Power Electronics

(i) SCR (ii) Phase controlled rectifiers
(iii) Inverters (iv) Choppers.

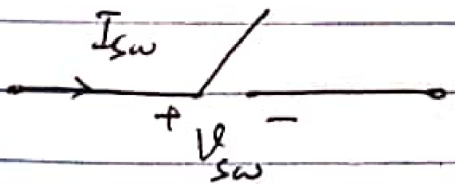
Power electronics ?
(i) controls the flow of power in a circuit.
(ii) conditioning of power.

To control → switches → power semiconductor devices.

Why control ?
To finish mismatch b/w supply and load.
eg AC supply → DC load.
↳ power electronics.

Switches

The difference b/w electrical and P.E circuits is only that of switches.



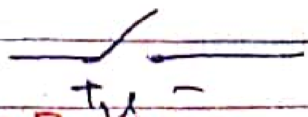
(i) Ideal case.

(a) When switch is closed

$V_{sw} = 0V$
I_{sw} = anything.

$$\text{Power loss} = V_{sw} I_{sw} = 0\ W$$

(b) when switch is open.



V_{sw} = anything
$I_{sw} = 0A$

Data: _ / _ / _

$\Rightarrow P_{sw} = 0\,W$

(c) Ideally, the time taken by a switch to turn ON or turn OFF is zero.

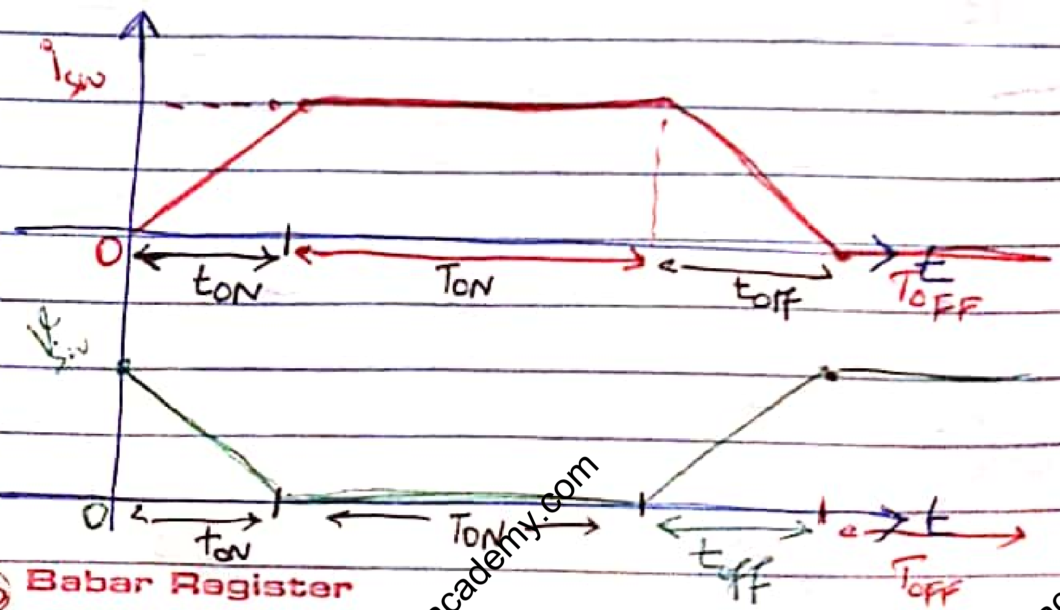
t_{ON} → time taken to turn ON the switch.
t_{OFF} → " " turn OFF " ".

ON → steady state ON   OFF → steady state OFF.
→ The voltage or current has reached its final value.

OFF → ON = t_{ON}
ON → OFF = t_{OFF}

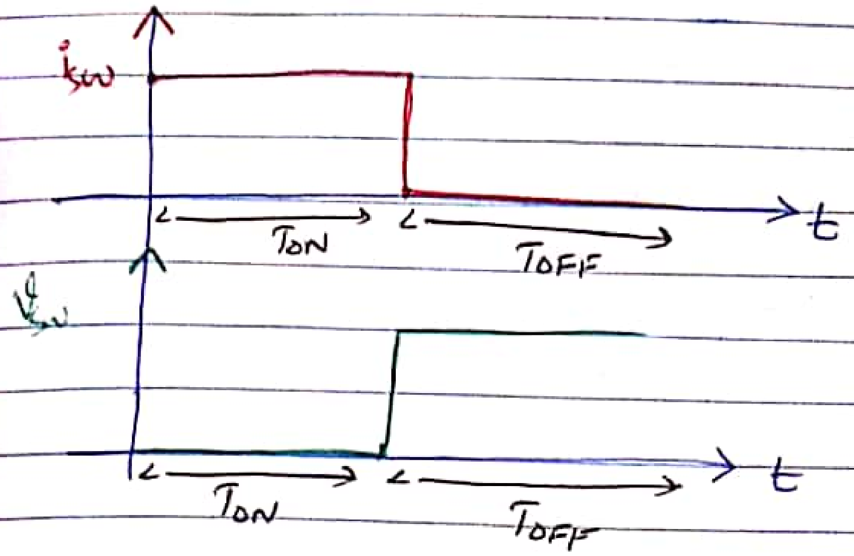
T_{ON} → The time during which the switch is under steady state ON condition.
T_{OFF} → time " " steady state OFF ".

For ideal switch → $t_{ON} = 0\,sec$
→ $t_{OFF} = 0\,sec$

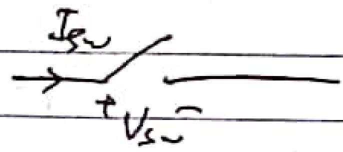


Date: / / Day

For ideal switch;

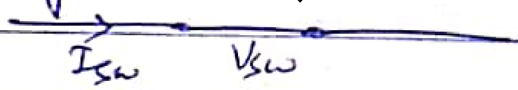


(II) <u>Practical Case</u>



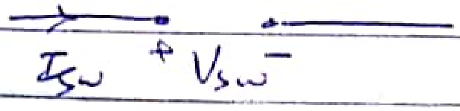
(a) ON state

practically there will be some drop across V_{sw}.



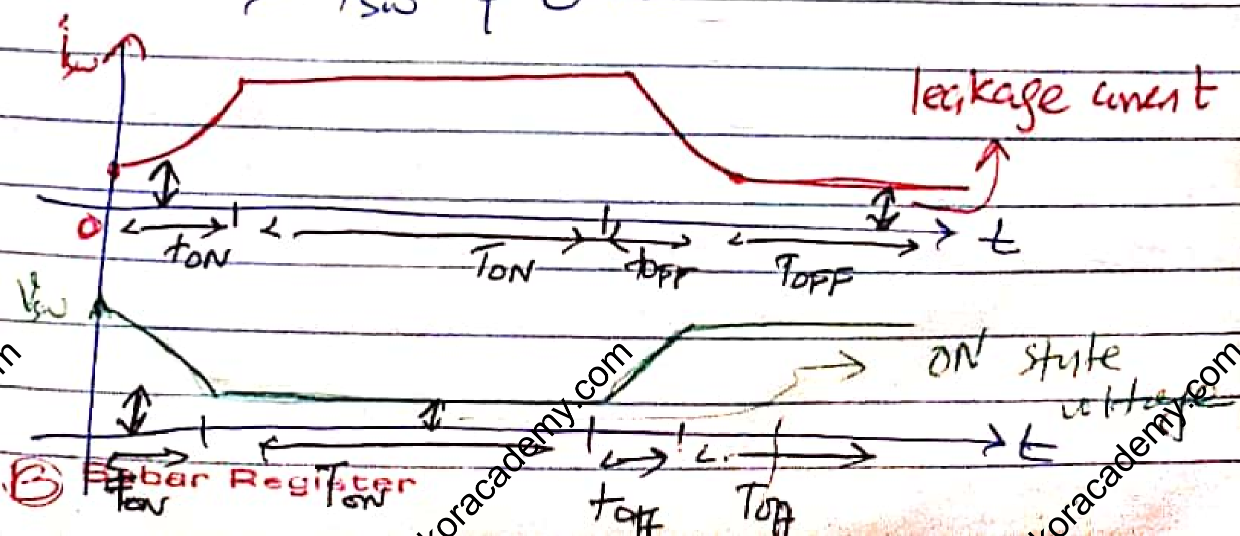
$\Rightarrow P = V_{sw} \cdot I_{sw} \neq 0\,W$

(b) OFF state



Here $I_{sw} \neq 0$
↳ leakage current

$\Rightarrow P_{sw} \neq 0\,W$



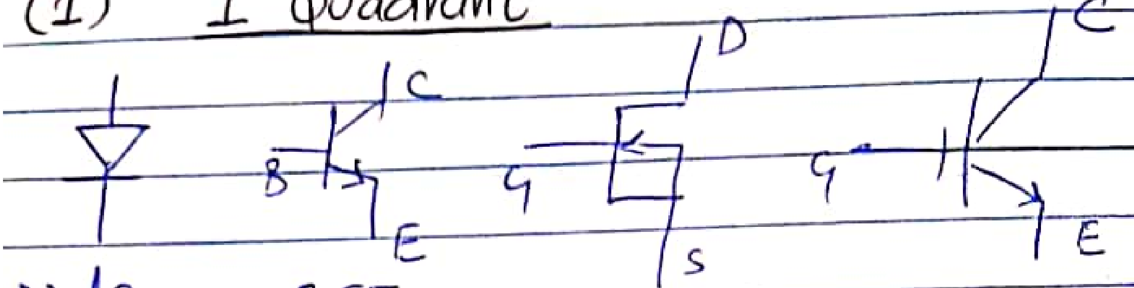
Date: / /

Quadrant Operation of Switches

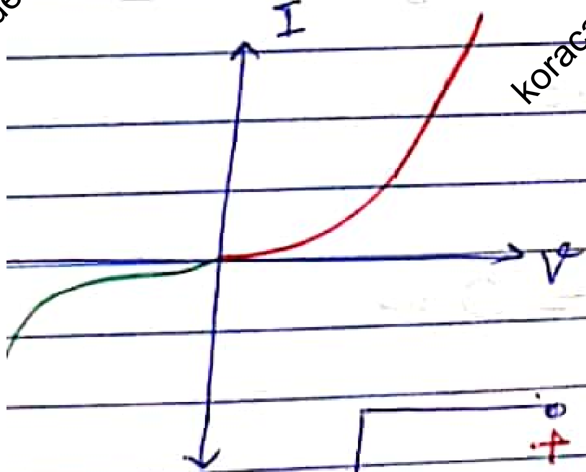
1 quadrant, 2 quadrant, 4 quadrant
No 3 quadrant.

The characteristics are I_{sw} vs V_{sw}

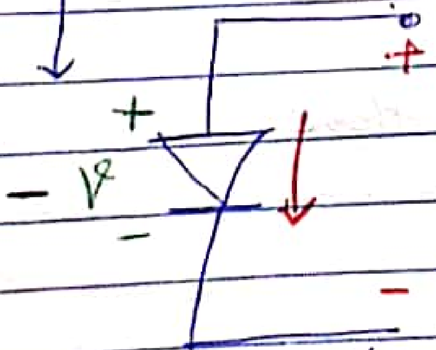
(1) 1 Quadrant

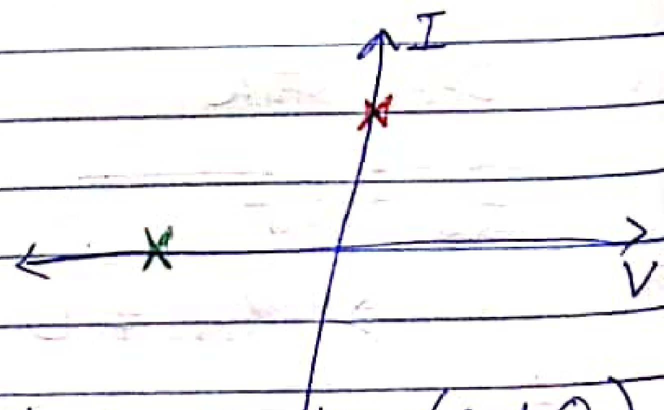


Diode current controlled



Current flows from anode to cathode → diode is ON.
↳ anode = +ve cathode = -ve
current flows from cathode to anode → diode is OFF.

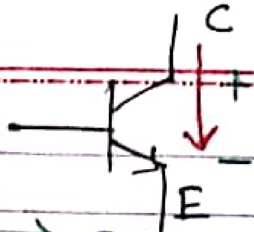


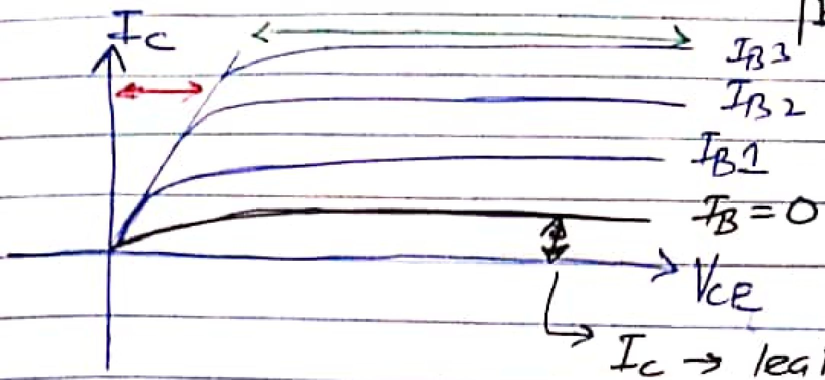


So this is a 1 quadrant operation (2nd Q)
which means → diode is a unidirectional current flow device → ON
→ diode is a unipolar device.] OFF
blocks negative voltage

Date: / / Day

BJT voltage controlled





↳ I_C → leakage current value

↳ cut off region

↓ OFF switch

↳ V_{CE} ↑ I_C ↓

saturation region.

Active / amplification region

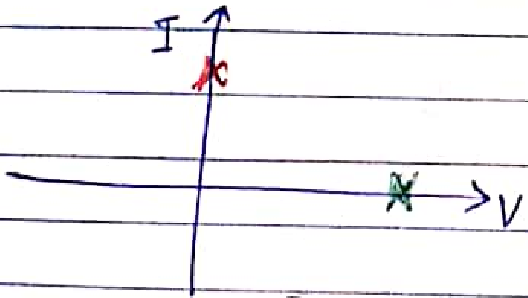
↳ amplifiers

↳ ON switch

↳ V_{CE} ↓ I_C ↑

BJT → +ve I flows → I_C → ON

↳ blocks +ve voltage → V_{CE} → OFF



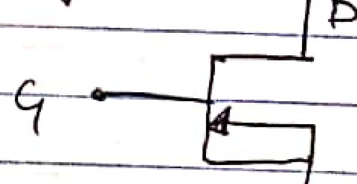
Single quadrant

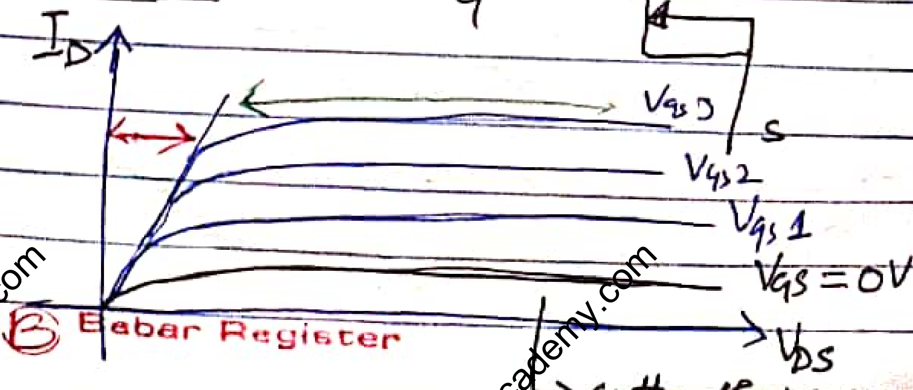
BJT → unidirectional current

Unipolar device

BJT is called bipolar in sense of mejority and minority carriers.

FET





Saturation

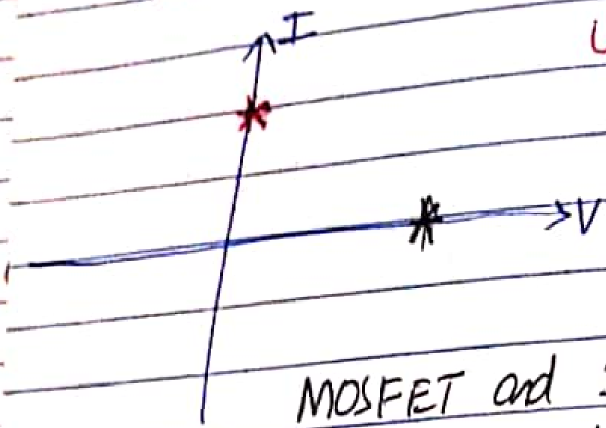
Active

↳ cutt off region

Date: / /

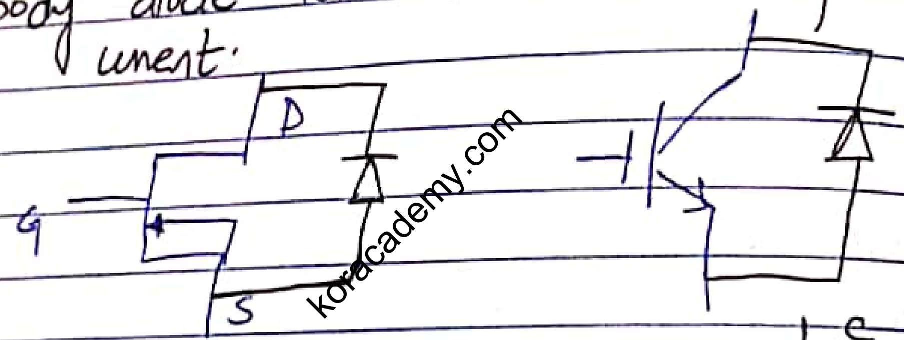
ON → saturation
current flows from D to S

OFF → cut off
voltage appears across D and S



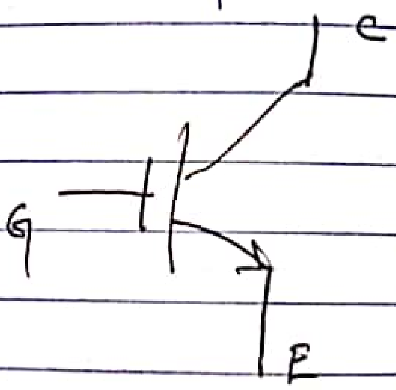
unidirectional current flow
Unipolar done

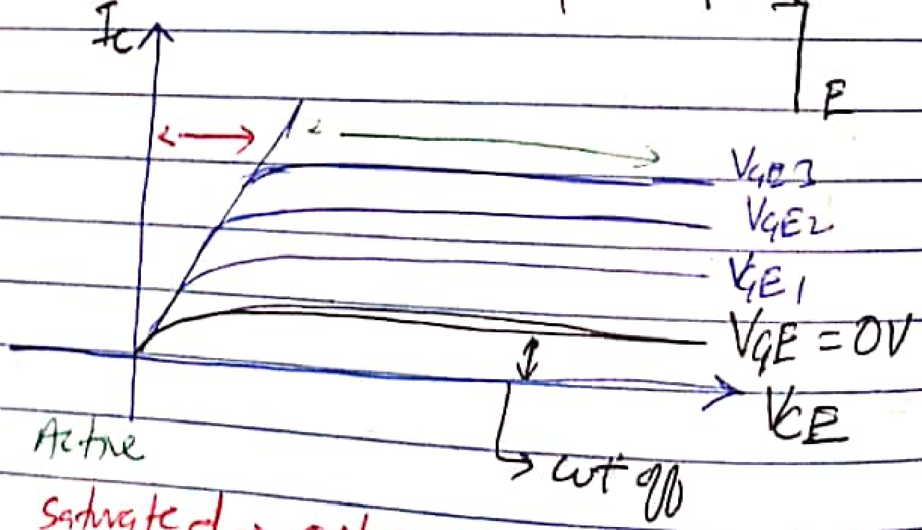
MOSFET and IGBT have internal body diode action → bidirectional flow of current.



IGBT

voltage controlled.



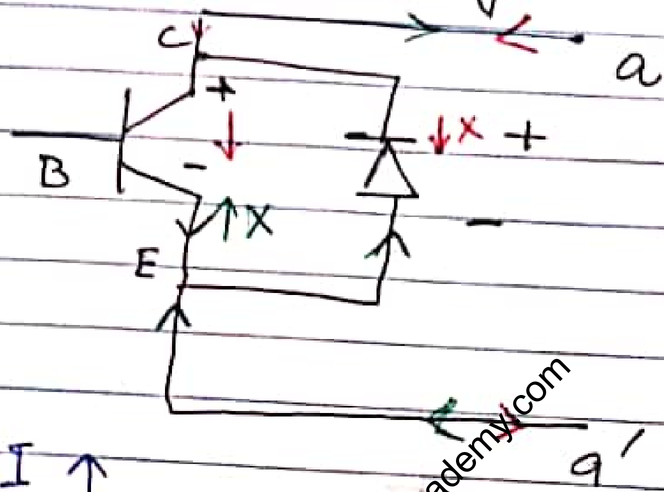


Saturated → ON → I_C flows → ideally $V_{CE} = 0$

OFF → $I_C = 0$, blocking voltage $= +V_{CE}$

unidirectional current flow direction
unipolar switch.

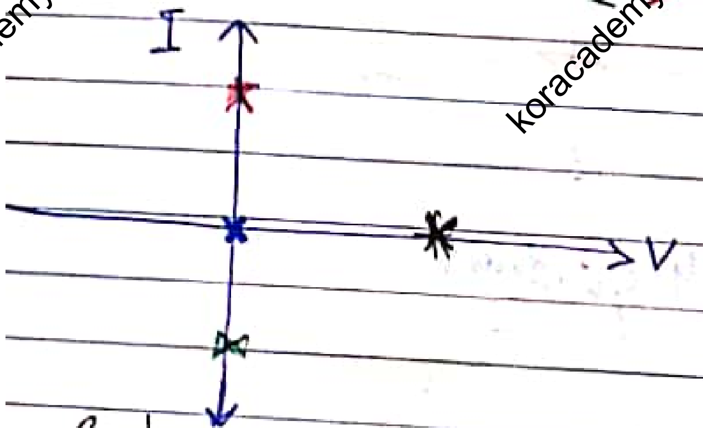
Consider the following.



Composite switch

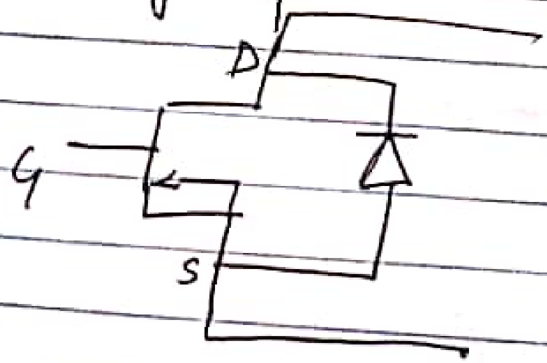
ON → voltage = 0
2 quadrant switch

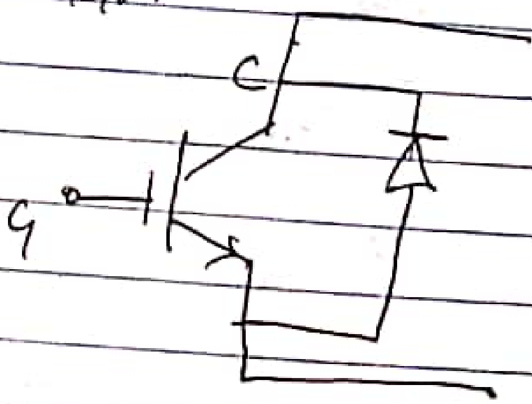
Bidirectional current flow.



Blocking single polarity
⇒ unipolar switch.

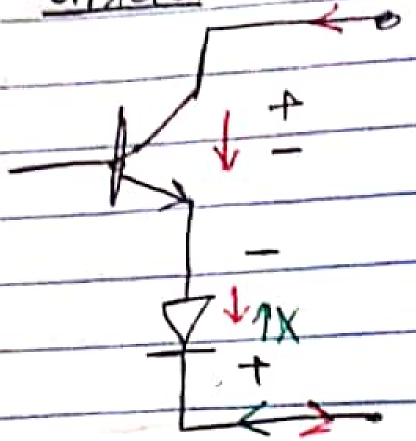
Similarly for MOSFET and IGBT.

