TSTE25 Power Electronics

Lecture 2

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Outline

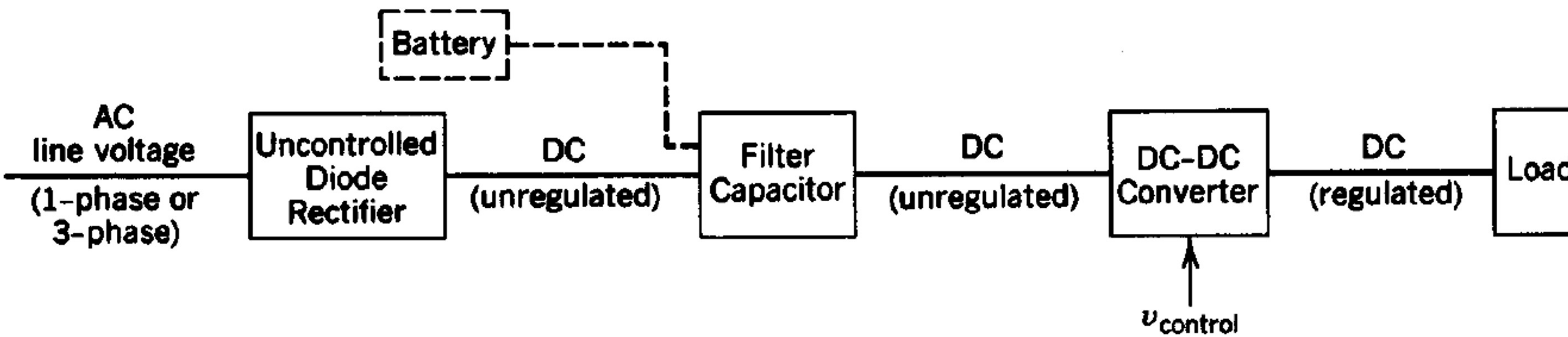
- DC-DC Converter
  - Step-down (Buck)
  - Step-up (Boost)
  - Buck/Boost (Self-study for interested)

Lecture 2

DC/DC (Buck) step-down converter

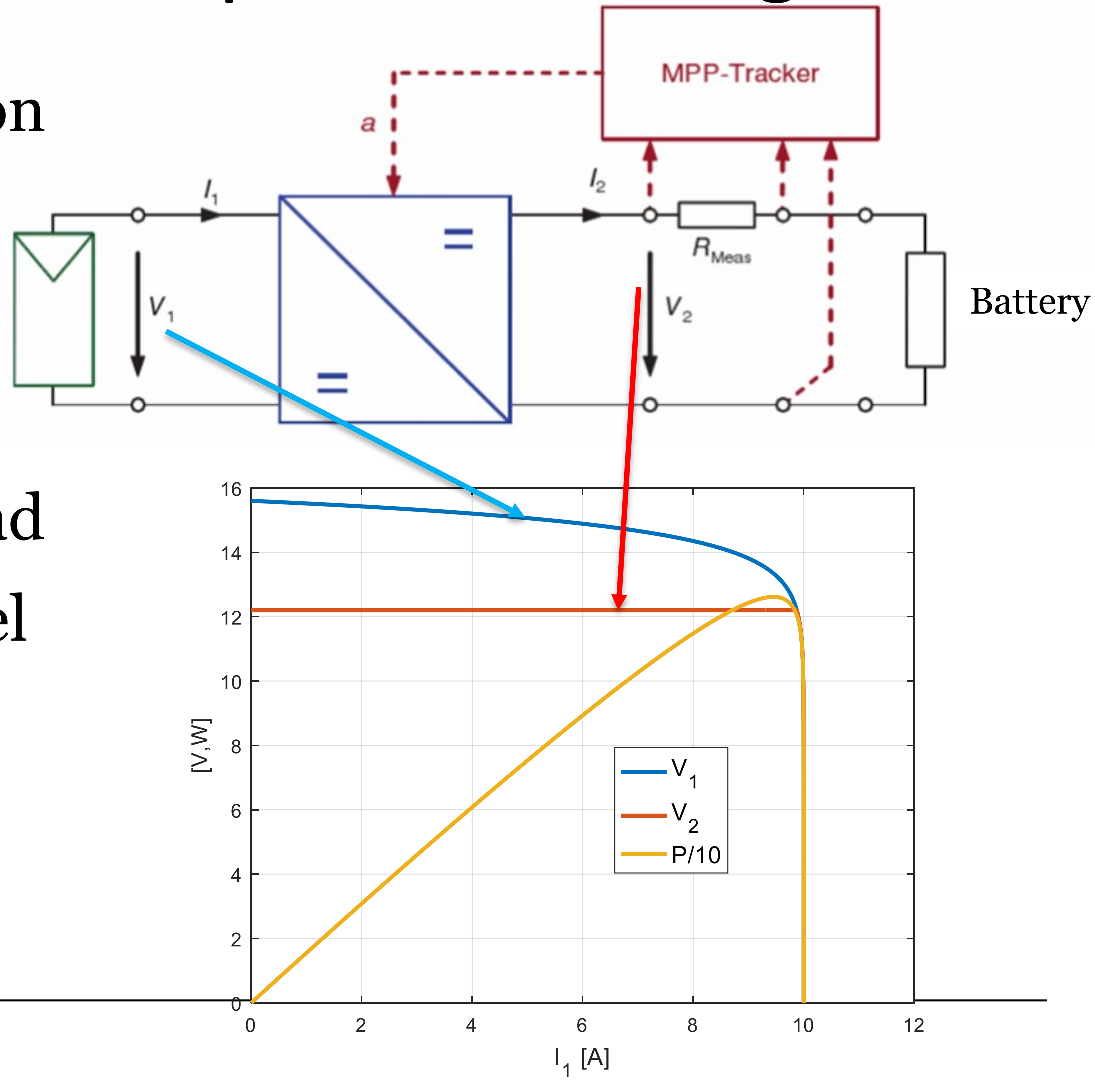
Basic use of DC-DC converter

- Unregulated DC input, controlled DC output
  - Regulated DC may be larger or smaller than the unregulated DC voltage
  - Input to the DC-DC converter may vary a lot



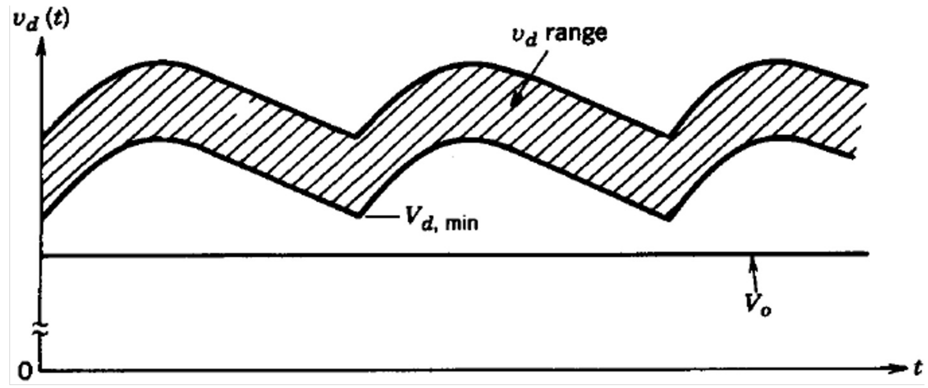
PV-panel maximum power tracking

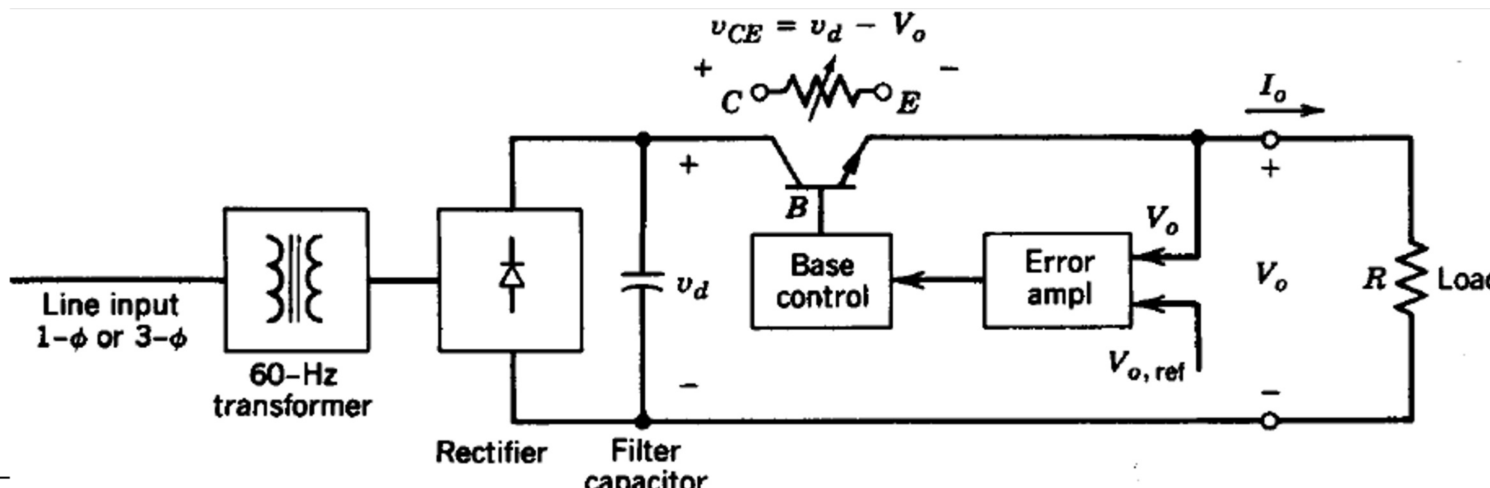
- DC/DC conversion to optimize PV-panel voltage for maximum power
- Constant (12V) across battery load
- Variable PV-panel voltage (12-16 V)



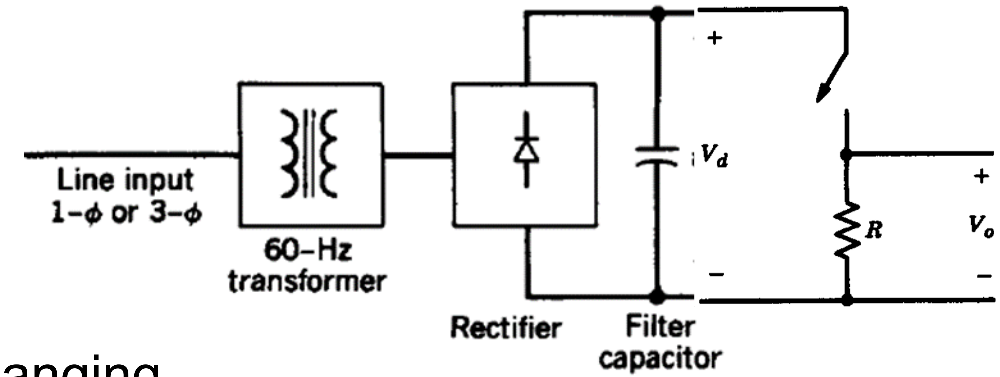
Linear power supply

- Bulky transformer
  - Low frequency
- Poor efficiency
  - 30 – 60 %
- Low EMI

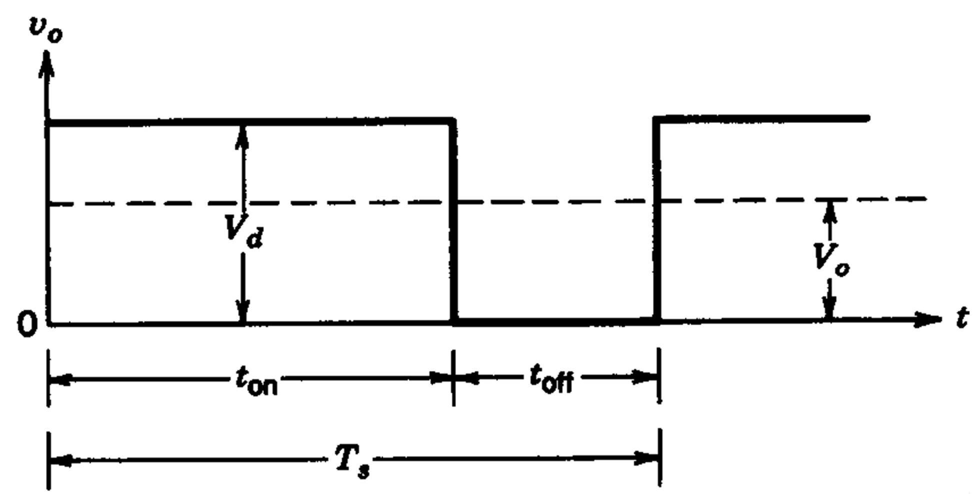




Step down converter principle

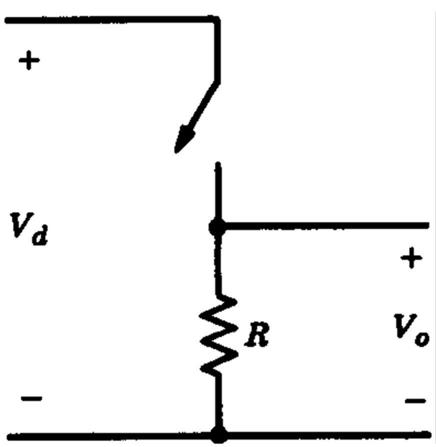


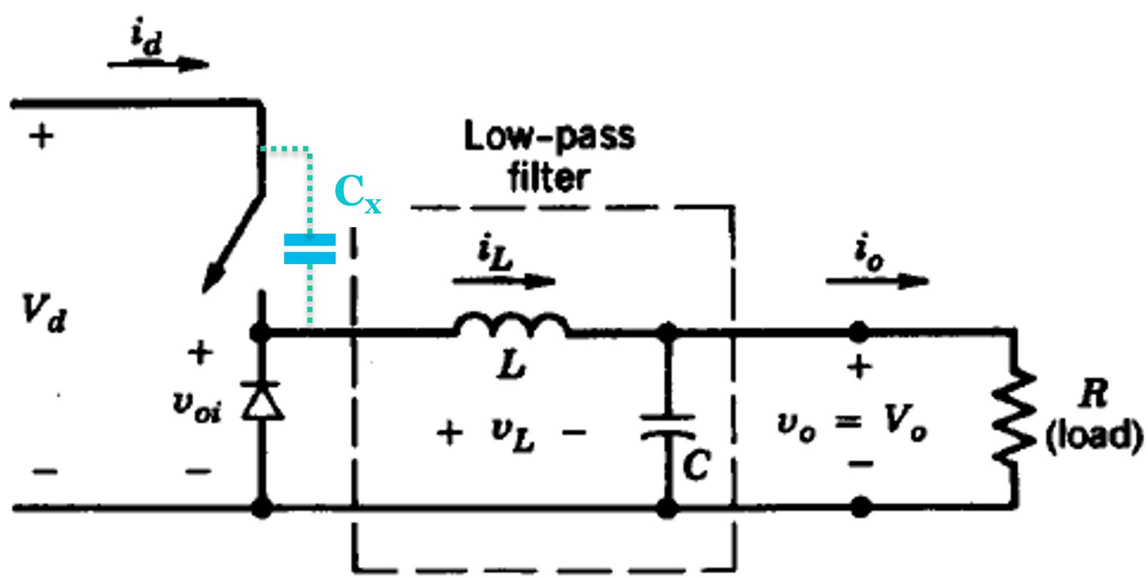
- $V_d > V_o$
- T_s constant, t_{on} and t_{off} changing
- Large ripple in V_o



