# DC-DC Converter
# -Buck-boost converter-

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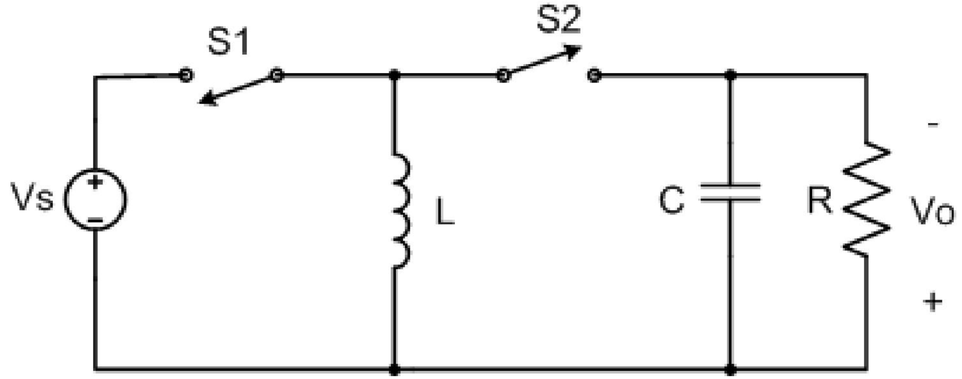
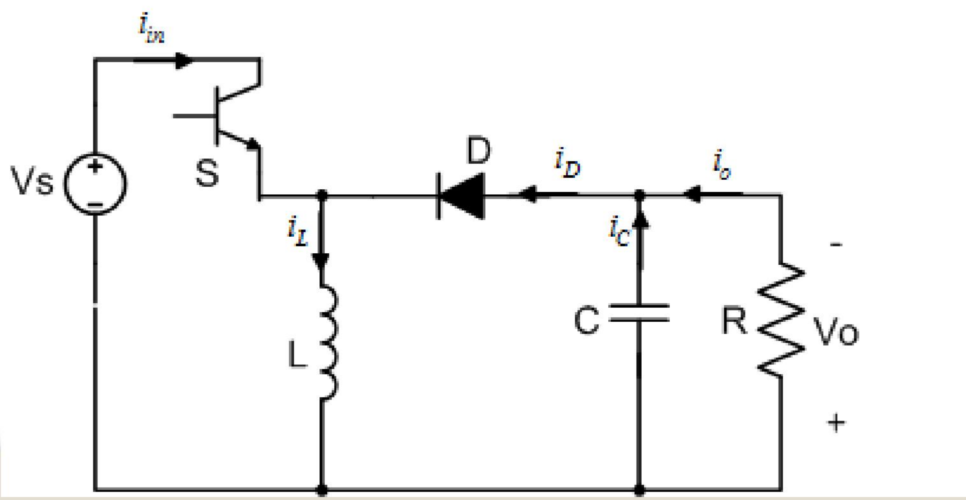
# Buck-boost converter

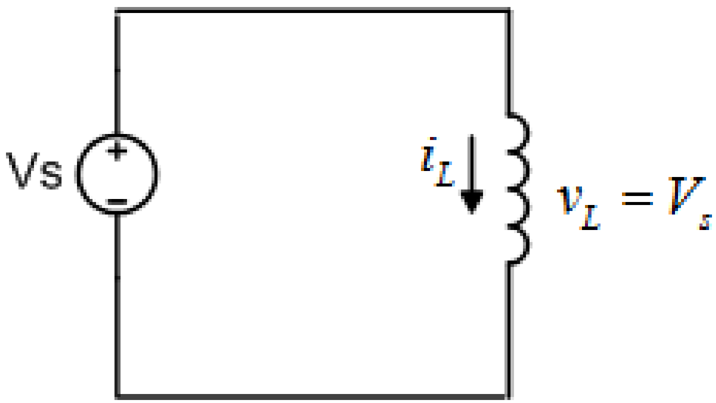
- The output voltage can be either higher or lower than the input voltage.
- The output voltage polarity is opposite of the input voltage, also known as an inverting regulator.
- In steady-state analysis, following assumptions are made:

- Inductor current is always continuous. - Average inductor voltage is zero.
- Average capacitor current is zero. - All components are ideal.



