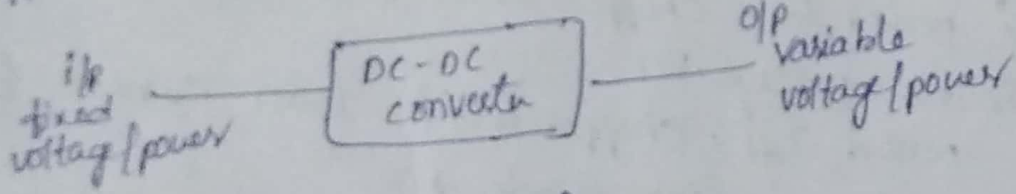
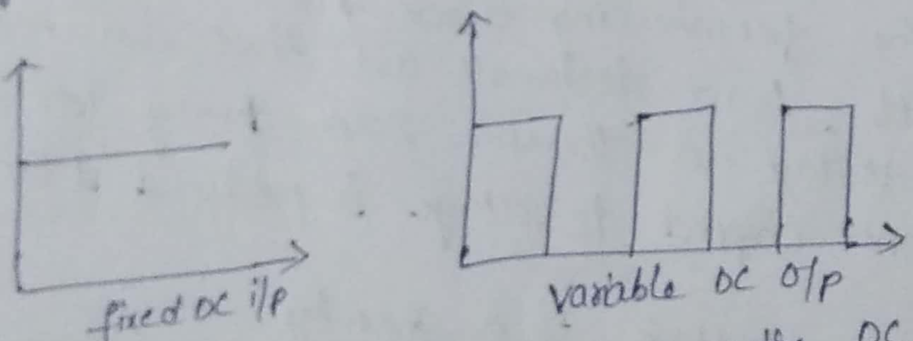
UNIT - III

DC-DC converter is very much needed nowadays as many industrial applications are dependent upon DC voltage Source. The performance of these applications will be improved if we use a variable DC supply. it will help to ~~control~~ improve controllability of the equipments also.
Ex: are subway cars, trolley buses, battery operated vehicles etc. we can control & vary a constant DC voltage with the help of a chopper

→ chopper is a basically static power electronics device which convert fixed DC voltage/power to variable DC voltage or power

→ it is nothing but a high speed switch which connects & disconnects the load from it at a high rate to get variable or chopped voltage at the o/p

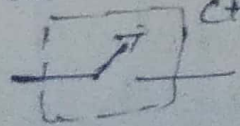




→ chopper ~~also~~ can ~~be~~ increase or decrease the DC voltage level at its opposite side. So, chopper serves the ~~DC voltage level at~~ same purpose in DC ckt transfers in case of ac circuit
So it is known as DC transformer

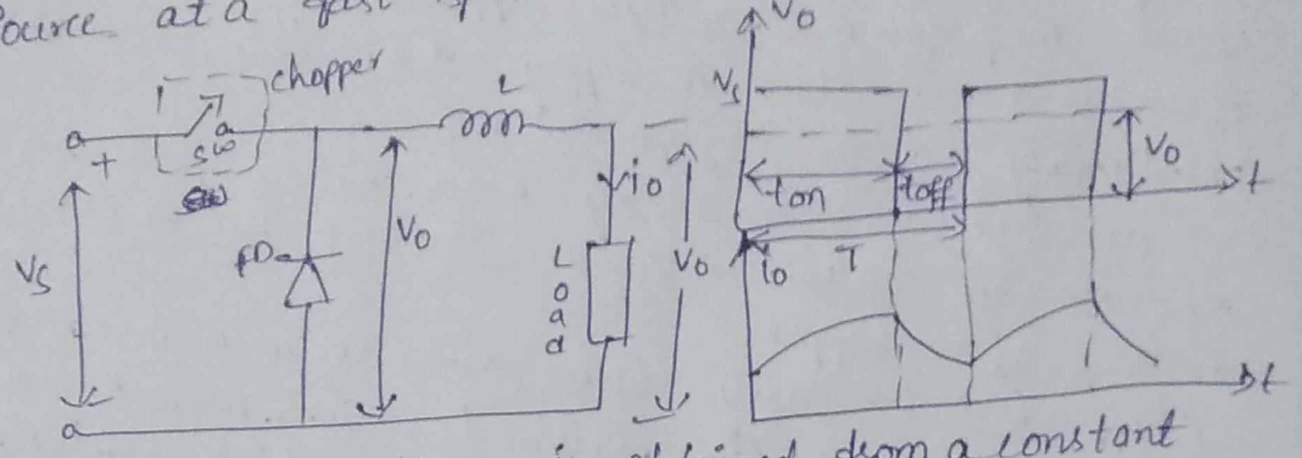
→ low power application: GTO, IGBT, power BJT, PMOSFET, etc
High power application: Thyristor (or) SCR.

→ These device are represented as a switch in a dotted box for simplicity when it is closed current can flow in the direction of arrow only



principle of chopper operation:-

→ A chopper is a high speed on/off semiconductor switch
→ it connects source to load & disconnects the load from source at a fast speed.



→ A chopped load voltage is obtained from a constant dc supply of magnitude V_s.
→ chopper is represented by a switch sw inside a dotted rectangle, which may be turned or turned - off as desired.
→ During the period T_{on}, chopper is on and load voltage is equal to source voltage V_s.
→ During the period T_{off}, chopper is off, load current flows through the freewheeling diode FD.
→ As a result, load terminals are short circuited by FD and load voltage is therefore zero during T_{off}.
→ In this manner chopped dc voltage is produced at the load terminals.

The avg load voltage V_0 is given by

$$V_0 = \frac{T_{on}}{T_{on}+T_{off}} V_s = \frac{T_{on}}{T} V = \alpha V_s$$

where T_{on} = on time, T_{off} = off-time

$T = T_{on} + T_{off}$

$\alpha = \frac{T_{on}}{T}$ = duty cycle

Thus load voltage can be controlled by varying duty cycle.
→ load voltage is independent of load current it can be written as $V_0 = f \cdot T_{on} \cdot V_s$

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where $f = \frac{1}{T}$ = chopping frequency.

Control strategies:-

The average value of o/p voltage V_0 can be controlled through 'α' by opening & closing the semiconductor switch periodically. The various control strategies for varying duty cycle α are as follows

1. Time ratio control (TRC) and
2. current limit control

⟹ Time ratio control (TRC):-

In this scheme, time ratio T_{on}/T (as duty cycle) is varied. This is realized in two different strategies called constant frequency s/m and variable frequency s/m

1. **Constant frequency s/m:-**

Here, the on-time T_{on} is varied but chopping frequency f (or chopping period T) is kept constant. Variation of T_{on} means adjustment of pulse width, as such this scheme is also called pulse width modulation

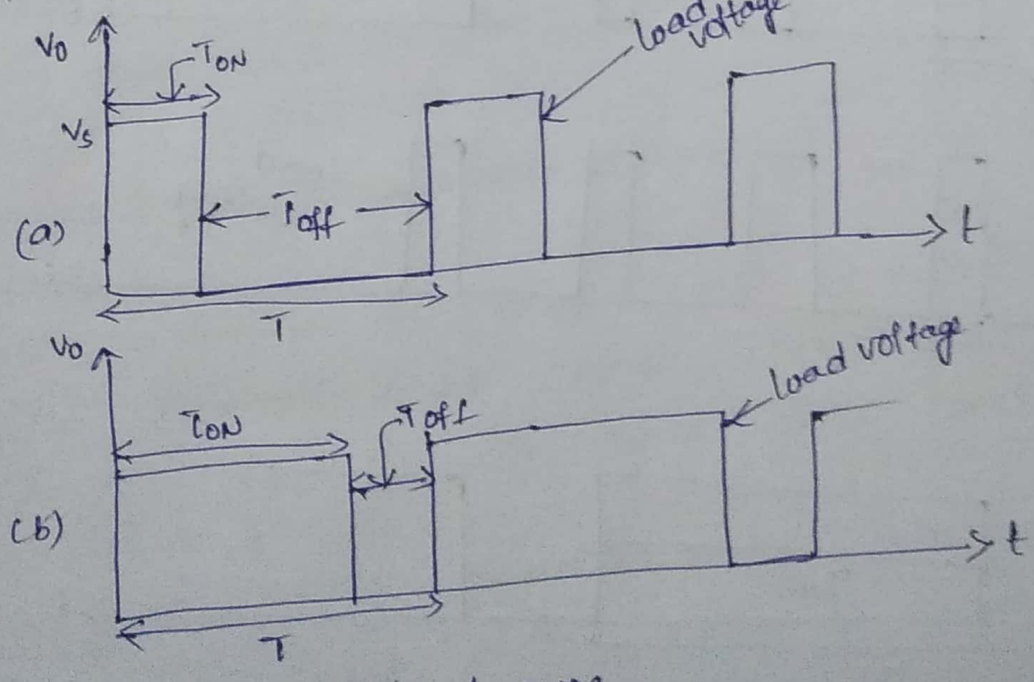

fig: principle of pwm

→ Here chopping period T is constant.

In (a) $T_{on} = \frac{1}{4}T$ so that $\alpha = 0.25$ (or) 25%.

(b) $T_{on} = \frac{3}{4}T$ so that $\alpha = 0.75$ (or) 75%

ideally α can be varied from zero to unity.

∴ o/p voltage V_0 can be varied b/w zero & source voltage V_s

2. Variable frequency s/m :-

Here, the chopping frequency f (or chopping period T) is varied and either i) on-time T_{on} is kept constant
ii) off-time T_{off} is kept constant

This method of controlling α is also called frequency modulation scheme.

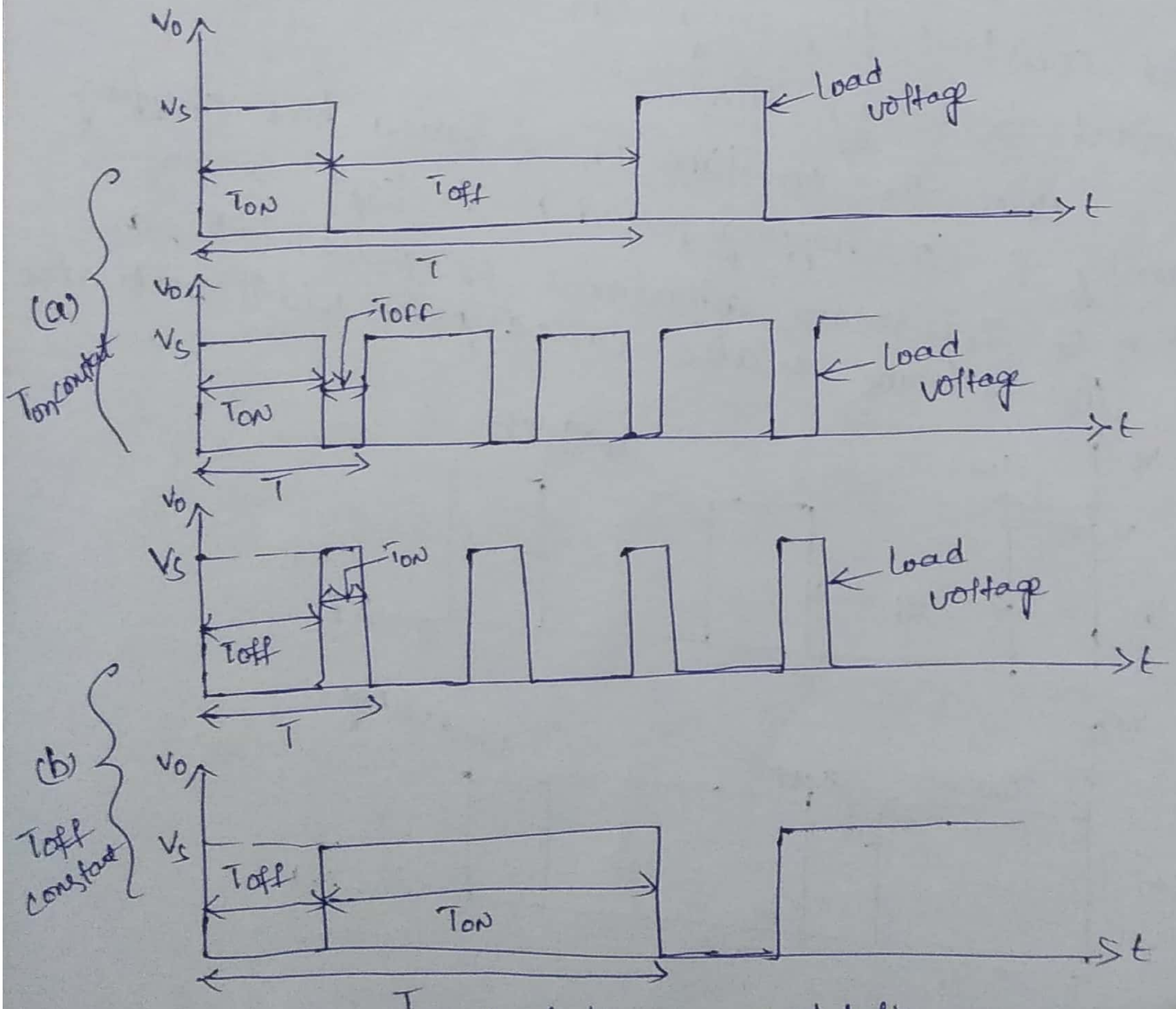

fig: principle of frequency modulation

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→ Here, fig(a) T_{on} is kept constant but T is varied.

fig (a) upper $T_{on} = \frac{1}{4}T$ so that $\alpha = 0.25$.

fig (a) lower $T_{on} = \frac{3}{4}T$ so that $\alpha = 0.75$

fig (b) T_{off} is kept constant and T is varied

In fig(b) upper, $T_{on} = \frac{1}{4}T$ so that $\alpha = 0.25$

lower, $T_{on} = \frac{3}{4}T$ so that $\alpha = 0.75$

→ frequency modulation scheme has some disadvantages as compared to PWM scheme

i) The chopping frequency has to be varied over a wide range for the control of o/p voltage in frequency modulation filter design for such wide frequency variation is quite difficult

ii) for the control of α, frequency variation would be wide. As such, there is a possibility of interference with signalling & telephone lines in frequency modulation scheme

iii) The large off-time in frequency modulation scheme may ~~take~~ make the load current discontinous which is undesirable

→ Constant frequency scheme is better than the variable frequency scheme

→ PWM technique has, T_{on} cannot be reduced to near zero for most of the communication ckts used in choppers. As such, low range of α control is not possible in PWM.

→ This can however, be achieved by increasing the chopping period of the ~~frequency~~ chopper

⟹ Current limit control:-

→ In this scheme, the on & off chopper ckt is guided by the previous set value of load current. These two set values are max. load current $I_{o.max}$ and min. load current. $I_{o.min}$.

→ when load current reaches the upper limit $I_{o.max}$, chopper is switched off. Now load current freewheels & begins to decay exponentially.

→ when it falls to lower limit $I_{o.min}$, chopper is switched on & load current begins to rise profile of load current shows that it fluctates b/w $I_{o.max}$ & $I_{o.min}$ & therefore cannot be discontinuous

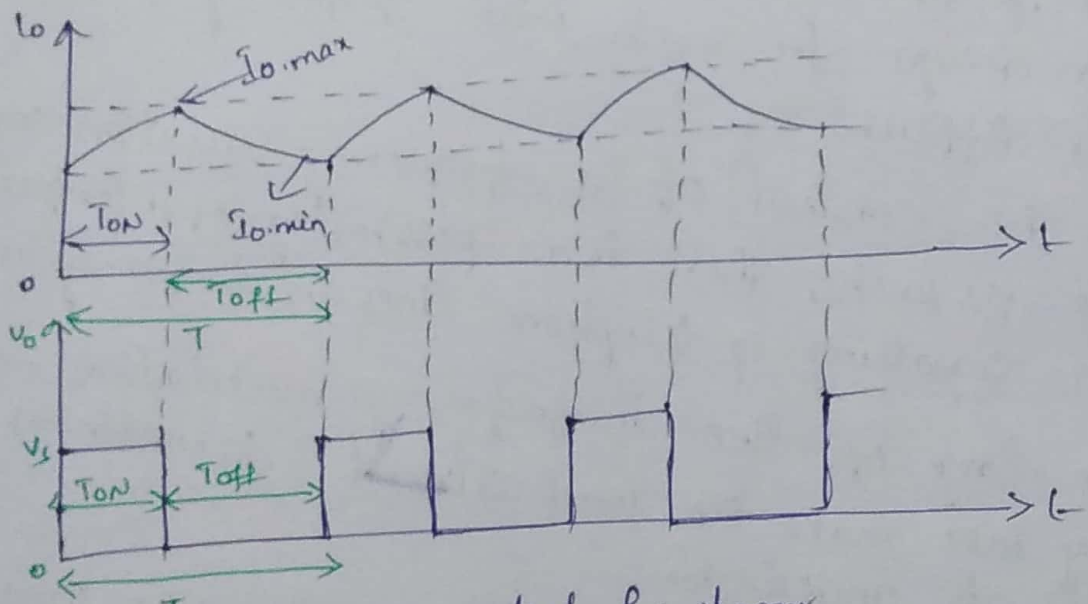


fig: Current limit control for chopper

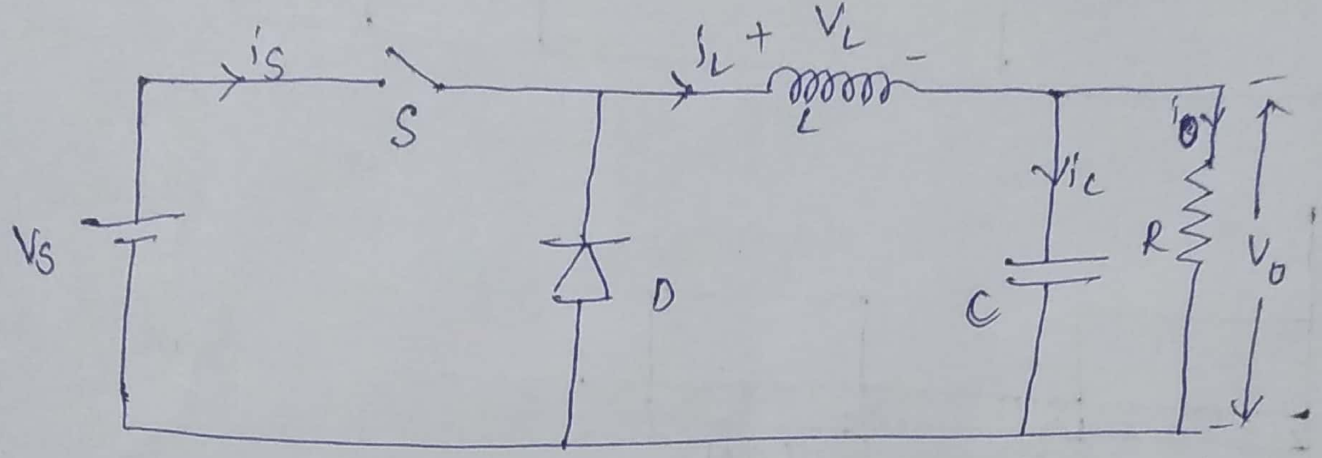
→ Switching frequency of chopper can be controlled by ~~switching~~ setting $I_{o.max}$ & $I_{o.min}$. Ripple current = $(I_{o.max} - I_{o.min})$ can be lowered & this in turn necessitates higher switching frequency & ∴ more switching losses

→ current limit control involves feedback loop, the trigger circuitry for the chopper is therefore more complex.

