frac{I_0}{\pi}\left[\left(\frac{\sin n\omega t}{n}\right)_\alpha^{\pi+\alpha} - \left(\frac{\sin n\omega t}{n}\right)_{\pi+\alpha}^{2\pi+\alpha}\right]$

$= \frac{I_0}{n\pi}\left[\sin n(\pi+\alpha) - \sin n\alpha - \sin n(2\pi+\alpha) + \sin n(\pi+\alpha)\right]$

$= \frac{I_0}{n\pi}\left[\sin(n\pi+n\alpha) - \sin n\alpha - \sin(2n\pi+n\alpha) + \sin(n\pi+n\alpha)\right]$

∴ $a_n = \frac{-4I_0}{n\pi}\sin n\alpha$

$n = 1, 3, 5 \ldots$

$a_n b_n = 0$ $n = 2, 4, 6 \ldots$

$$\rightarrow b_n = \frac{1}{\pi}\left[\int_{\alpha}^{\pi+\alpha} I_0 \cdot \sin n\omega t \cdot d\omega t + \int_{\pi+\alpha}^{2\pi+\alpha} -I_0 \cdot \sin n\omega t \cdot d\omega t\right]$$

$$\Rightarrow b_n = \frac{I_0}{\pi}\left[\left(\frac{-\cos n\omega t}{n}\right)_{\alpha}^{\pi+\alpha} - \left(\frac{-\cos n\omega t}{n}\right)_{\pi+\alpha}^{2\pi+\alpha}\right]$$

$$\Rightarrow b_n = \frac{I_0}{n\pi}\left[-\cos(n\pi+n\alpha)+\cos n\alpha + \cos(2\pi n+n\alpha) - \cos(n\pi+n\alpha)\right]$$

/ $b_n = \frac{4I_0}{n\pi}\cos n\alpha$ / $[n=1,3,5\ldots]$

/ $b_n = 0$ / $[n=2,4,6\ldots]$

$\therefore C_n = \sqrt{b_n^2 + a_n^2}$ $[n=1,3,5\ldots]$

$$\Rightarrow C_n = \sqrt{\left(\frac{4I_0}{n\pi}\cos n\alpha\right)^2 + \left(\frac{-4I_0}{n\pi}\sin n\alpha\right)^2}$$

$$= \sqrt{\frac{16I_0^2}{n^2\pi^2}\cos^2 n\alpha + \frac{16I_0^2}{n^2\pi^2}\sin^2 n\alpha}$$

$$= \sqrt{\frac{16I_0^2}{n^2\pi^2}} = \sqrt{\left(\frac{4I_0}{n\pi}\right)^2}$$

/ $C_n = \frac{4I_0}{n\pi}$ / $(n=1,3,5\ldots)$

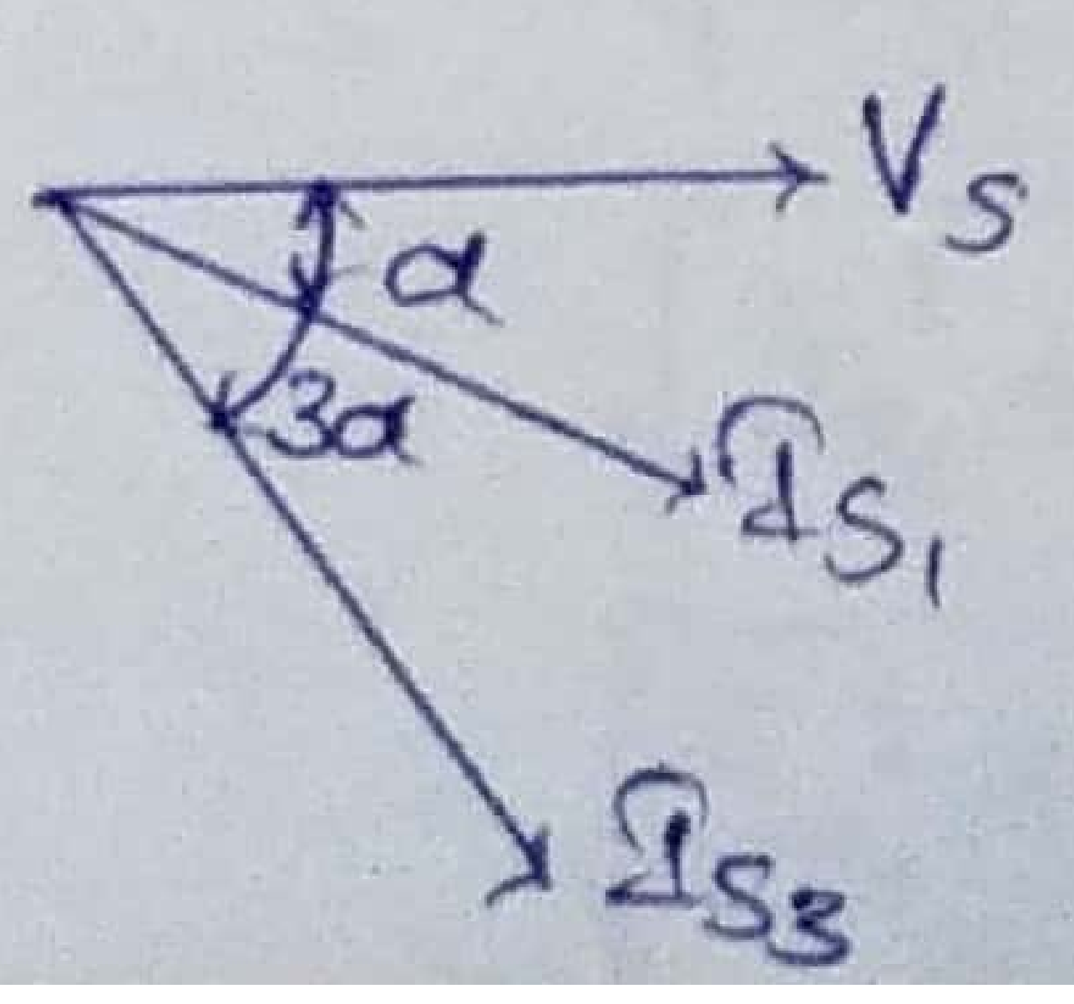
$$\therefore \theta_n = \tan^{-1}\left(\frac{a_n}{b_n}\right) \Rightarrow \tan^{-1}\left[\frac{-\frac{4I_0}{n\pi}\sin n\alpha}{\frac{4I_0}{n\pi}\cos n\alpha}\right]$$

$$= \tan^{-1}(-\tan n\alpha)$$

/ $\theta_n = -n\alpha$ / $(n=1,3,5\ldots)$

$\theta_1 = -\alpha$

$\theta_3 = -3\alpha$



$n\alpha$ - angle b/w Source Voltage and n^{th} Harmonic Current.

put a_0, C_n, θ_n in is eqn.

$$\Rightarrow i_s = a_0 + \sum_{n=0}^{\infty} C_n \sin(n\omega t + \theta_n)$$

$$= 0 + \sum_{n=1,3,5}^{\infty} C_n \sin(n\omega t + \theta_n).$$

$$\therefore i_s = \sum_{n=1,3,5}^{\infty} \frac{4I_0}{n\pi} \sin(n\omega t - n\alpha)$$

$$\Rightarrow I_{sn} = \sum_{n=1,3,5}^{\infty} \frac{4I_0}{n\pi} \sin(n\omega t - n\alpha) \quad (n^{th} \text{ Harmonic})$$

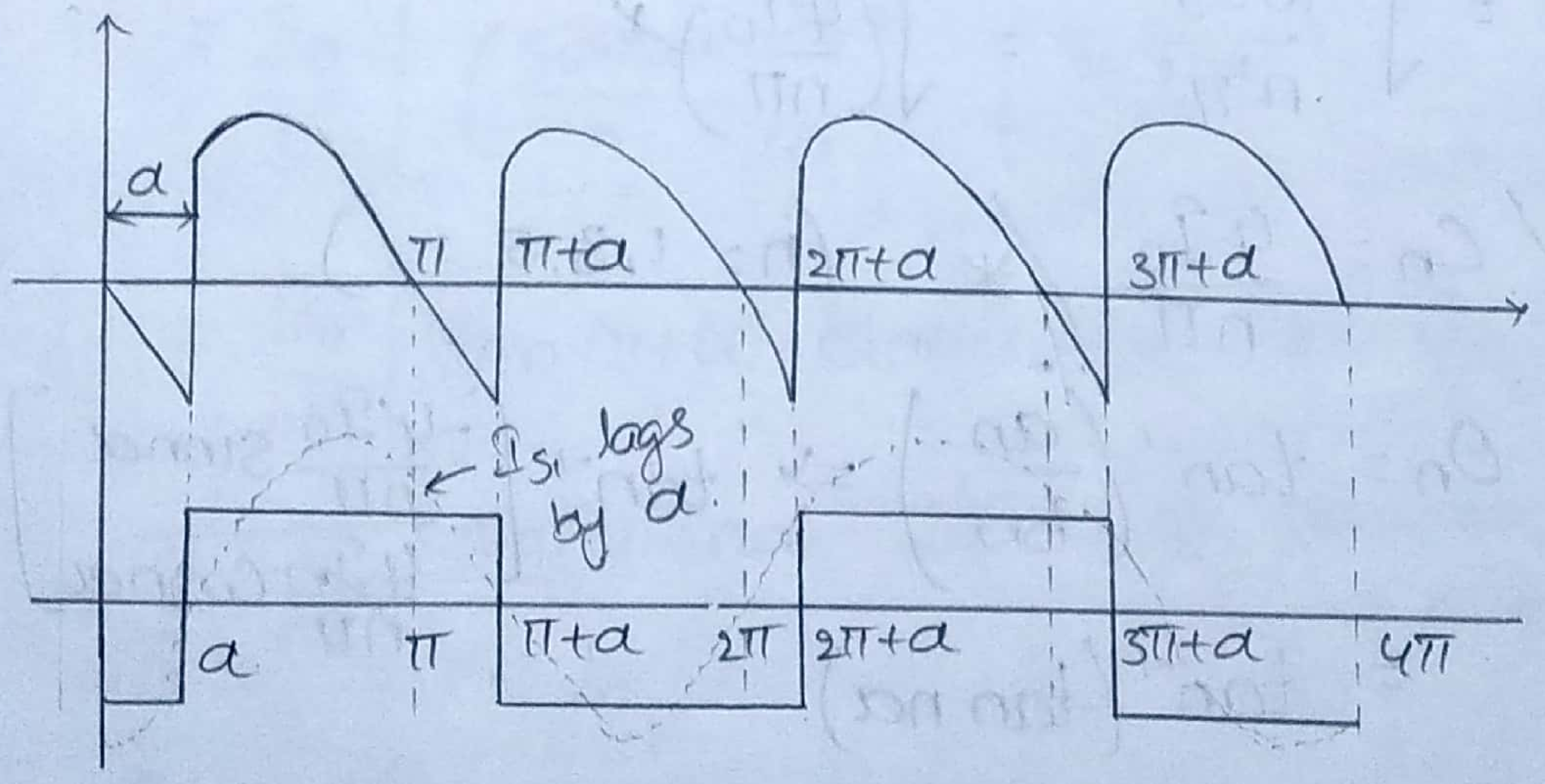
for fundamental,

$$I_{s_1} = \frac{4I_0}{\pi} \sin(\omega t - \alpha)$$

$$\therefore I_{s_1} = I_m \sin(\omega t - \alpha), \quad I_m = \frac{4I_0}{\pi}.$$

→ θ_n is the Displacement angle and it is defined as angle between source voltage and n^{th} Harmonic source current.

$$\therefore V_s = V_m \sin\omega t$$



→ RMS Value of fundamental Source current

$$I_{S_1} = \frac{I_m}{\sqrt{2}} = \frac{4I_0}{\pi\sqrt{2}} = \frac{2\sqrt{2}I_0}{\pi}$$

RMS Value of Source current

$$I_S = I_0.$$

→ fundamental Displacement factor FDF:-

→ It is the cosine of fundamental Displacement Angle.

$$FDF = \cos\alpha.$$

→ Current Distortion factor CDF:-

→ It is the ratio of RMS Value of fundamental Source current to RMS value of Source current

$$CDF = \frac{I_{S_1}}{I_S} = \frac{\frac{2\sqrt{2}I_0}{\pi}}{I_0} = \frac{2\sqrt{2}}{\pi}$$

→ Fundamental power factor:-

→ It is the product of fundamental Displacement factor and current Distortion factor.

$$FPF = FDF \times CDF$$

$$\therefore FPF = \frac{2\sqrt{2}}{\pi}\cos\alpha.$$

→ Total Harmonic Distortion (or) Harmonic factor:-

→ It is the ratio of Total Harmonic current to the RMS Value of fundamental Source current.

$$THD = \frac{I_h}{I_{S_1}}$$; we know that

$$I_S = \sqrt{I_{S_1}^2 + I_{S_2}^2 + I_{S_3}^2 + I_{S_4}^2 + \cdots}$$

$$= \sqrt{I_{S_1}^2 + I_{S_3}^2 + I_{S_5}^2 + \cdots}$$

$$= \sqrt{I_{S_1}^2 + I_h^2}$$

$$I_s^2 = I_{s_1}^2 + I_n^2$$

$$\therefore \; I_n = \sqrt{I_s^2 - I_{s_1}^2}$$

$$\Rightarrow \; THD = \sqrt{\frac{I_s^2 - I_{s_1}^2}{I_{s_1}^2}}$$

$$= \sqrt{\left(\frac{I_s^2}{I_{s_1}}\right)^2 - 1} \, .$$

$$* \!/ \; THD = \sqrt{\left(\frac{1}{CDF}\right)^2 - 1} \, . \; (*$$

→ Form factor :-

$$FF = \frac{V_{orms}}{V_0}$$

[1-∅ FWCR with RL-Load, High of L

$$V_{orms} = \frac{V_m}{\sqrt{2}} = V_s$$

$$V_0 = \frac{2V_m}{\pi} \cos\alpha \,]$$

$$RF = \sqrt{FF^2 - 1} \, .$$

→ Active power input (P_i) :-

→ It is product of RMS value of source voltage and RMS value of fundamental source current and cosine of angle between them.

$$\therefore \; P_i = V_s \cdot I_{s_1} \cdot \cos\alpha$$

$$= \frac{V_m}{\sqrt{2}} \times \frac{2\sqrt{2} \cdot I_0}{\pi} \cos\alpha$$

$$P_i = \frac{2V_m}{\pi} \cdot I_0 \cdot \cos\alpha = V_0 I_0 .$$

→ Reactive power input :-

→ It is product of RMS value of V_s and RMS value of fundamental I_s and sine of angle.

$$Q_i = V_s \cdot I_{s_1} \cdot \sin\alpha \, .$$

$$= \frac{V_m}{\sqrt{2}} \times \frac{2\sqrt{2} \cdot I_0}{\pi} \times \sin\alpha$$

$\Rightarrow Q_i = \frac{2V_m}{\pi} \cos\alpha \cdot \frac{\sin\alpha}{\cos\alpha}$.

$$* \,/\, Q_i = V_o \cdot I_o \cdot \tan\alpha \cdot /\, *$$

→ 1-ϕ Semiconverter:-

→ wave forms same as Semiconverter with RL Load of High value of L.

$$i_s = a_0 + \sum_{n=01}^{\infty} C_n (\sin(n\omega t + \theta_n))$$

$$C_n = \sqrt{b_n^2 + a_n^2} \;;\quad \theta_n = \tan^{-1}\left(\frac{a_n}{b_n}\right)$$

$$a_0 = \frac{1}{2\pi}\int_0^{2\pi} i_s \cdot d\omega t = 0$$

$$a_n = \frac{1}{\pi}\int_0^{\pi} i_s \cdot \cos n\omega t \cdot d\omega t = -\frac{2I_0}{n\pi} \sin n\alpha .$$

$$b_n = \frac{1}{\pi}\int_0^{\pi} i_s \cdot \sin n\omega t \cdot d\omega t = \frac{2I_0}{n\pi}(\cos n\alpha + 1)$$

$$C_n = \sqrt{b_n^2 + a_n^2} = \frac{4I_0}{n\pi}\cos\frac{n\alpha}{2}.$$

$$\theta_n = -\frac{n\alpha}{2}$$

→ Sub a_0, C_n, θ_n values in I_s

$$\Rightarrow I_s = a_0 + \sum_{n=1,3,5\ldots}^{\infty} C_n \sin(n\omega t + \theta_n)$$

$$= 0 + \sum_{n=1,3,5}^{\infty} \frac{4I_0}{n\pi}\cos\frac{n\alpha}{2} \sin\left(n\omega t - \frac{n\alpha}{2}\right)$$

$$\Rightarrow I_s = \sum_{n=1,3,5}^{\infty} \frac{4I_0}{n\pi}\cos\frac{n\alpha}{2} \cdot \sin\left(n\omega t - \frac{n\alpha}{2}\right)$$

for n^{th} Harmonic, Source current

$$I_{Sn} = \frac{4I_0}{n\pi} \cos\frac{n\alpha}{2} \sin\left(n\omega t - \frac{n\alpha}{2}\right)$$

for fundamental source current

$$I_{S_1} = \frac{4I_0}{\pi} \cos\frac{\alpha}{2} \sin\left(\omega t - \frac{\alpha}{2}\right)$$

$$I_{S_1} = I_m \sin\left(\omega t - \frac{\alpha}{2}\right); \quad I_m = \frac{4I_0}{\pi} \cos\frac{\alpha}{2}.$$

fundamental Source Voltage,

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

→ RMS Value of fundamental Source current.

$$I_S = I_0\left(\frac{\pi-\alpha}{\pi}\right)^{1/2}.$$

(1) $FDF = \cos\theta_1 = \cos\frac{\alpha}{2}.$

(2) $$CDF = \frac{I_{S_1}}{I_S} = \frac{\frac{2\sqrt{2}I_0}{\pi} \cdot \cos\frac{\alpha}{2}}{I_0 \cdot \left(\frac{\pi-\alpha}{\pi}\right)^{1/2}}$$

(3) $FPF = CDF \times FDF.$

(4) THD (or) HF $= \sqrt{\left(\frac{1}{CDF}\right)^2 - 1}.$

(5) $FF = \frac{V_{orms}}{V_0}$ [for 1-ϕ semiconverter with RL load for High-L

$$V_0 = \frac{V_m}{\pi}(1+\cos\alpha)$$

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

(6) Voltage $RF = \sqrt{FF^2 - 1}.$

(7) $$P_i = V_S \cdot I_{S_1} \cdot \cos\frac{\alpha}{2}.$$

$$= \frac{V_m}{\sqrt{2}} \times \frac{2\sqrt{2}I_0}{\pi} \cdot \cos\frac{\alpha}{2} \cdot \cos\frac{\alpha}{2}$$

$$= \frac{V_m}{\pi} 2\cos^2\frac{\alpha}{2} I_0. \qquad \left(1+\cos A = 2\cos^2\frac{A}{2}\right)$$

$$\Rightarrow P_i = \frac{V_m}{\pi}(1+\cos\alpha).I_o.$$

$$\therefore P_i = V_o I_o$$

(8) $Q_i = V_S \cdot I_{S_1} \cdot \sin\frac{\alpha}{2}$

$$= \frac{V_m}{\sqrt{2}} \times \frac{2\sqrt{2}}{\pi} I_o \cdot \cos\frac{\alpha}{2} \cdot \sin\frac{\alpha}{2}.$$

$$= \frac{V_m}{\pi} 2\cos\frac{\alpha}{2} \cdot \sin\frac{\alpha}{2} \cdot I_o.$$

$$= \frac{V_m}{\pi} \cdot \sin\alpha \cdot I_o.$$

$$= \frac{V_m}{\pi}(1+\cos\alpha) \cdot \frac{\sin\alpha}{(1+\cos\alpha)} \cdot I_o.$$

$\frac{\sin A}{1+\cos A} = \tan\frac{A}{2}.$

$\sin A = 2\sin\frac{A}{2}\cos\frac{A}{2}$

/ $Q_i = V_o I_o \cdot \tan\frac{\alpha}{2}$ /

1-φ FC Bridge Rectifier supplies inductive load. Assume that output current is constant and equals to I_o. find the following parameters, if $V_S = 230V$, $\alpha = 30°$.
(1) Avg. O/p Voltage (2) RMS Source current.
(3) RMS Value of fundamental Source current
(4) fundamental pf (5) Harmonic factor (6) VRF
(7) Active Power ip (8) Reactive power i/p.

Given, $V_S = 230V$

$\alpha = 30°$

(1) $V_o = \frac{2V_m}{\pi}\cos\alpha = \frac{2\times 230^{\times\sqrt{2}}}{\sqrt{2}\times\pi}\cos 30$

$V_o = 179.3V$

(2) $I_S = I_o.$

(3) $I_{S_1} = \frac{2\sqrt{2}}{\pi} I_o = 0.909 I_o.$

(4) $FPF = CDF \times FDF$

$FDF = \cos\alpha = \cos 30 = \frac{\sqrt{3}}{2} = 0.86$

$CDF = \frac{2\sqrt{2}}{\pi} = 0.9.$

$\Rightarrow FPF = 0.8 \times 0.9 = 0.77$ lags

(5) $HF = \sqrt{\left(\frac{1}{CDF}\right)^2 - 1} = \sqrt{\left(\frac{1}{0.9}\right)^2 - 1} = 0.484.$

(6) $VRF = \sqrt{FF^2 - 1}.$

$FF = \frac{V_{orms}}{V_o}$

$V_{orms} = \frac{V_m}{\sqrt{2}} = V_S = 230V$

$V_o = 179.3V$

$\Rightarrow VRF = \sqrt{\left(\frac{230}{179.3}\right)^2 - 1} = 0.803.$

(7) $P_i = V_o I_o \cdot \cos = 179.3 I_o \cdot W$

(8) $Q_i = V_o I_o \cdot \tan\alpha = 179.3 I_o \times \tan 30^\circ$

$= 103.51 I_o \cdot VAR.$

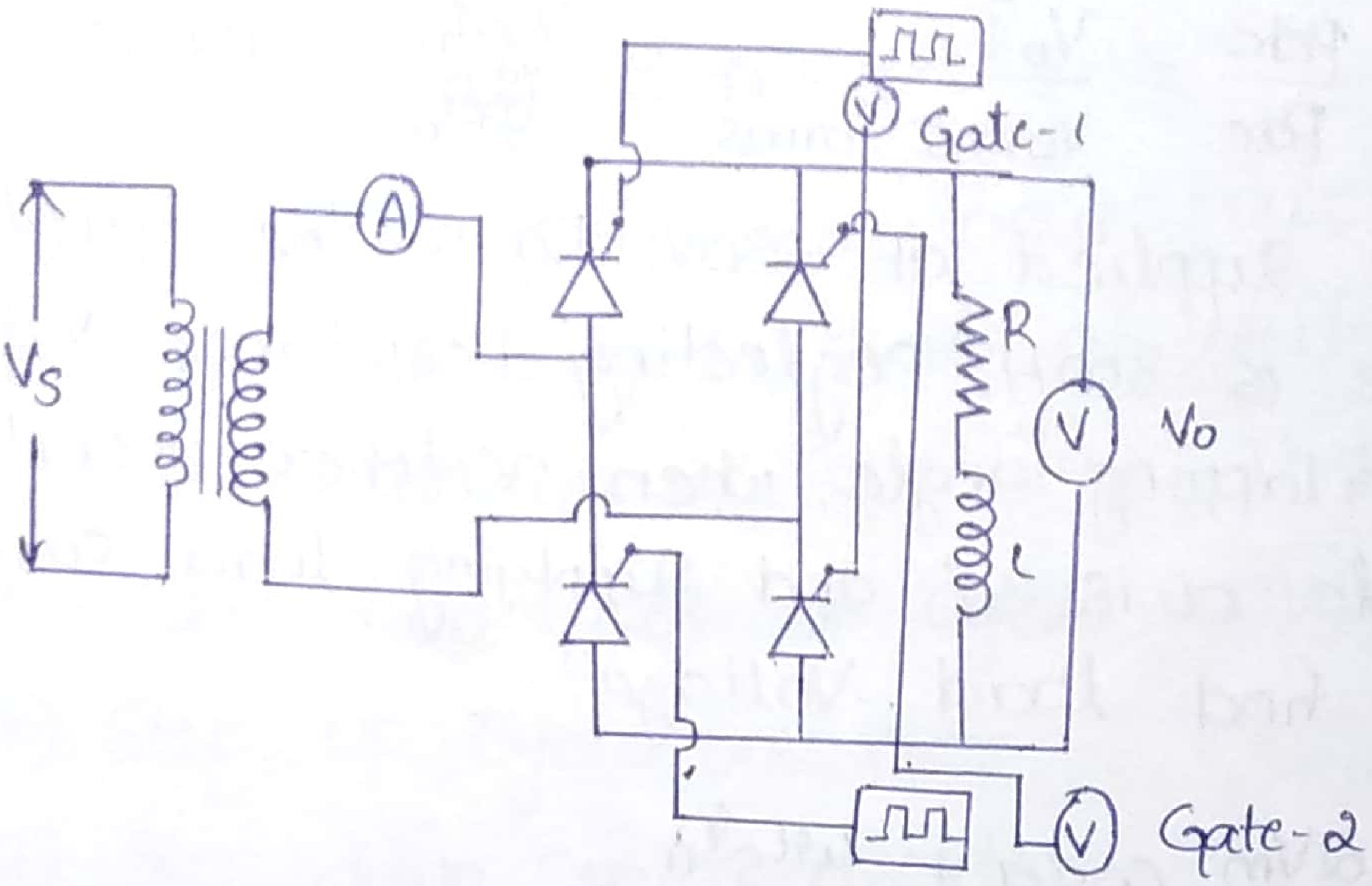
* Rectifier shown below have pure dc current and $V_s = 220 \sin 350t$. and unity T/F ratio. If it is required to obtain an average output voltage of 70% of max. possible output voltage. Find Delay angle, RF, Input Displacement factor, PIV, η.

Sol:- Given, $V_s = 220 \sin 350t$.

$V_o = 75\%$ of V_{omax}.

$I_o = 50A$ (constant).

It is 1-Ø FWCR with RL-Load for High values of L.



$V_o = 70\%$ of V_{omax}.

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

If $\alpha = 0$; we get max. i.e., V_{omax}.

$\Rightarrow V_{omax} = \frac{2V_m}{\pi} \cos 0 = \frac{2 \times 220}{\pi} = 140.05\,V$

$V_o = 70\%$ of V_{omax}

$= 0.7 \times 140.05$

$\therefore V_o = 98.03\,V$

Now, $V_o = \frac{2V_m}{\pi} \cos\alpha$

$\Rightarrow \alpha = \cos^{-1}\left[\frac{V_o \times \pi}{2V_m}\right] = 45.57^\circ$

(2) $RF = \sqrt{FF^2 - 1}$

$FF = \frac{V_{orms}}{V_o} = \frac{V_m/\sqrt{2}}{V_o} = \frac{220/\sqrt{2}}{98.03} = 1.596$

$RF = \sqrt{1.5^2 - 1} = 1.24$

(3) $FDF = \cos\alpha = \cos 45.6 = 0.7$

(4) $PIV = V_m = 220V$

(5) $\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_o I_o}{V_{orms} \cdot I_{orms}} = \frac{\cancel{V_o I_o}}{\cancel{V_o I_o}} = 100\%$

* 1-Ø FWCR supplied at 230V, 50 Hz. the Supply Source Inductance is 3mH, neglecting Resistance Voltage Drop. obtain overlapping angle, when rectifier operating at firing angle α is 30° and Supplying load current of 10 A. Also find load Voltage.

Sol:-

$$V_o = \frac{2V_m}{\pi}\cos\alpha + \frac{\omega L_s I_o}{\pi}$$

$$= \frac{2\times 230\times\sqrt{2}}{\pi} \times \frac{\sqrt{3}}{2} + \frac{2\pi\times 50\times 3m\times 10}{\pi}$$

$$V_o = 176.3\,V$$

$$\Rightarrow V_o = \frac{V_m}{\pi}\left(\cos\alpha + \cos(\alpha+\mu)\right)$$

$$\Rightarrow 176.3 = \frac{230\times\sqrt{2}}{\pi}\left(\cos 30 + \cos(30+\mu)\right)$$

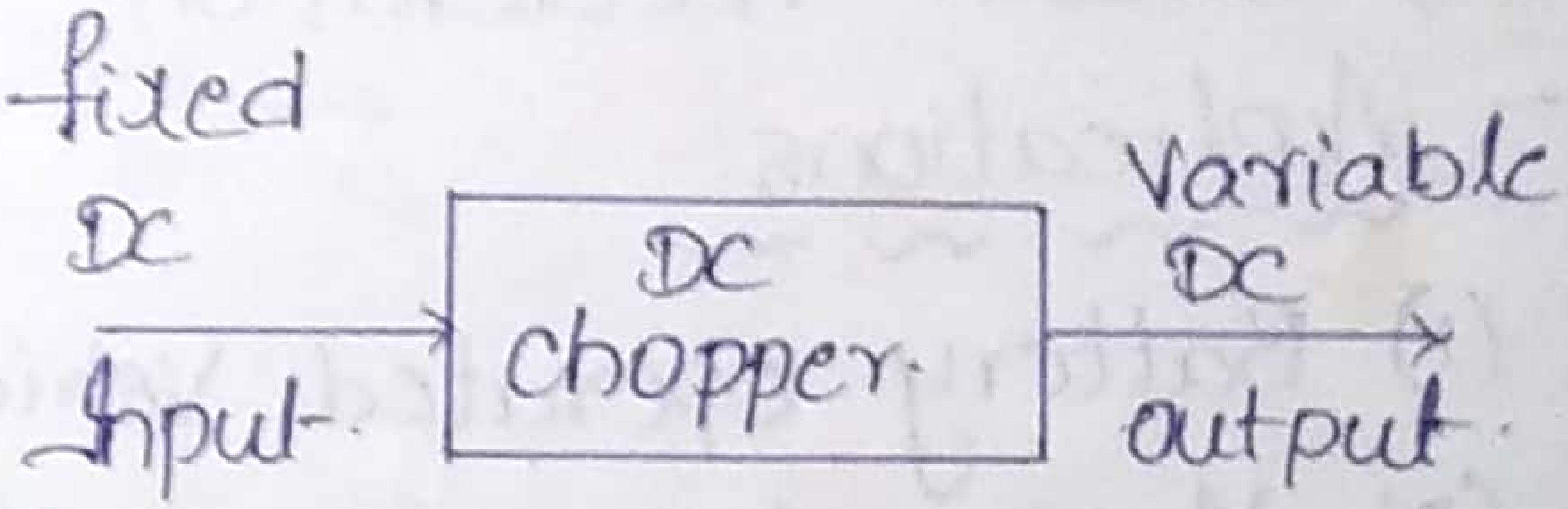
$$\therefore \mu = 3.27^\circ$$

* 1-Ø Bridge Converter feeds an RL load having R of 5.5Ω and L of Very High Causing perfect Smoothing. The Converter is fed from 400V, 50 Hz, 1-Ø. α = 75°. find (i) Avg. of V_o (ii) RMS of I_o (iii) Avg & RMS Thyristor I. (iv) pf.

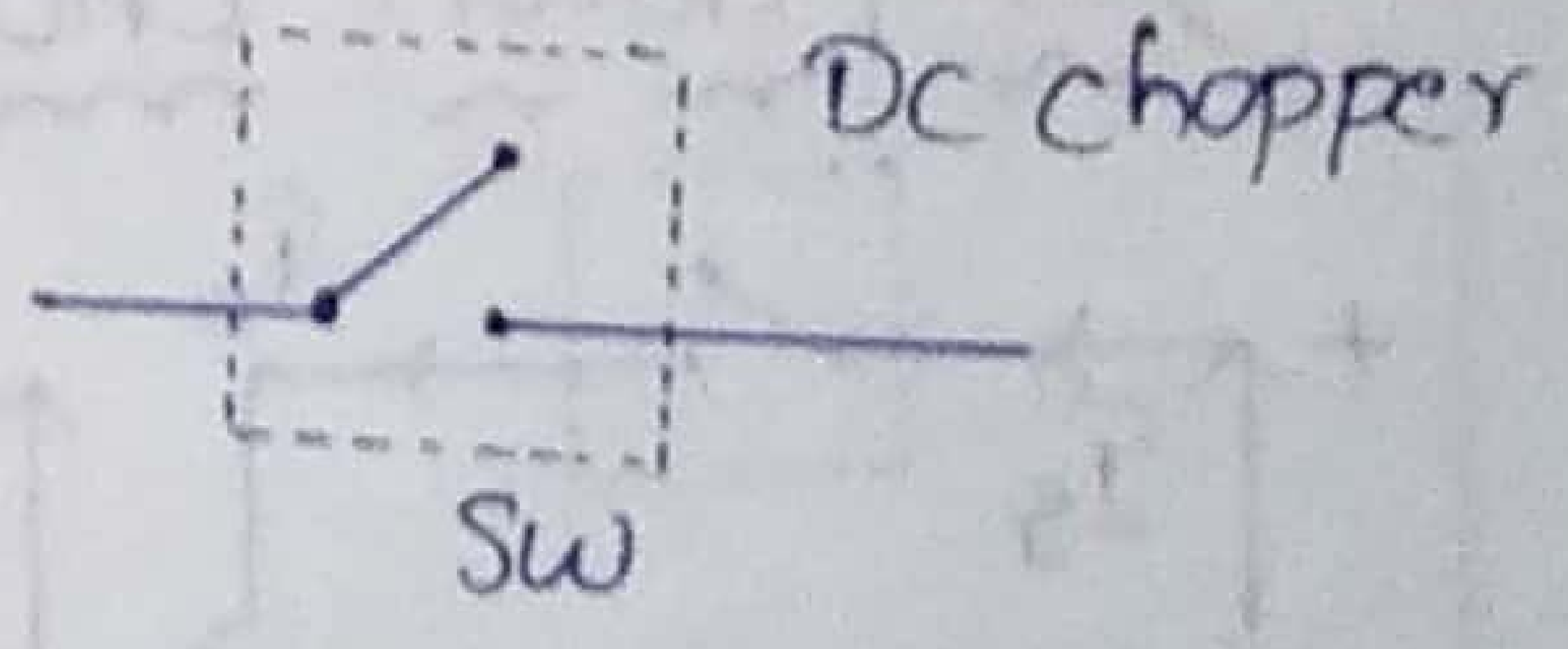
3. Choppers

- Dc chopper is a Static device which converts fixed Dc input Voltage to a Variable Dc output Voltage.
- To obtain Variable Dc output Voltage there are four methods.

(1) Motor-Generator Set.
(2) Resistance control.
(3) Ac link chopper.
(4) Dc chopper.



- Motor-Generator set method is costly, bulky and slow response because of Generator field time constant.
- Resistance control method is undesirable, because of power loss in Variable Resistor-R.
- Ac link chopper method requires two stages (Dc - Ac) & (Ac - Dc) inorder to obtain Variable Dc Voltage in output. So this method has less efficient.
- Dc chopper method requires only one Stage in order to obtain Variable Dc output Voltage. So this method is more efficient.
- Dc chopper circuit can be represented as switch with an arrow as shown in figure.
- when the Switch is open, flow of currents is not possible. when the Switch is closed, current can flow in the direction of



- Dc chopper circuit may be any power semiconducting device Such as forced commutator Thyristor, power BJT's, IGBT's and MOSFET's ,etc...

→ Practically, there is some ON state voltage drop which is nearly 0.5V to 2.5V during the ON period of chopper.

→ Advantages:-

(1) High Efficiency.
(2) Fast Dynamic Response.
(3) Smooth Acceleration.

→ Applications:-

(1) Battery operated Vehicles.
(2) Marine hoists and Mine haulers.
(3) Trolley cars and Electric Traction.

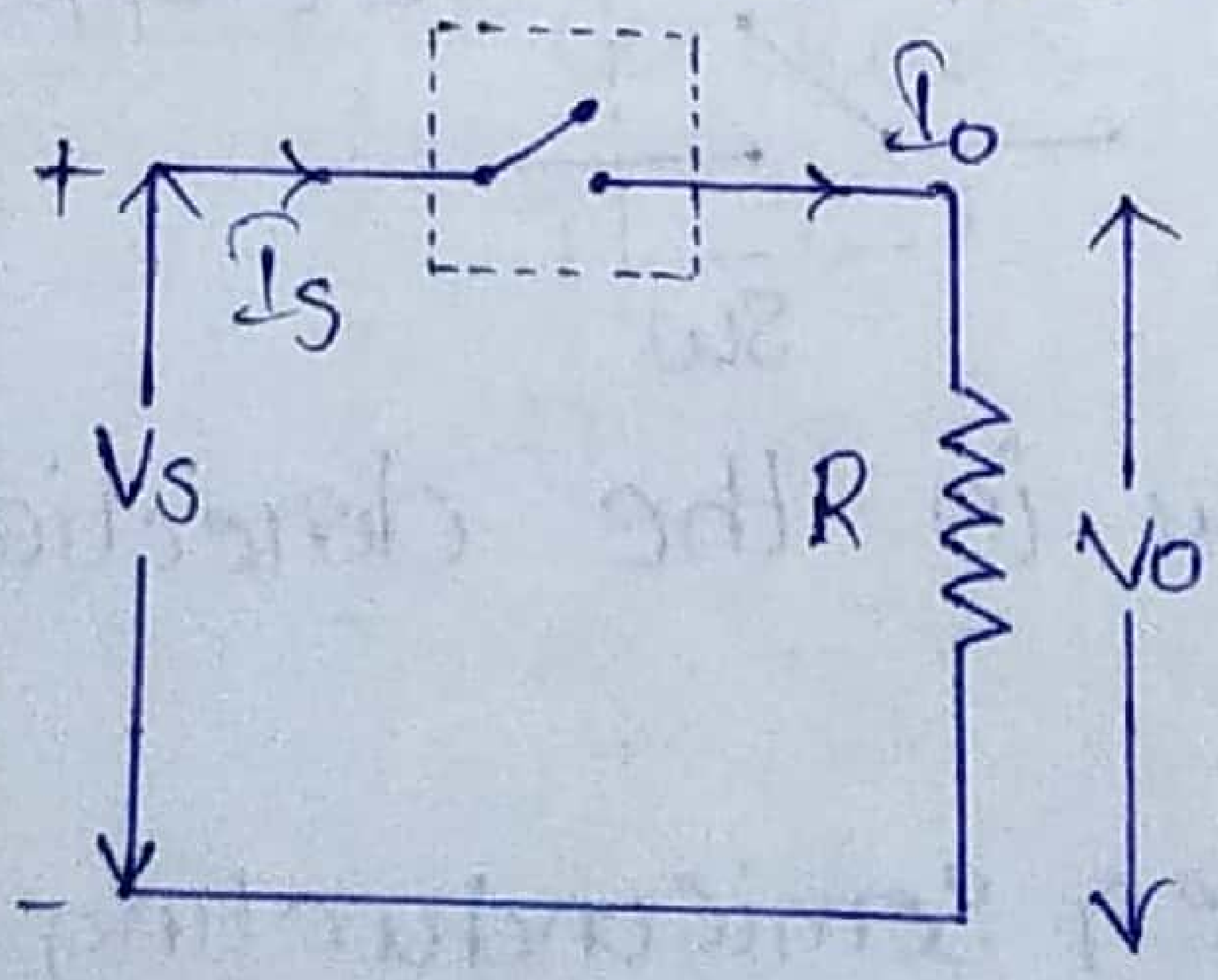
→ Types of Dc choppers:-

(1) Step Down chopper (or)
Type-A chopper (or)
Buck converter. $(V_o < V_s)$.
(2) Step up chopper (or)
Type-B chopper (or)
Boost converter $(V_o > V_s)$.

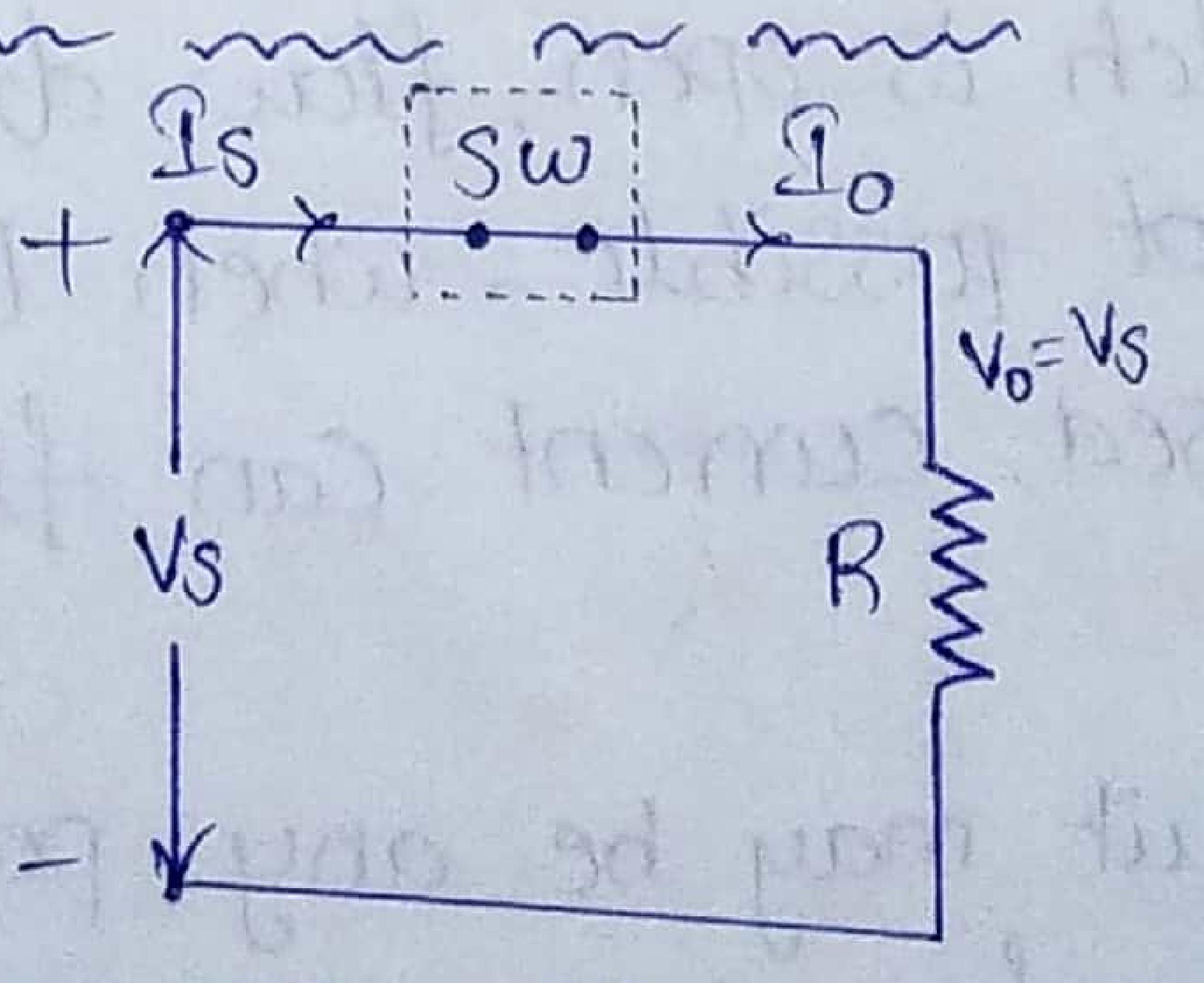
→ In Step down chopper $V_o < V_s$.

→ In Step up chopper $V_o > V_s$.

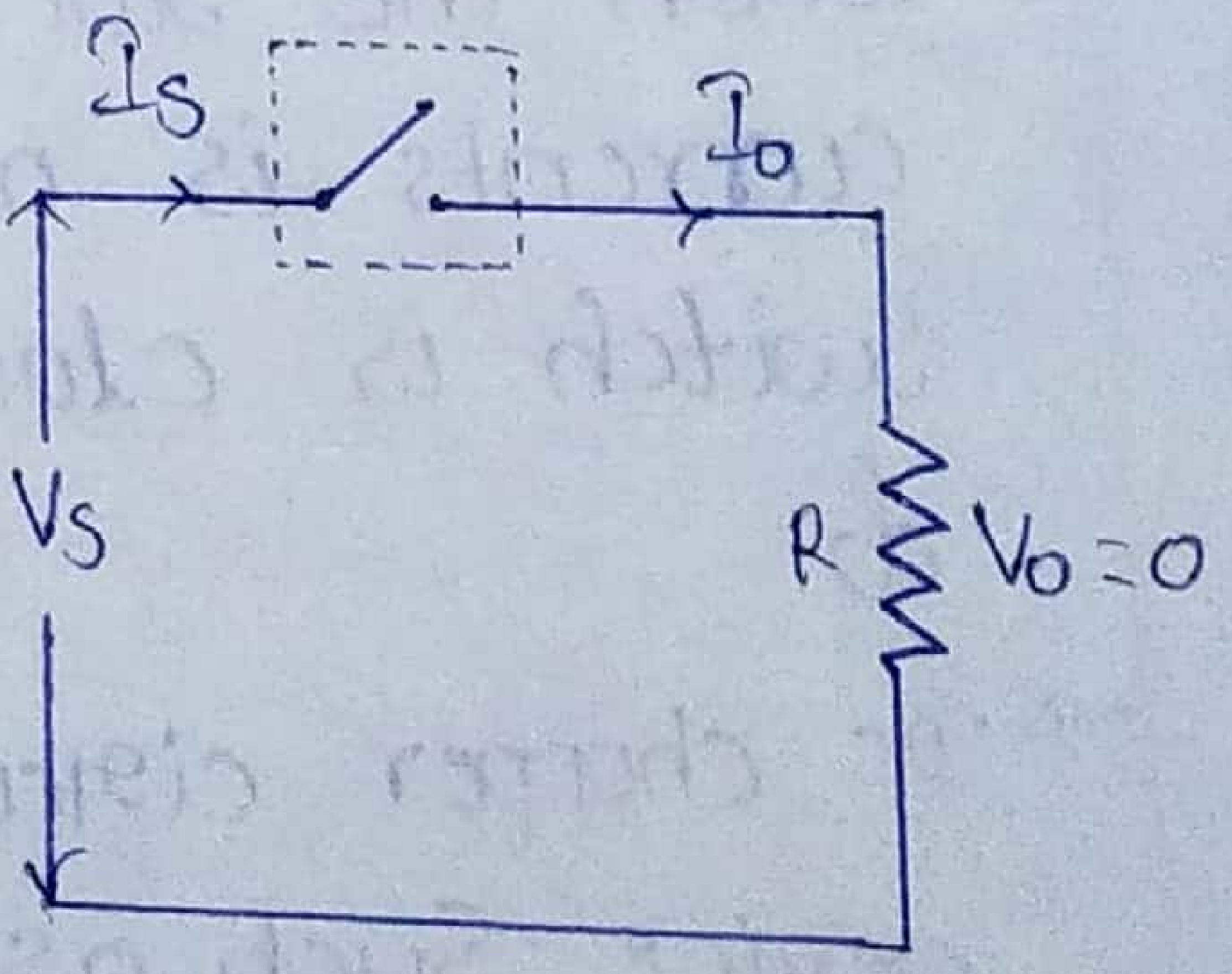
→ Stepdown chopper with R-Load:-



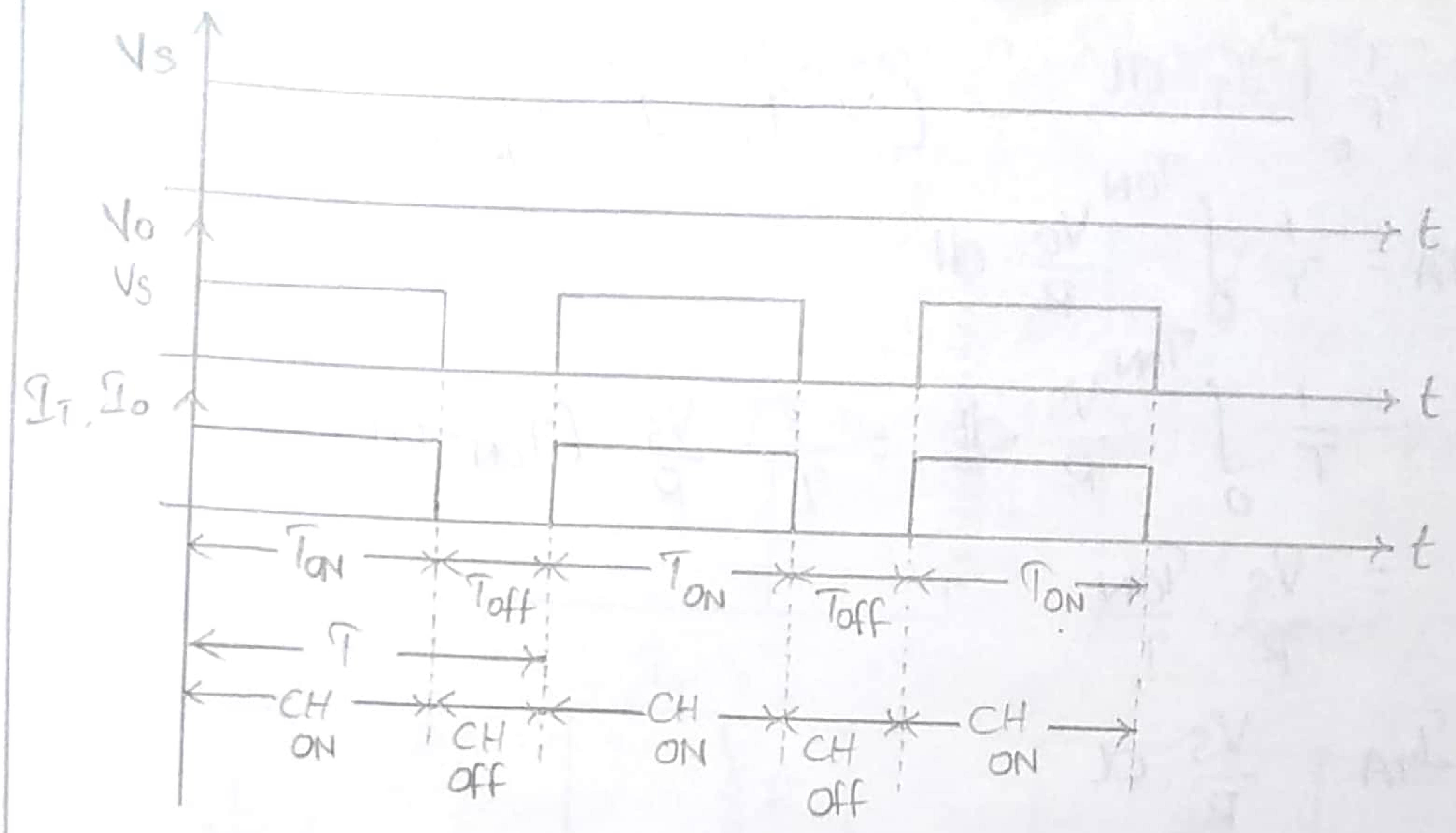
Step down chopper R-Load.



when Chopper is ON



when chopper is OFF.



(1) $V_o = \frac{1}{T}\int_0^T V_o \cdot dt$

$= \frac{1}{T}\left[\int_0^{T_{ON}} V_s \cdot dt + \int_{T_{ON}}^{T_{off}} V_s \cdot dt\right] = \frac{1}{T}\int_0^{T_{ON}} V_s\, dt + 0$

$= \frac{V_s}{T}(T_{ON} - 0). \quad = \frac{V_s}{T}(T_{ON}).$

/ $V_o = \alpha V_s.$ /

δ (or) $\alpha = \frac{T_{ON}}{T}$ = Duty cycle (or) Duty Ratio; Duty Angle i.e., (0-1) Range.

(2) $I_o = \frac{V_o}{R}.$

(3) $V_{orms} = \sqrt{\frac{1}{T}\int_0^T V_o^2 \cdot dt}$

$\Rightarrow V_{orms}^2 = \frac{1}{T}\int_0^T V_o^2 \cdot dt$

$= \frac{V_s^2}{T} \cdot (T_{ON}).$

$\therefore V_{orms} = V_s \left(\frac{T_{ON}}{T}\right)^{1/2}.$

/ $V_{orms} = V_s \cdot \sqrt{\alpha}.$ /

(4) $I_{orms} = \frac{V_{orms}}{R}.$

(5) $I_{TA} = \frac{1}{T}\int_0^T I_T \cdot dt$ $\quad (\because I_T = I_o = \frac{V_o}{R})$

$\Rightarrow I_{TA} = \frac{1}{T}\int_0^{T_{ON}} \frac{V_o}{R} \cdot dt$

$= \frac{1}{T}\int_0^{T_{ON}} \frac{V_s}{R} \cdot dt = \frac{1}{T} \cdot \frac{V_s}{R} (T_{ON} - 0).$

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

$\therefore I_{TA} = \frac{V_s}{R} \cdot \alpha$

(6) $I_{TR} = \sqrt{\frac{1}{T}\int_0^T I_T^2 dt} \Rightarrow I_{TR}^2 = \frac{1}{T}\int_0^{T_{ON}} I_o^2 \cdot dt$

$= \frac{1}{T}\int_0^{T_{ON}} \left(\frac{V_s}{R}\right)^2 dt$

$= \frac{V_s^2}{R^2} \cdot \frac{T_{ON}}{T}$

/ $I_{TR} = \frac{V_s}{R} \cdot \sqrt{\alpha}$ /

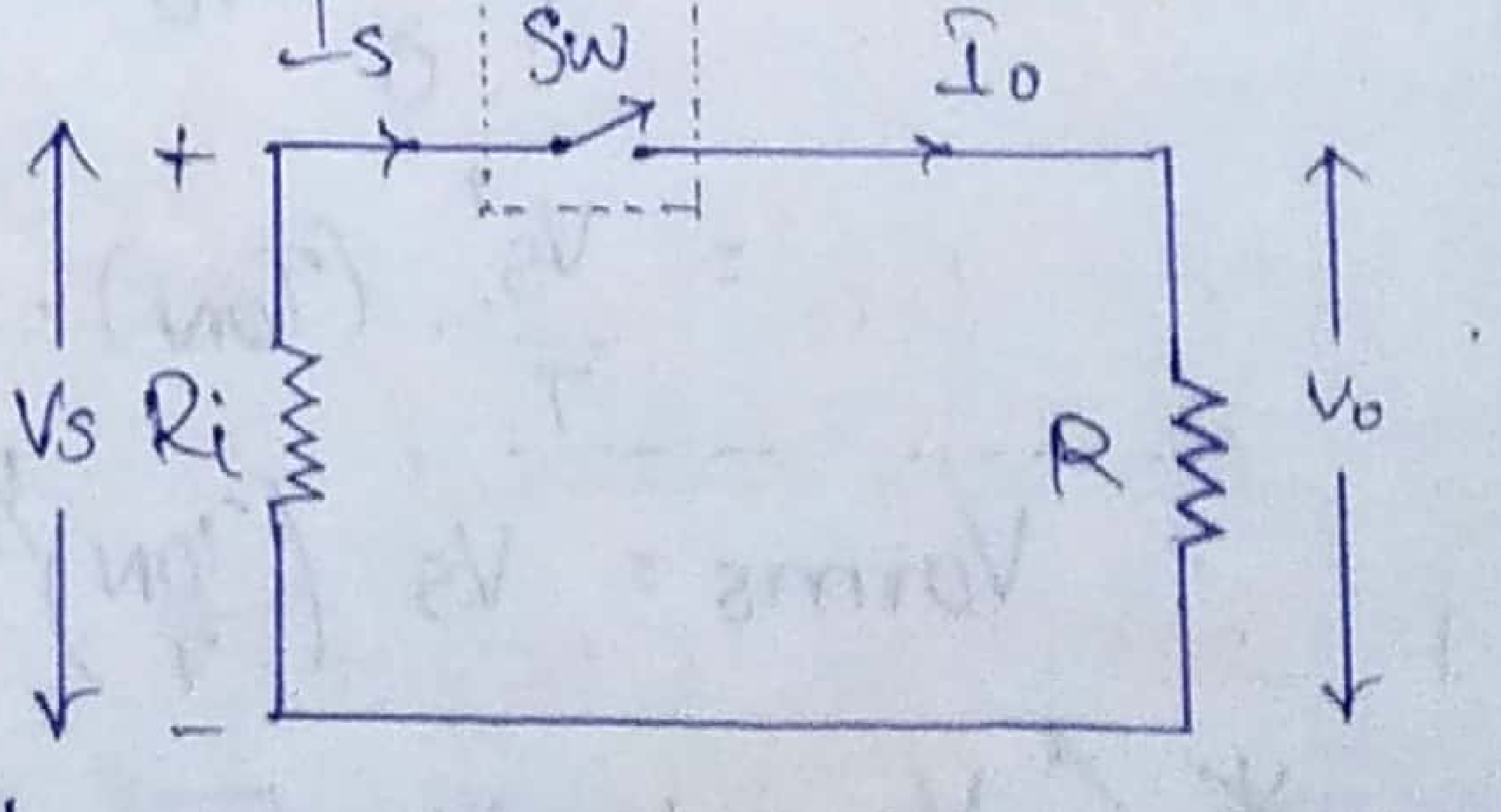
(7) Effective Input Resistance :-

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

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

(8) power Input to the chopper ;

$P_i = V_s I_s = V_s I_o.$

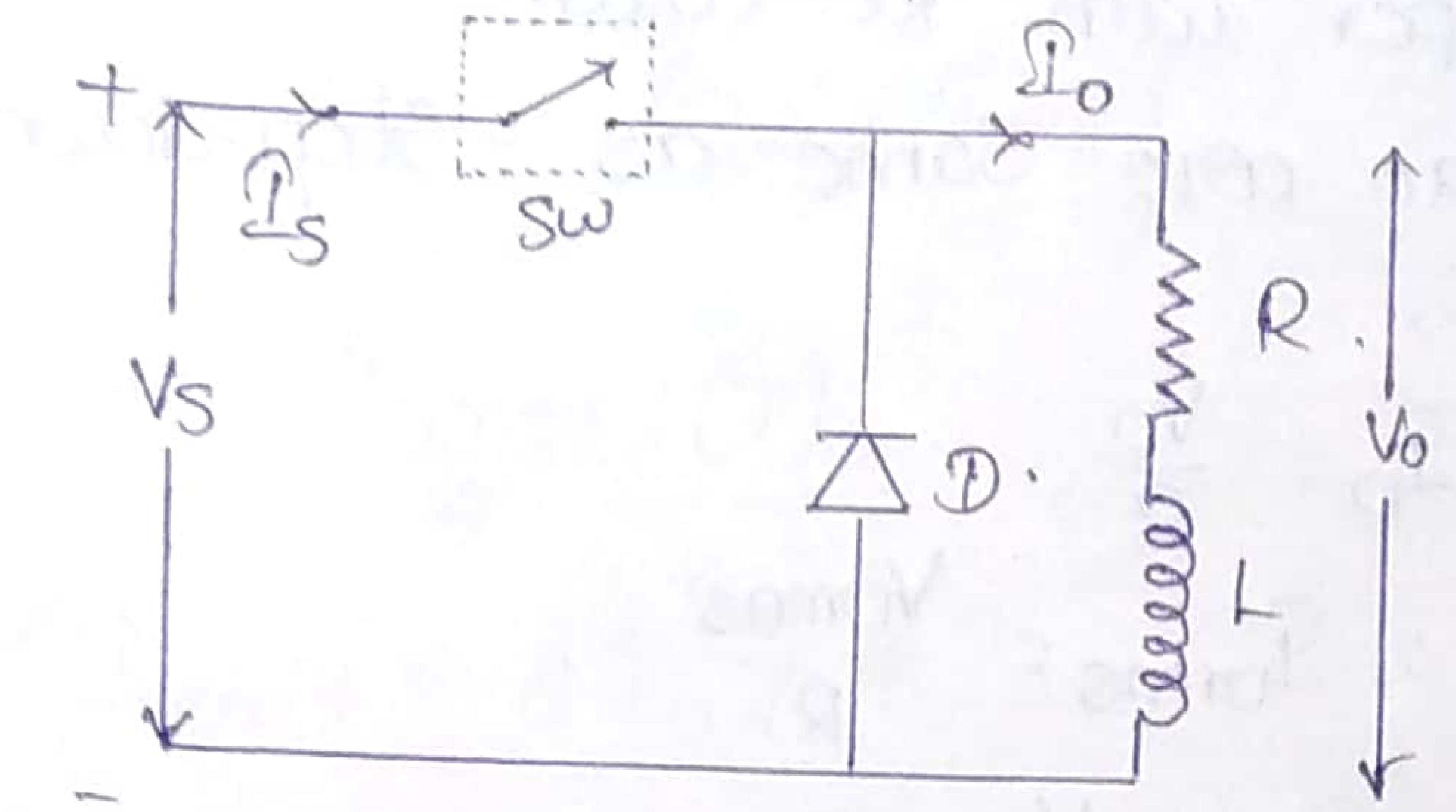


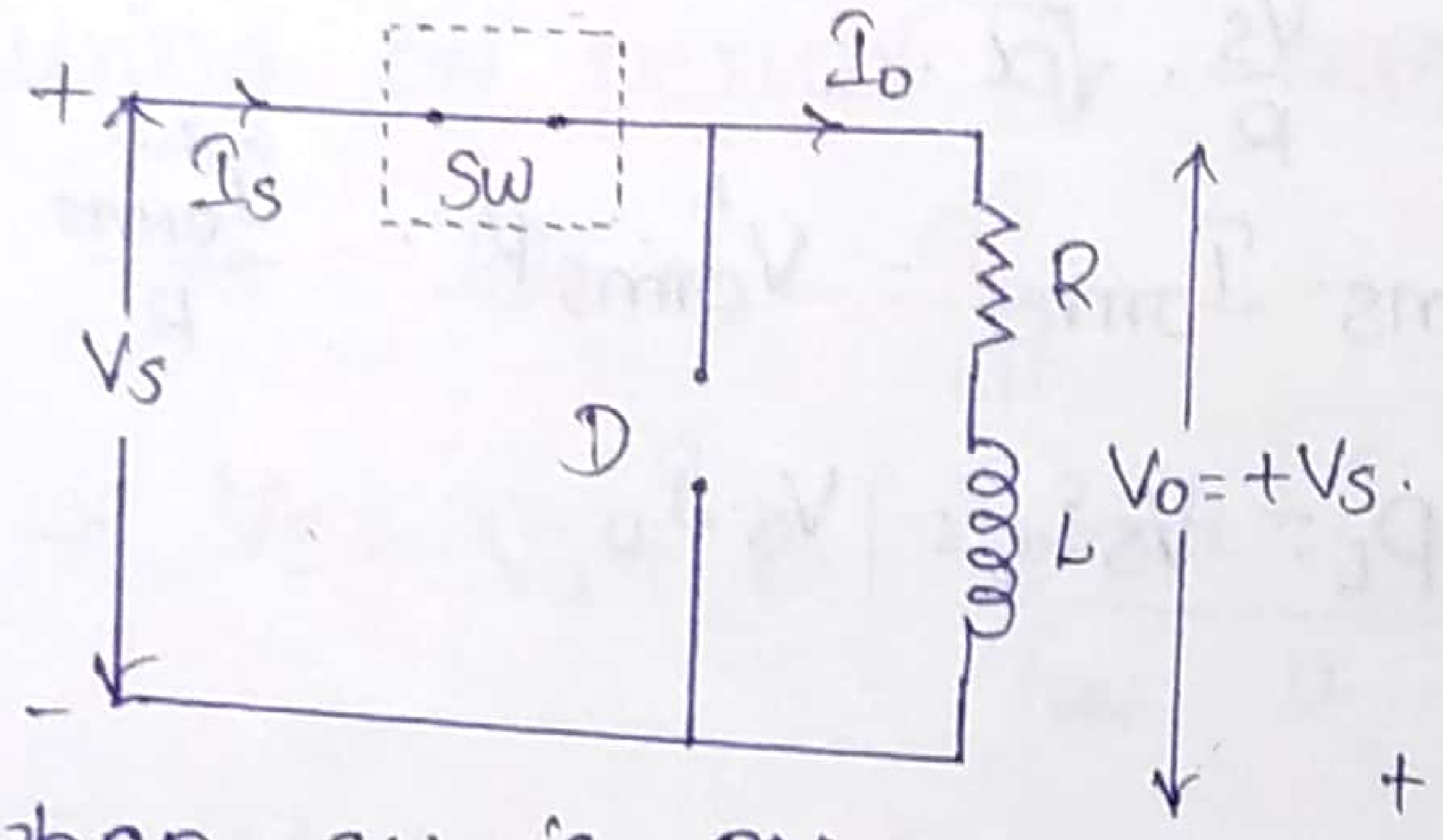
(9) power Delivered to Load ;

$P_o = V_{orms} \cdot I_{orms}.$

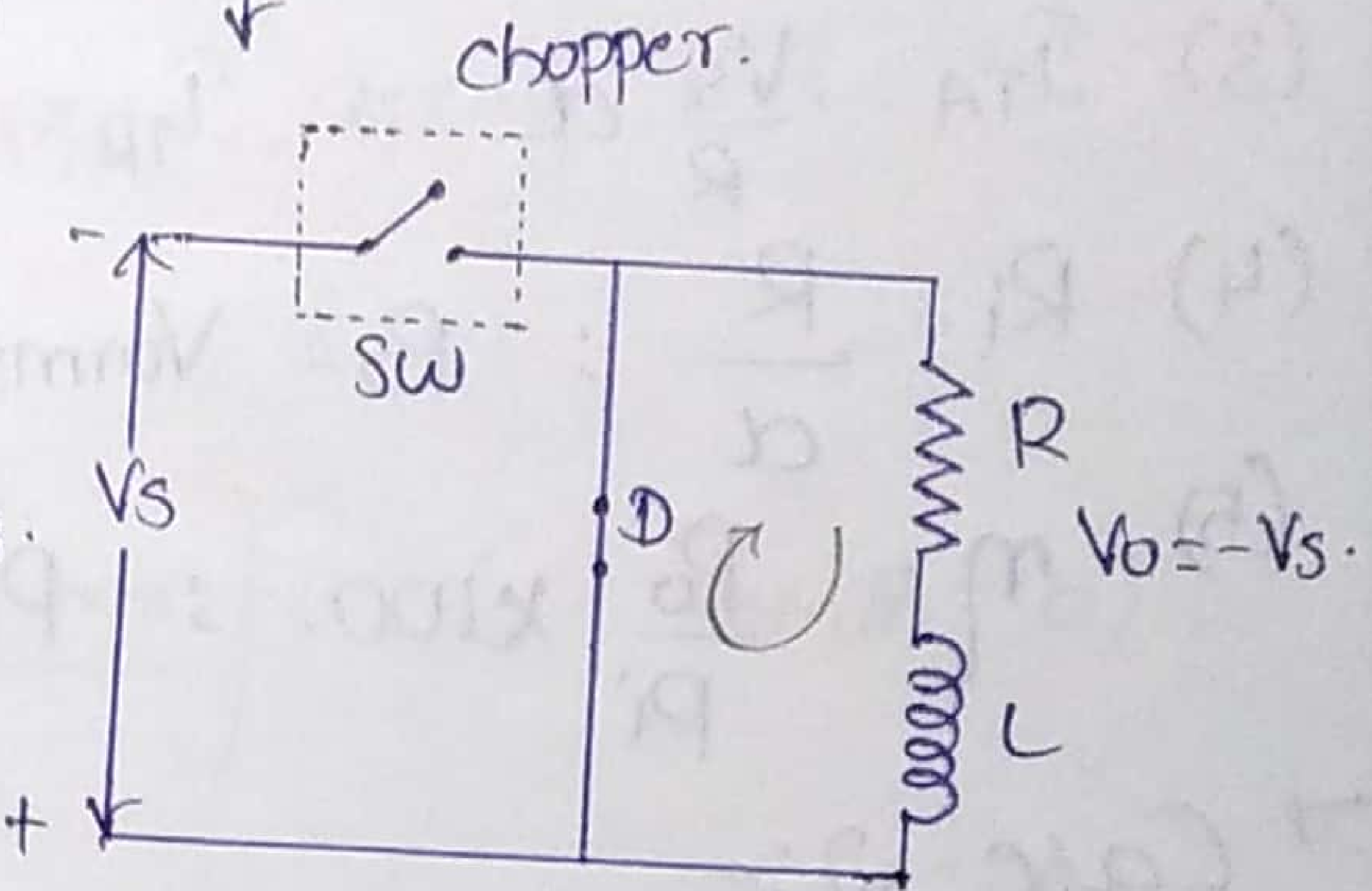
(10) chopping $\eta = \frac{P_o}{P_i} \times 100.$

→ Step down chopper with RL-Load:-

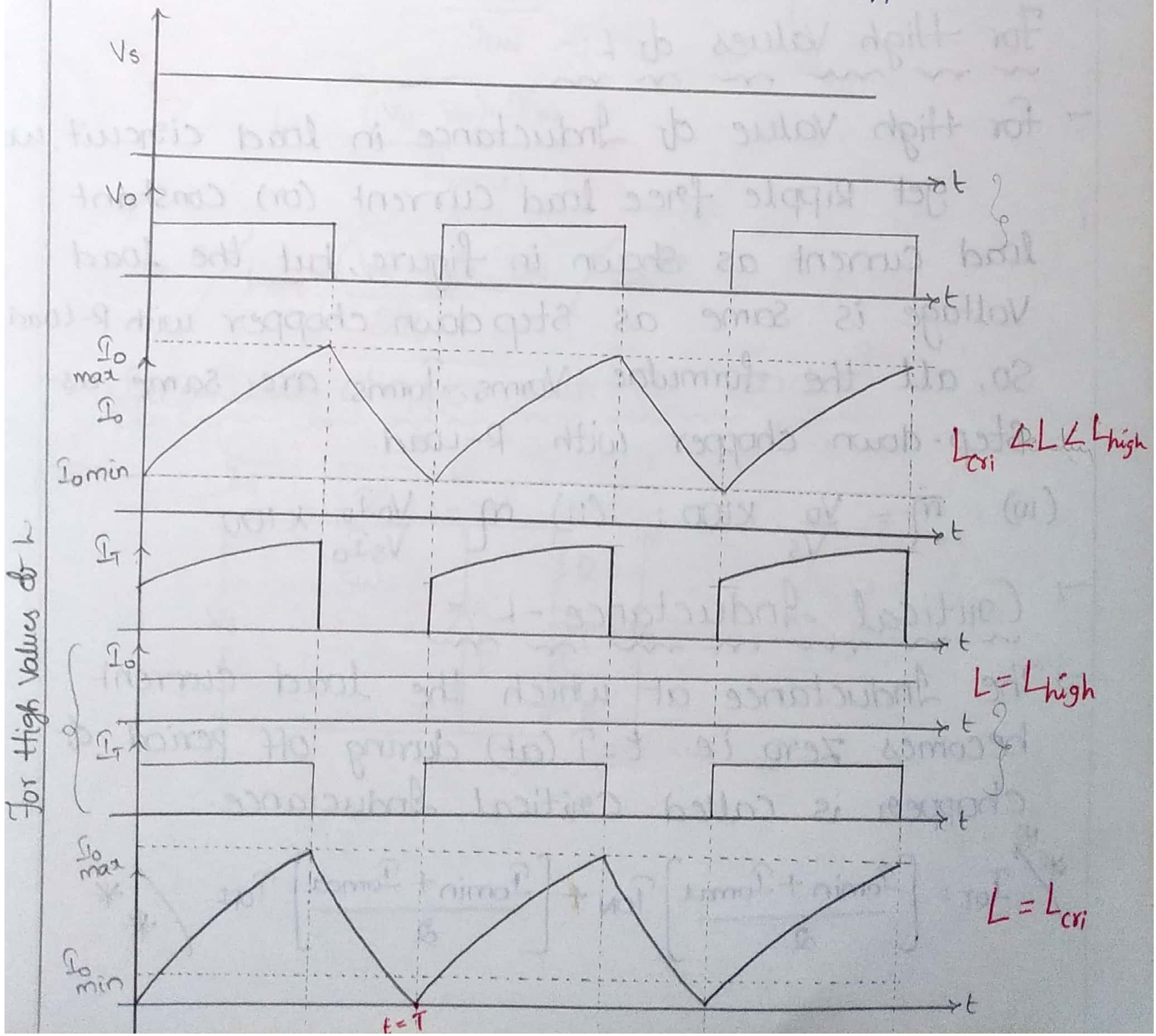




when CH is ON.



when CH is off



→ Here the load Voltage waveform is exactly similar to Step down chopper with RL-Load.