Step-down (Buck) converter

- Add filter to reduce ripple voltage
- Diode added to protect switch
  - Without diode: V_L very high when switch opens with current in L due to very high dI/dt.
  - Parasitic capacitances C_x would be charged by the inductor current





DC/DC-converter control

- Pulse width modulation, PWM,
  to control switching
- Switching frequency, $f_{s,}$ the repetition rate of turn-on/off

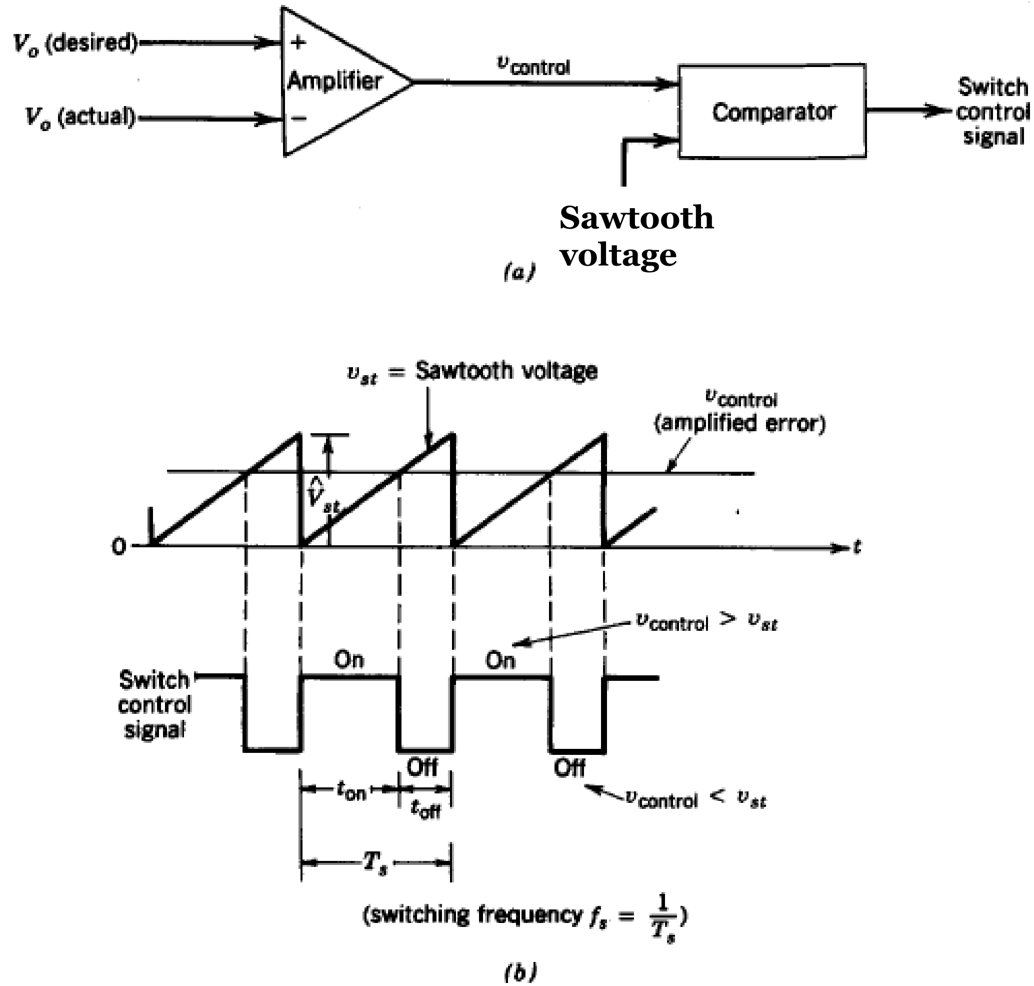
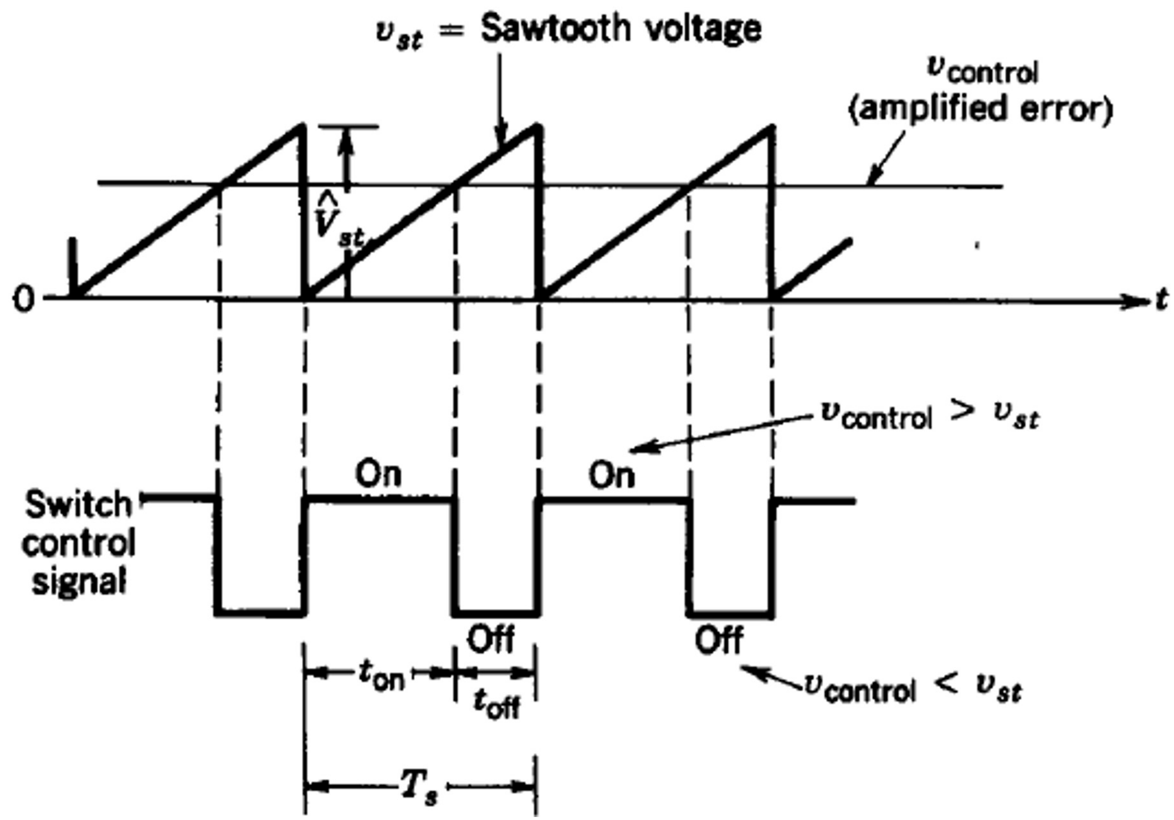


Figure 7-3 Pulse-width modulator: (*a*) block diagram; (*b*) comparator signals.

PWM waveform, duty cycle

- Switch duty cycle (duty ratio)

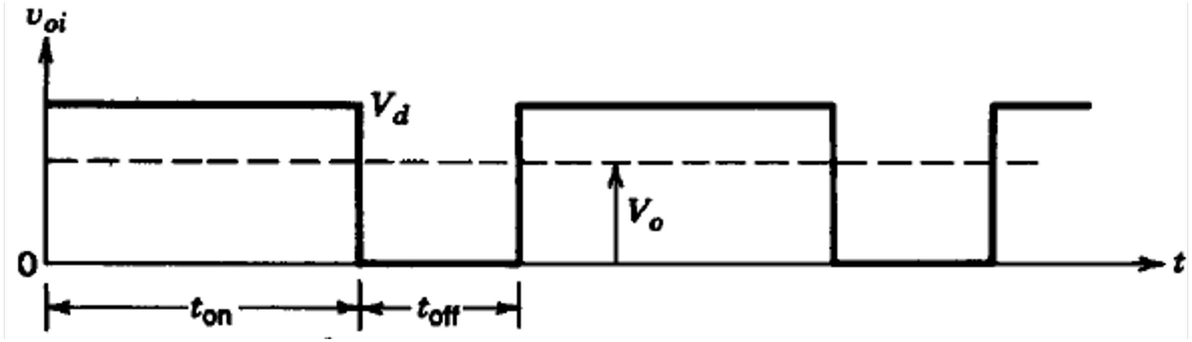
$$D = \frac{t_{on}}{T_s} = \frac{v_{control}}{\hat{V}_{st}}$$
$$0 < D < 1$$



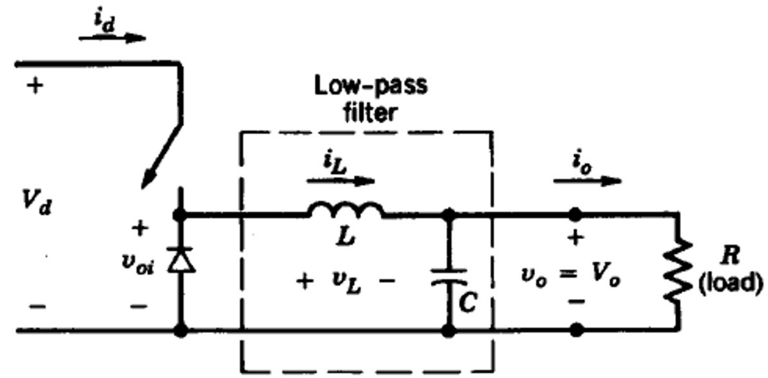
Step-down converter waveforms

- $T_s = t_{on} + t_{off}$
- Average output voltage

$$V_o = \frac{t_{on}}{T_s} V_d = D \cdot V_d$$



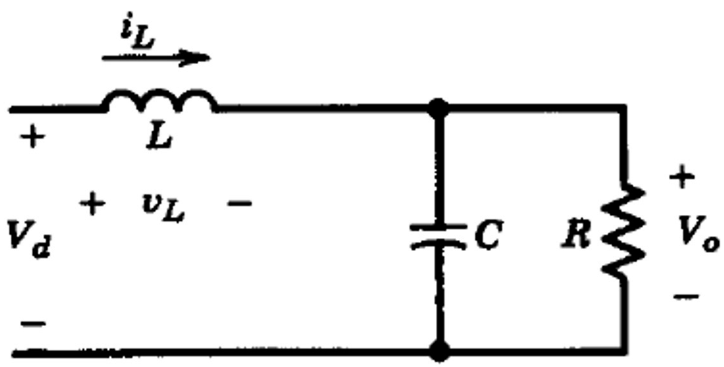
Current Conduction modes

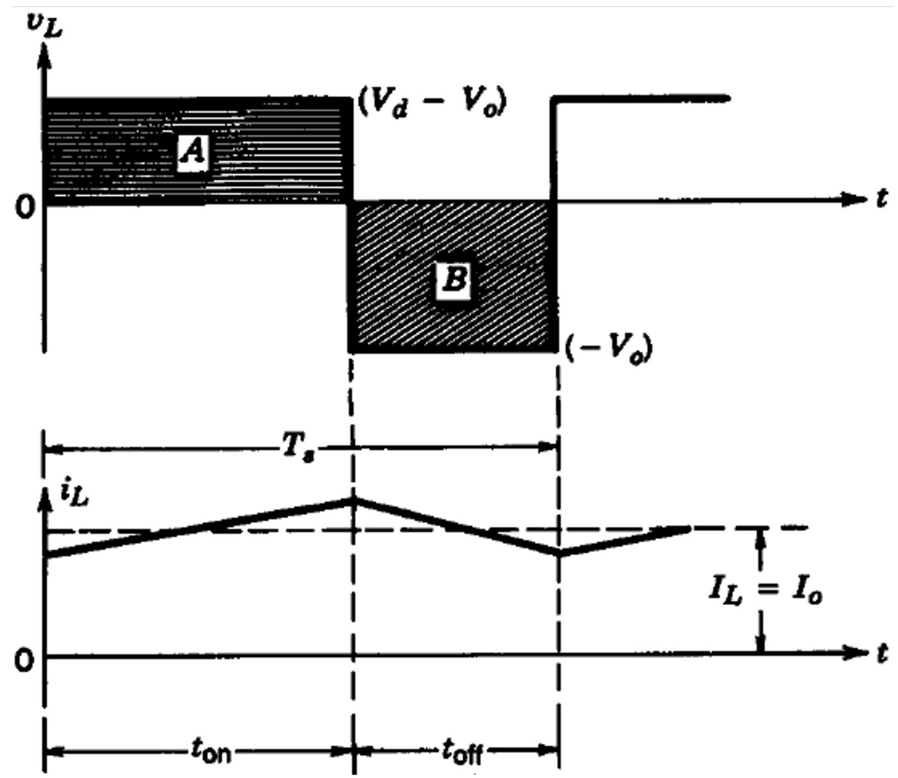


- Average i_L equals i_o
- Two current conduction modes (i_L)
  - Continuous current conduction
  - Non-continuous current conduction
- Converter characteristics different depending on mode
- Both modes can be supported by a converter
  - Mode applicable is depending on load

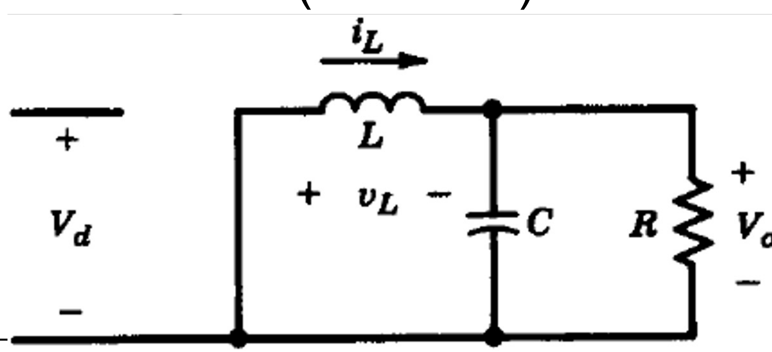
Continuous Conduction mode

- Switch on (diode off)



