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NEAR MADE EASY F-21A, LADO SARAI, NEW DELHI-30

(PHOTOSTAT, BOOK CENTER)

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HIND PHOTOSTAT AND HIND BOOK CENTER

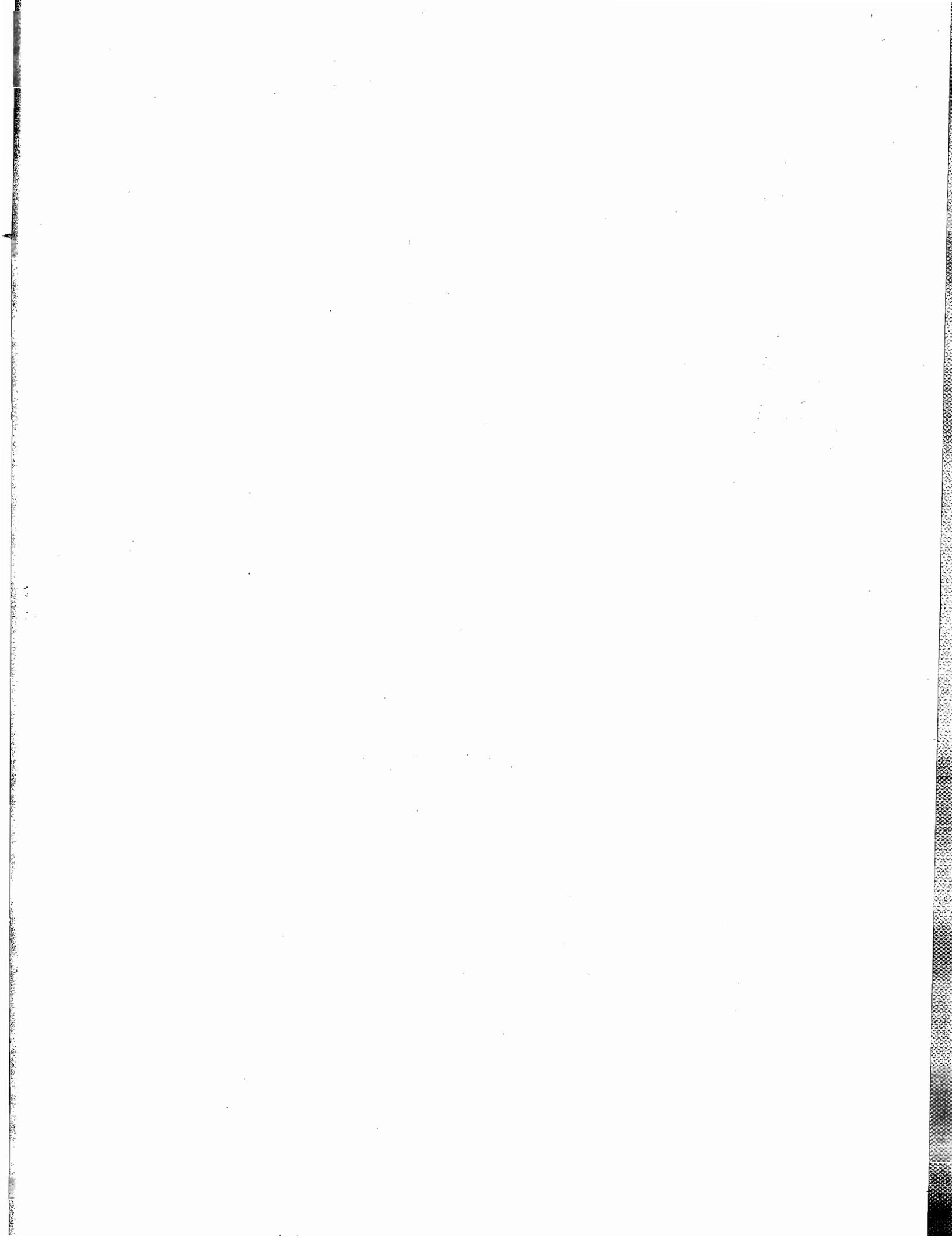
NAME:-.....

SUBJECT:- POWER ELECTRONICS

INSTITUTE:- MADE EASY

PLEASE CONTACT FOR:-

- PHOTOSTAT (LASER DIGITAL)
- PRINT OUT FROM COMPUTER
- SPIRAL BINDING, HARD BINDING
- TEST PAPER FOR PSU, GATE, IES
- ALL NOTES AVAILABLE
- ALL BOOK AVAILABLE



ANUPAM SHUKLA

DATE-04/08/14

Power electronics

Mugro secy,
8871453536

Topics→

- (1) Power semicond^r devices.
- (2) Phase controlled rectifiers & applications (charging battery..
(AC-DC)
Solar cell.
DC drives.)
- (3.) Inverters (DC-Ac)
- (4.) Choppers (DC-DC)
- (5.) AC voltage controllers & cycloConverters
(AC-AC) (V_o, F_o)
- (6.) Other appn:-
 - Ac drives
 - HVDC
 - Reactive power control
 - smps

Power electronics →

- * It deal with control & conversion of high power app.
- * Power s/c devices should be capable to handle large magnitudes of power with high η .

(1.) Power diode } (P↑ - Handle highest power)
(2.) Thyristor (SCR)

(3.) ACSR

(4.) LASCR

(5.) RCT

(6.) GTO

(8.) TRIAC

(9.) DIAC

(9.) Power transistors:-

→ Power BJT

→ Power MOSFET (F↑ - Highest switching devices)

→ IGBT.

Signal electronics →

- * It deal with control of low power app.

Signal devices handle low power at very high switching η .

g. → (1.) signal diode - Zener diode

LEDs

Vrector diode-----

(2.) Signal transistors - BJT, MOSFET, UJT -----

Signal devices - (P↓, F↑)

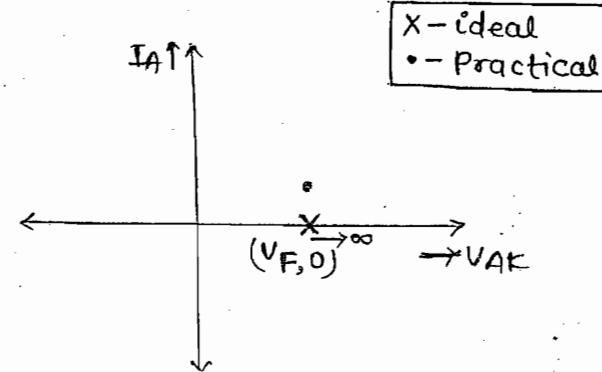
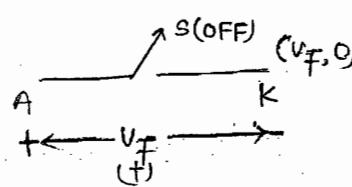
ste →

* We can't improve all the qualities in a single device, when we want to improve some of qualities the other qualities may be affected.

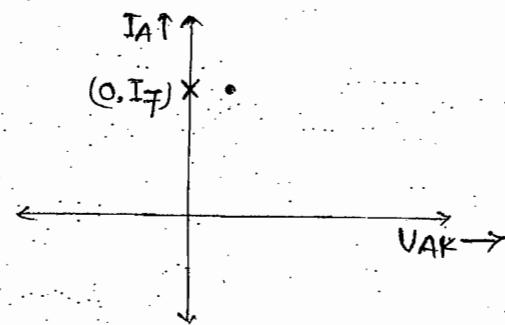
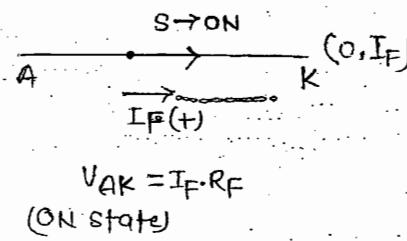
* We can utilize the switch in 4 diff mode but all the devices need not support all the 4 modes.

* Four modes of ideal switch \rightarrow

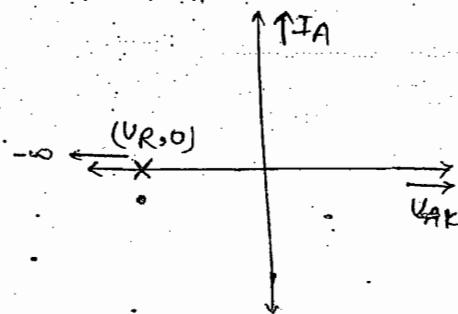
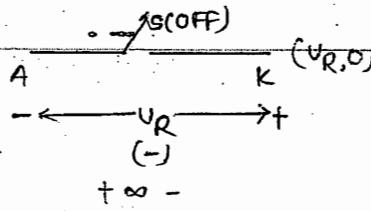
(1) Forward blocking mode \rightarrow



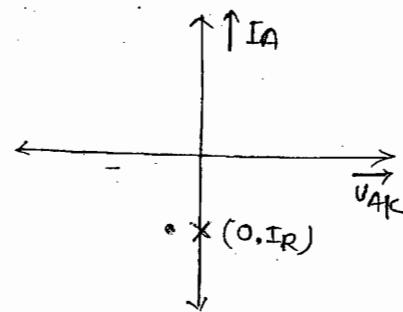
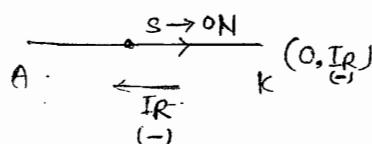
(2) Forward Conduction mode \rightarrow



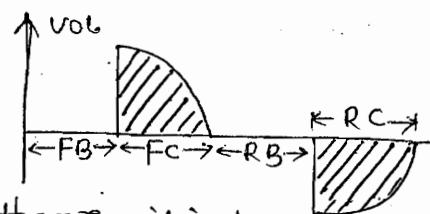
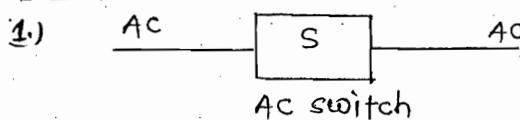
(3) Reverse Blocking mode \rightarrow



(4) Reverse Cond^h mode \rightarrow

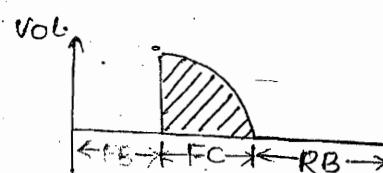
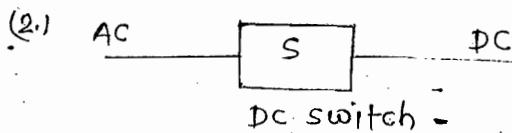


Note →



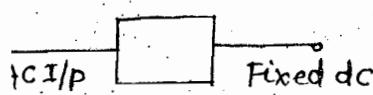
* TRIAC supports all the 4-modes therefore it is treated as an ac switch & used in AC vol. controllers.

Eg. → Fan regulator.



Eg. → SCR (This will support only 3 modes, RC is absent)

Diode Rectifier

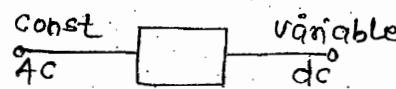


Applicn →

- 1) Electric traction
- 2) Battery charging
- 3) Electroplating
- 4) Welding

UPS (Uninterrupted Power supply)

AC to dc Converters



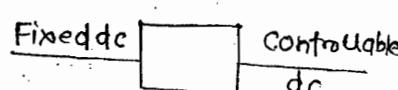
* Phase controlled Recti-

* Line/Naturally commutated AC to dc converter (Because they use line voltage for commutation)

Applicn →

- (1) DC drives
- (2) Excitation sys. for synchronous m/c.

DC to dc converters



* Dc choppers

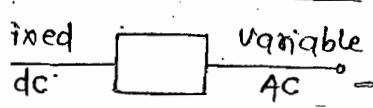
* Forced (or) load commutation.

* They may classify as there commutation & power flow.

Applicn →

- (1) dc drives
- (2) subway cars

DC to AC Converters



Inverters.

Line/load/Forced commutation.

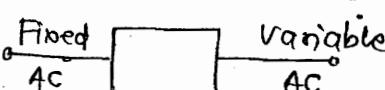
Applicn →

Indn/synchronous motor Induction Heating

UPS

HVDC

Ac to Ac Converter



(a) AC voltage controller

(b) Cyclo Converter

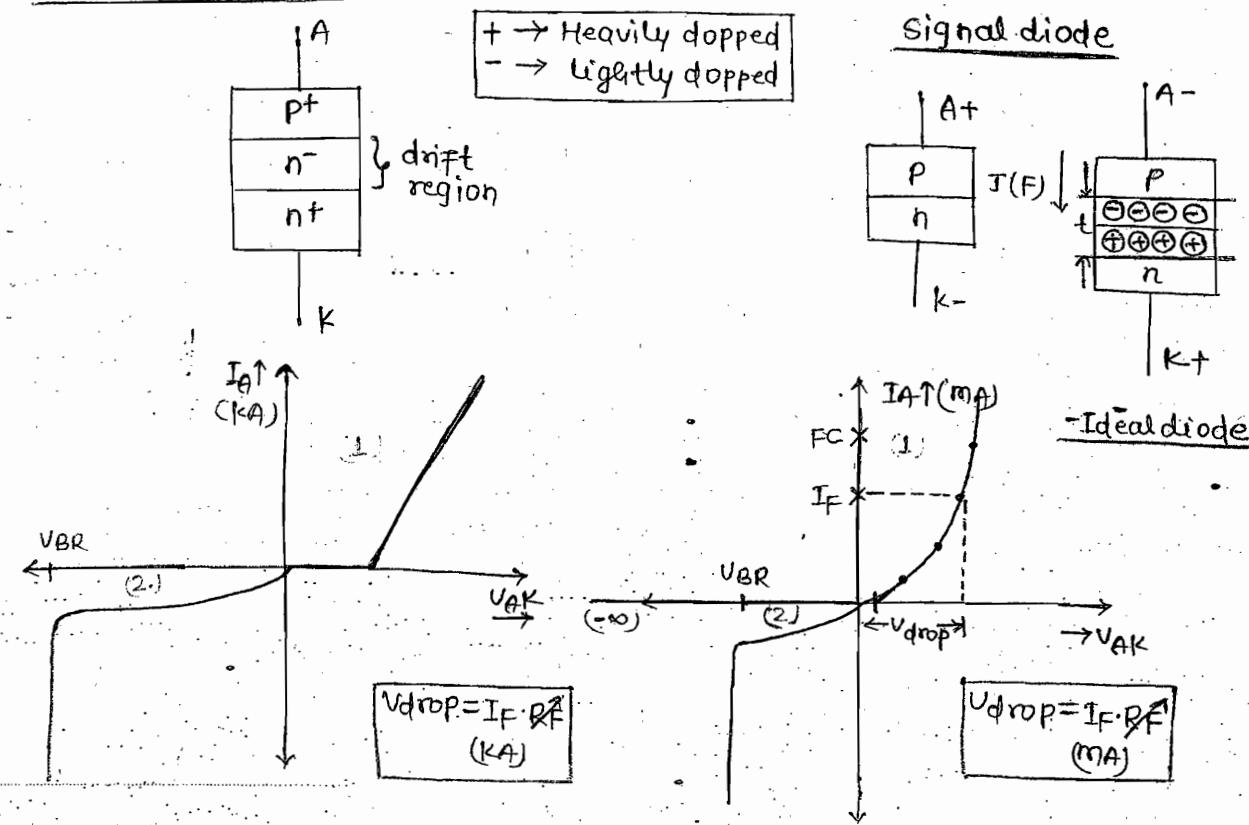
↓
slow speed

large ac drive (Rotary Kiln)

↓
lightning (or) speed control

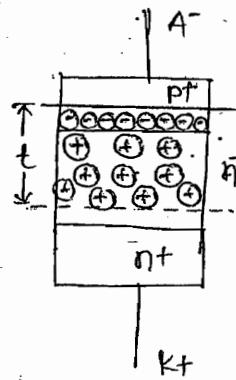
* (1) Power Semiconductor devices →

(1) Power diode →



- * The maximum thickness of depletion layer decides the reverse blocking capability of diode.
- * Signal diode will block 20V, whereas the power diode blocks 2000V (V_{BR})

Significance of drift region →



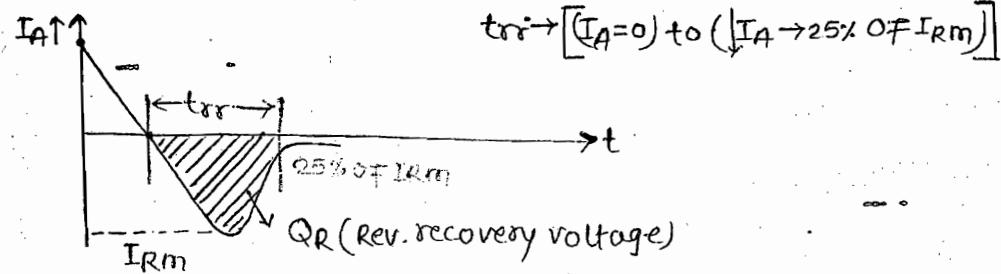
* If anode is made w.r.t cathode then the depletion layer across the junction the depletion layer penetrates more deeply into n' layer in order to equalise the charge on both the sides of junction.

* This increases the thickness of depletion layer & rev. blocking capability of diode.

** Higher the thickness of n' layer higher the rev. blocking capability of diode.

* Reverse recovery c/s \rightarrow

- * It explain the switching behaviour of power diode from ON state to OFF state.



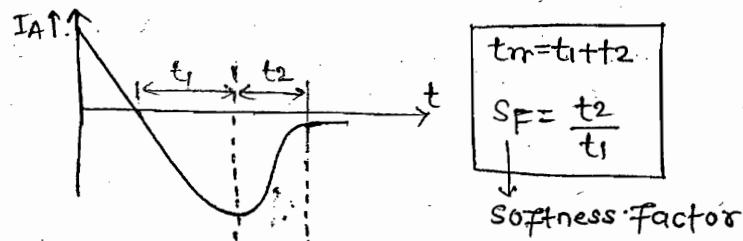
- * When diode is conducting in forward dirⁿ some excess charge carriers are stored in the device.
- * This charge carriers are mainly due to minority carriers.
- * When the diode is switching from ON state to OFF state this charge carriers are still present in the diode even after the anode current becomes 0.
- * In order to remove this charge carriers & regain its eq. state or normal state recombination process begins. & Hence reverse current flows in diode until all the charge carriers are completely removed.
- * This process is known as rev. recovery process & the transition time during this process is known as rev. recovery time (trr).
- * Area of the above Δ give →

$$QR = 1/2 \cdot trr \cdot I_{RM}$$

If the slope of the curve be (di/dt) then

$$I_{RM} = \left[2QR \left(\frac{di}{dt} \right) \right]^{1/2} \quad \dots \dots \text{(i)}$$

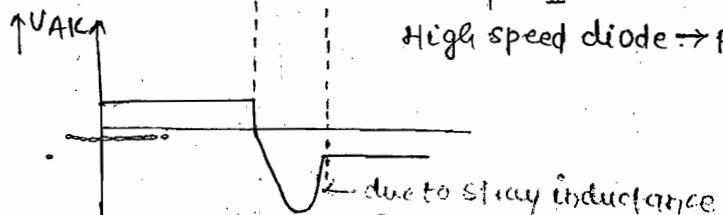
$$trr = \left[\frac{2QR}{\left(\frac{di}{dt} \right)} \right]^{1/2} \quad \dots \dots \text{(ii)}$$



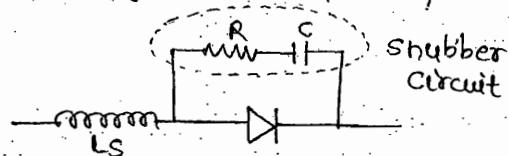
For High speed diode the softness factor

$$SF \ll 1$$

High speed diode \rightarrow fast recovery diode



* We have to limit this high voltage spike by using snubber circuit.



* Classification of power diodes based on trr \rightarrow

(I) General purpose diode \rightarrow
(Slow diode)

(i) $trr \rightarrow 25\text{ }\mu\text{s}$

(ii) Irating :-

1A to several 1000 AFA

Fast recovery
diode

(i) Irating :-

1A to several 100 of Amp

Schottky diode ($\neq 1$)

(ii) trr \rightarrow nano sec

(iii) Irating :- 3000 A

Vrating :- 100V

Vrating :- 50V to 5kV

Vrating :- 50V to 3kV

(iii) This has p-n jun?

* In this diodes the layers are dopped with gold (or) Pt

* This doping reduce the life time of charge carriers & increases its recombination speed.

* This redude the trr time.

* It has p-n jun?

* This has metal to s/c Junction diode

Al | Si (n-type)

* In this diode cond'n is only due to majority carriers.

* Due to the absense of minority charge carriers the trr is very much reduced Therefore it operate with very high switching freq.

Slow diodes are used in line freq. rectifiers. Therefore they are also known as rectifier diode.

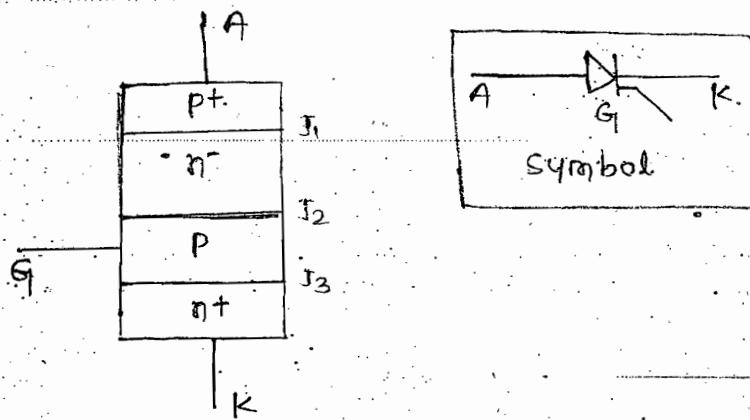
Application →

Rectifiers

Note →

- The trr decides the max^m switching speed of diode.
- Diode is an uncontrolled switch because there is no control terminal to decide its ON & OFF state.

2.1 Silicon Controlled Rectifier →



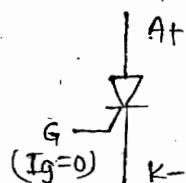
A, K → main control
G → Control terminal
(or)
semi controlled switch

a) Forward blocking mode →

* When anode is the work cathode then J₁, J₃ are forward & J₂ will reverse bias.

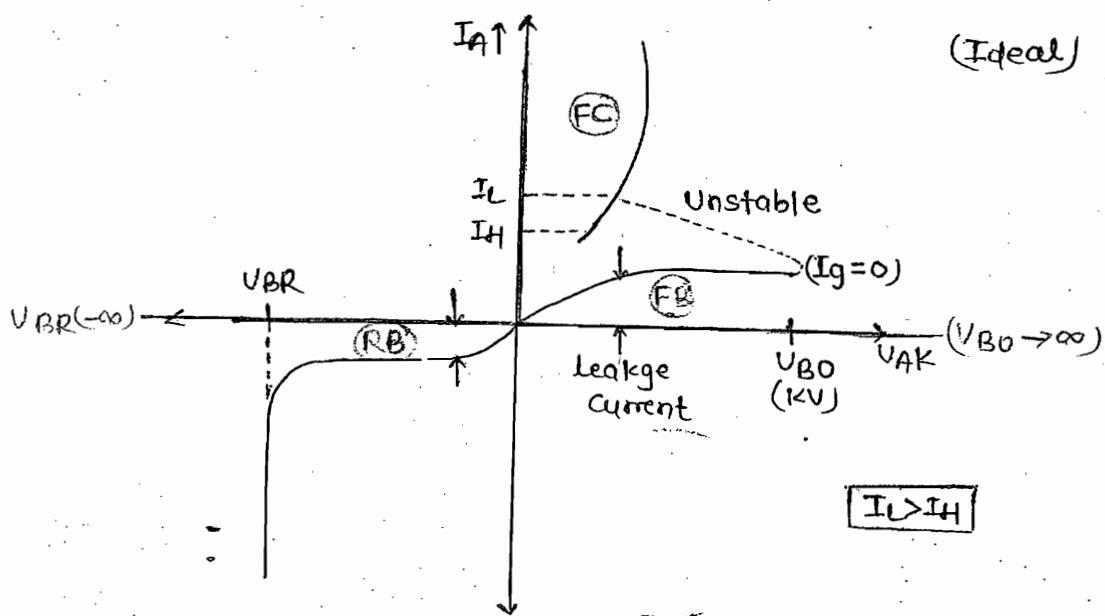
Hence the SCR will be off.

b) Forward conduction mode →



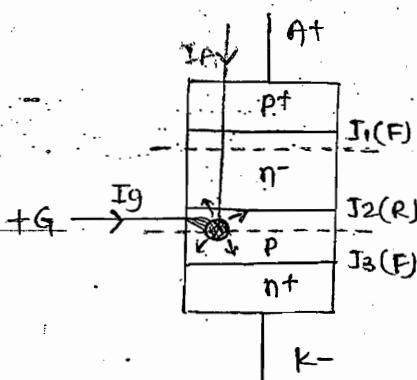
$V_{AK} \uparrow \Rightarrow V_{BO}$, breakdown occurs at J₂ & SCR → ON

$V_{BO} \rightarrow$ Forward breakdown voltage when $I_g = 0$



* If breakdown occurs at such a high voltage without gate pulse then SCR may damage due to high power loss during turn ON process.

Significance of gate signal \rightarrow

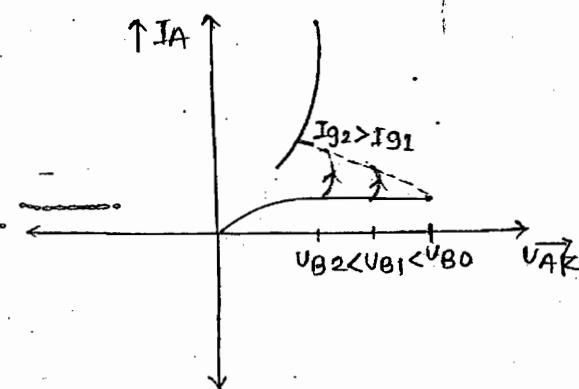


② \rightarrow Initial conducting area

$$I_g \uparrow \text{ or } \frac{dI_g}{dt} \uparrow \Rightarrow \frac{dI_A}{dt} \uparrow \text{ (Initial Rate)}$$

$t_{ON} \downarrow \text{ & } V_B \downarrow$
(Breakdown voltage)

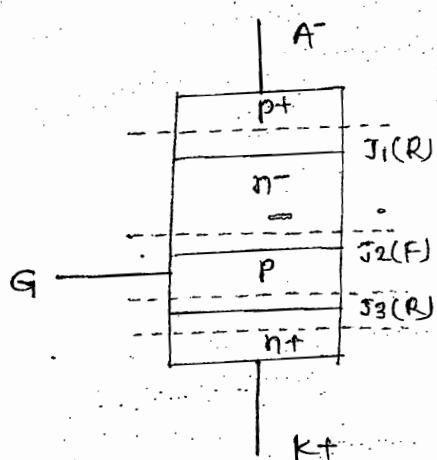
$I_g \uparrow, V_B \downarrow$



$$I_{g\min} \leq I_g \leq I_{g\max}$$

$$V_{g\min} \leq V_g \leq V_{g\max}$$

(C) Reverse blocking mode →



when A -ve w.r.t K

$J_2(F), J_1 \text{ & } J_3(R) \because \text{SCR} \rightarrow \text{OFF}$

J_1 blocks more reverse voltage compare with J_3 due to n layer.

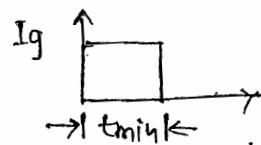
Que. → What happens if a +ve gate pulse is given to a reverse biased thyristor.

Significance of Latching Current →

Latching current is related to turn ON process.

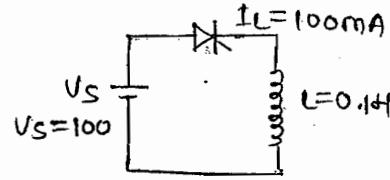
- Gate pulse initiates the turn ON process but once the thyristor is on the ON state gate loses control on the device. Therefore we can remove the gate pulse when SCR becomes on to avoid the continuous gate power loss.

- If gate pulse removed when anode current is less than the latching current then SCR fails to turn on. Therefore we must maintain the gate pulse width atleast for a period until anode current reaches latching current.



$t_{min} \rightarrow \text{minimum gate pulse required to turn ON SCR}$

Q. → what is the min^m gate pulse width required to turn off thyristor?



Solⁿ →

Applying KVL at loop

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

$$\int di = \frac{V_S}{L} dt$$

$$I_A = \frac{V_S}{L} t$$

Until the latching current = I_A the gate pulse is given

$$I_A = I_L = \frac{V_S}{L} t_{min}$$

$$t_{min} = \frac{I_L \cdot L}{V_S} = \frac{100 \times 10^{-3} \times 0.1}{100}$$

$$t_{min} = 10^4 \text{ sec}$$

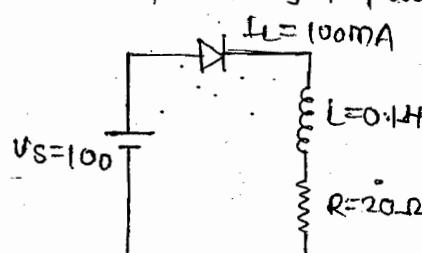
$$t_{min} = 100 \mu\text{s}$$

$t_{gate} \geq t_{min}$ to turn on the SCR.

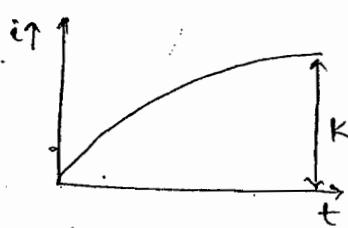
Note → The min^m width of the gate pulse depends on load parameter

Eg. → As the load inductance increases we have to increase t_{min}

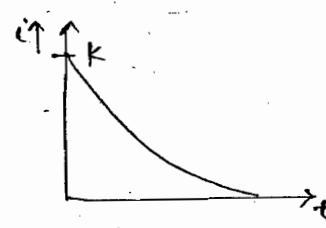
Q. → What is the value of min^m gate pulse



Solⁿ →



For inductor



For capacitor

DATE 05/08/14

$$i = k(1 - e^{-t/T})$$

↑
Final value
(V_s/R)

$$i = k e^{-t/T}$$

↑
Initial value
(V_s/R)

Applying KVL in the loop

$$V_s = R i_0 + \frac{d i_0}{dt}$$

$$T = \frac{L}{R} = \frac{0.1}{20}$$

$$I_A = k(1 - e^{-t/T})$$

$$T = \frac{1}{200}$$

$$I_A = \frac{V_s}{R}(1 - e^{-200t})$$

$$I_A = \frac{100}{20}(1 - e^{-200t})$$

$$I_A = 5(1 - e^{-200t}), I_L = 5(1 - e^{-200t_{min}})$$

$$t_{min} = 10ms$$

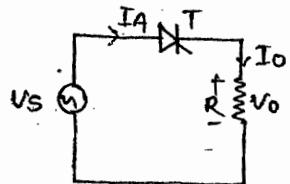
* significance of Holding current →

* Holding current is related to turn off process.

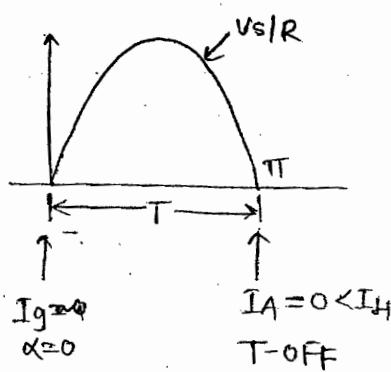
* Gate has no control to turn off the SCR.

* The transistor stops conducting only if anode current reduces below the holding current. ($\downarrow I_A < I_H$)

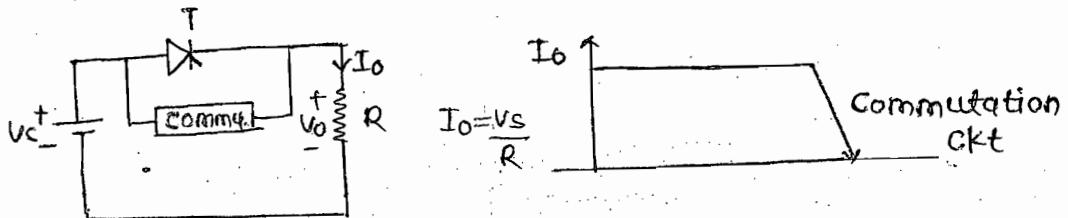
eg:- Half-wave rectifier (Natural Commutation)



$$T \rightarrow ON, I_0 = \frac{V_s}{R} = \frac{V_m \sin \omega t}{R}$$



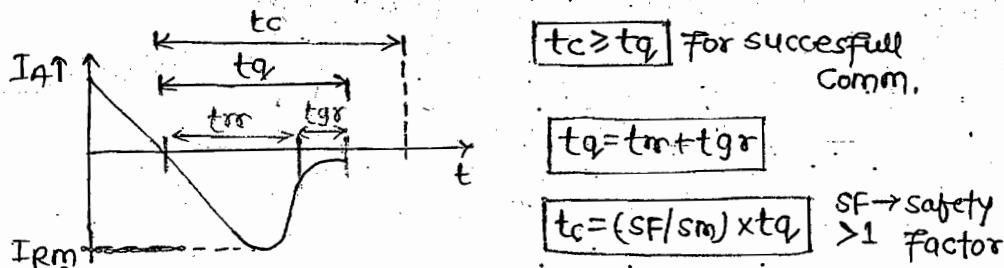
- * In some of the cases nature of supply supports the commutation process when supply is AC. Therefore it is known as natural Commutation.



- * In some of the cases when supply is DC natural commutation is not possible. We have to use commutation ckt to turn off the SCR.
- * The commutation ckt reduce the anode current below the holding current & then apply a reverse vol. across thyristor atleast for a period until all the charge carriers are completely removed.
- * This process is known as Commutation process.

* Circuit turn-OFF time (\$t_c\$) → It is the time for which the commutation circuit applies rev. vol. across thyristor after the anode current becomes 0.

* Reverse Recovery c/s of SCR → It explains the switching behaviour (Turn-off c/s) of thyristor from ON-state to OFF-state.



* During \$t_{rr}\$ the excess charge carriers present in the outer layers are removed.

Gate recovery time (\$t_{gr}\$) → During this time the charges present near the gate junction in the inner layer is removed.

* Device turn off time (t_{qf}) → During this time all the charges are completely removed in the device.

* The device turn off time (t_{qf}) decides the maxⁿ switching speed of thyristor.

* Based on the t_{qf} the thyristor may be classified as follows:-

Inverter grade thyristor

- Fast thyristor
- t_{qf} - (3μs to 50μs)

Application →

Inverters, choppers

Converter grade thyristor

- slow thyristor
- t_{qf} - (5ms to 20ms)

Application →

Rectifiers, AC voltage controller

* If $t_{c} < t_{qf}$ then comm. fails.

Q → What is meant by commutation failure?

Ans → * If $t_{c} < t_{qf}$ the commutation is not completed.

* Some charges present still in the device.

* For the next operation if anode is the wrt cathode then SCR starts conducting immediately before the gate pulse is given.

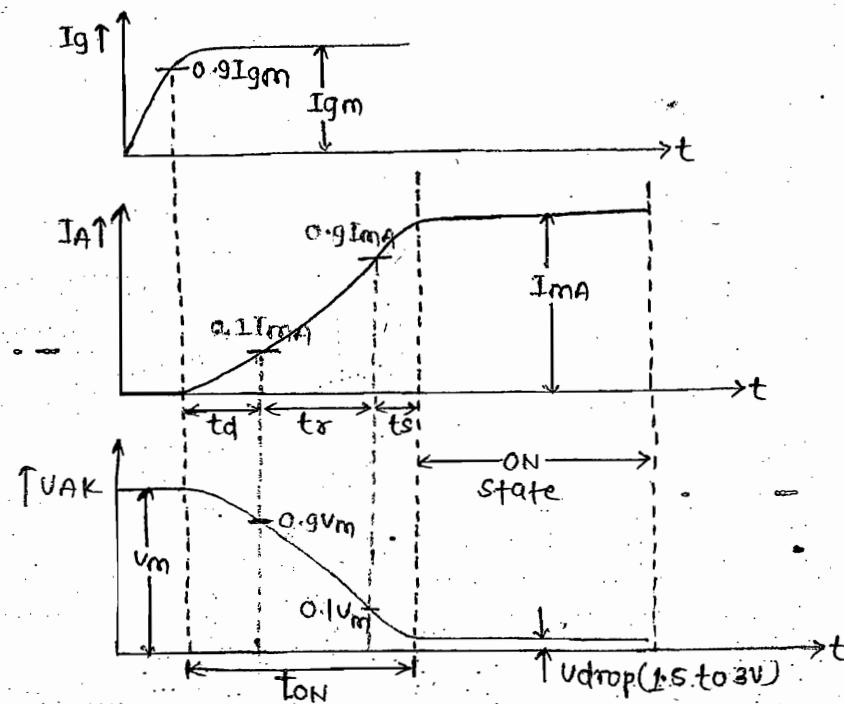
* Here SCR behaves as a diode & loses the forward blocking capability.

* This is known as comm. Failure.

Holding Current → It is the minⁿ anode current below which SCR stops conducting.

It regains the forward blocking capability only if $t_c \geq t_{qf}$.

Turn-ON c/s of thyristor → * It gives the switching behaviour of thyristor from OFF state to ON state.



* Delay time 'td' depends on $Ig \uparrow \propto \frac{dIg}{dt}$

- Initial conduction area ↑
- $\left(\frac{dI}{dt}\right) \uparrow$ initial rate
- $td \downarrow \therefore ton \downarrow$

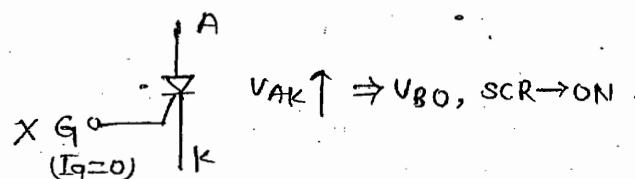
* Rise time 'tr' depends on the load parameters.

$$\Rightarrow L \uparrow, \frac{dI}{dt} \downarrow \therefore tr \uparrow \therefore ton \uparrow$$

* Spread time 'ts' depends on the physical geometrical structure of thyristor.

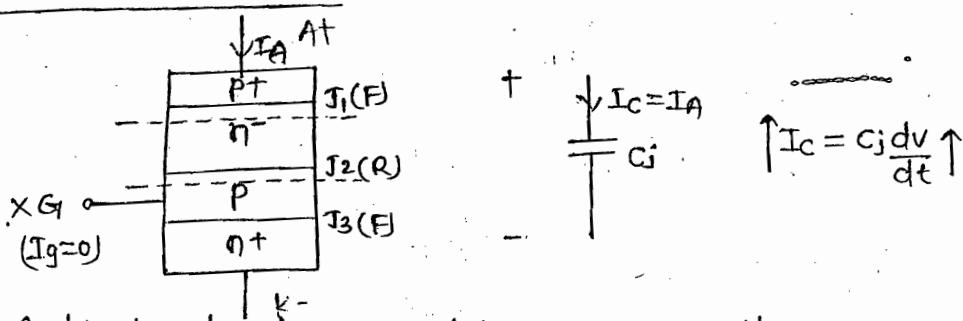
* Turn-ON topic methods of thyristor (Triggering method) →

(1.) Forward voltage triggering →



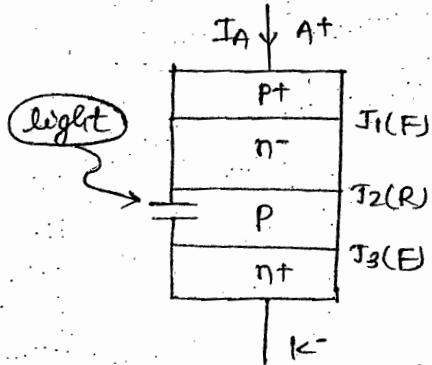
Due to high losses this is not preferred.

(2) $\frac{dv}{dt}$ triggering method →



At high $\frac{dv}{dt}$ the charging current increases. If the increasing charging current is more than latching current then SCR will turn-ON.

(3) Light triggering →



When a light radiation is incident near the gate junction the depletion layer absorb the light energy & produce more no. of e⁻ hole pairs. This initiates the turn ON process.

It is used in LASCR for HVDC application.

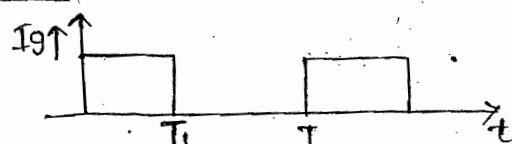
Light triggering is more efficient & reliable to trigger multiple no. of SCR simultaneously.

i) Gate triggering →

i.i. Continuous gate signal → Here we provide continuous gate signal until SCR is required to be in the ON state.

This is not an efficient method due to continuous gate power loss.

i) Pulse gate signal →



$T_1 \rightarrow$ Gate pulse

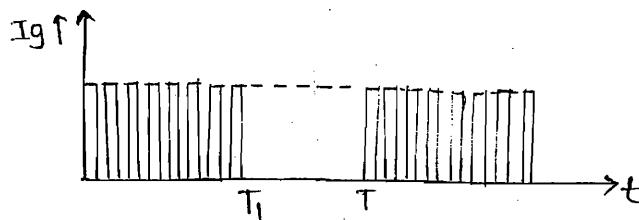
$T_1 > t_{min}$

$T \rightarrow$ time period

$$\delta = \frac{T_1}{T}$$

↳ duty cycle

(3.) High freq. gate pulse \rightarrow



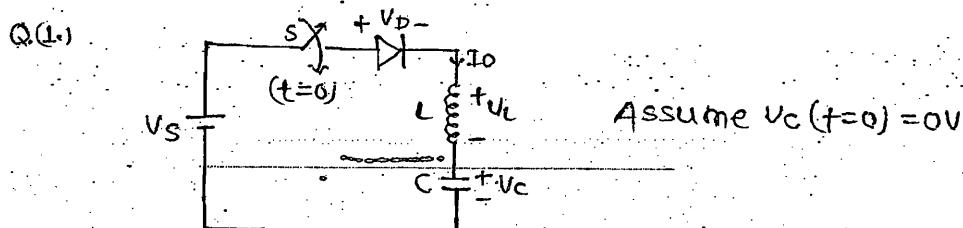
Advantage \rightarrow We can reduce the size of pulse Xmer used in firing ckt.

Q \rightarrow What is the need of pulse Xmer in gate firing ckt?

Ans \rightarrow Pulse Xmer provides ele. isolation b/w high power ckt & low power gate firing ckt.

* We can turn ON more than one SCR simultaneously at a time by using pulse Xmer.

* Diode circuits \rightarrow



i) When the switch is closed at $t=0$ sec. the diodes conducts for

- (a) $\frac{\pi}{2}\sqrt{LC}$ (b) $2\pi\sqrt{LC}$ (c) $\frac{3\pi}{2}\sqrt{LC}$ (d) $\pi\sqrt{LC}$

ii) What is the capacitance vol. when diode stops conducting.

- (a) V_s (b) $2V_s$ (c) $-V_s$ (d) $-2V_s$

SOLⁿ \rightarrow Applying KVL at loop then D \rightarrow ON

$$V_s = V_D + V_L + V_C$$

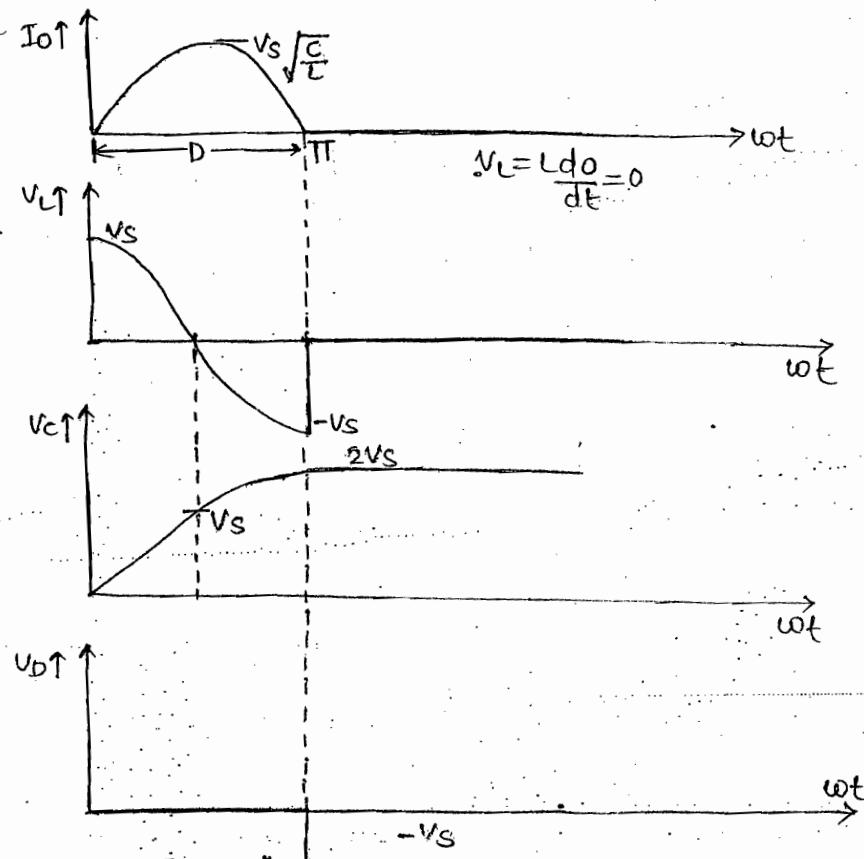
$$V_s = 0 + \frac{L di_o}{dt} + \frac{1}{C} \int i_o dt$$

$$I_o = V_s \sqrt{\frac{C}{L}} \sin \omega t$$

$$I_o = I_p \sin \omega t$$

where $I_p = V_s \sqrt{\frac{C}{L}}$

$$\omega_0 = \frac{1}{\sqrt{LC}} \text{ (Resonance freq.)}$$



$$\omega_0 t = \pi \text{ (rad)}$$

$$t = \frac{\pi}{\omega_0}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$t = \pi \sqrt{LC}$$

$$V_L = L \frac{d}{dt} (I_p \sin \omega_0 t)$$

$$V_S = V_D + V_L + V_C$$

$$V_L = L I_p \omega_0 \cos \omega_0 t$$

$$V_S = 0 + V_L + V_C$$

$$V_L = V_S \cos \omega_0 t$$

$$V_C = V_S - V_L$$

when $D \rightarrow \text{OFF}$

$$V_L = 0, \&$$

$$V_C = 2V_S$$

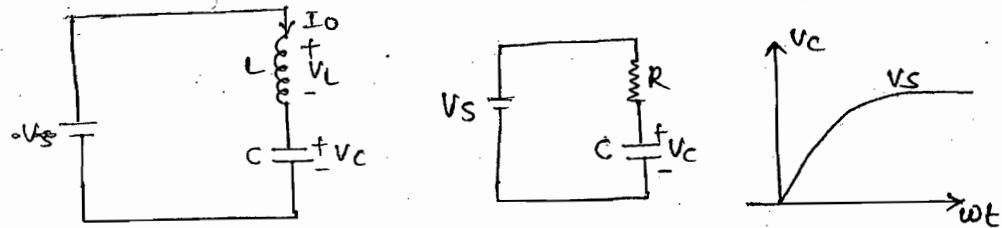
$$V_C = V_S (1 - \cos \omega_0 t)$$

$$-V_S + V_D + 0 + 2V_S = 0$$

$$V_D = -V_S \quad \& \quad PIU = V_S$$

PIU \rightarrow max^m Rev. voltage across diode when it is in OFF state

Because the value of the capacitance vol. ω vs t is $\frac{1}{2}CV^2$ — 19.

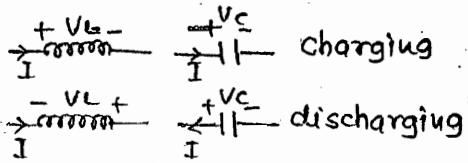


Mode(1) \rightarrow (0 to 90)

Source \rightarrow $L \& C \rightarrow \frac{1}{2}CV^2$
 \downarrow
 $(\frac{1}{2}Li^2)$
 $i \uparrow$

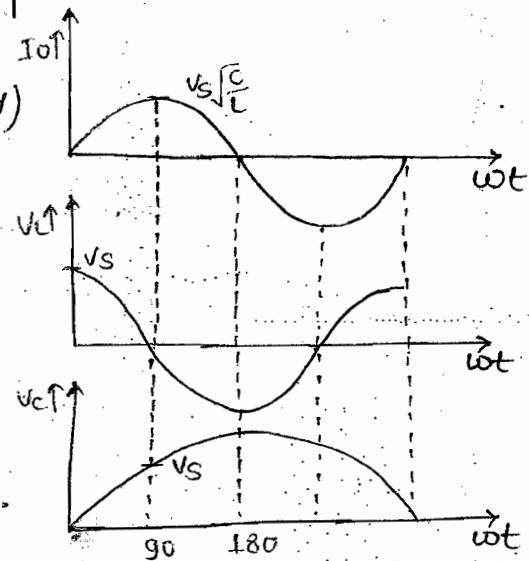
$$Vs = \sqrt{V_L + V_C} \uparrow \text{ (satisfy KVL)}$$

At $wot = 90^\circ$, $V_C = Vs \therefore V_L = 0$

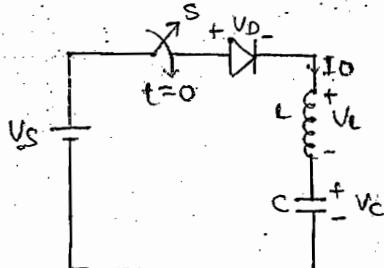


Mode(2) \rightarrow (90 to 180)

(Releasing energy) $\frac{1}{2}Li^2 \rightarrow \frac{1}{2}CV^2$
 \downarrow
 $i \downarrow$
 $V_C \uparrow$



Q(2)



Assume: $V_C(t=0) = V_0$ volts
~~where $V_0 < Vs$~~ $V_0 < Vs$

i. What is the capacitance vol. when diode stops conducting?

- (a) $2(V_s + V_0)$ (b) $2(V_s - V_0)$ (c) $2V_s - V_0$ (d) $2V_0 + V_0$

SOL \rightarrow Applying KVL

$$Vs = V_D + V_L + V_C$$

$$Vs = 0 + L \frac{di}{dt} + \left[\frac{1}{C} \int idt + V_0 \right]$$

$$Vs - V_0 = L \frac{di}{dt} + \frac{1}{C} \int idt$$

$$I_o = I_p \sin \omega t, I_p = (Vs - V_0) \sqrt{\frac{C}{L}}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$V_C = V_S - V_L$$

$$V_C = V_S - (V_S - V_0) \cos \omega_0 t$$

$$V_L = L \frac{di}{dt} (I_p \sin \omega_0 t)$$

$$V_L = (V_S - V_0) \cos \omega_0 t$$

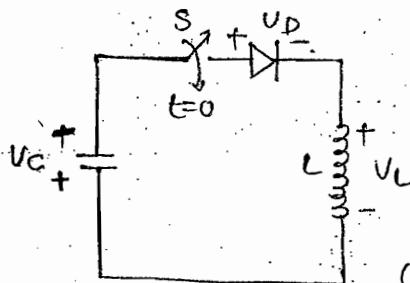
$$V_C = V_S (1 - \cos \omega_0 t) + V_0 \cos \omega_0 t$$

at $\omega t = 180^\circ$

$$V_C = V_S (1 - \cos(180^\circ)) + V_0 \cos 180^\circ$$

$$V_C = 2V_S - V_0$$

Q(2)



Assume: $-V_C(t=0) = -V_S$

What is capacitance vol. when diode stop conducting

- (a) $2V_S$ (b) $-V_S$ (c) V_S (d) $-2V_S$

Solⁿ → when we close the switch at $t=0$ then the diode will Forward biased because of $V_C(t=0) = -V_S$

Applying KVL in the loop;

$$+V_C + V_D + V_L = 0$$

$$-V_C = V_L + [-V_S + \frac{1}{C} \int i dt] + 0 + L \frac{di}{dt} = 0$$

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

$$di/dt = -L/C \cdot di/dt$$

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

$$I_0 = I_p \sin \omega_0 t$$

$$I_p = V_S \sqrt{C}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$V_L = L \frac{di}{dt} I_p \sin \omega_0 t$$

$$= L I_p \omega_0 \cos \omega_0 t$$

$$V_L = V_S \cos \omega_0 t$$

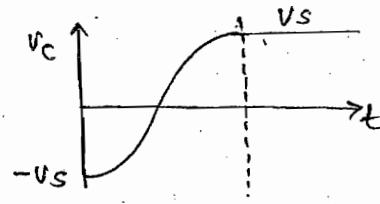
$$V_C + V_D + V_L = 0$$

$$V_C = -V_L$$

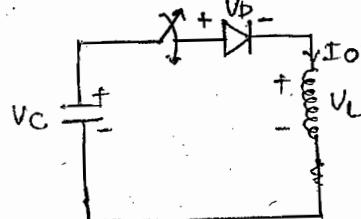
$$V_C = -V_S \cos \omega_0 t$$

$$PIV = V_S$$

$$V_C = V_S$$



Q.(4)

Assume: $V_C(t=0) = V_S$

$$V_C = ?$$

SOLⁿ →

$$-V_C + V_D + V_L = 0$$

$$V_C = V_L$$

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

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

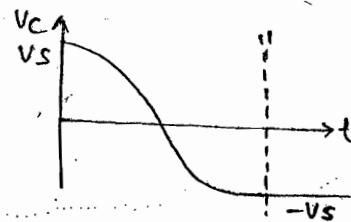
$$I_O = I_p \sin \omega_0 t, \quad I_p = V_S \sqrt{\frac{C}{L}}, \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

$$\therefore V_C = V_L$$

$$V_C = V_S \cos \omega_0 t$$

Initial vol: is V_S & final vol. will $-V_S$

$$V_C = -V_S$$

Note → In LC ckt if capacitance is initially charged with V_S volts then

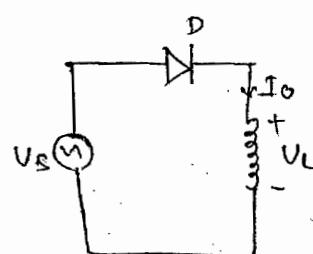
charging current of capacitor behaves as sine fn given by

$$I_C = I_p \sin \omega_0 t$$

And charging vol. of capacitor behaves as cosine-fn given by

$$V_C = V_S \cos \omega_0 t$$

Q.(5)



The diode conducts for

- (a) 90° (b) 180° (c) 270° (d) 360°

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SOLⁿ → Apply KVL: D → ON

$$V_S = V_m \sin \omega t = L \frac{d i_o}{dt}$$

$$L d i_o = V_m \sin \omega t$$

$$\int d i_o = \int \frac{V_m \sin \omega t}{L} dt$$

$$I_o = \frac{-V_m}{\omega L} \cos \omega t + K$$

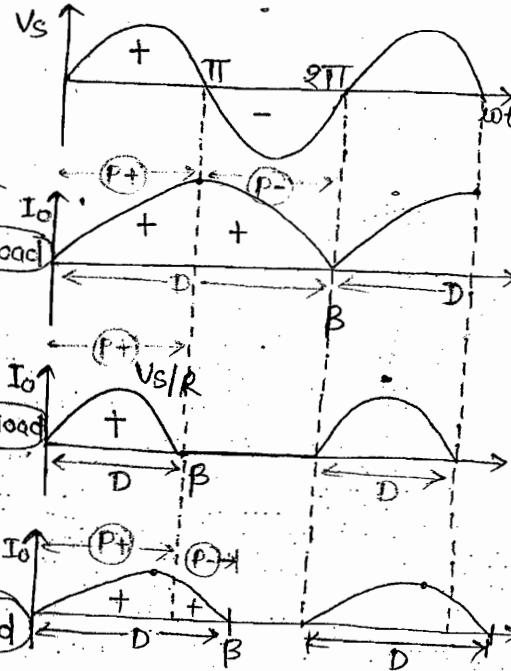
at $\omega t = 0, I_o = 0$

$$0 = \frac{-V_m}{\omega L} \cos 0 + K$$

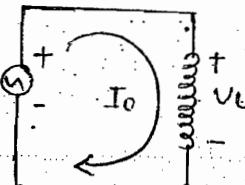
$V_L = V_S$
For L load

$$K = \frac{V_m}{\omega L}$$

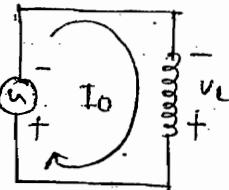
$$I_o = \frac{V_m}{\omega L} (1 - \cos \omega t)$$

mode(1) → $0 \text{ to } 180^\circ \Rightarrow P \rightarrow +ve$

Power flow from source to load

Source → P → Load ($\frac{1}{2} L I^2$)L → stores energy ($I_o \uparrow$)Mode(2) → $180^\circ \text{ to } 360^\circ \Rightarrow P \rightarrow -ve$

Power flow from load to source

Source ← Load ($\frac{1}{2} L I^2$)L → Releasing energy ($I_o \downarrow$)

Here the inductance energy makes the diode to conduct even in the -ve cycle until it releases its complete energy.

For pure inductor $\beta = \pi$

where $\beta = \text{extinction angle}$

The angle at which current zero & diode stops conducting.

For pure Resistor;

$$I_0 = \frac{V_s}{R} = \frac{V_m \sin \omega t}{R} \quad (\sin \theta = 0)$$

$$\boxed{\beta = \pi}$$

Note

* We will get -ve power only for reactive load not for pure resistive load.

