EE 238

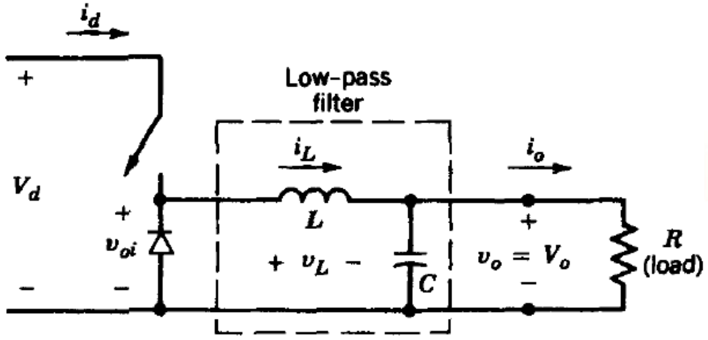
Power Engineering – II

Power Electronics

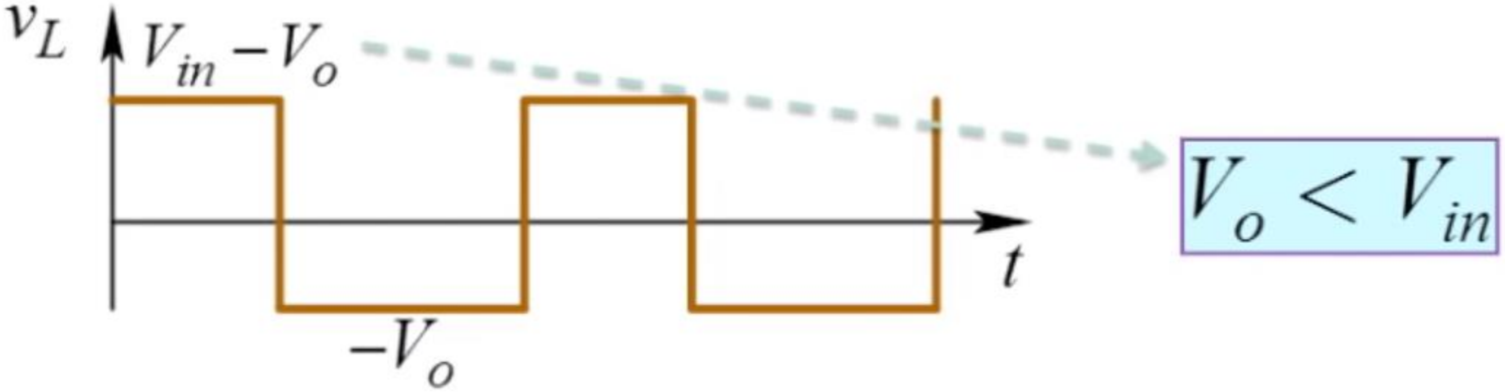
Lecture 13

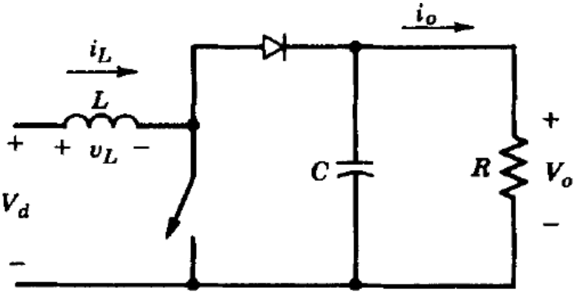
Instructor: Prof. Anshuman Shukla
Email: ashukla@ee.iitb.ac.in