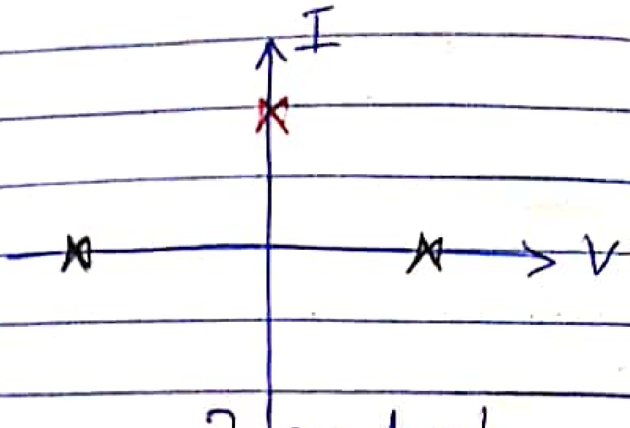




Application of these three?
Voltage source inverter.

Consider





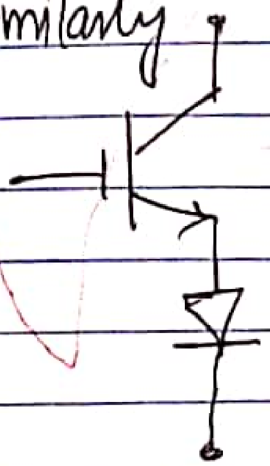
2 quadrant

Unidirectional current flow

no negative voltage

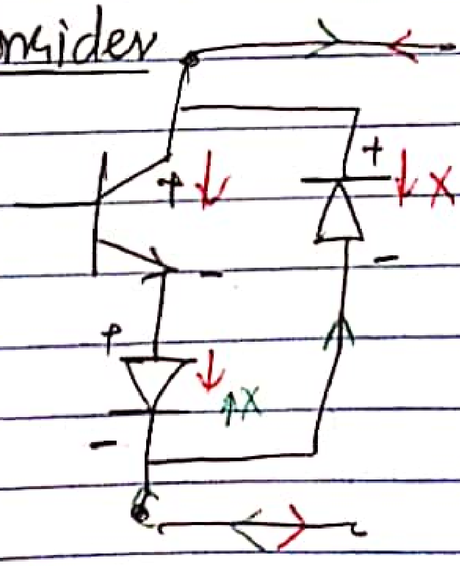
↳ Bipolar in nature.

Similarly

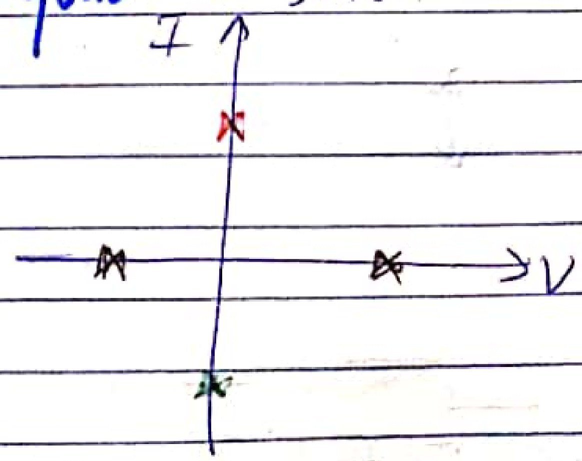


These two have the same [illegible] as the above

Consider



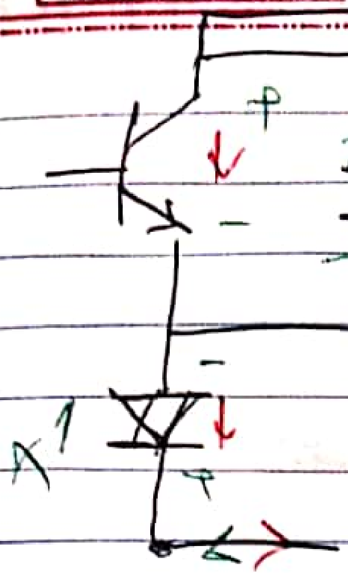
4 quadrant switch

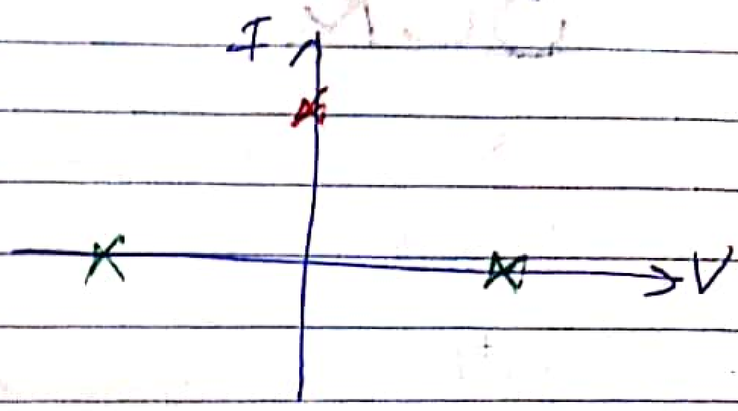


Bidirectional current flow

Bipolar switch → block both polarities

Date: / / Day ______





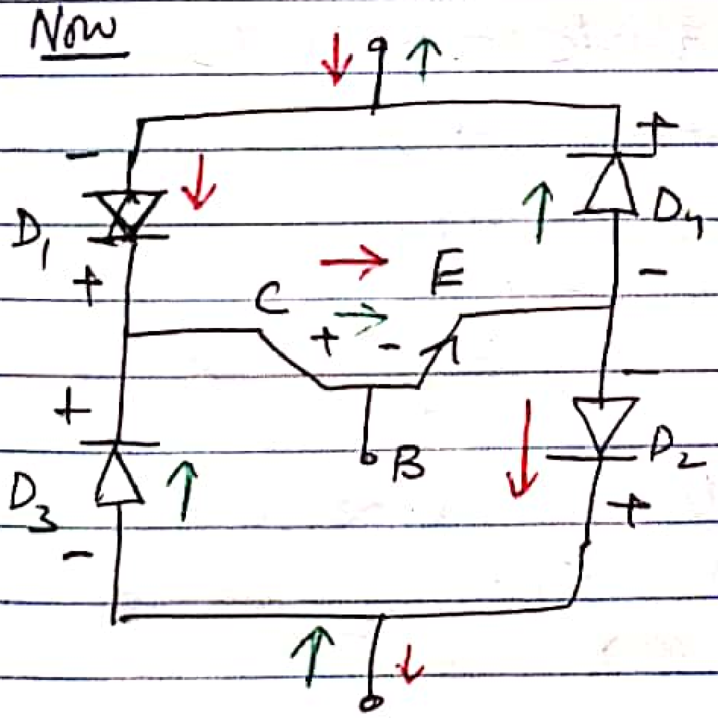
2 quadrant switch

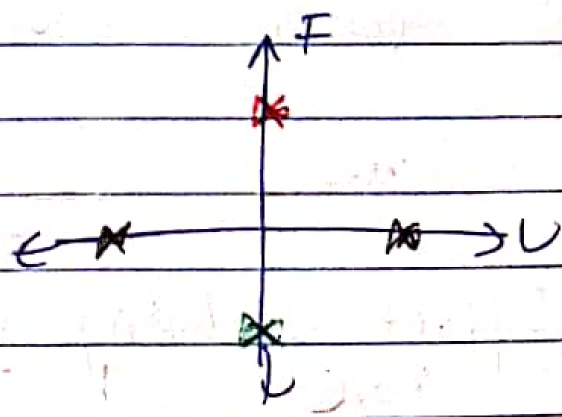
no negative current

unidirectional current.

Bipolar in nature and unidirectional current switches are used for current source inverters.

Now





bidirectional

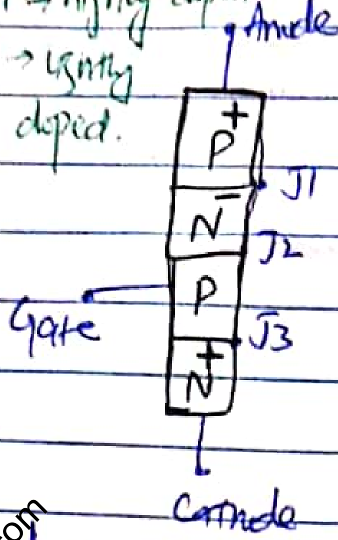
4 quadrant switch bipolar.

Date: / / 29/10/19

SCR

- SCR is a 4 layer device → 3 junctions.

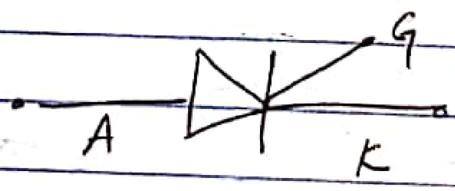
+ → highly doped
- → lightly doped.



- SCR is a 3 terminal device.
  A, K → princi. terminals
  G → control terminal
- SCR is a half controlled device.
  ↳ turn ON is controlled
- SCR is a DC switch
  ↳ unidirectional switch
  does not mean that DC supply ← but allows current in one directn.

- Current flows from anode to cathode. (diode is also a DC switch)

Symbol



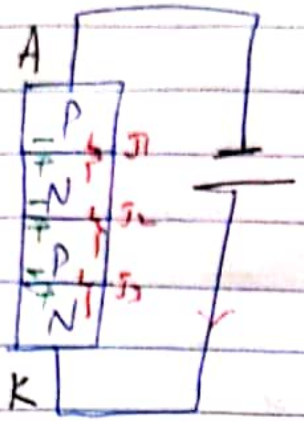
Effect of doping ?
More doped portion contributes less in the formation of depletion layer

Function of SCR.
It has three modes of operation
(i) Reverse blocking mode. (R.B.M)
(ii) Forward blocking mode. (F.B.M)
(iii) Forward conduction mode (F.C.M)

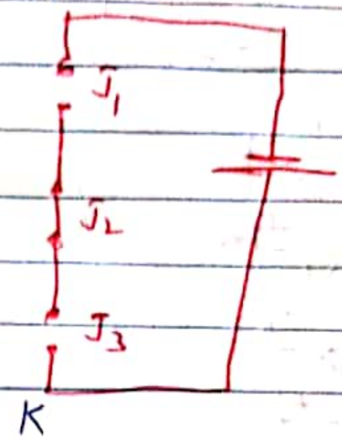
Date: / / Day

(1) RBM

$J_1 \rightarrow R.B$ $J_2 \rightarrow F.B$
$J_3 \rightarrow R.B$



⇒



$I = 0$

Ideally $I_{AK} = 0$

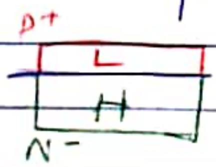
Practically I_{AK} = Reverse leakage current.

What will block the voltage V ?

Both the R.B junctions will block.

But ; which junction blocks more and which does less ?

↳ depends on the width of depletion layer.



~~Width of J1 is greater so more portion of the voltage is blocked by it.~~

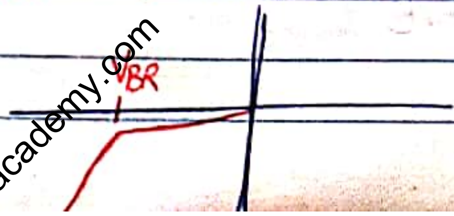
We want current to flow.

↳ Breakdown should occur at both the junctions.

↳ increase the reverse voltage continuously.

↳ Blocking voltage of both junctions will increase.

rapid current flows ← breakdown ↵



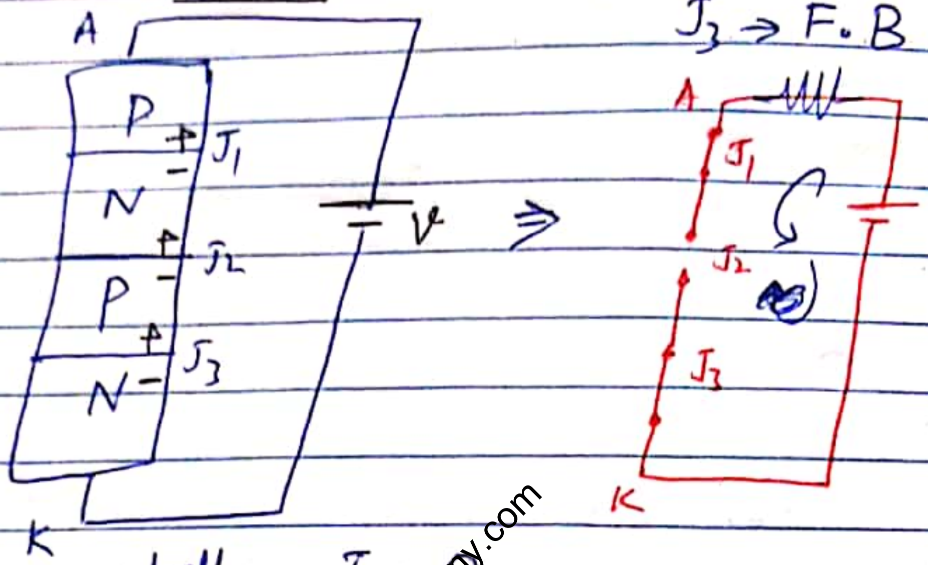
Baber Register

Date: / /

So in R.B.M the SCR acts as an OFF switch.

(ii) **F.B.M**

$J_1 \rightarrow F.B$, $J_2 \rightarrow R.B$, $J_3 \rightarrow F.B$



ideally $I_{AK} = 0$

Practically I_{AK} = Forward leakage current

Total voltage is blocked by junction J_2

For current to flow,

increase the voltage V, until breakdown occurs at the junction.

↳ forward current starts flowing.

So again in F.B.M SCR acts as an OFF switch.

(iii) **F.C.M**

Keep on increasing V → breakdown at J_2

→ current starts flowing from anode to cathode

↳ SCR has come into forward conduction mode

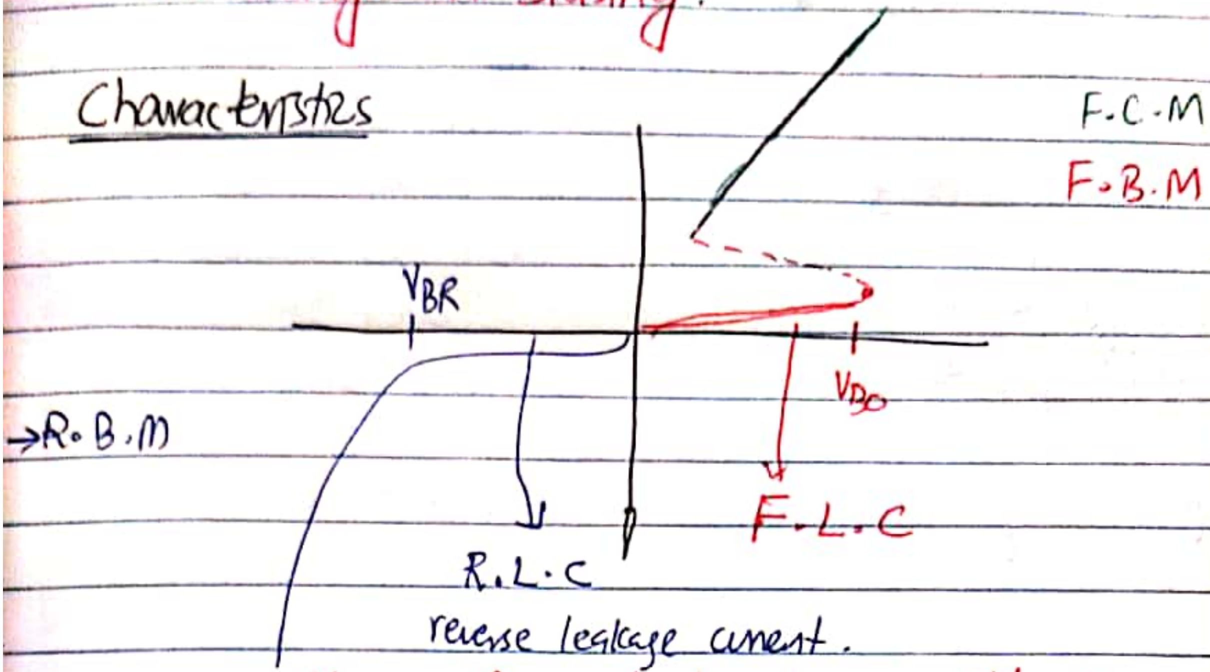
$J_1 \rightarrow F.B$ $J_2 \rightarrow R.B$ $J_3 \rightarrow F.B$

↳ achieving breakdown

Date: / / Day ______

No change in biasing.

Characteristics



reverse leakage current.

V_{BO} → forward breakover voltage

in conduction state anode to cathode voltage is very low almost zero (so KVL is not satisfied)
↳ it is never like this → there is always a limiting resistance.

{ $V_{AK} > V_{BO}$ → F.C.M
{ $V_{AK} < V_{BO}$ → F.B.M

Before seeing latching and holding currents we see:

Triggering Methods of SCR

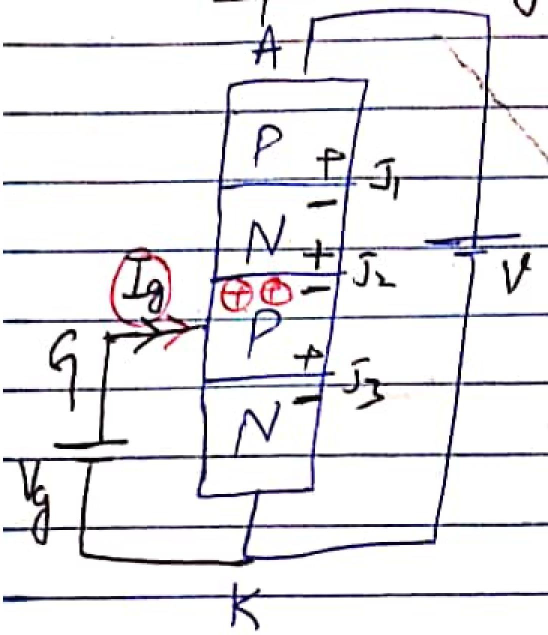
How to turn on SCR

↳(i) Supply voltage method.
it is not advisable.

Date: / /

31/10/19

(ii) Gate trigerring



Before trigerring first of all forward bias the SCR ie it should be in the forward blocking mode.

ie A = +ve K = -ve

Now connect the gate terminal to a supply.

Ig is entering +ve charge into the J2 in the p layer.

↳ So it will neutralize the already present -ve charges.

↳ will reduce its width → so the required amount of voltage to break J2 will decrease.

~~$V_{BO} \propto \frac{1}{\text{width of } J}$~~

$V_{BO} \propto$ Width of junction

~~Injected charge~~ $\propto \frac{1}{J2\ \text{width}}$

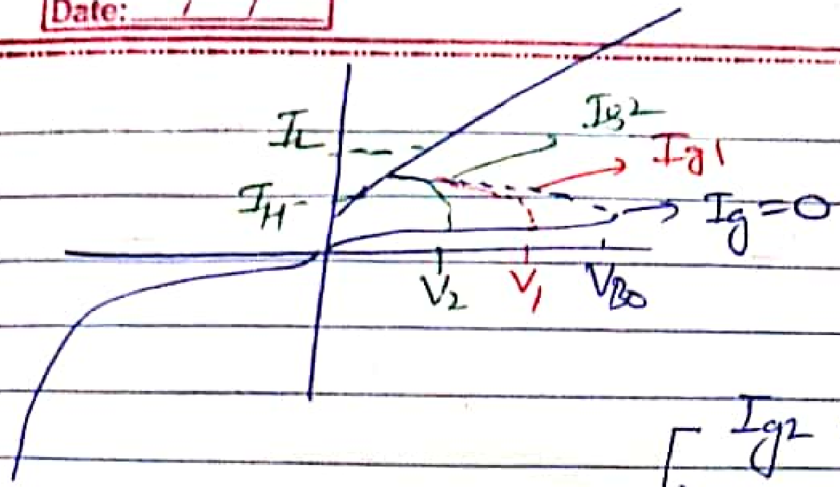
↓

$\propto \frac{1}{V_{BO}}$

How to increase charge?

$q = it$ i↑ or t↑

Date: / /   Day



$$\left[\begin{array}{c} I_{g2} > I_{g1} \\ V_2 < V_1 \end{array} \right]$$

Latching Current

The amount of anode to cathode current above which the SCR is in ON state.

if $I_{AK} \geq I_L \rightarrow$ SCR in F.C.M $\rightarrow$ ON.

Holding Current

The amount of current below which if there is anode to cathode current in SCR so the SCR goes into Forward blocking state.

$I_{AK} < I_H \rightarrow$ SCR in F.B.M $\rightarrow$ OFF

In b/w I_L and I_H, it is in transient state where we cannot decide wheter it is turning ON on turning OFF.

I_L and I_H are provided by man-ufactures.

$$I_L > I_H$$

Date: / /

$\frac{I_L}{I_H} = 2$ to 3 for SCRs above 60A rating.

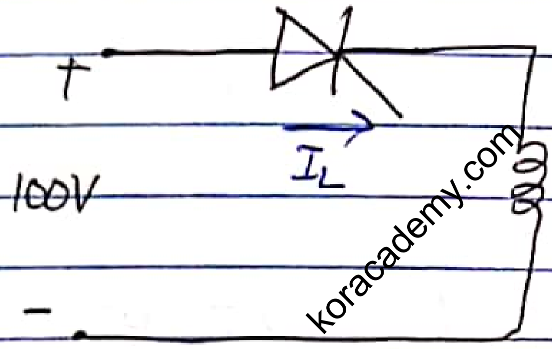
$\frac{I_L}{I_H} = 1.2$ to 1.8 for SCRs below 60A rating

The pulse width required (t)

$$t = \frac{L \times \text{inductor current}}{V_s}$$

→ This is not a formula (trick)

Q1.



latching current = 4mA

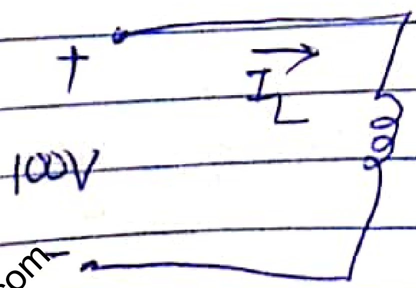
minimum pulse width required to turn ON SCR = ?

$$t = \frac{2 \times 4 \times 10^{-3}}{100} = \frac{8}{10^2} \times 10^{-3} = 8 \times 10^{-5}$$

$$\Rightarrow t = 80\,\mu s$$

Convential method

Minimum current $= I_L$ → SCR = ON → short circuit



$$V_L = L\frac{di}{dt}$$

$$100 = L\frac{di}{dt}$$

$$\int di = \int \frac{100}{L}\,dt$$

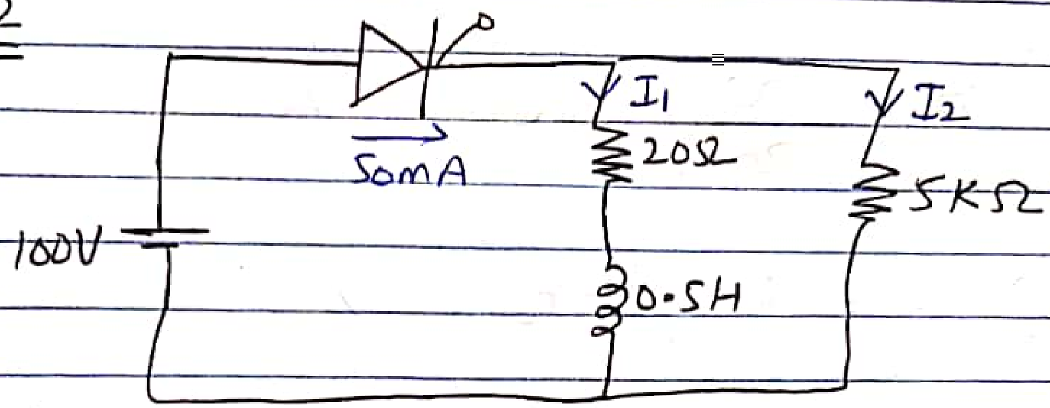
$$\Rightarrow i(t) = \frac{100}{L} \times t$$

Date: / / Day

$$t = \frac{L \times i(t)}{100} = \frac{2 \times 4 \times 10^{-3}}{100}$$

$$\Rightarrow t = 80\,\mu s$$

Q2



Latching current = 50mA

Minimum pulse width required = ?

