Module-3

CHOPPER: DC to DC Converter

Chopper is a static device which converts fixed dc input voltage into a variable dc output voltage.

Chopper circuit requires forced or load commutation

Advantages of chopper:

- Smooth voltage control ability
- High efficiency
- Fast response and regeneration capability.

Applications:

- speed control of dc drives
- Trollery cars.

Basically chopper is devided into 2 types; they are

- Ac link chopper
- DC link chopper

Ac link chopper:

In Ac link chopper dc is first converted to Ac by an inverter (DC to Ac converter). Ac is then stepped-up or stepped down by a transformer which is then converted back to dc by a diode rectifier.

It is costly, bulky and less efficient.

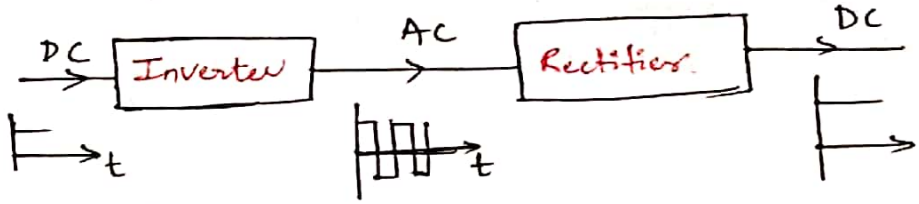

fig1. Ac chopper

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Dc link chopper:

A chopper is a static circuit, that converts fixed dc input voltage to a variable dc output voltage directly.

Fig2. DC link chopper

Devices used in chopper:

For low power applications: GTO, IGBT, power BJT, power MOSFETs

For high power applications: thyristor or SCR.

Symbol of a chopper:

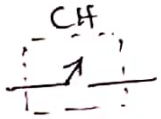

Fig3. Symbol of chopper

These devices are represented as a switch in a dotted box for simplicity.

Principle of ~~operation~~ of chopper operation:

A chopper is a high speed ON/OFF semiconductor switch. It connects source to load and disconnects the load from source at a fast speed.

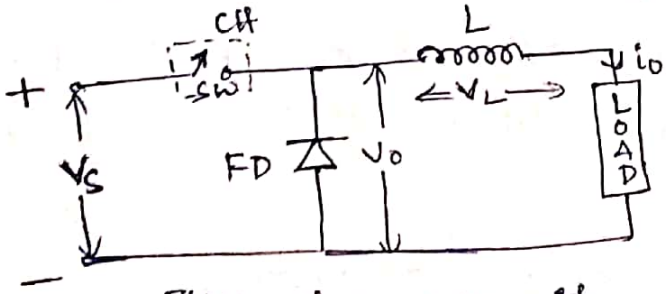

Fig4. chopper circuit

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$$\boxed{\alpha = \frac{T_{ON}}{T} = \text{duty cycle}}$$

Thus, Load voltage can be controlled by varying duty cycle α, it is independent of load current.

So, $\boxed{V_0 = f \cdot T_{ON} \cdot V_s}$

where $f = 1/T$ = chopping frequency.

Control strategies of chopper:

Control strategies are broadly divided into 2 types, they are,

1. Time ratio Control (TRC) and
2. Current limit control.

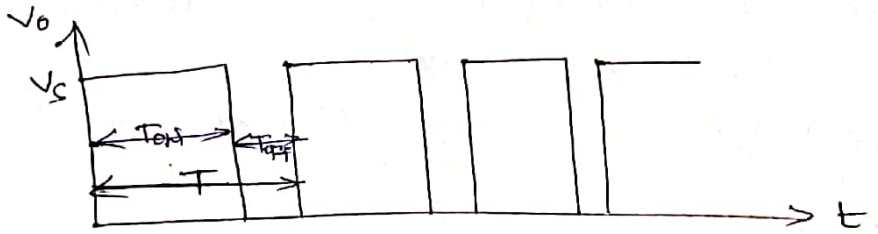
Time ratio Control (TRC):

In this control scheme, time ratio T_{ON}/T (duty cycle) is varied.

This is realized in 2 different strategies, called (a) Constant frequency system and (b) Variable frequency system.

(a) Constant frequency system:

In this type, the ON-time 'T_{ON}' is varied but chopping frequency "f" is kept constant. Variation of T_{ON} means adjustment of pulse width, as such system is called as pulse-width-modulation scheme.