* And also when $T \uparrow$, $\beta \uparrow$ ($T = \frac{L}{R}$) (T = time constant)

* For pure inductor the active power is 0. $S = P + jQ$ ($P = 0$)

$$P_0 = V_0 I_0 = V_L I_0$$

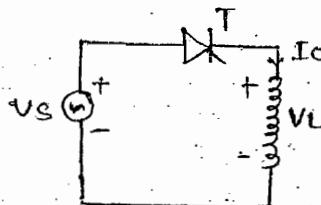
$$V_0 = 0 \quad (\text{avg. voltage})$$

** $I_0 \neq 0$ (avg. current) [From waveform of I_0 in \square]

$$\boxed{V_L(\text{avg.}) = 0}$$

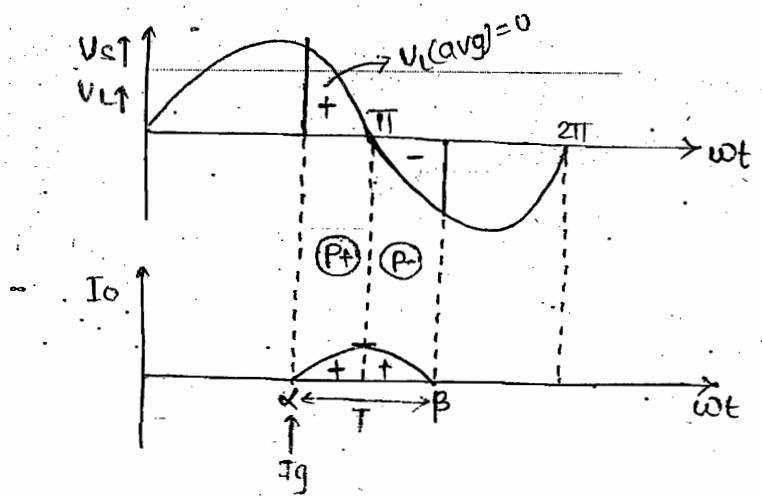
To make the avg. current 0, D is conducting for 360°

Q.(E.)



what is the value of β ?

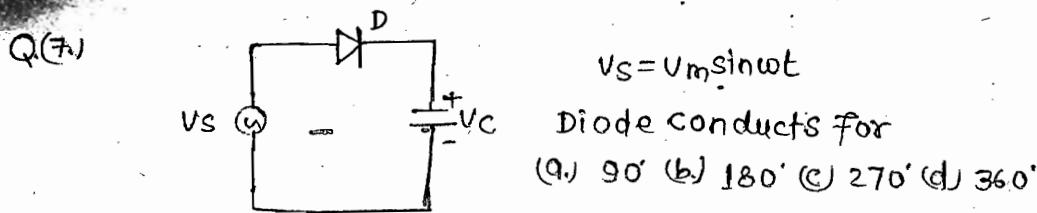
Solⁿ →



$$\beta = \pi + (\pi - \alpha)$$

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

$$\boxed{(1) T \uparrow, \beta \uparrow \quad (T = L/R)}$$



* Commutation Technique →

(1) Natural Commutation (Line Comm) → If nature of the supply supports the comm. process then it is known as natural comm.

- Eg. → (1) Rectifier ($AC \rightarrow DC$)
 (2) AC vol. controllers ($AC \rightarrow DC$)
 (3) Step down cycloconverter ($AC \rightarrow AC$)

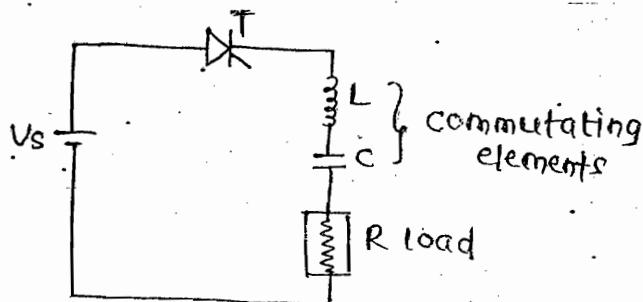
(2) Forced Commutation → DC supply will not support the comm. process.

* We require a comm. ckt to turn off the thyristor.

- Eg. → (1) Inverters ($DC \rightarrow AC$)
 (2) Choppers ($DC \rightarrow DC$)
 (3) Step up cycloconverter ($AC \rightarrow AC$)

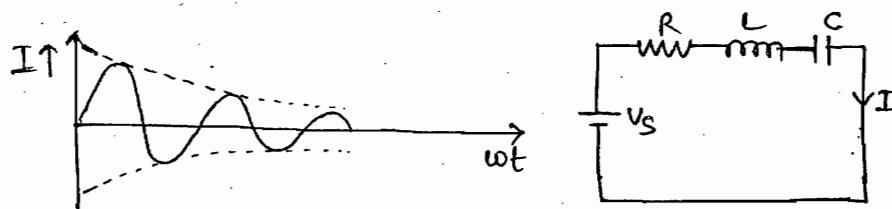
Classification of Forced Comm. →

(1) Class A →



* RLC should satisfy underdamped condn.

$$\text{Underdamped condn } \left(R^2 < \frac{4L}{C} \right) (X_C > X_L)$$



$$I = \frac{V_s}{\omega_r} e^{-\delta t} \sin \omega_r t$$

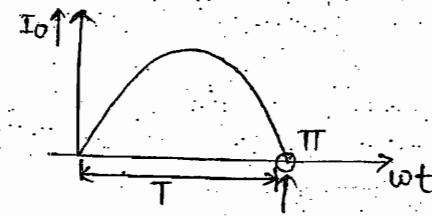
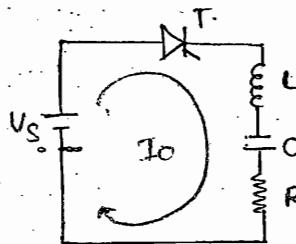
$\delta \rightarrow$ damping factor ($\frac{R}{\sqrt{LC}}$)

$$\omega_r \rightarrow \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad (\text{Ringing factor})$$

$$\text{For } R=0, \omega_r = \omega_0 = \frac{1}{\sqrt{LC}}$$

$$I = \frac{V_s}{\omega_0 L} (1) \sin \omega_0 t$$

$$I = V_s \sqrt{\frac{C}{L}} \sin \omega_0 t$$



$$\omega_r t = \pi \text{ (rad)}$$

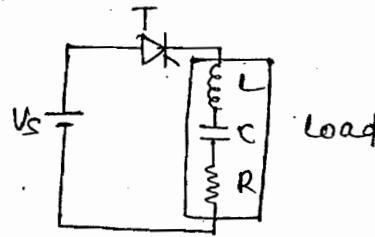
$$t = \frac{\pi}{\omega_r} \text{ sec}$$

$$\text{Cond'n time of thyristor} = \frac{\pi}{\omega_r} \text{ sec}$$

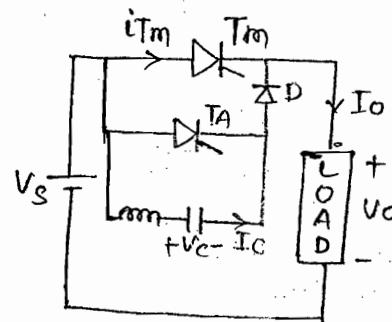
Q → what is load comm?

Ans → If the load elements support the comm. process then it is known as load comm.

Eg → Consider an RLC load satisfies underdamped cond'n as shown in fig given below.



(2.) Class-B Comm. (Current Comm.) \rightarrow



TA \rightarrow Auxiliary thyristor
Tm \rightarrow main thy.

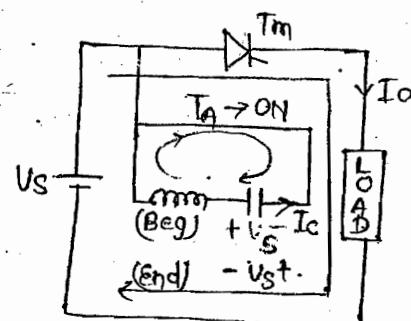
* To switch off the main thy. Tm we have to switch ON auxiliary thy. TA

Assume :- (1) $V_C(t=0) = V_S$ (capacitor is initially charged) with V_S)

(2) Let us consider the load to be high inductive so that the load current remains constant. ($L \uparrow \frac{di}{dt} \downarrow$)

(3) $T_m \rightarrow \text{ON}$ ($t < 0$) (main thy. is on state before $t=0$)

Mode (1) \rightarrow At $t=0$, $T_A \rightarrow \text{ON}$



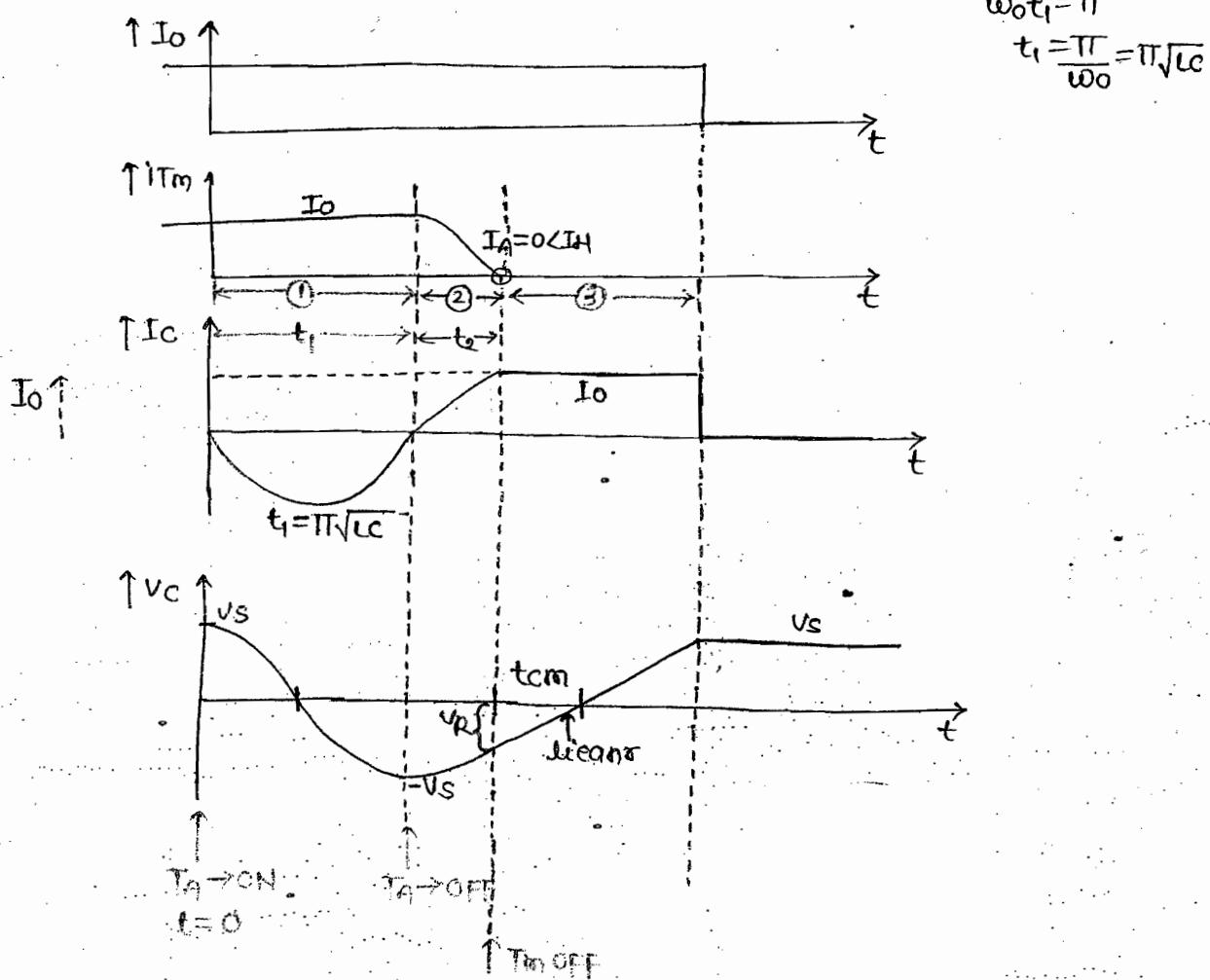
$$i_{Tm} = I_0, \quad i_C = -I_p \sin \omega t$$

$$V_C = V_S \cos \omega t$$

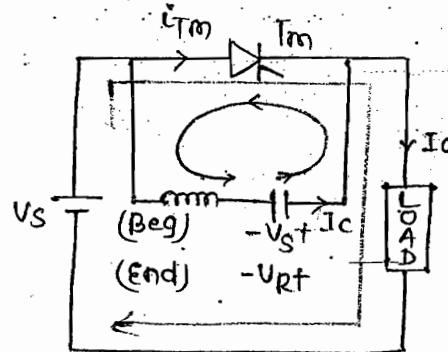
end:-

$$i_C = 0, \therefore T_A \rightarrow \text{OFF}$$

$$V_C = -V_S$$



Mode (2) →



The charging current is trying to reduce i_{TM} & Hence current comm.

$$i_{TM} = I_0 - I_C \uparrow$$

END :- When $I_C = I_0$, $i_{TM} = 0 < I_H$

$\therefore T_m \rightarrow OFF$

$$I_C = I_0$$

$$I_p \sin \omega t_2 = I_0$$

$$\omega_0 t_2 = \sin^{-1} \left(\frac{I_0}{I_p} \right)$$

$$t_2 = \frac{1}{\omega_0} \sin^{-1} \left(\frac{I_0}{I_p} \right)$$

$$t_2 = \sqrt{L C} \sin^{-1} \left(\frac{I_0}{I_p} \right)$$

* At the end of 2nd mode capacitance

$$VOL: V_C = V_S \cos(\pi + \omega_0 t_2)$$

$$V_C = -V_S \cos \omega_0 t_2$$

$$V_C = -V_S \cos \left[\sin^{-1} \left(\frac{I_0}{I_p} \right) \right]$$

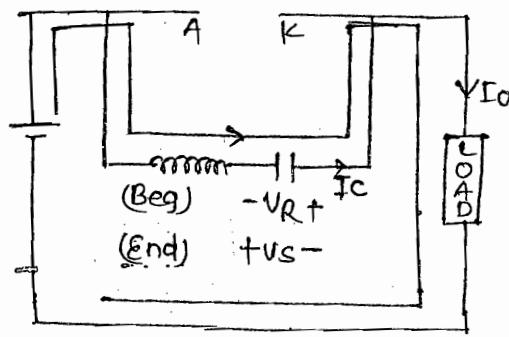
* Let V_R be the rev. vol. magnitude across the capacitor at the end of 2nd mode

$$V_R = V_S \cos \left[\sin^{-1} \left(\frac{I_0}{I_p} \right) \right]$$

$$\omega_0 t_1 = \pi^2$$

$$t_1 = \frac{\pi}{\omega_0} = \pi \sqrt{LC}$$

Mode (3) →



$$I_c = I_0$$

$$V_C = \frac{1}{C} \int I_c dt = \frac{I_0 t}{C}$$

t_{cm} = circuit turn OFF time

$$V_C = \frac{I_0 t}{C}$$

$$V_R = \frac{I_0}{C} t_{cm}$$

$$t_{cm} = \frac{V_R C}{I_0}$$

Objective question →

(1) $(I_{Tm})_{peak} = I_0$

(2) $(I_{TA})_{peak} = V_S \sqrt{\frac{C}{L}}$

(3) Cond' time of auxiliary thy. = $\pi \sqrt{LC}$ sec.

(4) The time taken to turn-off the main thy. after the auxiliary thy. is switched on $t = t_1 + t_2$

$$t = \pi \sqrt{LC} + \sqrt{LC} \sin^{-1} \left(\frac{I_0}{I_P} \right)$$

(5) The min^m time taken to turn off the main thy. = $\pi \sqrt{LC}$ sec.

$$\downarrow t_2 = \sqrt{LC} \sin^{-1} \left(\frac{I_0}{I_P} \right)$$

(6) The max^m time req. to turn-off the main thy. after the auxiliary thy. is switched on.

$$t_{max} = \pi \sqrt{LC} + \frac{\pi}{2} \sqrt{LC}$$

$$t_{max} = \frac{3\pi}{2} \sqrt{LC}$$

$$(I_0 = I_P) \quad \sqrt{LC} \sin^{-1} \left(\frac{I_0}{I_P} \right) = \sqrt{LC} \frac{\pi}{2}$$

(7) If $I_o > I_p$ then comm. is not possible. Therefore $I_o \leq I_p$ to make comm. possible.

$$I_o \leq I_p$$

$$(Or)$$

$$I_o = I_p$$

(8) The max^m rev. vol. across the main thy. when it is in the OFF state = V_R .

$$V_R = V_s \cos \left[\sin^{-1} \left(\frac{I_o}{I_p} \right) \right]$$

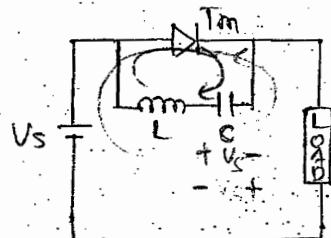
(9) $t_{cm} = \frac{C \cdot V_R}{I_o}$ (t_{cm} = circuit turn OFF time of main thy.)
 t_q = device turn off time

$$\begin{aligned} t_{cm} &> t_q && \text{for successful commutation} \\ t_{cm} &= (SF) t_q \end{aligned}$$

(10) We must consider the above eqn (7), (8) & (9) to design the commutating elements L & C.

Q → What is the purpose of diode in the comm. ckt?

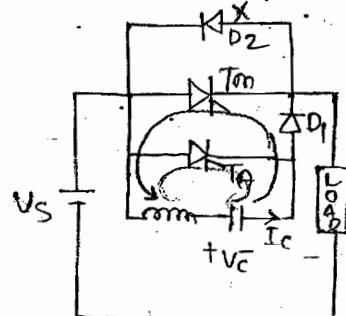
Ans →



* without a diode auxiliary thy. has no control on the comm. process.

* The Comm. takes place automatically before the auxiliary thy. is switched on.

Q → Check whether Comm. is possible or not in the following ckt?



Ans → 2 antiparallel devices can't conduct simultaneously because the Vol. drop of conducting device applies a rev. vol. across the other device. Therefore the diode D2 will not conduct in the 2nd mode.

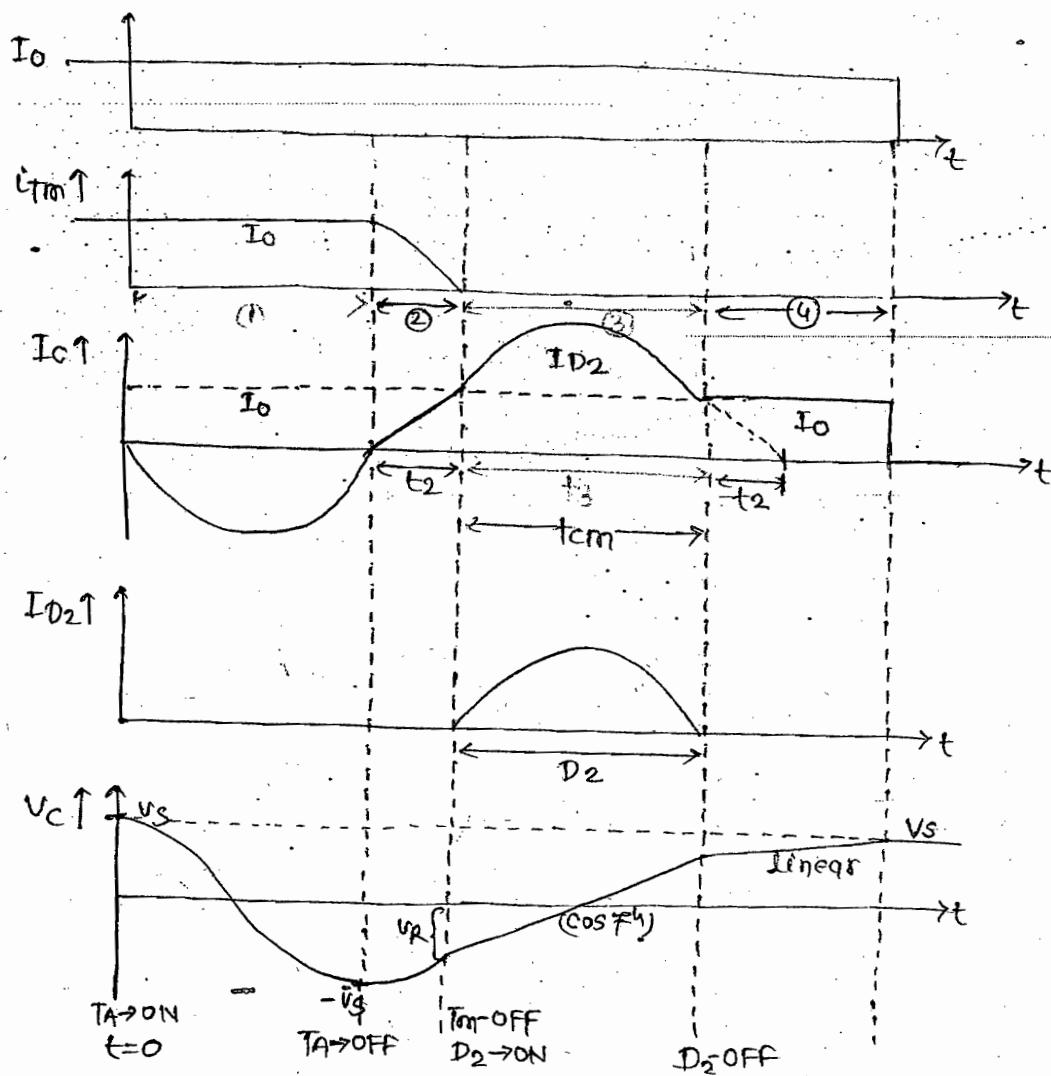
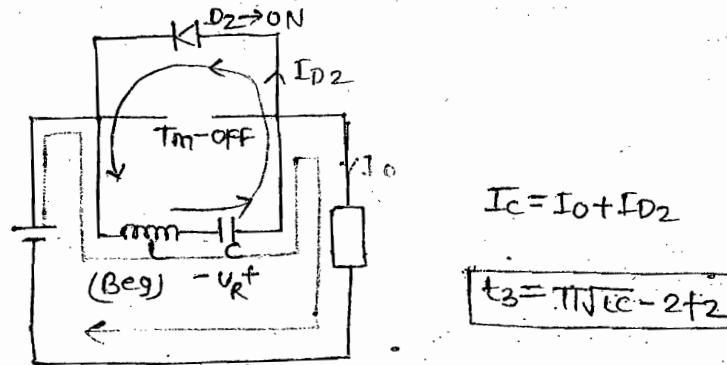
because main thy. is already conducting.

Therefore 1st 2 case modes are same as previous case. Hence comm. is possible.

Q → what is ckt turn-off time of main thy. in the above comm. ckt?

Soln → 1st 2 modes are same as previous case.

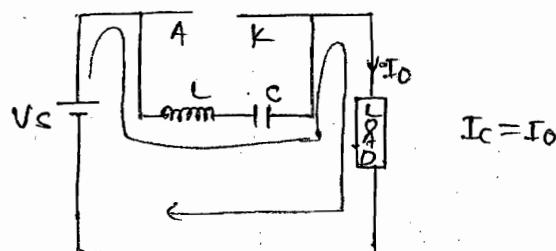
mode ③ →



$$I_C = I_0 + I_{D2}$$

END :- When $I_C = I_0$, $I_{D2} = 0 \therefore D_2 \rightarrow \text{OFF}$

mode(4) \rightarrow



- * In the 3rd mode the vol drop of the diode D_2 applies a rev. voltage across main thy. Therefore the cond'n time of diode D_2 applies a rev. v/s gives the ckt turn off time of main thy.

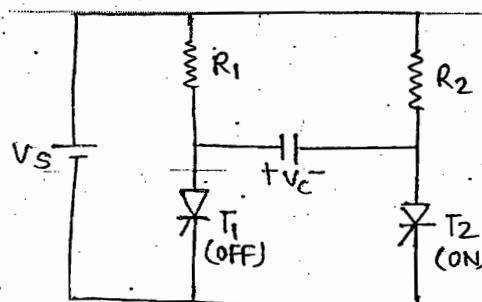
$$t_{cm} = \pi\sqrt{LC} - 2t_2$$

$$t_{cm} = \pi\sqrt{LC} - 2\sqrt{LC} \sin^{-1}\left(\frac{I_0}{I_P}\right)$$

- Application \rightarrow This type of comm. technique is used in stepdown chopper. Therefore it is also known as current comm. chopper.

DATE - 07/08/14

(3) Class C Comm. (Complementary Comm) \rightarrow



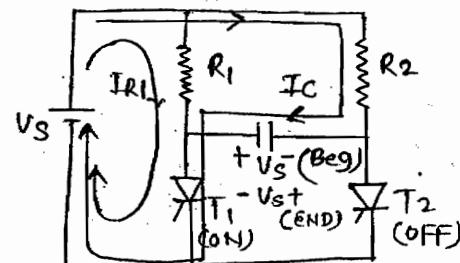
Assume:-

- (i) $V_C(t=0) = V_S$
 - (ii) $T_2 \rightarrow \text{ON}$
 - (iii) $T_1 \rightarrow \text{OFF}$
- $\} (t < 0)$

Mode(1) \rightarrow At $t=0$, $T_1 \rightarrow \text{ON}$
 $T_2 \rightarrow \text{OFF}$

Resultant current through T_1 :

$$I_{T1} = I_{R1} + I_C$$



Because the resistance (R_2) & capacitance value C the value of the current will exponentially decay

$$I_C = k e^{-t/R_2 C}$$



Initial value of current

$$k = \frac{2V_s}{R_2}$$

$$I_C = \frac{2V_s}{R_2} e^{-t/R_2 C}$$

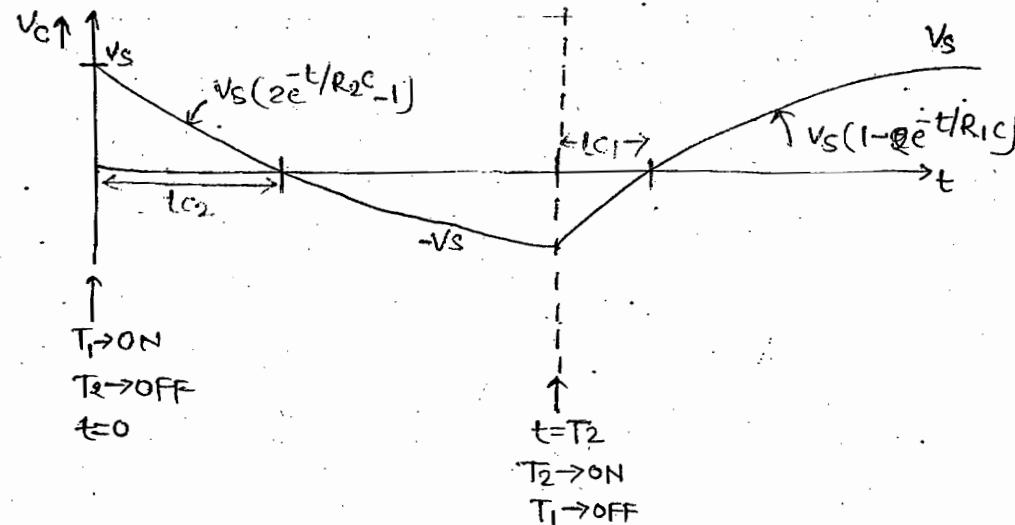
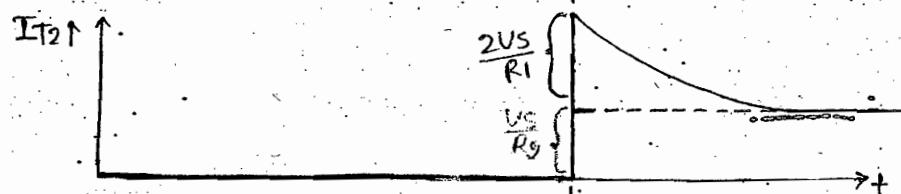
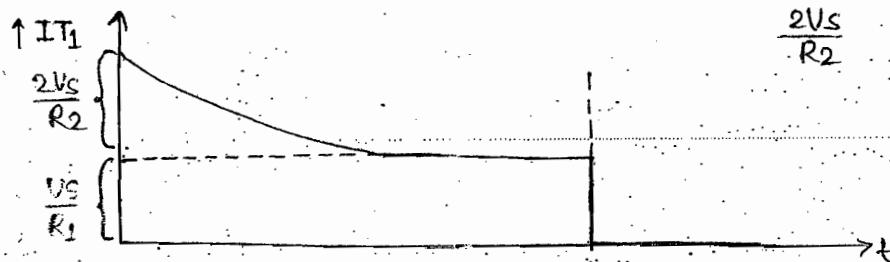
$$\text{Hence } I_{T_1} = \frac{V_s}{R_1} + \frac{2V_s}{R_2} e^{-t/R_2 C}$$

\downarrow
(Steady
current)

\downarrow
(Transient
current)

initial transient ($t=0$)

$$\frac{2V_s}{R_2}$$



Now, the circuit turn off time of 2nd thy.

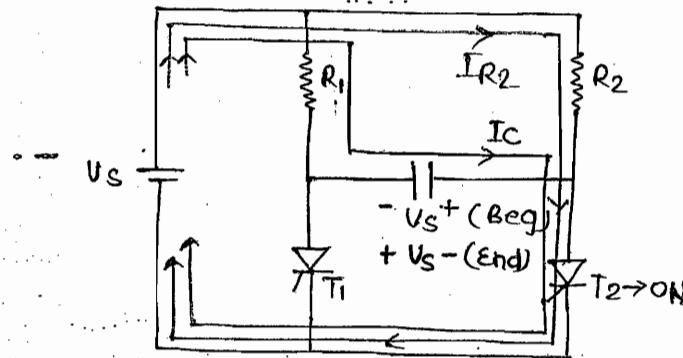
$$\text{At } t = t_{C_2}$$

$$V_C = 0$$

$$-V_S(2e^{-t_{C_2}/R_2 C} - 1) = 0$$

$$t_{C_2} = R_2 C \ln 2 \quad (\text{i})$$

Mode (2) → At $t = t_2$, $T_2 \rightarrow \text{ON}$



Circuit turn off time of 1st thy.

$$\text{At } t = t_{C_1}$$

$$t_{C_1} = R_1 C \ln 2 \quad (\text{ii})$$

$$I_{T_2} = I_{R_2} + I_C$$

$$I_{T_2} = \frac{V_S}{R_2} + \frac{2V_S}{R_1} e^{-t/R_1 C}$$

↓
Steady

↓
Transient

Objective questions →

$$(1) (I_{T_1})_{\text{peak}} = \frac{V_S}{R_1} + \frac{2V_S}{R_2} \quad (\text{iii})$$

$$(2) (I_{T_2})_{\text{peak}} = \frac{V_S}{R_2} + \frac{2V_S}{R_1} \quad (\text{iv})$$

$$\text{From eqn (i)} \quad C = \frac{t_{C_2}}{R_2 \ln 2}$$

$$C = \frac{(SF)t_q}{R_2 \ln 2} \quad (\text{v}) \quad t_c = (SF)t_q$$

$$\text{From eqn (ii)} \quad C = \frac{t_{C_1}}{R_1 \ln 2}$$

$$C = \frac{(SF)t_q}{R_1 \ln 2} \quad (\text{vi})$$

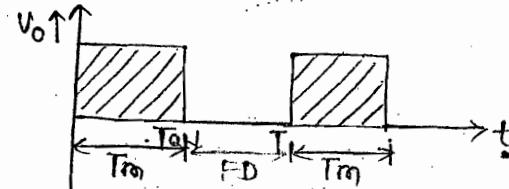
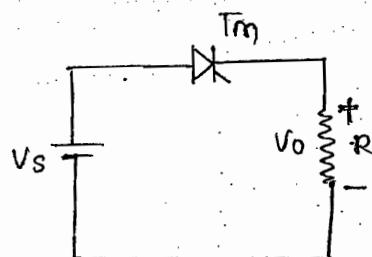
From eqn (5) & (6) we get 2 diff. values for the commutating capacitance. We must consider the highest value to make the comm. possible.

Application → Parallel inverter, Current source inverter.

Class D (Voltage Comm.) →

* This type of comm. technique is preferred in step down chopper.
Therefore it is also known as Vol. Comm. chopper.

Step down chopper → (without Comm. ckt)

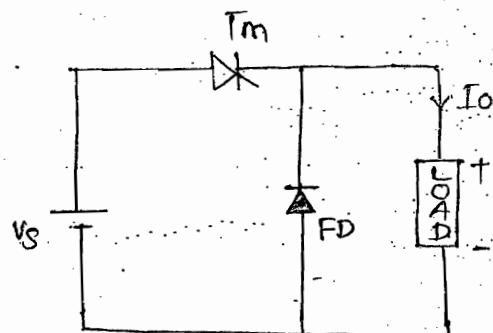


$$V_0 = \frac{V_s T_{ON}}{T}$$

$$y_0 = \frac{1}{R} V_s$$

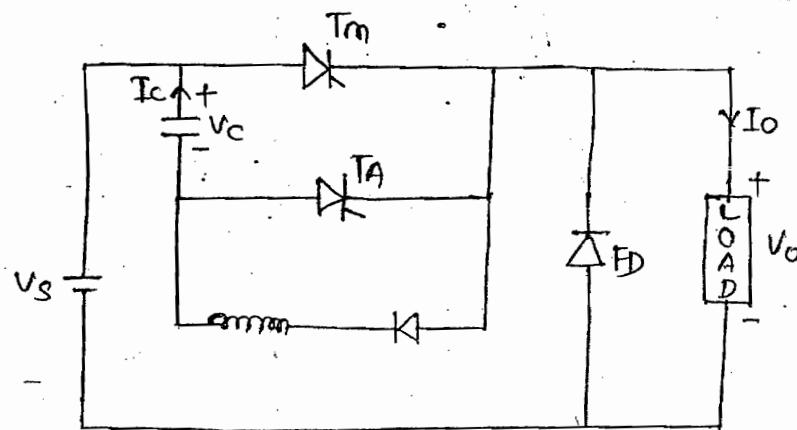
$$d = \frac{T_{ON}}{T}$$

duty cycle



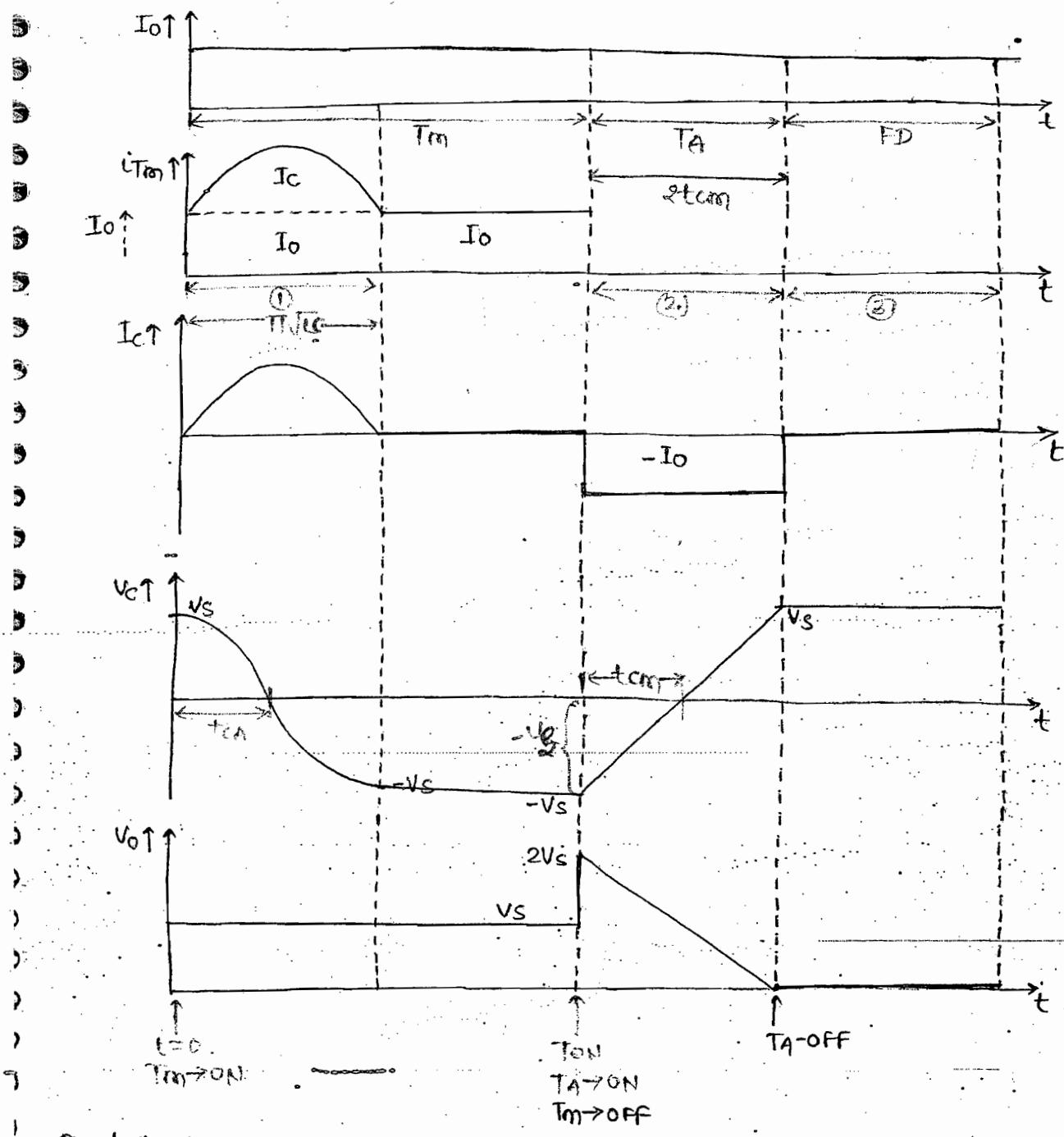
In the inductive load there is a need of FD; because the inductor will release the energy through FD.

Step down chopper / Vol. comm. chopper (with comm. ckt) →

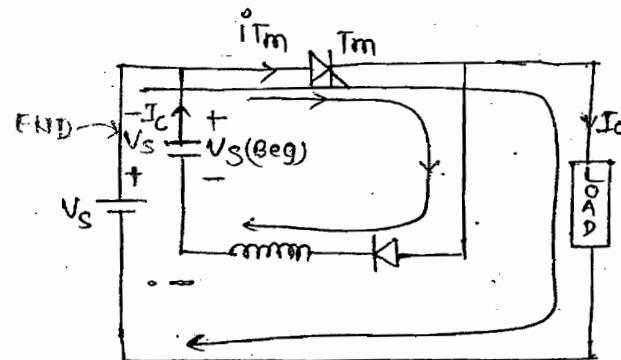


Assume:- (1) $V_C(t=0) = V_s$

(2) $I_o \rightarrow \text{const.}$ (High inductive load)



Mode (1) \rightarrow At $t=0$, $T_m \rightarrow ON$



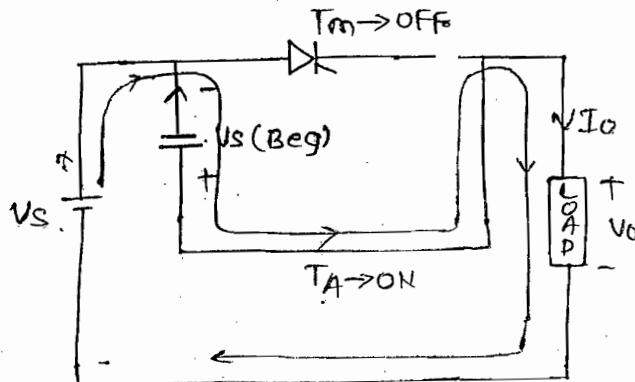
$$i_{Tm} = I_0 + I_c$$

$$I_c = I_p \sin \omega_0 t$$

$$V_C = V_S \cos \omega_0 t$$

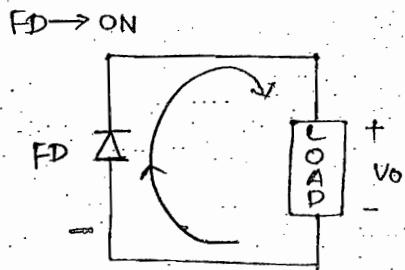
$$END: I_c = 0, V_C = V_S$$

mode(2) \rightarrow At $t = T_{ON}$, $T_A \rightarrow ON$



$$\begin{aligned} I_C &= -I_O \\ \text{Beg.} \rightarrow V_C &= -V_S \\ V_O &= 2V_S \\ \text{End} \rightarrow V_C &= V_S \\ V_O &= 0 \\ I_C &= 0 \end{aligned}$$

mode(3) \rightarrow



Without comm. of the 1st mode we can't turn-off the main thy. therefore $(T_{ON})_{min}$ of $T_m = \pi\sqrt{LC}$

$$\alpha_{min} = \frac{\pi\sqrt{LC}}{T} = \pi\sqrt{LC} \cdot f$$

$$② (I_{Tm})_{peak} = I_0 + I_p = I_0 + V_s \sqrt{\frac{C}{L}}$$

$$③ (I_{TA})_{peak} = I_0$$

$$④ \text{PIV of FD} = 2V_S$$

$$⑤ \text{PIV of } T_m = V_S$$

$$⑥ t_{cm} = \frac{CV_S}{I_0} = T_{OFF}$$

$$⑦ t_{CA} = \frac{\pi}{2}\sqrt{LC}$$

$$\begin{aligned} ⑧ \text{Conduction time of } T_A \\ = 2t_{cm} \end{aligned}$$

⑨ Comm. interval = $2t_{cm}$
It is a time for which or it is the time taken to disconnect the load from supply after the T_m stops conducting.

$$⑩ \text{Effective turn on time of chopper}$$

$$(T_{ON})_{eff} = T_{ON} + 2t_{cm}$$

$$(11) \quad \text{Avg. voltage } V_0 = \frac{(V_s T_{ON}) + (\frac{1}{2} \cdot 2t_{cm} \cdot 2V_s)}{T}$$

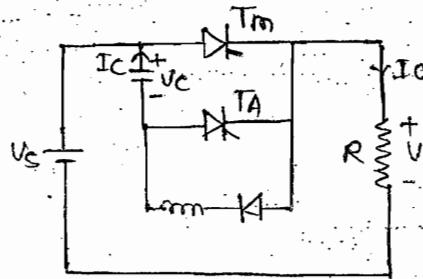
$$V_0 = V_s \left(\frac{T_{ON} + 2t_{cm}}{T} \right) = \frac{V_s (T_{ON})_{eff}}{T}$$

$$\boxed{V_0 = \frac{V_s (T_{ON})_{eff}}{T}}$$

$$(12) \quad (V_0)_{min} = V_s \left[\frac{\pi \sqrt{Lc} + 2t_{cm}}{T} \right]$$

$$\boxed{(V_0)_{min} = V_s (\pi \sqrt{Lc} + 2t_{cm}) f}$$

Q → What is the ckt turn-off time of thy, with resistive load?



Ans. → 1st mode same as previous case.

$$\text{mode(2)} \rightarrow I_o = k e^{-t/RC}$$

$$I_o = \frac{2V_s}{R} e^{-t/RC}$$

$$I_c = -\frac{2V_s}{R} e^{-t/RC}$$

$$\text{Beg: } V_c = -V_s$$

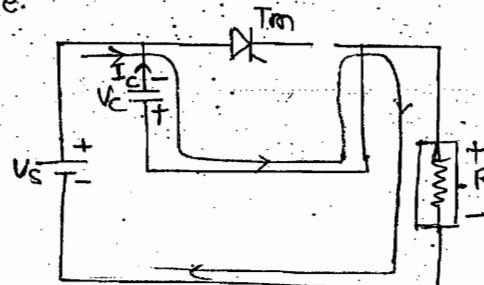
$$V_o = 2V_s$$

$$I_o = \frac{2V_s}{R}$$

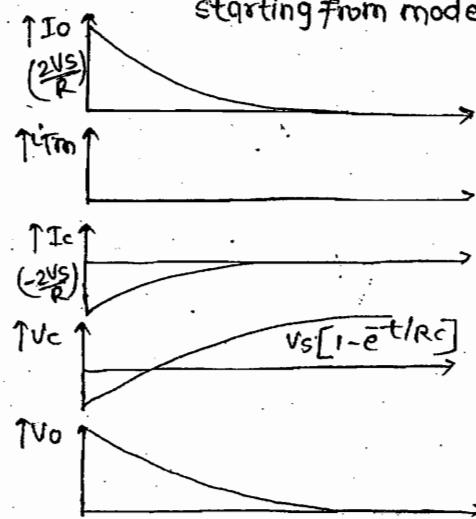
$$\text{At } t = t_{cm}, V_c = 0$$

$$V_s(1 - e^{-t_{cm}/RC}) = 0$$

$$t_{cm} = RC \ln 2$$



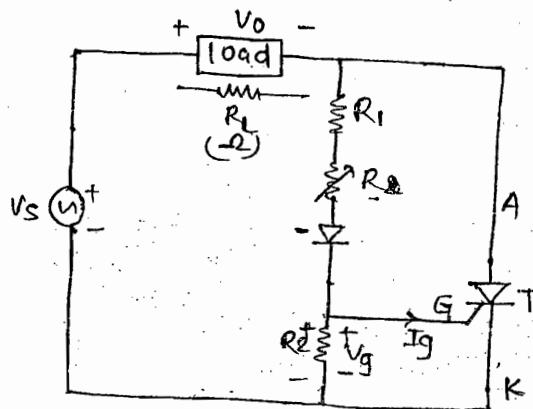
Starting from mode(2):



* Firing Circuits → It gives the necessary gate signal to turn on the SCR.

(i) Resistance Firing ckt → It is also known as R-Firing ckt

Main ckt → 1φ HWR



$$R_1 \leq \frac{(R_1 + R_2)}{KR}$$

$$I_{g\min} \leq I_g \leq I_{g\max}$$

$$V_{g\min} \leq V_g \leq V_{g\max}$$

Gate specification

* R_1 is added to limit the gate current within the \max^m value.

* For worst cond'n the \max^m gate current

$$I_{g\max} \geq \frac{V_m}{R_1}$$

$$R_1 \geq \frac{V_m}{I_{g\max}}$$

* Design R_2 to limit the gate vol. below the specified \max^m value.

* for worst cond'n the \max^m gate vol. = $\left(\frac{V_m}{R_1 + R_2} \right) R_2 \leq V_{g\max}$

From above eqn we can design value of R_2

* Variable resistor is used to vary the firing angle α .

* Diode is used to avoid the -ve gate pulse in the -ve cycle.

V_{gt} = Gate turn on voltage

It is the gate vol. at which SCR will turn on.

when $V_g \uparrow$ & it reaches V_{gt} , SCR → ON
($\omega t = \alpha$)

$$V_g = \left(\frac{V_m \sin \omega t}{R_1 + R_2} \right) \cdot R_2$$

$$V_g = \left(\frac{V_m R_2}{R_1 + R + R_2} \right) \sin \omega t$$

$$V_g = V_{gm} \cdot \sin \omega t \rightarrow T(\text{OFF}) \text{ then use eqn}$$

where; $V_{g,m} = \frac{V_m R_2}{R_1 + R + R_2}$ (Peak value of gate vol.)

From above eqn

$$V_{gt} = V_{gm} \sin \alpha, \text{SCR} \rightarrow \text{ON}$$

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

$$\alpha = \sin^{-1} \left(\frac{V_{gt}}{V_{gm}} \right)$$

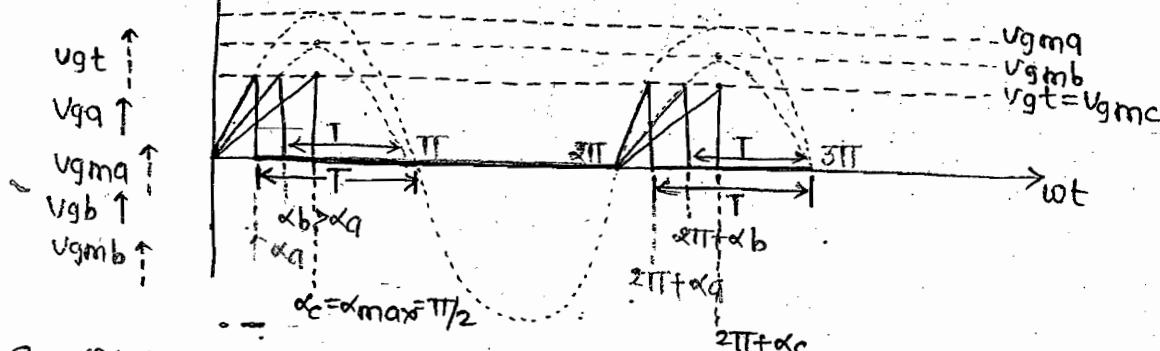
If $R \uparrow, V_{gm} \downarrow \therefore \alpha \uparrow$ (By increasing the variable resistor $\alpha \uparrow$)

Case(1) \rightarrow

$$\text{Let } R = R_q, \alpha = \alpha_q$$

$$V_{gq} = V_{gma} \cdot \sin \omega t$$

$$V_{gma} = \frac{V_m R_2}{R_1 + R_q + R_2}$$



Case(2) \rightarrow

$$\text{Let } R = R_b, \alpha = \alpha_b \quad R = R_b > R_q$$

$$V_{gb} = V_{gmb} \sin \omega t$$

$$V_{gmb} < V_{gma}$$

Case(3.) \rightarrow Let $R = R_C$, $\alpha = \alpha_C$

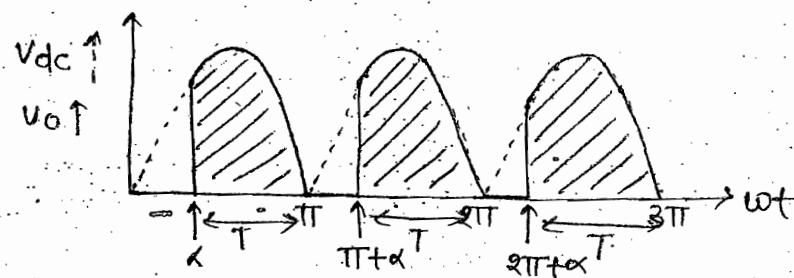
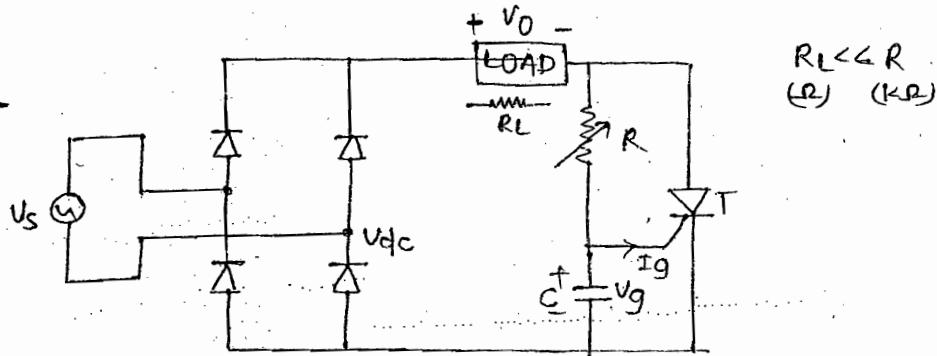
$$V_{gmc} = V_{gt}, \quad \alpha_{max} = \pi/2$$

Drawback \rightarrow

The max^m α is limited to 90°.

(ii) RC Firing ckt \rightarrow

Main ckt :- E ϕ FwR



Case(i) \rightarrow Let $R = R_q$, $\alpha = \alpha_q$

$$T_q = R_q C$$

Case(2.) \rightarrow

Let $R = R_b > R_q$

$$(\alpha = \alpha_b)$$

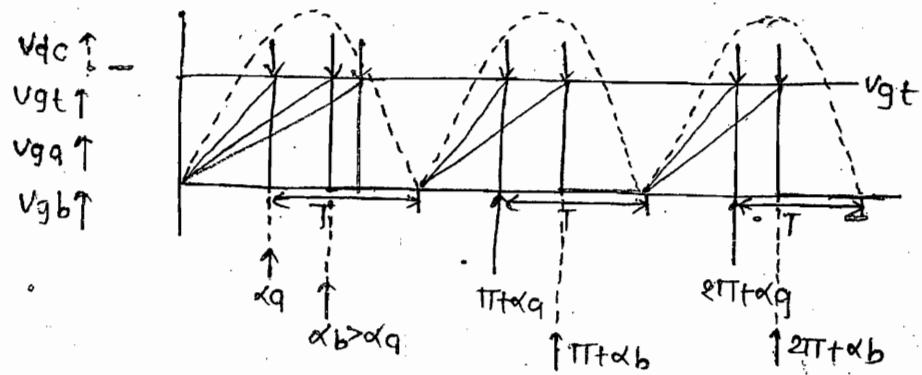
$$T_b > T_q$$

$$T_b = R_b C$$

$$RT, T \uparrow \therefore \alpha \uparrow$$

Because of the increasing the value of time constant the wave will take more time to take V_{gt} .

Hence the α will be increased.



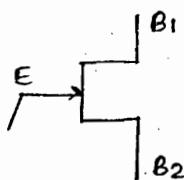
$$V_{gt} = 0 \text{ (ideal SCR)}$$

$$0 < \alpha < 180^\circ$$

$$(5^\circ) \leq \alpha \leq (165^\circ \text{ to } 175^\circ) \Rightarrow (\text{practical SCR})$$

UJT

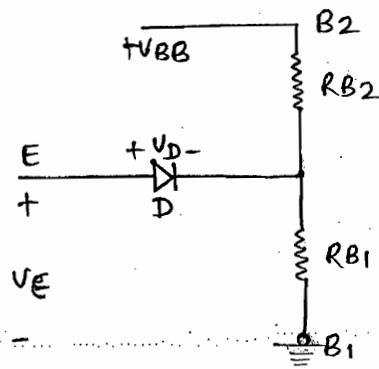
UJT



B_1 & B_2 are Base terminal
E - Emitter terminal.

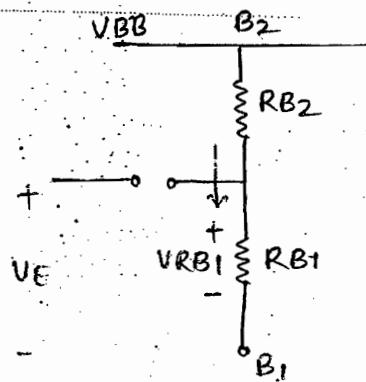
UJT - Unijunction transistor.

Equivalent circuit of UJT →



- * R_{B1} & $R_{B2} \rightarrow$ High value (off state)
- * Diode is on then UJT on
diode is off then UJT OFF

Suppose diode is OFF;



$$V_{RB1} = \left(\frac{R_{B1}}{R_{B1} + R_{B2}} \right) V_{BB}$$

$$V_{RB1} = \eta V_{BB}$$

$$\boxed{\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}}$$

Intrinsic stand off Ratio.

η = Intrinsic stand off ratio

Let; $V_p = V_{RB1} + V_D$

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

($V_p \rightarrow$ Peak point voltage)

↑ V_E & when it reaches to V_p then the UJT will turn on

↑ $V_E \Rightarrow V_p$, UJT → ON

* UJT exhibits -ve resistance character.

Therefore when UJT starts conducting the base resistance R_{B1} starts decreasing.

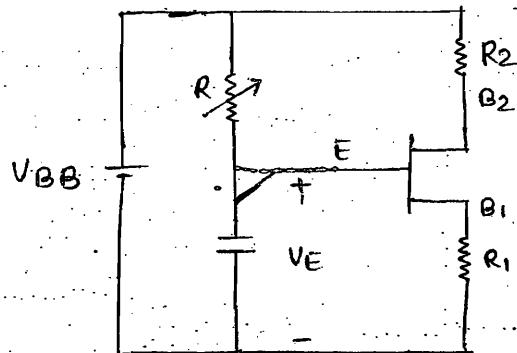
Therefore emitter vol. starts decreasing when UJT starts conducting.

$$\downarrow V_E \Rightarrow V_V, \text{ UJT} \rightarrow \text{OFF}$$

$$V_V = \text{Value Voltage}$$

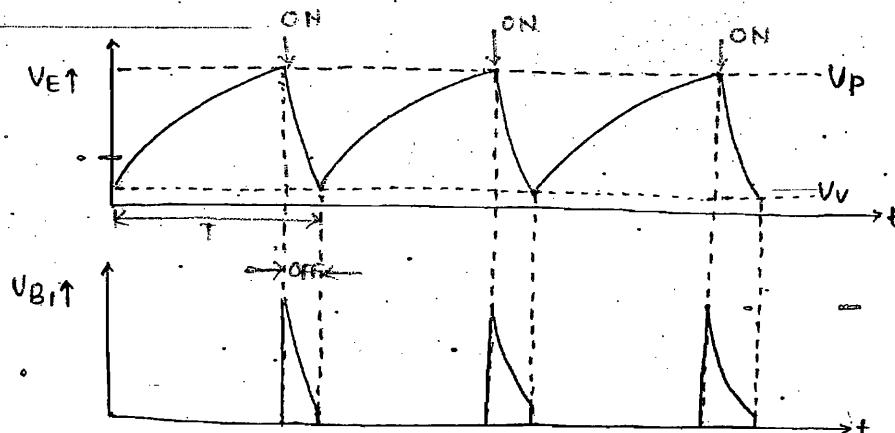
* When emitter vol. starts decreasing & reaches to V_V then $\text{UJT} \rightarrow \text{OFF}$

* UJT Working as Relaxation oscillator \rightarrow



$\text{UJT} \rightarrow \text{OFF}, V_{B1} = 0$

$\text{UJT} \rightarrow \text{OFF}, \text{base vol. will charge the capacitor.}$



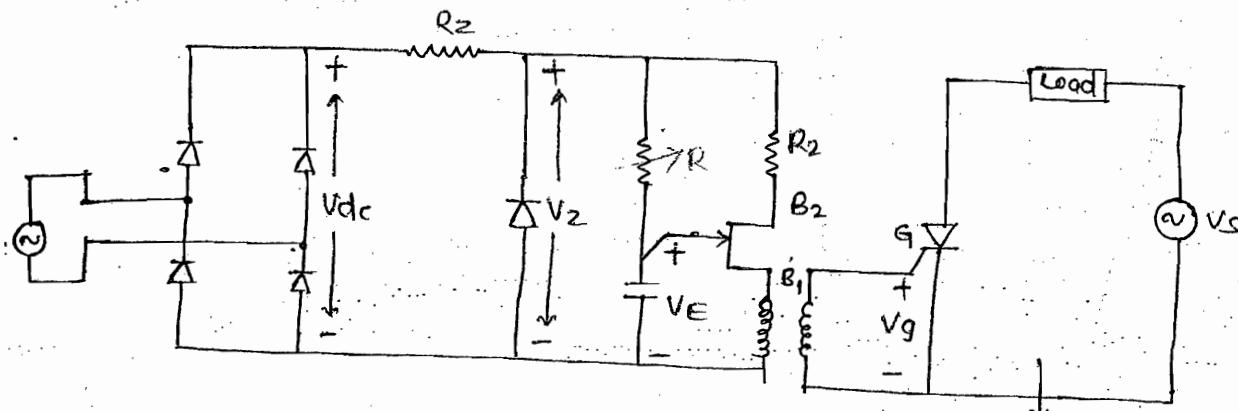
$$T = RCL \ln\left(\frac{1}{1-\eta}\right)$$

$$f = \frac{1}{RCL \ln\left(\frac{1}{1-\eta}\right)}$$

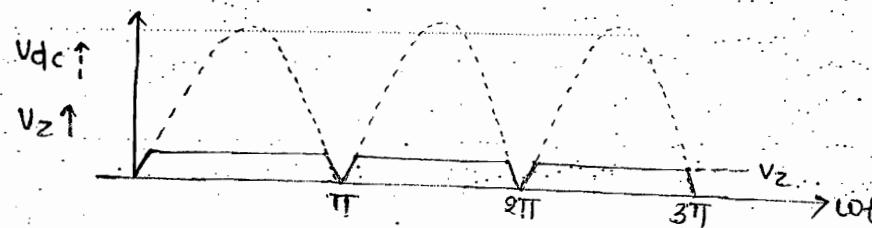
* Synchronised UJT firing ckt →

* We must synchronise the firing ckt wrt to the main ckt power supply to match the timings of gate pulse in both the ckt.