Method 1 $t = \frac{L \times I_{ind}}{V_s} = \frac{0.5 \times I_1}{100}$ (1)

$I_L = 50mA \Rightarrow$ this is flowing through ~~inductor~~ SCR ↲ SCR is ON

Once SCR is ON, the potential at all three branches is the same ie 100 V.

$$\Rightarrow I_2 = \frac{100}{5000} = 20\,mA$$

$$\Rightarrow I_1 = 50 - 20 = 30\,mA$$

$$(1) \Rightarrow t = \frac{0.5 \times 30 \times 10^{-3}}{100} = 1.5 \times 10^{-2} \times 10$$

$$= 1.5 \times 10^{-4}$$

$$\Rightarrow t = 150\,\mu s$$

Date: / /

method 2

$$I_L = I_1 + I_2$$

$$50 \times 10^{-3} = \frac{V_s}{R_1}\left(1 - e^{-t/\tau}\right) + 20mA$$

$$30mA = \frac{100}{20}\left(1 - e^{-20t/0.5}\right) \qquad \tau = L/R$$

$$300 \times 10^{-3} = 5\left(1 - e^{-20t/0.5}\right)$$

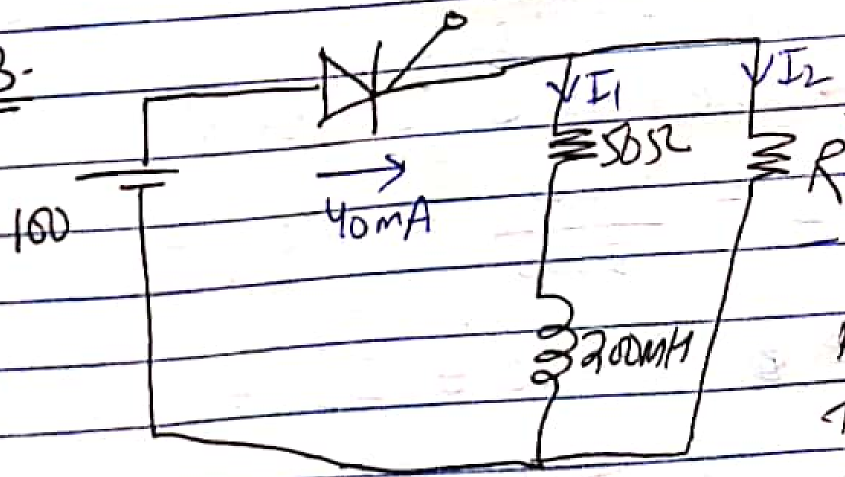
$$1 - e^{-20t/0.5} = 6 \times 10^{-3}$$

$$\ln\left(e^{-20t/0.5}\right) = \ln\left(1 - 6 \times 10^{-3}\right)$$

$$\frac{-20t}{0.5} = -6.01 \times 10^{-3}$$

$$\Rightarrow t = 150\,\mu s$$

Q3.



$I_L = 40mA$

$t = 50\mu s$

R → to ensure the reliable turn ON.

method 1

$$50 \times 10^{-6} = \frac{200 \times 10^{-3} \times I_1}{100}$$

$$\Rightarrow I_1 = 25mA$$

Hence $I_2 = 40 - 25 = 15\,mA$

Hence $R = \dfrac{V_R}{I_2} = \dfrac{100}{15 \times 10^{-3}}$

$\Rightarrow R = 6.67\ K\Omega$

Conventional method

$$I_2 = I_L - I_1$$

$$I_2 = 40 \times 10^{-3} - \frac{100}{50}\left(1 - e^{\frac{-50 \times 10^{-6} \times 50}{200 \times 10^{-3}}}\right)$$

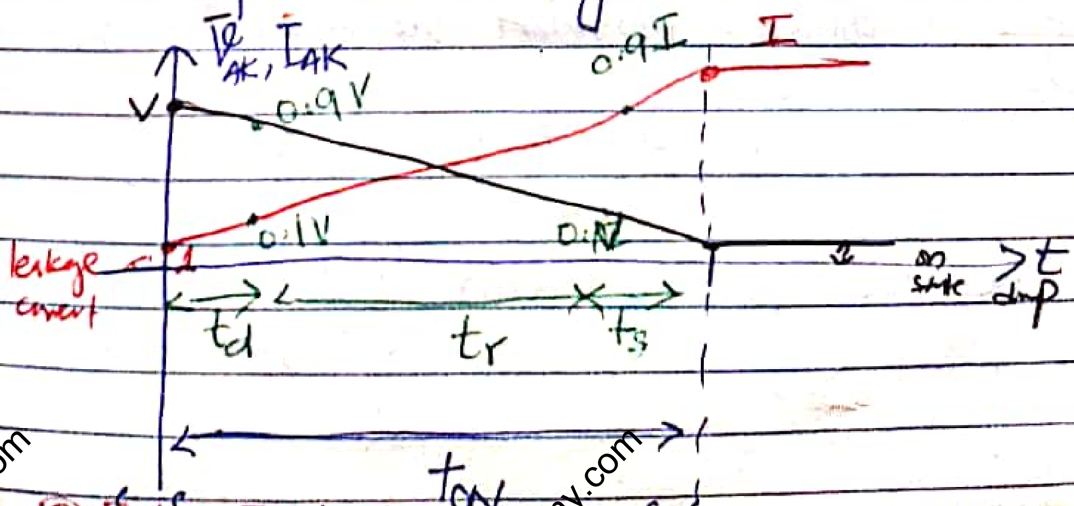
$\boxed{I_2 = 15.1\,mA}$ Sir $\rightarrow$ $I_2 = 16.5\,mA$

$R = \dfrac{100}{16.5 \times 10^{-3}}$

1/11/19 $\Rightarrow R = 6.06\ K\Omega$

Switching Characteristics of SCR

switch $\Rightarrow$ ON to OFF or OFF to ON.
↳ from one steady state to another.



S.S → S.S
$t_{ON} = t_d + t_r + t_s$ ON

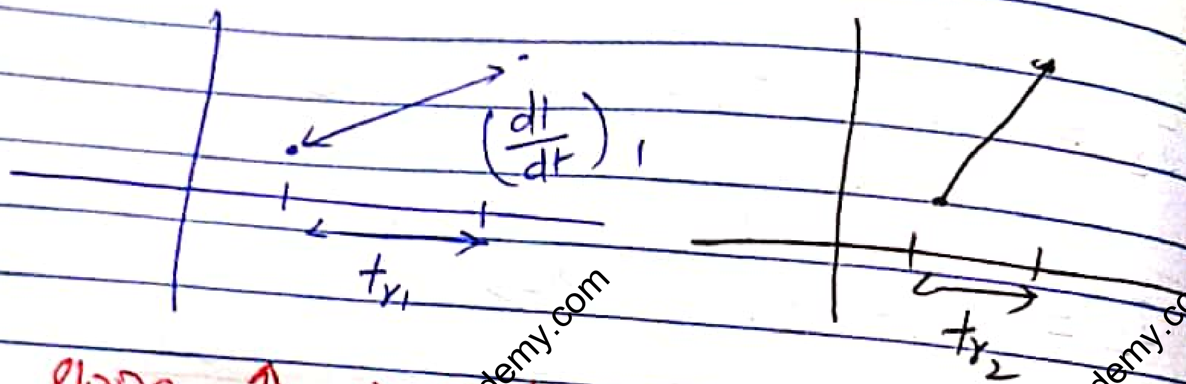
t_d → time delay r → rise s → spread

ton should be minimum for fast switching.

Dominant → t_r → most change.

For controlling ton control t_R.

slope → $\frac{di}{dt}$ i → I_{AK}



slope ↑ ⇒ x ↓ ⇒ t ↓

⇒ $\frac{di}{dt}$ ↑↑ $t_{r_2} < t_{r_1}$

For reliable turn ON $\frac{di}{dt}$ must be high.

But how much high?

↳ $\frac{di}{dt}$ is always provided by manufacturer.

let $\left(\frac{di}{dt}\right)_{specified}$.

let we are operating with $\left(\frac{di}{dt}\right)_{operated}$

$\left(\frac{di}{dt}\right)_{op} \gtrless \left(\frac{di}{dt}\right)_{sp}$ → SCR is safe → damage

Instantanous power = $P(t) = V(t)\, i(t)$

$$P_{avg} = \frac{1}{T} \int P(t)\, dt$$

$$p(t) = V(t)\, i(t) = \frac{d\, w(t)}{dt}$$

$$dw(t) = p(t)\, d(t)$$

$$w(t) = \int p(t)\, dt$$

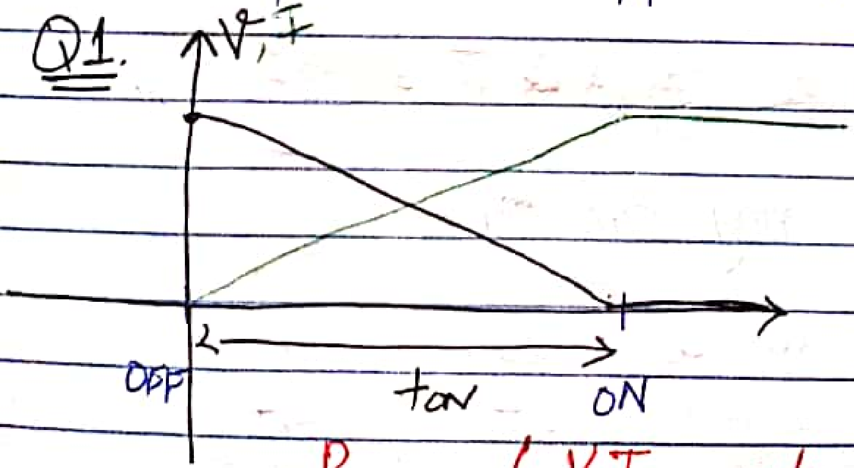
$$\Rightarrow \quad P_{avg} = \frac{w(t)}{T}$$

Time period is the position from where wave form repeats itself.
eg from going ON to ON.

ON ⟶ OFF ⟶ ON
t_{off} ↓ T_{OFF} t_{ON}

So time period = $t_{off} + T_{OFF} + t_{ON}$

Q1.



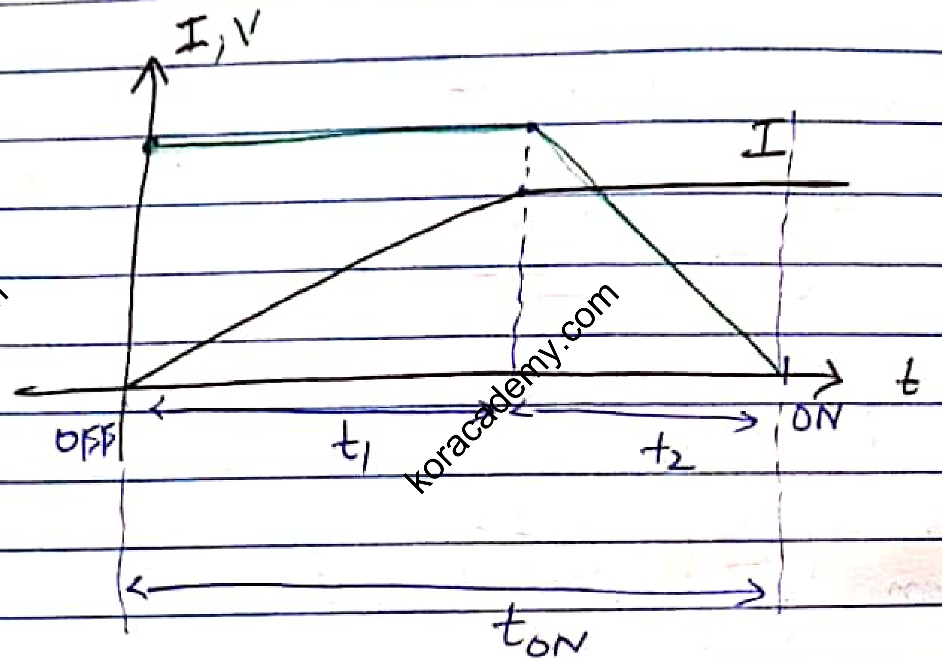
$$P_{avg} = \left(\frac{VI}{6} \cdot \frac{t_{ON}}{T} \right) \text{watt}$$

Data: / /

Energy = $P_{avg} \times T = \left(\frac{VI}{6} \cdot t_{ON}\right)$ joules

Q1 → was case 1 → in which voltage and current both were varying.

Q2 → case 2 → One varys the other is constant.



S.S. OFF ⇒ I = 0   S.S ON V = 0

$$P_{avg} = \frac{VI}{2}\left(\frac{t_{ON}}{T}\right)$$

$$\text{Energy} = P_{avg} \times T = \frac{VI}{2} \cdot t_{ON}$$

Q. SCR during turn ON

Anode Voltage   600 V   0V

Anode Current   0A   100A

Both are varying linearly

$t_{ON} = 5\mu s$ $f = 100Hz$ $P_{avg} = ?$

Date: / / Day

$T = \frac{1}{f} = \frac{1}{100}$ sec

As linearly $P_{avg} = \left(\frac{VI}{6} \times \frac{t_{on}}{T}\right)$

$= \left(\frac{600 \times 100}{6} \times \frac{5 \times 10^{-6}}{100}\right)$

$= 10^{6} \times 5 \times 10^{-6}$

$\Rightarrow P_{avg} = 5$ watt.

$E = P_{avg} \times T = 5 \times \frac{1}{100} = 5 \times 10^{-2}$ J

<u>Conventional approach</u>

$P_{avg} = \frac{1}{T} \int v(t)\, i(t)\, dt$

Expressions for $v(t)$ and $i(t)$.

$y = -mx + c$

$v(t) = \frac{-600}{t_{on}} \times t + 600$

$i(t)$ $y = mx + c$

$i(t) = \frac{100}{t_{on}} \times t + 0$

$\Rightarrow P_{avg} = \frac{1}{T} \int_0^{t_{on}} \frac{-600 \times 100}{t_{on}^2} \times t^2 + \frac{600 \times 100}{t_{on}} \times t$

$= \frac{600 \times 100}{T \times t_{on}} \left[-\frac{1}{t_{on}} \int_0^{t_{on}} t^2\, dt + \int_0^{t_{on}} t\, dt \right]$

Babar Register

$$= \frac{600 \times 100}{T \times t_{ON}} \left[\frac{-1}{t_{ON}} \left(\frac{t_{ON}^{3}}{3} \right) + \left(\frac{t_{ON}^{2}}{2} \right) \right]$$

$$= \frac{600 \times 100}{T \times t_{ON}} \times t_{ON}^{2} \left(\frac{1}{2} - \frac{1}{3} \right)$$

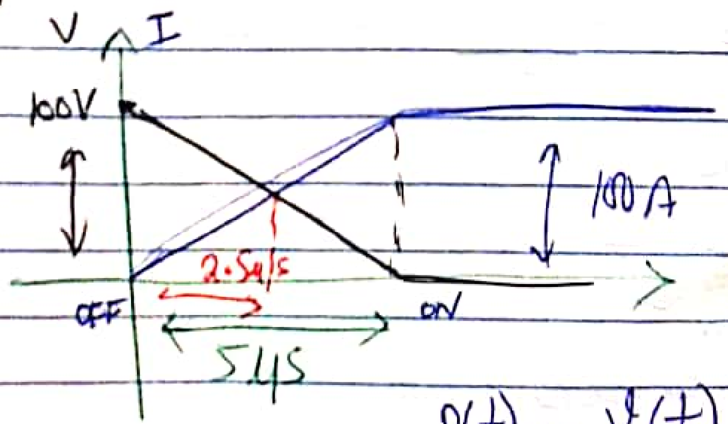
$$= \frac{600 \times 100 \times t_{ON}}{T} \left(\frac{3-2}{6} \right)$$

$$= \frac{600 \times 100}{6} \times t_{ON} \times \frac{1}{T}$$

$$= \frac{600 \times 100}{6} \times 5 \times 10^{-6} \times \frac{1}{100}$$

$$\Rightarrow P_{avg} = 5 \text{ watt.}$$

Q. For the switching waveform shown, state the condition at which the maximum power will occur.



$$T = \frac{1}{50} \text{ sec}$$

$$t_{ON} = 5\mu s$$

$$p(t) = v(t)\, i(t)$$

$$y = -\left(\frac{100}{t_{ON}} \right) \times t + 100 = V(t)$$

Date: / / Day

$$i(t) = \left(\frac{100}{t_{ON}}\right)t + 0$$

$$\Rightarrow P(t) = \frac{-100 \times 100}{t_{ON}} \times t^2 + \frac{100 \times 100 \times t}{t_{ON}}$$

t is the only variable → differentiate wrt t.

$$\frac{dp(t)}{dt} = 0 = \frac{-10^4}{t_{ON}^2} \cdot 2t + \frac{10^4 \cdot 1}{t_{ON}}$$

$$\frac{2t \cdot \times 10^4}{t_{ON}^{\not 2}} = \frac{10^4}{t_{ON}}$$

$$t = \frac{t_{ON}}{2} = \frac{5\mu s}{2}$$

$\Rightarrow t = 2.5\mu s$ → this is where maximum power will occur.

What is max power?

Put value of $t = 2.5\mu s$ in power equation.

$$P(t)_{max} = p(t)\Big|_{t=2.5\mu s} = \frac{-10^4 \times (2.5\mu)^2}{(5\mu s)^2} + \frac{10^4 (2.5\mu)}{(5\mu s)}$$

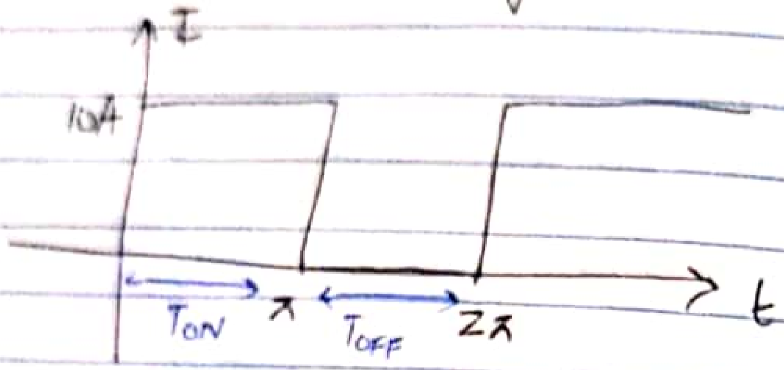
$$= -2499.98\ W \Rightarrow P(t) = 2.5\ kW$$

$$P_{avg} = \frac{100 \times 100}{6} \times 5 \times 10^{-6} \times 50$$

$$\Rightarrow P_{avg} = 0.416\ W$$

$$E = P_{avg} \times T = 8.32 \times 10^{-3}\ J.$$

Q. A MOSFET of rating 15A carries a periodic current as shown.
The ON state resistance of MOSFET is 0.15 Ω. The average ON state power loss?



$R_{ON} = 0.15\Omega$

A. $P_{avg} = I_{rms}^2 R = \left(\frac{10}{\sqrt{2}}\right)^2 (0.15)$

$\Rightarrow P_{avg} = 50 \times 0.15 = 7.50\ W.$

$I_{rms} = \text{Peak} \times \sqrt{\frac{\text{time for which exists}}{\text{total time period}}}$

As Here

$10 \times \sqrt{\frac{\pi}{2\pi}}$

Average

Power associated term is always RMS.

General approach.

$P(t) = \frac{1}{T}\int v(t)\ i(t)\ dt$

$P(t) = \int_0^T i(t)^2 R\, dt = \frac{1}{2\pi}\left[\int_0^{2\pi} i(t)^2 R\, dt\right]$

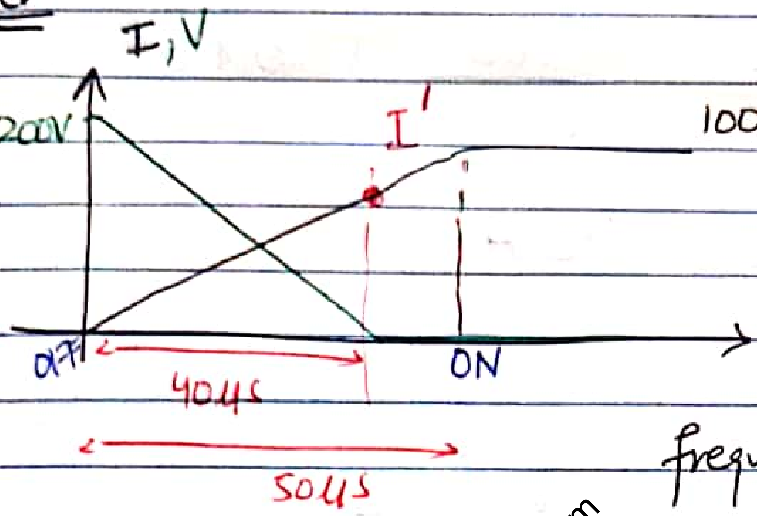
$= \frac{1}{2\pi}\left[\int^{\pi} 10^2 \times 0.15\, dt + \int_{\pi}^{2\pi} 0\ dt\right]$

Date: / / Day

$$= \frac{1}{2\pi} \times 100 \times 0.15 \left(t \right|_0^{\pi}$$

$$= \frac{100 \times 0.15 \times \pi}{2\pi} = 7.5\,W$$

Q.



If the P_{avg} loss is limited to 100W during its turn ON time. Then switching frequency will be ?

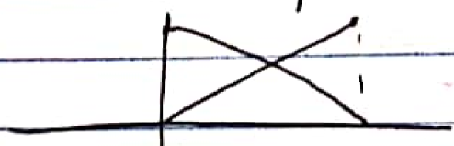
$P_{avg} = 100\,W$ during t_{ON}

$$P_{avg} = \frac{VI}{6} \times \frac{t_{ON}}{T}$$

X $$100 = \frac{200 \times 100}{6} \times \frac{50}{T}$$

$$\frac{1}{T} = \frac{100 \times 6}{200 \times 100 \times 50} \Rightarrow \frac{1}{T} = 6 \times 10^{-4}\,Hz$$

because this formula is for V↑ I0
I↑ V0



After I' there is no power loss; so modifying the above formula

$$100 = P_{avg} = \frac{200 \times I'}{6} \times \frac{40 \times 10^{-6}}{T}$$

We need to calculate I' first.

Babar Register

Date

$y = mx + c$

Equation $i(t) = \left(\frac{100}{50\times10^{-6}} \times t\right) + 0$

At $t = 40\mu s$ to find I'

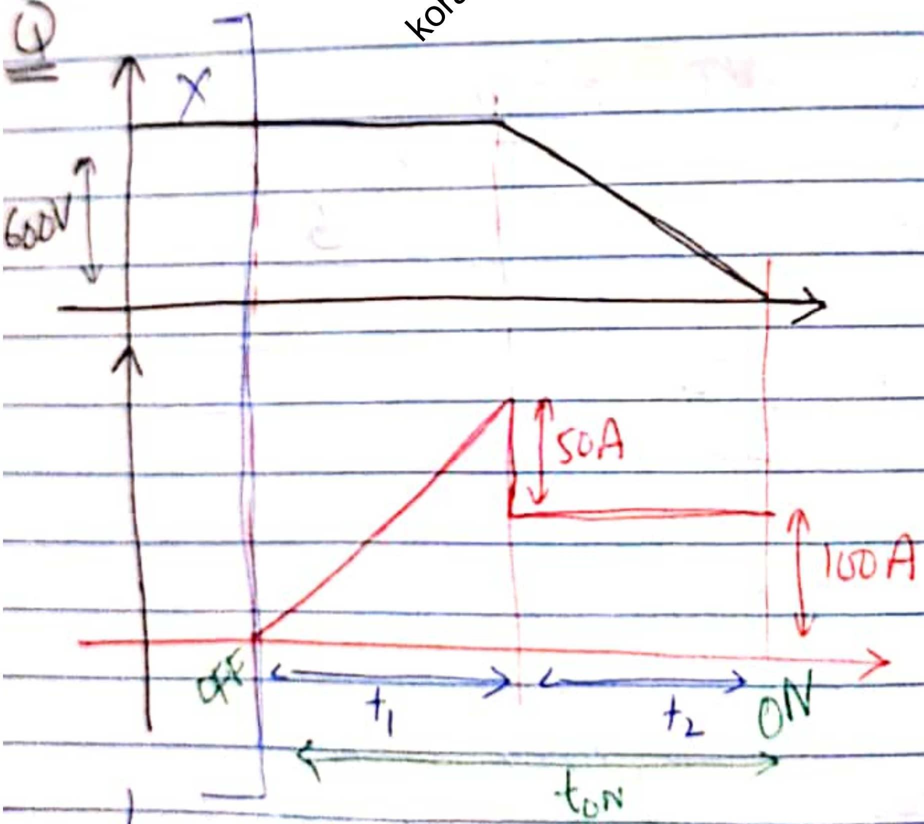
$i(40\mu s) = I' = \frac{100}{50\times10^{-6}} \times 40\times10^{-6}$

$\Rightarrow I' = 80 A$

$\Rightarrow P_{avg} = 100 = \frac{200\times80}{6} \times 40\times10^{-6} \times \frac{1}{T}$

$\Rightarrow \frac{1}{T} = f = 937.5 \ Hz.$

Q



↳ X → I = 0 → no power loss

$P = \frac{VI}{2} \frac{(t_1 + t_2)}{T} = \frac{VI}{2} \times \frac{t_{ON}}{T}$

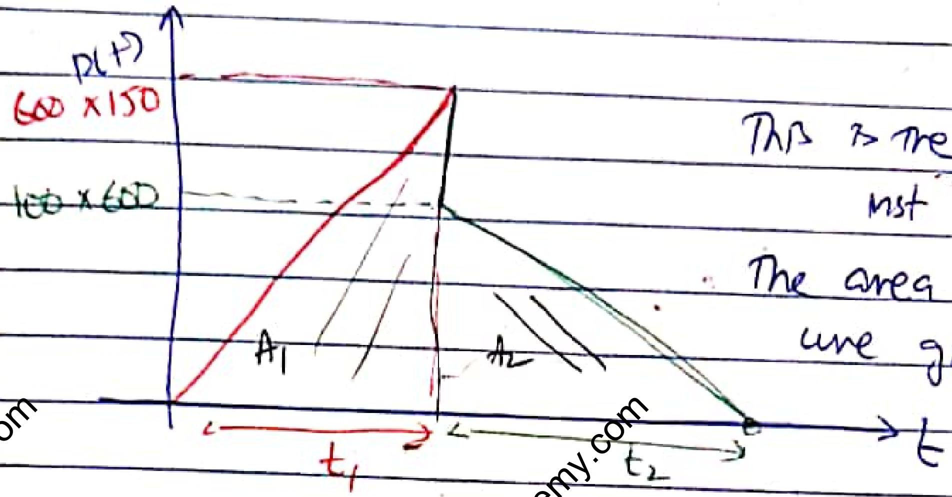
Date: / /

Day

$$E = P_{avg} \times T = \frac{VI}{T} \times (t_1 + t_2)$$

$$E = \int p(t)\, dt = \int v(t)\, i(t)\, dt$$

As $p(t) = v(t)\, i(t)$.