→ Hence, all formulae are Same as Step-down chopper with R-Load, i.e.,

(1) $V_0 = \alpha \cdot V_s$; $I_0 = \frac{V_0}{R}$.

(2) $V_{orms} = \sqrt{\alpha} \cdot V_s$; $I_{orms} = \frac{V_{orms}}{R}$

(3) $I_{TA} = \frac{V_s}{R} \cdot \alpha$; $I_{TR} = \frac{V_s}{R} \cdot \sqrt{\alpha}$.

(4) $R_i = \frac{R}{\alpha}$; $P_0 = V_{orms} \cdot I_{orms} = V_{orms}^2 R = \frac{I_{orms}^2}{R}$.

(5) $\eta = \frac{P_0}{P_i} \times 100$. ; $P_i = V_s I_s = V_s \cdot I_0$.

→ Case-2:-

For High Values of L:-

→ for High Value of Inductance in load circuit, we get Ripple free load current (or) Constant load current as shown in figure, but the load Voltage is Same as Step down chopper with R-Load. So, all the formulae V_{orms}, I_{orms} are same as Step-down chopper with R-Load.

(10) $\eta = \frac{V_0}{V_s} \times 100$; (11) $\eta = \frac{V_0 I_0}{V_s I_0} \times 100$.

→ Critical Inductance - L:-

→ The Inductance at which the load current becomes zero i.e., t=T (at) during off period of chopper is called Critical Inductance.

/ $I_{0T} = \left[\frac{I_{omin} + I_{omax}}{2}\right] T_{ON} + \left[\frac{I_{omin} + I_{omax}}{2}\right] T_{OFF}$. /

At $t = T$; $I_{omin} = 0$.

$$\Rightarrow I_{OT} = \frac{I_{omax}}{2}(T_{ON} + T_{OFF}).$$

$$\Rightarrow I_{OT} = \frac{I_{omax}}{2}(T)$$

$$*/\ I_{omax} = 2I_0^{\,T_{ON}}\ /*$$

→ During ON period of chopper, apply KVL.

$$V_S = I_0R + L \cdot \frac{dI_0}{dt}$$

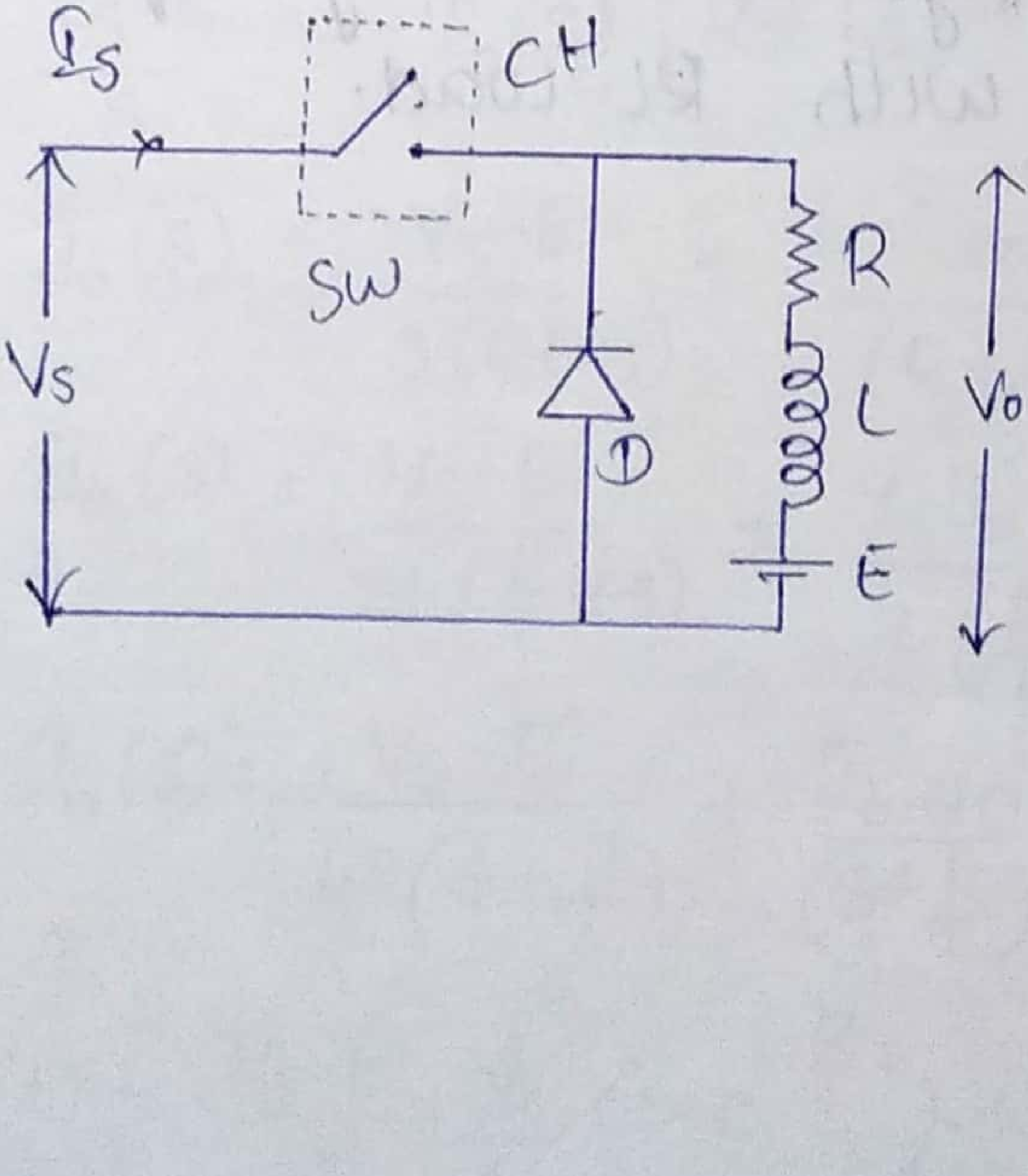
$$\Rightarrow V_S = V_0 + L \cdot \left[\frac{I_{omax} - I_{omin}}{T_{ON} - 0}\right]. \quad (\because I_{omin} = 0).$$

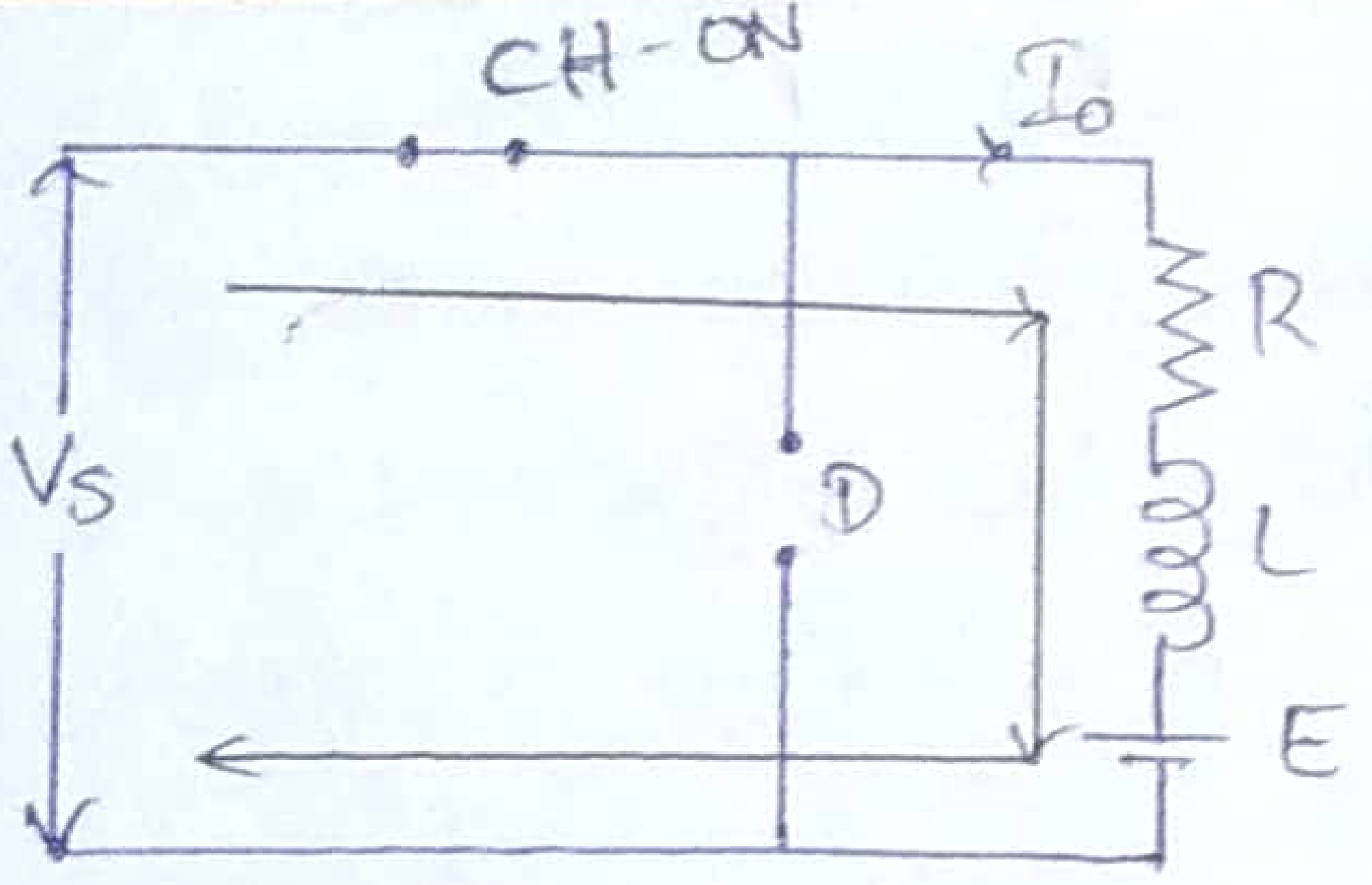
$$\Rightarrow V_S - V_0 = L \cdot \frac{I_{omax}}{T_{ON}}.$$

$$\Rightarrow L = \frac{(V_S - V_0) \cdot T_{ON}}{I_{omax}}.$$

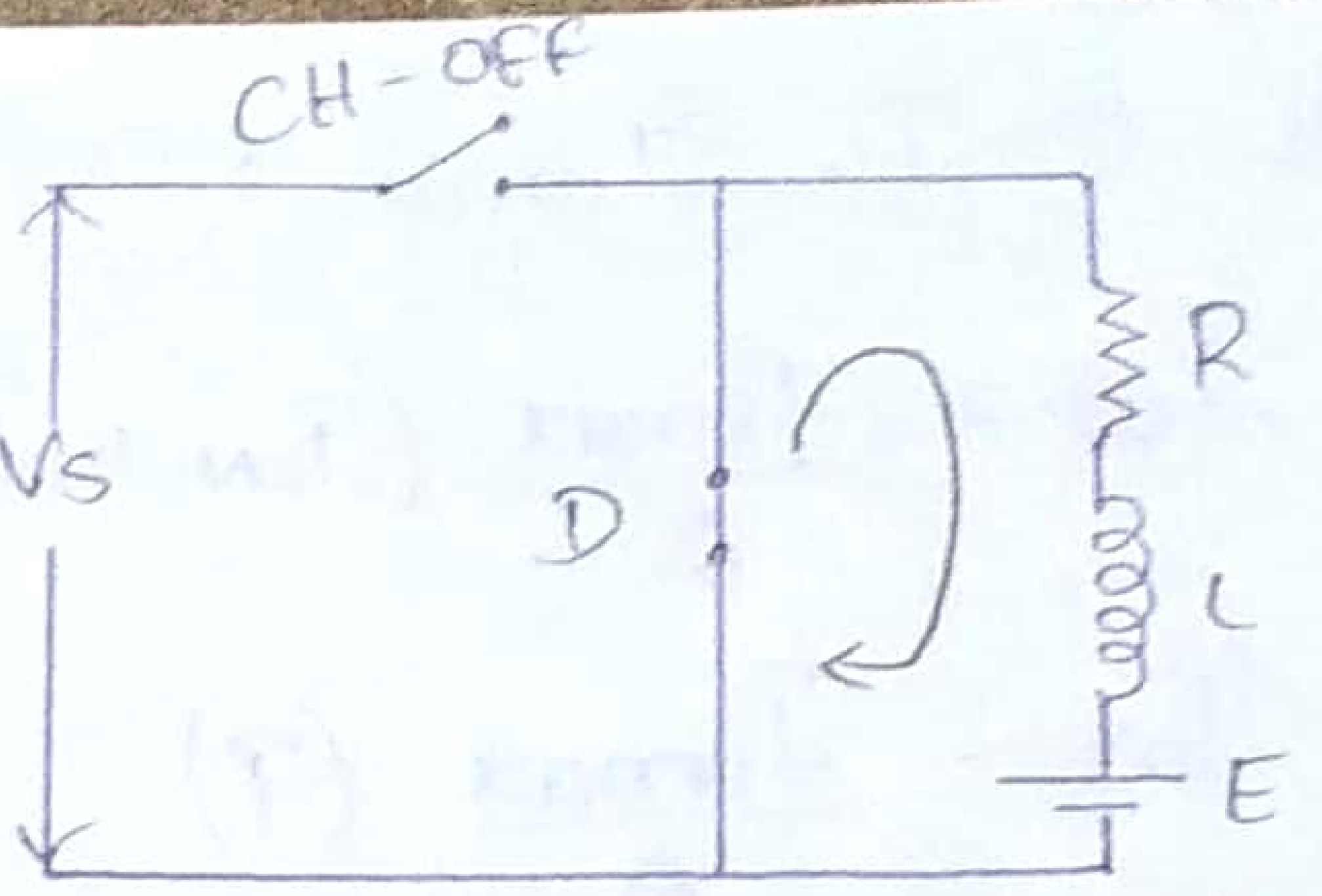
$$**/\ L = \frac{(V_S - V_0) \cdot T_{ON}}{2I_0}\ /**$$

→ Step Down chopper with RLE Load:-

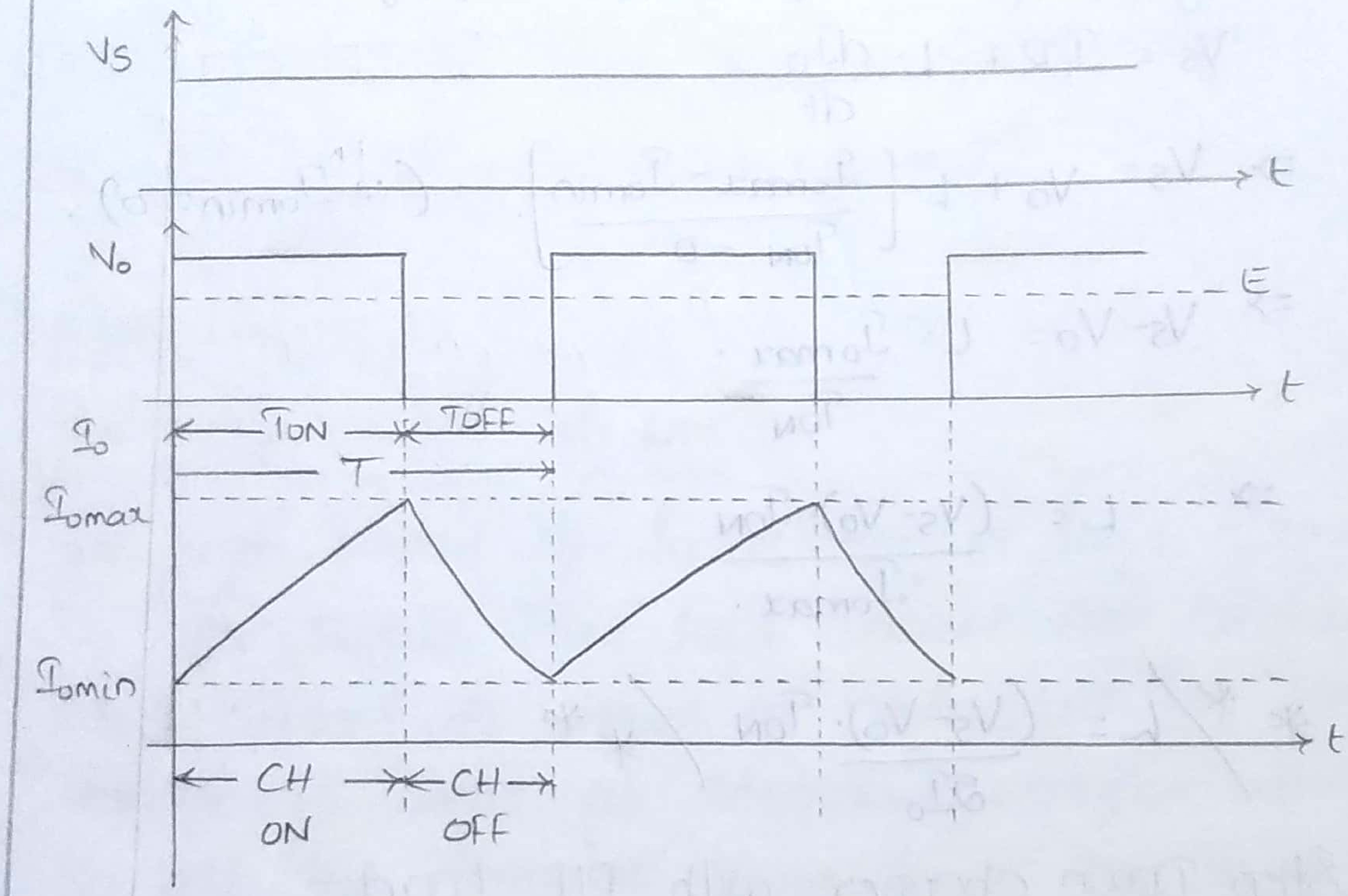




During the ON period of chopper



During OFF period of CHOPPER.



Here, the load Voltage is exactly equals to the Step down chopper with RL-Load.

(1) $V_o = \alpha \cdot V_s$

(2) $V_o = I_o R + E$

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

(3) $V_{orms} = \sqrt{\alpha} \cdot V_s$.

(4) $I_{orms} = \frac{V_{orms} - E}{R}$

(5) $I_{TA} = \alpha \cdot \frac{V_S}{R}$

(6) $I_{TR} = \sqrt{\alpha} \cdot \frac{V_S}{R}$.

(7) $R_i = \frac{R}{\alpha}$; (8) $\Rightarrow P_i = V_S I_S = V_S \cdot I_0$

(9) $P_0 = V_{orms} \cdot I_{orms} = I_{orms}^2 R = \frac{V_{orms}^2}{R}$.

*** → Steady state Analysis of Type-A chopper (or) Step Down chopper with RLE Load:-

→ when chopper is on, apply KVL

$$\Rightarrow V_S = I_0 R + L \cdot \frac{dI_0}{dt} + E \rightarrow (1) \quad \text{when } 0 < t < T_{on}.$$

→ when chopper is off, apply KVL.

$$\Rightarrow 0 = E + L \cdot \frac{dI_0}{dt} + I_0 R \rightarrow (2) \quad \text{when } T_{ON} < t < T.$$

$$(1) \Rightarrow V_S - E = I_0 R + L \cdot \frac{dI_0}{dt}$$

Applying laplace Transforms.

$$\Rightarrow \frac{V_S - E}{S} = R \cdot I_0(S) + L \cdot [S \cdot I_0(S) - I_{omin}]$$

$$\Rightarrow \frac{V_S - E}{S} = R \cdot I_0(S) + L \cdot S \cdot I_0(S) - L \cdot I_0 \, min.$$

$$\Rightarrow \frac{V_S - E}{S} = I_0(S)[R + LS] - L \cdot I_{omin}.$$

$$\Rightarrow I_0(S) = \frac{V_S - E}{S(R+LS)} + \frac{L \cdot I_{omin}}{(R+LS)}$$

$$\Rightarrow I_0(S) = \frac{V_S - E}{SL(\frac{R}{L}+S)} + \frac{L \cdot I_{omin}}{L(\frac{R}{L}+S)}$$

$$\because L^{-1}\left(\frac{1}{S+a}\right) = e^{-at}$$

$$\Rightarrow I_0(S) = \frac{V_S - E}{LS(S+\frac{R}{L})} + \frac{I_{omin}}{(S+\frac{R}{L})}$$

$$L^{-1}\left(\frac{1}{S(S+a)}\right) = L^{-1}\left[\frac{1}{S} - \frac{1}{S+a}\right]\frac{1}{a}$$

Apply I.L.T.

$$\Rightarrow I_0(t) = \frac{V_S - E}{L} \cdot \frac{1}{\frac{R}{L}}(1 - e^{-\frac{R}{L}t}) + I_{omin} e^{-\frac{R}{L}t}$$

$$L^{-1}\left(\frac{1}{S(S+a)}\right) = \frac{1}{a}(1 - e^{-at})$$

$$\Rightarrow I_0(t) = \frac{V_S - E}{R}(1 - e^{-R/L\, t}) + I_{omin} e^{-\frac{R}{L}t} \rightarrow (3)$$

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from (2), $\Rightarrow 0 = E + I_0 R + L \cdot \frac{dI_0}{dt}$

$$\Rightarrow -E = I_0 R + L \cdot \frac{dI_0}{dt}$$; Apply LT.

$$\Rightarrow \frac{-E}{S} = I_0(S) \cdot R + L\left[S \cdot I_0(S) - I_{omax}\right]$$

$$\Rightarrow \frac{-E}{S} = I_0(S)\left[LS + R\right] - L I_{omax}.$$

$$\Rightarrow I_0(S) = \frac{-E}{S(R+LS)} + L \cdot \frac{I_{omax}}{(R+LS)}$$

$$\Rightarrow I_0(S) = \frac{-E}{SL\left(\frac{R}{L}+S\right)} + \frac{L \cdot I_{omax}}{L\left(\frac{R}{L}+S\right)}$$

$$\Rightarrow I_0(S) = \frac{-E}{LS\left(S+\frac{R}{L}\right)} + \frac{I_{omax}}{\left(\frac{R}{L}+S\right)}$$

Applying Inverse Laplace Transforms.

$$\Rightarrow I_0(t) = \frac{-E}{L} \cdot \frac{1}{R/L}\left(1-e^{-\frac{R}{L}t}\right) + I_{omax} \cdot e^{-\frac{R}{L}t} \quad \left(\because \frac{R}{L} = \frac{t}{Ta}\right)$$

$$\Rightarrow I_0(t) = -\frac{E}{R}\left(1-e^{-\frac{R}{L}t}\right) + I_{omax} e^{\left(-\frac{R}{L}\right)t} \rightarrow (4)$$

when at $t = T_{ON}$; $I_0(t) = I_{omax}$.

$$(3) \Rightarrow I_{omax} = \frac{V_S - E}{R}\left(1-e^{-\frac{R}{L}T_{ON}}\right) + I_{omin} \cdot e^{-\frac{R}{L}T_{ON}}$$

$$\Rightarrow I_{omax} = \frac{V_S - E}{R}\left(1-e^{-T_{ON}/Ta}\right) + I_{omin}\, e^{-T_{ON}/Ta} \rightarrow (5)$$

where, $Ta = \frac{L}{R}$ = Time constant. when $0 < t < T_{ON}$.

when CH = OFF at $t = T_{OFF}$;

$t = T - T_{ON}$; $I_0(t) = I_{omin}$.

$$(4) \Rightarrow I_{omin} = -\frac{E}{R}\left(1-e^{-\frac{R}{L}(T-T_{ON})}\right) + I_{omax}\, e^{-\frac{R}{L}(T-T_{ON})}$$

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

$\rightarrow (6)$ when $T_{ON} < t < T$

→ Sub Eqn.(6) in Eqn.(5)

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

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

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

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

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

$$*/\ I_{omax} = \frac{V_s}{R}\left[\frac{1 - e^{-T_{ON}/T_a}}{1 - e^{-T/T_a}}\right] - \frac{E}{R}.\ /* \rightarrow (7)$$

→ Substitute Eqn.(7) in Eqn.(6)

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

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

$$= \frac{-E}{R} + \frac{V_s}{R}\left(\frac{1 - e^{-T_{ON}/T_a}}{1 - e^{-T/T_a}}\right) \cdot \frac{e^{T_{ON}/T_a}}{e^{T/T_a}}. \qquad \cancel{- \frac{E}{R} e^{-(T-T_{ON})/T_a}}$$

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

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

→ per unit Ripple Current:-

→ In continuous current mode of operation, the load current continuously varies from min value to max. value and max value to min. value

→ The continuous variation in load from min to max. and max to min will creates ripples in the load. The Load Ripple current is given by

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

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

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

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

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

$$\Rightarrow I_{r\,per\,unit} = \frac{\frac{\cancel{V_s}}{\cancel{R}}\left[\frac{\left(1-e^{-T_{ON}/T_a}\right)\left(1-e^{-(T-T_{ON})/(T_a)}\right)}{\left(1-e^{-T/T_a}\right)}\right]}{\cancel{V_s/R}}$$

$$\Rightarrow I_{rpu} = \frac{\left(1-e^{-T_{ON}/T_a}\right)\left(1-e^{-(T-T_{ON})/T_a}\right)}{\left(1-e^{-T/T_a}\right)}$$

Let, $\alpha = \frac{T_{ON}}{T}$; $T_{ON} = \alpha T$; $T - T_{ON} = T - \alpha T = (1-\alpha)T$.

$$\Rightarrow I_{rpu} = \frac{\left(1-e^{-\alpha T/T_a}\right)\left(1-e^{-(1-\alpha)T/T_a}\right)}{\left(1-e^{-T/T_a}\right)}$$

$$\Rightarrow I_{rpu} = \frac{1 - e^{-(1-\alpha)T/T_a} - e^{-\alpha T/T_a} + e^{-\alpha T/T_a} \cdot e^{-(1-\alpha)T/T_a}}{1 - e^{-T/T_a}}$$

$$\Rightarrow I_{rpu} = \frac{1 - e^{-(1-\alpha)T/T_a} - e^{-\alpha T/T_a} + \cancel{e^{-\alpha T/T_a}} \cdot e^{-T/T_a} \cdot \cancel{e^{\alpha T/T_a}}}{1 - e^{-T/T_a}}$$

$$** \; I_{rpu} = \frac{1 - e^{-(1-\alpha)T/T_a} - e^{-\alpha T/T_a} + e^{-T/T_a}}{1 - e^{-T/T_a}} \; **$$

→ Condition for max. value of PU Ripple current :-

→ Inorder to get the condition for max. value for PU Ripple current, diff. I_{rpu} with respect to α and equating the result to zero i.e.,

$$\frac{dI_{rpu}}{d\alpha} = 0.$$

$$\Rightarrow \frac{1}{1-e^{-T/T_a}} \left[0 - e^{-(1-\alpha)T/T_a} \left(\frac{T}{T_a}\right) - e^{-\alpha T/T_a} \left(\frac{-T}{T_a}\right) + 0 \right] = 0.$$

$$\Rightarrow e^{-\alpha T/T_a} \cancel{\left(\frac{T}{T_a}\right)} = e^{-(1-\alpha) \cdot T/T_a} \cdot \cancel{\left(\frac{T}{T_a}\right)}$$

$$\Rightarrow e^{-\alpha T/T_a} = e^{-(1-\alpha) \cdot T/T_a}.$$

$$\Rightarrow -\frac{\alpha T}{T_a} = -\frac{(1-\alpha)T}{T_a}.$$

$$\Rightarrow -\alpha = -1 + \alpha.$$

$$\Rightarrow \alpha = 1/2$$

$$\therefore \alpha = 0.5$$

***
***

→ Thus, The Ripple current is maximum when the Duty cycle, α is 0.5 ***
***

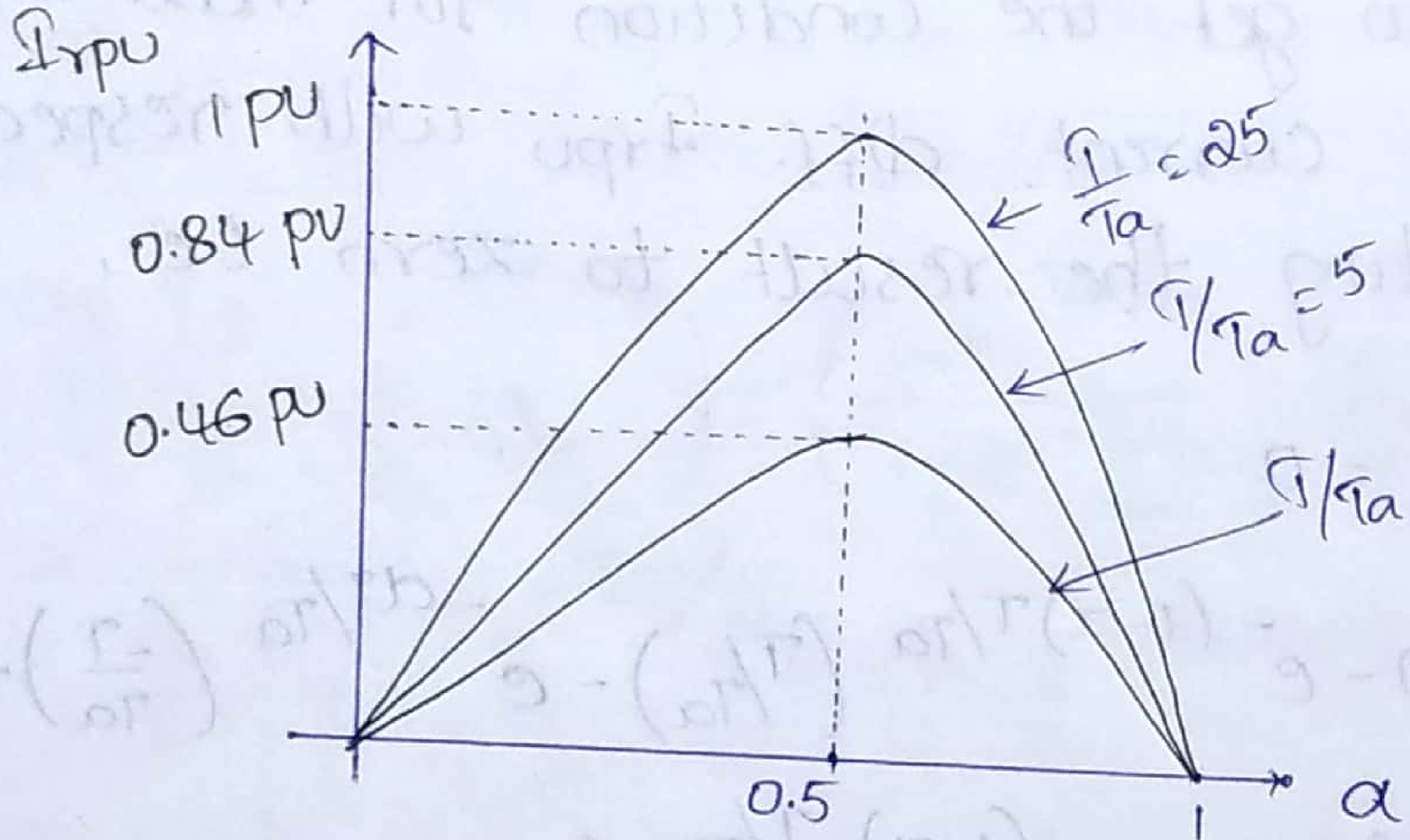
→ The max. Value of per unit Ripple current is inversely proportional to load Inductance (L) & choping frequency (f).

→ If $L\uparrow ; T_a\uparrow = \frac{L\uparrow}{R} ; \left(\frac{T\downarrow}{T_a\updownarrow}\right)\updownarrow ; T\downarrow ; f\uparrow$

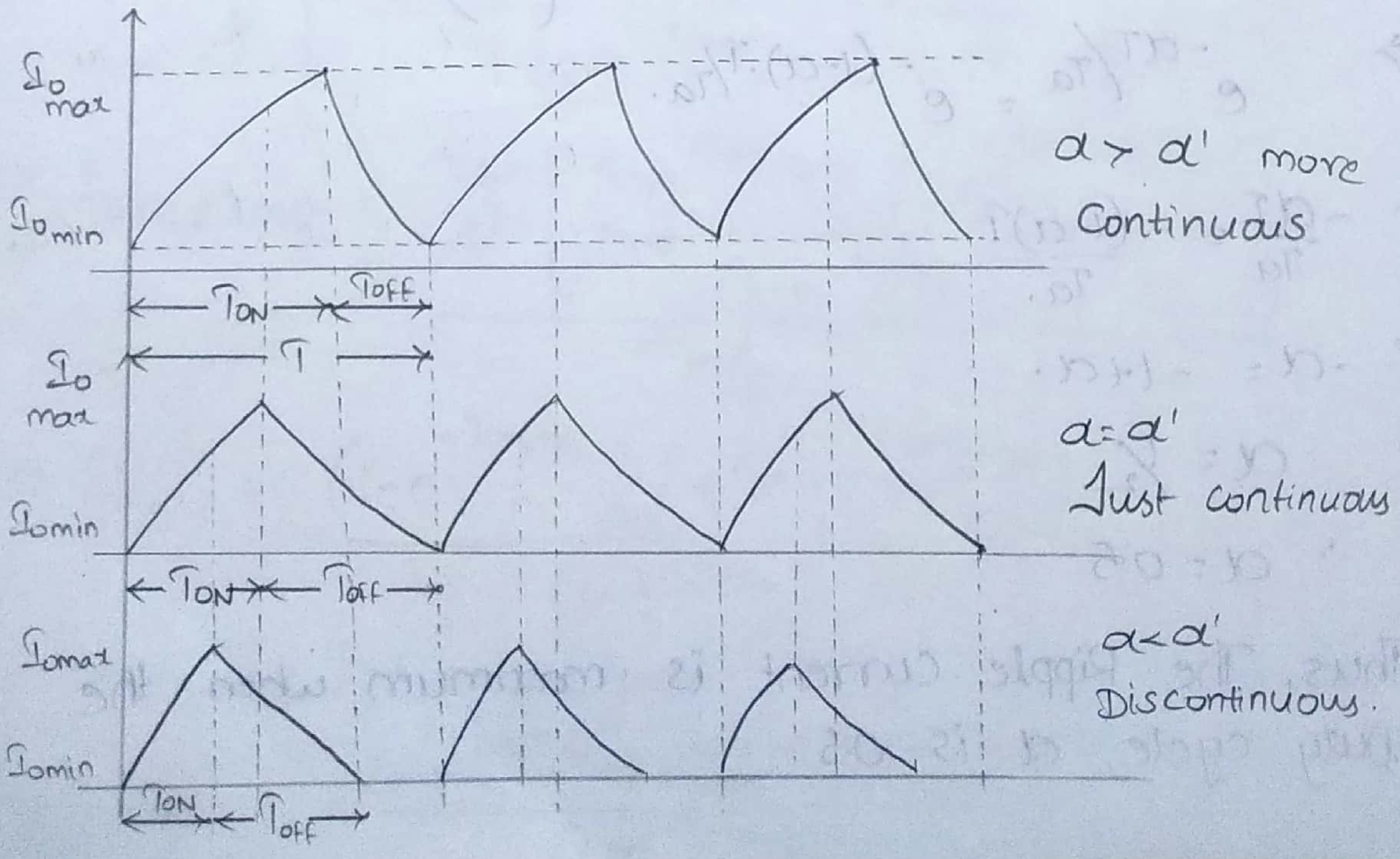
At $\alpha = 0.5 ; \left(\frac{T}{T_a}\right) = 25 ; I_{rpumax} = 1.$

$\alpha = 0.5 ; \left(\frac{T}{T_a}\right) = 5 ; I_{rpumax} = 0.848.$

$\alpha = 0.5 ; \left(\frac{T}{T_a}\right) = 2 ; I_{rpumax} = 0.462.$



→ Limit of Continuous Conduction :-



→ for constant chopping period T, if T_{ON} decreases, T_{OFF} increases. At some small value of T_{ON}, T_{OFF} is large and load current may falls to zero at $t=T$. The limit of continuous conduction is obtained when load current falls to zero at $t=T$.

we know that,

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

$$\Rightarrow 0 = \frac{V_s}{R}\left[\frac{e^{T_{ON}/T_a}-1}{e^{T/T_a}-1}\right]-\frac{E}{R} \quad (\because \text{At } t=T,\ I_{omin}=0)$$

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

$$\Rightarrow e^{T_{ON}/T_a}-1 = m(e^{T/T_a}-1)$$

$$\Rightarrow e^{T_{ON}/T_a} = 1+m(e^{T/T_a}-1).$$

$$\Rightarrow T_{ON}/T_a = \ln\left[1+m(e^{T/T_a}-1)\right]$$

$$\Rightarrow T_{ON} = T_a \ln\left[1+m(e^{T/T_a}-1)\right]$$

let $d' = \frac{T_{ON}}{T}$ = Duty cycle at limit of continuous conductio

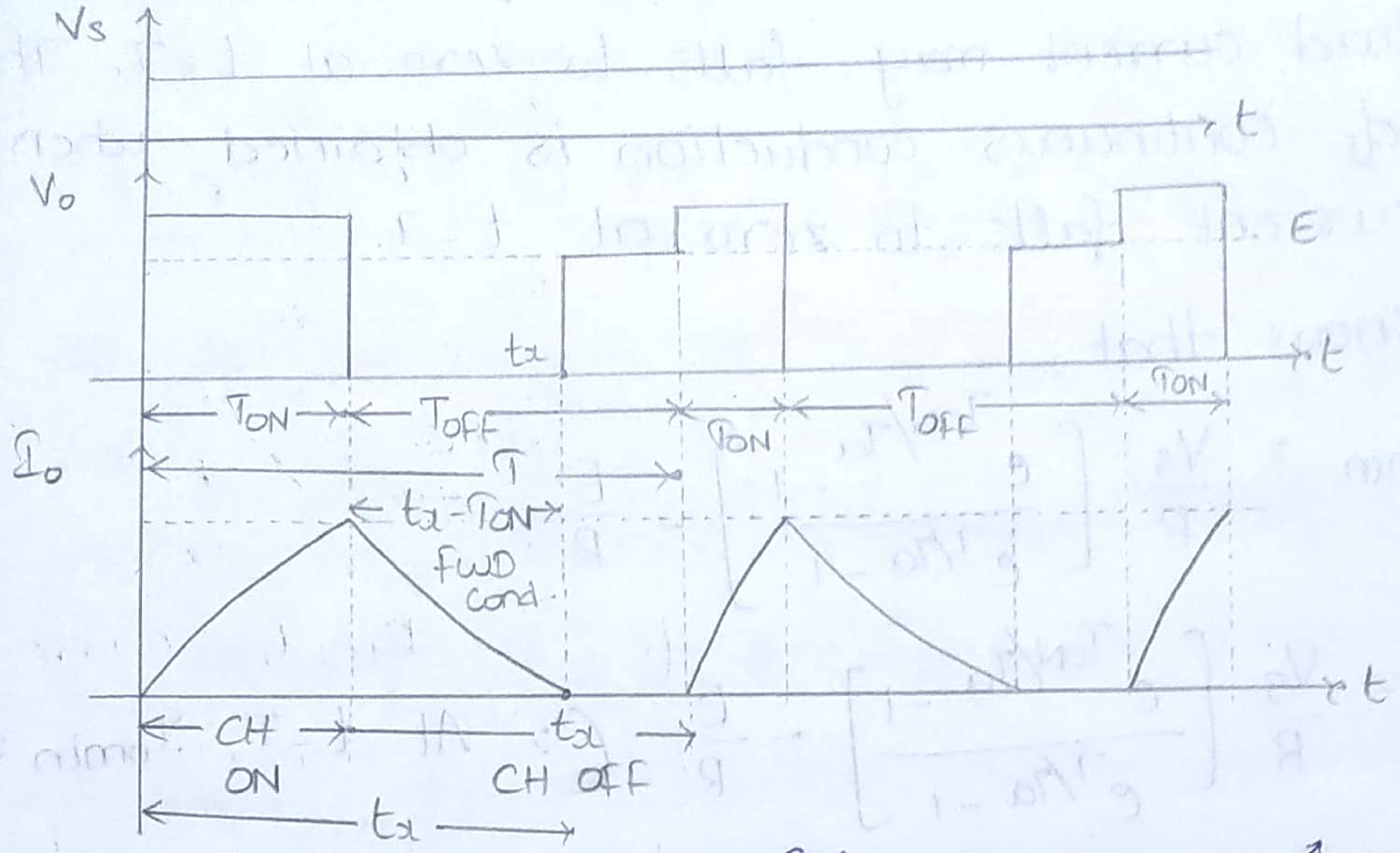
$$** \quad d' = \frac{T_a}{T}\ln\left[1+m(e^{T/T_a}-1)\right] \quad *$$

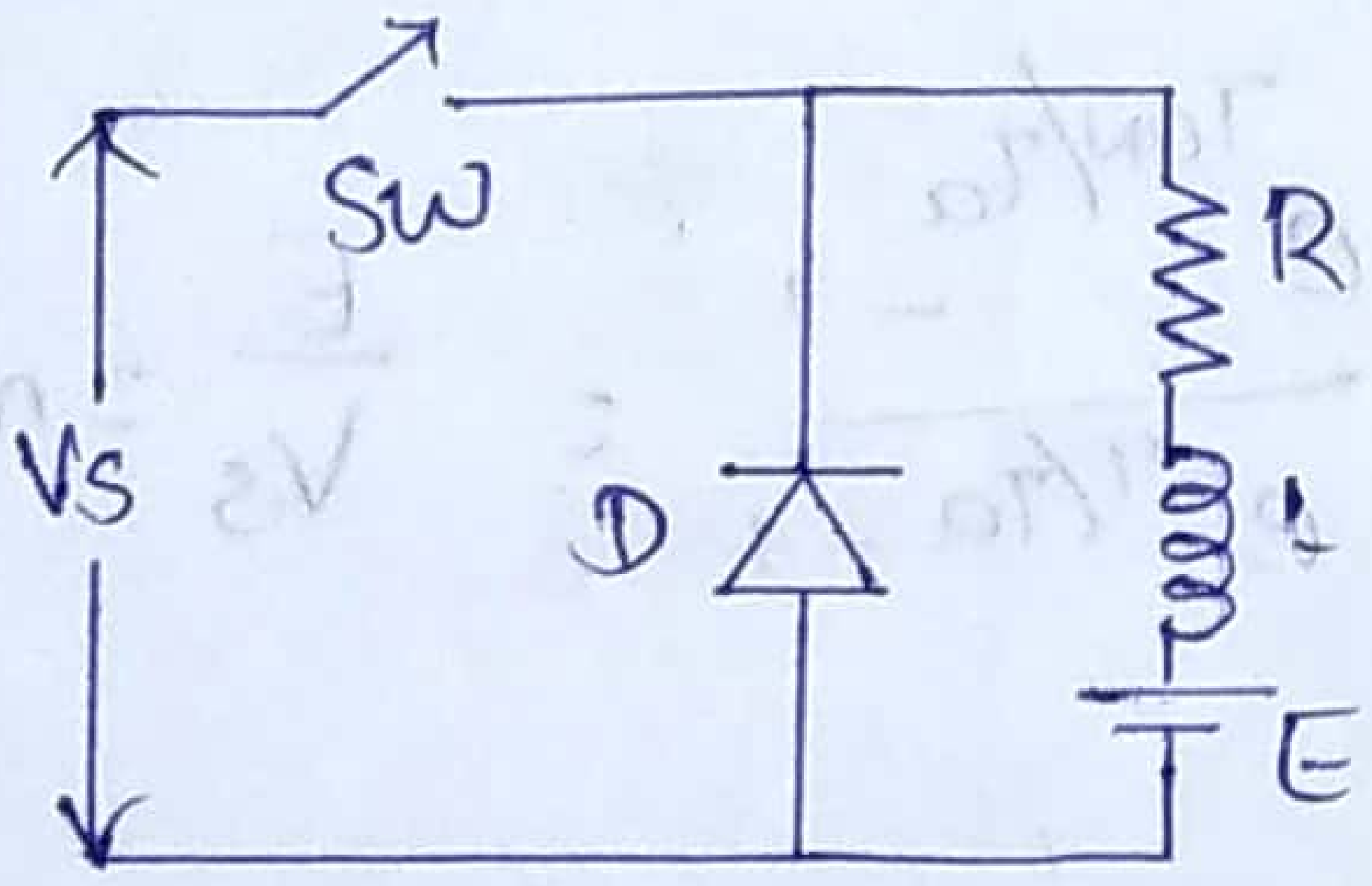
If ⇒ actual duty ~~d~~ cycle $d=d'$ then load current is just continuous.

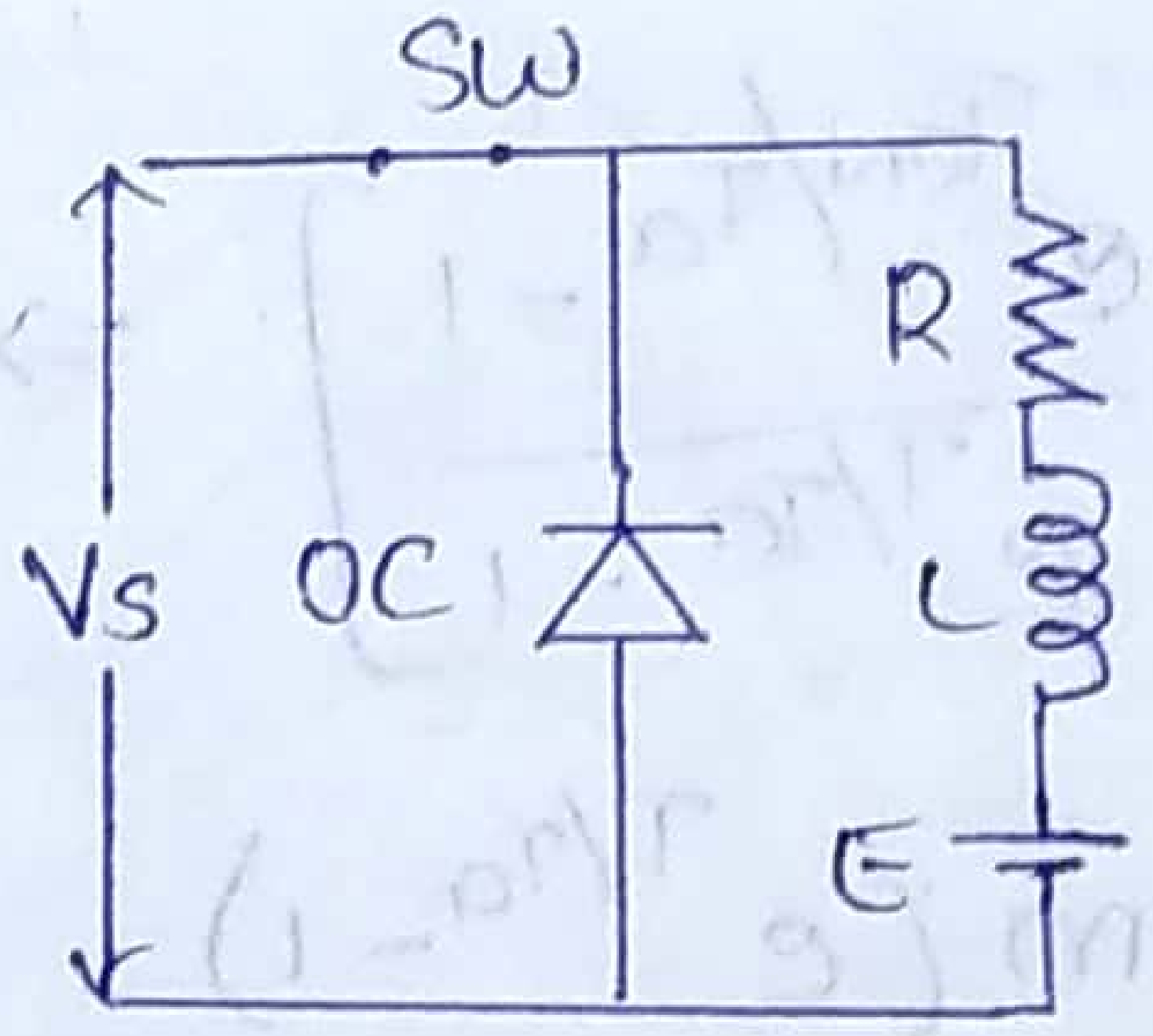
→ $d > d'$ ⇒ I_L is more continuous.

→ $d < d'$ ⇒ I_L is Discontinuous.

→ Step down chopper with RLE load

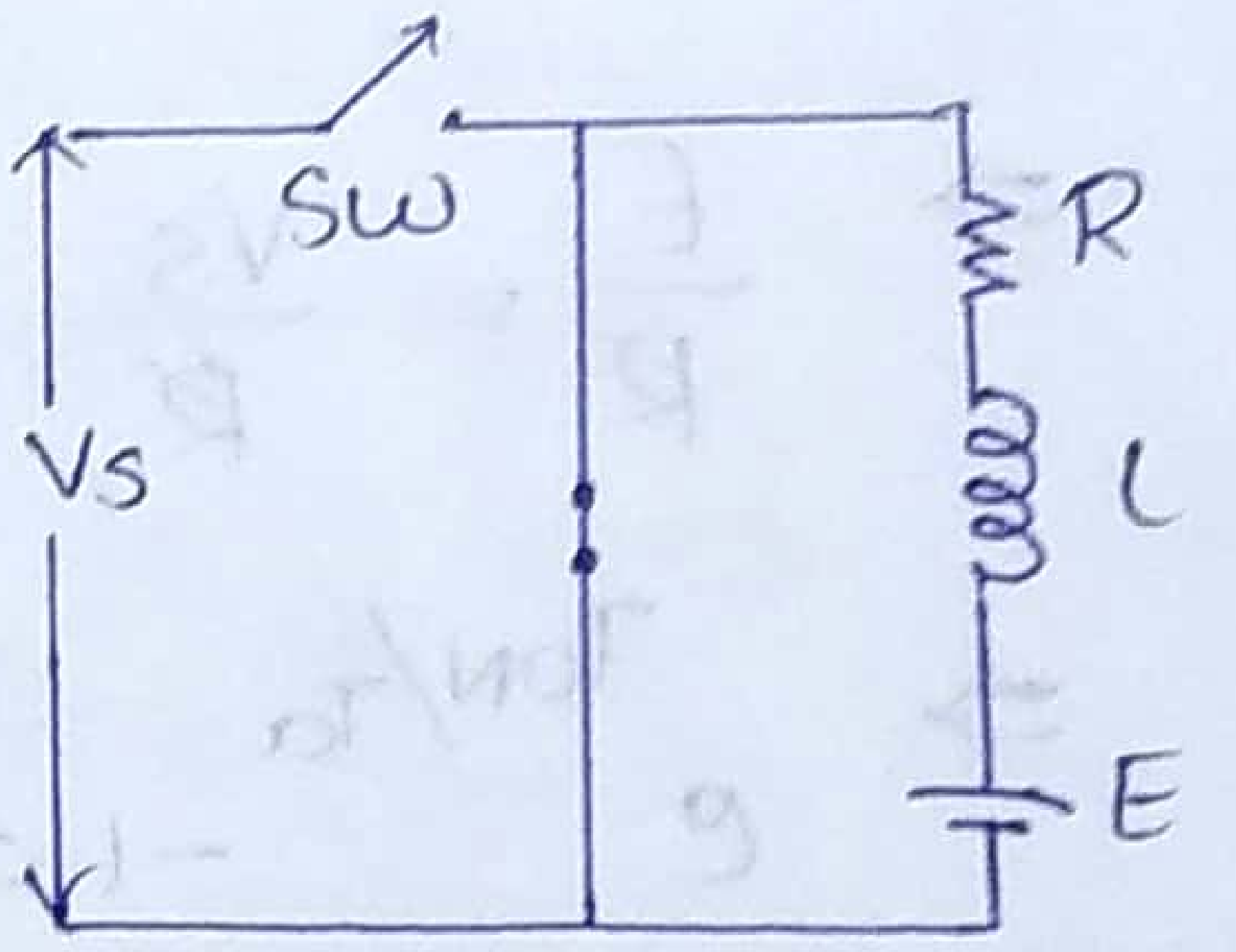






$-V_S + V_O = 0$

$V_O = -V_S$



$V_O = E$

→ Avg. output Voltage.

$$V_O = \frac{1}{T}\int_0^T V_O\, dt = \frac{1}{T}\left[\int_0^{T_{ON}} V_S\, dt + \int_{T_{ON}}^{\overset{T_x}{T_{OFF}}} 0\, dt + \int_{\underset{T_x}{T_{OFF}}}^{T} E\, dt\right]$$

$$\Rightarrow V_O = \frac{1}{T}\left[V_S\left(T_{ON} - 0\right) + E\left(T - t_x\right)\right]$$

$$= V_S \cdot \frac{T_{ON}}{T} + E\,\frac{(T - t_x)}{T}$$

$$*/\ V_O = \alpha \cdot V_S + E\left(1 - \frac{t_x}{T}\right) /*$$

$$I_O = \frac{V_O}{R}$$

→ Extension Time:-

→ It is the time between the instant at t=0 and the instant at which load current falls to zero during off period of chopper.

→ Commutation of Extension Time:-

→ when CH is ON;

$$I_o(t) = \frac{V_s - E}{R}(1-e^{-t/T_a}) + I_{omin}\, e^{-t/R_a} \rightarrow (1) \quad (0 < t < T_{ON}).$$

→ when CH is OFF;

$$I_o(t) = -\frac{E}{R}(1-e^{-t/T_a}) + I_{omax} \cdot e^{-t/T_a} \rightarrow (2) \quad (T_{ON} < t < T).$$

→ when CH ON at, $t = T_{ON}$; $I_o(t) = I_{omax}$.

$$(1) \Rightarrow I_{omax} = \frac{V_s - E}{R}(1-e^{-T_{ON}/T_a}) + I_{omin}\, e^{-T_{ON}/T_a} \rightarrow (3) \quad (0 < t < T_{ON})$$

→ when CH off at, $t = T_{OFF} = T - T_{ON}$; $I_o(t) = I_{omin}$.

$$(2) \Rightarrow I_{omin} = -\frac{E}{R}(1-e^{-\frac{(T-T_{ON})}{T_a}}) + I_{omax} \cdot e^{-(T-T_{ON})/T_a} \rightarrow (4) \quad (T_{ON} < t < T)$$

→ when CH off at $t = t_x - T_{ON}$; $I_o(t) = 0$.

$$(2) \Rightarrow 0 = -\frac{E}{R}(1-e^{-(t_x - T_{ON})/T_a}) + I_{omax} \cdot e^{-(t_x - T_{ON})/T_a}. \rightarrow (5) \quad (T_{ON} < t < T)$$

→ when load is Discontinuous

/ $I_{omin} = 0$. /

Sub $I_{omin} = 0$ in Eqn (3)

/ $I_{omax} = \frac{V_s - E}{R}(1-e^{-T_{ON}/T_a}) \rightarrow (6)$ /

Sub (6) in Eq (5)

$$\Rightarrow 0 = -\frac{E}{R}(1-e^{-(t_x - T_{ON})/T_a}) + \left[\frac{V_s - E}{R}(1-e^{-T_{ON}/T_a})\right] e^{-(t_x - T_{ON})/T_a}.$$

$$\Rightarrow \frac{E}{R}(1-e^{-(t_x - T_{ON})/T_a}) = \left[\frac{V_s - E}{R}\right](1-e^{-T_{ON}/T_a}) \cdot e^{-(t_x - T_{ON})/T_a}$$

⇒ $(1-e^{-(t_x-T_{ON})/T_a})e^{(t_x-T_{ON})/T_a} = \frac{V_s-E}{E}(1-e^{-T_{ON}/T_a})$

⇒ $e^{(t_x-T_{ON})/T_a}-1 = \frac{V_s-E}{E}(1-e^{-T_{ON}/T_a})$

⇒ $e^{(t_x-T_{ON})/T_a} = 1+\frac{V_s-E}{E}(1-e^{-T_{ON}/T_a})$

⇒ $(t_x-T_{ON})/T_a = \ln\left[1+\frac{V_s-E}{E}(1-e^{-T_{ON}/T_a})\right]$

/ $t_x = T_{ON}+T_a \ln\left[1+\frac{V_s-E}{E}(1-e^{-T_{ON}/T_a})\right]$ /

* Step-down chopper

(a) whether the load is continuous /not.

(b) Calculate Value of Avg. output Voltage

(c) Calculate Value of Avg. o/p Current.

(d) Compute min and max. Values of steady o/p current

$V_s = 220V$; $f = 500\,Hz$; $T_{ON} = 800\mu s$; $R = 1\Omega$; $L = 1mH$;

$E = 72V$; $T = 1/f$.