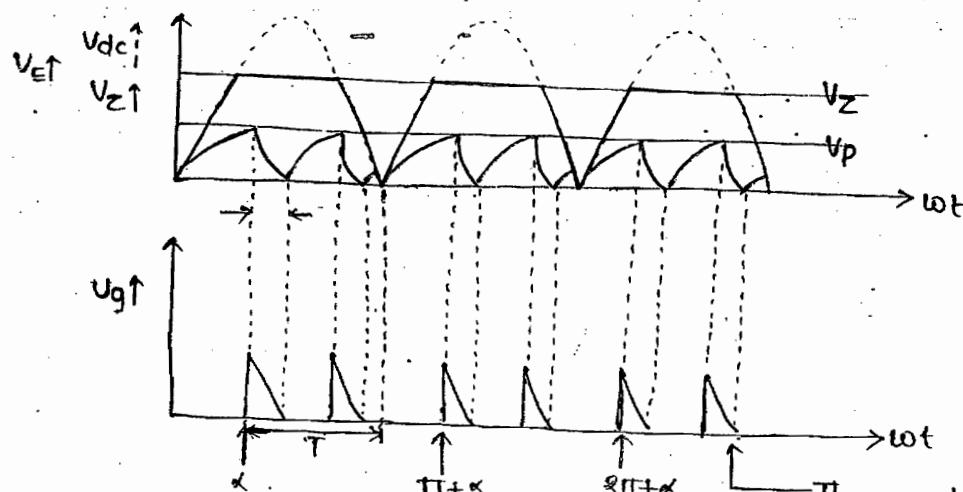
* Therefore we must use same power supply in both the cks for the purpose of synchronisation.



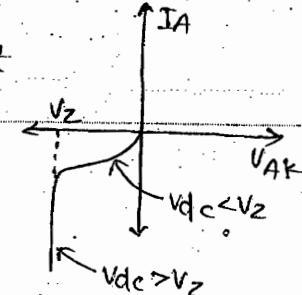
Power ckt 1-6
HWR



(Still we are not getting the pure dc in 2 π .
Variation)



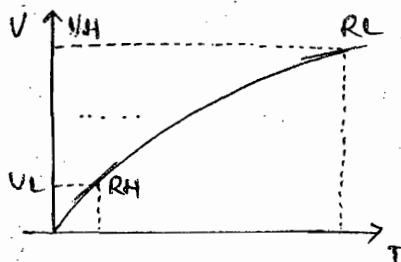
These extra gate pulse
will not effect



Protection OF Thyristor

(1) Over Current Protection → * We must connect either fuse (or) CB in series with thy. for OC protection.

(2) Over Voltage Protection →

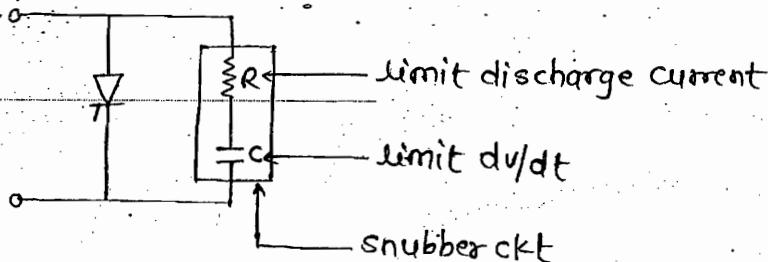


- * We must connect a varistor across the thy.
- * Varistor is a non-linear resistor
- * All metal oxide resistor behave as non-linear resistor.
- eg:- ZnO (zink oxide)

(3) $\frac{dv}{dt}$ protection →

$$\uparrow I_c = C_j \frac{dv}{dt} \uparrow \quad \& \uparrow I_c \text{ then SCR ON}$$

- * At high $\frac{dv}{dt}$ the SCR may turn ON before the gate pulse is given.
- * This is an accidental turn-on.
- * This unwanted turn-on is known as False turn-on.
- * dv/dt protection is needed to avoid the False turn ON.



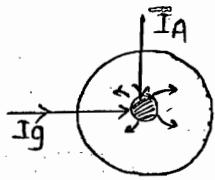
* This ckt is known as Vol. snubber because of dv/dt .

Ques → What is a snubber ckt?

Ans → When SCR is undergoing switching operation (ON \Rightarrow OFF) it is subjected to high ele. stress ($\frac{dv}{dt}$ stress, di/dt stress, overvol. etc).

* The snubber ckt will limit the ele. stress & protect the SCR during switching operations.

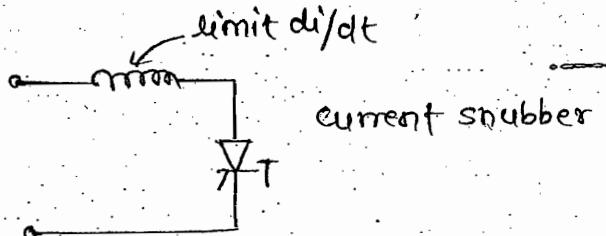
(iv) dI/dt Protection \rightarrow



$\uparrow \frac{dA}{dt} > \text{spread velocity of charge carrier}$

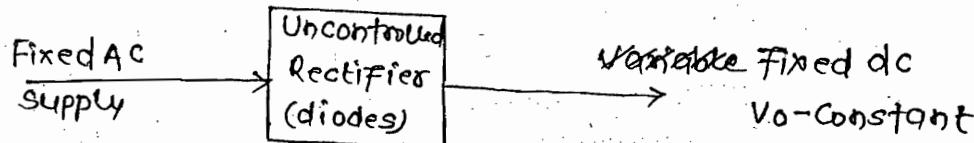
Effect of high dI/dt \rightarrow * If $dI/dt >$ spread velocity of charge carriers
then the charge density increases cumulatively
in a small cond'n area & this results in the formation of local
hotspots damaging the device

* We must connect an inductor in series with SCR for dI/dt
protection.

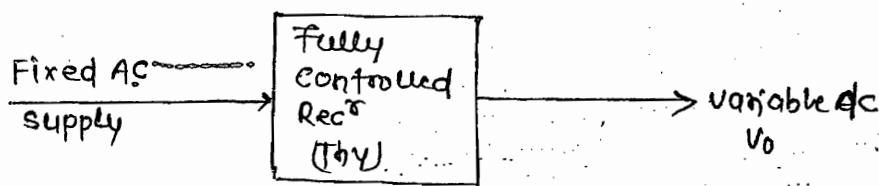


Phase Controlled
Rectifier

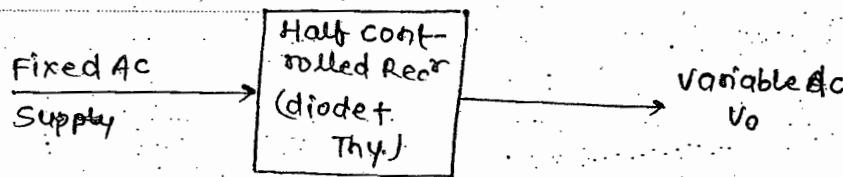
• Uncontrolled Rectifier →



Fully controlled Rectifier → (full converter)
2 quadrant operations



Half controlled Rectifier → (semiconductor)
one quadrant operation.

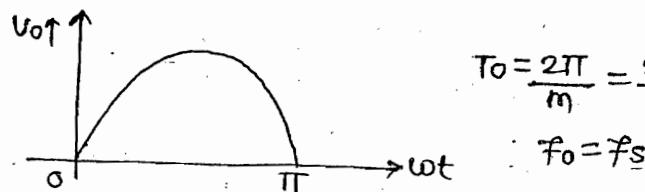


Classification of Converter based on pulse no. of the converter →

Pulse no. 'm' → pulse no. gives the no. of the o/p pulse for 1 cycle
AC source voltage.

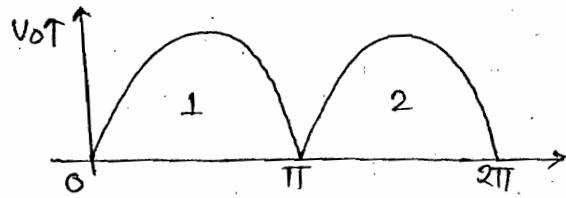
1. One pulse cont →

1-φ half wave rect.



(2) Two pulse con^r

1- ϕ full wave rec^r



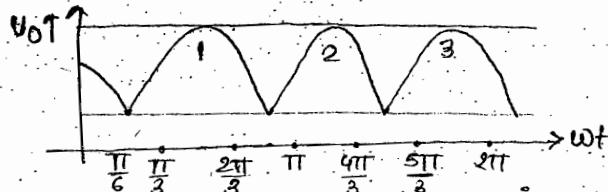
$$T_0 = \frac{2\pi}{2} = \pi \text{ rad.}$$

$$f_0 = 2fs$$

$$T_0 = \text{Time period pulse in rad} = \frac{2\pi}{m} (\text{rad})$$

3.1 3 pulse Con^r

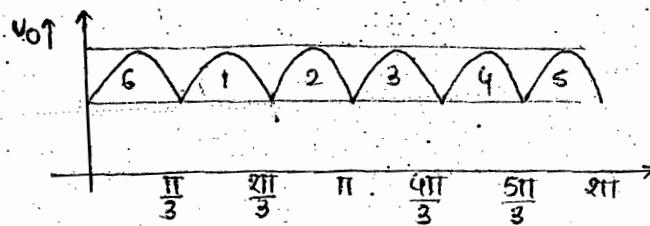
3- ϕ half wave rectifier



$$T_0 = \frac{2\pi}{3} = 120^\circ$$

$$f_0 = 3fs$$

4) 6 pulse con^r



$$T_0 = \frac{2\pi}{6} = \frac{\pi}{3} \text{ rad.}$$

$$f_0 = 6fs$$

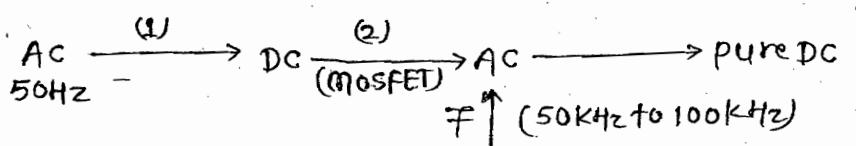
$$f_0 = mfs$$

where f_0 = o/p ripple freq.

f_s = supply freq;

$m \uparrow, T_0 \downarrow, f_0 \uparrow, \text{ripple vol.} \downarrow \therefore \text{Harmonics} \downarrow$

nps \rightarrow

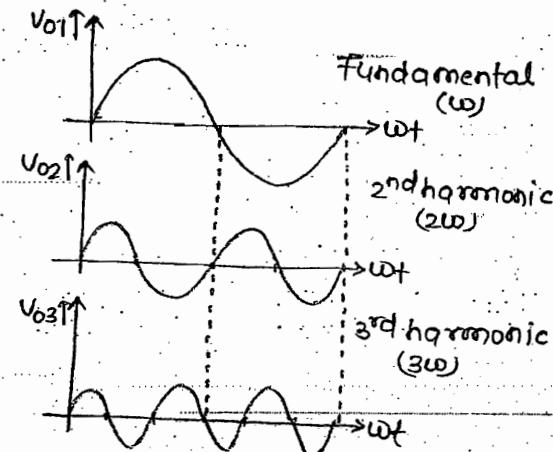
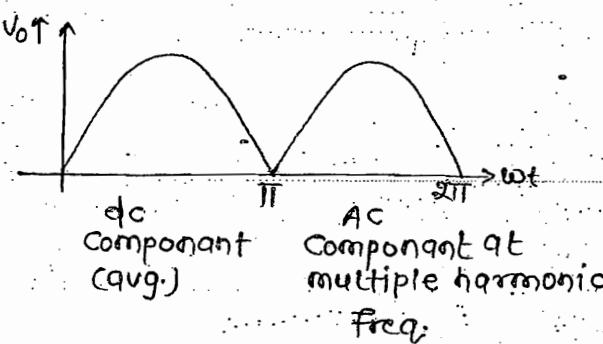


* Effect of harmonics on the performance of dc motor →

- * Harmonics overheat the m/c wdg, & Hence we can't use (utilise) the m/c to its full capacity.
- Therefore we must derate the m/c when fed to con^r.
- * Harmonics produce pulsating torque in rotor & hence smooth rotation may not be possible if it is used for power motors.
- * The rotor inertia will damp for
- * This pulsating torque produced by harmonics & hence smooth rotation is possible for bigger m/c.

Harmonics Analysis on the dc side of the converter →

Let us consider a 2 pulse converter



* Mathematical Formula for Fourier analysis →

$$V_0 = V_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)$$

$$V_0 = V_0 + \sum_{n=1}^{\infty} C_n \sin(n\omega t + \phi_n) \quad \text{where } C_n = \sqrt{a_n^2 + b_n^2}$$

O/P RMS voltage

$$V_{0\text{r}} = \sqrt{V_0^2 + V_{01}^2 + V_{02}^2 + V_{03}^2 + \dots}$$

ϕ_n = n th harmonic displacement angle.

For all the dc loads avg. value is responsible to deliver the useful power.

$$V_{0r}^2 = V_0^2 + V_{01}^2 + V_{02}^2 + \dots$$

$$V_{0r}^2 - V_0^2 = V_{01}^2 + V_{02}^2 + \dots$$

$$\sqrt{V_{0r}^2 - V_0^2} = \sqrt{V_{01}^2 + V_{02}^2 + \dots} = V_{0H}$$

Voltage Ripple factor (VRF) → It is a measure of harmonics on the dc side of converter.

$$VRF = \frac{\sqrt{V_{0r}^2 - V_0^2}}{V_0}$$

$$VRF = \sqrt{\left(\frac{V_{0r}}{V_0}\right)^2 - 1}$$

Form factor →

$$FF = \frac{V_{0r}}{V_0}$$

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

perfect dc → (1.) No ripple

(2.) $V_{0r} = V_0$.

(3.) $FF = 1$

(4.) $VRF = 0$ (No harmonics)

significance of FF :-

| Without harmonics $FF = 1$

| With harmonics $FF > 1$

| As the FF decreases & reaches to unity then smoothness of wave form is improved towards dc.

| FF gives the information on shape of waveform on dc side of converter.

Harmonics analysis off the AC side of converter →

Let us consider an inverter

* The o/p vol. waveform of the inverter may not be pure sinusoidal, it may contains harmonics.

* For all the ac loads fundamental component is responsible to deliver usefull power.

$$V_{or} = \sqrt{V_0^2 + V_{o1}^2 + V_{o2}^2 + \dots}$$

$$\sqrt{V_{or}^2 - V_{o1}^2} = \sqrt{V_0^2 + V_{o2}^2 + \dots}$$

Total harmonic distortion (THD) → It is measure of harmonics on AC side of the con?

$$THD = \frac{\sqrt{V_{or}^2 - V_{o1}^2}}{V_{o1}}$$

$$THD = \boxed{\sqrt{\left(\frac{V_{or}}{V_{o1}}\right)^2 - 1}}$$

Distortion factor 'g' → It gives the information of waveform on AC sides.

$$g = \frac{V_{o1}}{V_{or}}$$

$$THD = \sqrt{\frac{1}{g^2} - 1}$$

Perfect AC →

(1.) $V_{or} = V_{o1}$

(2.) $g = 1$

(3.) $THD = 0$ (No harmonics)

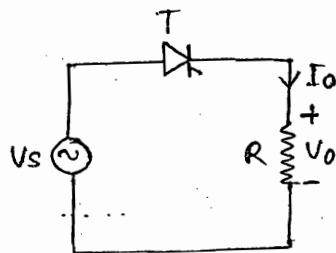
Significance of distortion factor →

(1.) Without harmonics $g = 1$

(2.) With harmonics $g < 1$

(3.) As g value is increased & approaches unity then smoothness of waveform is improved towards sinusoidal.

(1) 1-Φ Half wave Rectifier (One pulse converter) →



$$\omega t_c = \pi \text{ rad}$$

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

$$V_0 = \frac{1}{2\pi} \int_{-\alpha}^{\pi} V_m \sin \omega t d(\omega t)$$

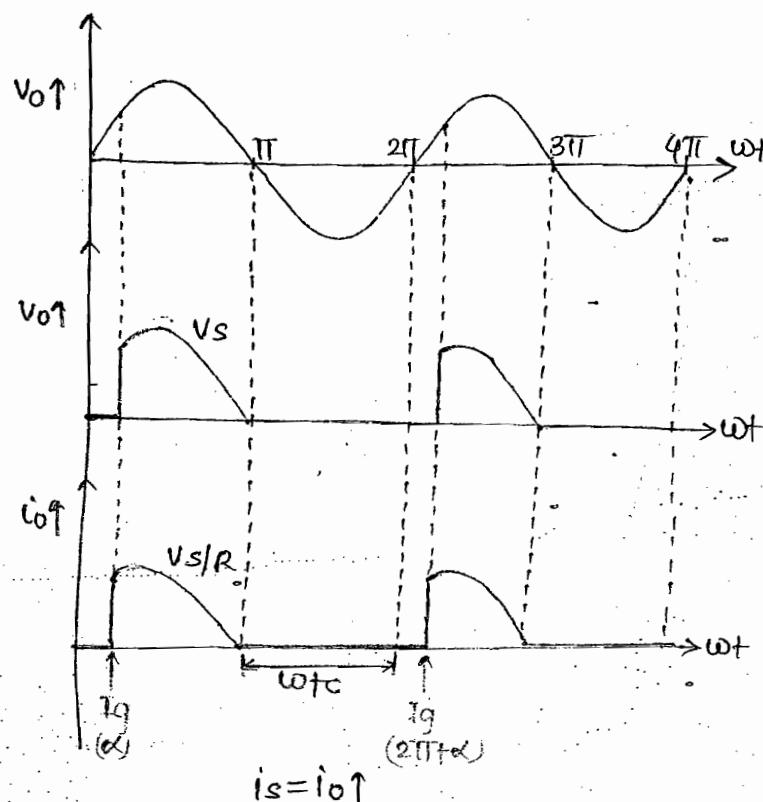
$$= \frac{V_m}{2\pi} (-\cos \omega t) \Big|_{-\alpha}^{\pi}$$

$$V_0 = \frac{V_m}{2\pi} [-\cos \pi + \cos \alpha]$$

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

$$I_0 = \frac{V_0}{R} = \frac{V_m}{2\pi R} (1 + \cos \alpha)$$

$$I_0 = \frac{V_m}{2\pi R} (1 + \cos \alpha) = (I_s) q v g.$$



Drawback → The source current contains dc components & saturates the supply T/F core.

Therefore HWR is generally not preferred for applications.

$$V_{or} = \left[\frac{1}{2\pi} \int_{-\alpha}^{\pi} V_m^2 \sin^2 \omega t d(\omega t) \right]^{1/2}$$

$$V_{or} = \left[\frac{V_m^2}{2\pi} \left\{ (\cos \omega t) \Big|_{-\alpha}^{\pi} - \frac{1}{2} (\sin 2\omega t) \Big|_{-\alpha}^{\pi} \right\} \right]^{1/2}$$

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

$$V_{or} = \frac{V_m}{\sqrt{2T_0}} \left[(U - U + \frac{1}{2}(\sin 2L - \sin 2U)) \right]^{1/2}$$

$$P_{in} = V_{sr} \cdot I_{sr} \cdot PF \quad \text{--- (i)}$$

$$V_s = V_m \sin \omega t, \quad V_{sr} = \frac{V_m}{\sqrt{2}}$$

$$I_{sr} = I_{or} = \frac{V_{or}}{R}$$

$$P_{in} = V_{sr} I_{sr} \cos \phi, \quad \text{--- (ii)}$$

$$P_o = V_o I_o X$$

i.e. For resistive load take RMS values ... i.e.,

$$P_o = V_{or} \cdot I_{or}$$

Assuming no losses in the thy.

$$V_{sr} \cdot I_{sr} \cdot PF = V_{or} \cdot I_{or}$$

$$\boxed{PF = \frac{V_{or}}{V_{sr}} \text{ for R load}}$$

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

- (i) The supply current contains harmonics on AC side of the converter
- In general (other than resistive load) fundamental source current is responsible to deliver useful power on AC side of the con.

Fundamental displacement factor (FDF) = $\cos \phi$,

$$V_{sr} \cdot I_{sr} \cdot PF = V_{sr} \cdot I_{sr} \cos \phi,$$

$$\boxed{PF = \frac{I_{sr}}{I_{or}} \cdot \cos \phi,}$$

$$PF = g \cdot \cos \phi,$$

$$\boxed{PF = g \cdot FDF}$$

(1) PF depends on firing angle α . As α increases PF is decreased.

(2) PF depends on the shape of supply current waveform, i.e. it depends on Harmonics on the AC side of conv.

$$PF = g \cdot FPF$$

(3) PF also depends on type of the conv & type of load.

Drawback of PE conv →

(1) The conv injects harmonics into the supply & reduce its power quality.

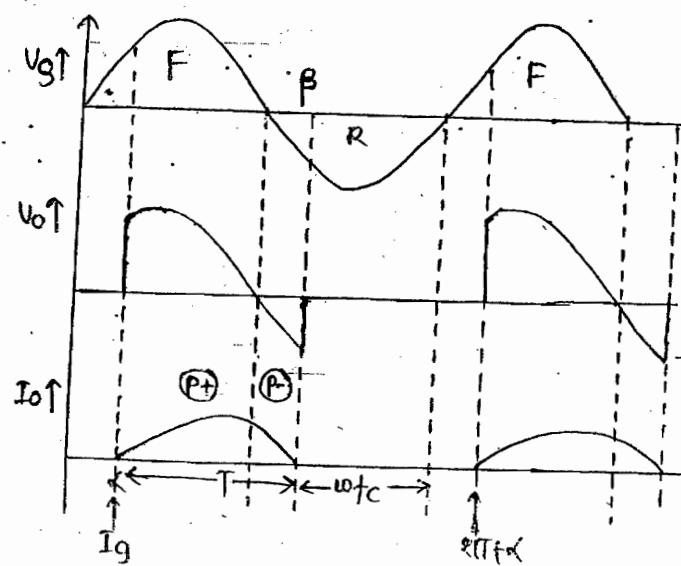
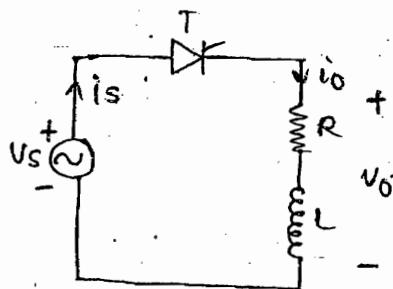
To rectify this problem we must use AC filter on AC side of the conv.

(2) At high values of firing angle α , the PF is very low.

Therefore it draws very high lagging reactive power from the supply.

* To rectify this problem we must connect a reactive power source on AC side of conv to compensate the required reactive power for the conv operation.

2) 1-φ HWR (RL Load) →



Mode(1) \rightarrow (α to π)

$$V_0 = V_s$$

* Power flows from source to the load
So power is +ve i.e. (P+)

Apply KVL;

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

$$i_o = I_{\text{steady}} + I_{\text{transient}}$$

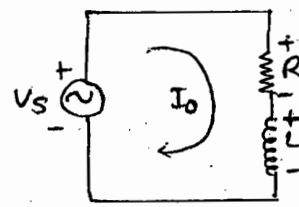
(PI) (CE)

$$i_o = \frac{V_m}{|Z|} \sin(\omega t - \phi) + K e^{-t/T}$$

$$\text{at } \omega t = \alpha, i_o = 0$$

$$K = \frac{V_m}{|Z|} (e^{t/T} / j_x \sin(\alpha - \phi))$$

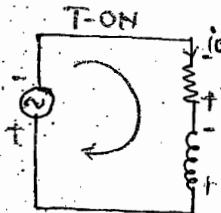
$$K = -\frac{V_m}{|Z|} \sin(\alpha - \phi) e^{-\frac{R\alpha}{WL}}$$



Mode(2) \rightarrow (π to β)

$$\frac{1}{2} L i^2 \longrightarrow \text{source} \& I^2 R$$

L is releasing energy



* Here the inductance energy makes the thy. to conduct even in the -ve cycle until it releases its complete energy at $\omega t = \beta$

$$\downarrow P_F = \frac{P_0}{V_{sr} I_{sr}}$$

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

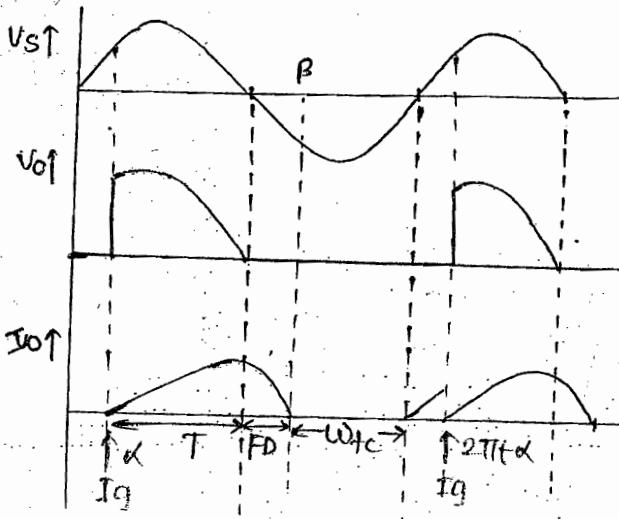
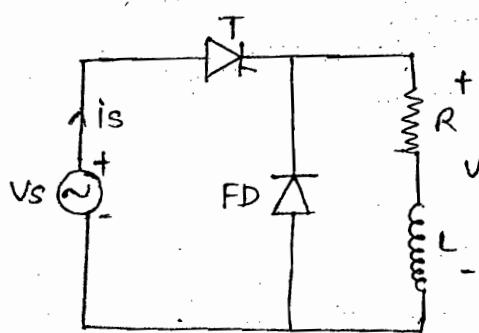
$$t_c = \frac{2\pi - \beta}{\omega} \text{ sec}$$

$$V_0 = \frac{1}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t (d\omega t)$$

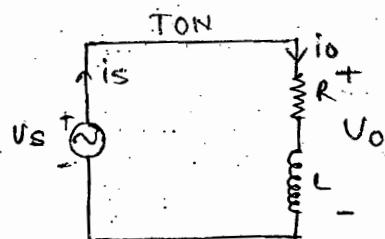
$$V_0 = \frac{V_m}{2\pi} (\cos \alpha - \cos \beta)$$

$$V_{0r} = \frac{V_m}{2\sqrt{\pi}} \left[(\beta - \alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right]^{1/2}$$

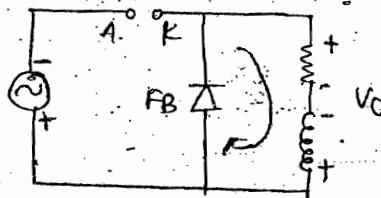
3) 1-φ HWR RL load with FD →



mode (1) →



mode (2) →



use P → load

$$\frac{1}{2} U^2 \rightarrow I^2 R$$

$$\text{PF improved, } \text{PF} = \frac{P_0}{V_{sr} I_{sr}}$$

$$U_0 = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t)$$

$$U_0 = \frac{V_m}{2\pi} (1 + \cos \alpha)$$

$$V_{0r} = \frac{V_m}{2\sqrt{\pi}} \left[(\pi - \alpha) + \frac{1}{2} (\sin 2\alpha)^2 \right]^{1/2}$$

$$\omega t_c = \pi \text{ rad}$$

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

* -ve power is removed i.e. avg. P_0 is increased; so PF is increased.

$$\uparrow \text{PF} = \frac{P_0}{V_{\text{sr}} I_{\text{sr}}}$$

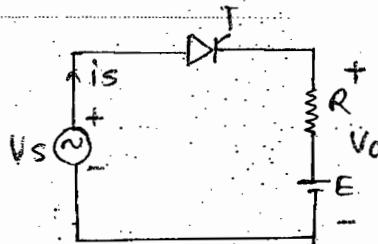
Advantage of FD →

- (1.) The PF is improved on AC side of the conv.
- (2.) -ve Voltage spikes in the O/P voltage waveform is removed; thus increased O/P voltage, active power & PF.
- (3.) The shape of the O/P current waveform is improved.
Hence the performance of the converter is improved with a FD.
- * The PF of the semi conv is better than full conv due to its freewheeling action.

Therefore the performance of the semiconv is superior to full conv.

Application →

1-Φ HWR charging a battery (RE load) →



$$+Vs > E, T(F)$$

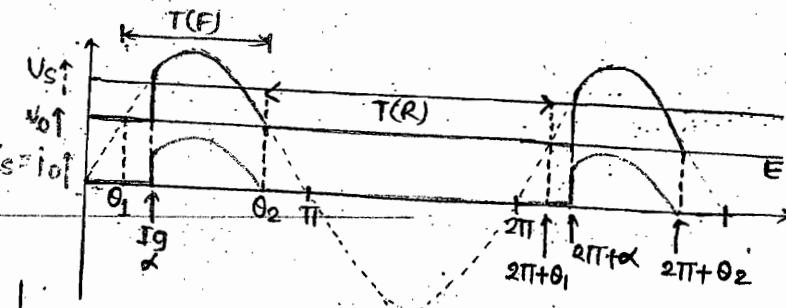
$$\text{At } \omega t = \theta_1, Vs = E$$

$$V_{ms} \sin \theta_1 = E$$

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

$$\theta_2 = \pi - \theta_1$$

$$\theta_1 \leq \alpha \leq \theta_2$$



T(OFF)

$$i_0 = 0, V_0 = E$$

$$V_S = R i_0 + E$$

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

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

T → (OFF)

$$i_0 = 0, V_0 = E$$

$$\omega t = 2\pi + \theta_1 - \theta_2$$

$$= 2\pi + \theta_1 - \pi + \theta_1$$

$$\omega t_c = \pi + 2\theta_1 \text{ rad.}$$

$$t_c = \frac{\pi + 2\theta_1}{\omega} \text{ sec}$$

* PIV OF thyristor = $V_m + E$

$$V_o(\text{avg}) = \frac{1}{2\pi} \left[\int_{\alpha}^{\theta_2} V_m \sin \omega t d(\omega t) + \int_{\theta_2}^{2\pi + \alpha} E d(\omega t) \right]$$

$$V_o(\text{avg}) = \frac{1}{2\pi} \left[V_m (\cos \alpha - \cos \theta_2) + E (2\pi + \alpha - \theta_2) \right] \text{ Rad.}$$

Charging current of battery

$$I_o = \frac{1}{2\pi} \int_{\alpha}^{\theta_2} \left(\frac{V_m \sin \omega t - E}{R} \right) d(\omega t)$$

$$I_o = \frac{1}{2\pi R} \left[V_m (\cos \alpha - \cos \theta_2) - E (\theta_2 - \alpha) \right] \text{ Rad.}$$

* when the diode rectifier is charging a battery substitute $\alpha = 0$,
in the above eqⁿ to find the V_o & I_o

$$P_{in} = U_{sr} I_{sr} \times PF$$

$$P_o = I_{or}^2 R + EI_o$$

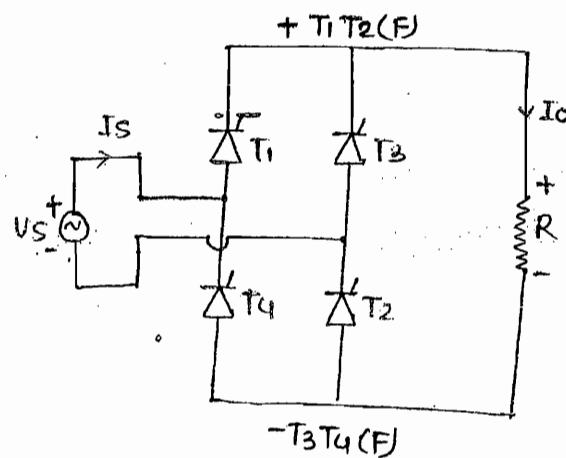
Assuming no losses in thy. i.e. we get;

$$\boxed{PF = \frac{I_{or}^2 R + EI_o}{U_{sr} I_{sr}}}$$

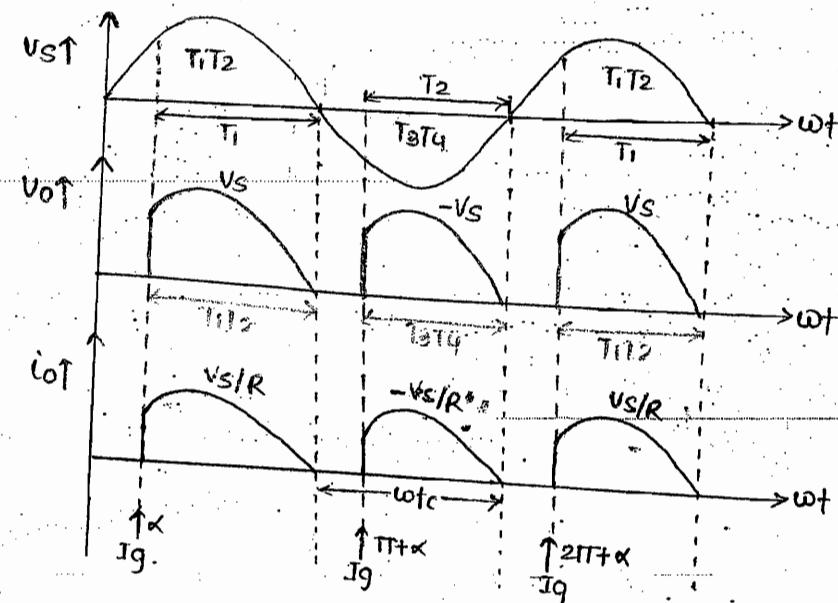
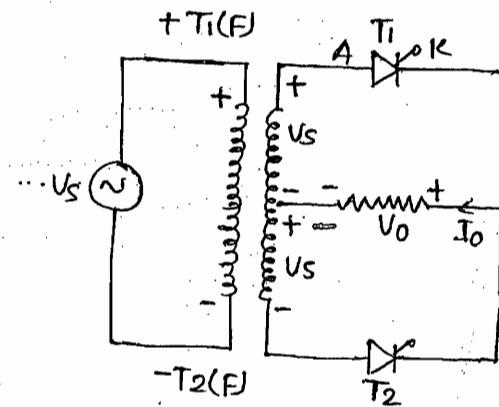
$$I_{or} = \left[\frac{1}{2\pi} \int_{\alpha}^{\theta_2} \left(\frac{V_m \sin \omega t - E}{R} \right)^2 d(\omega t) \right]^{1/2}$$

1-φ Full Wave Rectifier → (2-pulse converter)

* Bridge Rectifier



* Mid point rectifier



$T_1 T_2 \rightarrow \text{ON}$

i.e. $V_o = V_s$

$$i_o = \frac{V_s}{R}$$

$T_3 T_4 \rightarrow \text{ON}$

i.e. $V_o = -V_s$

$$i_o = -\frac{V_s}{R}$$

$T_1 \rightarrow \text{ON}$

i.e. $V_o = V_s$

$$i_o = \frac{V_s}{R}$$

$T_2 \rightarrow \text{ON}$

$V_o = -V_s$

$$i_o = -\frac{V_s}{R}$$

$$\omega t_c = \pi$$

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

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

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

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

For Resistive load; PF = $\frac{V_{or}}{V_{sr}}$

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

* For mid point rectifier PIV = $2V_m$

* For bridge rectifier PIV = V_m .

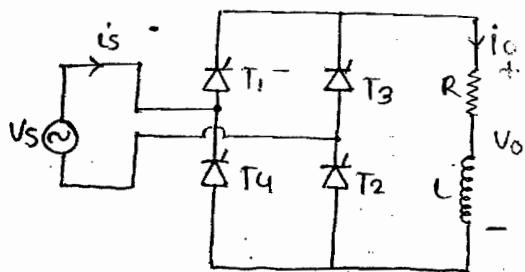
* In mid point rectifier V_m is the peak value of upper 2° Voltage.

Advantage of bridge rectifier →

The PIV of the thy. in bridge rectifier half of that when compared to mid point rectifier.

If same thy. are used in both the conv' then the avg. o/p vol. & power handled by bridge rectifier is double that of mid point rectifier.

Bridge Rectifier with RL load → (1φ Fully controlled rectifier)



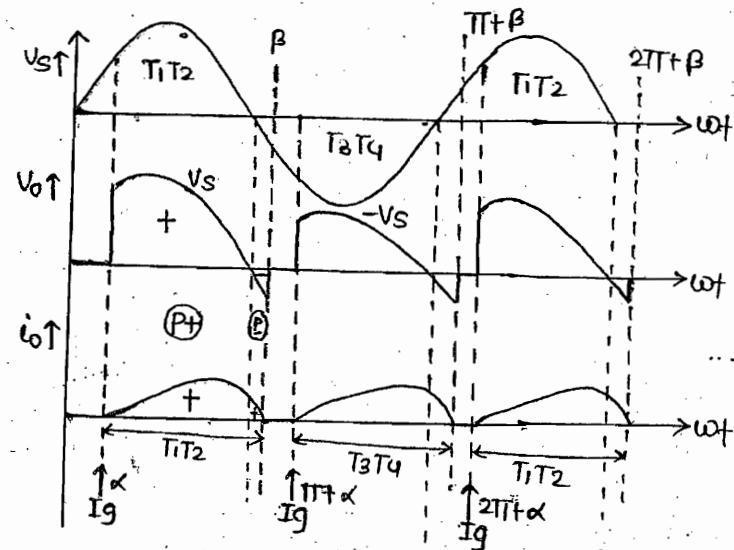
$$\omega t_c = 2\pi - \beta$$

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

$$V_0 = \frac{1}{\pi} \int_{\alpha}^{\beta} V_m \sin \omega t d(\omega t)$$

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

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



$$V_{0\delta} = \frac{V_m}{\sqrt{2\pi}} \left[(\beta - \alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right]^{1/2}$$

We get discontinuous condⁿ $\beta < (\pi + \alpha)$

Reasons → (1) $\downarrow T \downarrow$ i.e. $\beta \downarrow$

$$\because \downarrow T = \frac{L}{R} \uparrow$$

(2) $\alpha \uparrow \beta \downarrow$

(3) If avg o/p current is less the β is also less. ($I_{0\delta}, \beta \downarrow$)

RL Load with Continuous conduction →

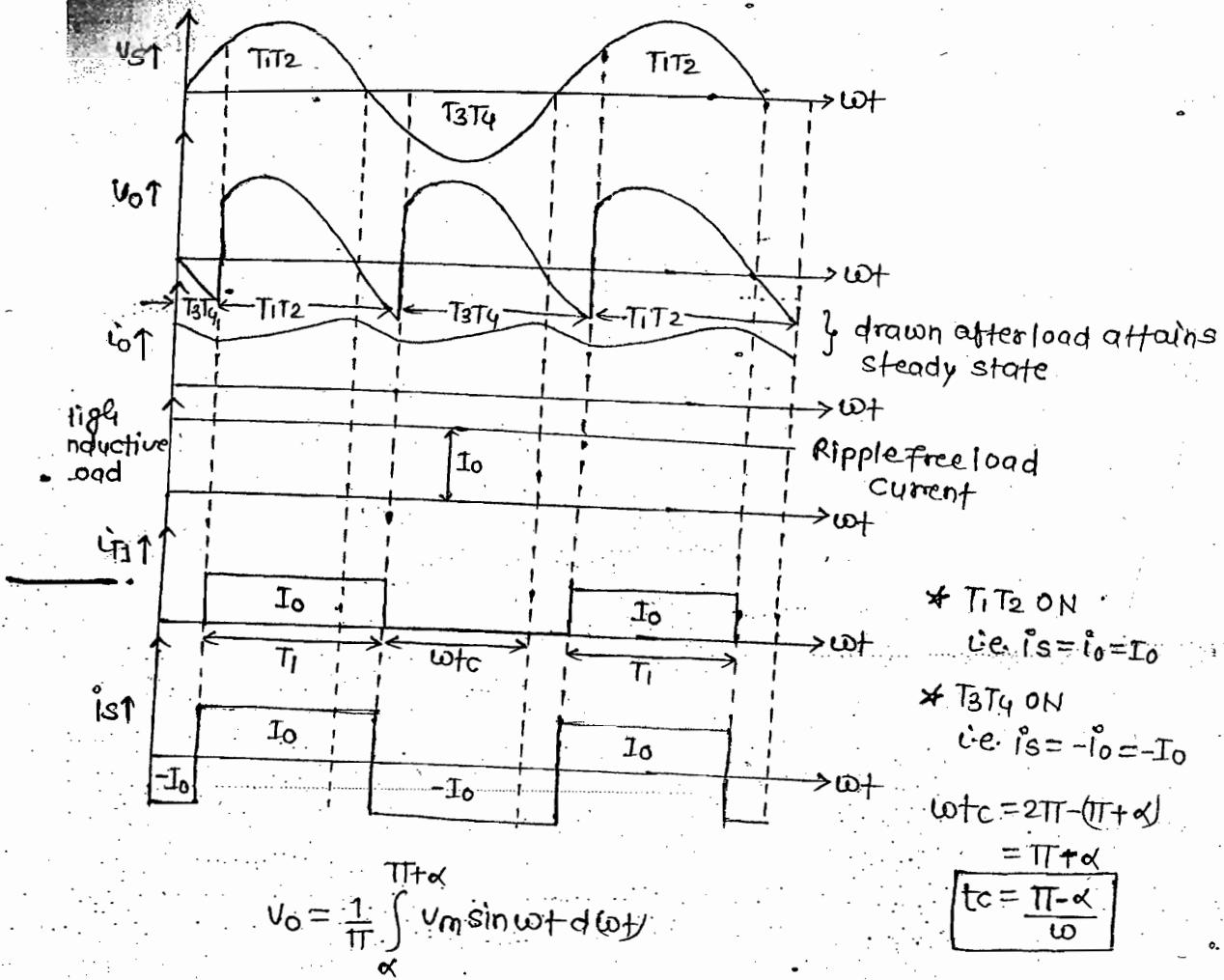
We get continuous condⁿ when $\beta \geq (\pi + \alpha)$

Reasons → (1) $L \uparrow T \uparrow$ i.e. $\beta \uparrow$

$$\uparrow T = \frac{L}{R} \downarrow$$

(2) $\alpha \downarrow \beta \uparrow$

(3) $I_{0\delta} \uparrow \beta \uparrow$



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

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

$$V_{Or} = \frac{Um}{\sqrt{2}} = V_{Sr}$$

$$I_{Sr} = I_0$$

Assume high inductive load \rightarrow

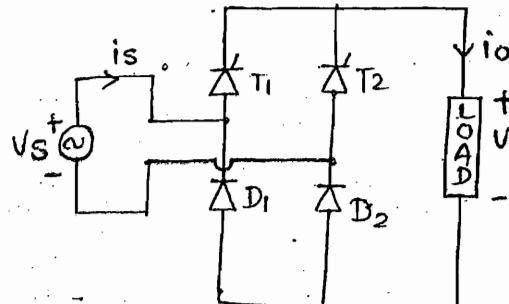
1) Conduction angle of each thy. = π rad for every cycle. $\{(\pi + \alpha) - \alpha\}$

2) Avg. thy. current (I_T)_{avg} = $\frac{I_0 \pi}{2\pi} = \frac{I_0}{2}$

$$(I_T)_{RMS} = I_0 \left(\frac{\pi}{2\pi} \right)^{1/2} = \frac{I_0}{\sqrt{2}}$$

1-Φ Half Controlled Rectifier →

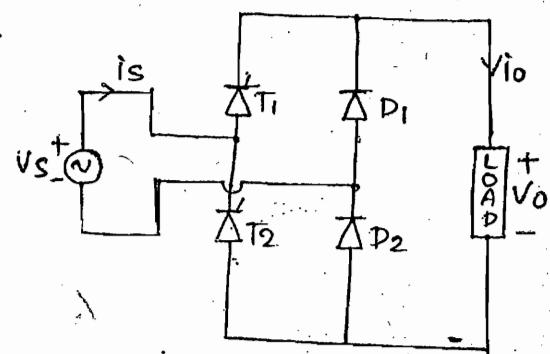
Symmetrical Connection



+ T₁ D₂ (F)

- T₂ D₁ (R)

Asymmetrical Connection



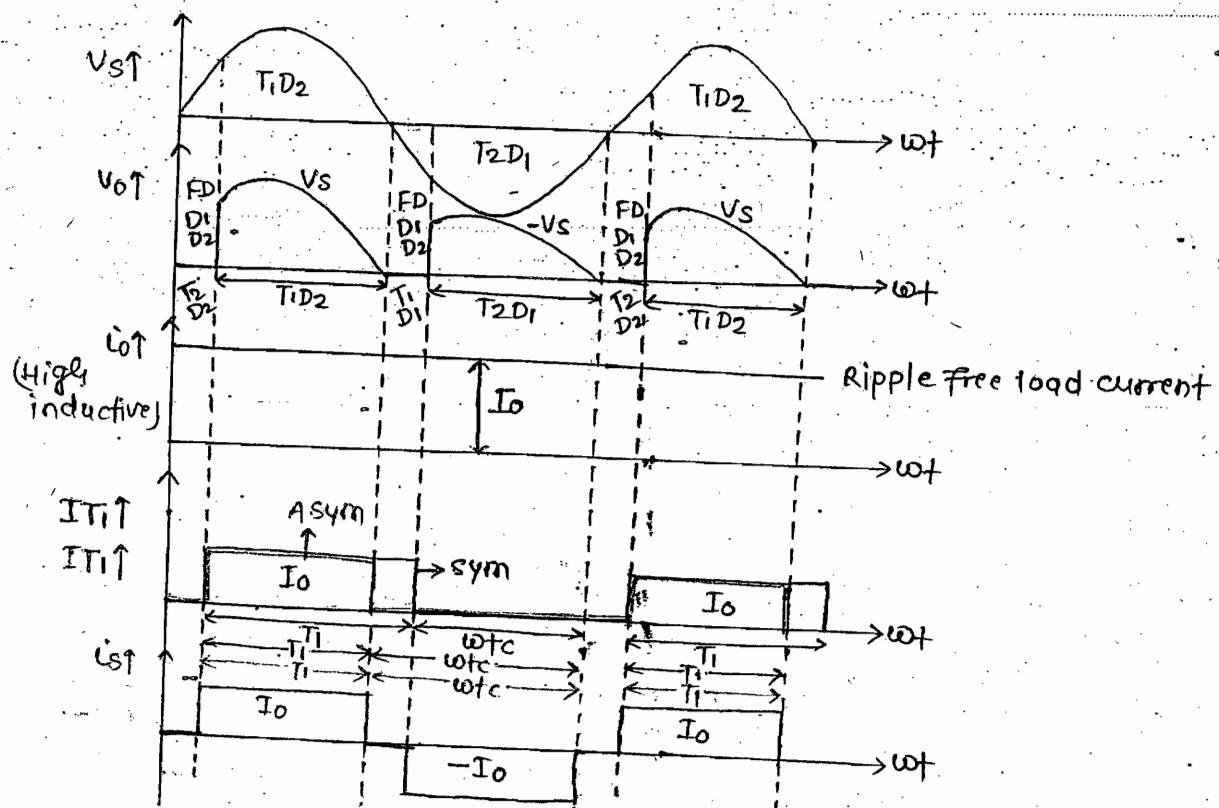
+ T₁ D₂ (F)

- T₂ D₁ (F)

* During FD period the -ve spikes are removed & the source current also becomes zero.

* For resistive load waveforms are same in full contr & semicontr.

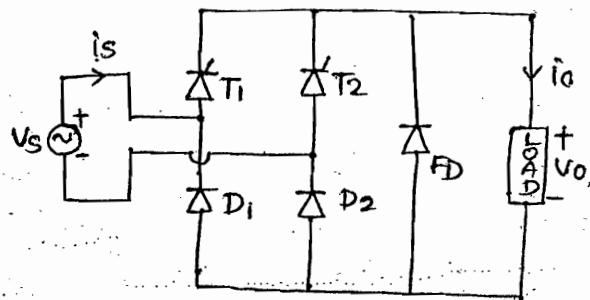
** Let us assume high inductive load.



Ques. → What is the problem with sym. connection?

Ans. → At $\alpha, \pi + \alpha, 2\pi + \alpha$ ----- There is a possibility of short circuit across the supply when incoming thy. stats conducting before the o/p (outgoing) thy. stops conducting.

* To rectify this problem we must connect a separate FD across the load as shown in the fig. given below:-



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

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

* In the semiconverter :-

(1) Cond'n angle of each thy. = $\pi - \alpha$ (for every 2π rad)

(2) Avg. thy. current $(I_T)_{avg} = I_0 \left(\frac{\pi - \alpha}{2\pi} \right)$

$$(I_T)_{RMS} = I_0 \left(\frac{\pi - \alpha}{2\pi} \right)^{1/2}$$

(3) Cond'n angle of FD is α rad. (for every π rad)

(4) Avg. FD current $(I_{FD})_{avg} = I_0 \left(\frac{\alpha}{\pi} \right)$

$$(I_{FD})_{RMS} = I_0 \left(\frac{\alpha}{\pi} \right)^{1/2}$$

$$I_{sr} = I_0 \left(\frac{\pi - \alpha}{\alpha} \right)^{1/2} \quad \left\{ \text{IF you have any symm. -ve wave form we col. for } \pi \text{ rads} \right\}$$

Ratings of Thyristor →

(1) Thyristor RMS Rating (I_T)_{RMS} →

* It gives the RMS value Rating of ON state current of thy.

* (I_T) _{RMS} value in cont should be less than thy. RMS Rating.

(2) Average thy. Rating (I_T)_{Avg} →

* It gives the avg. rating of ON state current of a thy.

$$(I_T)_{Avg} = \frac{(I_T)_{RMS} \text{ Rating}}{-FF}$$

FF → It is a FF of thy. current waveform in a cont.

Avg. Rating of thy. depends on :-

(1) Condⁿ angle of thy. ↑ FF ↓ → $(I_T)_{Avg}$ ↑

(2) Avg. Rating depends on type of the load.

e.g. → L ↑ $\frac{di}{dt}$ ↓ smoothness ↑ : FF ↓ → $(I_T)_{Avg}$ ↑

(3) I^2_t Rating → This Rating is provided for the thy. to select a proper fuse for over-current protection.

* I^2_t rating of thy. should always be greater than fuse.

(4) Surge Current Rating → Surge Current Rating is specified for short duration of time.

n cycle surge current Rating (I_{Sn}) → It is the surge current that the SCR can withstand for n cycle.

$$I_{Sn}^2 \left(\frac{nT}{2} \right) = I^2_t \text{ Rating of thy.}$$

From above we can find I_{Sn}

One cycle surge current Rating (I_{S1}) → It is the surge current that the SCR can withstand for 1 cycle.

$$I_{S1}^2 \left(\frac{T}{2}\right) = I_{Sh}^2 \cdot n \cdot \frac{T}{2}$$

$$I_{S1} = \sqrt{n} \cdot I_{Sh}$$

Sub cycle current Rating ($I_{S/n}$) \rightarrow It is the surge current that the SCR can withstand for $\frac{1}{n}$ th period of a cycle.