It illustrates the principle of pulse width modulation. Here chopping period 'T' is constant

Here, $T_{ON} = 1/4 T$, so that $\alpha = 0.25$, or $\alpha = 25\%$

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Output voltage and Current Waveforms:

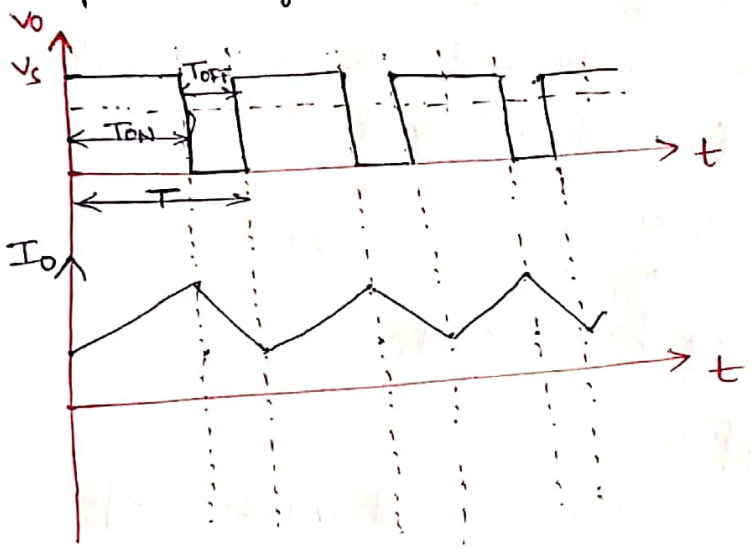

fig 5. Output voltage and current waveform.

A chopped 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~~ which may be turned-ON and OFF as desired.

During turn ON period, chopper is ON and load voltage is equal to V_s. ($V_L = V_s$)

During turn off period, chopper is OFF, load current flows through the free wheeling diode FD.

As a result, load terminals are short circuited by FD and load voltage is therefore zero, during T_{OFF}. In this manner a chopper dc voltage is product at the load terminals.

During T_{ON} period load current rises where as during T_{OFF} load current decays.

$$V_0 = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times V_s$$

$$= \frac{T_{ON}}{T} \times V = \alpha V_s$$

where, T_{ON} = ON time, T_{OFF} = OFF time, $\therefore T = T_{ON} + T_{OFF}$ = chopping period

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Here,

$T_{ON} = 3/4\,T$, so that $d = 0.75$ or 75%.

Ideally, d can be varied from zero to unity.

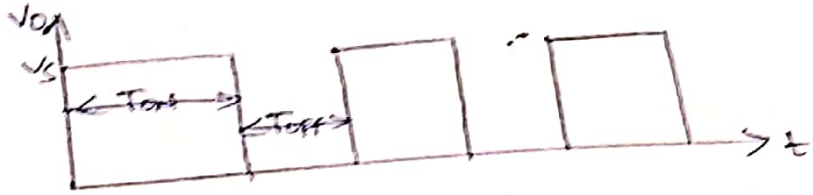
Therefore,

Vo can be varied between zero and source voltage V_s.

(b) Variable frequency system:

The chopping frequency "f" is varied and either (i) on-time T_{ON} is kept constant or (ii) off-time T_{off} is kept constant.

This method of controlling, d is also called frequency modulation scheme.



(a): $T_{ON} = 1/4\,T$, so that $d = 0.25$

(b):

(a) $T_{ON} = 3/4\,T$ so that $d = 0.75$

(b) T_{OFF} is kept constant and T is varied.

Frequency modulation scheme has some disadvantages as compared to pulse-width-modulation scheme.

1. The large off-time in frequency modulation scheme may make the load current discontinuous which is un desirable.

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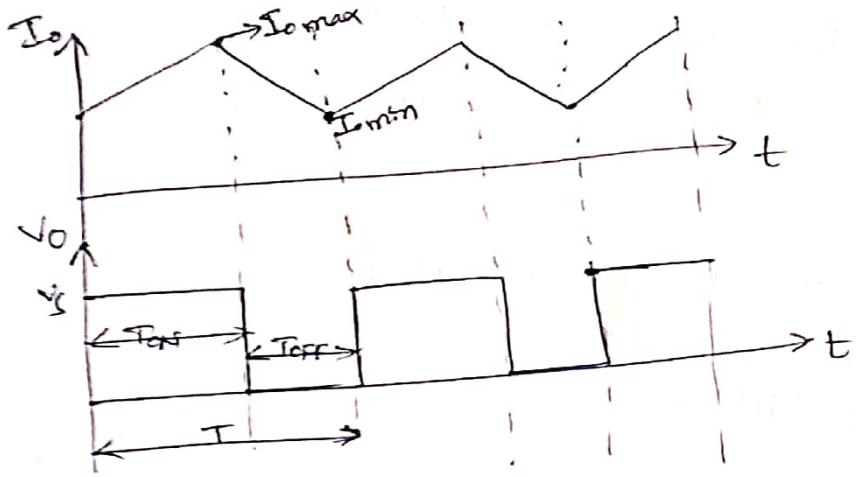
(ii) for the control of α, frequency variation would be wide. so there is a possible of interference with signalling and telephone line in frequency modulation scheme.