Comparison of v_L in Buck, Boost and Buck-Boost

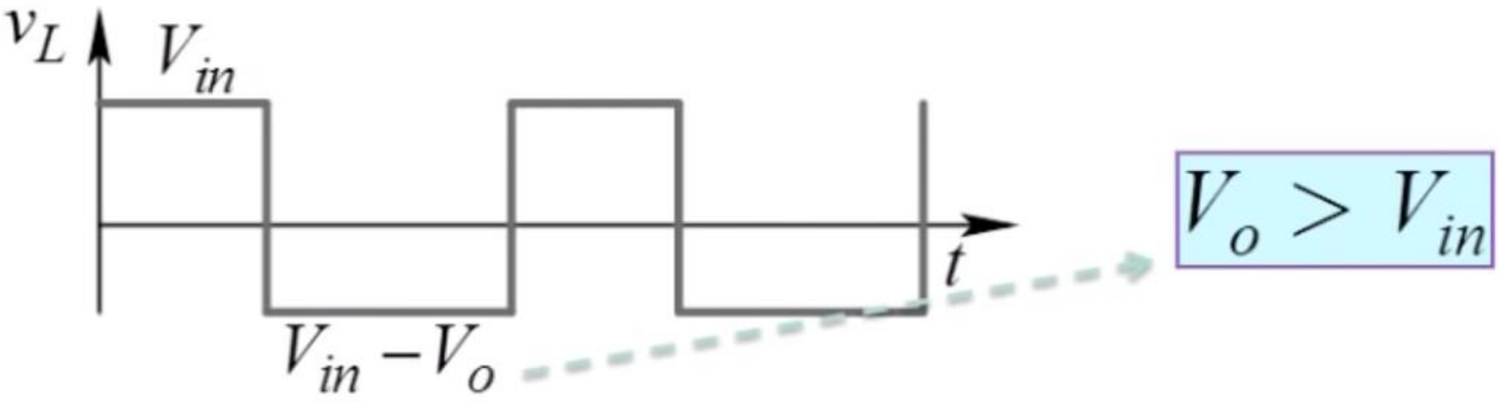


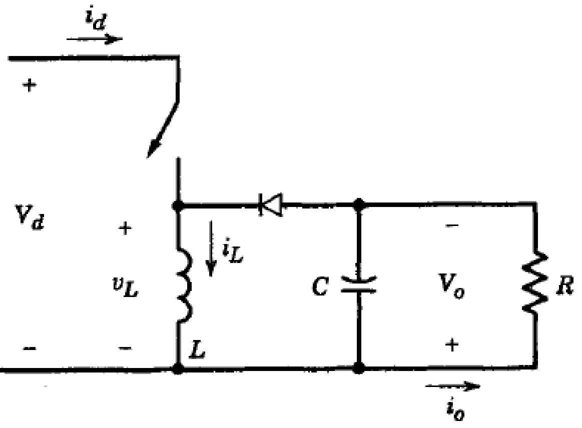
Buck



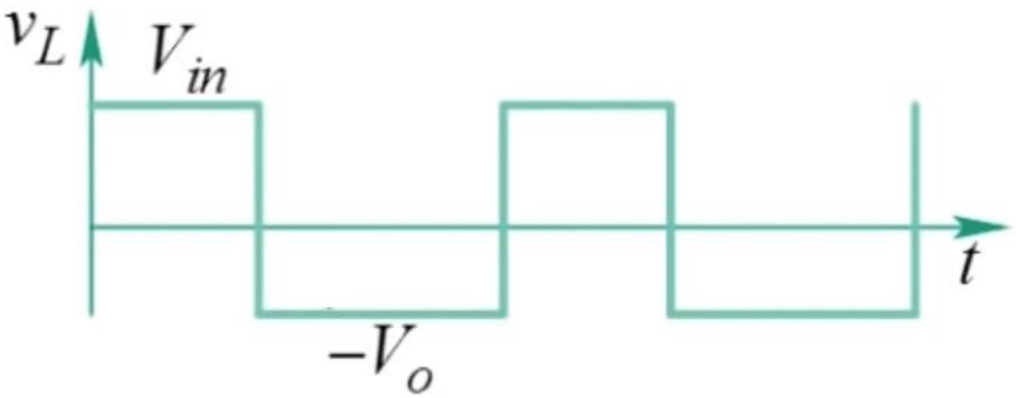


Boost



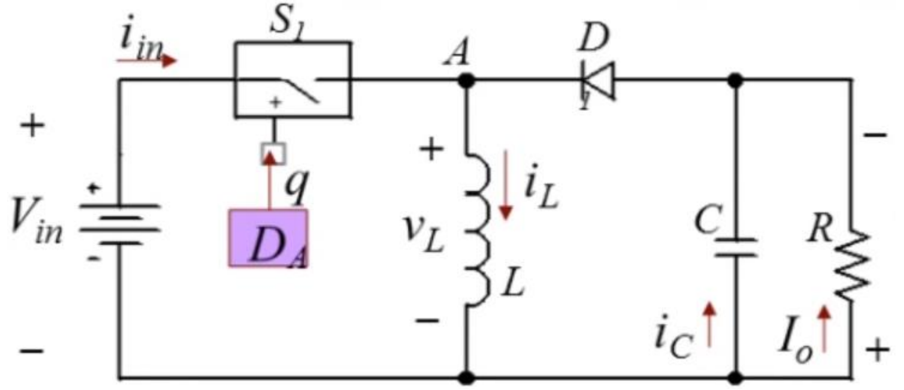


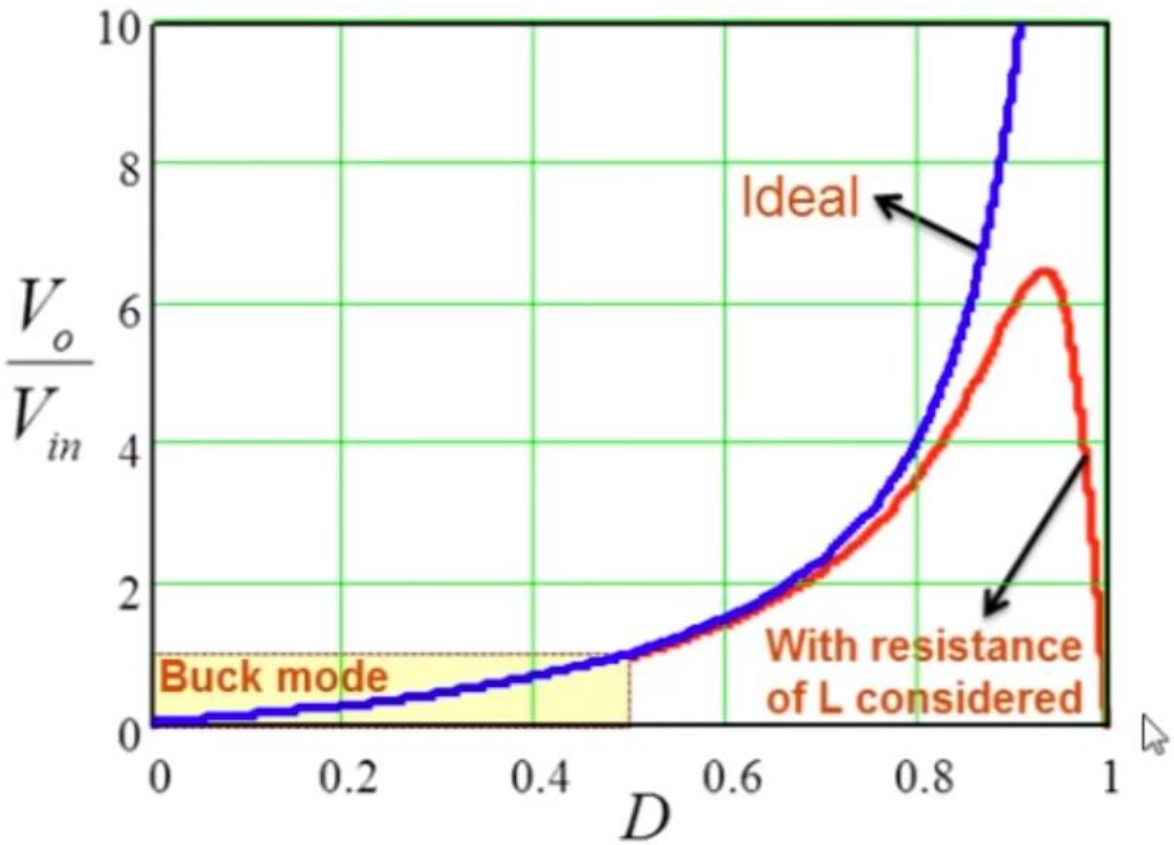
Buck-boost



Step-up and Step-down

Effect of non-idealities



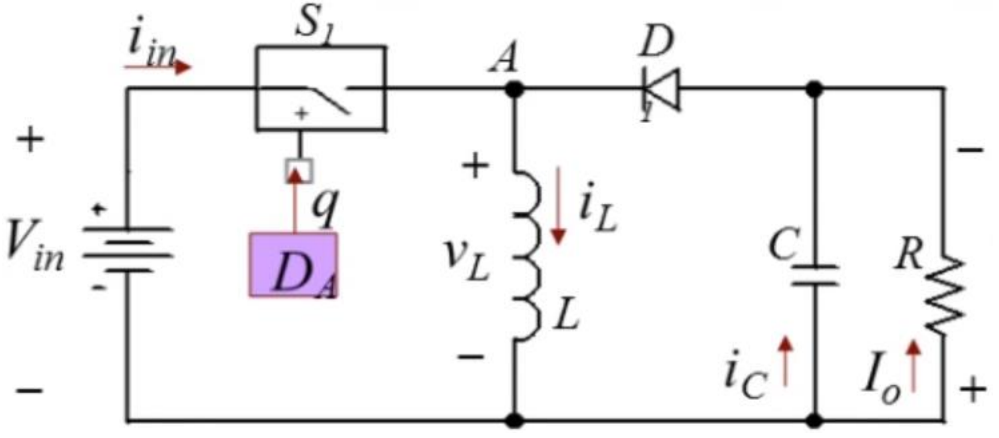


$$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

Ideal input-output relationship

- Resistances of inductor and MOSFET, and voltage drop across diode affect voltage conversion ratio
- Effect is dominant at high D
- Difficult to achieve large conversion ratios (> 10)
- No power transfer at D = 1

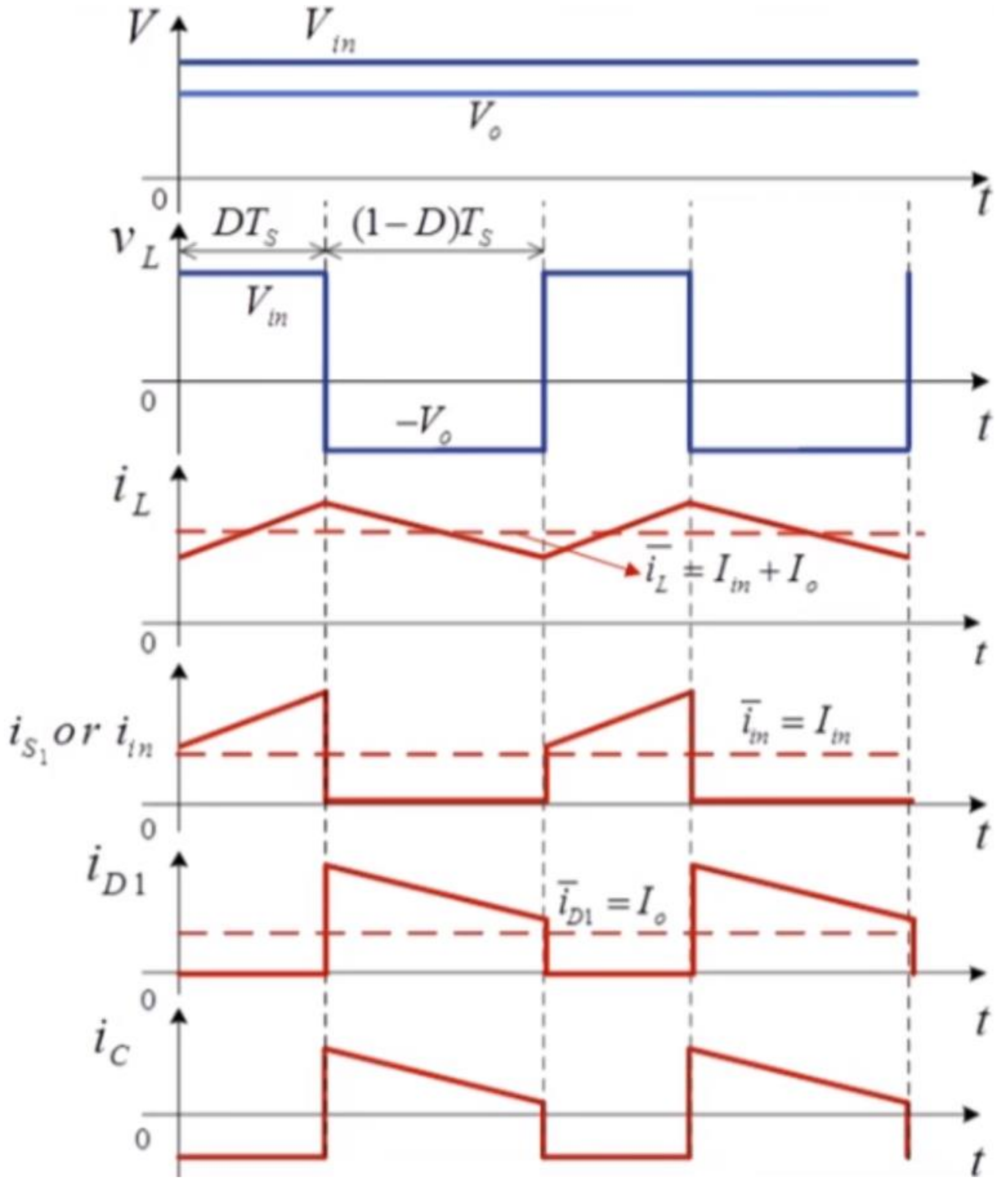
Buck-Boost Waveforms and Relationships



$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \Rightarrow D = \frac{V_o}{V_o + V_{in}}$$