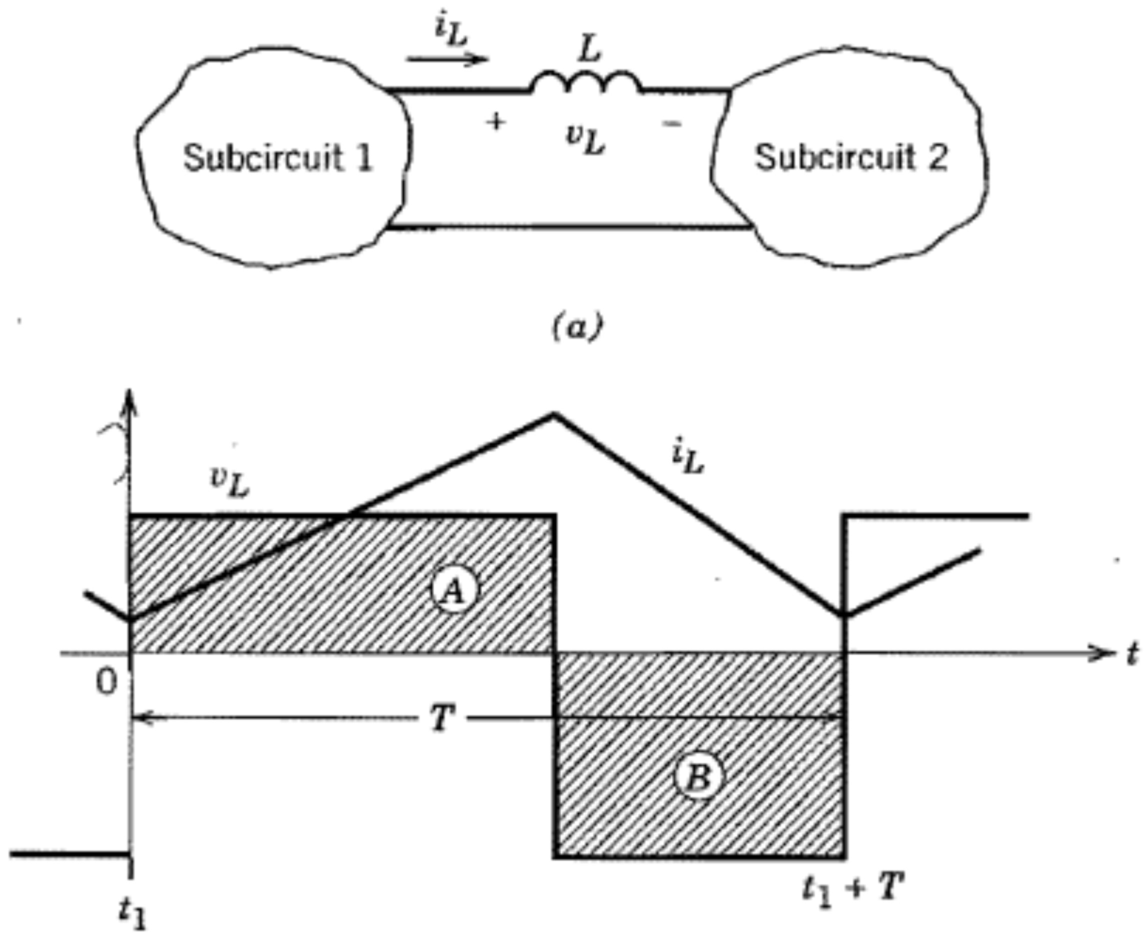


- Switch off (diode on)



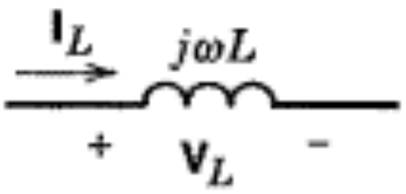
Inductor a current storage

- Voltage is required to change the current
- $v_L > 0$: i_L increase
- $v_L < 0$: i_L decrease
- Steady state:
  - Constant average current
  - Voltage-time area A=B
  - Average voltage=0



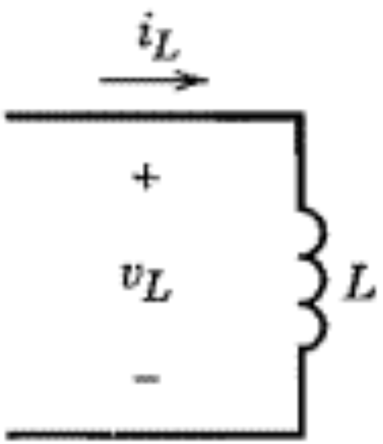
Inductor model

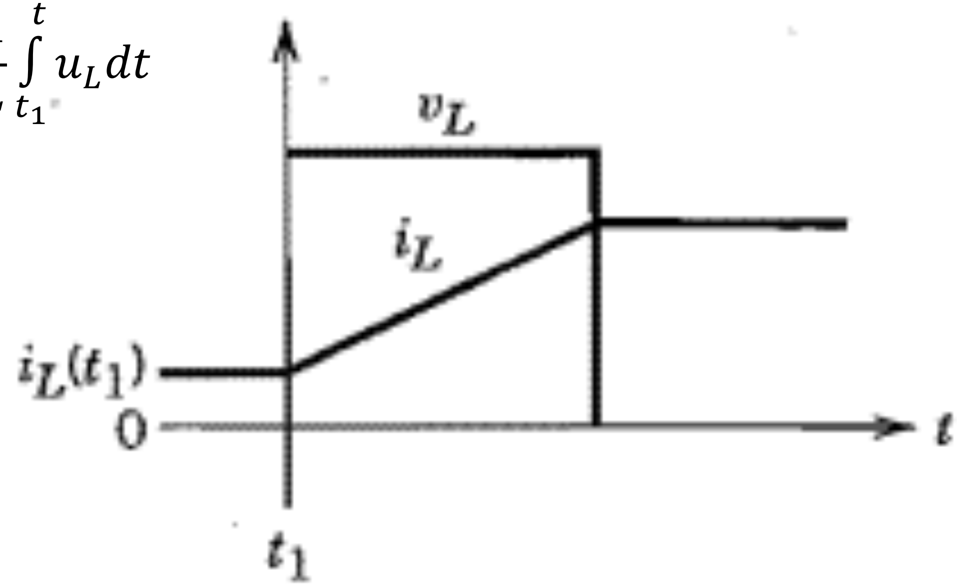
- Time and frequency domain
- $u_L = L\frac{di_L}{dt}$



$$\bar{U}_L = j\omega L \bar{I}_L$$

$$i_L(t) = i_L(t_1) + \frac{1}{L}\int_{t_1}^{t} u_L dt$$





Continuous conduction mode, cont.

- i_L never zero
- Steady state => A = B

$$t_{on}(V_d - V_o) = V_o(T_s - t_{on}) => \frac{V_o}{V_d} = \frac{t_{on}}{T_s} = D$$

  - Average v_L zero in steady state
- Average v_{oi} output voltage,

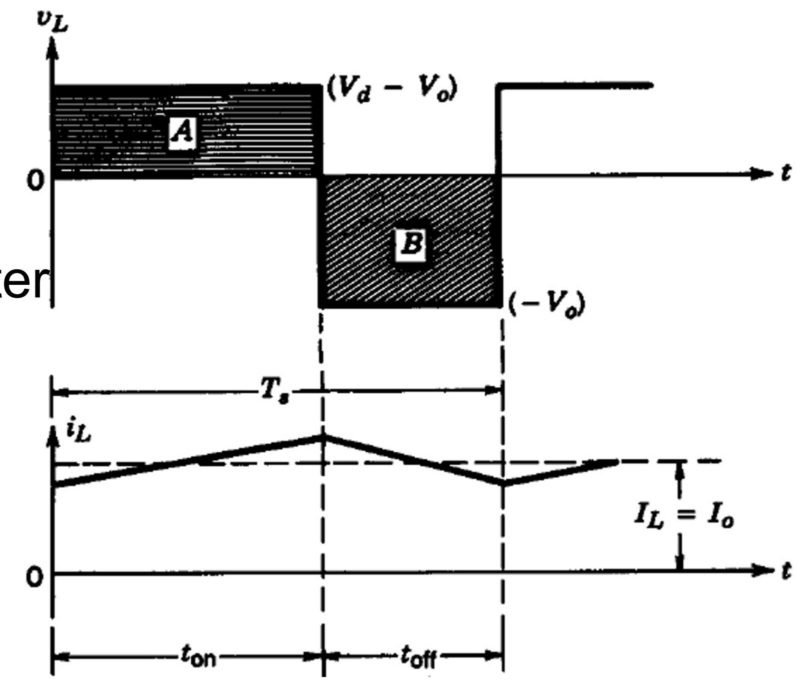
$$V_o = \frac{V_d t_{on} + 0 \cdot t_{off}}{T_s} = V_d \mathrm{D}$$

- Ideal conditions: No power loss in converter

$$P_d = P_o \Rightarrow V_d I_d = V_o I_o$$

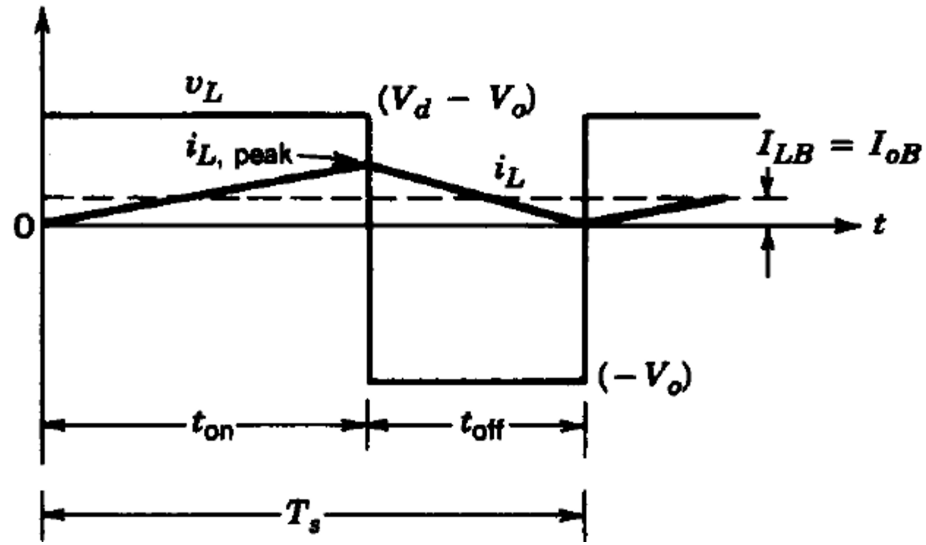
$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D}$$

- DC transformer with turns ratio equal to D



Discontinuous/Continuous Conduction mode boundary

- i_L reach zero at end of period
- Average inductor current equals the output current I_o
- Boundary current, I_{LB}, is the minimum average inductor current in **Cont**. mode



$$I_{LB} = \frac{1}{2} i_{L,peak} = \frac{t_{on}}{2L}(V_d - Vo)$$

$$I_{LB} = \frac{DT_s}{2L}(V_d - V_o)$$

$$I_{LB} = \frac{V_o}{2Lf_s}(1 - D)$$

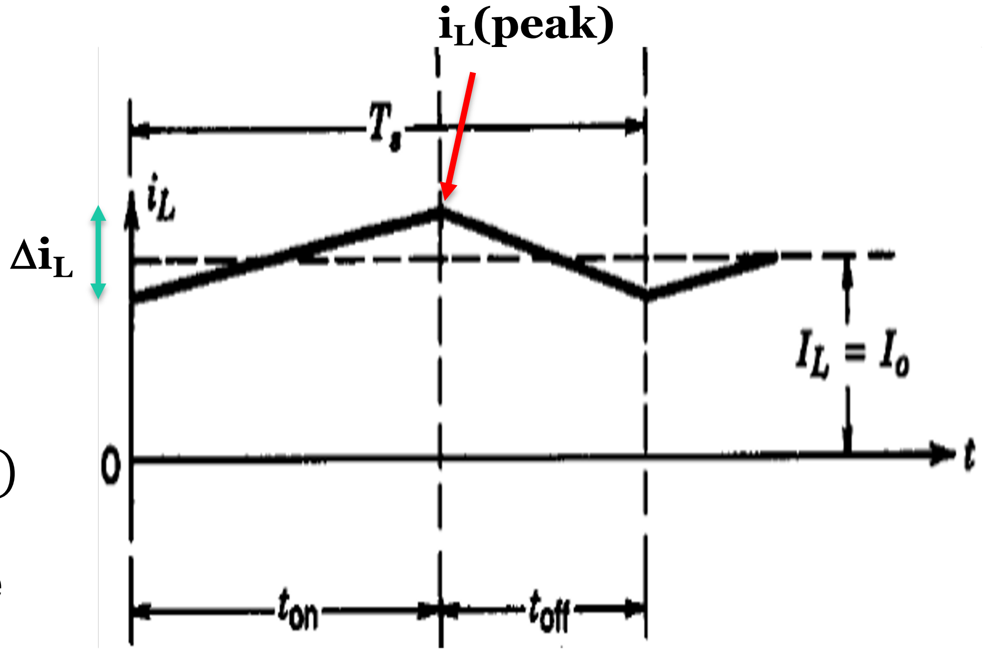
Inductance selection

- Inductance defines $\frac{di_L}{\mathrm{dt}}$
- Max inductor current

$$i_{L,peak} = I_o + \frac{\Delta i_L}{2}$$

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

- Inductance $\mathrm{L} = \frac{\mathrm{V_o}}{\Delta \mathrm{i_L}\ \mathrm{f_s}}(1 - \mathrm{D})$
- Minimum D is the worse case