2 Current limit Control:



In this control, the ON and OFF of chopper circuit is guided by the previous set values of load current. These 2 set values are maximum load current Iomax and minimum load current Iomin

when load current reaches the upper limit Iomx, chopper is switched off. Now, load current free wheels and begins to decay exponentially.

when it falls to lower limit Iomn, chopper is switched on and load current begins to rise.

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Classification of chopper:

* Based on the output voltage of the output, the choppers are classified as

(i) step - down chopper

In this case the average output voltage is less than the input voltage. It is also known as step down converter

⇒ This is also known as Buck converter

$$\boxed{V_0 < V_i}$$

(ii) step - up chopper

Here the average output voltage is more than the input voltage. It is also known as step up converter ⇒ This is also called boost converter

(iii) step - up / Down chopper.

This type of converter produces an output voltage that is either lower or higher than the input voltage.

⇒ This is also called as Buck - boost converter.

* Based on the direction of the output current and voltage, the converters can be classified into five classes namely,

(a) class A - (1st quadrant chopper only) - one quadrant operation

(b) class B - (2nd quadrant chopper only) - one quadrant "

(c) class C - (1,2 quadrant only) - Two quadrant "

(d) class D - (1,4 quadrant only) - " " "

(e) class E - (All quadrants) - Four quadrant operation

* Based on the turn off process: (Commutation process)

⇒ Natural commutated chopper (occurs in AC input circuits)

⇒ Forced " " " " DC " "

The forced commutated is further classified as.

(a) voltage commutated chopper (Ex. Jones chopper)

(b) current " " (Ex. Morgan chopper)

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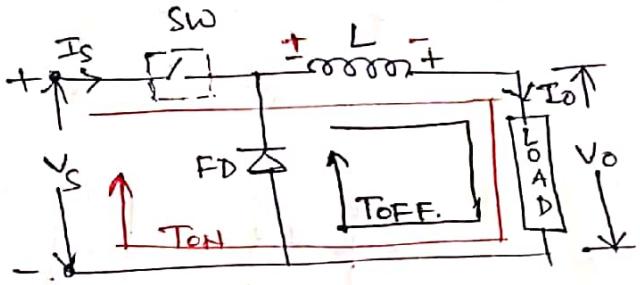
Step down chopper:

- It is also called as Buck Converter.
- An average output voltage (V_0) is less then the input voltage (V_s)

$$\boxed{V_0 < V_s}$$

- The basic circuit diagram of step down chopper is shown in the figure.

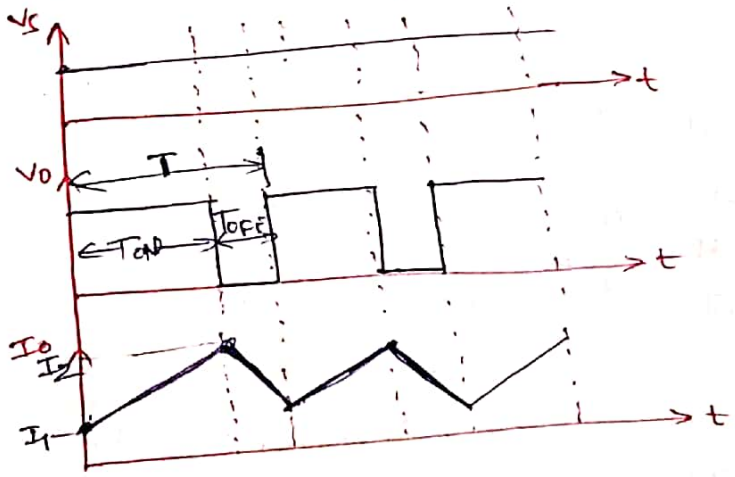


Mode I :

- when SW is turned ON, V_s is directly appears across the load so $\boxed{V_0 = V_s}$, output current rises from I_1 to I_2 because of Inductor.