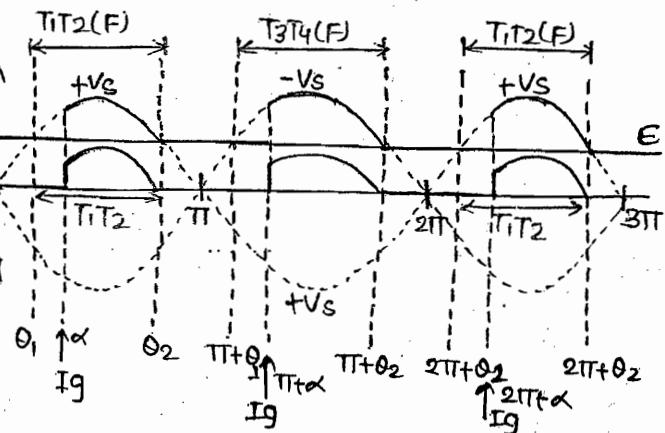
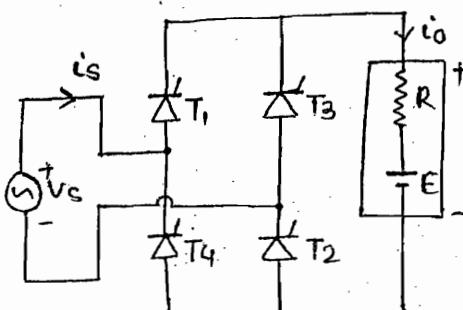
$$(I_{S/n})^2 \cdot \left(\frac{1}{n}\right) \frac{T}{2} = (I_{S1})^2 \frac{T}{2}$$

$$(I_{S/n})^2 = \sqrt{n} I_{S1}$$

Half cycle surge current Rating

$$(I_{S/2}) = \sqrt{2} I_{S1}$$

DATE-25/08/14

(i) 1φ Full Converter - Charging Battery →

$$+v_e, +v_s \geq E, T_1T_2(F)$$

$$-v_e, -v_s > E, T_3T_4(F)$$

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

$$0_1 \leq \alpha \leq 0_2$$

$$T_1T_2 \rightarrow ON$$

$$v_o = v_s$$

$$i_o = \frac{v_s - E}{R}$$

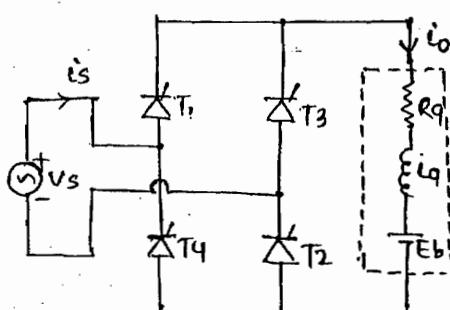
$$i_o = \frac{V_m \sin \omega t - E}{R}$$

$$v_o = \frac{1}{\pi} \left[\int_{\alpha}^{\theta_2} V_m \sin \omega t d(\omega t) + \int_{\theta_2}^{\pi + \alpha} E d(\omega t) \right]$$

$$v_o = \frac{1}{\pi} \left[V_m (\cos \alpha - \cos \theta_2) + E (\pi + \alpha - \theta_2) \right]$$

$$i_o = \frac{1}{\pi} \left[\int_{\alpha}^{\theta_2} \frac{V_m \sin \omega t - E}{R} d(\omega t) \right]$$

$$i_o = \frac{1}{\pi R} \left[V_m (\cos \alpha - \cos \theta_2) - E (\theta_2 - \alpha) \right]$$

1φ Full converter - DC motor (RL load) →

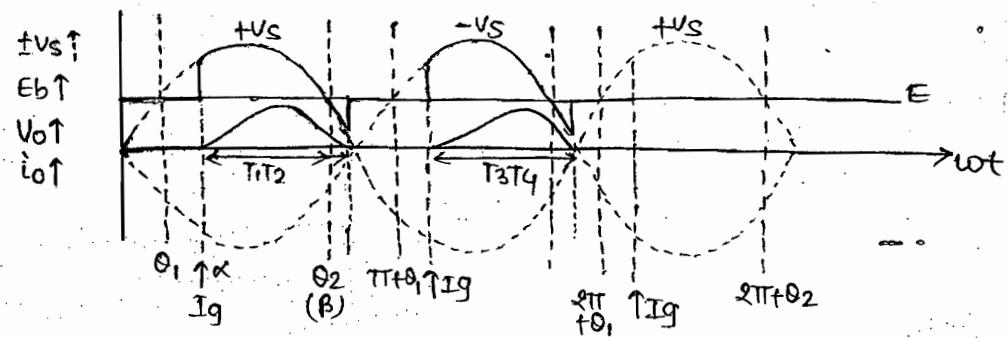
(i) Discontinuous Conduction

$$\theta_2 < \beta < (\pi + \alpha)$$

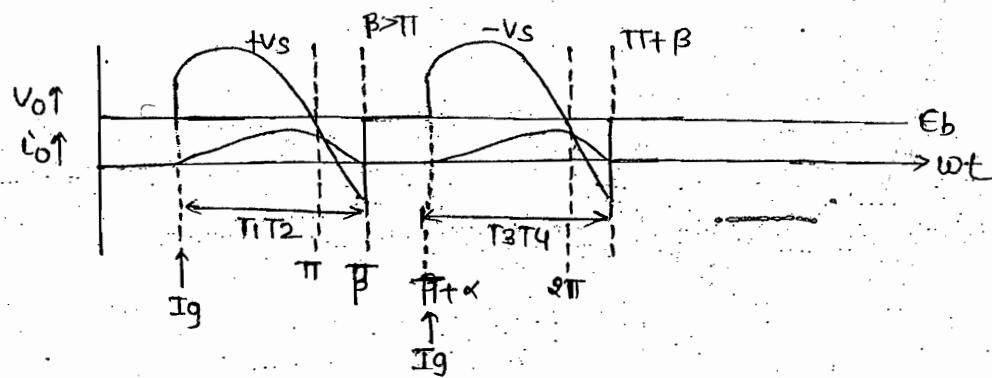
$$(a) \beta < \pi$$

$$(b) \beta \geq \pi$$

(i) B CTF



(ii) B > PI



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

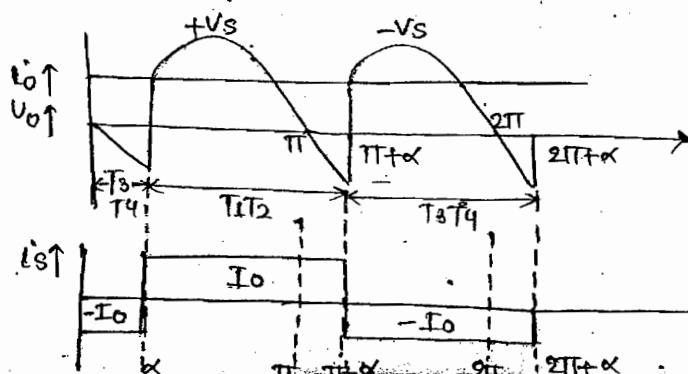
$$v_o = \frac{1}{\pi} \left[\int_{\alpha}^{\beta} V_m \sin \omega t d(\omega t) + \int_{\beta}^{2\pi + \alpha} E_b d(\omega t) \right]$$

$$v_o = \frac{1}{\pi} \left[V_m (\cos \alpha - \cos \beta) + E_b (\pi + \alpha - \beta) \right]$$

(2.1) Continuous Conduction →

$$\beta > (\pi + \alpha)$$

- * For continuous condⁿ there is no effect of back emf in the o/p vol- waveform therefore the o/p vol. waveform will remain same for RL & RLE load.



$$U_0 = \frac{2V_m}{\pi} \cos \alpha \rightarrow RL, RLE$$

$$I_{sr} = I_0$$

$$I_{sr} = I_0 \left(\frac{\pi + \alpha - \delta}{\pi} \right)^{1/2}$$

$$I_{sr} = I_0$$

Harmonic analysis on AC side of converter →

The Fourier Series for supply waveform is

$$i_s = \sum_{n=1,3,5,\dots}^{\infty} \frac{4I_0}{n\pi} \sin(n\omega t + \phi_n)$$

$$\text{where } \phi_n = -n\alpha, \phi_1 = -\alpha$$

$$i_{sn} = \frac{4I_0}{n\pi} \sin(n\omega t + \phi_n)$$

$$I_{sn} = \frac{2\sqrt{2}}{n\pi} I_0$$

i = instantaneous
I = RMS

$$|I_{s1}| = \frac{2\sqrt{2}}{\pi} I_0 \quad \text{--- (i)}$$

$$FDF = \cos \phi_1$$

$$FDF = \cos \alpha \quad \text{--- (ii)}$$

$$g = \frac{|I_{s1}|}{I_{sr}}$$

$$= \frac{2\sqrt{2}}{\pi} \frac{I_0}{I_0}$$

$$g = \frac{2\sqrt{2}}{\pi} \quad \text{--- (iii)}$$

$$PF = g \cdot FDF$$

$$PF = \frac{2\sqrt{2}}{\pi} \cos \alpha \quad \text{--- (iv)}$$

$$THD = \left(\frac{1}{g^2 - 1} \right)^{1/2}$$

$$= \left(\frac{\pi^2}{8} - 1 \right)^{1/2}$$

$$= 0.4834$$

$$THD = 48.34\% \quad \text{--- (v)}$$

Active power $P = V_{sr} \cdot I_{s1} \cos \alpha$
 (useful power)

$$P = \frac{V_m}{\sqrt{2}} \frac{2\sqrt{2}}{\pi} I_0 \cos \alpha$$

$$P = \frac{2V_m}{\pi} I_0 \cos \alpha$$

$$\boxed{P = V_0 I_0} \quad \text{where; } V_0 = \frac{2V_m}{\pi} \cos \alpha$$

Reactive power

$$Q = V_{sr} \cdot I_{s1} \sin \alpha \quad (\text{lag}) \rightarrow [\sin(-\alpha) = -\sin \alpha]$$

$$= V_{sr} \cdot I_{s1} \cos \alpha \frac{\sin \alpha}{\cos \alpha}$$

$$Q = P \tan \alpha$$

$$\boxed{Q = P \tan \alpha = V_0 I_0 \tan \alpha} \quad \text{--- (ii)}$$

Harmonics analysis on dc side of converter \rightarrow

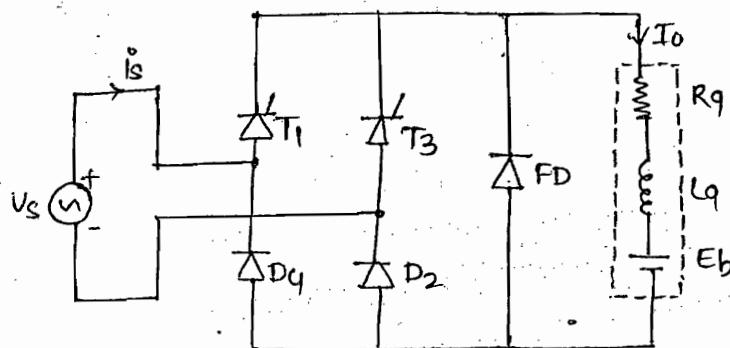
$$FF = \frac{V_{sr}}{V_0} = \frac{V_m / \sqrt{2}}{\frac{2V_m}{\pi} \cos \alpha}$$

$$\boxed{FF = \frac{\pi}{2\sqrt{2} \cos \alpha}}$$

$$URF = \sqrt{FF^2 - 1}$$

$$\boxed{URF = \sqrt{\frac{\pi^2}{8 \cos^2 \alpha} - 1}}$$

1ϕ semi Converter \rightarrow



(i) Discontinuous conduction:

$$0_2 < \beta < (\pi + \alpha)$$

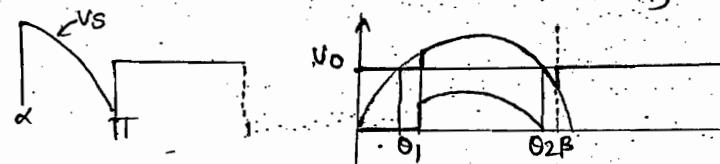
(a) $\beta < \pi$

(b) $\beta > \pi$

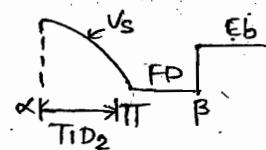
(c) $\beta < \pi \rightarrow * \text{ In this condition FD will not conduct (Because FD conduct after } \pi \text{ rad i.e., due to ind* the -ve spikes come after } \pi \text{)}$

$$U_0 = \frac{1}{\pi} [V_m (\cos \alpha - \cos \beta) + E_b (\pi + \alpha - \beta)]$$

due to ind* the -ve spikes come after π)



(b) $\beta > \pi \rightarrow * \text{ In this cond'n FD will conduct from } \pi \text{ to } \beta$



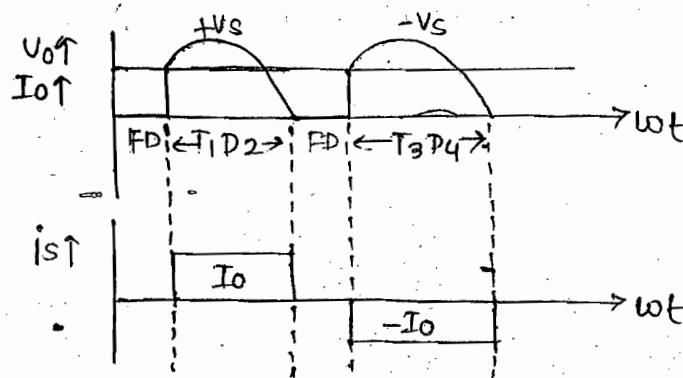
$$U_0 = \frac{1}{\pi} \left[\int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t) + \int_{\pi}^{\beta} 0 d(\omega t) + \int_{\beta}^{\pi + \alpha} E_b d(\omega t) \right]$$

FWR discontinuous

$$U_0 = \frac{1}{\pi} [V_m (1 + \cos \alpha) + E_b (\pi + \alpha - \beta)]$$

Continuous Conduction → For this cond'n there is no effect of back emf for o/p vol. waveform. Therefore

($B > (\pi\alpha)$) the o/p Vol. waveform will remain same for RL & RLE load.



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

$$I_{sr} = I_0 \left(\frac{\pi - \alpha}{\pi} \right)^{1/2}$$

Harmonic analysis on AC side of Conv →

The Fourier series for the supply current

$$i_s = \sum_{n=1,3,5,\dots}^{\infty} \frac{4I_0}{n\pi} \cos \frac{n\alpha}{2} \sin(n\omega t + \phi_n)$$

$$\text{where } \phi_n = -\frac{n\alpha}{2}, \phi_1 = -\frac{\alpha}{2}$$

$$i_{sn} = \frac{4I_0}{n\pi} \cos \frac{n\alpha}{2} \sin(n\omega t + \phi_n)$$

$$i_{sh} = \frac{2\sqrt{2}}{\pi} I_0 \cos \frac{\alpha}{2}$$

$$i_{s1} = \frac{2\sqrt{2}}{\pi} I_0 \cos \frac{\alpha}{2} \quad \text{--- (i)}$$

$$FDF = \cos \frac{\alpha}{2} \quad \text{--- (i')}$$

$$g = \frac{i_{s1}}{i_{sr}} = \frac{2\sqrt{2} I_0 \cos \frac{\alpha}{2}}{\frac{I_0 \left(\frac{\pi - \alpha}{\pi} \right)^{1/2}}{\pi}}$$

$$g = \frac{2\sqrt{2} \cos \alpha/2}{\sqrt{\pi(\pi-\alpha)}} \quad \text{--- (ii)}$$

$$PF = g \cdot PDF$$

$$= \frac{2\sqrt{2} \cos \alpha/2}{\sqrt{\pi(\pi-\alpha)}} \cos \alpha/2$$

$$= \frac{2\sqrt{2} \cos^2 \alpha/2}{\sqrt{\pi(\pi-\alpha)}}$$

$$PF = \frac{2\sqrt{2}(1+\cos \alpha)}{\sqrt{\pi(\pi-\alpha)}} \quad \text{--- (iv)}$$

$$THD = \left(\frac{1}{g^2} - 1 \right)^{1/2}$$

$$THD = \left[\frac{\pi(\pi-\alpha)}{8 \cos^2 \alpha/2} - 1 \right]^{1/2} \quad \text{--- (v)}$$

Active Power

$$P = V_{sr} \cdot I_s \cos \alpha/2$$

$$= \frac{V_m}{\sqrt{2}} \cdot \frac{2\sqrt{2}}{\pi} I_o \cos \alpha \cdot \frac{\cos \alpha}{2}$$

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

$$= V_o I_o$$

$$P = V_{sr} \cdot I_s \cos \alpha/2 = V_o I_o \quad \text{--- (vi)}$$

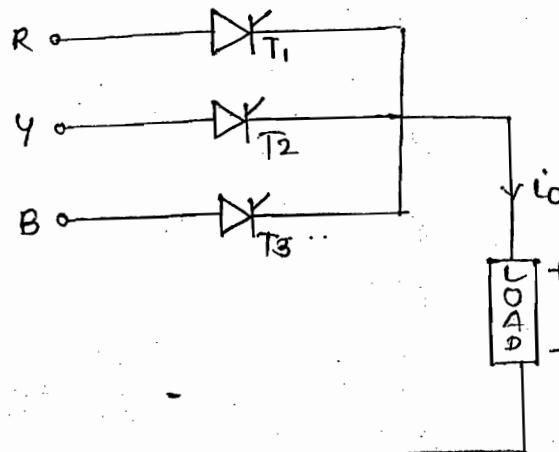
Reactive Power

$$Q = V_{sr} \cdot I_s \sin \alpha/2$$

$$Q = P \tan \alpha/2 \quad \text{--- (vii)}$$

SOAHR \rightarrow 3 pulse converter

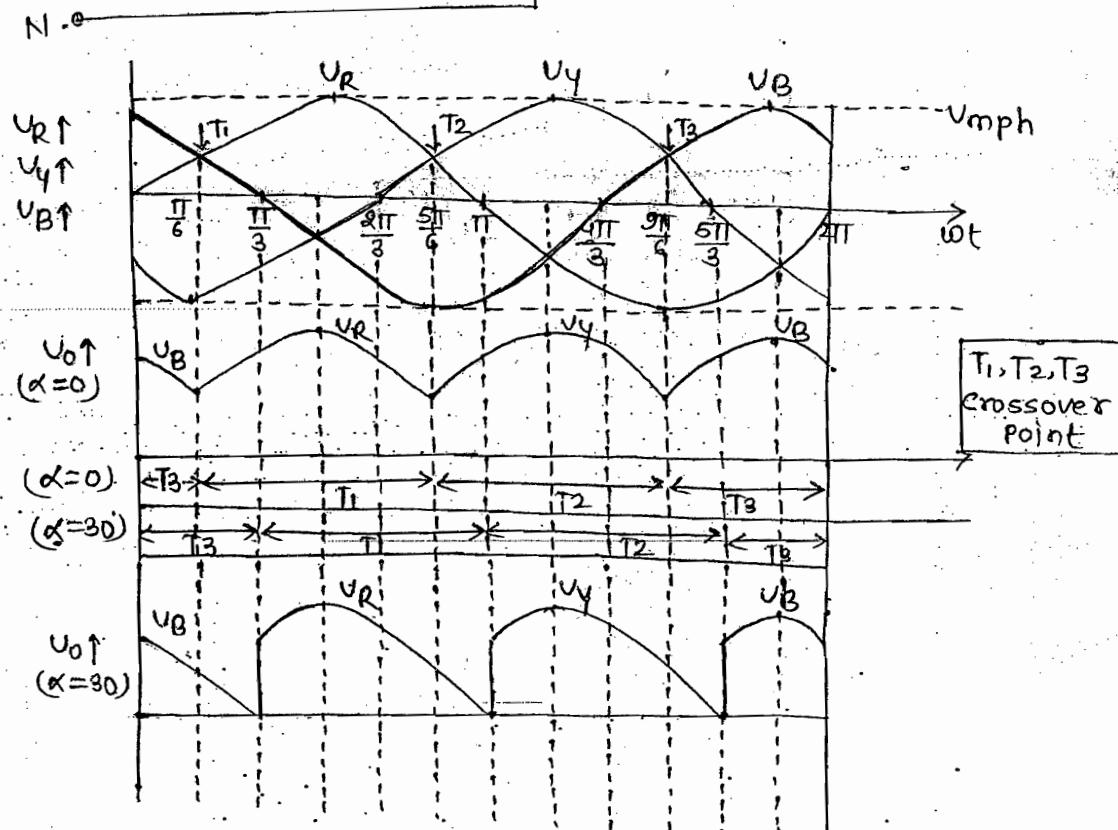
Phase seq. \rightarrow RYB



$$v_B = V_{mph} \sin(\omega t - 240^\circ)$$

$$v_R = V_{mph} \sin \omega t$$

$$v_Y = V_{mph} \sin(\omega t - 120^\circ)$$



(1) $\alpha \leq 30^\circ$ Continuous Condⁿ for R Load \rightarrow

$$\pi/6 + \alpha$$

$$V_o = \frac{1}{2\pi/3} \int_{\pi/6 + \alpha}^{2\pi/3} V_{mph} \sin \omega t d(\omega t)$$

$$V_o = \frac{3\sqrt{3}}{2\pi} V_{mph} \cos \alpha$$

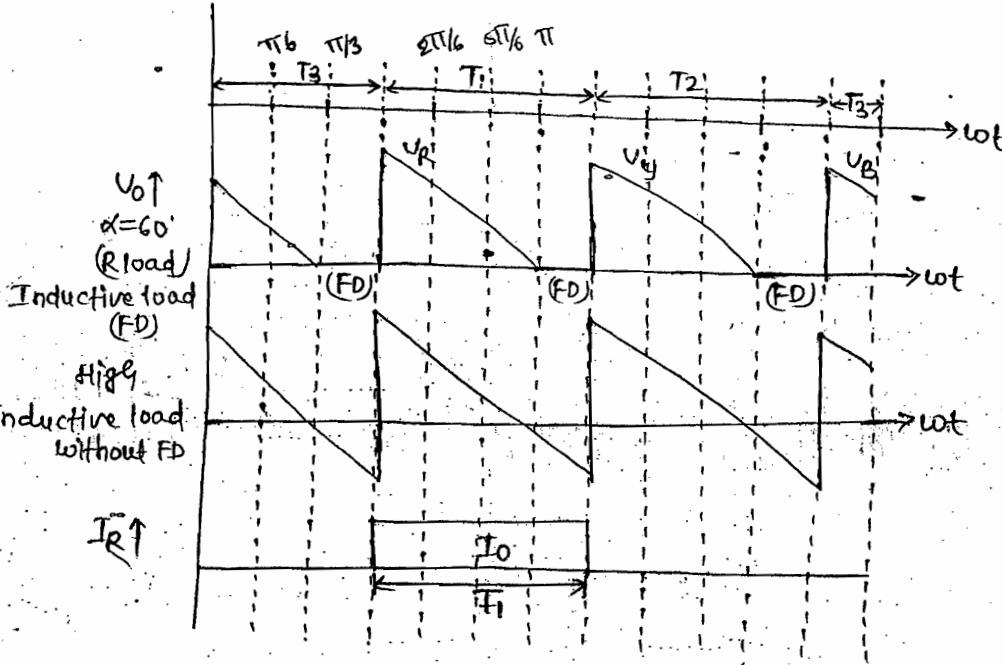
$$V_o = \frac{3V_m L}{2\pi} \cos \alpha$$

$R(\alpha \leq 30^\circ)$ $R_L, R_L E(90^\circ \alpha)$
(Continuous)

$\text{ST} \frac{\pi}{6} + \alpha$

$$V_{0r} = \left[\frac{1}{(2\pi/3)} \int_{\pi/6+\alpha}^{\pi} V_{mpb}^2 \sin^2 \omega t d(\omega t) \right]^{1/2}$$

$$V_{0r} = \frac{1}{V_m} \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right]^{1/2}$$



(2.) $\alpha > 30^\circ$: discontinuous conduction for R load:-

$$V_0 = \frac{1}{(2\pi/3)} \int_{\pi/6+\alpha}^{\pi} V_{mpb}^2 \sin \omega t d(\omega t)$$

$$V_0 = \frac{3V_{mpb}}{2\pi} \left[1 + \cos \left(\frac{\pi}{6} + \alpha \right) \right]^{1/2} \quad R (\alpha > 30^\circ)$$

R \hookrightarrow RLE (with FD $\alpha > 30^\circ$)

$$V_{0r} = \left[\frac{1}{(2\pi/3)} \int_{\pi/6+\alpha}^{\pi} V_{mpb}^2 \sin^2 \omega t d(\omega t) \right]^{1/2}$$

$$V_{0r} = \frac{V_{mpb}}{2\sqrt{\pi}} \left[\left(\frac{5\pi}{6} - \alpha \right) + \frac{1}{2} \sin \left(\frac{\pi}{3} + 2\alpha \right) \right]^{1/2}$$

Assume high inductive load with FD:-

(1) $\alpha \leq 30^\circ$:- FD will not conduct

Conduction angle of each thy. is $\frac{2\pi}{3}$ rad [For every $\frac{2\pi}{3}$ rad]

$$(I_T = I_{ph} = I_L)_{avg} = I_0 \left[\frac{\frac{2\pi}{3}}{2\pi} \right] = \frac{I_0}{3}$$

$$(I_T = I_{ph} = I_L)_{rms} = \frac{I_0}{\sqrt{3}}$$

(2) $\alpha > 30^\circ \rightarrow$ Conduction angle of FD = $(\alpha - \frac{\pi}{6})$ [For every $\frac{2\pi}{3}$ rad].

Conduction angle of each thy. is $(\frac{5\pi}{6} - \alpha)$ [For every $\frac{2\pi}{3}$ rad]

$$(I_T = I_{ph} = I_L)_{avg} = I_0 \left[\frac{\frac{5\pi}{6} - \alpha}{2\pi} \right]$$

$$(I_T = I_{ph} = I_L)_{rms} = I_0 \left[\frac{\frac{5\pi}{6} - \alpha}{2\pi} \right]^{1/2}$$

$$(I_{FD})_{avg} = I_0 \left(\frac{\alpha - \pi/6}{2\pi/3} \right)$$

$$(I_{FD})_{rms} = I_0 \left(\frac{\alpha - \pi/6}{2\pi/3} \right)^{1/2}$$

Assume high inductive load without FD:-

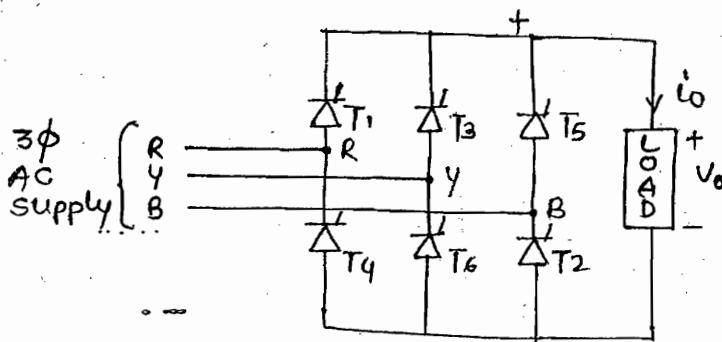
For any value of α

Conduction angle of each thy = $\frac{2\pi}{3}$ rad [For every $\frac{2\pi}{3}$ rad]

$$(I_T = I_{ph} = I_L)_{avg} = I_0 \left(\frac{\frac{2\pi}{3}}{2\pi} \right) = \frac{I_0}{3}$$

Drawback \rightarrow The source current contains dc component & saturates the supply Xmer core.

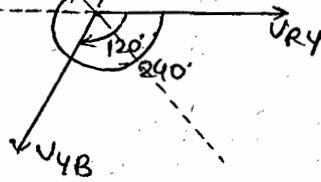
* 3φ Fully Controlled Rectifiers :- (6 pulse converter) →



+ve group thy T₁T₃T₅

-ve group thy T₄T₆T₂

V_{BR}



For 6 pulse → Line Vol.

3 pulse → Phase Vol.

(1.) $\alpha \leq 60^\circ$ - Continuous conduction for R load →

$$V_0 = \frac{1}{\pi/3} \int_{\pi/3}^{\pi/3 + \alpha} U_{mL} \sin \omega t \cdot d(\omega t)$$

$$V_0 = \frac{3U_{mL} \cos \alpha}{\pi} \quad \rightarrow R (\alpha \leq 60^\circ)$$

$\rightarrow RL, RLE$ (Any α) (Continuous)

$$V_{0r} = \left[\frac{1}{\pi/3} \int_{\pi/3}^{2\pi/3 + \alpha} U_{mL}^2 \cdot \sin^2 \omega t \cdot d(\omega t) \right]^{1/2}$$

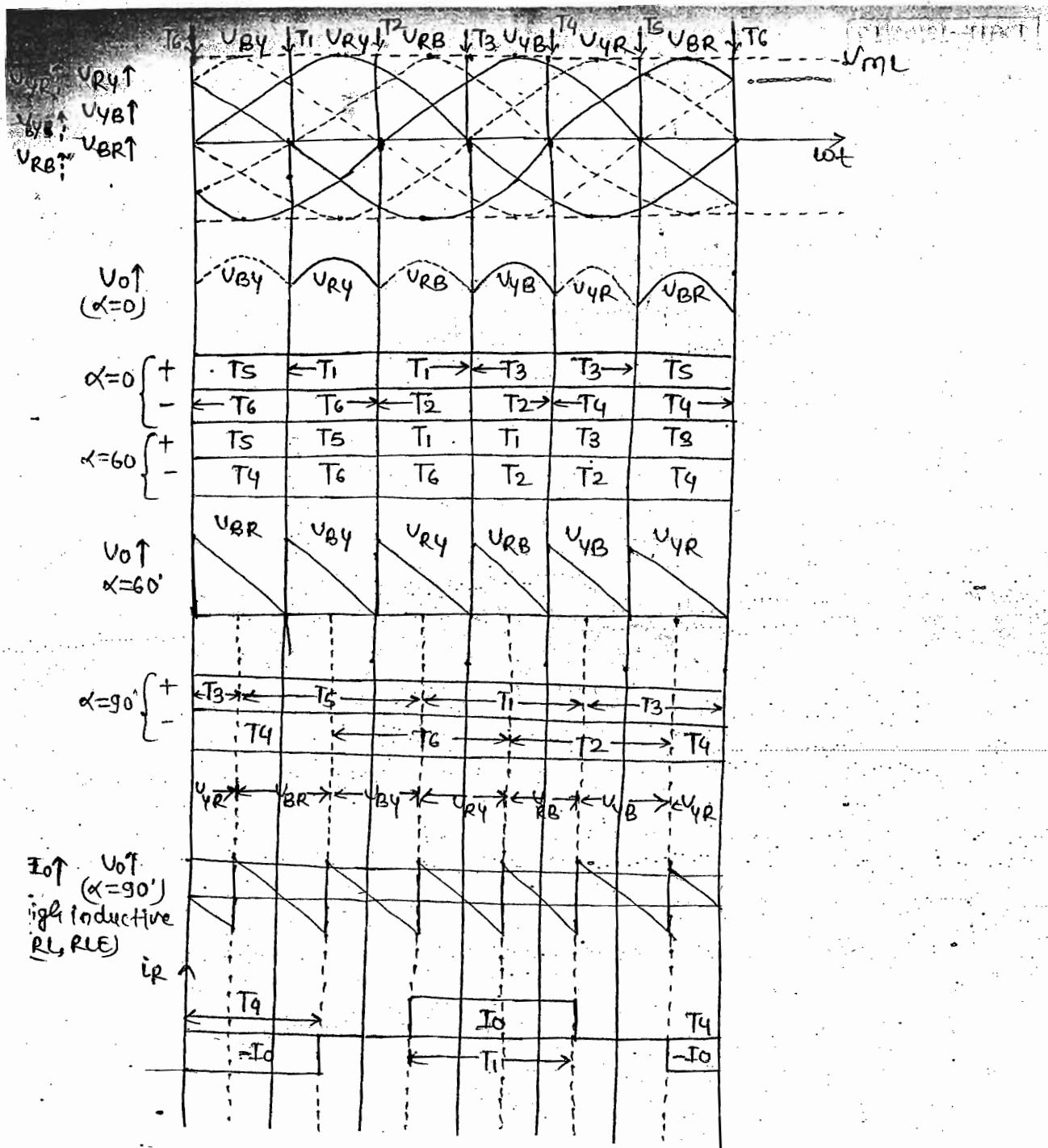
$$V_{0\delta} = \frac{U_{mL}}{\sqrt{\frac{2\pi}{3}}} \left[\frac{\pi}{3} + \frac{1}{2} \left\{ \sin \left(\frac{2\pi}{3} + 2\alpha \right) - \sin \left(\frac{4\pi}{3} + 2\alpha \right) \right\} \right]^{1/2}$$

(2.) $\alpha > 60^\circ$ - Discontinuous conduction for R load →

$$V_0 = \frac{1}{\pi/3} \int_{\pi/3}^{\pi} U_{mL} \cdot \sin \omega t \cdot d(\omega t) ; V_0 = \frac{3U_{mL}}{\pi} \left[1 + \cos \left(\frac{\pi}{3} + \alpha \right) \right] \quad R (\alpha > 60^\circ)$$

$$V_{0r} = \left[\frac{1}{\pi/3} \int_{\pi/3}^{\pi} U_{mL}^2 \cdot \sin^2 \omega t \cdot d(\omega t) \right]^{1/2}$$

$$V_{0\delta} = \sqrt{\frac{3}{2\pi}} U_{mL} \left[\left(\frac{2\pi}{3} - \alpha \right) + \frac{1}{2} \sin \left(\frac{2\pi}{3} + 2\alpha \right) \right]^{1/2}$$



Assume High inductive load \rightarrow

Conduction angle of each thy. $= \frac{2\pi}{3}$ rad. (for every 2π rad)

$$(I_T)_{AVG} = I_0 \left(\frac{2\pi/3}{2\pi} \right) = \frac{I_0}{3}$$

$$(I_T)_{rms} = \frac{I_0}{\sqrt{3}}$$

$$I_{ST} = I_0 \left(\frac{2\pi/3}{\pi} \right)^{1/2} = \sqrt{\frac{2}{3}} I_0$$

Harmonic analysis on AC side of converter

$$i_s = \sum_{n=1,3,5,\dots}^{\infty} \frac{4I_0}{n\pi} \sin \frac{n\pi}{3} \cdot \sin(n\omega t + \phi_n)$$

$$\boxed{\phi_n = -n\alpha, \phi_1 = \alpha}$$

$$n = 6k \pm 1$$

$$n = 1, 5, 7, 11, 13, \dots$$

Note:- Even & triple harmonics are not present in the waveform

$$i_{sn} = \frac{4I_0}{n\pi} \sin \frac{n\pi}{3} \cdot \sin(n\omega t + \phi_n)$$

$$I_{sn} = \frac{4I_0}{n\pi\sqrt{2}} I_0 \sin \frac{n\pi}{3} = \frac{2\sqrt{2}}{n\pi} I_0 \sin \frac{n\pi}{3}$$

$$I_{s1} = \frac{2\sqrt{2}}{\pi} I_0 \sin \frac{\pi}{3}$$

$$\boxed{I_{s1} = \frac{\sqrt{6}}{\pi} I_0} \quad \text{--- (i)}$$

$$\boxed{FDF = \cos \alpha} \quad \text{--- (ii)}$$

$$I_{s2} = \sqrt{\frac{2}{3}} I_0$$

$$g = \frac{I_{s1}}{I_{s2}} = \frac{\frac{\sqrt{6}}{\pi} I_0}{\sqrt{\frac{2}{3}} I_0} = \frac{\sqrt{6}/\pi}{\sqrt{2/3}}$$

$$\boxed{g = \frac{3}{\pi}} \quad \text{--- (iii)}$$

$$PF = g \cdot FDF$$

$$= \frac{3}{\pi} \cos \alpha$$

$$\boxed{PF = \frac{3}{\pi} \cos \alpha} \quad \text{--- (iv)}$$

$$THD = \left(\frac{1}{g^2} - 1 \right)^{1/2} = \left(\frac{\pi^2}{9} - 1 \right)^{1/2}$$

$$\boxed{THD = 0.31}$$

$$\boxed{THD = 3.1\%} \quad \text{--- (v)}$$

$$\boxed{m \uparrow, g \uparrow, THD \downarrow}$$

$$\boxed{m \uparrow, g \uparrow, PF \downarrow}$$

Active power →

$$P = \sqrt{3} V_{SS} I_S \cos \alpha$$

$$= \sqrt{3} \times \frac{U_{mL}}{\sqrt{2}} \times \frac{\sqrt{6}}{\pi} I_0 \cos \alpha$$

$$= \sqrt{3} \times V_m l \times \frac{\sqrt{2}\sqrt{3}}{\pi} I_0 \cos \alpha$$

$$= \frac{3V_m l}{\pi} \cos \alpha \cdot I_0$$

$$P = \frac{3 V_m l}{\pi} \cos \alpha \cdot I_0 = V_0 \cdot I_0 \quad \text{--- (vi)}$$

Reactive Power →

$$Q = \sqrt{3} \cdot U_{S2} \cdot I_{S1} \sin \alpha$$

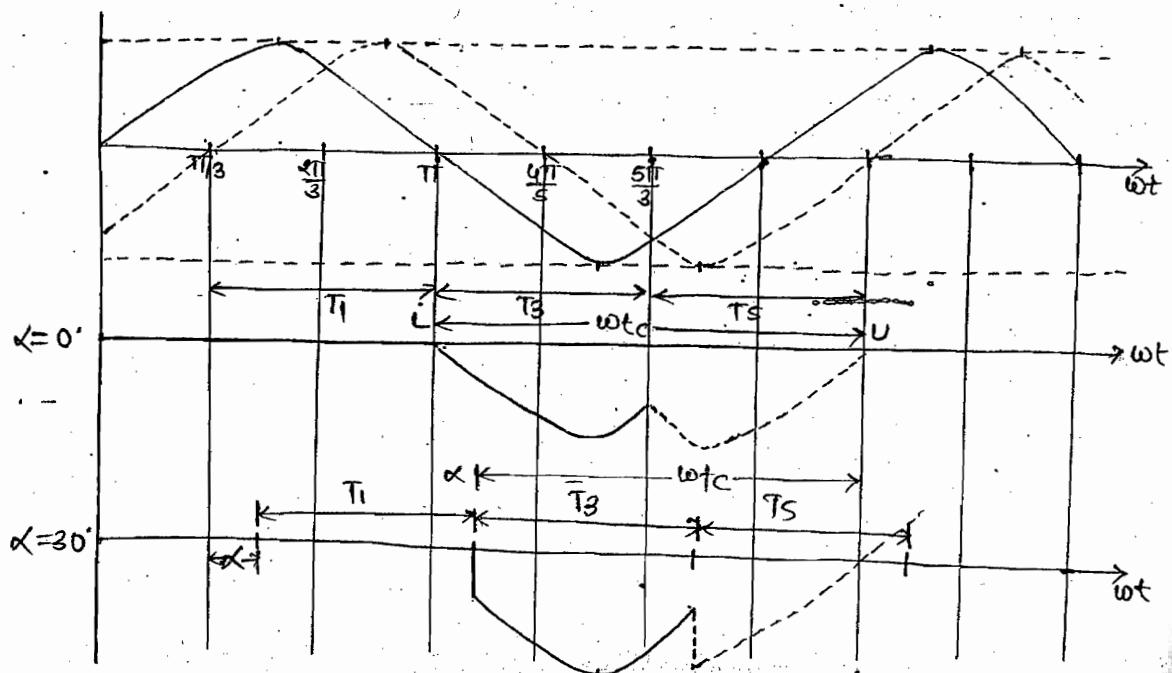
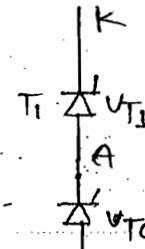
$$Q = P \tan \alpha \quad \text{--- --- (vij)}$$

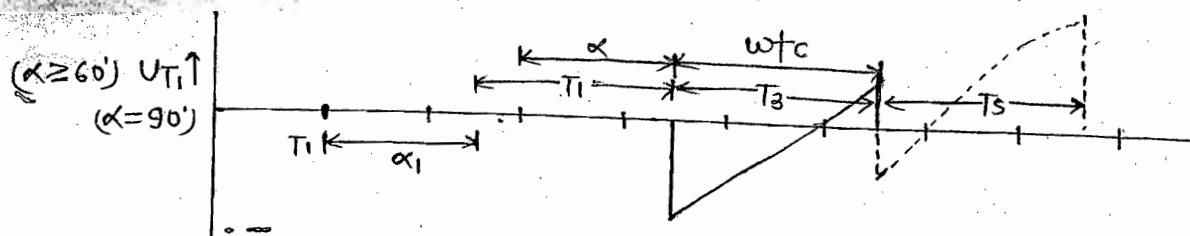
$$U_{AK} \rightarrow (U_{T_1})$$

$$T_1 \rightarrow ON, \bar{U}_{T_1} = \bar{0}$$

$$T_3 \rightarrow ON, \quad U_{T_1} = U_{R4}$$

$$T_5 \rightarrow 0N, \quad v_{T_1} = v_{\rho B}$$



 $\alpha = 0^\circ$

$$wT_c = \frac{4\pi}{3}$$

$$t_c = \frac{4\pi}{3w} \text{ sec}$$

$$PIV = V_{mL}$$

 $\alpha < 60^\circ$

$$\alpha + wT_c = \frac{4\pi}{3}$$

$$wT_c = \frac{4\pi - \alpha}{3}$$

$$t_c = \frac{\frac{4\pi - \alpha}{3}}{w}$$

 $\alpha > 60^\circ$

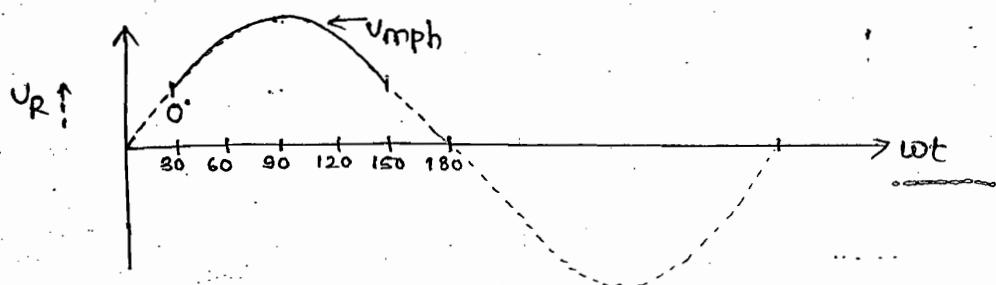
$$\alpha + wT_c = \frac{3\pi}{3}$$

$$\alpha + wT_c = \pi$$

$$wT_c = \pi - \alpha$$

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

Generation method For 3 pulse Converter →



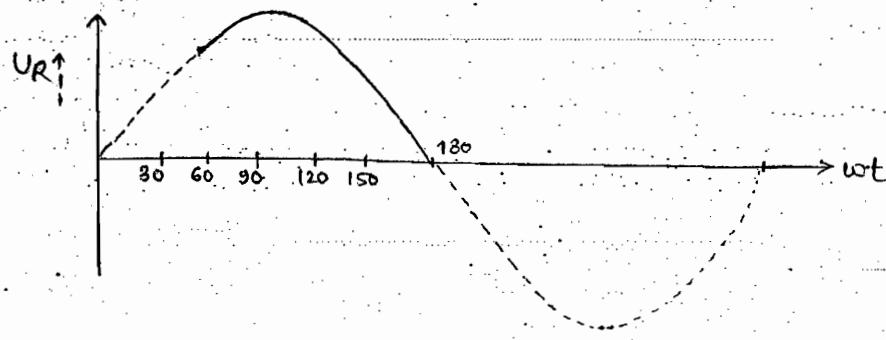
$$\alpha = \omega t - 30^\circ$$

$$\text{Pulse Length} = \frac{2\pi}{3} \text{ rad} = 120^\circ$$

$0 \leq \alpha \leq 150^\circ \rightarrow R \text{ Load}$

$0 \leq \alpha \leq 180^\circ \rightarrow \text{Inductive load.}$

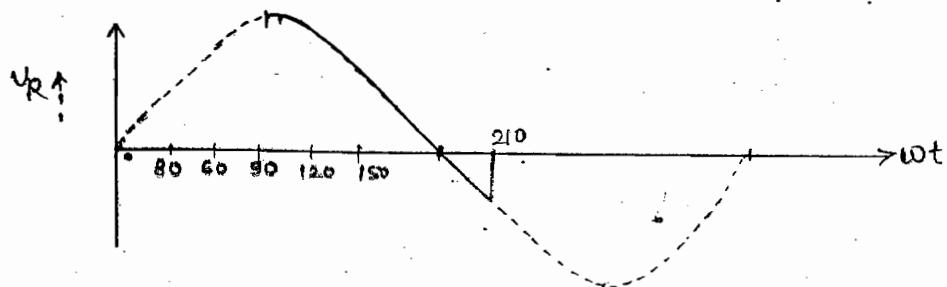
For $\alpha = 0^\circ$, $\omega t = 30^\circ$ (Fig (i))



$$\alpha = \omega t - 30^\circ$$

$$\text{Pulse length} = 120^\circ$$

For $\alpha = 30^\circ$, $\omega t = 60^\circ \& 60 + 120 = 180^\circ$



$$\alpha = 60^\circ, \omega t = 90^\circ, \text{ end } 90 + 120 = 210^\circ$$

* 6 pulse Converter \rightarrow

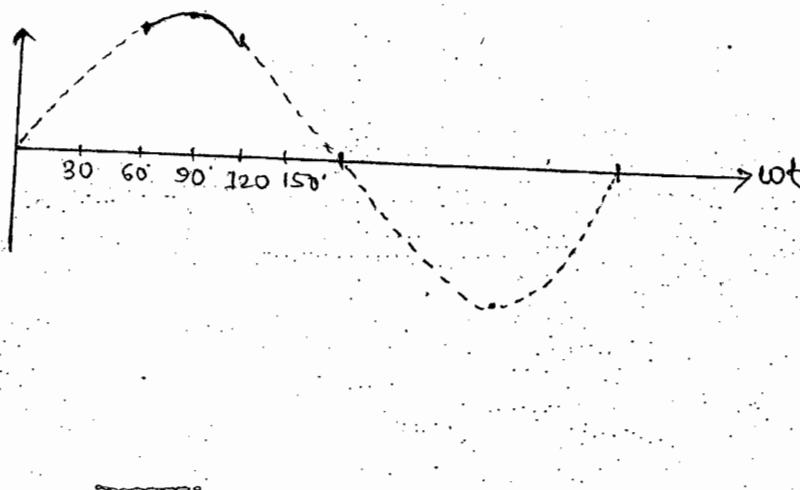
$$\alpha = \omega t - 60^\circ$$

$$\text{Pulse length} = \frac{2\pi}{6} \text{ rad} = \frac{\pi}{3} \text{ rad}$$

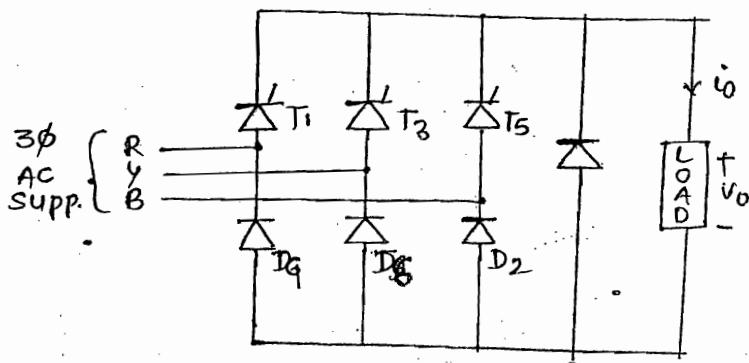
$$= 60^\circ$$

$0 \leq \alpha \leq 120^\circ$ R load
 $0 \leq \alpha \leq 180^\circ$ L load

$$\alpha = 0^\circ, \omega t = 60^\circ \quad \& \quad 60 + 60 = 120^\circ$$



* 3φ semi conv / 3φ Half Controlled Rectifier →



Assume High inductive load →

(1) $\alpha \leq 60^\circ \rightarrow$ FD will not conduct

* Conduction angle of each thy. = $\frac{2\pi}{3}$ rad { For every $\frac{2\pi}{3}$ rad }

$$(I_T)_{avg} = I_0 \left(\frac{2\pi/3}{2\pi} \right) = \frac{I_0}{3}$$

$$(I_T)_{rms} = \frac{I_0}{\sqrt{3}}$$

$$I_{sr} = I_0 \left(\frac{2\pi/3}{\pi} \right)^{1/2} = \sqrt{\frac{2}{3}} I_0$$

(2) $\alpha > 60^\circ \rightarrow$ Conduction angle of FD = $(\alpha - \frac{\pi}{3})$ { For every $\frac{2\pi}{3}$ rad }

* Conduction angle of each thy. = $(\pi - \alpha)$ [For every $\frac{2\pi}{3}$ rad]

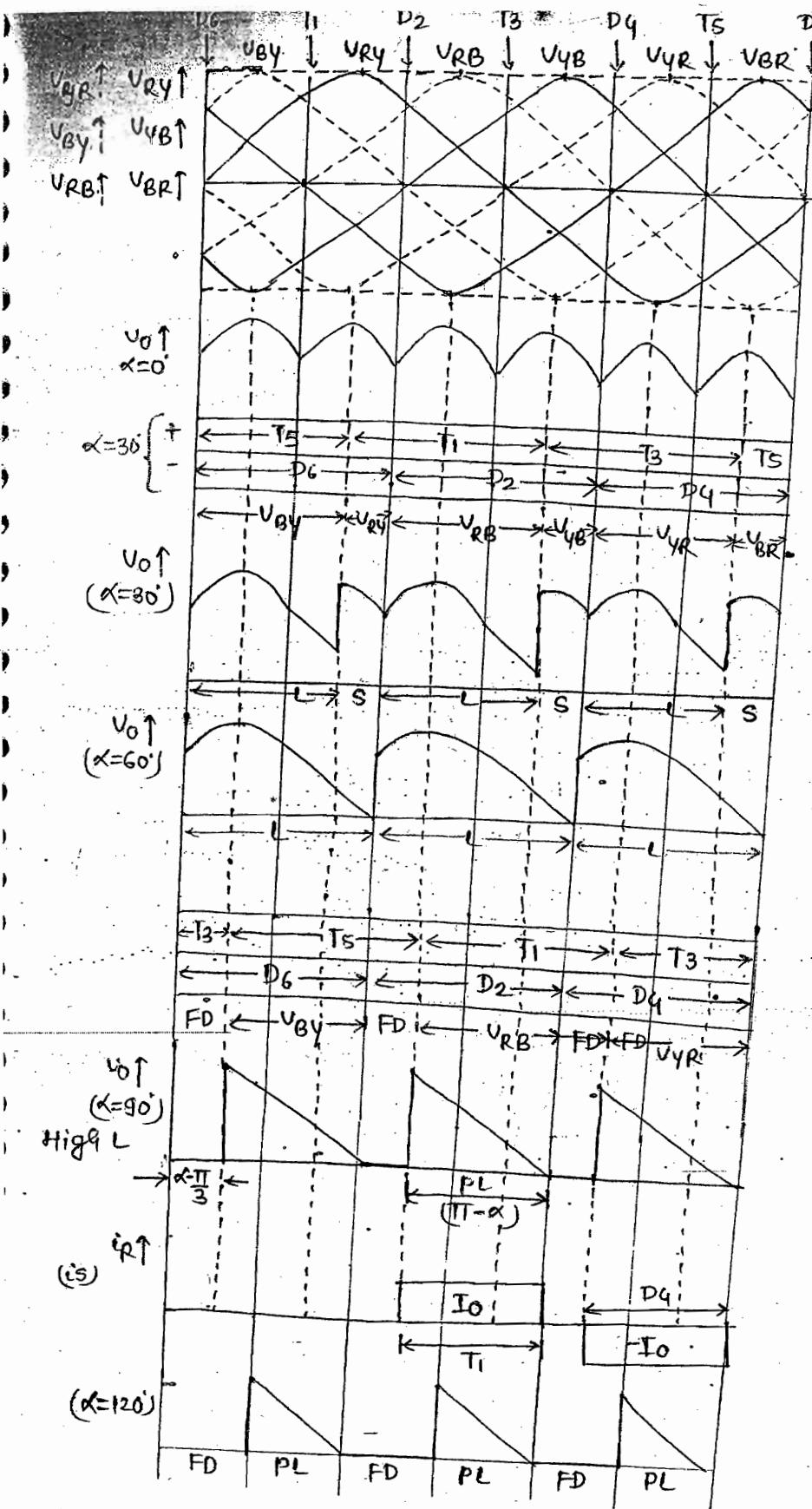
$$(I_T)_{avg} = I_0 \left(\frac{\pi - \alpha}{2\pi} \right) \quad (I_T)_{rms} = I_0 \left(\frac{\pi - \alpha}{2\pi} \right)^{1/2}$$

$$I_{sr} = I_0 \left(\frac{\pi - \alpha}{\pi} \right)^{1/2}$$

$$(I_{FD})_{avg.} = I_0 \left(\frac{\alpha - \pi/3}{2\pi/3} \right)$$

$$(I_{FD})_{rms} = I_0 \left[\frac{\alpha - \pi/3}{2\pi/3} \right]^{1/2}$$

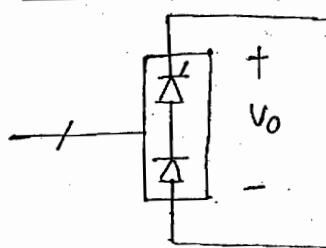
$$V_o = \frac{3V_m L}{2\pi} (1 + \cos \alpha)$$



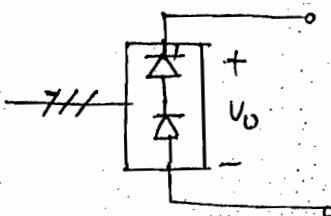
$$FD = (\alpha - \frac{\pi}{3})$$

$$\begin{aligned} T &= \frac{2\pi}{3} - (\alpha - \frac{\pi}{3}) \\ &= (\pi - \alpha) \end{aligned}$$

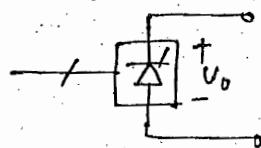
Pulse length = T

1φ semi converter →

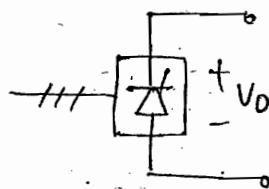
$$V_o = \frac{V_m}{\pi} (1 + \cos \alpha)$$

3φ semi converter →

$$V_o = \frac{3V_m L}{2\pi/3} (1 + \cos \alpha)$$

1φ Full Cond'r →

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

3φ Full Conv'r →

$$V_o = \frac{3V_m L}{\pi} \cos \alpha$$

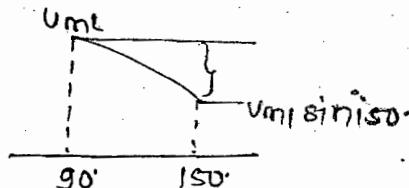
1
44

$$\alpha = 30^\circ$$

Peak to peak ripple voltage

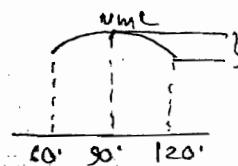
Peak o/p dc voltage

$$\frac{V_{ML} - V_m \sin 150^\circ}{V_{ML}} = 0.5$$

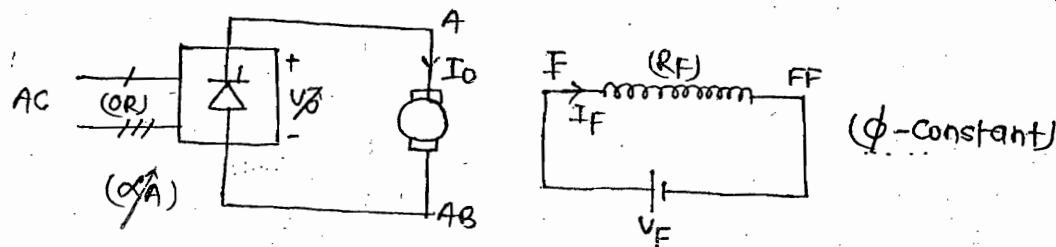


$$\alpha = 0^\circ$$

$$\frac{V_{ML} - V_m \sin 60^\circ}{V_{ML}} = 1 - \frac{\sqrt{3}}{2}$$



DATE 21/09/14

DC drives →(i) Armature Voltage Control method $\rightarrow (\omega < \omega_r)$ 

$$1\phi, V_B = \frac{2V_m}{\pi} \cos \alpha_A$$

$$3\phi, V_B = \frac{3V_m L}{\pi} \cos \alpha_A$$

We know that: $E_b \propto \phi N$

$$E_b \propto N \quad (\because \phi \rightarrow \text{const})$$

$$E_b = kN$$

$$\frac{\text{emf const}}{\text{motor const}} = \frac{V}{\text{rpm}}$$

$$E_b = (R) \omega$$

$$\frac{\text{emf const}}{\text{motor const}} = \frac{(V \cdot \text{sec})}{\text{rad}}$$

SI $\rightarrow \omega \text{ rad/sec}$

$$\omega = \frac{2\pi N}{60}$$

We know that:

$$T_q \propto \phi I_B$$

$$T_q \propto I_B$$

$$T_q = (k) I_B$$

$$\frac{\text{Motor const.}}{\text{Torque const.}} = \frac{(\text{Nm})}{\text{A}}$$

$$\frac{\text{Nm}}{\text{A}} = \frac{V \cdot \text{sec}}{\text{rad}}$$

$$I_0 = \frac{Tq}{K} ; \text{ For motoring mode}$$

$$V_0 = E_b + I_0 R_q$$

$$V_0 = K\omega + I_0 R_q$$

$$\omega = \frac{V_0}{K} - \frac{R_q I_0}{K^2 Tq}$$

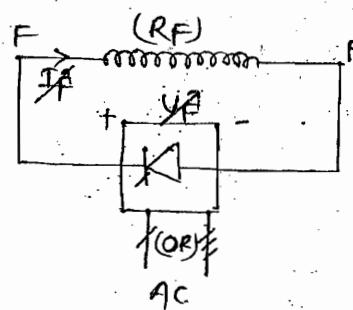
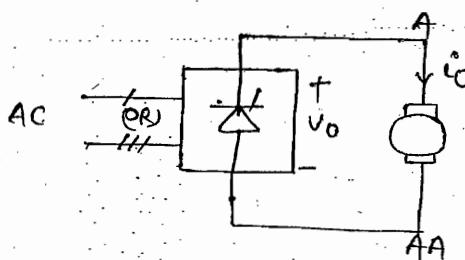
$$\omega = \frac{V_0}{K} - \frac{I_0 R_q}{K}$$

$$\boxed{\omega = \frac{V_0}{K} - \frac{R_q I_0}{K^2 Tq}}$$

speed-torque eqn

$$\Delta A \uparrow, V_0 \downarrow \therefore \omega \downarrow (\omega < \omega_r)$$

(2) Field Control method →



$$V_F = \frac{2V_m}{\pi} \cos \alpha_F \rightarrow 1\phi$$

$$V_F = \frac{3V_m}{\pi} \cos \alpha_F \rightarrow 3\phi$$

$$I_F = \frac{V_F}{R_F}$$

$$\phi \propto I_F$$

$$\boxed{\phi = K_F I_F}$$

($K_F \rightarrow$ Field constant)

$$E_b \propto \phi N$$

$$E_b = K_1 \phi N$$

$$E_b = K_1 K_F N I_F$$

$$\boxed{E_b = K_1 I_F N}$$

EMF const (OR) motor const $\left(\frac{V}{\text{r.p.m.}} \right)$

$$E_b = K_F \Phi I_a$$

→ EMF const (OR) motor const. $\frac{V_{sec}}{rad/A}$

$$T_q \propto \Phi I_a$$

$$T_q = K_1 \Phi I_a$$

$$T_q = K_1 (K_F I_F) I_o$$

$$T_q = K_F I_F I_o$$

→ Torque const (OR) motor const. $\frac{Nm}{A^2} = \frac{V_{sec}}{rad.A}$

$$I_o = \frac{T_q}{K_F}; \text{ For motoring mode;}$$

$$V_o = E_b + I_o R_q$$

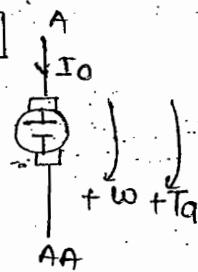
$$V_o = K_F \omega + I_o R_q$$

$$\omega = \frac{V_o}{K_F} - \frac{I_o R_q}{K_F}$$

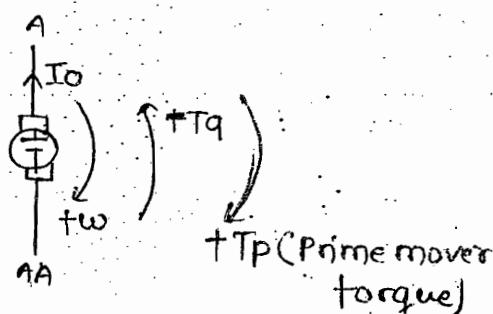
$$\dot{\omega} = \frac{V_o}{K_F^2} - \frac{R_q}{(K_F)^2} T_q$$

$\propto F \uparrow, V_F \downarrow, I_F \downarrow \therefore \omega \uparrow (\omega > \omega_r)$

motoring action



Generating action



Electrical Braking →

Brake energy

$$(1/2 J \omega^2)$$

→ Electrical Form

this energy is dissipated in external resistance

(1.) Dynamic Braking (slow)

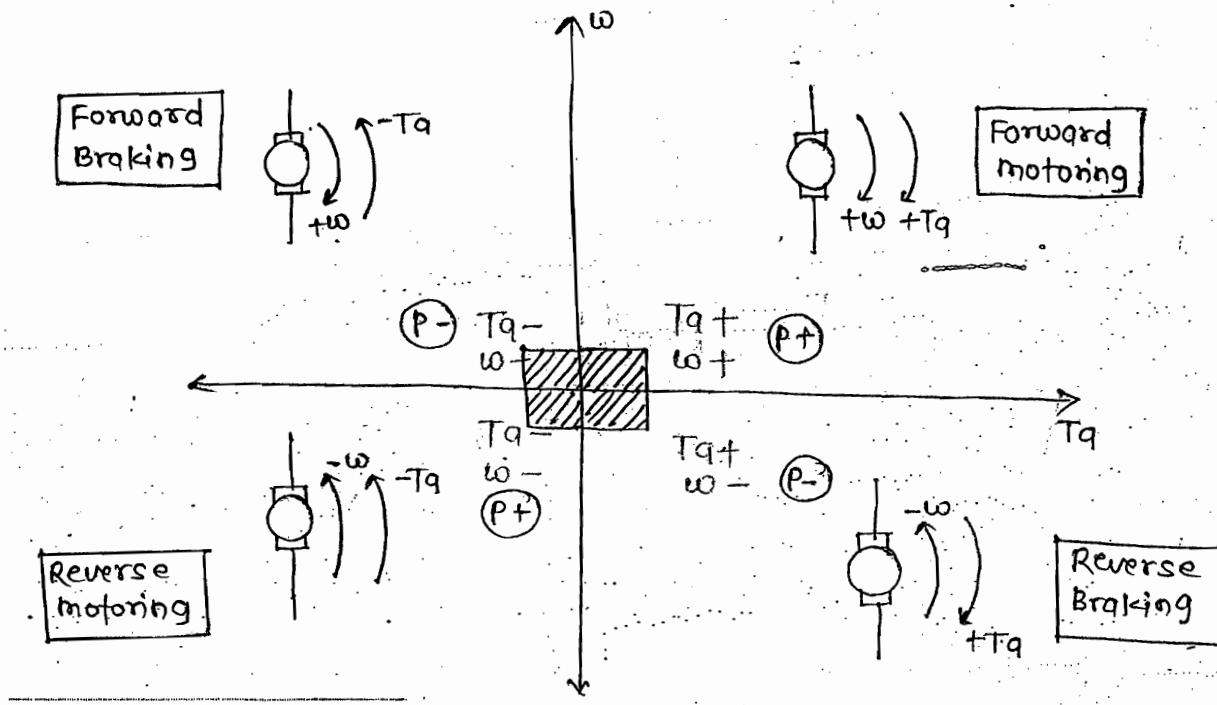
(2.) Plugging (fast)

Source

(3.) Regenerative Braking

- * During braking the m/c behave as generator & the brake energy available in the rotor inertia is converted into ele. form.
- * If this energy is given back to the supply then it is known as regenerative braking.