→ PWM techinque is more commonly used control strategy for the power control in chopper ckts

DC-DC Buck converter (or) Step down converter

→ A buck converter is a dc-dc converter. also avg o/p voltage is less than the i/p voltage $[V_o < V_s]$



→ The ckt diagram consists of voltage source V_s, switch, inductor, capacitor & Resistor

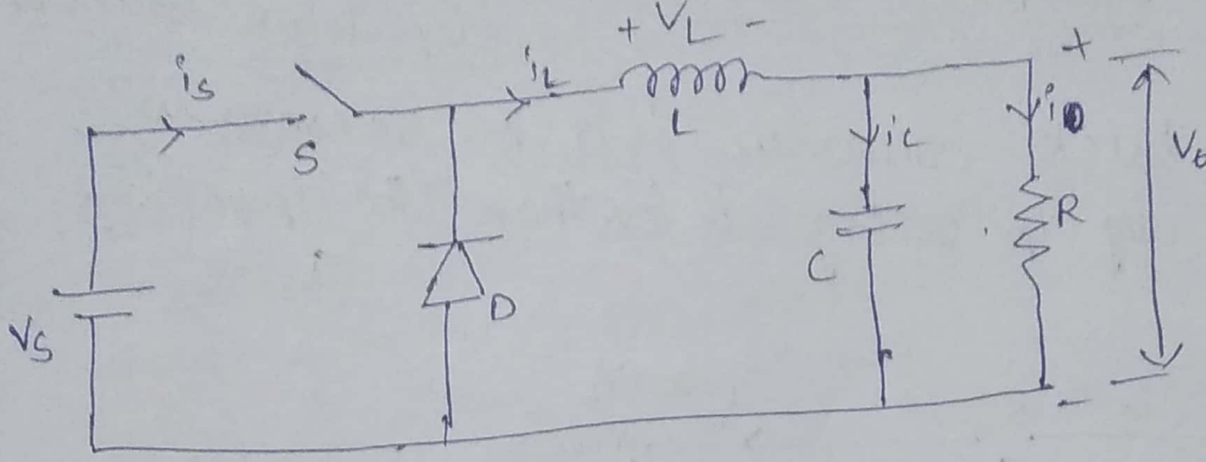
→ The 'c' in the o/p ckt is assumed to be large enough so that the time constant of RC circuit is very high & its ensures a o/p volage

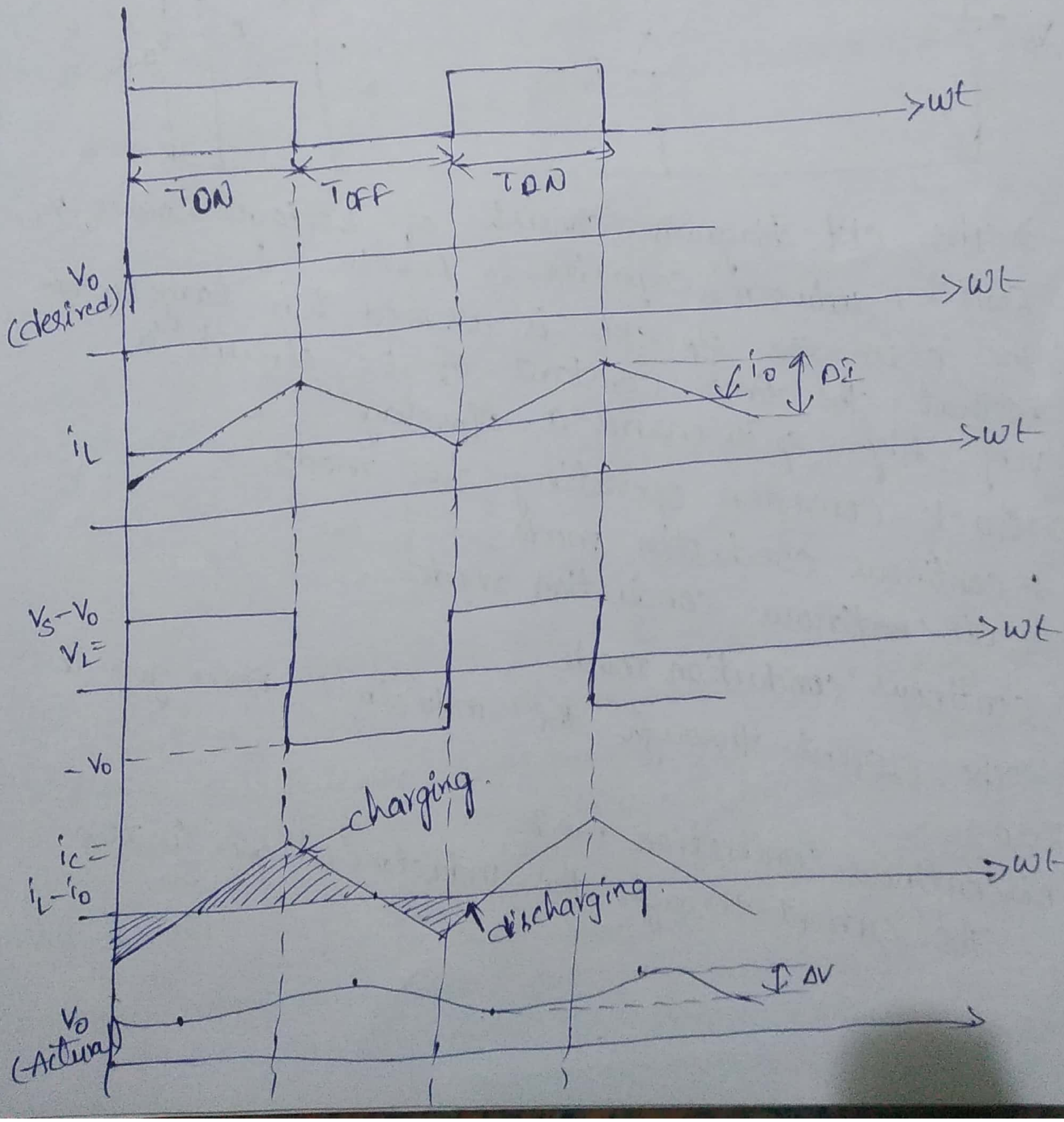
→ Buck converter operating two modes
1. continous conduction mode
2. Discontinous conduction mode.

1. continous conduction mode
The current through the inductor "L" never goes to zero

2. Discontinous conduction mode
The current through the inductor "L" goes to zero

Continous conduction mode :-





→ Already we know when the ~~co~~ inductor "L" value is large means the o/p voltage is constant

→ case i) when Swith "s" is ON

~~forward bias~~, the diode "D" becomes reverse bias & the i/p ~~voltage~~ current (I_s) flows through the ~~...~~, L, C, R

→ During this time the the inductor stores energy & inductor current increases gradually

→ During this time the voltage is → $-V_S + V_L + V_0 = 0$

$V_L = V_S - V_0$

case ii) when Switch "s" is OFF

the Diode "D" becomes forward bias and the stored energy in the "L" discharge through the diode & RC ckt

∴ The current through the inductor "i" I_L decreases gradually

In this case V_L is the voltage across the "L"

V_0 is the o/p voltage

Apply mesh Analysis, we get

$V_L + V_0 = 0$

$V_L = -V_0$

→ Again during the turn on time increases turn off time decreases

→ "i_c"

$i_L = i_c + i_o$

$\therefore\ i_c = i_L - i_o$

we already know i_L, in order to get i_c
we know V_o, & load is in resistive nature
∴ o/p current same as that as o/p voltage with reduced magnitude :

→ when capacitor current is "+ve" charging current
is "−ve" Dis charging current

→ Both R&C are connected parallel
∴ The voltage across the capacitor is same as that of the o/p voltage V_o
when capacitor is charging o/p voltage is maximum
& capacitor is discharging o/p voltage is decreases

→ observe desired o/p voltage & Actual o/p has some ripple content (ΔV)

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* o/p voltage is

$$(V_s - V_o)t_{on} + (-V_o)t_{off} = 0$$

$$V_s \cdot t_{on} = V_o \cdot (t_{off} + t_{on}) \qquad [\because T = t_{on} + t_{off})$$

$$V_s \cdot t_{on} = V_o \cdot T$$

$$V_o = \left[\frac{t_{on}}{T}\right] V_s$$

$$V_o = \alpha \cdot V_s \qquad [\because \alpha = \text{Duty cycle.}$$

Design of filter inductance (L) & capacitance (C) :-

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

when switch is ON

$$\therefore V_L = V_s - V_o$$

$$V_s - V_o = L \cdot \frac{di}{dt}$$

$$V_s - V_o = L \cdot \frac{\Delta I}{t_{on}} \Rightarrow t_{on} = \frac{L \cdot \Delta I}{V_s - V_o}$$

$$t_{on} = \frac{L \cdot \Delta I}{V_s - V_o} \rightarrow (1)$$

when switch is Off

$$\therefore V_L = -V_o$$

$$-V_o = L \cdot \frac{\Delta I}{t_{off}} \Rightarrow t_{off} = L \cdot \frac{\Delta I}{V_o}$$

$$t_{off} = L \cdot \frac{\Delta I}{V_o} \rightarrow (2)$$

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we know

$$T = T_{on} + T_{off}$$

$$= L \cdot \frac{\Delta I}{V_s - V_0} + L \cdot \frac{\Delta I}{V_0}$$

$$= L \cdot \Delta I \left[\frac{1}{V_s - V_0} + \frac{1}{V_0} \right]$$

$$= L \cdot \Delta I \left[\frac{\cancel{V_0} + V_s - \cancel{V_0}}{V_0 (V_s - V_0)} \right]$$

$$= L \cdot \Delta I \left[\frac{V_s}{V_0 (V_s - V_0)} \right]$$

$$\boxed{L = \frac{T \cdot V_0 (V_s - V_0)}{\Delta I \, V_s}}$$

C → we know $Q = C \cdot V$

In Buck converter $\Delta Q = C \cdot \Delta V \rightarrow (1)$ $A = \frac{1}{2} bh$

$$\Delta Q = \frac{1}{2} \frac{T}{2} \times \frac{\Delta I}{2} = \frac{T \Delta I}{8} \rightarrow (2)$$

Equ (1) & (2)

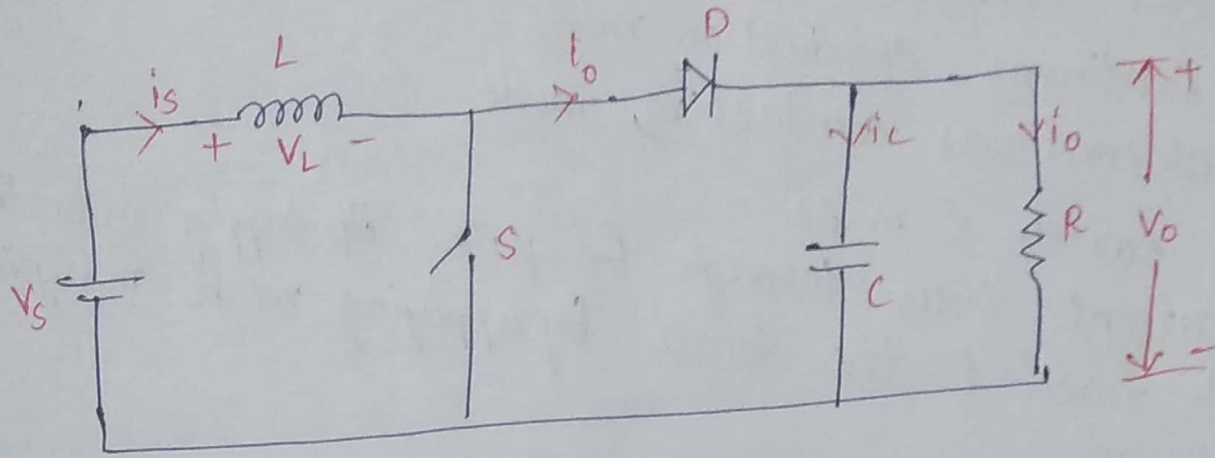
$$C \cdot \Delta V = T \cdot \frac{\Delta I}{8}$$

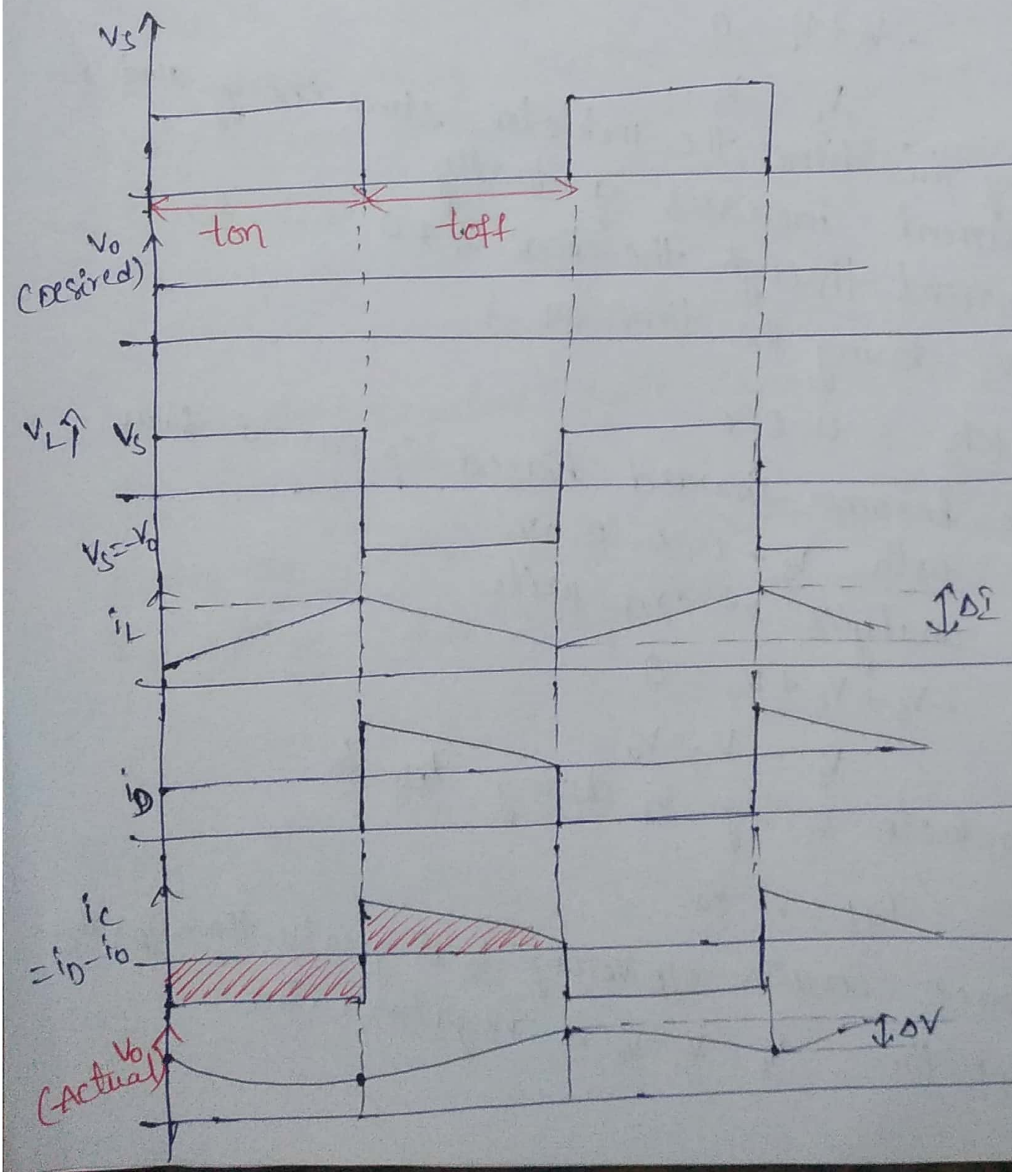
$$C = \frac{T \cdot \Delta I}{8 \cdot \Delta V} \Rightarrow \Delta I = \frac{T \cdot V_0 (V_s - V_0)}{L \cdot V_s}$$

$$\boxed{C = \frac{T^2 \cdot V_0 (V_s - V_0)}{L V_s \cdot 8 \cdot \Delta V}}$$

Boost converter:- (step up converter)

→ In a Boost converter the o/p voltage is greater than the i/p voltage hence named as boost ckt diagram of boost converter





$-V_S + V_L = 0$

$V_L = V_S$

$-V_S + V_L + V_o = 0$

$V_L = V_S - V_o$

$i_L = i_D$

$i_D = i_C + i_o$

$i_C = i_D - i_o$

→ it consists of i/p source V_s, inductor, switch, diode, capacitor & Resistor
Both resistor & capacitor connected in parallel
→ The boost converter can operate in two modes.