Inductance *L*

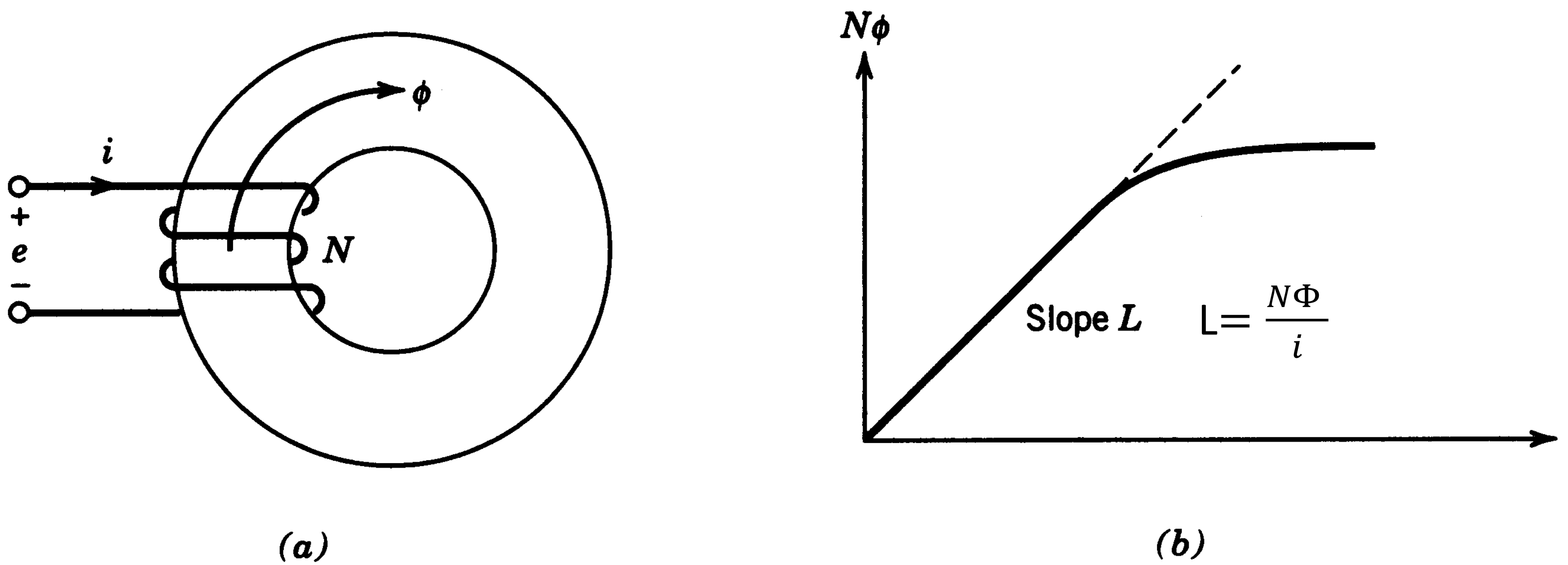


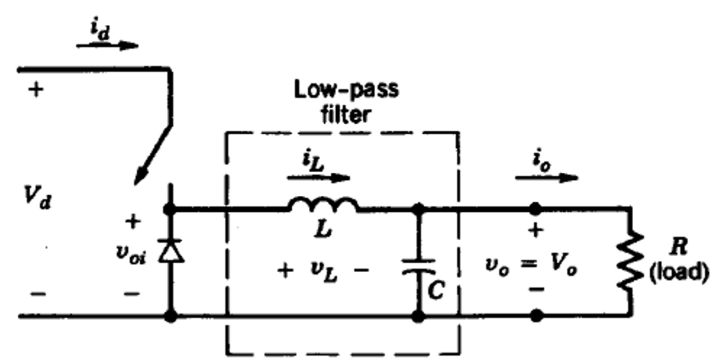
Figure 3-17 Self-inductance *L*.

- Faraday's voltage induction law: $e = N\frac{d\Phi}{dt} = L\frac{di}{dt}$
- Magnetic saturation, $B = \frac{\Phi}{A} > B_{max}$

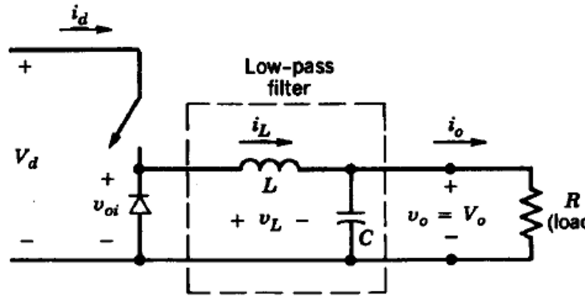
7-1

In a step-down converter, consider all components to be ideal. Let $v_o \approx V_o$ be held constant at 5 V by controlling the switch duty ratio D.

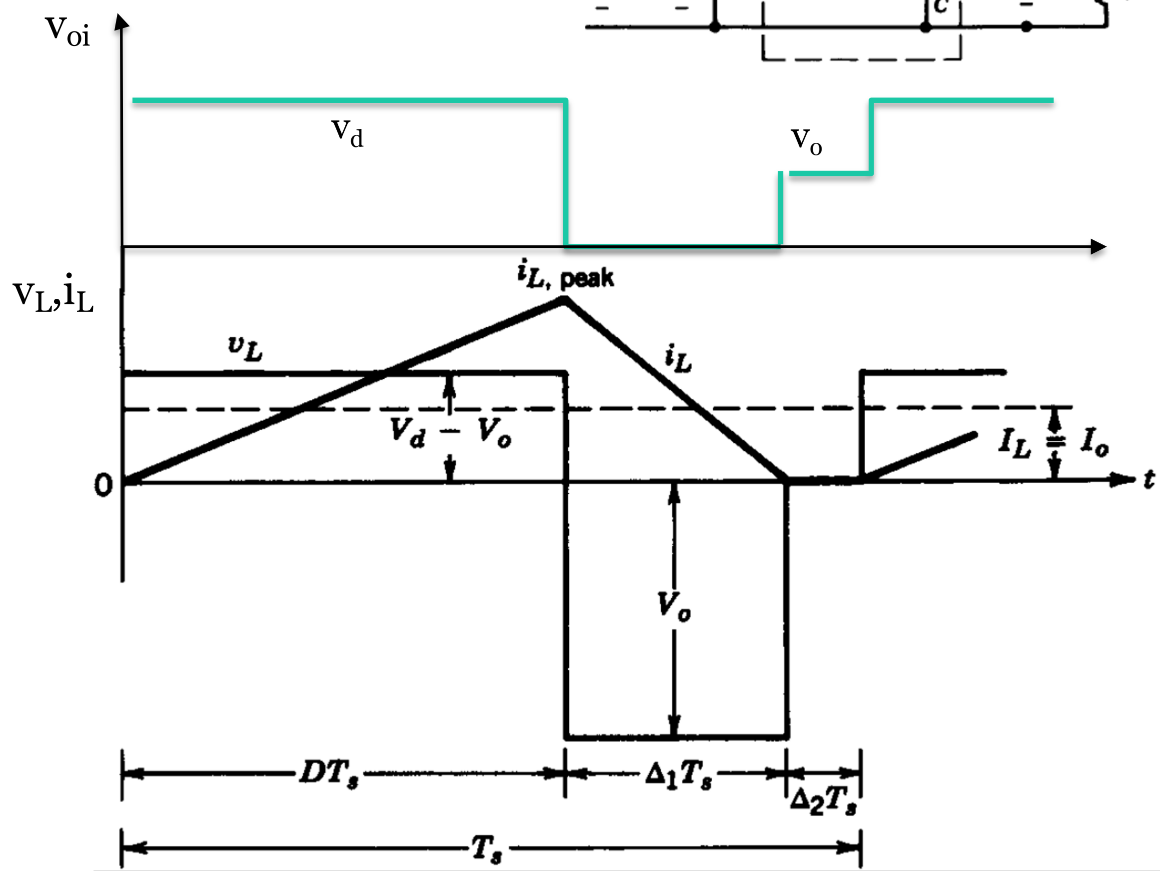
- Calculate the minimum inductance L required to keep the converter operation in a continuous-conduction mode under all conditions if:
  V_d is 10-40 V , $P_o \geq 5$ W, and $f_s = 50$ kHz.



Discontinuous conduction mode



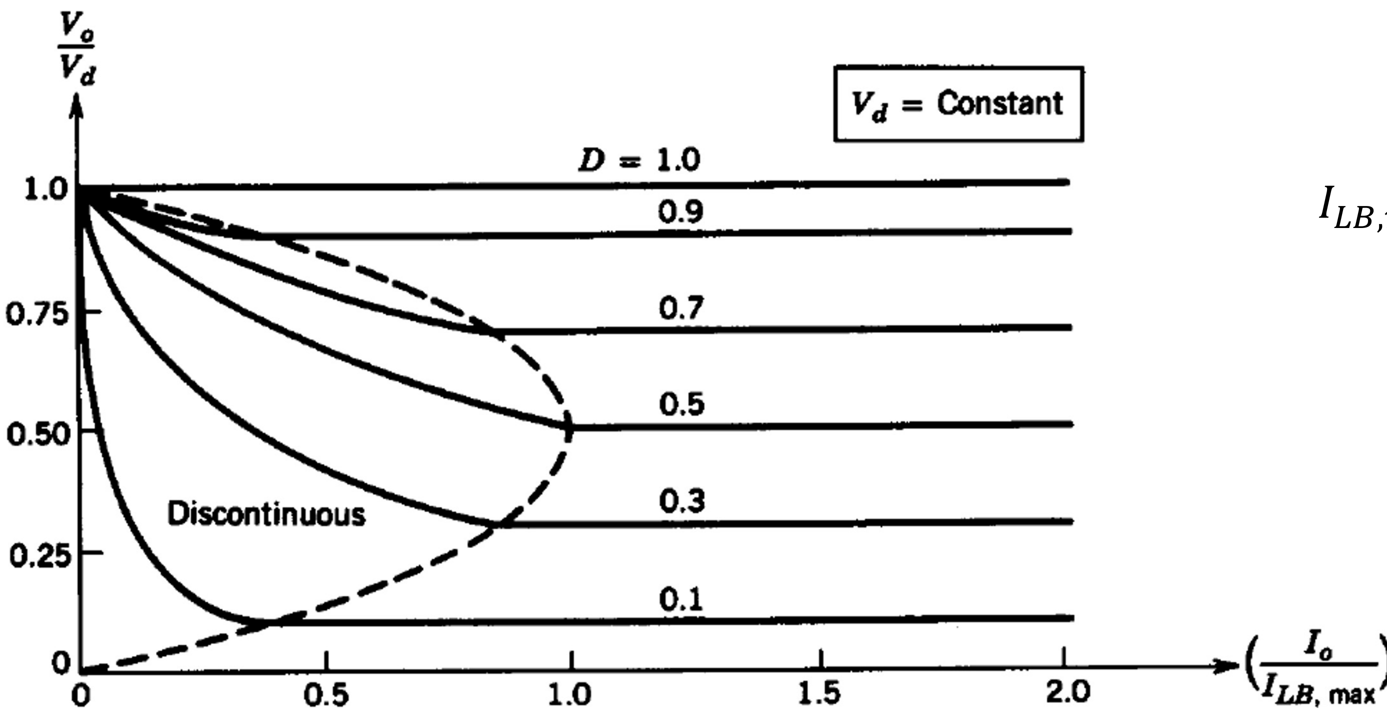
- $V_{oi} = V_d$ when switch on
- When switch off
  - $V_{oi} = 0$ if $i_L > 0$
  - $V_{oi} = V_o$ if $i_L = 0$
- Output vs. input voltage relation more complex



$$\frac{V_o}{V_d} = \frac{D^2}{D^2 + \frac{1}{4}\left(I_o / I_{LB,max}\right)}$$

Constant V_d step-down characteristic

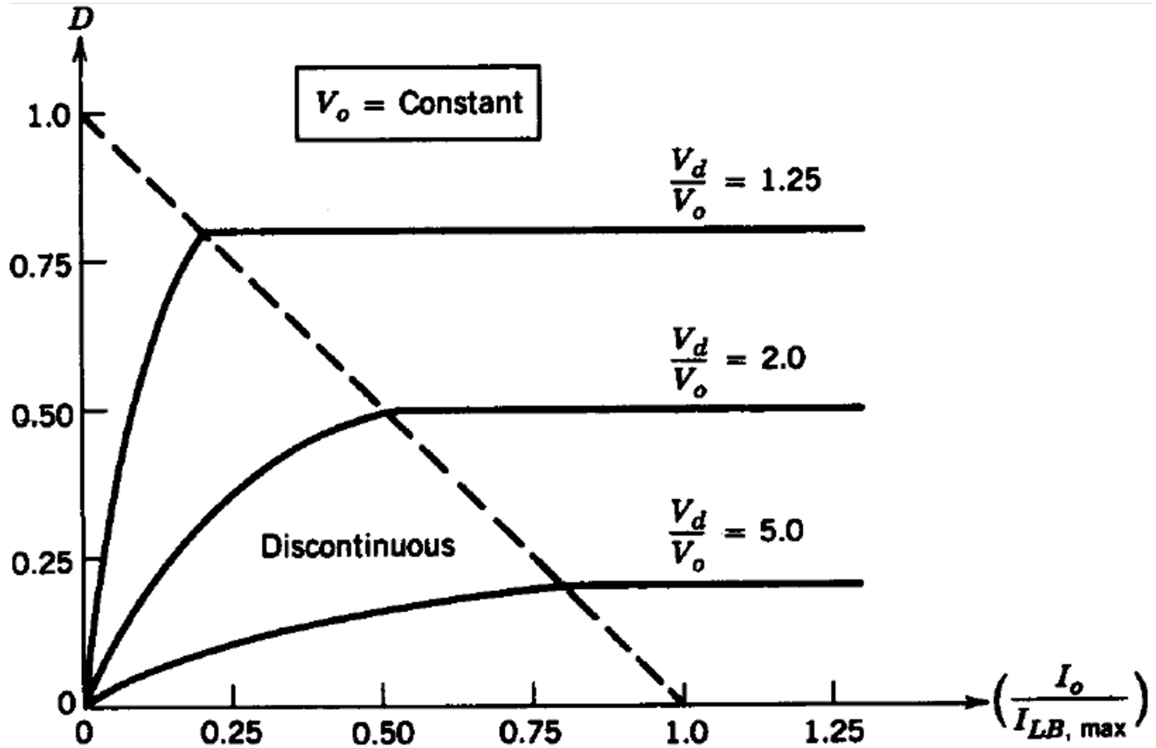
- Very low load result in increased output voltage!