* We can utilize a dc m/c in 4 modes:-



Quadrant operation of Full Converter → (Two quadrant)

1φ Full convr

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

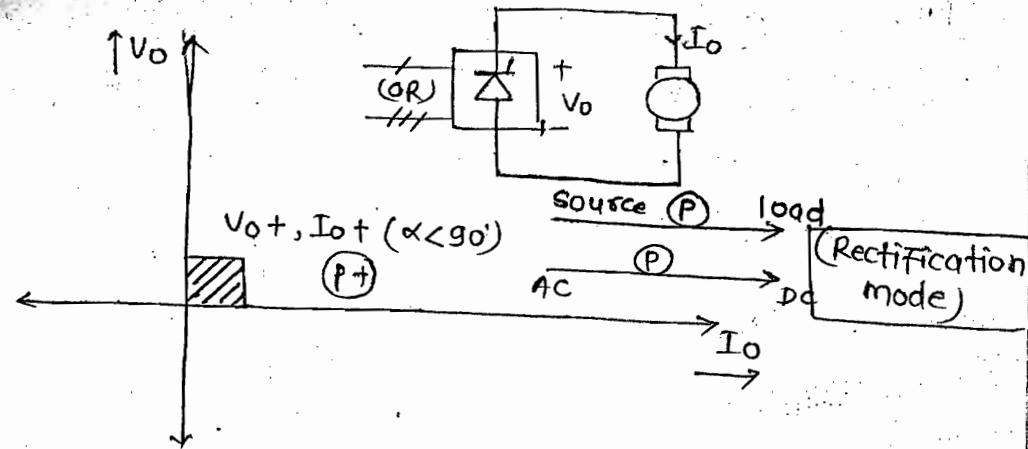
$\alpha \leq 90^\circ, V_o +$

$\alpha > 90^\circ, V_o -$

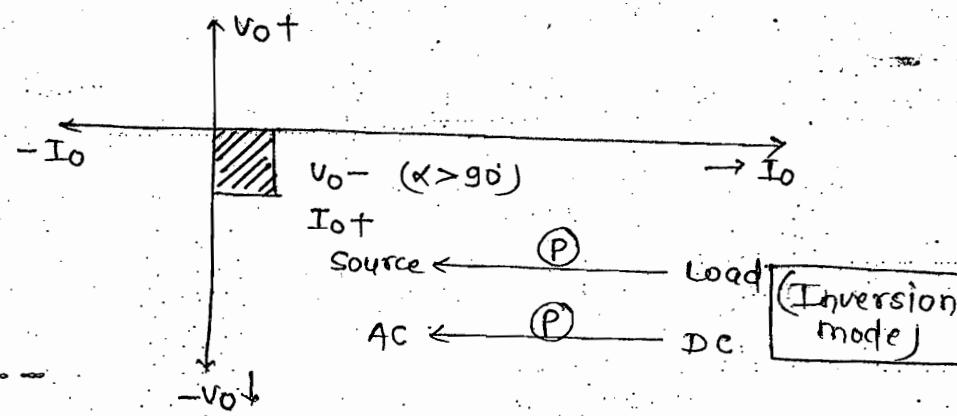
3φ Full convr

$$V_o = \frac{3Vm}{\pi} \cos \alpha$$

I_o (always) +



* Rectification mode can be used for motoring mode of a dc m/c & charging battery.

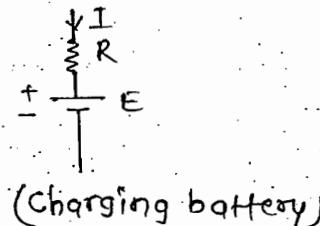
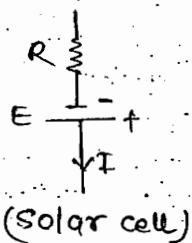
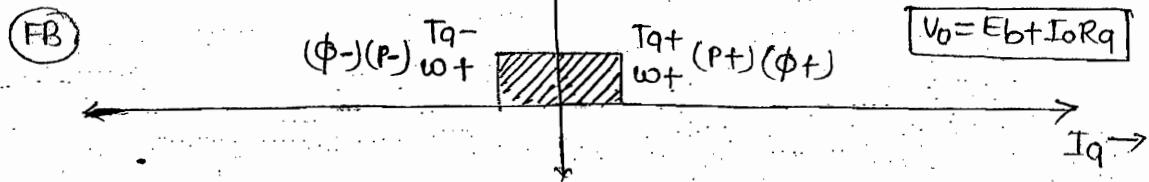
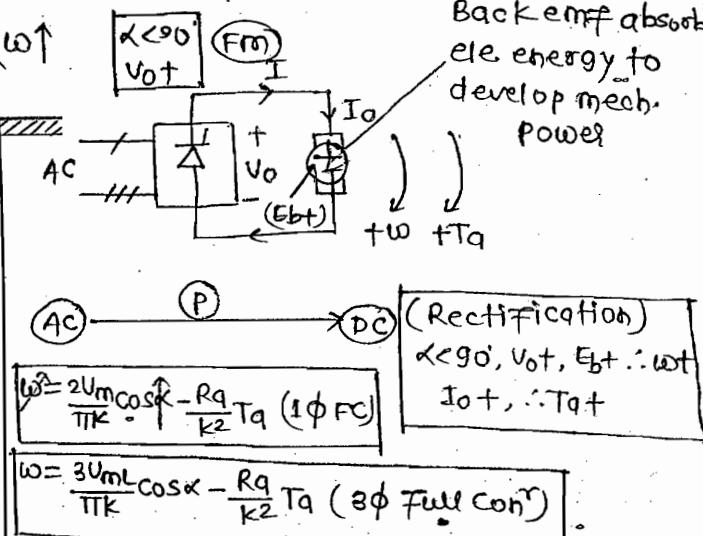
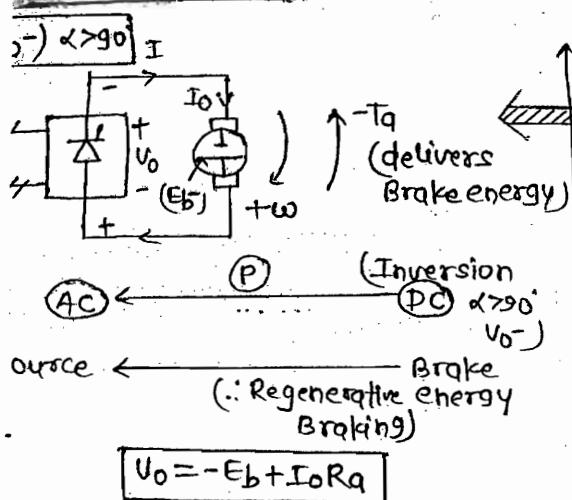


* Inversion mode can be used for regenerative braking of a dc m/c.

* Inversion mode is also used for solar cell.

(The solar energy stored in the form of dc is given to the AC side of cont when cont is supporting the inversion mode)

* Full Conv^r Fed DC m/c →



Quadrant Operation of semi converter →

1φ semi conv

$$V_o = \frac{Um}{\pi} (I + \cos \alpha)$$

3φ semi conv

$$V_o = \frac{3Um L}{\pi} (I + \cos \alpha)$$

V_o → always +ve

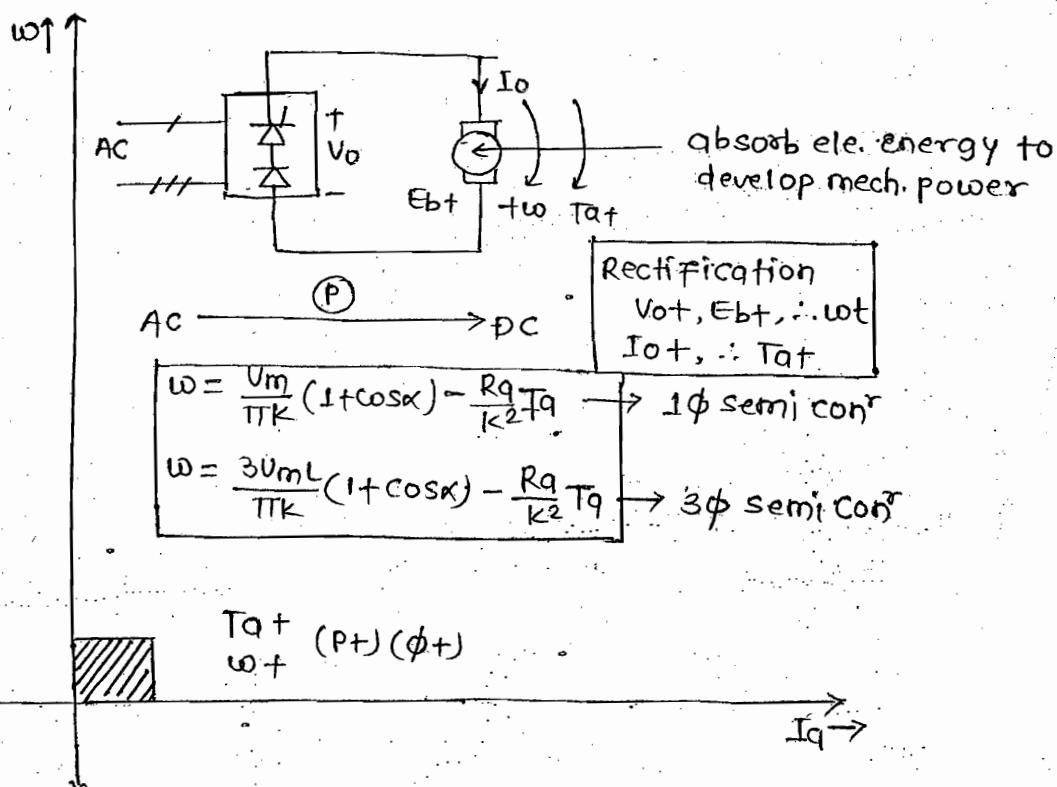
I_o → always +ve

* Semiconductor gives only one quadrant operation.

* Inversion of semiconductor is not accepted i.e. only charging battery

application is possible with semiconv.

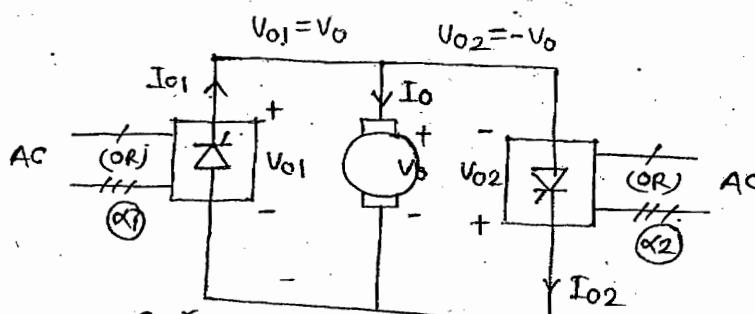
* solar cell application is not possible with semiconverter.



* Dual Conv. → * It gives 4 quadrant operation.

(1) Non-circulating current type :- * In this dual conv if one conv is in the ON state then other conv remains in the off state.

Advantage:- There is no circulating current b/w 2 conv.



Conv(1)

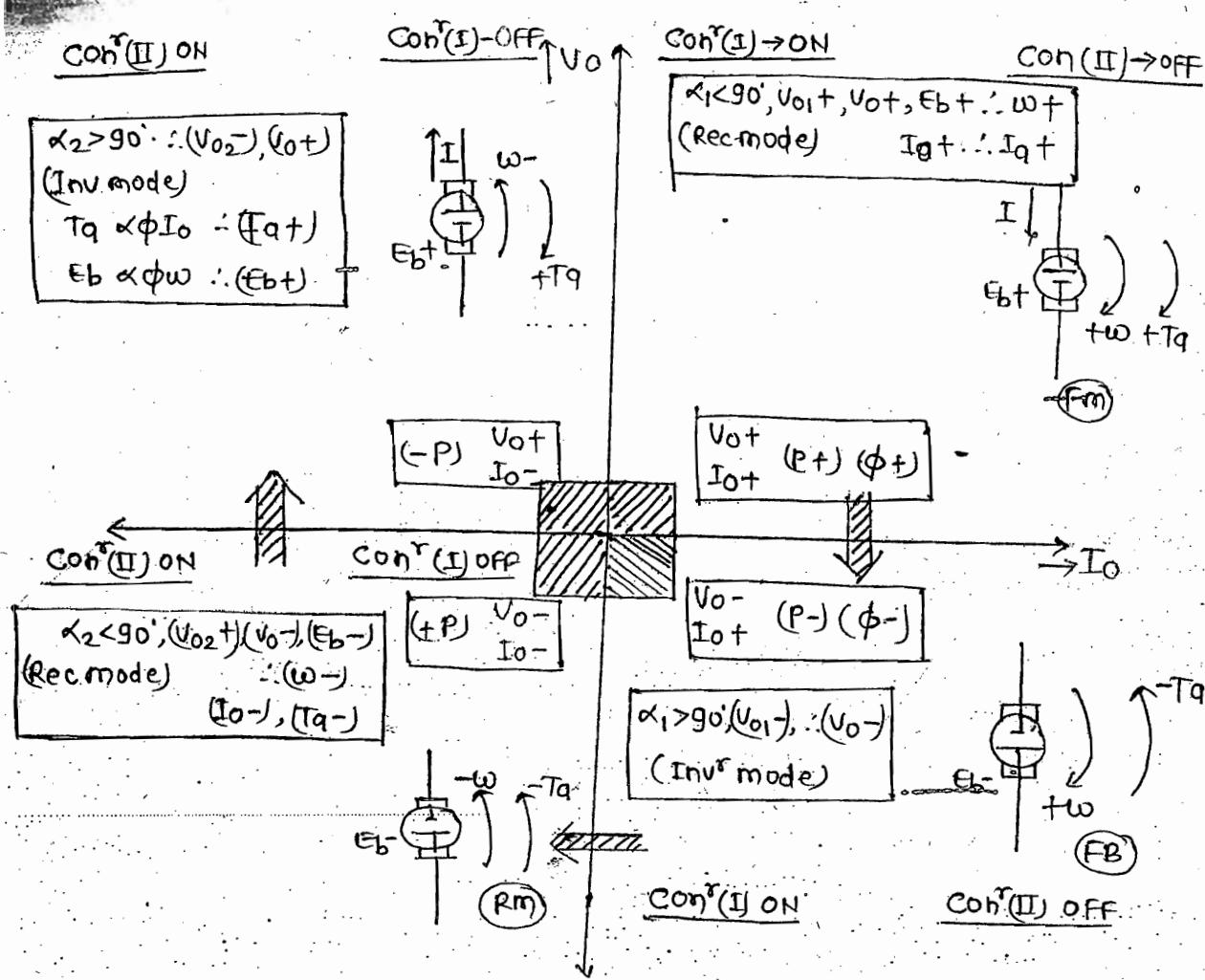
$$V_{o1} = \frac{2U_m}{\pi} \cos \alpha_1$$

$$V_{o1} = \frac{3U_m L}{\pi} \cos \alpha_1$$

Conv(2)

$$V_{o2} = \frac{2U_m}{\pi} \cos \alpha_2$$

$$V_{o2} = \frac{3U_m L}{\pi} \cos \alpha_2$$



* Disadvantage:- It gives slow speed response & the reversal of arm current is not smooth during switching operation of the con^r.

* Reason of slow speed response:- Here we must provide comm. delay time for outgoing con^r before the incoming con^r is switched on. to avoid high circulating current.

* This comm. delay time is responsible for slow speed response.

(2) Circulating current type → * In this dual con^r both the con^r are simultaneously in the on state.

Disadvantage:- There will be circulating current b/w 2 con^r & hence

Power Loss is responsible.

* we can reduce the circulating current if $V_{01} = -V_{02}$

$$V_{01} = -V_{02}$$

$$\frac{2V_m}{\pi} \cos \alpha_1 = -\frac{2V_m}{\pi} \cos \alpha_2$$

$$\cos \alpha_1 + \cos \alpha_2 = 0$$

$$\cos \alpha_1 + \cos(180 - \alpha_1) = 0 \quad (\alpha_2 = 180 - \alpha_1)$$

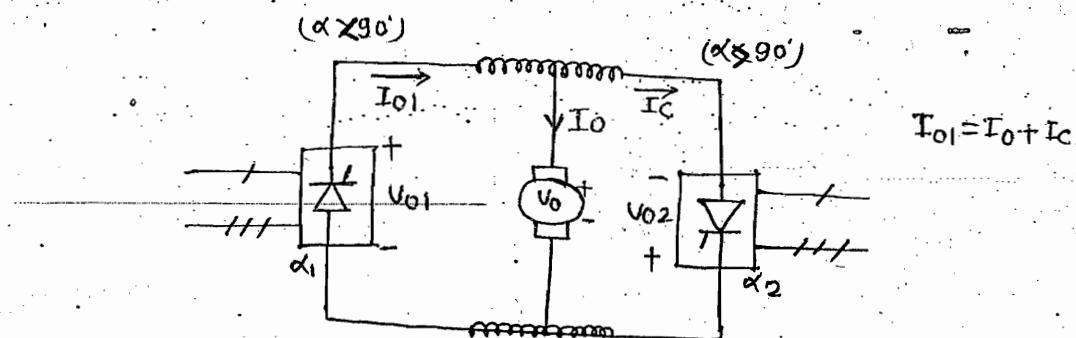
$$0 = 0$$

Hence $\alpha_2 = 180 - \alpha_1$

$$\boxed{\alpha_1 + \alpha_2 = 180^\circ}$$

* Even after satisfying the condn $\alpha_1 + \alpha_2 = 180^\circ$ still there is some circulating current due to the instantaneous vol. diff. between the 2 cont.

* To reduce this circulating current we must connect a reactor b/w the 2 cont as shown in fig. given below.

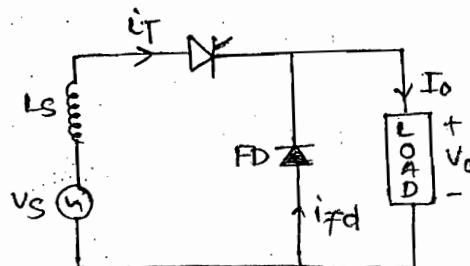


Advantage → It gives high speed response & reversal of arm. current is smooth during switching operation of cont.

DATE - 22/08/14

EFFECT OF SOURCE INDUCTANCE \rightarrow Let L_s be the source inductance

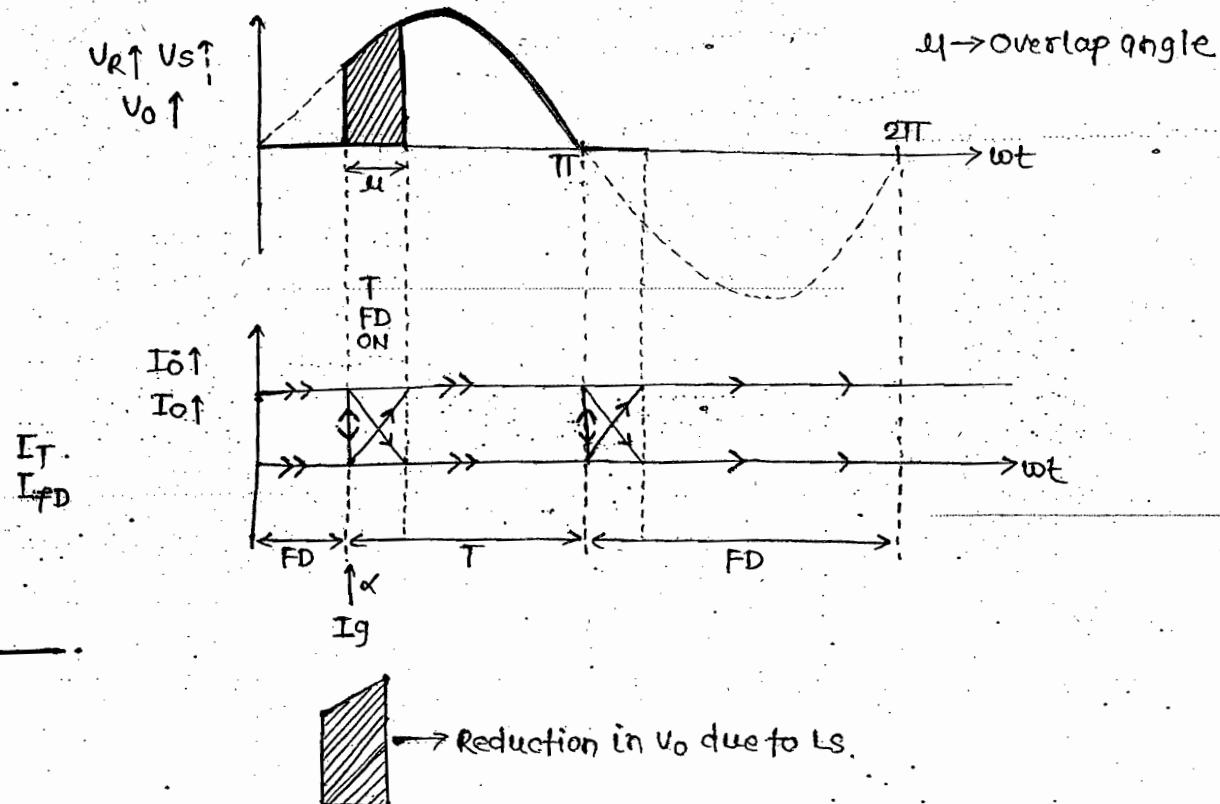
One pulse converter \rightarrow



Let us assume high inductive load.

without L_s (ideal source) \rightarrow

with L_s (non-ideal source) \rightarrow



\rightarrow Reduction in V_o due to L_s .

With L_s \rightarrow

During α , $T \& FD \rightarrow$ ON state $\therefore V_o = 0$

$$I_T + i_{FD} = I_O \quad (\text{during } \alpha)$$

The value of load current constant & value of thy. current suddenly increases. Hence I_{FD} .

$$\therefore V_S = L_s \frac{di}{dt}$$

$$V_m \sin \omega t \cdot dt = L_s dI_s$$

Multiplying ω by the both sides of eqn

$$V_m \sin \omega t \cdot dt (\omega) = L_s \omega dI_s$$

$$V_m \sin \omega t \cdot d(\omega t) = L_s \omega dI_s$$

Integrating both sides

$$\int_{\alpha}^{\alpha+u} V_m \sin \omega t \cdot d(\omega t) = \omega L_s \int_0^{I_o} dI_s$$

$$V_m [\cos \alpha - \cos(\alpha + u)] = \omega L_s I_o$$

Dividing both side by 2π ; then we will get average reduction in freq.

$$\frac{V_m}{2\pi} [\cos \alpha - \cos(\alpha + u)] = \frac{\omega L_s I_o}{2\pi}$$

$$\frac{V_m}{2\pi} [\cos \alpha - \cos(\alpha + u)] = f L_s I_o$$

$$\Delta V_{do} = \frac{V_m}{2\pi} [\cos \alpha - \cos(\alpha + u)] = f L_s I_o \quad \text{--- (i)}$$

Where: ΔV_{do} = average reduction in dc o/p voltage due to L_s

$$V_o = \frac{V_m}{2\pi} (1 + \cos \alpha) - \Delta V_{do}$$

$$V_o = \frac{V_m}{2\pi} (1 + \cos \alpha) - f L_s I_o \quad \text{--- (ii)}$$

$$V_o = \frac{V_m}{2\pi} [1 + \cos(\alpha + u)] \quad \text{--- (iii)}$$

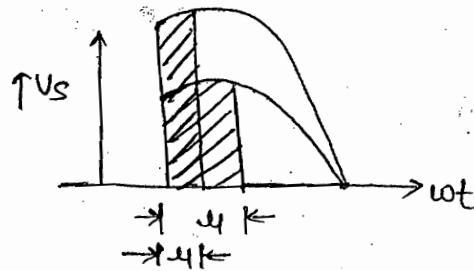
ΔV_{do} does not depend on u ; it depends on $f L_s I_o$ but u depend on the ΔV_{do} .

* ΔV_{do} depends only on f, L_s, I_o

* u depends on ΔV_{do} & hence f, L_s, I_o, V_s, α

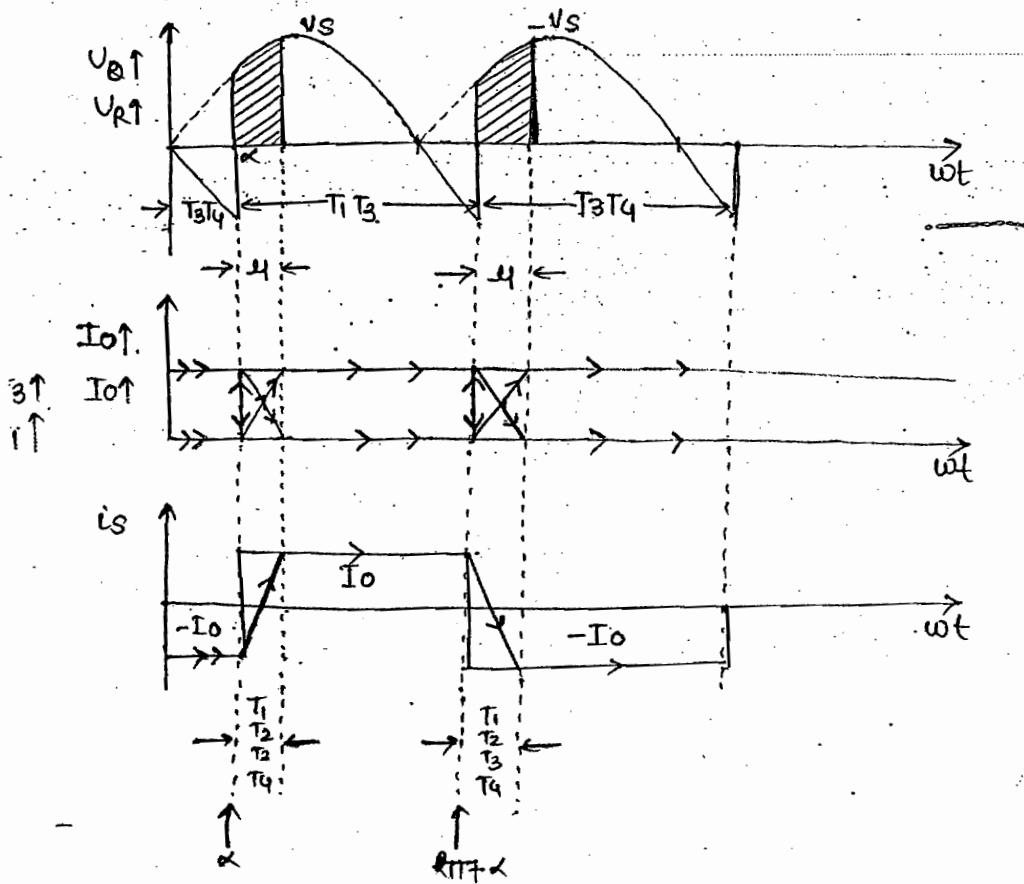
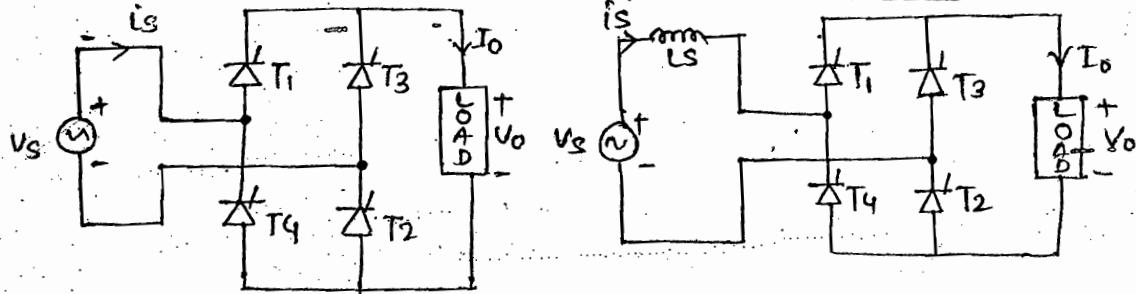
* If $f \uparrow$ or $L_s \uparrow$ (or) $I_o \uparrow$, without changing the overlap angle V_s & α then $u \uparrow$

* If $V_S \uparrow$, without changing $T, L_S; I_0$, & then \downarrow to remains the area constant.



2) Two pulse converter \rightarrow

without L_S (Ideal)
with L_S (Non-ideal)



$$\text{Let } V_{do} \rightarrow (V_o)_{\max} \quad V_{do} = \frac{2V_m}{\pi} \text{ (2 pulse)}$$

$$V_{do} = \frac{3V_m}{2\pi} \text{ (3 pulse)}$$

$$V_{do} = \frac{3V_m L}{\pi} \text{ (6 pulse)}$$

with $L_s \rightarrow$

During 4, $T_1 T_2 \& T_3 T_4 \rightarrow ON \therefore V_o = 0$

$$V_m \sin \omega t = L_s \frac{di}{dt}$$

$$V_m \sin \omega t dt = L_s di$$

$$V_m \sin \omega t d(\omega t) = \omega L s di$$

~~if t~~

$$\int_{-I_0}^{I_0} V_m \sin \omega t d(\omega t) = \omega L s \int_{-I_0}^{I_0} di$$

[source current change
from I_0 to $-I_0$]

$$V_m [\cos \alpha - \cos(\alpha + 4)] = 2\omega L s I_0$$

$$\frac{V_m}{\pi} [\cos \alpha - \cos(\alpha + 4)] = \frac{2\omega L s I_0}{\pi}$$

$$\Delta V_{do} = \frac{V_m}{\pi} [\cos \alpha - \cos(\alpha + 4)] = \frac{2\omega L s I_0}{\pi} \quad \text{--- (i)}$$

$$\Delta V_{do} = \frac{V_{do}}{2} [\cos \alpha - \cos(\alpha + 4)] \quad m=2,3,6$$

m	ΔV_{do}
1	$FLsI_0$
2	$4FLsI_0$
3	$3FLsI_0$
6	$6FLsI_0$

$$V_o = V_{do} \cos \alpha - \Delta V_{do} \quad \text{--- (ii)}$$

$$V_o = \frac{V_{do}}{2} [\cos \alpha + \cos(\alpha + 4)] \quad \text{--- (iii)}$$

$$\frac{V_m}{\pi} [\cos \alpha - \cos(\alpha + u)] = \frac{2 \omega L s I_0}{\pi}$$

$$I_0 = \frac{V_m}{2 \omega L s} [\cos \alpha - \cos(\alpha + u)]$$

$$I_0 = I_p [\cos \alpha - \cos(\alpha + u)]$$

$$\boxed{\frac{I_0}{I_p} = \cos \alpha - \cos(\alpha + u)}$$

$$\text{where } I_p = \frac{V_m}{2 \omega L s}$$

Ques. → What is meant by inductive Vol. regulation?

Ans. → It is a measure of reduction in o/p. vol. due to source inductance.

It is taken as a ratio of $= \frac{\Delta V_{d0}}{V_{d0}}$

$$= \frac{\frac{V_{d0}}{2} [\cos \alpha - \cos(\alpha + u)]}{V_{d0}}$$

$$\boxed{VR^n = \frac{[\cos \alpha - \cos(\alpha + u)]}{2}}$$

$$= \frac{1 - \cos u_0}{2}$$

u_0 = Overlap angle at $\alpha = 0^\circ$

Ques. → What is the effect of source inductance on the performance of conⁿ?

Ans. → (i) It reduces the avg. o/p. vol. of conⁿ.

(ii) It limits the maxⁿ range of fixing angle.

$$\boxed{\alpha_{max} = 180^\circ - [w t q + u_0]}$$

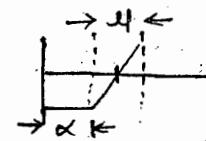
Ideal Vol. source, ideal thy. $\therefore \alpha_{max} = 180^\circ$

Ideal Vol. source, practical thy. $\alpha_{max} = 180^\circ - w t q$

Practical Vol. source, practical thy. $\alpha_{max} = 180^\circ - w t q - u$

(iii) Fundamental displacement factor

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

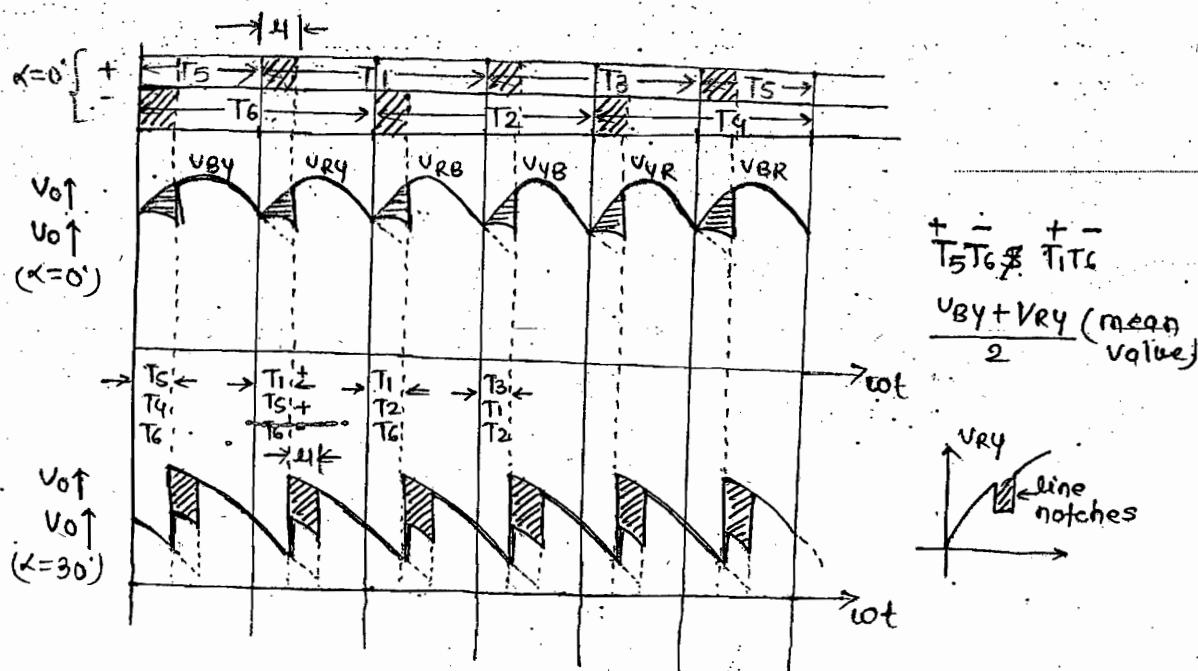
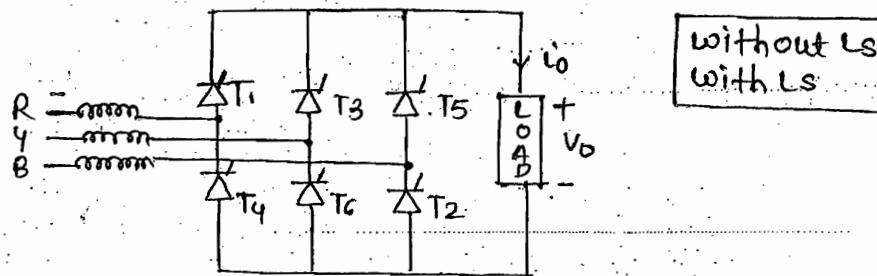


(iv) g_f , THD \downarrow & Harmonic on AC side \downarrow
(advantage)

(v) $PF = g_f FDF \downarrow$ (can't say)

Here the increase in g value is more than decrease in FDF
∴ the PF is slightly increased.

Q. 1. 6 pulse converter →



Ques → If α increases without changing other parameters then what happen to overlap angle?

Ans → Case(I.) $0 \leq \alpha \leq 90^\circ$ ($\alpha \uparrow, M \downarrow$)

If $\alpha \uparrow$, without changing f, L_s, I_o & V_s , then $M \downarrow$
 $\text{const } \Delta V_{do} \rightarrow \text{constant}$

$\alpha \uparrow$ ripple vol \uparrow , height of reduction \uparrow $\therefore M \downarrow$ to maintain same area of ΔV_{do} .

Overlap angle is max^m at $\alpha = 0^\circ$ & min^m at $\alpha = 90^\circ$

Case(2) $\alpha > 90^\circ$ ($\alpha \uparrow, M \uparrow$)

$\alpha \uparrow$, Ripple \downarrow , height \downarrow , $\therefore M \uparrow$

Conventional question →

Que. 3
48

$$\text{at } \alpha = 0^\circ, M_0 = 30^\circ$$

then M_0 at $\alpha = 30^\circ, 60^\circ, 90^\circ, 120^\circ$

$$\frac{I_o}{I_p} = \cos \alpha - \cos(\alpha + 90^\circ)$$

For $\alpha = 0^\circ$,

$$\frac{I_o}{I_p} = \cos 0^\circ - \cos(90^\circ)$$

$$\frac{I_o}{I_p} = 0.133$$

α	M	
0	30	$\rightarrow \text{max}^m$
30	8.66 12.85	$\alpha \uparrow, M \downarrow$
60	7.61 8.46	
90	7.61	$\rightarrow \text{min}^m$
120	9.21	$\alpha \uparrow, M \uparrow$

DATE-25/08/14

INVERTERS

Fixed dc \longrightarrow Variable Ac
(V_o, f_o)

*Classification of inverters \rightarrow

(1) Voltage source inverter (VSI) \rightarrow

* 1φ Half bridge Inverter.

\rightarrow Sq wave inverter

* 1φ Full bridge inverter.

* 3φ VSI

\rightarrow Pwm inverter.

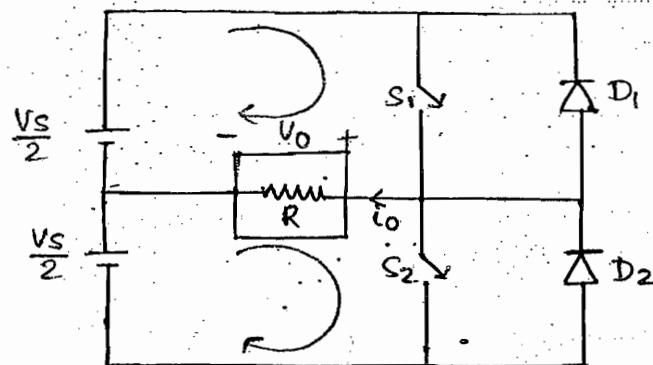
(2) Current source inverter (CSI) -

(3) Series inverter

(4) Parallel inverter.

(1) Voltage source inverter (VSI) \rightarrow

(a) 1-φ half bridge inverter \rightarrow



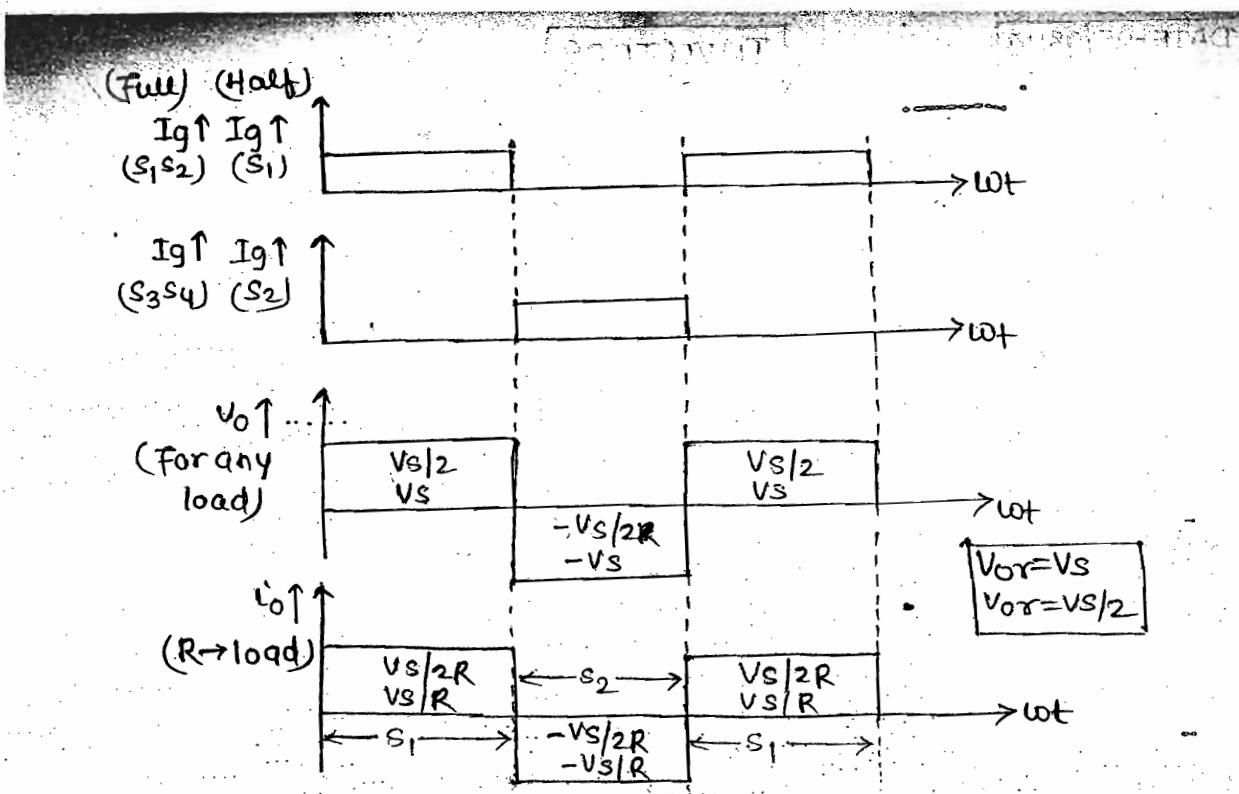
By the use of Fourier Series

$$V_o = \sum_{n=1,3,5,\dots}^{\infty} \frac{2V_s}{n\pi} \sin n\omega t$$

$$V_{on} = \frac{2V_s}{n\pi} \sin n\omega t$$

$$V_{o1} = \frac{\sqrt{2}V_s}{\pi}$$

$$V_{o1} = \frac{\sqrt{2}V_s}{\pi}$$



$$g = \frac{V_{o1}}{V_{o2}} = \frac{\sqrt{2}VS}{\frac{\pi}{2}Vs/2}$$

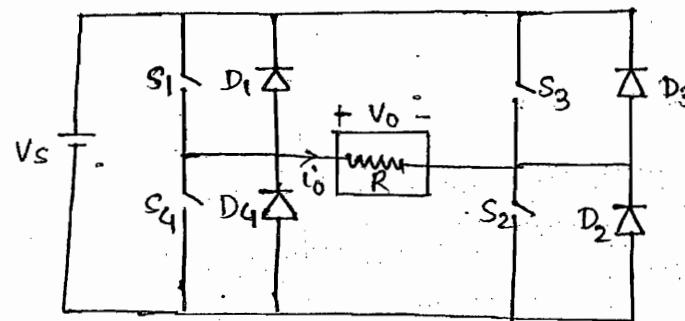
$$g = \frac{2\sqrt{2}}{\pi}$$

$$THD = \left(\frac{1}{g^2} - 1 \right)^{1/2}$$

$$THD = 48.34\%$$

- * For the true power, only R is present & Hence f/b diode will not conduct. They will conduct only in case of -ve power which is found only in reactive elements ($L \& C$)
- * The shape of the V_o is not depends on the load, but the current waveform is depend on load.

(i) 1-φ Full bridge inverter →



$S_1, S_2 \rightarrow ON$
 $V_0 \rightarrow VS$
 $i_0 \rightarrow VS/R$

$S_3, S_4 \rightarrow ON$
 $V_0 \rightarrow -VS$
 $i_0 \rightarrow -VS/R$

$$V_0 = \sum_{n=1,3,5,\dots}^{\infty} \frac{4VS}{n\pi} \sin n\omega t$$

$$V_{0n} = \frac{4VS}{n\pi} \sin n\omega t$$

$$V_{01} = \frac{2\sqrt{2}VS}{\pi}$$

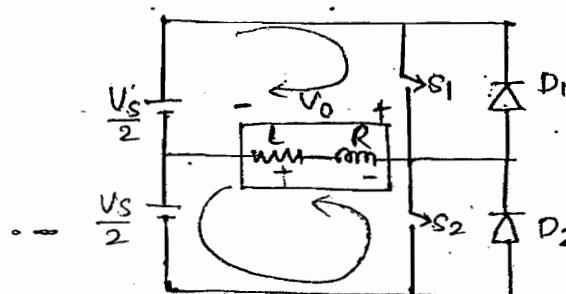
$$V_{01} = \frac{2\sqrt{2}VS}{\pi}$$

$$g = \frac{V_{01}}{V_{0\infty}} = \frac{2\sqrt{2}VS}{\pi VS}$$

$$g = \frac{2\sqrt{2}}{\pi}$$

$$\therefore g = 48.34 \%$$

1-φ Half bridge inverter (Other load) →



mode(1):- $S_1 \rightarrow ON$

$$V_0 = \frac{VS}{2}, V_{0t}, i_{0t}, P_t$$

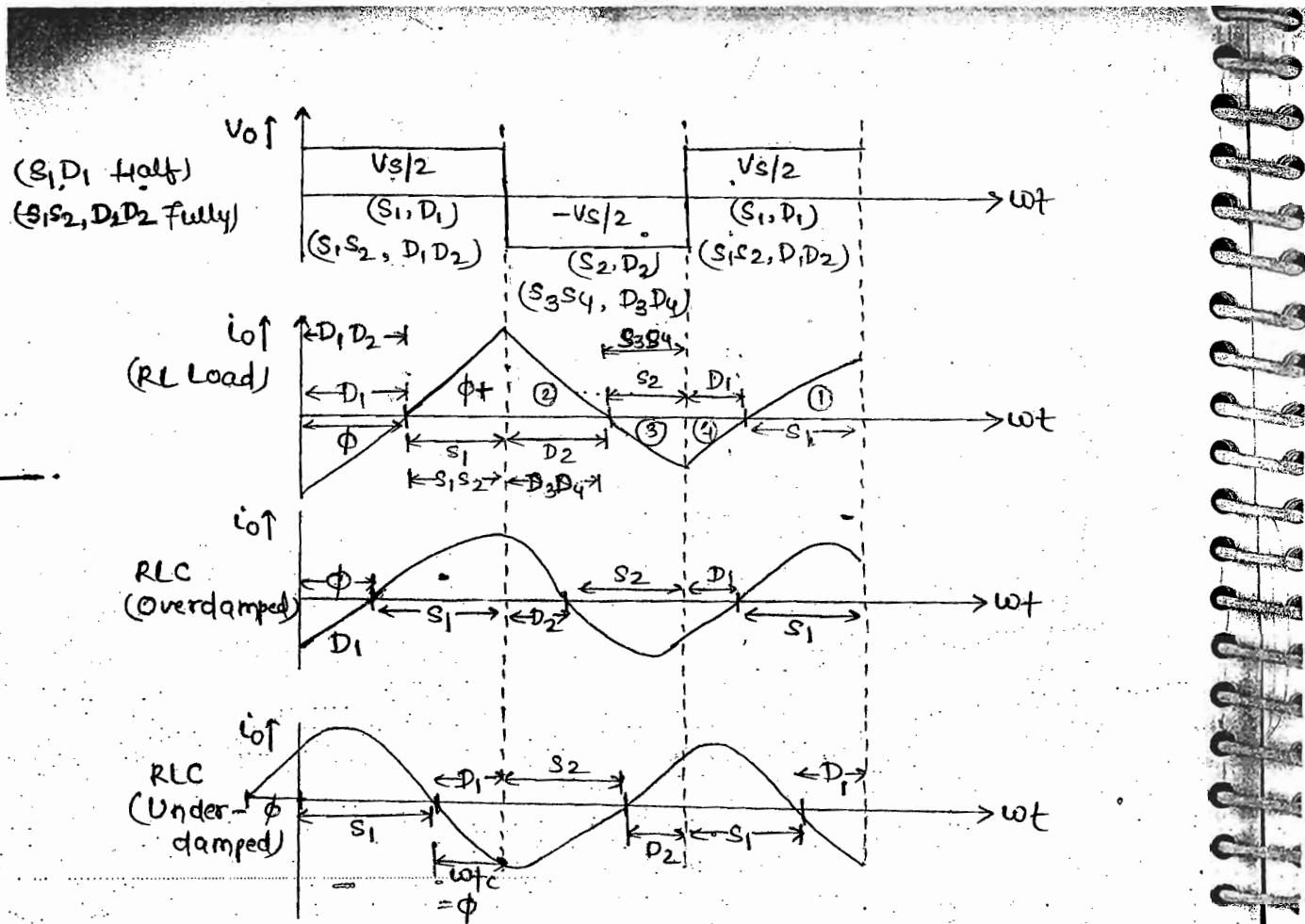
Source \xrightarrow{P} load
 $(I^2R, \frac{1}{2}LI^2)$

L → stores energy

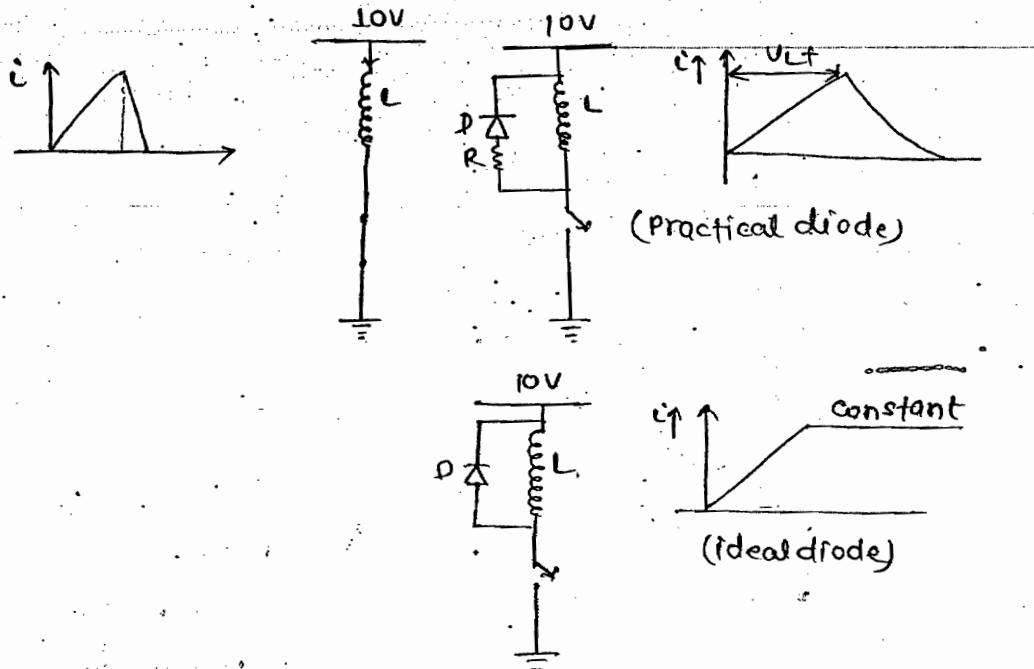
mode(2) → $D_2 \rightarrow ON$

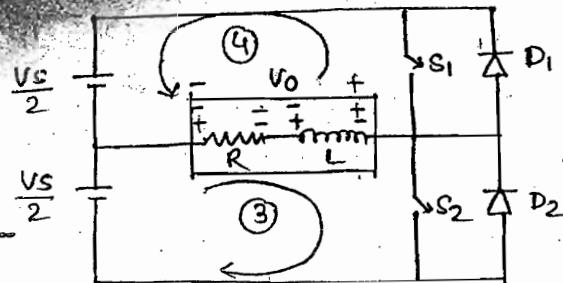
$$\frac{1}{2}L^2 \rightarrow \text{source } \frac{1}{2}i^2R$$

\hookleftarrow releasing energy



(1) RL Load → After reaching steady state, i_0 lags by ϕ by $\phi = \tan^{-1}(\frac{\omega L}{R})$





mode ③ \rightarrow $S_2 \rightarrow \text{ON}$

$$V_0 = -\frac{V_S}{2}, \quad V_0 = -i_0 \cdot \text{Pf}$$

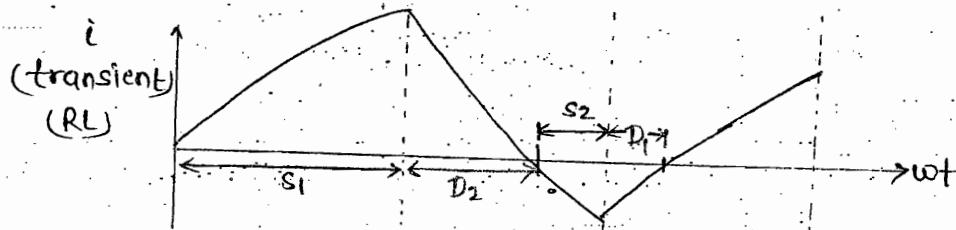
source $\xrightarrow{\text{P}}$ load ($i^2 R + \frac{1}{2} i^2 L^2$)

$L \rightarrow$ stored energy

mode ④ \rightarrow $D_1 \rightarrow \text{ON}$

$$\frac{1}{2} i^2 L^2 \rightarrow \text{source} + i^2 R$$

$L \rightarrow$ releasing energy



* Inductive load will draw dc component at the beginning.

V_0	I_0	P	device
+	+	+	S_1
+	-	-	D_1
-	-	+	S_2
-	+	-	D_2

lagging load \rightarrow diode

leading load \rightarrow switch

(2) RLC (Overdamped) \rightarrow ($X_L > X_C$)

\therefore lags V_o by $\phi = \tan^{-1} \left(\frac{X_L - X_C}{R} \right)$

$$\boxed{\phi = \tan^{-1} \left(\frac{X_L - X_C}{R} \right)}$$

Forced Comm. is required.

(3) RLC (Underdamped) \rightarrow

$$X_C > X_L$$

\therefore lags V_o by $\phi = \tan^{-1} \left(\frac{X_L - X_C}{R} \right)$

\therefore leads V_o by $\boxed{\phi = \tan^{-1} \left(\frac{X_C - X_L}{R} \right)}$

Load Comm. is required.

$$\boxed{\omega t c = \phi}$$

$$t_c = \frac{\phi}{\omega} = \frac{\tan^{-1}(X_C - X_L)}{R\omega}$$

If $t_c > t_q$, load Comm. is successful

$t_c < t_q$, load Comm. is fails

\therefore We require Forced Comm.

$$V_{oh} = \frac{2V_s}{\pi} \cdot \sin(\omega t) \quad (\text{Any load})$$

Let us consider RLC load;

$$i_{on} = \frac{V_{on}}{Z_n}$$

where $Z_n = R_n + j(X_{bn} - X_{cn})$

$$= \frac{V_{oh}}{|Z_n| \phi_n}$$

$$Z_n = |Z_n| \angle \phi_n$$

$$= \frac{V_{on} / \phi_n}{|Z_n|}$$

$$|Z_n| = \sqrt{R_n^2 + (X_{bn} - X_{cn})^2}$$

$$\phi_n = \tan^{-1} \left(\frac{X_{bn} - X_{cn}}{R_n} \right)$$

$$\boxed{i_{on} = \frac{2V_s}{\pi Z_n} \cdot \sin(\omega t - \phi_n)}$$

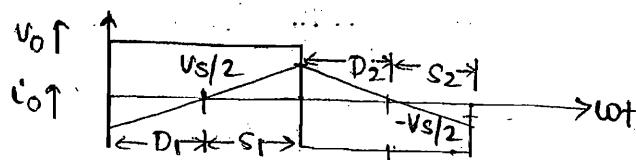
Eg - For pure inductive load.

$$|Z_L| = X_L = \omega L$$

$$\phi_L = 90^\circ$$

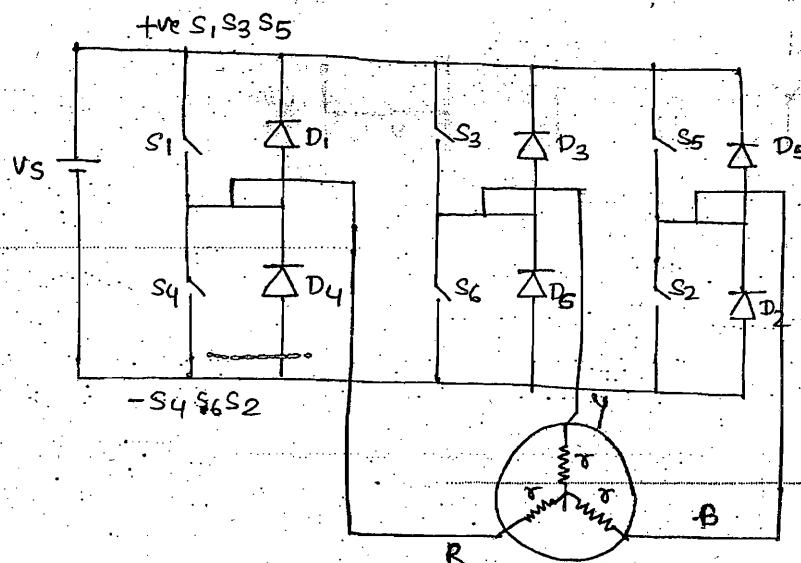
$$i_{L1} = \frac{2V_S}{\pi L(\omega L)} \cdot \sin(\omega t - 90^\circ)$$

$$i_{L1} \propto \frac{1}{n^2}$$

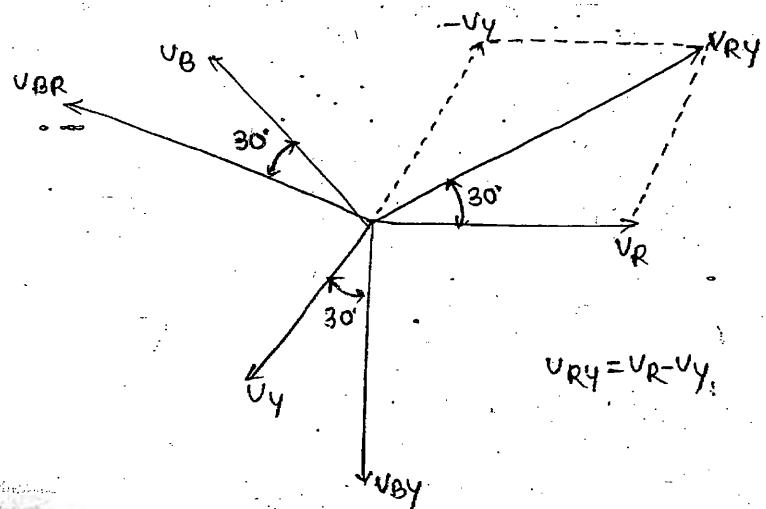


DATF-2G/OB/14

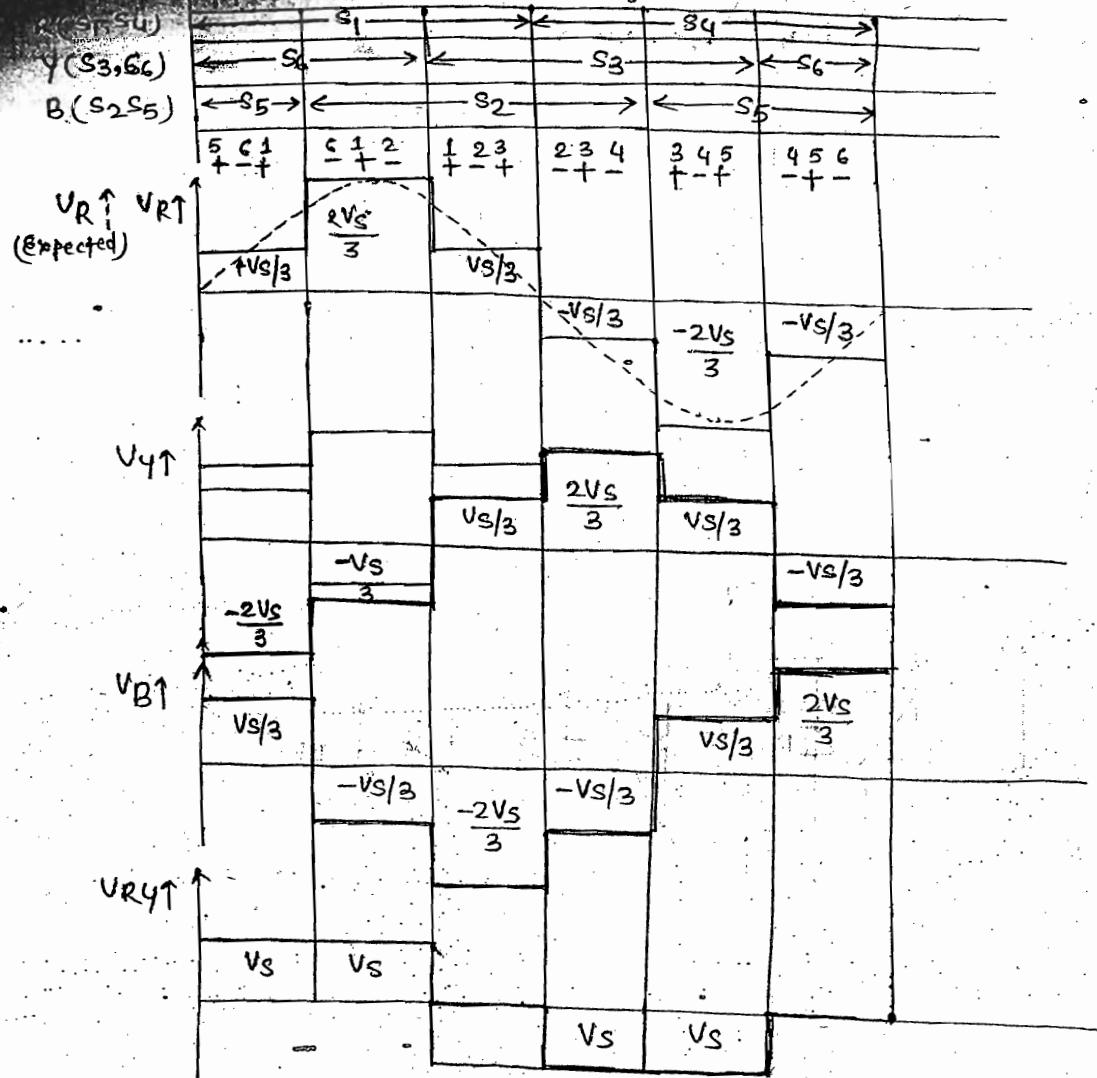
(iii) 3-φ VSIs →



* In 180° VSIs the conduction angle of switch & its anti-parallel diode is 180°.

