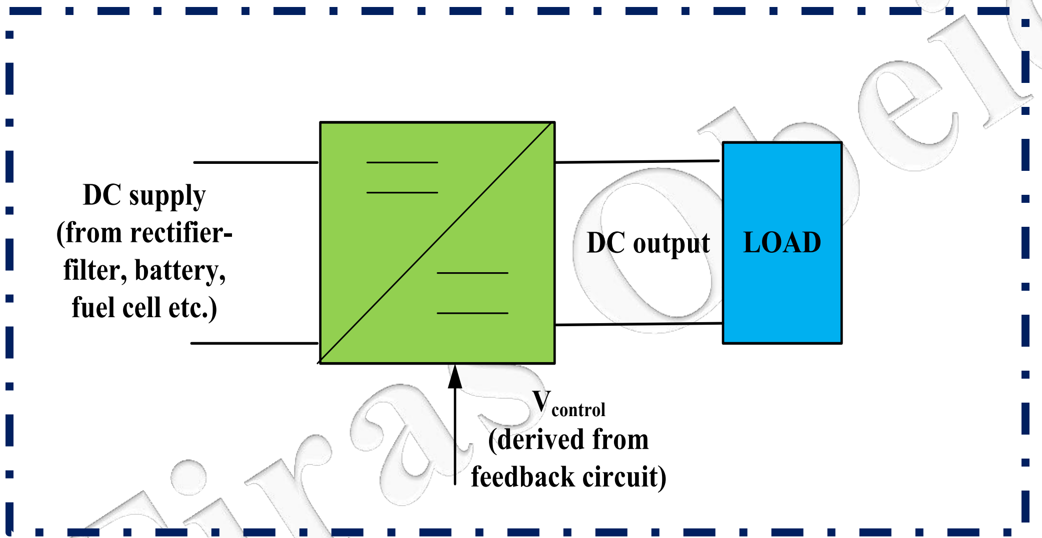
Introduction

DC-DC converters **are power electronic circuits that convert a DC voltage to a different DC voltage level, often providing a regulated output.**



General block diagram

***Applications*:**

– **Switched-mode power supply (SMPS), DC motor control, battery chargers, subway cars, trolley buses, vehicles, etc.**

Introduction

Main Types of Choppers

1- Step-down DC-DC converter.

In step down chopper output voltage is less than input voltage.

2- Step-up DC-DC converter.

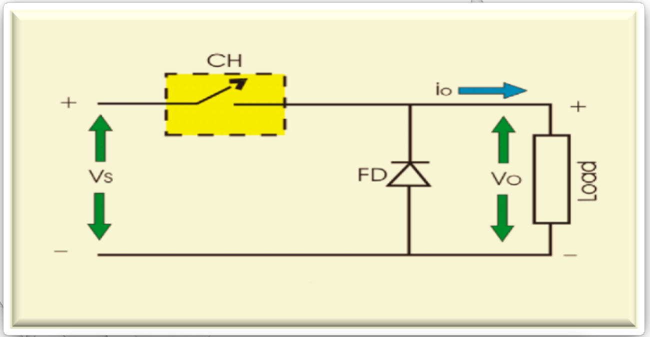
In step up chopper output voltage is more than input voltage.

3- Buck-Boost converter (Step-down/step-up converter).

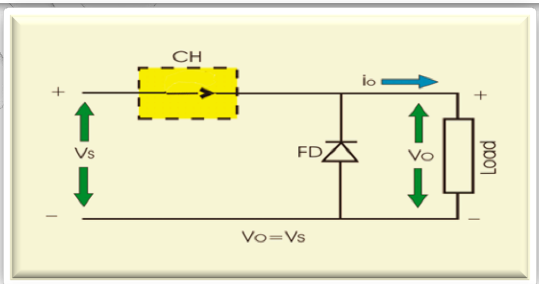
4- Cuk converter.

The Buck (Step-Down) Converter

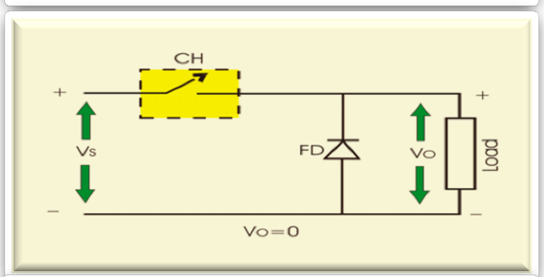
- Step down chopper as Buck converted is used to reduce the input voltage level at the output side. Circuit diagram of a step down chopper is shown in the figure.