$$I_{LB,max} = \frac{T_s V_d}{8L}$$

Discontinuous conduction mode with constant V_o

- $$I_{LB,max} = \frac{T_S V_o}{2L}$$
- Control ratio for constant V_o



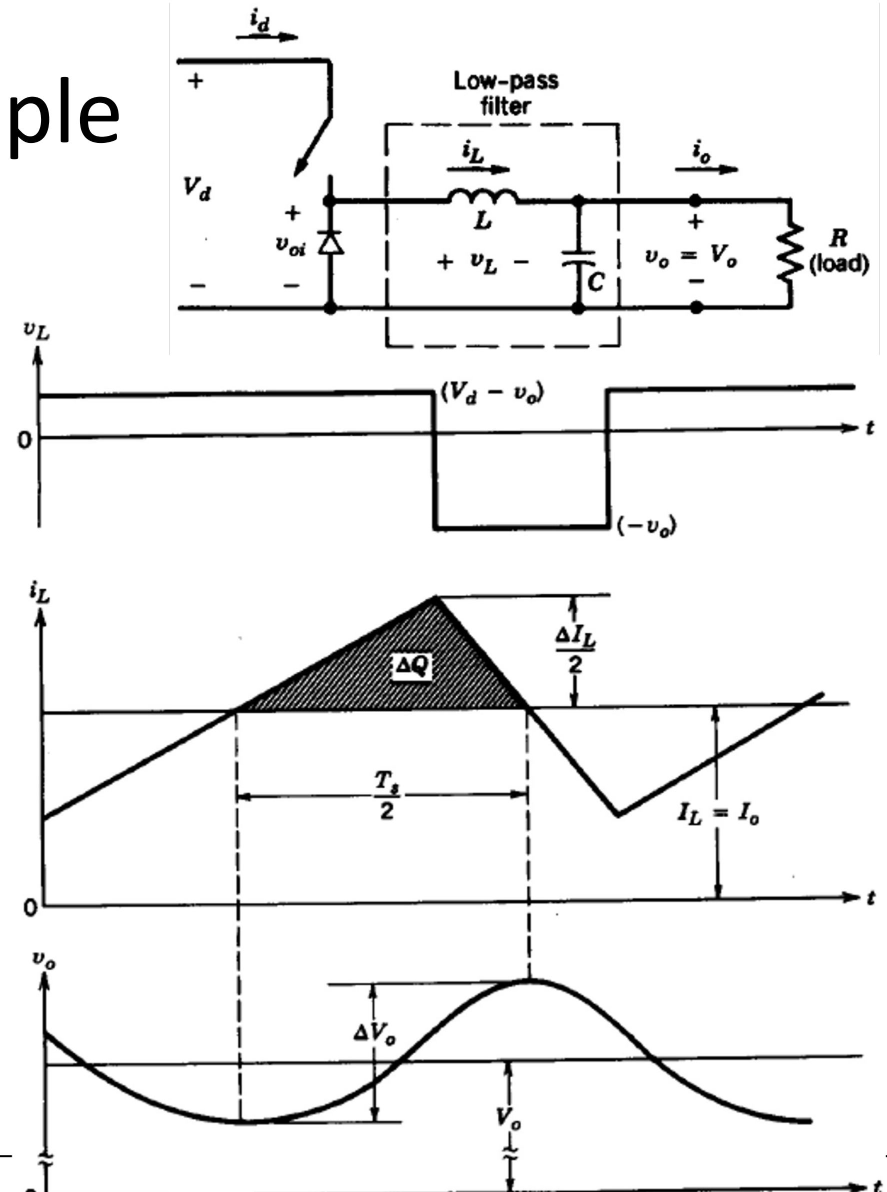
Output voltage ripple

- Assuming:
  - Continuous current
  - Inductor ripple current in C
  - Average inductor current in R

$$\Delta V_o = \frac{\Delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\Delta I_L}{2}\frac{T_s}{2}$$

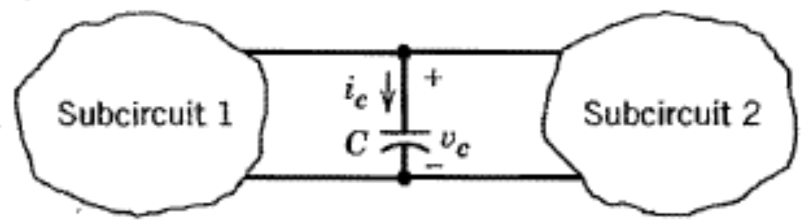
$$\Delta I_L = \frac{V_o}{L}(1-D)T_s$$

$$\frac{\Delta V_o}{V_o} = \frac{1}{8}\frac{T_s^2(1-D)}{LC}$$

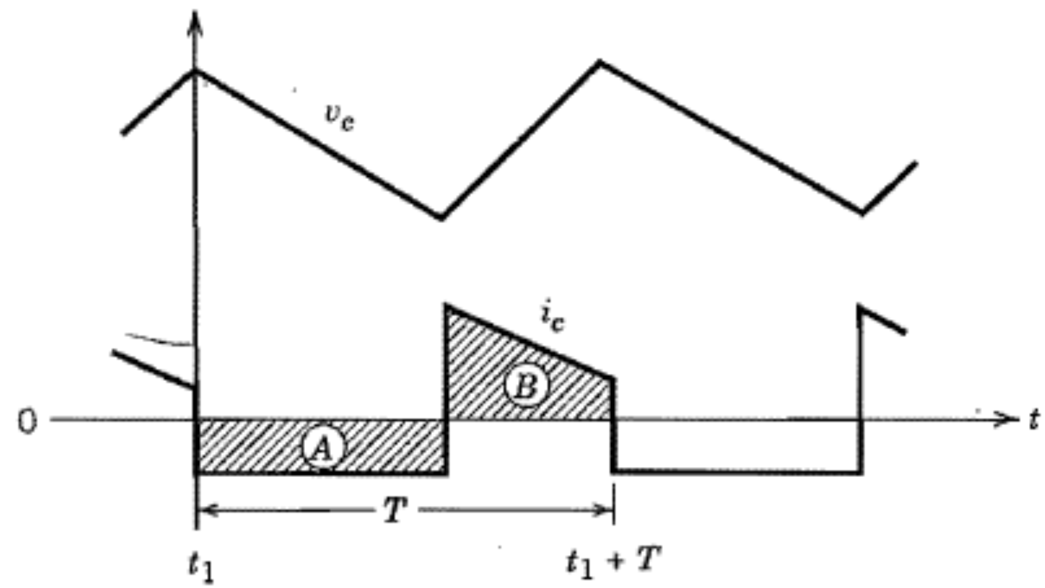


Capacitor a voltage storage

- Current is required to change the voltage
- $i_c>0$: u_c increase
- $i_c<0$: u_c decrease
- Steady state:
  - Constant average voltage
  - Current-time area (charge) A=B
  - Average current=0



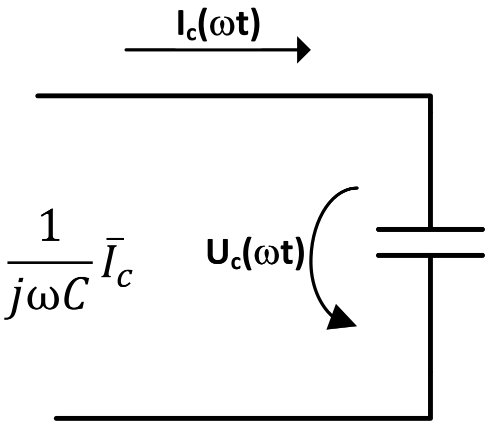
(a)



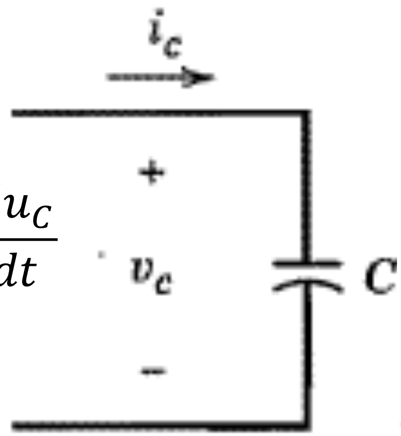
Capacitor model

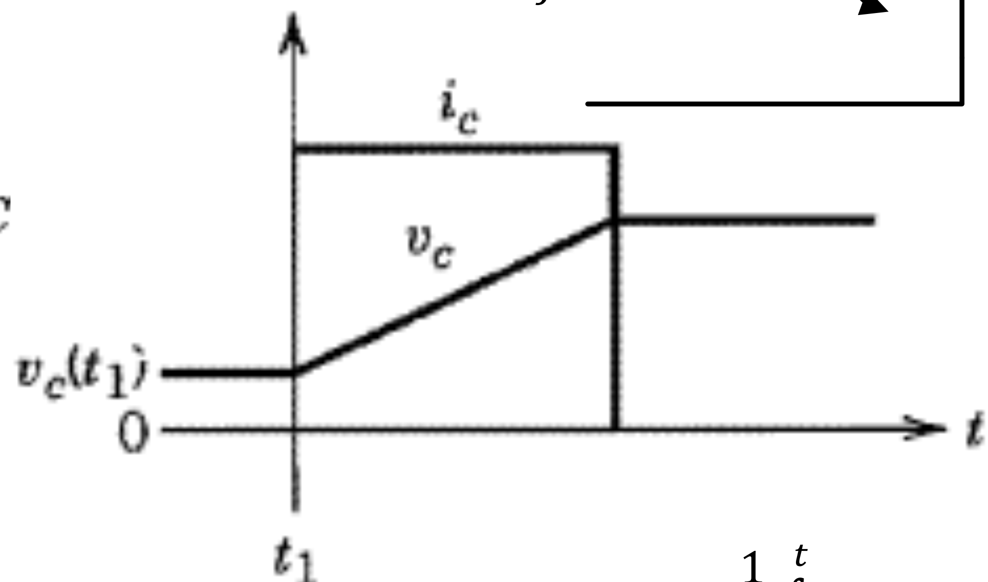
- Time and frequency domain

$$\bar{U}_c = \frac{1}{j\omega C}\bar{I}_c$$



$$i_C = C\frac{du_C}{dt}$$





$$u_C(t) = u_C(t_1) + \frac{1}{C}\int_{t_1}^{t} i_C dt$$

$$= u_C(t_1) + \frac{1}{C}\Delta Q$$

Step-down (Buck) converter summary

- Output vs input

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

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

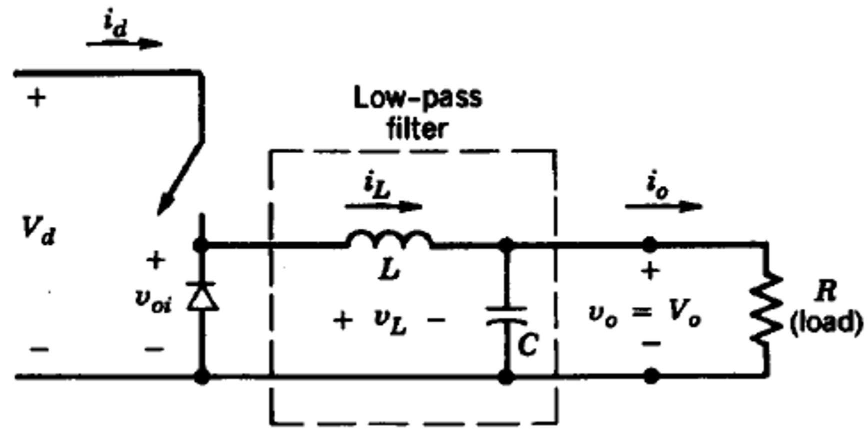
- High ripple current

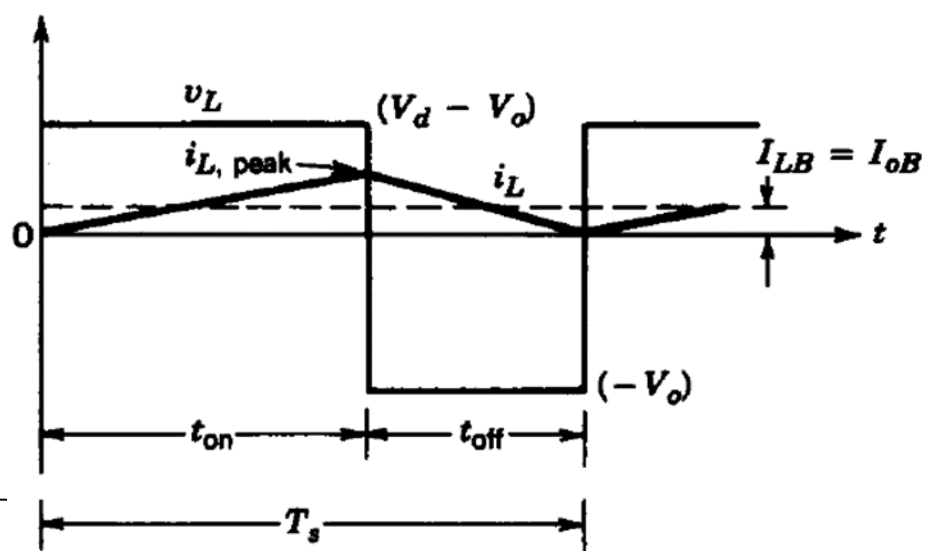
$$\Delta i_L = \frac{V_o}{L f_s}(1 - D)$$