Sol:- (i) $d = \frac{T_{ON}}{T} = \frac{800}{2ms} = 0.4$ $(\because T = 1/f = 1/500)$

→ $T_a = \frac{L}{R} = \frac{1m}{1} = 1ms.$

→ $\frac{T}{T_a} = \frac{2m}{1m} = 2$

→ $\frac{T_a}{T} = \frac{1}{2} = 0.5$

→ $\frac{T_{ON}}{T_a} = \frac{800\mu}{1m} = 0.8$

→ $m = \frac{E}{V_s} = \frac{72}{220} = 0.327.$

$\therefore\ d' = \frac{T_a}{T}\ln\left[1+m(e^{T/T_a}-1)\right]$

$$\Rightarrow \alpha' = \frac{1m}{2m} \ln\left[1 + 0.327\,(e^{2} - 1)\right]$$

$$\therefore \alpha' = 0.563$$

i.e., $\alpha < \alpha'$ $(0.4 < 0.563)$

→ Here, Actual Duty cycle α is less than α'. Hence Load current is Discontinuous.

(ii)

$$V_0 = \alpha V_s + E\left(1 - \frac{t_x}{T}\right)$$

$$\Rightarrow t_x = T_{ON} + T_a \ln\left[1 + \frac{V_s - E}{E}\left(1 - e^{-T_{ON}/T_a}\right)\right].$$

$$= (800\,\mu) + (1m) \ln\left[1 + \frac{220-72}{72}\left(1 - e^{-\frac{800\mu}{1m}}\right)\right]$$

$$\therefore t_x = 1.57\,ms$$

$$\Rightarrow V_0 = 0.4 \times 220 + 72\left[1 - \frac{1.57m}{2m}\right]$$

$$\therefore V_0 = 103.48\,V.$$

(iii) $I_0 = \frac{V_0 - E}{R} = \frac{103.48 - 72}{1\Omega} = 31.48\,A.$

(iv) for discontinuous current mode: $I_{omin} = 0$

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

$$= \frac{220 - 72}{1}\left(1 - e^{-0.8}\right) = 81.49\,A.$$

$$\therefore I_{omax} = 81.49\,A.$$

* A step down chopper, $V_s = 220$, $T = 2000\,\mu s$; $T_{ON} = 600\,\mu s$, $R = 1\Omega$ $L = 5mH$; $E = 24V$. find load current is Continuous or not ;

$\alpha = 0.3$

$\alpha' = 0.13$

$V_0 = 66V$

$I_0 = 42A$

$I_{omin} = 33.03$, $I_{omax} = 51.45$

* A DC ON-OFF CH operating at 1KHz and Duty cycle of 10% is supplied from 220V Source. If L = 10mH, R = 10Ω Compute (a) min. Instantaneous load current

(b) peak Instantaneous load current

(c) max. P-P Ripple load current.

(d) Avg. and RMS Values of load Voltage.

Sol:- Given, f = 1KHZ; V_s = 200V; R = 10Ω; L = 10mH

$a = 10\% = 0.1$

(a) $d = \frac{T_{ON}}{T} \Rightarrow T_{ON} = a.T = 0.1 \times \frac{1}{10^3} = 100\mu s$

$\therefore T_{ON} = 100\mu s.$

$T_a = \frac{L}{R} = \frac{10m}{10} = 1ms$

$\frac{T_{ON}}{T_a} = \frac{100\mu}{1m} = 100ms.$

$\frac{T}{T_a} = \frac{1/f}{T_a} = \frac{10^{-3}}{1\times10^{-3}} = 1S$

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

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

$\Rightarrow I_{omin} = \frac{200}{10}\left[\frac{e^{0.1}-1}{e^{1}-1}\right] = 1.22A$

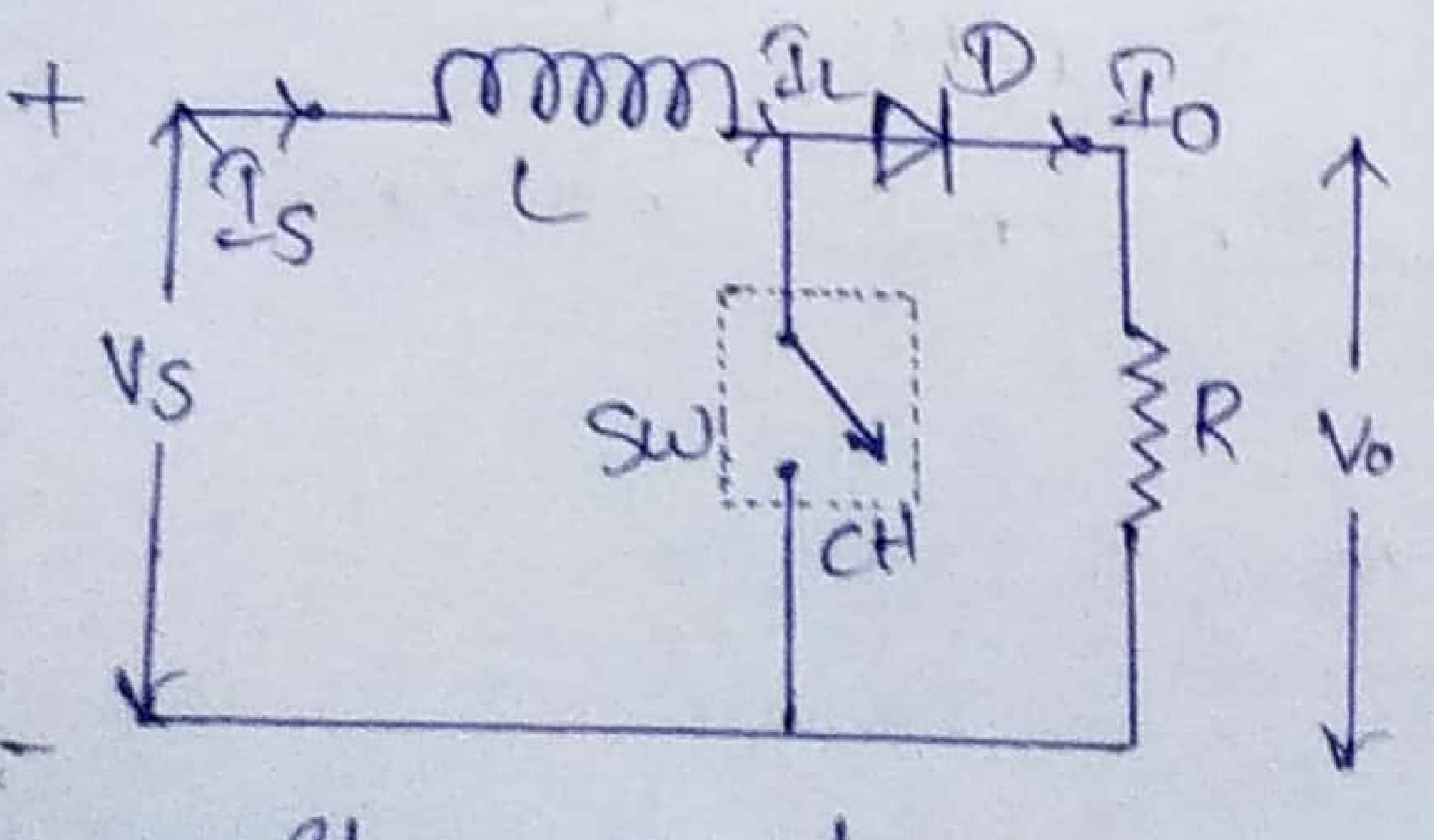
(b) $I_{omax} = \frac{V_s}{R}\left[\frac{1-e^{-T_{ON}/T_a}}{1-e^{-T/T_a}}\right]$

$= \frac{200}{10}\left[\frac{1-e^{-100m}}{1-e^{1}}\right] = 3.01A$

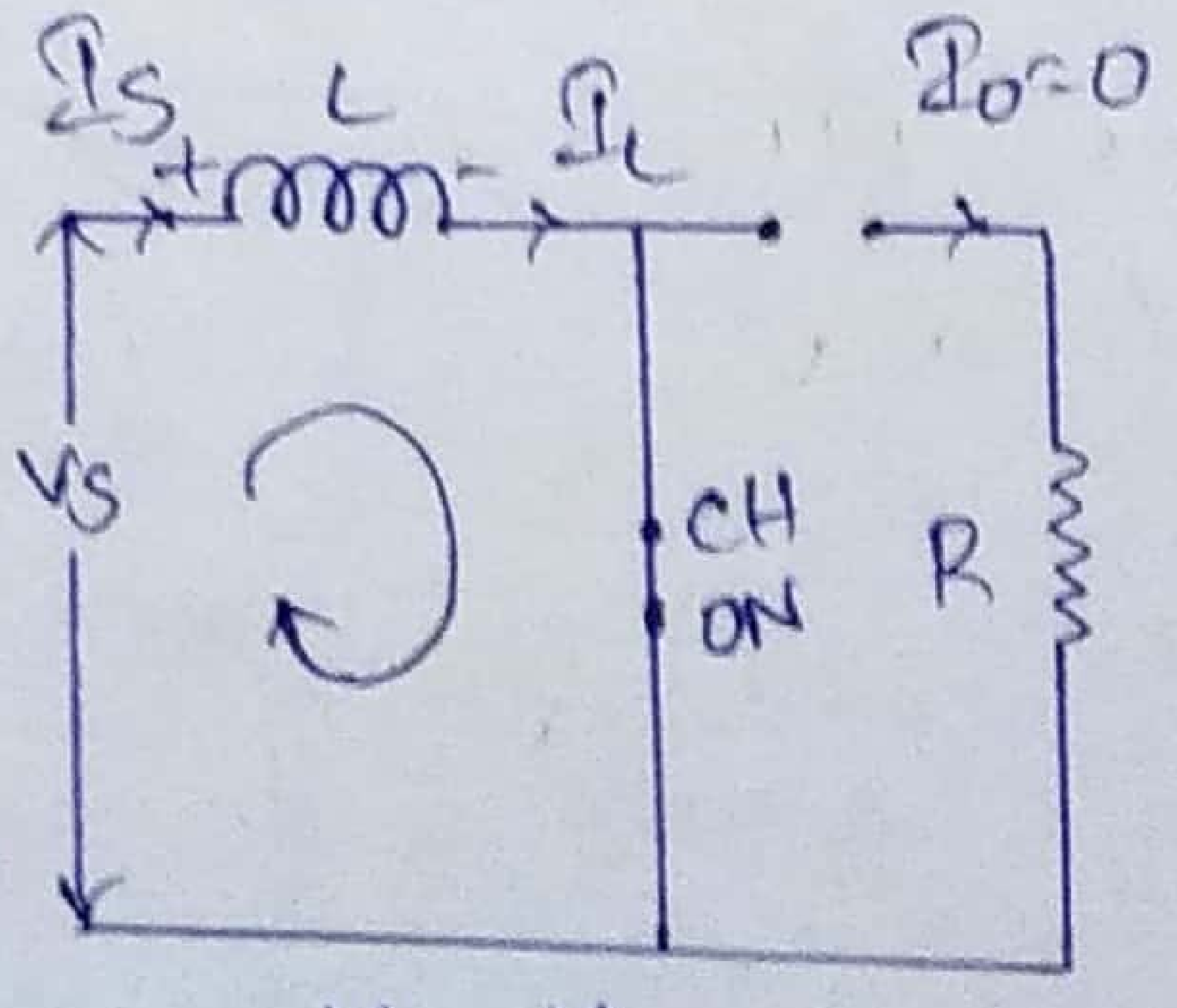
- Control Strategies :-

- The output Voltage of the chopper can be controlled by periodical opening and closing of CH-switch.
- To operate CH-switch there are two control strategies.
  (1) Time Ratio control (TRC)
    - constant frequency control. (pulse width Modulation scheme).
    - Variable frequency control. (frequency Modulation scheme).
  (2) Current limit control (CLC).

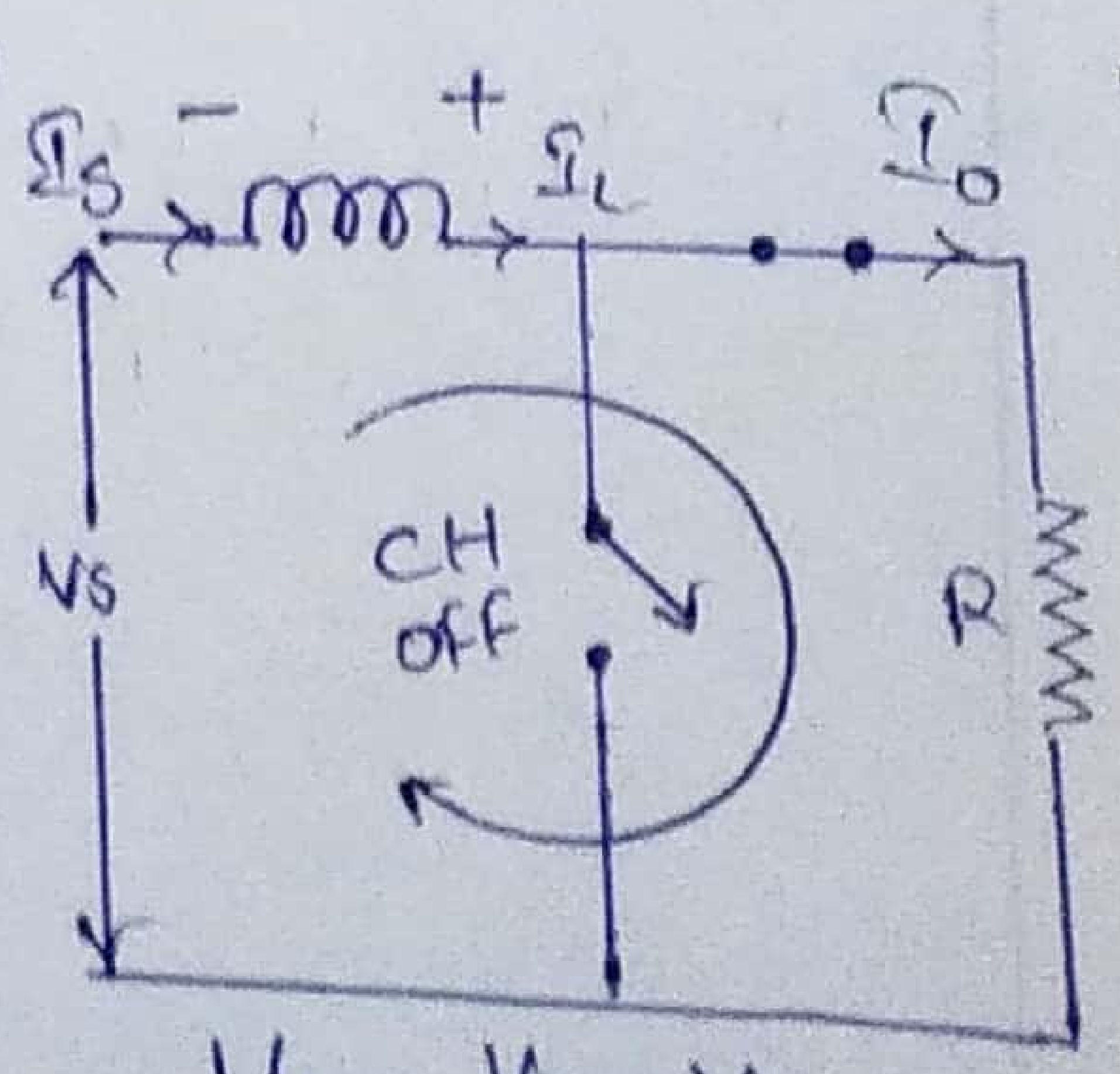
*** - In Time Ratio Control Method, the value of $\frac{T_{ON}}{T}$ is varied in order to control the output Voltage of chopper.
- In current limit ctrl method, load current is maintained between I_{omin} and I_{omax}.
- CLC method is used when the load has Energy Storing Element (Inductive load) only.
- CLC Method is possible to either constant freq. method (or) Variable frequency method.
- Step up chopper :-



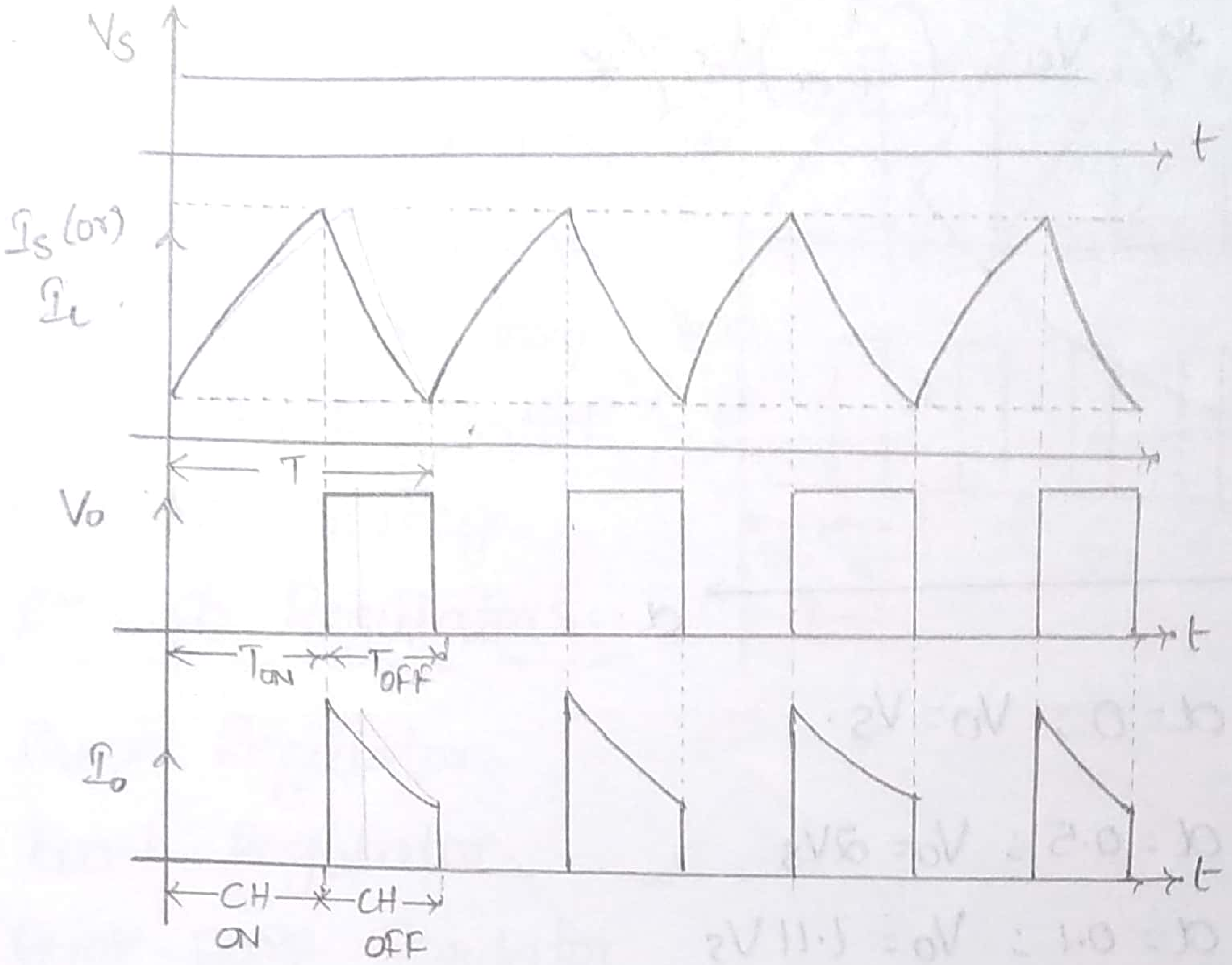
Step-up chopper.



$V_L = V_S$



$V_L = V_S - V_o$



→ when CH - ON

$$V_L = L\cdot\frac{dI}{dt}$$

$$V_S = L\cdot\frac{I_2 - I_1}{T_{ON} - 0}$$

$$V_S = L\cdot\frac{I_2 - I_1}{T_{ON}}$$

$$\Rightarrow V_S = L\cdot\frac{\Delta I}{T_{ON}}$$

$$\Rightarrow L\cdot\Delta I = T_{ON}\cdot V_S \rightarrow (1)$$

when CH - OFF

$$V_L = -L\cdot\frac{dI}{dt}$$

$$\Rightarrow V_S - V_0 = -L\cdot\frac{dI}{dt}$$

$$\Rightarrow V_0 - V_S = L\cdot\frac{I_2 - I_1}{T - T_{ON}}$$

$$\Rightarrow V_0 - V_S = L\cdot\frac{\Delta I}{T_{OFF}}$$

$$\Rightarrow L\cdot\Delta I = (V_0 - V_S)\cdot T_{OFF} \rightarrow (2)$$

Now, (1) = (2)

$$\Rightarrow T_{ON}\cdot V_S = (V_0 - V_S)\cdot T_{OFF}$$

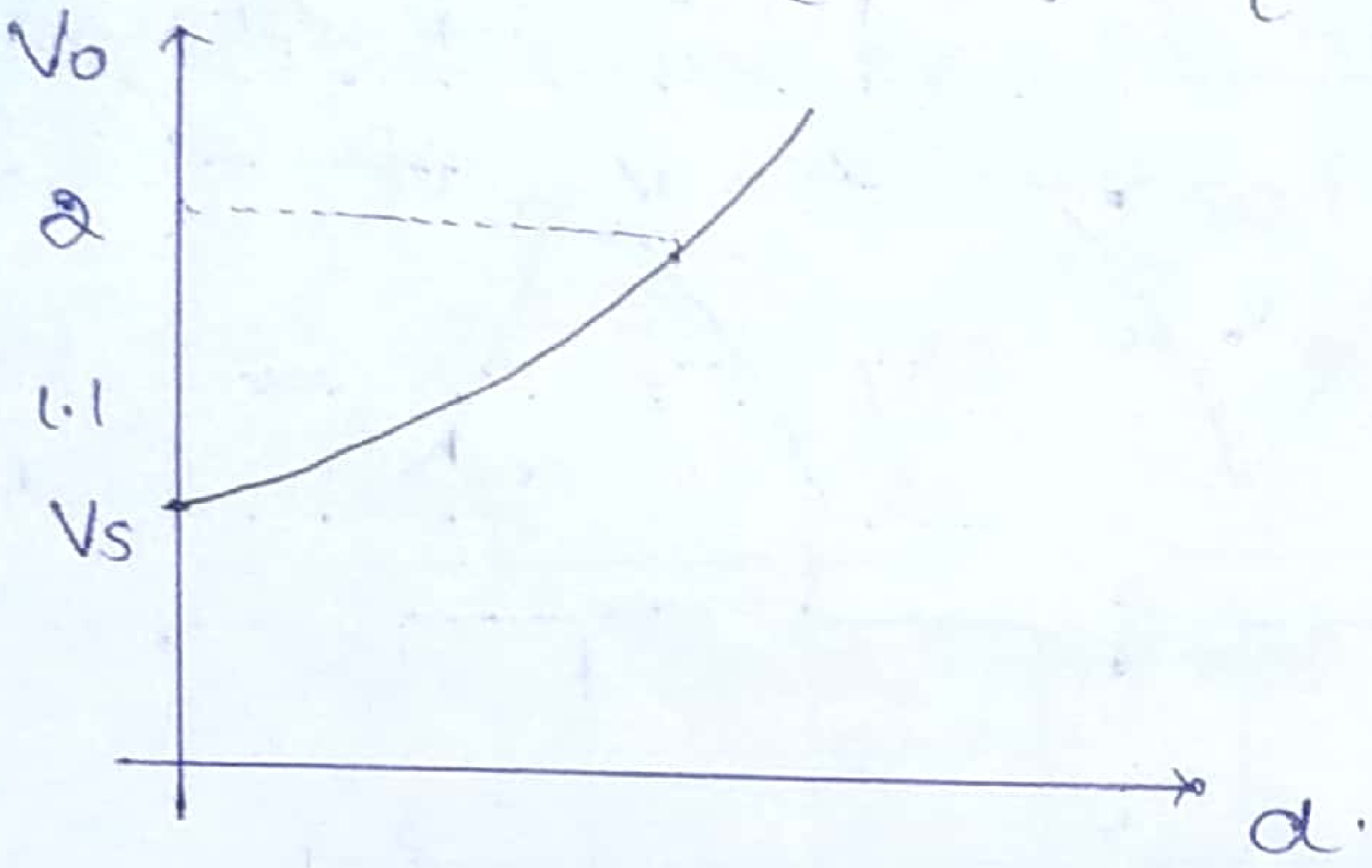
$$\Rightarrow T_{ON}\cdot V_S = V_0\cdot T_{OFF} - V_S\cdot T_{OFF}$$

$$\Rightarrow V_S\,(T_{ON} + T_{OFF}) = V_0\cdot T_{OFF}$$

$$\Rightarrow V_S\cdot T = V_0\cdot T_{OFF}$$

$$\Rightarrow \frac{V_0}{V_S} = \frac{T}{T_{OFF}} = \frac{T}{T - T_{ON}} = \frac{1}{1 - \frac{T_{ON}}{T}} = \frac{1}{1-\alpha}.$$

/ $V_o = \left(\frac{1}{1-\alpha}\right) V_s$ /



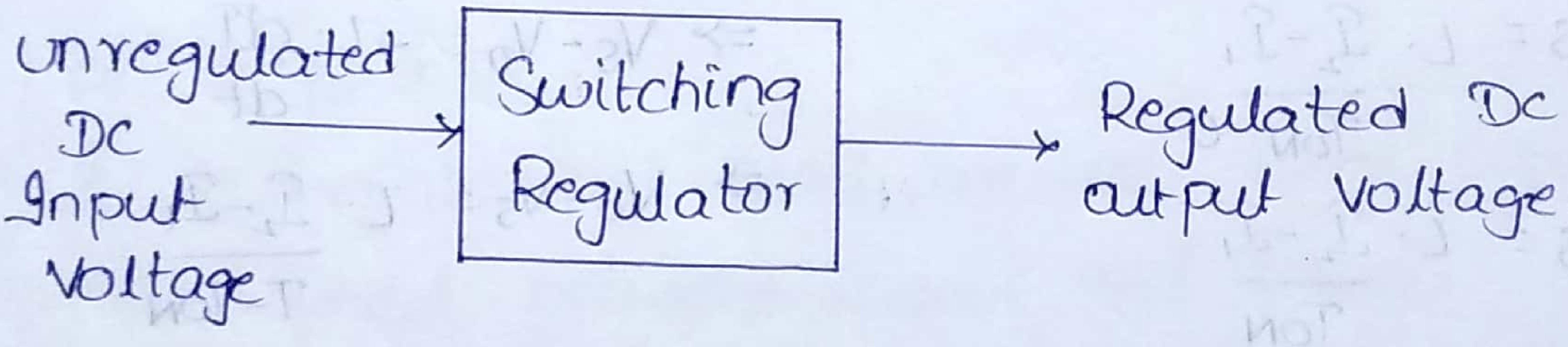
At $\alpha = 0$; $V_o = V_s$.

$\alpha = 0.5$; $V_o = 2V_s$

$\alpha = 0.1$; $V_o = 1.11 V_s$

→ Part - II :-

Switching Regulators.



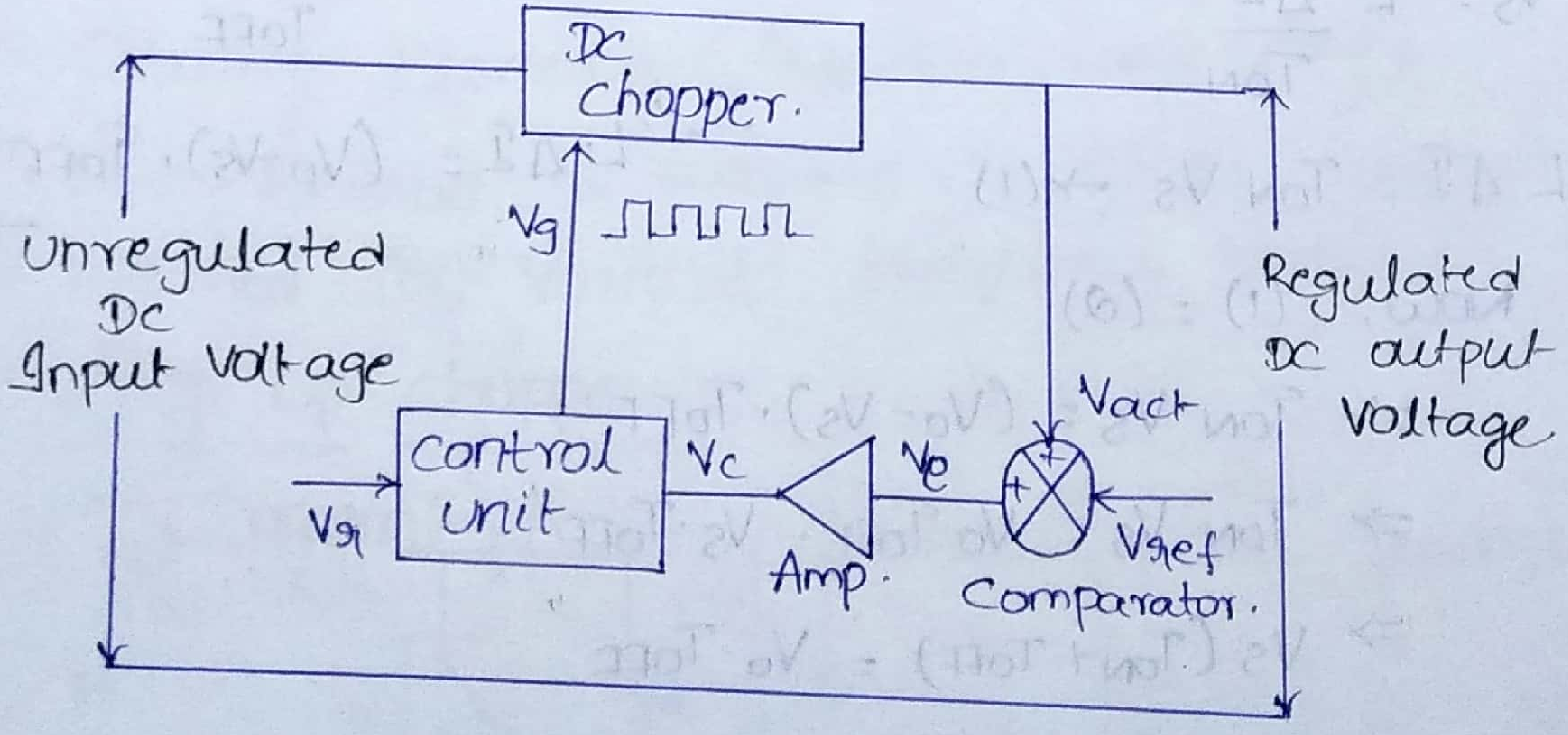
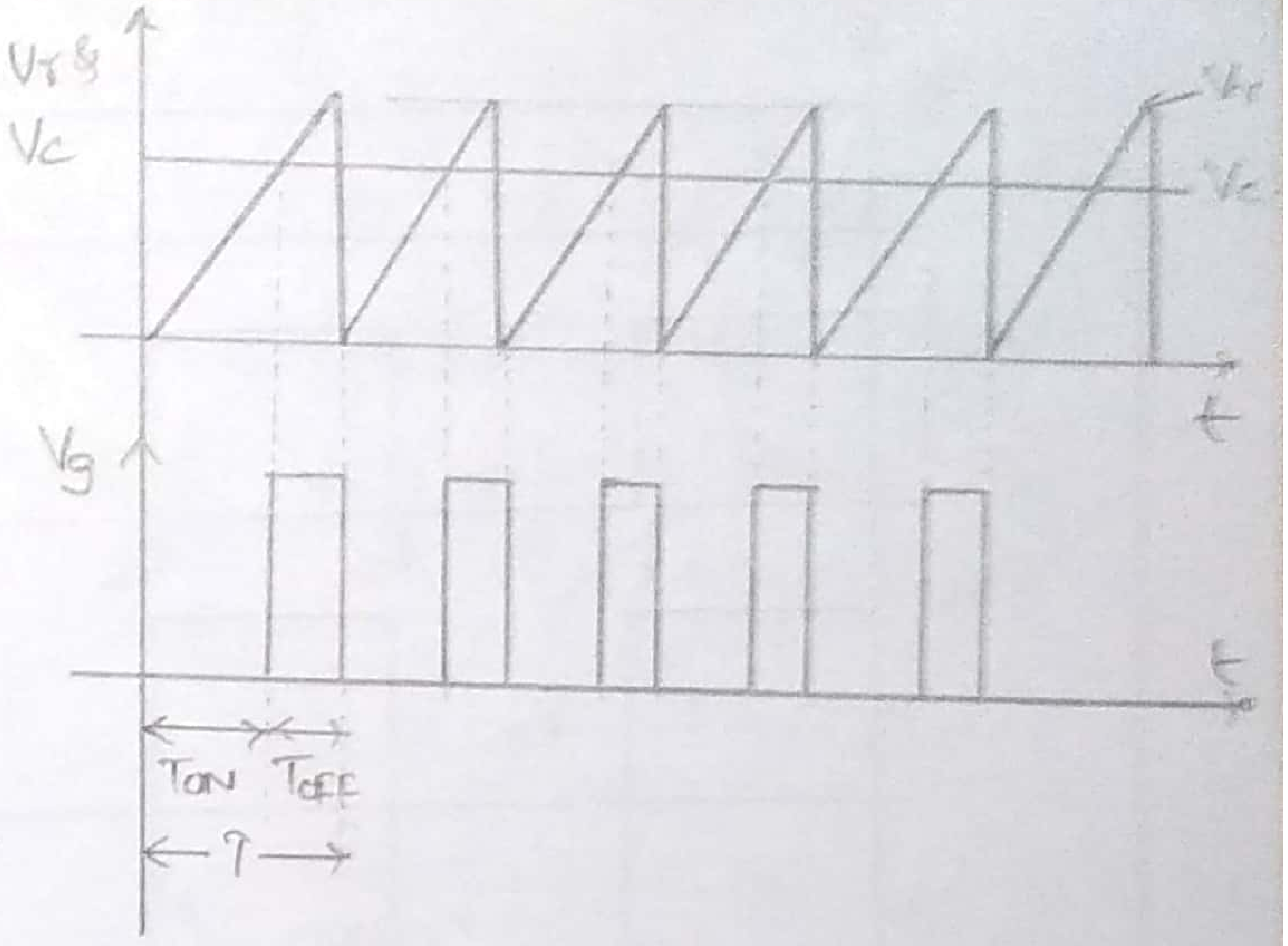


fig:- Switching Mode Regulator.

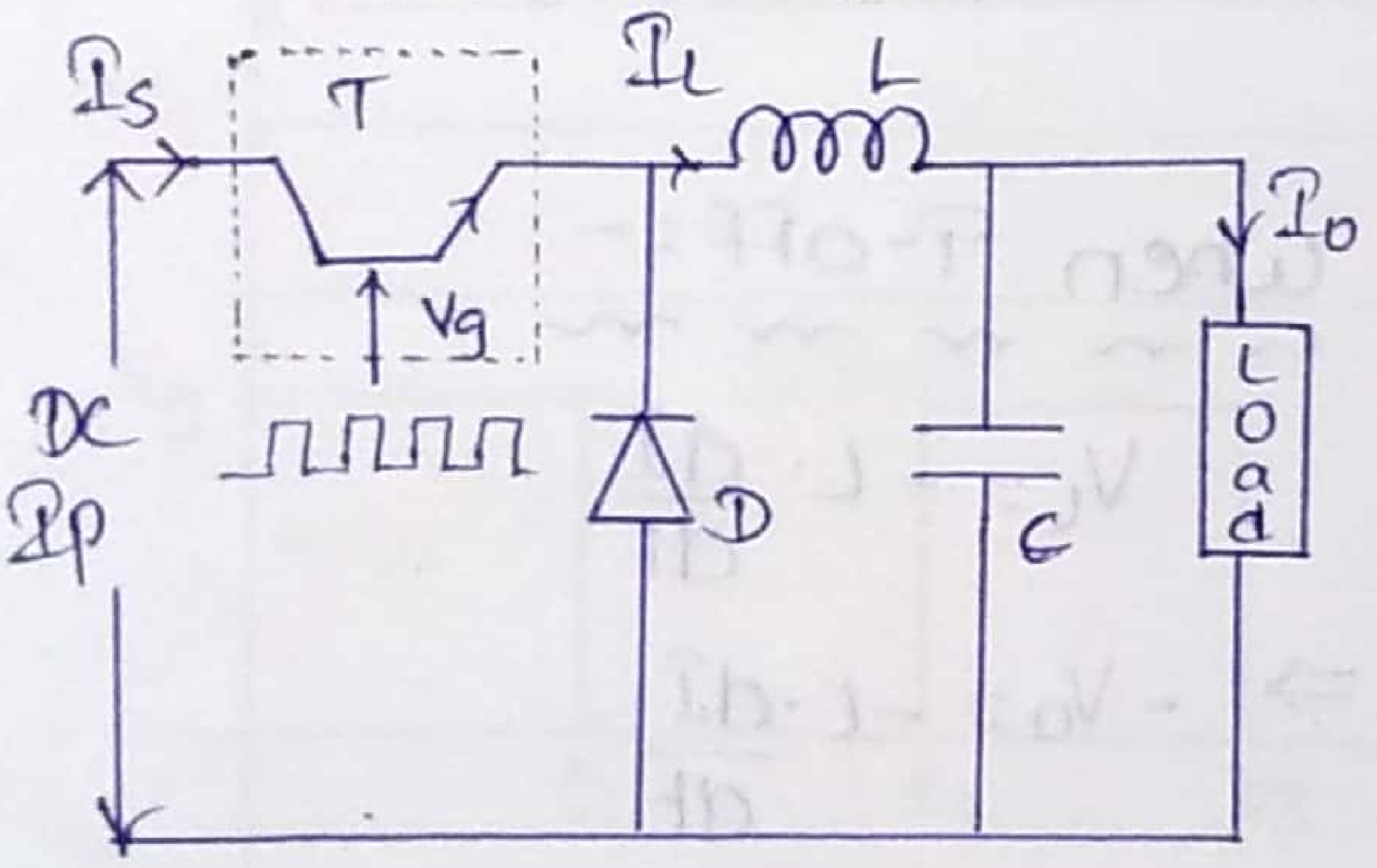
- Dc choppers can also be used as Switching Regulators. It converts unregulated DC Input Voltage to Regulated DC output Voltage.



- Types of Regulators:-

(1) Buck Regulator.
(2) Boost Regulator.
(3) Buck-Boost Regulator.
(4) CUK Regulator.

- Buck Regulator:-



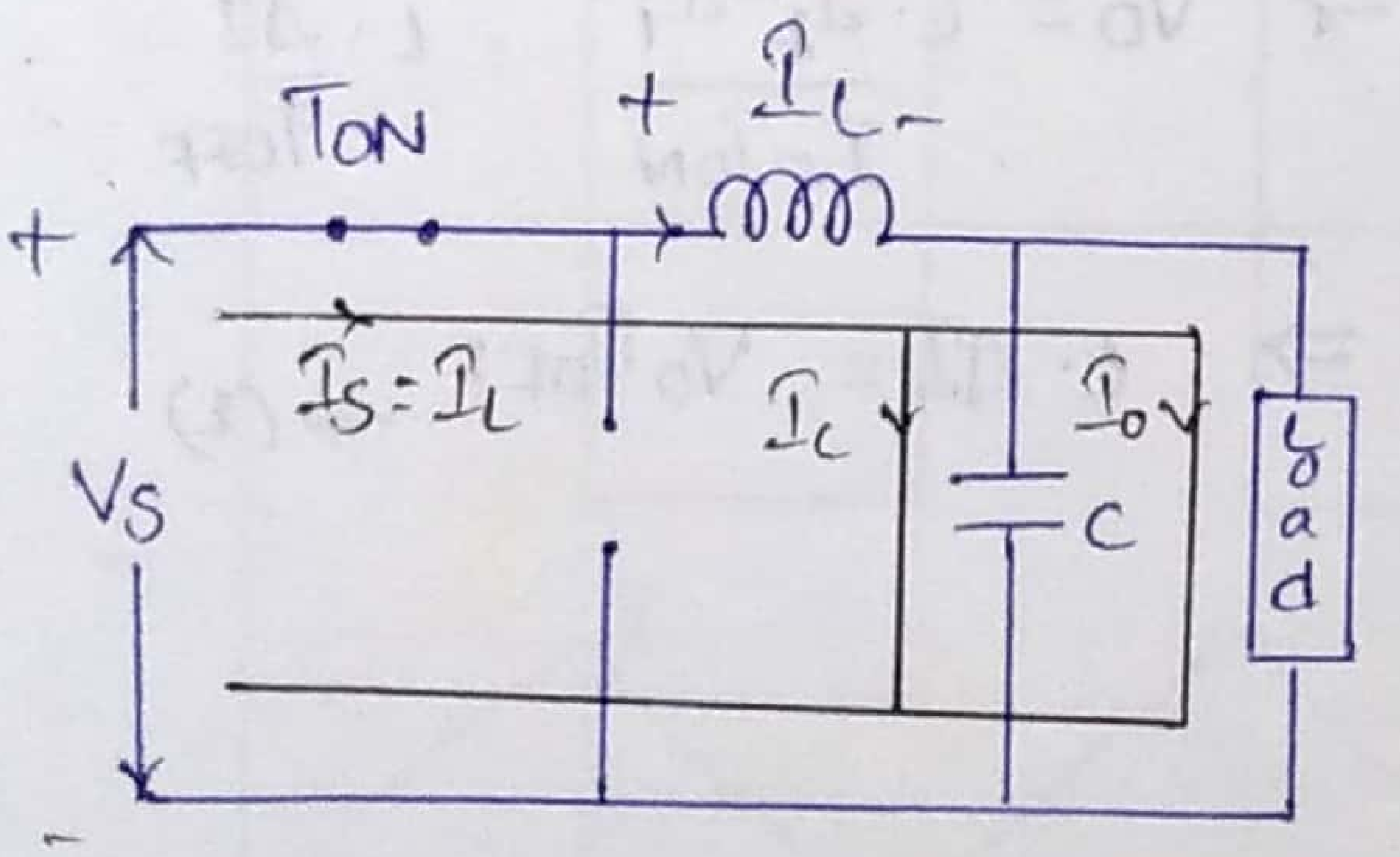
when, T-ON:- at t=0.

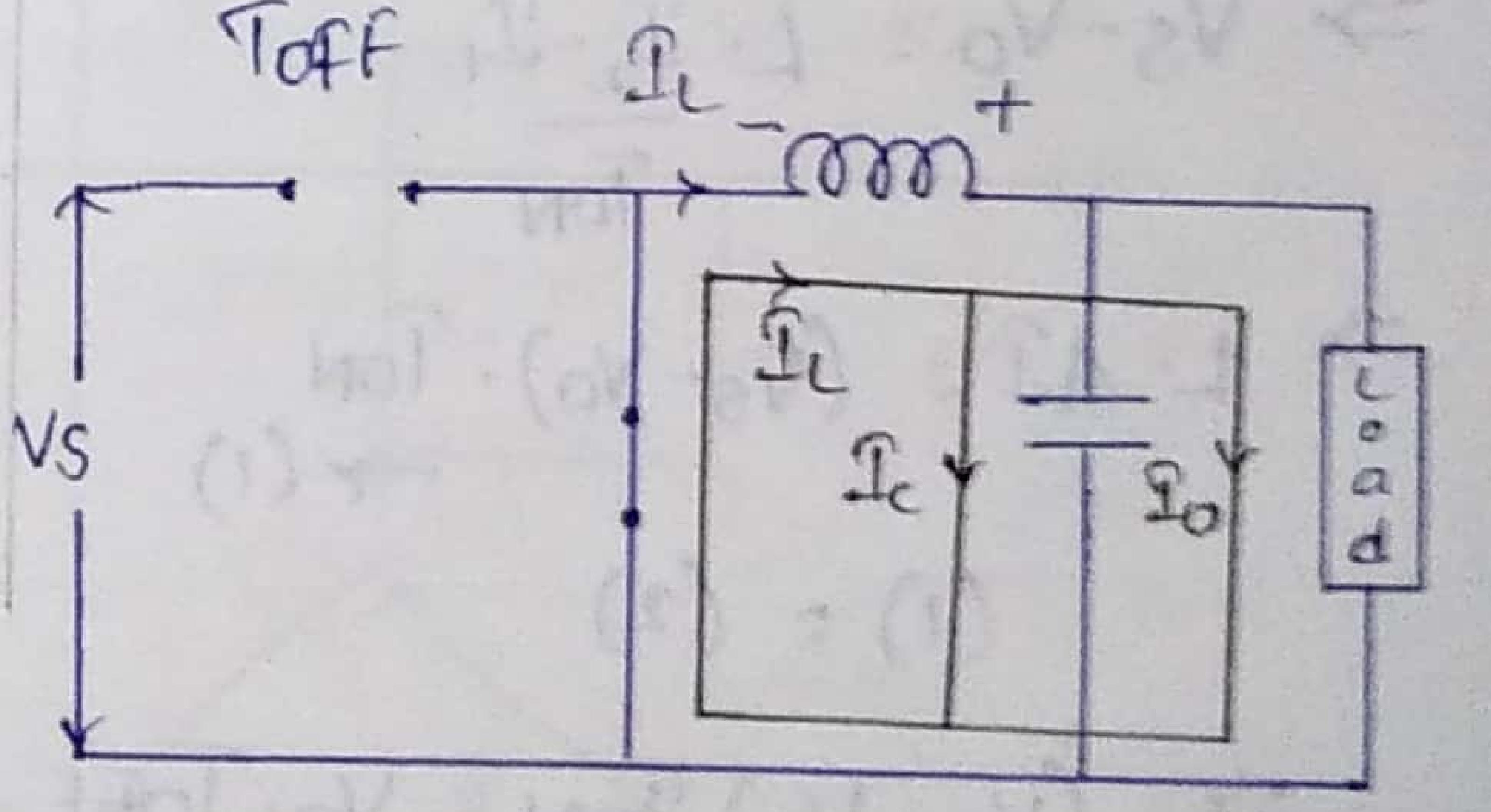
$-V_S + V_L + V_O = 0$

$\Rightarrow V_L = V_S - V_O$

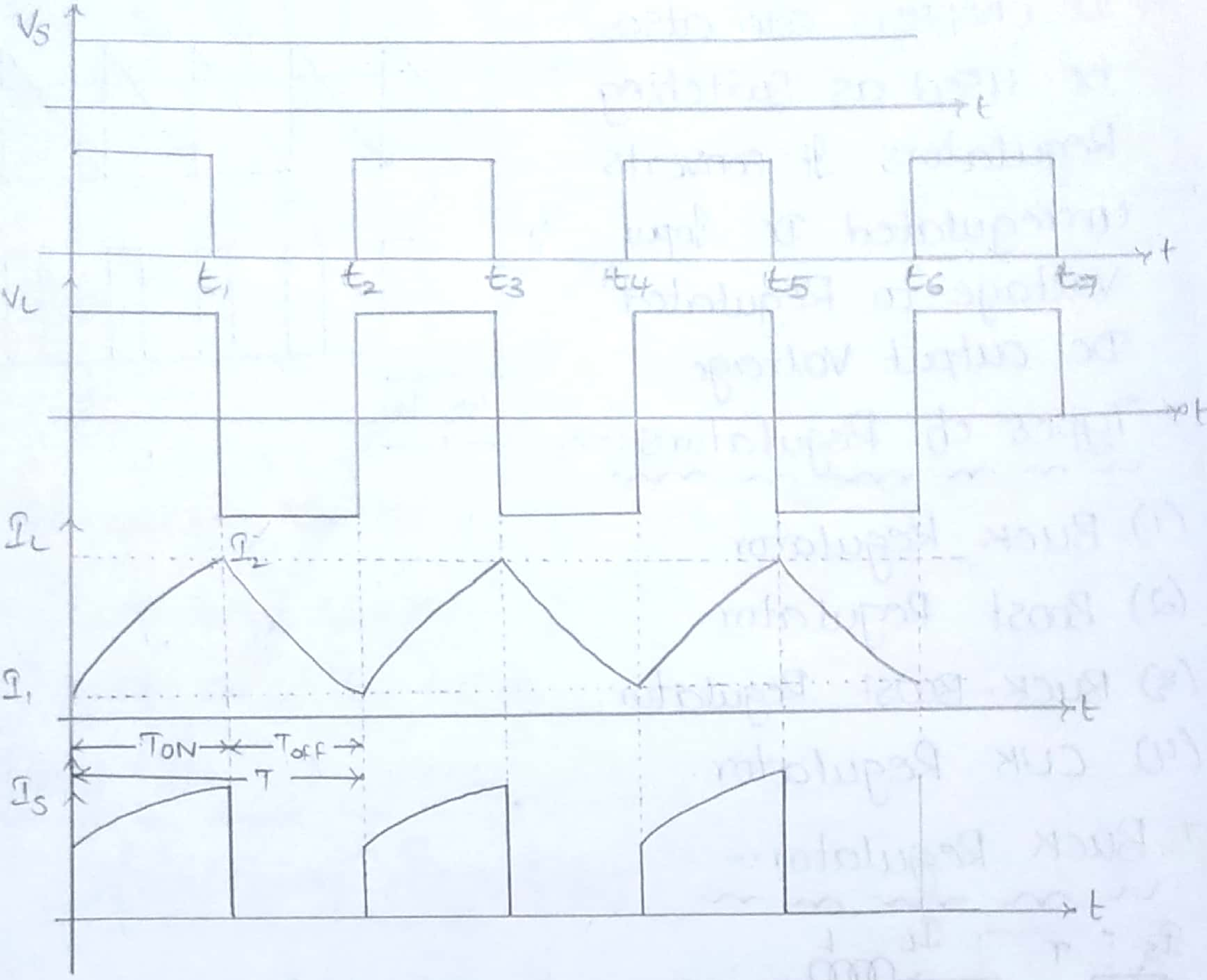
when, T-OFF; $V_L + V_O = 0$

$V_L = -V_O$





- Buck Regulator is an Equivalent of Step Down chopper i.e., the avg. output voltage of Buck Regulator is less than Input Voltage.
- In Buck Regulator, Input current (or) Source Current is Discontinuous.



when T- ON:-

$$V_L = L\cdot\frac{di}{dt}$$

$$\Rightarrow V_S - V_O = L\cdot\frac{I_2 - I_1}{T_{ON} - 0}$$

$$\Rightarrow V_S - V_O = L\cdot\frac{I_2 - I_1}{T_{ON}}$$

$$\Rightarrow L\cdot\Delta I = (V_S - V_O)\cdot T_{ON} \rightarrow (1)$$

when T-OFF:-

$$V_L = -L\cdot\frac{dI}{dt}$$

$$\Rightarrow -V_O = -L\cdot\frac{dI}{dt}$$

$$\Rightarrow V_O = L\cdot\frac{I_2 - I_1}{T - T_{ON}} = L\cdot\frac{\Delta I}{T_{OFF}}$$

$$\Rightarrow L\cdot\Delta I = V_O T_{OFF} \rightarrow (2)$$

$$(1) = (2)$$

$$\Rightarrow (V_S - V_O) T_{ON} = V_O\cdot T_{OFF}$$

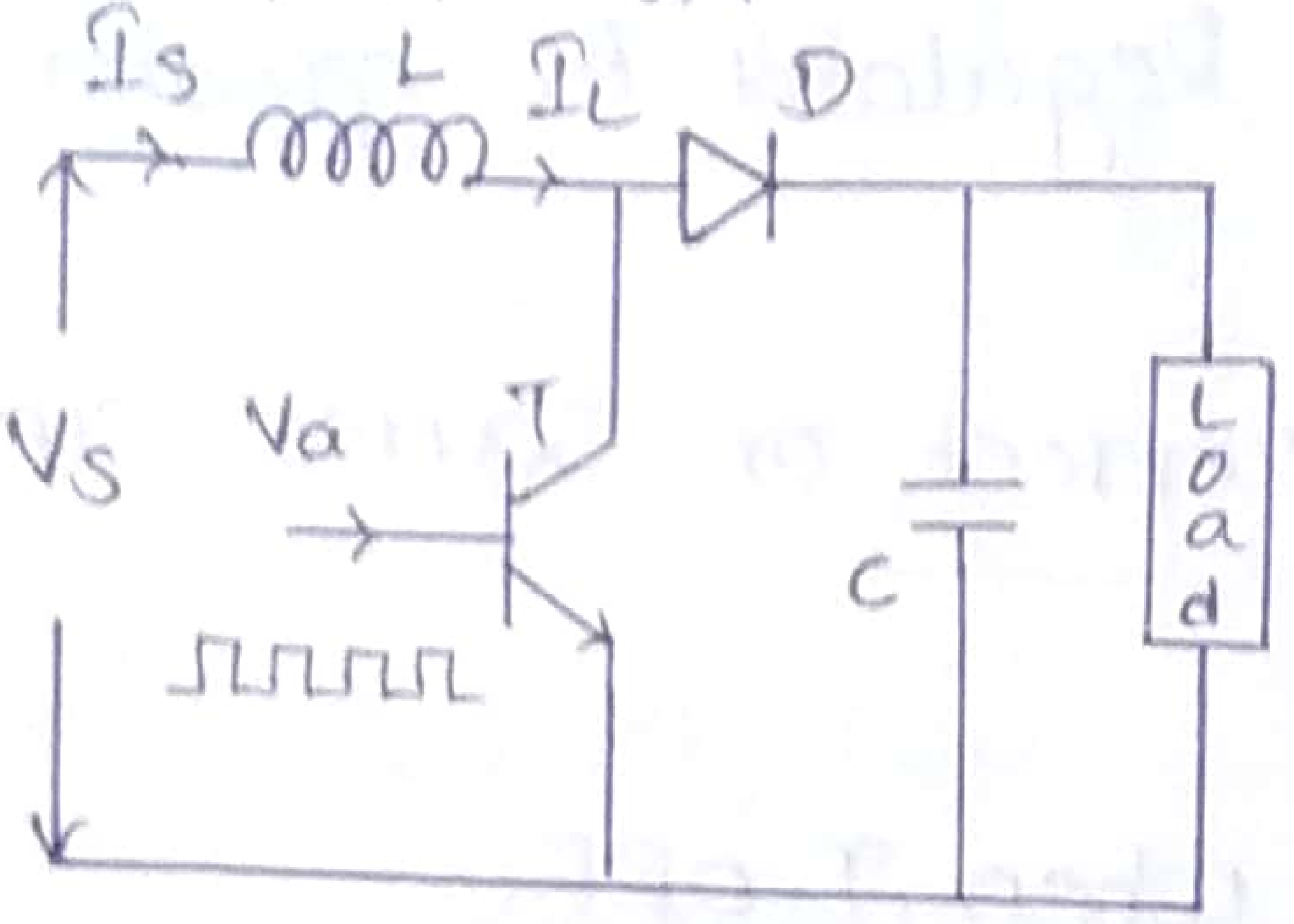
$$\Rightarrow V_S T_{ON} - V_O\cdot T_{ON} = V_O\cdot T_{OFF}$$

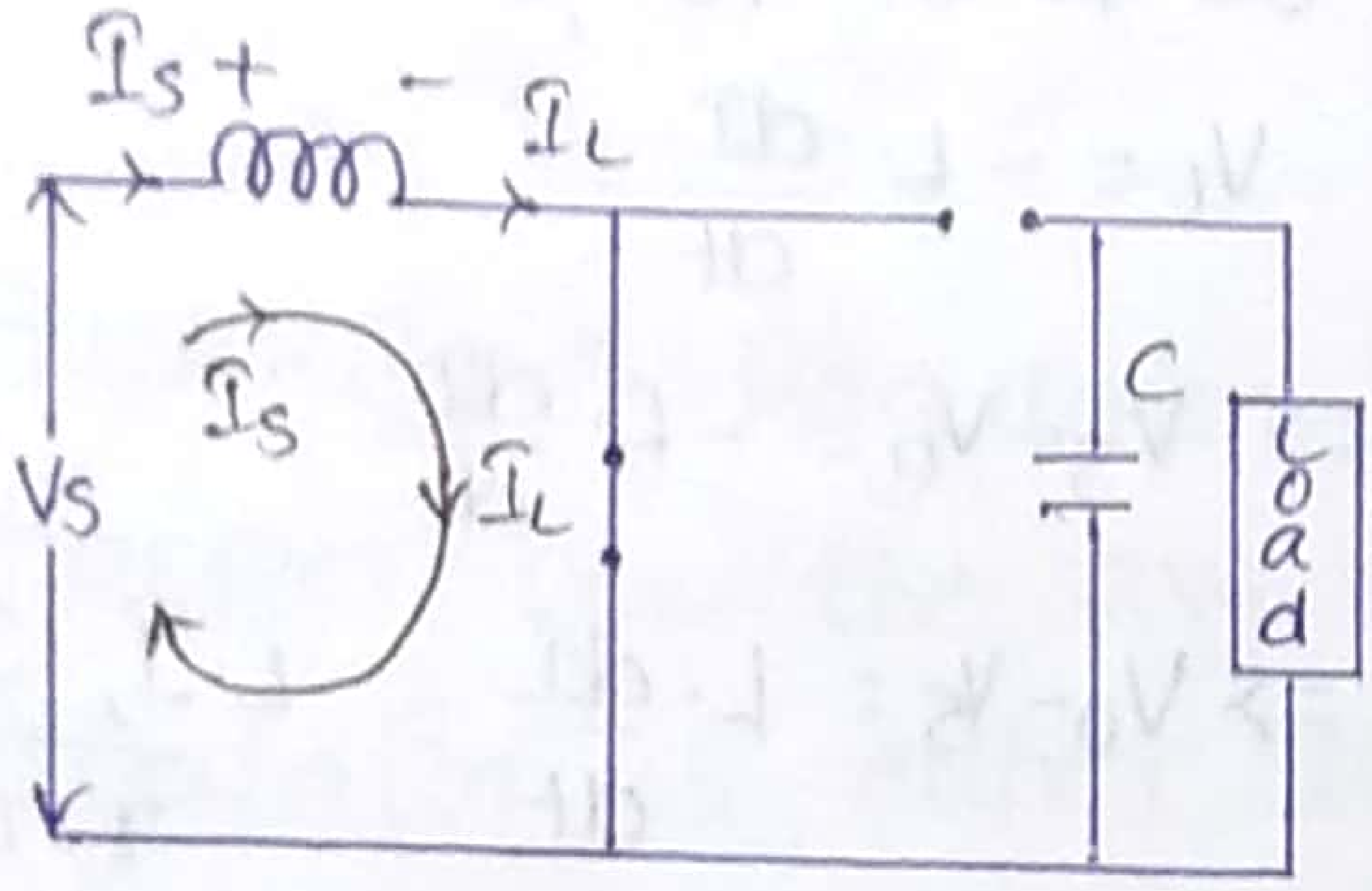
$$\Rightarrow V_S T_{ON} = V_O (T_{ON} + T_{OFF}) = V_O\cdot T$$

$$\Rightarrow \frac{V_O}{V_S} = \frac{T_{ON}}{T_{ON} + T_{OFF}} = \alpha$$

$$* / V_O = \alpha\cdot V_S / *$$

Boost Regulator:-

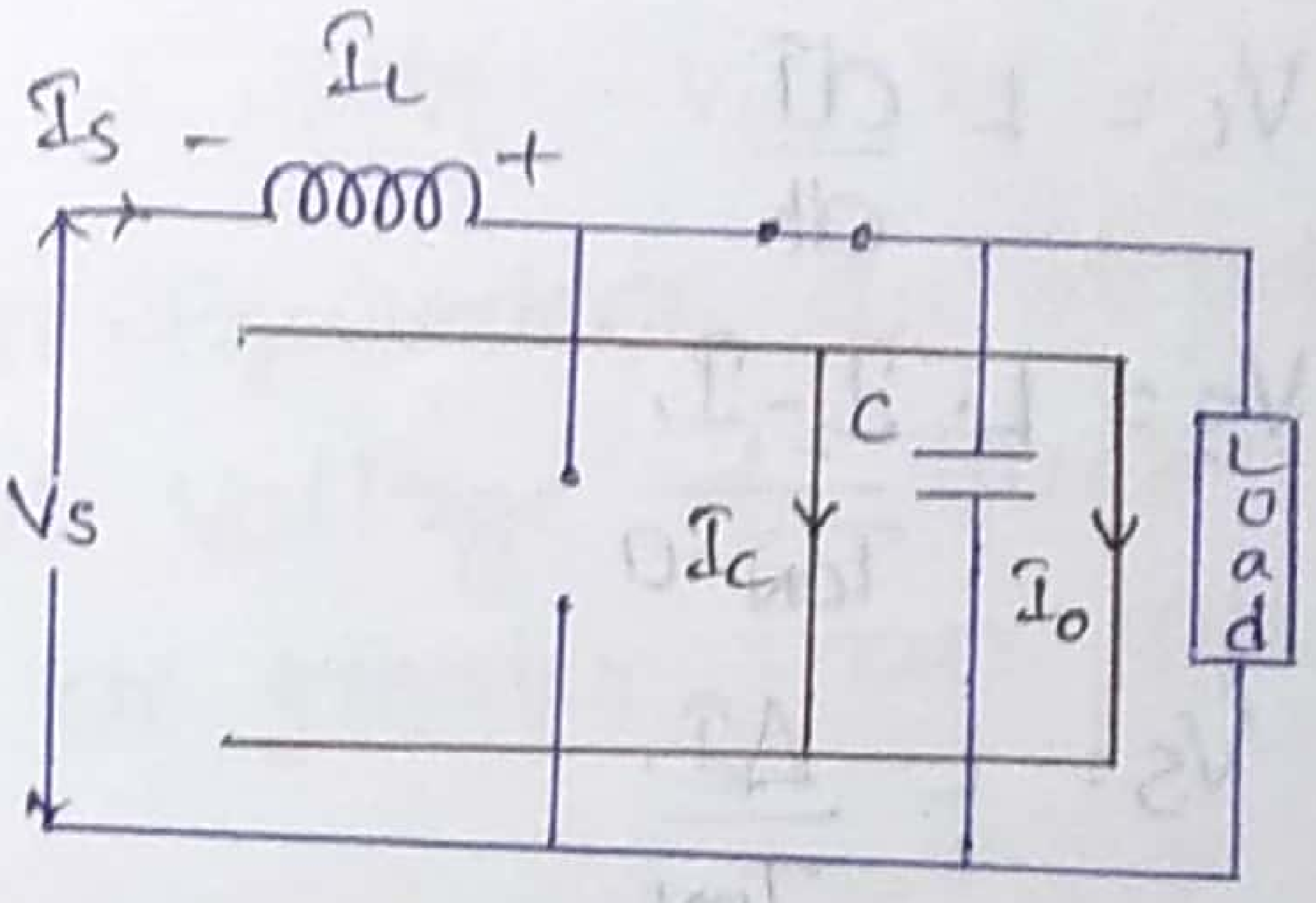




when T=ON; at t=0.

$$-V_S+V_L=0$$

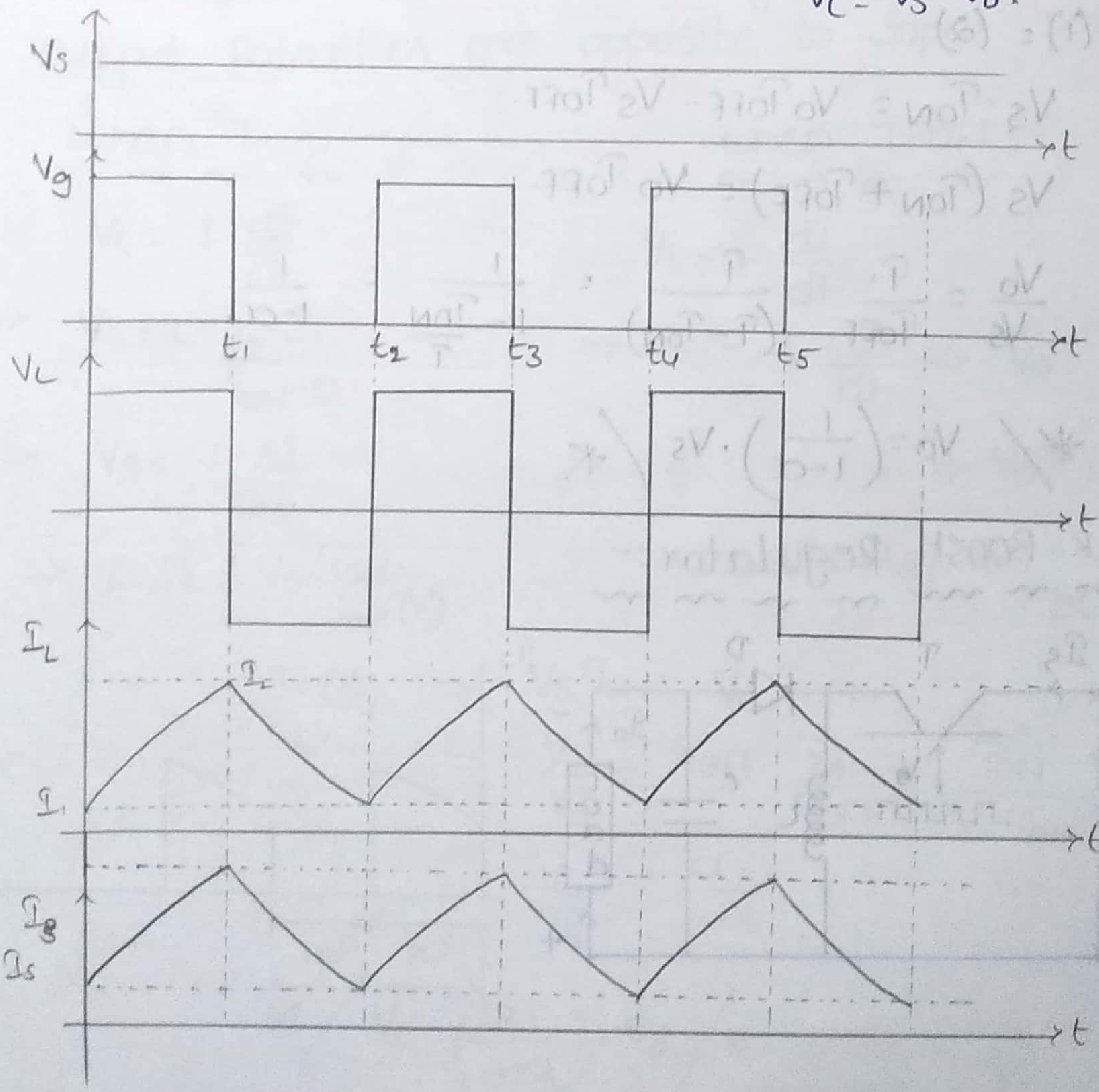
$$V_L=V_S.$$



when T=off at $t=t_1$.