When switch is closed in ccm:



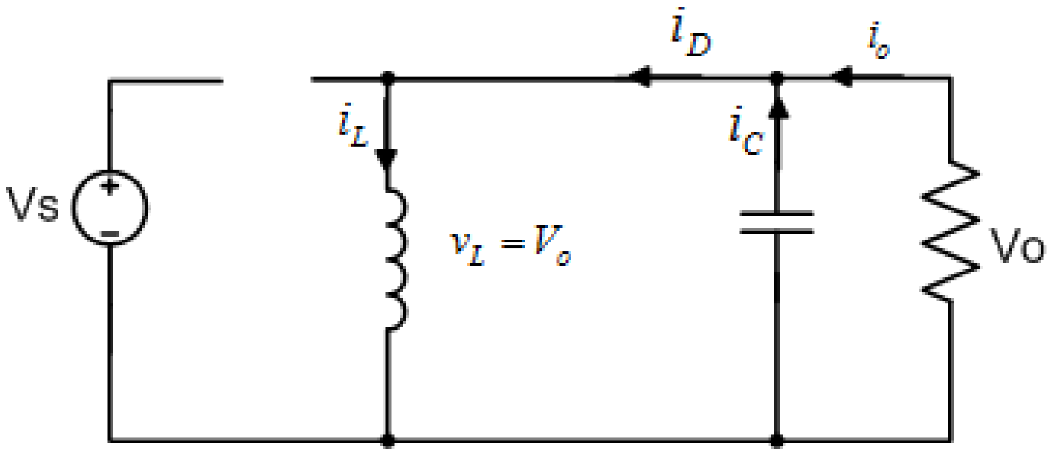

$$v_L = V_s = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s}{L}$$

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{DT}$$

$$\Delta i_{L(closed)} = \frac{V_s DT}{L}$$

When switch is opened in ccm:




$$v_L = V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_o}{L}$$

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

$$\Delta i_{L(open)} = \frac{V_o(1-D)T}{L}$$

For steady-state operation, the net change in inductor current must be zero over one period.

$$\Delta i_{L(closed)} + \Delta i_{L(open)} = 0$$

$$\frac{V_s DT}{L} + \frac{V_o(1-D)T}{L} = 0$$

$$Solve\ \ for\, V_o,$$

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

The required duty ratio can be expressed as:

$$D = \frac{|V_o|}{V_s + |V_o|}$$

The output voltage has opposite polarity from the source voltage. Output voltage magnitude of buck-boost converter can be less than the source or greater than the source, depending on the duty ratio of the switch.