For constant output voltage and variable input voltage applications

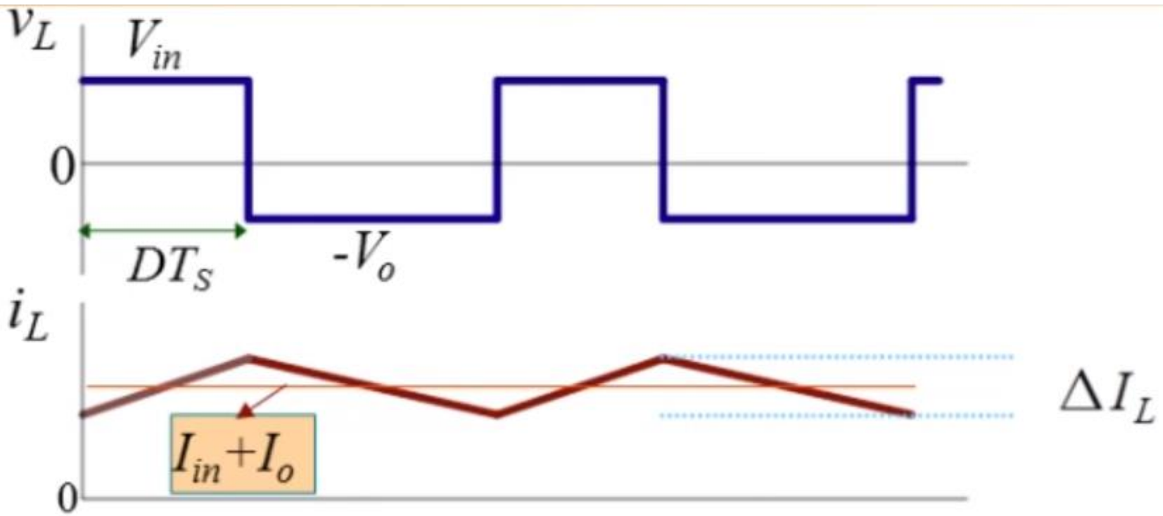
$$\frac{V_o}{V_o + V_{in,max}} \leq D \leq \frac{V_o}{V_o + V_{in,min}}$$



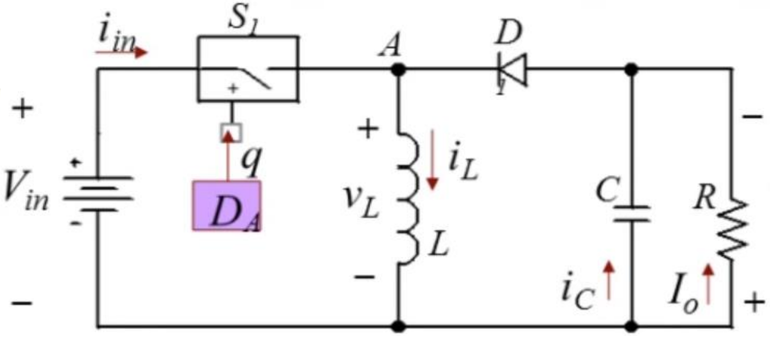
Selection of L

For constant output voltage and variable input voltage applications

$$\frac{V_o}{V_o + V_{in,max}} \le D \le \frac{V_o}{V_o + V_{in,min}}$$



Peak-peak ripple in inductor current



- L selected to limit peak-peak inductor current ripple to a chosen value
  - For example, 10-20% of max (I_{in} + I_o)
  - CCM considerations
- Worst-case condition is minimum D
- Choice of L does not significantly affect capacitor selection

Consider the T_{OFF} interval

$$L\frac{\Delta I_L}{(1-D)T_S} = V_o$$

$$L = \frac{V_o(1-D)T_S}{\Delta I_L}$$

Buck-boost analysis

CCM Considerations

Average inductor current

Assuming no power loss in the converter, power absorbed by the load must equal power supplied the by source, i.e.

$$P_o = P_s$$

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

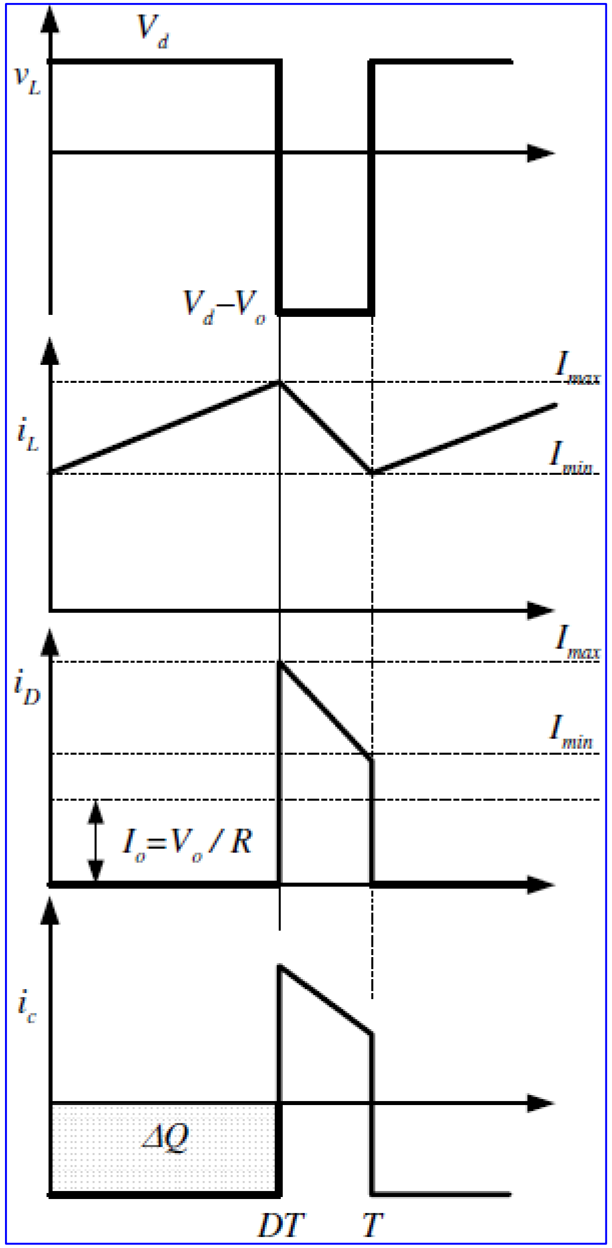
But average source current is related to average inductor current as :

