

Control strategies of chopper :-

\* In dc-dc converter the average output voltage is controlled by varying the ' $\alpha$ ' value.

\* This is achieved by varying the duty cycle of the switching pulse.

\* Duty cycle can be varied usually in two ways

1) Time ratio control      2) Current limit control.

\* The duty cycle is the ratio of ON time to time period of a pulse.

i.e.,  $D = \frac{T_{ON}}{T}$

1) Time ratio control :-

As the name suggest here the time ratio (i.e., the duty cycle ratio) is varied. This kind of control can be achieved in two ways

(i) Pulse Width Modulation      (ii) Frequency Modulation Control.

i) Pulse Width Modulation :-

In this technique the time period is keep constant but the ON time or OFF time is varied.

Using this, the duty cycle ratio can be varied.

Since, the ON time or pulse width is getting changed in this method

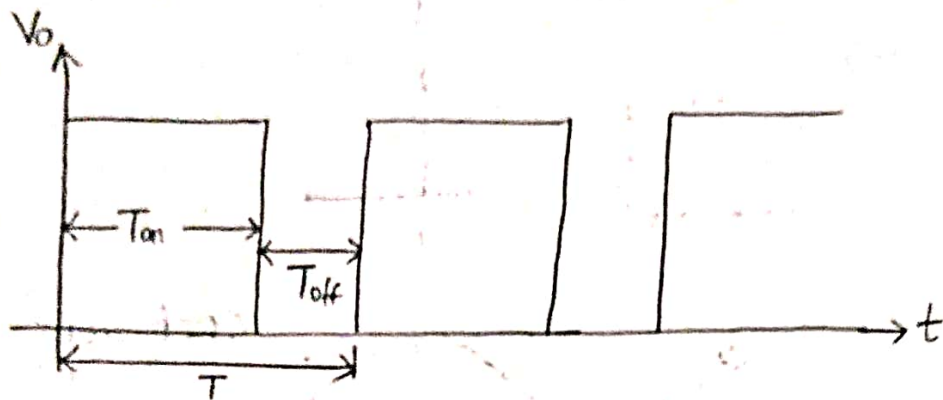
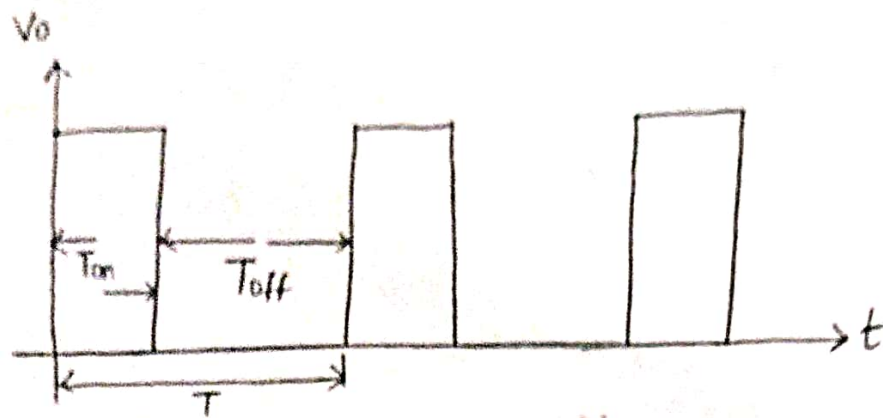
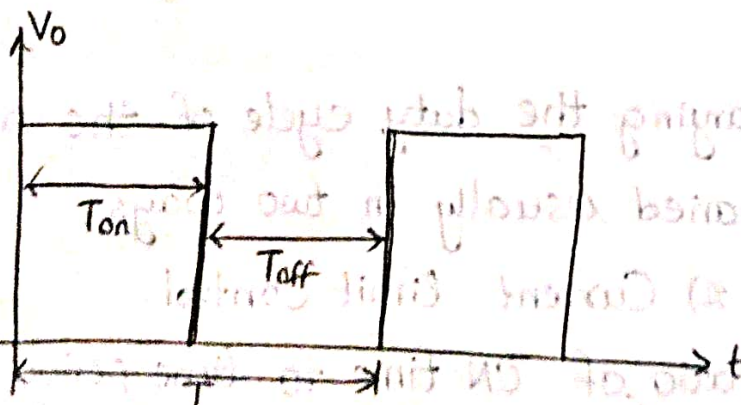


Fig: Pulse Width Modulation wave form.

### \*Frequency Modulation:-

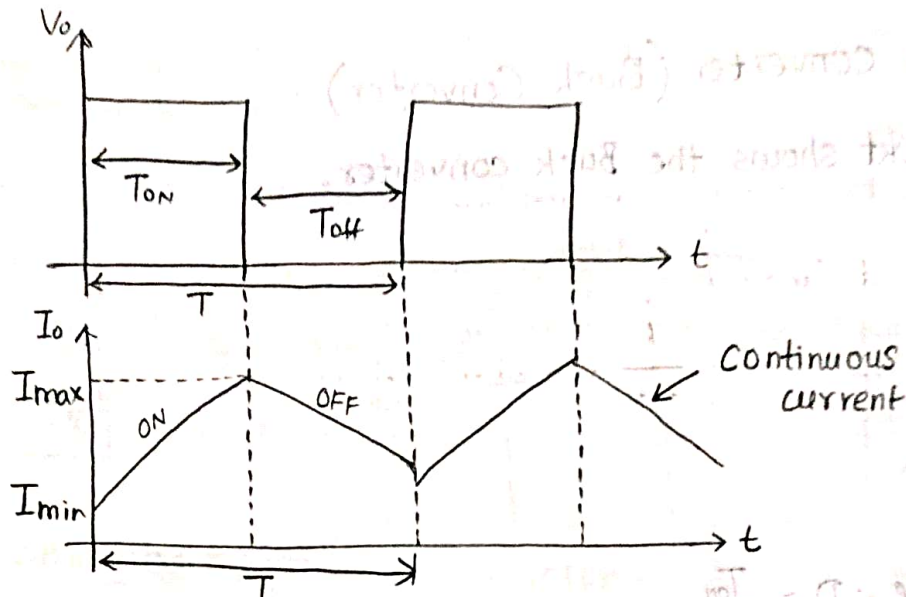
\*In this method, the time period is varying while keeping either of ON time or OFF time as constant.

\*Since the time period gets changed so the frequency also changes accordingly.



## 2) Current Limit Control:

- \* In this control strategy a specific limit is applied on the current variation.
- \* In this method current is allowed to fluctuate or change only between two values i.e., maximum current ( $I_{max}$ ) and the minimum current ( $I_{min}$ ).