$$-V_S+V_L+V_0=0$$

$$V_L=V_S-V_0.$$



- Boost Regulator is an Equivalent of step-up chopper
- The Avg. output of (V) Boost Regulator is greater than Supply Voltage.
- In Boost Regulator, Input current or source current is continuous.

when T-ON:-

$V_L = L \cdot \frac{dI}{dt}$

$\Rightarrow V_S = L \cdot \frac{I_2 - I_1}{T_{ON} - 0}$

$\Rightarrow V_S = L \cdot \frac{\Delta I}{T_{ON}}$

$\therefore L \cdot \Delta I = V_S \cdot T_{ON} \rightarrow (1)$

when T-OFF:-

$V_L = -L \cdot \frac{dI}{dt}$

$\Rightarrow V_S - V_O = -L \cdot \frac{dI}{dt}$

$\Rightarrow V_O - V_S = L \cdot \frac{dI}{dt} = L \cdot \frac{I_2 - I_1}{T - T_{ON}}$

$\Rightarrow V_O - V_S = \frac{\Delta I \cdot L}{T_{OFF}}$

$\therefore L \cdot \Delta I = (V_O - V_S) \cdot T_{OFF} \rightarrow (2)$

(1) = (2)

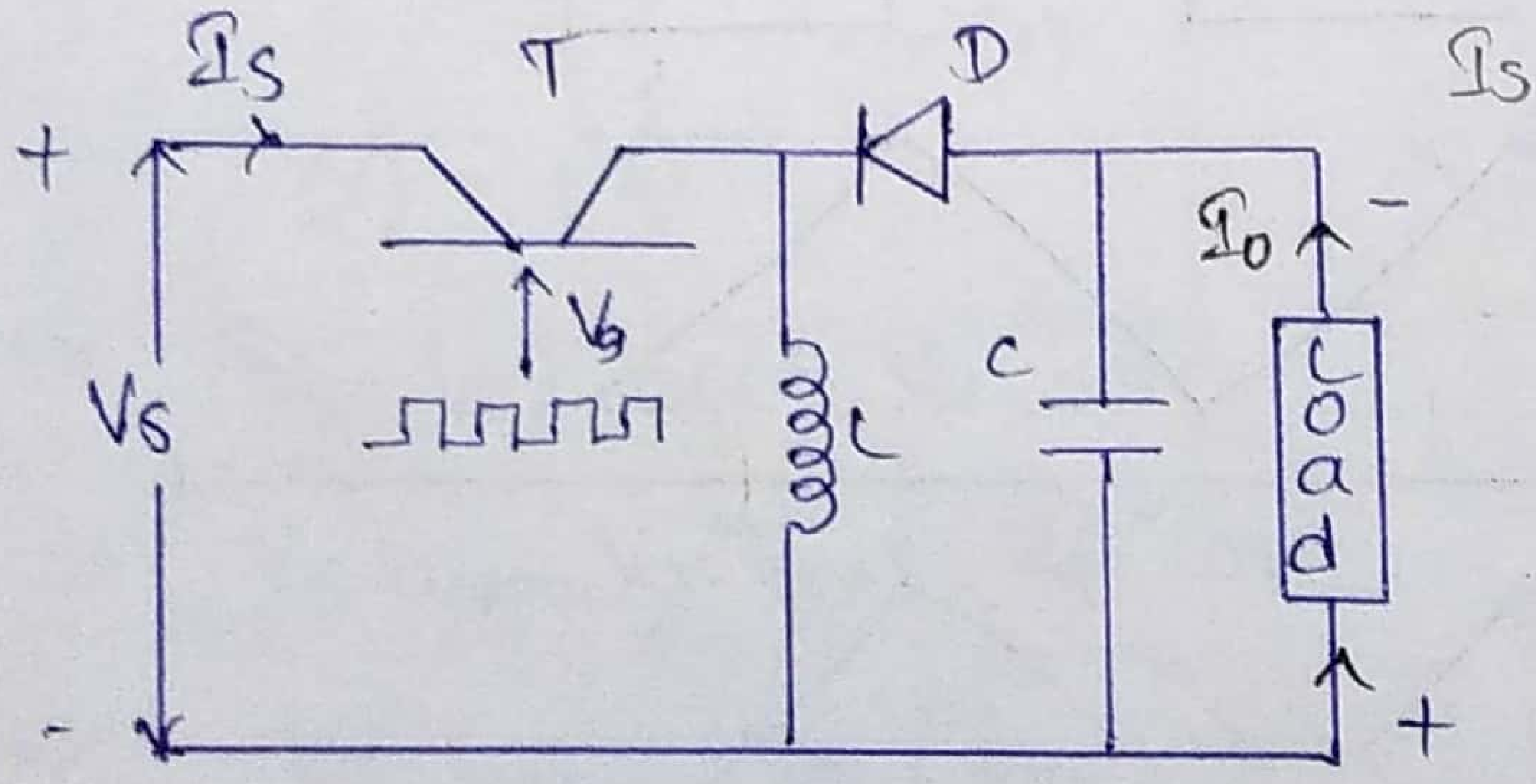
$\Rightarrow V_S \cdot T_{ON} = V_O T_{OFF} - V_S T_{OFF}$

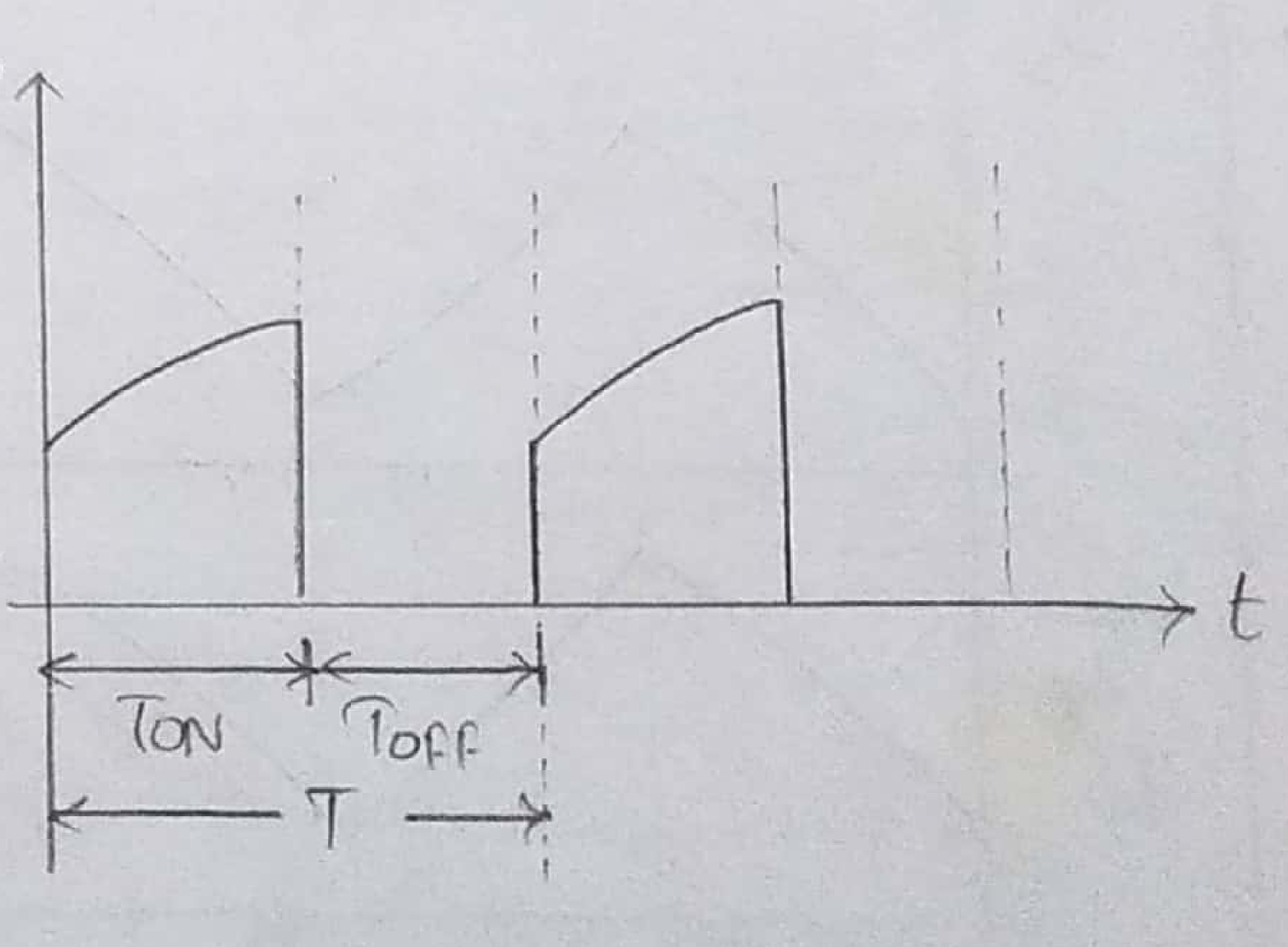
$\Rightarrow V_S (T_{ON} + T_{OFF}) = V_O \cdot T_{OFF}$

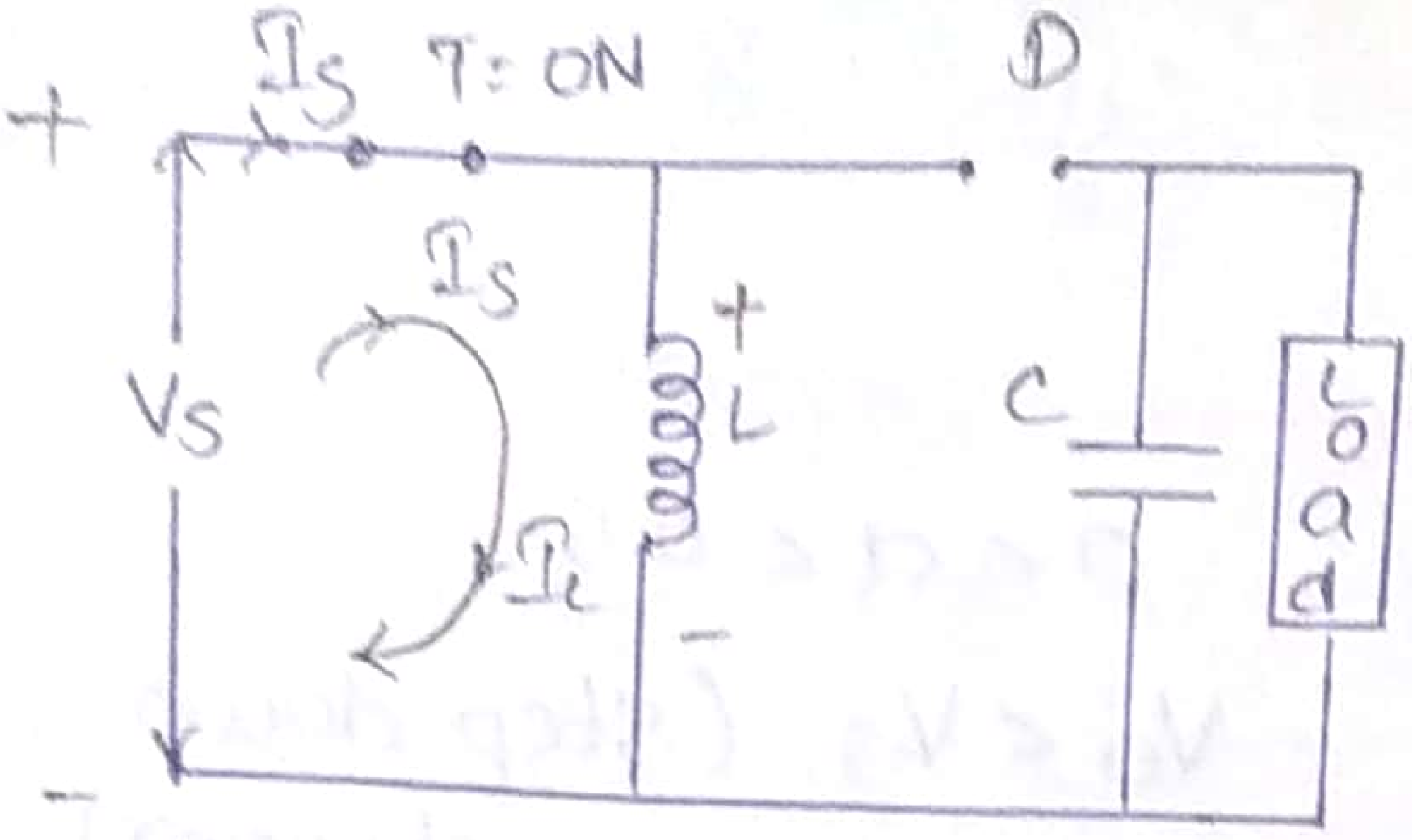
$\Rightarrow \frac{V_O}{V_S} = \frac{T}{T_{OFF}} = \frac{T}{(T - T_{ON})} = \frac{1}{1 - \frac{T_{ON}}{T}} = \frac{1}{1-a}.$

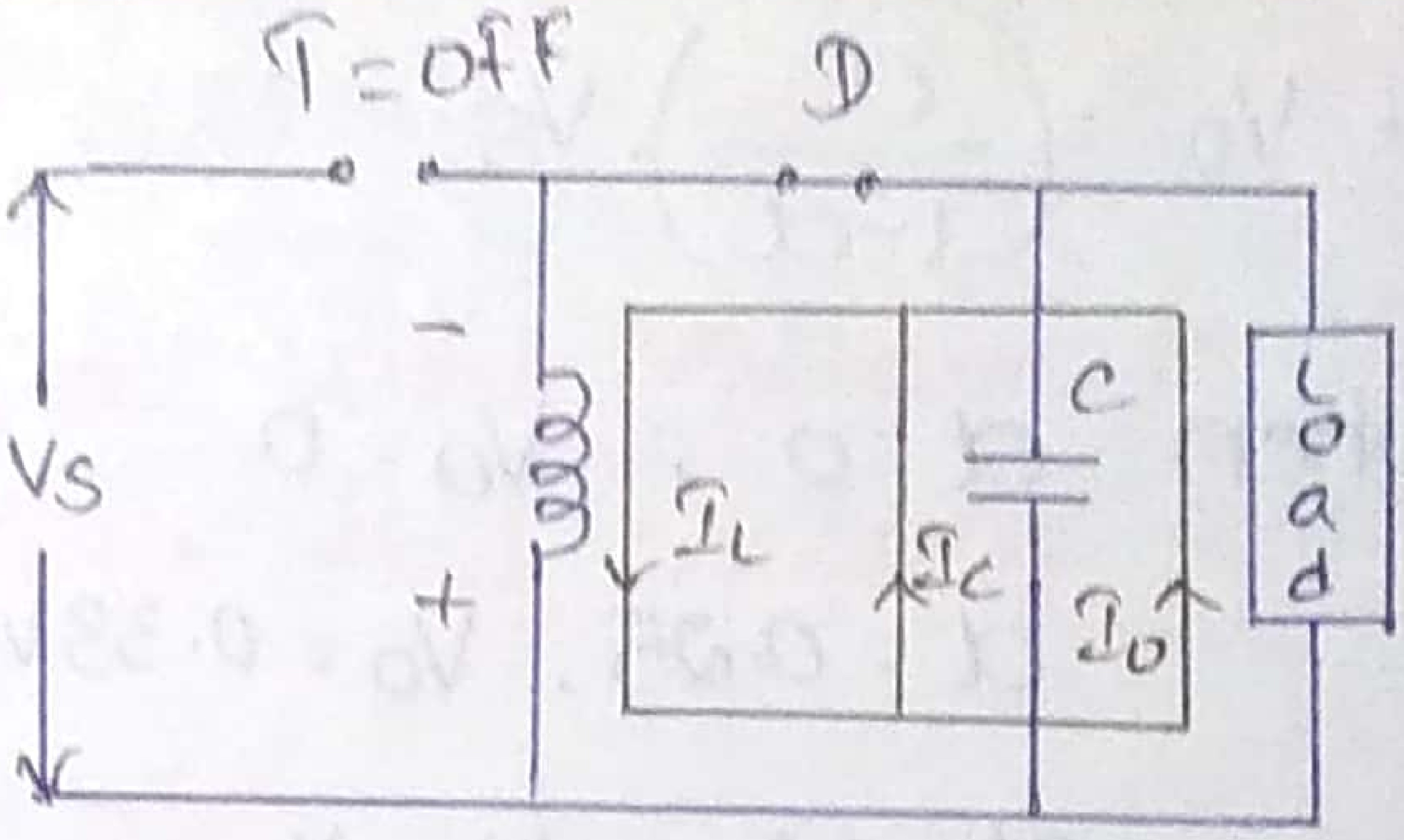
$$*/ \; V_O = \left(\frac{1}{1-a}\right) \cdot V_S \; /*$$

- Buck-Boost Regulator:-









when T_{ON} at $t=0$

$\Rightarrow -V_S + V_L = 0$.

$\Rightarrow V_L = V_S$.

when T-OFF at $t = t_1$.

$\Rightarrow V_0 + V_L = 0$

$\Rightarrow V_L = -V_0$.

- Buck-Boost Regulator is an Equivalent of Step up/Down chopper i.e., the avg. output Voltage of Buck-Boost Regulator is either lower or greater than input Voltage.
- In Buck-Boost Regulator, Source current is Discontinuous
- It is also known as Inverting Regulator, since it's output polarities are opposite to Input polarities.

when T-ON:-

$V_L = L \cdot \frac{dI}{dt}$.

$\Rightarrow V_S = L \cdot \frac{I_2 - I_1}{T_{ON} - 0}$.

$\Rightarrow V_S = \frac{L \cdot \Delta I}{T_{ON}}$.

$\Rightarrow L \cdot \Delta I = V_S \cdot T_{ON} \rightarrow (1)$

when T-OFF:-

$V_L = -L \cdot \frac{dI}{dt}$

$\Rightarrow -V_0 = -L \cdot \frac{dI}{dt} \Rightarrow V_0 = L \cdot \frac{I_2 - I_1}{T - T_{ON}}$.

$\Rightarrow V_0 = L \cdot \frac{\Delta I}{T_{OFF}}$.

$\Rightarrow L \cdot \Delta I = T_{OFF} \cdot V_0 \rightarrow (2)$

$(1) = (2) \Rightarrow V_S T_{ON} = V_0 T_{OFF}$.

$$\Rightarrow \frac{V_0}{V_S} = \frac{T_{ON}}{T_{OFF}} = \frac{T_{ON}}{T - T_{ON}} = \frac{T_{ON}/T}{1 - \frac{T_{ON}}{T}}$$

$$\Rightarrow \frac{V_0}{V_S} = \frac{\alpha}{1 - \alpha}.$$

$$* \Big/ V_0 = \left(\frac{\alpha}{1-\alpha}\right) \cdot V_S \Big/ *$$

$\therefore V_o = \left(\frac{\alpha}{1-\alpha}\right) V_s$

$$\left.\begin{array}{l} \text{when } \alpha = 0 \;;\; V_o = 0 \\ \alpha = 0.25 \;;\; V_o = 0.33 V_s \\ \alpha = 0.5 \;;\; V_o = V_s \end{array}\right\} \begin{array}{l} 0 < \alpha < 0.5 \\ V_o < V_s \text{ (step down chopper)} \end{array}$$

$$\left.\begin{array}{l} \alpha = 0.75 \;;\; V_o = 3V_s \\ \alpha = 1 \;;\; V_o = \infty \end{array}\right\} \begin{array}{l} 0.5 < \alpha < 1 \\ V_o > V_s \text{ (step up chopper)} \end{array}$$

* Type$^{(A)}$ chopper (A) $V_s = 230V$, $R = 10\Omega$. take Voltage drop of 2V across chopper. when it is ON. for Duty cycle of 0.4. Calculate

(a) the avg. and RMS output Voltage.

(b) chopping Efficiency.

(c) Effective Resistance.

Sol:- (a) $V_o = \alpha V_s$ (without V.d.)

$\Rightarrow V_o = \alpha [V_s - V_{ch}]$ (with V.d.)

$\Rightarrow V_o = 0.4 (230 - 02)$

$\therefore V_o = 91.2 V$

$V_{orms} = \sqrt{\alpha} (V_s - V_{ch})$

$= \sqrt{0.4} (230 - 02)$

$\therefore V_{orms} = 144.1V$

(b) $\eta_{ch} = \frac{P_o}{P_i} \times 100$ $\left[P_o = \frac{V_{orms}^2}{R} = \frac{144.1^2}{10} = 2076.28 w \right]$

$P_i = V_s . I_s = V_s I_o$

$= 230 \times \frac{V_o}{R}$

$= 230 \times \frac{91.2}{10} = 2097.6 w]$

$\therefore \eta = \frac{2076.2}{2097.6} \times 100 = 99.008\%$

(iii) $R_i = \frac{R}{\alpha} = \frac{10}{0.4} = \frac{100}{4} = 25\Omega$

* Step down chopper, Vs = 230V dc. Load Voltage is 150V, if the chopping frequency is 5KHz. find chopping period and blocking period of chopper.

Given, $V_s = 230V$

$f = 5KHz$; $V_0 = 150V$

(1) $T = \frac{1}{f} = \frac{1}{5\times10^3} = 0.2ms$

(2) Blocking period = T_{OFF}

we know that, $T = T_{ON} + T_{OFF}$

$\Rightarrow T_{OFF} = T - T_{ON}$

$V_0 = \alpha V_s$

$\Rightarrow \alpha = \frac{V_0}{V_s} = \frac{150}{230} = 0.65$

$\Rightarrow \alpha = \frac{T_{ON}}{T} \Rightarrow T_{ON} = T\cdot\alpha = 0.65\times0.2m = 0.13ms.$

∴ $T_{OFF} = 0.2ms - 0.13ms$

∴ $T_{OFF} = 0.07ms$ //

Dc chopper of Input Voltage 200V, remains ON for 25m and off for 10ms. find the avg. Voltage which appears across the load.

Given, $V_s = 230V$;

T_{ON} ; $T = T_{ON} + T_{OFF}$

$\Rightarrow \alpha = \frac{25m}{35m} = 0.714.$

∴ $V_0 = 0.714 \times 230$

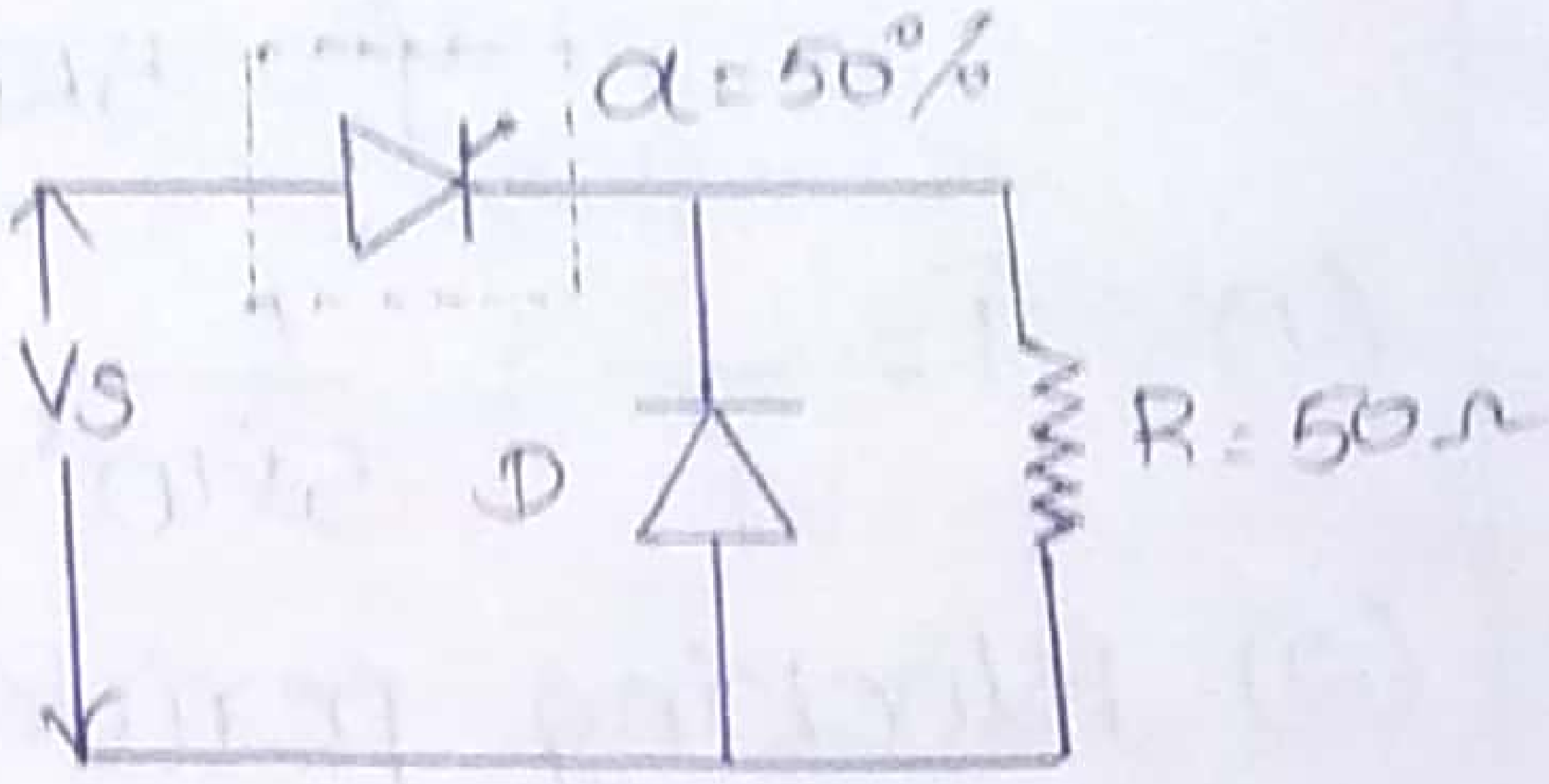
* Basic Dc chopper circuit shown in fig, $V_s = 230V$; $R = 50\Omega$, $\alpha = 50\%$ find

(a) output Voltage and current (avg.)

(b) output current at instant of commutation.

(c) Avg. and RMS free wheeling Diode currents.

(d) RMS value of output Voltage., avg. and RMS Thy. curr

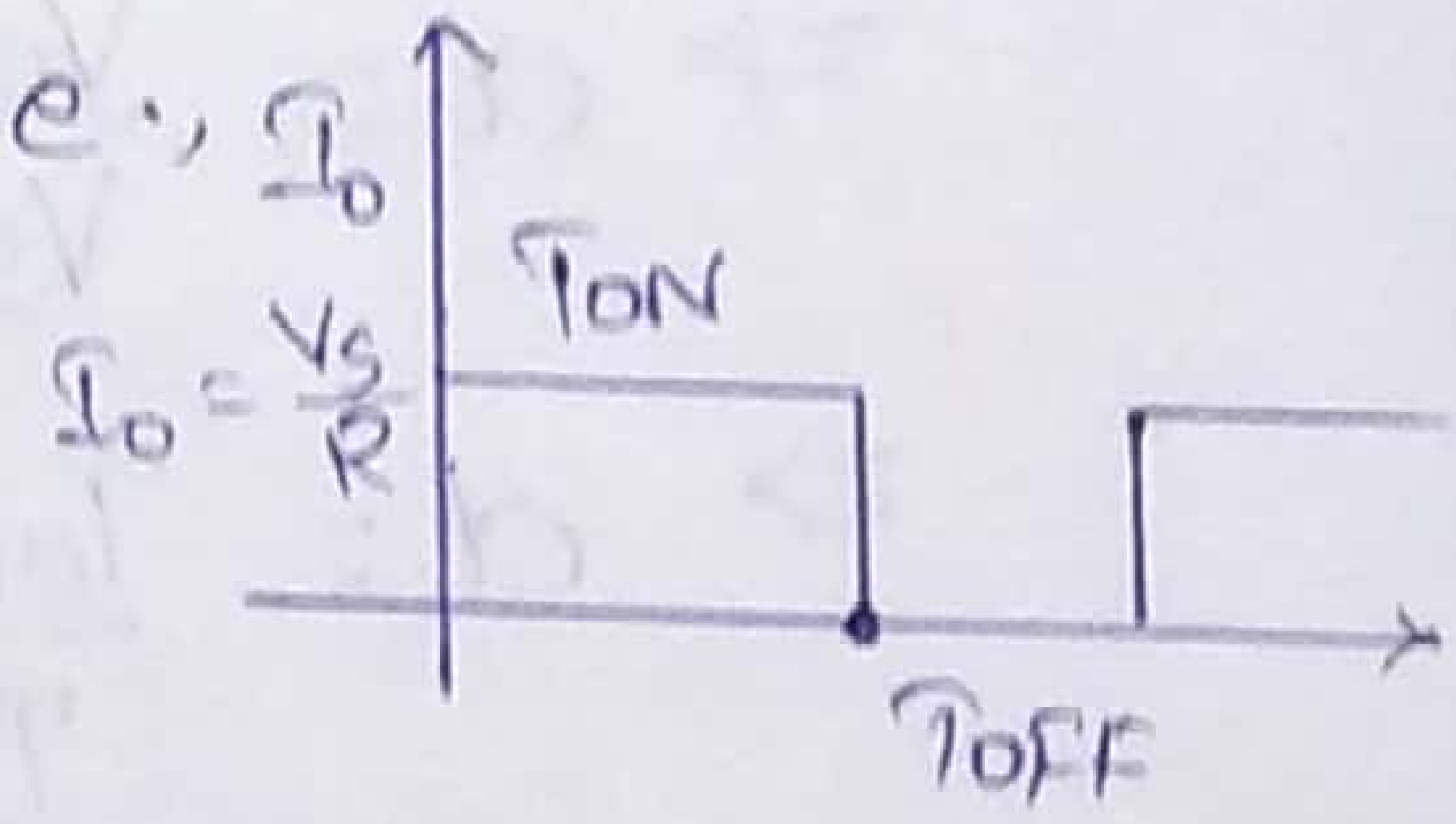


Sol:- (a) $\alpha V_s = V_0 \Rightarrow V_0 = 0.5 \times 30$

$\therefore V_0 = 15V.$

(b) At the instant of T_{OFF} of chopper, output current is given by, $I_0 = \frac{V_s}{R} = \frac{30}{50} = 0.6A.$

(c) for R-Load, FWD does not present. So RMS and Avg. Diode currents are zero i.e.,



$$I_{DA} = I_{DR} = 0.$$

(d)

$$V_{orms} = \sqrt{a} \cdot V_s = \sqrt{0.5} \times 30 = 21.21V.$$

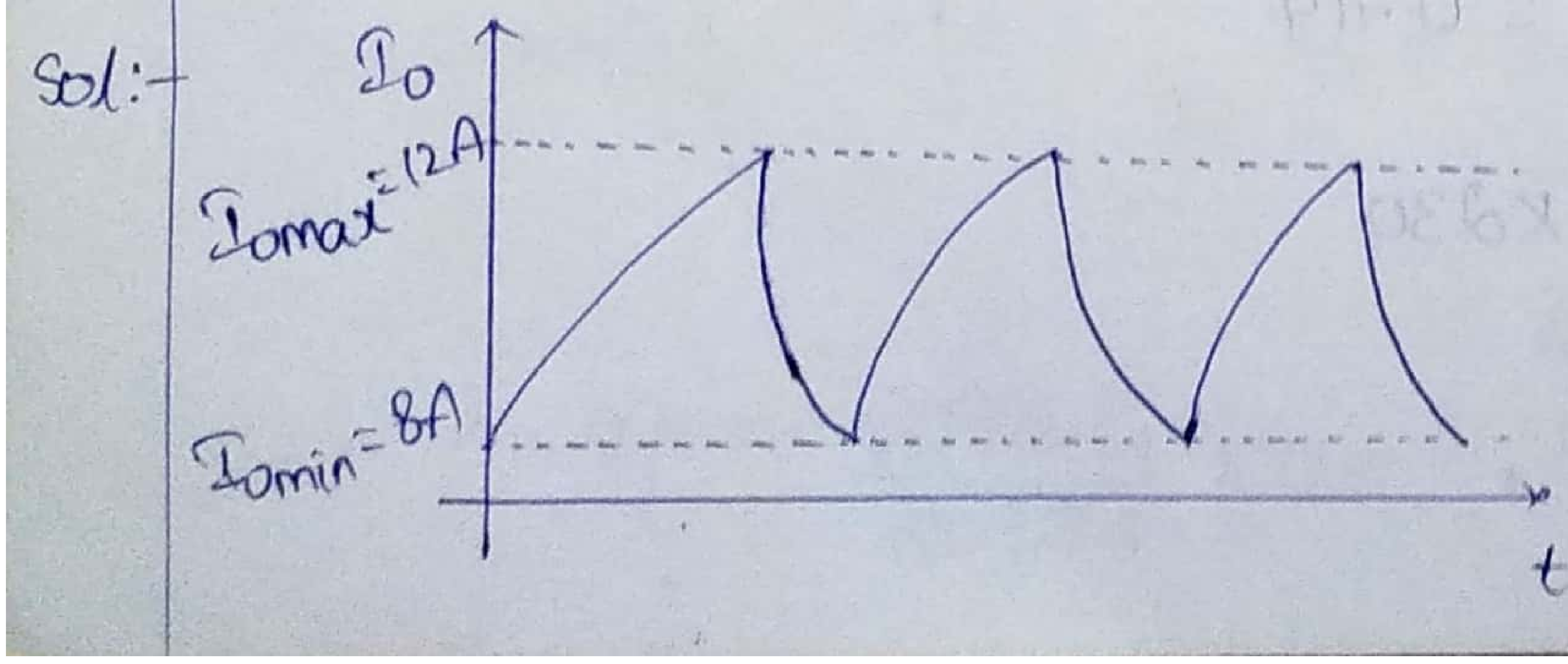
(e)

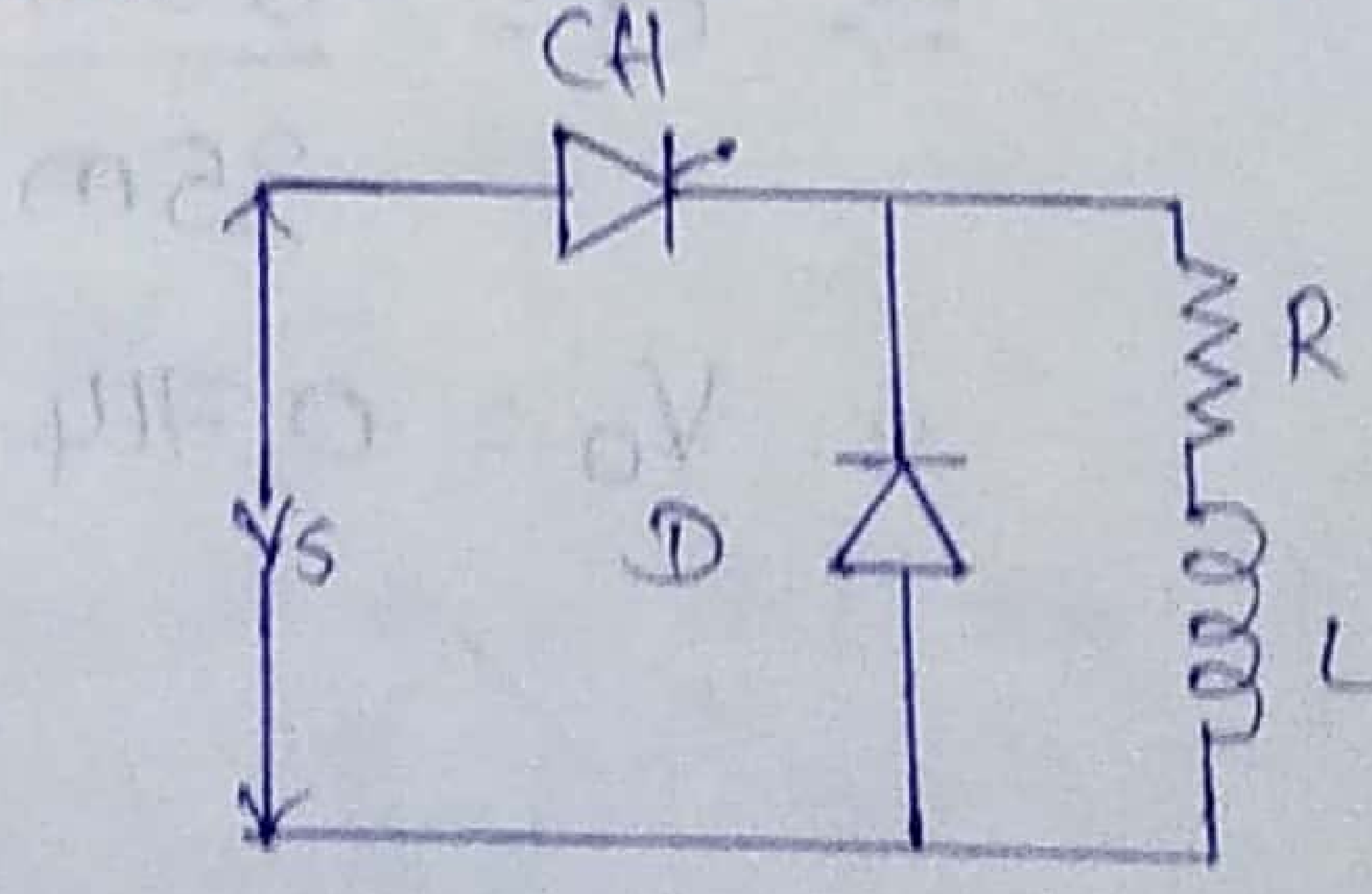
$$I_{TA} = \alpha \cdot \frac{V_s}{R} = 0.5 \times \frac{30}{50} = 0.3A$$

$$I_{TR} = \sqrt{a} \cdot \frac{V_s}{R} = \frac{21.21}{50} = 0.42A$$

*** Dc chopper circuit Connected to 100V Supply, Inductive Load having 30mH in Series with R of 8Ω. A FWD is placed across the load. The Load current Varies within limits of 8 & 12A find Time Ratio of chopper.

Sol:-





Sol (a) $I_0 = \frac{I_{omin} + I_{omax}}{2} = \frac{8+12}{2} = 10A$

(b) $V_0 = I_0 \cdot R = 10 \times 8 = 80V$.

$V_0 = \alpha \cdot V_s$

$\Rightarrow \alpha = \frac{80}{100} = 0.8$

$\Rightarrow \frac{T_{ON}}{T_{ON} + T_{OFF}} = 0.8$

$\Rightarrow \frac{1}{1 + \frac{T_{OFF}}{T_{ON}}} = 0.8$

$\Rightarrow 1.25 = 1 + \frac{T_{OFF}}{T_{ON}} \Rightarrow \frac{T_{OFF}}{T_{ON}} = 0.25$

$\therefore \frac{T_{ON}}{T_{OFF}} = 4.$

/ Time Ratio of chopper = $\frac{T_{ON}}{T_{OFF}}$ /

* A Stepdown chopper feeding RL Load with $V_s = 220V$, $R = 5\Omega$, $L = 75mH$, $f = 1KHz$ and $\alpha = 0.5$. find

(a) min. Instantenous Load current.

(b) Peak Instantenous Load current.

(c) P-P Ripple current. (max)

(d) Avg. & RMS Values of Load current.

Sol:- Given, $\alpha = 0.5$; $f = 1KHz$; $R = 5\Omega$; $L = 75mH$.

$\Rightarrow T = \frac{1}{f} = 1ms$.

$\Rightarrow T_a = \frac{L}{R} = \frac{75m}{5} = 15ms$.

$\Rightarrow T_{ON} = \alpha \cdot T = 0.5 \times 1m = 0.5ms$.

$\frac{T_{ON}}{T_a} = \frac{0.5m}{15m} = 0.03$; $T/T_a = 1m/15m = 0.06$

(1) $I_{omin} = \frac{V_S}{R}\left[\frac{e^{T_{ON}/\tau_a}-1}{e^{T/\tau_a}-1}\right]$

$= \frac{220}{5}\left[\frac{e^{0.03}-1}{e^{0.06}-1}\right]$

$I_{omin} = 21.6\ A$

(2) $I_{omax} = \frac{V_S}{R}\left[\frac{1-e^{-T/\tau_{ON}\ -T_{ON}/\tau_a}}{1-e^{-T/\tau_a}}\right] = \frac{220}{5}\left[\frac{1-e^{-0.03}}{1-e^{-0.06}}\right]$

$= 22.36\ A$

(3) $I_r = I_{omax} - I_{omin}$

$= 22.36 - 21.6$

$= 0.73\ A.$

(4) $V_o = \alpha \cdot V_S = 0.5 \times 220 = 110V$

$V_{orms} = \sqrt{\alpha}\cdot V_S = \sqrt{0.5}\times 220 = 155.8V.$

→ Problemson Step up chopper :-

* Step up chopper has Input of 220v and o/p Voltage of 660V, if Conducting Time of Thyristor chopper is 100μs. find the pulse width of output Voltage. If the output Voltage pulse width is half for constant freq. operation. find the new avg. output Voltage.

Sol:- Given, $V_o = 660V$

$V_S = 220V.$

$\Rightarrow V_o = \left(\frac{1}{1-\alpha}\right) V_S$

$\Rightarrow 1-\alpha = \frac{220}{660} = 1/3$

$\Rightarrow -\alpha = 0.333 - 1$

$\therefore \alpha = 0.6667.$

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

$$\Rightarrow T = \frac{100\mu}{0.667} = 149\mu s.$$

$$\therefore T_{OFF} = T - T_{ON} = \overset{149\mu s}{100\mu s} = 49\mu s.$$

$$\therefore T_{OFF} = 49\mu s.$$

→ In step-up chopper $V_0 = 0$ during ON period and during off period $V_0 = \left(\frac{1}{1-\alpha}\right) V_s$.

→ The pulse width of output Voltage is $T_{OFF} = 49\mu s$.

→ Pulse width is at during OFF period.

→ If the pulse width of output Voltage is Half. then

$$\text{new } T_{OFF} = \frac{T_{OFF}}{2} = \frac{49\mu}{2} = 24.5\mu\text{ sec}.$$

for Constant f i.e., constant T, $T_{OFF} \downarrow$, $T_{ON} \uparrow$.

$$\Rightarrow T_{ON\ New} = T - T_{OFF\ new}$$
$$= 149\mu - 24.5\mu$$
$$= 124.5\mu s.$$

$$\therefore \alpha = \frac{T_{ON}}{T} = \frac{124.5\mu}{149\mu} = 0.835$$

$\therefore$ New avg. output Voltage $\Rightarrow V_0 = \left(\frac{1}{1-\alpha}\right) \cdot V_s$

$$\Rightarrow V_0 = \left(\frac{1}{1-0.83}\right) \cdot 220$$

$$\therefore V_0 = 1333.33\, V.$$

* A step up chopper has input voltage of 220V and $V_0 = 660V$, if non-Conducting Time is 100µs. compute pulse width of V_0.

(a) If the pulse width is half for Constant freq. operation find new avg. output Voltage

Sol: / pulse width of output Voltage = T_{OFF} /

*/ pulse width = T_{ON} (Gate pulse width) / *

$$\Rightarrow V_0 = \frac{1}{1-\alpha} V_S$$

$$\Rightarrow \alpha = 0.667$$

$$\Rightarrow \alpha = \frac{T_{ON}}{T} = \frac{T_{ON}}{1 + \frac{T_{OFF}}{T_{ON}}}$$

$$\Rightarrow \alpha T = T_{ON}$$

∴ pulse width of output Voltage, $T_{OFF} = 100 \mu s$.

$$\Rightarrow \alpha = \frac{T_{ON}}{T} \Rightarrow T_{ON} = \alpha \cdot T$$

$$\Rightarrow T = T_{ON} + T_{OFF} = \alpha \cdot T + T_{OFF}$$

$$\Rightarrow T = \frac{T_{OFF}}{1-\alpha} = \frac{100\mu}{1-0.667} = 300 \mu s.$$

$$\therefore T_{ON} = 300\mu - 100\mu = 200 \mu s.$$

→ If pulse width (Gate pulse width) is reduced to half then

$$T_{ON\,new} = \frac{200\mu}{2} = 100 \mu s.$$

$$\Rightarrow \alpha_{new} = \frac{T_{ON\,new}}{T} = \frac{100\mu}{300\mu} = 0.333$$

$$\Rightarrow V_0 = \left(\frac{1}{1-\alpha}\right) V_S = \left(\frac{1}{1-0.33}\right) 220 = 328.35 V.$$

$$\therefore V_0 = 328.35 V$$

* Step up chopper has Supply Voltage of 250V. the output Voltage is 400V. if total chopping period of chopper is 100µs. find new avg. output Voltage

(a) If pulse width of output Voltage is reduced to $\frac{1}{3}$rd for constant frequency operation.

(b) pulse width is reduced to $1/3$rd for constant frequency operation.

Given, $V_S = 250V$;

$V_0 = 440V$;

$T = 100\mu sec$.

$$\Rightarrow k - \alpha = 440 = \frac{1}{1-a} \cdot 250$$

$$\Rightarrow 1-d = \frac{250}{440} = 0.56$$

$$\Rightarrow -d = 0.56 - 1$$

$$\therefore a = 0.37.$$

$$\therefore T_{ON} = dT = 0.37 \times 100\mu = 37\mu s$$

$$T_{OFF} = 63\mu s.$$

(a) $\text{new } T_{OFF} = \frac{63\mu}{3} = 21\mu.sec.$

→ If pulse width of output Voltage is reduced to $1/3$rd then new $T_{OFF} = 21\mu sec$.

$$T_{ON\,new} = T - T_{OFF\,new}$$

$$= 100\mu - 21\mu$$

$$= 79\mu.$$

$$\therefore d_{new} = \frac{79\mu}{100\mu} = 0.79.$$

$$\therefore V_0 = \frac{250}{1-0.79} = 1190.47V.$$

(b) If pulse width is reduced to $1/3$rd then $T_{ON\,new} = \frac{37\mu}{3}$

(Gate pulse width) $T_{ON\,new} = 12.33\mu sec$

$$\Rightarrow a = \frac{T_{ON}}{T} = \frac{12.33\mu}{100\mu} = 0.123$$

$$\Rightarrow V_{onew} = \left(\frac{1}{1-a}\right) V_s$$

$$= \left(\frac{1}{1-0.123}\right) \times 250$$

$$\therefore V_0 = 285.16\,V.$$

Inverters:

- Inverter is a device which converts Dc Input Voltage to ac output Voltage.
- The Dc Input Voltage to the Inverter
- The Ac output of Ideal Inverter is Sinusiodal, but practically it is not sinusiodal and Contains Harmonics.
- The output of practical Inverter may be a Square or Quasi-Square wave.
- There are two types of Inverters:-
  (1) Voltage Source Inverter (V - fed).
  (2) Current Source Inverter (I - fed).
- when the Input Voltage is maintained constant then the Inverter is called VSI.
- when the Input current is maintained constant then the Inverter is called CSI.
- Voltage Source Inverters using SCR's requires forced Commutation to Turn off devices.
- VSI using GTO's, power MOSFET's, IGBT's etc..., requires Natural Commutation to Turn off devices.
- Applications:-

(1) Used in air craft power Supply.
(2) UPS
(3) HVDC Transmission System.

→ Based on connection of Commutating elements, Inverters are of 3 types:-

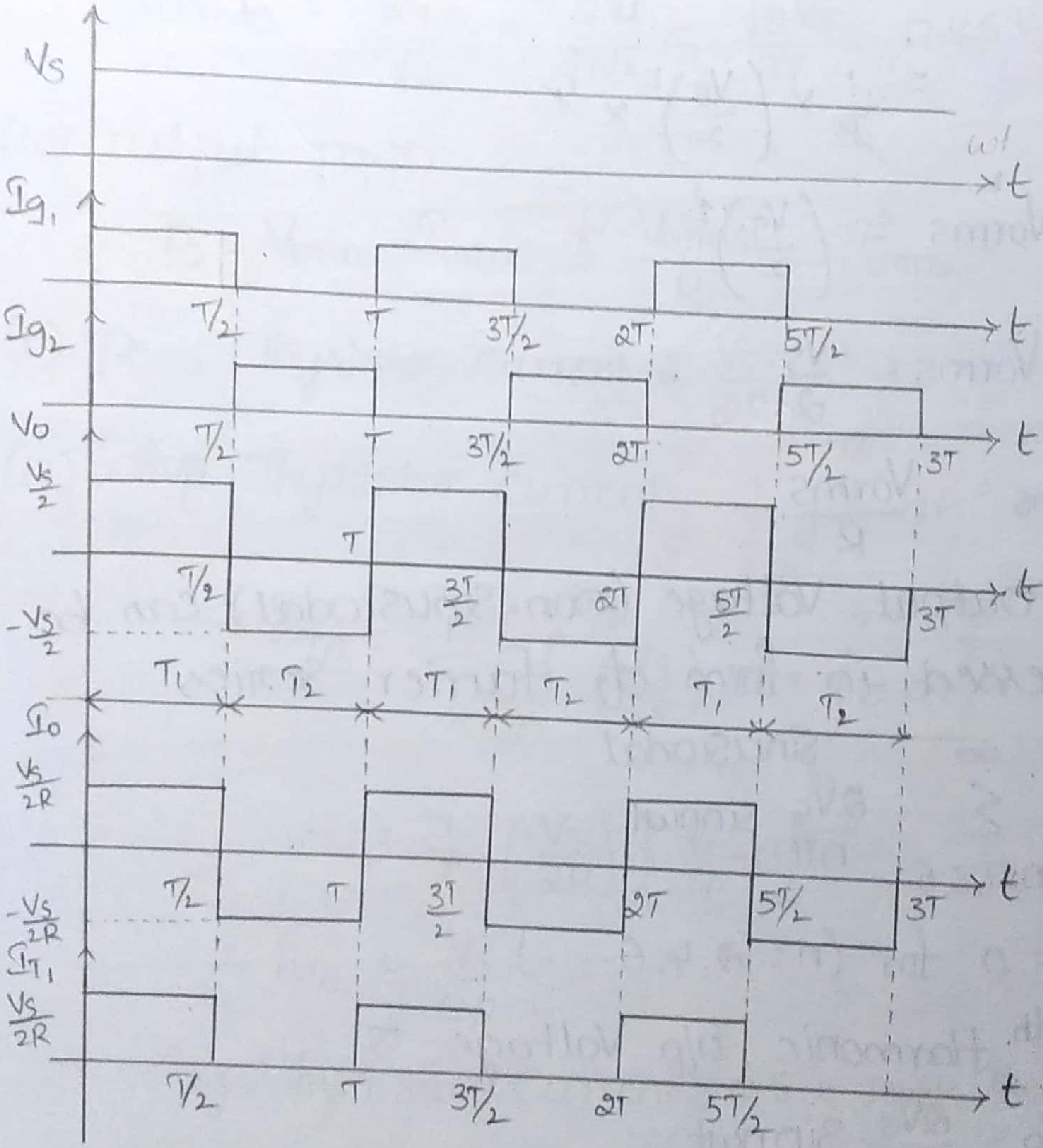
(a) Bridge Inverter.

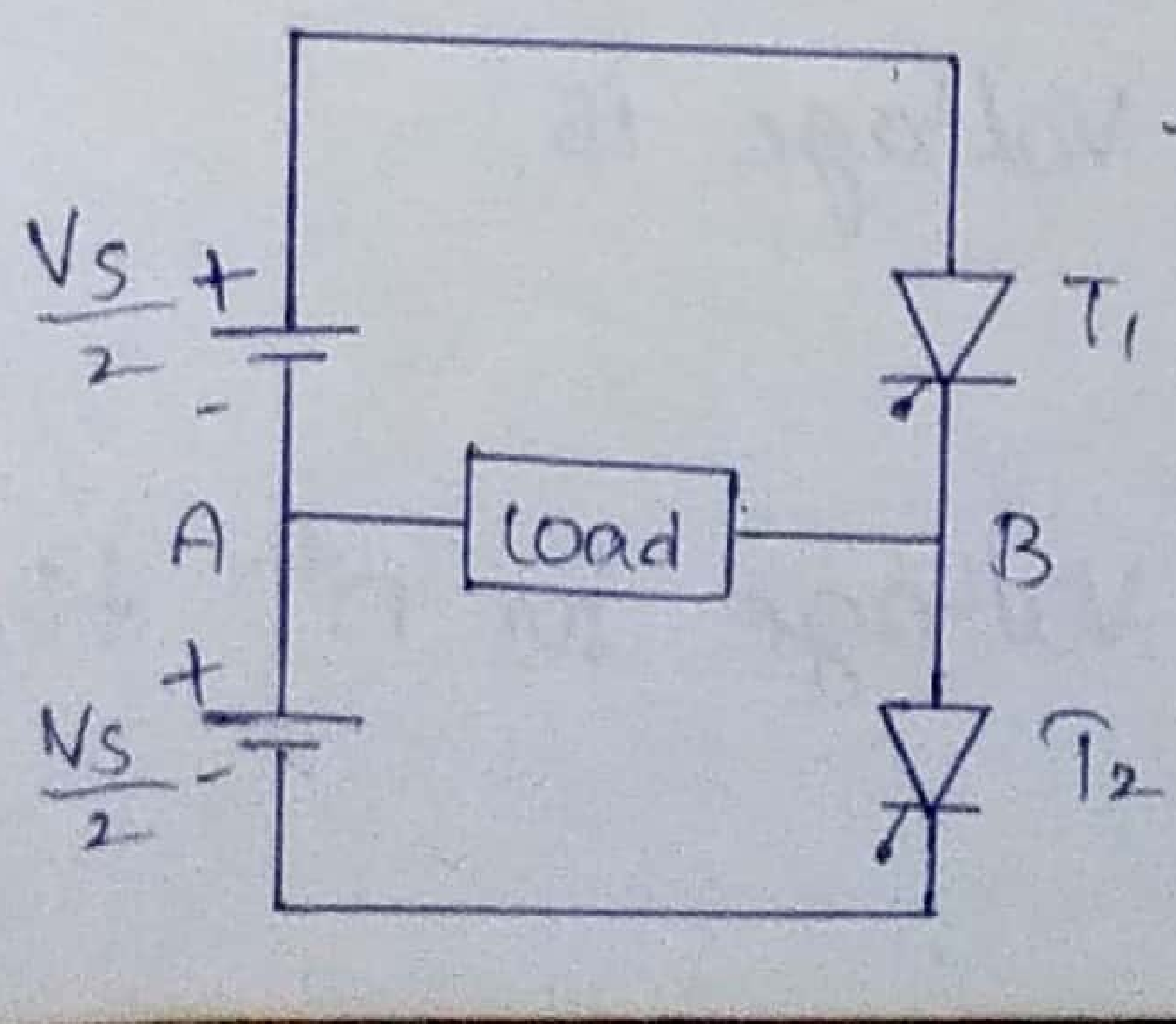
(b) Series Inverter.

(c) Parallel Inverter.

→ Bridge Inverter:-

(a) 1-ϕ Half Bridge Inverter:-





$$-\frac{V_s}{2}+V_0=0$$

$$V_0=\frac{V_s}{2}.$$

$0-T/2$	$T/2-0$.
$T_1 = ON$	$T_2 = ON$.
$V_0 = \frac{V_s}{2}$	$V_0 = -\frac{V_s}{2R}$.
$I_0 = \frac{V_s}{2R}$.	$I_0 = -V_s/2R$.
$I_0 = B-A$.	$I_0 = A-B$

→ By observing output voltage waveforms, i.e., Symmetric wave Hence. $V_{avg} = I_{avg} = 0$.

(1) $V_{orms} = \sqrt{\frac{1}{T}\int_0^T V_o^2 \cdot dt}$

$$\Rightarrow V_{orms}^2 = \frac{1}{T}\left[\int_0^{T/2}\left(\frac{V_s}{2}\right)^2 \cdot dt + \int_{\cancel{0}T/2}^{-T/2}\left(-\frac{V_s}{2}\right)^2 \cdot dt\right]$$

$$= \frac{1}{T}\left(\frac{V_s}{2}\right)^2 \left[\left(\frac{T}{2}-0\right)+\left(\frac{T}{2}-0\right)\right]$$

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

$$\Rightarrow V_{orms}^2 = \left(\frac{V_s}{2}\right)^2$$

$$\therefore V_{orms} = \frac{V_s}{2}.$$

(2) $I_{orms} = \frac{V_{orms}}{R}$.

(3) The output Voltage (non-Sinusiodal) can be expressed in form of fourier series sinusiodal

$$V_o = \sum_{n=1,3,5\ldots}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t.$$

$V_o = 0$ for $(n = 2, 4, 6 \ldots.)$

(4) for nth Harmonic, o/p Voltage is

$$V_o = \frac{2V_s}{n\pi} \sin n\omega t.$$

(5) for fundamental, output Voltage is

$$V_{o1} = \frac{2V_s}{\pi} \sin \omega t.$$

(6) peak value of output voltage for nth Harmonic,

$$V_{onm} = \frac{2V_s}{n\pi}.$$

(6) Peak Value of output Voltage for fundamental.
(7)

$$V_{o1m} = \frac{2V_s}{\pi}.$$

(8) RMS Value of output Voltage for nth Harmonic.

$$V_{orms} \approx V_{rms_{on}}$$

$$V_{onrms} = \frac{V_{onm}}{\sqrt{2}} = \frac{2V_s}{n\pi\sqrt{2}} = \frac{\sqrt{2}V_s}{n\pi} = \frac{0.45V_s}{n}.$$

(9) RMS Value of output Voltage for fundamental.

$$V_{o1rms} = \frac{V_{o1m}}{\sqrt{2}} = \frac{2V_s}{\pi\sqrt{2}} = \frac{\sqrt{2}V_s}{\pi} = 0.45V_s.$$

(10) output power,

$$P_o = V_{orms} \cdot I_{orms} = \frac{V_{orms}^2}{R} = I_{orms}^2 \cdot R.$$

(11) Peak Thyristor current $= \frac{V_s}{2R}$.

(12) Avg. Thyristor current $= \frac{1}{T}\int_0^{T/2} I_T \, dt$

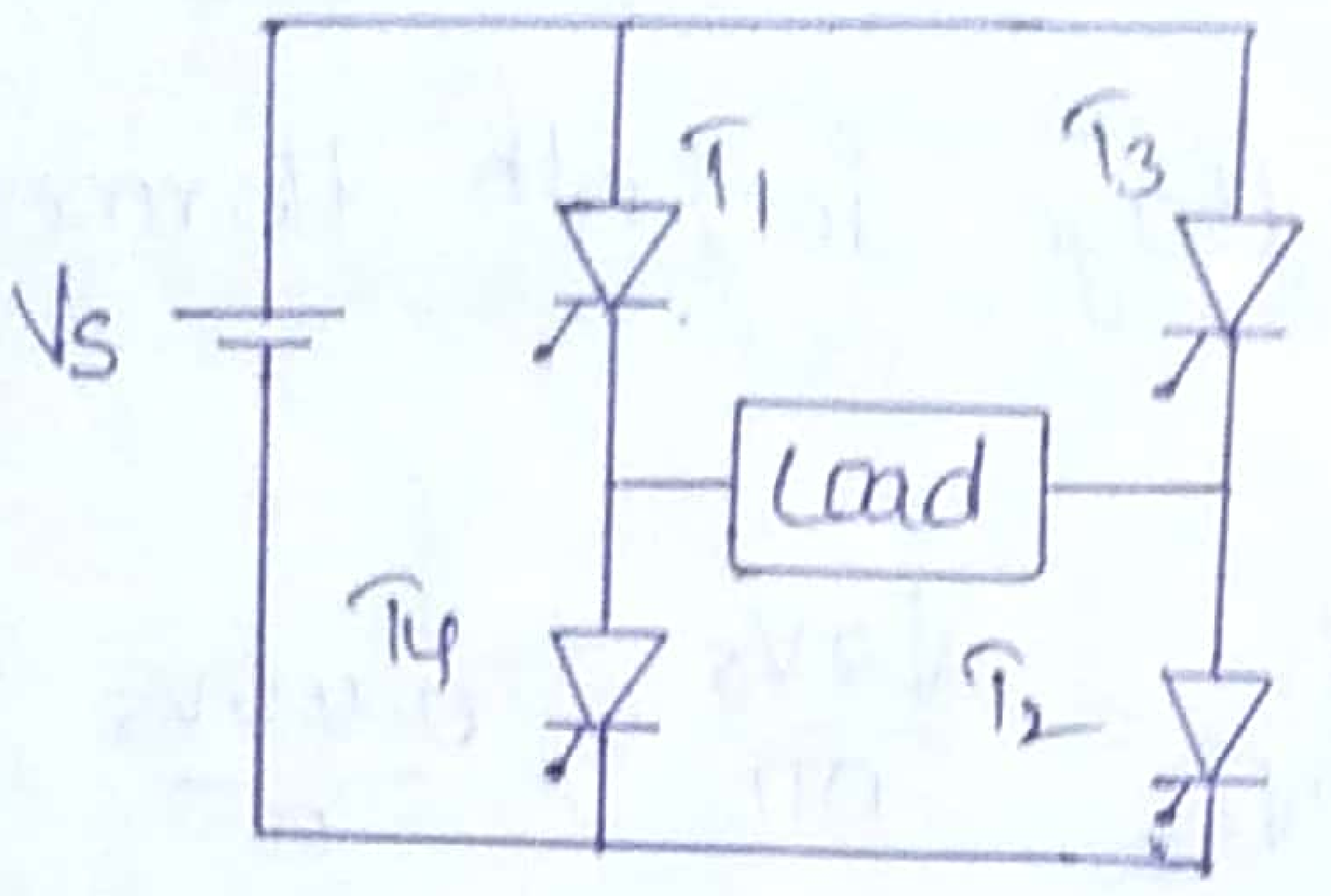
$$\Rightarrow I_{TA} = \frac{1}{T}\left[\int_0^{T/2}\left(\frac{V_s}{2R}\right).dt + \int_{T/2}^{T} 0.dt\right]$$

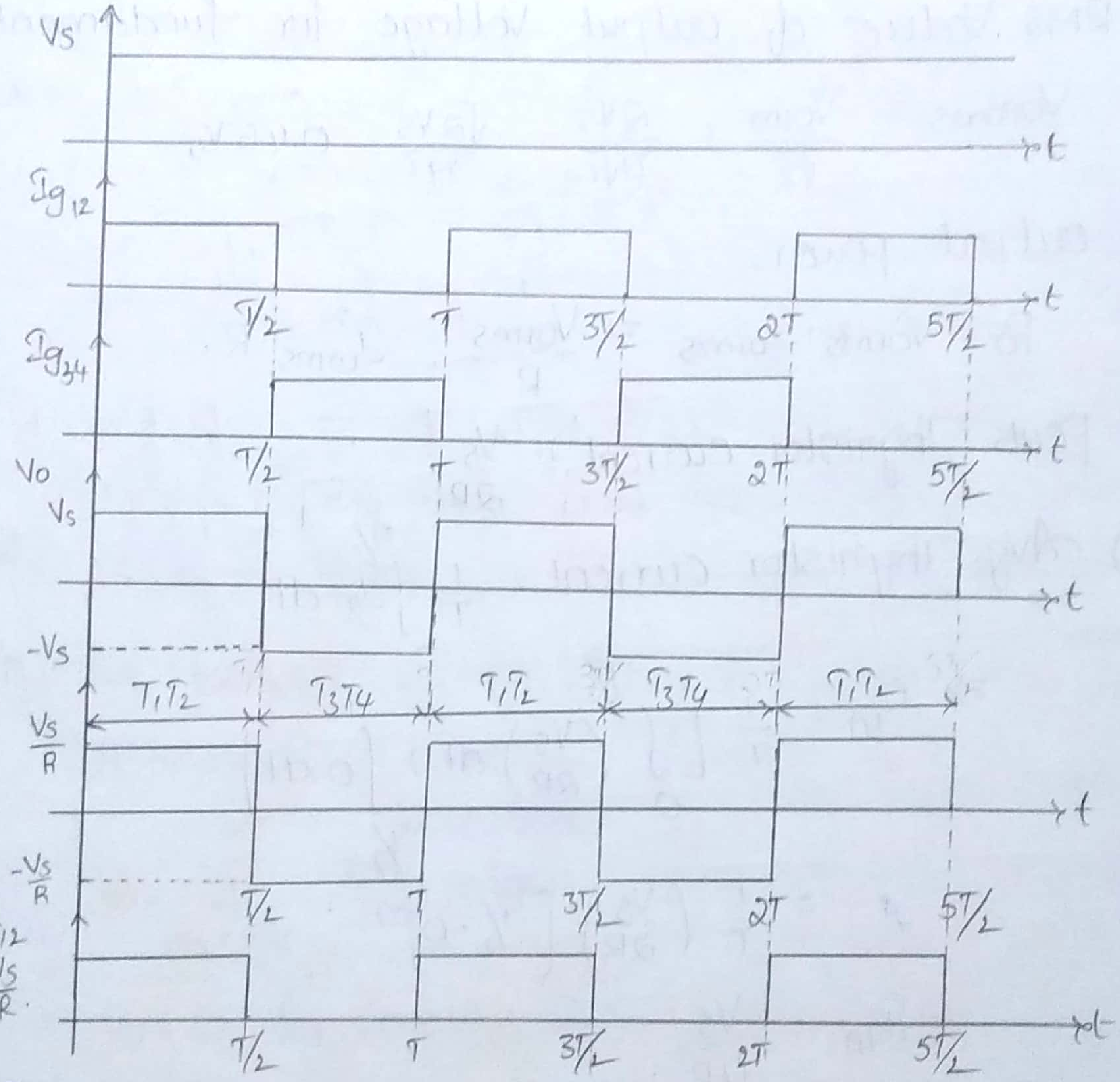
$$= \frac{1}{T}\left(\frac{V_s}{2R}\right)\left[T/2 - 0\right]$$

$$\therefore I_{TA} = \frac{V_s}{4R}.$$

$\therefore$ Avg. Thyristor Current = 0.5 x peak Thy. current.