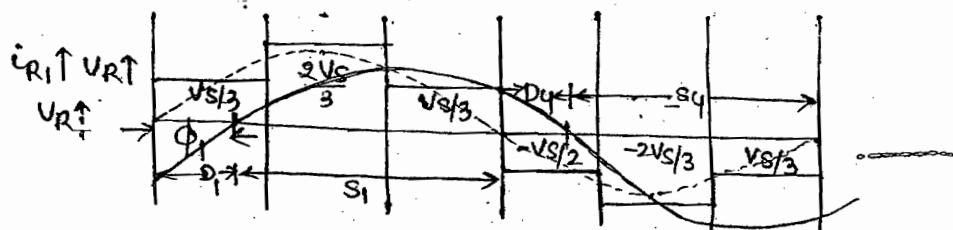


$$V_{RY} = V_R - V_Y$$



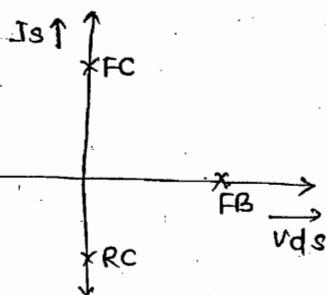
$$(V_{R4})_{RMS} = V_s \left(\frac{2\pi}{3} \right)^{1/2}$$

$$V_L = \sqrt{\frac{2}{3}} V_s$$



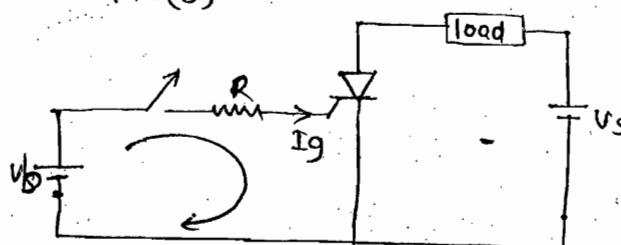
Chapter-1 Question

(1)



ans(b)

(2.)



$$V_b = 12 \pm 4V$$

$$I_g = 10mA$$

$$I_{g\min} \leq I_g \leq I_{g\max}$$

For worst condn

min^m gate current

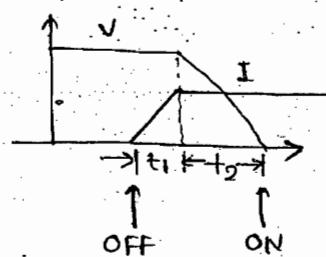
$$= \frac{(V_b)_{\min}}{R}$$

$$= \frac{12 - 4}{R} = \frac{8}{R} \geq I_{g\min}$$

$$\therefore R \leq \frac{8}{I_{g\min}}$$

$$R \leq \frac{8}{(10) \times 10^{-3}}, R \leq 800\Omega$$

(3.)



Turn on process

$$E_{t1} = \int_0^{t_1} V \cdot \frac{I}{t_1} t dt = \frac{1}{2} V I t_1$$

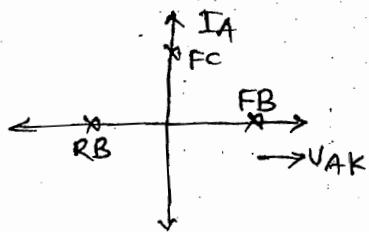
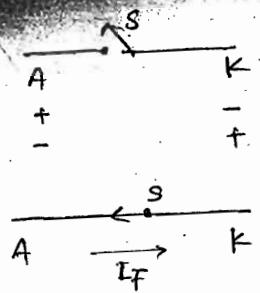
$$E_{t1} = V (\frac{I}{2} t_1) \text{ area} = \frac{I}{2} V t_1$$

$$E_{t2} = I (\frac{V}{2}) \text{ area}$$

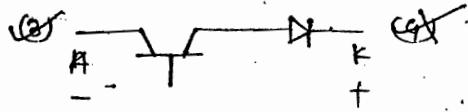
$$= I (\frac{1}{2}) V t_2 \\ = \frac{1}{2} V I t_2$$

$$\boxed{\text{Total } E = \frac{1}{2} V I (t_1 + t_2)}$$

ans.(q)

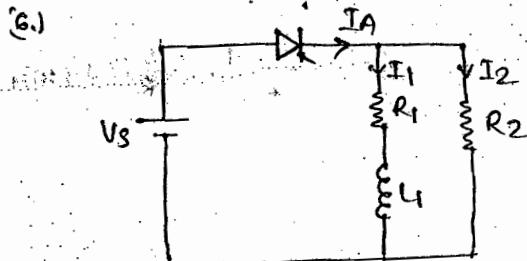


Ans(C)



Ans(C)

$$(5) C = \frac{SFItq}{R \ln 2} = \frac{2(50 \times 10^6)}{50 \ln 2} \quad [C = 2.88 \mu F]$$



$$IA = I_1 + I_2$$

$$I_1 = \frac{Vs}{R_1} (1 - e^{-t/\tau_1}) = \frac{100}{20} (1 - e^{-40t})$$

$$I_1 = 5(1 - e^{-40t})$$

$$I_2 = \frac{Vs}{R_2} = \frac{100}{5 \times 10^3} = 20 \times 10^{-3}$$

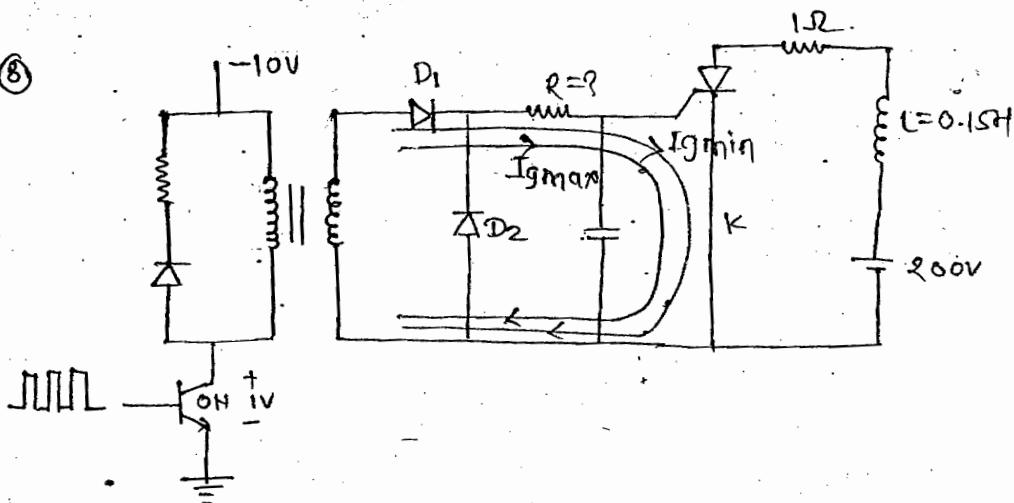
$$\tau_1 = \frac{R_1}{L_1} = \frac{1}{40}$$

$$IA = I_1 + I_2$$

$$I_L = 5(1 - e^{-40t}) + 20 \times 10^{-3}$$

$$t_{min} = 150 \mu s$$

Q8



$$9V = 1V + (I_{gmax} R) + 1V$$

$$R \geq 46.67\Omega$$

$$9V = 1V + (I_{gmin} R) + 1V$$

$$R \leq 70\Omega$$

If we consider both then $46.6 \leq R \leq 70\Omega$

Ans. (C) 47Ω

(8.) Volt sec rating of pulse X_{mer} = $10 \times t_{gpw}$

- $t_{gpw} > t_{min}$

g_{pw} = Gate

Pulse width

$$I_A = \frac{V_S}{R} (1 - e^{-t/T})$$



$$I_L = \frac{200}{1} (1 - e^{-t_{min}/0.15})$$

$$t_{min} = 187.45s$$

$$= 10 \times t_{gpw}$$

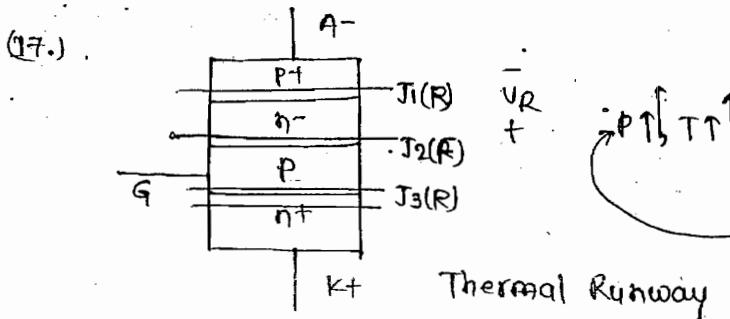
$$= 10 \times t_{min} = 10 \times 187.45s$$

Volt-sec rating of pulse X_{mer} > 1870.4Vs

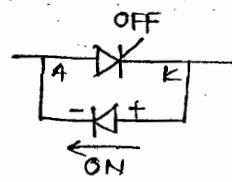
i.e. 2000 μVs

(9.) (c) (10.) MOSFET (11.) (a.) (12.) (a.) (13.) (c) (14.) $I_g \uparrow$ (b) $\frac{d}{dt} I_g \uparrow$ (d)

(15.) (c.) (16.) (c.) (17.) (d.)



(18.)



$$V_R \uparrow, t q \downarrow, \therefore P \uparrow$$

$$V_R \downarrow, t q \uparrow, \therefore P \downarrow$$

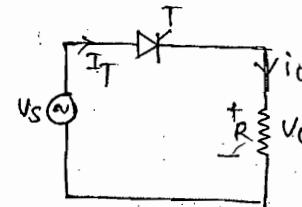
ans(b)

(19.) $I_{S2} = \sqrt{2} I_{S1} \Rightarrow 3000 = \sqrt{2} I_{S1}, I_{S1} = 2121.3 \text{ A}$

(20.) $(I_T)_{\text{avg. Rating}} = \frac{(I_T)_{\text{rms Rating}}}{FF}$

$$\begin{aligned} FF &= \frac{I_T(\text{avg})}{(I_T)_{\text{avg}}} = \frac{I_{\text{or}}}{I_0} \\ &= \frac{V_{\text{or}}/R}{V_0/R} \end{aligned}$$

$$\begin{aligned} &= \frac{V_{\text{or}}}{V_0} = \frac{V_{\text{m}}}{\sqrt{2\pi}} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]^{1/2} \\ &\quad \times \frac{\sqrt{m}}{8\pi} \cos \alpha \\ &= 3.98 \end{aligned}$$



$$(I_T)_{\text{avg Rating}} = \frac{35}{3.98}$$

$$= 8.84$$

21) more than 20A 22) (B) 23) (b.)

conventional Q.(1)(b.)

Heat sink

J . C S A

$$T_J = 125^\circ\text{C}; \quad T_{Si} = 70^\circ\text{C}$$

$$PAV_1 = \frac{T_J - T_{Si}}{0.16 + 0.08} = \frac{125 - 70}{0.16 + 0.08} = 229.16 \text{ W}$$

$$\downarrow T_{S2} = 60^\circ\text{C} \text{ (cool down)}$$

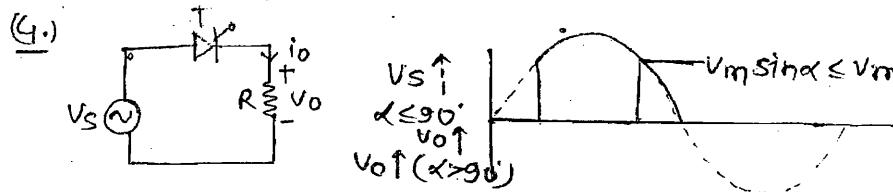
$$\therefore PAV_2 = \frac{125 - 60}{0.16 + 0.08} = 270.8 \text{ W}$$

$$\% \text{ increase in Rating} = \frac{\sqrt{PAV_2} - \sqrt{PAV_1}}{\sqrt{PAV_1}} \times 100 = 8.79\%$$

Chap. (2)

(2.) (b.) (3.) PIV = $2V_m = 2(50)\sqrt{2} = 100\sqrt{2}$

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If $\alpha \geq 90^\circ$, $[V_0(\omega t)]_{\text{peak}} = V_m$

If $\alpha > 90^\circ$, $[V_0(\omega t)]_{\text{peak}} = V_m \sin \alpha = 230V$

$230\sqrt{2} \sin \alpha = 230$

$230\sqrt{2} \sin 135^\circ = 230$

$$\sin \alpha = \frac{1}{\sqrt{2}}$$

$$\alpha = 135^\circ$$

(5.) $\alpha = 60^\circ$

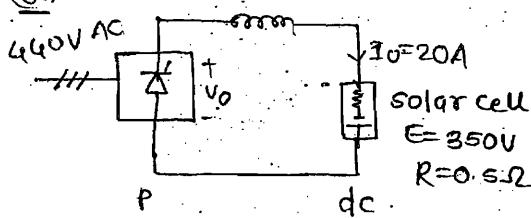
FDF = $\cos \alpha$

$= \cos 60^\circ = 0.5$

PF = $g \cos \alpha = 0.478$

[Ans. (c)]

(6.)



AC \rightarrow INV ($\alpha > 90^\circ$) DC

$V_0 = -E + I_0 R$

$\frac{8U_m L}{\pi} \cos \alpha = -E + I_0 R$

$\frac{3(440\sqrt{2})}{\pi} \cos \alpha = -350 + (20 \times 0.5)$

$\alpha = 125^\circ$

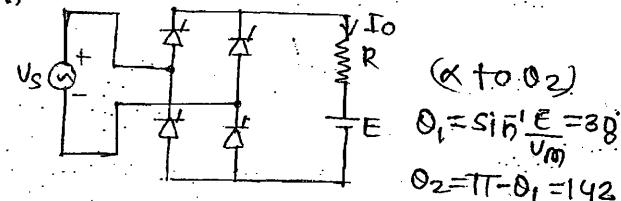
$\alpha \geq 60^\circ$

$\alpha + \omega t c = \pi$

$\omega t c = \pi - \alpha = 180^\circ - 125^\circ$

$\omega t c = 55^\circ$

(7.)



$$I_0 = \frac{1}{2\pi R} [V_m (\cos \alpha - \cos \theta_2) - E (\theta_2 - \alpha)]$$

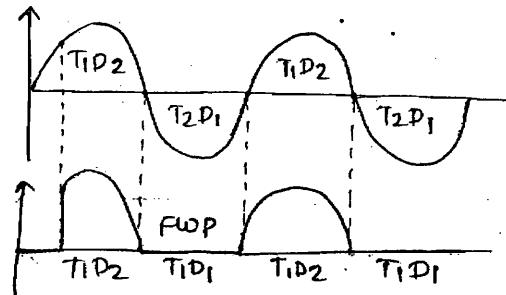
$$= \frac{1}{2\pi R} [V_m (\cos \theta_1 - \cos \theta_2) - E (\theta_2 - \theta_1)] - E (142 - 38) \frac{\pi}{180}$$

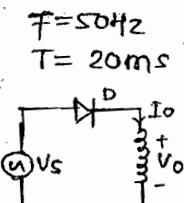
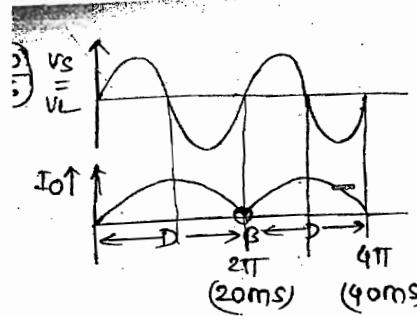
$I_0 = 15.9A$

(8.) $\alpha = 25^\circ$, $\omega = 10^\circ$

FDF = $\cos(\alpha + \frac{\omega}{2}) = 0.866$

(9.)





(14) 46 $V_S = 100\sqrt{2} \sin(100\pi t)$

$I_S = 10\sqrt{2} \sin\left(100\pi t - \frac{\phi}{3}\right) + 5\sqrt{2} \sin\left(300\pi t + \frac{\pi}{4}\right)$

$+ 2\sqrt{2} \sin\left(500\pi t - \frac{\pi}{6}\right)$

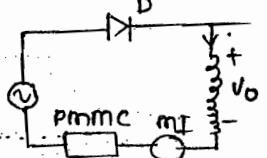
$I_{SR} = V_S R_I \cos \alpha = 100(2) \cos(\pi/3) = 500$

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(15) 46 $PF = g \cdot FDF$

$g = \frac{I_{S1}}{I_{ST}} = \frac{10}{\sqrt{10^2 + 5^2 + 2^2}}$

$$PF = \frac{10}{\sqrt{129}} \cos 60^\circ = 0.44$$



$$I_O = \frac{V_m}{\omega L} (1 - \cos \omega t)$$

$$= \frac{V_m}{\omega L} - \frac{V_m}{\omega L} \cos \omega t$$

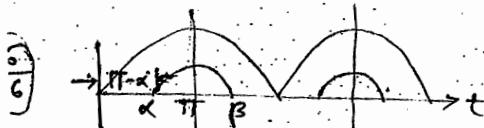
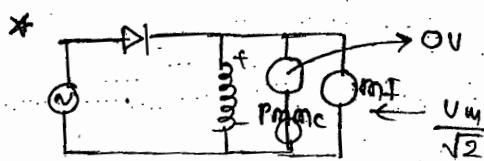
(18) 47

$$V_O = \frac{V_m}{\pi} (1 + \cos \alpha); (V_O)_{max} = \frac{2V_m}{\pi}$$

$$= I_F (100 + R_S)$$

$$(I_O)_{avg} = \frac{V_m}{\omega L}; I_{OR} = 1.225 \frac{V_m}{\omega L}$$

$$I_{OR} = \sqrt{\left(\frac{V_m}{\omega L}\right)^2 + \left(\frac{V_m}{\sqrt{2}\omega L}\right)^2} = 1.225 \frac{V_m}{\omega L}$$



$$\beta = \pi + (\pi - \alpha) = 2\pi - \alpha = 360 - 120 = 240^\circ$$

(19) 47 RLE Load 2 pulse, $\alpha = 110^\circ$, $\mu = ?$

$$\Delta V_{d0} = \frac{V_{d0}}{2} [\cos \alpha - \cos(\mu + \alpha)] = 4fLs I_0$$

$$V_{d0} = \frac{2V_m}{\pi}; V_O = -E_g + I_0 R_Q [Because \alpha < 90^\circ]$$

$$V_O = V_0 \cos \alpha - 4fLs I_0 \quad \dots \text{(ii)}$$

$$I_0 = 35.7A \quad \mu = 8.35^\circ$$

Conventional que (2) \rightarrow

$$3 \text{ pulse: } V_{d0} = \frac{3V_m L}{2\pi}$$

$$\alpha_{max} = 180^\circ - [\omega t_{q2} + \mu_0] \quad \mu_0 = \text{overlap angle at } \alpha = 0$$

$$\Delta V_{d0} = \frac{V_{d0}}{2} [\cos \alpha - \cos(\alpha + \mu)] = 3fLs I_0$$

$$\frac{V_{d0}}{2} [1 - \cos \mu_0] = 3fLs I_0$$

Because at $\alpha = 0$ (Rec-mode)

$$V_O = E_b + I_0 R_Q \quad \dots \text{(i)}$$

$$V_O = V_{d0} \cos \alpha = 3fLs I_0 \quad \dots \text{(2)}$$

$$I_0 = 14.7A, \quad I_0 = 17^\circ$$

$$\omega t_q = 2\pi f t_q = 2\pi \cdot 50 \cdot 250 \times 10^6 \times \frac{180}{\pi} = 4.5$$

$$\alpha_{max} = 180^\circ - [\omega t_q + \mu_0] = 180^\circ - [4.5 + 17^\circ]$$

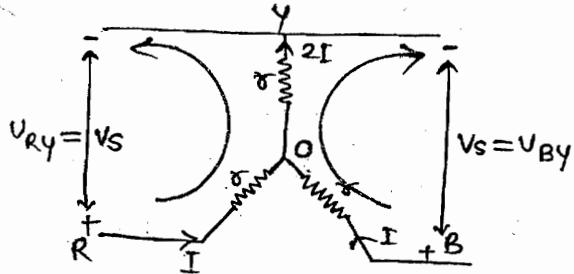
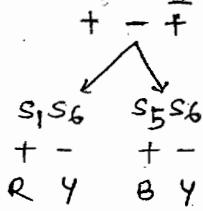
$$\alpha_{max} = 158.5^\circ$$

$$KVA \text{ rating of Tr} = \sqrt{3} V_{sr} I_{sr}$$

$$I_{sr} = \sqrt{\frac{2}{3}} I_0$$

$$Tr = \sqrt{3} \cdot 400 \times \sqrt{\frac{2}{3}} I_0$$

$$Tr = 22.6 \text{ kVA}$$

(1) $0 \rightarrow \pi/3 \rightarrow$ $s_5 s_6 s_1 \rightarrow ON$ By using KVL \rightarrow

$$V_s = I\tau + 2I\tau$$

$$V_s = 3I\tau$$

$$I\tau = \frac{V_s}{3}$$

$$V_R = +I\tau = +\frac{V_s}{3}$$

$$V_Y = -2I\tau = -\frac{2V_s}{3}$$

$$V_B = +I\tau = +\frac{V_s}{3}$$

$$(V_R)_{RMS} = \left[\frac{1}{\pi} \left[\left(\frac{V_s}{3} \right)^2 \times \frac{\pi}{3} + \left(\frac{2V_s}{3} \right)^2 \frac{\pi}{3} + \left(\frac{V_s}{3} \right)^2 \frac{\pi}{3} \right] \right]^{1/2}$$

$$V_{ph} = \frac{\sqrt{2}V_s}{3}$$

$$I_L = I_{ph} = \frac{V_{ph}}{\tau} = \frac{\sqrt{2}V_s}{3\tau}$$

$$\downarrow \begin{array}{l} (I_s)_{RMS} = \left[\frac{1}{\pi} \left[\left(\frac{V_s}{3\tau} \right)^2 \frac{\pi}{3} + \left(\frac{2V_s}{3\tau} \right)^2 \frac{\pi}{3} + \left(\frac{V_s}{3\tau} \right)^2 \frac{\pi}{3} \right] \right]^{1/2} \\ \text{Switch} \\ = \frac{V_s}{3\tau} \end{array}$$

$$(I_s)_{RMS} = \frac{V_s}{3\tau}$$

$$(1) V_{ph} = \frac{\sqrt{2}V_s}{3}$$

$$(4) V_L = \sqrt{3}V_{ph}$$

$$(2) I_{ph} = \frac{V_{ph}}{\tau}$$

$$(5) P = 3I_{ph}^2 \tau$$

$$(3) (I_s)_{RMS} = \frac{I_{ph}}{\sqrt{2}}$$

$$P = \frac{3V_{ph}^2}{\tau}$$

The Fourier Series of $V_R = \sum_{n=6k+1}^{\infty} \frac{2V_s}{n\pi} \sin(n\omega t)$

$$n=1, 5, 7, 11, 13, 17, 19, \dots$$

Note:- Even & triple harmonics are not present.

$$g = \frac{8}{\pi}, THD = 31\%$$

$$V_{Rn} = \frac{2V_s}{n\pi} \sin(n\omega t) \rightarrow \text{Any load}$$

Let us consider RLC load in each phase & let ($x_L > x_C$)

$$i_{Rn} = \frac{V_{Rn}}{Z_n} = \frac{V_{Rn}}{|Z_n| L \phi_n} = \frac{V_{Rn} L \phi_n}{|Z_n|}$$

$$i_{Rn} = \frac{2V_s}{n\pi |Z_n|} \sin(n\omega t - \phi_n)$$

$$i_{R1} = \frac{2V_s}{\pi |Z_1|} \sin(\omega t - \phi_1)$$

* Condⁿ angle of each diode

$$D \rightarrow \phi = \tan^{-1} \left(\frac{x_L - x_C}{R} \right)$$

* Condⁿ angle of each switch

$$s = (\pi - \phi)$$

Fourier Series For Line voltages :-

$$V_{RY} = \sum_{n=1,3,5, \dots}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\pi}{3} \sin(\omega t + \pi/6)$$

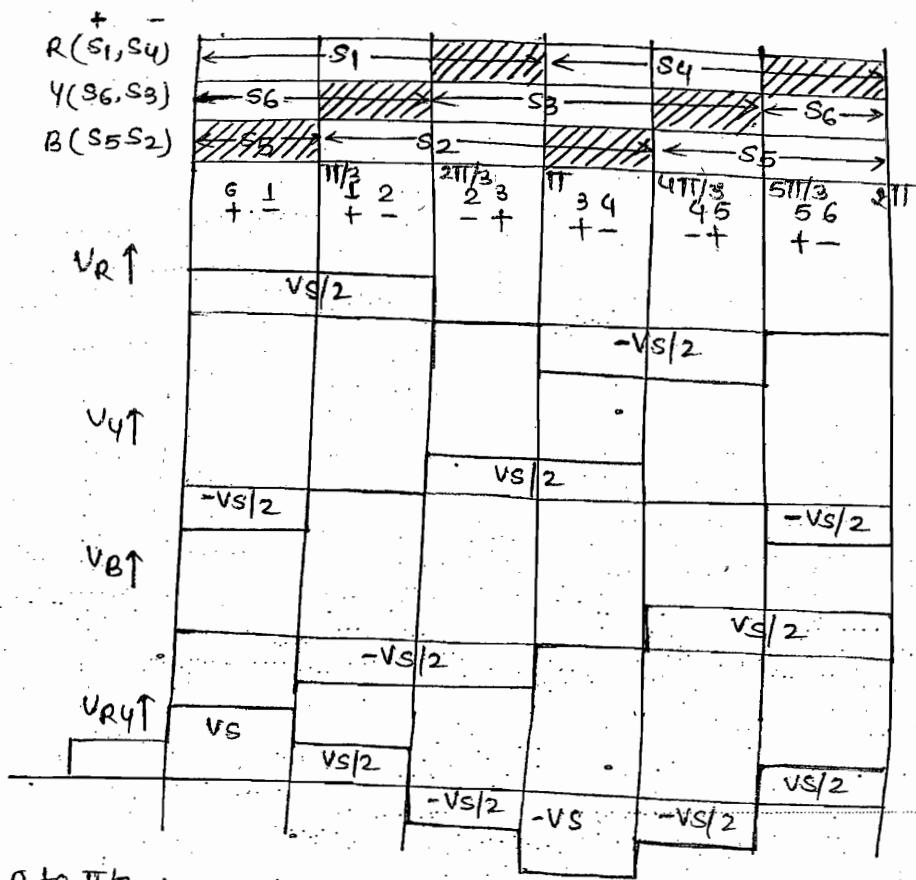
$$n=6k+1$$

Note:- Even & odd triple harmonics are not present.

$$g = \frac{3}{\pi}, THD = 31\%$$

Drawback \rightarrow There is a possibility of SC across the supply when the incoming switch starts conducting before the outgoing switch belonging to the same phase stops conducting.

120° VSI → In this case a cond'n angle of 120° is allotted for each switch & the last 60° is allotted for commutation.



0 to $\pi/3 \rightarrow$

S₁, S₆ → ON

R Y -

$$V_R = \frac{VS}{2}, V_Y = \frac{-VS}{2}, V_B = 0$$

* $(V_R)_{\text{rms}} = \frac{VS}{2} \left[\frac{2\pi/3}{\pi} \right]^{1/2}$

$$(V_R)_{\text{rms}} = \frac{VS}{\sqrt{6}}$$

* $I_{ph} = \frac{V_{ph}}{\gamma}$

* $V_L = \sqrt{3} V_{ph}$

* $(I_s)_{\text{rms}} = \frac{I_{ph}}{\sqrt{2}}$

* $P = 3 I_{ph}^2 \gamma = \frac{3 V_{ph}^2}{\gamma}$

$$V_R = \sum_{n=1,3}^{\infty} \frac{2VS}{n\pi} \cdot \frac{\sin(n\pi)}{3} \cdot \sin(\omega t + \frac{\pi}{8})$$

$n=6k \pm 1$

Note:- even & triple harmonic are not present

$\gamma = \frac{8}{\pi}, THD = 31x$

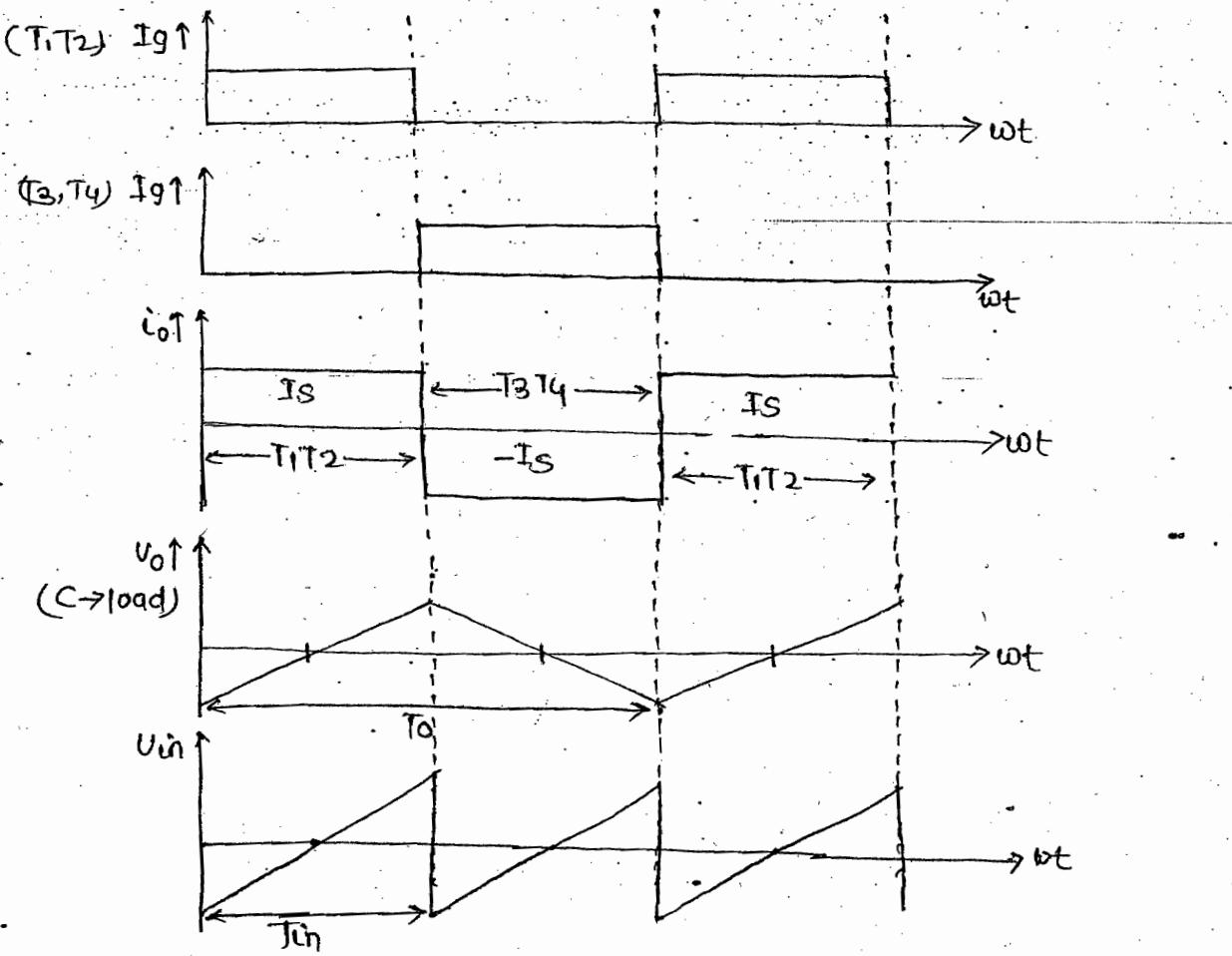
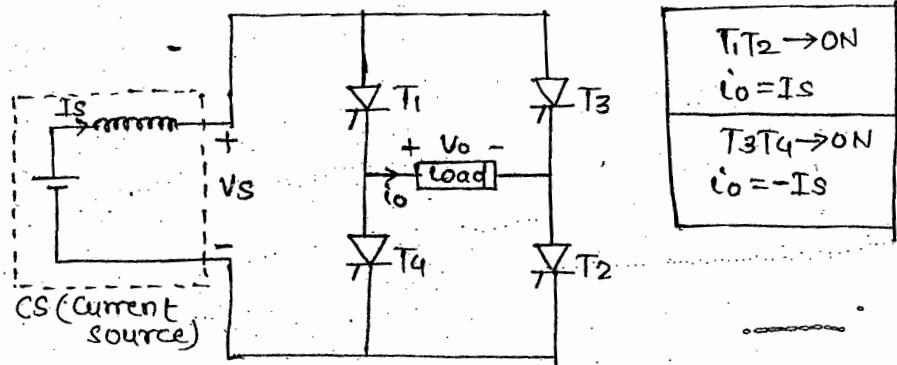
$$V_{RY} = \sum_{n=1,3,5}^{\infty} \frac{3Vs}{n\pi} \sin n\omega t$$

$n = 6k \pm 1$
 $n = 1, 5, 7, 11, 13, 17, \dots$

Note → even & triple harmonic are not present.

- $\text{g} = \frac{3}{\pi}$, THD = 3.1%

Current Source Inverter → (CSI)



$$i_s = \sum_{n=1,3,\dots}^{\infty} \frac{4I_s}{n\pi} \sin n\omega t$$

$$g = \frac{2\sqrt{2}}{\pi}, \text{ THD} = 48.34\%$$

$$i_{on} = \frac{4I_s}{n\pi} \sin n\omega t$$

Let us consider RLC Load.

$$V_{on} = i_{on} Z_n = |Z_n| i_{on} \angle \phi_n$$

$$V_{on} = \frac{4I_s}{n\pi} |Z_n| \sin(n\omega t + \phi_n)$$

Eq:- For pure capacitive load; (load comm.)

$$|Z_n| = X_{cn} = \frac{1}{n\omega C}$$

$$T_0 = 2T_{in}$$

$$\phi_n = -90^\circ$$

$$\begin{array}{c} f_{in} \quad 2f_0 \\ \downarrow \quad \downarrow \\ q_c \quad 4C \end{array}$$

$$V_{on} = \frac{4I_s}{n\pi} \cdot \frac{1}{n\omega C} \sin(\omega t - 90^\circ)$$

$$T_i = 2f_s$$

$$V_{on} \propto \frac{1}{n^2}$$

Advantage of CSI

- (1) Feedback diodes are not reqd. in CSI.
- (2) Comm. is very simple.
- (3) For capacitive load there is a possibility of load comm.
- (4) Inherently there is SC protection for the supply when the incoming thy. are switched on before the outgoing thy. becomes off.

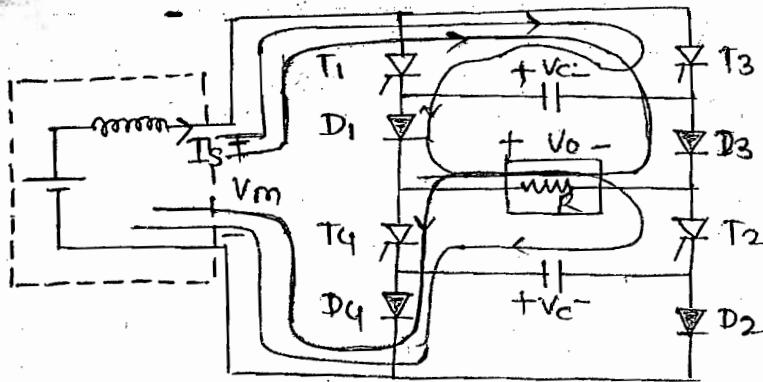
Disadvantage * During comm. process the commutating capacitor (load) applies ^{high} rev.vol. across the device therefore the device.

having low rev.vol. blocking capability such as GTO's, IGBT's & other transistors are generally not preferred in CSI.

* If the comp. comm. capacitor is connected directly across the load then it will be continuously discharging through the load.

To avoid this prob we must connect blocking diode b/w the load & commutating capacitor as shown in fig. given below.

It is also called as
ASCI
(Auto sequential
commutated inverter)



mode(1) →

mode(2) →

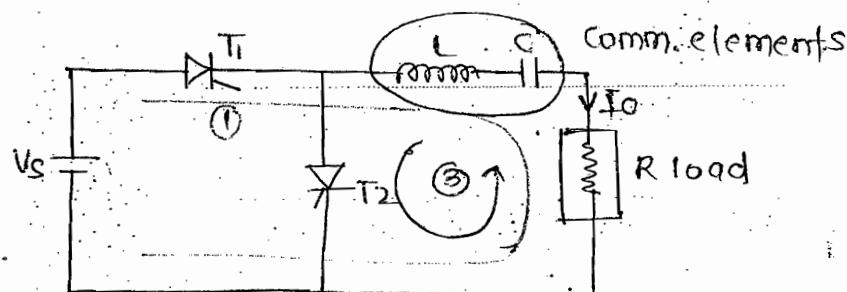
mode(3) →

(at the end of mode 2 → becomes 0)

* (i) The commutating capacitance limits the max^m freq. of inverter

$$\therefore f_{\max} = \frac{1}{4RC}$$

* Series Inverter →



* Here RLC should satisfy underdamped condn

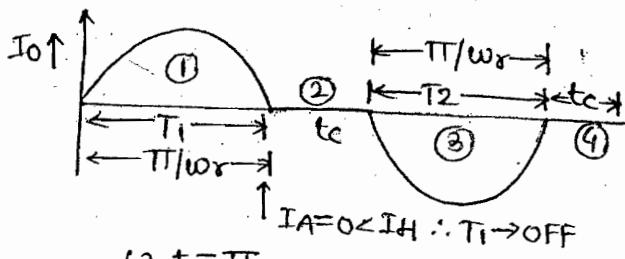
* Here the commuting device is series hence called series inverter

$$I = \frac{V_s}{w_r L} e^{-st} \sin w_r t$$

$$w_r = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad s = \frac{R}{2L} \quad (s = \text{damping factor})$$

mode② In this mode we have to provide comm. time for the outgoing thy. T1 before the incoming thy. T2 is switched.

- ($t_c > t_q$)



$$\omega_r t = \pi$$

$$t = \pi/\omega_r$$

$$T = 2\left(\frac{\pi}{\omega_r} + t_c\right)$$

$$f = \frac{1}{2\left(\frac{\pi}{\omega_r} + t_c\right)}$$

$$f_{max} = \frac{1}{2\left(\frac{\pi}{\omega_r} + t_c\right)}$$

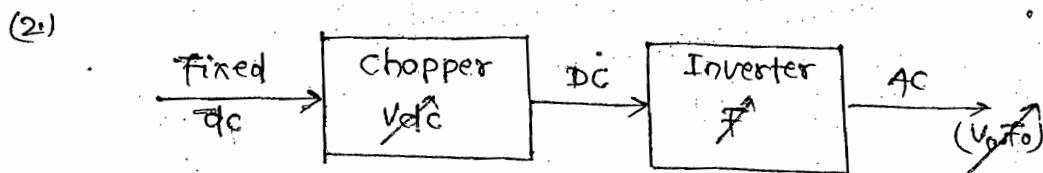
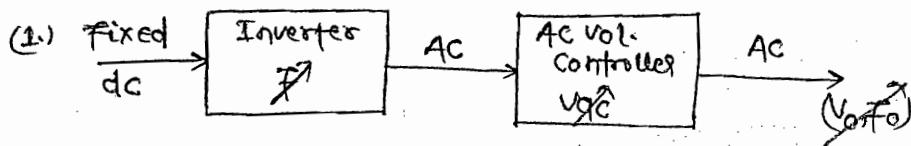
For ideal thy.

$$t_c = 0$$

$$f_{max} = \frac{\omega_r}{2\pi}$$

$$\boxed{f_{max} < \omega_r}$$

- * At low freq. harmonic distortion is higher. Therefore series inverter is not beneficial at low freq.
- Resonant Converters → * In this con' Comm. takes place at current 0 (or) voltage 0.
- * This reduce the switching power loss even at high freq.
- * If comm. takes place at current 0 then it is known as 0 current switching (ZCS)
- * If comm. takes place at vol. 0 then it is known as 0 Vol. switching (ZVS)
- * In this con' we must use LC elements for getting current 0 (or) voltage 0.
- Advantage of series inverter → In series inverter Comm. takes place at current 0 & this minimise the switching power loss even at high freq.

Voltage Control of inverters →(1) External Control →

Drawback → (1) As the no. of stages increases there is a increase in additional power loss along with the size & weight of the equipment.

(2) The filtering requirement becomes costlier due to the increased in harmonics as the no. of stages increased.

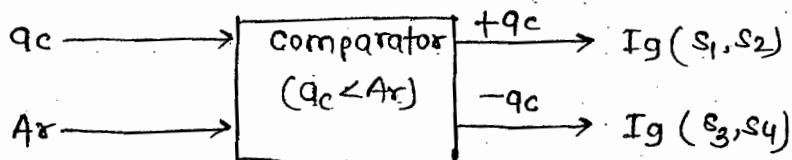
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(2) Internal Vol. Control using PWM methods →

Advantage → (1) We can control the vol. within the inverter itself.

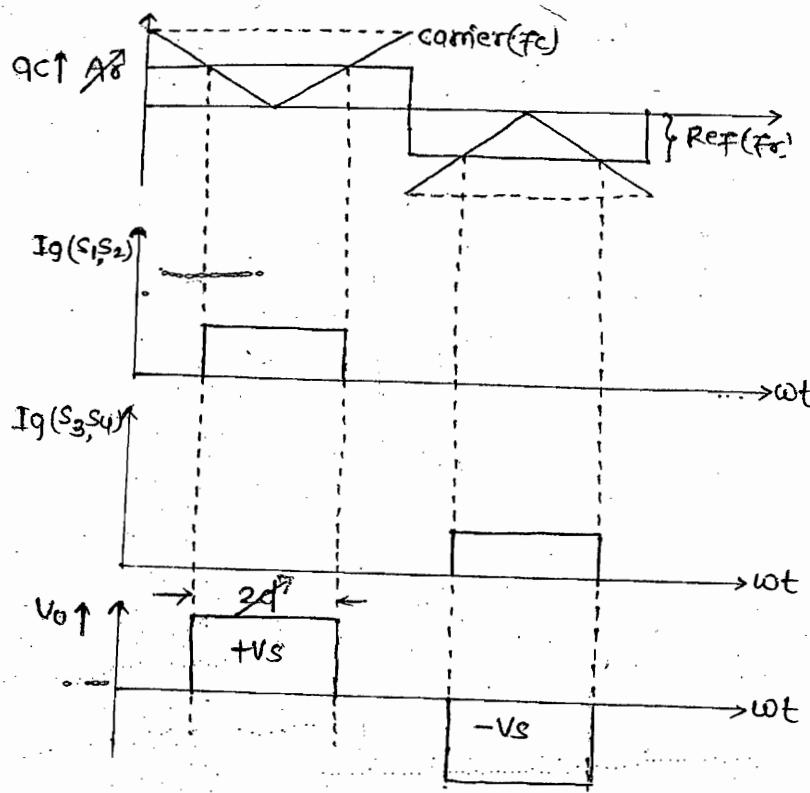
(2) We can eliminate some of the lower order harmonics & this improves the quality of o/p waveform.

(a) Single pulse width modⁿ tech: → Let us realize this PWM tech. For 1φ full bridge inverter:



$$V_{ofo} = V_s \left(\frac{2d}{\pi} \right)^{1/2}$$

2d → total pulse width in each 1/2 cycle



$$V_o = \sum_{n=1,3,5,\dots}^{\infty} \frac{4Vs}{n\pi} \sin \frac{n\pi}{2} \cdot \sin nd \cdot \sin n\omega t$$

$$V_{on} = \frac{4Vs}{n\pi} \sin \frac{n\pi}{2} \cdot \sin nd \cdot \sin n\omega t$$

$$V_{on} = 0, \text{ if } nd = \pi, 2\pi, 3\pi, \dots$$

$$d = \frac{\pi}{n}, \frac{2\pi}{n}, \frac{3\pi}{n}, \dots$$

$$2d = \frac{2\pi}{n}, \frac{4\pi}{n}, \frac{6\pi}{n}, \dots$$

Valid only if $2d \leq \pi$
condⁿ to eliminate the harmonics

Ques: What is the pulse width req. to eliminate the 3rd harmonic?

Ans. \rightarrow * To eliminate the 3rd harmonic...

$$2d = \frac{2\pi}{3}, \frac{4\pi}{3}, \frac{6\pi}{3}, \dots$$

$$2d = \frac{360}{3}$$

$$2d = 120^\circ$$

* To eliminate the 5th harmonic.

$$2d = \frac{2\pi}{5}, \frac{4\pi}{5}, \frac{6\pi}{5} \dots$$

$$2d = \frac{2\pi}{5}, \frac{4\pi}{5}$$

There are only 2 option to eliminate the 5th harmonics

$$2d = 72', 144'$$

* Here we can eliminate the selected harmonics depending upon the width of the pulse.

* For eliminating the low order harmonics (3rd) there is only one option.

* so there is many option to eliminate the higher order harmonics.

$$V_{0h} = \frac{2\sqrt{2}}{n\pi} Vs \sin nd$$

$$V_{01} = \frac{2\sqrt{2}}{\pi} Vs \sin d$$

$$g = \frac{V_{01}}{V_{0r}} = \frac{2\sqrt{2} vs \sin d}{\pi} \cdot \frac{1}{\sqrt{s} \left(\frac{2d}{\pi} \right)^{1/2}}$$

$$g = \frac{2\sqrt{2} \cdot \sin d}{\sqrt{(2d) \cdot \pi}}$$

Radians

$$THD = \sqrt{\left(\frac{1}{g^2} - 1\right)}$$

e.g:- Let $2d = \frac{2\pi}{3}$, $d = 120^\circ$

$$g = \frac{2\sqrt{2} \cdot \sin d}{\sqrt{(2d) \cdot \pi}} = \frac{2\sqrt{2} \cdot \sin 60^\circ}{\sqrt{\left(\frac{2\pi}{3}\right) \cdot \pi}} = \frac{3}{\pi}$$

$$THD = 31\%$$

whether the even & 3rd order harmonics is not present then always

$$g = \frac{3}{\pi} \quad THD = 31\%$$

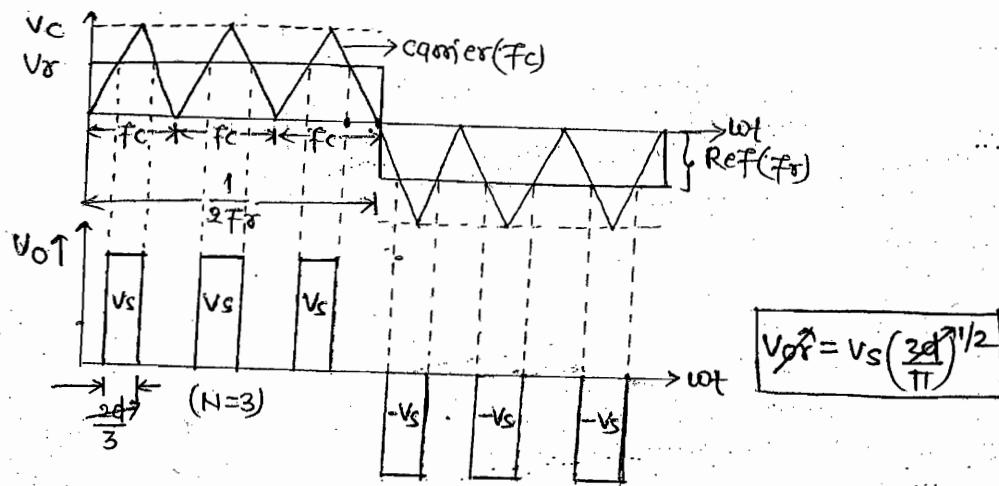
So by wing power in 1/2 VSI THD = 31%

$$2d = 120^\circ$$

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- * We are using V-shape carrier, but if we use inverted V then the result is same.
- V-shape carrier [carrier is higher]

- (2) multiple PWM tech. \rightarrow 3 pulse



$$\frac{3}{f_C} = \frac{1}{2f_R} \quad \therefore 3 = \frac{f_C}{2f_R}$$

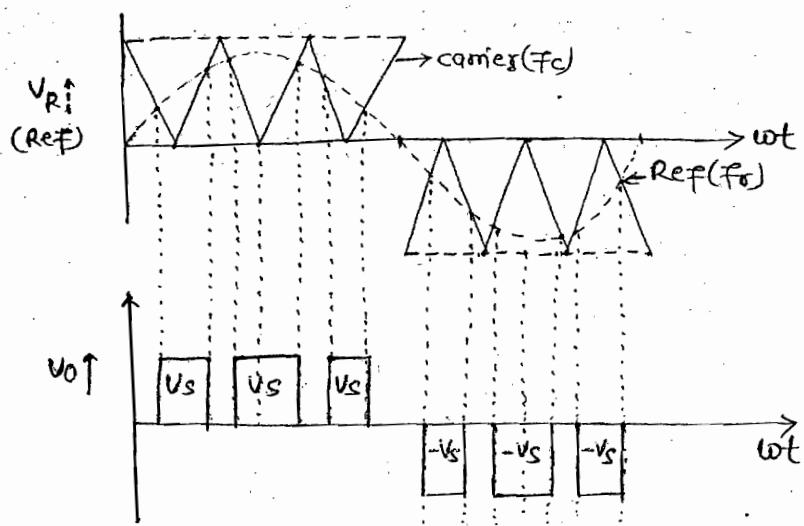
$$N = \frac{f_C}{2f_R}$$

$$\text{Pulse width} = \frac{2d}{N} = \left(1 - \frac{V_R}{V_C} \right) \frac{\pi}{N}$$

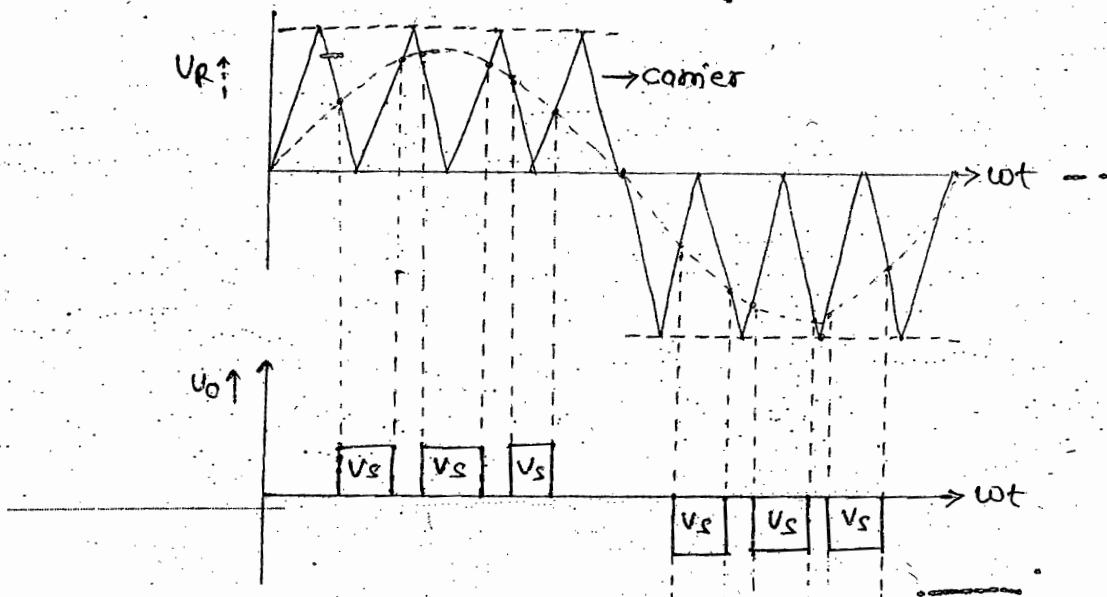
$$\text{P.W} = \left(1 - \frac{V_R}{V_C} \right) \frac{\pi}{N}$$

- (3) Sinusoidal PWM tech. \rightarrow

- (I) Peak carrier coincident with zero of ref:-



(II.1) Zero of carrier, coincident with zero of ref:-



$$N = \frac{f_c}{2f_r} - 1$$

Note:- Dominant Harmonics $\rightarrow 2N \pm 1$

If $N=3$, $2(3) \pm 1 = 5, 7$

If $N=9$, $2(9) \pm 1 = 17, 19$

$$\text{modulation index (m)} = \frac{V_r}{V_c}$$

* If the domination is shown by lower order it is diff. to filter them.

* We can easily filter the higher order dominant harmonics.

* Therefore in sinusoidal Pwm tech. we increase the no. of pulses in each half cycle & increase the order of dominant harmonics. So that they can be filtered very easily.