## Operating modes:-

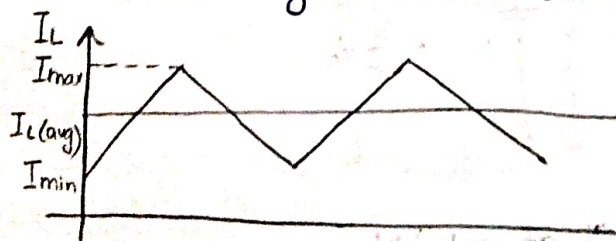
- \* Two modes of operation in dc to dc converters based on inductor current

1) Continuous conduction mode (CCM)

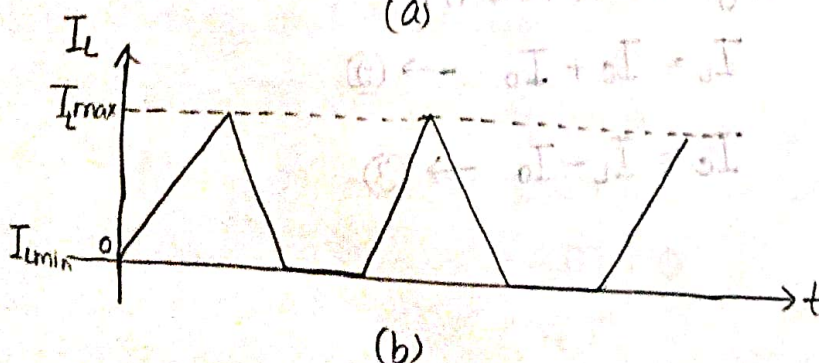
i) Inductor current is greater than zero (i.e.,  $I_L > 0$ )

2) Discontinuous conduction

i) Inductor current goes to zero and stays at zero for some time



⇒ CCM



⇒ DCM

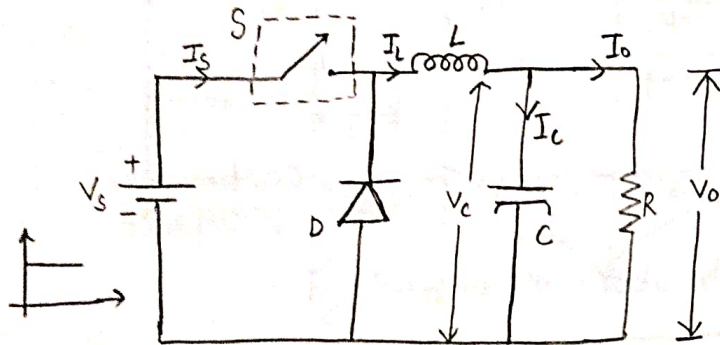
# Classification of Choppers:- (DC-DC Converters)

Depending on the output voltage the choppers are classified as

- 1) Step down converter or Buck converter
- 2) Step up converter or Boost converter
- 3) Step up/down converter or Buck-Boost converter

## 1) Step down converter (Buck Converter):-

The below ckt shows the Buck converter,



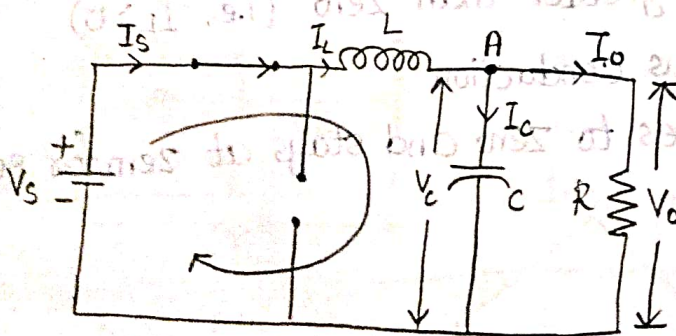
$$\therefore \text{Duty cycle, } D = \frac{T_{ON}}{T}$$

$$\therefore \text{The output voltage, } \boxed{V_o = V_s \cdot D}$$

Operation:-

Case(i):- Chopper or switch is 'ON'

\* Then diode is Reverse biased.



Apply KVL at loop,

$$V_s = V_L + V_c$$

$$V_L = V_s - V_c$$

where,  $V_c = V_o$

$$\boxed{V_L = V_s - V_o} \rightarrow \textcircled{1}$$

Apply KCL at node 'A',

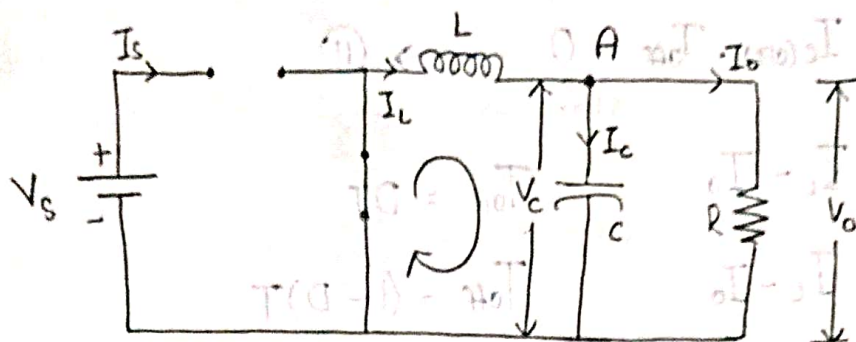
$$I_L = I_c + I_o \rightarrow \textcircled{2}$$

$$I_c = I_L - I_o \rightarrow \textcircled{3}$$

Case (ii): Switch is 'OFF'.

\* Then  $V_s$  becomes zero

\* And Diode is forward biased



Apply KVL at loop,

$$0 = V_L + V_c$$

$$\therefore V_L = -V_c \quad \{\because V_c = V_o\}$$

$$\therefore \boxed{V_L = -V_o} \rightarrow (4)$$

Apply KCL at node A,

$$\boxed{I_L = I_c + I_o} \rightarrow (5)$$

$$I_c = I_L - I_o \rightarrow (6)$$

Volt-sec Balanced equation in Inductor:-

$$\boxed{V_{L(ON)} \cdot T_{ON} + V_{L(OFF)} \cdot T_{OFF} = 0} \rightarrow (7)$$

We know that,

$$\text{Duty cycle, } D = \frac{T_{ON}}{T}$$

$$\& \quad T = T_{ON} + T_{OFF}$$

$$\Rightarrow T_{ON} = D \cdot T \rightarrow (8)$$

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

from eq (1),

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

$$V_{L(ON)} = V_s - V_o \rightarrow (9)$$

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

from eq (4),

$$V_{L(OFF)} = -V_o \rightarrow (10)$$

from eq (7),  $V_{L(ON)} \cdot T_{ON} + V_{L(OFF)} \cdot T_{OFF} = 0$

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

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

$$V_s DT - V_o DT - V_o T + V_o DT = 0$$

$$V_s DT = V_o T$$

$$\boxed{V_o = V_s \cdot D}$$

Amp-sec Balanced equation in capacitor,

$$I_{C(ON)} \cdot T_{ON} + I_{C(OFF)} \cdot T_{OFF} = 0 \rightarrow \textcircled{II}$$

from eq ③,  $I_{C(ON)} = I_L - I_o$        $T_{ON} = DT$

from eq ⑥,  $I_{C(OFF)} = I_L - I_o$        $T_{OFF} = (1-D)T$

from eq ⑫,  $I_{C(ON)} \cdot T_{ON} + I_{C(OFF)} \cdot T_{OFF} = 0$

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

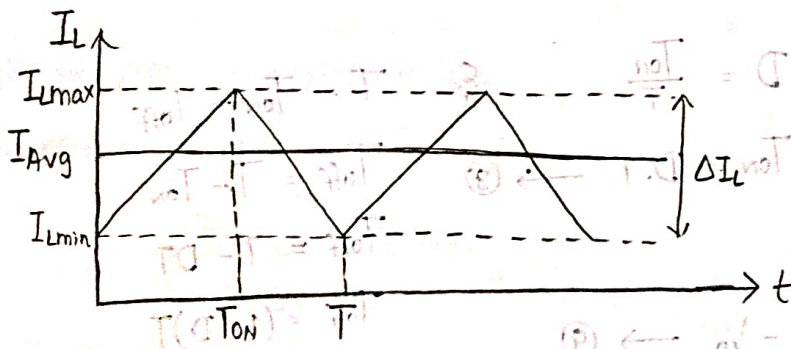
$$\Rightarrow (I_L - I_o)DT + (I_L - I_o)(T - DT) = 0$$