- Output ripple voltage

$$\frac{\Delta V_o}{V_o} = \frac{1}{8}\frac{T_s^2(1 - D)}{LC}$$

- Practical for D not lower than 0.2



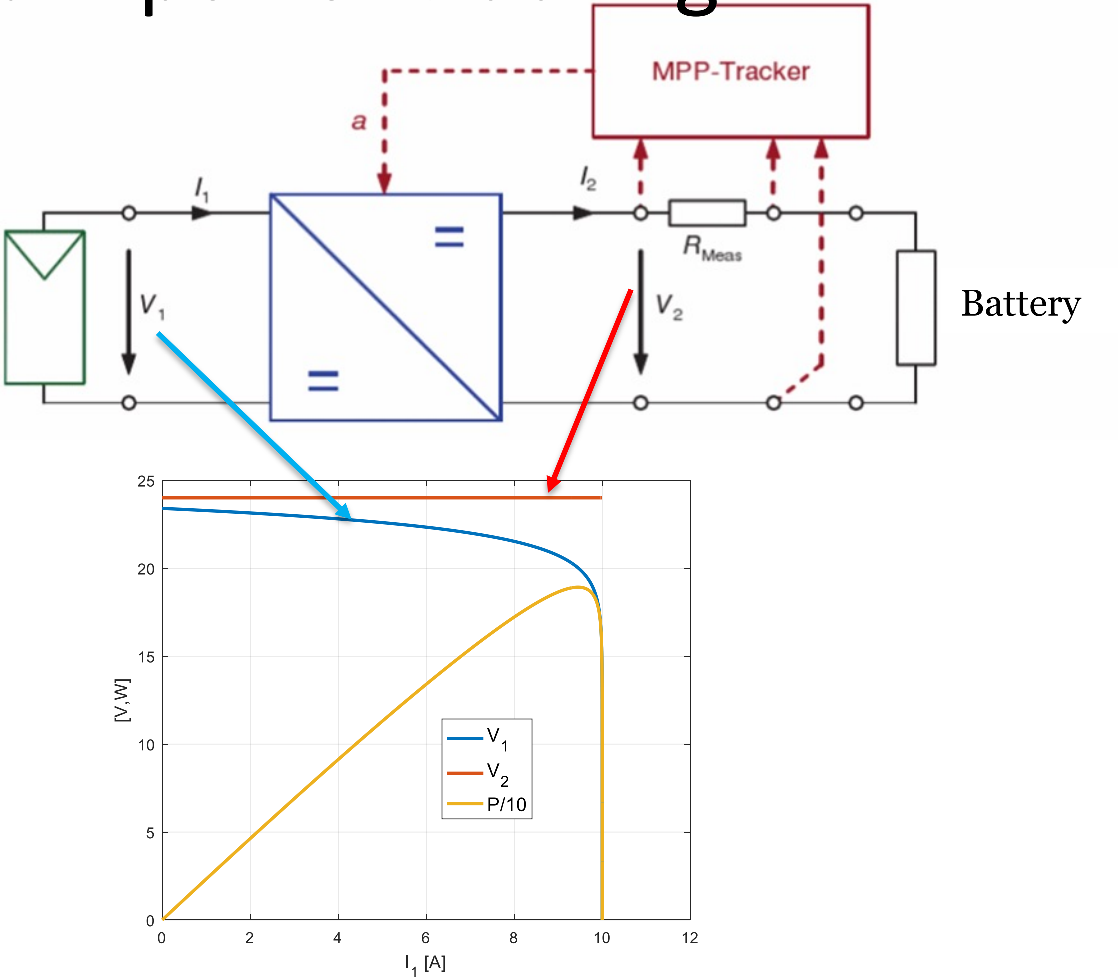


Lecture 2

DC/DC (Boost) up converter

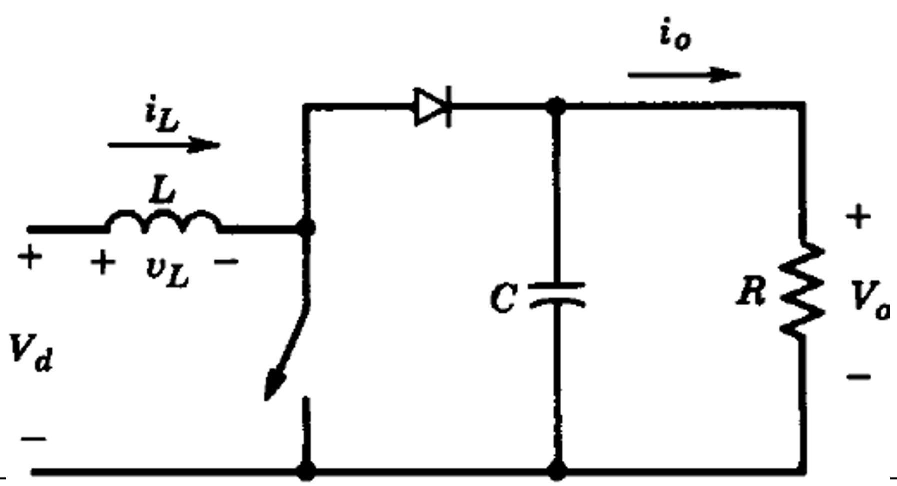
PV-panel maximum power tracking

- DC/DC conversion to optimize PV-panel voltage for maximum power
- Constant (24V) across battery load
- Variable PV-panel voltage (0-23 V)



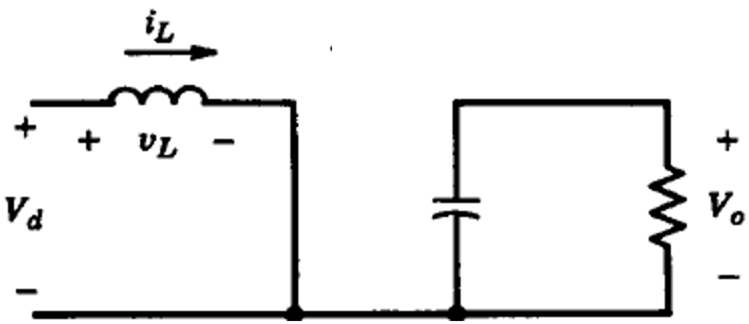
Step-up (Boost) converter

- Output must be larger than input voltage
  - Otherwise V_d is driving V_o directly through the diode => $V_o = V_d$
- Load energy into inductor, then output energy into load while still consuming energy from source
- C large enough to give low ripple, $v_o(t) \approx V_o$

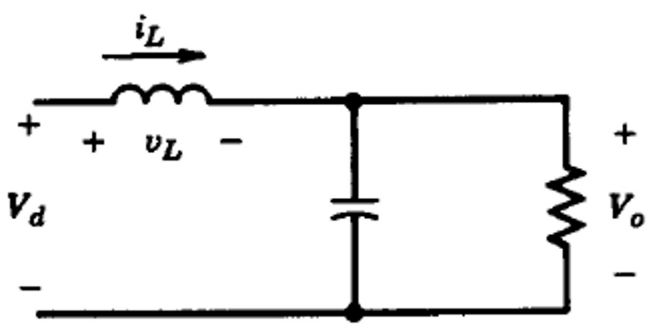


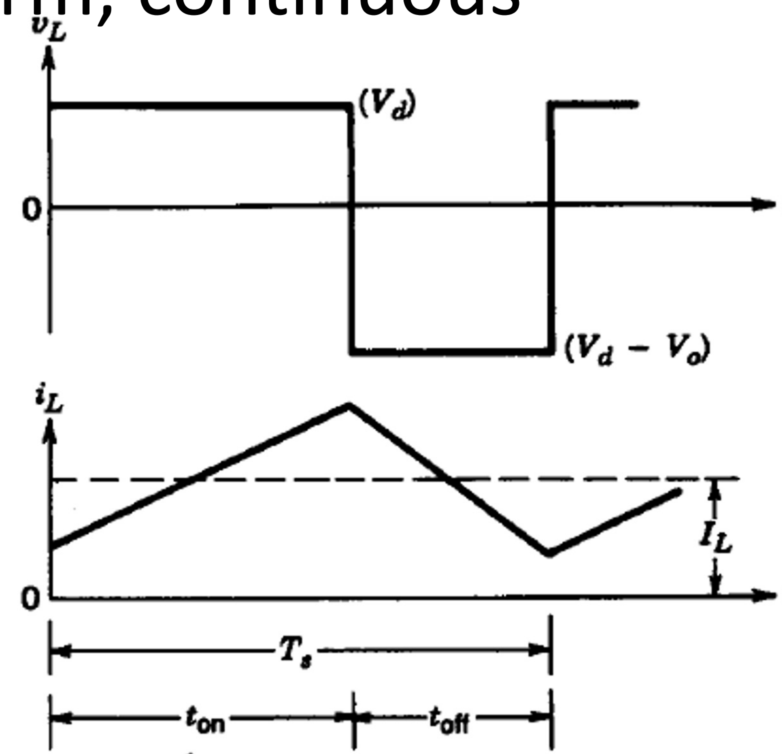
Step-up converter waveform, continuous conduction mode

- Switch on, diode off



- Switch off, diode on





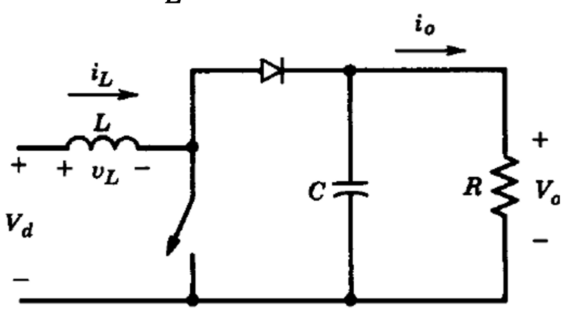
Step-up converter, continuous mode

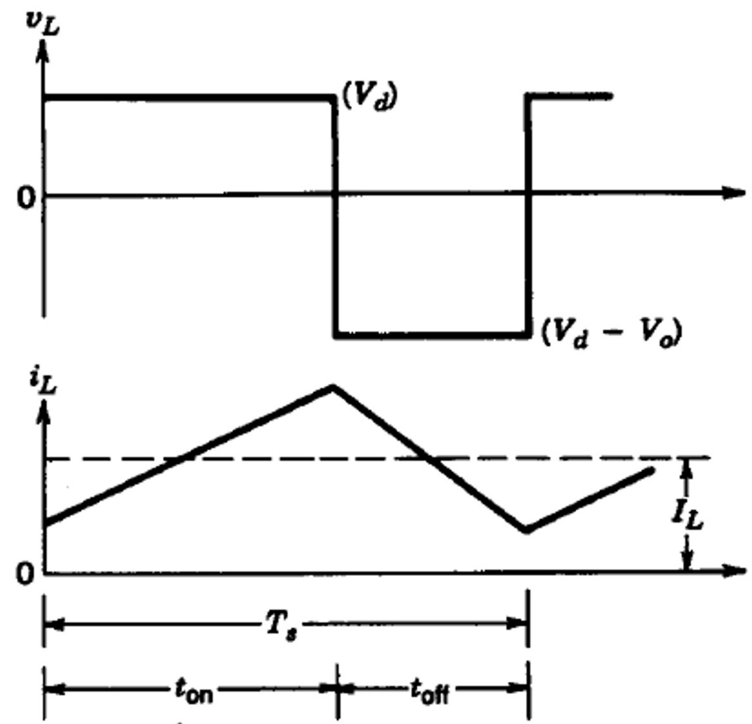
$$V_d t_{on} + (V_d - V_o) t_{off} = 0$$

$$V_o / V_d = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

$$\textit{Lossless circuit}: V_d I_L = V_o I_o$$

$$\Rightarrow \frac{I_o}{I_L} = (1 - D)$$





Boundary between continuous and discontinuous mode

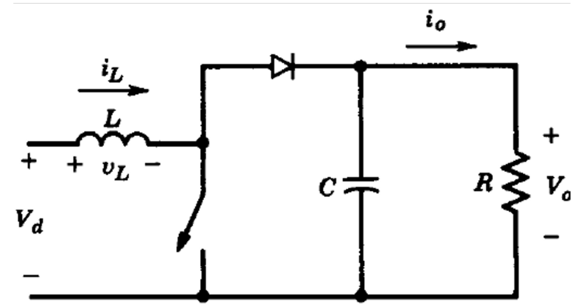
- Inductor current boundary

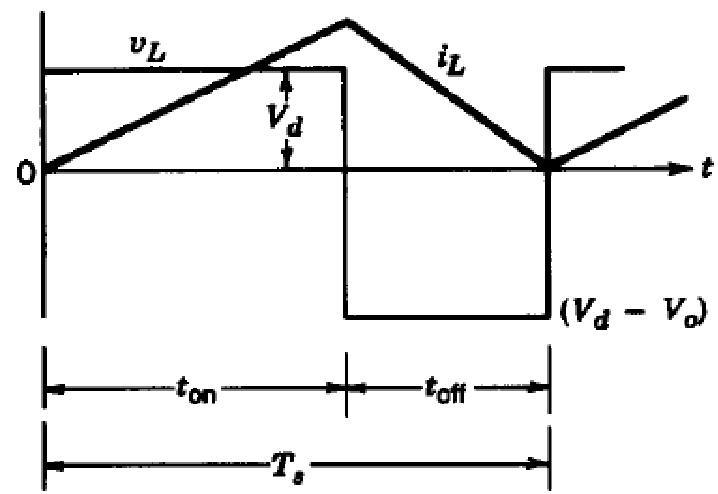
$$I_{LB} = \frac{1}{2} i_{L,peak} = \frac{1}{2} \frac{t_{on}}{L} V_d$$

$$I_{LB} = \frac{T_s D}{2L} V_o (1 - D)$$

- Output current boundary

$$I_{oB} = \frac{T_s D}{2L} V_o (1 - D)^2$$





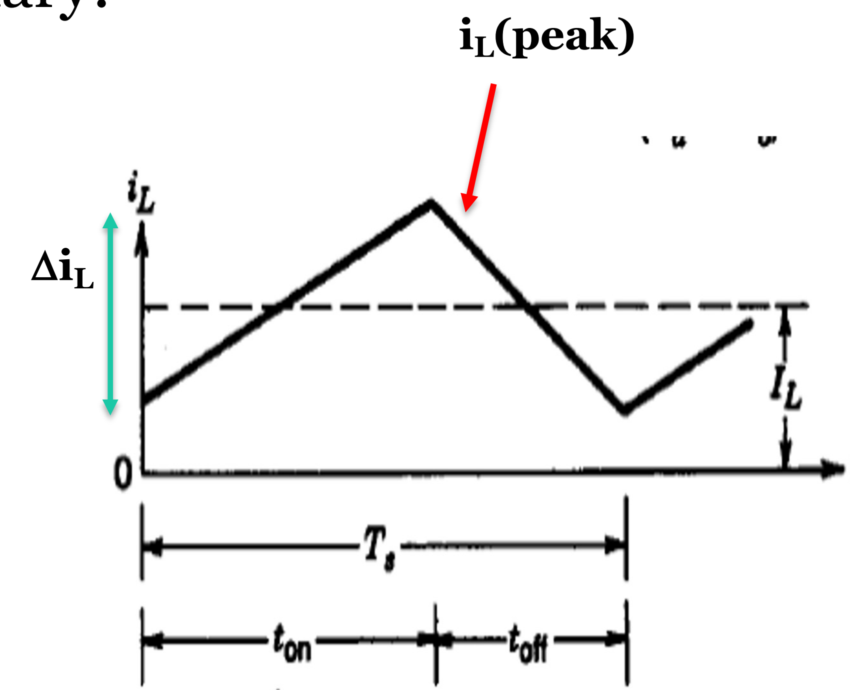
Step-up converter, inductance choice

Continuous current boundary:

- Max inductor current

$$i_{L,peak} = I_L + \frac{\Delta i_L}{2}$$

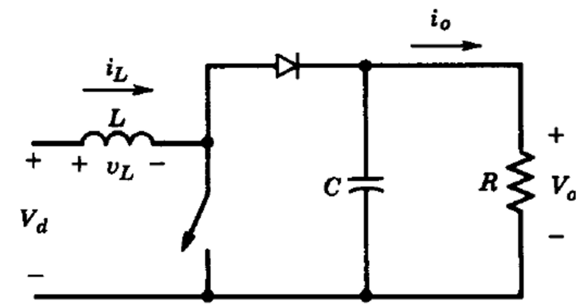
$$\Delta i_L = \frac{DV_o}{Lf_s}(1 - D)$$