1. continous conduction mode
2. Discontinous conduction mode

Case i) switch 's' is ON
The current flows through the path i/p supply inductor switch back to the source. by applying mesh analysis we will get

$$-V_s + V_L = 0$$
$$V_L = V_s$$

also during this time the inductor stores energy and the inductor current increases gradually.
and also current through the diode $I_d = 0$
So, $V_L = V_s$ during the time on

Case ii) Switch 's' is Off
The diode becomes forward biased & current flows through the path $V_s - L, D - R \rightarrow V_s$
using mesh analysis we can write

$$-V_s + V_L + V_o = 0$$
$$V_L = V_s - V_o$$

∴ The inductor voltage V_L during ~~toff~~ is

$$T_{off} = V_s - V_o$$

In case of buck converter o/p voltage V_o is greater than i/p voltage
∴ During T_{off} time $V_L = V_s - V_o$ is negative value

→ During this interval the energy stored in the inductor is released to the load

∴ inductor current decreases gradually

→ Here, when switch is off $i_L = i_D$

∴ $i_L = i_D$

The diode current i_D can be divided into i_C & i_O

Apply nodal analysis we will get

$$i_D = i_C + i_O$$

So, if we want to draw the current through the capacitor i_C we have to draw i_O

Here we are using Resistive load therefore i_O is a straight line with the reduced magnitude

→ using i_O & i_d we can draw i_C, because i_C is equal to $i_d - i_O$

$$i_C = i_d - i_O$$

→ During the negative cycle capacitor is discharges minimum o/p voltage

During the positive cycle capacitor is charging maximum o/p voltage. This magnitude is ΔV. i.e., voltage ripple

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output ^{load} voltage

$$V_s \times t_{on} + (V_s - V_o)\, t_{off} = 0$$

$$V_s (t_{on} + t_{off}) - V_o t_{off} = 0$$

$$V_s (t_{on} + t_{off}) = V_o t_{off}$$

$$V_s \cdot T = V_o \cdot T_{off}$$

$$V_o = \frac{V_s \cdot T}{T_{off}} \qquad \therefore t_{off} = T - T_{on}$$

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

$$V_o = \frac{V_s}{1 - \frac{T_{on}}{T}} \qquad \therefore \frac{T_{on}}{T} = \alpha$$

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

filter inductance :-

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

when switch is ON, $V_L = V_s$

$$V_s = L \cdot \frac{\Delta I}{t_{on}} \Rightarrow t_{on} = \frac{L \cdot \Delta I}{V_s} \rightarrow (1)$$

when switch is OFF, $V_L = V_s - V_o$

$$V_s - V_o = L \cdot \frac{\Delta I}{t_{off}} \Rightarrow t_{off} = \frac{L \cdot \Delta I}{V_s - V_o} \rightarrow (2)$$

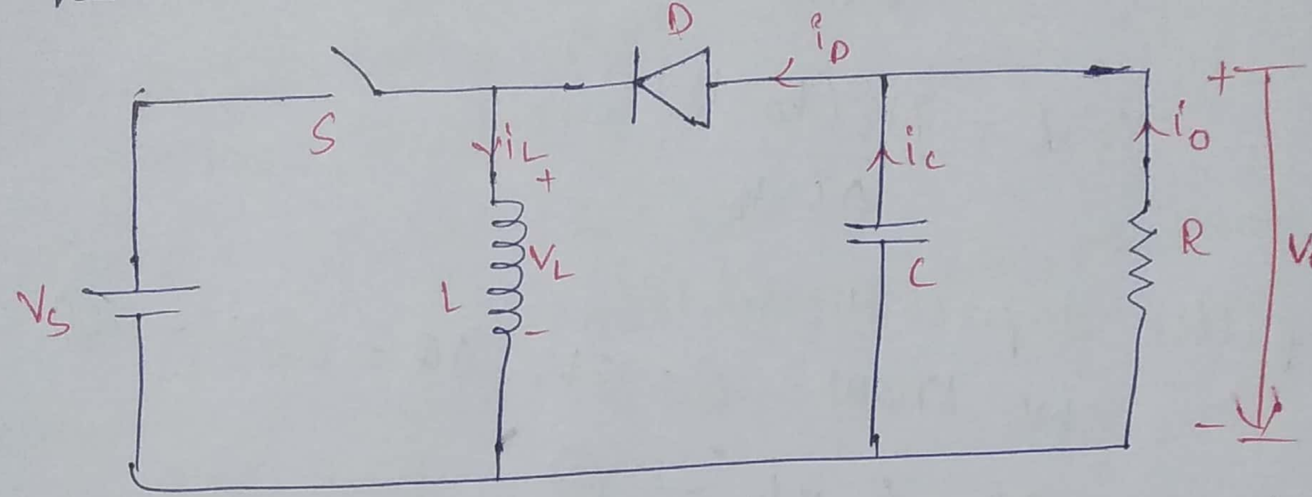
we know $T = t_{on} + t_{off}$

$$= \frac{L \cdot \Delta I}{V_s} + \frac{L \cdot \Delta I}{V_s - V_o}$$

$$= L \cdot \Delta I \left[\frac{1}{V_s} - \frac{1}{V_s - V_o}\right]$$

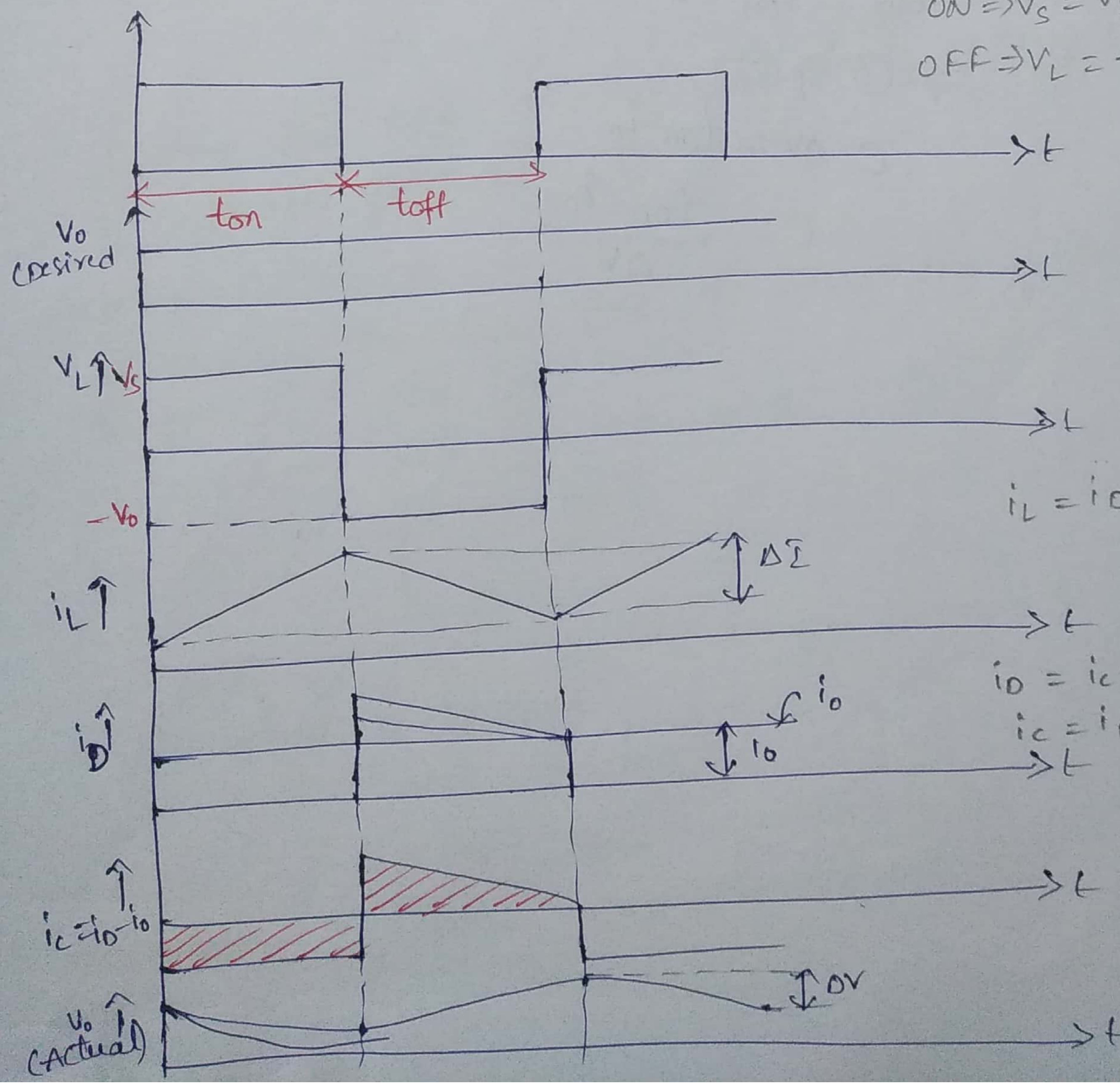
Buck- Boost converter:

→ A Buck- Boost converter provides o/p voltage that may less than or greater than the i/p voltage hence named as Buck- Boost converter



ON ⇒ $V_s = V_L$

OFF ⇒ $V_L = -V_0$



$i_L = i_D$

$i_D = i_c + i_0$

$i_c = i_D - i_0$

$$= L \cdot \Delta I \left[\frac{\cancel{V_S} - V_o - \cancel{V_S}}{V_S (V_S - V_o)} \right]$$

$$\therefore T = \frac{-L \cdot \Delta I \, V_o}{V_S (V_S - V_o)}$$

$$\therefore L = \frac{T V_S (V_o - V_S)}{\Delta I \cdot V_o}$$

Filter capacitance :- (c)

we know , $Q = CV$, $\Delta Q = C \, \Delta V \rightarrow (1)$

$\Delta Q = t_{on} \times i_o \longrightarrow (2)$

Equ (1) & (2)

$$C \cdot \Delta V = t_{on} \times i_o$$

$$C = \frac{t_{on} \cdot i_o}{\Delta V}$$

B

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→ in ~~consists~~ case of o/p voltage polarity ~~of~~ opposite to that of i/p voltage

∴ Buck-Boost ~~converter~~ regulator is also known as inverting regulator

→ it can divide two modes

i) circulating ~~mode~~ current mode.

ii) non circulating current mode

case(i) Switch is 'S' ON

Diode 'D' becomes ~~forward~~ reverse bias, the current flows through the path $V_S - S - L - V_S$

Apply mesh analysis

$$V_S = V_L$$

During this times the inductor ~~Hoards~~ stores energy & i_L increases gradually. & $i_D = 0$

case(ii) Switch is 'S' OFF

During the toff time the stored energy can be transferred to the load

∴ current path $L - C - D - R$

Apply mesh analysis

$$V_L = -V_0$$

During this time toff the energy stored in the inductor is transferred to the load

∴ I_L decreases gradually

$I_L = I_D$, This magnitude is ΔI

→ ~~Apply~~ we need to draw capacitor current i_C

~~Sm~~ Apply node analysis

$\therefore i_D = i_c + i_o$

$i_c = i_D - i_o$

→ Actual o/p voltage V_o

During turn on time capacitor current is discharging after discharging V_o is minimum value.

During +ve i_c capacitor current C is charging

V_o is maximum value.

This magnitude is ΔV

⟹ o/p voltage using volt second balance theory

$$t_{on} \times V_s + t_{off} \times (-V_o) = 0$$

$$V_s \cdot t_{on} = V_o \cdot t_{off}$$

$$V_o = \frac{V_s \cdot t_{on}}{t_{off}}$$

$$V_o = V_s \cdot \frac{t_{on}}{T - t_{on}}$$

$$V_o = \frac{V_s \cdot \frac{t_{on}}{T}}{1 - t_{on}/T}$$

$$= \frac{V_s \cdot \alpha}{1 - \alpha}$$

$$\therefore V_o = \frac{V_s \cdot \alpha}{1 - \alpha}$$

The value of 'α' is 0 to 1

$0 < \alpha < 0.5$, Buck ($V_0 < V_s$)

$0.5 < \alpha < 1$, Boost ($V_0 > V_s$)

filter inductance L:-

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

Switch 'S-ON', $V_L = V_s$

$$V_s = L \cdot \frac{\Delta I}{t_{on}} \Rightarrow t_{on} = \frac{L \cdot \Delta I}{V_s} \rightarrow (1)$$

Switch S-OFF $V_L = -V_0$

$$-V_0 = L \cdot \frac{-\Delta I}{t_{off}} \Rightarrow t_{off} = \frac{L \cdot \Delta I}{V_0} \rightarrow (2)$$

we know that

$$T = t_{on} + t_{off}$$

$$T = \frac{L \cdot \Delta I}{V_s} + \frac{L \cdot \Delta I}{V_0}$$

$$= L \cdot \Delta I \left[\frac{1}{V_s} + \frac{1}{V_0}\right]$$

$$T = L \Delta I \left[\frac{V_0 + V_s}{V_s \cdot V_0}\right]$$

$$L = \frac{T \times V_0 \cdot V_s}{\Delta I \left[V_0 + V_s\right]}$$

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filter capacitance 'c' :-

$$Q = CV \Rightarrow \Delta Q = C \cdot \Delta V \rightarrow (1)$$

$$\Delta Q = t_{on} \cdot i_o \rightarrow (2)$$

equ (1) & (2), we get

$$C \cdot \Delta V = t_{on} \cdot i_o$$

$$\therefore C = \frac{t_{on} \cdot i_o}{\Delta V}$$

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Classification of chopper circuits:-

1. Class-A Chopper :-

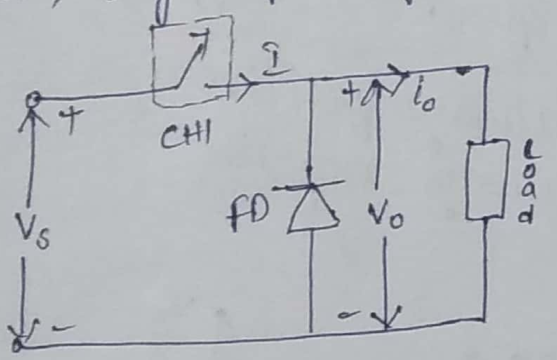
Chopper:- it is a static power electronic device which fixed DC voltage to variable DC voltage

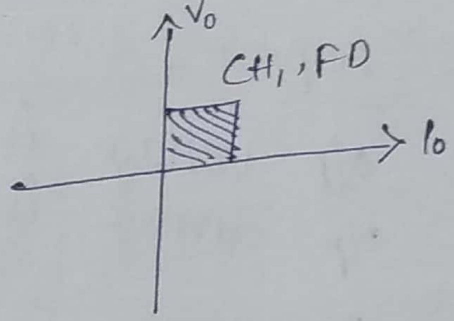
it is nothing but a high speed switch.

which connects & disconnects the load from source at a high rate to get variable voltage at o/p

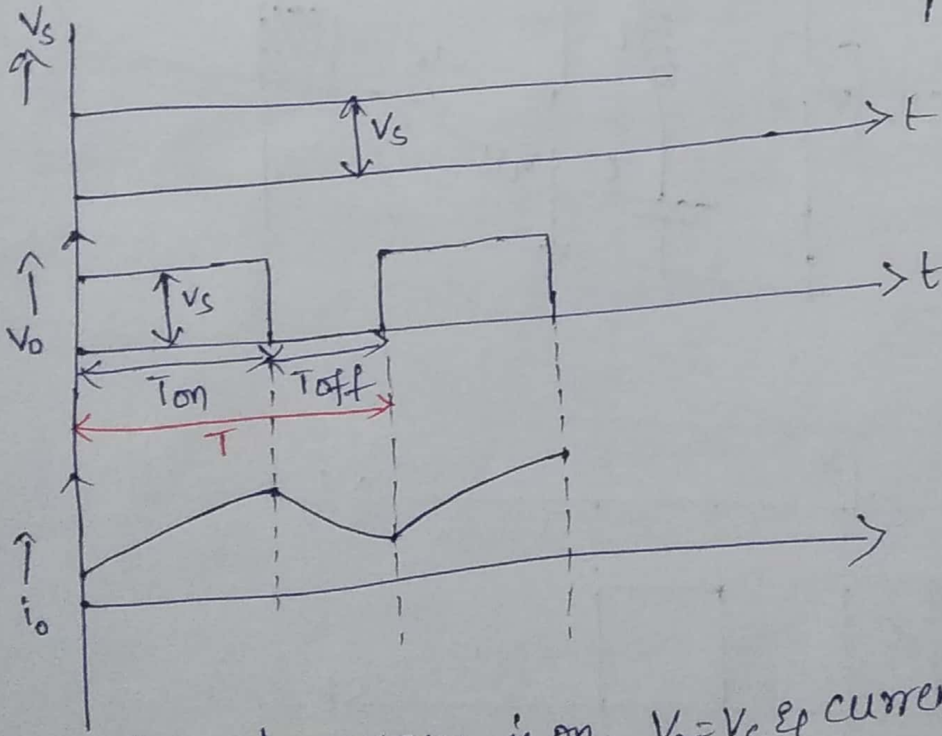
→ class A chopper is also known as step down/first quadrant chopper

So, avg o/p voltage is always less than the i/p dc voltage





$T = T_{on} + T_{off}$



→ when chopper CH1 is on, $V_o = V_s$ & current i_o flows in the arrow direction

→ when chopper CH1 is off, $V_o = 0$, but i_o in the load ~~cont~~ continous flowing in the same direction through freewheeling diode FD.

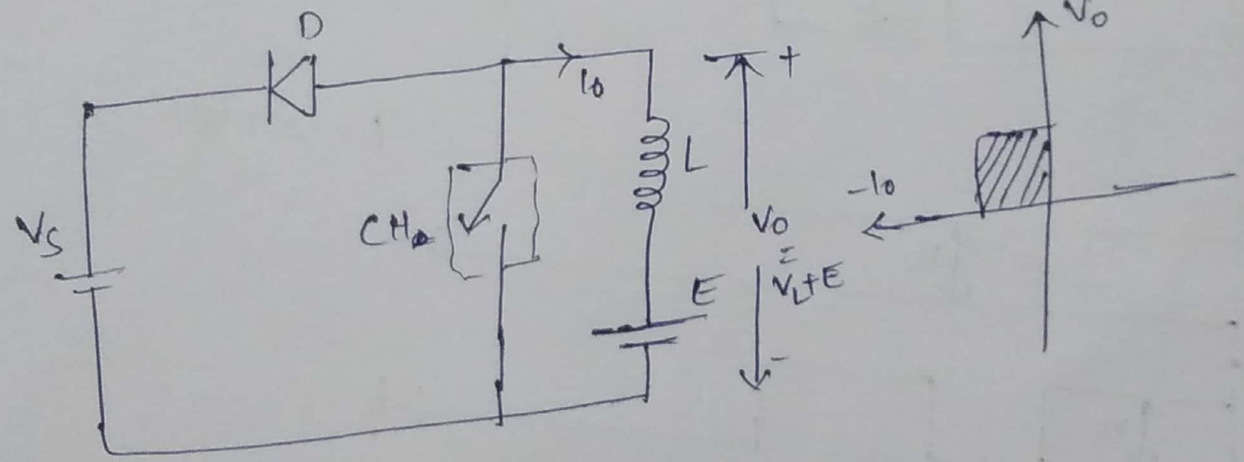
The average values of both load voltage and current V_0 & I_0 are always positive.

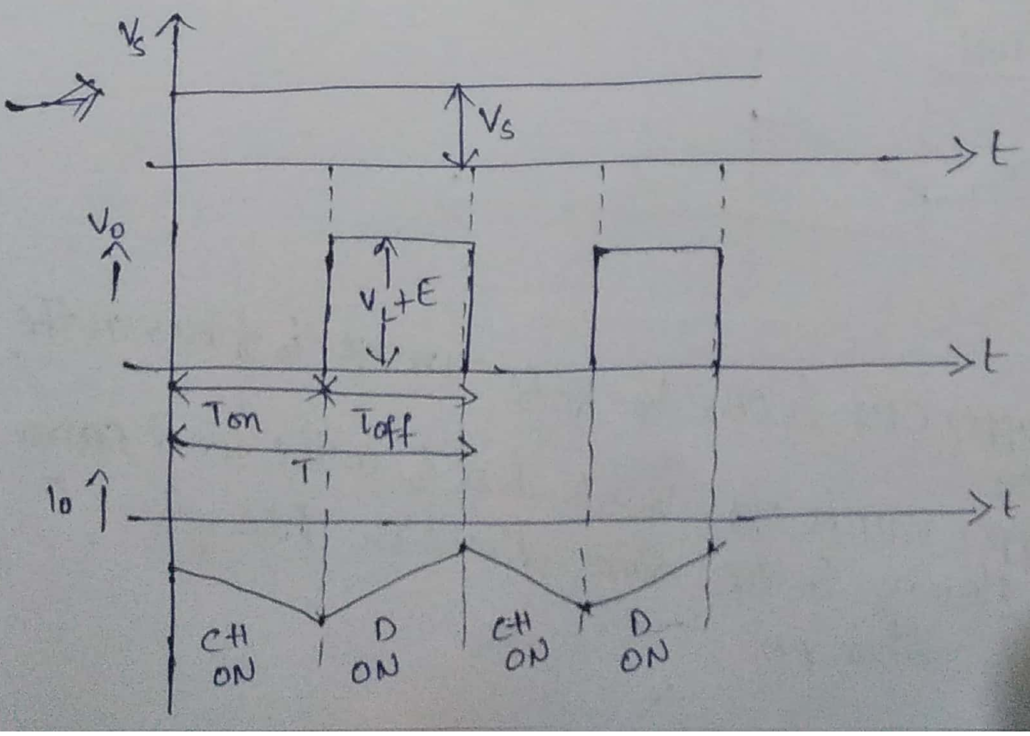
$$V_0 = \frac{\int_0^{T_{on}} V_s \cdot dt}{T} = \frac{V_s}{T}\int_0^{T_{on}} dt = \frac{V_s}{T} \cdot T_{on} \qquad \left[\frac{T_{on}}{T} = \alpha\right]$$

$$V_0 = \alpha \cdot V_s \implies V_0 = 0 \text{ (minimum value)}$$
$$V_0 = V_s \text{ (maximum value)}$$

⟹ **Class-B chopper [second quadrant chopper]**

because o/p voltage is always positive &
o/p current is always negative





→ when CH is on, $V_0 = 0$ but load voltage E drives current through L and CH.