1-ϕ Full Bridge Inverter:-





→ By observing the output voltage wave forms i.e, symmetric form. Hence, Vavg = Iavg = 0.

→ $V_{orms} = \sqrt{\frac{1}{T}\int_0^T V_0^2 \cdot dt}$

$\Rightarrow V_{orms}^2 = \frac{1}{T}\left[\int_0^{T/2} V_s^2 \cdot dt + \int_{T/2}^{T} (-V_s)^2 \cdot dt\right]$

$\Rightarrow V_{orms}^2 = \frac{1}{T}(V_s^2)\left\{\left[\frac{T}{2}-0\right]+\left[T-T/_2\right]\right\}$

$\Rightarrow V_{orms}^2 = V_s^2$

$\therefore V_{orms} = V_s.$

(2) $I_{orms} = \frac{V_{orms}}{R}$

(3) The output Voltage is non sinusiodal, hence it can be expressed in sinusiodal by using Fourier Series.

$\rightarrow V_0 = \sum_{n=1,3,5....}^{\infty} \frac{4V_s}{n\pi} \sin n\omega t.$

$\rightarrow V_0 = 0$ (for $n=2,4,6....$)

(4) for n^{th} Harmonic, output voltage is

$V_{on} = \frac{4V_s}{n\pi} \sin n\omega t.$

(5) for fundamental, output voltage is

$V_{o1} = \frac{4V_s}{\pi} \sin \omega t.$

(6) Peak Value of output Voltage for n^{th} Harmonic

$V_{onm} = \frac{4V_s}{n\pi}$

(7) Peak Value of output voltage for fundamental.

$V_{o1m} = \frac{4V_s}{\pi}$

(8) RMS Value of output voltage for n^{th} Harmonic.

$V_{onrms} = \frac{V_{onm}}{\sqrt{2}} = \frac{4V_s}{n\pi\sqrt{2}} = \frac{0.9V_s}{n}.$

(9) for fundamental, $V_{o1rms} = 0.9V_s.$

(10) output power = $\frac{V_{orms}^2}{R}$; $I_{orms}^2 \cdot R$.

(11) peak Thyristor current = $\frac{V_s}{R}$.

(12) Avg. Thy Current = $\frac{1}{T}\int_0^T I_T \cdot dt$

$$= \frac{1}{T}\left[\int_0^{T/2} \frac{V_s}{R} \cdot dt + \int_{T/2}^{T} 0\, dt\right]$$

$$= \frac{1}{T} \cdot \left(\frac{V_s}{R}\right)\left(\frac{T}{2} - 0\right)$$

$$\therefore I_{TA} = \frac{1}{2} \cdot \left(\frac{V_s}{R}\right)$$

/ Avg. Thy current = 0.5 x peak Thy current /

1) A 1-Ø Half Bridge Inverter has DC of 48V. R = 4.8Ω. find (a) Vorms (b) RMS Value of fundamental (c) output power. (d) peak and Avg. Thyristor current. (e) Total Harmonic Distortion.

Sol:- Given, $V_s = 48V$.

$R = 4.8\Omega$

(a) $V_{orms} = \frac{V_s}{2} = \frac{48}{2} = 24\ V$

(b) fundamental of RMS = $0.45\ V_s$

$= 0.45 \times 48$

$= 21.6\ V$

(c) $P_o = \frac{V_{orms}^2}{R} = \frac{(24)^2}{4.8} = \frac{24 \times 24}{48} = 120\ W$

(d) $I_{TP} = \frac{V_s}{2R} = \frac{48}{2(4.8)} = 5A$

(e) $I_{TA} = 0.5 \times I_{TP} = 0.5 \times 5 = 2.5A$

(e) Total Harmonic Distortion

$$= \frac{V_h}{V_{o1rms}} = \frac{\sqrt{V_{orms}^2 - V_{o1rms}^2}}{V_{o1rms}}$$

$$= \sqrt{\frac{V_{orms}^2 - V_{o1rms}^2}{V_{o1rms}^2}}$$

$$= \sqrt{\left(\frac{V_{orms}}{V_{o1rms}}\right)^2 - 1} = \sqrt{\left(\frac{24}{21.6}\right)^2 - 1} = 0.484.$$

$$= 48.4\%$$

1-Ø fwBI has dc of 48V, R = 2.4Ω. find

(a) V_{orms} (b) fundamental Component RMS Value.

(c) P_o (d) I_{TA} ; I_{TP} (e) Total Harmonic Distortion.

Given, $V_S = 48V$

$R = 2.4\Omega$

(1) $V_{orms} = V_S = 48\ V$

(2) $V_{o1ms} = 0.9\ V_S = 0.9 \times 48 = 43.2\ V$

(3) $P_o = \frac{(48)^2}{2.4} = 960\ w$

(4) $I_{TP} = \frac{V_S}{R} = \frac{48}{2.4} = 20\ A$

(5) $I_{TA} = 0.5 \times I_{TP} = 0.5 \times 20 = 10A$

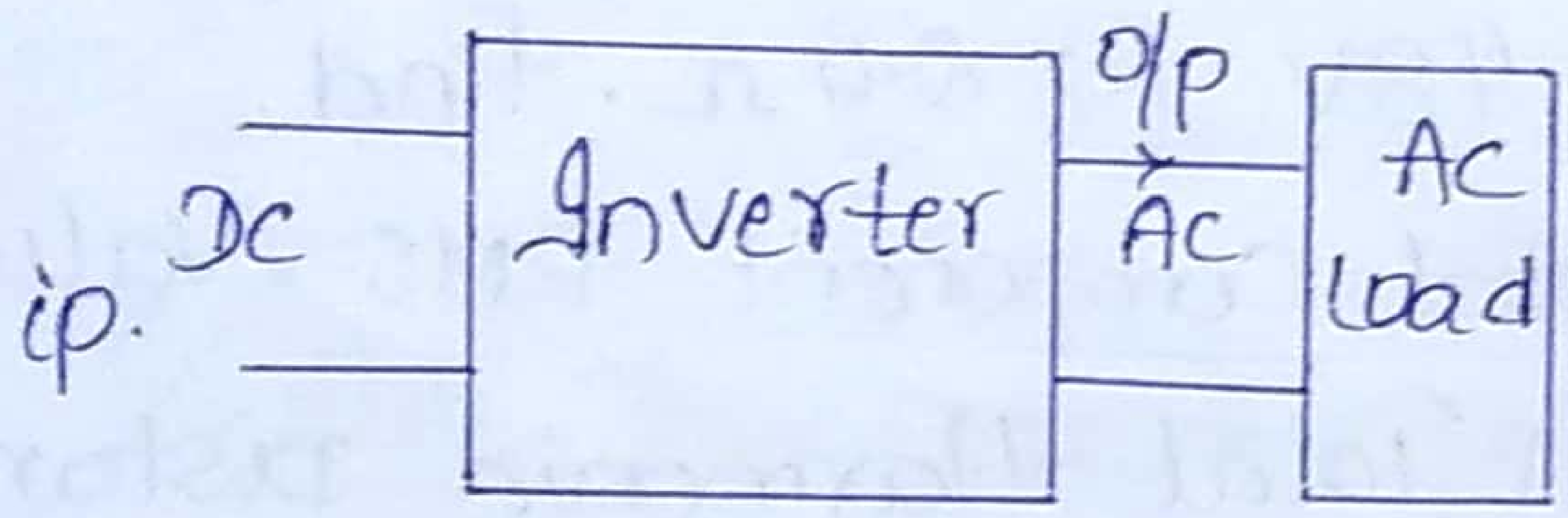
(6) $THD = \sqrt{\left(\frac{48}{43.2}\right)^2 - 1} = 0.484 = 48.4\ \%$

→ Voltage Control Techniques in 1-ø Inverters:-

→ Actually, Ac loads requires constant or controlled ac input voltage at its input terminals. when such ac loads fed through inverter, the output voltage of Inverter should be controlled as per load requirement.

→ To control the output voltage of inverter, there are 3 methods:

constant (or) controlled ac input.



$\frac{V}{f}$ = Constant.

(1) External control of ac $\overset{o/p}{\text{input}}$ Voltage.

(2) External control of dc input Voltage.

(3) Internal Control of Inverter.

→ External control of Ac Input Voltage:-

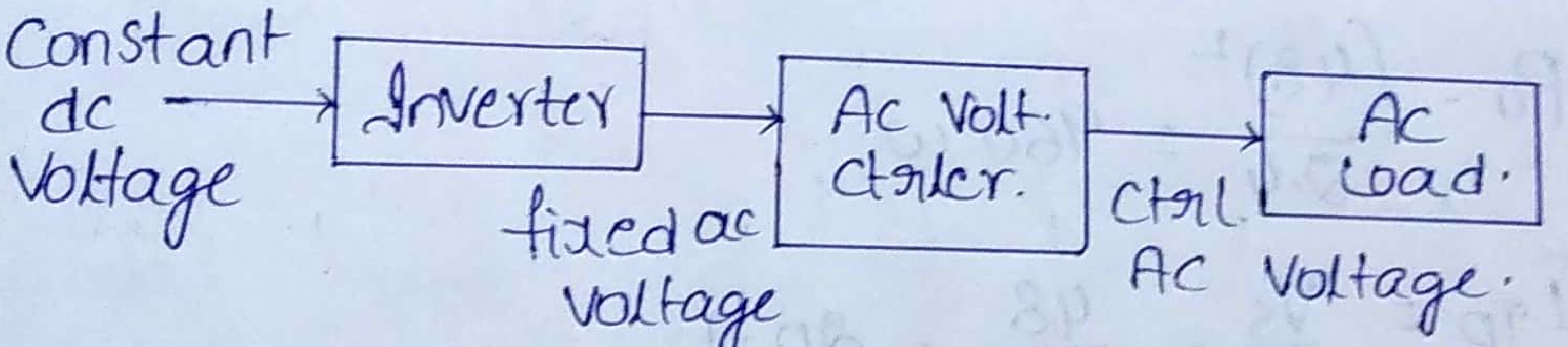


fig:- Ac Voltage control Method.

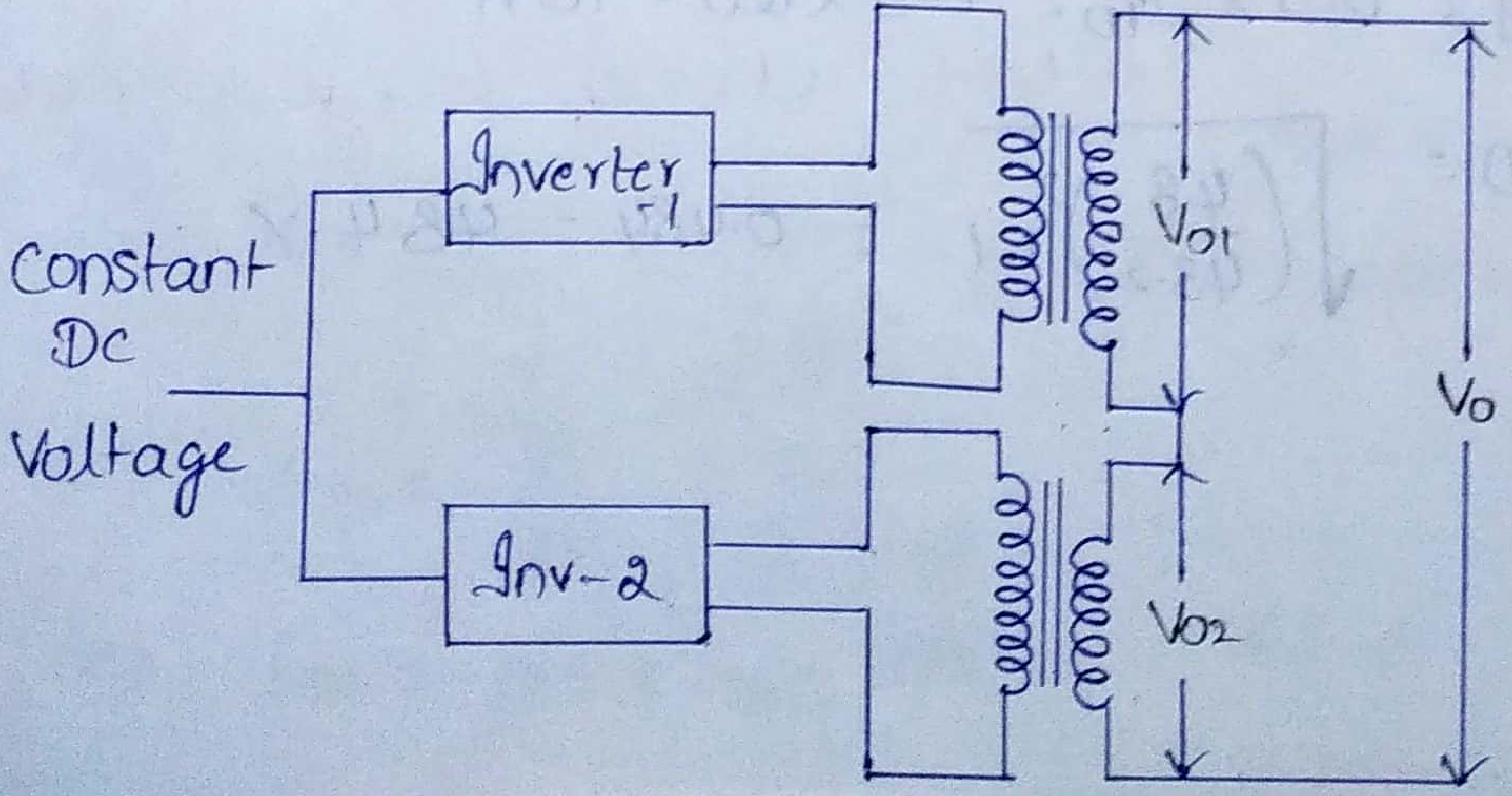
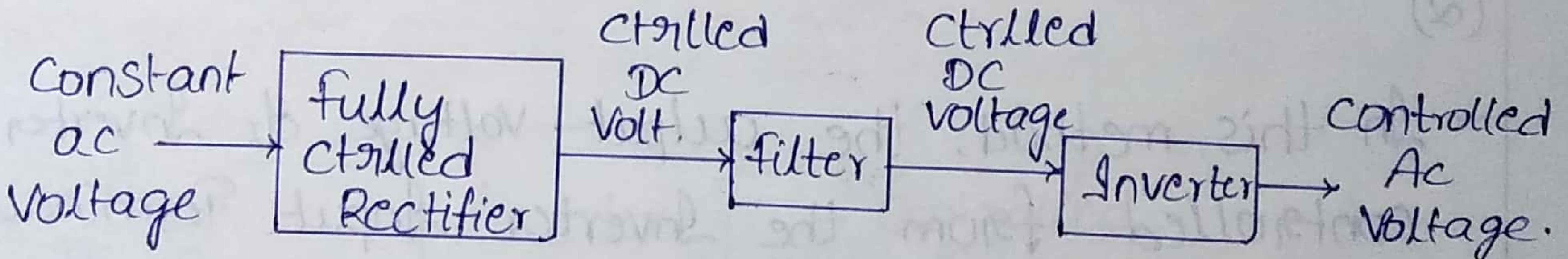
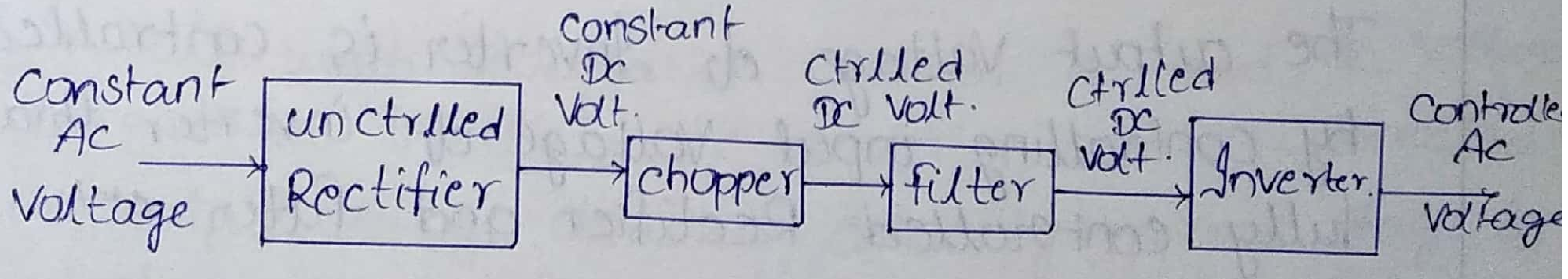


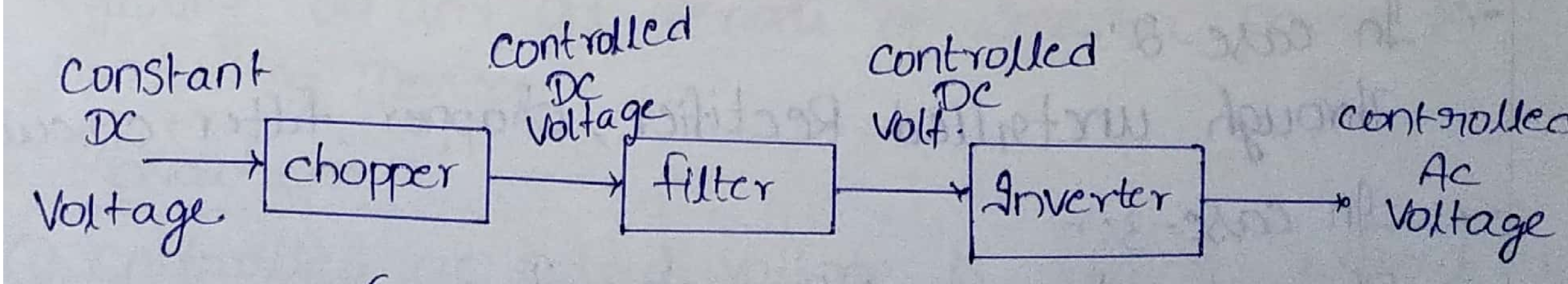
fig:- Series Inverter ctrl. Method.

- In this method, the o/p Voltage of Inverter can be Controlled from the Inverter output terminals.
- There are two methods of External Control of ac output Voltage.
  (a) Ac Voltage control Method.
  (b) Series Inverter Control Method.
- In Ac Voltage control Method, ac voltage controller is inserted between Inverter and Ac load inorde to control the o/p voltage of Inverter from the o/p terminals of Inverter.
- In Series Inverter ctrl method, two or more Inverters can be connected in series with the Transformers in order to ctrl the o/p Voltage of Inverter, from the output terminals of Inverte

(2) External control of DC Input Voltage:-







(ctrl. Voltage) = (Variable Voltage).

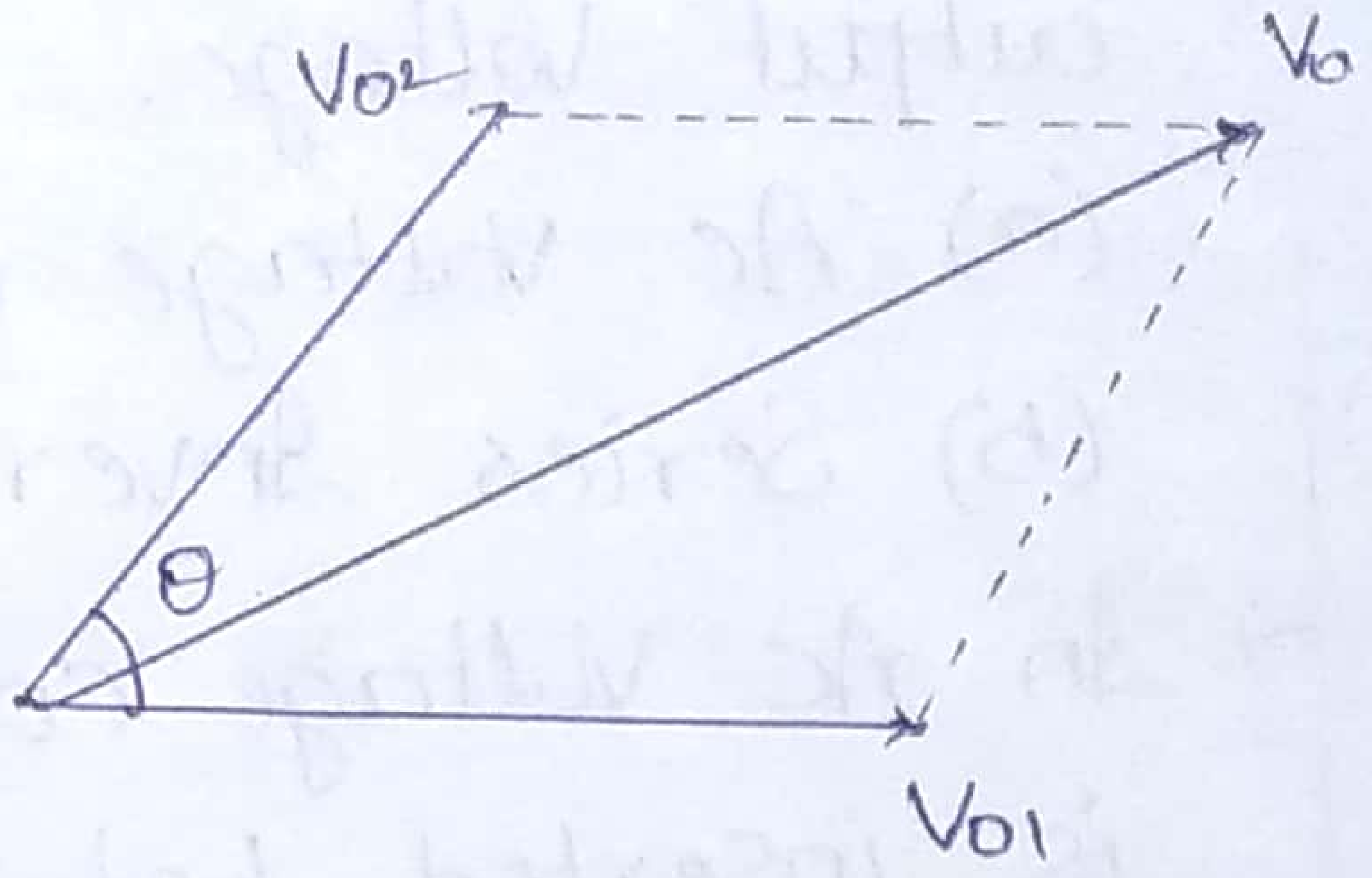
(1) $V_0 = \sqrt{V_{01}^2 + V_{02}^2 + 2V_{01}\cdot V_{02}\cdot\cos\theta}$

Case-1:- At $\theta = 0$

$V_0 = \sqrt{V_{01}^2 + V_{02}^2 + V_a \cdot V_{02} \cdot 2}$

$= \sqrt{(V_{01}+V_{02})^2}$

$= V_{01} + V_{02}$.



when, $V_{01} = V_{02}$.

$\therefore V_0 = 2V_{01}$ or $2V_{02}$

[θ- Varied by varying firing angles of SCR]

Case-2:- when $\theta = \pi$

$V_0 = \sqrt{V_{01}^2 + V_{02}^2 + V_{01} V_{02} (-1) 2}$

$= \sqrt{(V_{01}-V_{02})^2}$

$\therefore V_0 = V_{01} - V_{02}$

when $V_{01} = V_{02}$ $\therefore V_0 = 0$.

(2)

→ In this method, the output voltage of Inverter controlled from the Inverter Input Terminals.

→ In case-1:-
The output voltage of Inverter is controlled by controlling input voltage of inverter through fully controlled Rectifier and filter ckt.

→ In case-2:-
Through unctrolled Rectifier, chopper, filter circuit.

→ In case-3:-
Through chopper, filter circuit.

→ Drawbacks:-

→ filters are used inorder to reduce the ripples, it will increases the cost, weight and size of filter.

→ Inorder to obtain the controlled output voltage of Inverter it requires more number of stages. More number of stages leads to more power loss and then decreases the efficiency.

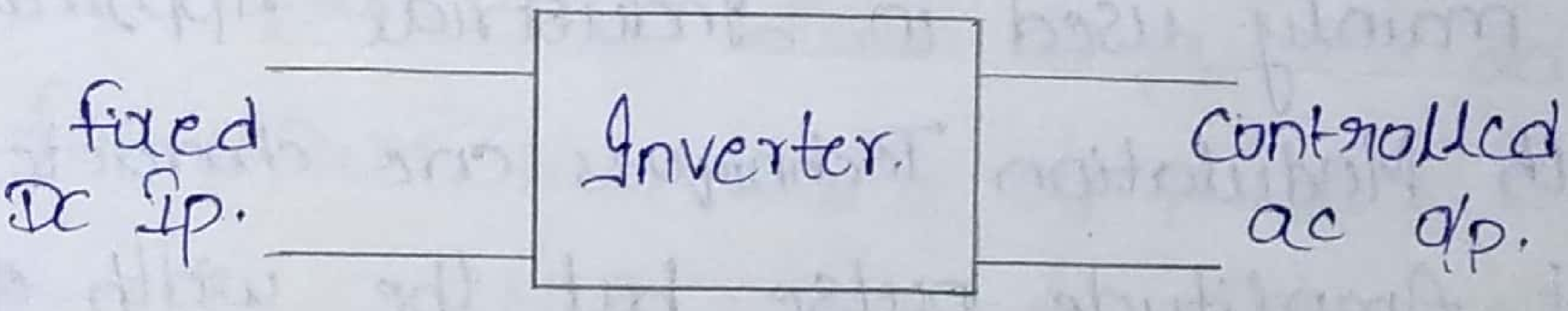
→ As number of stages is more, it is very difficult to control output voltage of Inverter.

(3) Internal control of Inverter:-

→ In this method, the output voltage of Inverter can be controlled within the Inverter itself.

→ The most efficient method of controlling output voltage within the Inverter itself is pulse width Modulation control.

→ Pulse width Modulation control:-



→ In pulse width Modulation control, a fixed dc voltage is given as input to the Inverter and a controlled ac output voltage obtained directly in one stage by adjusting ON and off periods of Inverter power semi conducting Devices.

→ Advantages:-

(1) Controlled ac output voltage is obtained without using any additional components.

(2) Lower order Harmonics can be eliminated along with ctrl action, Higher order Harmonics can be eliminated easily by using filter circuit.

→ Disadvantages:-

(1) Thyristors used in this method must have low Turn on and Turn off times i.e., Inverter Grade SCR's used to ctrl o/p Voltage of Inverter.

(2) It is expensive.

xxx → PWM Techniques (or)

xxx Harmonic Reduction Techniques:-

→ Various pulse width Modulation Techniques are:-

(1) Single pulse width Modulation.
(2) Multiple pulse width Modulation.
(3) Sinusiodal pulse width Modulation.

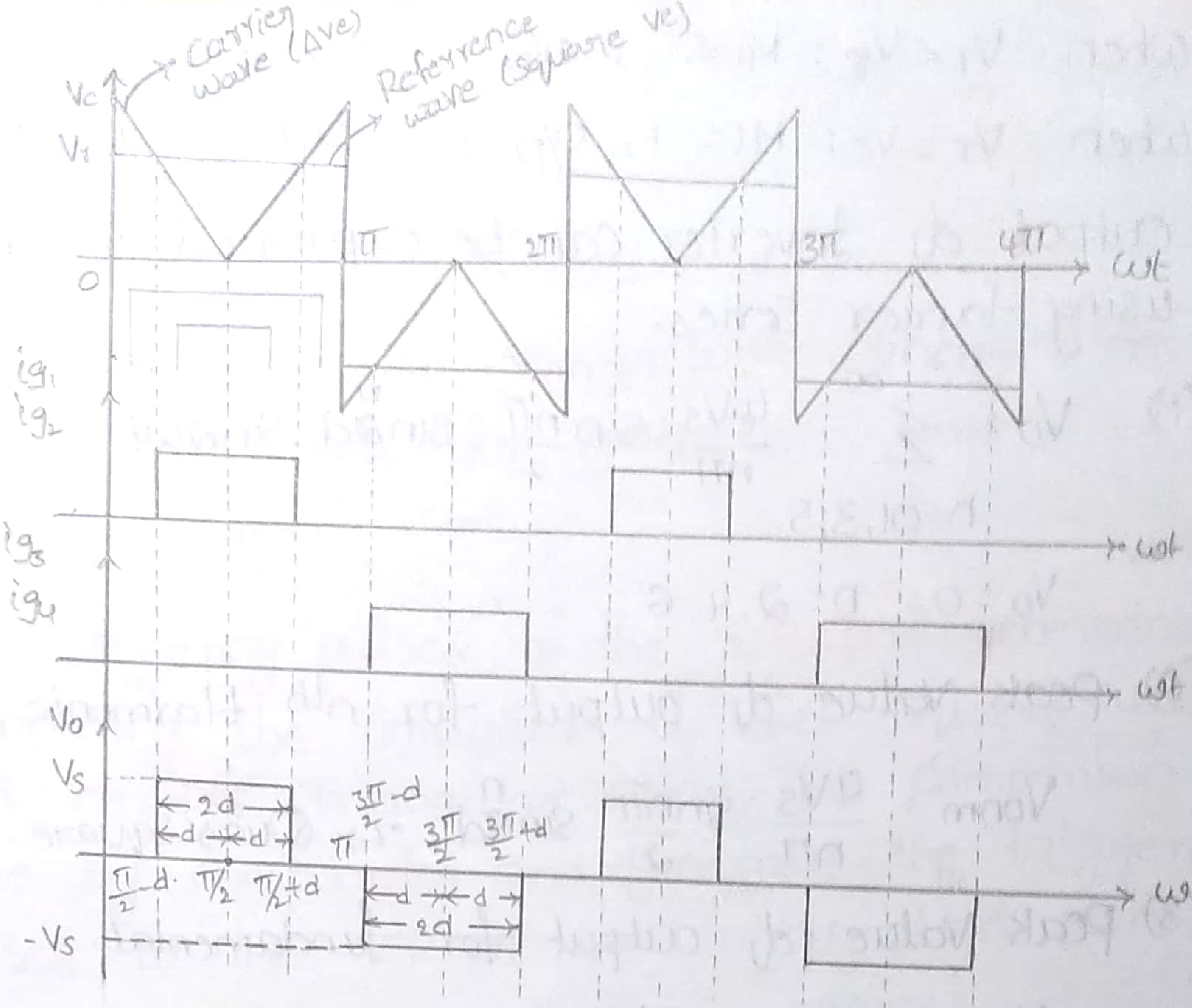
→ If any Inverter uses pulse width Modulation ctrl. then the Inverters are called PWM Inverters which are mainly used in Industrial Applications.

→ Pulse width Modulation Techniques are characterised by Constant Amplitude pulse, but the width of the pulse is varied inorder to ctrl op Voltage of Inv and then to reduce harmonic content in the output Voltage.

(1) Single pulse width Modulation (SPWM):- xxx

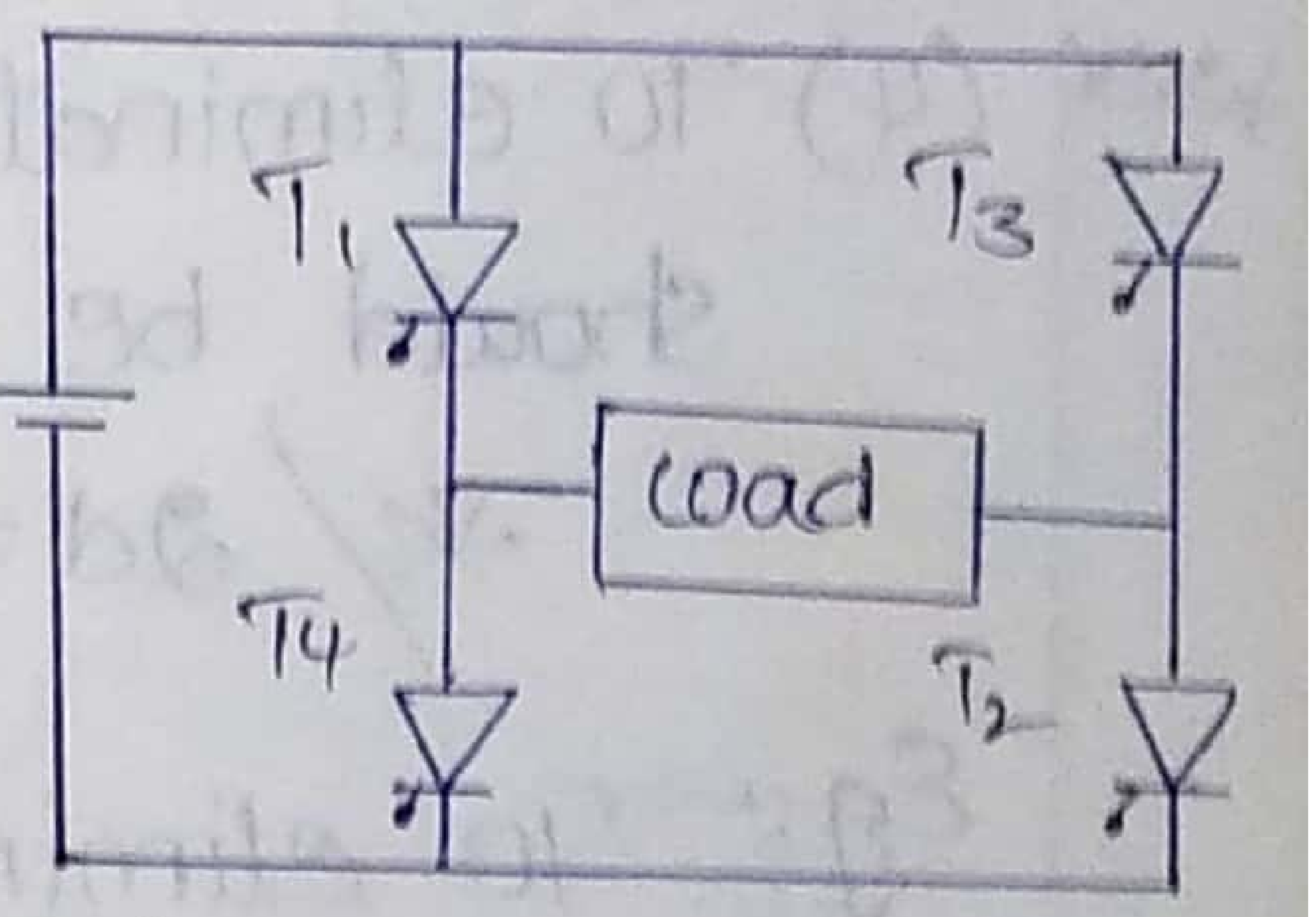
→ It uses Referrence wave as Square wave and Carrier waves as Triangle wave.

→ In SPWM Technique, single pulse per Half cycle is present.



→ [Here V_o is a Quasi-Square wave]

→ In General, the width of the pulse is given by, $\frac{2d}{n}$ where N = No. of pulses / Half cycle.



→ for SPWM, N=1. width of pulse = 2d.

→ for MPWM, N=2, width of pulse = d.

N=3, width of pulse = $\frac{2d}{3}$ .....

→ width of pulse is varied in order to control the output Voltage of Inverter. The width of pulse is varied from 0-π, by varying amplitude of Referrence Signal 0 - V_c.

→ Modulation Index:-

→ It is the ratio of Amplitude of Ref. Signal to the Amplitude of Carrier signal, $MI = \frac{V_r}{V_c}$.

→ when $V_r < V_c$; MI<1, O/p is Quasi Square wave

→ when $V_r = V_c$; MI = 1, O/p is Square wave

→ output of Inverter can be expressed in Sine by using fourier series.

(1) $$V_0 = \sum_{n=01,3,5\ldots}^{\infty} \frac{4V_s}{n\pi} \sin\frac{n\pi}{2} \cdot \sin \overset{n}{2}d \cdot \sin 2\omega t$$

$V_0 = 0$; $n = 2, 4, 6 \ldots\ldots$

(2) peak Value of output for n^{th} Harmonic;

$$V_{onm} = \frac{4V_s}{n\pi} \sin\frac{n\pi}{2} \cdot \sin \overset{n}{2}d \Rightarrow \text{Quasi square.}$$

(3) peak Value of output for fundamental.

$$V_{o1m} = \frac{4V_s}{\pi} \sin 2d. \quad \left(\because \sin\frac{\pi}{2} = 1\right)$$

*** (4) To eliminate n^{th} Harmonic, the width of pulse should be

$$*/\ 2d = \frac{2\pi}{n}\ /*$$

Eg:- To eliminate 3^{rd} Harmonic, the width of pulse should be, $2d = \frac{2\pi}{3} = 120°$.

→ To eliminate 5^{th} Harmonic,

$$2d = \frac{2\pi}{5} = 72°.$$

(5) $$V_{orms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 \cdot d\omega t}$$

$$\Rightarrow V_{orms}^2 = \frac{1}{2\pi}\int_{\pi/2-d}^{\pi/2+d} V_s^2 \cdot d\omega t + \int_{\frac{3\pi}{2}-d}^{\frac{3\pi}{2}+d} (-V_s)^2 \cdot d\omega t$$

$$= \frac{V_s^2}{2\pi}\left[\left(\frac{\pi}{2}+d\right) - \left(\frac{\pi}{2}-d\right) + \left(\frac{3\pi}{2}+d\right) - \left(\frac{3\pi}{2}-d\right)\right]$$

$$\Rightarrow V_{orms}^2 = \frac{V_s^2}{2\pi}(4d)$$

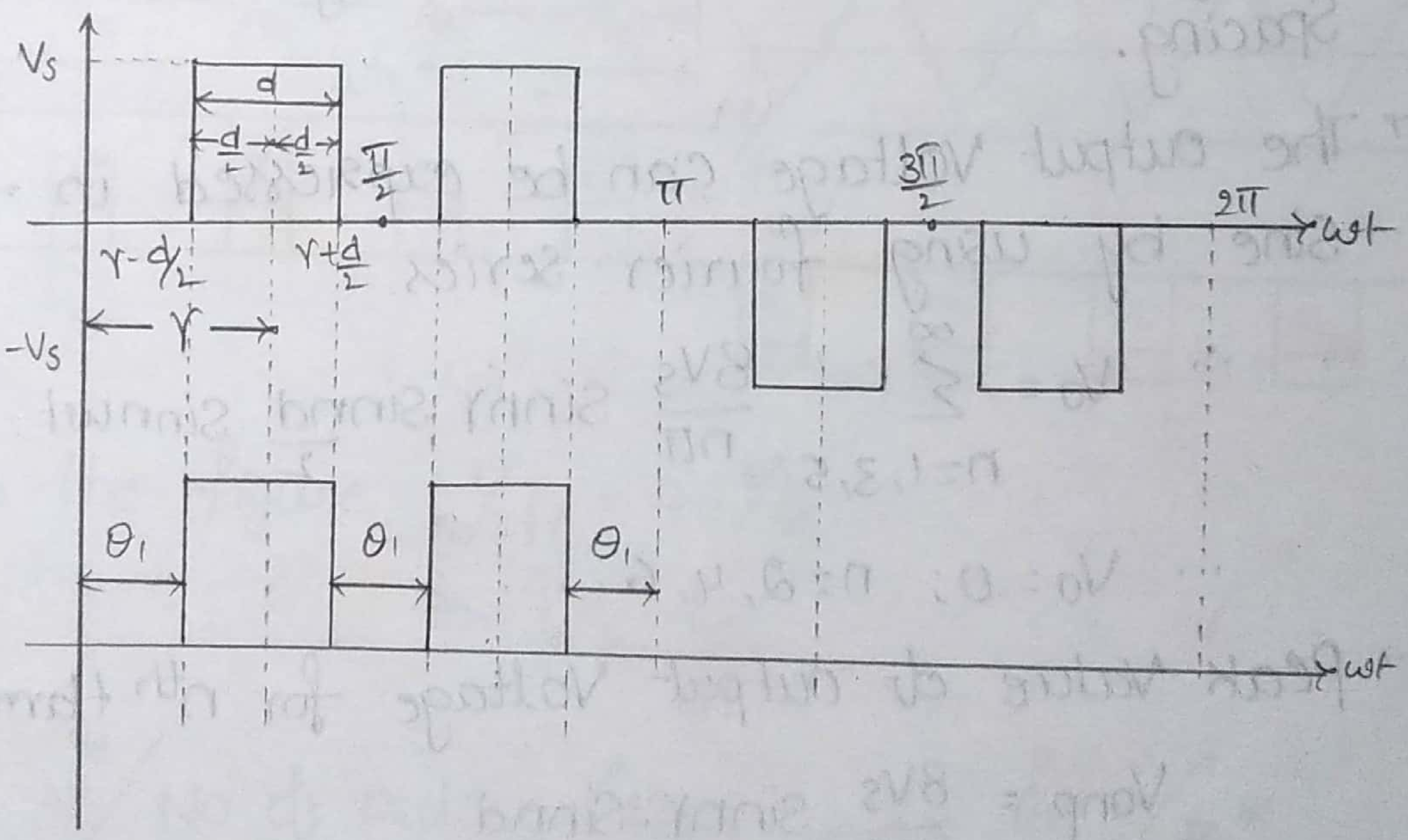
$$\therefore V_{orms} = V_s\left(\frac{2d}{\pi}\right)^{1/2}$$

→ for Half wave also, Vorms = Same since, no need to consider full cycle for Symmetric wave.

(6) $I_{orms} = \frac{V_{orms}}{R}$

→ The Triggering pulses to the SCR are generated by Comparing the Amplitude of Ref. Square wave and carrier Triangular wave. This comparison is done by Comparator and generates the triggering pulses to the SCR at the intersection point of Referrence Signal and carrier signal.

(2) Multiple pulse width Modulation (MPWM):-



→ for Single pulse there are 2 Equidistance Spaces

→ for Two pulse / Half cycle 3 Equidistance Spaces.

→ Similarly for N pulses / Half cycles there are (N+1) Equidistances Spaces, Each of width θ_1.

→ Therefore, the (width of) Total width of (N+1) Equidistance Spaces given by,

$$\theta_1 = \frac{\pi - 2d}{N+1} \quad ; \quad (N+1)\theta_1 = \pi - \text{Total width of N pulses}$$

→ from fig, $\gamma = \theta_1 + \theta_2$; $(N+1)\theta_1 = \pi - 2d$.

$$\theta_2 = d/2 \; ;$$

$$*/ \quad \gamma = \frac{\pi - 2d}{N+1} + \frac{d}{2} \quad /*$$

→ The above Eqn valid for only when the pulses having equal width and are Symmetrically Spacing.

→ The output Voltage can be expressed in form of sine by using fourier series.

$$\therefore \; V_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{8V_s}{n\pi} \sin n\gamma \, \sin\frac{nd}{2} \, . \sin n\omega t .$$

$$\therefore \; V_0 = 0 ; \; n = 2, 4, 6 \ldots\ldots$$

→ Peak Value of output Voltage for nth Harmonic,

$$V_{onp} = \frac{8V_s}{n\pi} \sin n\gamma . \sin\frac{nd}{2} .$$

→ Peak Value of output Voltage for fundamental.

$$V_{o1p} = \frac{8V_s}{\pi} \sin\gamma . \sin\frac{d}{2} .$$

(In SWMP $\sin\frac{n\pi}{2} = 1$ (∵ n=1))

→ The RMS Value of output Voltage is

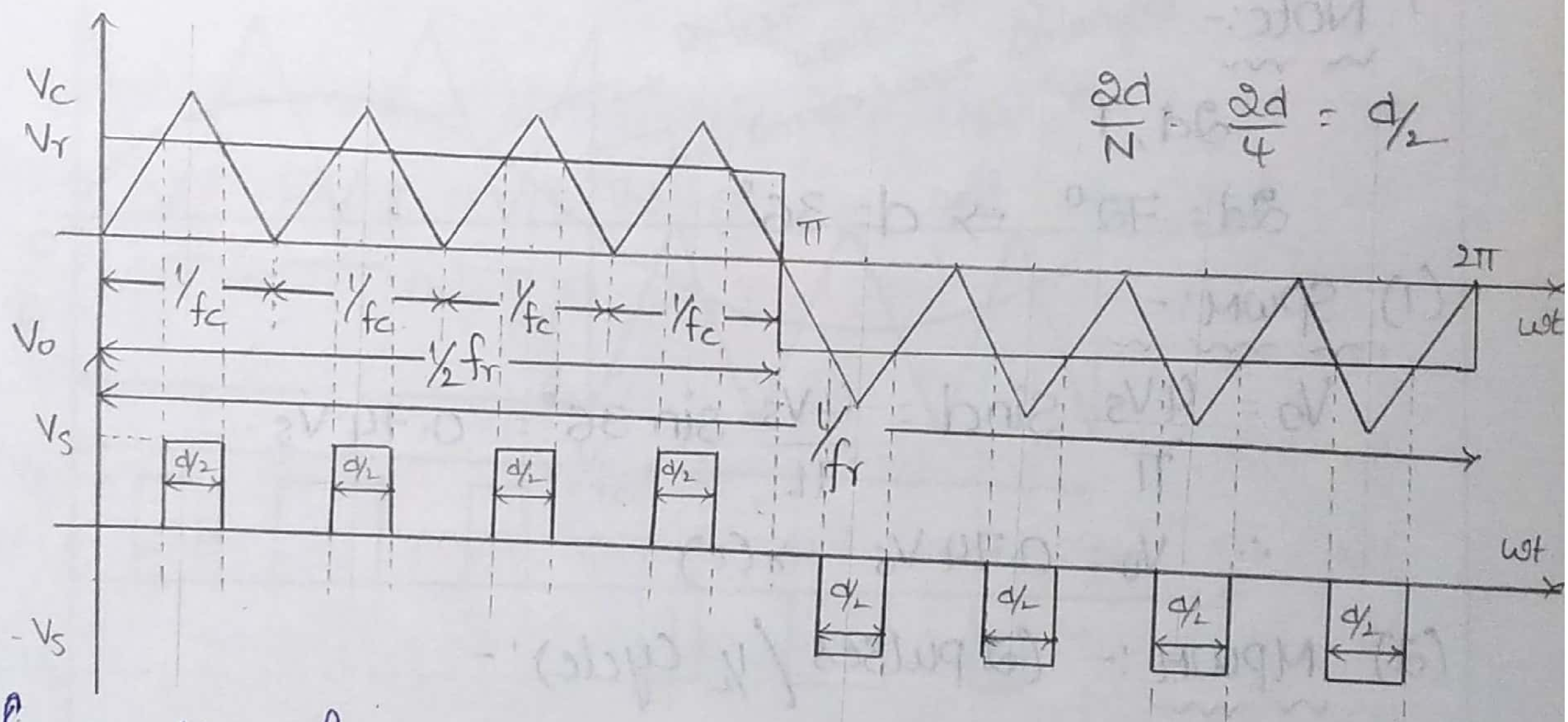
$$V_{orms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} V_0^2 \cdot d\omega t}$$

$$\Rightarrow V_{orms}^2 = \frac{1}{\pi}\int_{\gamma-\frac{\pi d}{2}}^{\gamma+\frac{\pi d}{2}} V_s^2 \cdot d\omega t \times 2 \left(\text{no. of } \frac{\text{pulses}}{\text{cycles}}\right)$$

$$\Rightarrow V_{orms}^2 = \frac{1}{\pi}(V_s^2)\left[\left(\gamma+\frac{d}{2}\right)-\left(\gamma-\frac{d}{2}\right)\right]\times 2.$$

$$*/\therefore V_{orms} = V_s \cdot \left(\frac{2d}{\pi}\right)^{1/2} /*.$$

→ Four pulses per Half cycle :-



$$\frac{2d}{N} = \frac{2d}{4} = d/2$$

from the figure, $\frac{1}{2f_r} = 4 \cdot \frac{1}{f_c}$.

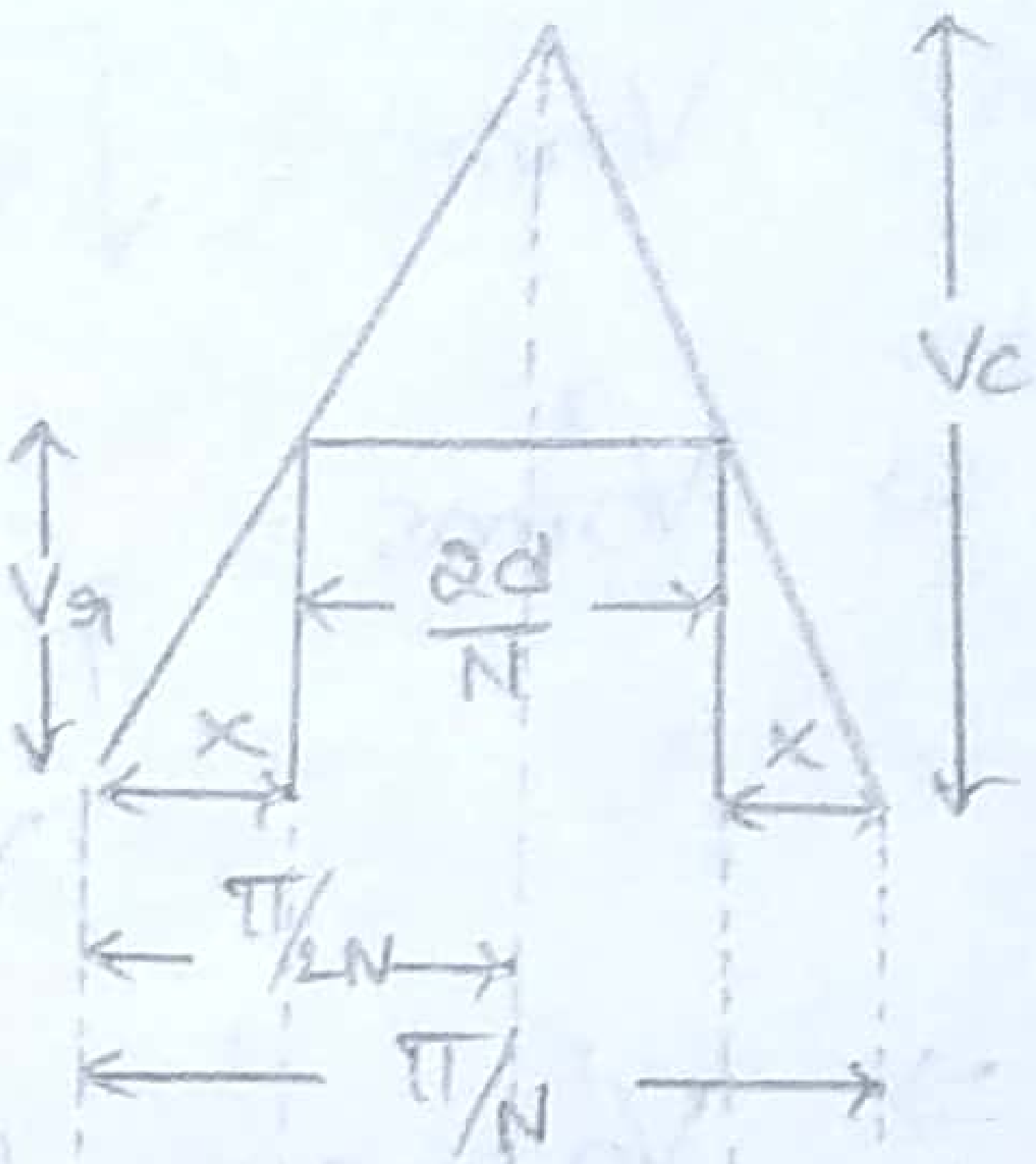
$$\Rightarrow 4 = \frac{f_c}{2f_r}.$$

$$**/ \text{No. of pulses / Half cycle} = \frac{f_c}{2f_r} /**$$

→ width of pulse $\left(\frac{2d}{N}\right) = \frac{\pi}{N} - 2x$

$$\frac{V_c}{\frac{\pi}{2N}} = \frac{V_r}{x} \qquad [\text{from fig}]$$

→ $x = \frac{V_r \times \frac{\pi}{2N}}{V_c} = \frac{V_r \pi}{V_c 2N}$.



⇒ width of pulse

$$\left(\frac{2d}{N}\right) = \frac{\pi}{N} - 2\left(\frac{V_r \pi}{V_c \cancel{2} N}\right)$$

$$= \frac{\pi}{N}\left(1 - \frac{2V_r}{V_c}\right)$$

∴ **/ width of pulse = $\frac{\pi}{N}\left(1 - \frac{V_r}{V_c}\right)$ /**

→ In Multiple pulse width Modulation, multiple no. of Equidistances pulses per cycle are present (first note this point at starting).

→ Note:-

$2d, \gamma$

$2d = 72^{0} \Rightarrow d = 36^{\circ}$.

(1) SPWM:-

$V_0 = \frac{4V_s}{\pi} \sin d = \frac{4V_s}{\pi} \sin 36^{\circ} = 0.74\,V_s$.

∴ $V_0 = 0.74\,V_s \rightarrow (1)$

(2) MPWM :- (2 pulses / ½ cycle):-

$V_0 = \frac{8V_s}{\pi} \sin\gamma . \sin\frac{d}{2}$.

$\gamma = \cancel{2}\,\frac{\pi - 2d}{N+1} + \frac{d}{2} = \frac{\pi - 72}{2+1} + \frac{36}{2}$.

∴ $\gamma = 54^{\circ}$.

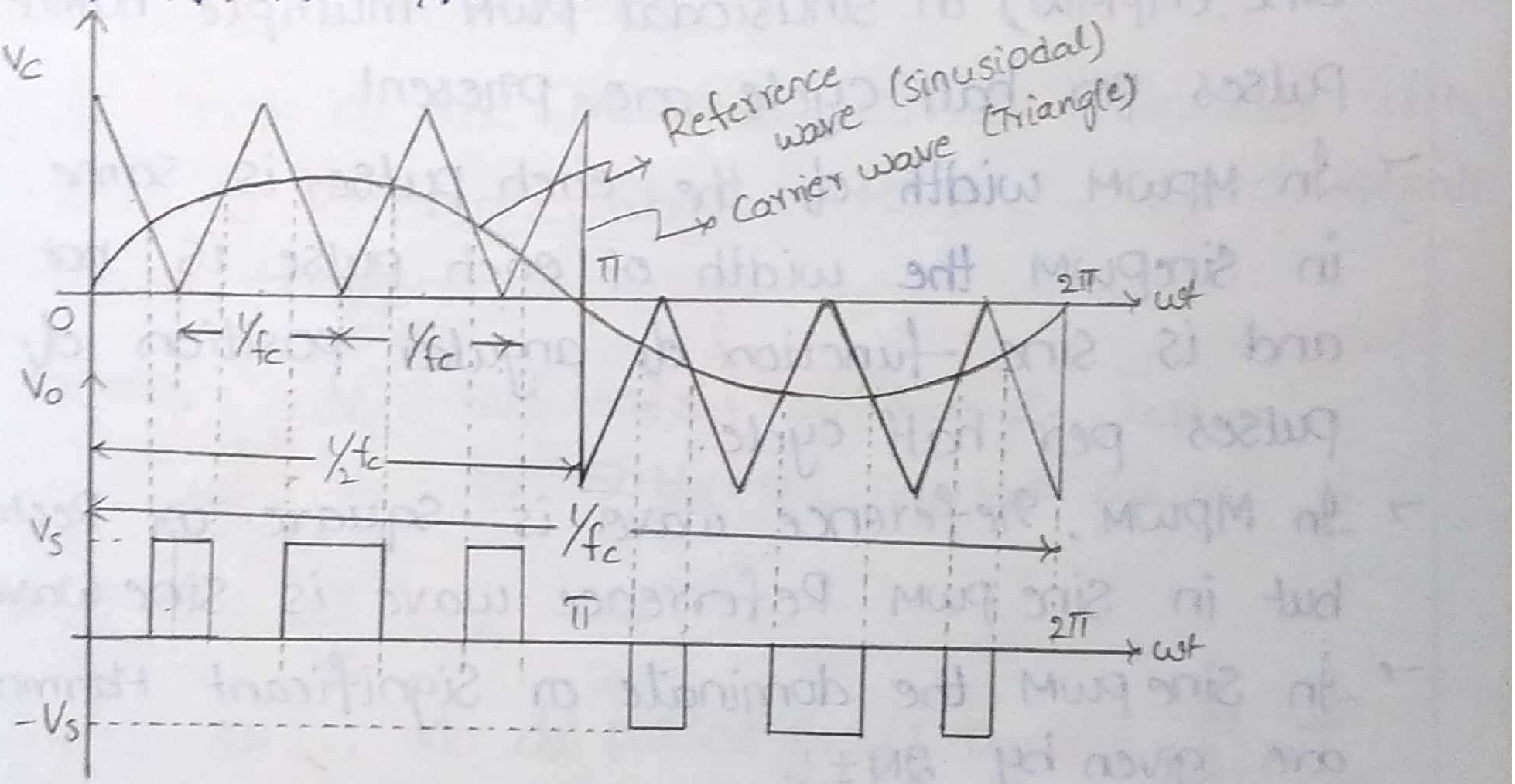
$V_0 = \frac{8V_s}{\pi} \sin 54^{\circ} . \sin 18$

∴ $V_0 = 0.636\,V_s \rightarrow (2)$

- The fundamental Component of output voltage is lower in case of two pulse width modulation than Spwm. It indicates lower order Harmonics are low in case of two pulse width modulation than Spwm.
- As the number of pulses per half cycle increases, the lower order Harmonics can be reduced.
- The Higher order Harmonics is eliminated by using filter circuits.

(3) Sinusiodal pulse width Modulation:-

(a) Peak of the carrier coincidence with zero of Ref.

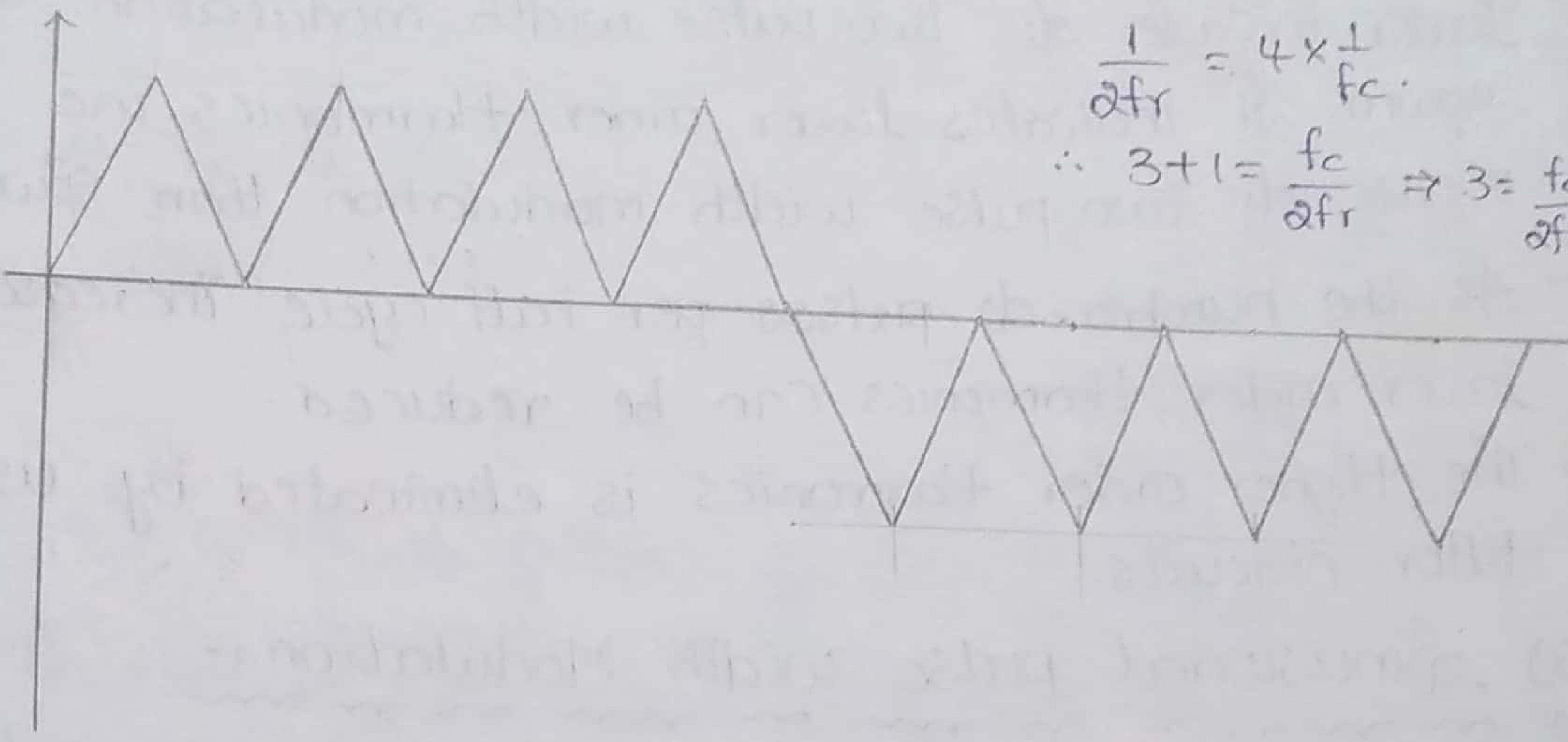


$$\frac{1}{2f_r} = 3 \times \frac{1}{f_c}$$

$$\Rightarrow 3 = \frac{f_c}{2f_r}$$

/ No. of pulses / ½ cycle = $\frac{f_c}{2f_r}$ /

(b) Zero of the carrier (coincidence with zero of ref



$$\frac{1}{2fr} = 4 \times \frac{1}{fc}.$$

$$\therefore 3+1 = \frac{fc}{2fr} \Rightarrow 3 = \frac{fc}{2fr} - 1$$

→ Like, (MPMW) in sinusiodal PWM multiple number of pulses per half cycle are present.

→ In MPWM width of the each pulse is same, but in SinePWM the width of each pulse is not same and is sine function of angular position of pulses per half cycle.

→ In MPWM, reference wave is square or Rectangular but in sine PWM Referrence wave is sine wave.