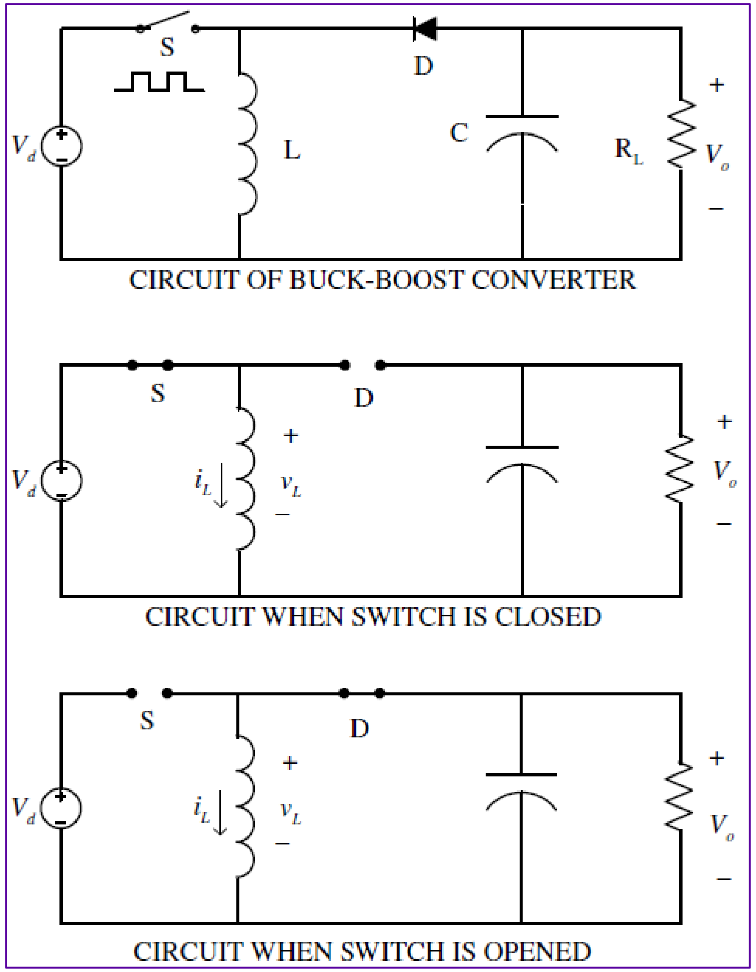
$$I_s = I_L D$$

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

Substituting for V_o,

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





Buck-boost analysis

Max and min inductor current,

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

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

For CCM

$$\frac{\mathrm{V_d} D}{R(1-D)^2} + \frac{V_d DT}{2L} = 0$$

$$\Rightarrow L_{\min} = \frac{(1-D)^2 R}{2f}$$

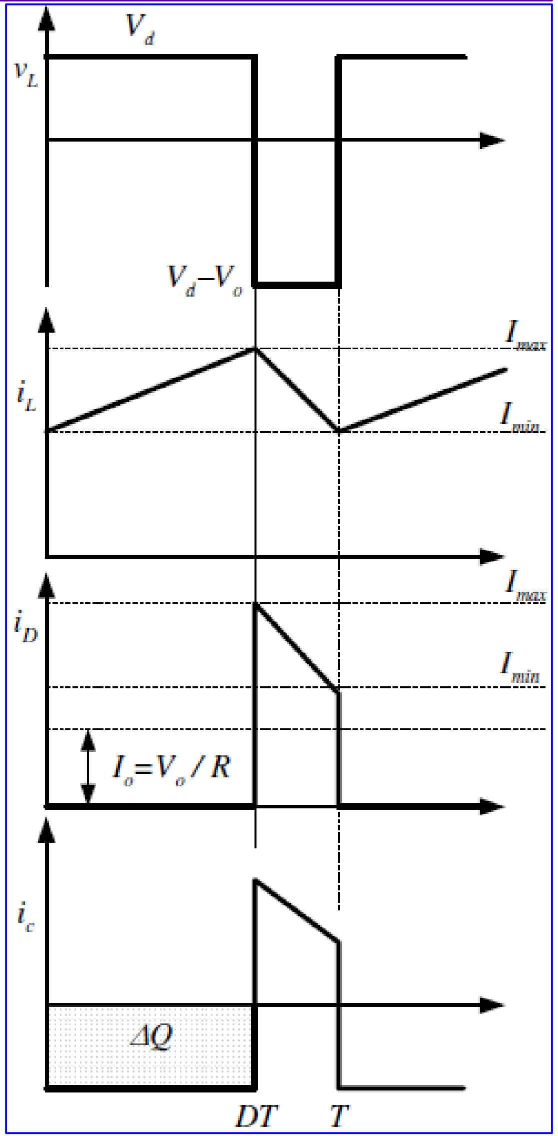
For constant output voltage and variable input voltage applications

$$\frac{V_o}{V_o + V_{in,max}} \le D \le \frac{V_o}{V_o + V_{in,min}}$$

L and C values

Substituting for V_o,

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



Buck-boost analysis

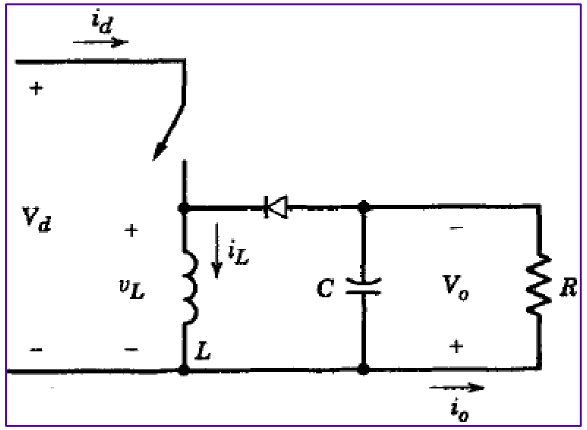
Boundary between Cont. and Discont. Conduction

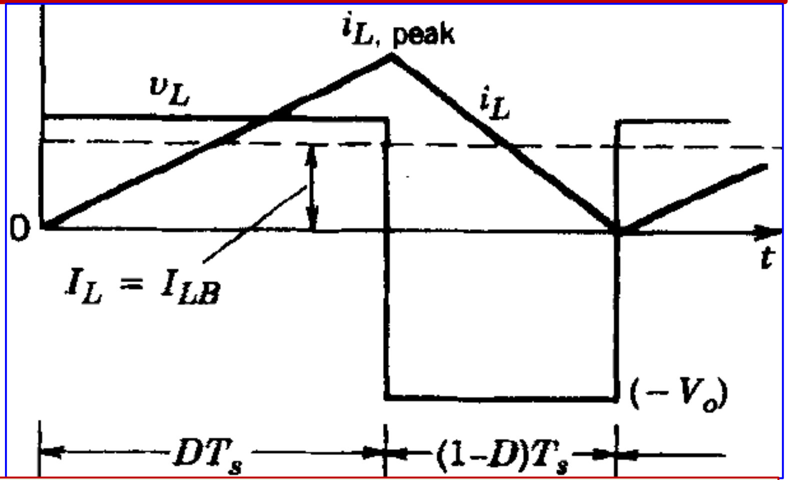
$$I_{LB} = \frac{1}{2} i_{L,\text{peak}} = \frac{T_s V_d}{2L} D$$

$$I_o = I_L - I_d$$

Since the average capacitor current is zero.

$$\frac{V_o}{V_d} = \frac{D}{1-D} \qquad \frac{I_o}{I_d} = \frac{1-D}{D}$$





The average inductor current and the output current at the border of the continuous conduction in terms of V_0, $I_{LB} = \frac{T_s V_o}{2L}(1-D)$ and $I_{oB} = \frac{T_s V_o}{2L}(1-D)^2$

Most applications in which a buck-boost converter may be used require that V_0 be kept constant, though V_d (and, hence, *D*) may vary.

Both I_{LB} and I_{0B} result in their maximum values at *D* = 0.

$$I_{LB,\max} = \frac{T_s V_o}{2L} \quad \text{and} \quad I_{oB,\max} = \frac{T_s V_o}{2L}$$

$$I_{LB} = I_{LB,\max}(1-D) \qquad I_{oB} = I_{oB,\max}(1-D)^2$$

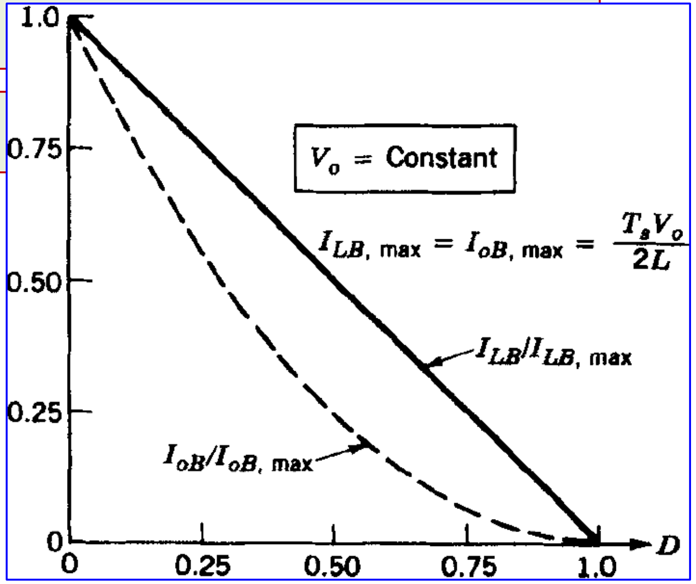
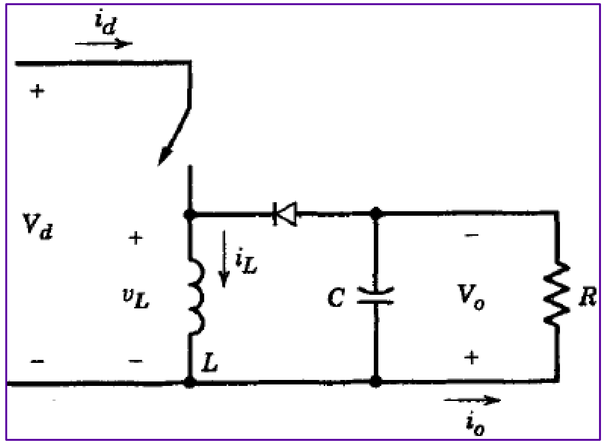


Figure shows *ILB* and *IoB* as a function of *D*, keeping *V0* = const.