- Inductance

$$L = \frac{DV_o}{\Delta i_L\, f_S}(1 - D)$$

Step-up, discontinuous mode

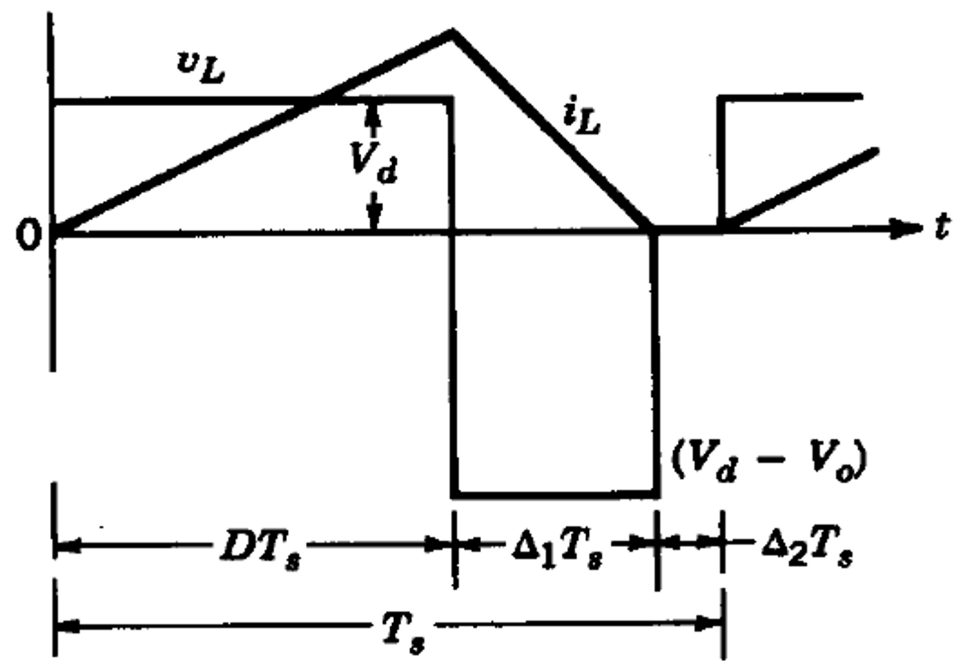


Comparing with continuous mode for same duty cycle

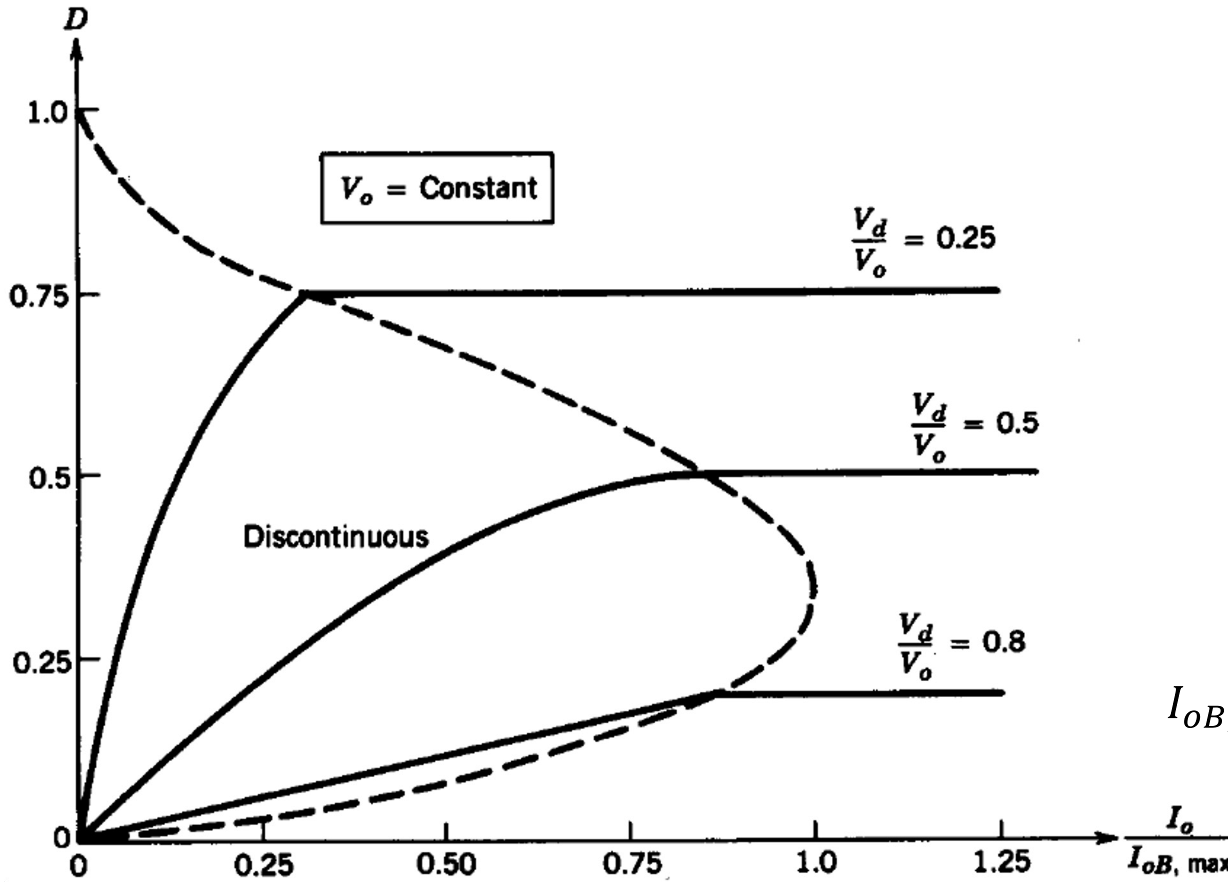
- Current I_L up ramp same
- Current I_L down ramp shorter due to current zero
- Higher dI_L/dt
- Higher V_o for equal area in inductor voltage

- How to control D in discontinuous mode

$$D = \left[\frac{4}{27}\frac{V_o}{V_d}\left(\frac{V_o}{V_d} - 1\right)\frac{I_o}{I_{oB,max}}\right]^{1/2}$$



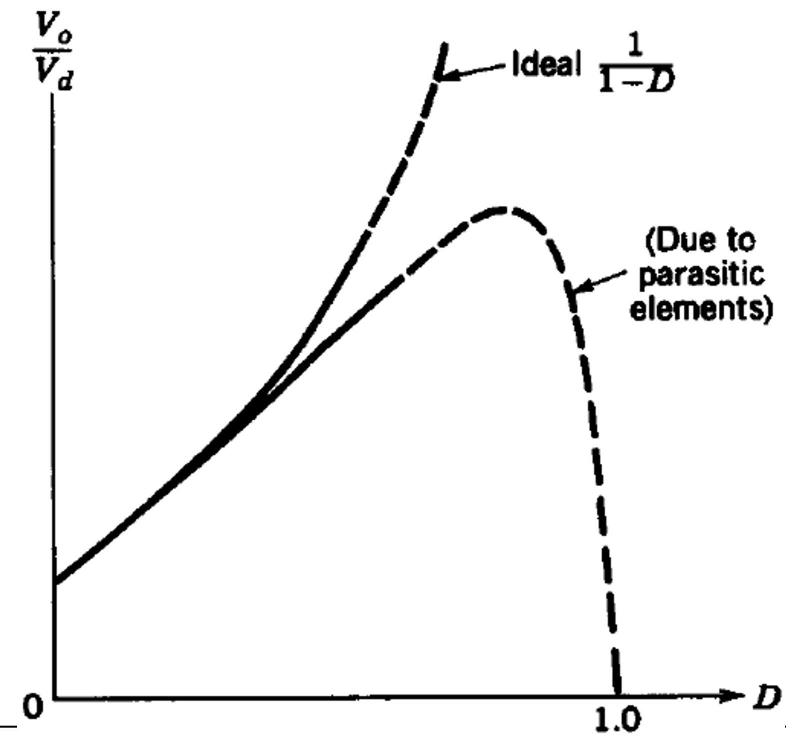
Step up converter characteristics, V_o constant



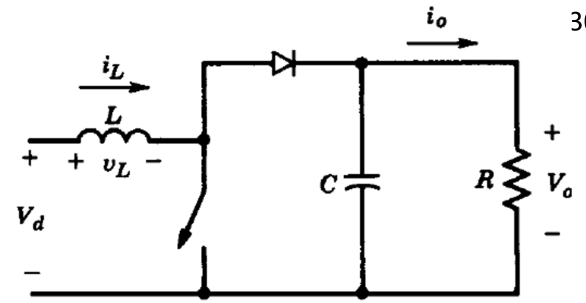
$$I_{oB,max} = 0.074 \frac{T_s V_o}{L}$$

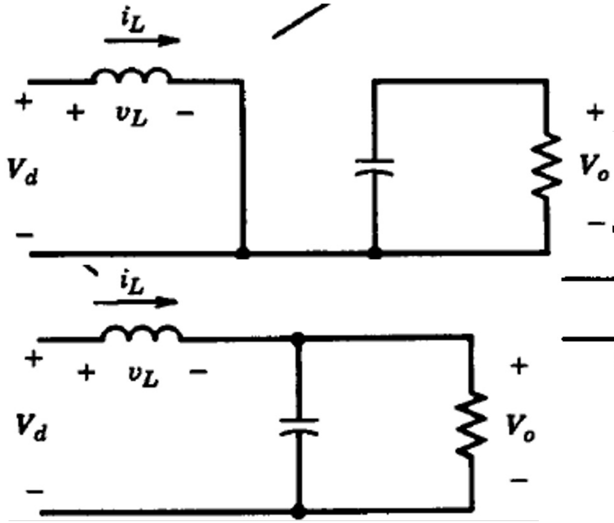
Effects of parasitics

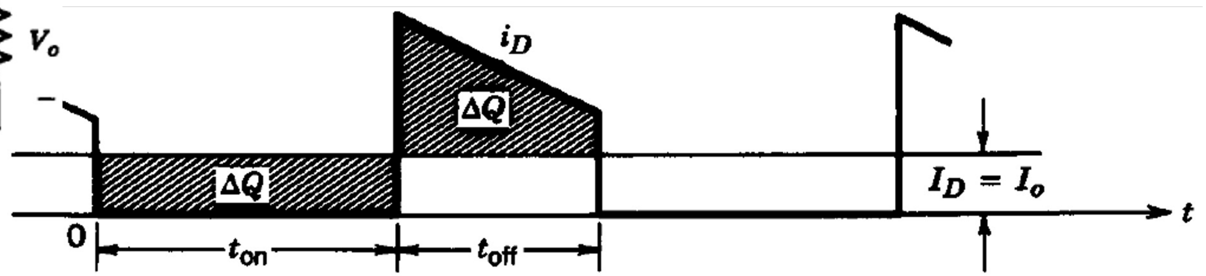
- Losses in L, diode, switch, C
- Limited also by acceptable D ratio (approx. <3)

