Buck Converter Theory

Introduction

A Buck Converter, also known as a step-down converter, is a DC-to-DC power converter that steps down the input voltage to a lower output voltage while stepping up the current. The main components of a buck converter are:

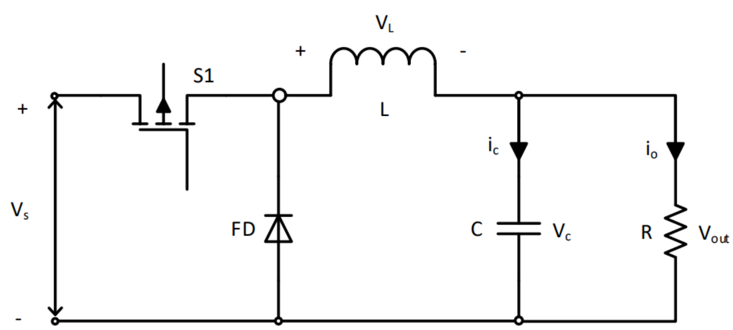
1. **Inductor (L):** Smoothens the current supplied to the load and stores energy during the switch ON state.
2. **Switch (usually a MOSFET):** Controls the flow of current from the input source.
3. **Diode (D):** Provides a path for inductor current when the switch is OFF, ensuring continuous load current.
4. **Capacitor (C):** Reduces voltage ripples and stabilizes the output voltage.

Working Principle

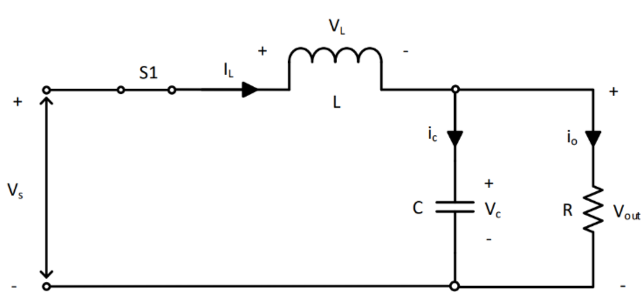
The operation of the buck converter can be divided into two main states:

1. **Switch ON ($0<t<DT$):**
   - ➢ The MOSFET conducts, allowing current to flow from the source through the inductor to the load.
   - ➢ The inductor stores energy, and the capacitor helps stabilize the output voltage.
2. **Switch OFF ($DT<t<T$):**
   - ➢ The MOSFET turns OFF, and the inductor releases its stored energy to the load via the diode.
   - ➢ The capacitor continues to provide current to the load, maintaining a stable output voltage.

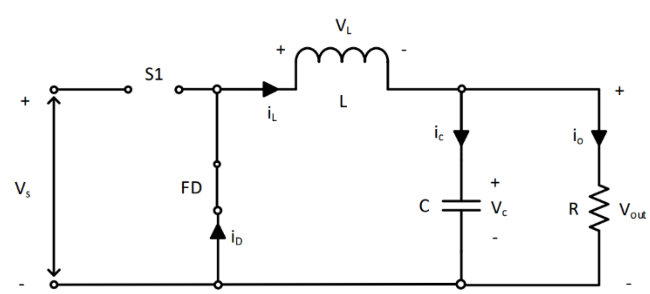
Circuit



Switch ON:



Switch OFF:



By volt-sec balance: $\int V_L.dt\ = 0$

For 0<t<DT,
$V_L = V_s - V_o$

For DT<t<T,
$V_L = -V_o$

So,
$\Rightarrow (V_s - V_o) \times DT + (-V_o) \times (T - DT) = 0$
$\Rightarrow V_s DT = V_o T$
$\therefore V_o = DV_s$
Here, $D \leq 1$, so $V_o < V_s$ always.

By ampere-sec balance: $\int i_c.dt = 0$
For 0<t<DT,
$i_c = i_L - i_o$

For DT<t<T,
$i_c = i_L - i_o$

So,
$\Rightarrow (i_L - i_o) \times DT + (i_L - i_o)(T - DT) = 0$
$\Rightarrow (i_L - i_o)T = 0$
$\therefore i_L = i_o$
Since, $i_o = \frac{V_o}{R} = \frac{DV_s}{R}$, so $i_L = \frac{DV_s}{R}$

Note: This i_L is the average inductor current. So, $i_L = i_L(avg)$.

Some Important Parameter

- Ripple in Inductor Current: $\Delta i_L = \frac{D(1-D)V_s}{fL}$
- RMS Inductor Current: $i_L(rms) = \sqrt{i_L^2 + \left(\frac{\Delta i_L}{2\sqrt{3}}\right)^2}$
- Source Current: $i_s(avg) = Di_o$
- Switch or MosFET Current: $i_{sw}(avg) = Di_L$ and $i_{sw}(rms) = \sqrt{D}i_L(rms)$ and this works only for time 0 to DT.
- Diode Current: $i_D(avg) = (1 - D)i_L$ and $i_D(rms) = \sqrt{(1 - D)}i_L(rms)$ and works only for time DT to T.
- Ripple in Output Voltage: $\Delta V_o = \frac{D(1-D)V_s}{8f^2LC}$
- Critical Inductance: $L_c = \frac{(1-D)R}{2f}$
- Critical Capacitance: $C_c = \frac{1}{8fR}$

Efficiency and Losses

Buck converter efficiency (η) is the ratio of output power (P_{out}) to input power (Pin) :

$$\eta = \frac{\mathrm{P_{out}}}{P_{in}}$$

Losses in a buck converter can be minimized through proper design and component selection. Key types of losses include:

- **Conduction Losses:** Caused by resistance in the inductor, switch (MOSFET), and diode. Choosing components with low resistance reduces these losses.
- **Switching Losses:** Occur during MOSFET state transitions between ON and OFF. Optimizing switching frequency and using MOSFETs with low on-state resistance helps minimize these.
- **Diode Forward Voltage Drop Losses:** When the diode conducts during the switch OFF state, its forward voltage drop leads to power loss. Using Schottky diodes with lower forward voltage reduces these losses.
- **Magnetic Core Losses:** Energy dissipates as heat in the inductor's core due to the alternating magnetic field. Selecting suitable core materials and optimizing design helps reduce these.
- **Capacitor Losses:** Result from the Equivalent Series Resistance (ESR) of the output capacitor. Low-ESR capacitors reduce these losses and enhance efficiency.

Applications

Buck converters are widely used in applications where stepping down the voltage is required:

- **Power Supplies:** Provide stable lower output voltages for devices like smartphones, laptops, and microcontrollers.
- **Battery Management Systems:** Regulate voltage levels to safely charge batteries or power circuits.
- **LED Drivers:** Maintain consistent LED illumination in lighting systems by stepping down voltage while regulating current.
- **Automotive Systems:** Step down battery voltage for components like infotainment systems, sensors, and lighting.
- **Telecommunications:** Power low-voltage circuits in RF transmitters, base stations, and communication systems.
- **Renewable Energy Systems:** Step down solar or wind-generated voltage to match the required levels for storage or load.