Buck-boost analysis

DISCONTINUOUS-CONDUCTION MODE

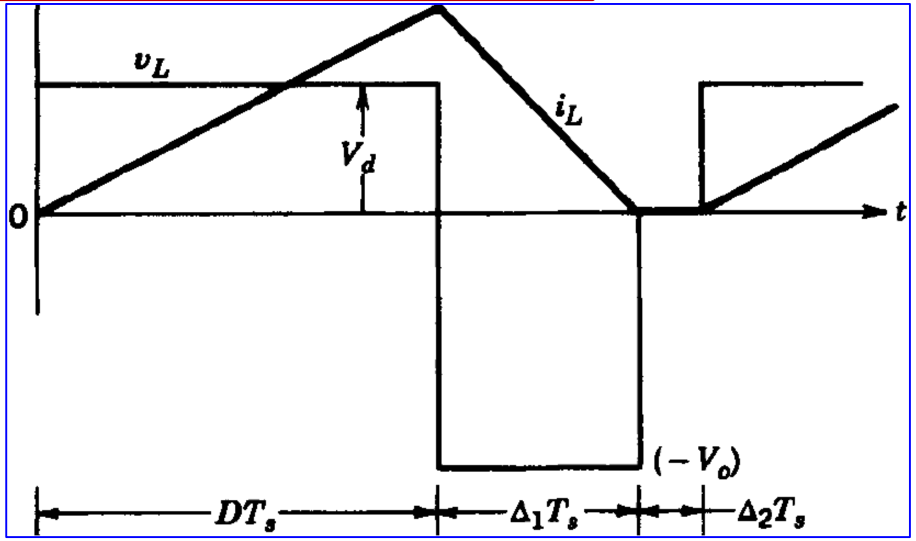


If we equate the integral of the inductor voltage over one time period to zero,

$$V_d D T_s + (-V_o)\Delta_1 T_s = 0 \qquad \therefore \frac{V_o}{V_d} = \frac{D}{\Delta_1}$$

and $$\frac{I_o}{I_d} = \frac{\Delta_1}{D} \quad (\text{since } P_d = P_o)$$

From Fig. $$I_L = \frac{V_d}{2L} D T_s (D + \Delta_1)$$

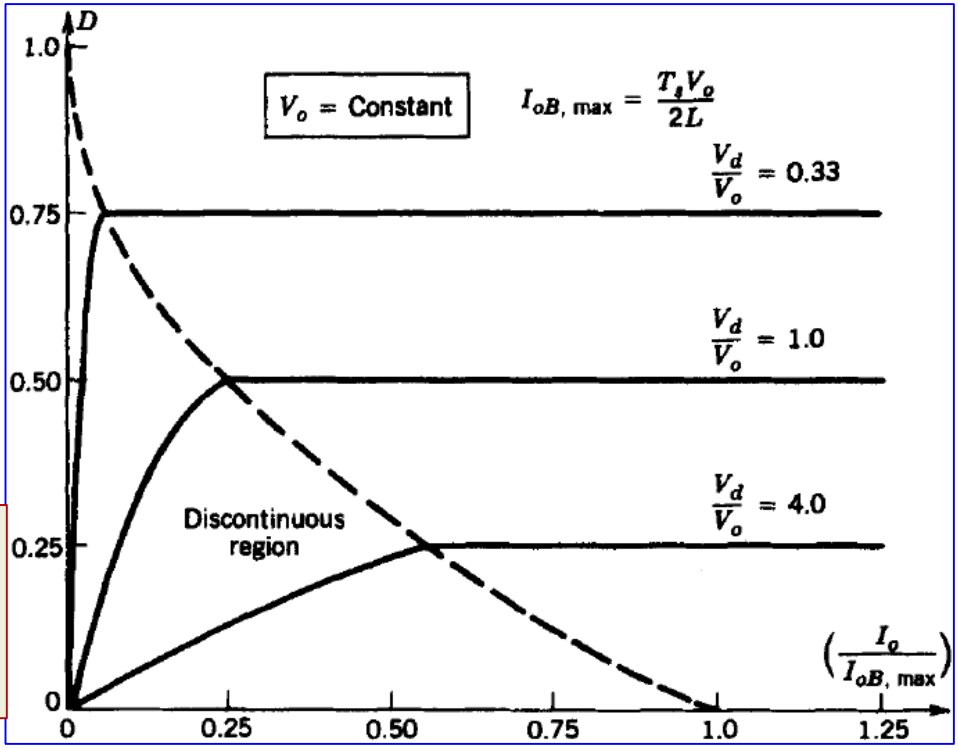


Since V_0 is kept constant, it is useful to obtain *D* as a function of the output load current I_0 for various values of V_0/V_d.

Using the equations derived earlier, we find that

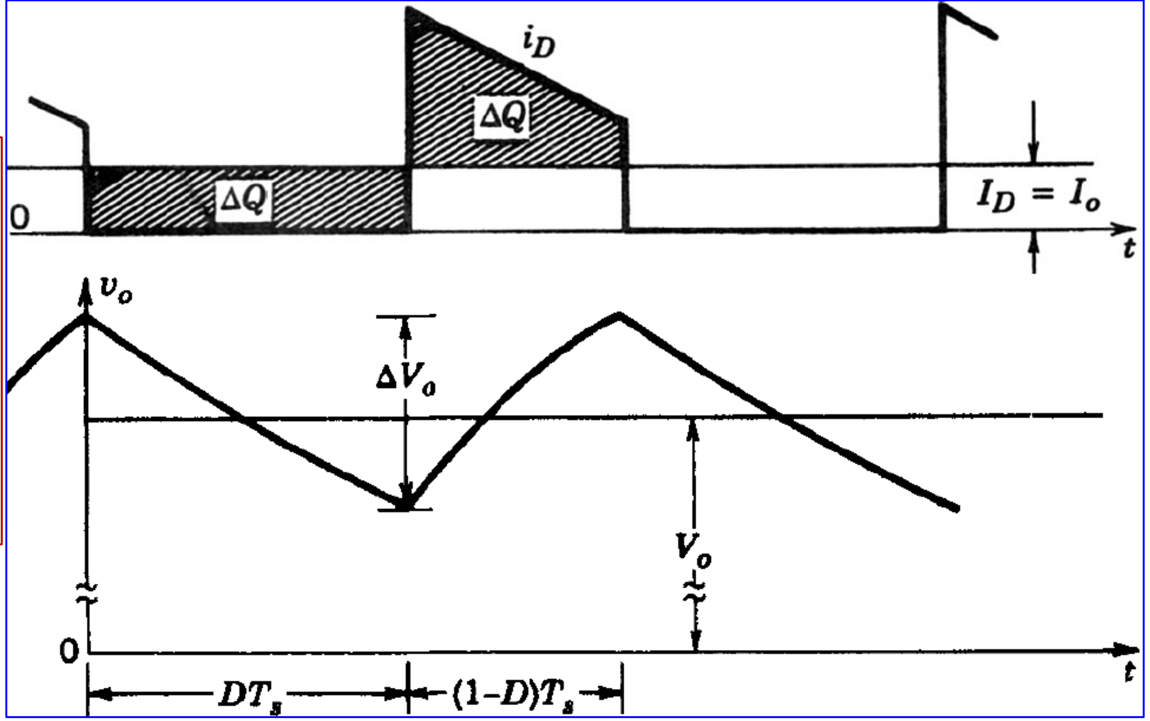
$$D = \frac{V_o}{V_d}\sqrt{\frac{I_o}{I_{oB,\max}}} \qquad I_o = I_L - I_d$$