1 PWM

$$\textcircled{X} V_{0r} = V_s \left(\frac{2d}{\pi} \right)^{1/2}$$

$$\textcircled{X} V_0 = \frac{4V_s \sin n\pi}{n\pi} \cdot \frac{\sin nd}{2} \cdot \frac{(\sin n\omega t)}{(\sin n\omega t)}$$

$$\textcircled{X} V_{0n} = \frac{4V_s \sin n\pi}{n\pi} \cdot \frac{(\sin nd)}{2} \cdot \frac{(\sin n\omega t)}{(\sin n\omega t)}$$

• $\textcircled{X} V_{0n}=0, \quad nd=\pi, 2\pi, 3\pi \dots$

$$d = \frac{\pi}{n}, \frac{2\pi}{n}, \frac{3\pi}{n}$$

$$2d = \frac{2\pi}{n}, \frac{4\pi}{n}, \frac{6\pi}{n} \dots$$

If $n=3, 2d=120^\circ$

$n=5, 2d=72, 144^\circ$

$$\textcircled{X} V_{0r} = \frac{4V_s \sin d}{\pi \sqrt{2}}$$

$$V_{01} = \frac{2\sqrt{2}V_s \sin d}{\pi}$$

$$\textcircled{X} g = \frac{V_{0r}}{V_{0r}} = \frac{2\sqrt{2}V_s \sin d n / \pi}{V_s \left(\frac{2d}{\pi} \right)^{1/2}}$$

$$g = \frac{2\sqrt{2} \sin d n}{\sqrt{2d} \pi}$$

$$\textcircled{X} g = \frac{3}{\pi}, \quad THD = 31\%$$

Multi PWM

$$\textcircled{X} N = \frac{f_c}{2f_r}$$

$$\textcircled{X} PW = \left(1 - \frac{V_d}{V_c} \right) \frac{\pi}{N}$$

Sinusoidal Pwm

$$\textcircled{X} N = \frac{f_c}{2f_r} - 1$$

$$\textcircled{X} \text{Dominant} = 2N \pm 1 \\ \text{Harmonic}$$

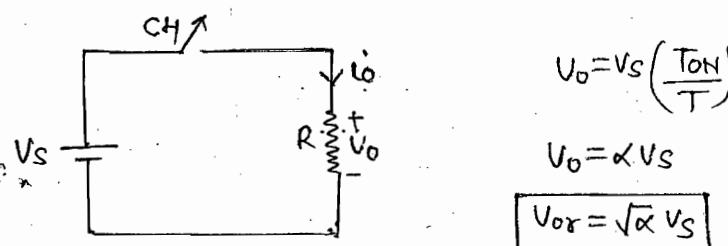
Choppers

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fixed dc \longrightarrow variable dc
 (V_S) (V_O)

(1) Step down chopper \rightarrow ($V_O < V_S$) (Buck converter)

For R load



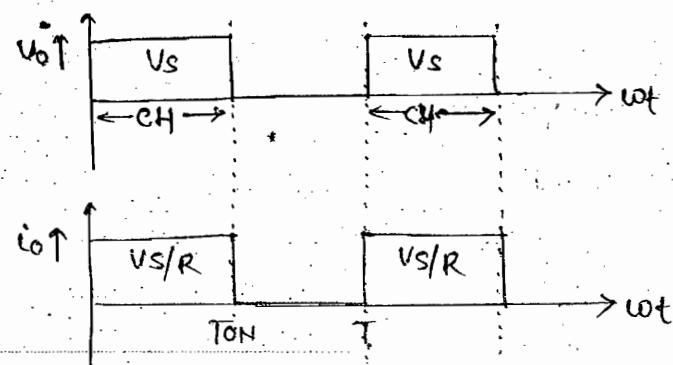
$$V_O = V_S \left(\frac{T_{ON}}{T} \right)$$

$$V_O = \alpha V_S$$

$$V_{OR} = \sqrt{\alpha} V_S$$

$$\alpha = \frac{T_{ON}}{T}$$

(duty cycle)



Fourier Series for O/p voltage.

$$V_O = \alpha V_S + \sum_{n=1}^{\infty} \frac{2V_S}{n\pi} \sin(n\pi\alpha) \cdot \sin(n\omega t + \phi_n)$$

$$\text{where } \phi_n = \tan^{-1} \left(\frac{\cos n\alpha}{\sin n\alpha} \right)$$

$$V_{O,n} = \frac{2V_S}{n\pi} \sin(n\pi\alpha) \sin(n\omega t + \phi_n)$$

$$V_{O,n} = 0 \text{ . then } n\alpha = 1$$

$$\alpha = \frac{1}{n}$$

Cond'n to eliminate n th harmonics

$$FF = \frac{V_{OR}}{V_O} = \frac{\sqrt{\alpha} V_S}{\alpha V_S}$$

$$FF = \frac{1}{\sqrt{\alpha}}$$

$$V_{RF} = \sqrt{FF^2 - 1}$$

$$VRF = \sqrt{\frac{1}{\alpha} - 1}$$

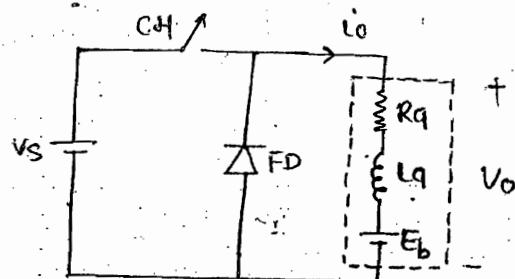
$\alpha \uparrow, VRF \downarrow \therefore \text{Harmonics} \downarrow$

effect of

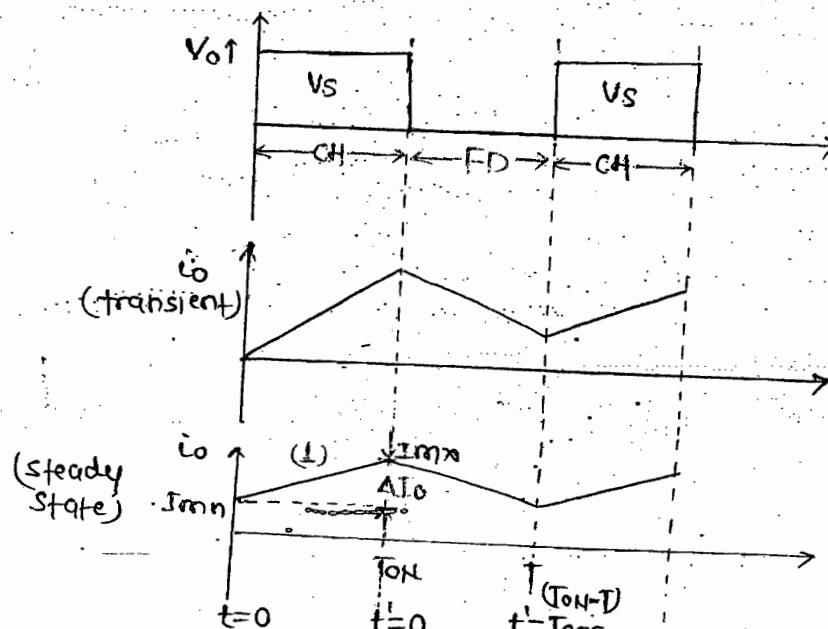
* If it is continuous conduction there is no back emf in the o/p voltage waveform.

Therefore the o/p Vol. waveform is remain same for RL & RLE load.

For RLE load →



DC Motor



At transient the value of current will first starts from 0 value & then goes to steady state value

$$V_o = V_s \left(\frac{T_{ON}}{T} \right)$$

$$V_o = \alpha V_s$$

$$V_{o,r} = \sqrt{\alpha} V_s$$

} RL & RLE

$$I_o = \frac{V_o - E_b}{R_q}$$

$$I_o = \frac{\alpha V_s - E_b}{R_q}$$

RLE

$$I_o = \frac{\alpha V_s}{R_q}$$

RL

* Avg. current does not depend on load inductance but the ripple current depends on the load inductance.

* mod(i.) ($0 \leq t \leq T_{ON}$)

CH \rightarrow ON (KVL)

$$V_S = R_{AI} + L_q \frac{dI_{AO}}{dt} + E_b$$

$$V_g - E_b = R_{AI} + L_q \frac{dI_{AO}}{dt}$$

$$\left(\tau_q = \frac{L_q}{R_q} \right)$$

$$i_0 = \frac{V_S - E_b}{R_q} (1 - e^{-t/\tau_q}) \quad [\text{eqn from starting to } 0] \quad (\text{transient})$$

$$i_0 = \frac{V_S - E_b}{R_q} (1 - e^{-t/\tau_q}) + I_{m0} e^{-t/\tau_q} \quad [\text{From the } I_{m0} \text{ value}] \quad (\text{steady state})$$

--- (i)

$$I_{m0} = \frac{V_S - E_b}{R_q} (1 - e^{-T_{ON}/\tau_q}) + I_{m0} e^{-T_{ON}/\tau_q} \quad --- (ii)$$

Mode (II) $\rightarrow (T_{ON} \leq t \leq T)$ (or) ($0 \leq t' \leq T_{OFF}$)

FD \rightarrow ON : (KVL)

$$R_{AI} + L_q \frac{dI_{AO}}{dt'} + E_b = 0$$

$$-E_b = R_{AI} + L_q \frac{dI_{AO}}{dt'}$$

$$i_0 = -\frac{E_b}{R_q} (1 - e^{-t'/\tau_q}) + I_{m0} e^{-t'/\tau_q} \quad --- (iii)$$

$$I_{m0} = -\frac{E_b}{R_q} (1 - e^{-T_{OFF}/\tau_q}) + I_{m0} e^{-T_{OFF}/\tau_q} \quad --- (iv)$$

By solving the eqn (ii) & (iv), we can find the values of I_{m0} & I_{mn}

$$I_{m0} = \frac{V_S}{R_q} \left[\frac{1 - e^{-T_{ON}/\tau_q}}{1 - e^{-T/\tau_q}} \right] - \frac{E_b}{R_q} \quad --- (v)$$

$$I_{m0} = \frac{V_S}{R_q} \left[\frac{e^{T_{ON}/\tau_q} - 1}{e^{T/\tau_q} - 1} \right] - \frac{E_b}{R_q} \quad --- (vi)$$

Ripple current = $I_{max} - I_{min}$

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$$\Delta I_o = \frac{V_s}{Rq} \left[\frac{(1-e^{-T_{ON}/\tau_q}) - (e^{T_{ON}/\tau_q} - 1)}{(1-e^{-T/\tau_q}) - (e^{T/\tau_q} - 1)} \right]$$

$$\Delta I_o = \frac{V_s}{Rq} \left[\frac{(1-e^{-T_{ON}/\tau_q})(1-e^{-T_{OFF}/\tau_q})}{(1-e^{-T/\tau_q})} \right] \quad (T = T_{OFF} + T_{ON})$$

$$\Delta I_o = \frac{V_s}{Rq} \left[\frac{(1-e^{-\alpha T/\tau_q})(1-e^{-(1-\alpha)T/\tau_q})}{1-e^{-T/\tau_q}} \right]$$

$$T_{ON} = \alpha T$$

$$T_{OFF} = (1-\alpha)T$$

For maxⁿ value of the max^m Ripple current

$$\frac{d(\Delta I_o)}{d\alpha} = \frac{d}{d\alpha} \left\{ \frac{V_s}{Rq} \left[\frac{(1-e^{-\alpha T/\tau_q})(1-e^{-(1-\alpha)T/\tau_q})}{(1-e^{-T/\tau_q})} \right] \right\} = 0$$

$$\alpha = 0.5$$

$$(\Delta I_o)_{max} = \frac{V_s}{Rq} \left[\frac{(1-e^{-0.5T/\tau_q})(1-e^{-0.5T/\tau_q})}{(1-e^{-T/\tau_q})} \right]$$

$$(\Delta I_o)_{max} = \frac{V_s}{Rq} \tanh \frac{T}{4\tau_q} \quad (\tanh x \approx x)$$

$$(\Delta I_o)_{max} = \frac{V_s}{Rq} \times \frac{T}{4\tau_q} = \frac{V_s}{Rq} \times \frac{T}{4 \times Lq} = \frac{V_s}{F} \times \frac{1}{4Lq}$$

$$(\Delta I_o)_{max} = \frac{V_s}{4F \cdot Lq}$$

(max^m value of Ripple current at $\alpha=0.5$)

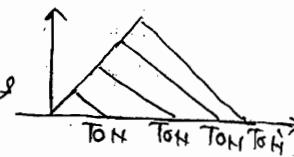
$$(1) \downarrow (\Delta I_o) \propto \frac{1}{F(L \uparrow)} \quad (\text{But equipment size will increase})$$

* By increasing the load inductance the ripple current reduce.

$$(2) \downarrow (\Delta I_o) \propto \frac{1}{(F) L}$$

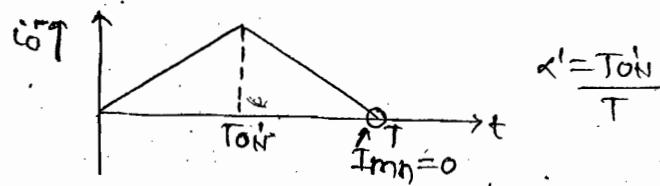
- * At high chopping freq; we can eliminate the ripple current without increase the size of inductor.
- * Smps operates based on the above chopper principle.
- * At low values of T_{ON} it gives discontinuous.

α' = duty cycle limit for continuous



Duty cycle limit for continuous conduction →

- * α' is the duty cycle at the boundary between continuous & discontinuous conduction.



at $t=T$, $I_{max}=0$

$$\frac{V_s}{Rq} \left[\frac{e^{T_{on}/cq-1}}{e^{T/cq-1}} \right] - \frac{E_b}{Rq} = 0$$

$$\frac{V_s}{Rq} \left[\frac{e^{T_{on}/cq-1}}{e^{T/cq-1}} \right] = \frac{E_b}{Rq}$$

$$m \left[\frac{e^{T_{on}/cq-1}}{e^{T/cq-1}} \right] = \frac{E_b}{V_s}$$

$$(e^{T_{on}/cq-1}) = m(e^{T/cq-1}) \quad (\frac{E_b}{V_s} = m)$$

$$\frac{T_{on}/cq}{T/cq} = m \cdot 1 + m(e^{T/cq-1})$$

$$\frac{T_{on}}{cq} = \ln [1 + m(e^{T/cq-1})]$$

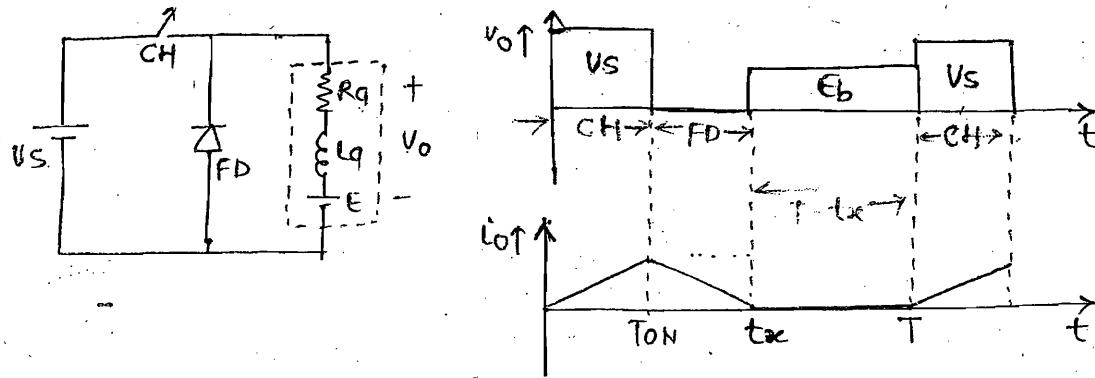
$$\Rightarrow \frac{T_{on}}{T} = \frac{cq}{T} \ln [1 + m(e^{T/cq-1})]$$

$$\boxed{\alpha' = \frac{T_{on}}{T} = \frac{cq}{T} \ln [1 + m(e^{T/cq-1})]}$$

$\alpha < \alpha'$ → discontinuous

$\alpha > \alpha'$ → continuous

* Discontinuous Conduction →



$$v_o = V_s \left(\frac{T_{ON}}{T} \right) + E_b \left(\frac{T-t_{ex}}{T} \right)$$

$$v_o = V_s \alpha + E_b \left(1 - \frac{t_{ex}}{T} \right)$$

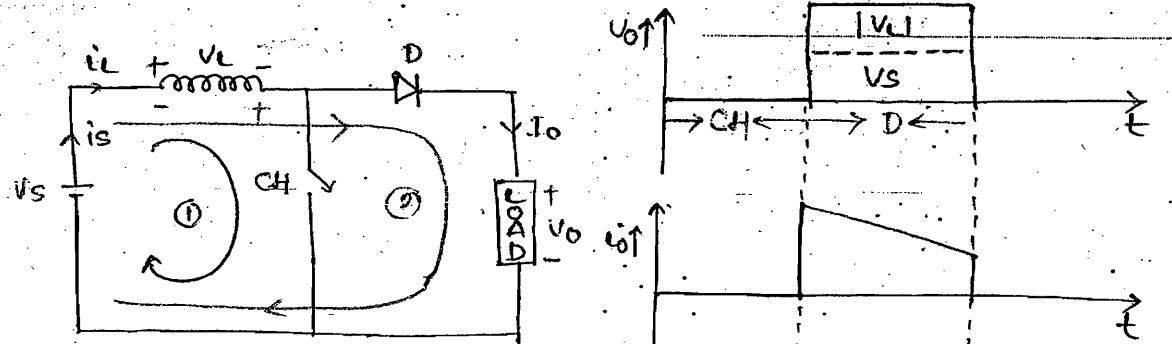
(t_{ex} → extinction time)

$$v_{o\text{r}} = \left[V_s^2 \left(\frac{T_{ON}}{T} \right) + E_b^2 \left(\frac{T-t_{ex}}{T} \right) \right]^{1/2}$$

$$v_{o\text{r}} = \left[\alpha^2 V_s^2 + E_b^2 \left(1 - \frac{t_{ex}}{T} \right) \right]^{1/2}$$

DATE-28/08/14

Step up chopper →



(I) $0 \leq t \leq T_{ON} \rightarrow$

CH → ON, D → OFF, $v_o = 0$

$$i_o = 0$$

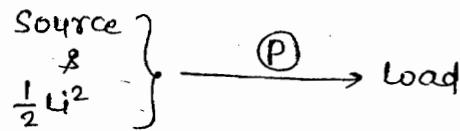
$$V_s = V_L = \frac{d i_{st}}{dt}$$

$L \rightarrow$ stores energy

(iii) $T_{ON} \leq t \leq T \rightarrow$

CH \rightarrow OFF, D \rightarrow ON, $i_S = i_o$

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Step up chopper
Boost converter



L \rightarrow Releasing energy

$$V_o = V_s + |V_L|$$

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

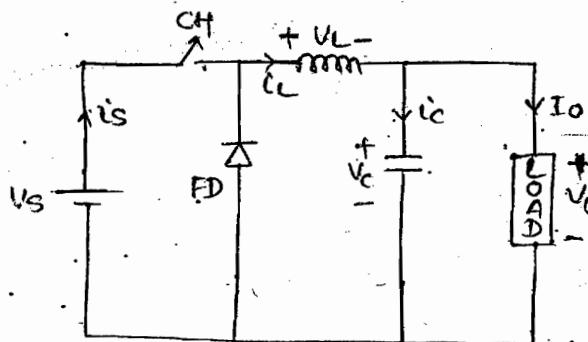
$$\alpha < 1, V_o > V_s$$

* In step up chopper power flows from low vol. side to high voltage side

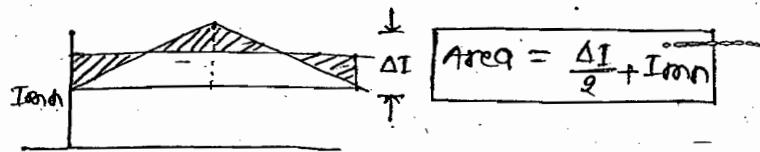
* Step up chopper principle can be used for regenerative braking of dc m/c.

* Choppers with filters \rightarrow * In order to reduce the harmonics & improve the quality of o/p waveform we have to use filters.

* Step down chopper (Buck converter) \rightarrow For 1st order low pass filter we use resistance but in the resistance power loss occurs.



$i_L \rightarrow$ DC Component ($I_L q_{avg}$)
 $i_L \rightarrow$ AC Component (At multiple Harmonic freq.)



- * Let us assume very large value of filter capacitance. So that the o/p voltage remains almost constant.

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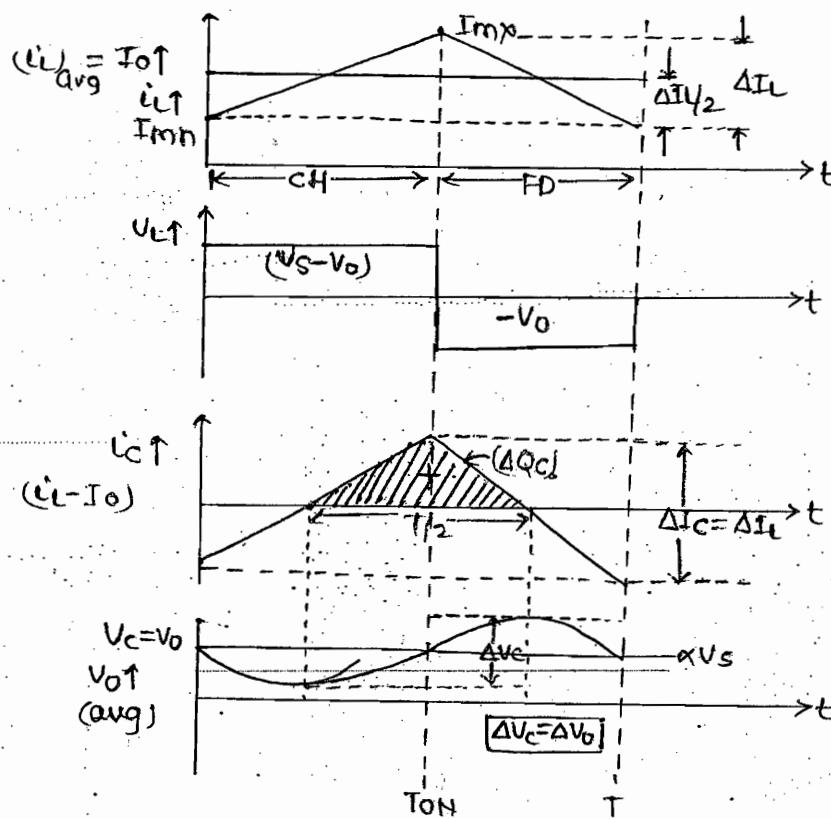
$$X_C = \frac{1}{\omega C} \approx 0 \text{ (AC comp) (short circuited)}$$

$$X_C = \frac{1}{\omega C} \approx \infty \text{ (DC comp.) (open circuited)}$$

- * Capacitor will only allow only AC comp. (Ripple).

- * All the AC comp. will bypass through capacitor then;

$$(\Delta I_L) = (\Delta I_C)$$



Integral of (parabolic)
Linear = $\int x dx = \frac{x^2}{2}$

discharge
Charging →
of capacitor

④ 0 ≤ t ≤ T_{ON} → CH → ON

$$-V_s + V_L + V_o = 0$$

$$V_L = V_s - V_o$$

$$\frac{dI_L}{dt} = V_s - V_o$$

$$\frac{dI_L}{dt} = \frac{V_s - V_o}{L}$$

$$I_{mx} = \int_{I_{mn}}^{I_{mx}} \frac{V_s - V_o}{L} dt$$

$$\Delta I_L = \frac{V_s - V_o}{L} \cdot T_{ON}$$

$$= \frac{V_s - \alpha V_s}{L} \cdot \frac{\alpha}{f}$$

$$\left\{ \begin{array}{l} T_{ON} = \alpha T \\ = \frac{\alpha}{f} \end{array} \right.$$

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

$$(\Delta I_L)_{max} = \frac{V_s}{4fL} \rightarrow \alpha = 0.5$$

(III) $T_{ON} \leq t \leq T \rightarrow C_1 \rightarrow OFF, F_D \rightarrow ON$

$$+V_L + V_0 = 0$$

$$V_L = -V_0$$

$$(V_L)_{avg} = 0$$

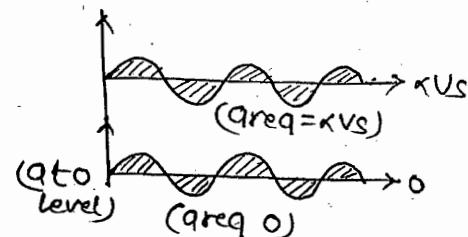
$$+ve \text{ area} + (-ve) \text{ area} = 0$$

$$(V_S - V_0) T_{ON} + V_0 T_{OFF} = 0$$

$$V_S T_{ON} = V_0 [T_{ON} + T_{OFF}]$$

$$V_0 = V_S \kappa$$

$$\kappa = \frac{T_{ON}}{T}$$



From the area of Δ in the waveform

$$\Delta Q = C \cdot \Delta V_C$$

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

$$\Delta V_C = \frac{\Delta I_L}{8 f C}$$

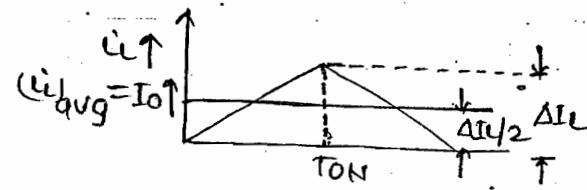
$$\text{where } \Delta Q = \frac{1}{2} \cdot \frac{T}{2} \cdot \frac{\Delta I_L}{2}$$

$$\Delta Q = \frac{\Delta I_L}{8f}$$

$$\Delta V_C = \frac{\kappa(1-\kappa)V_S}{8f^2LC} \quad \text{--- (2.)}$$

* If we increase the value of $f \uparrow$ then ΔV_C will decrease, & we will get pure dc current ($\Delta V_C = 0$)

Critical inductance $\rightarrow (L_c)$ It is the value of inductance at which I_L waveform is just discontinuous.



$$I_0 = \frac{\Delta I_L}{2}$$

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

$$L_c = \frac{(1-\kappa)R}{2f} \quad \text{--- (3.)}$$

* Critical Capacitance → It is the value of capacitance at which the v_c waveform is just discontinuous.

(C_c)

$$V_o = \frac{\Delta v_c}{2} (\text{at } C_c)$$

$$V_o = \frac{\alpha(1-\alpha) V_s}{16\pi^2 LC}$$

$$\alpha V_s = \frac{\alpha(1-\alpha) V_s}{16\pi^2 L C_c}$$

$$C_c = \frac{(1-\alpha)}{16\pi^2 L C}$$

----- (4.)

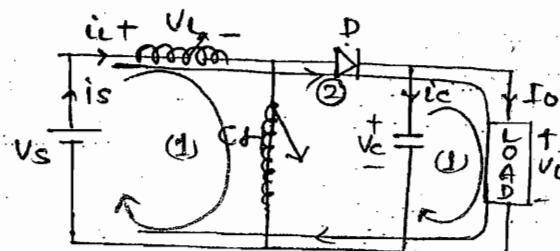
$$P_o = P_{in}$$

$$V_o I_o = V_s I_s$$

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

$$I_s = \alpha I_o$$

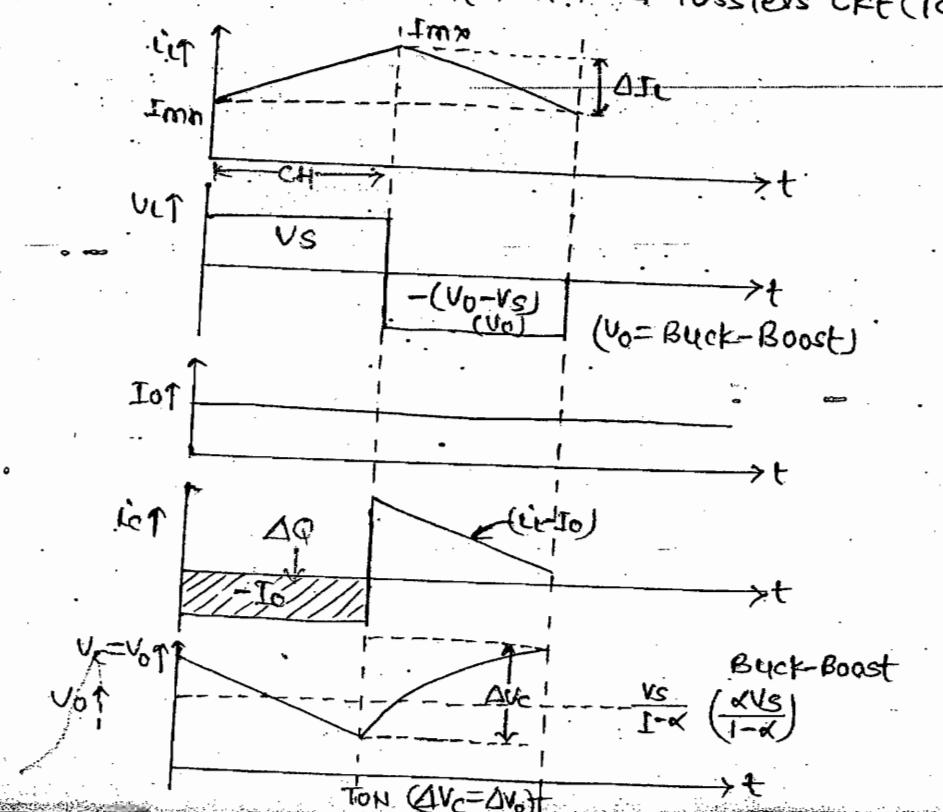
* Step up chopper (Boost Converter) →



$$i_i = i_{cto} + \\ (I_{min}) > (I_o)$$

* Let's assume large value of filter capacitance so that the o/p vol. remains const

* Let's assume const load current & it is a lossless ckt (ideal ckt)



(I) $0 \leq t \leq T_{ON} \rightarrow$ CH \rightarrow ON, D \rightarrow OFF

$$i_c = -I_0$$

$$V_L = V_S$$

$$\frac{dil}{dt} = \frac{V_S}{L}$$

$$\text{Imp. } \int dil = \int \frac{V_S}{L} dt$$

$$I_{mn} = 0$$

$$\Delta I_L = \frac{V_S}{L} \cdot T_{ON}$$

$$\Delta I_L = \frac{\alpha V_S}{fL} \quad \text{--- (1)}$$

$$(V_L)_{avg} = 0$$

$$V_S T_{ON} = (V_0 - V_S) T_{OFF} = 0$$

$$V_S (T_{ON} + T_{OFF}) = V_0 T_{OFF}$$

$$V_S f = V_0 (1-\alpha) f$$

$$V_0 = \frac{V_S}{1-\alpha}$$

$$P_0 = P_{in}$$

$$V_0 I_0 = V_S I_S$$

$$\frac{V_0}{V_S} = \frac{I_S}{I_0} = \frac{1}{(1-\alpha)}$$

$$I_S = \frac{I_0}{(1-\alpha)}$$

$$\Delta Q = C \Delta V_C$$

$$\Delta V_C = \frac{\Delta Q}{C} = \frac{I_0 T_{ON}}{C}$$

$$\Delta V_C = \frac{\alpha I_0}{fC} \quad \text{--- (2)}$$

$$T_{ON} = \alpha T = \frac{\alpha}{f}$$

(II) $T_{ON} \leq t \leq T \rightarrow$ CH \rightarrow OFF; D \rightarrow ON

$$i = i_c + i_0$$

$$-V_S + V_L + V_0 = 0$$

$$V_L = V_S - V_0$$

$$* V_L = -(V_S - V_0)$$

* ($V_0 > V_S$)
step up

Critical inductance (L_c) →

$$I_0 = \frac{\Delta IL}{2} \text{ (at } L_c\text{)}$$

$$\frac{V_s}{(1-\alpha)R} = \frac{\alpha V_s}{2FL_c}$$

$$L_c = \frac{\alpha(1-\alpha)R}{2F} \quad \text{--- (3.)}$$

Critical capacitance (C_c) →

$$V_0 = \frac{4Vc}{2}$$

$$I_0 R = \frac{\kappa I_0}{2F C_c}$$

$$C_c = \frac{\kappa}{2FR} \quad \text{--- (4.)}$$

Non-ideal case → (Practical)

$r \rightarrow$ internal resistance of inductance

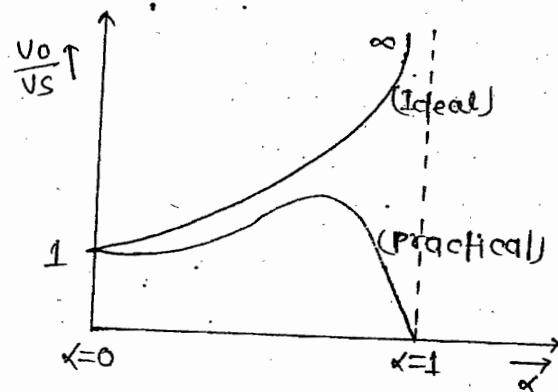
$R \rightarrow$ Load resistance.

$$V_0 = V_s(1-\alpha)$$

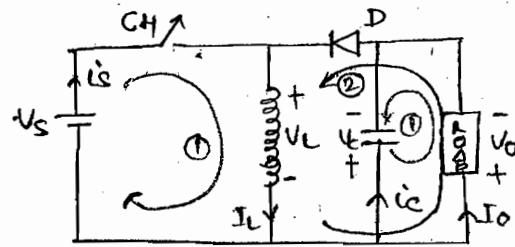
$$\frac{r}{R} + (1-\alpha)^2$$

(Not in syllabus)

If question is ask in the form of ^{resistor} internal ~~resistance~~ of inductance



Step down/up chopper (Buck-Boost Converter) →



* Let us assume constant o/p vol & current & it is a lossless ckt.

(I) $0 \leq t \leq T_{ON} \rightarrow CH \rightarrow ON, D \rightarrow OFF$

$$i_C = -I_0$$

$$V_L = V_S$$

$$\begin{aligned} \frac{d i_L}{d t} &= V_S \\ \int_{I_{m0}}^{I_m} d i_L &= \frac{V_S}{L} \int_0^{T_{ON}} dt \\ I_m - I_{m0} &= \frac{V_S}{L} T_{ON} \end{aligned}$$

$$\boxed{\Delta I_L = \frac{\alpha V_S}{fL}} \quad \text{--- (i)}$$

(II) $T_{ON} \leq t \leq T \rightarrow$

$CH \rightarrow OFF, D \rightarrow ON$

$$i_L = i_C + I_0$$

$$+V_L + V_0 = 0$$

$$V_L = -V_0$$

$$(V_L)_{avg} = 0$$

$$V_S T_{ON} - V_0 T_{OFF} = 0$$

$$V_S T_{ON} = V_0 T_{OFF}$$

$$V_S (\alpha T) = V_0 (1 - \alpha) T$$

$$\boxed{V_0 = \frac{\alpha V_S}{(1-\alpha)}} \quad \text{--- (ii)}$$

$$V_0 I_0 = V_S I_S$$

$$\boxed{\frac{V_0}{V_S} = \frac{I_S}{I_0} = \frac{\alpha}{(1-\alpha)}} \quad \text{--- (iii)}$$

$$\boxed{I_S = \frac{\alpha I_0}{(1-\alpha)}} \quad \text{--- (iv)}$$

$$\Delta Q = C \cdot \Delta V_C$$

$$\Delta V_C = \frac{\Delta Q}{C} = \frac{I_0 T_{ON}}{C}$$

$$\boxed{\Delta V_C = \frac{\alpha I_0}{fC}} \quad \text{--- (v)}$$

Critical Inductance (L_c) →

$$I_0 = \frac{\Delta I_L}{2} \text{ (at } L_c\text{)}$$

$$\frac{\alpha V_s}{(1-\alpha)R} = \frac{\alpha V_s}{2fLc}$$

$$L_c = \frac{(1-\alpha)R}{2f} \quad \dots \dots (3)$$

Critical Capacitance (C_c) →^{143}

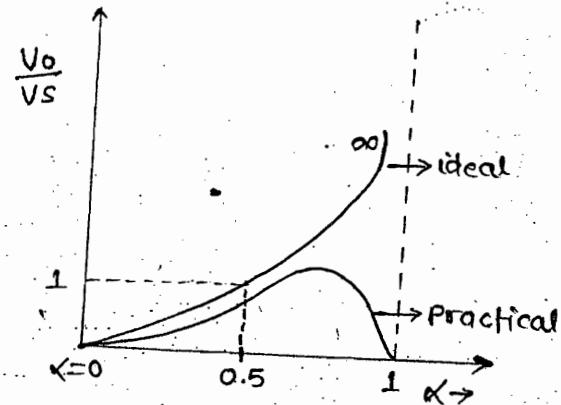
$$V_0 = \frac{\Delta V_C}{2}$$

$$I_0 R = \frac{\alpha I_0}{2fC_c}$$

$$C_c = \frac{\alpha}{2fR} \quad \dots \dots (4.)$$

Non-ideal Case →

$$V_0 = \frac{V_s \alpha (1-\alpha)}{\frac{\pi}{R} + (1-\alpha)^2}$$

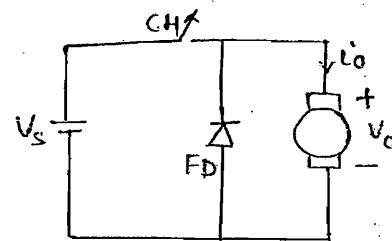


$$\begin{aligned} \alpha < 0.5, V_0 &< V_s \\ \alpha > 0.5, V_0 &> V_s \end{aligned}$$

Parameters	Step down (Buck Config)	Step up chopper (Boost Config)	Step up/down chopper (Buck-Boost Config)
* ΔI_L	$\frac{\alpha(1-\alpha)V_S}{fL}$	$\frac{\alpha V_S}{fL}$	$\frac{\alpha V_S}{fL}$
* $(\Delta I_U)_{max}$ ($\alpha=0.5$)	$\frac{V_S}{4fL}$	$\frac{V_S}{2fL}$	$\frac{V_S}{2fL}$
* V_0	αV_S	$\frac{V_S}{(1-\alpha)}$	$\frac{\alpha V_S}{(1-\alpha)}$
* ΔQ_C	$\frac{\Delta I_L}{8f}$	-	-
* ΔV_C	$\frac{\alpha(1-\alpha)V_S}{8f^2LC}$	$\frac{\alpha I_0}{fC}$	$\frac{\alpha I_0}{fC}$
* L_C	$\frac{(1-\alpha)R}{2f}$	$\frac{\alpha(1-\alpha)R}{2f}$	$\frac{(1-\alpha)R}{2f}$
* C_C	$\frac{(1-\alpha)}{16f^2LC}$	$\frac{\alpha}{2fR}$	$\frac{\alpha}{2fR}$
* Ratio	$\frac{V_0}{V_S} = \frac{I_S}{I_0} = \alpha$	$\frac{V_0}{V_S} = \frac{I_S}{I_0} = \frac{1}{(1-\alpha)}$	$\frac{V_0}{V_S} = \frac{I_S}{I_0} = \frac{\alpha}{1-\alpha}$
* I_S	αI_0	$I_0 \left(\frac{1}{1-\alpha}\right)$	$\frac{\alpha I_0}{(1-\alpha)}$
* V_0 (Practical)	$V_{SIR} =$	$\frac{V_S(1-\alpha)}{\frac{r}{L} + (1-\alpha)^2}$	$\frac{V_S\alpha(1-\alpha)}{\frac{r}{L} + (1-\alpha)^2}$

Classification of chopper based on quadrant operation →

(1) First quadrant chopper: (Type A) → (step down chopper)

 $V_o \uparrow$

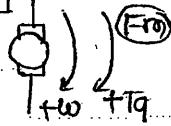
(I) CH → ON, $V_o = V_s \therefore E_b + I_o t$
 $I_o t \therefore T_{q+}$

(II) CH → OFF, FD → ON [FWP - Free wheeling period]

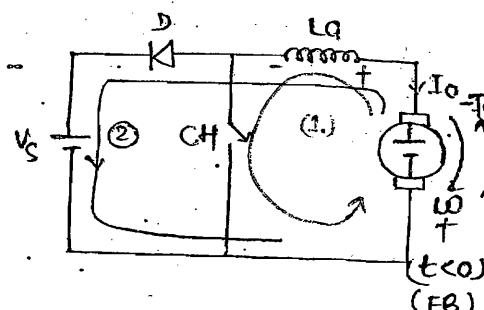
$$V_o = \alpha V_s = E_b + I_o R_q$$

$$\omega = \frac{\alpha V_s}{K} - \frac{R_q}{K^2} T_q$$

$$\frac{V_o t}{I_o t} = \frac{P(t)}{P(t)} \phi(t)$$

 $\rightarrow I_o \rightarrow$

(2) 2nd quadrant Chopper (Type B) →



Let us assume that the m/c is running at rated speed in the forward direction before $t=0$.

$$\text{Brake energy at } t=0 = \frac{1}{2} J \omega^2$$

(I) $0 \leq t \leq T_{ON} \rightarrow$

CH → ON, D → OFF

$$(V_o = 0) \because (I_o = 0), \therefore (T_q = 0)$$

$$\frac{1}{2} J \omega^2 \rightarrow \frac{1}{2} L_i^2$$

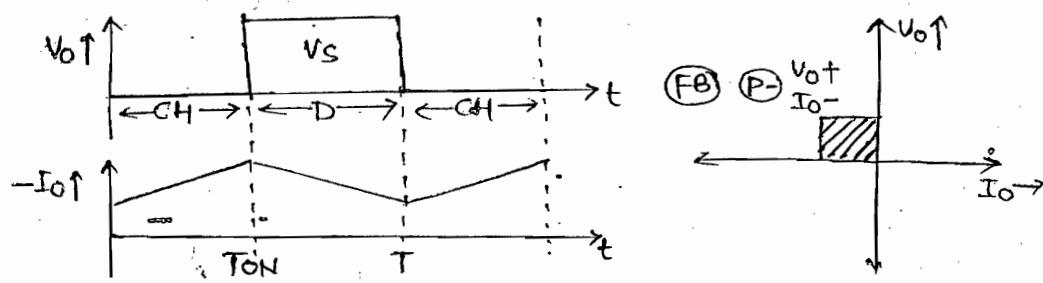
(II) $T_{ON} \leq t \leq T \rightarrow$

CH → OFF, D → ON

$$\frac{1}{2} L_i^2 \rightarrow \text{Source}$$

L → releasing energy

$$V_o = V_s$$

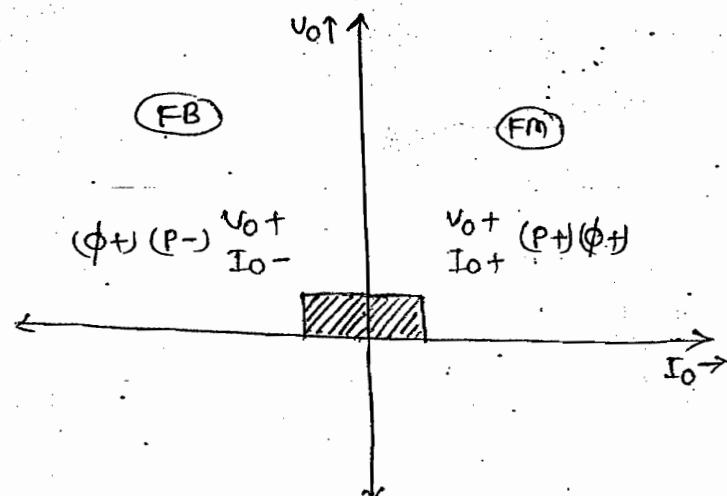
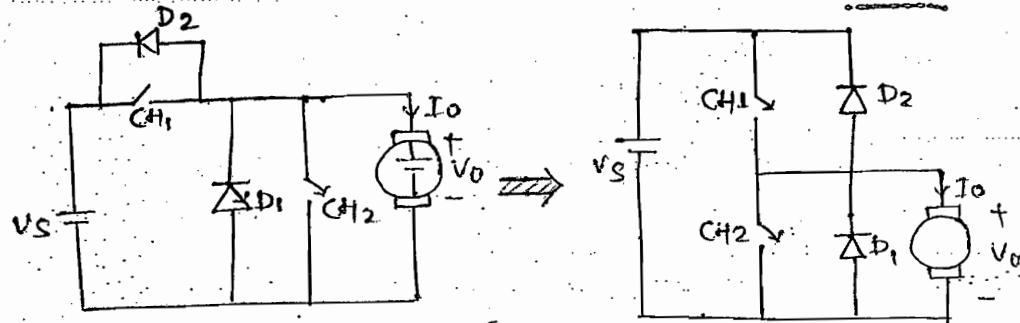


Source $\xleftarrow{(P)}$ Brake energy
 \therefore Regenerative Braking

HU $\xleftarrow{ }$ LV

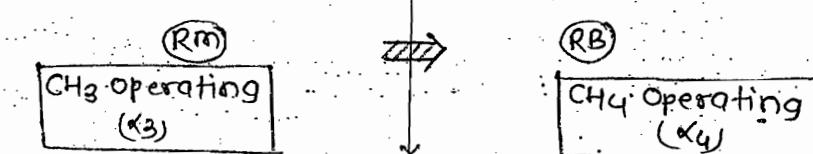
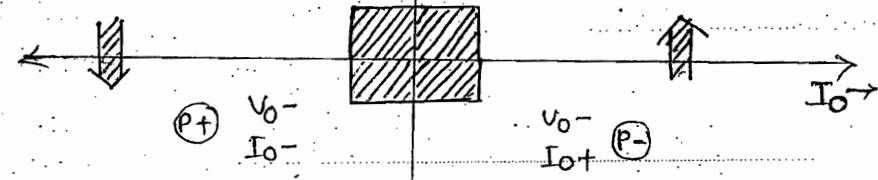
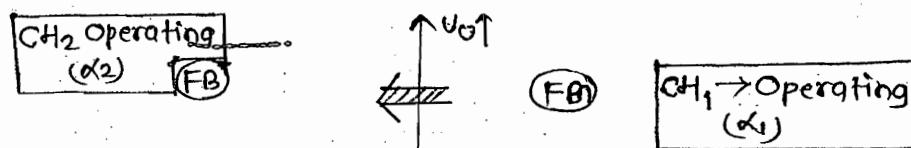
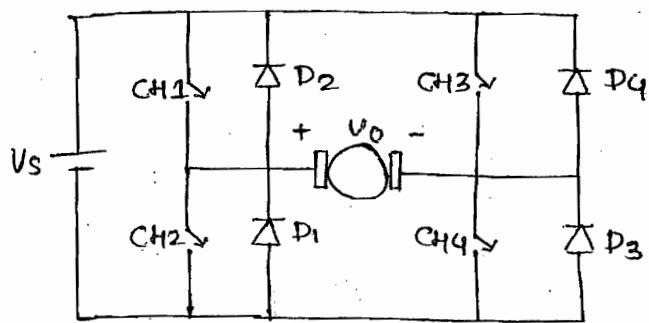
$$\text{Regenerative Power} = V_o I_o \quad (V_o < V_S) \\ = (1 - \alpha) V_S \cdot I_o$$

3) Two quadrant Chopper \rightarrow



(4) Four Quadrant Chopper →

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(1) CH₂, D₃ → ON
 $V_o = 0 \because I_o = 0 \therefore T_q$
 $\frac{1}{2} J w^2 \rightarrow \frac{1}{2} Q^2$

(2) CH₂ → OFF

D₂, D₃ → ON

$\frac{1}{2} J w^2 \rightarrow \text{source}$

(1) CH₁, CH₄ → ON, $V_o = V_s \therefore E_{bt}, \therefore w + I_{ot}, \therefore T_q f$

(2) CH₁ → OFF

CH₄ → D₁ → ON (FW P)

$V_o + I_{ot} P(t) \phi(t)$

AC Voltage Controller

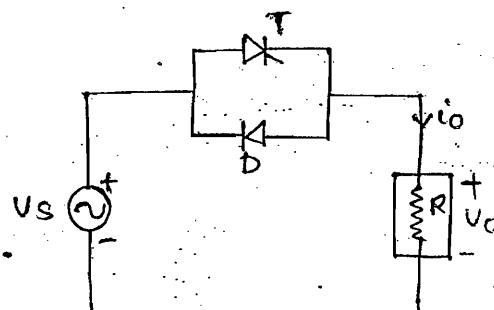
Fixed AC \rightarrow Variable AC
 $f(\text{const})$

(1) Phase Control tech.

(2) Integral cycle control (ON/OFF)

(1) Phase Control tech \rightarrow

(i) Single phase half controlled AC Vol. Controller \rightarrow

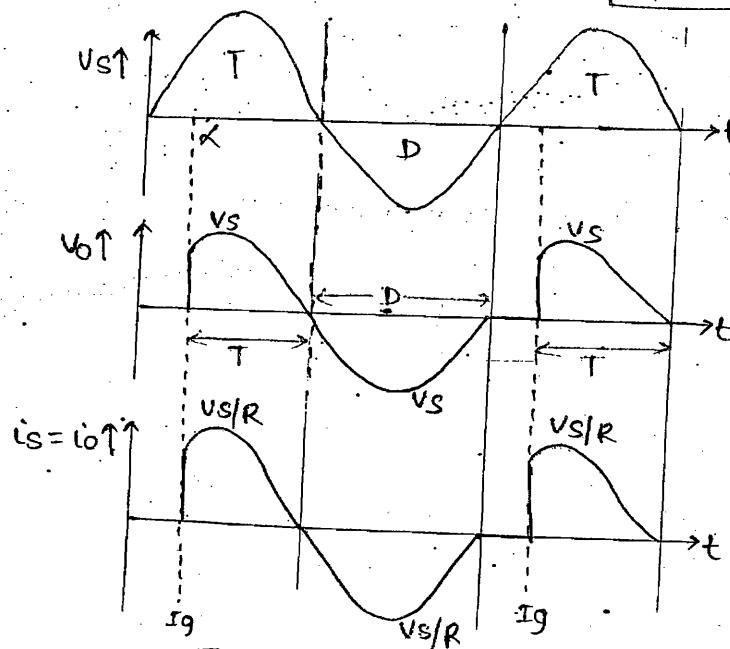


$$V_o = \frac{1}{2\pi} \int_{0}^{2\pi} V_m \sin \omega t \cdot d(\omega t)$$

$$V_o = \frac{V_m}{2\pi} [\cos \alpha - 1]$$

$$(I_s)_{\text{avg}} = I_0 = \frac{V_m}{2\pi R} [\cos \alpha - 1]$$

↓ DC Comp.



Drawback \rightarrow

* The source current contains dc comp. & saturates the supply Xmer core.
 Therefore this type of AC vol. controllers are not preferred in applications.

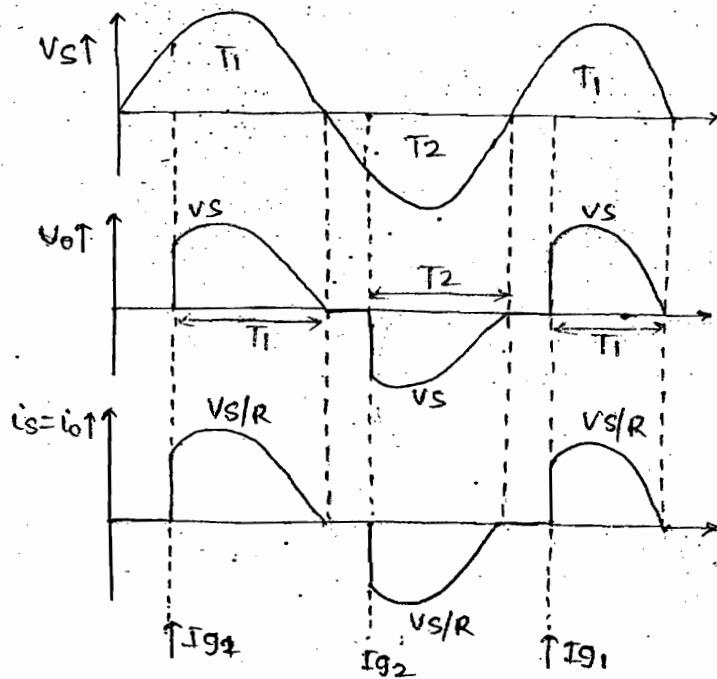
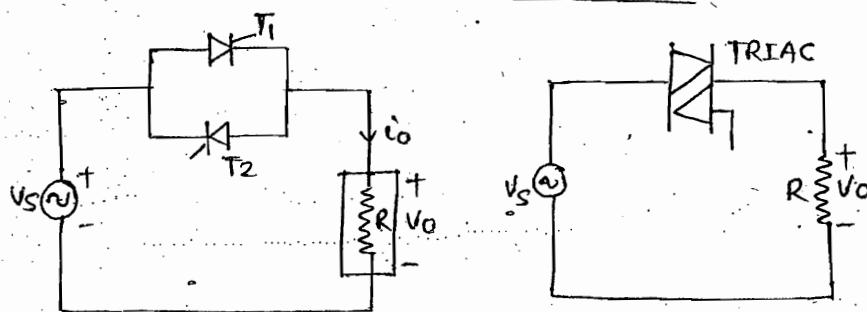
$$V_{or} = \left\{ \frac{1}{2\pi} \int_0^{2\pi} V_m^2 \sin^2 \omega t \cdot d(\omega t) \right\}^{1/2}$$

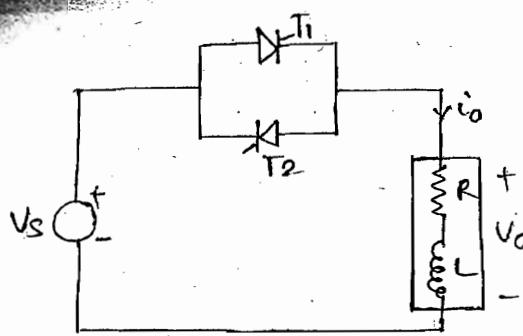
$$V_{or} = \frac{V_m}{2\sqrt{\pi}} \left\{ (2\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right\}^{1/2}$$

For R Load \rightarrow

$$PF = \frac{V_{or}}{V_{sr}} = \frac{1}{\sqrt{2\pi}} \left\{ (2\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right\}^{1/2}$$

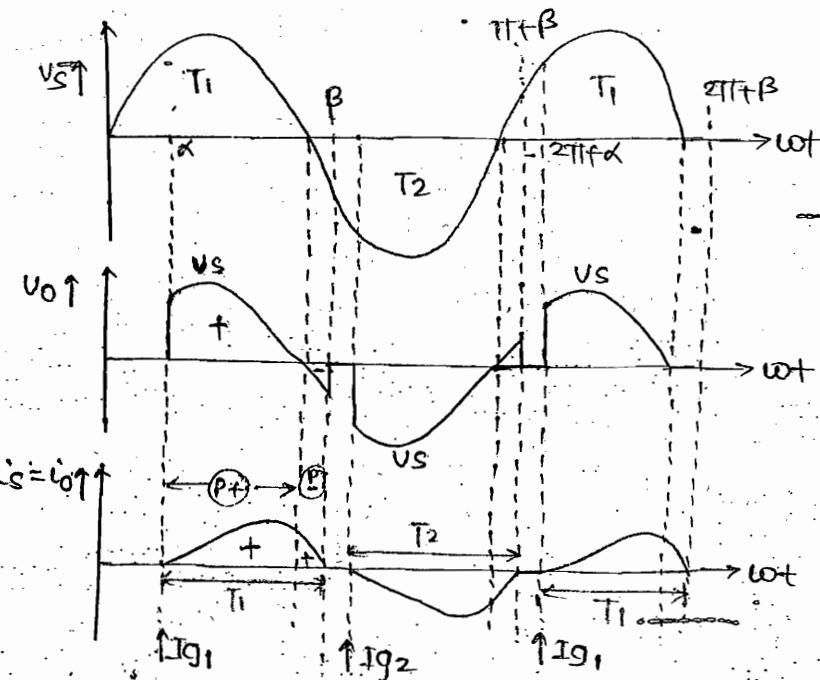
(2) 1φ Full Controlled AC Voltage Controller \rightarrow





After reaching steady state,
 v_o lags V_s by $\phi = \tan^{-1} \frac{wL}{R}$

- (i) $\alpha > \phi$, v_o is controlled
- (ii) $\alpha \leq \phi$, v_o is uncontrolled.



(i) $\alpha > \phi$, v_o is controlled \rightarrow

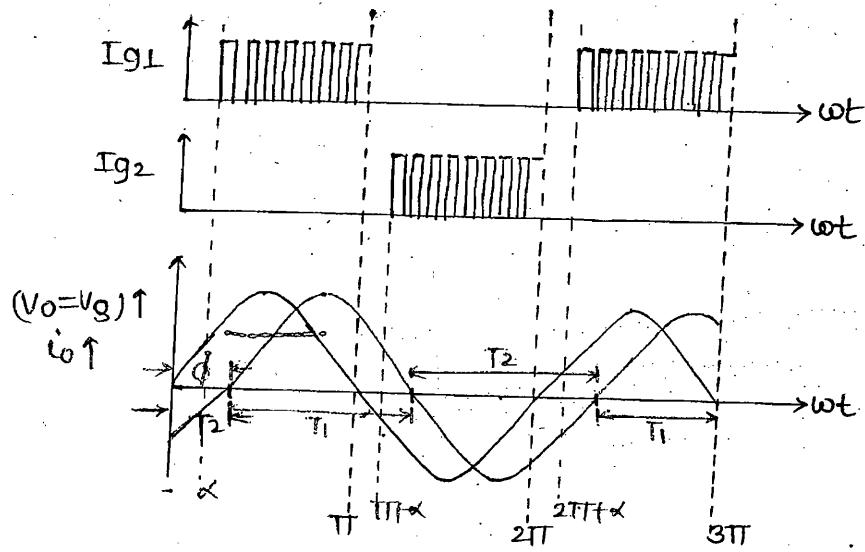
$$V_{\phi r} = \frac{V_m}{\sqrt{2T}} \left[(\beta - \phi) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right]^{1/2}$$

$$I_{\phi r} = \frac{V_{\phi r}}{|z|} \quad \text{where } |z| = \sqrt{R^2 + (\omega L)^2}$$

(ii) $\alpha \leq \phi$, v_o is uncontrolled \rightarrow

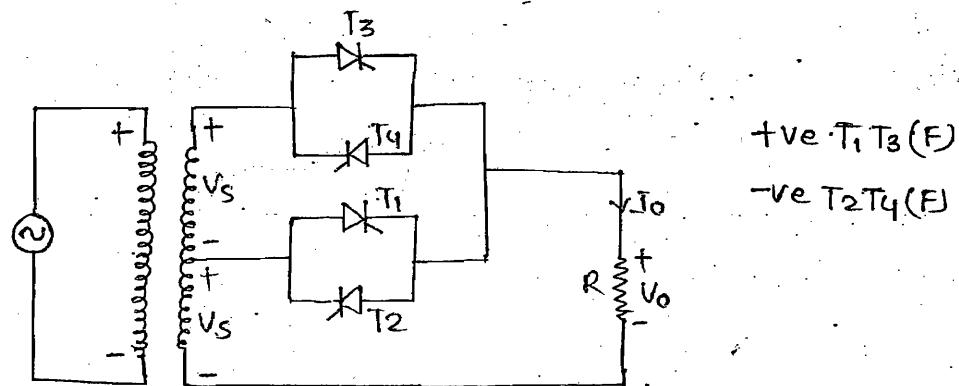
$$(V_{\phi r})_{max} = V_{sr} = \frac{V_m}{\sqrt{2}}$$

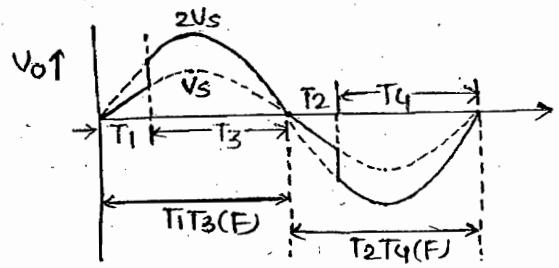
$$(I_{\phi r})_{max} = \frac{(V_{\phi r})_{max}}{|z|}$$



- If pulse gate signal is given to the thy. in AC vol. controller with inductive load then it may behave like half wave rectifier.
- To rectify this prob. we must provide continuous gate pulse (or) high freq. gate pulse as shown in fig.
- Drawback → In phase control tech. at high values of α harmonics distortion is higher & is operated at high 1000 PF.