→ In sine PWM the dominate or significant Harmonics are given by $2N \pm 1$.

when, N = 2, Dominant Harmonics = 3, 5.
N = 3, = 5, 7.
N = 4, = 7, 9.
N = 5, = 110, 9.
N = 6, = 9, 11, 13.

i.e., in sine PWM, we can raise the order of Dominant Harmonics by increasing no. of pulses per Half cycle. If Dominant Harmonics belongs to Higher order, which can be easily filtered out, by using filters.

→ The RMS output Voltage is given by,

$$*/ \; V_{orms} = V_S \left[\sum_{m=1}^{N} \frac{P_m}{\pi} \right]^{1/2} /*$$

where P_m = width of m^{th} pulse.

In Sinusiodal PWM Inverter, Amplitude and freq of Triangular carrier and sine reference signals, are 5V, 1KHz and 1V, 50Hz.

(a) If zeroe's of Triangle carrier and Ref. Sine coincide, what is modulation index and order of Significant Harmonics.

(b) If peak of the Triangular carrier, coincides with zero of Reference, what is MI and order of significant harmonics.

Given, V_c = 5V ; 1KHz → Triangle wave

V_r = 1V ; 50Hz. → Square wave

(a) (1) $MI = \frac{V_r}{V_c} = \frac{1}{5} = 0.2$.

(2) $2N \pm 1$; No. of pulses (Half cycle $= \frac{f_c}{2f_r} - 1$

$= \frac{10^3}{2 \times 50} - 1 = 9$.

∴ $2N \pm 1$ = Dominant Harmonics

⇒ Dom. Harmonics = $2(9) \pm 1$

= 17 & 19.

(b) No. of pulses / Half cycle $= \frac{f_c}{2f_r} = \frac{10^3}{2 \times 50} = 10$.

∴ Dom. Harmonics = $2(10) \pm 1$

= 19, 21.

* In MPWM Inverters, the amplitude and freq of Triangle carrier and Square Ref. wave signals are 4V, 6KHz and 1V, 1KHz. find No. of pulses /Half cycle pulse width.

Sol:- $V_c = 4V ; 6KHz \rightarrow$ Triangle
$V_r = 1V ; 1KHz \rightarrow$ Square.

(1) $N = \frac{f_c}{2f_r} = \frac{6K}{2K} = \cancel{3KHz}\ 3.$

(2) pulse width $= \frac{2d}{N} = \frac{\pi}{N}\left[1 - \frac{V_r}{V_c}\right]$

$= \frac{\pi}{3}\left(1 - \frac{1}{4}\right) = 45^\circ.$

∴ pulse width $= 45^\circ$.

180° Mode

Inter.	Thyristor Conducts.	Line to phase Voltage			Line to Line V.		
		V_{ao}	V_{bo}	V_{co}.	V_{ab}	V_{bc}	V_{ca}.
I	T_1 T_5 T_6.	$V_s/3$	$-2V_s/3$	$V_s/3$	V_s	$-V_s$	0
II	T_1 T_2 T_6	$2V_s/3$	$-V_s/3$.	$-V_s/3$.	V_s	0	$-V_s$
III.	T_1 T_2 T_3.	$V_s/3$	$V_s/3$.	$-2V_s/3$.	0	V_s	$-V_s$
IV.	T_2 T_3 T_4.	$-V_s/3$.	$2V_s/3$	$-V_s/3$	$-V_s$	V_s	0
V	T_3 T_4 T_5.	$-2V_s/3$	$V_s/3$.	$V_s/3$	$-V_s$	0	V_s
VI.	T_4 T_5 T_6.	$-V_s/3$.	$-V_s/3$.	$2V_s/3$.	0.	$-V_s$	V_s

→ 120° Mode:-

Inter	T-Conducts.	V_{ao}	V_{bo}	V_{co}	V_{ab}	V_{bc}	V_{ca}.
I	T_1 T_6	$V_s/2$	$-V_s/2$	0	V_s	$-V_s/2$	$-V_s/2$
II	T_1 T_2	$V_s/2$	0	$-V_s/2$	$V_s/2$	$V_s/2$	$-V_s$
III	T_2 T_3	0	$V_s/2$.	$-V_s/2$	$-V_s/2$	V_s	$-V_s/2$
IV	T_3 T_4.	$-V_s/2$	$V_s/2$	0	$-V_s$	$V_s/2$	$V_s/2$
V	T_4 T_5	$-V_s/2$	0	$V_s/2$	$-V_s/2$	$-V_s/2$	V_s
VI.	T_5 T_6.	0	$-V_s/2$	$V_s/2$	$V_s/2$	$-V_s$	$V_s/2$

5. Ac-Ac Converters

14-09-18

Cyclo Converters.

→ Cyclo converter converts input power at one frequency to output power at different frequency. It is also known as one stage freq changer.

→ There are two types of cyclo converters.

(1) Step up cycloconverter.
(2) Step down cyclo converter.

→ **Step up cyclo converter:-**

→ In this converter output frequency is greater than supply frequency ($f_o > f_s$).

→ **Step down cycloconverter:-**

→ In step down cyclo converter, output freq is less than supply frequency ($f_o < f_s$).

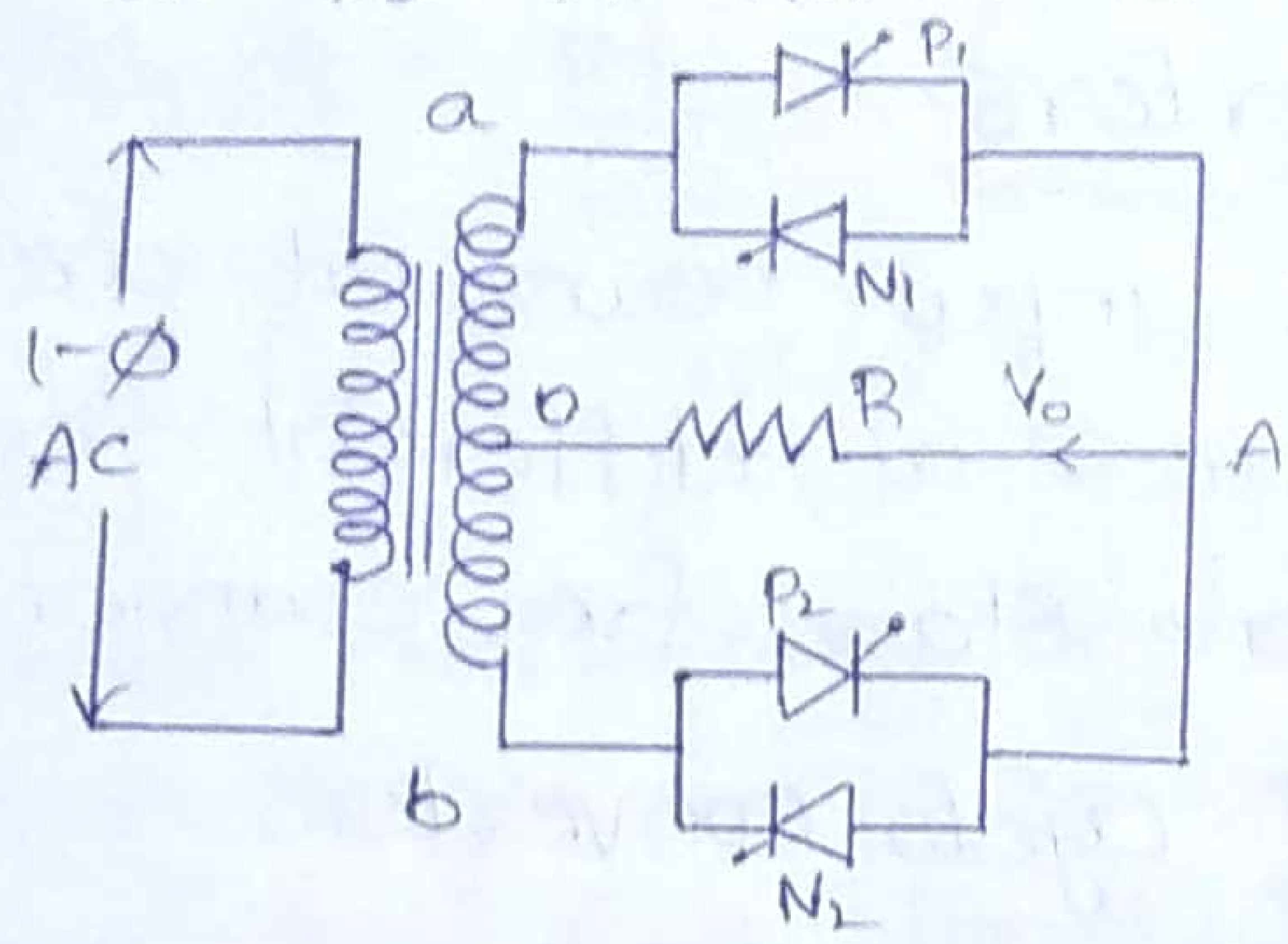
→ Step up cyclo converter uses forced commutation inorder to turn off the SCR's.

→ Step down cycloconverter uses Natural commutation which is provided by ac supply inorder to Turn off the SCR's.

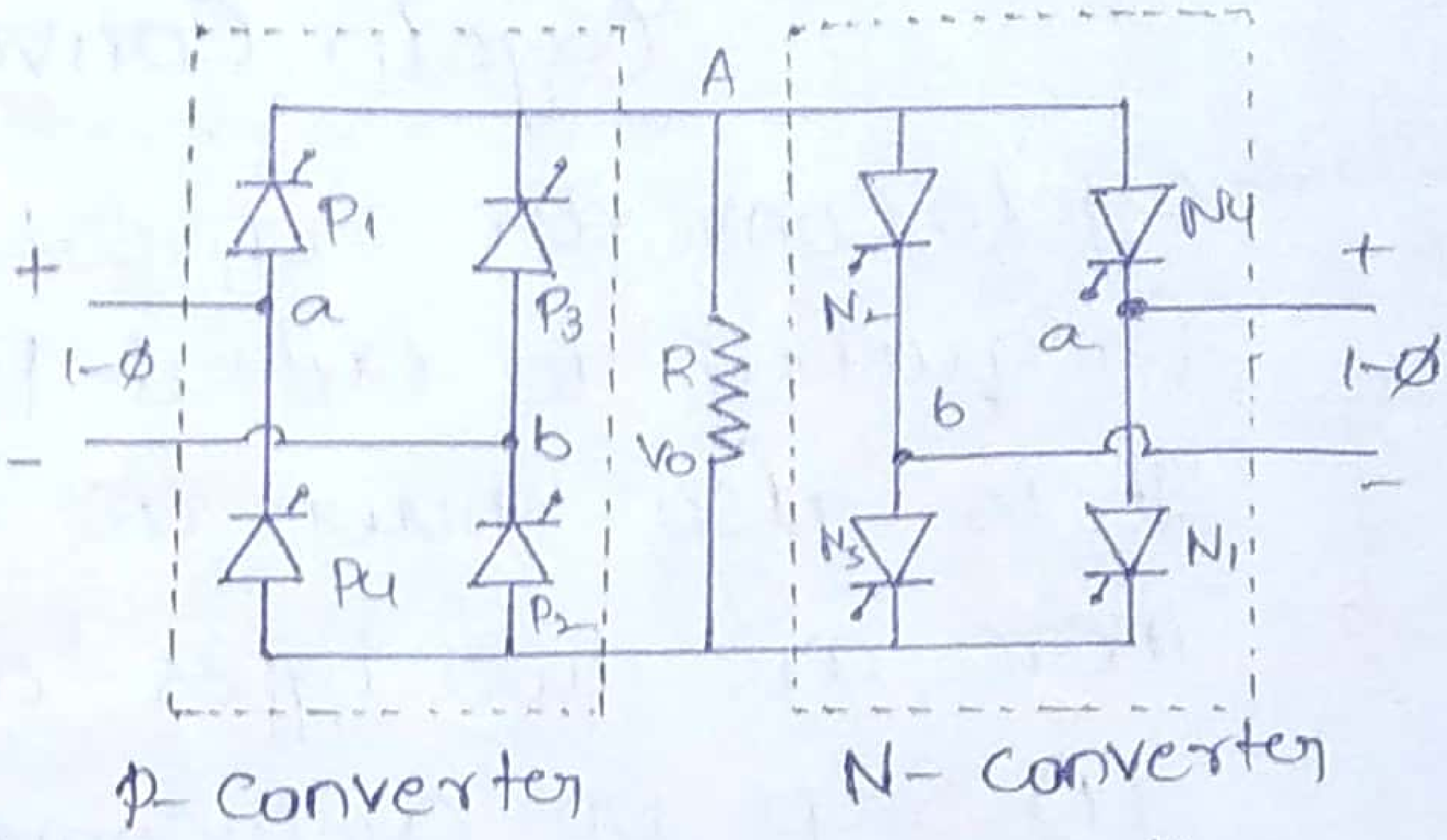
→ **Applications:-**

(1) Used in High power applications.
(2) Used in aircrafts.
(3) Used in Induction Heating.
(4) Used in Electric Traction.

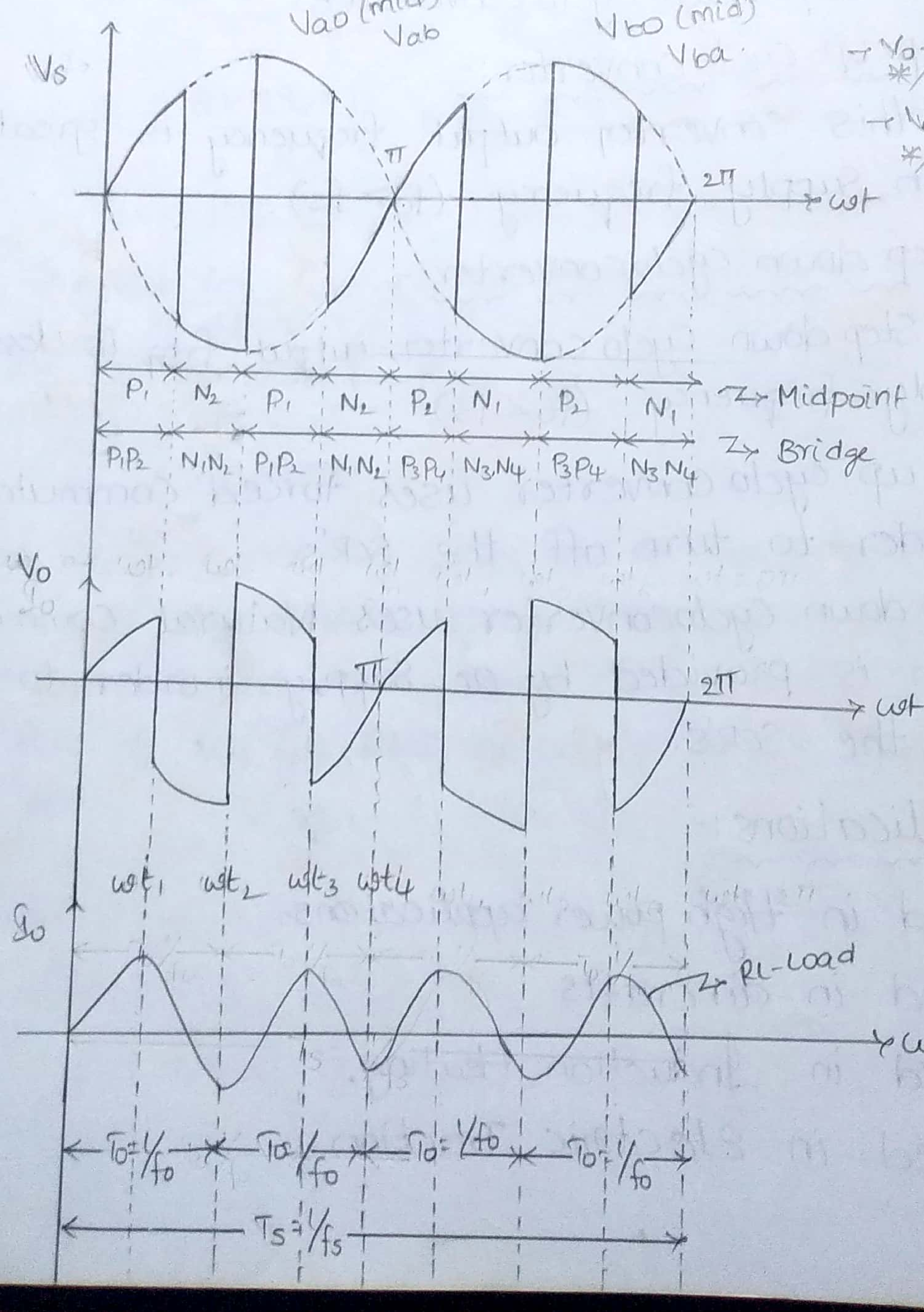
→ Step up converter with R-Load:-



Midpoint Configuration



Bridge Configuration.



→ $V_0 - V_{ao} = 0$
/ $V_a = V_{ao}$ /

→ $V_0 - V_{bo} = 0$
/ $V_a = V_{bo}$ /

→ **Operation:-**

Mid point configuration.

During +HC ($0 < \omega t < \pi$)

$P_1 N_2 \rightarrow fB$; $P_2 N_1 = R.B.$

At $\omega t = 0$; $P_1 = ON$; $V_0 = V_{ao}$; $i_0 = A \rightarrow 0$

ωt_1 ; $P_1 = OFF$ (forcely) $N_2 = ON$; $V_0 = V_{bo}$; $i_0 = 0 \rightarrow A$.

ωt_2 ; $N_2 = OFF$ (forcely) $P_1 = ON$; $V_0 = V_{ao}$; $i_0 = A \rightarrow 0$.

ωt_3 ; $P_1 = OFF$ (forcely) $N_2 = ON$; $V_0 = V_{bo}$; $i_0 = 0 \rightarrow A$.

$\omega t = \pi$; $V_S = 0$; $V_0 = 0$; $I_0 = 0$.

During -HC ($\pi < \omega t < 2\pi$):-

$P_2 N_1 \rightarrow fB$; $P_1 N_2 \rightarrow RB$.

At $\omega t = \pi$; $P_2 = ON$; $V_0 = V_{bo}$; $i_0 = A \rightarrow 0$

ωt_4 ; $P_2 = OFF$ (forcely), $N_1 = ON$; $V_0 = V_{ao}$; $i_0 = 0 \rightarrow A$.

ωt_5 ; $N_1 = OFF$ (Forcely), $P_2 = ON$; $V_0 = V_{bo}$; $i_0 = A \rightarrow 0$.

ωt_6 ; $P_2 = OFF$ (forcely), $N_1 = ON$; $V_0 = V_{ao}$; $i_0 = 0 \rightarrow A$.

$\omega t = 2\pi$; $V_S = 0$; $V_0 = 0$; $i_0 = 0$.

→ **Bridge Configuration:-**

During +HC:-

$P_1 P_2 N_1 N_2 = FB$; $P_3 P_4 N_3 N_4 = RB$.

At $\omega t = 0$; $P_1 P_2 = ON$; $V_0 = V_{ab}$; $i_0 = A \rightarrow 0$.

ωt_1 ; $P_1 P_2 = OFF$ (forcely),
$N_1 N_2 = ON$; $V_0 = V_{ba}$; $i_0 = 0 \rightarrow A$.

ωt_2 ; $N_1 N_2 = OFF$ (Forcely), $P_1 P_2 = ON$, $V_0 = V_{ab}$, $i_0 = A \rightarrow 0$

ωt_3 ; $P_1 P_2 = OFF$ (forcely), $N_1 N_2 = ON$; $V_0 = V_{ba}$; $i_0 = 0 \rightarrow A$

$\omega t = \pi$; $V_S = 0$; $V_0 = 0$; $I_0 = 0$.

→ During -HC:-

$P_3P_4N_3N_4$ = FB ; $P_1P_2N_1N_2$ = RB.

At $\omega t = \pi$; P_3P_4 = ON ; $V_0 = V_{ba}$; $i_0 = A \to 0$

ωt_4 ; P_3P_4 = OFF (forcely) ; N_3N_4 = ON ;

$V_0 = V_{ab}$; $i_0 = 0 \to A$.

ωt_5 ; N_3N_4 = OFF (forcely), P_3P_4 = ON ; $V_0 = V_{ba}$

$i_0 = A \to 0$.

ωt_6 ; P_3P_4 = OFF (forcely), N_3N_4 = ON ; $V_0 = V_{ab}$; $i_0 = 0 \to A$

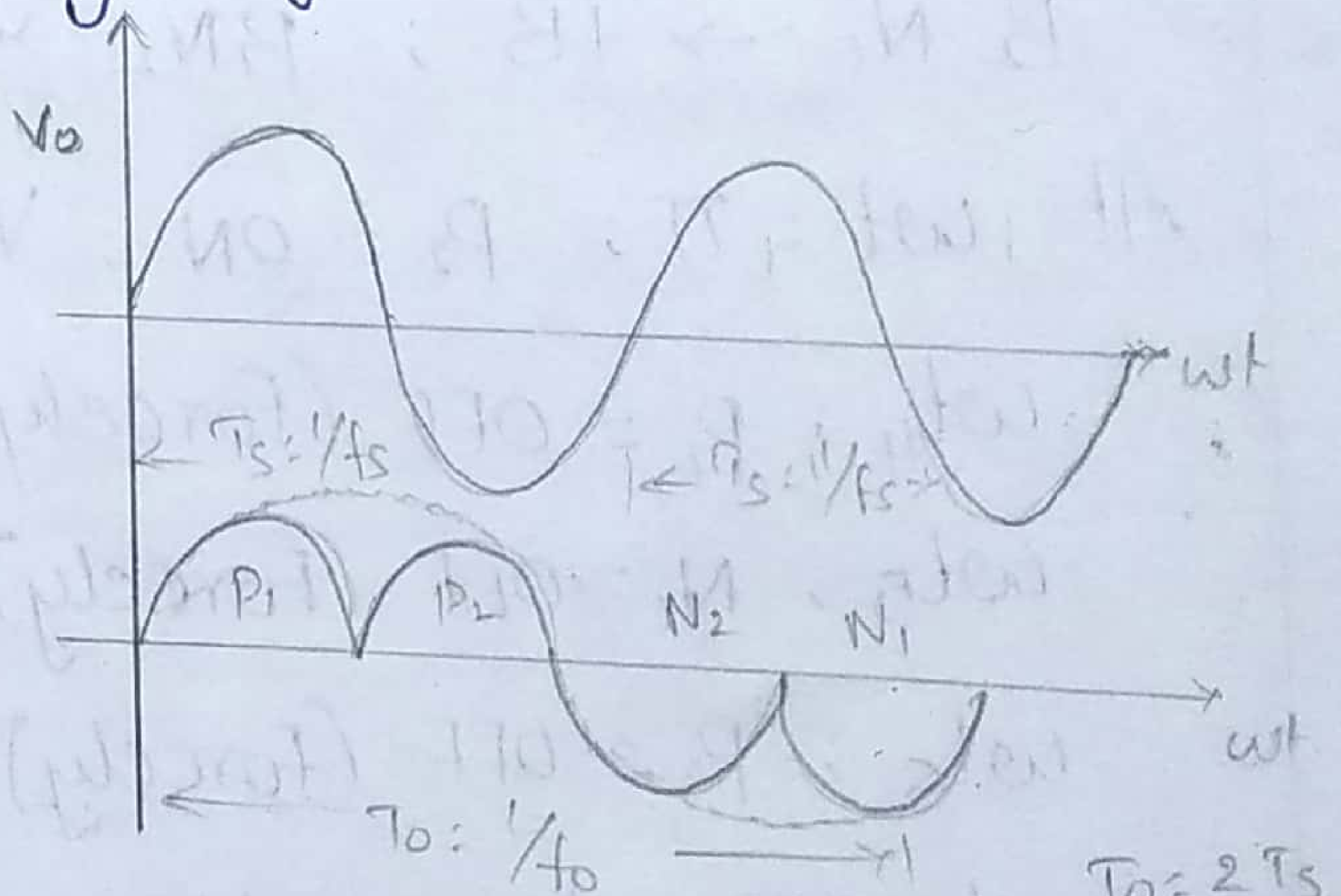
$\omega t = 2\pi$; $V_S = 0$; $i_0 = 0$; $V_0 = 0$.

→ In one complete supply cycle, output has four supply cycles. then

$T_S = 4T_0$.

$1/f_s = 4/f_0$

$f_0 = 4 \cdot f_s$



$T_0 = 2T_s$

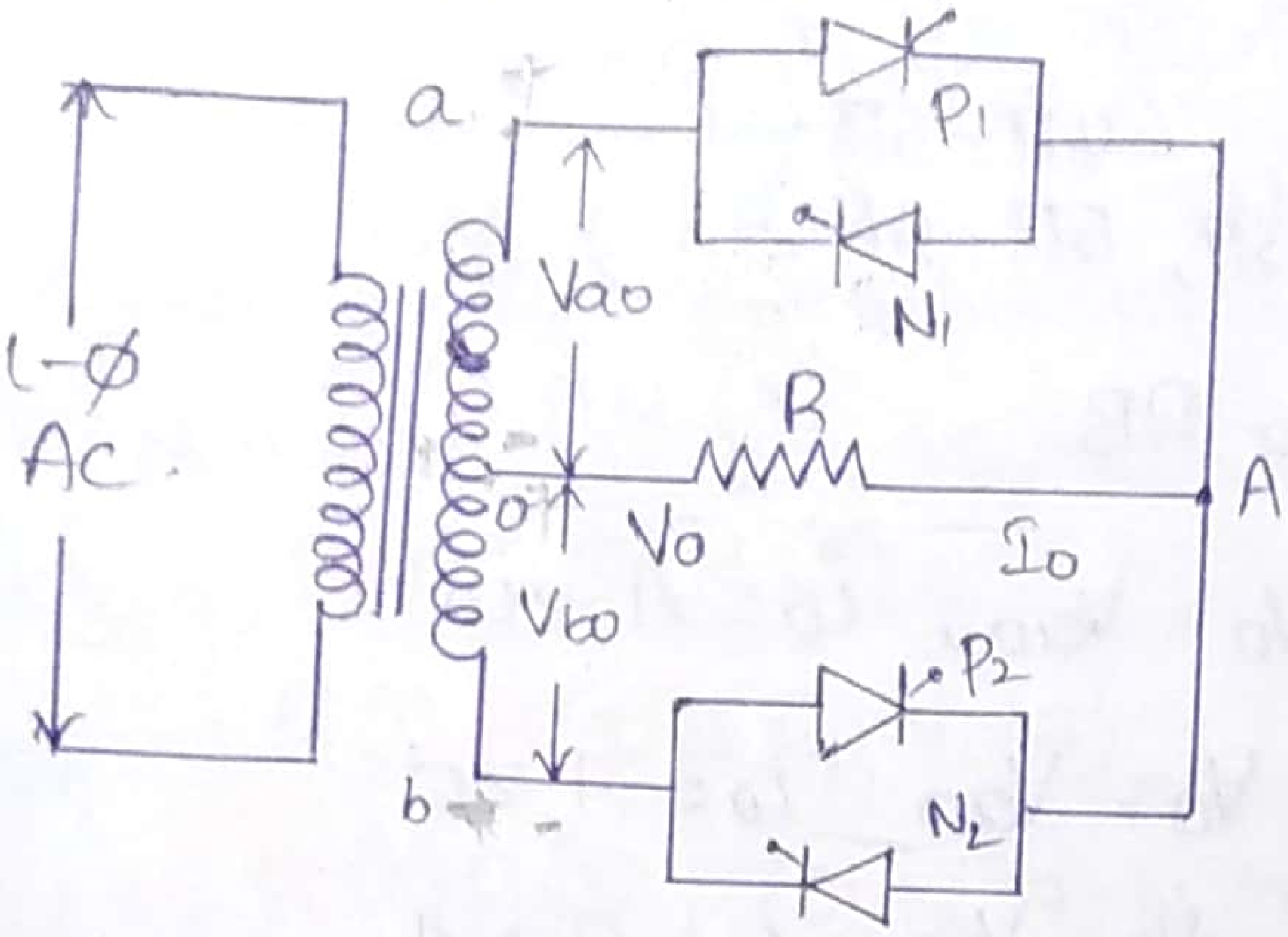
$f_0 : \frac{f_s}{2}$

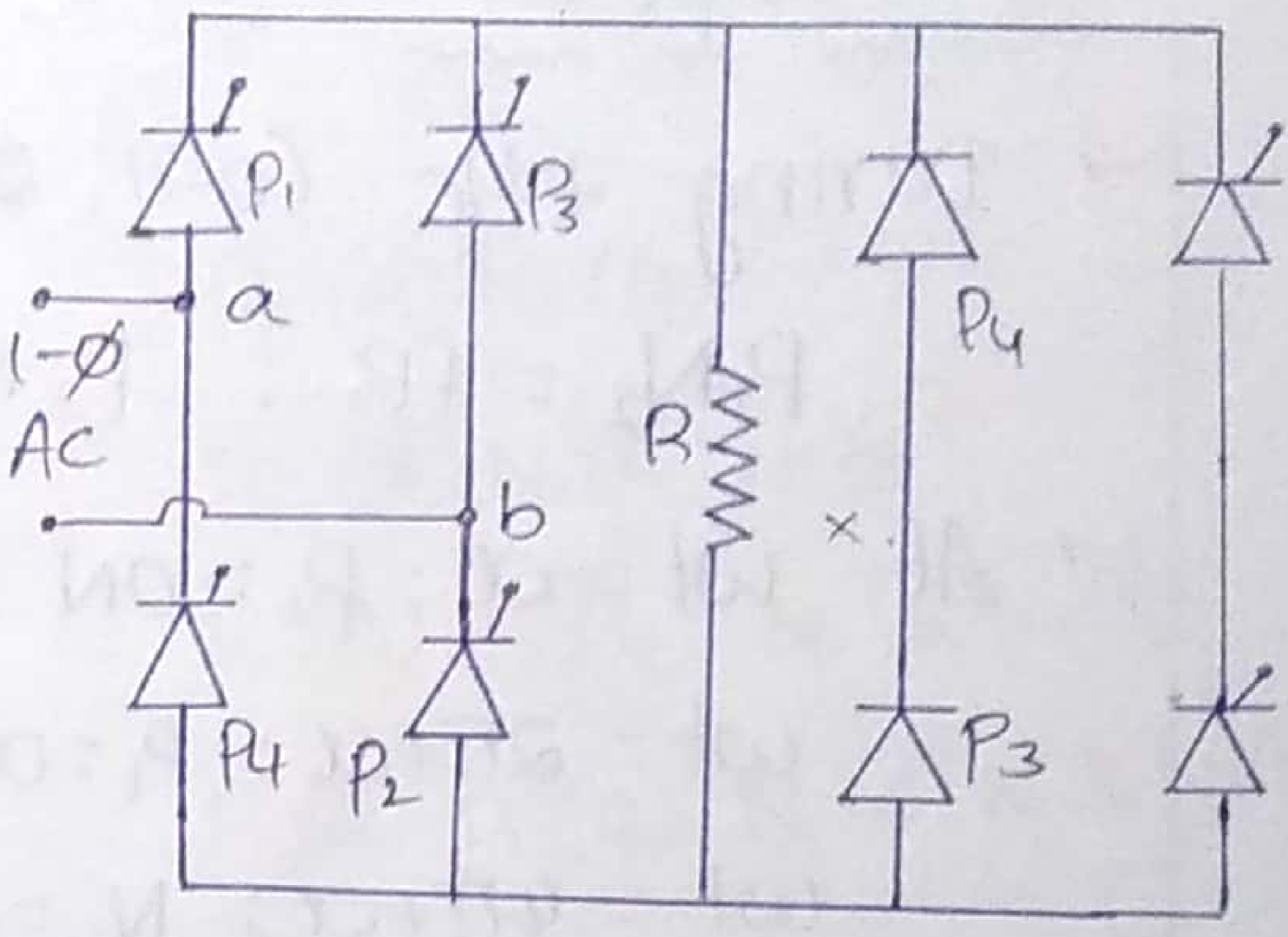
→ Conclusion:-

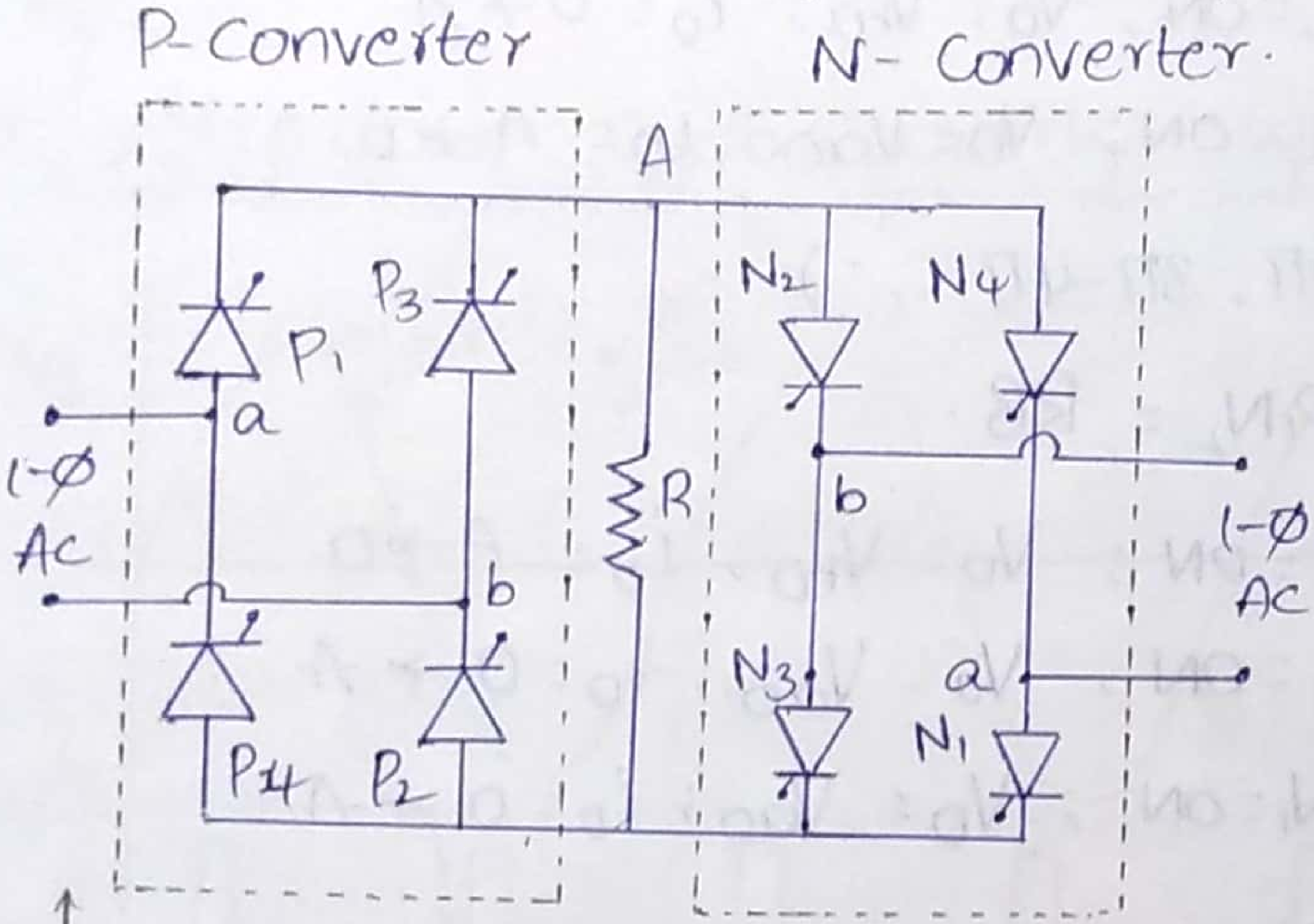
	During +HC	During -HC
→ $f_0 = 2f_s$;	P_1N_2	P_2N_1.
→ $f_0 = 3f_s$;	$P_1N_2P_1$	$P_2N_1P_2N_1$.
→ $f_0 = 4f_s$;	$P_1N_2P_1N_2$	$P_2N_1P_2N_1$
→ $f_0 = 5f_s$;	$P_1N_2P_1N_2P_1$	$N_1P_2N_1P_2N_1$
→ $f_0 = 6f_s$;	$P_1N_2P_1N_2P_1N_2$	$P_2N_1P_2N_1P_2N_1$.

→ For R-Load; V_0 I_0 - Same.

Step Down Cyclo converter :-







$V_0 - V_{a0} = 0$

$\Rightarrow V_0 = V_{a0}$

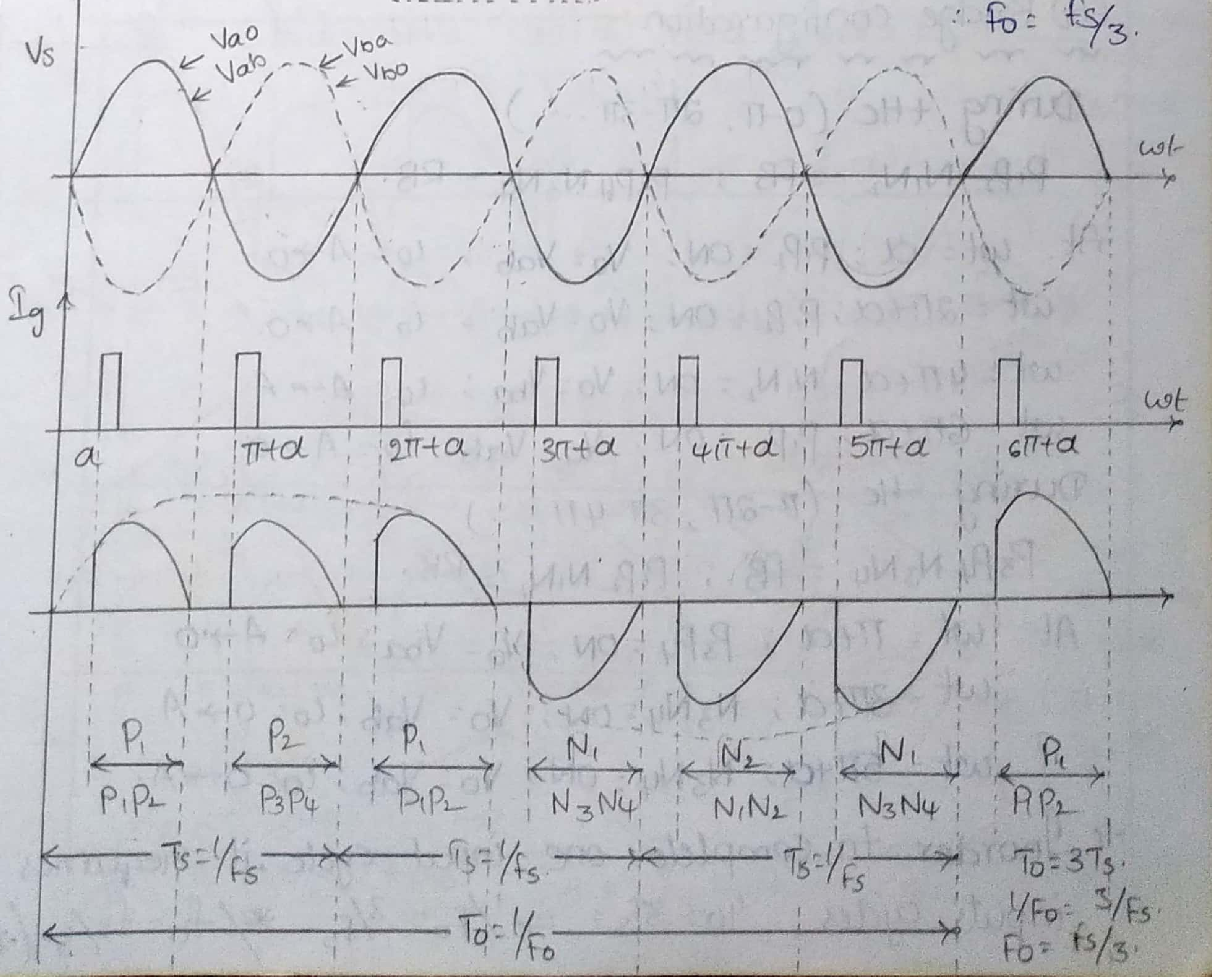
$V_0 - V_{b0} = 0$

$\Rightarrow V_0 = V_{b0}$

$T_0 = 3T_s$

$1/f_0 = 3/f_s$

$\therefore f_0 = f_s/3.$



→ Operation:-

(a) Midpoint:-

→ During +HC $(0-\pi, 2\pi-3\pi, \overset{4\pi-5\pi}{5\pi-6\pi} \ldots\ldots)$

$P_1N_2 = FB \; ; \; P_2N_1 = RB$

→ At $\omega t = \alpha ; P_1 = ON ; V_0 = V_{ao} ; i_0 = A \to 0.$

$\omega t = 2\pi+\alpha ; P_1 = ON ; V_0 = V_{ao} ; i_0 = A \to 0$

$\omega t = 4\pi+\alpha ; N_2 = ON ; V_0 = V_{bo} ; i_0 = 0 \to A$

$\omega t = 6\pi+\alpha ; P_1 = ON ; V_0 = V_{ao} ; i_0 = A \to 0.$

→ During −HC $(\pi-2\pi, 3\pi-4\pi \ldots)$

$P_2N_1 = FB \; ; \; P_1N_2 = RB.$

At $\omega t = \pi+\alpha ; P_2 = ON ; V_0 = V_{bo} ; i_0 = A \to 0.$

$\omega t = 3\pi+\alpha ; N_1 = ON ; V_0 = V_{ao} ; i_0 = 0 \to A$

$\omega t = 5\pi+\alpha ; N_1 = ON ; V_0 = V_{ao} ; i_0 = 0 \to A$

(b) Bridge configuration:-

During +HC $(0-\pi, 2\pi-3\pi \ldots)$

$P_1P_2 N_1N_2 = FB \; ; \; P_3P_4N_3N_4 = RB.$

At. $\omega t = \alpha ; P_1P_2 = ON ; V_0 = V_{ab} ; i_0 = A \to 0.$

$\omega t = 2\pi+\alpha ; P_1P_2 = ON ; V_0 = V_{ab} ; i_0 = A \to 0.$

$\omega t = 4\pi+\alpha ; N_1N_2 = ON ; V_0 = V_{ba} ; i_0 = A \to A$

$\omega t = 6\pi+\alpha ; P_1P_2 = ON ; V_0 = V_{ab} ; i_0 = A \to 0.$

During −HC $(\pi-2\pi, 3\pi-4\pi \ldots)$

$P_3P_4N_3N_4 = FB \; ; \; P_1P_2 N_1N_2 = RB.$

At $\omega t = \pi+\alpha ; P_3P_4 = ON ; V_0 = V_{ba} ; i_0 = A \to 0$

$\omega t = 3\pi+\alpha ; N_3N_4 = ON ; V_0 = V_{ab} ; i_0 = 0 \to A.$

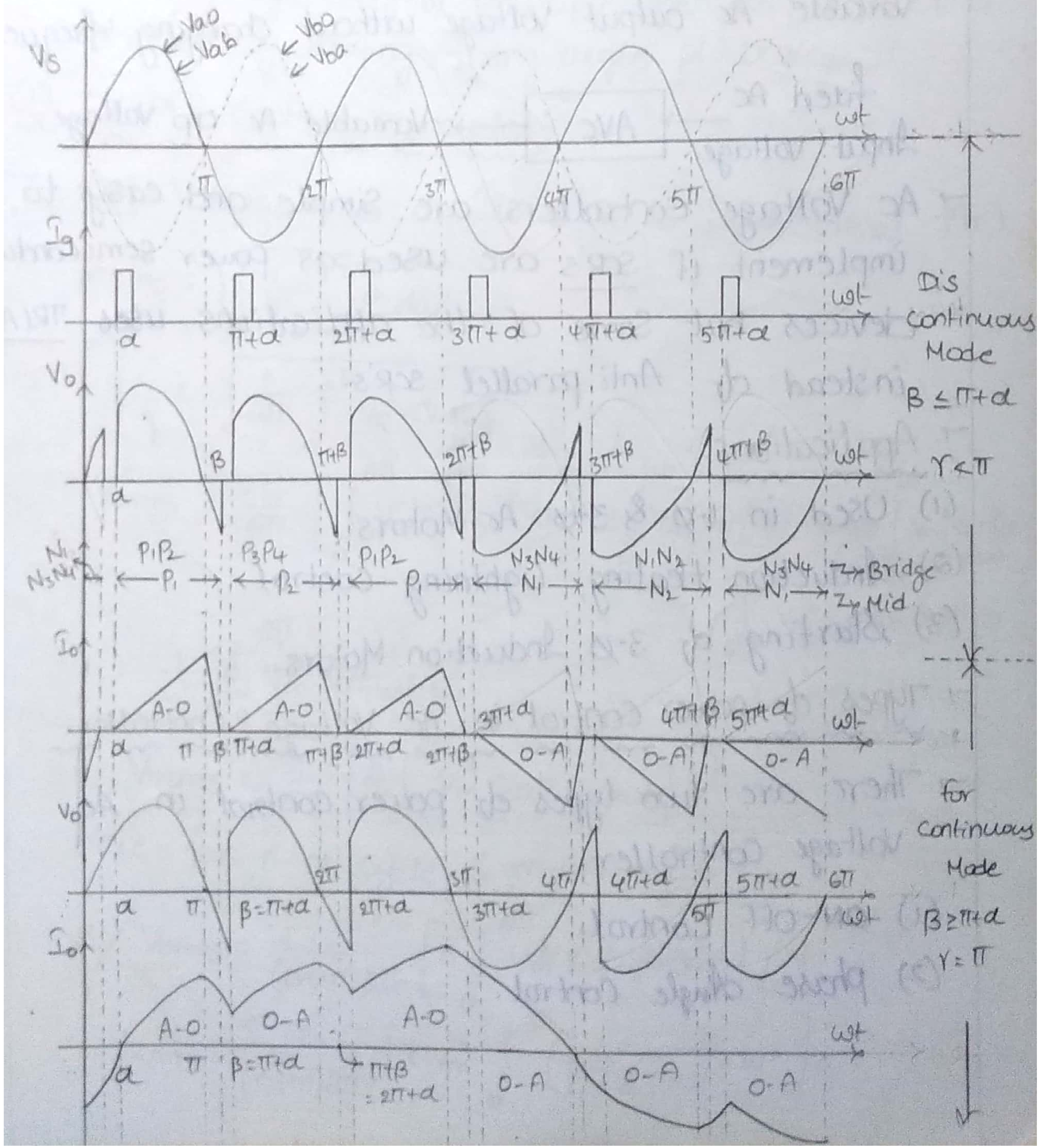
$\omega t = 5\pi+\alpha ; N_3N_4 = ON ; V_0 = V_{ab} ; i_0 = 0 \to A.$

→ Inorder to complete one input cycle, it requires three inputs cycles, $T_0 = 3T_s$; $\Rightarrow 1/F_0 = 3/F_s$ */ $f_0 = f_s/3$. /*

→ Conclusion:-

	During +HC	During -HC
	P_1N_2 = FB	P_2N_1 = FB.
$f_o = f_s/2$	$P_1(1)\ P N_2(3)$	$P_2(2)\ N_1(4)$
$f_s/3$	$P_1(1)\ P_1(3)\ N_2(5)$	$P_2(2)\ N_1(4)\ N_1(6)$
$f_s/4$	$P_1(1)\ P_1(3)\ N_2(5)\ N_2(7)$	$P_2(2)\ P_2(4)\ N_1(6)\ N_1(8)$
$f_s/5$	$P_1(1)\ P_1(3)\ P_1(5)\ N_2(7)\ N_2(9)$	$P_2(2)\ P_2(4)\ N_1(6)\ N_1(8)\ N_1(10)$

→ Step down cyclo converter with RL - load:-



→ Ac Voltage Controllers:-

→ Most of the loads such as lights, fans, Blowers, Induction Motors etc.., are Variable loads which requires Variable Ac Supply, this Variable Ac is provided by Ac Voltage controllers i.e., Ac Voltage controllers used to drive Variable loads.

→ Voltage controller:-

→ Ac Voltage Controller Converts fixed Ac Input V to Variable Ac output Voltage without changing frequency.

→ Ac Voltage Controllers are simple and easy to implement if SCR's are used as power semiConductor devices, but Some of the applications uses TRIAC instead of Anti parallel SCR's.

→ Applications:-

(1) Used in 1-ϕ & 3-ϕ Ac Motors
(2) Induction Heating, Lightning control.
(3) Starting of 3-ϕ Induction Motors.

→ Types of power Control in Ac Voltage Controller:-

→ There are two types of power control in Ac Voltage Controller:-

(1) ON-OFF Control.
(2) phase Angle control.

→ **ON-OFF Control:-**

→ In ON-OFF Control principle, Thyristor is fully ON for few cycles (n) and Thyristor is fully OFF for few cycles (m). Here no. of ON & OFF cycles are such that they transfer require power to the load i.e., in ON-OFF Control principle o/p Power is controlled by Controlling no of ON and OFF cycles.

→ **Phase-Angle Method:-**

In phase Angle control principle the output power is controlled by Varying firing angle of Device.

(1) ON-OFF Control principle:-

→ Avg. Voltage ⇒ $V_o = 0$. (Since V_o is Symmetrical ~~to~~).

→ $$V_{orms} = \sqrt{\frac{1}{T}\int_0^T V_o^2 . d\omega t}$$

$$= \sqrt{\frac{1}{6\pi}\int_0^{\pi} V_o^2 . d\omega t}$$

$$\Rightarrow V_{orms}^2 = \frac{1}{6\pi}\left[\int_0^{2\pi} V_m^2 \sin^2\omega t . d\omega t + \int_{2\pi}^{4\pi} V_m^2 \sin^2\omega t . d\omega t + \int_{4\pi}^{6\pi} V_m^2 \sin^2\omega t \, d\omega t\right]$$

$$\int_{4\pi}^{6\pi} V_m^2 \sin^2\omega t \, d\omega t = 0$$

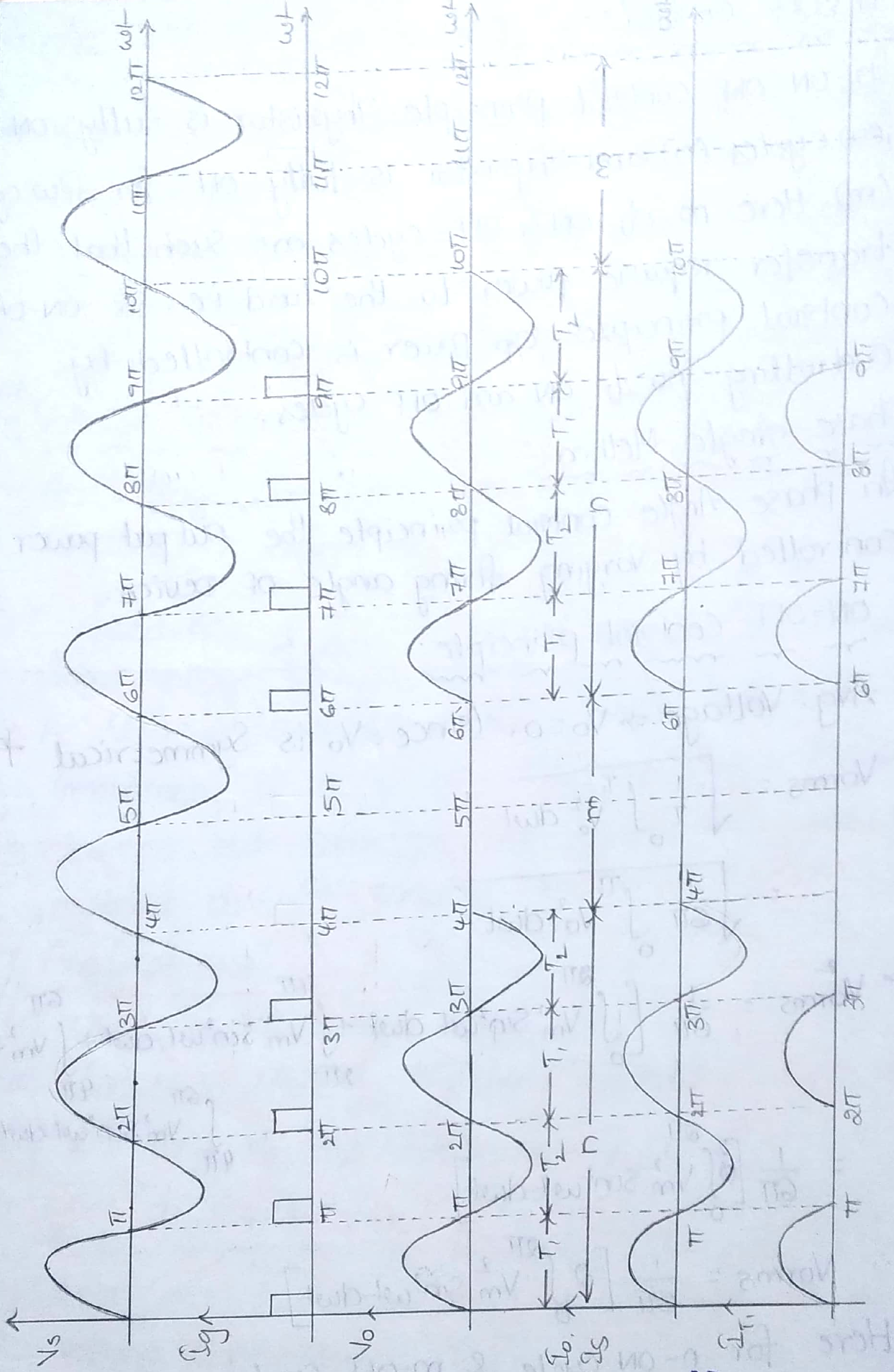
$$= \frac{1}{6\pi}\left[\overset{2}{\phi}\int_0^{2\pi} V_m^2 \sin^2\omega t . d\omega t\right]$$

$$\therefore V_{orms} = \frac{1}{6\pi}\left[2\int_0^{2\pi} V_m^2 \sin^2\omega t \, d\omega t\right]$$

Here for n-ON cycle & m-OFF cycle.

$$*/\ V_{orms} = \frac{1}{(n+m)2\pi}\left[n\int_0^{2\pi} V_m^2 \sin^2\omega t \, d\omega t\right] /*$$

$$V_{orms} = \frac{1}{(n+m)2\pi}\left[nV_m^2 \int_0^{2\pi}\left(\frac{1-\cos 2\omega t}{2}\right). d\omega t\right]$$



$$\Rightarrow V_{orms} = \frac{1}{(n+m)2\pi}\left[\frac{nV_m^2}{2}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_0^{2\pi}\right]$$

$$= \frac{1}{(n+m)2\pi}\left[\frac{nV_m^2}{2}\left(2\pi - \frac{\sin 2\pi}{2} - (0-0)\right)\right]$$

$$\Rightarrow V_{orms}^2 = \frac{nV_m^2}{(n+m)4\pi}(2\pi-0)$$

$$\Rightarrow V_{orms} = \frac{V_m^2}{2}\cdot\frac{n}{n+m}$$

$$\therefore V_{orms} = \frac{V_m}{\sqrt{2}}\cdot\sqrt{\frac{n}{n+m}} = V_s\sqrt{K}.$$

where, $V_s = \frac{V_m}{\sqrt{2}}$; $K = \frac{n}{n+m}$ = Duty cycle for ON-OFF control principle

/ $V_{orms} = V_s\cdot\sqrt{K}$. /

(3) $I_{orms} = \frac{V_{orms}}{R}$.

(4) power delivered to load (P_{ac}) = $V_{orms}\cdot I_{orms}$

$= I_{orms}^2\cdot R$.

(5) Source current, $I_s = I_{orms}$ ($I_s = I_o$).

(6) Input VA = $V_s I_s = V_s I_{orms}$.

(7) Input pf = $\frac{\text{Power delivered to load}}{\text{I/p VA}}$

$= \frac{V_{orms}\cdot I_{orms}}{V_s\cdot I_{orms}}$

/ Input pf = $\frac{V_{orms}}{V_s}$ /

(8) Avg. Thyristor current (I_{TA}):-

$$I_{TA} = \frac{1}{6\pi}\int_0^{6\pi} I_T\,d\omega t$$

$$= \frac{1}{6\pi}\left[\int_0^{\pi} I_m\cdot\sin\omega t\cdot d\omega t + \int_{2\pi}^{3\pi} I_m\sin\omega t\,d\omega t\right]$$

$$: \frac{1}{6\pi}\left[\int_0^{\pi} I_m\sin\omega t\cdot d\omega t + \int_0^{\pi} I_m\sin\omega t\,d\omega t\right]$$

$$\therefore I_{TA} = \frac{1}{6\pi}\left[2\int_0^{\pi} I_m \sin\omega t \, d\omega t\right]$$

for n-ON cycle & m-off cycles.

$$\Rightarrow I_{TA} = \frac{1}{(n+m)2\pi}\left[n\int_0^{\pi} I_m \cdot \sin\omega t \, d\omega t\right]$$

$$= \frac{nI_m}{(n+m)2\pi}\left(-\cos\omega t\right)_0^{\pi}$$

$$= \frac{nI_m}{(n+m)2\pi}\left(-\cos\pi + \cos 0\right)$$

$$= \frac{nI_m}{(n+m)2\pi}(2) = \left[\frac{n}{(n+m)}\right]\cdot\frac{I_m}{\pi} = \frac{I_m}{\pi}K.$$

$$*/ \; I_{TA} = \frac{I_m}{\pi}K. /* \quad ; \; I_{TR} = \frac{I_m}{\sqrt{2}} \frac{I_m}{2} \times \sqrt{K}.$$

→ Advantages:-

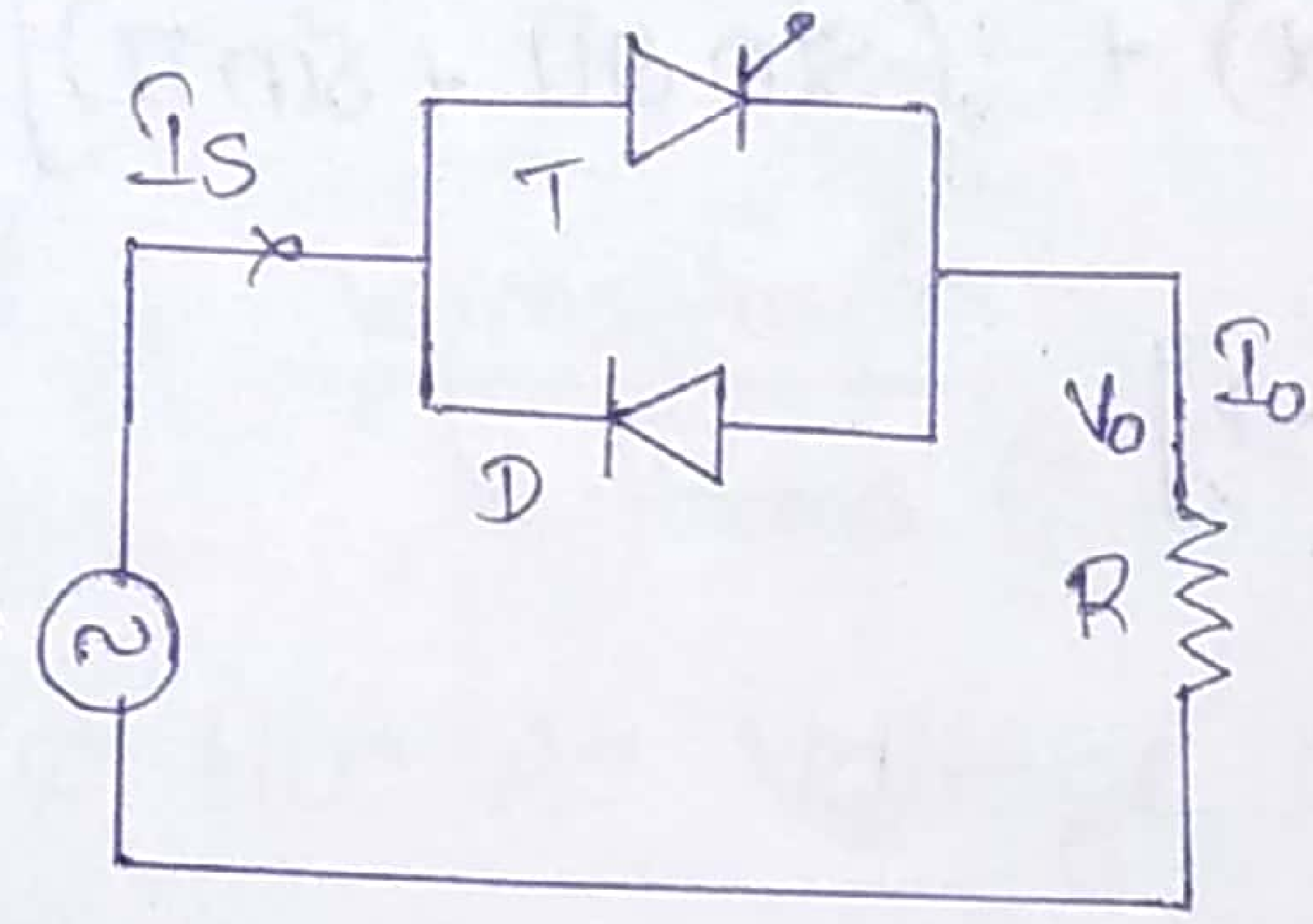
→ During Zero Voltage & Zero current switching of T's Harmonics generated during the switching action are reduced.

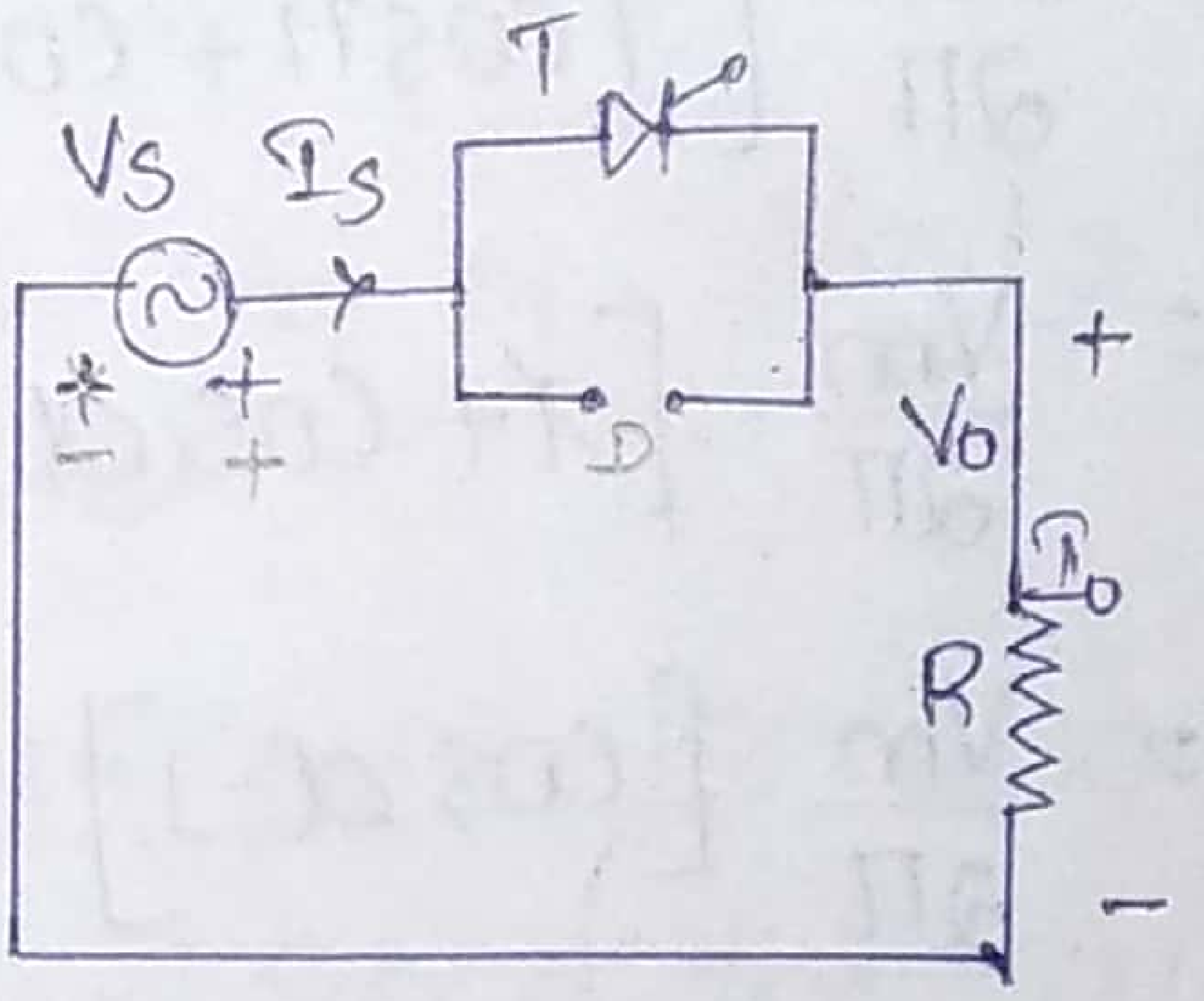
→ Disadvantage:-

→ During ON period full Supply Voltage will appear across load and during off period no voltage appear across the load Hence load is not Continuou
Therefore Load has to Sustain these Variations.