Mode II :

- when SW is turned OFF, V_s is dis connected from load. so output voltage $\boxed{V_0 = 0}$, because of inductor discharge the current fall from I_2 to I_1 as shown in the wave form



$T > T_{ON}$

$(0.75)V_s = V_0$

$V_s < V_0$

Average output voltage

$$V_{avg} = V_s\left(\frac{T_{ON}}{T}\right) \qquad T = T_{ON} + T_{OFF}$$

$$= V_s(\alpha) \quad (\because \alpha < 1)$$

$$\boxed{V_{avg} < V_s}$$

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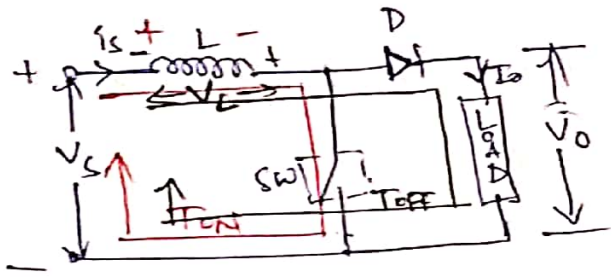
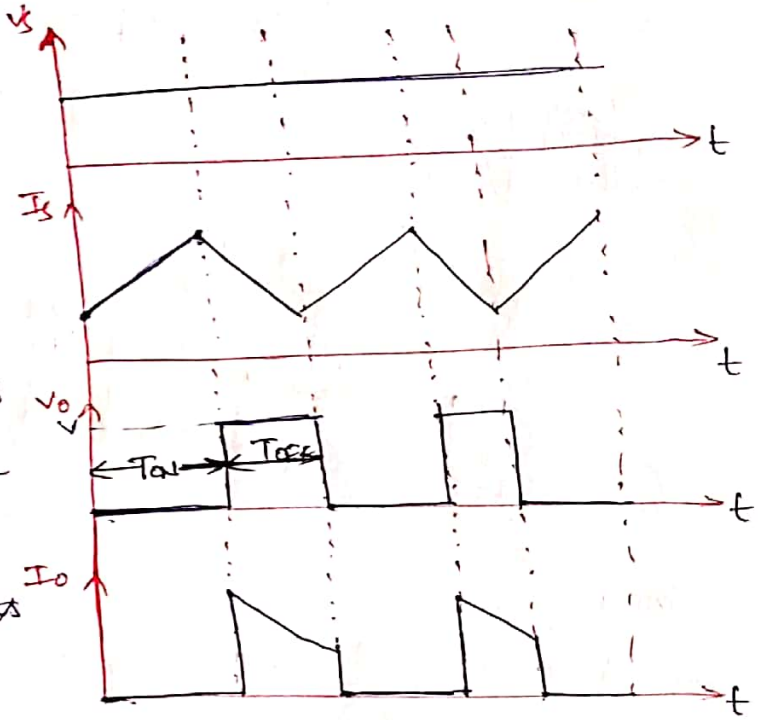
Step up chopper:

- It is also called as boost converter.
- output voltage more than the input voltage $\boxed{V_0 > V_s}$
- The basic circuit diagram of step up chopper is shown in figure.





Mode I:

- when SW is ON it short circuits the load. Hence output voltage is zero during T_{ON}.

During this period Inductor gets charged. So $V_s = V_L$

$$L\frac{di}{dt} = V_s \Rightarrow \frac{\Delta I}{T_{ON}} = \frac{V_s}{L}$$

$$\Delta I = \frac{V_s}{L} T_{ON} \longrightarrow (1)$$

, where ΔI is peak to peak inductor current.

Mode II:

- when SW is OFF, inductor 'L' discharges through the load. So, we will get summation of both source voltage V_s and inductor voltage V_L as output voltage

$$\boxed{V_0 = V_s + V_L}$$

$$V_L = V_0 - V_s \Rightarrow L\frac{di}{dt} = V_0 - V_s$$

$$\frac{\Delta i}{T_{OFF}} = \frac{V_0 - V_s}{L}$$

$$\Delta I = \left(\frac{V_0 - V_s}{L}\right) T_{OFF} \longrightarrow (2)$$

Now by equating eqn (1) & (2),

$$\frac{V_s}{\cancel{L}} T_{ON} = \left(\frac{V_0 - V_s}{\cancel{L}}\right) T_{OFF} \Rightarrow V_s T_{ON} = V_0 T_{OFF} - V_s T_{OFF}$$

$$\Rightarrow V_0 = \frac{V_s (T_{ON} + T_{OFF})}{T_{OFF}} = \frac{T V_s}{T_{OFF}}$$

$$= \frac{V_s}{(T - T_{ON})/T} = V_s\left(\frac{1}{1-\alpha}\right)$$

$$\boxed{V_0 > V_s}$$

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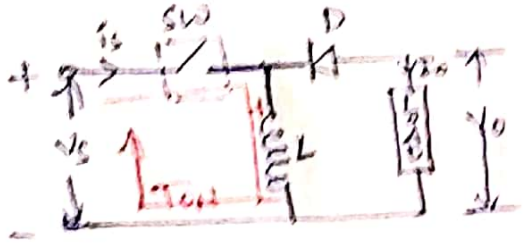
Step down/step up converter:

- It is also called as Buck-boost converter.
- With the help of Buck-boost converter, we can increase or decrease the input voltage level at its output side as per our requirement.
- The circuit diagram as shown in figure