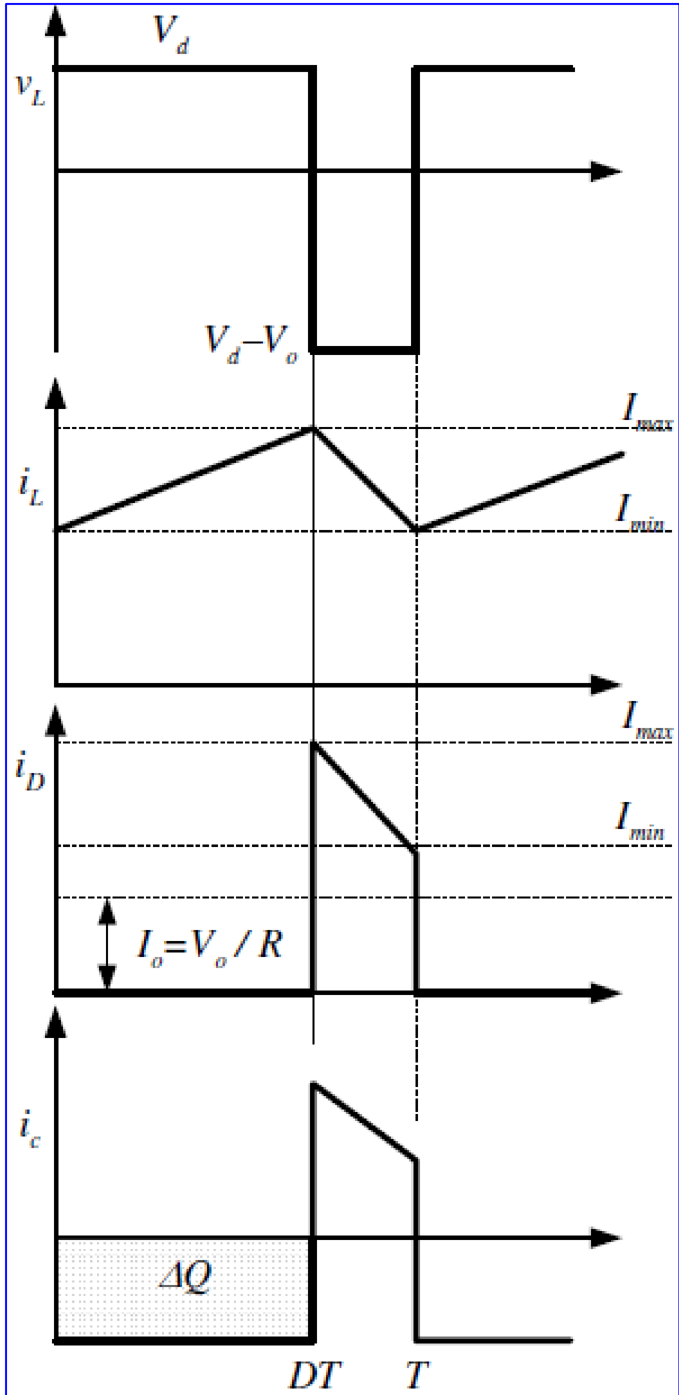
Figure shows the plot of *D* as a function of $I_0/I_{0B,max}$ for various values of *Vd/V0.* The boundary between the continuous and the discontinuous mode is shown by the dashed curve.



OUTPUT VOLTAGE RIPPLE

Assuming that all the ripple current component of i_D flows through the capacitor and its average value flows through the load resistor, the shaded area represents charge ΔQ.

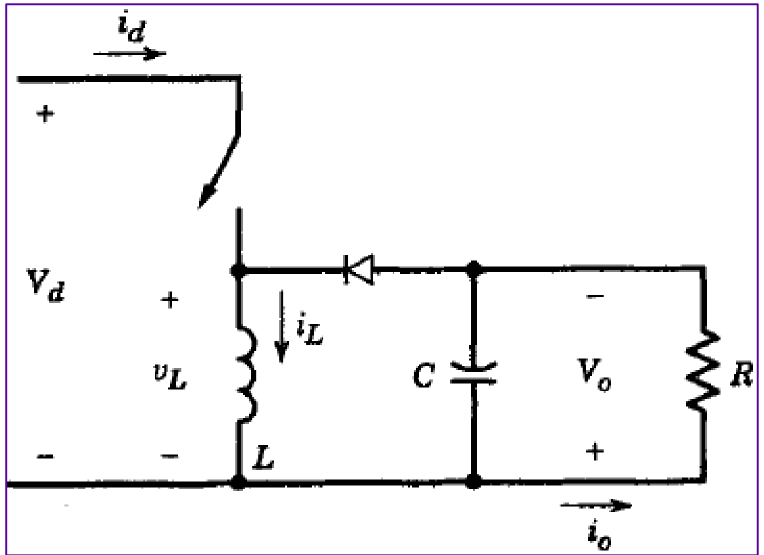




Therefore,

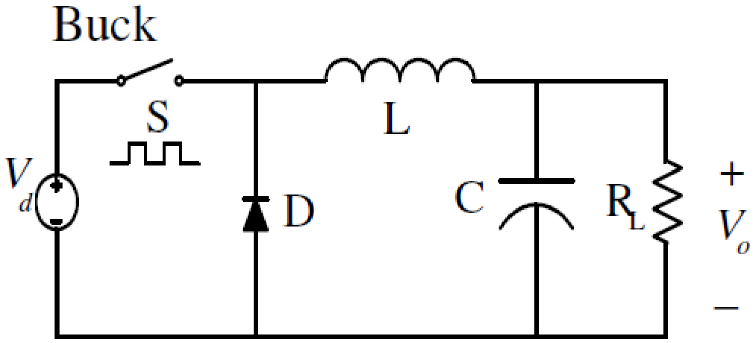
$$\Delta V_o = \frac{\Delta Q}{C} = \frac{I_o D T_s}{C} \quad \text{(assuming a constant output current)} = \frac{V_o}{R}\frac{DT_s}{C}$$

$$\frac{\Delta V_o}{V_o} = \frac{DT_s}{RC} = D\,\frac{T_s}{\tau}$$ where $\tau = RC$ time constant.



A similar analysis can be performed for the discontinuous mode of operation.