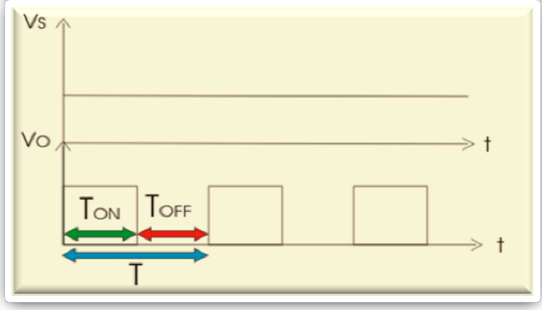
- When CH is turned ON, Vs directly appears across the load as shown in figure. So $V_O=V_S$.



- When CH is turned OFF, Vs is disconnected from the load. So output voltage $V_O = 0$.



- The voltage waveform of step down chopper

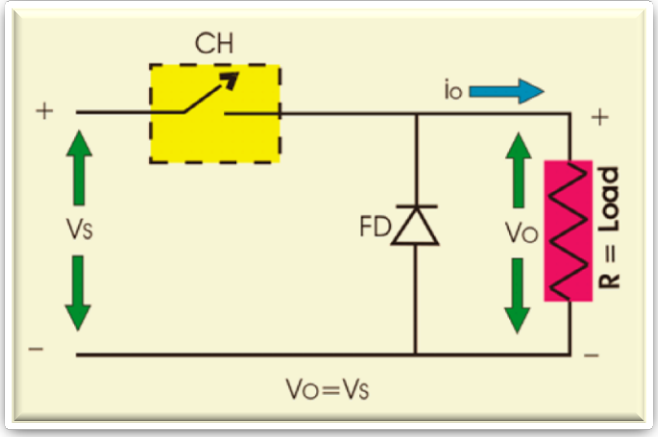


The Buck (Step-Down) Converter

- T_{ON} → It is the interval in which chopper is in ON state.
- T_{OFF} → It is the interval in which chopper is in OFF state.
- V_S → Source or input voltage.
- V_O → Output or load voltage.
- T → Chopping period = $T_{ON} + T_{OFF}$
- F=1/T is the frequency of chopper switching or chopping frequency

Operation of Step Down Chopper with Resistive Load

- When CH is ON, $V_O = V_S$ When CH is OFF, $V_O = 0$



The Average output voltage is

$$V_{dc} = V_o = \frac{1}{T}\int_0^{T_{ON}} V_s dt = \frac{V_s T_{ON}}{T} = DV_s$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{DV_s}{R}$$

The Buck (Step-Down) Converter

Step Down Chopper with Resistive Load

$$D = \frac{T_{ON}}{T} \qquad T = T_{ON} + T_{OFF}$$

- ***Where,***
- ***D is <u>duty cycle</u> = T_{ON}/T. T_{ON} can be varied from 0 to T, so $0 \le D \le 1$.***
- ***The output voltage V_O can be varied from 0 to V_S.***

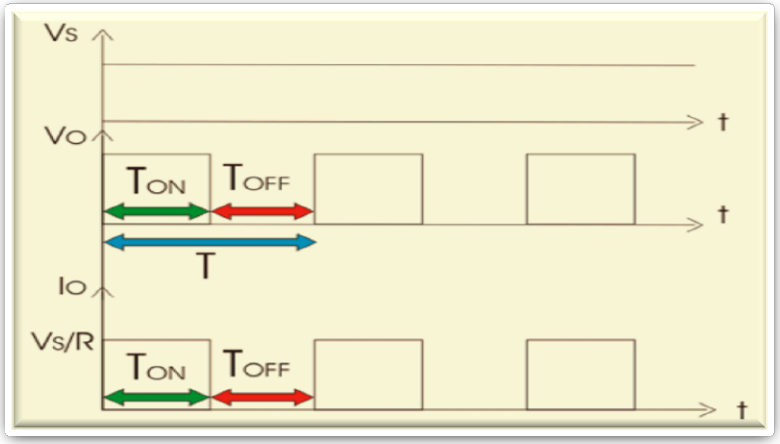
The *rms* output voltage is

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^{T_{ON}} {V_s}^2 dt} = V_s\sqrt{\frac{T_{ON}}{T}} = \sqrt{D}V_s$$

$$I_{rms} = \frac{V_{rms}}{R} = \frac{\sqrt{D}V_s}{R}$$

$$P_o = V_{rms}I_{rms} = \frac{{V_{rms}}^2}{R} = D\frac{{V_s}^2}{R}$$

The output voltage is always less than the input voltage and hence the name step down chopper is justified.