→ inductance L stores energy during T_{on} (= on period) of CH.

→ when CH is off,

$V_0 = \left[E + L\frac{di}{dt}\right]$ exceeds source voltage V_s.

As a result, diode 'D' is forward-biased and begins conduction

thus allowing power to flow to the source.

→ Chopper CH may be on (or) off, current I_0 flows out of the load, current I_0 is treated as negative.

∴ V_0 is +ve, I_0 is −ve

→ power flow is always from load to source

As load voltage is

$V_0 = \left[E + L\cdot\frac{di}{dt}\right]$ is more than source voltage V_s.

type-B chopper is also called step-up chopper

⇒ Class-C chopper [Single quadrant chopper]

→ it can operate first two quadrants means the power can transfer from source to load (or) load to source.

we know that class A operate in first quadrant

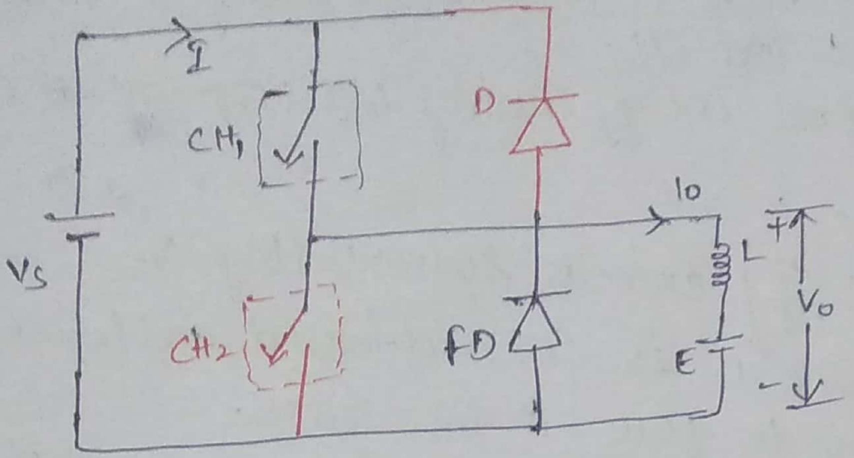
class B operate in second quadrant

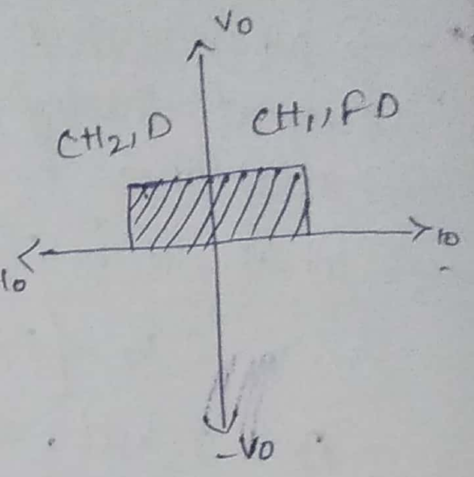
∴ class C chopper can be obtained as the parallel connection of class A and class B chopper

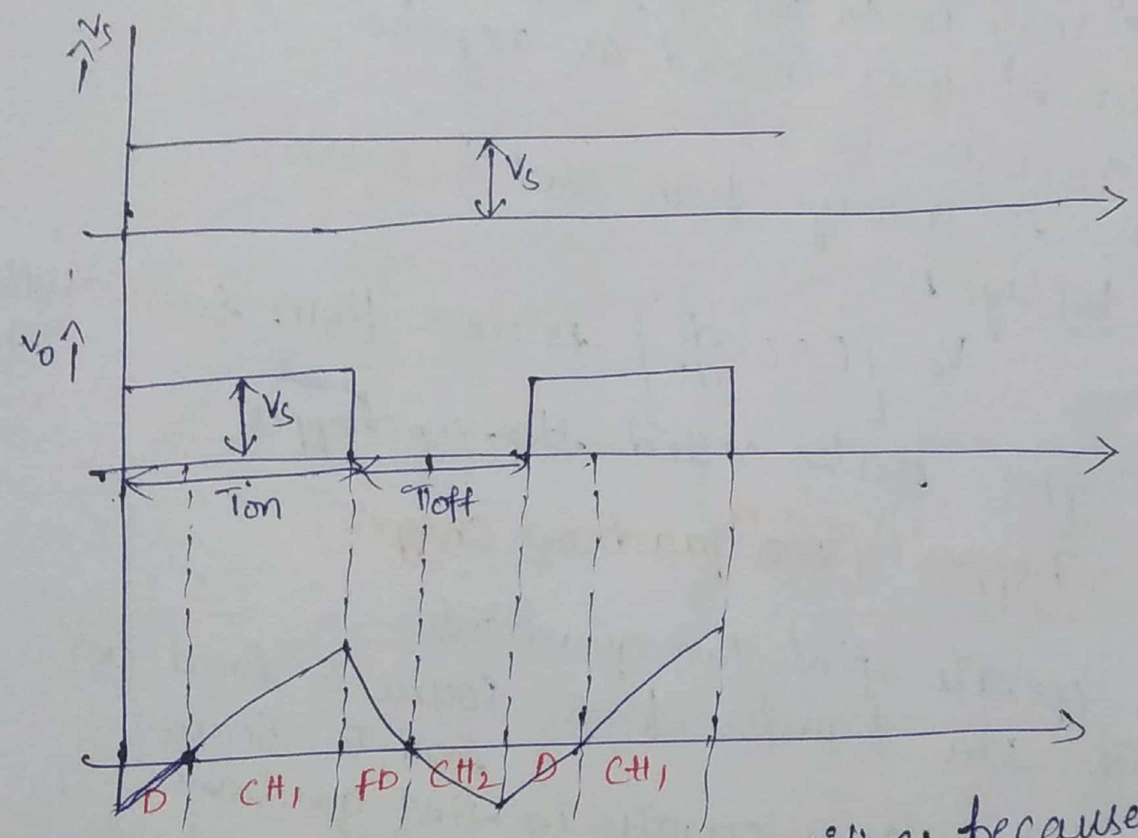
from the ckt diagram

$V_s - CH_1 - FD -$ load are flowing class-A chopper

$D - CH_2 -$ load are flowing class-B.







→ The o/p voltage V_0 is always positive. because of the presence of freewheeling diode FD across the load

→ when CH_2 is on, or FD conducts,

o/p voltage $V_0 = 0$ &

CH_1 is on, or Diode D_2 conducts

o/p voltage $V_0 = V_s$

The load current i_0 can reverse its dircetion

→ when CH_1 is on or FD conducts at load current is +ve

→ load current is -ve if CH_2 is on on (or) D_2 conducts

→ class D chopper is also known as two quadrant chopper because the operation of this type of chopper is confined to the first & fourth quadrant means the o/p voltage V_0 is either positive or −ve. but o/p current is always positive.

→ Here CH_1 & CH_2 represents two choppers & D_1, D_2 are two diodes

Case(i) Both CH_1 & CH_2 are 'ON'

current flows path $V_s - CH_1 - L - CH_2 - V_s$

∴ The load is directly connected to the V_s

$$\therefore V_0 = V_s$$

and o/p current is +ve & increases gradually

→ Here D_1, D_2 are reverse biased by the source voltage V_s hence they can be treated as open switch

Case(ii) Both CH_1 & CH_2 are OFF simultaneously

when the choppers are made simultaneously the current through the load does not suddenly drops to zero due to the inductive nature of the load because of the presence of induced voltage in inductor diode D_1 D_2 becomes forward biased

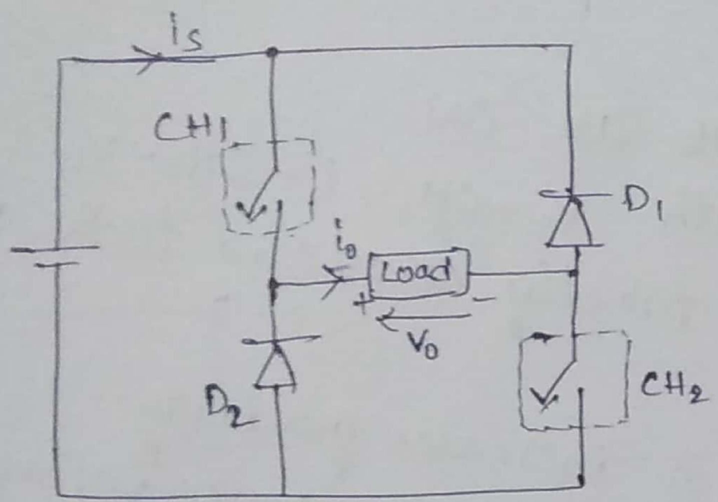
→ thus $D_1 D_2$ starts conducting & connects the load to the source

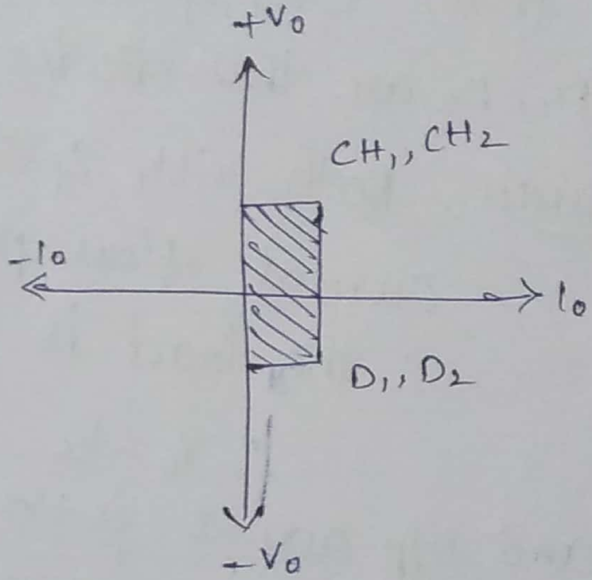
→ ~~Here the induced voltage in inductor is~~ ~~here~~ negative induced voltage in the inductor V_L the diode D_1 & D_2 are forward biased & current flows from the load to the source.

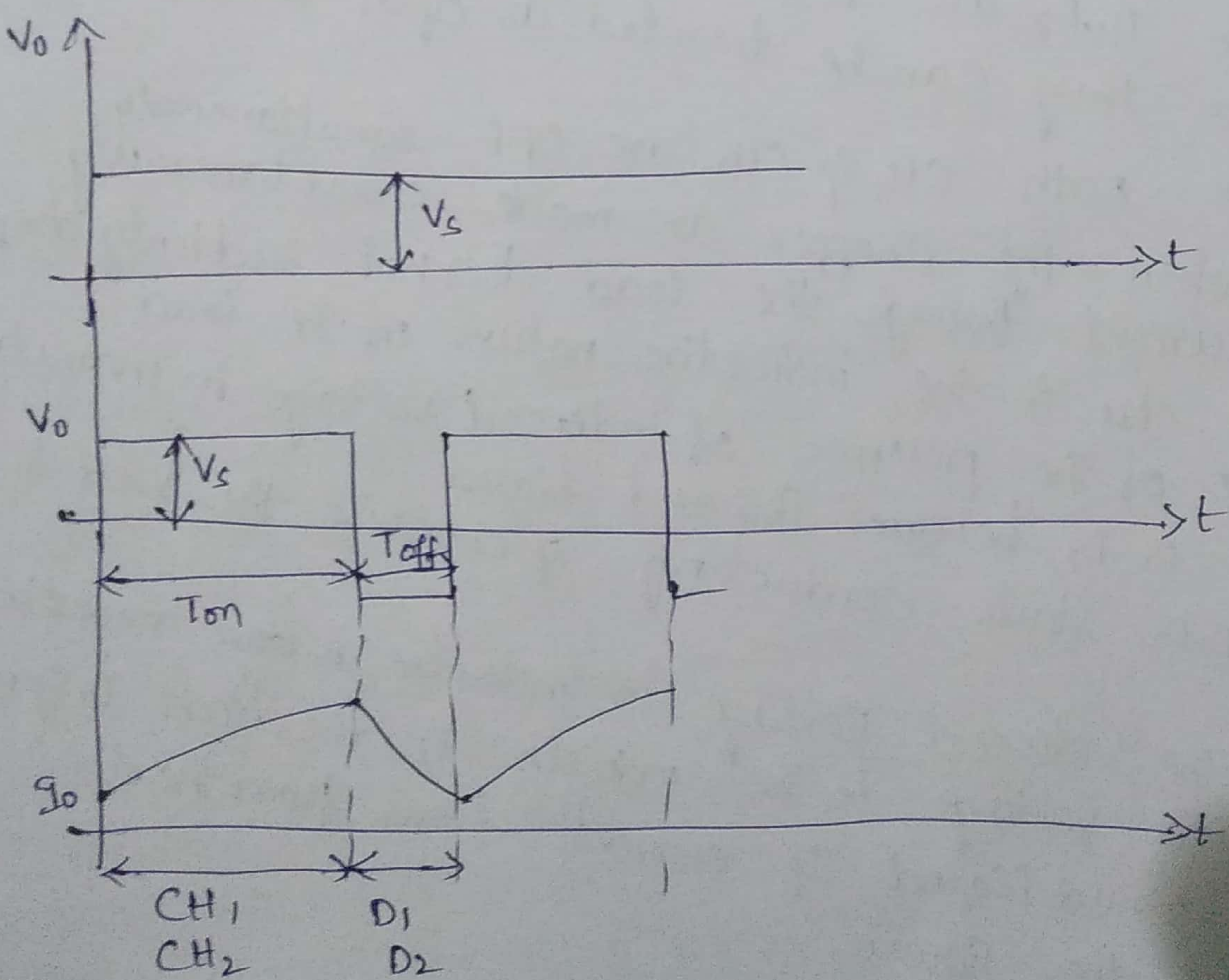
→ Avg load voltage is always positive but avg load current may be positive or negative

→ This type of chopper configuration is used for motoring & regenerative braking of dc motors

⇒ Class-D chopper [Two quadrant chopper]







→ ∴ o/p voltage is +ve & o/p V_0 is −ve
hence the operation of chopper is in the fourth quadrant and the power flows from load to the source

→ when CH1 & CH2 ON → ~~o/p~~ $V_0 = +ve$, $I_0 = +ve$
first quadrant operation
powerflows from source to load

→ when CH1 & CH2 OFF → $V_0 = -ve$, $I_0 = +ve$
fourth quadrant operation
power flows from load to source

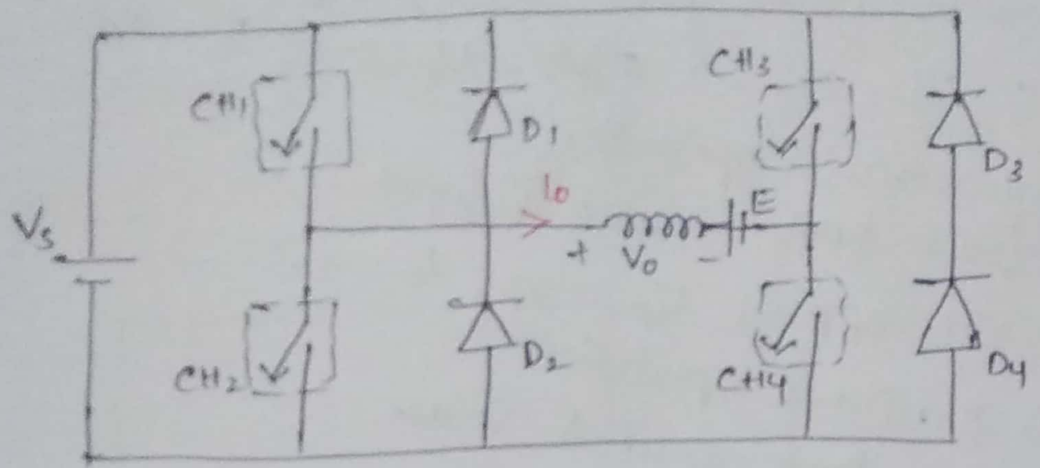
Average value of o/p voltage

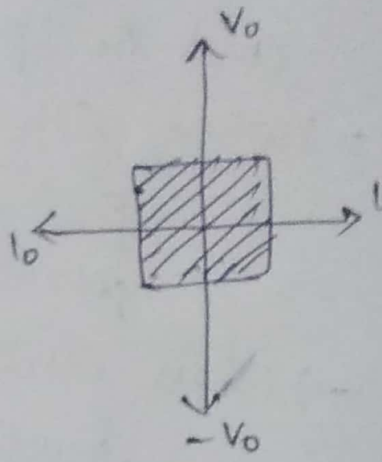
$$V_0 = \frac{V_s \cdot T_{on} - V_s \cdot T_{off}}{T}$$

$$V_0 = V_s \cdot \frac{T_{on} - T_{off}}{T}$$

i) In case $T_{on} > T_{off}$, $\alpha > 0.5$, V_0 is +ve
ii) In case $T_{on} < T_{off}$, $\alpha < 0.5$, V_0 is −ve
iii) In case $T_{on} = T_{off}$, $\alpha = 0$, $V_0 = 0$.

→ class-E chopper [four quadrant chopper]:-





V_o

CH_2 operated

$CH_2 - D_4$; L stores energy

CH_2 - OFF ; then

$D_1 - D_4$ conduct

CH_1 operated

$CH_1 - CH_4$ on

CH_4 - off ; then $CH_4 - D_2$ conduct

$-I_o$ ← → I_o

CH_3 operated

$CH_3 - CH_2$: ON

CH_3 - off ; then

$CH_2 - D_4$ conduct

E reversed

CH_4 operated

$CH_4 - D_2$; L stores energy

CH_4 - off ; then D_2, D_3 conduct

E reversed.

$-V_o$

→ four quadrant chopper can operate in all four quadrants

∴ The power can flow either from source to load or from load to source

→ it basically consists of four semiconductor switches $[CH_1, CH_2, CH_3, CH_4]$ and four diodes $[D_1, D_2, D_3, D_4]$

→ In first quadrant operation the chopper CH_1 is operated & CH_4 is ON, CH_1 is either ON/OFF

→ In Second quadrant operation CH_2 is operated

→ In third quadrant operation CH_3 is operated & CH_2 is always ON

→ In fourth quadrant operation CH_4 is operated

case i :- CH_1 is ON, Here both CH_1 & CH_4 are ON simultaneously

∴ current flows through the path

$V_s - CH_1 - \text{Load} - CH_4 - V_s$

∴ $I_0 = +ve$, $V_0 = +ve$ & $V_0 = V_s$

∴ The power flows from source to the load & also when the current flows through the load the inductor stores the energy the voltage induced in the inductor

case ii :- CH_1 is OFF.

current freewheels through CH_4, D_2.