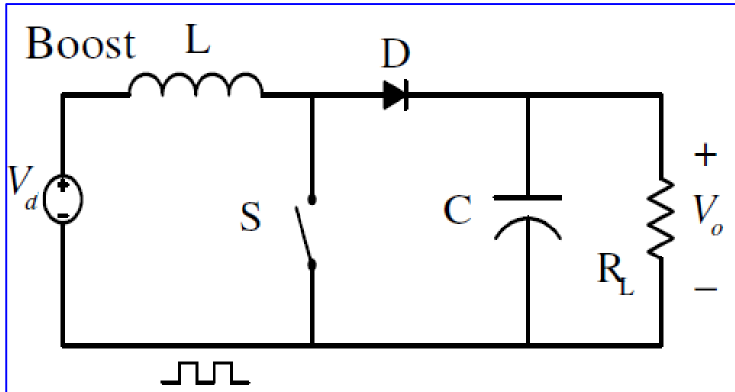
Converters in CCM: Summary



$$\frac{V_o}{V_d} = D$$

$$\frac{\Delta V_o}{V_o} = \frac{1-D}{8LCf^2}$$

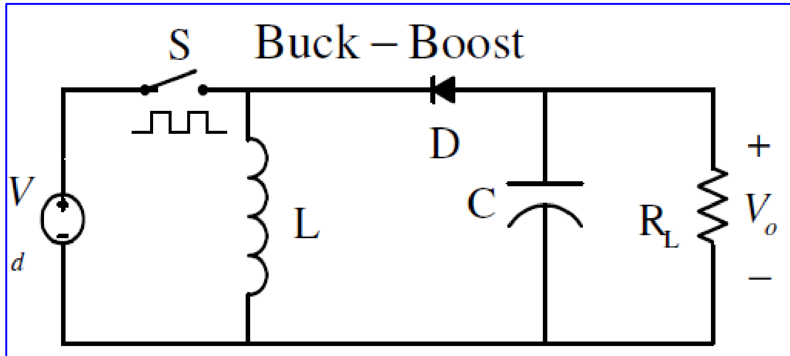
$$L_{\min} = \frac{(1-D)R}{2f}$$



$$\frac{V_o}{V_d} = \frac{1}{1-D}$$

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

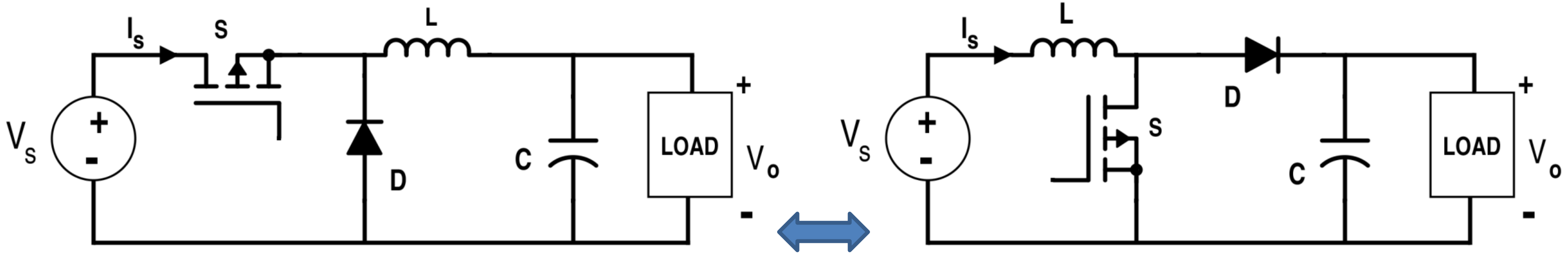
$$L_{\min} = \frac{D(1-D)^2 R}{2f}$$



$$\frac{V_o}{V_d} = -\frac{D}{1-D}$$

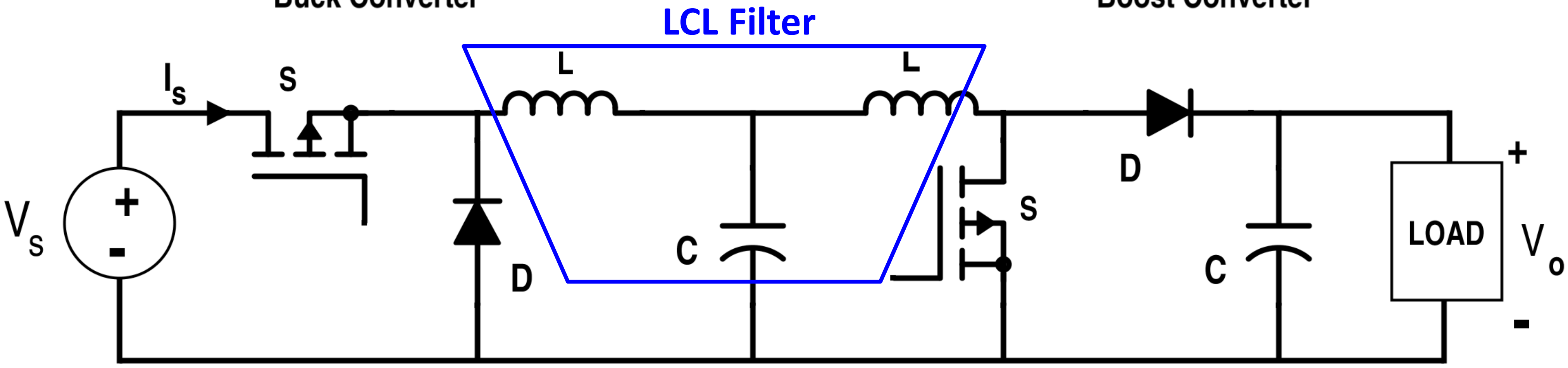
$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf}$$

