Buck-Boost Converter Theory

Introduction

A **Buck-Boost Converter** is a type of DC-to-DC power converter that can either step up or step down the input voltage to the desired output voltage. It is a versatile converter that provides a stable output voltage even when the input voltage is lower or higher than the output voltage. The main components of a buck-boost converter are:

1. **Inductor (L)**: Stores energy during the switch ON state and releases it during the OFF state to regulate the output.
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 current flow to the load.
4. **Capacitor (C)**: Smoothens the output voltage and reduces voltage ripples.

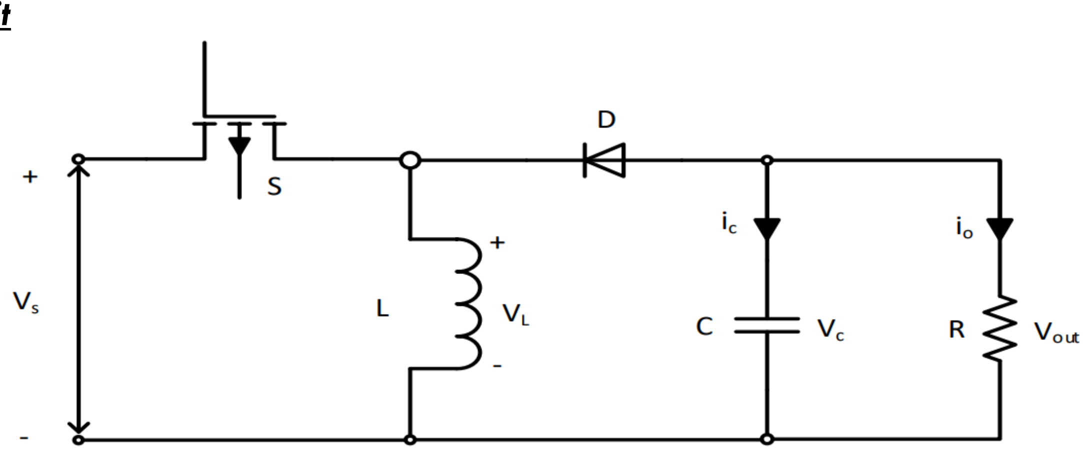
Working Principle

The operation of a buck-boost converter can be divided into two main states, with both stepping up and stepping down the voltage:

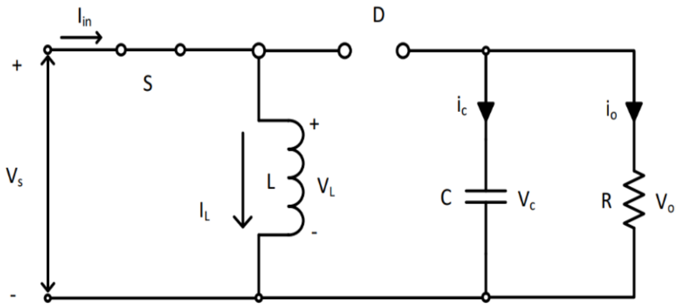
1. **Switch ON (0 < t < DT)**:
    - The MOSFET is turned ON, and current flows from the input source through the inductor to the load.
    - The inductor stores energy during this phase, and the capacitor helps smooth the output voltage.
2. **Switch OFF (DT < t < T)**:
    - The MOSFET turns OFF, and the inductor releases its stored energy to the load via the diode.
    - The capacitor continues to maintain the output voltage, supplying current to the load.

During both phases, the buck-boost converter can either increase or decrease the voltage depending on the duty cycle (D) of the switch.

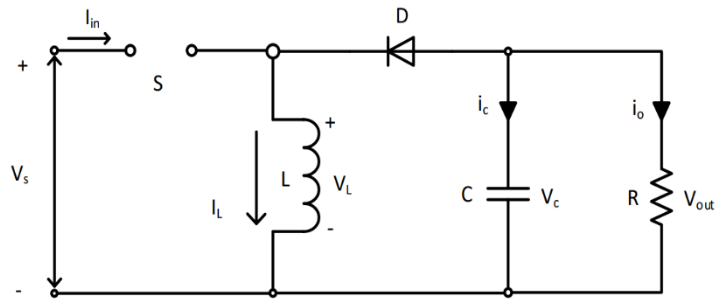
Circuit



Switch ON:



Switch OFF:



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

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

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

So,
$\Rightarrow V_s \times DT + (-V_o) \times (T - DT) = 0$
$\Rightarrow V_s DT = V_o (1 - D) T$
$\therefore V_o = \dfrac{D}{1 - D} V_s$
Here, for $0 < D < 0.5$; $V_o < V_s$ acts as buck and for $0.5 < D < 1$; $V_o > V_s$ acts as boost.

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

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

So,
$\Rightarrow (-i_o) \times DT + (i_L - i_o)(T - DT) = 0$
$\Rightarrow i_L (1 - D) T = i_o T$
$\therefore i_L = \dfrac{i_o}{1 - D}$

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

Some Important Parameter

- Ripple in Inductor Current: $\Delta i_L = \frac{DV_s}{fL}$
- RMS Inductor Current: $i_L(rms) = \sqrt{i_L^2 + \left(\frac{\Delta i_L}{2\sqrt{3}}\right)^2}$
- 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.
- Source Current: $i_s = i_{sw}$, so $i_s(avg) = Di_L$ and $i_s(rms) = \sqrt{D}i_L(rms)$
- Ripple in Output Voltage: $\Delta V_o = \frac{Di_o}{fc}$
- Critical Inductance: $L_c = \frac{(1-D)^2R}{2f}$
- Critical Capacitance: $C_c = \frac{D}{2fR}$

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-boost converter can occur due to various factors, similar to a buck converter. Key types of losses include:

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

Applications

Buck-boost converters are used in applications where the input voltage is unpredictable, and the output voltage needs to be regulated. Some common applications include:

- **Power Supplies**: Used to provide a stable output voltage in systems where the input voltage may be higher or lower than the required output voltage, such as power supplies for embedded systems, portable devices, and microcontrollers.

- **Battery Management Systems**: Regulate voltage to ensure safe charging or discharging of batteries, especially when the battery voltage may vary above or below the required voltage.
- **LED Drivers**: Used to drive LEDs in lighting systems where the input voltage can vary significantly, ensuring stable LED operation at the desired current and voltage.
- **Automotive Systems**: In vehicles, buck-boost converters can step up or step down the battery voltage to power different components such as sensors, lights, or infotainment systems.
- **Telecommunications**: Used in telecom equipment, such as RF transmitters and base stations, where the input voltage can fluctuate, but a stable output voltage is required to ensure proper operation.
- **Renewable Energy Systems**: In solar and wind power systems, buck-boost converters are used to step up or step down the generated voltage to match the voltage level required for storage or load applications.