This is the curve for inst power.
The area of this curve gives energy
↓
2 triangles.

$$E = A_1 + A_2$$

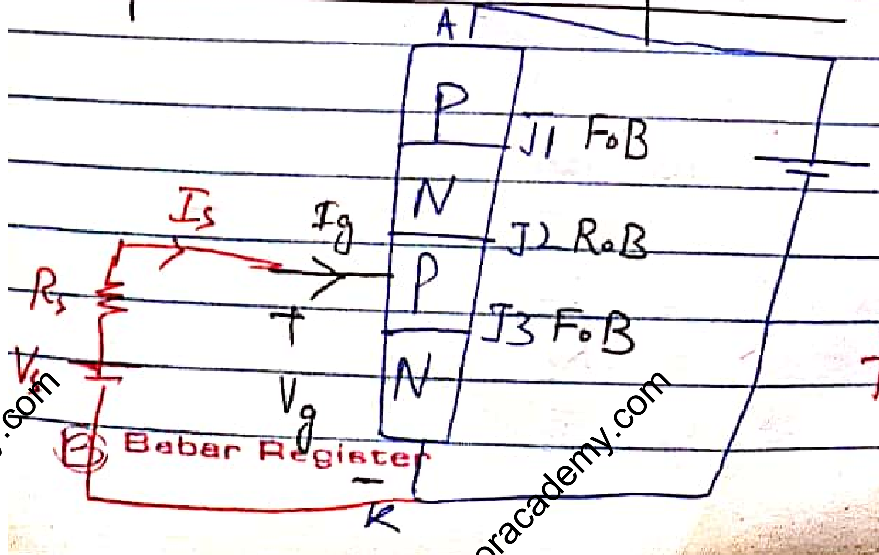
$$E = \frac{1}{2} \times 600 \times 150 \times t_1 + \frac{1}{2} \times 100 \times 600 \times t_2$$

$t_1 = 1\mu s \quad t_2 = 1\mu s$

$\Rightarrow \quad E = 0.0453 = 45\, mJ$

Sir → 75 mJ

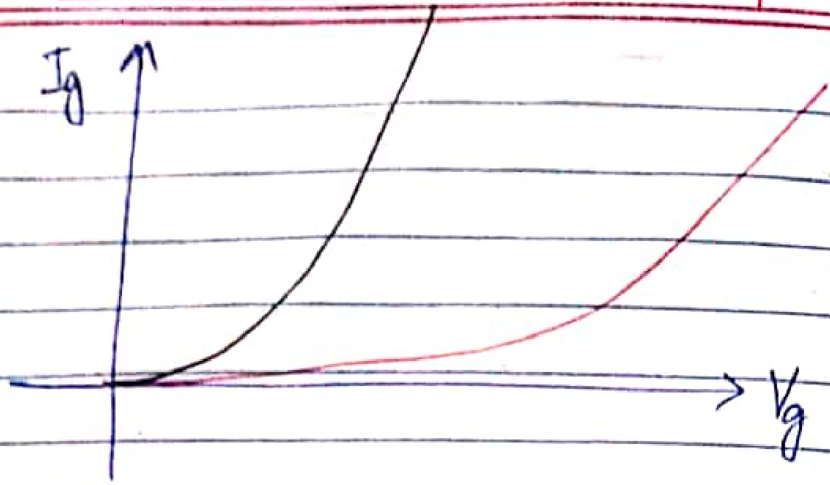
Gate characteristics of SCR



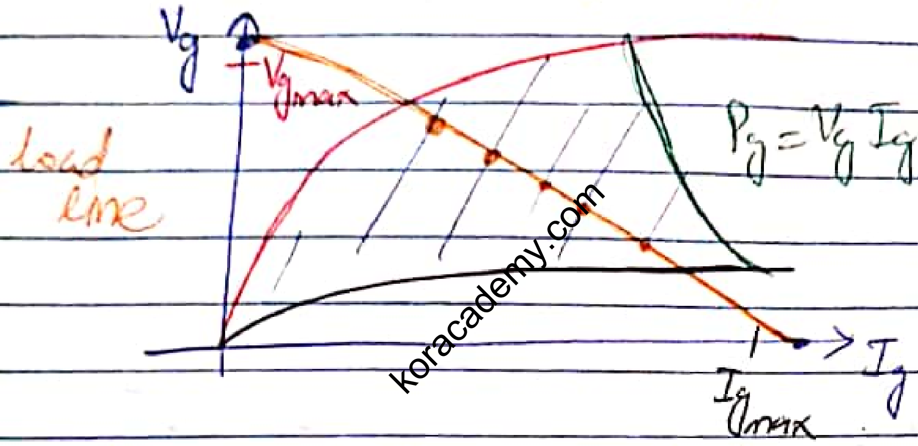
B/w gate and cathode we have PN junction in forward bias.

Data: / /

heavily doped junction
lightly doped junction



The same are on V_g Vs I_g (in books).



$P_{g(avg)} = V_g I_g$ = constant

↳ so the chs lie within.

To provide I_g we need to connect a source.

$$\Rightarrow \quad I_g = I_s$$

$$V_s = I_s R_s + V_g$$

$$\boxed{V_s = I_g R_s + V_g}$$

↳ finding load line from here.

$$V_g = 0 \Rightarrow I_g = \frac{V_s}{R_s}$$

$$I_g = 0 \Rightarrow V_g = V_s \quad (V_s > V_g)$$

Date: / / Day ____

In slope form $V_g = V_s - I_g R_s$

$y = c - mx$

$m = R_s$
↳ negative slope

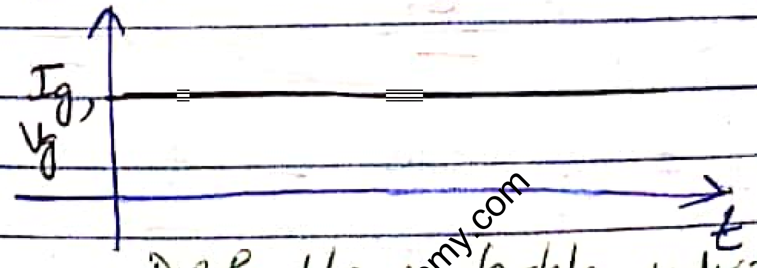
V_g Vs I_g ch (" ") wherever touches the load line gives the Q point.

V_s → gate source voltage I_s → gate source current
R_s → gate source resistance V_g → gate voltage] triggering V.
I_g → gate current or triggering current

Two types of SCR triggering.
- Continuous pulse triggering.
- Pulse gate triggering.

Gate signal is required till anode to cathode current becomes greater than the latching current.
↳ once it does, you dont need the gate pulse anymore.
↳ SCR is ON.

If SCR becomes ON and still you dont remove the gate pulse → this is continuous pulse triggering



$P_{g_{avg}} = I_g V_g$

Preferable for highly inductive loads.

Data: / /

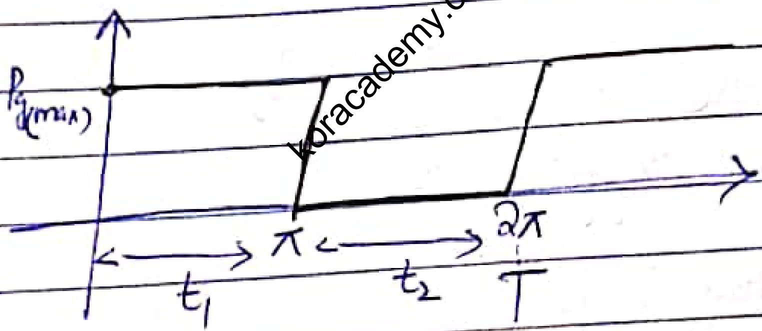
$$t = \frac{L \times \text{Inductor current}}{V_s}$$

$$L\uparrow\uparrow \Rightarrow t\uparrow\uparrow$$

In such type of signals (ie constant)

$$P_{g(avg)} = V_g I_g = P_{g(max)}$$

- When the SCR goes ON (ie $I_{AK} > I_L$) and you remove the gate pulse, This is called pulse gate triggering.



$P_{g(max)} = (V_g \cdot I_g)$ → instantaneous

Here $P_{g(avg)} = V_g \cdot I_g$ ✗

t_1 → time for which gate signal is applied.
t_2 → " " " " removed.

$$P_{g(avg)} = P_{g(max)} \times \frac{t_1}{T} = V_g I_g \cdot \frac{t_1}{T}$$

$$\text{Duty cycle} = \frac{\text{on time}}{\text{total period}} = \frac{t_1}{T}$$

Here

$$\Rightarrow \boxed{P_{g(avg)} = D \cdot P_{g(max)}}$$

Practically

SCR triggering is approximately 10 KHz.

Hence $T = \frac{1}{f} = 100\,\mu s$

Hence if $t_1 < 100\,\mu s \rightarrow$ pulse gate triggering.

Here $P_{g(avg)} < P_{g(max)}$

$P_{g(avg)} = D \cdot P_{g(max)}$

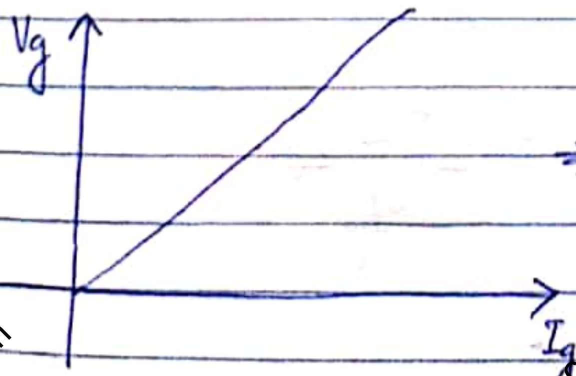
where $P_{g(max)} = V_g I_g$

$t_1 > 100\,\mu s \Rightarrow$ continuous pulse triggering

Here $P_{g(avg)} = P_{g(max)} = V_g I_g$

As $D = 1$

Q. I_g vs V_g Xtics of an SCR is a straight line passing through origin with a gradient of 2.5×10^3. If $P_g = 0.015\,W$, the value of gate voltage is?



gradient = slope

$\Rightarrow \frac{V_g}{I_g} = 2.5 \times 10^3$ — (1)

$P_g = V_g \cdot I_g = 0.015$ — (2)

Date: / /

① in ② ⇒ $2.5 \times 10^3 \times I_g^2 = 0.015$

putting V

$\Rightarrow I_g = 2.4\ mA$

↳ Similarly if put value of I

$$V_g \times \frac{V_g}{2.5 \times 10^3} = 0.015$$

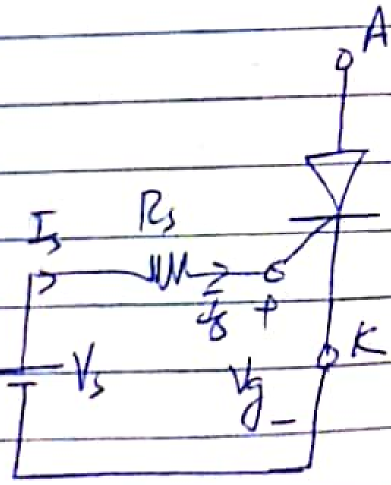
$$\Rightarrow V_g = 6.125\ V$$

Q. For SCR gate cathode Xtcs is

$$V_g = 10 I_g + 1 \rightarrow ①$$

The gate source voltage a pulse of 15 V with 20 μs of an average power dissipation is 0.3 W and peak power is 5 W.

The value of R_s to be connected in series with SCR gate terminal is ?



$t_1 = 20\ \mu s$

$P_{g(avg)} = 0.3\ W$

$P_{g(max)} = 5\ W$

$P_{g(avg)} < P_{g(max)}$

↳ ⇒ this is pulse gate triggering (P.G.T)

$$R_s = \frac{V_s - V_g}{I_s / I_g} = \frac{15 - V_g}{I_g}$$

We know that in P.G.T.

$P_{g(max)} = V_g \cdot I_g = 5 \rightarrow ②$

Date: / / Day

② in ① ⇒ $V_g = 10 \times \frac{5}{V_g} + 1$

$V_g^2 = 50 + V_g$

$\Rightarrow V_g^2 - V_g - 50 = 0$

$V_g = 7.588\ V$ → second root ?

↳ ⇒ $I_g = 0.6588\ A$

$\Rightarrow R_s = \left(\frac{15 - 7.588}{0.6588}\right) = 11.25\ \Omega$

for duty cycle.

As $P_{g(avg)} = D\, P_{g(max)}$

$\Rightarrow D = \frac{P_{g(avg)}}{P_{g(max)}} = \frac{0.3}{5} = 0.06$

Triggering frequency

As $D = \frac{t_1}{T}$

$\Rightarrow \frac{1}{T} = \frac{D}{t_1} = \frac{0.3}{20 \times 10^{-6}}$

$\Rightarrow f = 3\ KHz$

Time period.

$T = \frac{1}{f} = \frac{1}{3 \times 10^3} = 0.3\ m\,Sec$

Date: / /

2/10/19.

Rectifiers

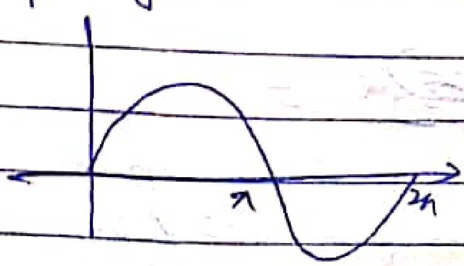
(i) fixed AC = amplitude does not change.
Rectifier converts fixed AC to DC.

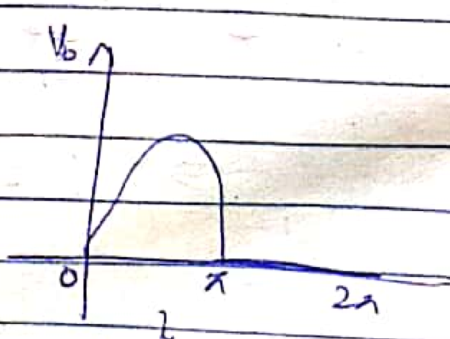
fixed AC ⟶ DC

- fixed DC
  - average = fixed
  - ↓ Uncontrolled rectifier
    - ↳ diodes are used
    - 1 φ
    - 3 φ
- Variable DC
  - average ≠ fixed
  - ↓ Controlled Rect.
    - ↓ two type
    - SCR
      - 1 φ
      - 3 φ
    - SCR + diode
      - ↓ Semiconverter
        - 1 φ
        - 3 φ

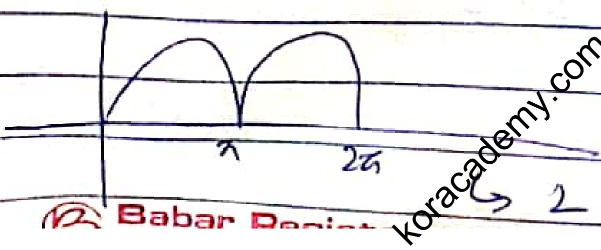
(ii) Output pulse

let i/p cycle





↳ 1 pulse converter.



↳ 2 pulse converter

Date: / / Day

How much of the output pulse is being created in one cycle of input.

$$T_0 = \frac{2\pi}{n} \quad n \to \text{no. of pulses}$$

$$f_0 = n f_s$$

(iii) Firing angle (α)

It is the point at which the device will start conduction

At $\omega t = \alpha \Rightarrow i_{device} = 0A$

Extinction angle (β)

The point at which device will stop its conduction.

At $\omega t = \beta \Rightarrow i_{device} = 0A$

Conduction Angle (γ)

$\gamma = \beta - \alpha$

The time for which device has conducted.

(iv) Circuit turn off time ($t_{c\,off}$)

The duration during which the device is under reverse bias condition.

→ related with SCR.

↳ -ve voltage

↳ due to available supply voltages

↓

(i) $V_s = V_m \sin\omega t$

(ii) E = battery voltage.

Date: / /

(v) To turn ON any device especially Diode and SCR
↓ F.B voltage (Diode)
↓ F.B voltage + Firing pulse (SCR)

Turn OFF is decided by current.

Reverse bias negative voltage does not decide the turning OFF of the device.

→ Once the device gets ON, then.

(vi) Source inductance is negligible.
All ~~ideal~~ devices are ideal.
$I_H = 0A$
→ assumptions

(vii) Continuous conduction
↳ is decided by the output current.
If o/p current ≠ 0 anywhere
↳ this is continuous conduction

Continuous conduction ripple free
o/p I ≠ 0 and it is at a fixed amount
i.e pure DC ⇒ no AC component.

Continuous discontinuous word is always for current.

Date: / /　　Day

Discontinuous conduction.
o/p current = 0 somewhere in the graph.
↳ discontinuous mode of operation.

R and RE load → always discontinuous conduction.
except in 3φ rectifier.

RL, RLE or L load → can give any type of conduction.
b/c inductor → storing capability. (energy)
L → continous.

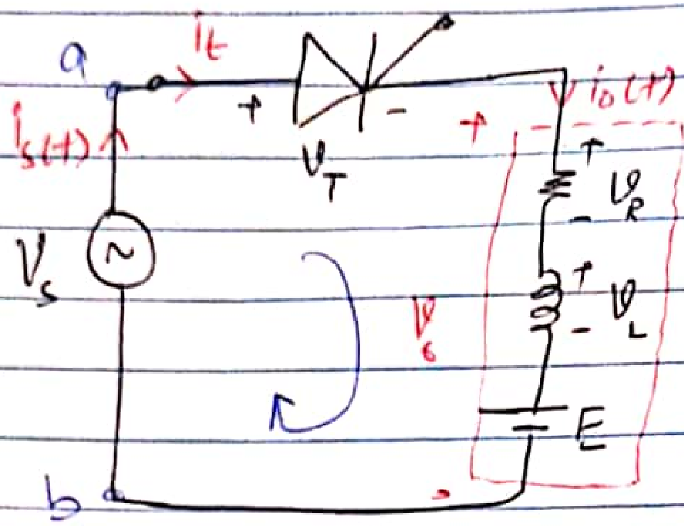
(viii) Whenever there is inductor in the load (eg RL, RLE, L),
- The device will always conduct even when the reverse voltage is there.

+ve voltage across device → inductor absorbs energy
-ve voltage " " → inductor supplies energy.

L in load ⇒ conduction will be there even after some time the -ve voltage has started.
↳ R.B

Data: / /

1 φ Half Wave Controlled Rectifier with RLE load.



$V_s = V_m \sin \omega t$

KVL in the loop

$$V_s(t) = V_t + V_o(t)$$

$$① \leftarrow V_o(t) = i_o(t)R + L\frac{di_o(t)}{dt} + E$$

$$V_{ab} = V_s(t) = V_m \sin \omega t$$

$$V_{ba} = -V_m \sin \omega t$$

For SCR to be ON A = +ve K = -ve

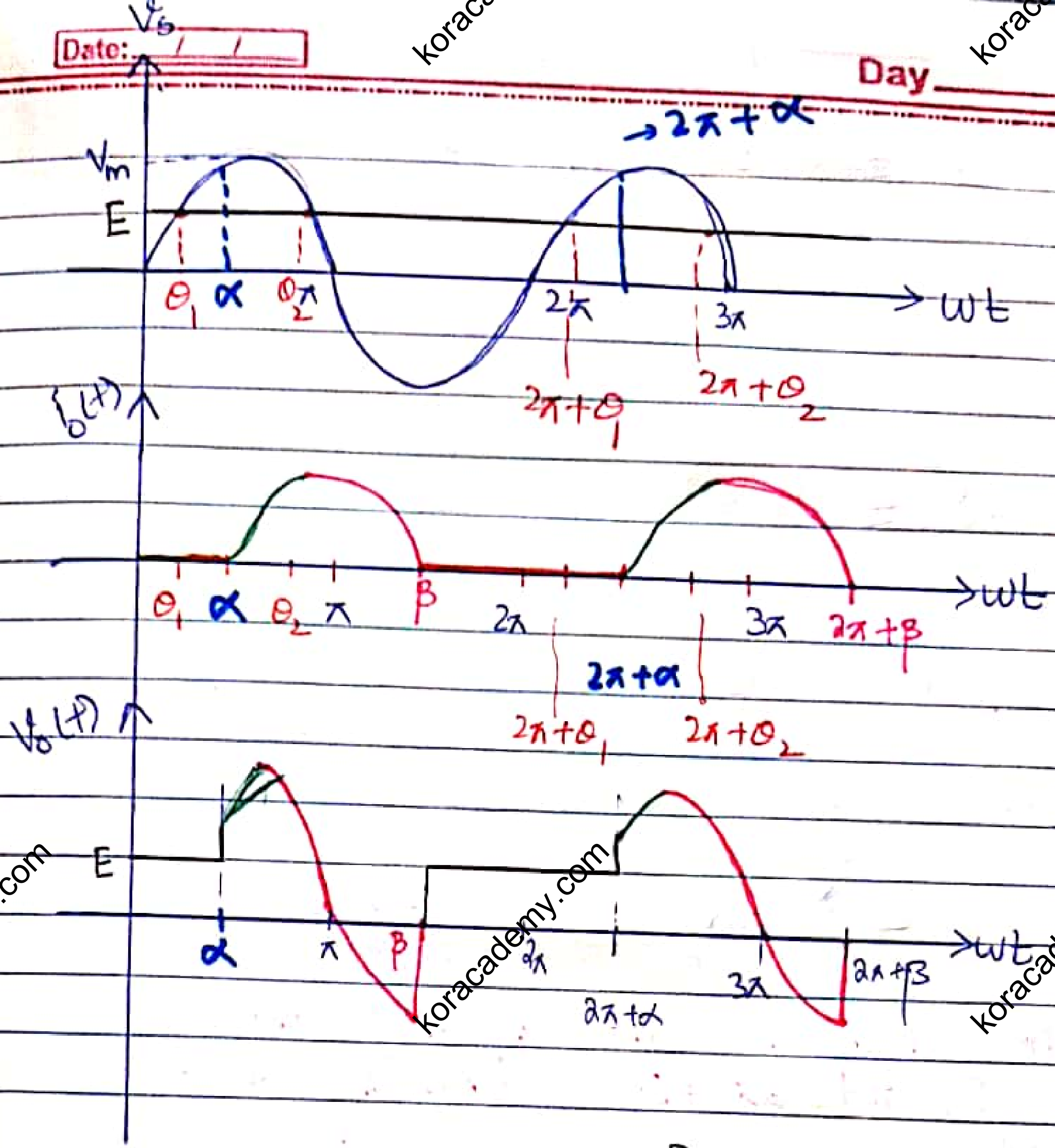
$\Rightarrow V_T = +ve \rightarrow SCR = F.B$

ON ← α ← ↳ F.B.M

At θ_1 $V_m \sin\theta_1 = E$

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

$$\theta_2 = 180° - \theta_1$$



• $0 \le \omega t < \theta_1$ → R.B.M → off

$V_s < E$ $i_o(t) = 0A$

⇒ $V_o(t) = E$ from ①

$\theta_1 \le \omega t \le \theta_2$ $V_s > E$ → forward bias mode

so the SCR could turn ON if gate pulse is applied.