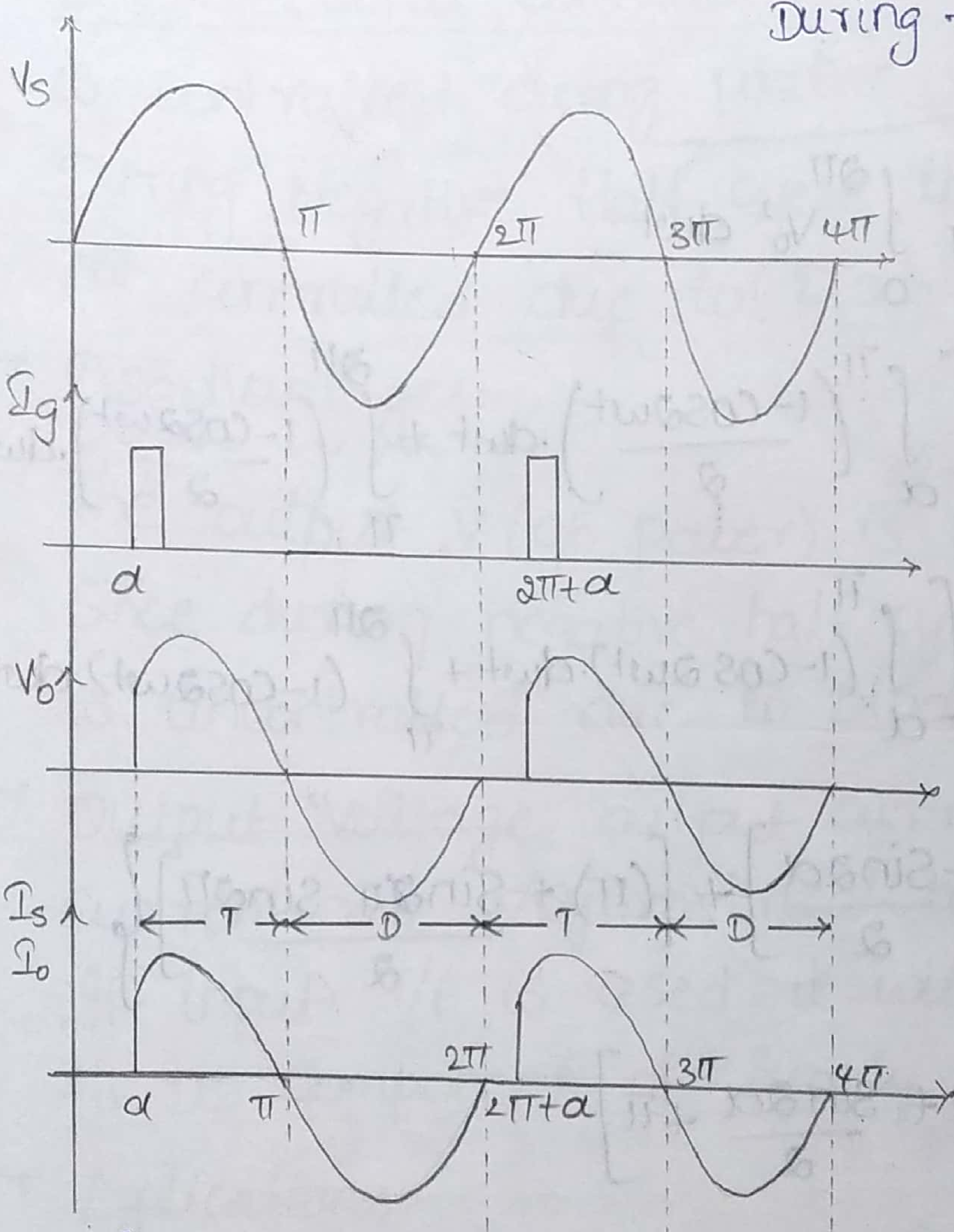
→ Phase Angle Method:- (or) Uni-Directional ctrl

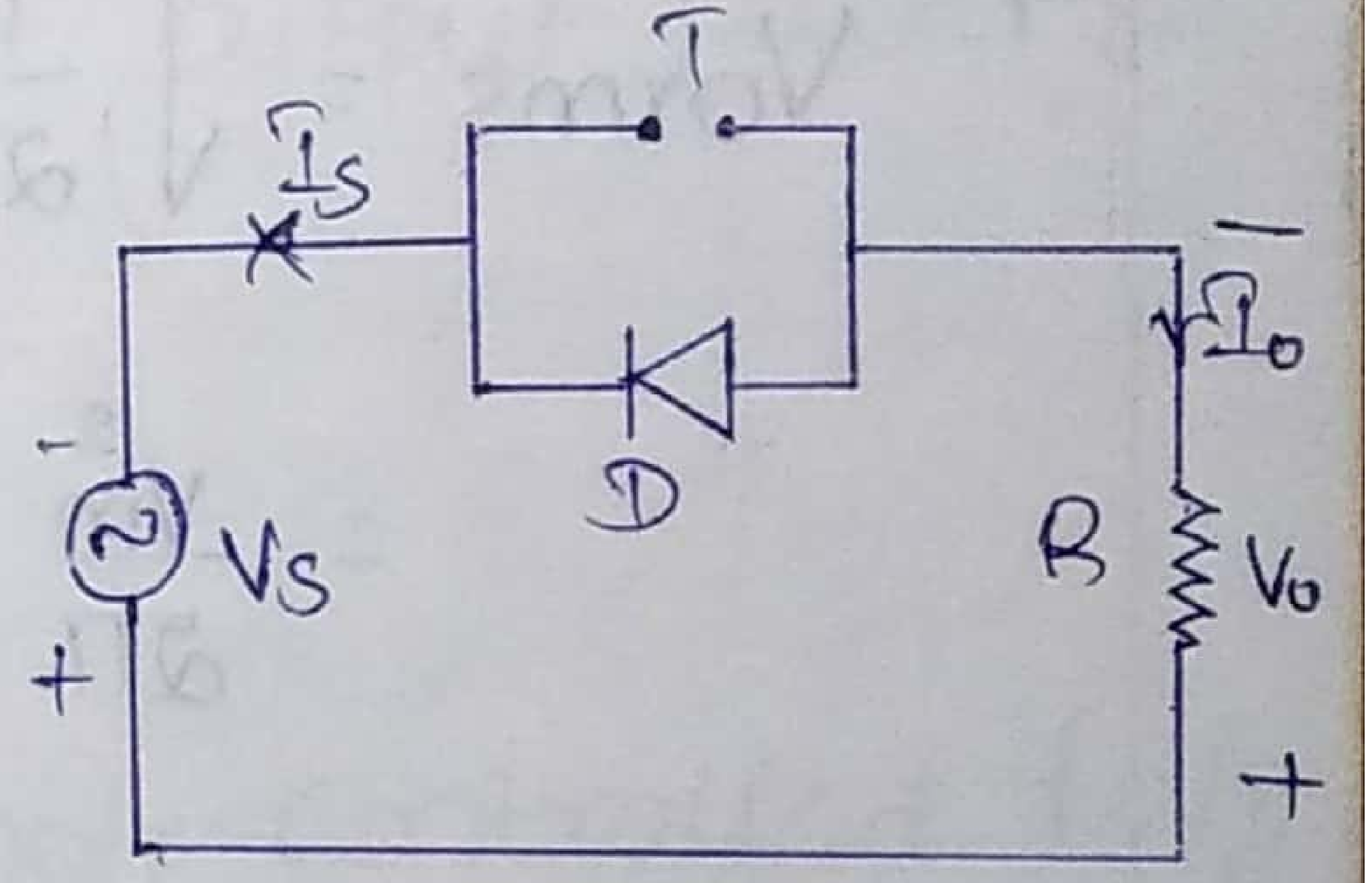
→ 1-ϕ HW AC Voltage Controller with R-load:-





During +HC :- $V_o = V_s$.





During -HC:-

$V_o = +V_s$

$(-V_s + V_o = 0$

$\Rightarrow V_o = V_s)$.

→ Symmetric wave form is both +ve cycle & -ve cycle has Same Magnitude.

→ Avg. Voltage Can be calculated only for Asymmetric since in Symmetric +V & -V both cancel.

(1) $V_o = \frac{1}{2\pi} \int_0^{2\pi} V_o \cdot d\omega t$.

$$\Rightarrow V_o = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m \sin\omega t \cdot d\omega t + \int_{\pi}^{2\pi} V_m \sin\omega t \cdot d\omega t\right]$$

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

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

$$\therefore V_o = \frac{V_m}{2\pi}\left[\cos\alpha - 1\right]$$

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

$$V_{orms} = \sqrt{\frac{1}{2\pi}\int_{0}^{2\pi} V_o^2 \cdot d\omega t}$$

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

$$= \frac{V_m^2}{4\pi}\left[\int_{\alpha}^{\pi}(1-\cos 2\omega t)\cdot d\omega t + \int_{\pi}^{2\pi}(1-\cos 2\omega t)\cdot d\omega t\right]$$

$$= \frac{V_m^2}{4\pi}\left\{\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right] + \left[(\pi) + \frac{\sin 4\pi - \sin 2\pi}{2}\right]\right\}$$

$$= \frac{V_m^2}{4\pi}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2} + \pi\right]$$

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

$$\therefore V_{orms} = V_m\left[\frac{2\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2}$$

$$\therefore I_{orms} = \frac{V_{orms}}{R}.$$

- $P_{dc} = V_{orms} \cdot I_{orms} = I_{orms}^2 \cdot R = \frac{V_{orms}^2}{R}$, (power delivered to load).

- Input VA Rating $= V_s I_s$
  $= V_s \cdot I_{orms}$. $(I_s = I_{orms})$.

- $Pf = \frac{V_{orms} \cdot I_{orms}}{V_s \cdot I_{orms} \; (\because I_s = I_{orms})} \Rightarrow pf = \frac{V_{orms}}{V_s}$.

- 1-ø HW Ac Voltage controller is also known as <u>uniDirectional controller</u>. Since the output power is controlled during positive Half cycle only. During Negative Half cycle the output power is not controlled due to Diode.

- Disadvantages:-

- The output V (o/p Power) is not controlled fully Since during negative half cycle the o/p-V (op-P) is uncontrolled due to Diode.

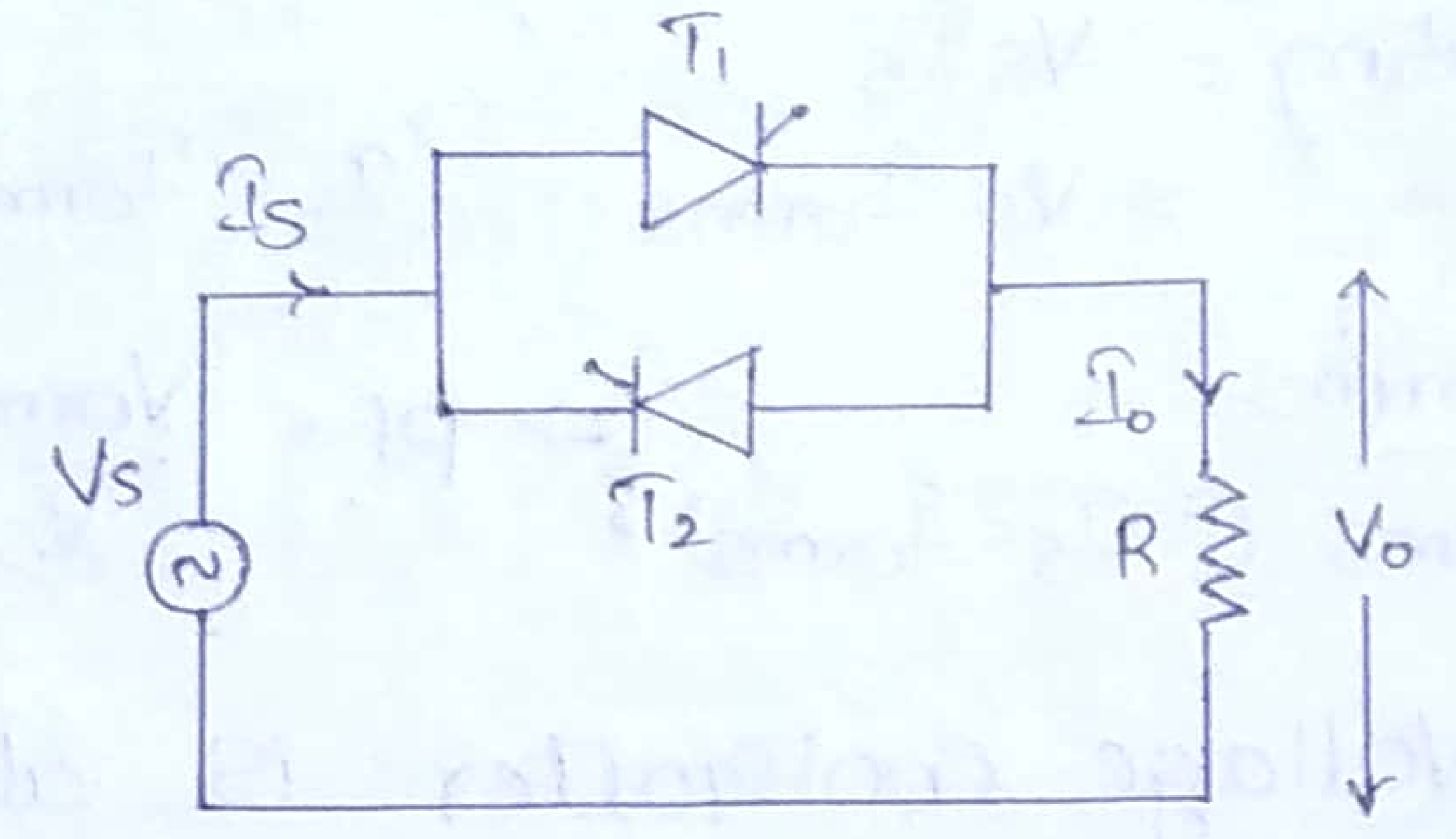
- Output Voltage, output current and Source current are Asymmetrical and have Dc Component If input T/f is used, it will be Saturated due to Dc Component of Supply

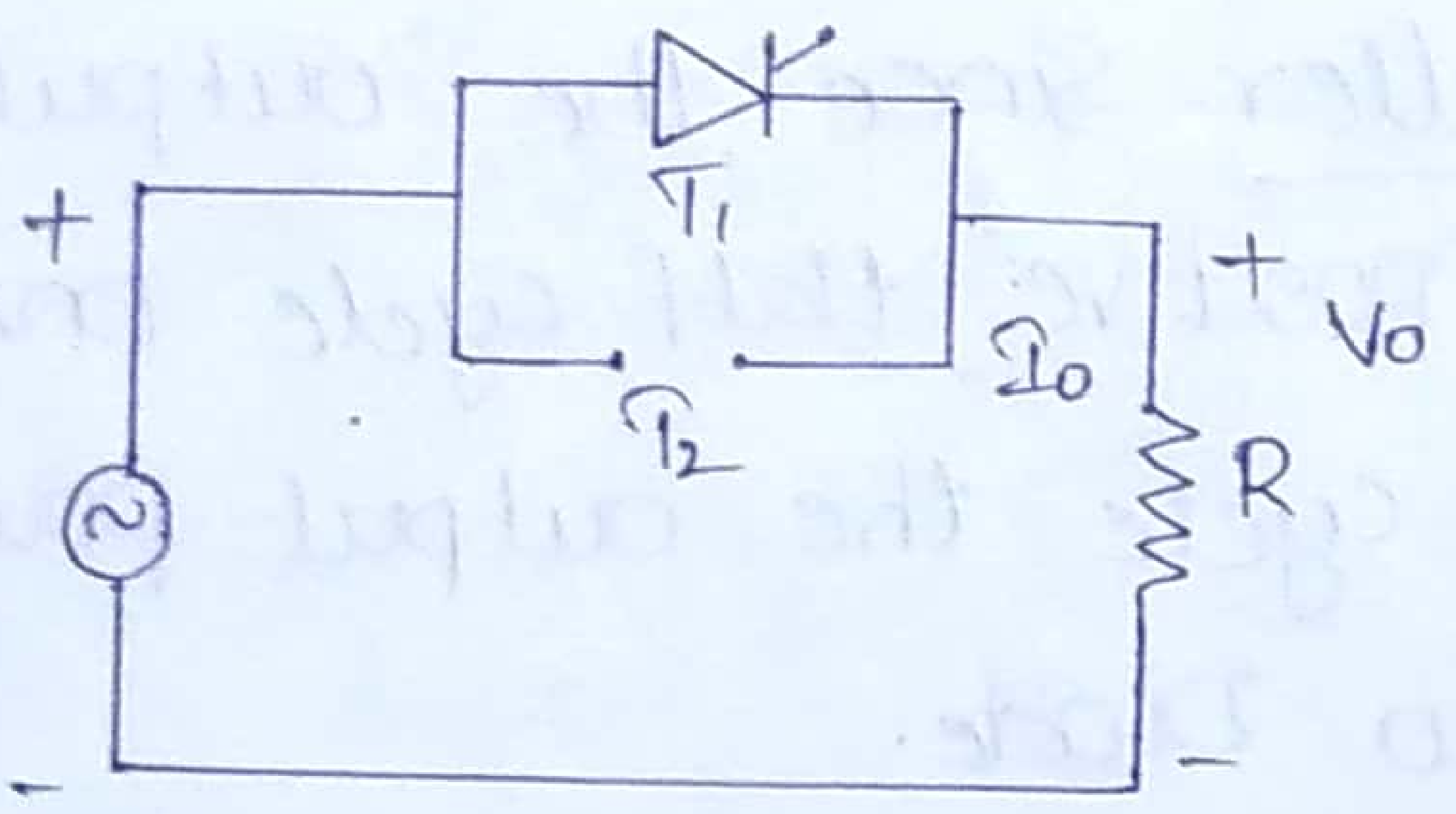
- Applications:-

- Used for low power Resistive loads Such as Heating & Lightning control.

- The Drawbacks of uniDirectional Controller can be overcome by using 1-ø fwAcVc

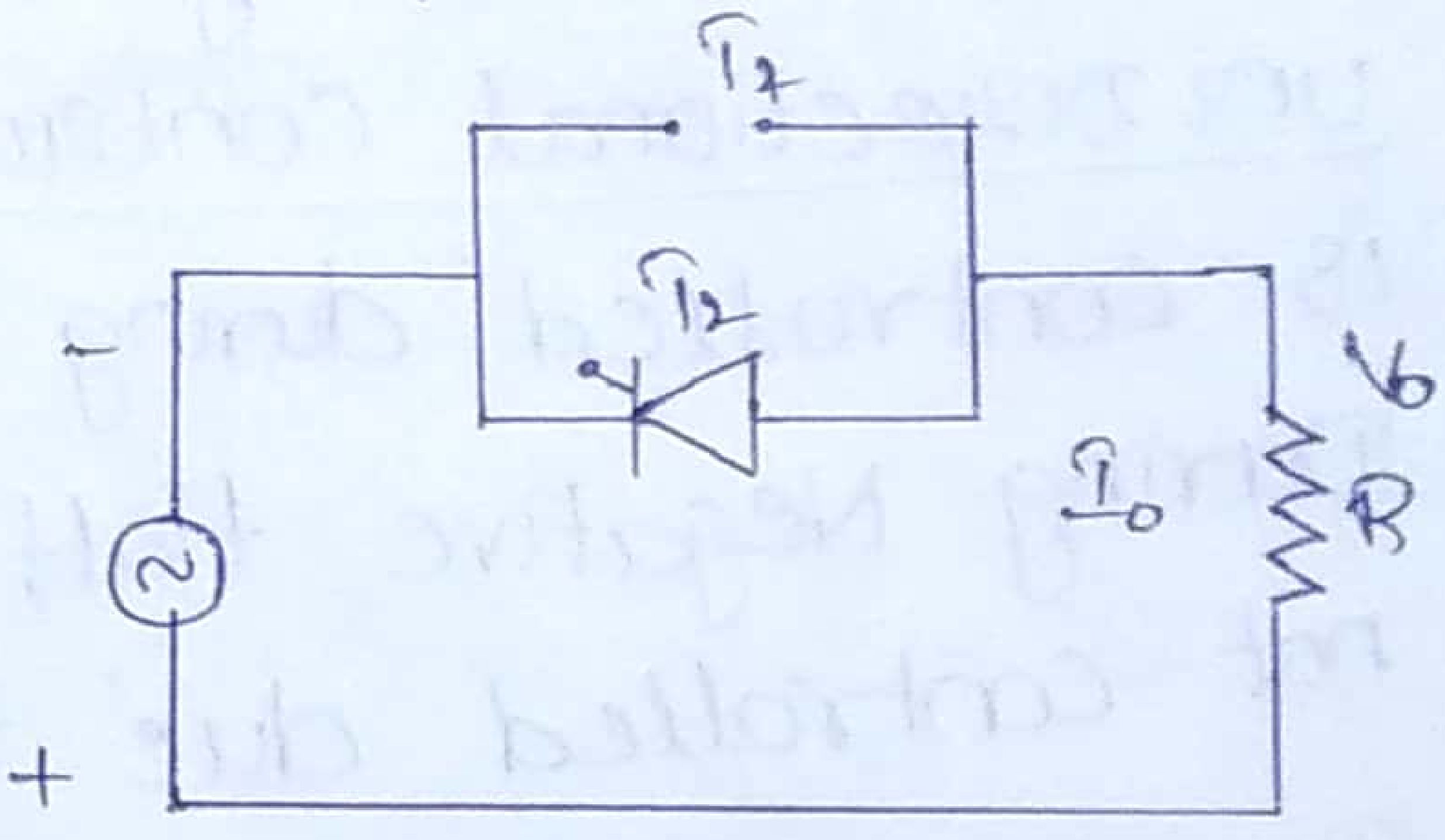
1-Ø fw Ac VC ; Bi Directional controller :-





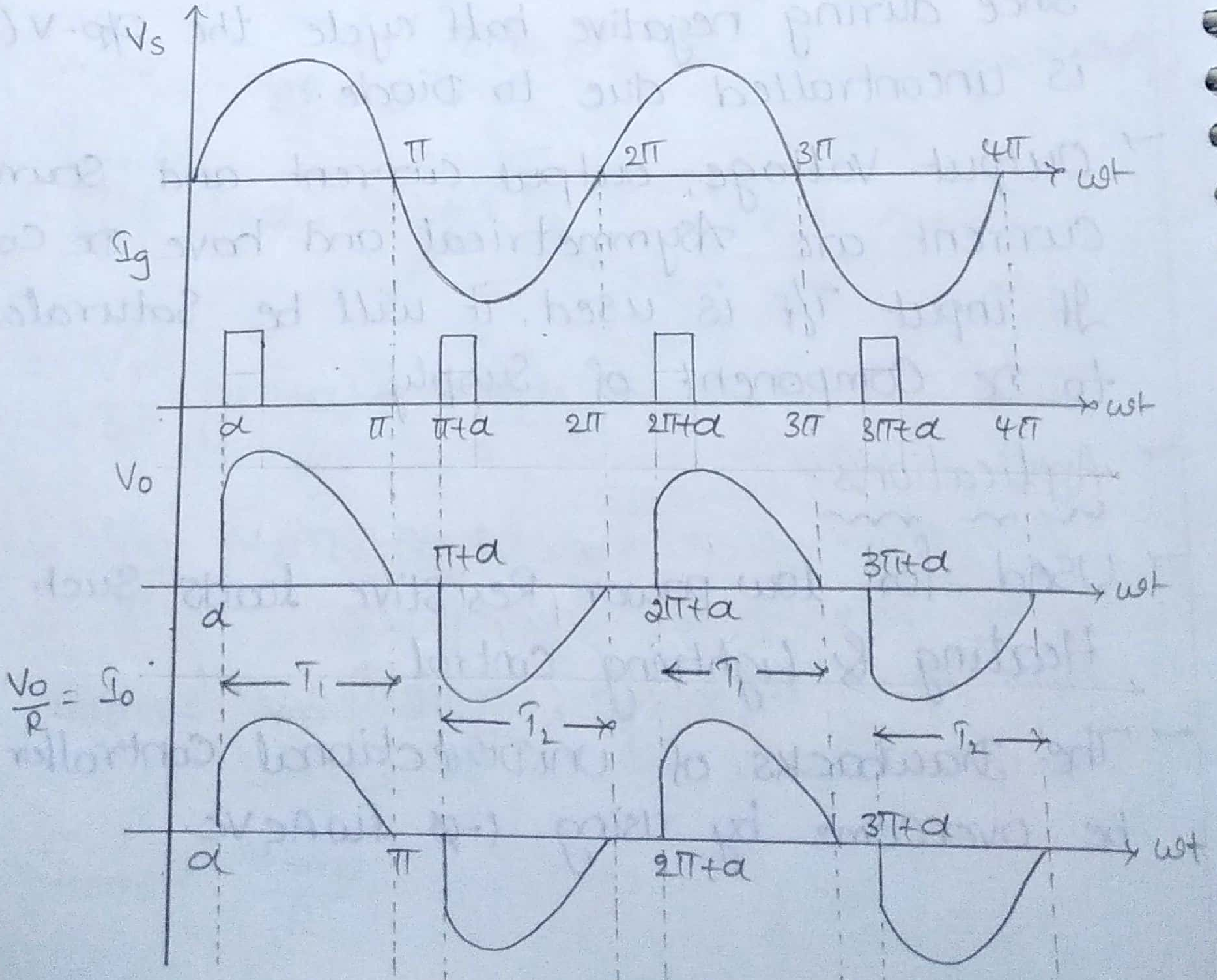
During positive Halfcycle.

$-V_S + V_O = 0$; $V_O = V_S$



During Negative cycle

$-V_S + V_O = 0$; $V_O = V_S$



→ 1-φ FWACVC is also called as BiDirectional ctrler since output power is controlled in both positive and Negative cycles.

→ Vavg & Iavg is zero.

→ $V_{orms} = \sqrt{\frac{1}{2\pi} \surd \int_0^{2\pi} V_0^2 \cdot d\omega t}$

$$\Rightarrow V_{orms}^2 = \frac{V_m^2}{2\pi}\left[\int_\alpha^\pi \sin^2\omega t \cdot d\omega t + \int_{\pi+\alpha}^{2\pi} \sin^2\omega t \cdot d\omega t\right]$$

$$= \frac{V_m^2}{4\pi}\left[\int_\alpha^\pi (1-\cos 2\omega t)\, d\omega t + \int_{\pi+\alpha}^{2\pi} (1-\cos 2\omega t)\, d\omega t\right]$$

$$\Rightarrow V_{orms}^2 = \frac{V_m^2}{4\pi}\left[(\pi+\alpha)+(\cos 2\alpha - \cos 2\pi)+\right.$$

$$= \frac{V_m^2}{4\pi}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2} + (\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]$$

$$= \frac{V_m^2}{4\pi}\left[2(\pi-\alpha) + \frac{\cancel{2}\sin 2\alpha}{\cancel{2}}\right]$$

$$= V_m^2\left[\frac{2(\pi-\alpha)}{4\pi} + \frac{\sin 2\alpha}{4\pi}\right]$$

$$\therefore V_{orms} = V_m\left[\frac{(\pi-\alpha)}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2}.$$

→ $I_{orms} = \frac{V_{orms}}{R}$

→ $pf = \frac{V_{orms}}{V_s}$; $P_{ac} = V_{orms} \cdot I_{orms} = \frac{V_{orms}^2}{R} = I_{orms}^2 R$.

→ Input VA = $V_s I_s = V_s I_{orms}$.

→ $I_{TA} = \frac{1}{2\pi}\int_0^{2\pi} I_T \cdot d\omega t$

$= \frac{1}{2\pi}\int_\alpha^{\pi} \frac{I_m}{R} \sin\omega t \cdot d\omega t$

$I_{TA} = \frac{I_m}{2\pi}(1+\cos\alpha)$

$\therefore I_{TA} = \frac{V_m}{2\pi R}(1+\cos\alpha)$

→ $I_{TR} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_T^2 \cdot d\omega t}$

$\Rightarrow I_{TR}^2 = \frac{1}{2\pi}\int_\alpha^{\pi} I_m^2 \cdot \sin^2\omega t \cdot d\omega t$

$= \frac{I_m^2}{2\pi}\int_\alpha^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) \cdot d\omega t$

$= \frac{I_m^2}{4\pi}\left[(\pi-\alpha)+\frac{\sin 2\alpha}{2}\right]$

$= \frac{I_m^2}{4\pi}\left[\frac{(\pi-\alpha)}{4\pi}+\frac{\sin 2\alpha}{8\pi}\right]$

$\therefore I_{TR} = I_m\left[\frac{\pi-\alpha}{4\pi}+\frac{\sin 2\alpha}{8\pi}\right]^{1/2}$

$\therefore I_{TR} = \frac{I_m}{R}\,\frac{V_m}{R}\left[\frac{\pi-\alpha}{4\pi}+\frac{\sin 2\alpha}{8\pi}\right]^{1/2}$

* Ac Voltage controller uses ON-OFF (Controller) principle for meeting a R-load $R = 4\Omega$, $V_s = 208$ V, 60Hz. If desired output power $P_0 = 3$KW. find Duty cycle - K and input pf

Given $R = 4\Omega$

$V_s = 208V ; f = 60Hz$

$P_o = 3KW$.

we have ; $V_{orms} = V_s \cdot \sqrt{K}$.

$\Rightarrow P_o = V_{orms} \cdot I_{orms}$

$\Rightarrow P_o = \frac{V_{orms}^2}{R} \Rightarrow V_{orms} = \sqrt{P_o \cdot R}$

$= \sqrt{3K \times 4}$.

$\therefore V_{orms} = 109.5V$

$\Rightarrow V_{orms} = V_s \cdot \sqrt{K}$

$\Rightarrow K = \sqrt{\frac{V_{orms}}{V_s}} = \sqrt{\frac{109.5}{208}} = 0.27$.

$\therefore K = 0.27$

Ip $\cos\phi = \frac{V_{orms}}{V_s} = \frac{109.5}{208} = 0.52$ lags.

1-ϕ AC VC Supplies power to a Resistive load of 20Ω The RMS Value of Input Voltage is 220V, 50Hz. Thyristors switched on for 30 cycles and off for 70 cycles. Calculate

(a) Vorms (b) Input pf (3) Vavg I_{TA}, I_{TR}.

Given, $R = 20\Omega$

$n = 30$ cycles ; $m = 70$ cycles.

$V_s = 220V ; f = 50Hz$.

(1) $V_{orms} = V_s \cdot \sqrt{K}$.

$K = \frac{n}{n+m} = \frac{30}{70+30} = \frac{30}{100} = 0.3$

$\Rightarrow V_{orms} = 220 \times \sqrt{0.3} = 120.49V$

(2) Input pf $= \frac{V_{orms}}{V_s} = \frac{120.49}{220} = 0.547$ lag

(3) $I_{TA} = \frac{I_m}{\pi \times K} K = \frac{V_m}{\pi R \cancel{K}} K = \frac{\overset{11}{22}\cancel{0} \times \sqrt{2} \times 0.3}{\pi \times \cancel{2}\cancel{0}}$

$\therefore I_{TA} = 1.48\,A.$

$I_{TR} = \frac{I_m}{2}\sqrt{K} = \frac{V_m}{2R}\sqrt{K} = \frac{220 \times \sqrt{2}}{2 \times 20} \times \sqrt{0.3}$

$= 4.25\,A$

$\therefore I_{TR} = 4.25\,A$

* An ACVC uses ON-OFF principle for meeting R-load of 4Ω, $V_s = 208\,V$, 60Hz. If desired P_o is 3kW. Sketch waveforms for Duty cycle obtained.

S) Refer 1-problm., $K = \frac{n}{n+m} = 0.27$

$\Rightarrow n = 11;\ m = 29;\ K = 0.275$

$\Rightarrow n = 2;\ m = 5;\ K = 0.28.$ Draw waveforms.

* A 1-ø ACVC has input Voltage of 230V, 50Hz & load of 75Ω Resistor. for 6 on cycles & 4 off cycles. find Vorms

S) $V_{orms} = V_s \cdot \sqrt{K}$; $K = \frac{6}{10} = 0.6$

$= 230 \times \sqrt{0.6}$

$= 178.157\,V.$

* Two SCR's are connected Back-Back has load R of 400Ω and supply 110 AC. If $\alpha = 60°$, find Vorms, Po.

S) Given, $R = 400\Omega$

$\alpha = 60°$

$V_s = 110\,V$

$V_{orms} = ?$

$$V_{orms} = V_S \times \sqrt{2} \left[\frac{(\pi - 60)^{\times \frac{\pi}{180}}}{2\pi} + \frac{\sin(120)}{8\pi} \right]^{1/2}$$

$$= 98.6\,V.$$

$$\therefore P_o = \frac{V_{orms}^2}{R} = \frac{98.6^2}{20} = 24.3\,W.$$

1-∅ Bidirectional ACVC has $R = 1.5\,\Omega$ with input Voltage 120V at 50Hz. If the designed output power is 7.5kW. find Delay angle of Thyristor, Vorms, Input pf, I_{TA}, I_{TR}.

Given, $R = 1.5\,\Omega$

$P_o = 7.5\,KW$;

$V_s = 120V$, $f = 50\,Hz$

$$\Rightarrow P_o = \frac{V_{orms}^2}{R}$$

$$\Rightarrow V_{orms} = \sqrt{7.5K \times 1.5} = 106.06\,V$$

$$\therefore V_{orms} = 106.066\,V$$

(1) $$V_{orms} = V_m \left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi} \right]^{1/2}$$

$$\Rightarrow 106.066 = 120 \times \sqrt{2} \left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi} \right]^{1/2}$$

$$\Rightarrow \sqrt{\frac{106.066}{120\sqrt{2}}}^{\,2} = \left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi} \right]$$

$$\Rightarrow \frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi} = 0.394$$

$$\Rightarrow \frac{2(\pi - \alpha) + \sin 2\alpha}{4\pi} = 0.394$$

$$\Rightarrow \sin 2\alpha - 2\alpha = (0.394 \times 4\pi) - 2\pi$$

$$\Rightarrow \sin 2\alpha - 2\alpha = -1.38$$

$$\Rightarrow 2\alpha - \sin 2\alpha = 1.38.$$

At, $\alpha = 30°$; 0.18

$\alpha = 60°$; 1.22

$\alpha = 62°$; 1.33

$\alpha = 63°$; 1.39.

$$\rightarrow I_{TA} = \frac{V_m}{2\pi R}(1+\cos\alpha)$$

$$= \frac{120\times\sqrt{2}}{2\pi\times 1.5}(1+\cos(63))$$

$$= 26.177A$$

$$\rightarrow I_{TR} = \frac{V_m}{2\pi R}\left[\frac{(\pi-\alpha)}{2\pi\times 2} + \frac{\sin 2\alpha}{4\pi\times 2}\right]^{1/2}$$

$$= \frac{\cancel{V}\,120\times\sqrt{2}}{2\pi\times 1.5}\left[\frac{(\pi)-(63\times\frac{\pi}{180})}{2\pi\times 2} + \frac{\sin 2(63)}{8\pi}\right]^{1/2}$$

$$= 50.01A.$$

$$\rightarrow \cos\phi = \frac{106.06}{120} = 0.883$$

* 230V, 1KW Heater is fed through an AC Voltage Reg. from 230V, 50Hz source. find load power for $\alpha = 70°$

Sol:-

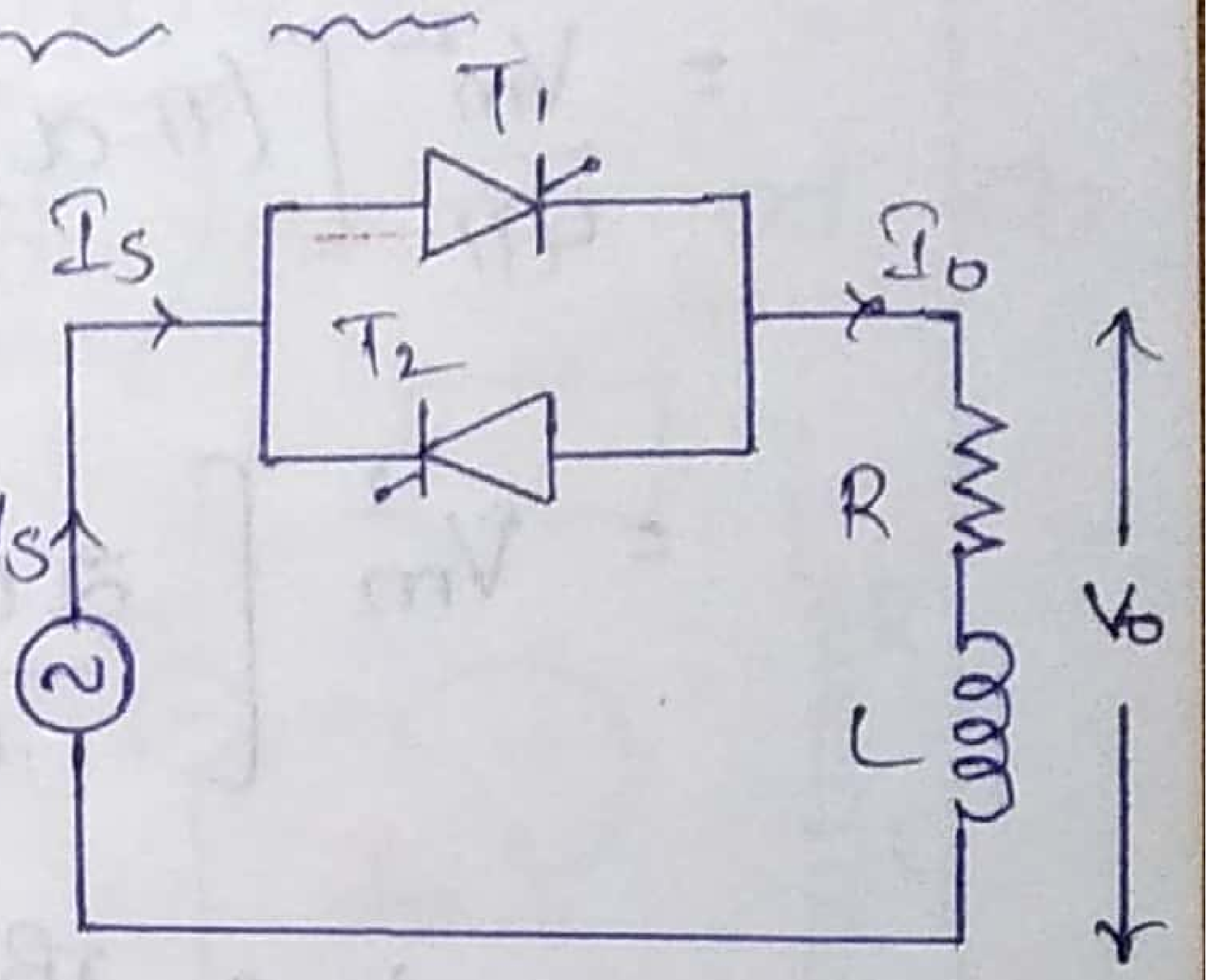
$$V_{orms} = \overset{\cancel{(V_m)}}{230\sqrt{2}}\left[\frac{\pi-(70\times\frac{\pi}{180})}{2\pi} + \frac{\sin(140)}{4\pi}\right]^{1/2} = 194.26V$$

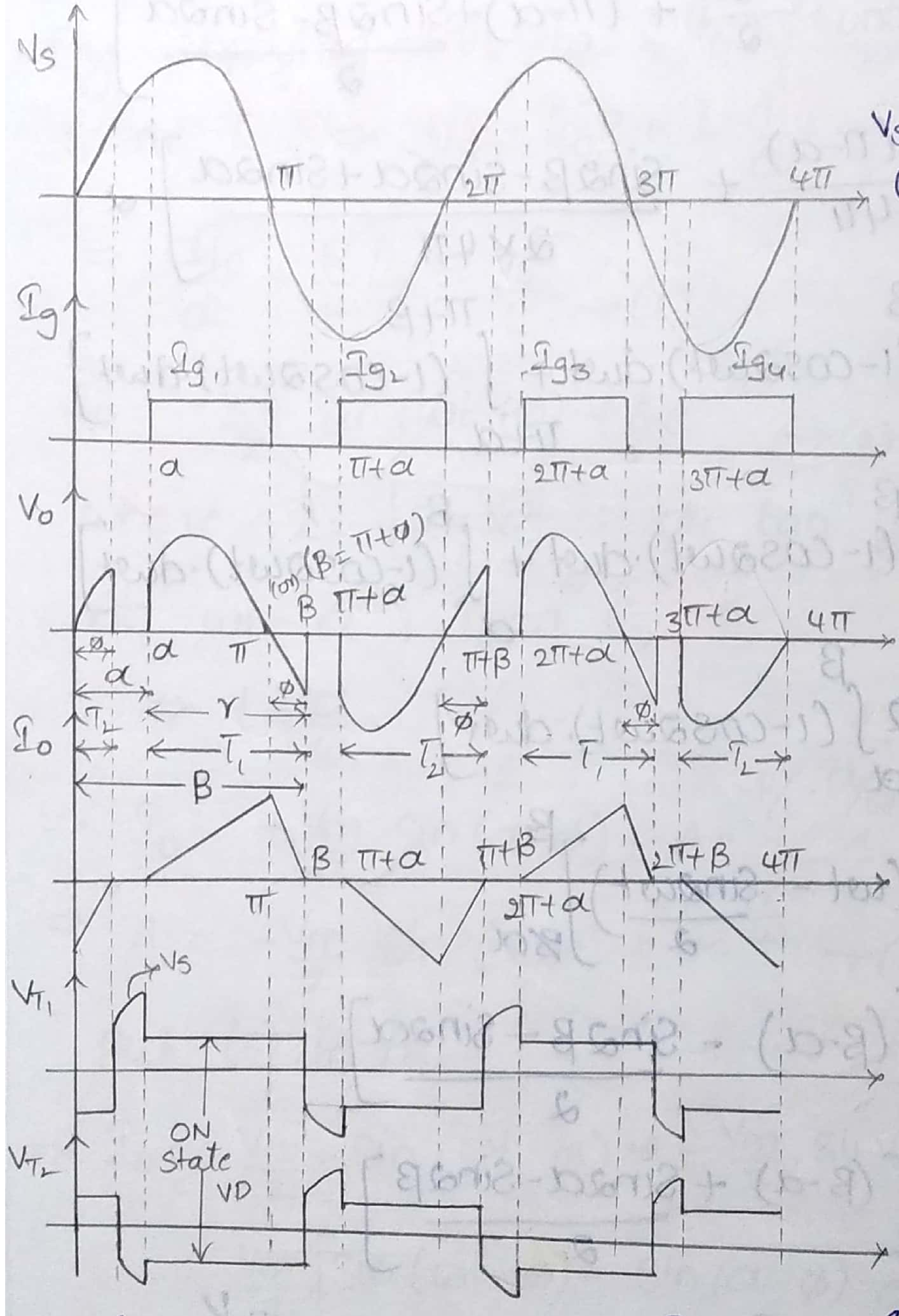
$$\text{Output power} = \frac{V^2}{R}$$

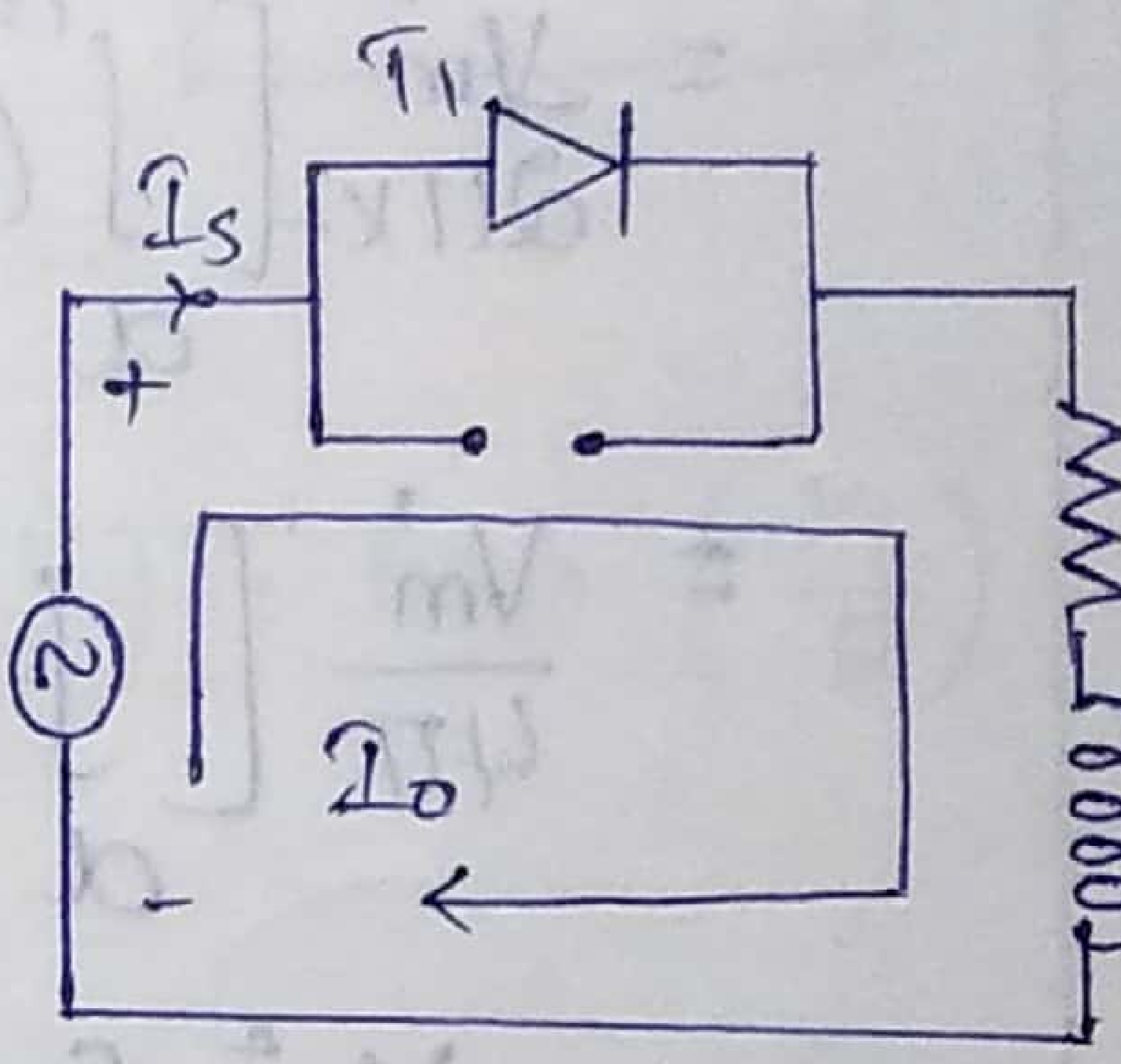
$$\Rightarrow R = \frac{230^2}{1\times10^3} = 52.9\,\Omega.$$

$$\Rightarrow P_0 = \frac{V_{orms}^2}{R} = \frac{194.26^2}{52.9} = 713.36\,W.$$

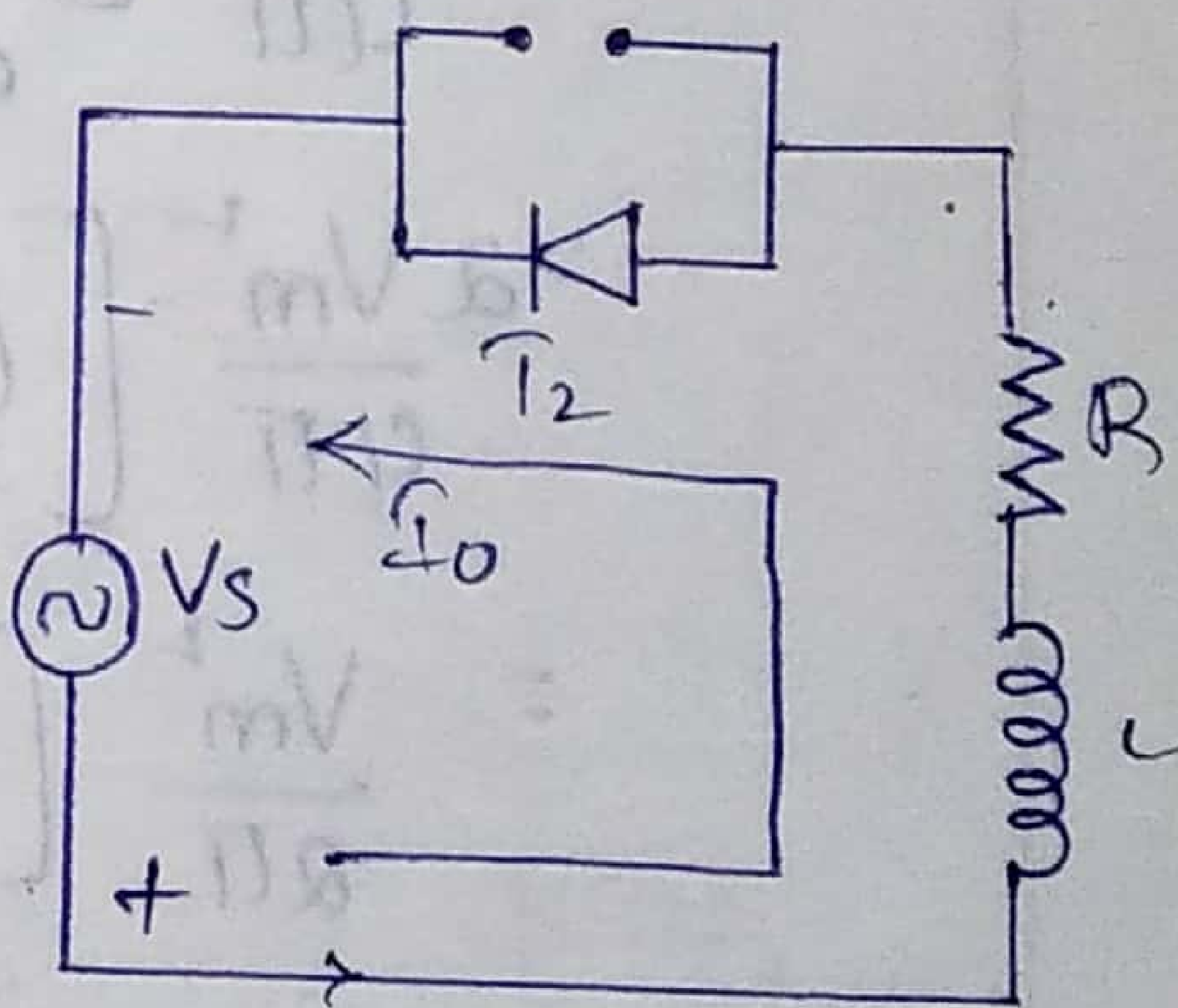
→ 1-∅ fw Ac Voltage with RL- Load:-







During +Hc; Vo=Vs



During -Hc; Vo=Vs

→ Since the o/p V and I are Symmetric,

V_{avg}; $I_{avg} = 0$.

($\alpha > \phi$)

fig:- Discontinuous Current Mode ($\gamma < \pi$)

$$\rightarrow \quad V_{orms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_o^2 \cdot d\omega t}$$

$$\Rightarrow V_{orms}^2 = \frac{1}{2\pi}\left[\int_\alpha^{\cancel{\pi}\beta} V_m^2 \sin^2\omega t \cdot d\omega t + \int_{\pi+\alpha}^{\pi+\beta} V_m^2 \cdot \sin^2\omega t \cdot d\omega t\right]$$

$$= \left[\frac{V_m^2}{4\pi}\left[\int_\alpha^{\pi}(1-\cos 2\omega t)\cdot d\omega t + \int_{\pi+\alpha}^{\pi+\beta}(1-\cos 2\omega t)\cdot d\omega t\right]\right.$$

$$= \frac{V_m^2}{4\pi}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2} + (\pi-\alpha) + \frac{\sin 2\beta - \sin 2\alpha}{2}\right]$$

$$= V_m^2\left[\frac{2(\pi-\alpha)}{4\pi} + \frac{\sin 2\beta - \sin 2\alpha + \sin 2\alpha}{2\times 4\pi}\right]\alpha$$

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

$$= \frac{V_m^2}{4\pi}\left[\int_\alpha^{\beta}(1-\cos 2\omega t)\cdot d\omega t + \int_\alpha^{\beta}(1-\cos 2\omega t)\cdot d\omega t\right]$$

$$= \frac{V_m^2}{4\pi}\left[2\int_\alpha^{\beta}(1-\cos 2\omega t)\cdot d\omega t\right]$$

$$= 2\frac{V_m^2}{4\pi}\left[\left(\omega t - \frac{\sin 2\omega t}{2}\right)\right]_{\cancel{\beta}\alpha}^{\beta}$$

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

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

$$\therefore \quad V_{orms} = V_m\left[\frac{(\beta-\alpha)}{2\pi} + \frac{\sin 2\alpha - \sin 2\beta}{4\pi}\right]^{1/2} \quad //$$

(2) $I_{orms} = \frac{V_{orms}}{R}$

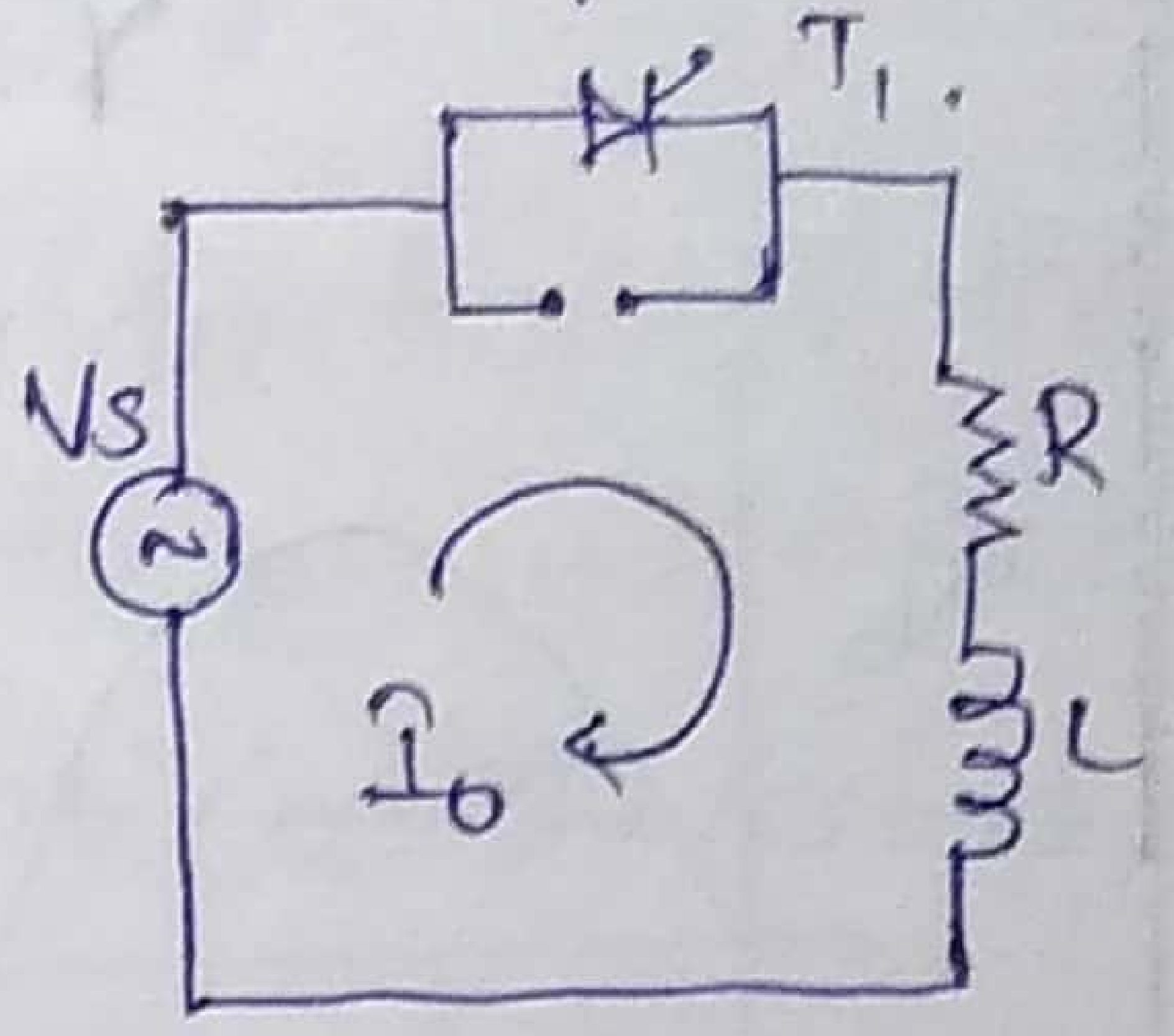
(3) $P_o = P_{ac} = V_{orms} \cdot I_{orms} = \frac{V_{orms}^2}{R} = I_{orms}^2 \cdot R.$

(4) $pf = \frac{V_{orms}}{V_s}$

(5) Input $VA = V_S I_S = V_s I_{orms}$.

→ Calculation of Extension Angle (β):-

By applying KVL to either conduction period of T_1 or T_2. ⇒ $V_S = I_O R + L \cdot \frac{di_o}{dt}$



$$\Rightarrow \frac{dI_o}{dt} + \frac{R}{L} I_o = \frac{V_s}{L} \rightarrow (1)$$

$$I_o = +\frac{V_m}{Z} \sin(\omega t - \phi) + A \cdot e^{-R/L\, t} \rightarrow (2)$$

where, $Z = \sqrt{R^2 + X_L^2}$; $\phi = \tan^{-1}\left(\frac{R}{Z}\right)$; $\tan^{-1}\left(\frac{X_L}{R}\right)$.

At $\omega t = \alpha$; $I_o = 0$

$$\Rightarrow t = \frac{\alpha}{\omega}$$

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

$$\Rightarrow A = -\frac{V_m}{Z} \sin(\alpha - \phi) \cdot e^{\frac{R}{L} \cdot \frac{\alpha}{\omega}} \rightarrow (3)$$

put (3) in (2)

$$\Rightarrow I_o = \frac{V_m}{Z} \cdot \sin(\omega t - \phi) + -\frac{V_m}{Z} \cdot \sin(\alpha - \phi) \cdot e^{\frac{R}{L} \cdot \frac{\alpha}{\omega}}$$

$$= \frac{V_m}{Z} \cdot \left[\sin(\omega t - \phi) - \sin(\alpha - \phi) \cdot e^{\frac{R}{L}\left(\frac{\alpha}{\omega} - t\right)}\right]$$

At $\omega t = \beta$; $I_o = 0$

$$\Rightarrow t = \beta/\omega$$

$$\Rightarrow 0 = \frac{V_m}{Z}\left[\sin(\beta-\phi) - \sin(\alpha-\phi)\, e^{\frac{R}{L}\left(\frac{\alpha}{\omega}-\frac{\beta}{\omega}\right)}\right].$$

$$*/ \sin(\beta-\phi) = \sin(\alpha-\phi).e^{\frac{R}{\omega L}(\alpha-\beta)} /*$$

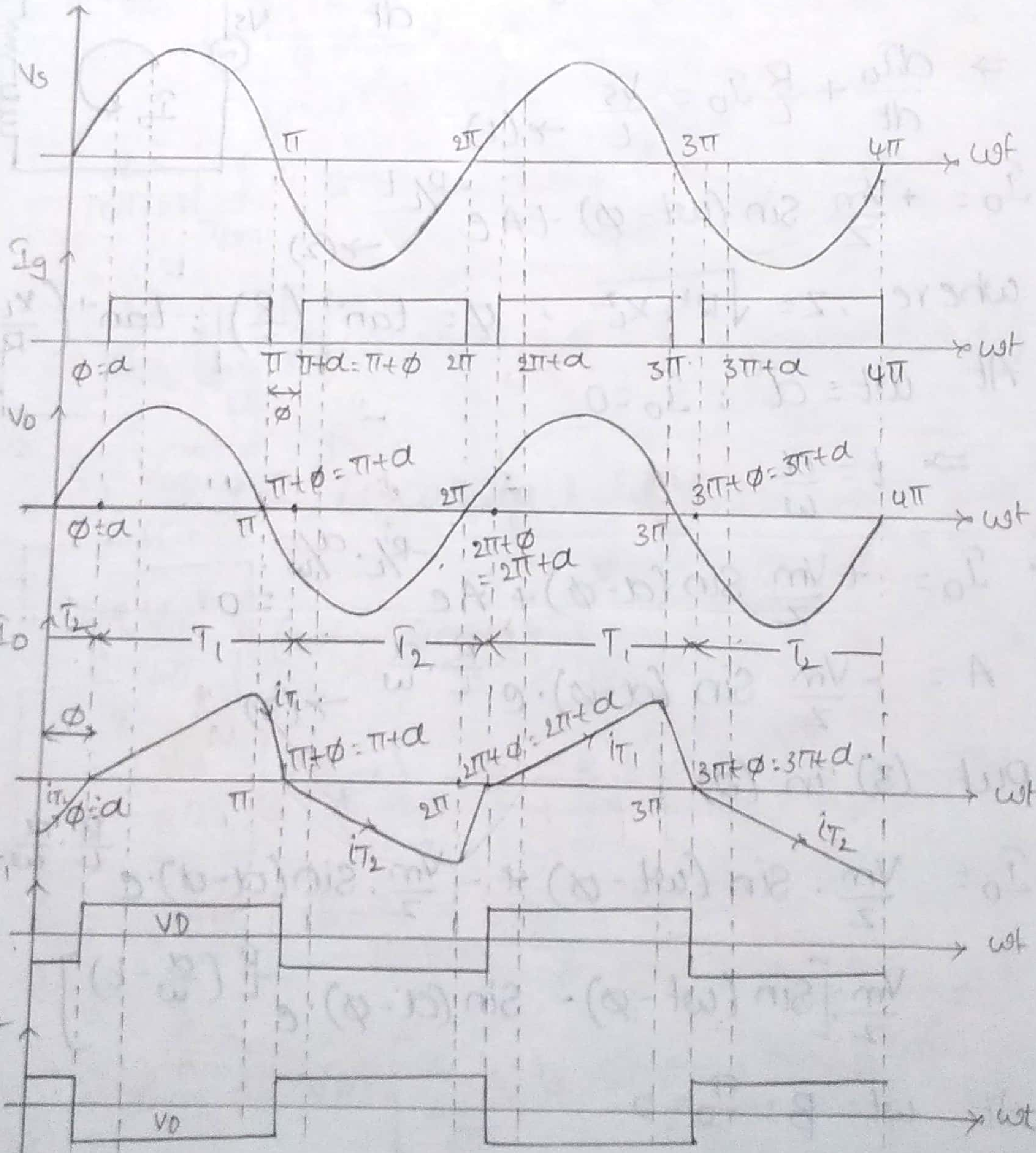
$\gamma = \beta-\alpha$ can be calculated by using β

→ In Discontinuous Mode. $\alpha > \phi$; $\pi > \gamma$.

$\alpha - \pi+\phi \rightarrow T_1$
$\pi+\alpha - 2\pi+\phi \rightarrow T_2$
$2\pi+\alpha - 3\pi+\phi = T_1$
$3\pi+\alpha - 4\pi+\phi \rightarrow T_2$

$\gamma = \beta-\alpha$.

$\gamma = \pi$ $\left(\because \alpha=\phi \text{ \& } \beta = \pi+\phi.\ \gamma = \pi+\phi-\phi = \pi\right)$



fig(2). Continuous Mode $\alpha \leq \phi$; $\gamma = \pi$.

→ For $\alpha > \phi$, Conduction Angle γ is less than π ($\gamma < \pi$) then load current is Discontinuous. Under this Condition Ac Voltage Controller operates as shown in fig.(1)

$\alpha - \pi + \phi \rightarrow T_1$ ON

$\pi + \alpha - 2\pi + \phi \rightarrow T_2$ ON.

$2\pi + \alpha - 3\pi + \phi \rightarrow T_1$ ON

$3\pi + \alpha - 4\pi + \phi$. $\rightarrow T_2$ ON.