Mode I:

- When SW is ON, source voltage will be applied across inductor L and it will be charged so $\boxed{V_L = V_s}$

$$L\,di/dt = V_s \Rightarrow \frac{\Delta I}{T_{on}} = \frac{V_s}{L} \Rightarrow \Delta I = \frac{V_s}{L} T_{on}.$$

$$\Rightarrow \Delta I = \frac{V_s}{L}\frac{T_{on}}{T}\cdot T$$

$$\Rightarrow \boxed{\Delta I = \frac{V_s}{L} d \cdot \frac{1}{f} = \frac{dV_s}{Lf}} \longrightarrow (1) \qquad \left(\because \frac{T_{on}}{T} = d \;\&\; T = \frac{1}{f}\right)$$

Mode II:

- When SW is OFF, inductor L reverses its polarity and discharge through load and diode, so

$$V_o = -V_L$$

$$L\frac{di}{dt} = -V_o \Rightarrow \frac{\Delta I}{T_{OFF}} = \frac{-V_o}{L} \Rightarrow \boxed{\Delta I = \frac{-V_o}{L} T_{OFF}} \longrightarrow (2)$$

By equating (1) & (2), we get

$$\frac{dV_s}{\cancel{L}f} = \frac{-V_o}{\cancel{L}} T_{OFF} \Rightarrow dV_s = -V_o T_{OFF} f.$$

$$\Rightarrow dV_s = -V_o \frac{T - T_{on}}{T} = -V_o\left(1 - \frac{T_{on}}{T}\right) \Rightarrow V_o = \frac{dV_s}{1-d}$$

d can be varied from 0 to 1

when, $d = 0$, $V_o = 0$

$d = 0.5$, $V_o = V_s$

$d = 1$, $V_o = \infty$

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- Hence, in the interval $0 \leq d \leq 0.5$, output voltage varies in the range $0 \leq V_o \leq V_s$ and we get step down of buck converter.
- whereas, in the interval $0.5 \leq d \leq 1$, output voltage varies in the range $V_s \leq V_o \leq \infty$ and we get step-up of Boost converter.

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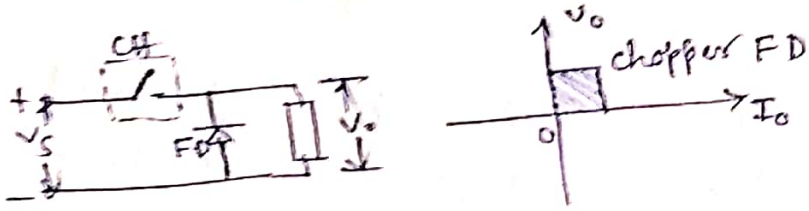
Types of chopper:

Type A chopper or 1st quadrant chopper:

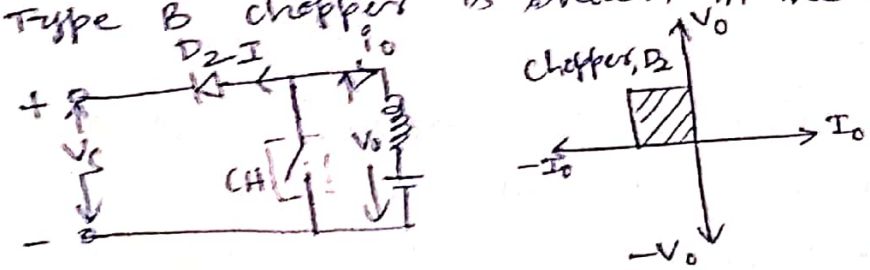
- It is known as 1st quadrant chopper or type-A chopper.
- Type A chopper shown in the figure.



- When the chopper is on, $V_0 = V_s$ as a result and the current flows in the direction of the load.
- But when the chopper is OFF V_0 is zero but I_0 continues to flow in the same direction through the freewheeling diode FD.
- Thus average value of voltage and current say V_0 and I_0 will be always positive as shown in the graph
- In type A chopper the power flow will be always from source to the load. As the average voltage V_0 is less than the dc input voltage V_s.

Type B chopper or 2nd quadrant chopper:

- In type B or 2nd quadrant chopper load must always contain a dc source E.
- Type B chopper is shown in the figure.