+ve current freewheels in the first quadrant

Here, both V_0, I_0 can be controlled in the first quadrant

case iii :- CH_1 is OFF, when CH_1 is off due to the induced voltage in the inductor the diode D_2 becomes forward biased

∴ The current flows through the path

$CH_4 - D_2 - \text{Load}$

∴ $I_0 = +ve$

Case ii :- CH_2 is operated
CH_1, CH_3 & CH_4 are kept off.
with CH_2 - ON, reverse (or negative) current flows
L - CH_2 - D_4 - E
inductor L stores energy during the time CH_2 is ON.
→ when CH_2 is OFF,
current fed back to the source through diodes D_1, D_4
→ Here $\left[E + L\cdot\frac{di}{dt}\right]$ is more than the source voltage V_s.

$\therefore V_0 = +ve,\ I_0 = -ve$
it is second quadrant operation of chopper.
power is fed back from load to source.

Case iii :- CH_1 is kept off, CH_2 is kept ON
CH_3 is operated.
→ polarity of load emf E must be reversed for this quadrant working
→ when CH_3 is ON,
load gets connected to source V_s
$\therefore V_0, i_0$ are negative leading to the third quadrant operation.

→ when CH_3 is OFF
negative current freewheels through CH_2, D_4
So, V_0, I_0 are controlled in third quadrant

Case iv :- CH_4 is operated &
other devices are kept off.
Load emf E has its reverse polarity.
operation in the fourth quadrant.

→ when CH_4 – ON
+ve current flows through
$CH_4 - D_2 - L - E$
inductor L stores energy

→ when CH_4 – Off
current is fed back to source through diodes D_2, D_3.

Here load voltage is negative
but load current is positive
power is fed back from load to source

Thyristor chopper circuits:-

→ Actually, a chopper consists of main power semiconductor device together with their turn-on & turn-off mechanisms

→ In low power chopper ckts: ptransistors, GTOS, PMOSFET etc
In high power chopper ckts: thyristors are in common use

→ The process of opening, or, turning-off, a conducting thyristor is called commutation

→ All these commutation ckts can, be broadly classified into two groups as

a) forced commutation:- In this commutation, external elements L and C which do not carry the load current continously, are used to turn-off a conducting thyristor. forced commutation can be achieved in the following two ways

i) ~~forced~~ Voltage commutation:- In this scheme, a conducting thyristor is commutated by the application of a pulse of large reverse voltage. This reverse voltage is usually applied by switching a previously charged capacitor.
The sudden application of reverse voltage across the conducting thyristor reduces the anode current to zero rapidly.
Then the presence of reverse voltage across the SCR aids in the completion of its turn-off process.

ii) current commutation:- In this scheme, an external pulse of current greater than the load current is passed in the reversed direction through the conducting SCR.
when the current pulse attains a value equal to the load current, net pulse current through thyristor becomes zero and the device is turned off.
The current pulse is usually generated by an initially charged capacitor

→ An important feature of current commutation is the connection of a diode in antiparallel with the main thyristor so that voltage drop across the diode reverse biases ~~under~~ the main SCR.

b) **load commutation**:- In load commutation, a conducting thyristor is turned off. when load current flowing through a thyristor either

i) either zero due to the nature of load circuit parameter (or)

ii) is transferred to another device from the conducting thyristor

⟹ Voltage commutated chopper:-

This chopper is generally used in high-power ckts where load fluctation is not very large. This chopper is ~~generally used in high power circuits~~ also known as parallel-capacitor turn-~~off~~ chopper, impulse commutated chopper (or) classical chopper

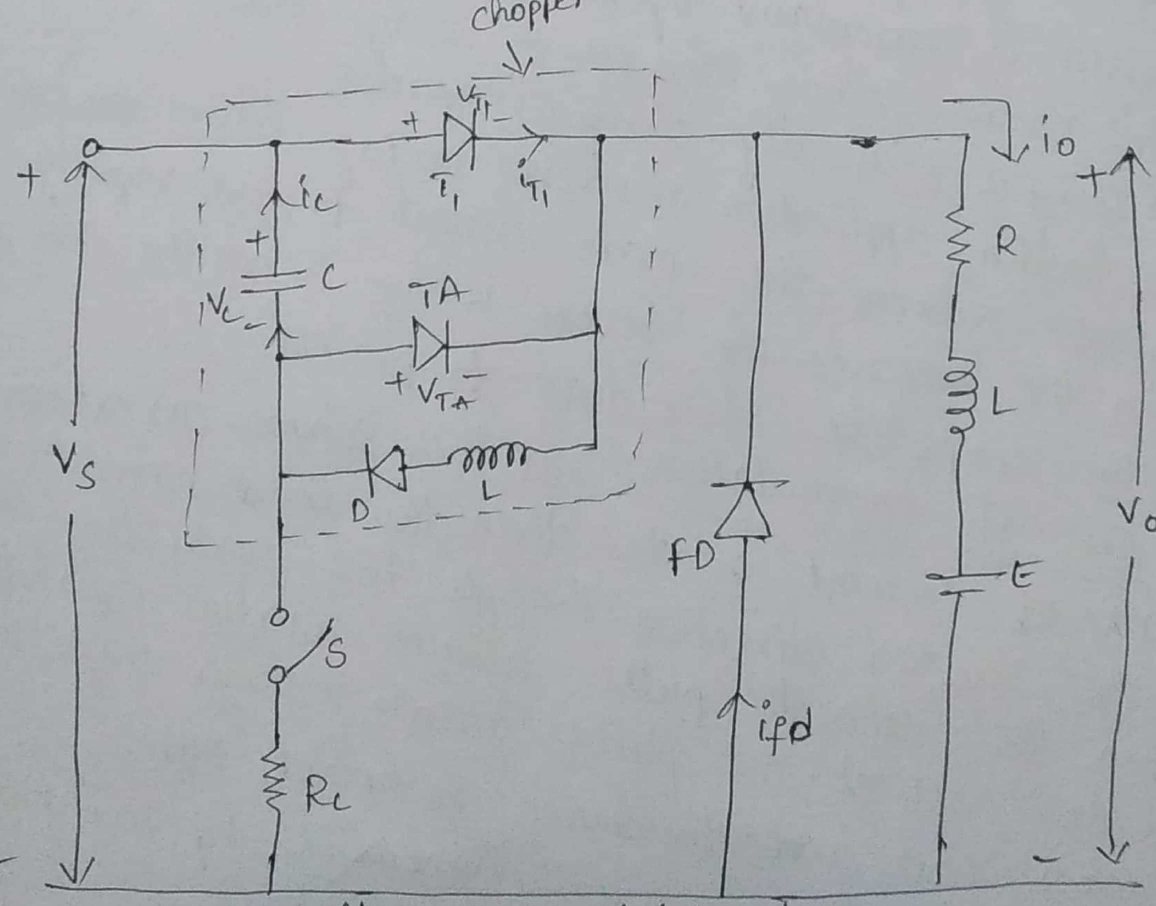
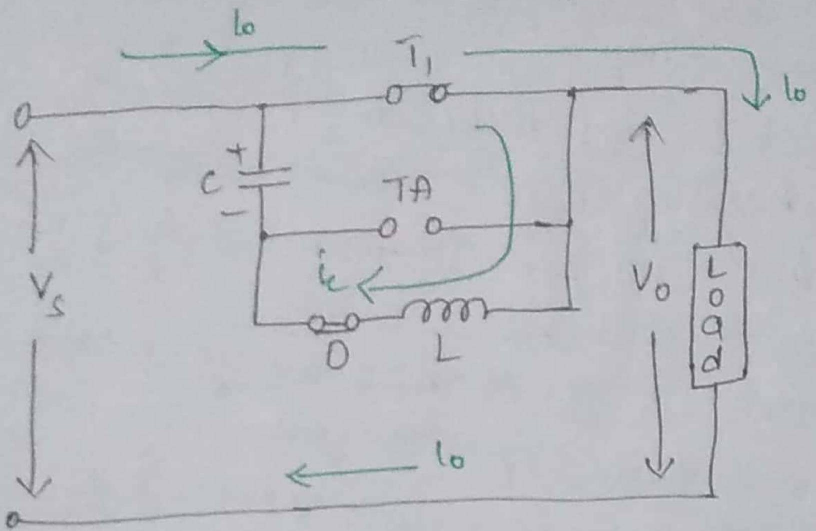


fig: voltage commutated chopper

→ Thyristor T_1 is the main power switch. commutation circuitry for this chopper is made up of an Auxiliary SCR TA, capacitor C, diode D and inductor L.
FD is the freewheeling diode connected across the RLE type load
→ working of this chopper can start only if the capacitor C is charged with polarities as marked.
This can be achieved in one of the two ways as under
i) close switch S so that capacitor gets charged to voltage V_s through source V_s, C, S, & charging Resistor R_c.
Switch S is then opened
ii) Auxiliary thyristor TA is triggered so that C gets charged through source V_s, C, TA and the load.
The charging current through capacitor C decays and as it reaches zero, $V_c = V_s$ and TA is turned off.
→ with capacitor C charged with polarities, the chopper ckt is ready for operation. This current i_c, i_{T_1}, i_{fd} & i_0 are taken as positive in the arrow directions marked.
Similiarly, the voltages V_c, V_{T_1}, V_{TA} & V_0 across C, T_1, TA and load are taken as positive with the polarities marked.
Simplifying assumptions for this chopper are
i) load current is constant and
ii) Thyristors & diodes are ideal elements
The chopper operation, for convenience, is divided into certain modes & is explained as.

Mode I:- The main thyristor is triggered at $t=0$ and RLE load gets connected across source V_s so that load voltage $V_0 = V_s$.
During this mode, there are two current paths.
load current I_0 flows through source V_s, main SCR T_1 and load whereas the current i_c flows through oscillatory circuit formed by C, T_1, L and D



a) Mode I, $0 < t < t_1$

→ The capacitor current first rises from zero to a maximum value when voltage across is zero at $t = t_1/2$

→ As i_c decreases to zero, capacitor is charged to $(-V_s)$ at $t = t_1$

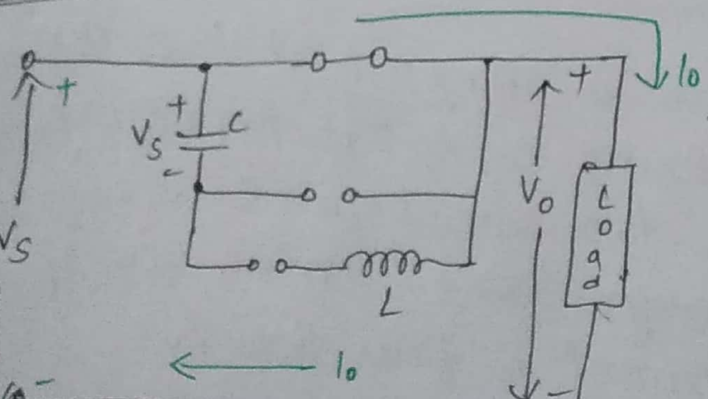
→ The capacitor current changes sinusoidally whereas the capacitor voltage cosinusoidally from $t=0$ to $t=t_1$. This voltage is held constant at $(-V_s)$ by diode D.

→ Voltage across TA is $(-V_s)$ at $t=0$, zero at $t_1/2$ and V_s at t_1

The thyristor current i_{T_1} has a peak at $t_1/2$, because $i_{T_1} = I_c + I_o$ between $t=0$ and $t=t_1$

At the end of mode I at t_1; $I_c = 0$, $i_{T_1} = I_o$, $V_c = -V_s$, $V_{TA} = V_s$, $V_o = V_s$

Mode : II



b) Mode II, $t_1 \leq t < t_2$

→ The condition existing at t_1 continue during mode II

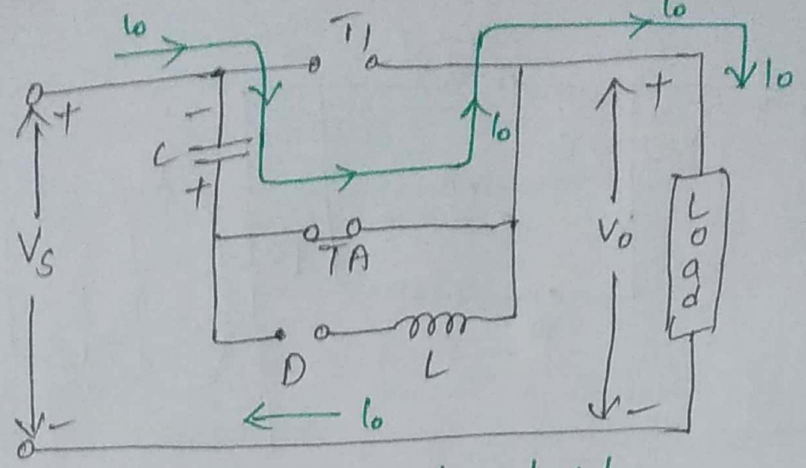
→ In other words, for $t_1 \leq t \leq t_2$,

$I_c = 0$, $I_{T_1} = I_o$, $V_c = -V_s$

$V_{TA} = V_s$, $V_o = V_s$, $I_D = 0$

Note:- only main SCR T_1 is conducted

Mode III :-



c) Mode III : $t_2 \le t \le t_3$

→ when main thyristor T_1 is to be turned off, auxiliary thyristor TA is triggered at desired instant t_2.

→ with the turning on of TA at t_2, capacitor voltage $(-V_s)$ appears across T_1, it is therefore reverse biased & turned off.

→ As the capacitor voltage does the required job of commutating the main thyristor T_1, it is called voltage commutated chopper. current I_{T_1} becomes zero at t_2.

→ After T_1 is turned off, capacitor C and auxiliary SCR TA provide the path for load current I_0 through V_s, C, TA and the load.

The load voltage is sum of the source voltage and the voltage across capacitor C.

∴ at instant t_2, load voltage at $V_0 = V_s + V_s = 2V_s$, and it decreases linearly as the voltage across capacitor decreases.

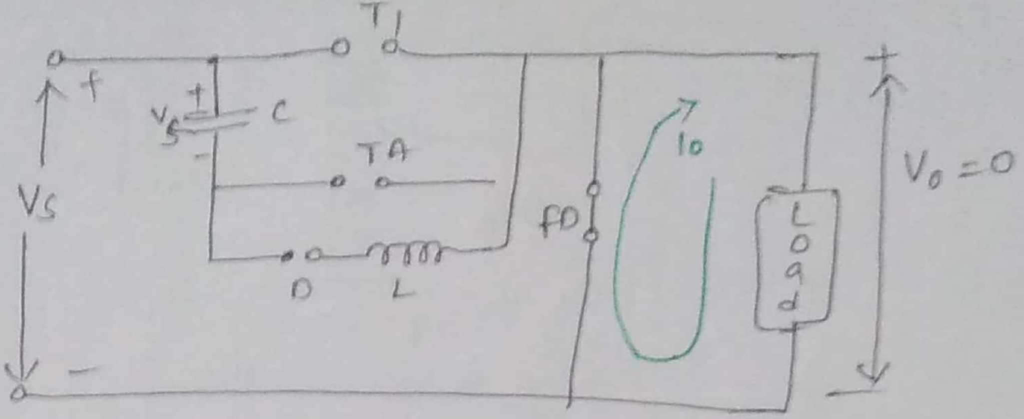
→ During this mode $V_C = V_{T_1}$, because capacitor is directly connected across T_1 through TA.

load voltage V_0 changes from $2V_s$ at t_2 to V_s at (t_2+t_c)

→ After (t_2+t_C), V_C & V_{T_1} starts rising from zero towards V_s whereas V_0 starts falling towards zero.

Note :- $i_c = -I_0$ & $I_{TA} = I_0$

Mode IV :-



d) Mode IV, $t_3 \le t < T$

→ for this mode, $t_3 < t < T$. At t_3, $V_C = V_{T_1} = V_S$ & $V_0 = 0$
At t_3 capacitor is slightly overcharged, freewheeling Diode FD, therefore gets forward biased at t_3.

→ In the load circuit formed by FD, TA, C & V_S $V_C > V_S$ at t_3
∴ current i_C tends to go negative.

→ As i_C or i_{TA}, tends to reverse, auxiliary thyristor TA is turned off naturally at t_3.

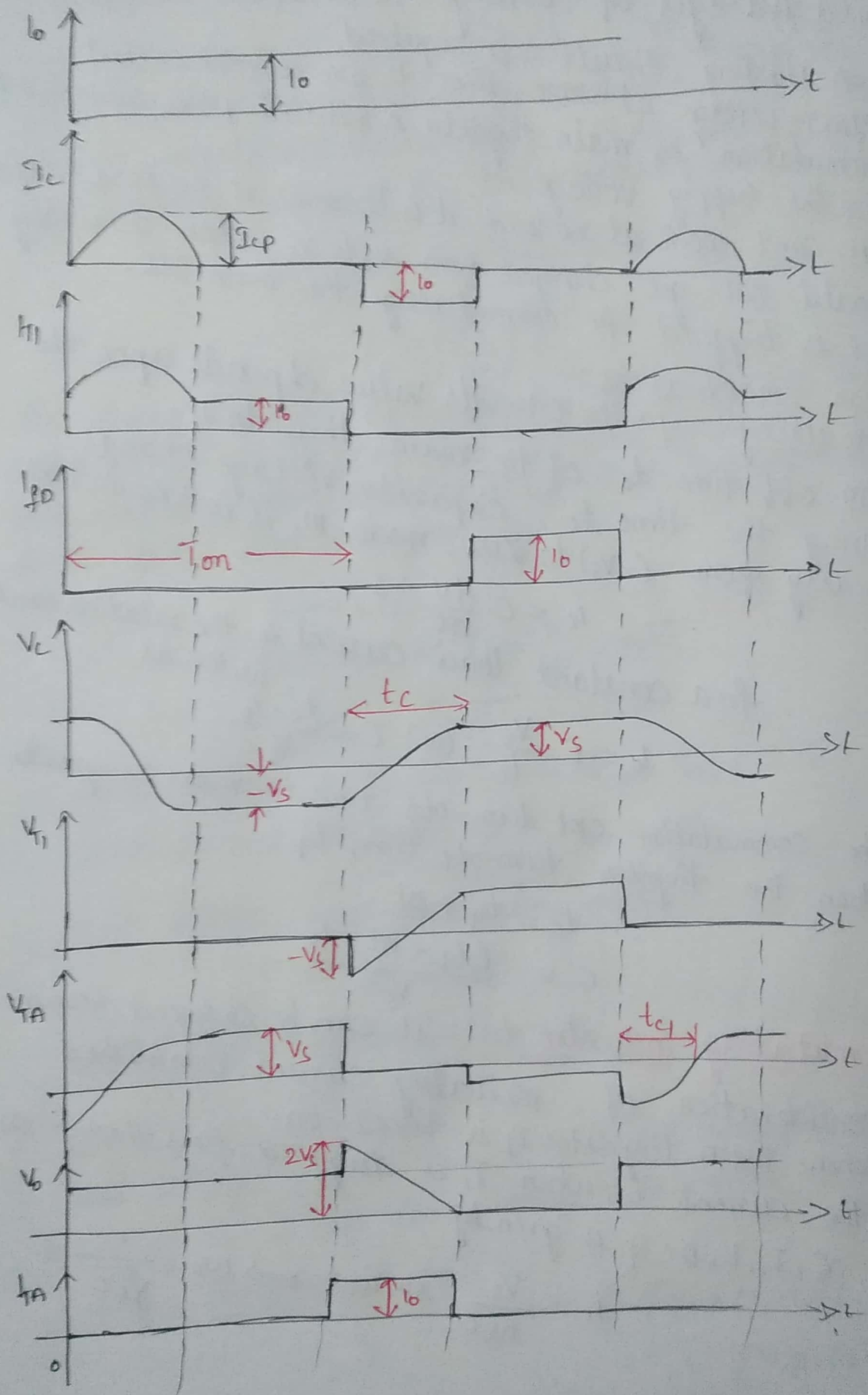
→ Thus at time t_3, FD gets turned on & TA is turned off.