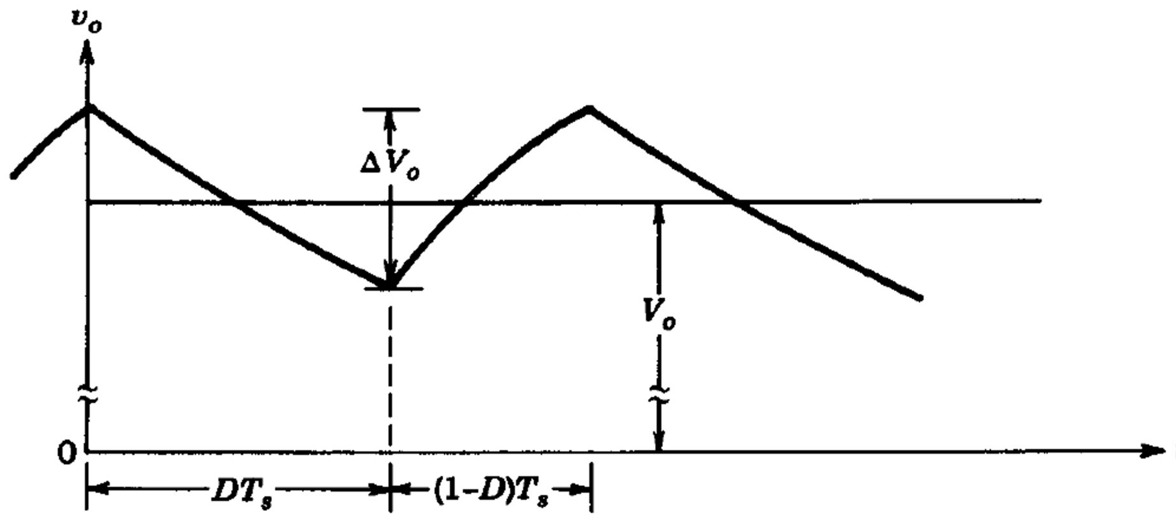


Output voltage ripple









$$\Delta V_o = \frac{\Delta Q}{C} = \frac{I_o D T_s}{C}$$

$$\frac{\Delta V_o}{V_o} = \frac{D T_s}{RC} = D\,\frac{T_s}{\tau}$$

where

$\tau = RC$ *time constant*

$\min(i_L) > 0$

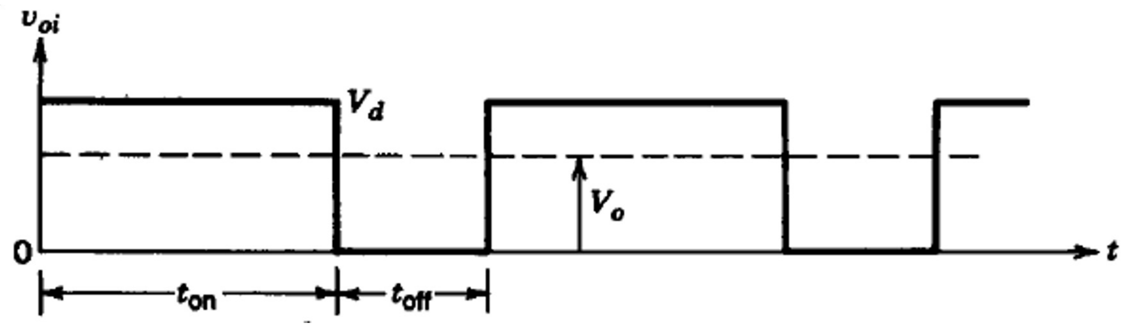
Lecture 2

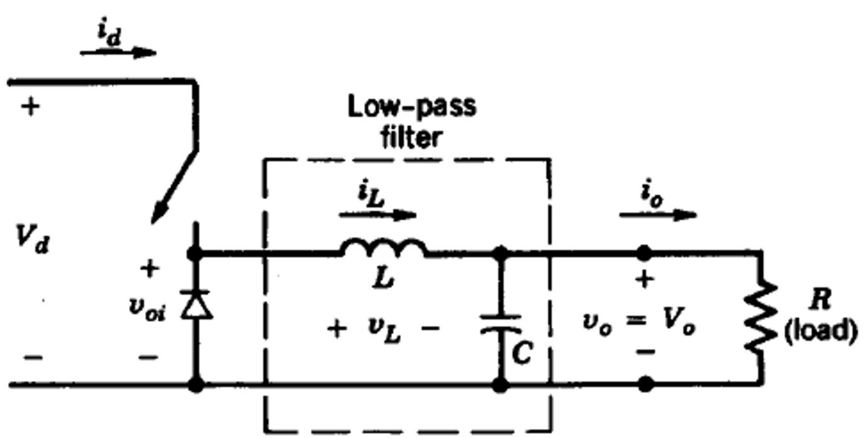
Buck/Boost DC/DC Converter

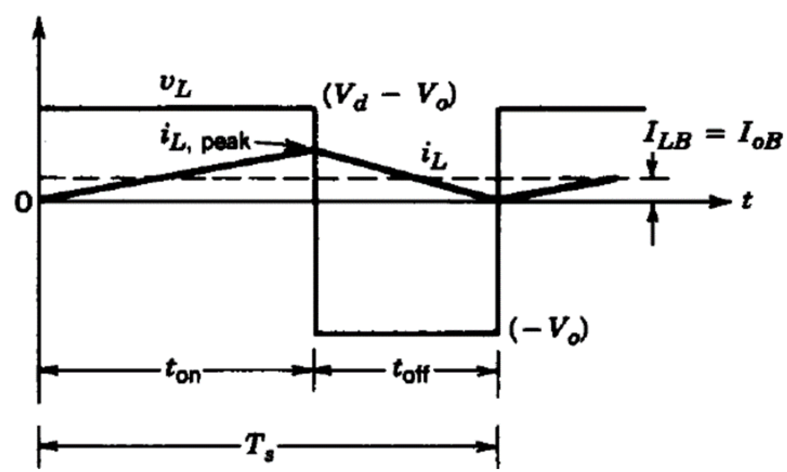
Step-down (Buck) converter

- Output voltage lower than input voltage

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

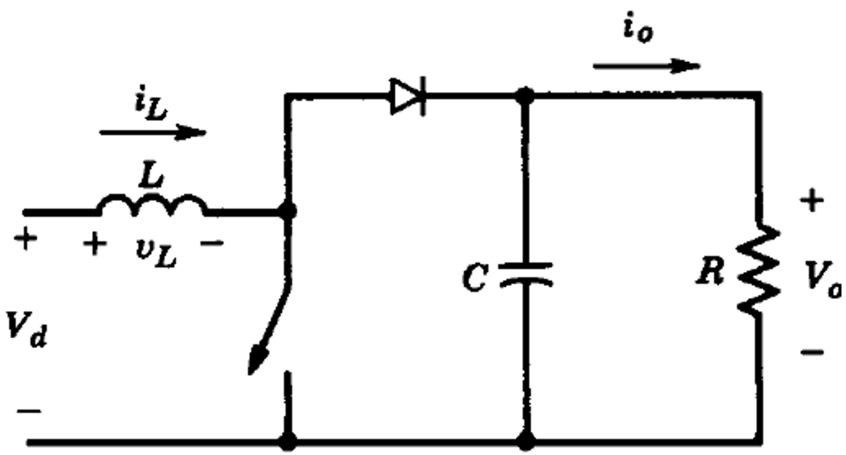


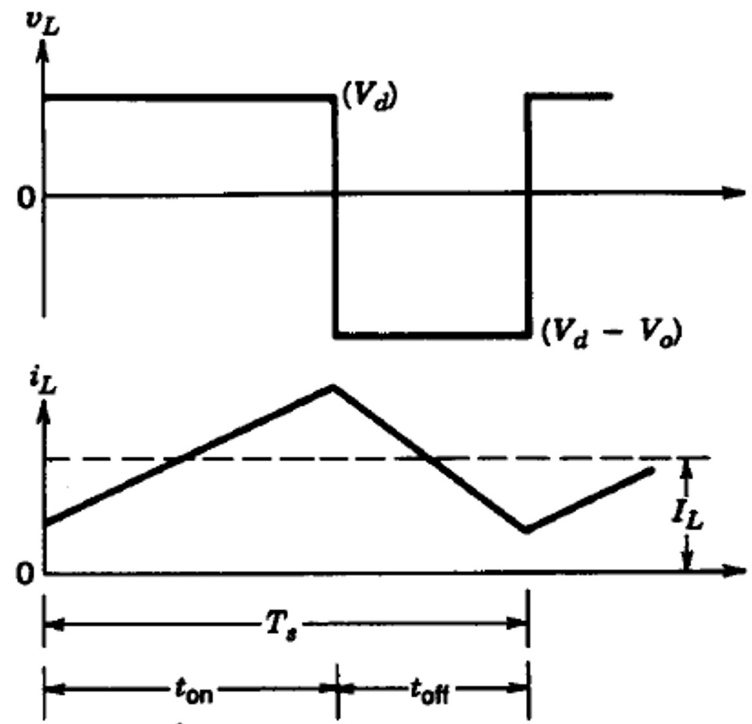




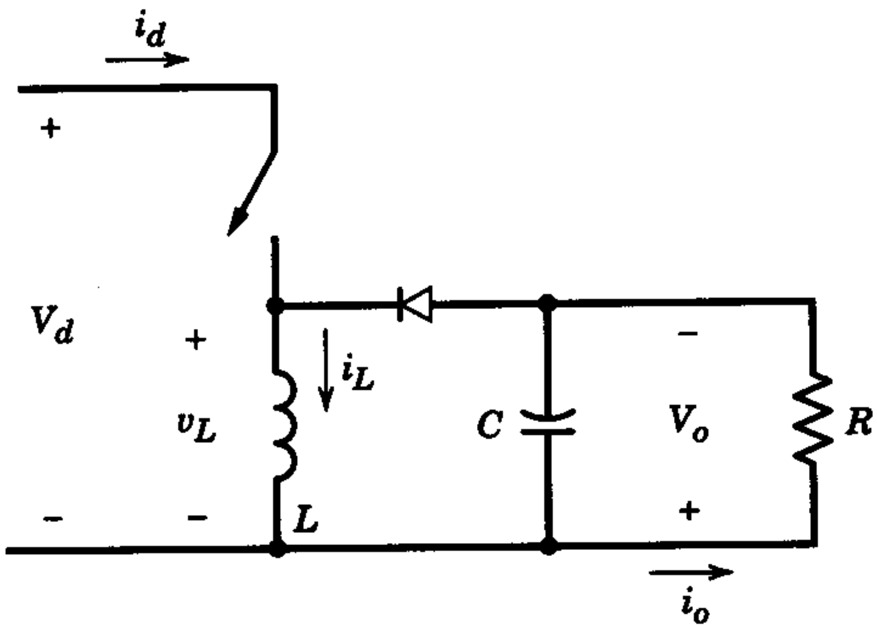
Step-up (boost) converter

- Output must be larger than input voltage
- $\frac{V_o}{V_d} = \frac{T_s}{t_{off}} = \frac{1}{1-D}$





Step-Down/Up (buck-boost) DC-DC Converter



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

Figure 7-18 Buck–boost converter.

- Negative output voltage
- The output voltage can be higher or lower than the input voltage

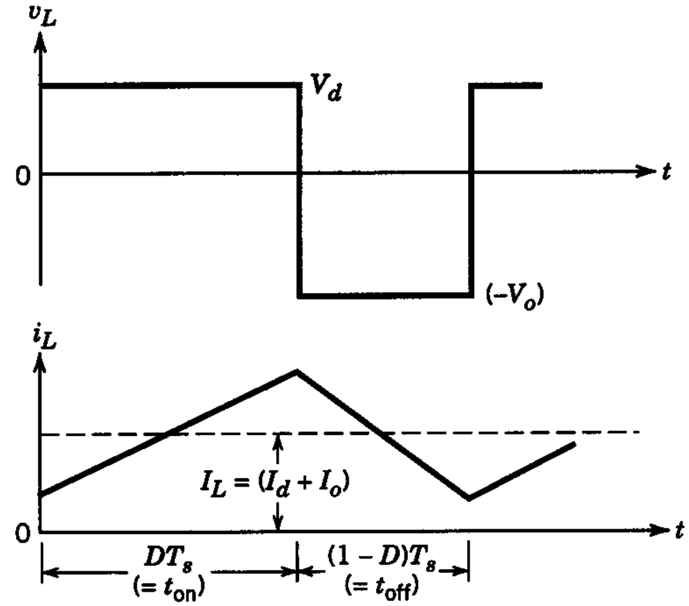
Buck-boost DC-DC Converter: Waveforms

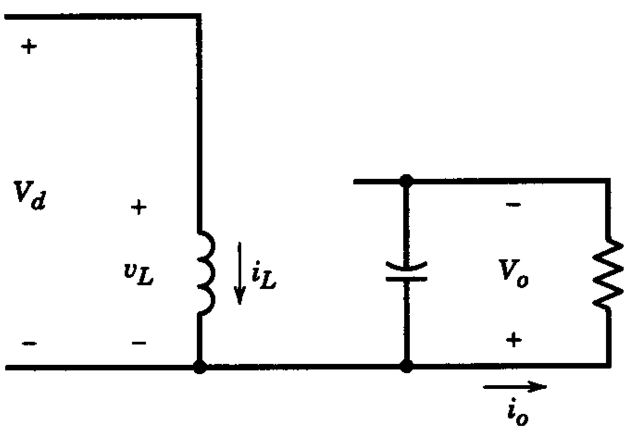
Buck-boost converter

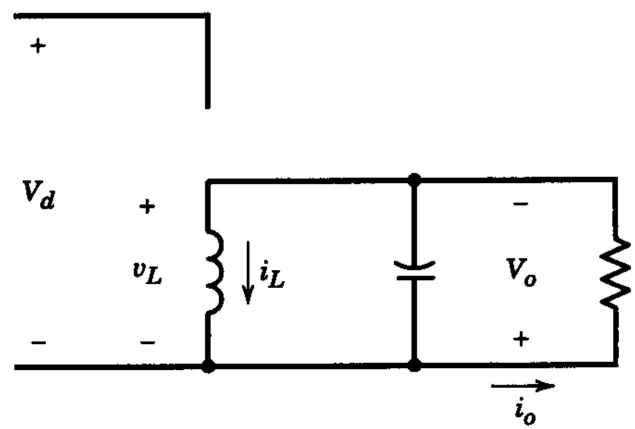
$i_L > 0$

a) Switch on

b) Switch off

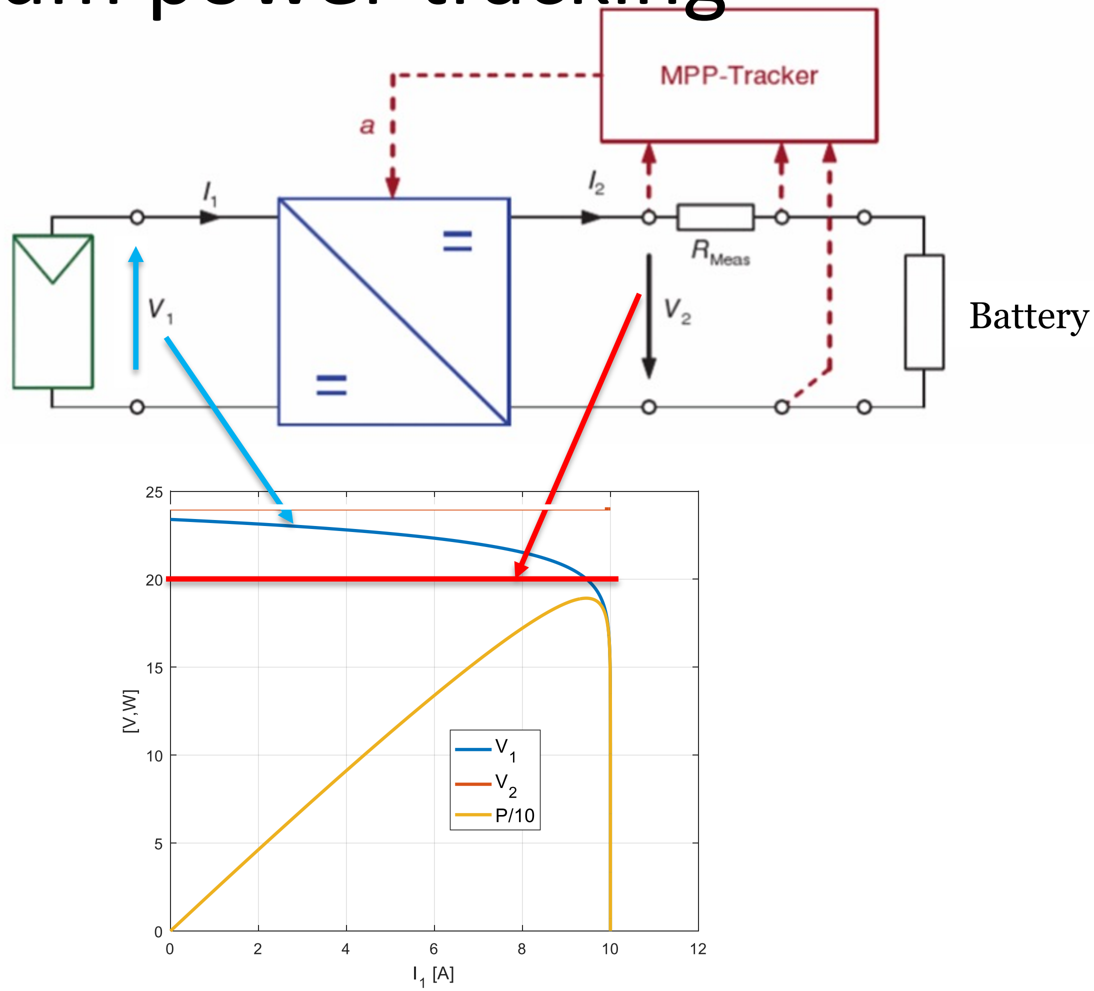






PV-panel maximum power tracking

- DC/DC conversion to optimize PV-panel voltage for maximum power
- Constant (20 V) across load
- Variable PV-panel voltage (0-23 V)
- <u>Reversed PV-polarity</u>



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