# ECEN405: Design Considerations of Converters



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# Design Considerations of Converters

- What do we design for?
  - Cost
  - Size
  - Weight
  - Energy efficiency
  - Reliability

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- What do we design for?
  - Cost
  - Size
  - Weight
  - Energy efficiency
  - Reliability
- What are our tools?
  - Switching frequency (already discussed)
  - Transistor/diode selection (already discussed)
  - Magnetic components
  - Capacitor selection
  - Thermal design

# Design Considerations of Converters

- Magnetic components
  - Size depends on switching frequency
  - Finite values (unless you wind your own)
  - Current rating and saturation
  - Resistance
  - Many types (different cores, toroidal – low magnetic flux)

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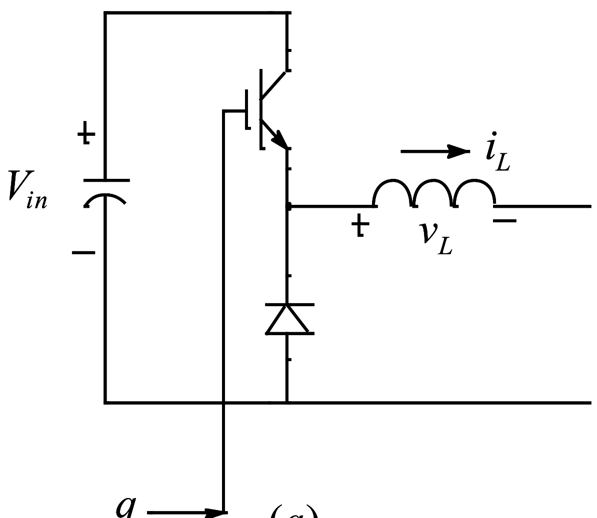
  - Voltage rating
- Thermal design
  - Switching losses = heat
  - Resistance in a circuit = heat
  - Heat sinks increase size but also reliability
  - Normal air convection, forced and liquid
  - Increases cost
  - Will talk about heat calculations in more depth later

# Steady-state operation



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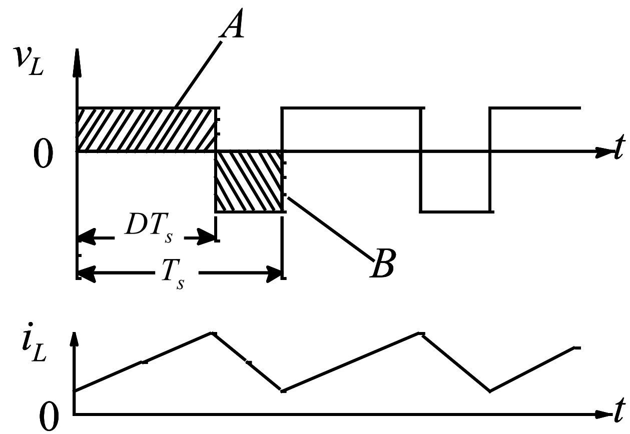
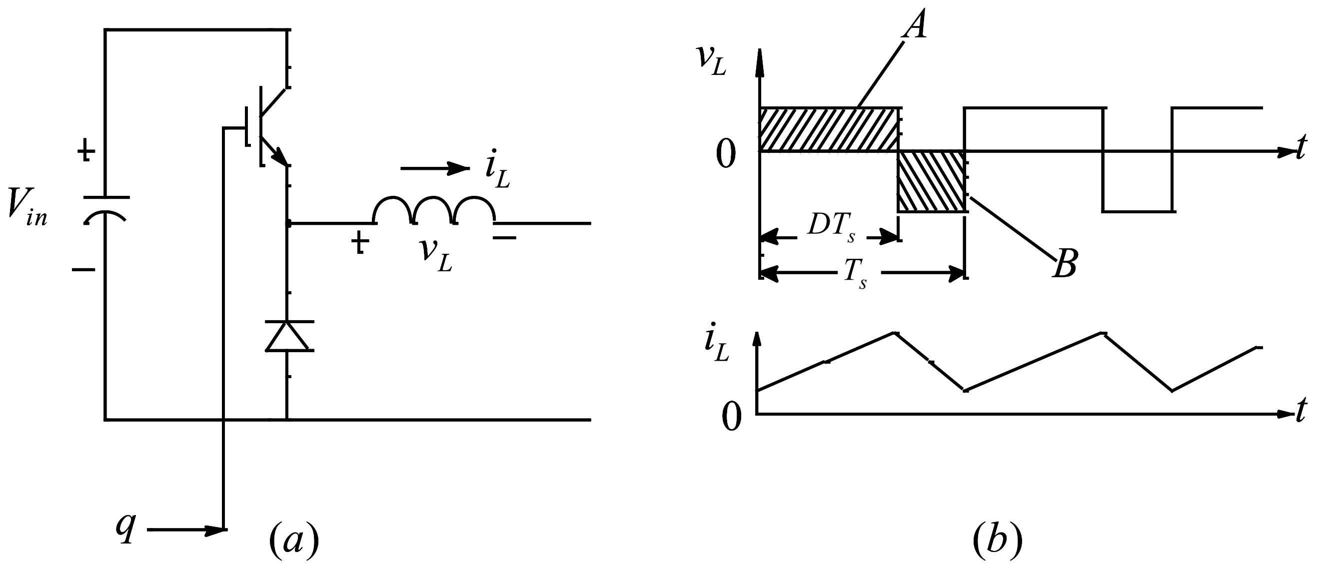