→ As a result, load current after t_3 free wheels through the load & FD.
through t_3, freewheels through freewheeling period from t_3 to T.

→ Note that during freewheeling period from t_3 to T. V_{TA} is slightly negative as C is some what overcharged

→ During this mode, $i_C = 0$, $i_{T_1} = 0$, $i_{fd} = I_0$, $I_{TA} = 0$
$V_{T_1} = V_S$, $V_C = V_S + \Delta V_S$, $V_{TA} = -\Delta V$
$V_0 = 0$.

At $t = T$, the main thyristor T_1 is triggered & the cycle as described from $t = 0$ to $t = T$ repeats



Io
Io
t
Ic
Icp
t
Io
iT1
Io
t
iFD
Ton
Io
t
Vc
tc
Vs
t
-Vs
VT1
t
-Vs
VTA
Vs
tq
t
Vo
2Vs
t
iTA
Io
t
0

Disadvatages of voltage commutated chopper:

i) A starting circuit is required

ii) load voltage at once rises to $2V_s$ at the instant commutation of main thyristor is initiated. FD is subjected to twice the supply voltage

iii) It can't work at no load. it is because at no load, capacitor would not get charged from $-V_s$ to V_s. when auxiliary SCR is triggered for commutating the main SCR.

Design considerations:-

Commutating capacitor C:- its value depends upon the turn-off time t_c of the main thyristor T_1.

During the time t_c, capacitor voltage changes linearly from $(-V_s)$ to zero, mode-III, it is known that

$$i_c = C \cdot \frac{dV}{dt}$$

for a constant load current I_o, the relation can be written as

$$I_o = C \cdot \frac{V_s}{t_c} \quad (or) \quad C = \frac{t_c \cdot I_o}{V_s}$$

The commutation ckt turn-off time t_c, must be greater than the thyristor turn off time t_q,

$$\therefore \; t_c = t_q + \Delta t$$

$$C = \frac{(t_q + \Delta t) \cdot I_o}{V_s}$$

Commutating inductor L:- It can be designed from a consideration of oscillatory current established when main thyristor T_1 is turned-on.

The current i_c, when T_1 is triggered, flows through the C, T_1, L, D Ep is given by

$$i_c = \frac{V_s}{\omega_0 L} \sin \omega_0 t \Rightarrow \omega_0 = \frac{1}{\sqrt{LC}}$$

The peak capacitor-current $i_{cp} = \frac{V_s}{\omega_0 L} = V_s \cdot \sqrt{\frac{C}{L}}$

This current flows through T_1 when it is turned-on. As T_1 handles load current as well as I_{cp}, peak capacitor current should not be too large. it is usual to take I_{cp} less than, or equal to, load current I_0. i.e.,

$$I_{cp} \leq I_0 \quad \text{or} \quad V_s\sqrt{\frac{C}{L}} \leq I_0$$

$$L \geq \left(\frac{V_s}{I_0}\right)^2 C$$

The second method of designing the value of L is from a consideration of the ckt turn-off time for TA.

it is seen from time variation of V_{TA} that turn off time for TA is t_{c1} and it is given by

$$t_{c1} = t_1/2$$

$$\omega_0 t_1 = \pi \quad \text{or} \quad t_1 = \frac{\pi}{\omega_0} = \pi\sqrt{LC}$$

$$t_{c1} = \frac{\pi}{2}\sqrt{LC}$$

peak voltage across T_1 & TA is $V_{T1p} = V_{TAp} = \pm V_s$

peak current through TA is $i_{TAp} = \frac{CV_s}{t_c} = I_0$

peak voltage across freewheeling diode,

$$V_{fdp} = 2V_s.$$

peak diode current, $i_{DP} = V_s\sqrt{\frac{C}{L}}$

Voltage commutated chopper:-

i) load voltage V_s from $t=0$ to t_2 and it varies from $2V_s$ at t_2 to zero at t_3. $\therefore$ avg load voltage V_0 is given by

$$V_0 = \frac{V_s \cdot t_2 + 2V_s(t_3 - t_2)(1/2)}{T} = \frac{V_s}{T}\left[T_{on} + (t_3 - t_2)\right]$$

$[\because \text{As } t_2 = T_{on}]$

During the interval $(t_3 - t_2)$, the voltage across C changes from $-V_s$ to V_s i.e., total change is $2V_s$

$$I_0 = C \cdot \frac{2V_s}{(t_3 - t_2)} \quad (\text{or}) \quad t_3 - t_2 = \frac{2CV_s}{I_0}$$

$$V_0 = \frac{V_s}{T}\left[T_{on} + \frac{2V_s}{I_0} C\right] = \frac{V_s}{T} T_{on}'$$

where $T_{on}' = T_{on} + \frac{2V_s}{I_0} C$ = effective on period

ii) Charge on capacitor must be reversed from $+V_s$ to $-V_s$ when T_1 is turned on.

Therefore minimum on period for this chopper is

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

minimum duty cycle, $\alpha_{mn} = \frac{t_1}{T} = \pi f \sqrt{LC}$

minimum load voltage, $V_{0,mn} = \alpha_{mn} \cdot V_s + \frac{2V_s \cdot 2t_c}{2T}$

$$= V_s(\alpha_{mn} + 2ft_c)$$

$$= V_s[\pi f\sqrt{LC} + 2ft_c]$$

$$V_{0,mn} = f \cdot V_s[t_1 + 2t_c]$$

Max on period is $(T - 2t_c)$. This gives max. value of duty cycle as

$$\alpha_{mx} = \frac{T - 2t_c}{T} = 1 - 2ft_c.$$

Max. load or o/p voltage, V_{0mx} is given by

$$V_{0,mx} = \alpha_{mx} \cdot V_s + \frac{2V_s \cdot 2t_c}{2T} = V_s[\alpha_{mx} + 2ft_c]$$

sub. the value of α_{mx}, gives

$$V_{0,mx} = V_s[1 - 2ft_c + 2ft_c] = V_s$$

→ If main thyristor T_1 fails to turn off when TA is triggered, C is completely discharged. The commutation ∴ cannot be resumed in the next cycle & ∴ control lost must be regained by turning off T_1 by interrupting the supply

→ The circuit cannot be operated at no load.

Current - commutated chopper:-

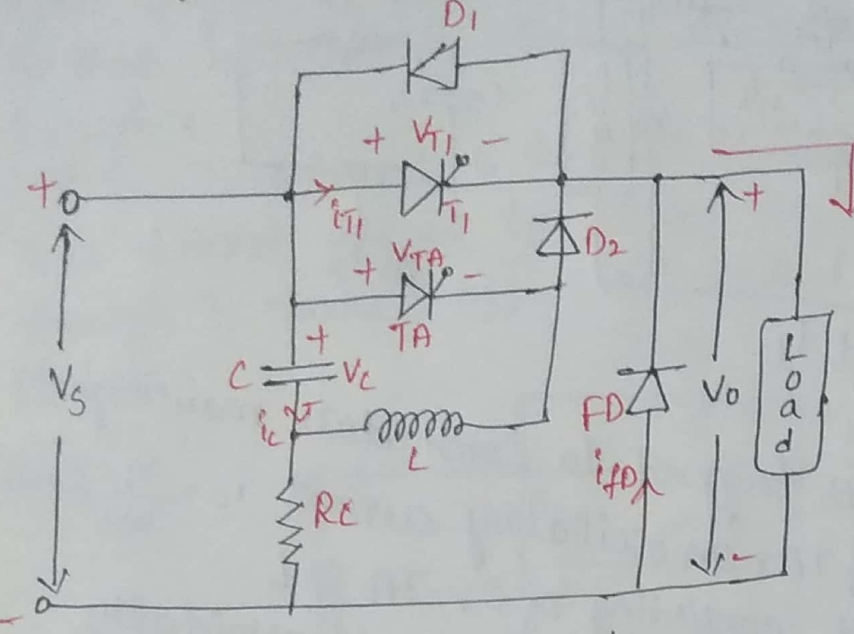


fig: current commutated chopper

→ The circuit diagram consists of T_1 is the main thyristor. The other components, namely, auxiliary thyristor TA, capacitor C, inductor L, diodes D_1 & D_2 constitute commutation circuitry.

→ FD is freewheeling diode and R_C is charging resistor

→ Simplifying assumptions for the chopper are as follows:

i) load current is constant

ii) SCRs & diodes are ideal switches

iii) charging Resistor R_C is so large that it can be treated as open circuit during the commutation interval.

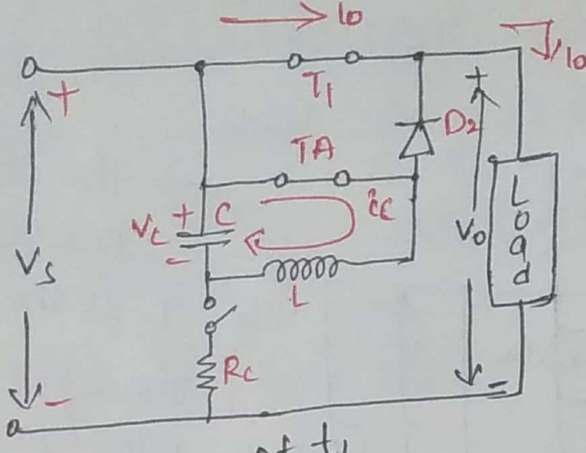
→ currents i_c, i_{T_1}, i_{fd} and i_0 are treated as positive when these are in the arrow directions marked. voltages V_c, V_{T_1}, V_{TA} and V_0 are taken as positive with the polarities as marked.

→ energy stored in capacitor C. C is charged to a voltage V_s. So that energy for commutation process is available. C is charged through source V_s, capacitor C & the charging Resistor R_C to a voltage V_s.

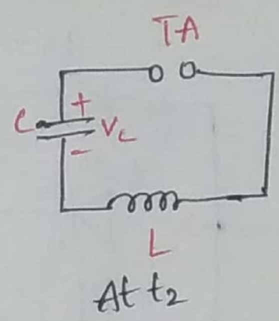
→ After main thyristor T_1 is fired at $t=0$ so that load voltage $V_0 = V_s$ & load current $i_0 = I_0$ upto $t = t_1$

→ with the turning on of T_1, commutation circuitry remains inactive. initiation of commutation process begins with the turning on of thyristor TA

Mode: I:-



At t_1



At t_2

(a) Mode I, $t_1 < t < t_2$

→ At time $t = t_1$, TA is triggered to commutate main thyristor T_1. An oscillatory current $i_c = \frac{V_s}{\omega_0 L} \sin\omega_0 t$ with the turning-on of TA, an oscillatory current is set up in the circuit consisting of C, TA & L.

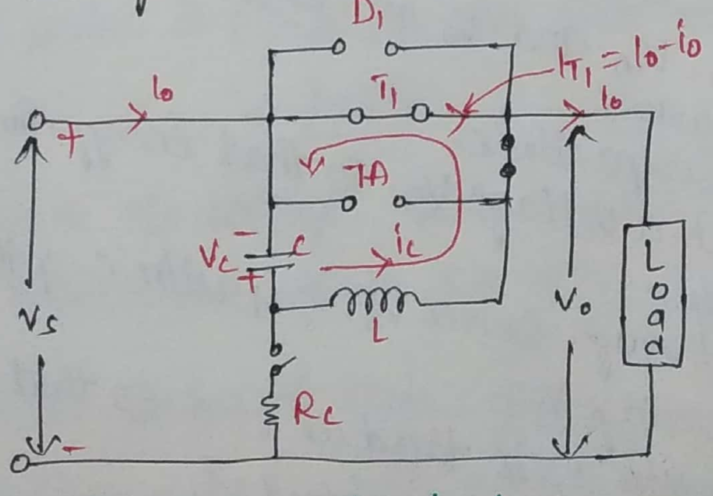
→ For the time interval $(t_2 - t_1)$ i_c & V_c vary sinusoidally through half cycle.

→ During this mode when V_c is zero, i_c is max though negative.

→ At t_2, as i_c tends to reverse in the auxiliary Thyristor TA, it gets naturally commutated.

→ At t_2, $V_c = -V_s$, lower plate is +ve & upper plate is -ve. During this mode T_1 remains uneffected, therefore load current & load voltage remains I_0 & V_s respectively.

Mode II :-



b) Mode II, $t_2 < t < t_3$

→ As TA is turned off at t_2, oscillatory current i_c begins to flow through C, L, D_2 & T_1.

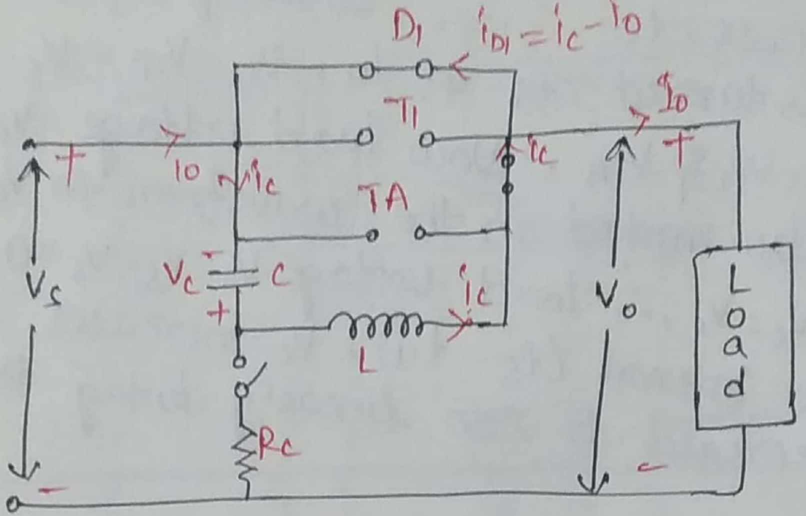
→ After t_2, i_c would flow through T_1 and not through D_1. It is because D_1 is reverse biased by a small voltage drop across conducting thyristor T_1.

So, after t_2, i_c would pass through T_1 & not through D_1

→ In Thyristor T_1, i_c is in opposition to load current i_o. So that $i_{T_1} = I_o - i_c$. So, i_{T_1} is in the forward direction through T_1.

→ At t_3, i_c rises to I_o so that $i_{T_1} = 0$; as a result main SCR T_1 is turned off at t_3. Since the oscillatory current through T_1 turns it off, it is called current commutated chopper.

Mode: III :-



(C) Mode III, $t_3 < t < t_4$

→ AS T_1 is turned off, i_c becomes more than I_o. After t_3, i_c supplies load current I_o & the excess current $i_{D_1} = i_c - i_o$ is conducted through diode D_1.

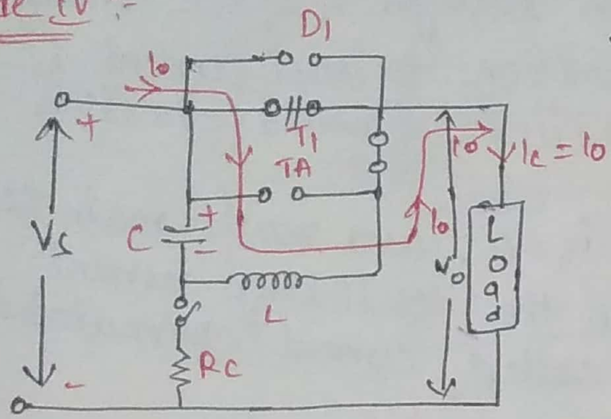
→ The voltage drop in D_1 due to $(i_c - I_o)$ keeps T_1 reverse biased for $(t_4 - t_3) = t_c$;

→ As t_4 in case V_c exceeds V_s, FD comes into conduction, mode IV would follow.

otherwise

During mode III, when i_c is at its peak value of $I_{cp} = \frac{V_c}{\omega_o L}$, $V_c = 0$. After this peak, capacitor voltage reverses. & at t_4, upper plate is +ve & lower plate is -ve.

Mode IV :-



→ At t_4, i_c reduces to I_o, as a result $i_{D1} = 0$ & diode D_1 is therefore turned off.

→ After t_4, a constant current equal to I_o flows through source V_s, C, L, D_2 & load & ∴ C is charged linearly to V_s at t_5 so during time $(t_5 - t_4)$, $i_c = I_o$.

d) Mode IV, $t_4 < t < t_5$

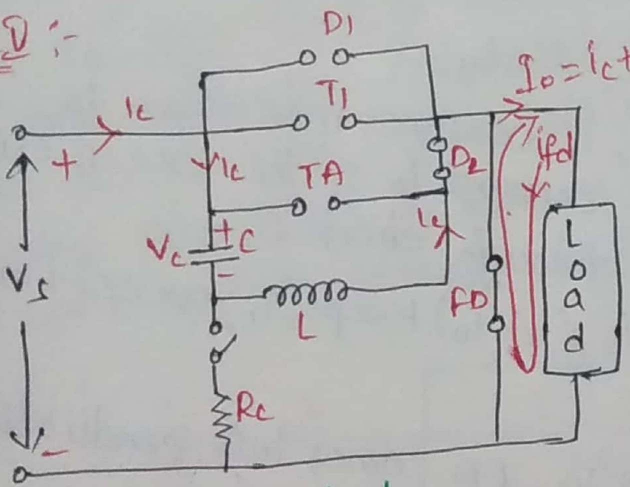
→ As D_1 is turned off at t_4, $V_{T_1} = V_{TA} = V_c$; this is in ab

→ for V_c, V_{T_1} & V_{TA}. Now load voltage $V_o = V_s - V_c = V_s - V_{ab}$ This is also marked in the waveform for V_o at t_4.

→ At t_5, $V_c = V_s$, ∴ load voltage $V_o = V_s - V_s = 0$ at t_5

→ During the interval $(t_5 - t_4)$, V_c increases linearly. ∴ V_o decreases to zero linearly during this interval

Mode V :-



→ At t_5, capacitor C is actually overcharged to a voltage somewhat more than V_s ∴ FD gets forward biased & starts to conduct load current I_o at t_5.