The Buck (Step-Down) Converter

Step Down Chopper with Resistive Load

Ripple factor (*RF*) can be found from

$$RF = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1} = \sqrt{\frac{DV_s^{\,2}}{D^2 V_s^{\,2}} - 1} = \sqrt{\frac{1}{D} - 1} = \sqrt{\frac{1-D}{D}}$$

Methods of Control

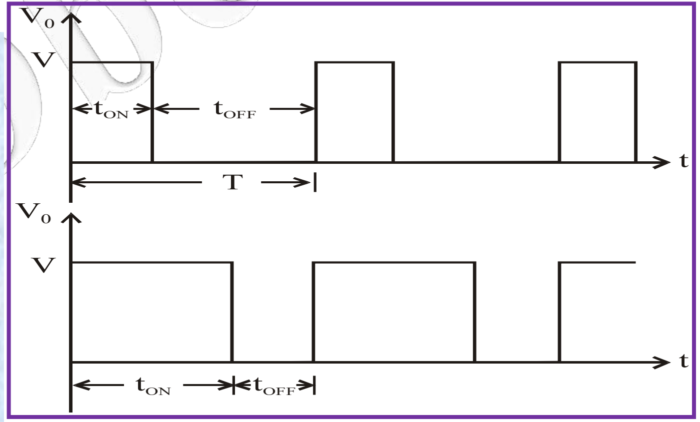
1- Pulse Width Modulation

- **t_{ON} is varied keeping chopping frequency '*f*' & chopping period 'T' constant.**
- **Output voltage is varied by varying the ON time t_{ON}**

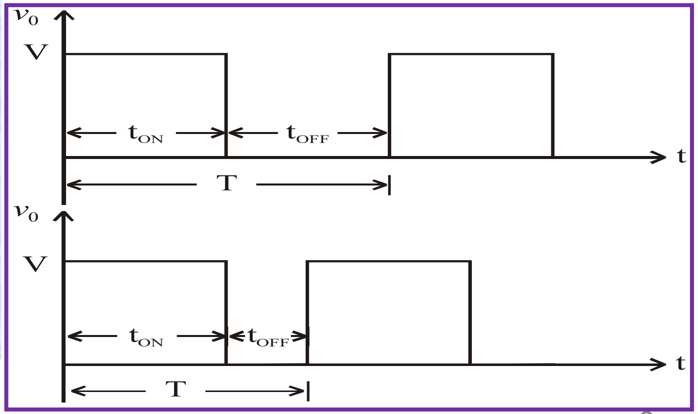
2- Variable Frequency Control

- **Chopping frequency '*f*' is varied keeping either t_{ON} or t_{OFF} constant.**
- **To obtain full output voltage range, frequency has to be varied over a wide range.**
- **This method produces harmonics in the output and for large t_{OFF} load current may become discontinuous**