(b)

# Steady-state operation

- We make some assumptions
  - Load = constant
  - Input voltage = constant
- Waveforms repeat with the period $T_s$
- Let's consider the inductor of a switching power-pole
- If the waveform repeats, the current at $i(T_s) = i(0)$
- The average inductor voltage over $T_s = 0$:



# Steady-state operation

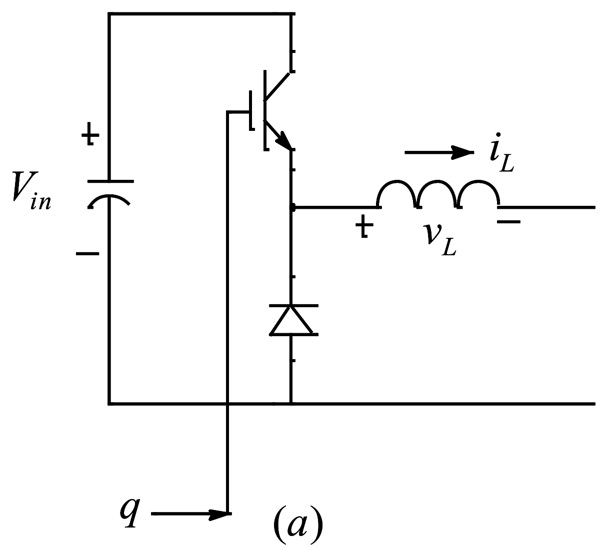
- The average inductor voltage over $T_s = 0$:

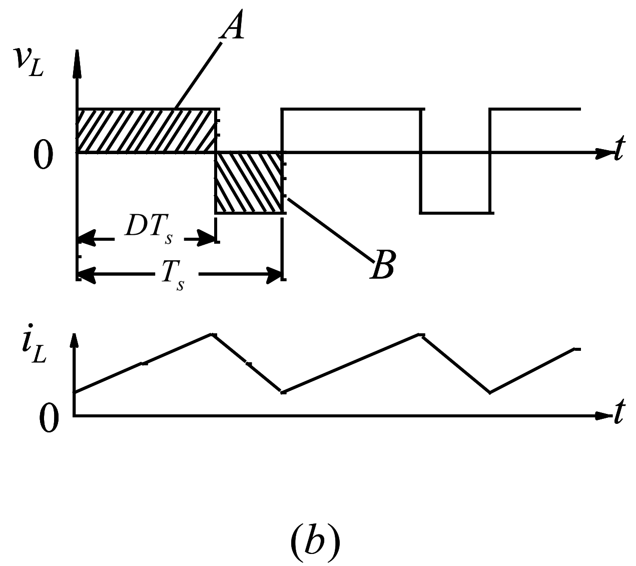
$$v_L = L\frac{di_L}{dt} \quad \Rightarrow \quad i_L(t) = \frac{1}{L}\int_{\tau} v_L \cdot d\tau$$

$$i_L(t) = i_L(0) + \frac{1}{L}\int_0^t v_L \cdot d\tau$$

$$i_L(T_s) = i_L(0)$$

$$\frac{1}{L}\int_0^{T_s} v_L \cdot d\tau = 0 \quad \Rightarrow \quad V_L = \frac{1}{T_s}\left(\underbrace{\int_0^{DT_s} v_L \cdot d\tau}_{\text{area } A} + \underbrace{\int_{DT_s}^{T_s} v_L \cdot d\tau}_{\text{area } B}\right) = 0$$