* Two-Stage AC Vol. Controller →

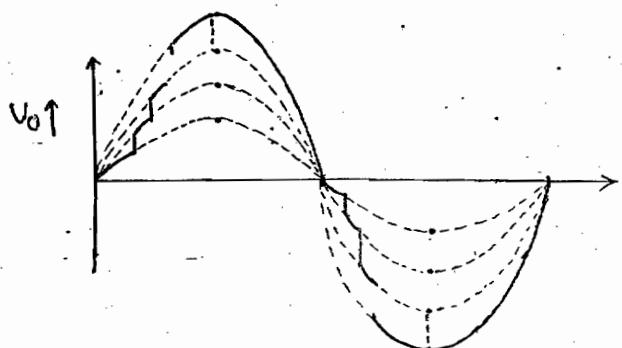
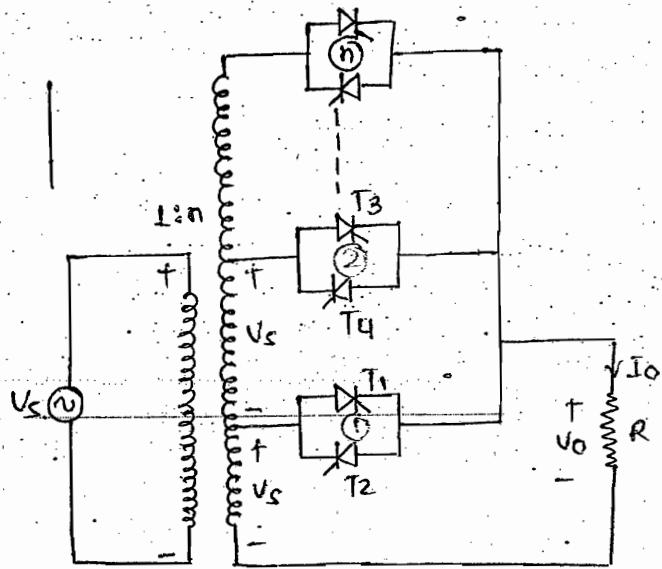




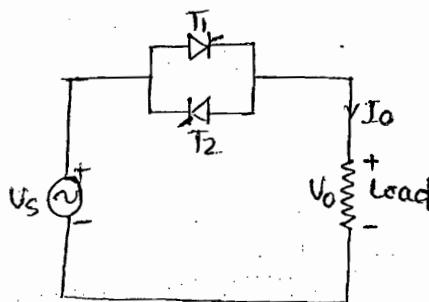
$$V_{o,r} = \left[\frac{1}{\pi} \left[\int_0^{\alpha} V_m^2 \sin^2 \omega t \cdot d(\omega t) + \int_{\alpha}^{\pi} 4V_m^2 \sin^2 \omega t \cdot d(\omega t) \right] \right]^{1/2}$$

$$V_{o,r} = \frac{V_m}{\sqrt{2\pi}} \left\{ \left[\alpha - \frac{1}{2} \sin 2\alpha \right] + 4 \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right] \right\}^{1/2}$$

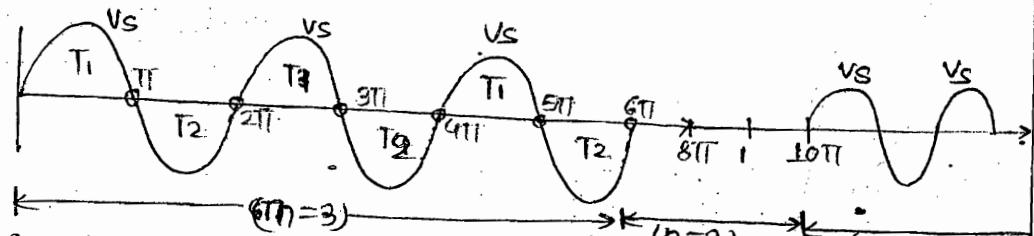
multi-stage AC Voltage Controller →



2) Integral Cycle Control → (ON/OFF)



m cycles → ON ($V_0 = V_s$) let $m=3$
 n cycles → OFF ($V_0 = 0$) $n=2$



$$Ig_1 = (0, 2\pi, 4\pi, 6\pi \cancel{, 8\pi}, 10\pi, 12\pi, 14\pi, 16\pi \cancel{, 18\pi}, \dots)$$

$$Ig_2 = (\pi, 3\pi, 5\pi, 7\pi \cancel{, 9\pi}, 11\pi, 13\pi, 17\pi \cancel{, 19\pi}, 21\pi, \dots)$$

$$V_{sr} = V_s \cdot \left(\frac{m}{m+n} \right)^{1/2}$$

$$V_{sr} = \sqrt{k} \cdot V_s \quad (k = \frac{m}{m+n})$$

$$PF = \sqrt{k}$$

Application → It can be used for the AC loads with high time constant.

For eg:- It can be used for Indⁿ motor with high M_T & mech. time constant.

Limitation → We can't get wide range of voltage control with this method.

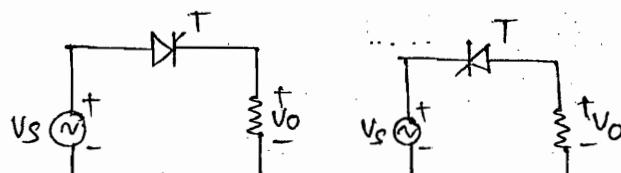
* Cycloconverter →

Cycloconverter

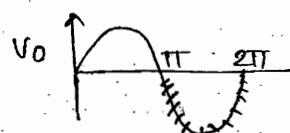
Fixed AC \longrightarrow Variable AC
 (V_s, f_s) $\quad (V_o, f_o)$

$f_o < f_s \rightarrow$ step down cycloconv.

$f_o > f_s \rightarrow$ step up cycloconv.

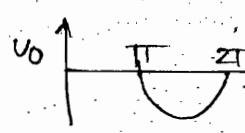


AC \longrightarrow DC



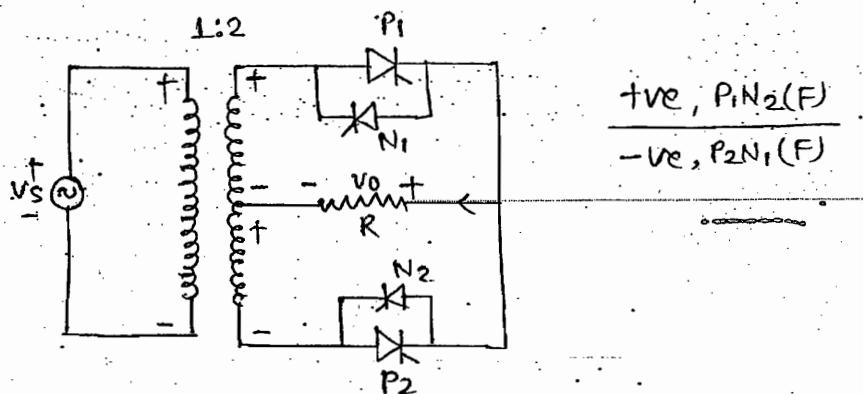
+ve rectifier

AC \longrightarrow DC

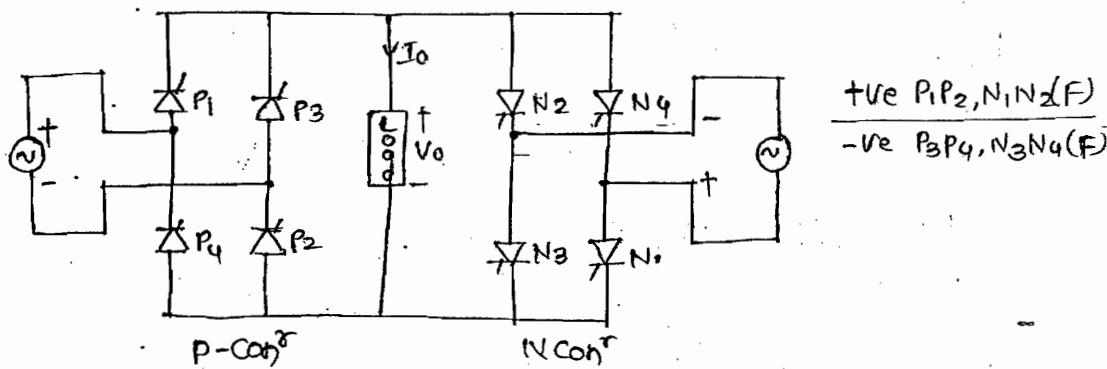


-ve rectifier

* Mid point cycloconverter \rightarrow

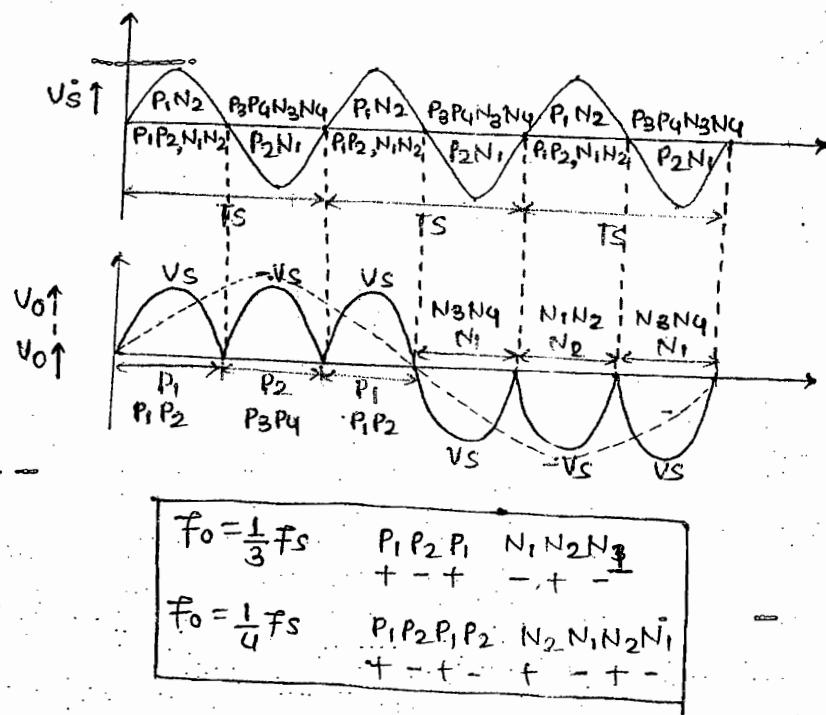


* Bridge cycloconverter \rightarrow



Stepdown cyclo [$f_0 < f_s$] \rightarrow Let $f_0 = \frac{1}{3}f_s$, $T_0 = 3T_s$

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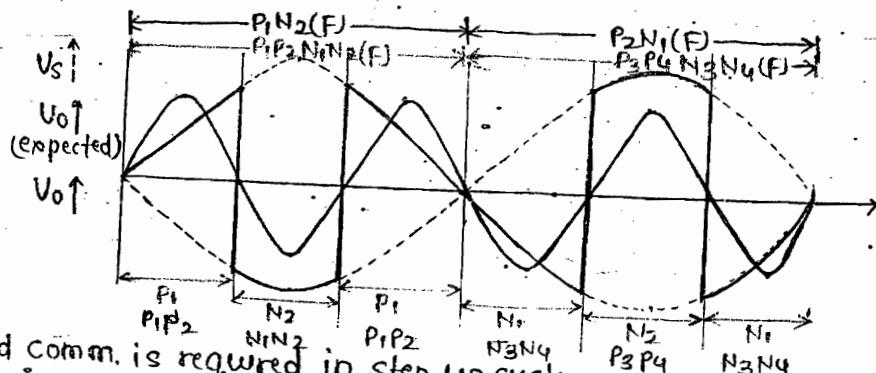
R Load \rightarrow

$$V_{0r} = \frac{V_m}{\sqrt{2\pi}} \left\{ (\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right\}^{1/2}$$

RL Load \rightarrow

$$V_{0r} = \frac{V_m}{\sqrt{2\pi}} \left\{ (\beta - \alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right\}^{1/2}$$

Stepup cycloconverter \rightarrow ($f_0 > f_s$) Let $f_0 = 3f_s$, $T_0 = 3T_s$



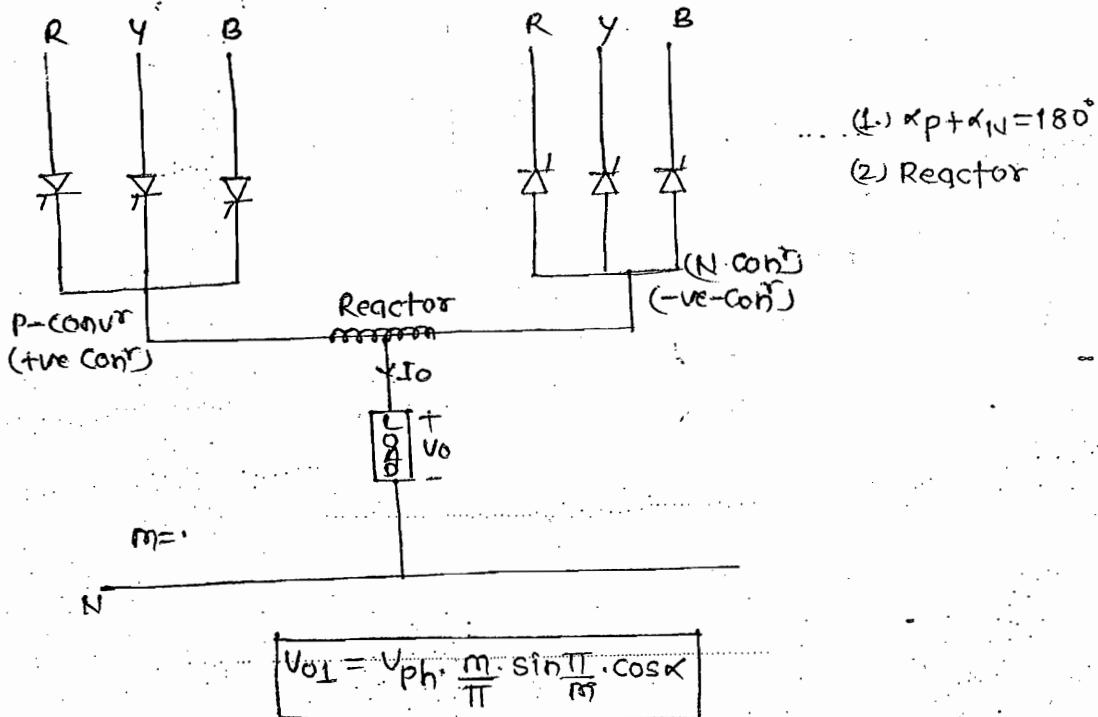
* Forced comm. is required in step up cyclo.

* Harmonic distortion is high in cyclocon therefore it operates with low PF.

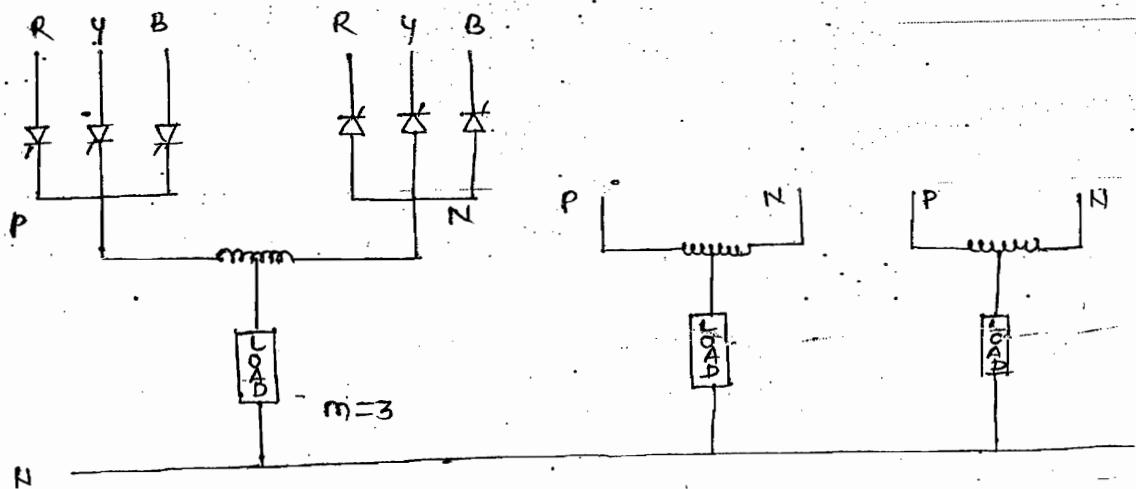
Application → It is used for high power, low speed & reversible AC drives.

DATE - 01/09/14

* 3φ to 1φ cycloconverter →



3φ to 3φ cycloconverter → (18 thy. cycloconverter)



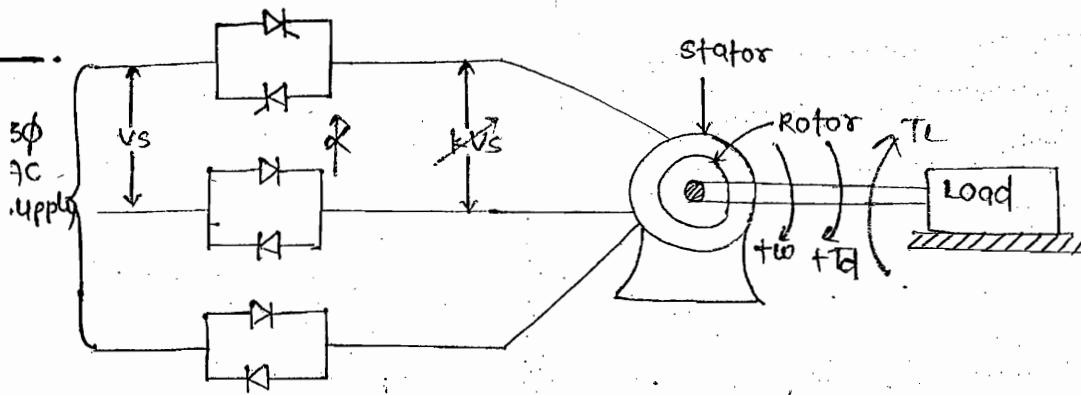
If 6 pulse cont is used in 3ph to 3ph. cycloconverter then we require 36 thy.

Therefore it is also known as 36 thy. cyclo.

$$V_{\text{out/phase}} = V_L \cdot \frac{m}{\pi} \sin \frac{\pi}{m} \cdot \cos \alpha$$

Ac drives →

1) Stator voltage control of IM, using AC voltage controllers:-



* At starting, $T_d > T_L \therefore \omega \uparrow$

* After reaching steady state speed, $T_d = T_L$

* If developed torque (T_d) $< T_L$, $\omega \downarrow$ (m/c retard).

Mech Loads :-

(i) $T_L = \text{const}$ (load torque is independent of speed)

(ii) $T_L \propto \frac{1}{\omega}$ [$(T_L \cdot \omega = \text{const})$ Constant power load]

(iii) $T_L \propto \omega^2$

(iv) $T_L \propto \omega$

2) Check whether the constant torque loads are suitable (or) not for the given ele. drive? case (i) $T_L = \text{const}$.

Ans - * Let us consider that the m/c is running at rated load & rated speed.

If ($kV_s \downarrow$), $T_d \downarrow$, ($T_d < T_L \therefore \omega \downarrow$, $s \downarrow$, $I \uparrow$).

* Here the m/c will slow down & draws more current from supply to build up the torque until $T_d = T_L$

* Here the m/c draws more current from the supply to build up the torque this overheats the m/c windgs & much degrading is required for const. torque loads

Therefore this type of mech. loads are not preferred for a given ele. drive. ^{15%}

Case(2) $T_L \propto \omega^2$

$$(kvs) \downarrow, T_d \downarrow, (T_d < T_L) \therefore \omega \downarrow, T_L \downarrow$$

* Here the m/c will slowdown until $T_L = T_d$

* Here T_L reduces along with the speed & developed torque.

Therefore there is no necessity to build up the torque

* Hence the m/c will not draw more current from supply.

Therefore much derating is not required & hence this type of mech. loads can be used for given ele. drives. Eg:- Fan loads, compressors, reciprocating pump

Case(3) $T_L \propto \omega$

Case(2) & Case(3) are same; but in case(3.) speed is less as compare to above.

Case(4) $T_L \propto \frac{1}{\omega}$

$$\uparrow T_L \propto \frac{1}{\omega} \downarrow$$

(2) Stator Frequency Control \rightarrow

(i) $\omega < \omega_r \therefore \frac{V}{F}$ control

$$\downarrow N_s = \frac{120f}{P} \downarrow \downarrow N_s = (1-s)N_{sr} \downarrow \downarrow V_s \propto \phi F \downarrow \frac{V_s}{F} \text{ constant} \therefore \phi \rightarrow \text{const}$$

* In this case V/F ratio should be kept constant in the entire range of speed control in order to maintain constant F_{air} .

* We can realise the V/F control by using cycloconverter.

* With cyclo. the max^m speed is limited to 40% of its rated value.

* We can also use PWM inverter for V/F control of IM.

$$\downarrow P_d = T_d \cdot \omega \downarrow$$

(ii) $\omega > \omega_r \rightarrow$

$$\uparrow V_s \propto \phi F \uparrow \quad P_d = |T_d \cdot \omega| \uparrow$$

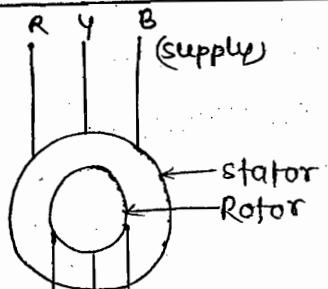
* In this case V/F ratio can't be kept constant because we can't increase the stator vol. more than its rated value.

Therefore the stator vol. is fixed that its rated value.

* To increase the speed ($\omega \uparrow$), $f \uparrow \therefore \phi \downarrow$ ($\because V_s \rightarrow$ Rated value) $\therefore T_d \downarrow$

* In this case we can use sq. wave inverter or pulse inverter.

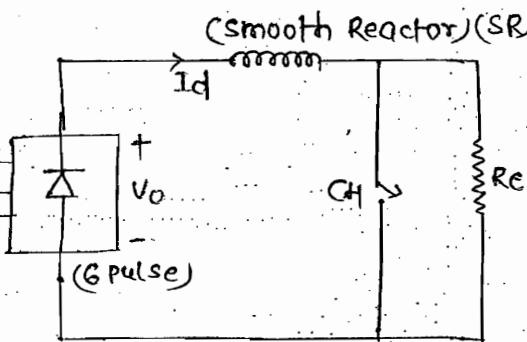
3.) static resistance control (using chopper control) \rightarrow



$$f_0 = 6f_r$$

$$f_0 = 6s f_s$$

$s \downarrow, f_0 \downarrow \therefore$ Ripple in $I_d \uparrow$
∴ size of the SR should be increased.



$$\text{Total Cu loss} = 3I_r^2 R_r + I_d^2 (1-\alpha) R_E$$

$$(1-\alpha) R_E = R_{eff}$$

$$I_{sr} = \sqrt{\frac{2}{3}} I_o$$

$$I_r = \sqrt{\frac{2}{3}} I_d$$

$$I_d = \sqrt{\frac{3}{2}} I_r$$

$$\text{Total Cu loss} = 3I_r^2 R_r + \left(\frac{3}{2}\right) I_r^2 (1-\alpha) R_E$$

$$SPg = 3I_r^2 [R_r + 0.5(1-\alpha) R_E]$$

\therefore Effective resistance connected in series with motor ckt = $0.5(1-\alpha) R_E$

(2)
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$$\text{Avg. Resistance} = \text{series R} + [0.5(1-\alpha) R_E]$$

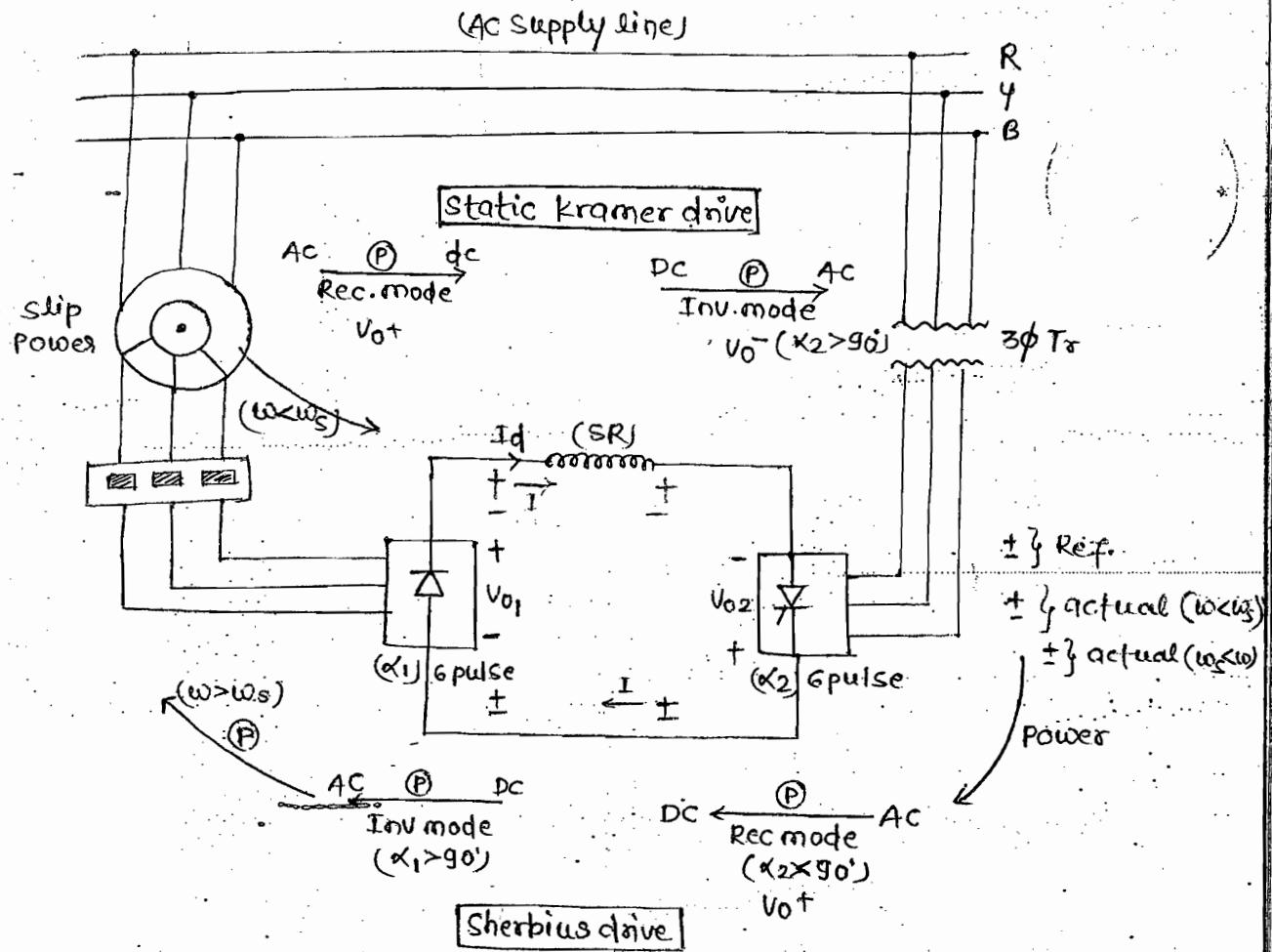
$$= 2 + [0.5(1-\alpha) 4]$$

$$(1-\alpha) = \frac{T_{off}}{T} = T_{off} \cdot f = 4 \times 10^{-3} \times 2 \phi \alpha = 0.8$$

$$\text{Avg. resistance} = 2 + [0.5 \times 0.8 \times 4] = 18/5$$

* This is not an efficient method because the slip power is dissipated in the external resistance in order to slow down the speed.¹⁶¹

4) Slip power recovery method → * This is an efficient method & the~~s~~
because the slip power is recovered &
it can be utilised to the load itself (or) given back to the supply line.

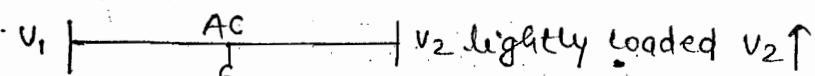


HVDC

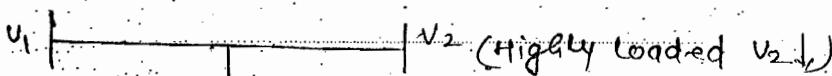
* We can xmit the power by using EHVAC (or) HVDC.

Features of AC lines :-

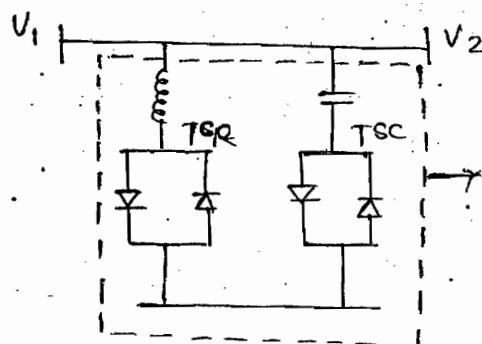
- (1) The power flow magnitude & dirn can't be quickly & easily control.
- (2) The transient stability limit is lesser in the AC line when compared with dc line.
- (3) The other prob. associated with AC lines are skin effect; corona losses, radio & TV interference b/w the comm. lines & power lines.



TCR → Thyristorised Control
Reactor

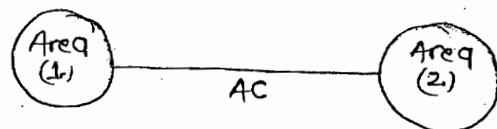


TSC → Thyristorised switch capacitor

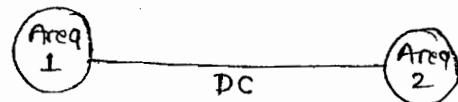


→ SVC (static vars compensating)

- (4) Intermediate substation are installed in the ac line to compensate the reactive power automatically as per the requirement of the line.



Synchronous tie [frequencies must be same]



Asynchronous tie [freq. need not be same]

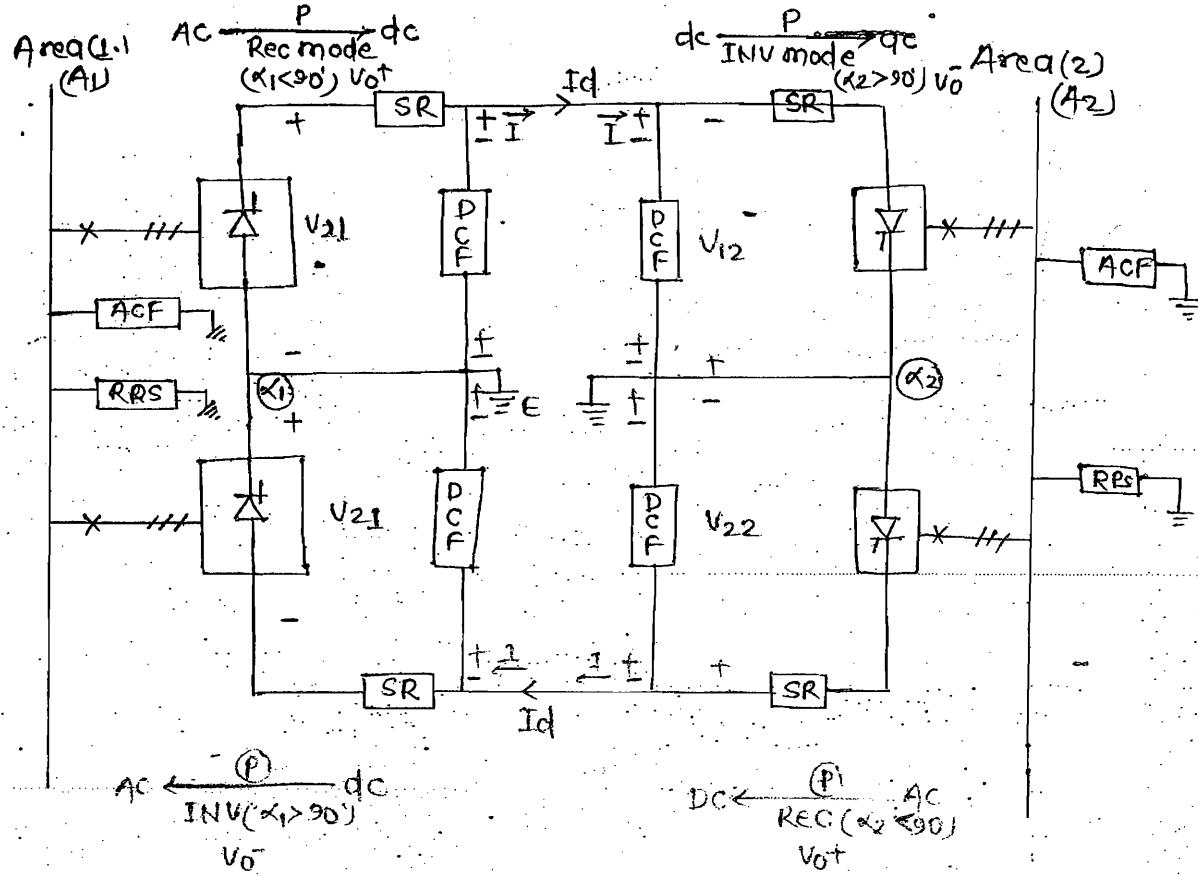
- 5) The sys. disturbance in one of area results in power swings.
If the power swings are unstable then it may lead to cascading of tripping the alternators & this results in large scale blackouts.
- 6.) With ac interconnection the freq. disturbance in one area is transferred to other area.
- 7.) If multiple no. of areas is interconnected by ac line then the fault level of the system increases.

- 8) * HVDC → It is economical to xmit bulk power over long distance.
- 9) Advantages →
 - (1.) The power flow magnitude & dirn can be quickly & easily controlled.
 - (2.) The transient stability limit is improved in the dc line.
 - (3.) There is no skin effect prob. in the dc line.
 - (4.) The other prob. like corona losses, radio & tv interference is very much reduced in the dc lines.
 - (5.) HVDC is used for underground or submarine cables even for short distance (because dc cables will not charge continuously)
 - (6.) HVDC can utilise earth for its return path.
 - (7.) The power xⁿ capacity of a bipolar HVDC line is almost same as that of 3φ single ckt ac line.
 - (8.) We can interconnect 2 independant areas at different freq. because it is an asynchronous type.
 - (9.) With dc interconnection the freq. disturbance in one area can't be transferred to other area.

(10) If multiple no. of areas are interconnected with dc line then the fault level of the sys. will not be substantially increased.

Type of HVDC →

(1) Bipolar HVDC →



SR → smoothing Reactor

DCF → DC Filter

ACF → AC Filter

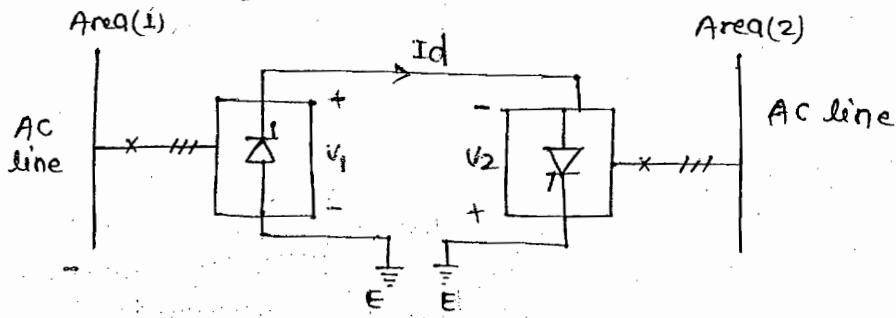
RPS → Reactive power source (To compensate the required Power for converter operation)

{ ± Ref

{ ± Actual ($A_1 \xrightarrow{P} A_2$)

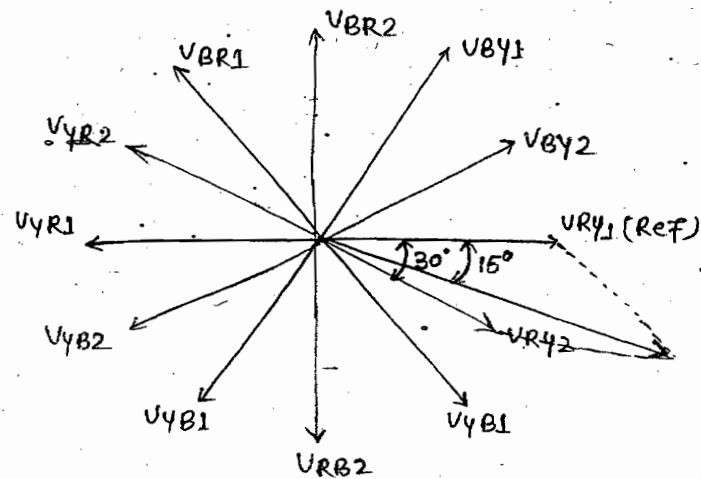
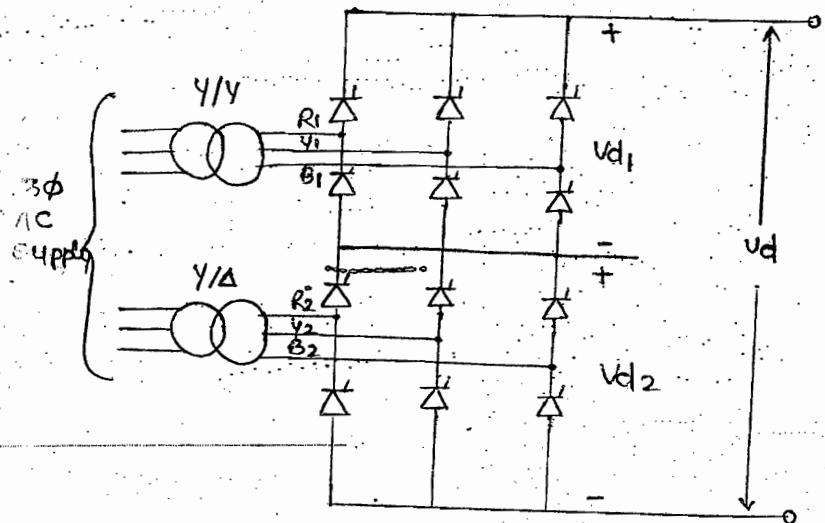
{ ± Actual ($A_1 \xleftarrow{P} A_2$)

2.1 Monopolar HVDCC →



* In order to reduce the harmonics the 6 pulse con is replaced by the 12 pulse con.

12 pulse converter →



Inverter Question

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(1)
49

$$2d = 120^\circ$$

$$d = 60^\circ$$

$$V_{01} = \frac{2\sqrt{2}}{\pi} \sin d \cdot V_s$$

$$V_{01} = \frac{2\sqrt{2}}{\pi} \sin d \cdot V_s$$

$$= \frac{2\sqrt{2}}{\pi} \cdot 1 \cdot \sin d$$

$$= 0.78V$$

(4)
49

$$\frac{V_{03}}{(V_{01})_{\max}} = \frac{2\sqrt{2} V_s \sin 3d}{3\pi}$$

$$= \frac{2\sqrt{2} V_s}{3\pi}$$

$$= \frac{\sin 3d}{3} = 19.6V$$

(5)
49

$$g = \frac{2\sqrt{2} \sin d}{\sqrt{(2d)\pi}}$$

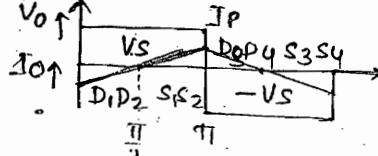
$$2d = 150 = \frac{5\pi}{6} \text{ rad}$$

$$d = 75^\circ$$

$$g = \frac{2\sqrt{2} \cdot \sin 75}{\sqrt{\frac{5\pi}{6}}} \quad g = 0.95$$

$$THD = 31.8\%$$

(7)
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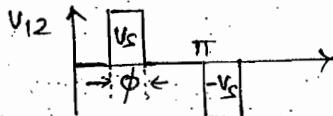
$$\pi/2 \text{ to } \pi; S_1, S_2 \rightarrow ON, V_0 = V_s$$

$$\frac{dI}{dt} = V_s; \int dI = \frac{V_s}{\omega L} \int d(\omega t)$$

$$I_p = \frac{V_s}{\omega L} \frac{\pi}{2} = \frac{V_s}{4fL} = 10A$$

(11)
50

$$V_{12} = V_1 - V_2$$



$$V_{12} = V_s \left(\frac{\phi}{\pi} \right)^{1/2}$$

(12)
50

$$|Z_n| = X_n = n\omega L$$

$$V_{0n} = X_n \cdot V_{01} \quad (X_n < 1)$$

$$I_{0n} = \frac{V_{0n}}{|Z_n|} = \frac{X_n V_{01}}{n \cdot \omega L} = \frac{X_n}{n} I_{01}$$

Conv. (1) \rightarrow

$$(1) RLC; \omega t c = \phi = \tan^{-1} \frac{X_C - X_L}{R}; \omega = \frac{2\pi}{T} = \frac{2\pi}{0.2 \times 10^3}$$

$$\tan(\omega t c) = \frac{X_C - X_L}{R}$$

$$t c = (\text{SF}) t q$$

$$= 2.42 \times 10^{-6}$$

$$\tan \left[\frac{2\pi}{0.2 \times 10^3} \times \frac{24 \times 10^6}{x(180)} \right] = \frac{X_C - X_L}{R} = \frac{24 \times 10^6}{3}$$

$$X_C = 14.7 \Omega, \frac{1}{\omega C} = 14.7$$

$$C = 2.15 \mu F$$

(13)
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$$D \rightarrow \phi = \tan^{-1} \frac{X_C - X_L}{R}$$

$$= \tan^{-1} \left(\frac{X_C - 0}{0} \right) = 90^\circ$$

$$\omega t = \pi/2 \text{ rad}$$

$$t = \pi/2\omega \text{ rad} = \frac{1}{4f} \text{ sec}$$

$$t = 5 \text{ ms}$$

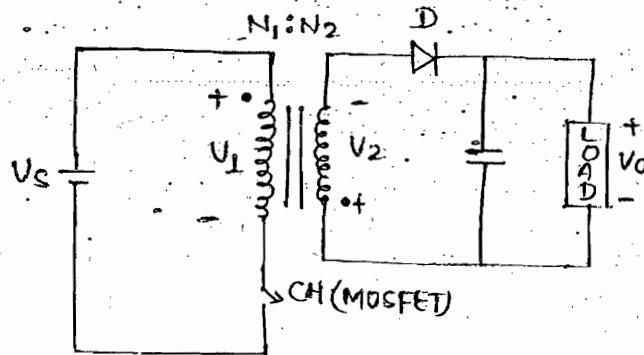
- * In SMPS the transistor operates in the switch mode in very high freq. (cut off region is used for off state & saturation region is used for on state).
- * At such an high freq. we can reduce the size of filter as well as Xmer.
- * Here we use ferrite core for high freq. Xmer used in SMPS.
- * With the availability of high speed device like power MOSFET SMPS is popularly used in now a days.
- * SMPS is highly efficient & compact in size.
- * In linear power supply the transistor operates in the active region & therefore it is not efficient power supply & it occupy more space & weight (because we use 50Hz Xmer in linear power supply).

Types of SMPS →

1. Flyback Converter → * It is derived from Buck-Boost Converter.

* It is also known as isolated Buck-Boost converter.

* Here in place of the inductor we are using Xmer here because both stores magnetic energy.



mode(1) → $0 \leq t \leq T_{ON}$

CH → ON

Xmer stores energy in the form of magnetic field

$$V_1 = U_S$$

$$V_2 = \frac{N_2}{N_1} U_S$$

$$V_2 = q V_S$$

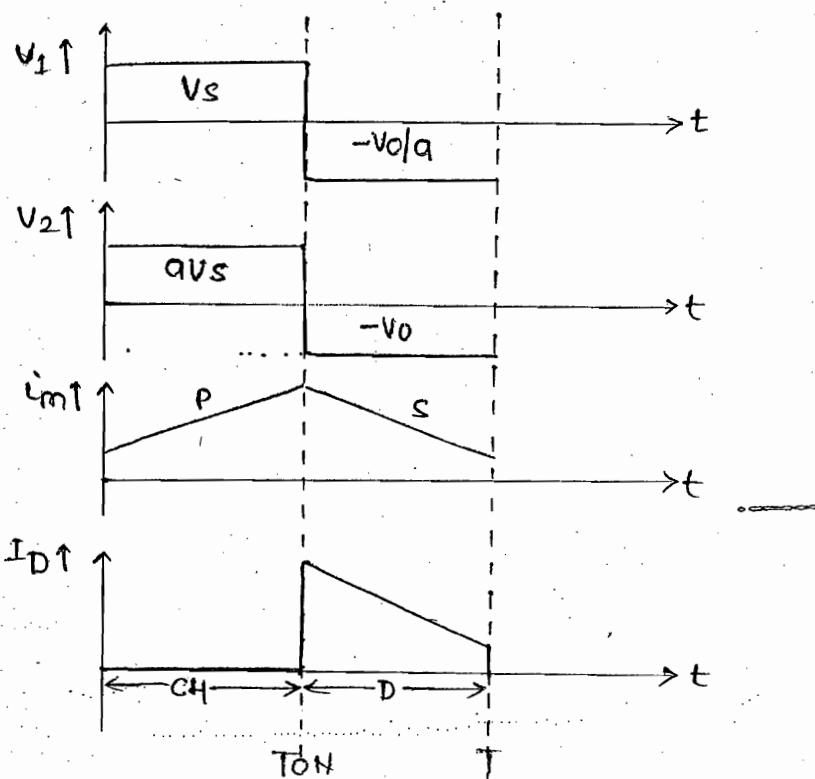
mode(2) → $T_{ON} \leq t \leq T$

CH → OFF, D → ON

$$V_2 = -V_0$$

$$V_1 = \frac{N_1}{N_2} V_2$$

$$V_1 = -\frac{V_0}{q}$$



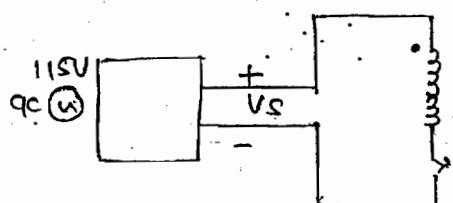
$$V_o = q \cdot \frac{V_s}{(1-\alpha)}$$

* The peak forward blocking voltage of CH switch = $V_s + \frac{V_o}{q}$

Note:- The O/p voltage of front end rectifier without voltage doubling = V_M
 V_M (Peak value of ac i/p vol.)

O/p voltage of front end rectifier with voltage doubling = $2V_M$

(3)
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$$V_S = 115\sqrt{2} \text{ (peak)}$$

$$V_O = q \cdot \frac{V_S}{1-\alpha}$$

$$35 = q \times 0.3 \times 115\sqrt{2} \over (1-0.3)$$

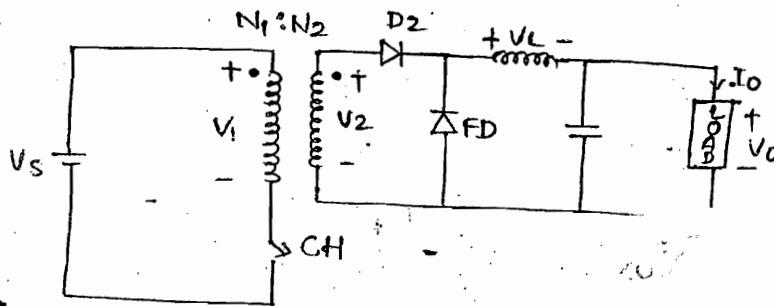
$$q = 0.5$$

$$\text{Forward blocking Vol.} = V_s + \frac{V_o}{q} = 115\sqrt{2} + \frac{35}{0.5} \\ = 232.5V$$

(2) Forward Converter \rightarrow *It is derived from Buck Conv.

Case(1) \rightarrow Ideal Xmer;

- $\rightarrow I_m = 0$
- \rightarrow No Losses
- \rightarrow No leakage inductance



mode(1) \rightarrow $0 \leq t \leq T_{ON}$

CH \rightarrow ON

$$V_1 = V_S \quad ; \quad V_2 = \frac{N_2}{N_1} V_1$$

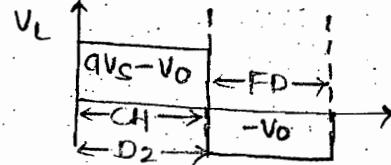
$$V_2 = q V_S$$

Applying KVL;

$$-V_2 + V_L + V_0 = 0$$

$$V_L = V_2 - V_0$$

$$V_L = q V_S - V_0$$



mode(2) \rightarrow $T_{ON} \leq t \leq T$

CH \rightarrow OFF, D2 \rightarrow OFF

FD \rightarrow ON

$$+V_L + V_0 = 0$$

$$V_L = -V_0$$

$$(V_L)_{avg} = 0$$

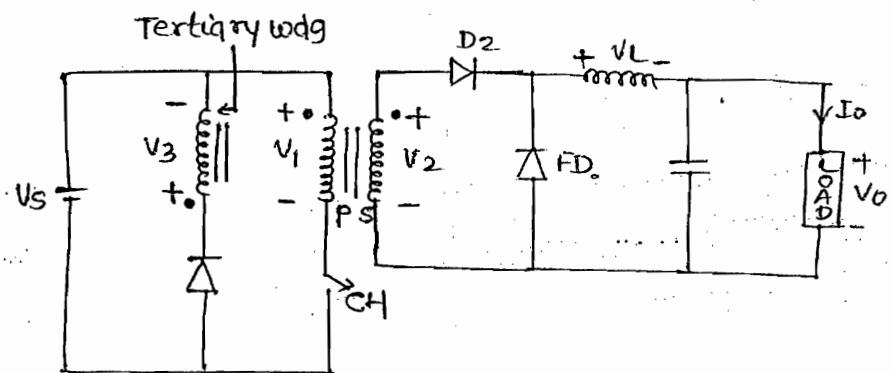
$$(qV_S - V_0) T_{ON} - V_0 T_{OFF} = 0$$

$$qV_S T_{ON} = V_0 T$$

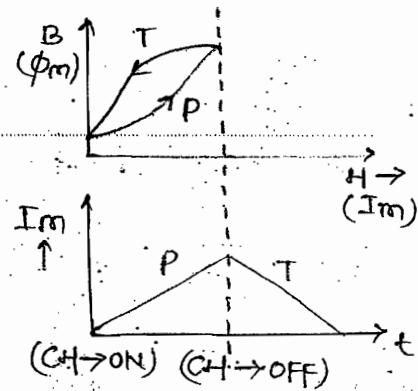
$$V_0 = q \cdot \frac{T_{ON}}{T} \cdot V_S$$

$$\boxed{V_0 = q \cdot V_S}$$

Case(2) → For non-ideal Xmer
 $\rightarrow I_m \neq 0$



- * Tertiary wdg is wed to provide a path to magnetising current when the CH switch becomes off.
- * Here Xmer magnetises through 1° wdg & demagnetises through 3° wdg.



* In flyback & forward Converters the Xmer is excited only in one dirn.

It is called unidirectional core excitation.

(iii) Push-Pull Converter → * In this conv the Xmer core is excited bi-directionally.

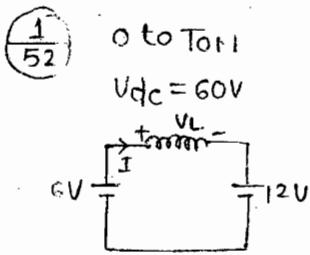
Therefore it is called bidirectional core excitation.

Fig is que (5)/59.

$$V_o = 2.9 \times V_s$$

$$V_o = 2 \cdot \frac{N_2}{N_1} \cdot \frac{T_{ON}}{T_{ON} + T_{OFF}} \cdot V_s$$

Chopper Question



KVL $\rightarrow -60 + V_L + 12 = 0$
 $V_L = 48$
 $L \frac{dI}{dt} = 48$
 $I_{min} \int_{min}^{T_{ON}} dI = \frac{48}{L} \int_0^{T_{ON}} dt$
 $\Delta I = \frac{48}{L} T_{ON} = 0.48A.$

(2) $\frac{2}{52} I_0 = \frac{\alpha V_S}{R} = \frac{0.8 \times 100}{10} = 8A$

$$(iD)_{avg} = I_0 \left(\frac{T_{OFF}}{T} \right) = I_0 (1 - \alpha) = 8 (1 - 0.8) = 1.6A$$

(3) $\frac{3}{52} (t_{on})_F = \frac{x \times 10^6 \times 250}{min \cdot R} = \pi \sqrt{LC} = 140\mu s.$

(4) $\frac{4}{52} (V_o)_{min} = V_S \frac{(T_{ON})_{eff.}}{T} = 47.5V$

(5) $\frac{5}{52} (i_m)_{max} = I_0 + V_S \sqrt{\frac{C}{L}} = 12A, (i_A)_{max} = I_0 = 10A$

Conventional question \rightarrow

(a) (i) $(T_{ON})_{eff.} = T_{ON} + 2t_{cm}$ (ii) $t_{cm} = \frac{CV_S}{I_0} = 137.5\mu s$
 $= 1075\mu s$

(b) $(i_m)_{max} = I_0 + V_S \sqrt{\frac{C}{L}}$ & $(i_A)_{max} = I_0$

(c) $t_{CA} = \frac{\pi}{2} \sqrt{LC} = 49\mu s$ & $t_{cm} = \frac{CV_S}{I_0}$

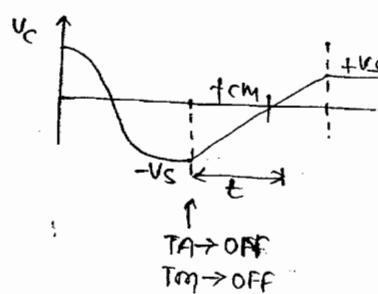
(d) $2t_{cm} = 275\mu s$

(e)

$$V_C = \frac{V_S}{t_{cm}} t - V_S$$

$$= \frac{220}{137.5} (150) - 220$$

$$V_C = 20V$$



$$(8.) T_{ON}' = T_0 \ln \left[1 + m \left(e^{T/\tau_0} - 1 \right) \right]$$

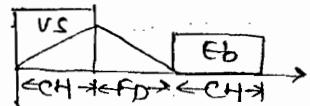
$$(20.) t_{min} \leq t \leq T_{max}$$

$$\pi\sqrt{LC} \leq t \leq \frac{3\pi}{2}\sqrt{LC}$$

$$50\mu s \leq t \leq 75\mu s$$

$$(11) I_0 + I_p \sin \omega t$$

(12)



$$V_o = \frac{V_s t_r + E_b t_f}{t_r + t_f + t_o}$$

$$(13.) I_{mp} = I_0 + \frac{\pi \sqrt{LC}}{2}$$

$$= 5 + \frac{1.6}{2}$$

$$= 5.8 A$$

1- ϕ Half Wave Rectifier

Rectifier Load	v_o	v_{or}	t_c	I_o	Other
R	$\frac{v_m}{2\pi} (1+\cos\alpha)$	$\frac{v_m}{2\sqrt{\pi}} \left[(\pi-\alpha) + \frac{1}{2} \sin 2\alpha \right]^{1/2}$	$\frac{\pi}{\omega}$	$(I_s)avg = \frac{v_m}{2\pi R} (1+\cos\alpha)$	$I_{sr} = I_{or} = \frac{v_{or}}{R}$
R-L	$\frac{v_m}{2\pi} (\cos\alpha - \cos\beta)$	$\frac{v_m}{2\sqrt{\pi}} \left[(\beta-\alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right]^{1/2}$	$\frac{2\pi - \beta}{\omega}$	$i_o = \frac{v_m}{ z } \sin(\omega t - \phi) + k e^{j\theta}$	$v_{sr} = \frac{v_m}{\sqrt{2}}$
RL+FD	$\frac{v_m}{2\pi} (1+\cos\alpha)$	$\frac{v_m}{2\sqrt{\pi}} \left[(\pi-\alpha) + \frac{1}{2} \sin 2\alpha \right]^{1/2}$	$\frac{\pi}{\omega}$	$PF = \frac{P_o}{v_{sr} \cdot I_{sr}}$	
RE	$(v_o) = \frac{1}{2\pi} \left[v_m (\cos\alpha - \cos\beta) \right. \\ \left. + E (2\pi + \alpha - \theta_2) \right]$	$\frac{\pi + 2\theta_1}{\omega}$	$\frac{1}{2\pi R} \left[v_m (\cos\alpha - \cos\beta) \right. \\ \left. - E (\theta_2 - \alpha) \right]$	$(1) PF = \frac{I_{or}^2 R + E I_o}{v_{sr} I_{sr}}$	$(2) I_{or} = \left[\frac{1}{2\pi} \int_{-\pi}^{\theta_2} \left(\frac{v_m \sin \omega t - E}{R} \right)^2 dt \right]^{1/2}$

Spec: 1φ-full converter

$$i_s = \frac{4I_0}{\pi} \sin(\omega t + \phi_n)$$

$$Is = \frac{2\sqrt{2}}{\pi} I_0$$

$$DF = \cos \alpha$$

$$g = \frac{2\sqrt{2}}{\pi} \cos \alpha$$

$$PF = \frac{2\sqrt{2} \cos \alpha}{\pi}$$

$$THD = 48.34\%$$

1φ semi-converter

$$i_s = \frac{4I_0}{\pi} \sin(\omega t + \phi_n) + \frac{4I_0}{\pi} \sin \frac{n\pi}{2} \sin(n\omega t + \phi_n)$$

$$Is = \frac{2\sqrt{2}}{\pi} I_0 \cos \frac{\alpha}{2}$$

$$\cos \frac{\alpha}{2}$$

$$g = \frac{2\sqrt{2} \cos \alpha / 2}{\sqrt{\pi(\pi - \alpha)}}$$

$$PF = \frac{2\sqrt{2}(1 + \cos \alpha)}{\sqrt{\pi(\pi - \alpha)}}$$

$$THD = 48.34\%$$

3-φ full converter

$$i_s = \frac{4I_0}{\pi} \sin(\omega t + \phi_n)$$

$$Is = \frac{2\sqrt{2}}{\pi} I_0 \sin \frac{n\pi}{2} \sin(n\omega t + \phi_n)$$

$$\cos \alpha$$

$$\frac{3}{\pi}$$

$$\frac{3}{\pi} \cos \alpha$$

$$31\%$$

$$\left[\frac{\pi(5\pi - \alpha)}{8 \cos^2 \frac{\alpha}{2}} \right]^{1/2}$$

	<u>Current Commutated Chopper (class B)</u>	<u>Voltage Commutated Chopper (class D)</u>
* $I_{(im)}$ peak	I_o	$I_o + I_p = I_o + V_s \sqrt{\frac{C}{L}}$
* $I_{(IA)}$ peak	$I_p = V_s \sqrt{\frac{C}{L}}$	I_o
OnCond'n time of the TA	$\pi\sqrt{LC}$	$2t_{cm}$
* t_{cm}	$\frac{V_s C}{I_o}$	$\frac{V_s C}{I_o}$ $RCLenz$ (with R load)
total		
* Time req. to turn off the Tm after TA is on.	$t_1 + t_2 = \pi\sqrt{L} + \sqrt{C} \sin^{-1}\left(\frac{I_o}{I_p}\right)$	
* $t_{(im)}$ min		
t_{min} (min)	$\pi\sqrt{LC}$	
time req. to turn off the Tm after TA ON		
* t_{max}	$\frac{3\pi}{2}\sqrt{LC}$	
* Reverse vol.	$V_R = V_s \cos\left[\sin^{-1}\left(\frac{I_o}{I_p}\right)\right]$	
* T_{OH}/min		$\pi\sqrt{LC}$
* PIV of FD		$2V_s$
* PIV of Tm		V_s
* t_{CA}		$\frac{\pi}{2}\sqrt{LC}$
* commutation interval		$2t_{cm}$
* $(T_{ON})_{eff}$		$T_{OH} + 2t_{cm}$
* V_o		$\frac{V_s (T_{ON})_{eff}}{T}$
* V_{olmin}		$V_s (\pi\sqrt{LC} + 2t_{cm}) / T$