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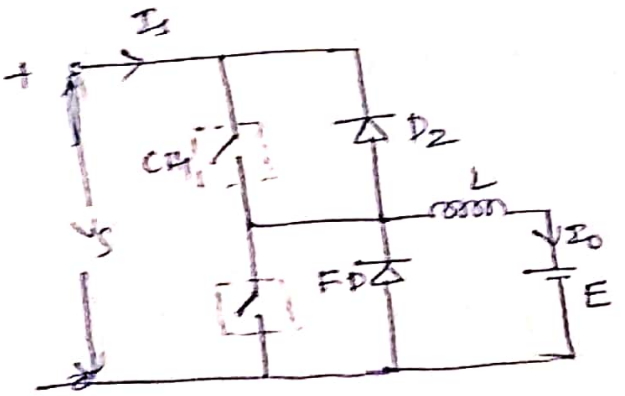
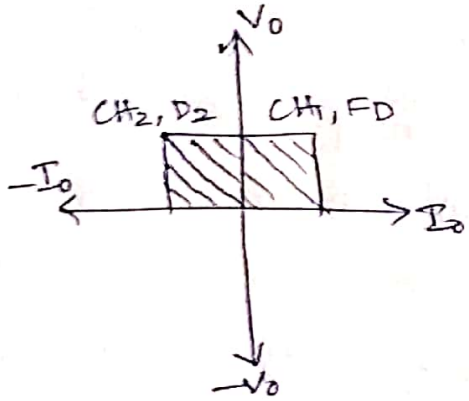
- When the chopper is on, V_0 is zero but the load voltage E drives the current through the inductor L and the chopper. L stores the energy during the time T_{on} of the chopper.
- When the chopper is off, $V_0 = (E + L\, di/dt)$ will be more than the source voltage V_s.
- Because of this the diode D_2 will be forward biased and begins conducting and hence the power starts flowing to the source. No matter the chopper is either ON or OFF the current I_0 will be flowing out of the load and is treated negative.
- Since V_0 is positive and the current I_0 is negative, the direction of the power flow will be from load to source. The load voltage $V_0 = (E + L\, di/dt)$ will be more than the voltage V_s so the type B chopper is also known as a step up chopper.

Type-C chopper or Two-quadrant chopper or 1st & 2nd quadrant chopper:

- Type C chopper is obtained by connecting type-A and type B chopper in parallel.
- Type C chopper is shown in the figure.





- We will always get a positive output voltage V_0 as the FD present across the load.
- When the chopper is on the FD starts conducting and the output voltage V_0 will be equal to V_s.

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- The direction of the load current i_o will be reversed. The current i_o will be flowing towards the source and it will be positive regardless the chopper is on or the FD conducts.

- The load current will be negative if the chopper is or the diode D_2 conducts. ~~The load current will be negative~~

- We can say the chopper and FD operates together as type-A chopper in first quadrant. In the second quadrant, the chopper and D_2 will operate together as type-B chopper.

- The average voltage will be always positive but the average load current might be positive or negative.

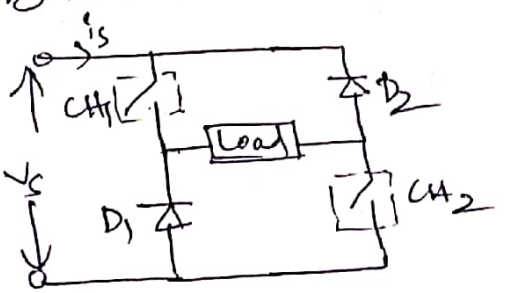
- The power flow may be like the first quadrant operation i.e; from source to load or from load to source like the second quadrant operation.

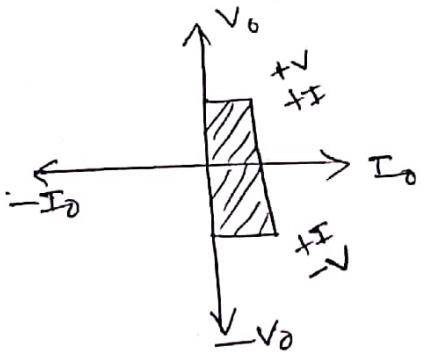
- The two choppers should not be turned on simultaneously as the combined action may cause a short circuit in supply lines.

- For regenerative braking and motoring these type of chopper configuration is used.

Type D chopper or Two-Quadrant Type-B chopper:

- The circuit diagram of the type D chopper is shown in figure.





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- when the two choppers are on the output voltage V_o will be equal to V_s
- when $V_o = -V_s$ the two choppers will be off but both the diodes D_1 and D_2 will start conducting.
- V_o the average output voltage will be positive when the choppers turn-on the time T_{on} will be more than the turn off time T_{off}..
- As the diodes and chopper conducts current only in one direction the direction of load current will be always positive.
- The power flow from source to load as the average values of both V_o and I_o is positive

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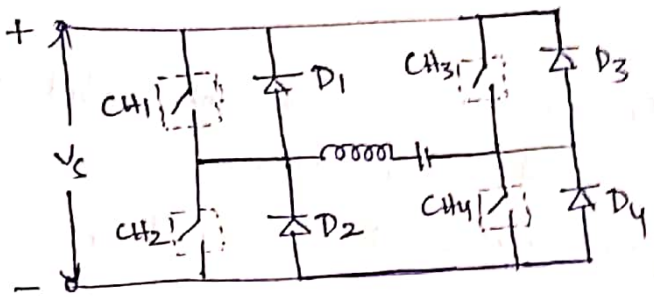
Type E chopper or the four-quadrant chopper:

- Type E or the fourth quadrant chopper consist of four semiconductor switches and four diodes arranged in antiparallel.
- The 4 choppers are numbered according to which quadrant they belong.
- Their operation will be in each quadrant and the corresponding chopper only be active in its quadrant.