But before α

ie $\theta_1 \le \omega t < \alpha$ → $V_s > E$ → F.B.M

OFF &

$i_o(t) = 0$ A

$V_o(t) = E$

Data: / /

$\alpha \le \omega t \le \theta_2$ $V_s > E \Rightarrow$ F.C.M

ON state ↲

$i_o(t) \neq 0$ → will increase

↳ $V_T = 0$

$V_{o(t)} = V_m \sin \omega t$

$\theta_2 \le \omega t \le 2\pi + \theta_1$ $V_s < E$ → ~~R.B.M~~

↳ reverse bias. although both are +ve

reverse voltage - $I_{SCR} \neq 0$ at θ_2

↳ because L.

Current direction never changes along L.

L ↑ E ↓ L ↓ E ↑

The extinction point can arise anywhere b/w θ_1 and $2\pi + \theta_1$ depending on the value of L.

output voltage

Whenever the SCR is ON (α to β) output voltage is equal to the supply voltage.

The current wave is not a sine wave → it is a function of sine and exponential.

Here firing angle α

Extinction angle β

conduction angle $\gamma = \beta - \alpha$

conduction time $t_c = \dfrac{\beta - \alpha}{\omega}$

Date: / / Day

$$t_{cut\,off} = \frac{2\pi + \theta_1 - \beta}{\omega}$$

PIV = peak inverse voltage
↳ peak value of the reverse voltage applied.

R.B → β to $2\pi + \theta_1$

$$PIV = -(V_m + E)$$

How?

KVL $V_m \sin\omega t = v_T + V_o$

~~$v_T = V_m \sin\omega t - V_o$~~

$= V_m \sin\omega t - E$

$\sin\omega t = 1$ for max

$$v_T = -V_m - E$$

$$I_{avg} = \frac{1}{T}\int \frac{V_m \sin\omega t - E}{R}\, d\omega t$$

↳ no need to take L in average.

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

$$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos\beta) + E(\alpha - \beta)\right]$$

The average inductor voltage is always zero.

$$V_o = i_o(R) + L\frac{di}{dt} + E$$

$$V_{o(avg)} = I_{o(avg)} \cdot R + E$$

Data: / /

→ controlled RLE

How to get all relations of 1 φ half wave rectifiers.

Firing angle $= \alpha$ Extinction angle $= \beta$

Conduction $\gamma = \beta - \alpha$ $t_c = \frac{\beta - \alpha}{\omega}$

$t_{off} = \frac{2\pi + \theta_1 - \beta}{\omega}$ $|PIV| = V_m + E$

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

$$V_{avg} = I_o R + E$$

For uncontrolled rectifiers

$\alpha = \theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right)$

↳ any load.

For controlled and uncontrolled;

$\beta = \theta_2$ for R and RE load.

$= 180^\circ - \theta_1$

$\beta > \theta_2$ for RL or RLE load.

(i) Controlled with RL load

Firing angle $= \alpha$

Extinction angle $= \beta > \theta_2$

As $\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right)$

$E = 0 \Rightarrow \theta_1 = 0^\circ$

Date: / /   Day

$\theta_2 = 180^\circ - \theta_1 \Rightarrow \theta_2 = 180^\circ$

$\Rightarrow \beta > 180^\circ$

Conduction $\gamma = \beta - \alpha$ $t_c = \frac{\beta - \alpha}{\omega}$

$t_{cut\ off} = \frac{2\pi + 0 - \beta}{\omega} = \frac{2\pi - \beta}{\omega}$

$PIV = V_m$

$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos\beta)\right]$

$V_{o\,avg} = I_o R$

(ii) <u>Uncontrolled RL Load</u>.

$\theta_1 = \sin^{-1}\left(\frac{0}{V_m}\right) = 0$ $\theta_2 = 180^\circ$

Firing angle, $\alpha = \theta_1 = 0^\circ$

Extinction angle, $\beta = \beta > \theta_2$

$\Rightarrow \beta > 180^\circ$

Conduction angle, $\gamma = \frac{\beta - \alpha}{\gamma} = \frac{\beta}{\gamma}$

Circuit turn OFF time is not defined for uncontrolled ie diode.

$PIV = V_m$

$I_{avg} = \frac{1}{2\pi R}\left[V_m(1 - \cos\beta)\right]$

$V_{o\,avg} = I_o R$

Date: / /

(iii) Un Controlled With R Load

$$\theta_1 = \sin^{-1}\left(\frac{0}{V_m}\right) = 0 \qquad \theta_2 = 180^\circ$$

Firing $\alpha = \theta_1 = 0^\circ$

Extinsion $\beta = \theta_2 = 180^\circ$

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

$$PIV = V_m + 0 = V_m$$

$$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(1+1) + 0\right] = \frac{2V_m}{2\pi R}$$

$$\boxed{I_{o\,avg} = \frac{V_m}{\pi R}}$$

$$V_o = I_o R = \frac{V_m}{\pi R} \cdot R \Rightarrow \boxed{V_{o\,avg} = \frac{V_m}{\pi}}$$

(iv) Controlled rectifier with R Load

$$\theta_1 = 0^\circ \qquad \theta_2 = 180^\circ$$

Firing angle $= \alpha$ Extinsion $\beta = \theta_2 = 180^\circ$

$$t_c = \frac{180^\circ - \alpha}{\omega} \qquad t_{cutoff} = \frac{2\pi + 0 - 180^\circ}{\omega}$$

$$\Rightarrow t_{cutoff} = \frac{\pi}{\omega}$$

$$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(\cos\alpha - (-1)\right]$$

$$V_{o\,avg} = I_{o\,avg} R + \cdots$$

Date: / /   Day

(v) Controlled with RE load

$$\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right) \quad ; \quad \theta_2 = 180^\circ - \theta_1$$

Firing angle $= \alpha$ Extinction $= \beta = \theta_2 = 180^\circ - \theta_1$

$$t_c = \frac{\beta - \alpha}{\omega} = \frac{\theta_2 - \alpha}{\omega} = \frac{180^\circ - \theta_1 - \alpha}{\omega}$$

$$t_{ckt\,off} = \frac{2\pi + \theta_1 - \beta}{\omega} \qquad PIV = V_m + E$$

$$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(\cos\alpha - \cos\theta_2) + E(\alpha - \theta_2)\right]$$

$$V_{o\,avg} = I_o R + E$$

(vi) Uncontrolled with RE load

$$\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right) \qquad \theta_2 = 180^\circ - \theta_1$$

Firing angle $(\alpha) = \theta_1$
↳(start)

Extinction angle $\beta = \theta_2 = 180^\circ - \theta_1$

$$t_c = \frac{\beta - \alpha}{\omega} = \frac{180^\circ - \theta_1 - \theta_1}{\omega}$$

$$PIV = V_m + E$$

$$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(\cos\theta_1 - \cos\theta_2) + E(\theta_1 - \theta_2)\right]$$

$$V_{o\,avg} = I_o R + E$$

Date: / /

(vii) Uncontrolled RLE load

$$\theta_1 = \sin^{-1}\left(\frac{E}{V_m}\right) \quad , \quad \theta_2 = 180° - \theta_1$$

Firing angle $\alpha = \theta_1$

Extinction angle $\beta > \theta_2$

$$t_c = \frac{\beta - \alpha}{\omega} = \frac{\beta - \theta_1}{\omega}$$

$$PIV = V_m + E$$

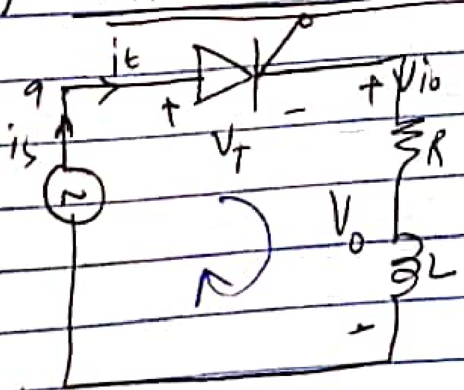
$$I_{o\,avg} = \frac{1}{2\pi R}\left[V_m(\cos\theta_1 - \cos\beta) + E(\theta_1 - \beta)\right]$$

$$V_{o\,avg} = I_{avg} R + E$$

3/11/19

How to Draw Waveforms for any load

(i) Controlled with RL load



$V_{ab} = V_s = V_m \sin\omega t$

$V_{ba} = -V_m \sin\omega t$

SCR can be one of

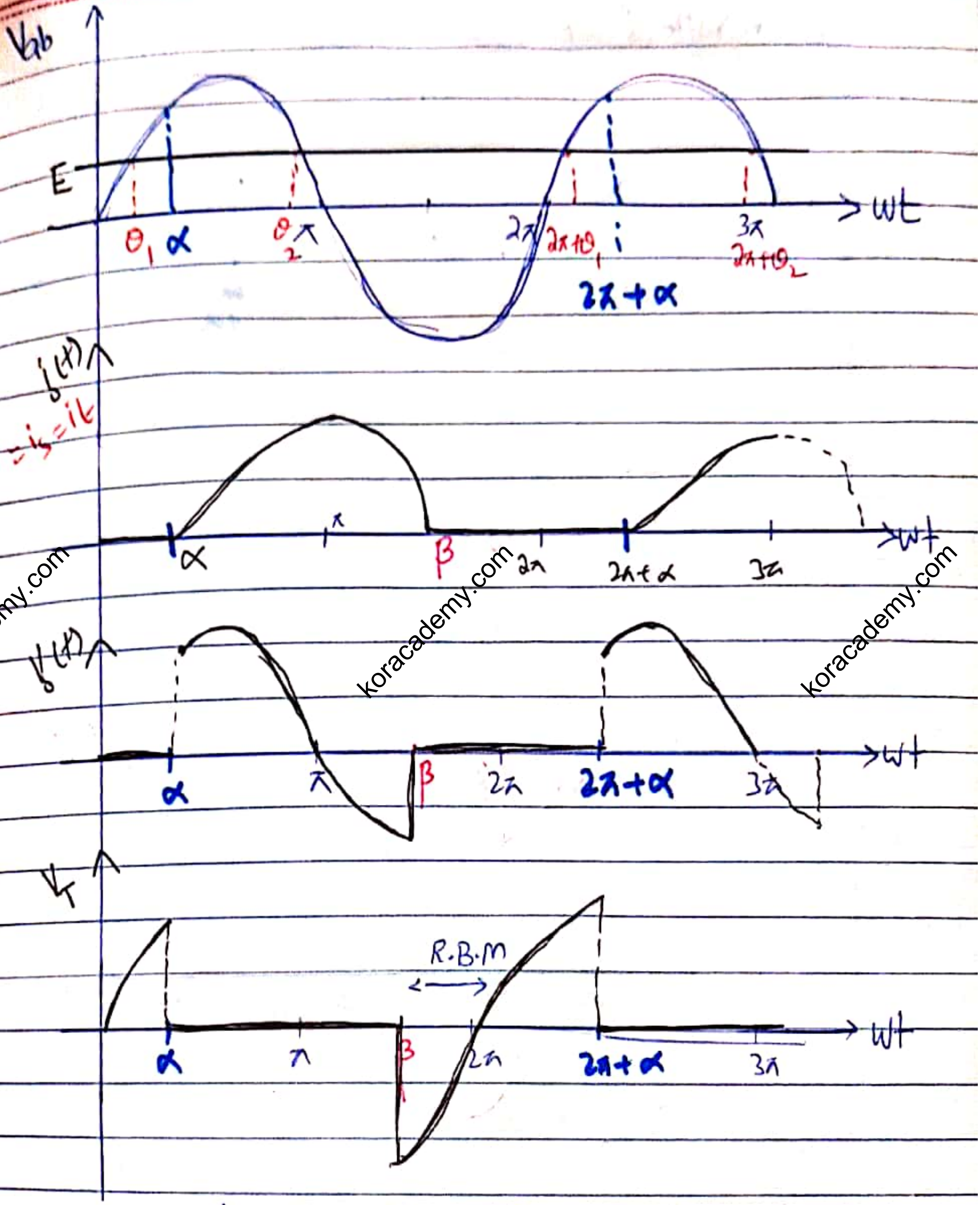
~~(i) ON → $V_T = 0, i_0 \neq 0$~~

~~(ii) OFF~~

(i) ON → $V_T = 0V$, $i_0 \rightarrow$ exists, $V_0 = V_{ab} = V_m \sin\omega t$

(ii) OFF → $i_0 = 0$, $V_0 = 0$, $V_T = V_m \sin\omega t$

$\Rightarrow V_m \sin\omega t = V_T + V_0$



As $\theta_1 = 0^\circ$ $\theta_2 = 180^\circ$

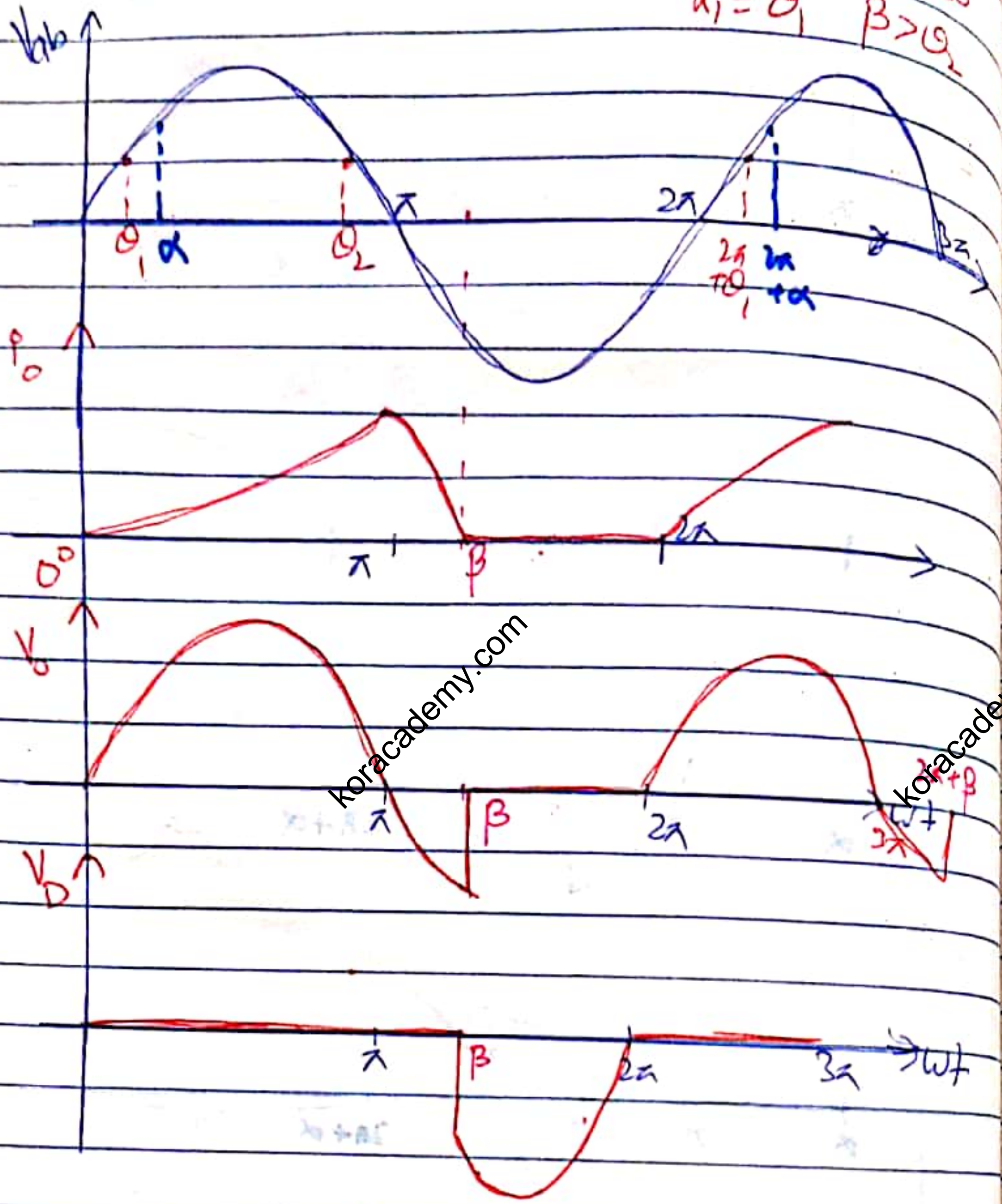
$\alpha, \quad \beta > 180^\circ$

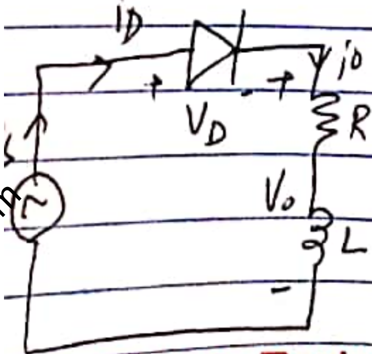
Data: / /

(ii) Uncontrolled RL Load

$\theta_1 = 0^\circ$ $\theta_2 = 180^\circ$

$\alpha_1 = \theta_1$ $\beta > \theta_2$





When

D is ON → $V_D = 0$ $\beta = end\,t$

D is OFF → $i_o = 0$ $V_o = 0$

$V_D = V_m \sin\omega t$

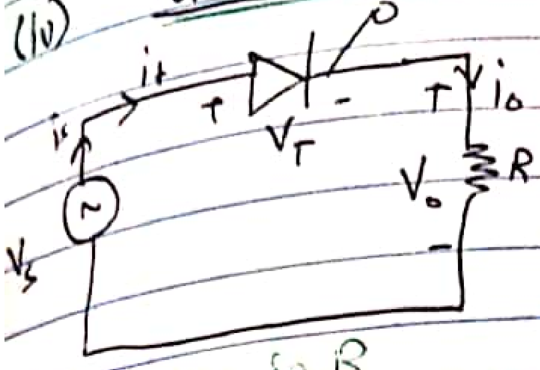
$\theta_1 = 0^\circ$ as $\sin^{-1}\left(\frac{E}{V_m}\right)$ $\quad \theta_2 = 180^\circ$

$\alpha = \theta_1 = 0^\circ \qquad \beta > \theta_2 \Rightarrow \beta > 180^\circ$