Pulse Width Modulation Method



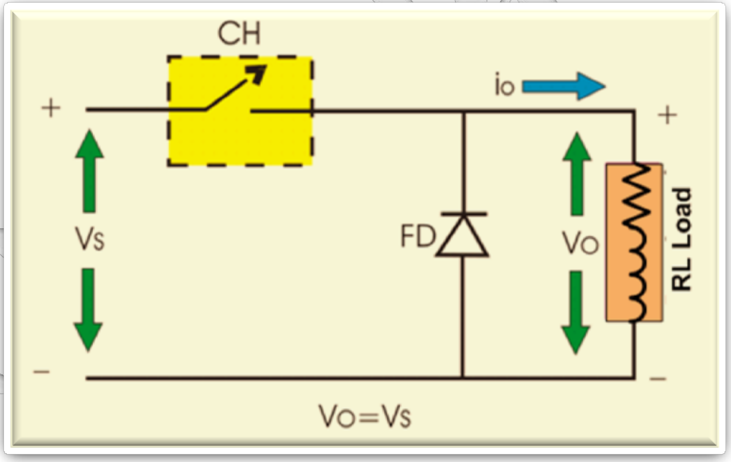
Variable Frequency Control Method



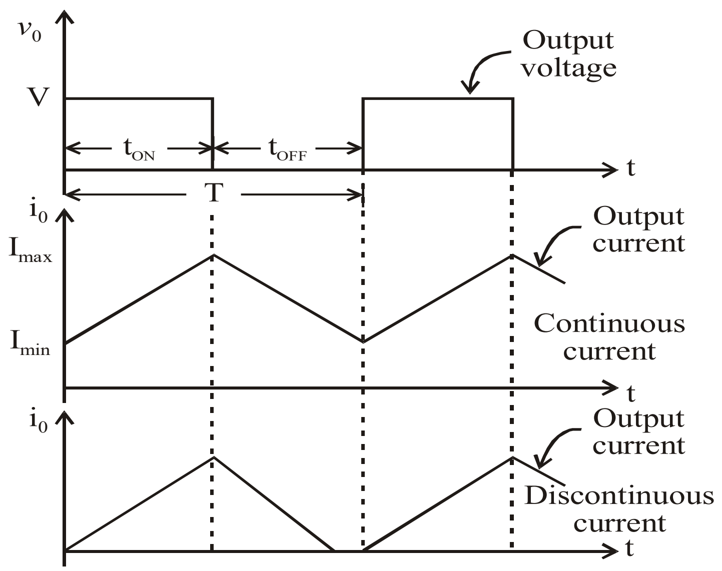
The Buck (Step-Down) Converter

Step Down Chopper with RL Load

- When chopper is ON, supply is connected across load. Current flows from supply to load.
- When chopper is OFF, load current continues to flow in the same direction through FWD due to energy stored in inductor 'L'.



- Load current can be continuous or discontinuous depending on the values of '*L*' and duty cycle '*D*'
- For a continuous current operation, load current varies between two limits I_{max} and I_{min}.
- When current becomes equal to I_{max} the chopper is turned-off and it is turned-on when current reduces to I_{min}.

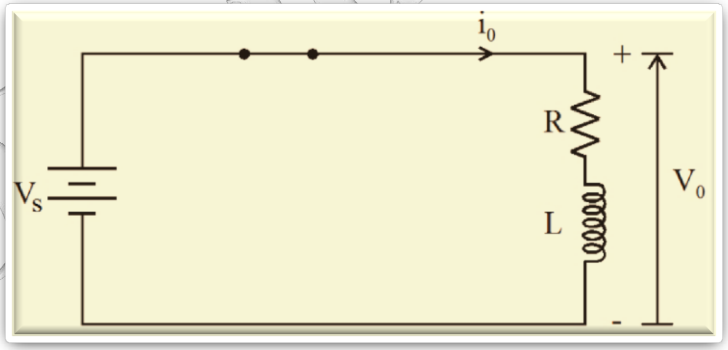


The Buck (Step-Down) Converter

Step Down Chopper with RL Load

Continuous Current Operation When Chopper Is ON ($0 \le t \le t_{ON}$)

- **When the switch is closed in the buck converter, the circuit will be as shown in the figure, the diode is reverse-biased.**



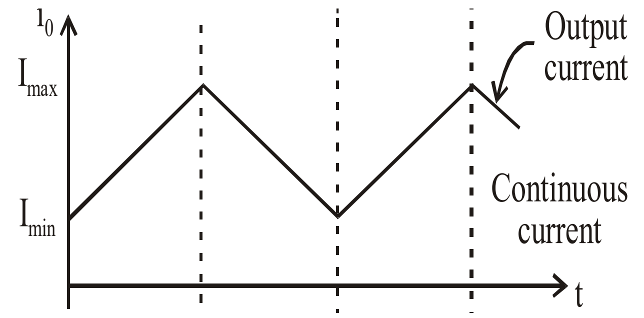
The voltage across the inductor is

$$V_s = V_R + V_L$$

$$V_s = V_R + L\frac{di}{dt} \quad \rightarrow \quad \frac{di}{dt} = \frac{V_s - V_R}{L}$$

$$\Delta i = \int_0^{DT} \frac{V_s - V_R}{L} dt = \frac{V_s - V_R}{L} DT = \frac{V_s - V_R}{L} t_{ON} \qquad (1)$$

$$\frac{di}{dt} = \frac{\Delta i}{t_{ON}} = \frac{I_{max} - I_{min}}{t_{ON}} = \frac{V_s - V_R}{L}$$