$$\Rightarrow (I_L - I_o)[DT + T - DT] = 0$$

$$\Rightarrow (I_L - I_o)T = 0$$

$$\therefore \boxed{I_L = I_o}$$

Ripple in Inductor Current :- ( $\Delta I_L$ )



for Inductor current,

Ripple current,  $\Delta I_L = I_{L(max)} - I_{L(min)}$

from eq ①,  $V_L = V_s - V_o$

The voltage across the inductor,

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

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

from the waveform,

Ripple current,  $\Delta I_L = \dots$

Time period,  $DT = dt$

$$\text{and } V_o = V_s \cdot D$$

$$\therefore L \frac{di_L}{dt} = V_s - V_o$$

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

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

$$\therefore \Delta I_L = \frac{V_s (1-D) DT}{L}$$

$$*** \boxed{\therefore \Delta I_L = \frac{V_s (1-D) D}{Lf}}$$

$$I_{Lmax} = I_L + \frac{\Delta i_L}{2}$$

$$I_{Lmin} = I_L - \frac{\Delta i_L}{2}$$

$$= I_{RL} - \frac{\Delta i_L}{2}$$

$$= \frac{V_o}{R} - \frac{\Delta i_L}{2} = \frac{V_o}{R} - \frac{V_s (1-D) \cdot D}{2Lf}$$

$$= \frac{V_s \cdot D}{R} - \frac{V_s (1-D) D}{2Lf} = V_s \cdot D \left[ \frac{1}{R} - \frac{(1-D)}{2Lf} \right]$$

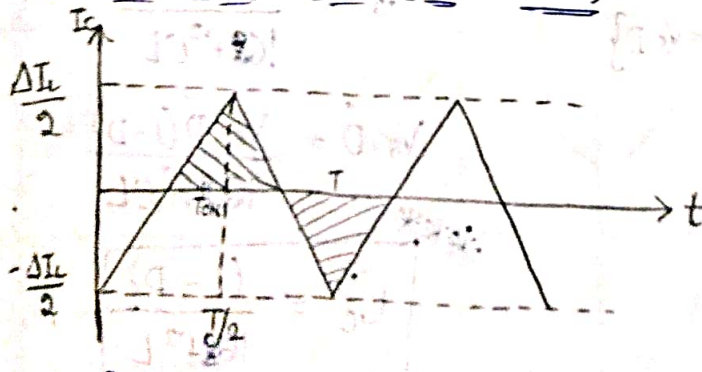
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$$\boxed{I_{min} = V_o \left[ \frac{1}{R} - \frac{(1-D)}{2Lf} \right]}$$

\*\*\*

$$\boxed{I_{max} = V_o \left[ \frac{1}{R} + \frac{(1-D)}{2Lf} \right]}$$

Ripple in Capacitor voltage:- ( $\Delta V_C$ )



We know that; the charge,  $Q = CV$

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

$$\therefore \Delta Q = C \Delta V$$

from the wave form

$\Delta Q = \text{Area of triangle}$

$$= \frac{1}{2} \times \text{base} \times \text{height}$$

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

$$\Delta Q = \frac{\Delta I_L T}{8}$$

$$C \Delta V = \frac{\Delta I_L T}{8} \quad \left\{ \because T = \frac{1}{f} \right\}$$

$$C \Delta V = \frac{\Delta I_L}{8f}$$

$$\therefore \Delta V_c = \frac{\Delta I_L}{8Cf}$$

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

$$*** \Delta V_c = \frac{V_s (1-D) D}{8f^2 CL}$$

Critical Inductance ( $L_c$ ):

If  $I_{\min} = 0$ .

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

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

$$I_0 = \frac{V_s (1-D) DT}{2L}$$

$$\frac{V_0}{R} = \frac{V_s (1-D) D}{2Lf} \quad \left\{ \because V_0 = V_s D \right\}$$

$$\frac{V_s D}{R} = \frac{V_s D (1-D)}{2Lf}$$

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

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

Critical Capacitance ( $C_c$ ):

$V_{\min} = 0$

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

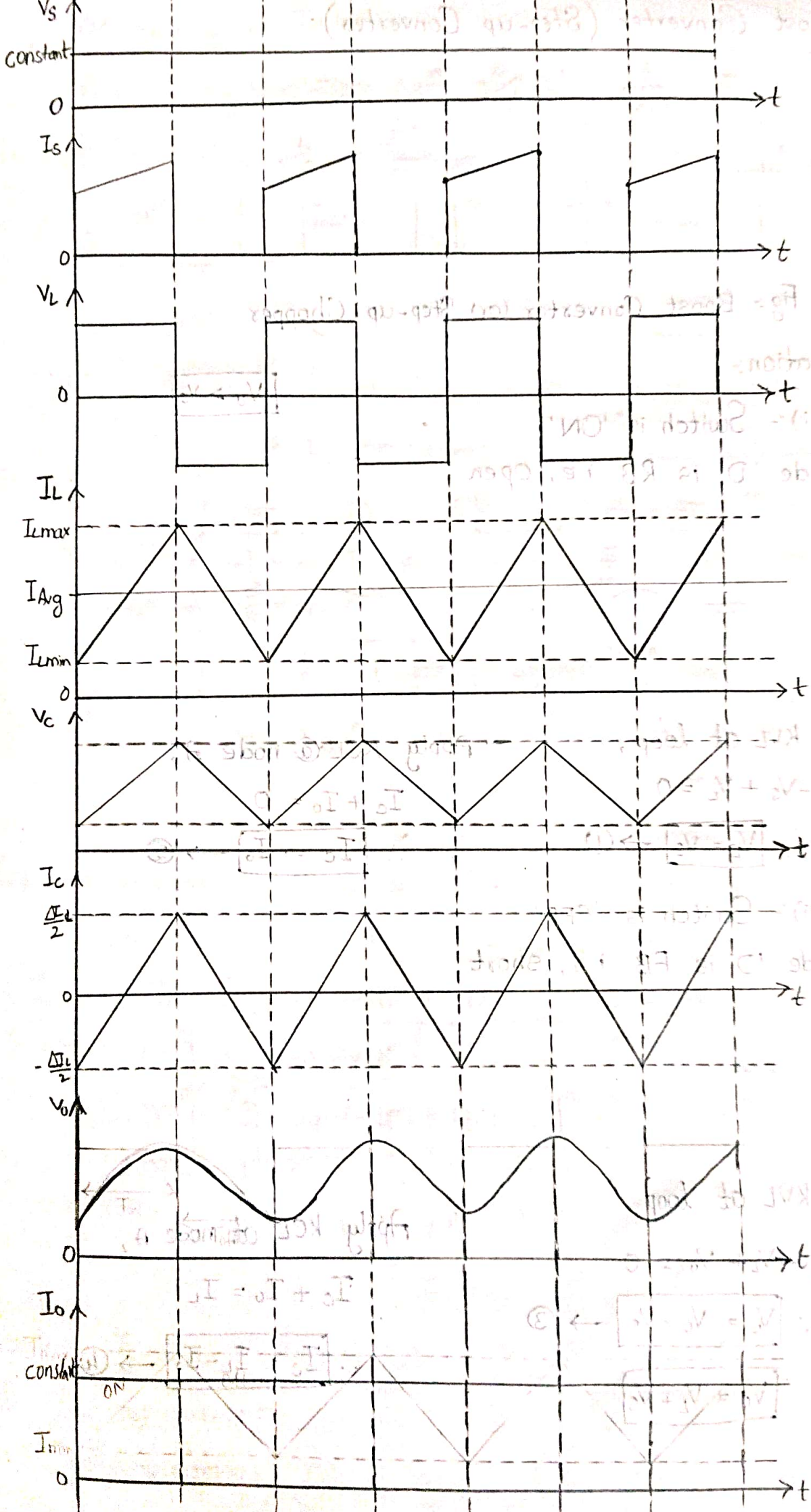
$$V_c = \frac{\Delta V_c}{2}$$

$$V_0 = \frac{V_s (1-D) D}{16f^2 CL} \quad \left\{ \begin{array}{l} V_c = V_0 \\ V_0 = V_s D \end{array} \right\}$$