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



Buck Converter

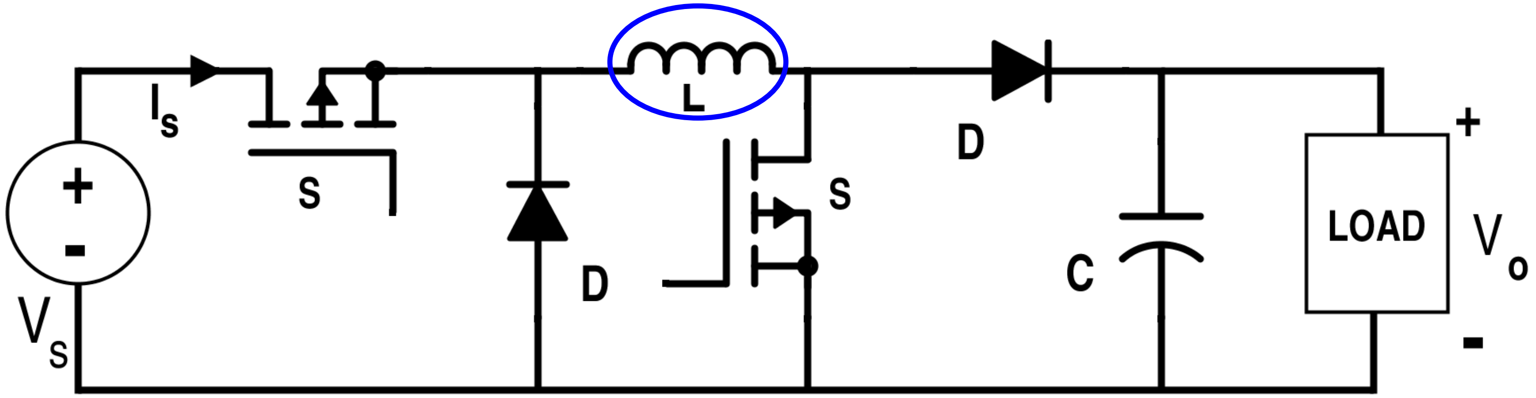
Boost Converter

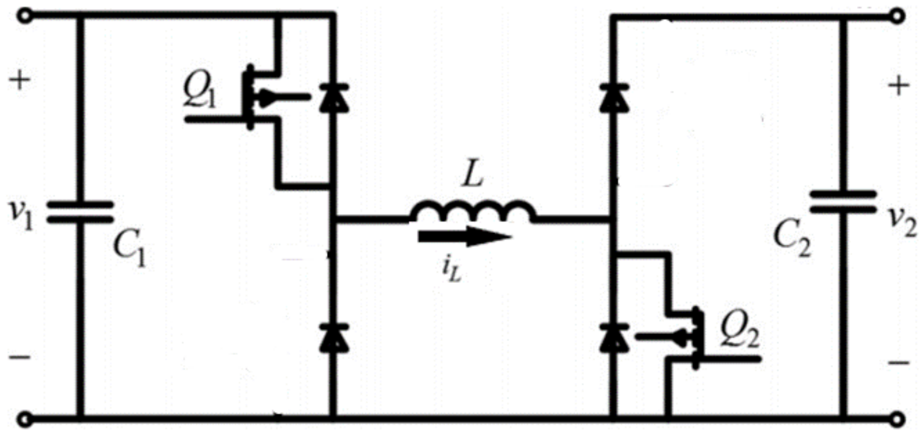


Buck Converter

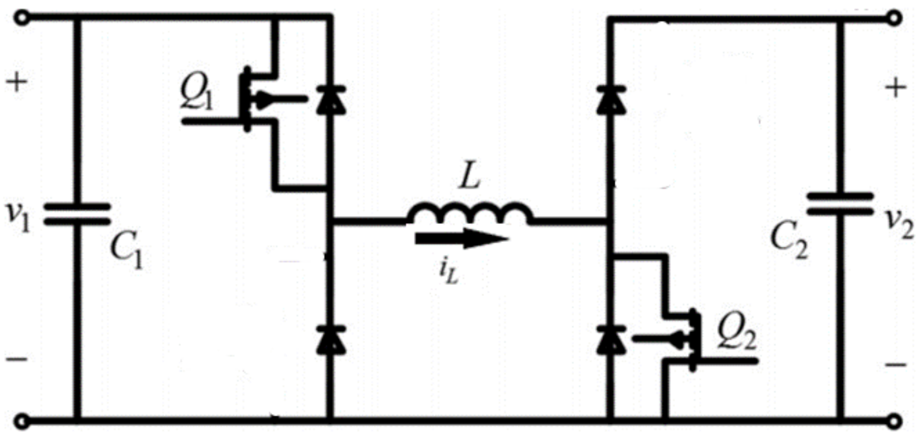
Boost Converter

Non-inverting Buck-Boost Converter





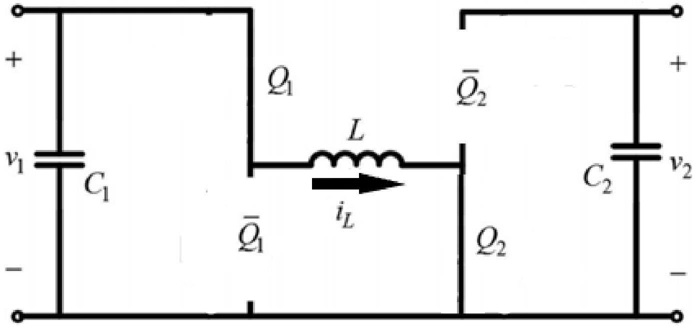
Non-inverting Buck-Boost Converter



Buck-Boost Mode

Q1 & Q2 ON

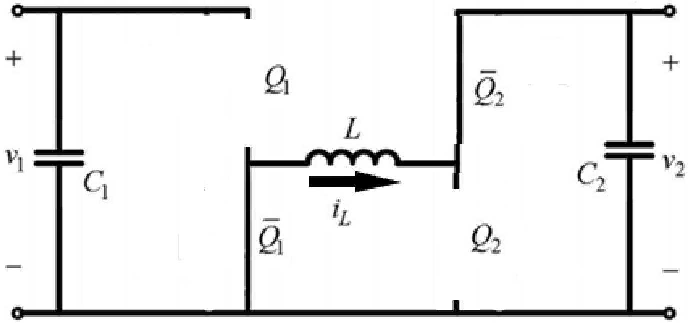
$\overline{Q1}$ & $\overline{Q2}$ OFF



DTs

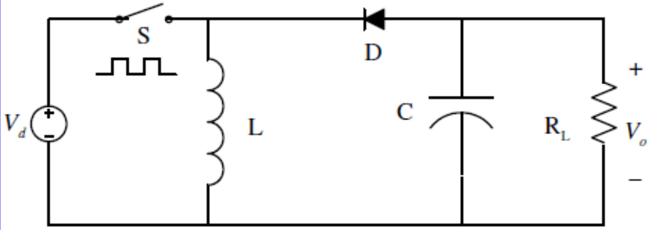
Q1 & Q2 OFF

$\overline{Q1}$ & $\overline{Q2}$ ON

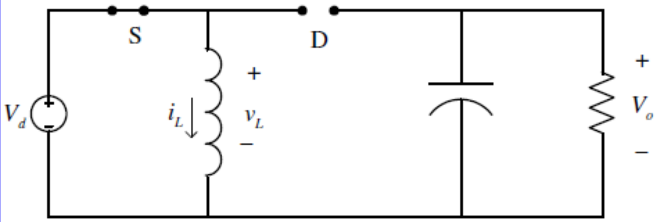


(1-D)Ts

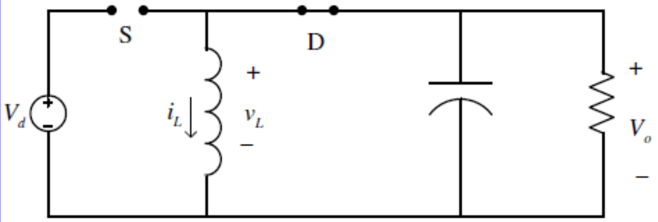
$$\therefore \frac{V_o}{V_d} = \frac{D}{1-D}$$



CIRCUIT OF BUCK-BOOST CONVERTER



CIRCUIT WHEN SWITCH IS CLOSED



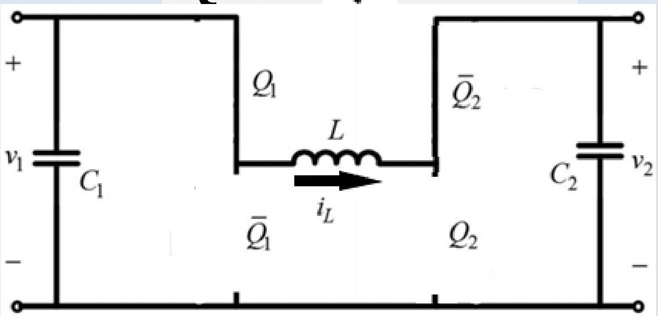
CIRCUIT WHEN SWITCH IS OPENED

Buck Mode

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D}$$

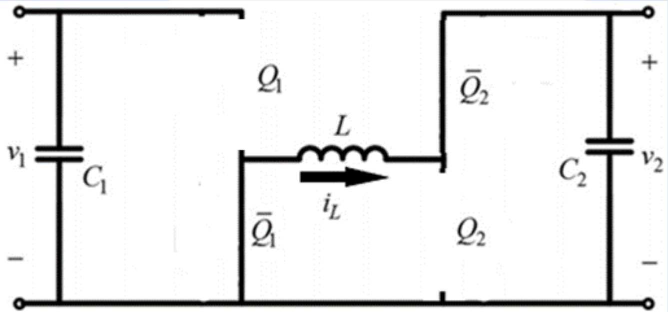
DTs

Q1 & $\overline{Q2}$ ON



(1-D)Ts

$\overline{Q1}$ & $\overline{Q2}$ ON



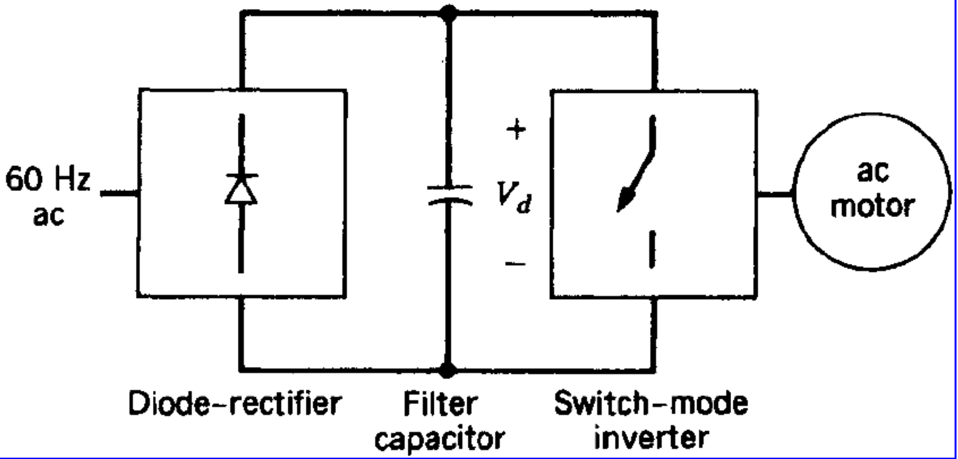
Inverters

Converting dc to ac

- Inverters convert dc power into ac power at desired output voltage and frequency.
- Applications: variable frequency ac drives, induction heating, standby aircraft, UPS, HVDC, FACTS, and custom power devices, etc.

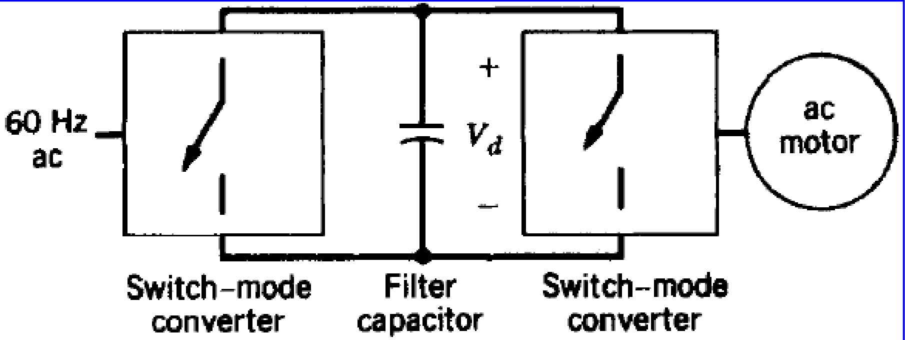
The voltage at the machine terminals is desired to be sinusoidal and adjustable in its magnitude and frequency. This is accomplished by means of the switch-mode dc-to-ac inverter.

Switch-mode inverter in ac motor drive.



To slow down the ac motor, the kinetic energy associated with the inertia of the motor and its load is recovered and the ac motor acts as a generator. During the so-called braking of the motor, the power flows from the ac side to the dc side of the switch-mode converter and it operates in a rectifier mode.

Power flow is reversible.



Switch-mode converters for motoring and regenerative braking in ac motor drive.

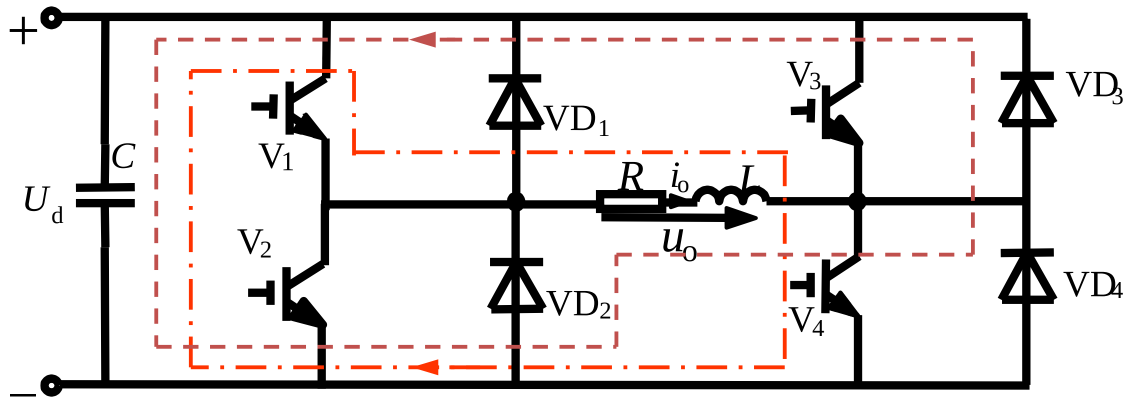
Regenerative braking may be performed where the energy recovered from the motor load inertia is fed back to the utility grid.

Inverters Classification

VSI

Most commonly used topology.

The input is from a dc source and the ac output functions as a voltage source.



The input dc voltage may be from the rectified output of an ac power supply, in which case it is called a ‘dc link’ inverter.

Alternatively, the input dc may be from an independent source such as a battery.