(iv) Controlled R Load

$\theta_1 = 0^\circ \quad \theta_2 = 180^\circ$

$\alpha \quad \beta = 180^\circ = \theta_2$

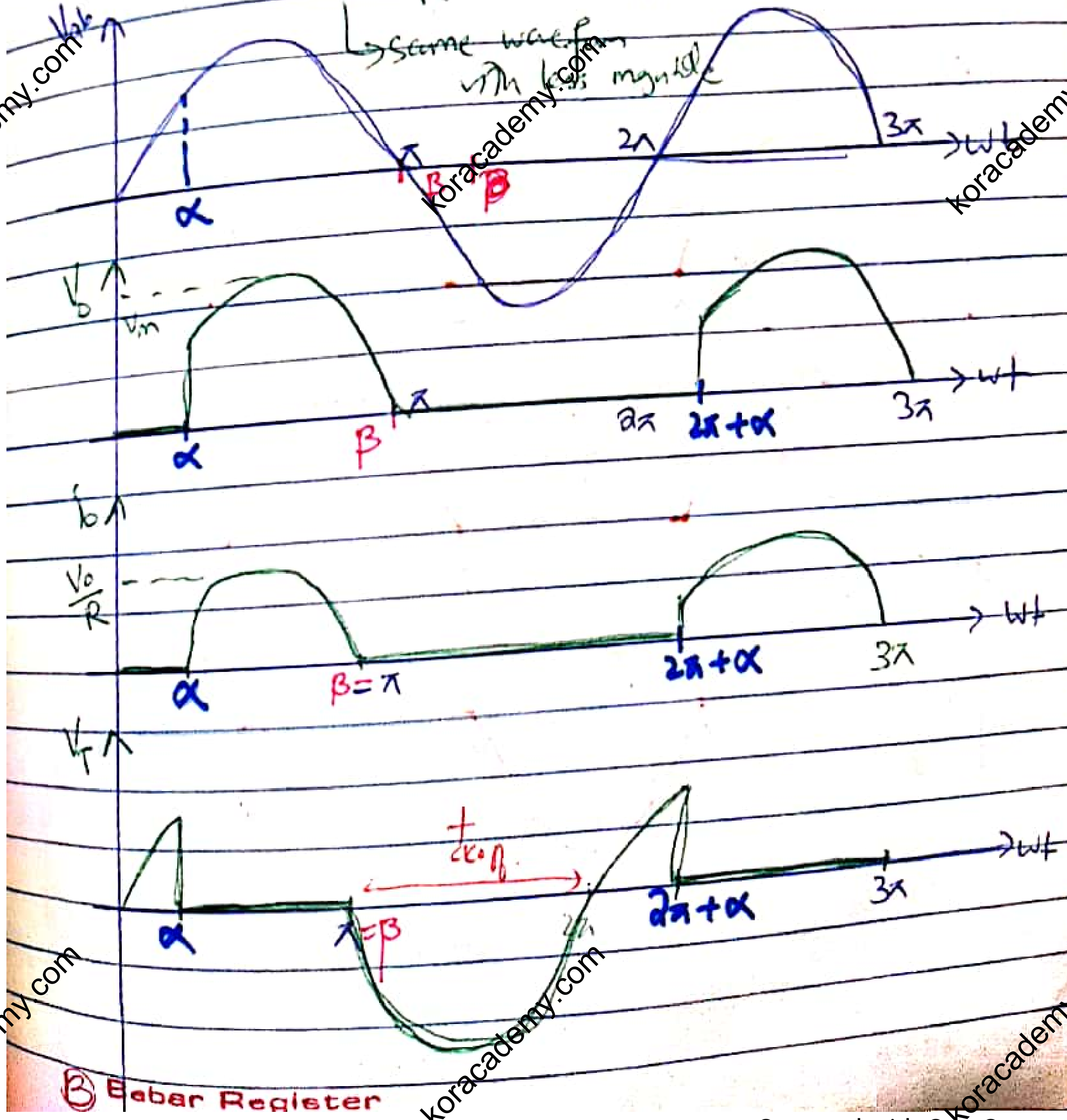


SCR = ON
↳ $V_T = 0V$ $\quad i_o$ exists
$V_o = V_s = V_m \sin\omega t$

SCR = OFF
↳ $i_o = 0 \quad V_o = 0$
↳ $V_T = V_m \sin\omega t$

$V_o = i_o R$

$i_o = \frac{V_o}{R}$
↳ same waveform with less magnitude

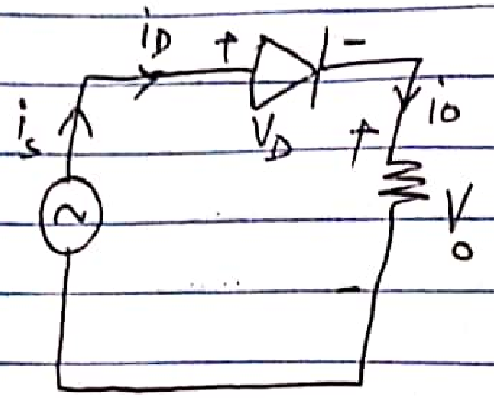


Date: / /

(iii) Uncontrolled R Load

$\alpha = \theta_1 = 0^\circ$

$\beta = \theta_2 = \pi$



D → ON

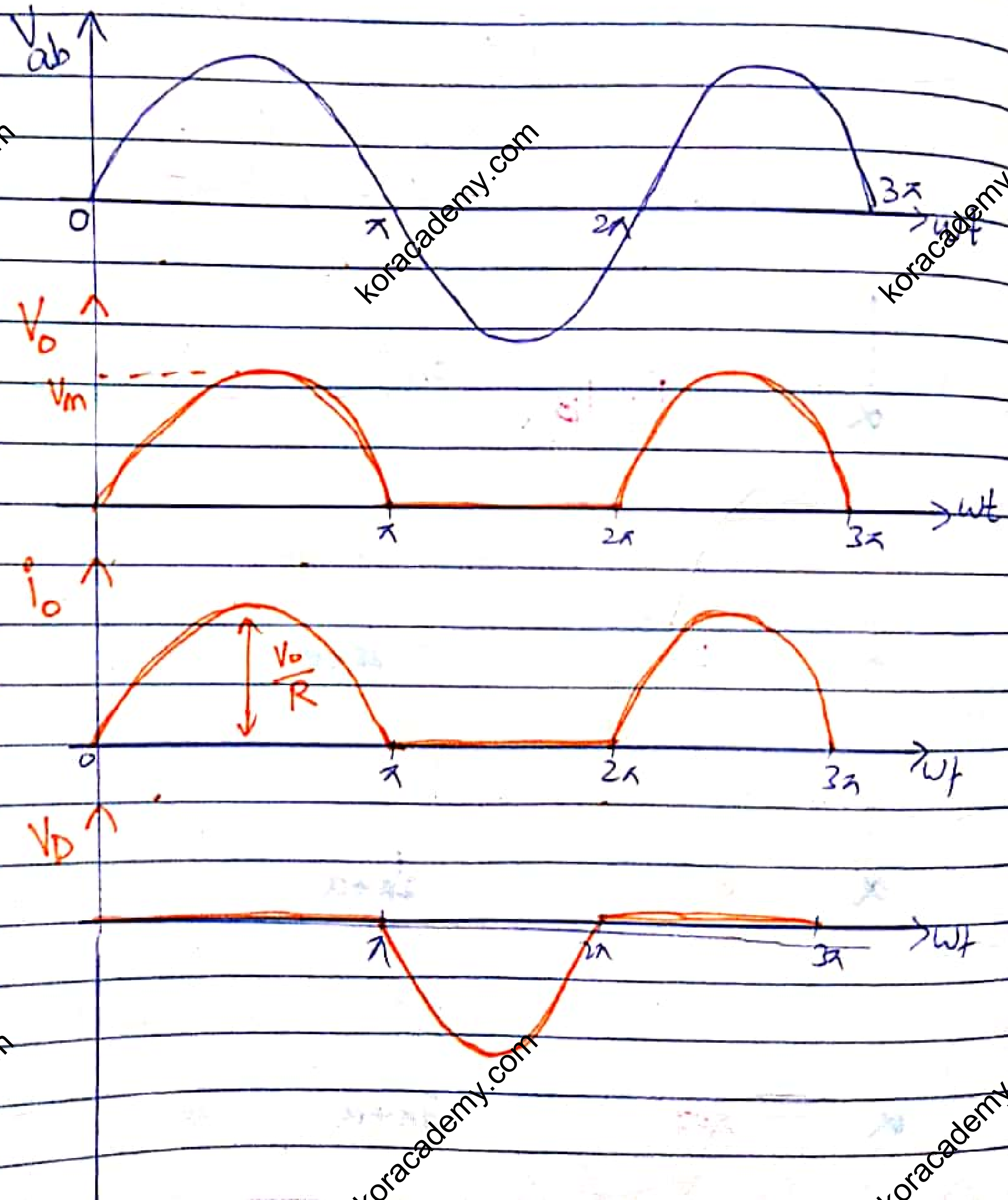
↳ $V_D = 0$ i_o exists

↳ follows voltage

D → OFF

↳ $i_o = 0A$ $V_o = 0$

$V_D = V_m \sin \omega t$

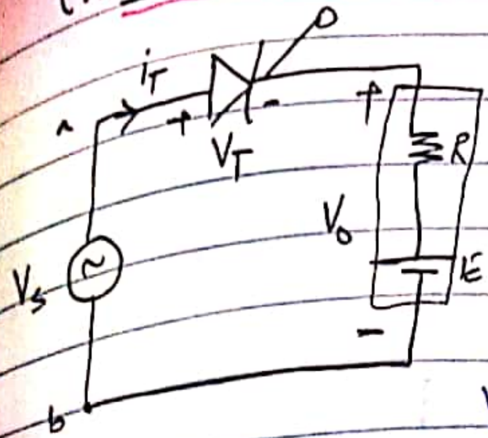


Date: / / Day____

(v) RE load Controlled Rectifier

$\theta_1 \neq 0$ $\theta_2 = 180° - \theta_1$

α, $\beta = \theta_2 = 180° - \theta_1$



SCR = ON
↳ $V_T = 0$ i_0 exists

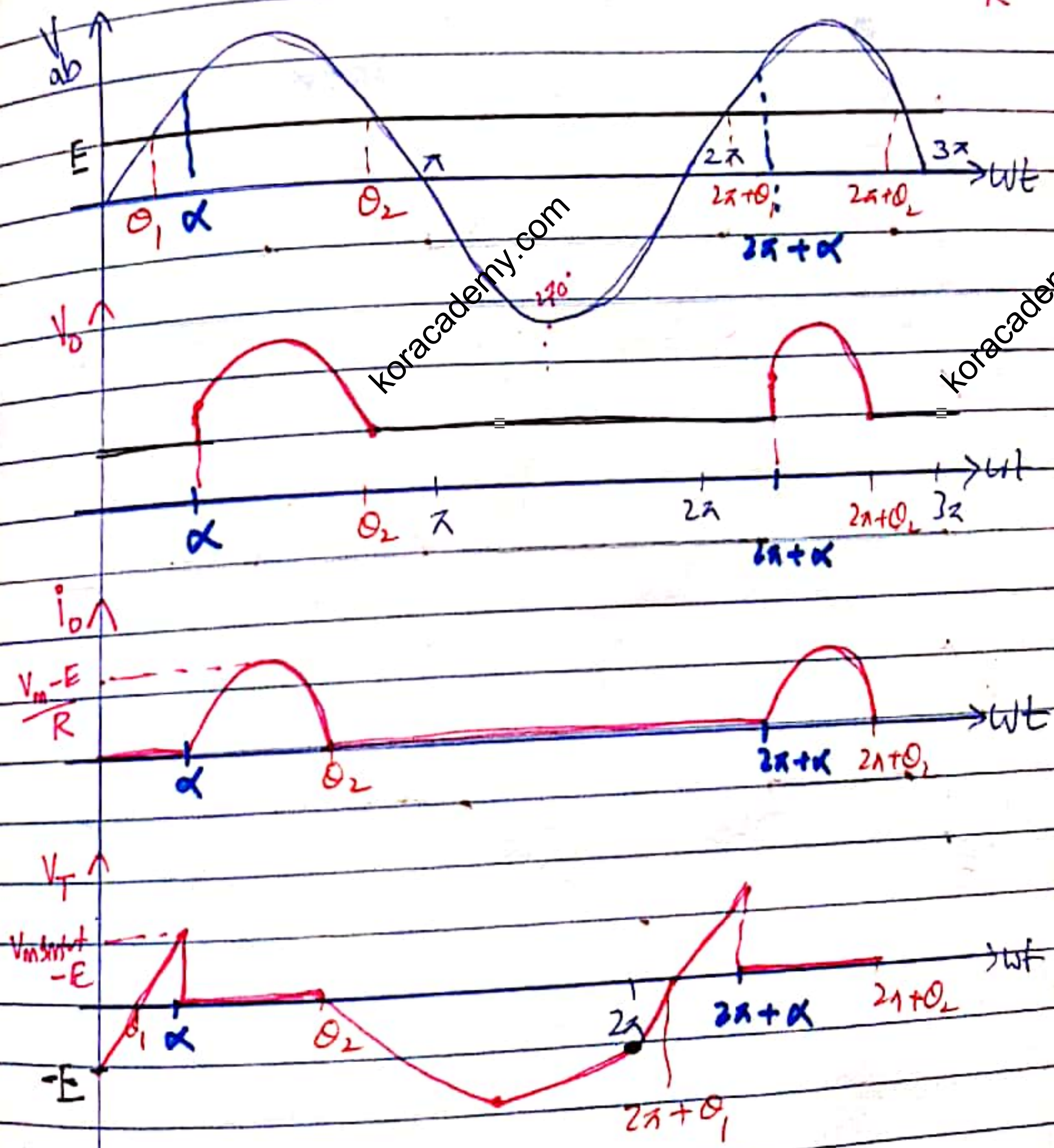
$i_0 = \frac{V_0 - E}{R}$

↓

$i_0 = \frac{V_m \sin\omega t - E}{R}$

SCR = OFF
↳ $i_0 = 0$ $V_0 = E$

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



At $\theta_1 \Rightarrow V_T = 0$

At $\omega t = 0 \Rightarrow V_T = -E$

At $\theta_2 \Rightarrow V_T = 0$

At $2\pi \Rightarrow V_T = -E$

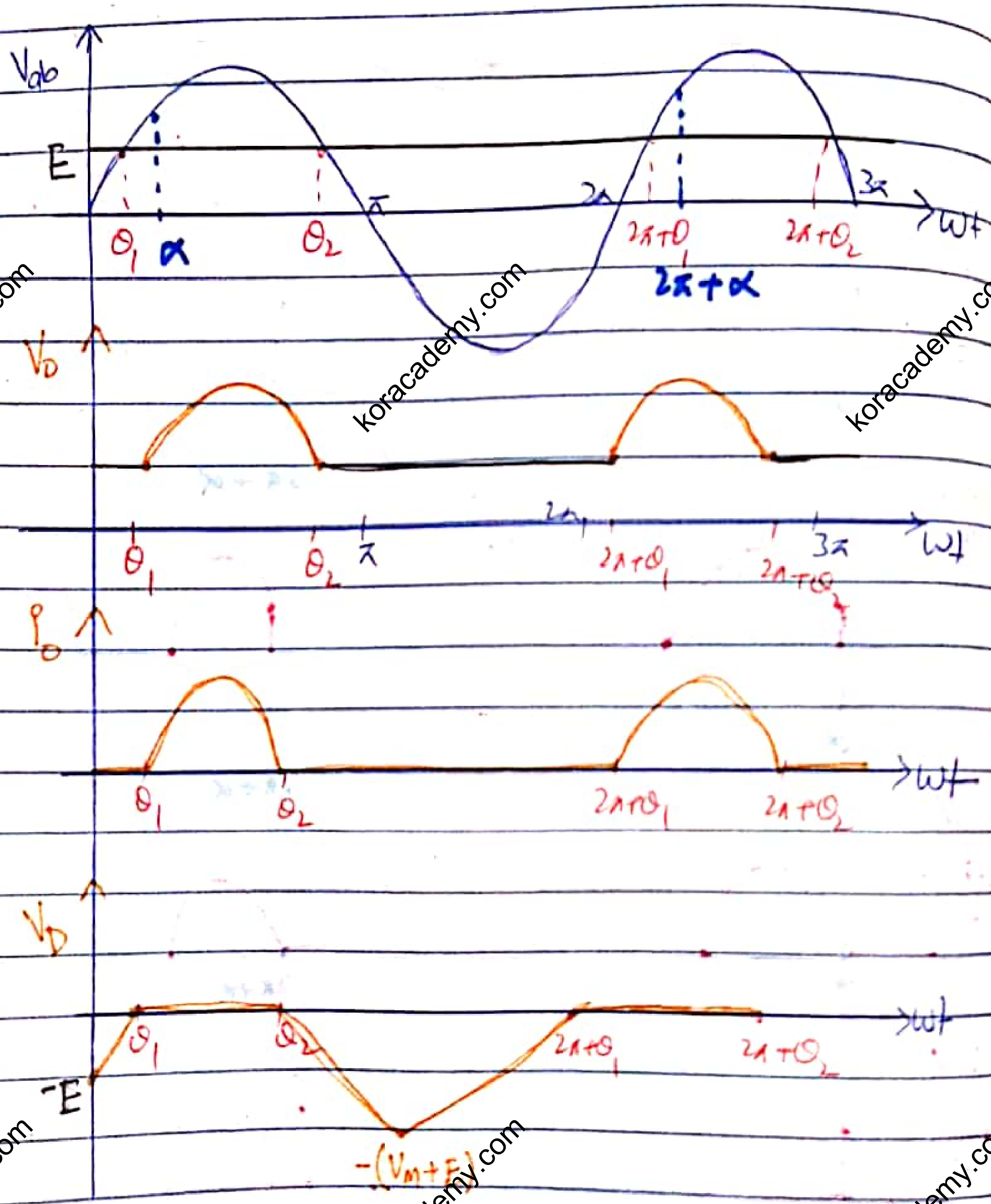
At $\omega t = 270° \Rightarrow V_T = -(V_m + E)$

Data: __/__/__

(vi) Uncontrolled with RE load

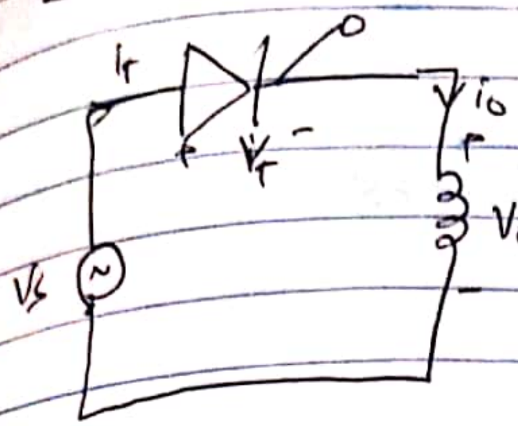
$\theta_1 \neq 0$ $\theta_2 = 180° - \theta_1$

$\alpha = \theta_1 \neq 0$ $\beta = \theta_2$



Date: / / Day

L Load controlled.



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

$0 < \omega t < \alpha$

↳ F.b.M

b/c no firing angle

↳ SCR = OFF

↳ $i_o = 0A$

↳ $V_o = 0V$

$\omega t > \alpha$

↳ SCR = ON → $V_T = 0$ → $V_o = V_s = V_m \sin\omega t$

As $V_o = L\frac{di}{dt}$ → $L\frac{di_o}{dt} = V_m \sin\omega t$

Turn OFF of any device is decided by current.

$$\int_{\alpha/\omega}^{t} di_o = \int_{\alpha/\omega}^{t} \frac{V_m}{L} \sin\omega t \, dt$$

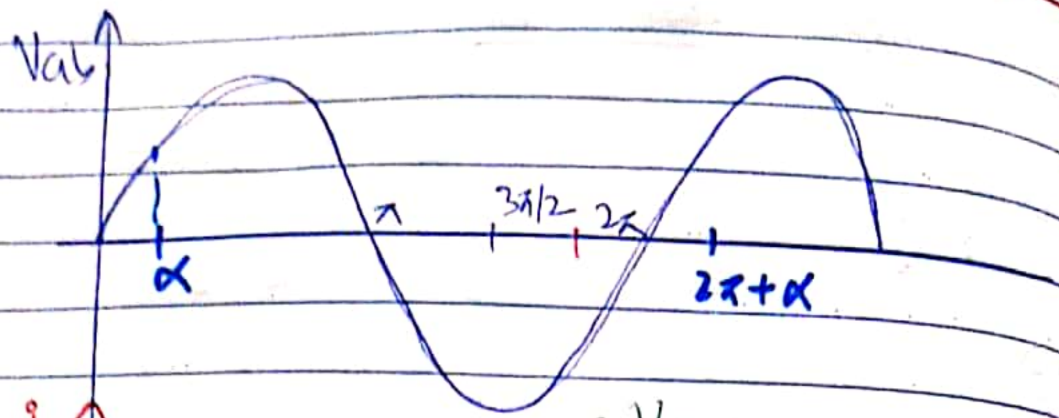
$$i_o(t) - i_o(\alpha) = \frac{V_m}{\omega L}\left[-\cos\omega t\right]_{\alpha/\omega}^{t}$$

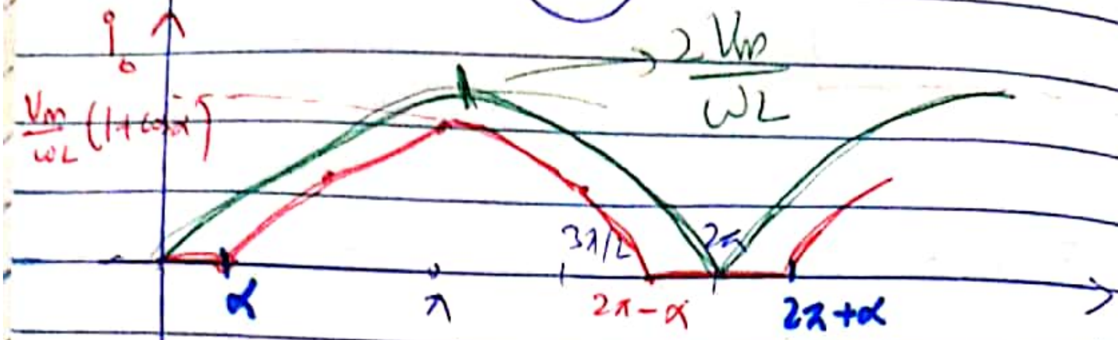
At instant firing angle point current is zero.

$$i_o(t) = \frac{V_m}{\omega L}\left[\cos\alpha - \cos\omega t\right]$$

If uncontrolled $\alpha = 0°$

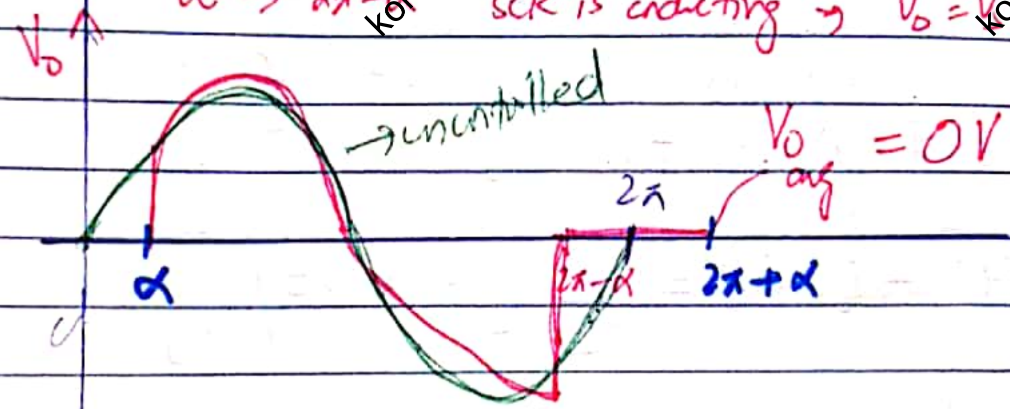
Date: / /





$\Rightarrow \beta = 2\pi - \alpha$

$\alpha \to 2\pi - \alpha$ SCR is conducting $\to V_o = V_s$



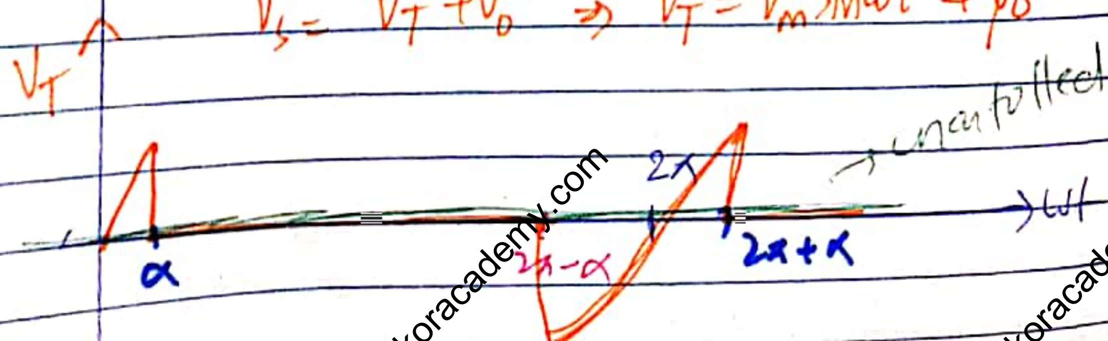
for V_T

α to $2\pi-\alpha$ SCR is ON

$\hookrightarrow V_T = 0$ here

SCR is off $V_T = ?$

$V_s = V_T + V_o \Rightarrow V_T = V_m \sin\omega t - V_o$ ($V_o \to 0$)



$$I_{o(avg)} = \frac{1}{2\pi}\int_{\alpha}^{2\pi-\alpha} i_o(t)\, d\omega t$$

If uncontrolled $\alpha = 0^\circ$

$$i_o(t) = \frac{V_m}{\omega L}\left(\cos 0^\circ - \cos\omega t\right)$$

$$i_o(t) = \frac{V_m}{\omega L}\left[1 - \cos\omega t\right]$$

$$\beta = 2\pi - \alpha = 2\pi - 0^\circ$$

$$\Rightarrow \beta = 2\pi \text{ rad}$$

$V_D = 0$ $\qquad V_{o\,avg} = 0$

Max energy stored ? $= \boxed{\frac{1}{2} L i^2}$

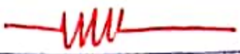
for diode put $i = \frac{2V_m}{\omega L}$

for SCR put $i = \frac{V_m}{\omega L}(1 + \cos\alpha)$

Form factor $= \frac{V_{rms}}{V_{avg}}$

The form factor of a pure sine wave is 1.11.

$P_{input} = P_{output}$


$P = I_{rms}^2 R$ → dissipated

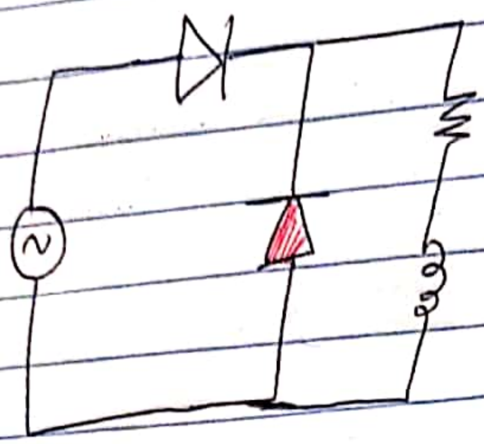

$P = E \times I_{o\,avg}$ → stored / delivered


$P = 0$ Watt

5/11/19.

Date: / /

Half Wave Uncontrolled Rectifier with RL Load and free wheeling diode

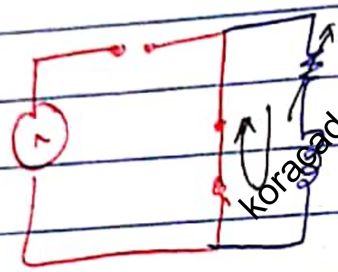


0 to π

$V_0 = V_s = V_m \sin \omega t$

After π

F.W.D will be active ie shorted

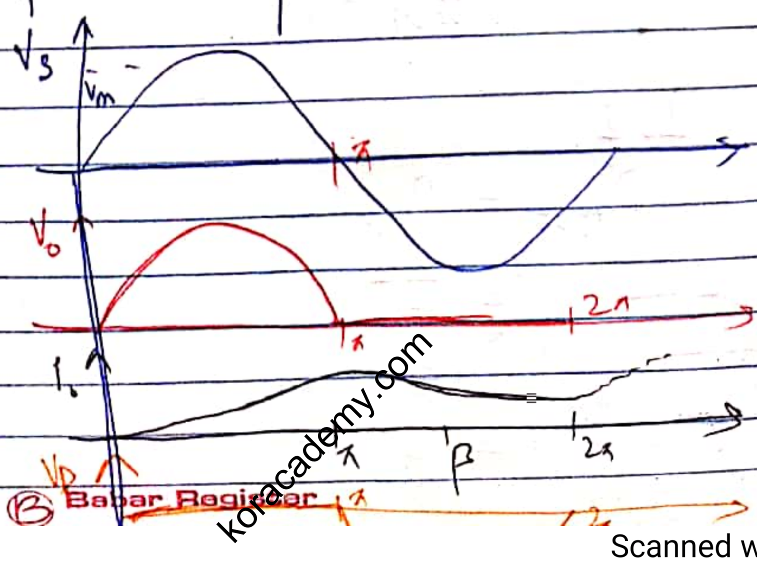


The energy across inductor will discharge across resistor.

$I_0(t) = I_0 e^{-t/\tau}$ $\tau = L/R$

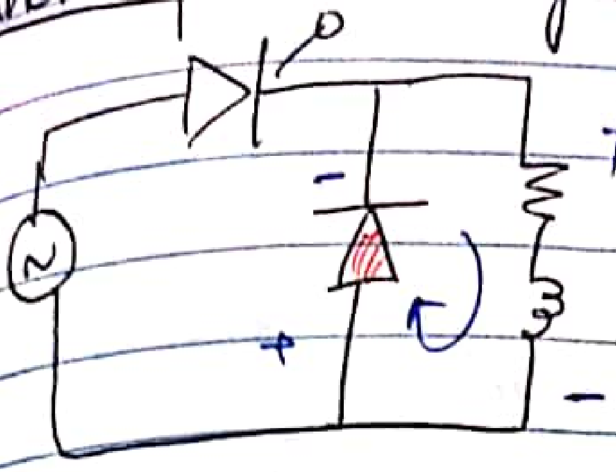
With F.W.D all energy of the inductor is dissipated across the resistor and nothing is supplied back to the source.

After 2π repeats.