$$V_s D = \frac{V_s D (1-D)}{16f^2 CL}$$

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

$$C_c = \frac{(1-D) 2f}{16f^2 R(1/D)} = \frac{1}{8Rf} = C_c$$



## 2) Boost Converter (Step-up Converter):-

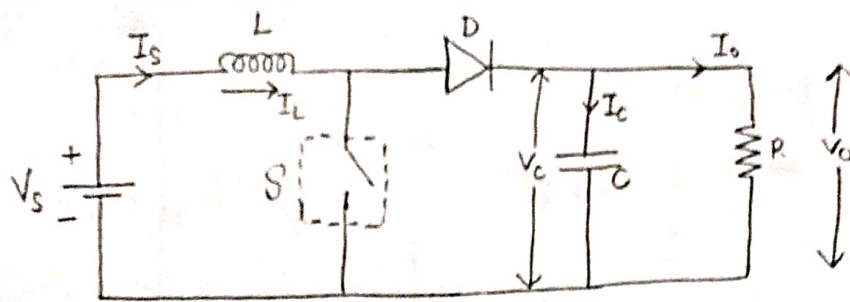


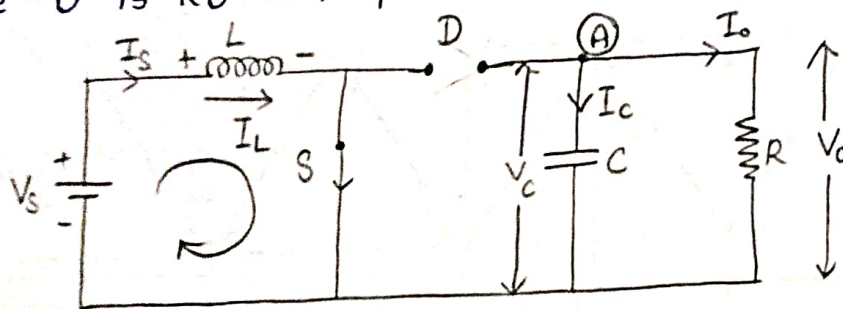
Fig:- Boost Converter (or) Step-up Chopper

Operation:-

$$V_o > V_s$$

Case(i):- Switch is 'ON'

\* Diode 'D' is RB i.e., Open



Apply KVL at loop,

$$-V_s + V_L = 0$$

$$\therefore V_L = V_s \rightarrow \textcircled{1}$$

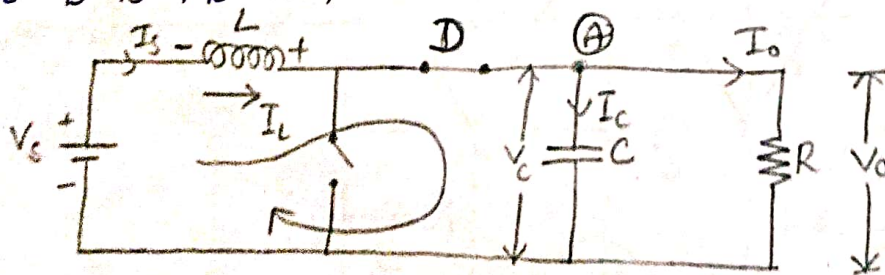
Apply KCL @ node A,

$$I_c + I_o = 0$$

$$\therefore I_c = -I_o \rightarrow \textcircled{2}$$

Case(ii):- Switch is 'OFF'

\* Diode 'D' is FB i.e., short



Apply KVL at loop,

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

$$\therefore V_L = V_o - V_s \rightarrow \textcircled{3}$$

$$V_o = V_L + V_s$$

Apply KCL at node A,

$$I_c + I_o = I_L$$

$$\therefore I_c = I_L - I_o \rightarrow \textcircled{4}$$

Volt-sec balance in Inductor :-

$$V_{LON} \cdot T_{ON} + V_{LOFF} \cdot T_{OFF} = 0 \rightarrow \textcircled{5}$$

we know that,  $D = \frac{T_{ON}}{T} \Rightarrow T_{ON} = DT$

And  $T = T_{ON} + T_{OFF}$

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

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

And,  $V_{LON} = V_s$  {  $\therefore$  from eq ① }

$V_{LOFF} = V_o - V_s$  {  $\therefore$  from eq ② }

$$\textcircled{5} \Rightarrow V_s \cdot DT + (V_o - V_s)(T - DT) = 0$$

$$\Rightarrow V_s \cancel{DT} + V_o T - V_o DT - V_s T + V_s \cancel{DT} = 0$$

$$\cancel{V_s DT} \Rightarrow V_o T (1 - D) = V_s T$$

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

(or)  $V_s = V_o \cdot (1 - D)$

Amp-sec balance in Capacitor :-

$$I_{C.ON} \cdot T_{ON} + I_{C.OFF} \cdot T_{OFF} = 0 \rightarrow \textcircled{6}$$

$I_{C.ON} = -I_o$  {  $\therefore$  from eq ② }

$I_{C.OFF} = I_L - I_o$  {  $\therefore$  from eq ④ }

$$\therefore -I_o \cdot DT + (I_L - I_o)(T - DT) = 0$$

$$-I_o \cancel{DT} + I_L T - I_L DT - I_o T + I_o \cancel{DT} = 0$$

$$T \cdot I_L (1 - D) = I_o T$$

$$\therefore I_o = I_L (1 - D) \quad (\text{or}) \quad I_L = \frac{I_o}{(1 - D)}$$

Ripple in Inductor Current ( $\Delta I_L$ ):

for Inductor current,

$\times$  (Ripple current,  $\Delta I_L = I_{L(max)} - I_{L(min)}$ )  $\times$

$\Delta I_L$ :

$$V_L = V_S$$

And the voltage in inductor,

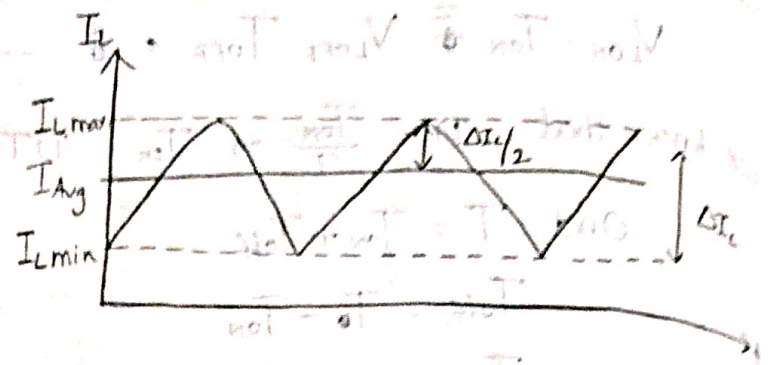
$$V = L \frac{di}{dt}$$

$$V = L \frac{\Delta I_L}{DT}$$

$$V_S = L \cdot \frac{\Delta I_L}{DT}$$

$$\Delta I_L = \frac{V_S \cdot DT}{L}$$

$$\Delta I_L = \frac{V_S D}{Lf}$$



Critical Inductance ( $L_c$ ):