→ V_o is reduced to zero at t_5

e) Mode V, $t_5 < t < t_6$

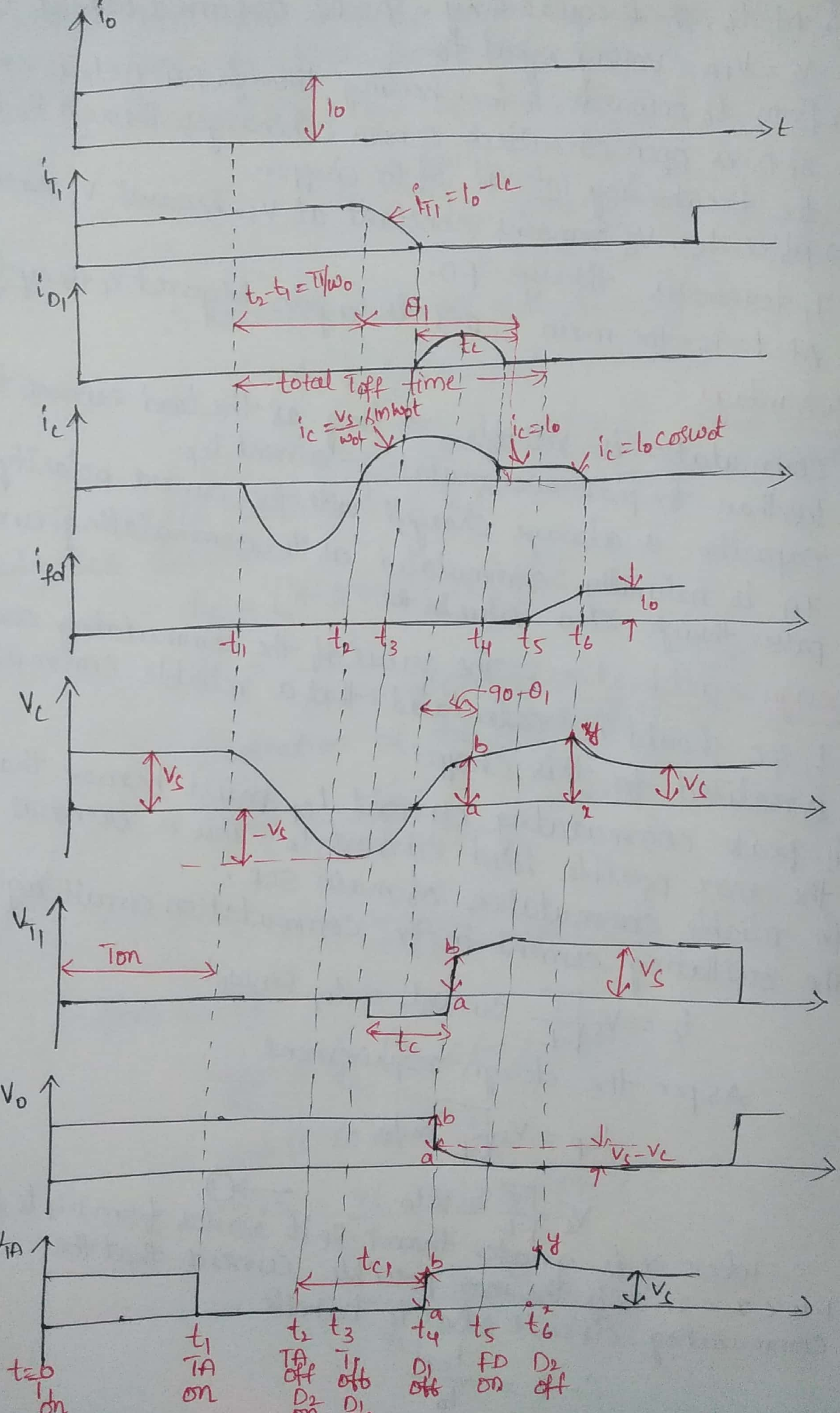
→ As i_c is not zero at t_5, the capacitor C is still connected to load through source V_s, C, L, & D_2; as a consequence C is overcharged by the transfer of energy from L to C. becomes more than V_s

→ At t_6, $i_c = 0$ & V_c becomes more than V_s with the build up of i_{fd}, i_c decays

→ During $(t_6 - t_5)$, $i_c + i_{fd} = I_o$, & finally at t_6, $i_c = 0$ & $i_{fd} = I_o$

→ Commutation process is completed at t_6.

→ Commutation interval is $(t_6 - t_1)$ total turn-off time, or commutation interval is $(t_6 - t_1)$



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→ At t_6, V_c is equal to xy. As D_2 is turned off at t_6.
$V_c = V_{TA}$ = Voltage xy at t_6.

→ from t_6 onwards, i_0 freewheeling through FD. As i_c is zero & D_2 is open circuited. C now discharges through R_c for the freewheeling interval of the chopper.

→ After t_5, V_{T_1} remains constant at V_s, because V_s reaches T_1 terminals through FD.

At t=T, the main SCR T_1 is again triggered & the cycle repeats

Advantages :-

1) Commutation is reliable so long as the load current is less than the peak commutating current I_{cp}.
2) Capacitor is always charged with the current polarity
3) TA is naturally commutated as its commutating current passes through zero value.

Design considerations:- The value of the commutating components L & C should be calculated that a reliable commutation is realised for this chopper

i) peak commutating current I_{cp} must be more than the max possible load current I_0. This is essential for reliable commutation of main SCR.

The oscillating current in the commutation circuit is given by

$$i_c = V_s\sqrt{\frac{C}{L}}\sin\omega_0 t = I_{cp}\sin\omega_0 t$$

As per the design requirement

$$I_{cp} = V_s\sqrt{\frac{C}{L}} > I_0$$

$$V_s\sqrt{\frac{C}{L}} = x I_0 \longrightarrow (1)$$

where x is greater than 1 & it varies from 1.4 to 3.
1.4 < x < 3, I_0 is the max possible current that the commutating circuit has to handle

$$\therefore x = \frac{I_{cp}}{I_0}$$

ii) Circuit turn-off time t_c must be greater than thyristor turn-off time for the main SCR.

That is $t_c = t_q + \Delta t$. $\Rightarrow t_c = t_4 - t_3$

$$\omega_0 t_c = \pi - 2\theta_1$$

$$I_{cp} \sin\theta_1 = I_0$$

$$\theta_1 = \sin^{-1}\left(\frac{I_0}{I_{cp}}\right) = \sin^{-1}\left(\frac{1}{x}\right)$$

$\therefore$ circuit turn-off time for main SCR,

$$t_c = \frac{1}{\omega_0}(\pi - 2\theta_1) \longrightarrow (2)$$

$$t_c = \frac{1}{\omega_0}\left[\pi - 2\sin^{-1}\left(\frac{I_0}{I_{cp}}\right)\right] \longrightarrow (3)$$

it reveals load current I_0 increases, turn-off time of main SCR decreases.

$$t_c = \left[\pi - 2\sin^{-1}(1/x)\right]\sqrt{LC} \longrightarrow (4)$$

$$\sqrt{C} = \frac{t_c}{\left[\pi - 2\sin^{-1}(1/x)\right]\sqrt{L}}$$

substitution of this value of $\sqrt{C}$, in equ (1) gives

$$\frac{V_s}{L} \cdot \frac{t_c}{\left[\pi - 2\sin^{-1}(1/x)\right]} = x \cdot I_0$$

$$L = \frac{V_s \cdot t_c}{x I_0 \left[\pi - 2\sin^{-1}(1/x)\right]} \longrightarrow (5)$$

from equ (4).

$$\frac{1}{\sqrt{L}} = \frac{1}{t_c}\left[\pi - 2\sin^{-1}(1/x)\right]\sqrt{C}$$

sub $\sqrt{L}$ in equ (1)

$$x \cdot I_0 = \frac{V_s}{t_c}\left[\pi - 2\sin^{-1}(1/x)\right] C$$

$$C = \frac{x \cdot I_0 \cdot t_c}{V_s\left[\pi - 2\sin^{-1}(1/x)\right]}$$

Total commutation interval :-

The total turn-off time, or the commutation interval is (t_6-t_1)

$$t_6-t_1 = (t_2-t_1)+(t_4-t_2)+(t_5-t_4)+(t_6-t_5)$$

t_2-t_1: wave form of current i_c, oscillating frequency ω_0, completes one negative half cycle of π radians

$$(t_2-t_1) = \text{time period of half cycle of oscillating current}$$

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

t_4-t_2: At t_2, $i_c=0$, & at t_4, i_c attains a value I_0 after passing through its peak, Angle by i_c from t_2 to t_4 is $\pi-\theta_1$ radians and as ω_0 is the angular frequency for i_c

$$t_4-t_2 = \frac{\pi-\theta_1}{\omega_0} = (\pi-\theta_1)\sqrt{LC}$$

t_5-t_4: The time (t_5-t_4) can be obtained from voltage across C at t_4 and at t_5. As this voltage across C at $t_4 = ab = V_c$ at t_4. Voltage across C at t_4 is $(90-\theta_1)°$ away from zero crossing at the instant of V_c sine wave, $ab = V_s \sin(90-\theta_1)$

voltage across C at $t_5 = V_s$

voltage across C during (t_5-t_4) = increase in voltage across C during (t_5-t_4) = $V_s - V_s\sin(90-\theta_1)$

we know that $i = C\cdot\frac{dv}{dt}$. As I_0 is constant

$$I_0 = C\cdot\frac{V_s - V_s\sin(90-\theta_1)}{(t_5-t_4)}$$

$$(t_5-t_4) = C\cdot V_s\cdot\frac{1-\sin(90-\theta_1)}{I_0}$$

$$= C\cdot V_s\,\frac{1-\cos\theta_1}{I_0}$$

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(t_6-t_5) :- During (t_6-t_5), current i_c is assumed to be $I_0 \cos \omega_0 t$. As (t_6-t_5) is equal to the quater cycle ($\pi/2$ rad). of a sine wave

$$t_6 - t_5 = \frac{1}{2}\frac{\pi}{\omega_0} = \frac{\pi}{2}\sqrt{LC}$$

$\therefore$ $t_6 - t_1$ = total commutation period

$$= \left(\frac{5\pi}{2} - \theta_1\right)\sqrt{LC} + C \cdot V_s \cdot \frac{1-\cos\theta_1}{I_0}$$

$$= \left(\frac{5\pi}{2} - \theta_1\right)\sqrt{LC} + 2CV_s \cdot \frac{\sin^2\theta_1/2}{I_0}$$

Turn-off times: for main SCR, turn-off time is

$$t_4 - t_3 = t_c = (\pi - 2\theta_1)\sqrt{LC}$$

$$t_c = \left[\pi - 2\sin^{-1}(1/x)\right]\sqrt{LC}$$

turn-off time for TA, is

$$t_4 - t_2 = t_{c_1} = (\pi - \theta_1)\sqrt{LC}$$

$$= \left[\pi - \sin^{-1}(1/x)\right]\sqrt{LC}$$

peak capacitor voltage:-

wave form of V_c reveals the max. capacitor voltage V_{xy} is reached at t_5

$\therefore$ Voltage at $t_6 = V_{cp}$ = Voltage at t_5 + Voltage rise due to L & C

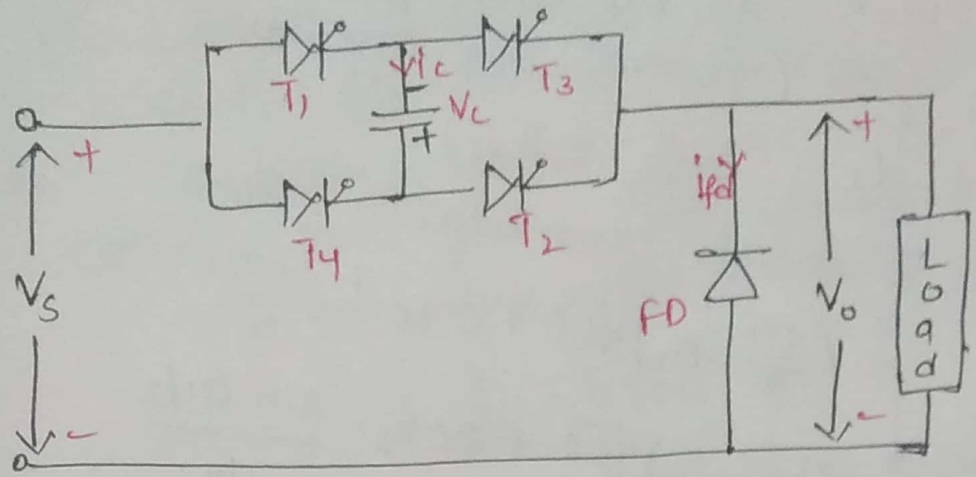
At t_5, energy in L is $\frac{1}{2}LI_0^2$ & at t_5, the entire energy is transferred to C. The voltage rise of C due to this energy is

$$\frac{1}{2}CV_c^2 = \frac{1}{2}LI_0^2$$

$$V_c = I_0\sqrt{L/C}$$

$$V_{cp} = V_s + I_0\sqrt{\frac{L}{C}} = V_{xy}$$

Load- Commutated chopper:-



→ It consists of four thyristors $T_1 - T_4$ and one Commutating capacitor C. The thyristor T_1, T_2 act together as one pair & thyristors T_3, T_4 act together as the second pair for conducting the load current alternately.

→ when T_1, T_2 are conducting, these act as main thyristors and T_3, T_4 and C as the commutating components.

→ with the conduction of T_3, T_4; these become main thyristors and T_1, T_2 and C as the commutating components

→ FD is the freewheeling diode across the load

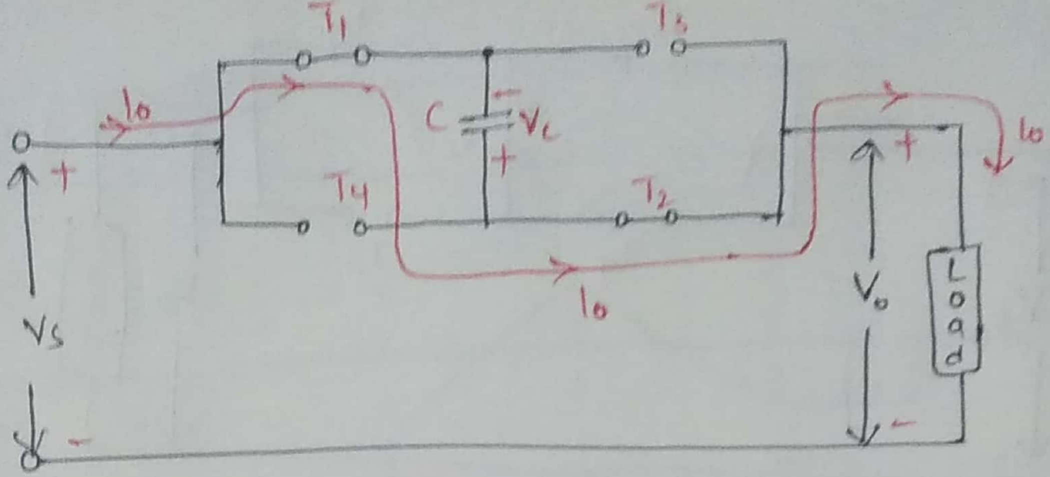
→ initially, the capacitor is charged to a voltage V_s with upper plate negative & lower plate positive.

→ Assumptions made in current- commutated chopper also apply here. The working of this chopper can be explained in various modes as under.

Mode 1:-

→ with the capacitor 'c' charged with lowerplate +ve, the load commutated chopper is ready for operation.

→ when thyristor pair T_1, T_2 is triggered at t=0, circuit consisting of V_s, T_1, C, T_2 & load. shows that load voltage at once shoots to $V_o = V_s + V_c = 2V_s$.



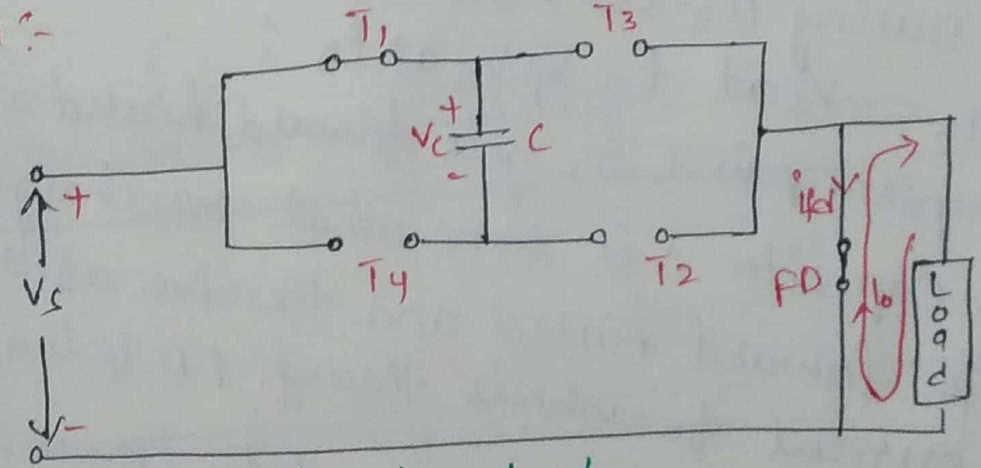
a) Mode 1, $0 < t < t_1$

→ The capacitor C is charged linearly by constant load current I_o from V_s at $t=0$ to $(-V_s)$ at t_1.

→ when the capacitor voltage becomes $(-V_s)$, the load voltage falls from $2V_s$ to $V_o = V_s - V_s = 0$ at t_1

→ At $t=0$, when T_1, T_2 are turned on, T_3, T_4 are reverse biased by capacitor voltage, i.e., at $t=0$, $V_{T3} = V_{T4} = V_s$. i.e., T_3, T_4 are forward biased at t_1. $V_{T3} = V_{T4} = -V_s$. at t_1,

Mode II :-



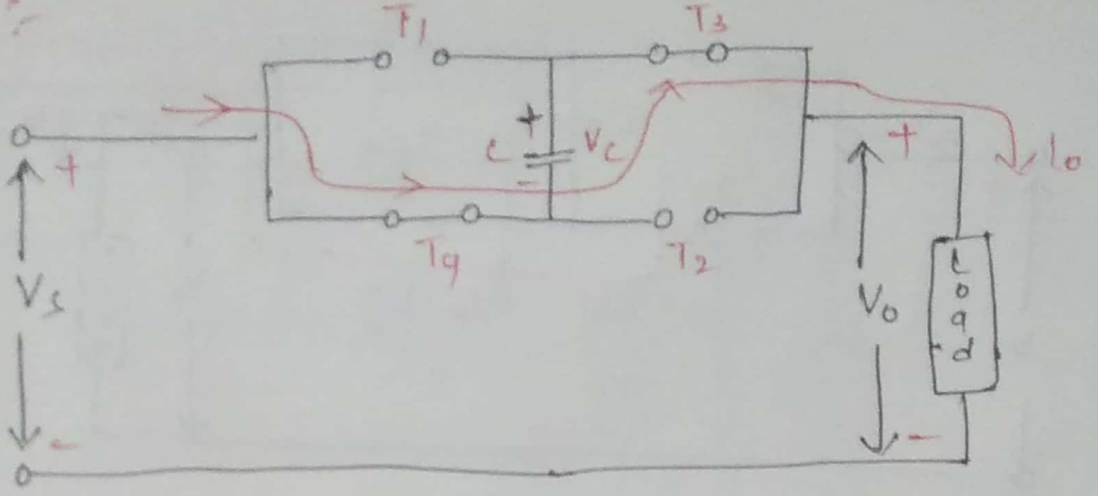
b) Mode II, $t_1 < t < t_2$

→ At t_1, capacitor C is slightly overcharged, as a result freewheeling diode gets forward biased and load current is transferred from T_1, T_2 to FD.

→ from t_1 onwards, load currents freewheels through FD.