Date: / / Day

Half Wave Controlled rectifier with RL load and free wheeling diode



α to π
↳ Thyristor conducts
↳ o/p V is equal to i/p voltage

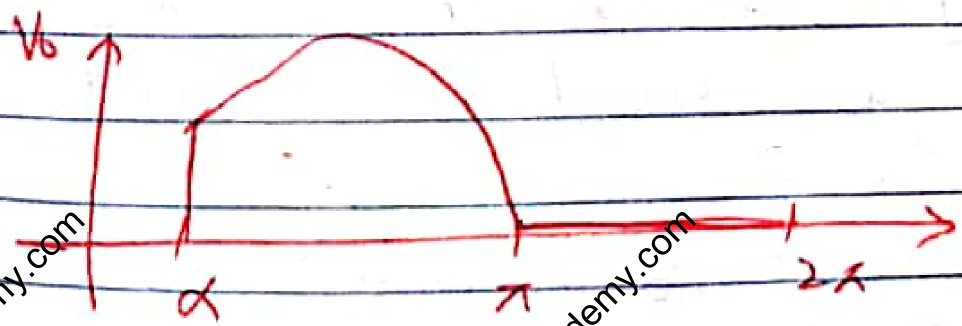
After π F.W.D conducts → shorted

KVL $V_D + V_o = 0$

$V_D = -V_o$

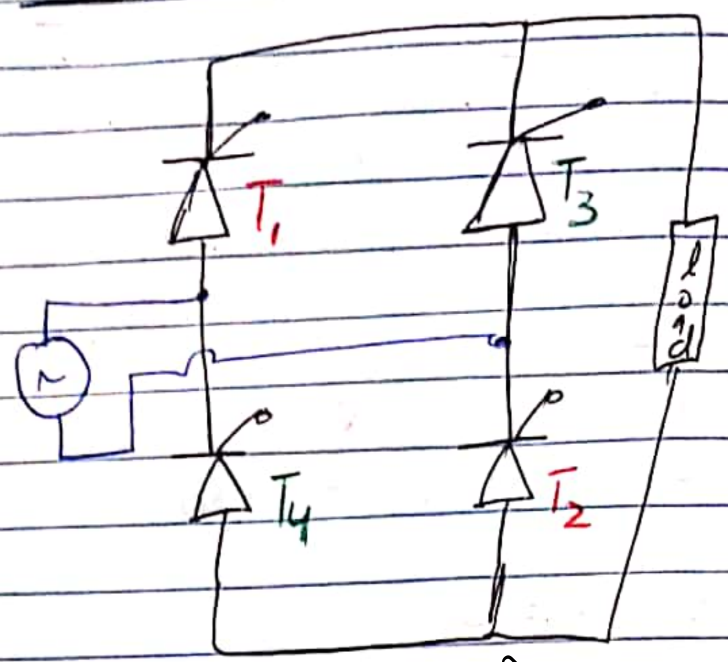
0α to π inductor charges.
π to 2π " discharges.
↳ so I_o is continous.

$I_{rms\ sce} \neq I_{rms\ load}$ only in this case.



Date: / /

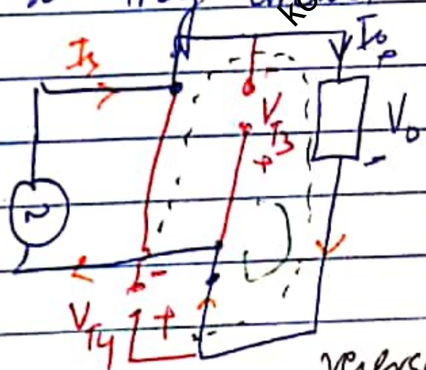
Single Phase Full Wave controlled Bridge Rectifier



Assuming I_o = constant
↓
RLE or RL
Highly inductive load.

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

At $\omega t = \alpha$ triggering T_1 and T_2
so they conduct from α to $\pi + \alpha$



$V_o = V_s = V_m \sin\omega t$

$V_o = V_{BA}$

After π, thyristors are reverse biased so they should stop conduction ?
We assume that I_o is constant
for turning OFF $I_o \leq I_H$

At $\pi + \alpha$ we trigger T_3 and T_4
So T_1 and T_2 go to reverse mode and stop conducting.
As T_3 and T_4 are not triggered from α to $\pi + \alpha$, so they are open circuit in this region.

Date: / /

Day

KVL $V_{T4} + V_0 = 0$

$V_{T4} = -V_0$ $(\alpha \text{ to } \pi + \alpha)$

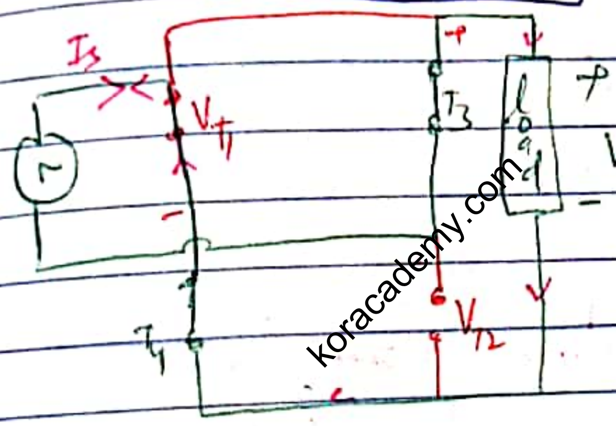
Similarly in the inner loop

$V_{T3} + V_0 = 0$

$V_{T3} = -V_0$ $(\alpha \text{ to } \pi + \alpha)$

When T_1 and T_2 are conducting, then

$$\boxed{V_{T3T4} = -V_0}$$



$V_0 + V_{ab} = 0$

$V_0 = -V_{ab}$

$= V_{ba}$

$V_{T1T2} = -V_0$

T_1, and T_2 stops conducting.

0 to α T_3T_4 is conducting

↳ load current is constant.

↳ At any time, any two thyristors must be conducting.

Source current

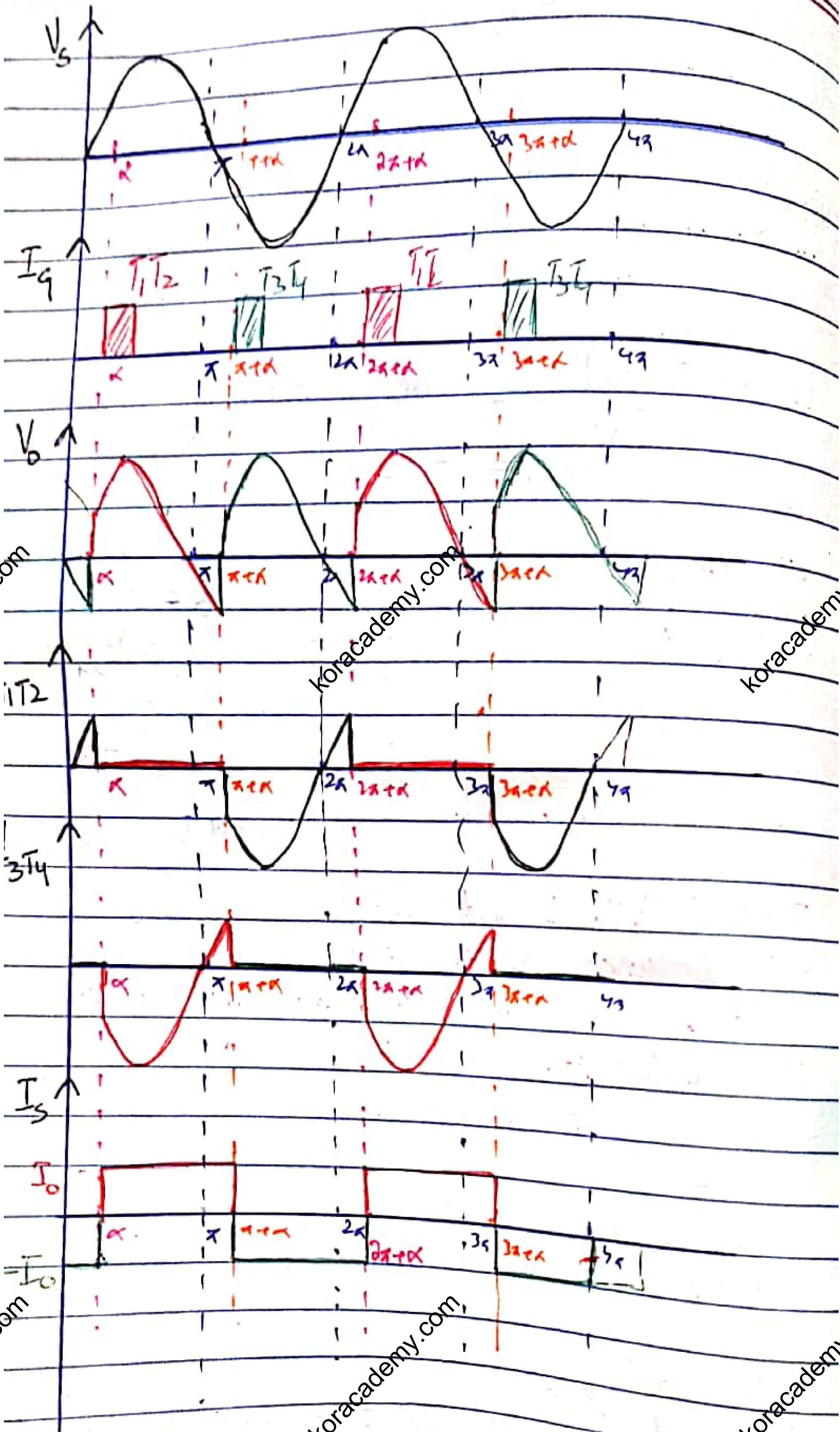
α to $\pi + \alpha$ ⇒ $I_0 = I_s$

$\pi + \alpha$ to $2\pi + \alpha$ ⇒ $I_s = -I_0$

Parameters

$$V_{avg} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d\omega t = \frac{2V_m}{\pi} \cos\alpha$$

Date: / /



Date: / /

Day

$$t_c = \frac{\pi - \alpha}{\omega}$$

Thyristor current.

Each Thyristor is conducting for a period of π.

$$I_{T avg} = I_o \left(\frac{\pi}{2\pi}\right) = \frac{I_o}{2}.$$

$$I_{T rms} = I_o \sqrt{\frac{\pi}{2\pi}} = \frac{I_o}{\sqrt{2}}$$

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

① $\alpha < 90°$, $V_o > 0$, $I_o > 0$

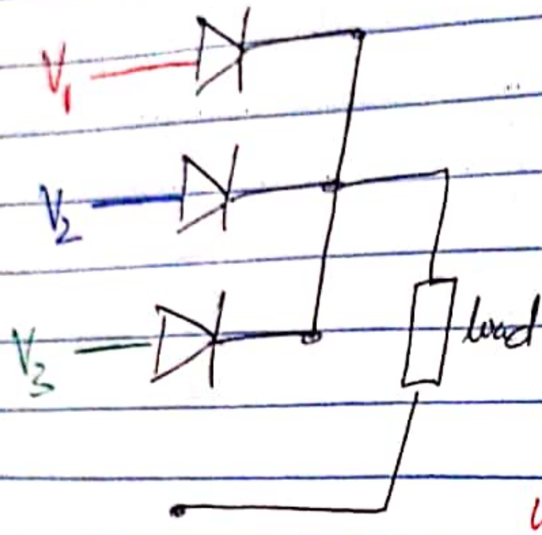
$P_o > 0$ → power is transfered from source to load.

② $\alpha > 90°$, $V_o < 0$, $I_o < 0$

$P_o < 0$ → power is transfered from load to source.

→ inverter

3 phase Half Wave Uncontrolled Rectifier



From $\omega t = 30^\circ$ to 150°
$V_1 > V_2$ and V_3
D_1 will conduct
$\Rightarrow V_0 = V_1$

$\omega t = 150^\circ$ to ~~180°~~ 270°
$V_2 > V_1$ and V_3
so D_2 will conduct
$V_0 = V_2$

$270^\circ - 360^\circ$
$V_3 > V_1$ and V_2
so D_3 will conduct
and will follow i/p voltage

For resistive load;
current follows the voltage waveform.

For inductive load, I_0 is constant.

This is also known as 3 pulse converter.
as we have 3 pulses in o/p waveform.

$f_0 = 3 f_s$

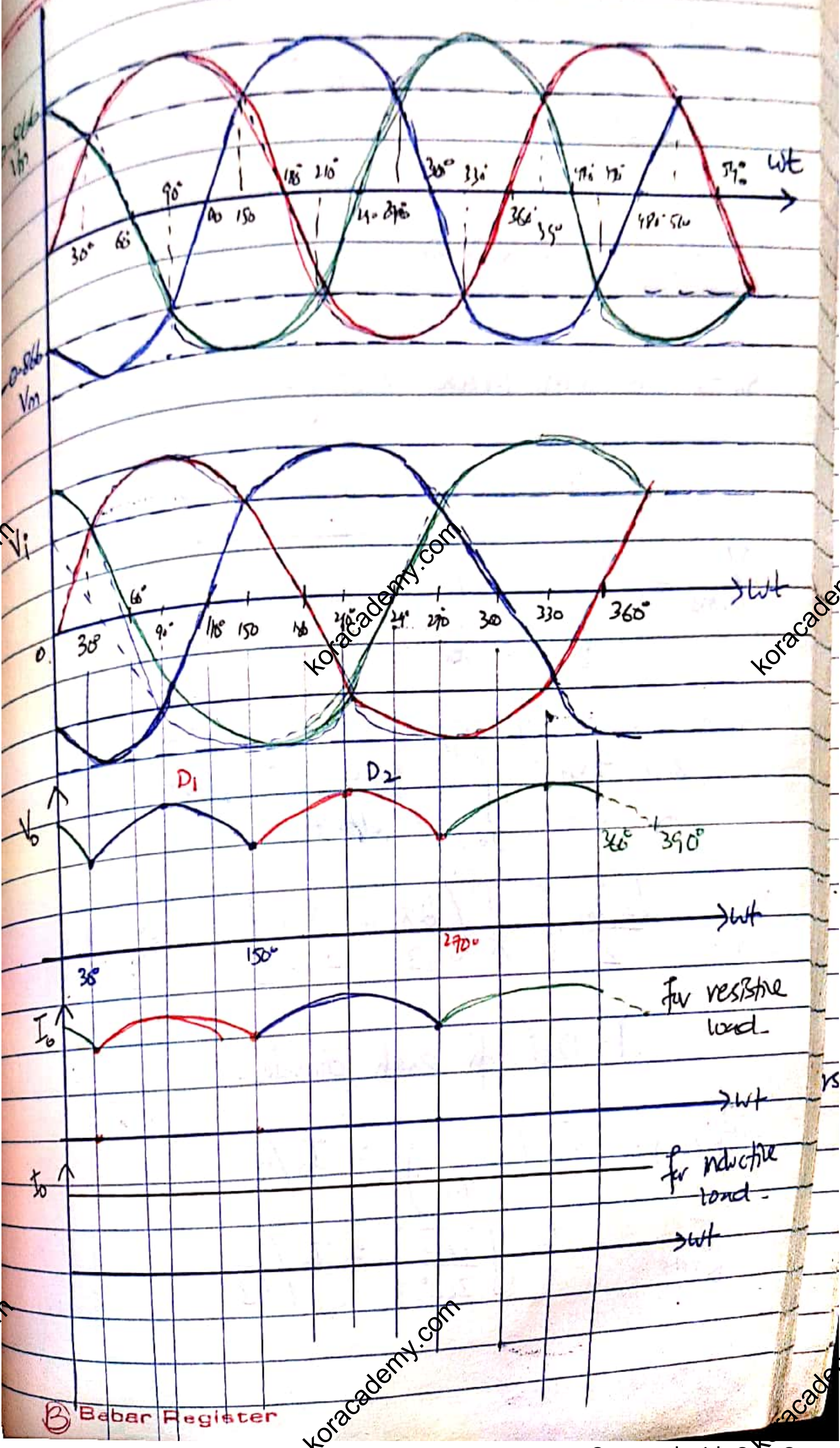
Each diode is conducting for 120° in each cycle.

Date: / /   Day

$V_A = V_m \sin \omega t$

$V_b = V_m \sin(\omega t - 120°)$

$V_c = V_m \sin(\omega t + 120°)$



$$V_{avg} = \frac{1}{120^\circ} \int_{30}^{150} V_m \sin\omega t \, d\omega t$$

$$= 3 \frac{V_m}{2\pi} \left[-\cos\omega t \right]_{30^\circ}^{150^\circ}$$

$$V_{o_{avg}} = \frac{3\sqrt{3} V_m}{2\pi}$$

$V_m \rightarrow$ maximum phase voltage

$$V_m = \sqrt{\frac{2}{3}} V_\ell$$

$$V_{o_{rms}} = \sqrt{\frac{1}{2\pi/3} \int_{30}^{150} V_m^2 \sin^2\omega t \, d\omega t}$$

$$= \sqrt{\frac{3 V_m^2}{2\pi} \int_{30}^{150} \frac{1 - \cos 2\omega t}{2} \, d\omega t}$$

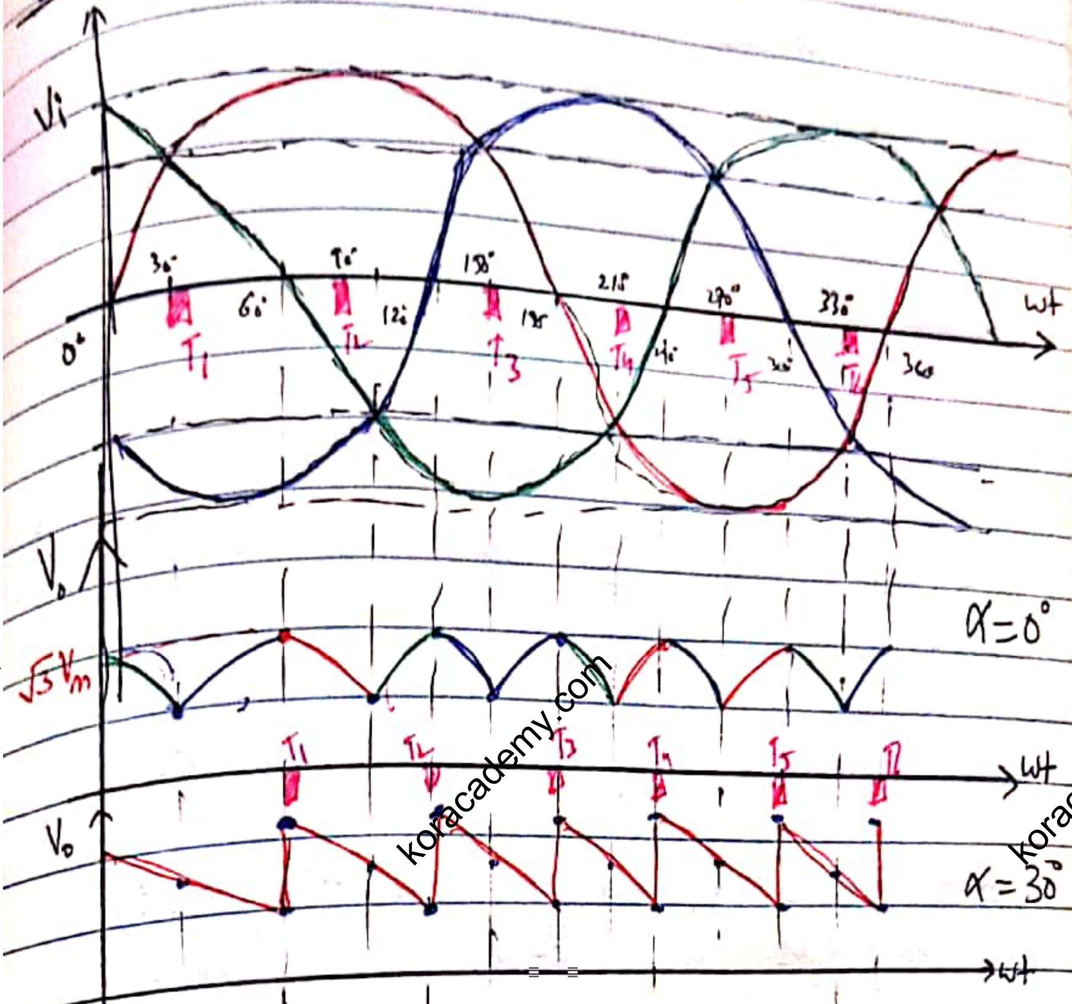
$$V_{o\,rms} = \frac{\sqrt{3} V_m}{2} \left[\frac{1}{\pi} \left(\frac{2\pi}{3} + \frac{\sqrt{3}}{2} \right) \right]^{1/2}$$

$\gamma = 120^\circ$ for each diode

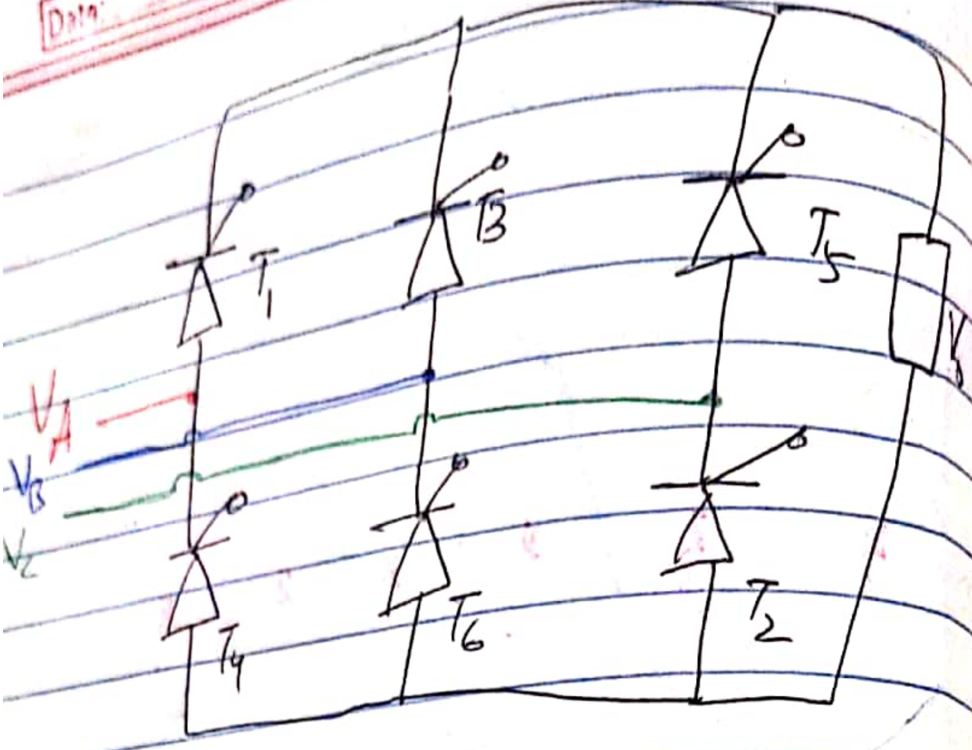
$$I_{D(avg)} = I_o \left(\frac{120}{360} \right) = I_o/3$$

$$I_{D\,rms} = I_o \sqrt{\frac{120}{360}} = I_o/\sqrt{3}$$

Three Phase Controlled Full Wave Bridge Rectifier



Date: / /



$V_A = V_m \sin\omega t$ $V_B = V_m \sin(\omega t - 120°)$

$V_C = V_m \sin(\omega t + 120°)$

Each thyristor is triggered at 60° duration.

When i/p voltage is given to this circuit, two thyristors will conduct at a time.

The sequence is like this;

$T_6T_1 \rightarrow T_1T_2, T_2T_3 \rightarrow T_3T_4 \rightarrow T_4T_5 \rightarrow T_5T_6$

$\alpha = 0°$

~~Suppose that~~ we trigger T_1 at $\alpha = 30°$

so it means T_2 will be triggered at 90°, T_3 at 150°, T_4 at 210°, T_5 at 270° and T_6 at 330°

$\Rightarrow \omega t = 30°$

Date: / / Day

At $\omega t = 30^\circ \rightarrow T_6$ and T_1 are conducting.

$$V_0 = V_{AB} = V_A - V_B$$

Put $\omega t = 30^\circ$

$$V_0 = V_m \sin 30^\circ - V_m \sin 90^\circ$$

$$V_0 = 1.5 V_m .$$

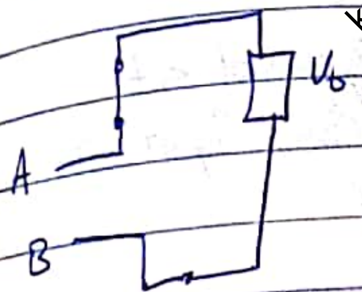
At $\omega t = 60^\circ \rightarrow T_6, T_1$ will conduct.

$$V_0 = V_m \sin 60^\circ - V_m \sin(-60^\circ)$$

$$V_0 = \sqrt{3} V_m .$$

At $\omega t = 90^\circ$.

T_1 and T_2 will conduct.



$$V_0 = V_{AC} = V_A - V_C$$

put $\omega t = 90^\circ$

$$V_m \sin 90^\circ - V_m \sin(90^\circ - 240^\circ)$$

$$V_0 = 1.5 V_m$$

The o/p voltage represents line to line voltage.