• When the duty ratio is:
D > 0.5 = boost
D < 0.5 = buck
D = unity gain = 1

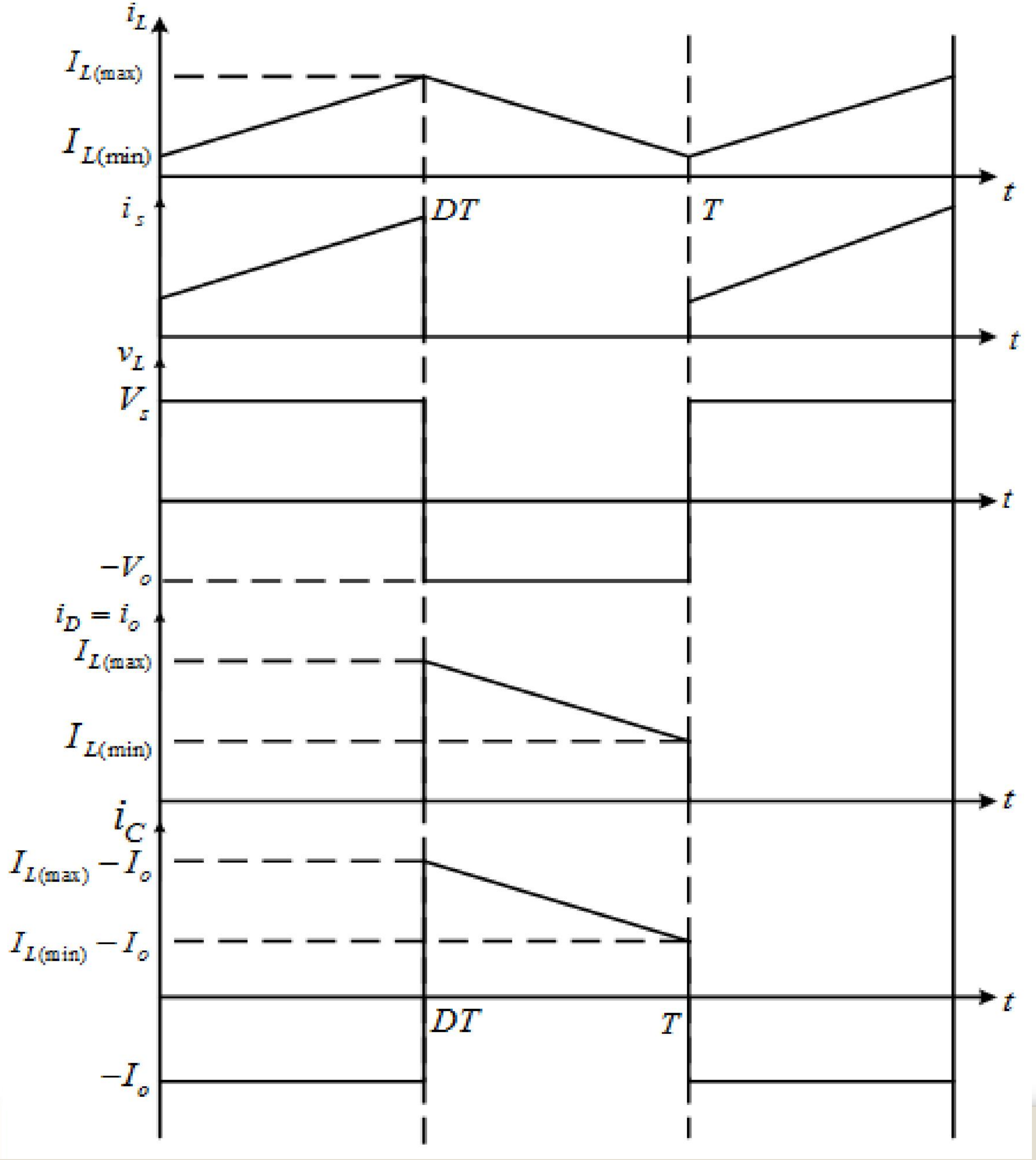
• This converter combine the capabilities of buck and boost converter.

• Noted that the source is never connected directly to the load. Energy is stored in the inductor when the switch is on and transferred to the load when the switch is off.

• Buck-boost converter is also called as indirect converter.

• Power absorbed by the load is the same as power supplied by the source (Pin=Pout).

# Voltage and current waveforms



Analysis for determining average inductor current, $i_L$

$$P_o = \frac{V_o^2}{R}$$

$$P_s = V_s I_s$$

$$\frac{V_o^2}{R} = V_s I_s$$

Average source current is related to average inductor current by:

$$I_s = I_L D$$

$$\frac{V_o^2}{R} = V_s I_L D$$

*Substitute for $V_o$ equation and solve $I_L$,*

$$I_L = \frac{V_o^2}{V_s R D} = \frac{P_o}{V_s D} = \frac{V_s D}{R(1-D)^2}$$

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} + \frac{V_s D T}{2L}$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} - \frac{V_s D T}{2L}$$

For continuous current, the inductor current must remain positive. To determine the boundary between continuous and discontinuous mode, $I_{L(min)}$ equation is set to zero.