→ During $(t_2 - t_1)$, $V_c = -V_s$, $V_o = 0$, $i_c = 0$, $i_{fd} = I_o$, $i_{T_1} = i_{T_2} = 0$,
$V_{T3} = V_{T4} = V_s$ & $V_{T_1} = V_{T_2} = -\Delta V_s$ as capacitor is overcharged by a small voltage ΔV_s

Mode III:-



c) Mode III, $t_2 < t < t_3$

→ At t_2, thyristor pair T_3, T_4 is triggered, load voltage at once becomes, $V_o = V_s + V_c = 2V_s$.

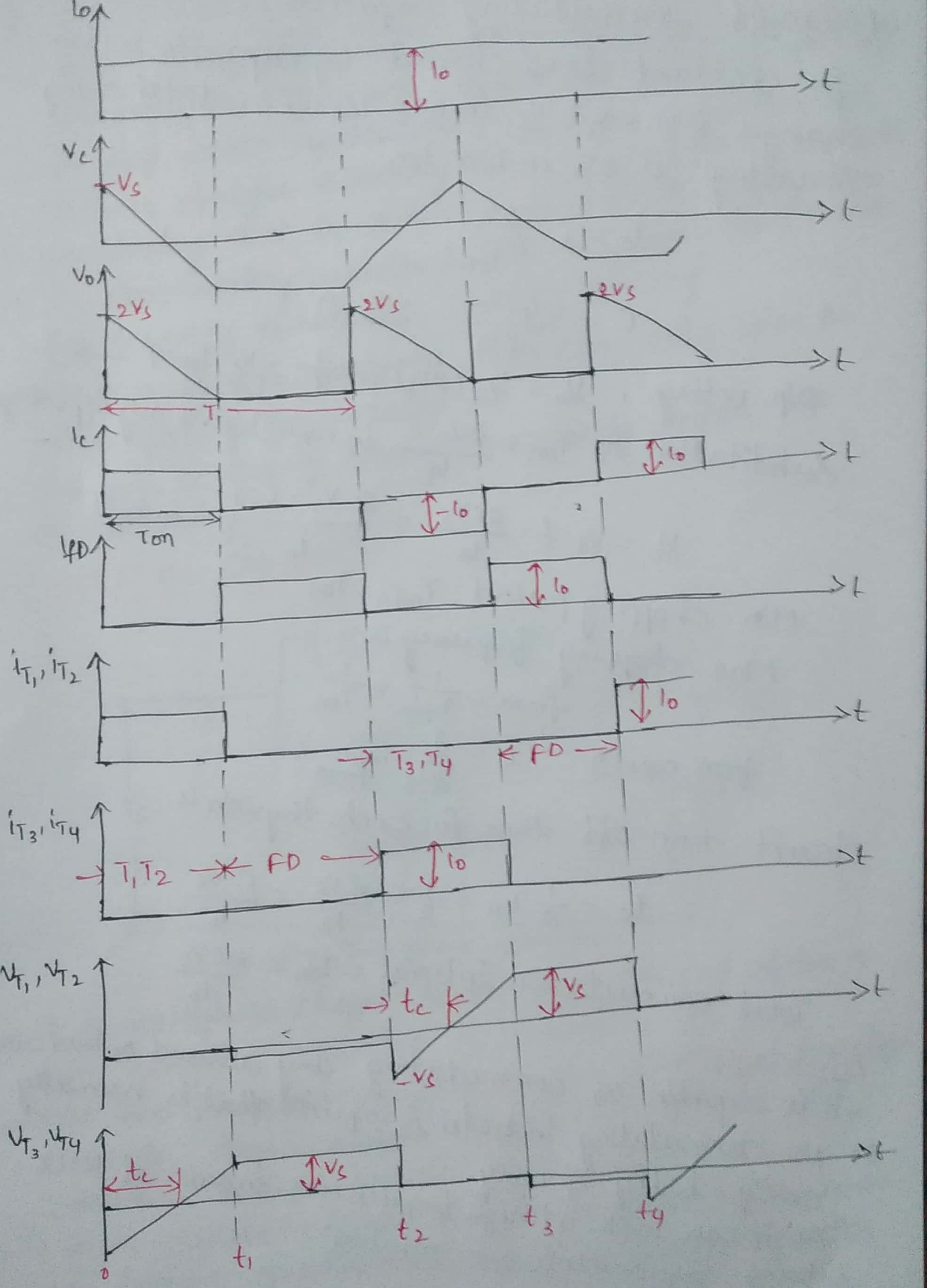
→ Thyristor pair T_1, T_2 is reverse biased by V_c, this pair is therefore turned off at t_2.

→ The load current, now flowing through V_s, T_4, C, T_3 and load charges capacitor linearly from $(-V_s)$ at t_2 to V_s at t_3.

→ load voltage accordingly falls from $2V_s$ at t_2 to zero at t_3. During $(t_3 - t_2)$; $i_c = -I_o$, $i_{T_3} = I_{T_4} = I_o$ but $V_{T_1} = V_{T_2} = -V_s$ at t_2 & V_s at t_3;

i.e., thyristor pair T_1, T_2 gets forward biased at t_3. Capacitor c is some what overcharged,

→ At t_3, FD gets froward biased and therefore after t_3. load current freewheels through FD & load. mode I repeats when T_1, T_2 are turned on at t_4,



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t
iT1, iT2
Io
t
T3, T4
FD
iT3, iT4
t
T1 T2
FD
Io
VT1, VT2
Vs
t
tc
-Vs
VT3, VT4
t
tc
Vs
0
t1
t2
t3
t4

Design of commutating capacitance:-

for constant load current I_0, capacitor voltage changes from $-V_s$ to V_s in time T_{on}, i.e., total change in voltage is $2V_s$ in Time T_{on}.

$$I_0 = C \cdot \frac{2V_s}{T_{on}}$$

$$C = \frac{I_0 \cdot T_{on}}{2V_s} \longrightarrow (1)$$

o/p voltage, $V_0 = \frac{1}{2}(2V_s) T_{on} \cdot \frac{1}{T} = V_s \cdot T_{on} \cdot f \longrightarrow (2)$

substitution of $T_{on} = \frac{2V_s \cdot C}{I_0}$ in equ (2) gives avg o/p voltage as

$$V_0 = V_s \cdot f \cdot \frac{2CV_s}{I_0} = \frac{2 \cdot V_s^2 \cdot C \cdot f}{I_0} \longrightarrow (3)$$

Min. chopping period, $T_{min} = T_{on}$

Max. chopping frequency,

$$f_{max} = \frac{1}{T_{min}} = \frac{1}{T_{on}}$$

from equ (1), $C = \frac{I_0}{2V_s} \cdot \frac{1}{f_{max}}$.

circuit turn-off time for each thyristor is

$$t_c = \frac{1}{2} T_{on} = \frac{1}{2} C \cdot \frac{2V_s}{I_0} = \frac{C \cdot V_s}{I_0}$$

Total commutation interval $= T_{on} = \frac{2CV_s}{I_0}$

Advantages:-

1) it is capable of commutating any amount of load current
2) No commutating inductor is required that is normally costly, bulky & noisy
3) As it can work at high frequencies in order of KHz. filtering requirements are minimal.

Disadvantages:-

1) peak load voltage is equal to twice the supply voltage. This peak can however be reduced by filtering
2) for high-power applications, efficiency may become low because of higher switching losses at high operating frequencies
3) freewheeling diode is subjected to twice the supply voltage.
4) The commutating capacitor has to carry full load current at a frequency of half the chopping frequency
5) one pair of SCRs should be turned on only when the other pair is commutated.
This can be done by sensing the capacitor current that is alternating.

Multiphase Choppers:-

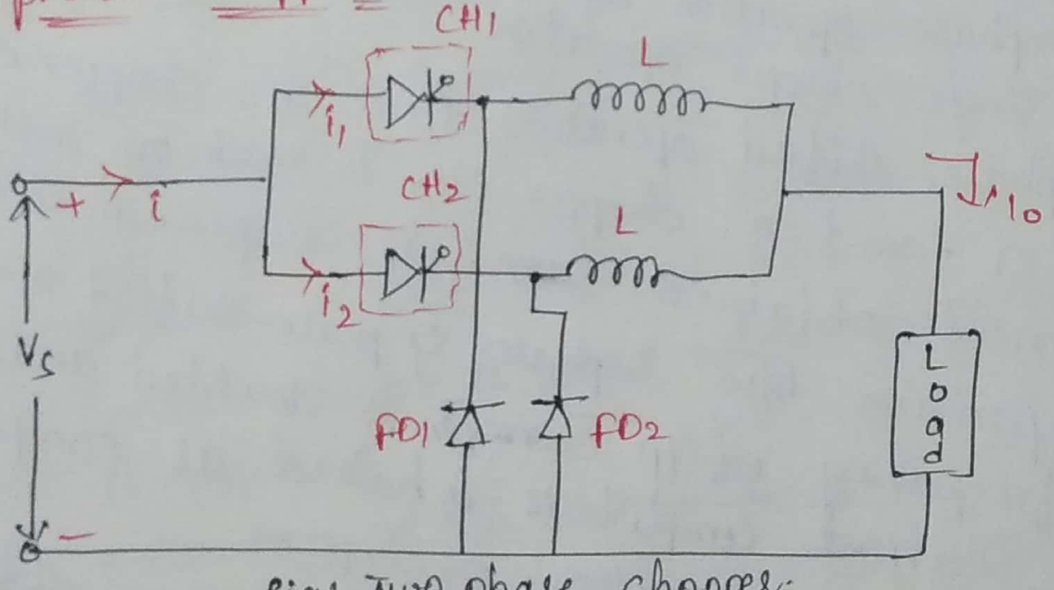


fig: Two phase chopper.

→ A multiphase chopper is one that consists of two or more choppers connected in parallel
→ The two choppers configuration is called a two-phase chopper similiarly, three choppers connected in parallel will constitute a 3-ϕ chopper
→ A multiphase chopper maybe operated in two modes i.e., inphase operation mode & phase shifted operation mode.

→ In the in-phase operation mode, all the parallel connected choppers are on & off at the same instant.

→ In phase shifted mode operation, different choppers are on & off at different instants of time

→ In fig. consists of inductance 'L' in series with each chopper is assumed to be sufficiently large in that each chopper operates independent of each other.

→ let the load current be lo & ripple free

→ for a duty cycle of $\alpha = 30\%$, inphase operation of this chopper when both the choppers are on & off at the same instant.

→ The i/p current i, obtained by the addition of i_1 & i_2 is seen to be doubled.

→ the inphase operation of multiphase chopper is equivalent to a single chopper operation.

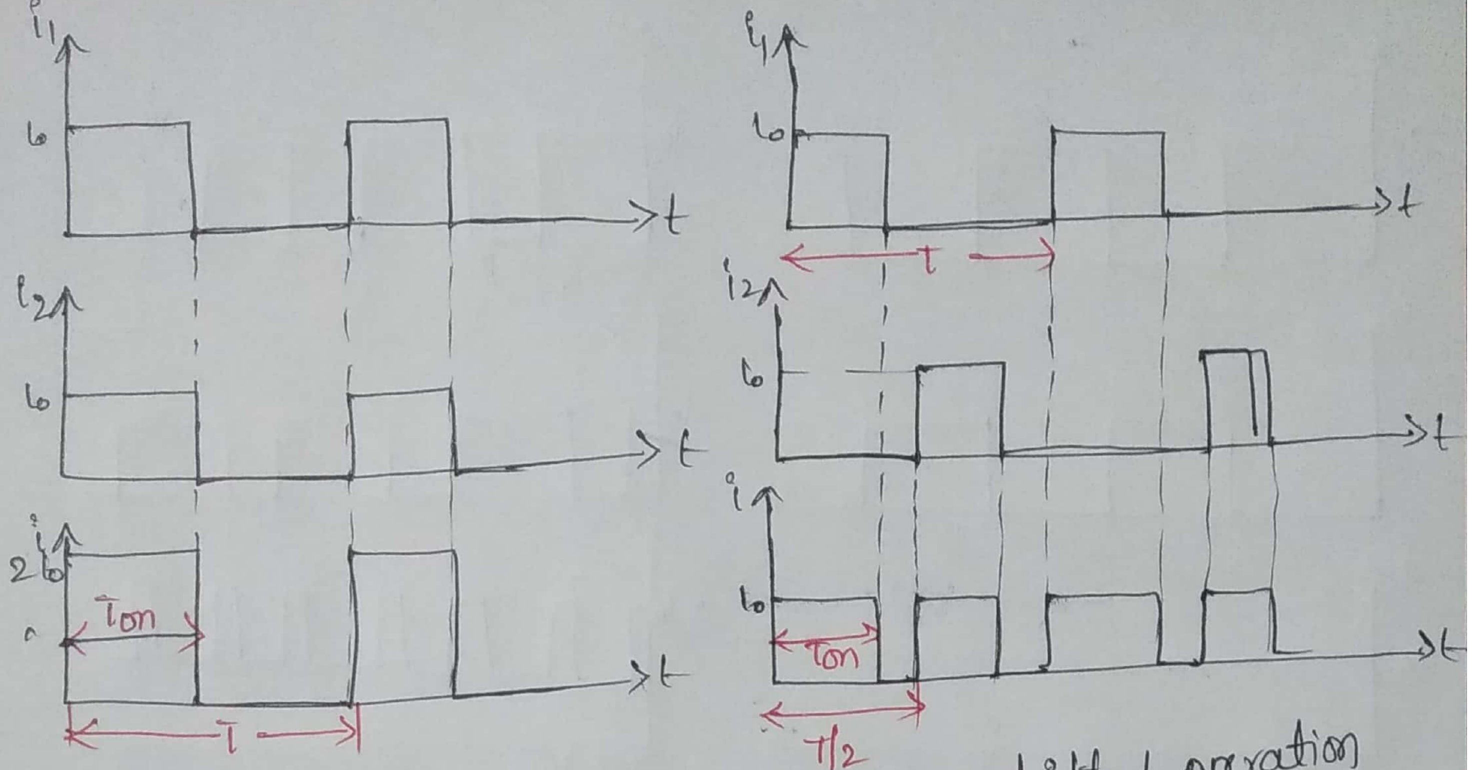
→ The phase shifted operation for $\alpha = 30$, chopper CH1 is on for 0.3T from t = 0. chopper CH_2 is made on, such that i/p current obtained from $i_1 + i_2$ is periodic in nature

→ comparision b/w inphase & phase-shifted operation the frequency of i/p current is doubled and its ripple current amplitude is halved as compared to the inphase operation of chopper.

→ In the inphase operation mode frequency of harmonics in the i/p current is equal to switching frequency. (= 1/T) of each chopper.

→ In phase shift operating mode, frequency of harmonics in the i/p current is twice the switching frequency. of each chopper

→ As the frequency of harmonics in the i/p current is twice the switching frequency, the size of filter is reduced in the phase shifted chopper



a) in phase operation

b) phase shifted operation

fig:- i/p waveforms for $\alpha = 0.30$.

→ for $\alpha = 50\%$, the i/p supply current of phase-shifted operation is continous & without any ripples

→ for $\alpha = 60\%$ the supply current is continous but with a pedestal of half the load current

→ A multiphase chopper is used where large load current is required.

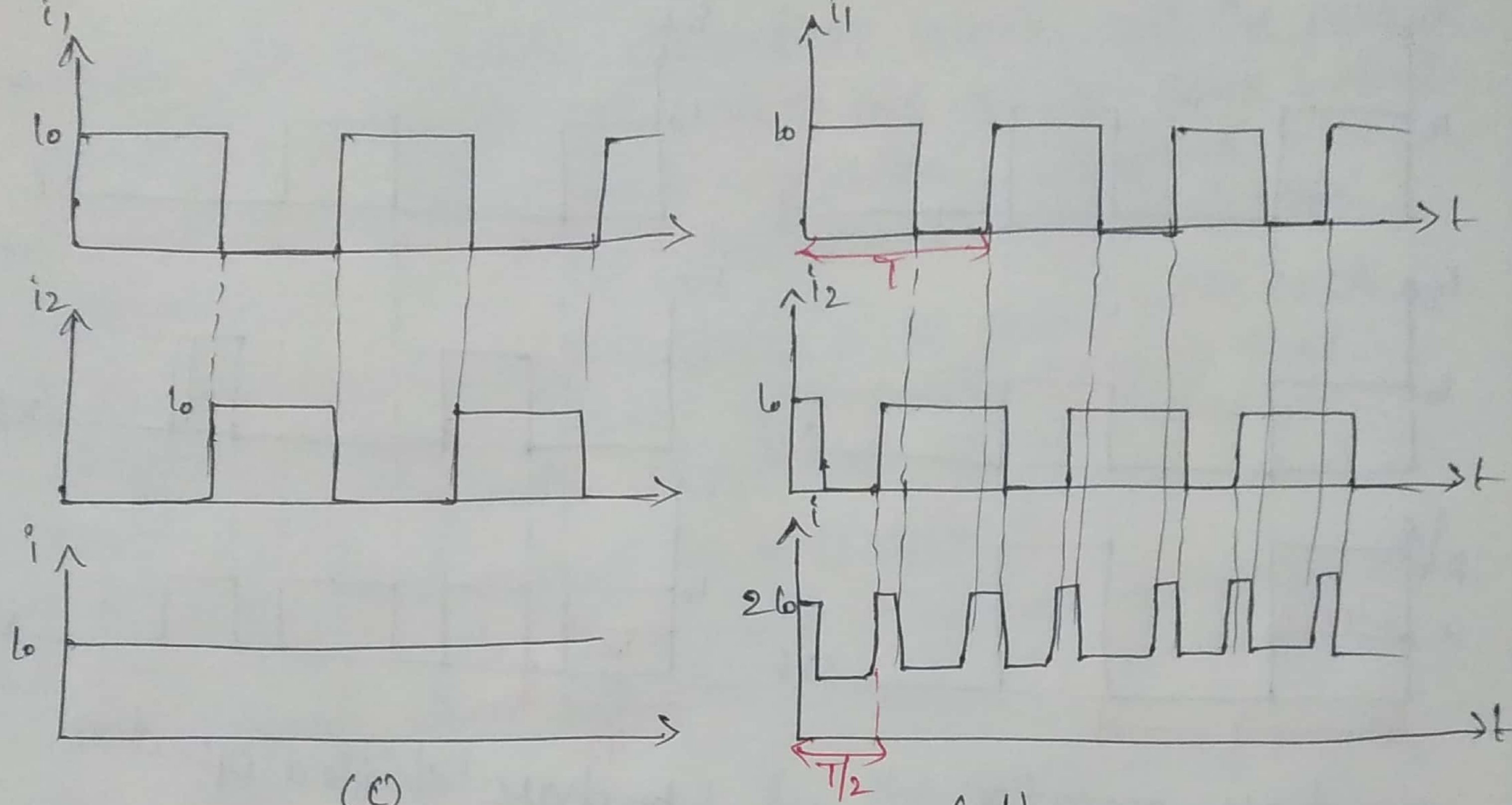
→ The main advantage of this chopper over a single chopper is that its i/p current has reduced ripple amplitude & increased ripple frequency. As a consequence of it, size of filter for a multiphase chopper is reduced.

→ disadvantages of a multiphase chopper are

1) extra commutation circuits

2) additional external inductors &

3) complexity in the control logic.



current wave forms for phase shifted operation for (c) $\alpha = 0.50$. & (d) $\alpha = 0.60$.