If  $I_{min} = 0$

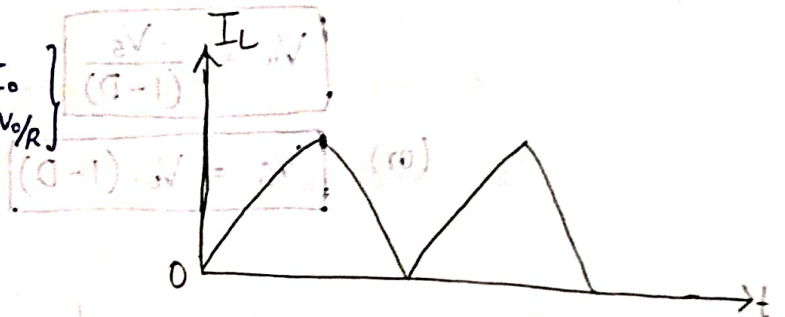
$$I_L - \frac{\Delta I_L}{2} = 0$$

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

$$\frac{I_o}{1-D} = \frac{V_S \cdot D}{2Lf}$$

$$\frac{V_o}{R(1-D)} = \frac{V_S \cdot D}{2Lf}$$

$$\begin{cases} I_L = I_o \\ \therefore I_o = V_o/R \end{cases}$$



We know that,  $V_o = \frac{V_S}{(1-D)}$

$$\frac{V_S}{R(1-D)^2} = \frac{V_S \cdot D}{2Lf}$$

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

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

Ripple in Capacitor Voltage ( $\Delta V_C$ ):