From straight line equation

$$i_{o1} = I_{min} + \frac{I_{max} - I_{min}}{t_{ON}} t = I_{min} + \frac{I_{max} - I_{min}}{DT} t = I_{min} + \frac{V_s - V_R}{L} t \qquad (2)$$

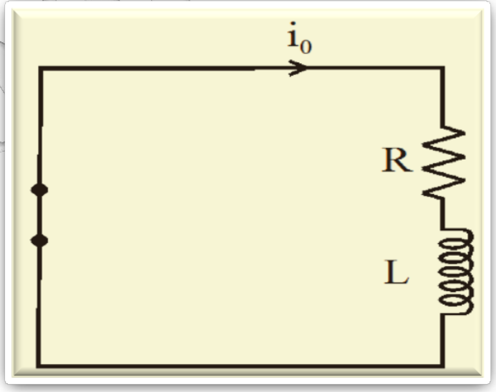
The Buck (Step-Down) Converter

Step Down Chopper with RL Load

Continuous Current Operation When Chopper Is <u>OFF</u> ($t_{ON} \le t \le T$)

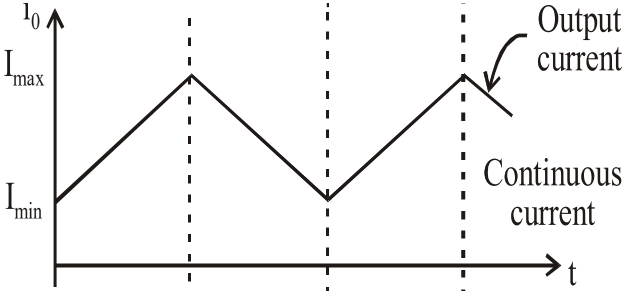
$$0 = V_R + V_L$$

$$0 = V_R + L\frac{di}{dt} \quad \rightarrow \quad \frac{di}{dt} = -\frac{V_R}{L}$$



$$\Delta i = \int_0^{t_{OFF}} -\frac{V_R}{L}\,dt = -\frac{V_R}{L}t_{OFF} \qquad (3)$$

$$\frac{di}{dt} = \frac{\Delta i}{t_{OFF}} = \frac{I_{min} - I_{max}}{t_{OFF}} = -\frac{I_{max} - I_{min}}{t_{OFF}} = -\frac{V_R}{L}$$



From straight line equation

$$i_{o2} = I_{max} + \frac{I_{min} - I_{max}}{t_{OFF}}(t - t_{ON}) = I_{max} - \frac{V_R}{L}(t - t_{ON}) \qquad (4)$$

The Buck (Step-Down) Converter

Step Down Chopper with RL Load

Steady-state operation requires that the inductor current at the end of the switching cycle be the same as that at the beginning, meaning that the net change in inductor current over one period is zero. This requires

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

$$\frac{V_s - V_R}{L} t_{ON} - \frac{V_R}{L} t_{OFF} = 0 \longrightarrow \frac{V_s - V_R}{V_R} = \frac{t_{OFF}}{t_{ON}}$$

$$\frac{V_s}{V_R} - 1 = \frac{t_{OFF}}{t_{ON}} \longrightarrow \frac{V_s}{V_R} = \frac{t_{OFF}}{t_{ON}} + 1$$

$$\frac{V_s}{V_R} = \frac{t_{OFF} + t_{ON}}{t_{ON}} = \frac{T}{t_{ON}} \longrightarrow V_R = DV_s$$

From equation (1)

since $D = \frac{t_{ON}}{T}$

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

$$\boxed{\Delta i = \frac{V_s - DV_s}{L} DT = \frac{V_s(1-D)D}{Lf}}$$

The Buck (Step-Down) Converter

Step Down Chopper with RL Load

At steady state operation, the average inductor current must be the same as the average current in the load resistor.

$$I_L = I_R = \frac{V_R}{R}$$

The maximum and minimum values of the inductor current are computed as

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

$$\boxed{I_{max} = I_L + \frac{V_s(1-D)D}{2Lf} = I_L + \frac{V_R(1-D)}{2Lf}}$$

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

$$\boxed{I_{min} = I_L - \frac{V_s(1-D)D}{2Lf} = I_L - \frac{V_R(1-D)}{2Lf}}$$

The average dc output voltage and current can found as

$$V_{dc} = DV_s$$

$$I_{dc} \cong \frac{I_{max} - I_{min}}{2}$$