- First Quadrant
  - During the first quadrant operation the chopper CH4 will be on chopper CH3 will be off and CH1 will be operated.
  - As CH1 and CH4 is on the load voltage V_o will be equal to the source voltage V_s and the load current i_o will begin to flow.
  - V_o and i_o will be positive as the first quadrant operation is taking place.
  - As soon as the chopper CH1 is turned off, the positive current freewheels through CH4 and the diode D_2. The type E chopper acts as a step-down chopper in the first quadrant.
- Second quadrant:
  - In this case the chopper CH_2 will be operational and the other three kept off.
  - As CH_2 is ON negative current will starts flowing through the inductor L. CH_2, E and D_4.
  - ~~CH2, E and D4~~ Energy stored in the inductor L as the chopper CH_2 is on.
  - When CH_2 is off the current will be fed back to the source through the diodes D_1 and D_4.

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- Here $(E + L_o di/dt)$ will be more than the source voltage V_s.
- In second quadrant the chopper will act as a step-up chopper.

• Third quadrant

- In third quadrant operation CH_1 will be kept off, CH_2 will be ON and CH_3 is operated.
- For this quadrant working the polarity of the load should be reversed.
- As the chopper CH_3 is ON, the load gets connected to the source V_s and V_o, and i_o will be negative.
- The third quadrant operation will takes place.
- This chopper acts as a step-down chopper.

• Fourth-quadrant:

- CH_4 will be operated and CH_1, CH_2 and CH_3 will be off.
- When the chopper CH_4 is turned on positive current starts to flow through CH_4, D_2, E and L will store energy.
- As the CH_4 is turned off the current is feed back to the source through the diodes D_2 and D_3.
- The operation will be in fourth quadrant as the load voltage is negative but the load current is positive.
- The chopper acts as a step-up chopper as the power is fed back from load to source.

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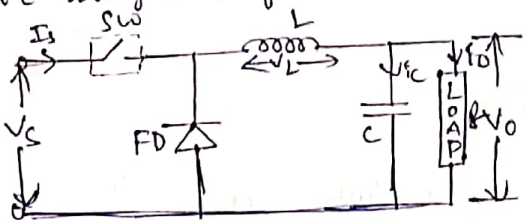
Buck Converter:

- Step down chopper

- It is also called as Buck regulator.
- In a buck converter, the average output voltage (V_o) is than the input voltage (V_s).

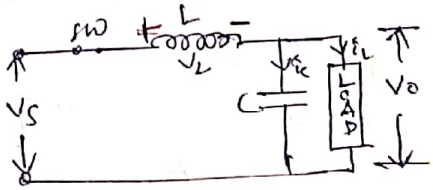
$$\boxed{V_o < V_s}$$

- Here the L and C acts as filters and stores the chop DC.
- Circuit diagram of the Buck Converter is shown in figure.



- The Buck Converter has two modes of operation.

Mode I: Switch is ON, diode is off.



- When the switch is ON at $t=0$, the input current flows through inductor 'L', capacitor and load resistor R.
- The voltage across capacitor in the steady state is equal to the output voltage.
- Let us analyse the buck converter in steady state operation for this mode using KVL,

$$V_s = V_L + V_o \quad , \quad I_c = I_L - I_o$$

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

$$\frac{di}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{\alpha T} = \frac{V_s - V_o}{L}$$

Since the switch is closed for a time $T_{ON} = \alpha T$ we can say that $\Delta t = \alpha T$.

$$(\Delta i_L)_{closed} = \left(\frac{V_s - V_o}{L}\right)\alpha T.$$

- The inductor current in steady state rises from a value with a positive slope to a maximum value during the ON state and then drops back down to the initial value with a negative slope.