$$I_C = -I_o \quad \{T_{on} \text{ state}\}$$

And the current in capacitor,

$$I_C = C \frac{dv}{dt}$$

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

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

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

$$\Delta V_c = \frac{-I_o D}{Cf} \quad (\text{or})$$

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

Critical Capacitance ( $C_c$ ) :-

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

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

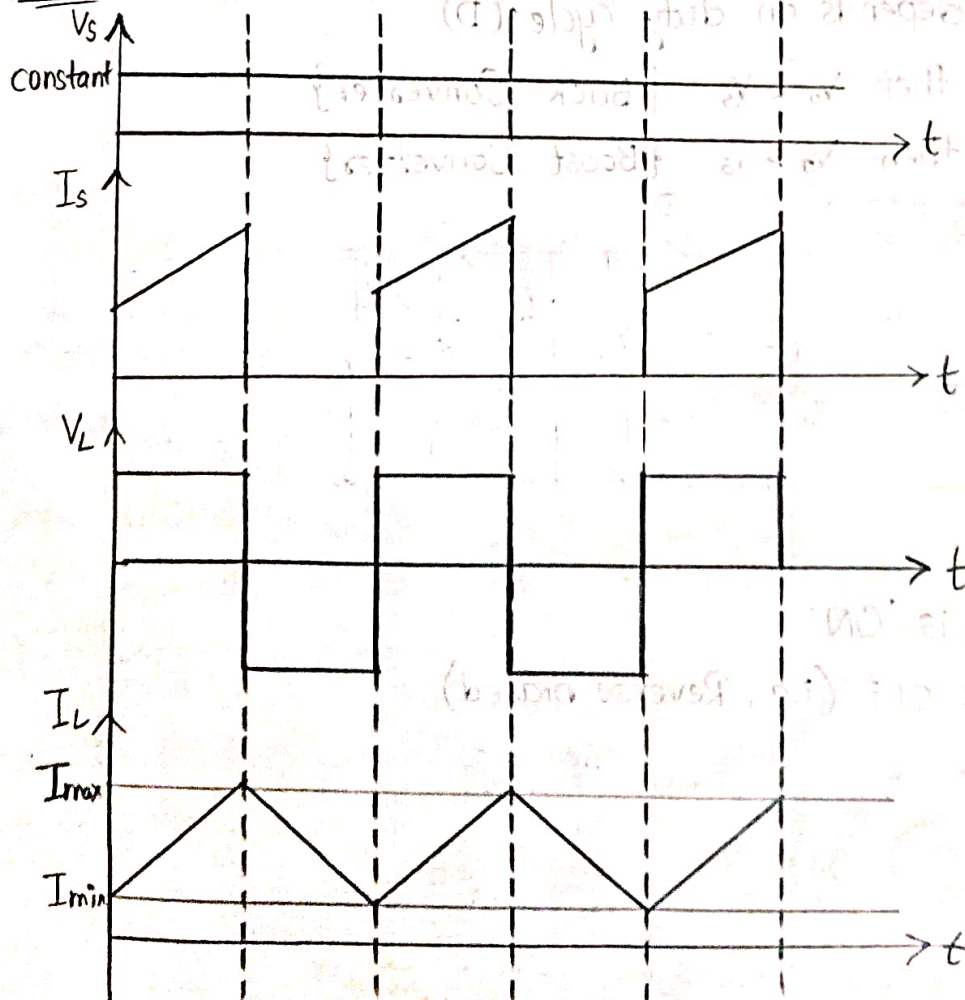
$$V_c = \frac{\Delta V_c}{2}$$

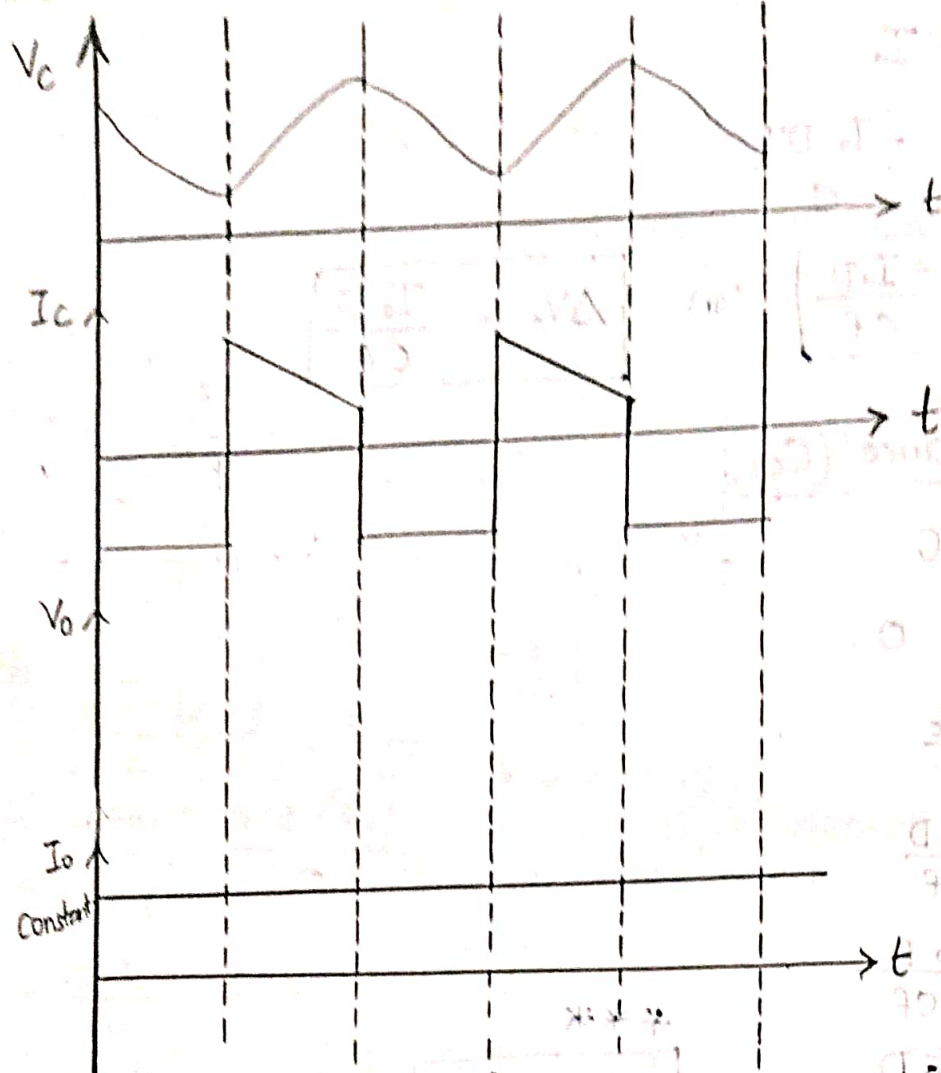
$$V_c = \frac{I_o D}{2Cf}$$

$$V_c = \frac{V_o D}{2RCf}$$

$$V_o = \frac{V_o D}{2RCf} \Rightarrow C_c = \frac{D}{2Rf}$$

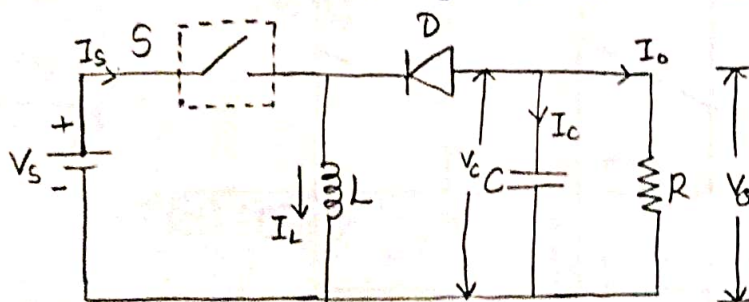
Waveforms:-





### (3) Buck-Boost Converter:-

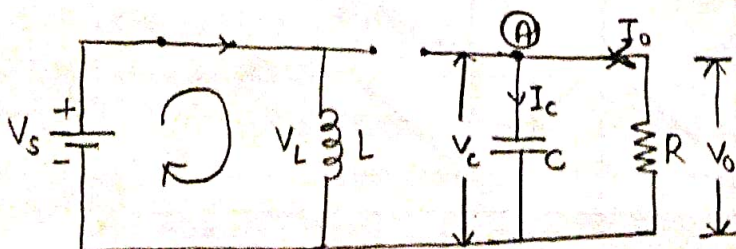
- \* It is a DC-DC Converter.
- \* Output voltage depends on duty cycle (D).
- \* If  $0 < D < 0.5$  then  $V_o < V_s$  { Buck Converter }
- \* If  $0 < D < 1$  then  $V_o > V_s$  { Boost Converter }



#### Operation:-

Case (i):- Switch is 'ON'.

- \* The Diode is OFF (i.e., Reverse biased)



Apply KVL to the ckt,

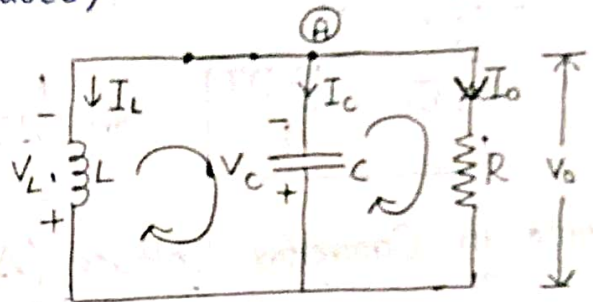
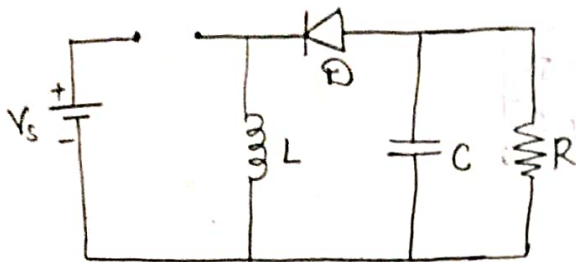
$$V_s = V_L \rightarrow (1)$$

Apply KCL at node A,

$$I_c = -I_o \rightarrow (2)$$

Case (ii): Switch is 'OFF'.

\* The Diode is ON (i.e., Forward Biased)



Apply KVL to the loop,

$$V_L = V_C ; V_C = V_o ; V_L = V_o \rightarrow (3)$$

Apply KCL at node A,

$$I_L + I_o + I_c = 0$$

$$I_c = -(I_L + I_o) \rightarrow (4)$$

Volt-sec balanced equation in Inductor :-

$$V_{LON} \cdot T_{ON} + V_{LOFF} \cdot T_{OFF} = 0$$

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

$$V_s \cdot DT = -V_o T + V_o DT$$

$$V_s \cdot DX = V_o T (D-1)$$

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

(or)

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

We know that

$$D = \frac{T_{ON}}{T} \Rightarrow T_{ON} = D \cdot T \text{ \&}$$

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

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

Amp-sec balanced equation in Capacitor :-

$$I_{CON} \cdot T_{ON} + I_{COFF} \cdot T_{OFF} = 0$$

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

$$-I_o \cdot DT - (I_L T - I_L DT + I_o T - I_o DT) = 0$$

$$-I_o \cancel{DT} - I_L T + I_L DT - I_o T + I_o \cancel{DT} = 0$$

$$I_L (-1+D)X = I_o X$$

$$I_o = -I_L (1-D)$$

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

$$(or) I_L = \frac{I_o}{D-1}$$

$$(or) I_o = I_L (D-1)$$

## Ripple in Inductor Current ( $\Delta I_L$ ):

$$V_{LON} = V_S$$

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

$$\left\{ \because V_L = L \frac{di}{dt} \right\}$$

$$L \frac{\Delta I_L}{DT} = V_S$$

$$\boxed{\Delta I_L = \frac{V_S DT}{L}}$$

(or)

$$\boxed{\Delta I_L = \frac{V_S \cdot D}{Lf}}$$

## Ripple in Capacitor Voltage ( $\Delta V_C$ ):

During ON time,  $I_C = -I_O$

$$C \frac{dv}{dt} = -I_O \quad \left\{ \because I_C = C \frac{dv}{dt} \right\}$$

$$\therefore \frac{dv}{dt} = -\frac{I_O}{C}$$

$$\frac{\Delta V_C}{dt} = -\frac{I_O}{C} = \frac{I_C}{C}$$

Integrate on both sides,

$$\int_{V_{\min}}^{V_{\max}} \frac{dv}{dt} = \int_0^{T_{\text{ON}} = DT} -\frac{I_O}{C} dt$$

$$\boxed{\Delta V_C = \frac{DI_O}{fC}}$$

## Critical Inductance ( $L_C$ ):

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

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

put  $I_{L\min} = 0$

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

$$\Rightarrow I_L = \frac{\Delta I_L}{2} \Rightarrow \frac{-I_O}{1-D} = \frac{\Delta I_L}{2}$$