→ By Decreasing firing angle α, conduction γ increase and becomes equal to ~~ϕ~~π ($\gamma = \pi$). we will get Continuous mode of operation. ↳at ($\alpha = \phi$) ($\alpha = \phi$)

→ for $\alpha = \phi$, the load Voltage and load current waves are Sinusiodal, but load current lags load Voltage by an angle ϕ. under this Condition Ac VC operates as,

$\phi - \pi + \phi \rightarrow T_1$ ON

$\pi + \phi - 2\pi + \phi \rightarrow T_2$ ON.

$2\pi + \phi - 3\pi + \phi \rightarrow T_1$ ON

$3\pi + \phi - 4\pi + \phi \rightarrow T_2$ ON

→ In either cases, ϕ is angle between V & I.

→ when firing angle α is decreased to a Value which is less than ϕ ($\alpha < \phi$), Thyristor -T_1 should Conduct but Thyristor T_1 is not Triggered, when firing angle $\alpha < \phi$ due to reverse voltage appeared across T_1 by Thyristor - T_2. Now,

→ when α less than ϕ, Thyristor -T_2 is in conduction and current flowing through T_2 is I_{T_2}. Now, the Thyristor-T_1 will conducts only when current flowing through Thyristor-T_2, I_{T_2} falls to zero at $\alpha=\pi$. Now, Thyristor-T_1 conducts from $\phi \rightarrow \pi+\phi$.

→ Similarly, when $(\pi+\alpha) < (\pi+\phi)$, Thyristor-$T_2$ should be conducts, but it is not Triggered when $(\pi+\alpha) < (\pi+\phi)$, due to reverse Voltage appeared across Thyristor-T_2 by Thyristor-T_1.

→ when $(\pi+\alpha) < (\pi+\phi)$, Thyristor-$T_1$ is in conduction and current flowing through it is I_{T_1}. Thyristor T_2 will conducts only when current flowing through Thyristor-T_1 I_{T_1} falls to zero at $(\pi+\alpha) = (\pi+\phi)$. Now, Thyristor T_2 conducts from $(\pi+\phi) \rightarrow (2\pi+\phi)$.

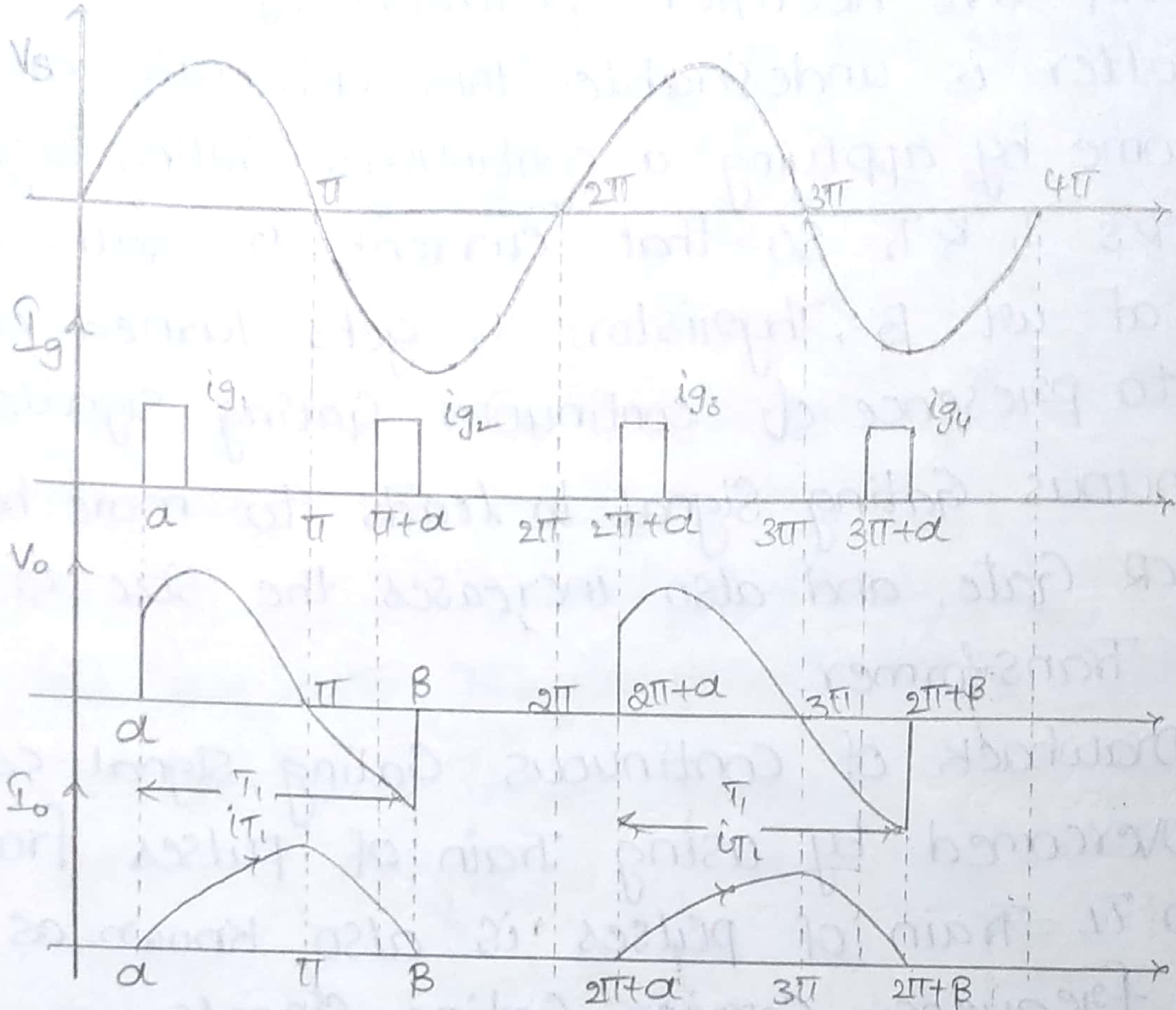
→ for $\alpha<\phi$, there is no change in load Voltage and load current, from what they are obtained at $\alpha=\phi$. ie., the output Voltage and output current is same for $\alpha<\phi$; $\alpha=\phi$.

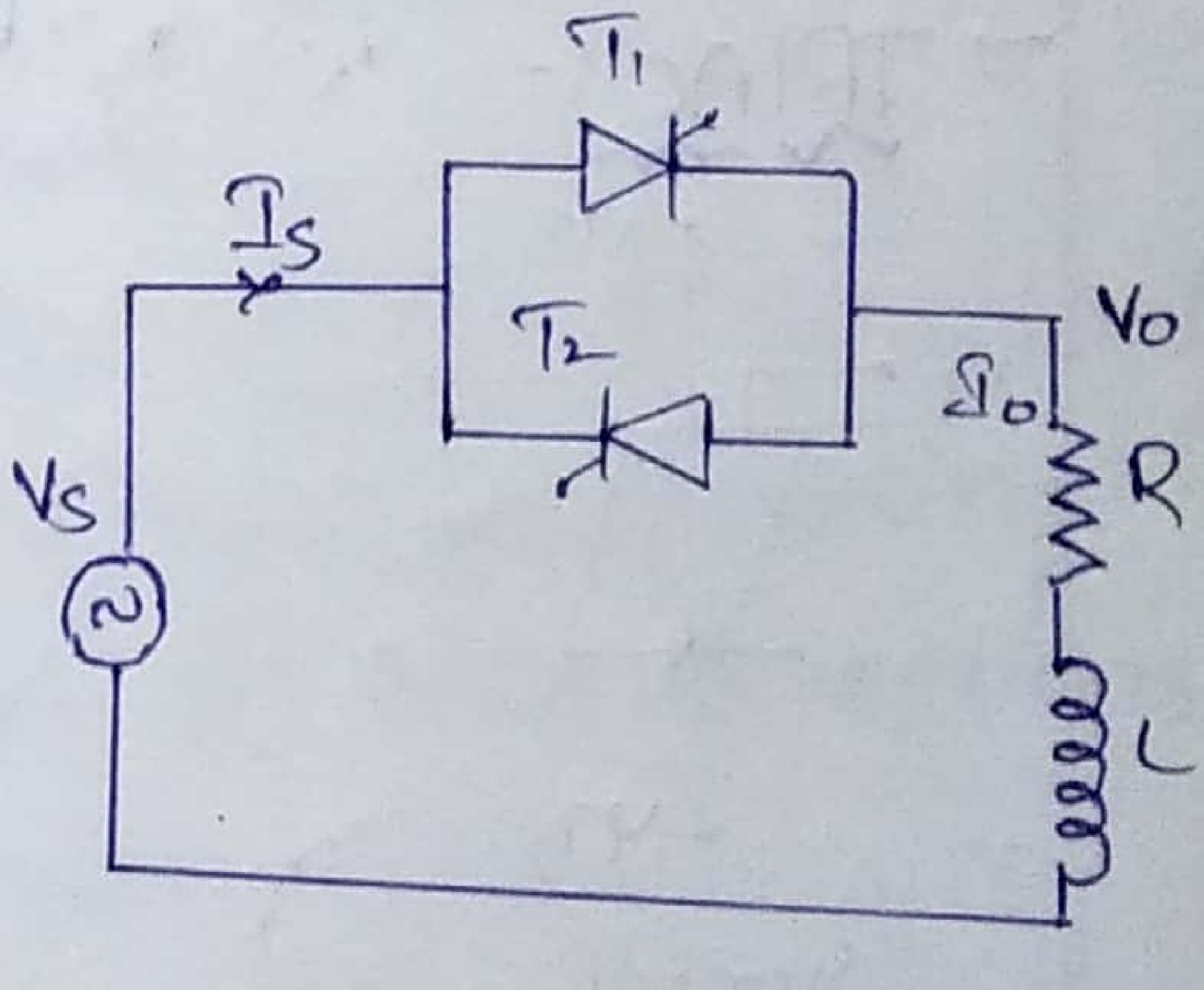
→ The output voltage and output current is not controlled for $\alpha<\phi$. The output voltage and output current will control only for $\alpha>\phi$.

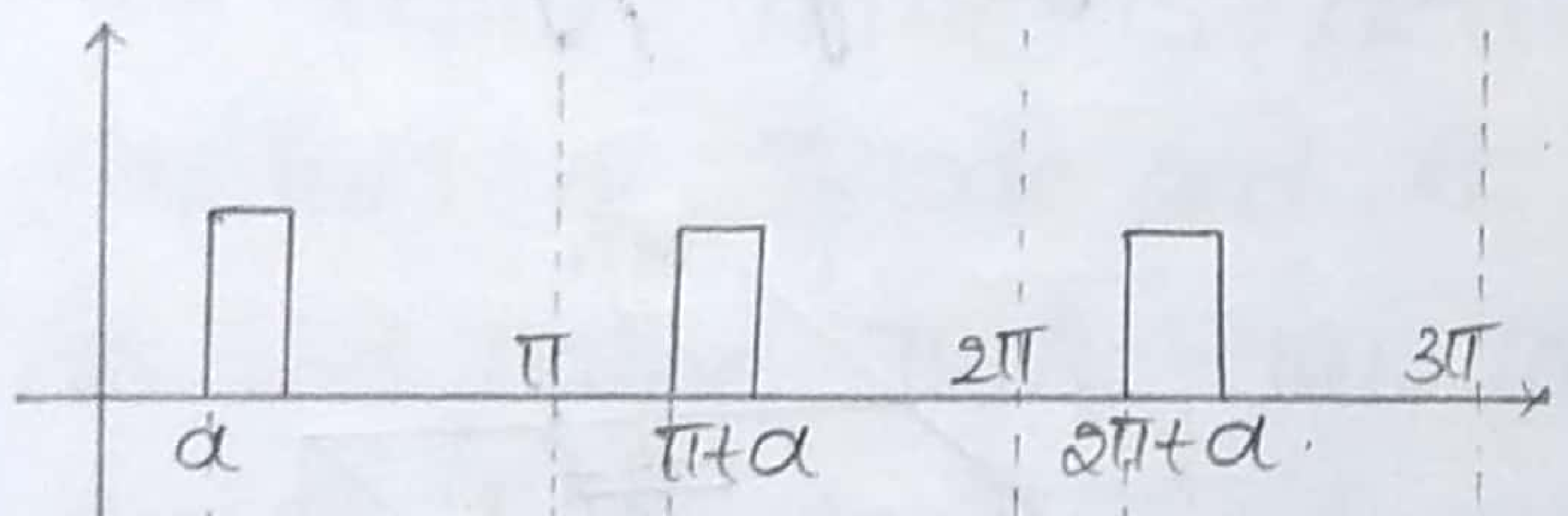
→ The control range of firing angle for Ac Vc with RL-Load is given by

$$** / \phi < \alpha < \pi / **$$

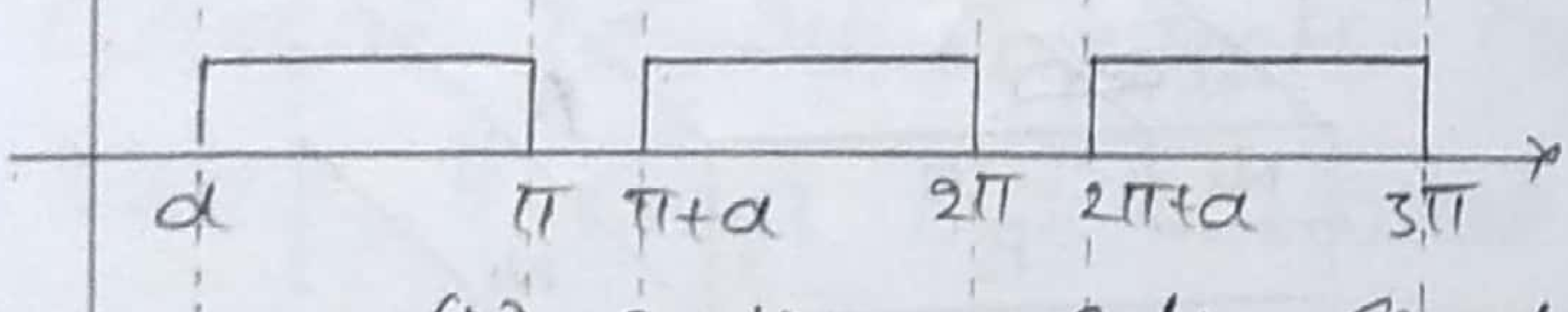
→ Ac Voltage Controller as Half wave Rectifier:-



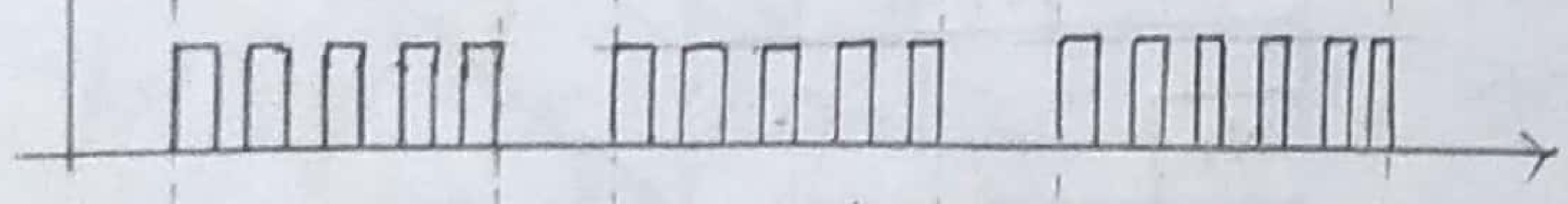




(a) pulse Gating Signals



(b) Continuous Gating Signals.

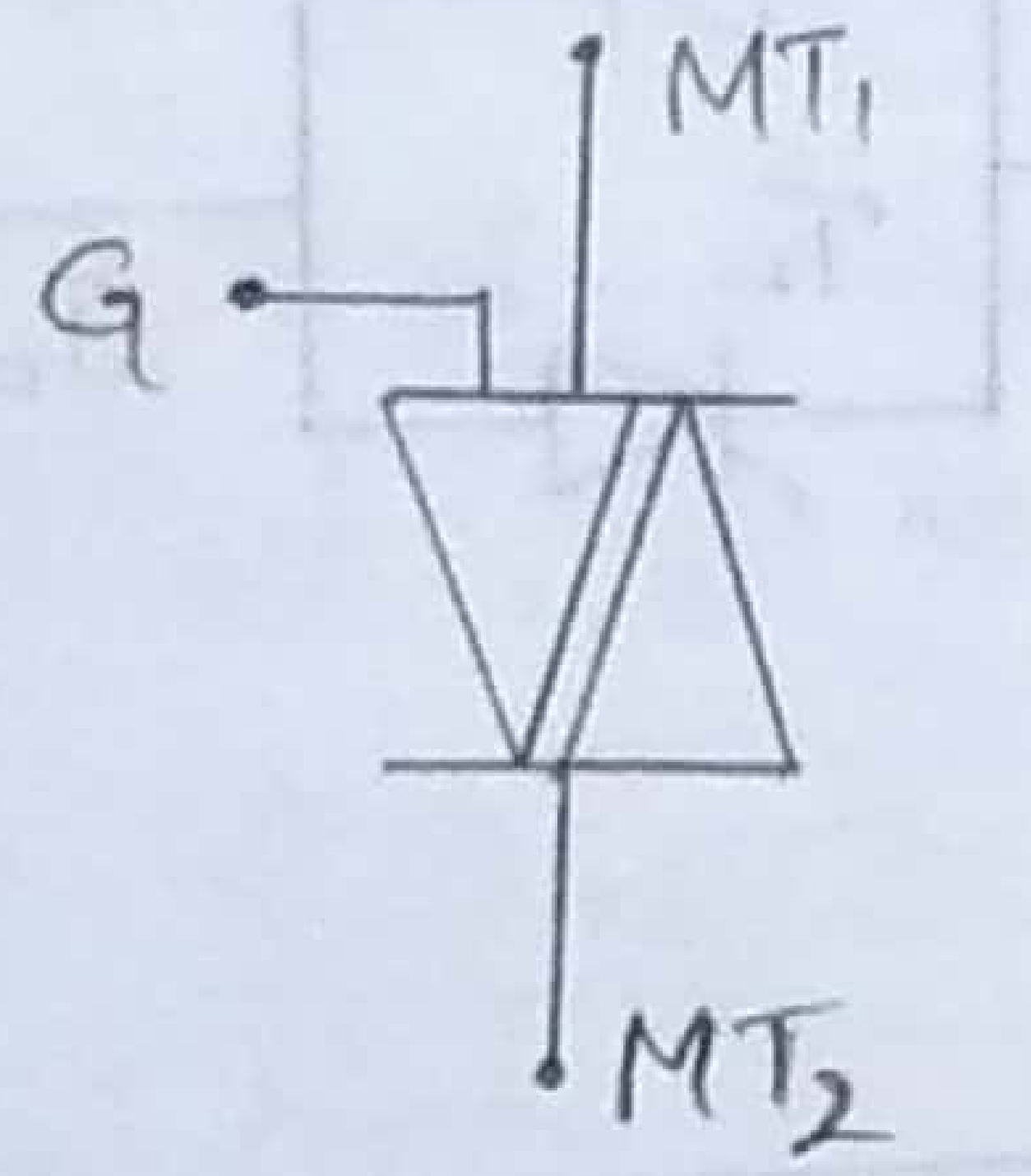


(c) Train of pulses (or)
High frequency Carrier Signals.

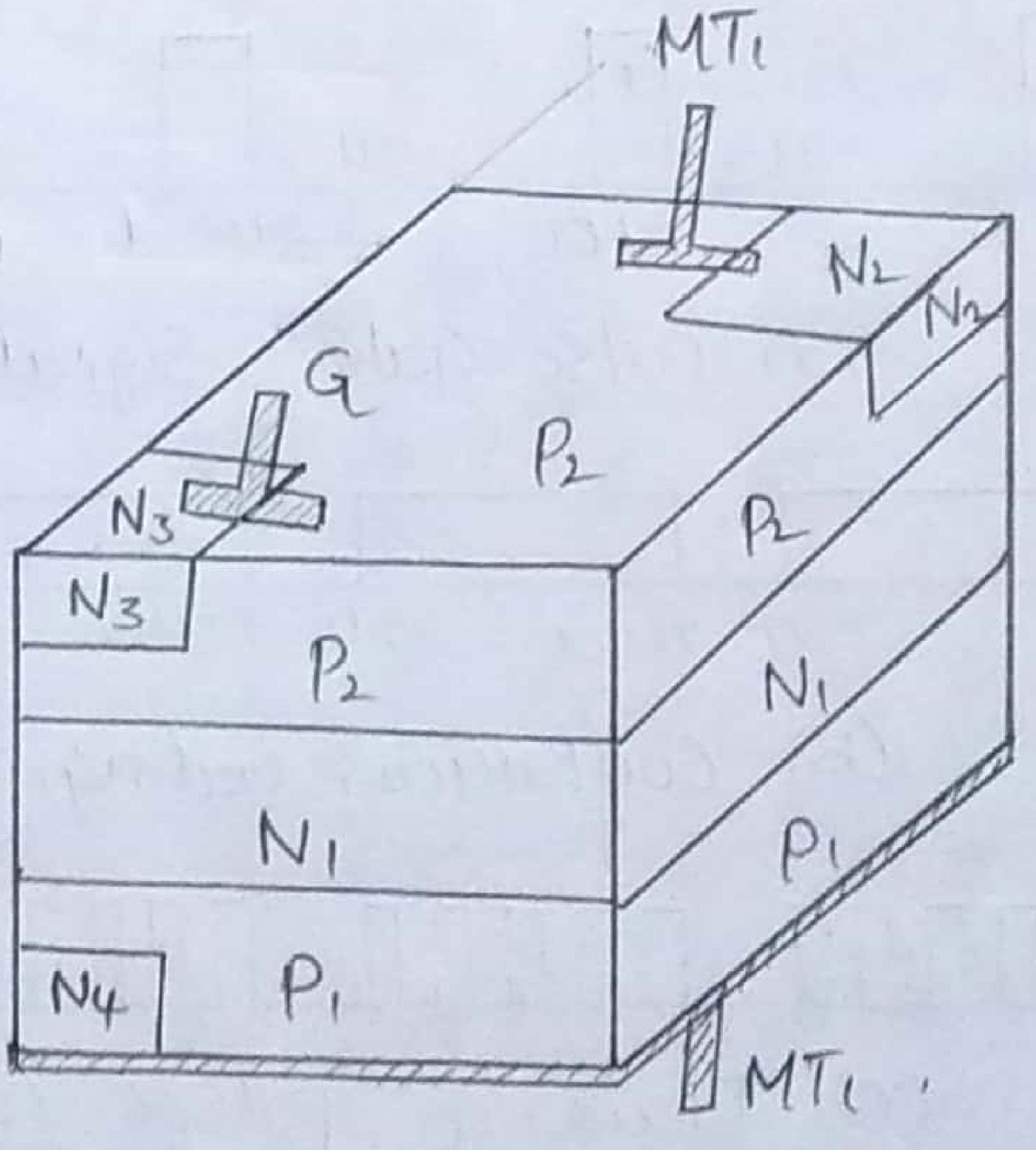
→ If we use pulse Gating signals for SCR's in case of Ac VC with RL-Load instead of Continuous Gating Signals. The Ac Voltage controller gives Halfwave Rectifier operation (or) gives Asymmetrical output due to conduction of SCR - T_1 alone.

- The Half wave Rectifier operation of Ac Voltage Controller is undesirable. This difficulty can be overcome by applying a continuous Gating Signals to SCR's T_1 & T_2 So that when current I_{T_1} falls to zero at $\omega t = \beta$, Thyristor - T_2 gets Turned ON due to presence of continuous Gating Signals.
- Continuous Gating Signal to leads to more heating at SCR Gate, and also increases the size of pulse Transformer.
- The Drawback of continuous Gating signal can be overcomed by using Train of pulses from α to π. Train of pulses is also known as High frequency Carrier Gating Signals.

→ TRIAC :-

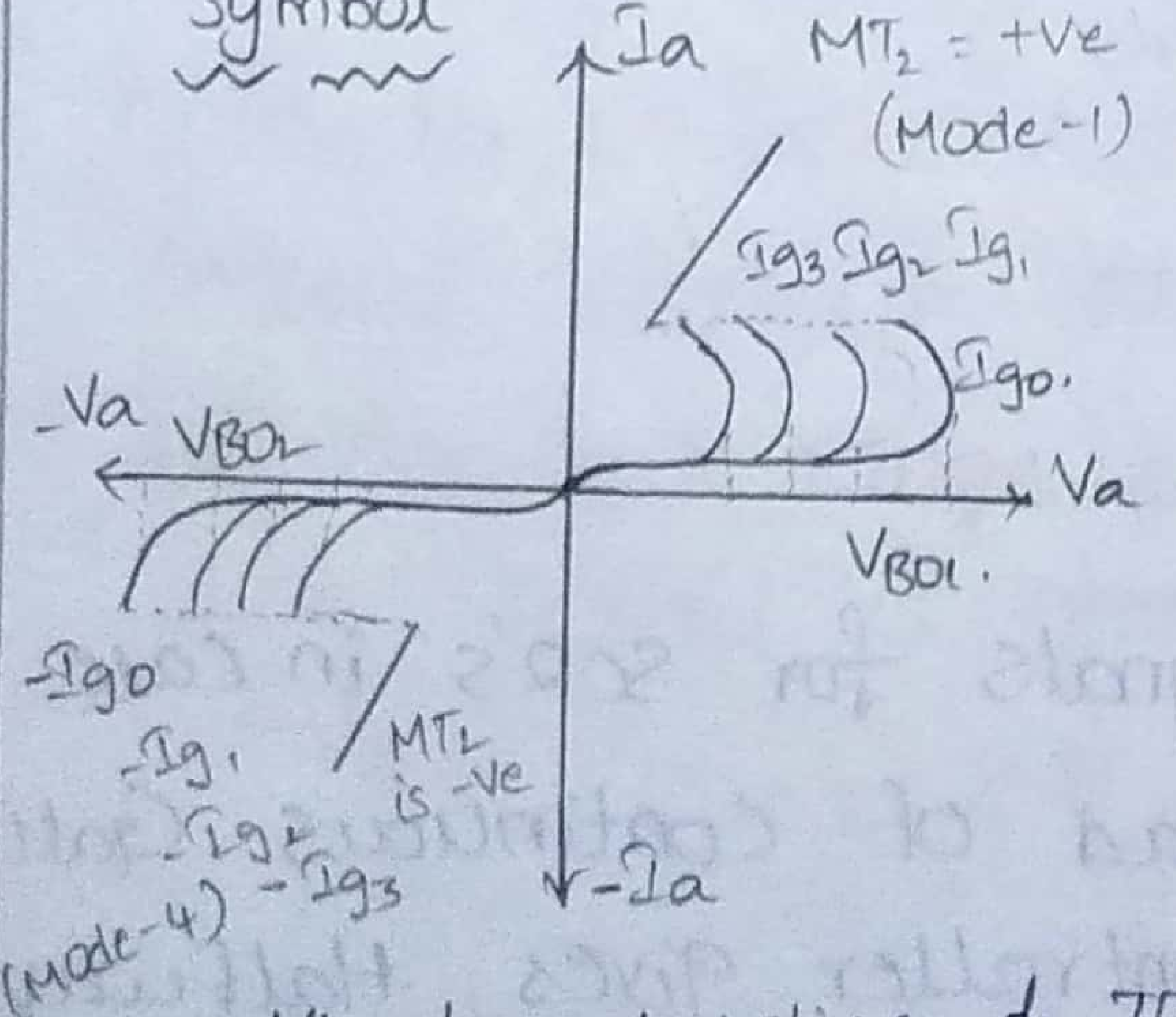


Symbol



Construction of TRIAC

MT₁ - Main Terminal - 1
MT₂ - Main Terminal - 2.



VI - characteristics of TRIAC.

- In case of Thyristors current flows from Anode to Cathode only, it does not allows current from the Cathode to Anode as it has reverse blocking capabi. But some of applications requires Bidirectional Conduction. In order to meet Bidirectional Conduction, two SCR's should be connected in Anti-parallel. The Anti parallel connection of two SCR's have drawbacks of

(1) Cost of SCR's will be more.

(2) Heat sinks requirement will be more.

- To overcome these drawbacks, two Antiparallel SCR's are integrated into a single Device known as TRIAC.
- The name TRIAC is derived by combining the capitals of TRIode and AC Switch.
- In the name TRIAC, TRI indicates it is 3-terminal device and AC indicates it controls alternating current i.e., it conducts current in both directions. Hence, it is a Bidirectional Device.
- TRIAC is triggered by applying either positive Gate Voltage or Negative Gate Voltage between Gate & MT-1 Terminals.

Modes of TRIAC:-

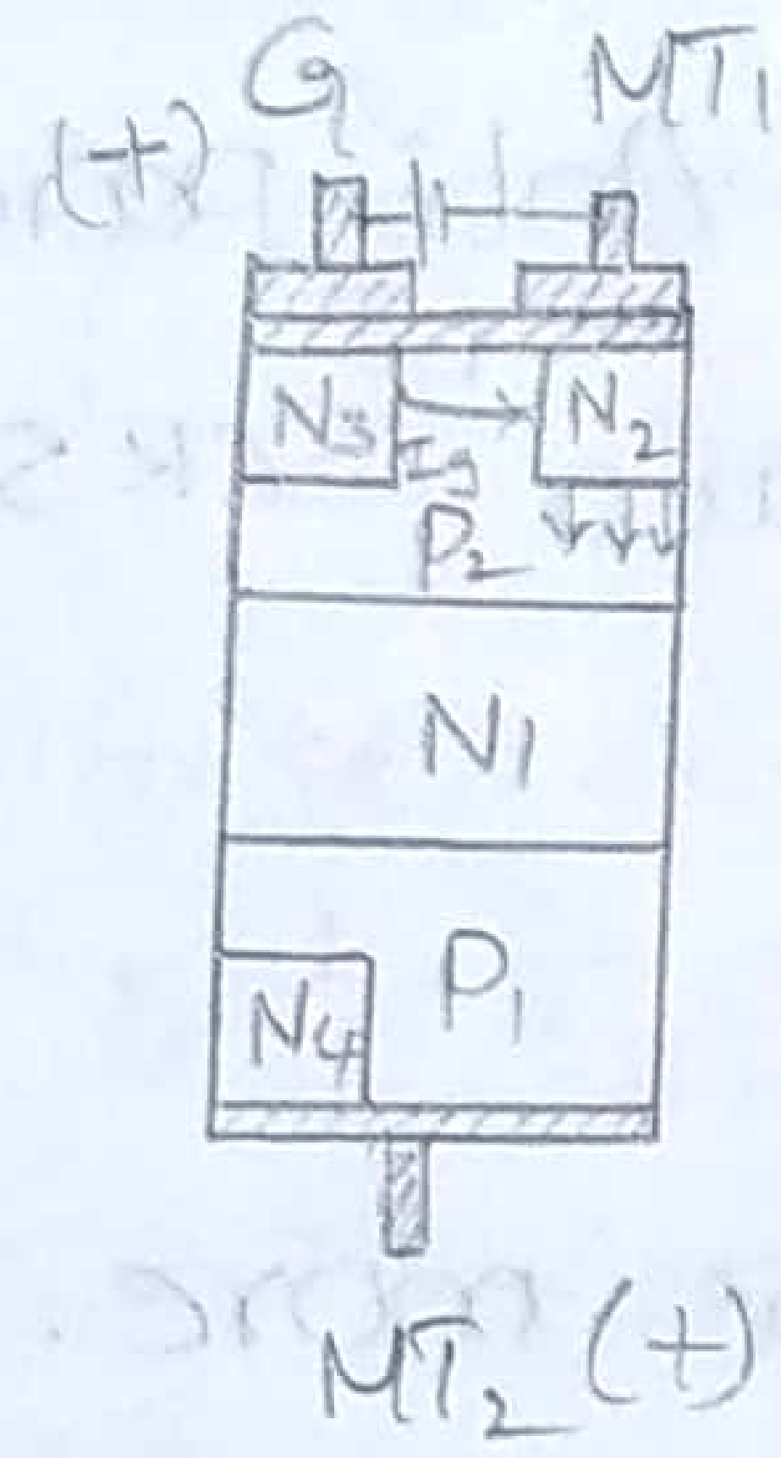
- By keeping MT_2 Terminal at positive or negative, the TRIAC can be triggered by applying either positive Gate current or Negative Gate current between Gate and MT_1 Terminals.

(1) MT_2 is positive, Gate current is +ve.

(2) MT_2 is positive, Gate current is -ve.

(3) MT_2 is Negative, Gate current is +ve.

(4) MT_2 is Negative, Gate current is -ve



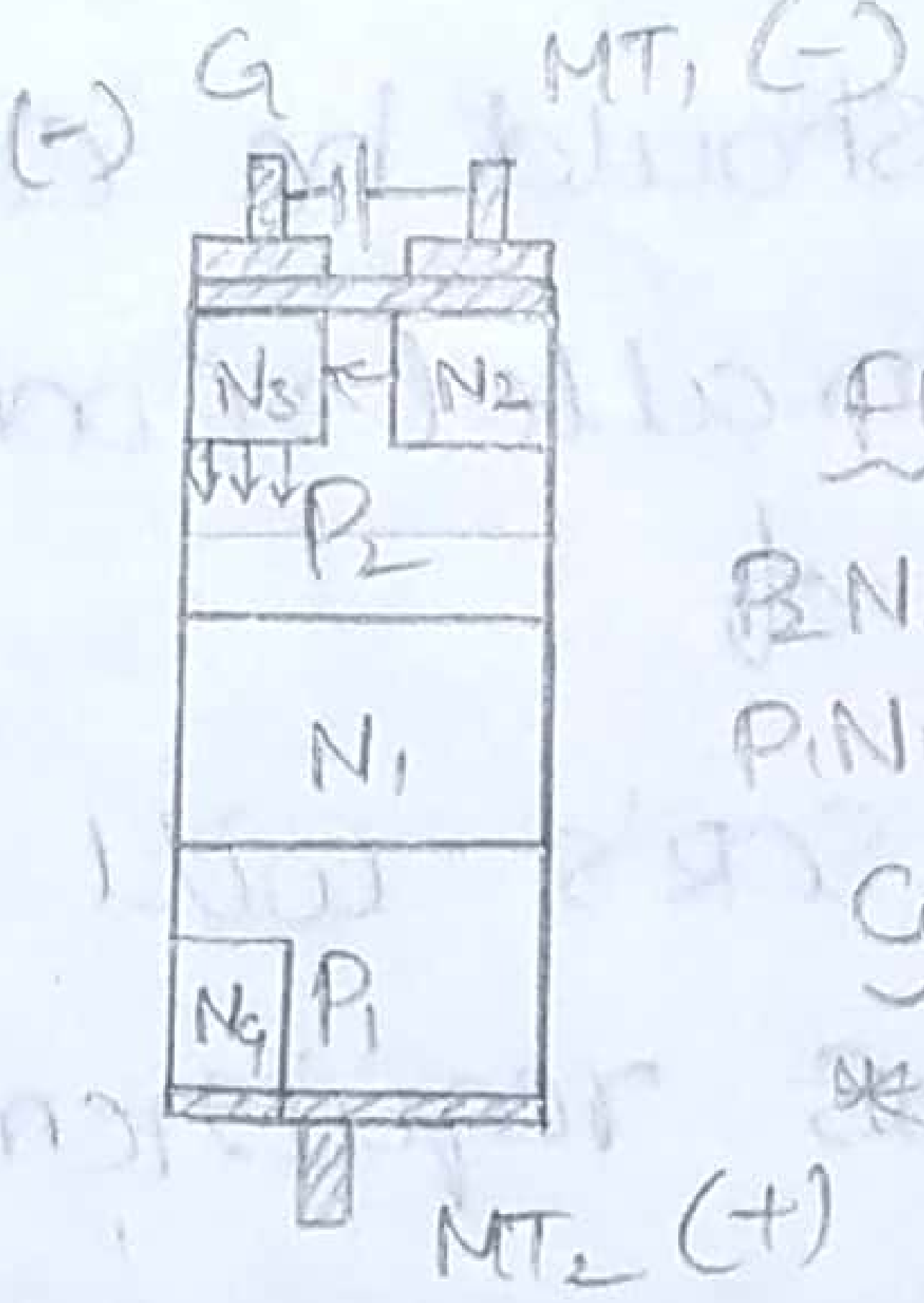
FB: P_2N_2, P_1N_1

RB: P_2N_1

Conduction:-

* $P_1N_1P_2N_2$ *

Mode-1



FB: P_2N_2, P_1N_1

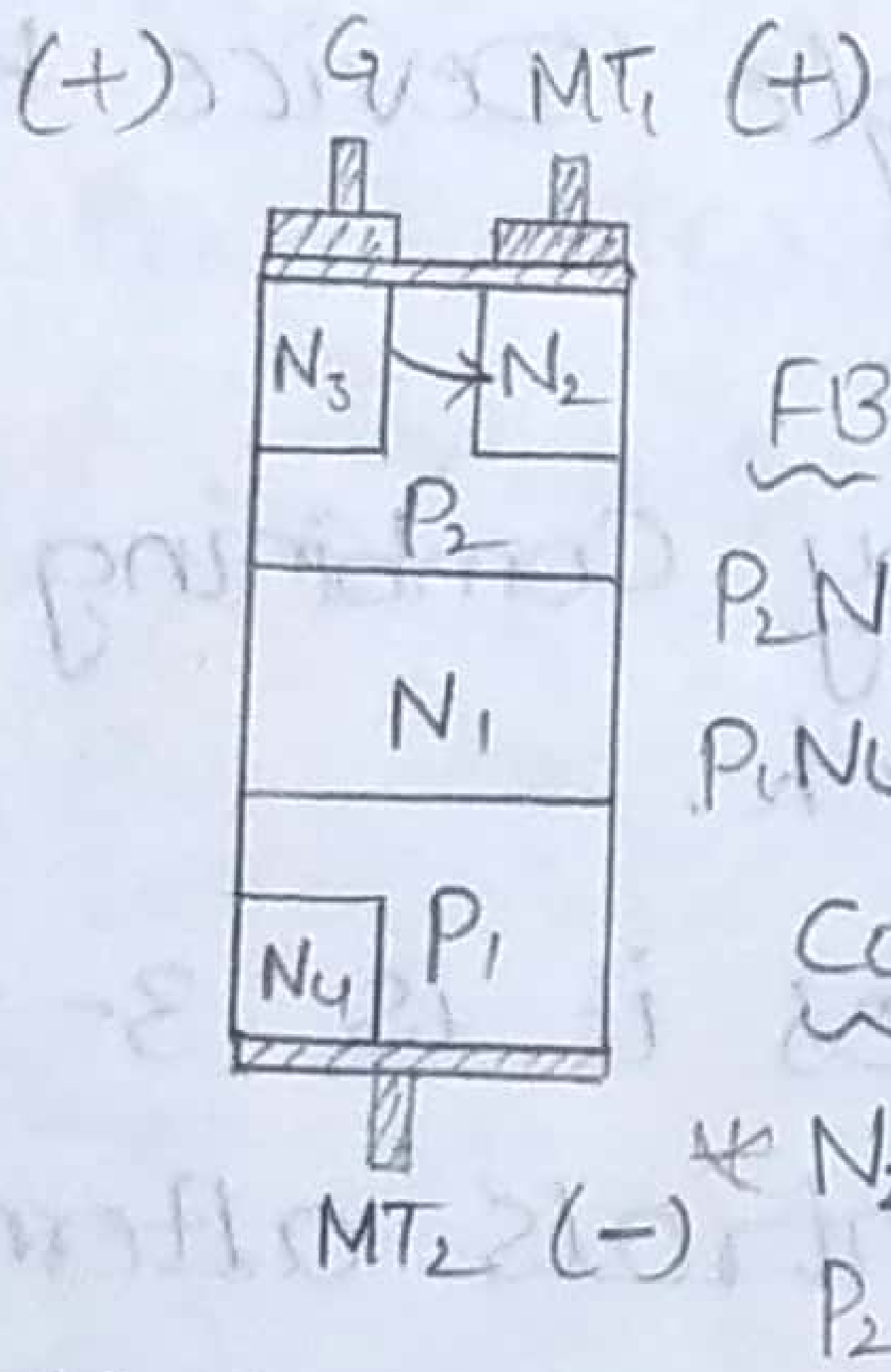
RB: P_2N_1

Conduction:-

* $P_1N_1P_2N_3$ (Initial condu)

$P_1N_1P_2N_2$ * (final conduction)

Mode-2



FB: P_2N_1, P_1N_4

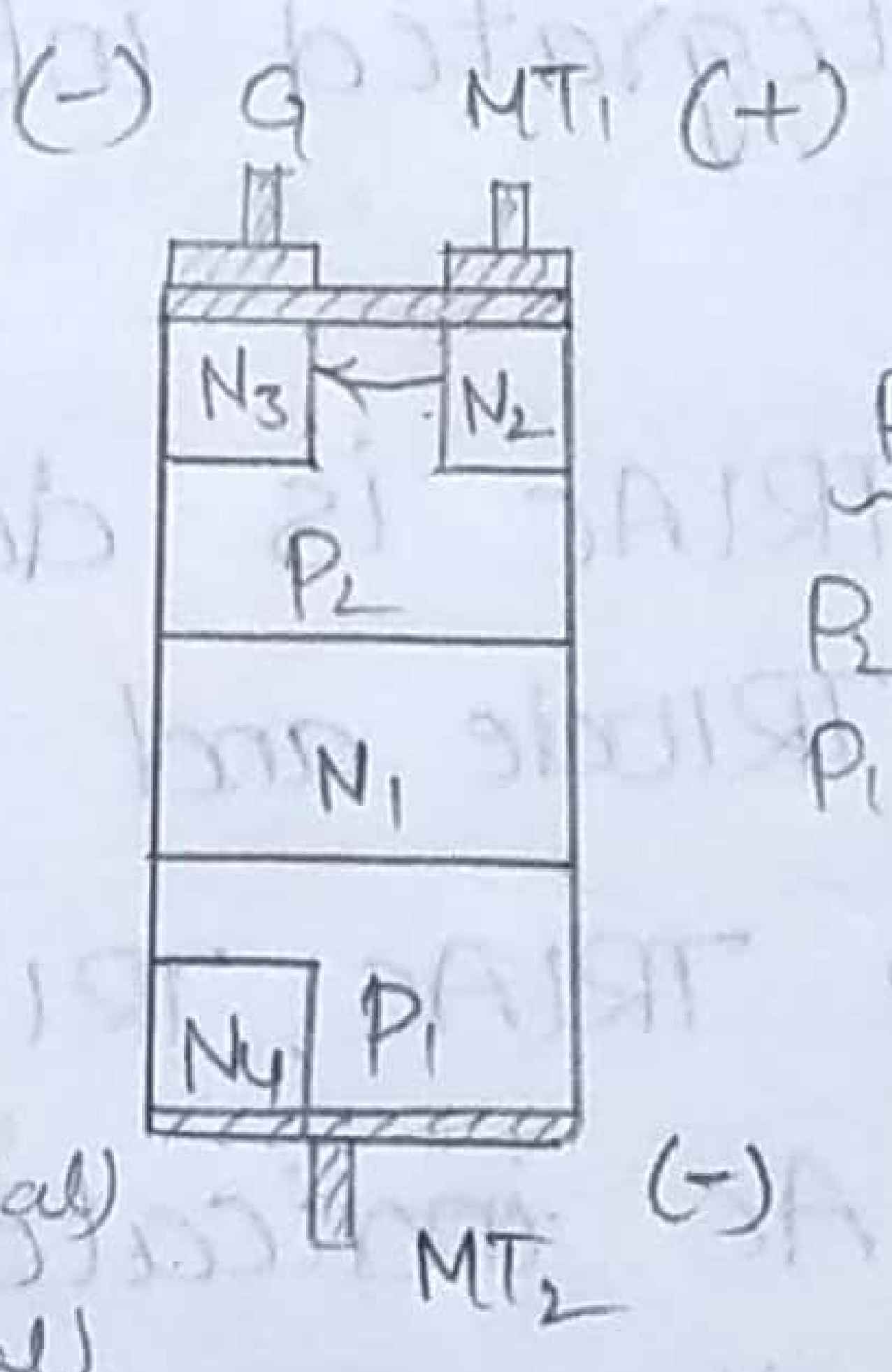
RB: P_1N_1.

Conduction:-

* $N_2P_2N_1P_1$ (Initial)

$P_2N_1P_1N_4$ (final) *

Mode-3



FB: P_2N_1, P_1N_4

RB: P_1N_1

conduction:-

* $P_2N_1P_1N_4$ *

Mode-4.

→ Note:-

→ In the 4 modes, TRIAC is rarely operated in Mode-2 & 3 because in these modes TRIAC is more sensitive compared to Mode-1 & 4.

→ i.e., TRIAC mainly operated in Mode-1 & 4.

→ Advantages:-

(1) TRIAC is a Bidirectional Device i.e., Conducts in both directions.

(2) TRIAC is triggered by using either positive or Negative Gate Signals.

(3) TRIAC requires single Heat Sink of Slightly larger in size. where as two anti parallel SCR's requires two Heat Sinks.

(4) TRIAC has Very Small Switching frequency.

(5) Gate has no control once TRIAC is ON.

→ Disadvantages:-

(1) It has low $\frac{dv}{dt}$ rating, Compared with SCR's.

(2) TRIAC's are available in low ratings Compared to SCR's.

(3) Reliability of TRIAC is less.

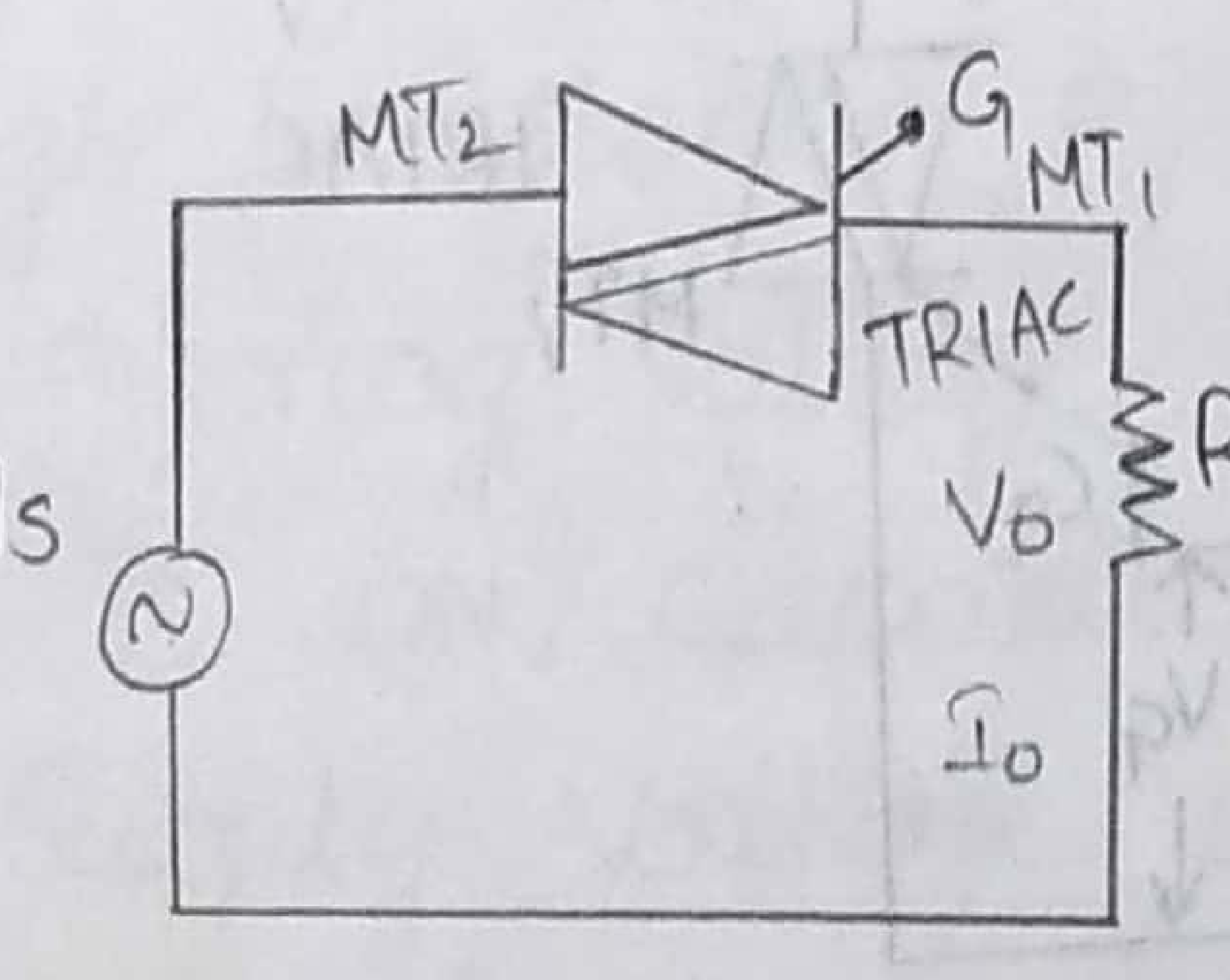
→ Applications:-

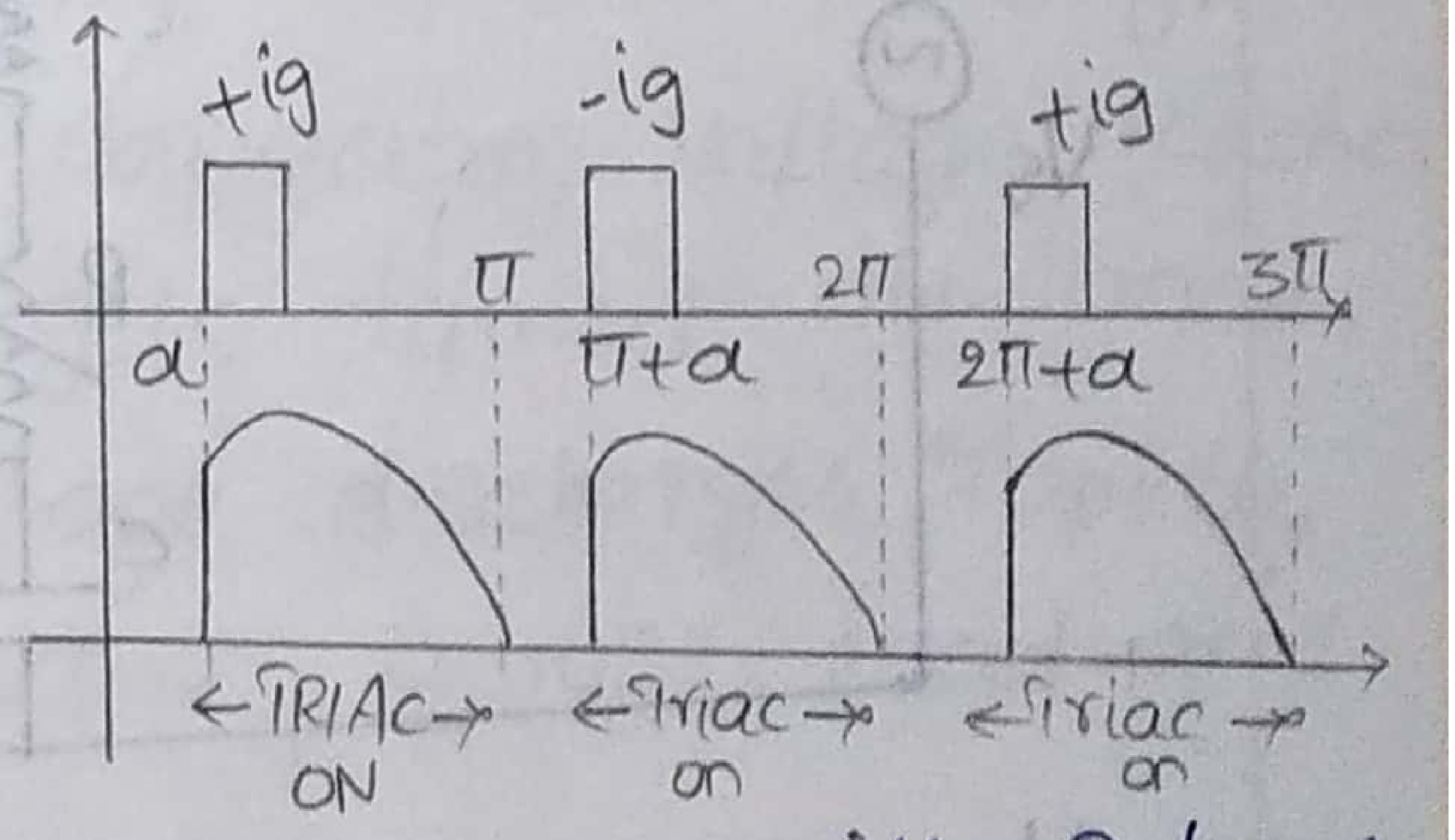
(1) Used in Ac Voltage controllers, Heaters, fans ...

(2) Used as firing circuits for SCR's.

(3) Used for Speed control of Series Motors.

→ 1-Ø Ac Voltage Controller using TRIAC; R-Load:-





→ waveforms and formulae for 1-Ø AcVc with R-Load with TRIAC is same as 1-Ø AcVc with R-Load using Two Antiparallel SCR's.

→ $T_1 = T_2 =$ ON = TRIAC = ON. [But mention, Gate currents as +ve for 1st Mode & -ve for 4-Mode]

→ 1-Ø ACVC with RL-Load using TRIAC:-

→ The wave forms and formulae for 1-Ø ACVC with RL Load using TRIAC are same as 1-Ø ACVC using Anti parallel SCR's with RL-Load.

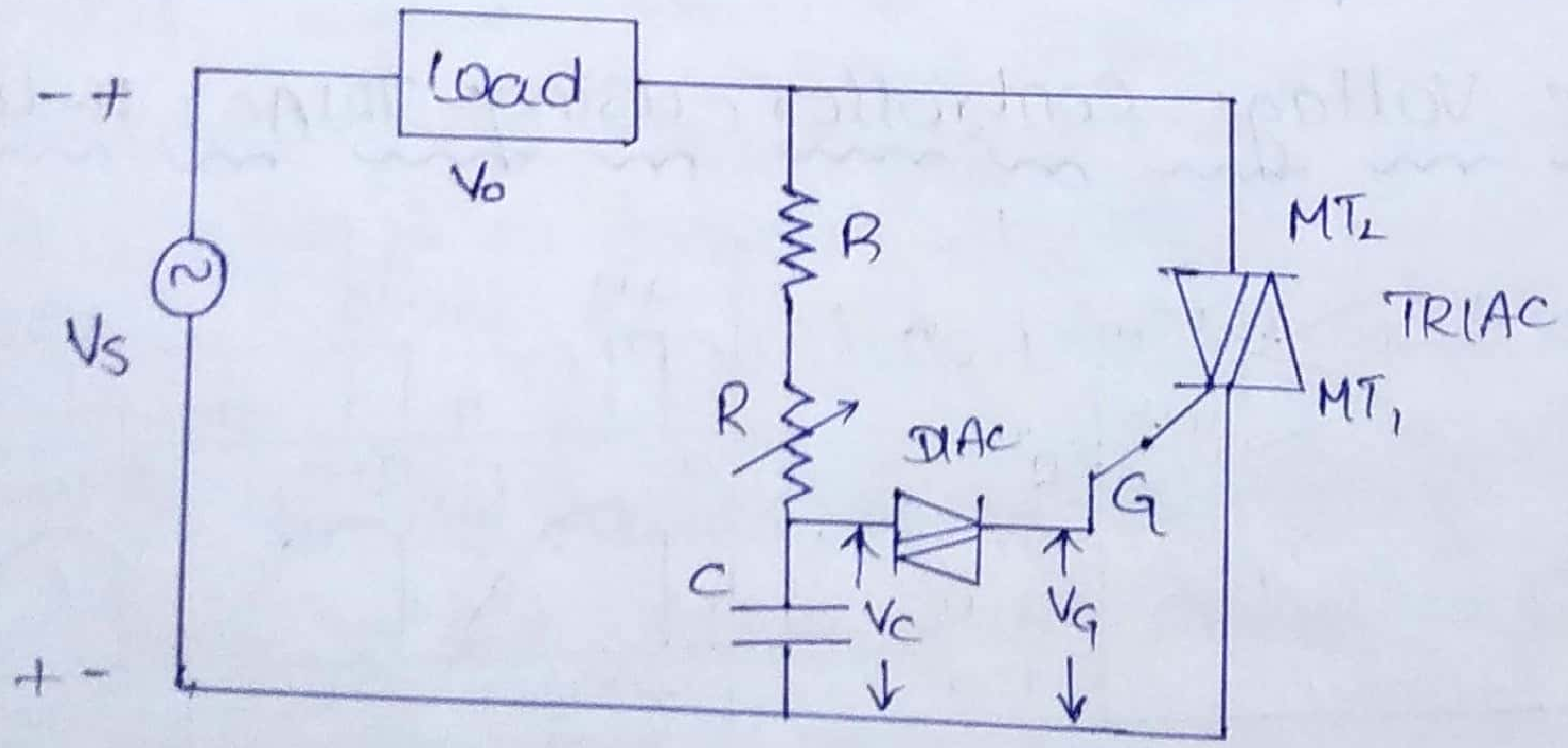
→ $T_1 = ON = T_2$; TRIAC = ON.

XXX → Diff between ACVC using TRIAC circuit and two Anti parallel SCR circuit:-

→ with two Anti parallel SCR's each SCR is fully off for complete half cycle where as with TRIAC circuit, TRIAC is turned off during the brief instant of time while load current falls to zero (i.e., $\alpha = \pi$, $\pi - (\pi + a)$. . . . .)

→ Firing Circuits:

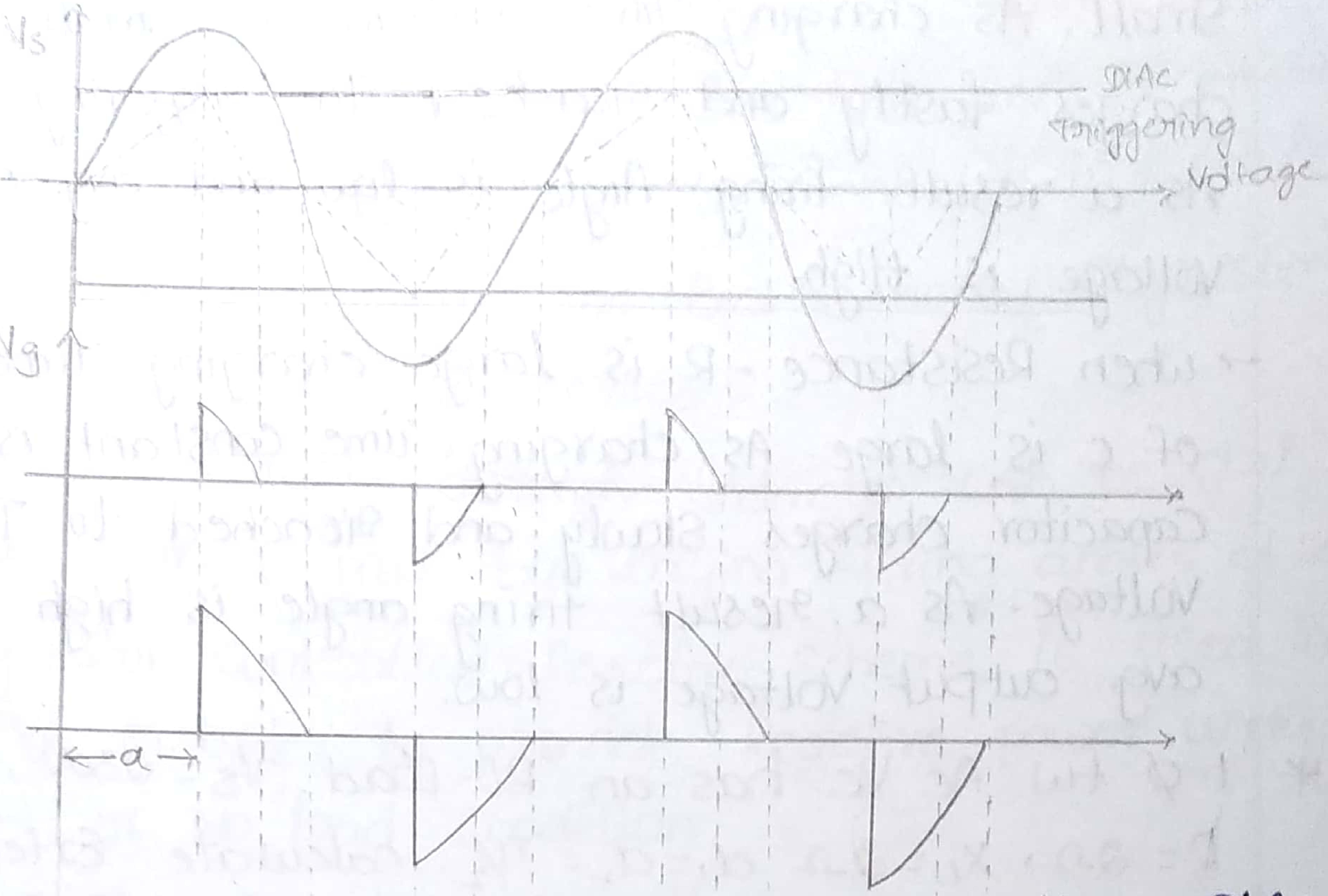
→ TRIAC firing circuit using DIAC:-



→ Here, TRIAC is Triggered with help of DIAC.

→ Resistance-R_1 is used to protect the DIAC and TRIAC, when Variable Resistance, R is zero.

→ During positive Half cycle, the capacitor charges through Resistance-R. when capacitor



Voltage reaches to DIAC Triggering Voltage, TRIAC gets Turned on.

- when TRIAC is ON, Capacitor discharges rapidly as shown in figure. once, TRIAC is ON Total supply Voltage will appear across the load shown in fig.
- At $\omega t = \pi$; the TRIAC gets Turned off naturally.
- During negative half cycle, the capacitor charges through Resistance R. when Capacitor Voltage reaches to Triggering Voltage, TRIAC gets turned ON. once TRIAC is ON, Capacitor Voltage discharges rapidly and Supply Voltage will appear across load and Shown in fig.(2).
- At $\omega t = 2\pi$: TRIAC gets turned off naturally.
- The Variable Resistance R is used to control the charging time of Capacitor.
- when R is Small, charging Time constant of c is

Small. As charging Time constant is Small, capacitor charges fastly and reached to Triggering Voltage. As a result firing Angle is low and avg. output Voltage is High.

→ when Resistance - R is large, charging Time constant of c is large. As charging Time constant is large. Capacitor charges slowly and reached to Triggering Voltage. As a result firing angle is high and avg. output Voltage is low.

* 1-ϕ fw Ac Vc has an RL-Load. $V_s = 230V$, 50Hz & $R = 2\Omega$, $X_L = 2\Omega$ $\alpha_1 = \alpha_2 = \pi/2$. calculate Extension angle until thyristor (which) conducts.

(ii) Conduction angles of Thyristors.

(iii) Vorms.

Sol:- Given, $V_s = 230V$.

$R = X_L = 2\Omega$.

$\alpha_1 = \alpha_2 = 90^\circ$.

$$\therefore \sin(\beta - \phi) = \sin(\alpha - \phi) \cdot e^{\frac{R}{\omega L}(\alpha - \beta)}$$

$$\Rightarrow \phi = \tan^{-1}\left(\frac{X_L}{R}\right) = \tan^{-1}\left(\frac{2}{2}\right) = 45^\circ.$$

$$\Rightarrow \sin(\beta - 45^\circ) = \sin(90 - 45) \cdot e^{\frac{2}{2}(90 - \beta)}$$

$$\Rightarrow \sin(\beta - 45) = 0.707 \cdot e^{(90 - \beta)}$$

$$\alpha > \phi$$

The approximate formula for Extension Angle

$$*/ \beta = \pi + \phi - 5^\circ /*$$

$\therefore$ (1) $\beta = 180 + (45 - 5^\circ)$

$\therefore \beta = 220^\circ$ //

- **Thyristor Controlled Reactors:-**
- It Consists of Switched Inductors and Bidirection Thyristor Switches (two SCR's connected in anti (ll)
- Here fixed Inductor and Bidirectional Thyristor switch connected in series.
- Current flowing through Inductor can be ctrl from zero to max. by varying firing angles of SCR
- Thyristor controlled Reactor scheme is used in EHVL in order to provide Reactive power under light or No load Condition.
- **Thyristor Switched Capacitor:-**
- It Consists of fixed Capacitor and Bidirectional Thyristor switches and both are connected in series.
- The current through capacitor is controlled from [zero to max by fα]
- Thyristor Switched Capacitor scheme is used in EHVL in order to provide Reactive power under Heavy load conditions.