$$L_{\min} = \frac{RT(1-D)^2}{2}$$

**Noted that for the same frequency and load resistance, the buck converter has the highest minimum value of inductor when compared to boost and buck-boost. Boost converter has the smallest $L_{min}$ which results in wider range of inductor design.**

The output voltage ripple for buck-boost converter is:

$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf}$$

# The effect of parasitic elements in dc-dc converter

The parasitic elements in a dc-dc converter are due to the losses associated with the inductor, capacitor, switch and diode.
The non-ideal characteristic of parasitic elements are:

- Series resistance of capacitor ($r_C$)
- Series resistance of inductor ($r_L$)
- Transistor and diode voltage drops ($V_Q$, $V_D$)
- Switching and conduction losses ($r_{sw}$)

## Series resistance of capacitor ($r_C$)

Buck converter

- A practical capacitor cam be modeled as a capacitance with an equivalent series resistance (ESR) and an equivalent series inductance (ESL).
- ESR may have a significant effect on the output voltage ripple while ESL often omitted due to its small effect.

$$\Delta V_{o,ESR} = \Delta i_C r_C = \Delta i_L r_C$$ → The voltage variation across the capacitor resistance

$$\Delta V_o < \Delta V_{o,C} + \Delta V_{o,ESR}$$ → Worst-case condition

$$\Delta V_o \approx \Delta V_{o,ESR} = \Delta i_C r_C$$ → When ripple voltage due to ESR much larger than ripple due capacitance.

Note that capacitor ESR is inversely proportional to the capacitance value – a larger capacitance results in a lower ESR.

<u>Boost converter and buck-boost converter</u>

- Similar to buck converter, ESR of the capacitor can contribute significantly to the output voltage ripple.
- The peak-to-peak variation in capacitor current is the same as the maximum current in the inductor.
- The voltage ripple due to ESR is:

$$\Delta V_{o,ESR} = \Delta i_C r_C = I_{L,\max} r_C$$

## Limitation of single-stage conversion

- Buck, boost and buck-boost regulators use only one transistor (switch), thus employing only one stage conversion, and they require inductors or capacitors for energy transfer.
- Due to current handling limitation of a single transistor, the output power of these regulators is small.
- At a higher current, the size of these components increases, with increased component losses, and the efficiency decreases.
- Furthermore, there is no isolation between the input and output voltage, which is a highly desirable criteria in most application.
- For high-power applications, multistage conversions are used, where a dc voltage is converted to ac by an inverter. The ac output is isolated by a transformer and then converted to dc by rectifiers.

# Conclusion

| Parameter | Buck | Boost | Buck-boost |
|---|---|---|---|
| $V_o$ | $V_s D$ | $\dfrac{V_s}{1-D}$ | $-V_s = \left(\dfrac{D}{1-D}\right)$ |
| $I_L$ | $\dfrac{V_o}{R}$ | $\dfrac{V_s}{(1-D)^2 R}$ | $\dfrac{V_s D}{(1-D)^2 R}$ |
| $L_{\min}$ | $\dfrac{(1-D)RT}{2}$ | $\dfrac{RT(1-D)^2 D}{2}$ | $\dfrac{RT(1-D)^2}{2}$ |
| $\dfrac{\Delta V_o}{V_o}$ | $\dfrac{1-D}{8LCf^2}$ | $\dfrac{D}{RCf}$ | $\dfrac{D}{RCf}$ |

## Conclusion

- DC-DC converters are capable of transferring energy only in one direction. This is due to their capabilities of producing only unidirectional voltage and unidirectional current.
- A switched-mode dc-dc converter is much more efficient than a linear converter because of reduced losses in the electronic switch.
- Discontinuous-current modes for dc-dc converters are possible and sometimes desirable, but input-output relationships are different from those for the continuous-current modes.
- Output voltage is generally reduced from the theoretical value when switch losses and inductor resistances are included in the analysis.
- A buck converter has an output less than the input. Boost converter has an output greater than the input while buck-boost can has either greater or lower output than the input.