$$\Rightarrow \frac{-D \cdot V_S}{R(1-D)^2} = \frac{-V_O}{R(1-D)}$$

$$\left\{ \because V_O = \frac{DV_S}{1-D} \right\}$$

$$\Rightarrow \frac{-V_S D}{R(1-D)^2} = \frac{1}{2} \frac{V_S D}{Lf}$$

$$\Rightarrow \boxed{L = \frac{R(1-D)^2}{2f}}$$

## Critical Capacitance ( $C_c$ ):

$$V_{cmin} = 0$$

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

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

$$V_c = \frac{DI_o}{2fC}$$

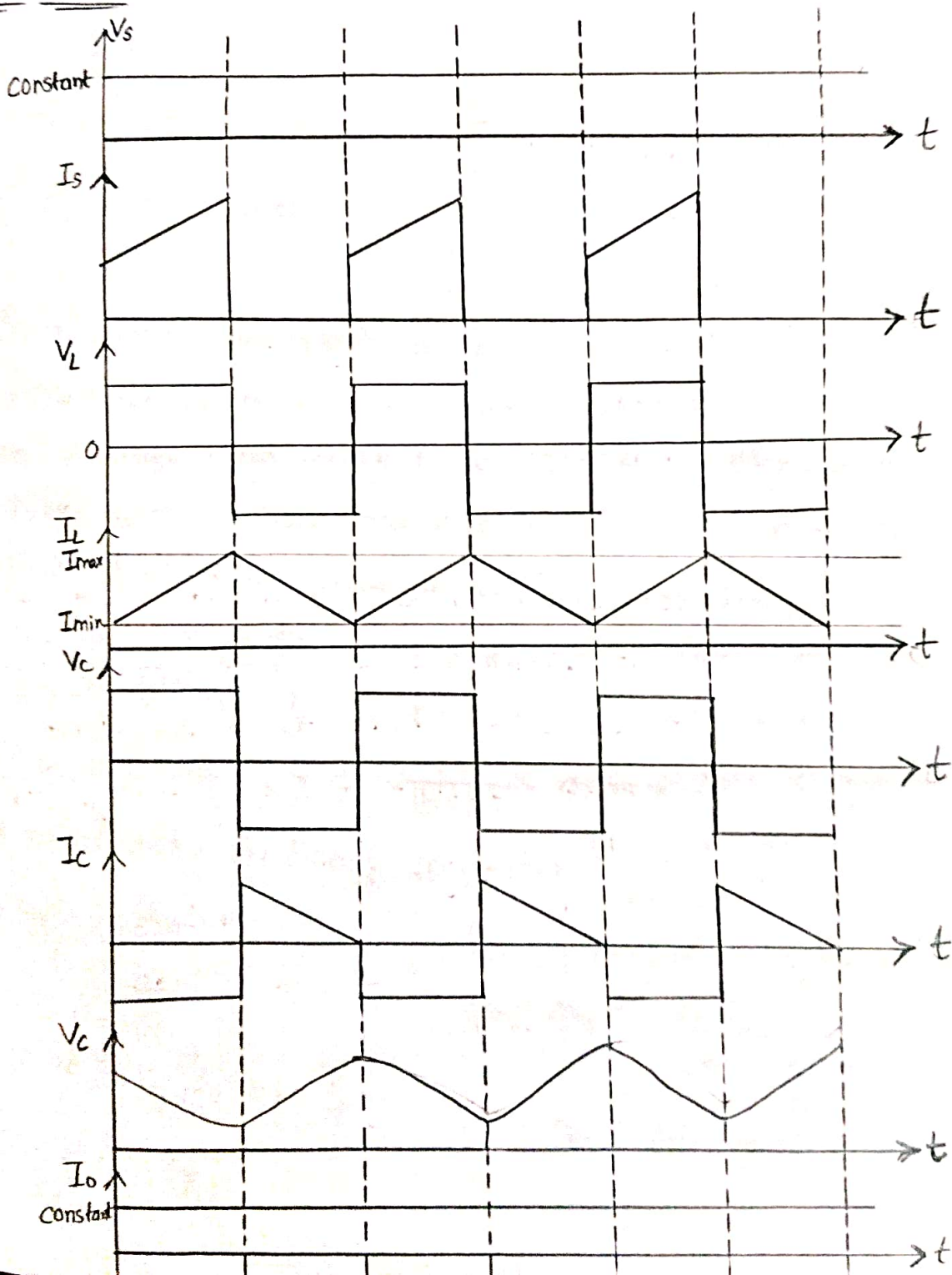
$$V_o = \frac{DI_o}{2fC}$$

$$\Rightarrow \frac{I_o R}{R} = \frac{DI_o}{2fC}$$

$$\begin{cases} \because V_o = V_c \\ V_o = \frac{I_o R}{R} \end{cases}$$

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

## Waveforms:



① In a buck converter the average load current 30A, chopping frequency is 250Hz, supply voltage is 110V. Calculate the ON and OFF periods of the chopper if the load resistance is  $2\Omega$ .

A: In Buck converter,

$$I_L = I_o \Rightarrow I_o = 30 \text{ amp}$$

$$f = 250 \text{ Hz}; V_s = 110 \text{ V}; R = 2\Omega$$

$$\text{Chopping time, } T = \frac{1}{f} = \frac{1}{250} = 4 \text{ msec}$$

$$I_o = \frac{V_o}{R} \quad \{V_o = V_s D\}$$

$$I_o = \frac{V_s \cdot D}{R}$$

$$\therefore D = \frac{I_o R}{V_s}$$

$$D = \frac{30 \times 10^{-3} \times 2}{110} = 0.545$$

$$T_{ON} = D \cdot T = 0.545 \times 4 \times 10^{-3}$$

$$T_{ON} = 2.18 \text{ msec}$$

$$T = T_{ON} + T_{OFF}$$

$$T_{OFF} = T - T_{ON} = (4 - 2.18) \times 10^{-3}$$

$$T_{OFF} = 1.82 \text{ msec}$$

② In a boost converter, as an input voltage is 8V and required output voltage is 18V at 15kHz when  $L = 100\mu\text{H}$ ,  $C = 250\mu\text{F}$  and average load current of 0.3Amps. Determine

- (i) Duty cycle (ii) Peak-Peak ripple voltage (iii) Critical value of capacitor (iv) Critical value of inductor (v)  $I_{L\max}$  &  $I_{L\min}$ .

A:  $V_s = 8\text{V}$ ;  $V_o = 18\text{V}$ ;  $f = 15\text{kHz}$ ;  $L = 100\mu\text{H}$ ;  $C = 250\mu\text{F}$ ;  $I_o = 0.3\text{A}$

- i)  $D = ?$  (ii)  $\Delta V_c = ?$  (iii)  $C_c = ?$  (iv)  $L_c = ?$  (v)  $I_{L\max}$ ,  $I_{L\min} = ?$

(i) Chopping time,  $T = \frac{1}{f} = \frac{1}{15 \times 10^3} = 0.06 \times 10^{-3} = 0.06 \text{ msec}$

We know that, In Boost converter

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

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

$$\therefore D = 1 - \frac{V_s}{V_o} = 1 - \frac{8}{18}$$

$$D = 0.55$$

(ii) The peak-peak ripple voltage

$$\Delta V_c = \frac{I_o D}{C f} = \frac{0.3 \times 0.55}{250 \times 10^{-6} \times 15 \times 10^3}$$

$$\Delta V_c = 44 \text{ mV}$$

$$(iii) C_c = \frac{D \cdot S}{2 R f}$$

$$\therefore R = \frac{V_o}{I_o} = \frac{18}{0.3} = 60 \Omega$$

$$C_c = \frac{0.55}{2 \times 60 \times 15 \times 10^3} = 0.3 \mu F$$

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

$$= \frac{60(1-0.55)^2 \cdot (0.55)}{2 \times 15 \times 10^3} = 0.22 mH$$

$$(v) I_{max} = V_o \left[ \frac{1}{R} + \frac{(1-D)}{2Lf} \right]$$

$$= 18 \left[ \frac{1}{60} + \frac{(1-0.55)}{2 \times 100 \times 10^{-6} \times 15 \times 10^3} \right]$$