At $\omega t = 120^\circ$ T_2 and T_1 conduct.

$$V_0 = V_A - V_C$$

$$V_m \sin(120^\circ) - V_m \sin(-120^\circ)$$

$$V_0 = \sqrt{3} V_m$$

At $\omega t = 150°$ T_2, T_3 conducting.

$V_0 = V_B - V_C = V_{BC}$

At $\omega t = 150°$

$V_0 = V_m \sin(150° - 120°) - V_m \sin(150 - 240°)$

$\Rightarrow V_0 = 1.5\,V_m$

In this way repeat.

Each thyristor conducts for 120°.

Same current we will get for 240°

The second sketch is for $\alpha = 30°$
which means that T_1 is triggered at
$\omega t = 60°$, T_2 at 120°, T_3 at 180°, T_4 at 240°,
T_5 at 300 and T_6 and 360°

At $\omega t = 60°$ T_6 and T_1 will conduct.

$V_0 = V_{AB} = V_A - V_B$

$V_0 = \sqrt{3}\,V_m$

At $\omega t = 90°$

$V_0 = V_{AB} = V_A - V_B$

$V_0 = 1.5\,V_m$

At $\omega t = 120°$ T_1 and T_2

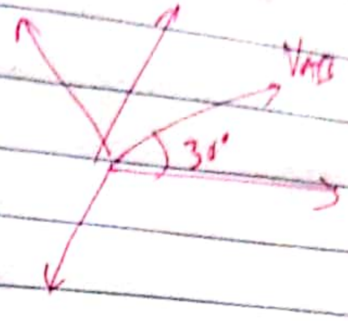
$V_0 = V_A - V_C$

$V_0 = \sqrt{3}\,V_m$

for $\omega t = 120°$ - $T_1 T_6$.

$V_0 = V_{AB} = V_A - V_B = \sqrt{3}/2 \, V_m$.

$V_{AB} = V_m \sin(\omega t + 30°)$



Chopper

chopper is nothing but a DC to DC converter.

D → duty cycle $\quad D = \frac{T_{ON}}{T}$

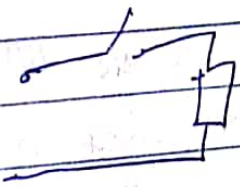
$T_{ON} = DT \qquad T = T_{ON} + T_{OFF}$

$T_{OFF} = T - T_{ON} = T - DT$

$T_{OFF} = (1-D)T$

Proper value of L and C, diode as switching element → converter.

Chopper → switch



→ cannot be used for practical purposes.

Volt second balance

$V_{L(ON)} T_{ON} + V_{L(OFF)} T_{OFF} = 0$

$V_{L(avg)} = 0$

Date: / /

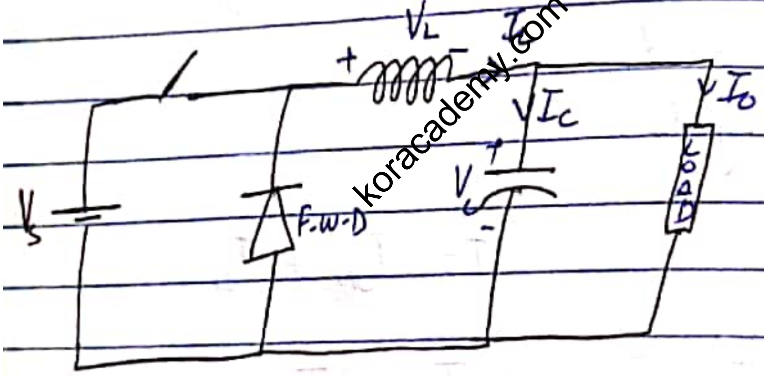
Ampere Second Balance.

$$I_{C(ON)} T_{(ON)} + I_{C(OFF)} T_{(OFF)} = 0$$

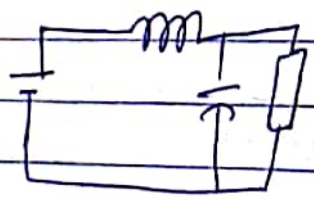
$$I_{C(avg)} = OFF$$

In all converters we will assume that load current i.e. I_o is constant.
↳ i.e. we will talk about continuous conduction mode only.

Buck Converter.



When switch is closed at $t=0$.

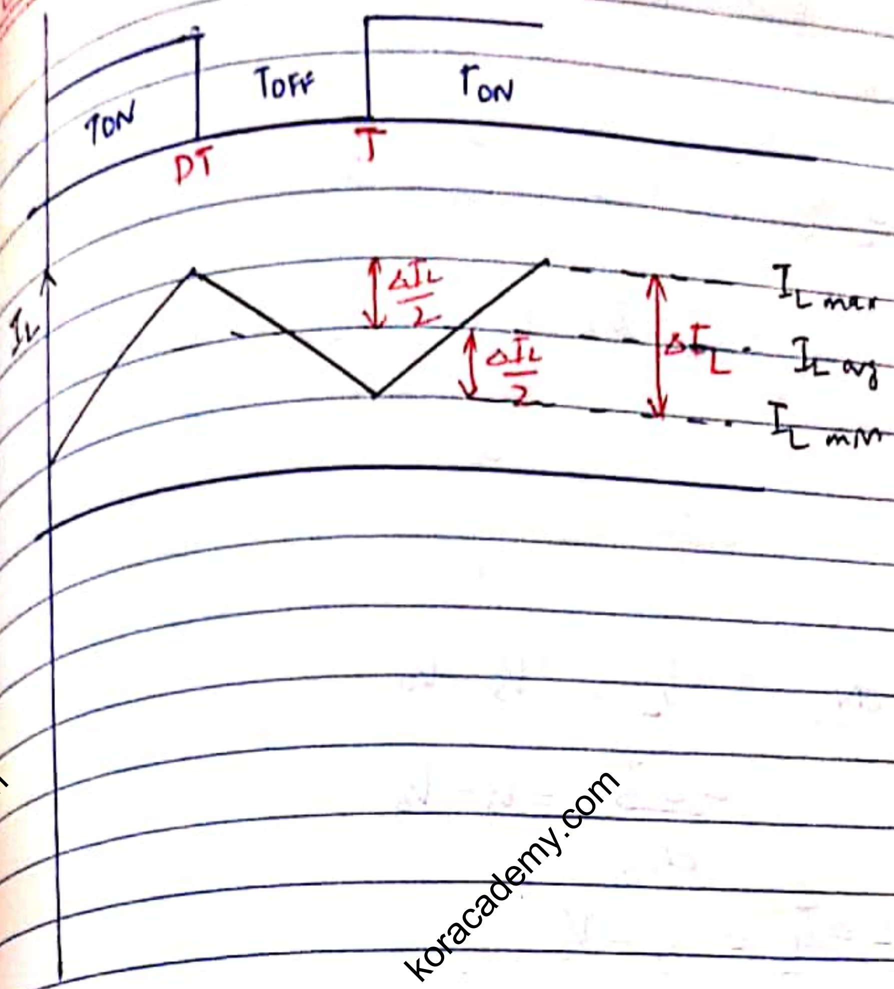


Inductor will charge untill the switch is on (closed).

let the switch is ON till DT.

If you open the switch now, the inductor discharges through the load as current free wheels through the diode.

– The inductor acts as a current source here.



Switch is ON

$$V_{L(ON)} = V_s - V_o$$

$$I_{C(ON)} = I_L - I_o$$

Switch off

$$V_{L(OFF)} + V_o = 0$$

$$V_{L(OFF)} = -V_o$$

$$I_{C(OFF)} = I_L - I_o$$

$$\Rightarrow V_{L(ON)} T_{ON} + V_{L(OFF)} T_{OFF} = 0$$

$$(V_s - V_o) DT - V_o (1-D) T = 0$$

$$\boxed{V_o = DV_s}$$

Date: / /

As $0 \le D \le 1$
So this is a step down converter.

$$I_{C(ON)} T_{ON} + I_{C(OFF)} T_{OFF} = 0$$

$$(I_L - I_o) DT + (I_L - I_o)(1-D)T = 0$$

$$\boxed{I_L = I_o}$$

$\Delta I_L \rightarrow$ Ripple in inductor current = ?

During ON $\quad V_L = V_S - V_o$

$$L \frac{di_L}{dt_{on}} = V_S - V_o$$

$$\Rightarrow L \frac{\Delta I_L}{DT} = V_S - V_o$$

$$V_o = DV_S$$

$$\Rightarrow \boxed{\Delta I_L = \frac{D(1-D)V_S}{fL}}$$

$$I_{L\,max} = I_L + \frac{\Delta I_L}{2} = I_o + \frac{\Delta I_L}{2}$$

As $I_L = I_o$

$$I_{L\,min} = I_{L\,avg} - \frac{\Delta I_L}{2} = I_o - \frac{\Delta I_L}{2}$$

Source current.

Always put i/p power equal to o/p power

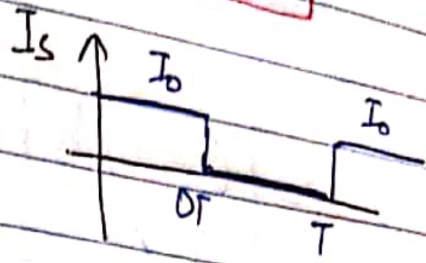
$P_{in} = P_{out}$

Day

$V_s I_s = V_o I_o$

$$I_s = \frac{V_o I_o}{V_s}$$

switch current $I_{sw} = I_s$

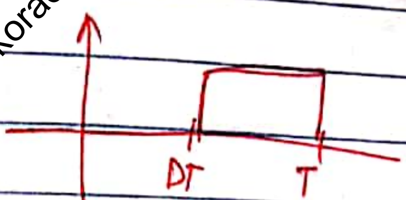


$$I_{sw(avg)} = I_o \frac{DT}{T}$$

$$I_{sw(avg)} = I_o D = D I_{L_{avg}}$$

$$I_{s_{rms}} = I_{sw_{rms}} = I_o \sqrt{\frac{DT}{T}} = \sqrt{D}\, I_o$$

Diode current



$$I_{D_{avg}} = I_o \frac{(1-D)T}{T} = (1-D) I_o$$

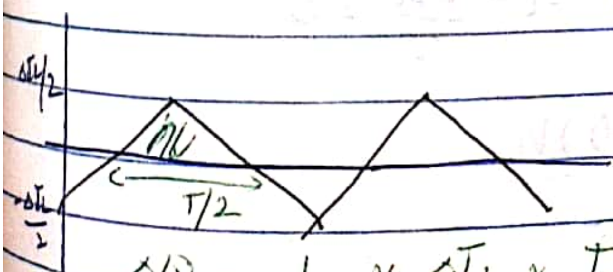
ΔV_c or $\Delta V_o = ?$

$I_c = I_L - I_o$

$Q = CV$

$\Delta Q = C \Delta V$

$\Delta V = \frac{\Delta Q}{C}$



$$\Delta Q = \frac{1}{2} \times \frac{\Delta I_L}{2} \times \frac{T}{2} = \frac{\Delta I_L}{8f}$$

$\Delta I_L = \frac{D(1-D)V_s}{fL}$

Babar Register

Scanned with CamScanner

For what value of D (duty cycle) ripple in capacitor voltage is maximum.
↳ or inductor current.

$$\frac{d\Delta V_c}{dD} = 0$$

$$\frac{8f^2LC\left[(1-2D)V_s\right] - D(1-D)V_s \times 0}{(8f^2LC)^2} = 0$$

$1-2D=0 \Rightarrow D = \frac{1}{2} = 0.5$

$$\Delta V_{c_{max}}\Big|_{D=0.5} = \frac{V_s}{32f^2LC}$$

$$\Delta I_{L_{max}}\Big|_{D=0.5} = \frac{V_s}{4fL}$$

Critical Inductance

Minimum value of inductor for which inductor current is just continuous.

$$I_{L_{min}} \approx 0$$

$$I_L - \frac{\Delta I_L}{2} = 0$$

for R load

$$\frac{V_o}{R} = I_o = \frac{D(1-D)V_s}{2fL}$$

$$L_c = \frac{R(1-D)}{2f}$$

Critical capacitance

minimum value of capacitance for which o/p voltage is just continuous.

$$\Delta V_{C_{min}} \approx 0$$

$$V_c - \frac{\Delta V_c}{2} = 0 \Rightarrow V_o - \frac{\Delta V_c}{2} = 0$$

$$\downarrow$$

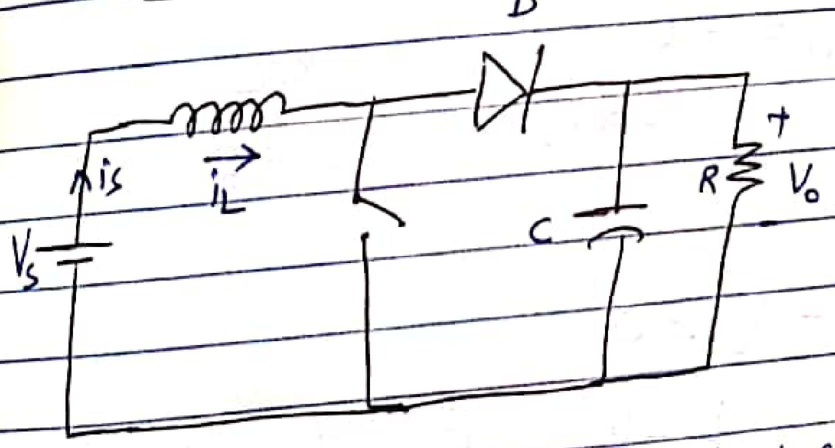
$$DV_s = \frac{1}{2}\frac{D(1-D)V_s}{8f^2LC}$$

$$C_c = \frac{(1-D)}{16f^2L}$$

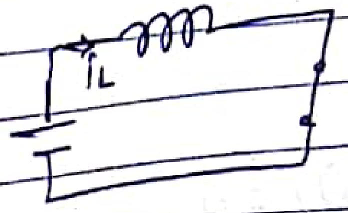
As for R load $L_c = \frac{R(1-D)}{8f}$

$$\Rightarrow C_c = \frac{1}{8fR}$$

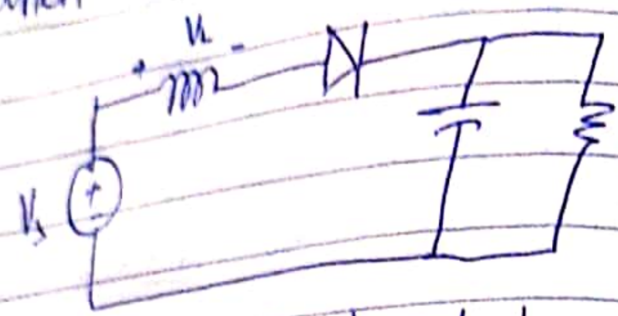
Boost Converter



When switch is closed → short circuit → source has no effect on load
↳ Inductor is charging
↳ current will increase linearly.



When switch is opened;



source voltage and inductor energy will get dissipated across the load.
↳ will deliver power to the load through diode

diode is short circuited ↵

we can adjust I_{Lmin} and switching frequency.

When switch is ON.

$$-V_s + V_L = 0$$

$$V_{L(ON)} = V_s$$

$$I_{C(ON)} = -I_o$$

KCL

$$\hookrightarrow A_3 + I_C + I_o = 0$$

when switch is open.

$$-V_s + V_{L_{off}} + V_o = 0$$

$$V_{L(off)} = V_s - V_o$$

$$I_{C(off)} = I_L - I_o$$

Volt second balance

$$V_s D_T + (V_s - V_o)(1-D)T = 0$$

$$V_s D T + V_s (1-D) T - V_o (1-D) T = 0$$

Date: / /   Day

$V_o(1-D) = V_s$

$$V_o = \frac{V_s}{1-D}$$

$0 \le D \le 1$

↳ $V_o > V_s$ → step up chopper

↳ $\approx \infty$

Ampere second balance

$-I_o DT + (I_L - I_o)(1-D)T = 0$

$-I_o DT + I_L(1-D)T - I_o(1-D)T = 0$

$$I_L = \frac{I_o}{1-D}$$

Ripple in inductor current, ΔI_L.

$V_{L_{ON}} = L\frac{di_{on}}{dt_{on}} = V_s$

$$\Delta I_L = \frac{DV_s}{fL}$$

$I_{L_{max}} = I_L + \frac{\Delta I_L}{2}$

↳ $\frac{I_o}{1-D} + \frac{DV_s}{fL}$

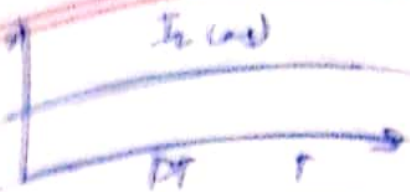
$I_{L_{min}} = I_L - \frac{\Delta I_L}{2}$

Source current $P_{in} = P_{out}$

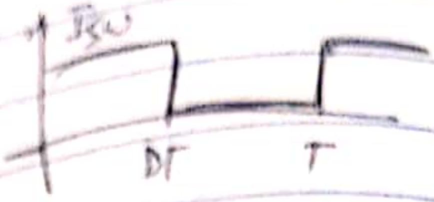
$V_s I_s = V_o I_o$

$$I_s = \frac{V_o I_o}{V_s}$$

Switch current



$$I_{sw(avg)} = \frac{I}{I_{avg}}\left(\frac{DT}{T}\right)$$



$$I_{sw(avg)} = D\, I_{L\,avg} = D\,\frac{I_o}{1-D}$$

$$I_{sw\,rms} = \sqrt{D}\, I_{L\,avg} = \sqrt{D}\,\frac{I_o}{1-D}$$

Diode current

$$I_{D(avg)} = I_L\,\frac{(1-D)T}{T} = I_L(1-D)$$

$$\frac{I_o}{1-D} \times (1-D)$$

$$I_{D\,avg} = I_o$$

$$I_{D\,rms} = I_L\sqrt{\frac{(1-D)T}{T}} = \sqrt{(1-D)}\; I_L$$

Ripple in o/p voltage $\Delta V_c = \Delta V_o$

During ON.

↳ capacitor will deliver power to the load.

$$I_c = -I_o$$

$$C\,\frac{dV_c}{dt} = -I_o \qquad \int_{V_{max}}^{V_{min}} dV = \int_0^{DT} -\frac{I_o}{C}\,dt$$

$$V_{min} - V_{max} = -\frac{I_o}{C}\,DT$$

Bahar Registe[illegible]

Date: Day

$\Delta V_c = V_{max} - V_{min}$

$-\Delta V_c = -\frac{I_o}{C} DT$

$\Delta V_c = \frac{D I_o}{f C}$

Critical inductance.

$I_{L\,min} = 0$

$I_L - \frac{\Delta I_L}{2} = 0$

$\frac{I_o}{1-D} = \frac{1}{2}\left(\frac{D V_s}{f L_c}\right) = \frac{V_o}{R(1-D)}$

$= \frac{V_s}{(1-D) R (1-D)}$

$L_c = \frac{D(1-D)^2 R}{2f}$

Critical capacitance

$V_{c\,min} = 0.$

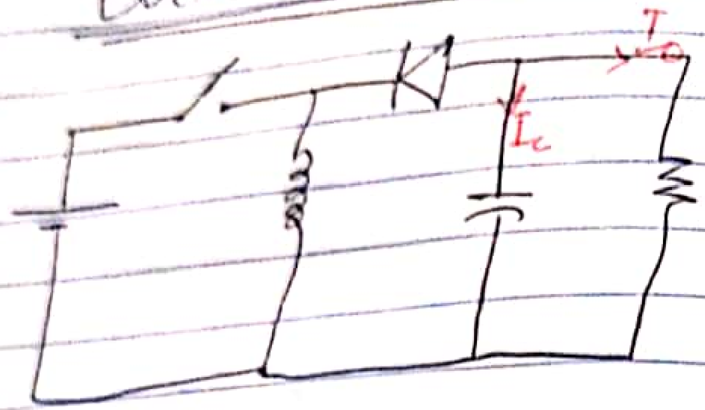
$V_c - \frac{\Delta V_c}{2} = 0$

$V_o = \frac{1}{2}\left(\frac{I_o D}{f C}\right) = \frac{D V_o}{2 R f C}$

$C_c = \frac{D}{2 f R}$

4 to 8 same in all converters.

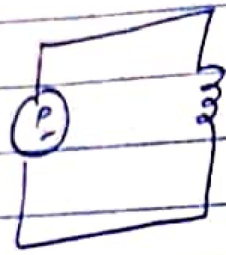
Buck Boost Converter



When switch is closed at $t=0$

supply will charge L.

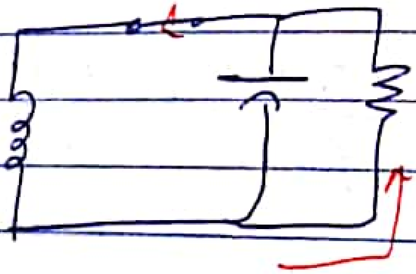
↳ I_L increase till DT.



$V_L = V_s$

During ON condition → capacitor is delivering power to load.

Switch open at $t=DT$



Inductor will deliver energy to load.

Switch ON: 0 to DT	Switch OFF: DT to T
$V_{L_{ON}} = V_s$	$V_{L_{off}} - V_o = 0$
$I_{L_{ON}} = -I_o$	$V_{L_{off}} = V_o$
	$I_{L_{off}} = -(I_L + I_c)$

Date: Day

Volt second balance.

$$V_s DT + V_o (1-D) T = 0$$

$$V_o = \frac{-D}{(1-D)} V_s$$

Ampere second balance

$$-I_o DT - (I_L + I_o)(1-D) T = 0$$

$$I_L = \frac{-I_o}{1-D}$$

ΔI_L . $V_{L_{on}} = V_s = L\frac{di}{dt} = L\frac{\Delta I_L}{DT}$

$$\Delta I_L = \frac{DV_s}{fL}$$

$$I_{L_{max}} = I_L + \frac{\Delta I_L}{2}$$

$$|I_{L_{avg}}| = \frac{I_o}{(1-D)}$$

$$I_{L_{min}} = I_L - \frac{\Delta I_L}{2}$$

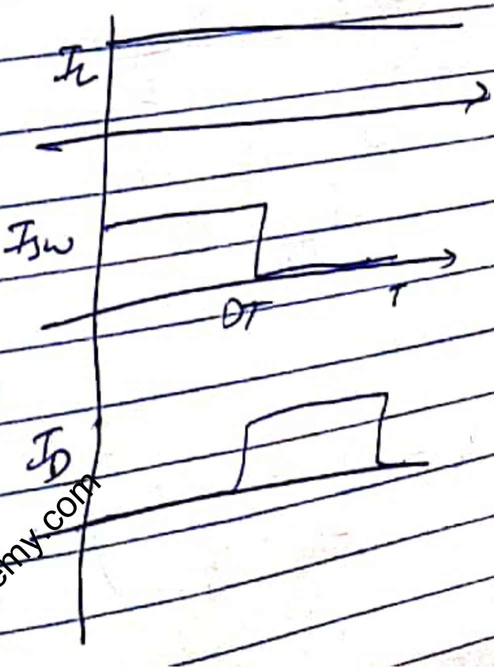
$P_{in} = P_{out}$ $\qquad I_s = \frac{V_o I_o}{V_s}$

$$I_{sw(avg)} = D I_L$$

$$I_{sw\,rms} = \sqrt{D}\, I_L$$

$$I_{D_{avg}} = (1-D) I_L$$

$$I_{D_{rms}} = \sqrt{(1-D)}\, I_L$$



Date

$\Delta V_c =$

during ON.

$I_{c_{ON}} = -I_o$

$$C\frac{dV_c}{dt} = -I_o$$

$$\int_{V_{min}}^{V_{max}} dV_c = \int_0^{DT} \frac{-I_o}{C} dt$$

$$\Delta V_c = \frac{D I_o}{fC}$$

$D = 1 \Rightarrow \Delta V_c$ is maxim

↳ ripple ↑.

Critical inductance

$I_{L_{min}} = 0 \qquad I_L - \frac{\Delta I_L}{2} = 0$

$$\frac{D V_s}{R(1-D)^2} = \frac{-V_o}{R(1-D)} = \frac{-I_o}{(1-D)} = \frac{1}{2}\left(\frac{D V_s}{f L_c}\right)$$

$$L_c = \frac{R(1-D)^2}{2f}$$

Critical capacitance

$V_{c_{min}} = 0 \qquad V_c - \frac{\Delta V}{2} = 0$

$$V_o = \frac{\Delta V_c}{2}$$

$$V_o = \frac{1}{2}\left(\frac{D I_o}{fC}\right) = \frac{1}{2}\left(\frac{D V_o}{fCR}\right)$$

$$C_c = \frac{D}{2fR}$$