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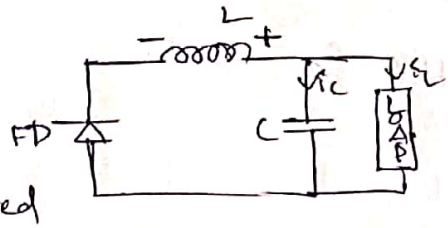
Mode II : Switch is OFF, Diode is ON



- When the switch is OFF, $(t = t_1)$ FD is ON condition.
- FD conducts due to the charge stored in the inductor. This current flows through L, C and Load and diode
- Buck converter in steady state operation for Mode II using KVL.

$$0 = V_L + V_o$$

$$V_L = -V_o \quad , \quad I_c = I_L - I_o$$

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

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-\alpha)T} = \frac{-V_o}{L}$$

Since the switch is open for a time $T_{OFF} = T - T_{ON} = T - \alpha T = (1-\alpha)T$, we can say $\Delta t = (1-\alpha)T$.

$$(\Delta i_L)_{open} = \left(\frac{-V_o}{L}\right)(1-\alpha)T$$

- It is already established that the net change of the inductor current over any one complete cycle is zero.

$$\therefore (\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

$$\left(\frac{V_s - V_o}{L}\right)\alpha T + \left(\frac{-V_o}{L}\right)(1-\alpha)T = 0$$

$$\left(\frac{V_s - V_o}{\cancel{L}}\right)\alpha T = \left(\frac{V_o}{\cancel{L}}\right)(1-\alpha)T$$

$$(V_s - V_o)\alpha T = V_o(1-\alpha)T$$

$$V_s\alpha T - \cancel{V_o\alpha T} = V_o T - \cancel{V_o\alpha T}$$

$$V_s\alpha \cancel{T} = V_o \cancel{T}$$

$$\boxed{V_o = \alpha V_s}$$

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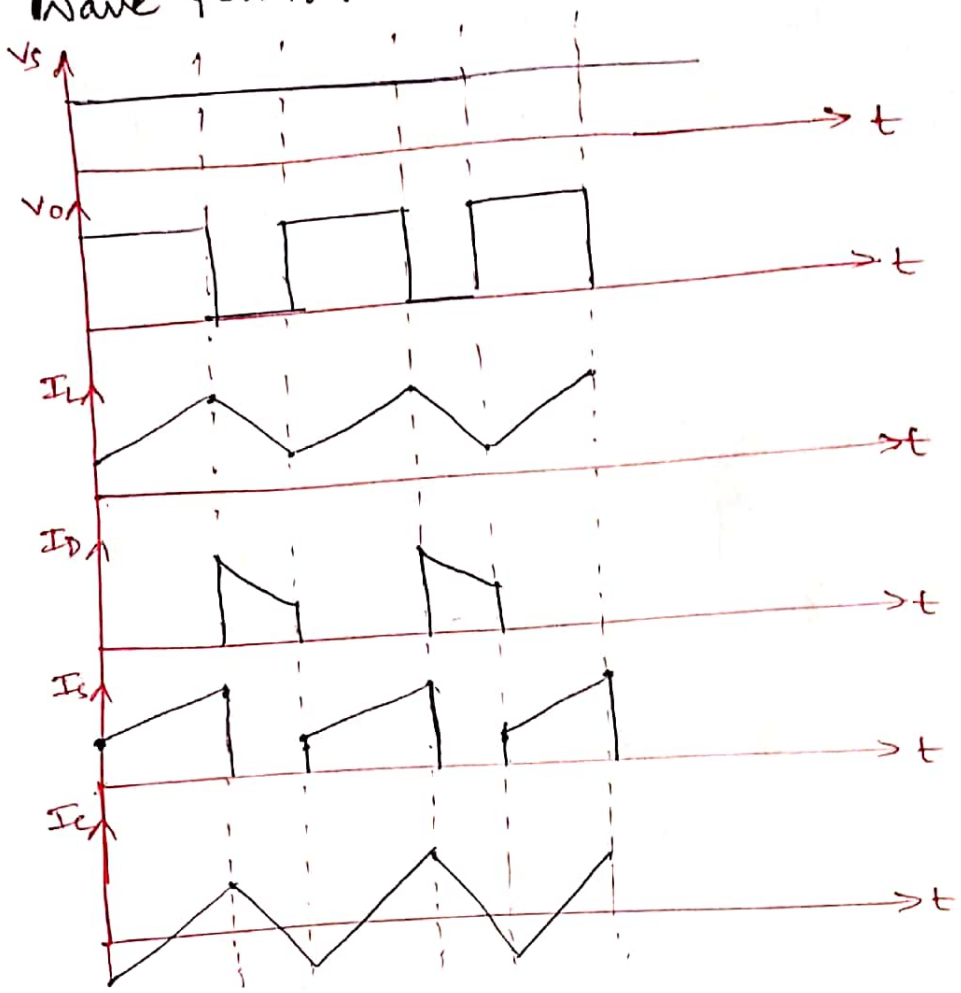
Wave forms :



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