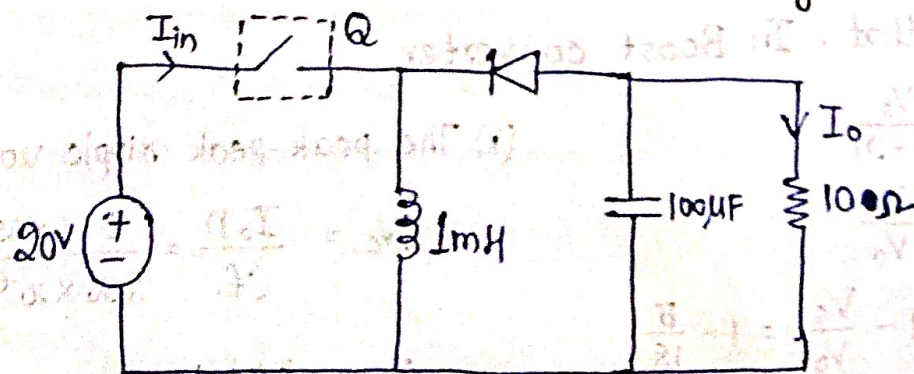
$$I_{max} = 3 \text{ Amps}$$

$$I_{min} = V_o \left[ \frac{1}{R} - \frac{(1-D)}{2Lf} \right]$$

$$= 18 \left[ \frac{1}{60} - \frac{(1-0.55)}{2 \times 100 \times 10^{-6} \times 15 \times 10^3} \right]$$

$$I_{min} = -2.4 \text{ Amps}$$

③ Consider the Buck-Boost converter shown in the figure below. Switch Q is operating at 25kHz and 0.75 Duty cycle. Assume that diode and switch to be ideal. Under the steady state condition what is the average current following through the inductor is



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

$$I_o = \frac{V_o}{R}$$

$$V_o = \frac{V_s \cdot D}{1-D} = \frac{20 \times 0.75}{1-0.75} = 60 \text{ V}$$

$$I_o = \frac{60}{10} = 6 \text{ Amp}$$

$$I_{L(avg)} = \frac{6}{1-0.75} = \frac{6}{0.25} = 24 \text{ Amp}$$

### Buck Converter:

⇒ Source Current ( $I_s$ ):

$$P_{in} = P_{out}$$

$$V_s I_s = V_o I_o$$

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

⇒ Switch Current ( $I_{sw}$ ):

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

$$\boxed{I_{sw(avg)} = I_o D}$$

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

$$\boxed{I_{sw(rms)} = I_o \sqrt{D}}$$

⇒ Diode Current ( $I_D$ ):

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

$$\boxed{I_D(avg) = I_o (1-D)}$$

$$\boxed{I_D(rms) = I_o \sqrt{1-D}}$$

Summary:

$$1) V_o = V_s \cdot D$$

$$2) I_o = I_L \quad \left\{ I_o = \frac{V_o}{R} \right\}$$

$$3) \Delta I_L = \frac{V_s (1-D) D}{Lf}$$

$$4) \Delta V_c = \frac{V_s (1-D) D}{8f^2 LC}$$

$$5) I_{L(max)} = V_o \left[ \frac{1}{R} + \frac{(1-D)}{2Lf} \right]$$

$$6) I_{L(min)} = V_o \left[ \frac{1}{R} - \frac{(1-D)}{2Lf} \right]$$

$$7) I_s = \frac{V_o I_o}{V_s}$$

$$8) I_{sw(avg)} = I_o D$$

$$9) I_{sw(rms)} = I_o \sqrt{D}$$

$$10) I_D(avg) = I_o (1-D)$$

$$I_D(rms) = I_o \sqrt{1-D}$$

$$11) L_c = \frac{R(1-D)}{2f}$$

$$12) C_c = \frac{(1-D)}{16f^2 L} = \frac{1}{8Rf}$$

## Boost Converter

⇒ Switch Current ( $I_{sw}$ ):

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

$$I_{sw(rms)} = \sqrt{D} I_{avg}$$

$$I_{sw(rms)} = \sqrt{D} \left( \frac{I_o}{1-D} \right)$$

⇒ Diode Current ( $I_D$ ):

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

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

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

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

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

⇒ Source Current ( $I_s$ ):

$$P_{in} = P_{out}$$

$$V_s I_s = V_o I_o$$

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

## Summary:

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

$$2) I_o = I_L(1-D)$$

$$3) \Delta I_L = \frac{V_s D}{Lf}$$

$$4) \Delta V_c = \frac{I_o D}{Cf}$$

$$5) I_{L(max)} = V_o \left[ \frac{1}{R} + \frac{(1-D)}{2Lf} \right]$$

$$6) I_{L(min)} = V_o \left[ \frac{1}{R} - \frac{(1-D)}{2Lf} \right]$$

$$7) I_s = \frac{V_o I_o}{V_s}$$

$$8) I_{sw(avg)} = I_{L(avg)} \sqrt{\frac{DT}{T}}$$

$$I_{sw(rms)} = \frac{I_D}{1-D} \cdot \sqrt{D}$$

$$9) I_{D(avg)} = I_o$$

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

$$10) L_c = \frac{R(1-D^2)D}{2f}$$

$$11) C_c = \frac{R}{2Rf}$$

## Performance Parameters of DC-DC Converters

### 1) Efficiency

\* Ratio of output power to input power

\* Higher efficiency reduce heat dissipation and power loss.

\* Typically ranges from 80% to 98%.

### 2) Voltage Regulation

\* Measures the stability of output voltage despite input or load changes

\* formula:  $\text{Voltage Regulation} = \left[ \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \right] \times 100\%$

\* Lower values indicate better performance.

### 3) Load Regulation

- \* Measures variation in output voltage with changing load current.
- \* Important for applications with varying loads.

### 4) Line Regulation

- \* Measures how well the output voltage remains constant despite input variations.

\* formula: 
$$\text{Line Regulation} = \left( \frac{\Delta V_{\text{out}}}{\Delta V_{\text{in}}} \right) \times 100 \%$$

### 5) Ripple and Noise

- \* Small AC voltage fluctuations in the DC output.
- \* Measured in mV peak-to-peak ( $\text{mV}_{\text{pp}}$ ).
- \* Lower ripple is preferred in sensitive applications.

### 6) Switching Frequency

- \* The frequency at which the converter switches power devices.
- \* Common values: 100 kHz to several MHz.
- \* Higher frequencies allow smaller components but increases switching losses.

### 7) Transient Response

- \* Converter's ability to respond to sudden load or input changes.
- \* Measured in microseconds ( $\mu\text{s}$ ).
- \* Fast response prevents voltage dips and overshoots.

### 8) Power Density

- \* Power delivered per unit volume.
- \* Higher power density allows compact designs for portable applications.

### 9) Thermal Performance

- \* Determines heat dissipation and cooling requirements.
- \* Efficient converters produce less heat, improving reliability.

### 10) Isolation (for Isolated Converters)

- \* Electrical separation between input and output.
- \* Isolation voltage typically ranges from 1kV to 5kV.
- \* Essential for safety-critical applications.