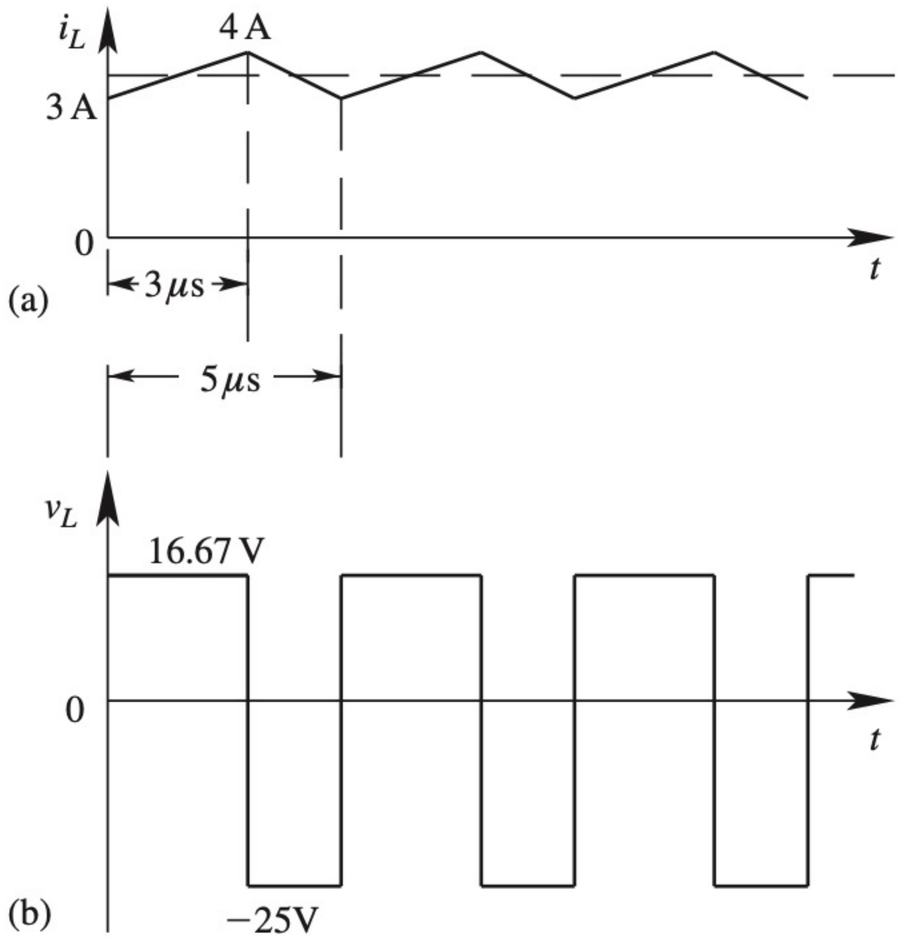


# Steady-state operation

Lets do an example:
We have a 50uH inductor…

$$v_L = L\frac{di_L}{dt} \quad \Rightarrow \quad i_L(t) = \frac{1}{L}\int_{\tau} v_L \cdot d\tau$$



# Steady-state operation

And for the capacitor?

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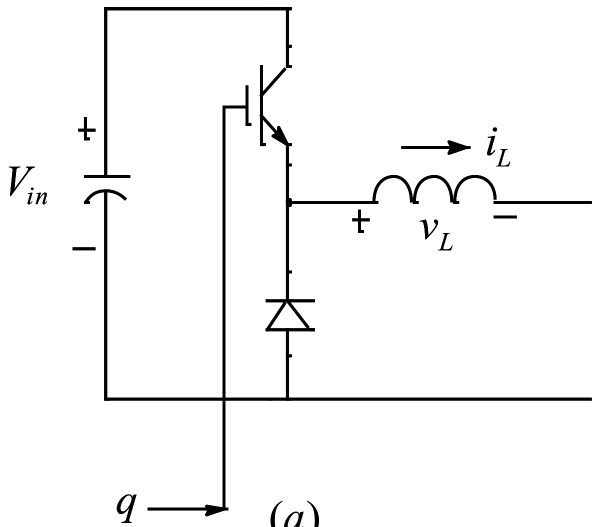


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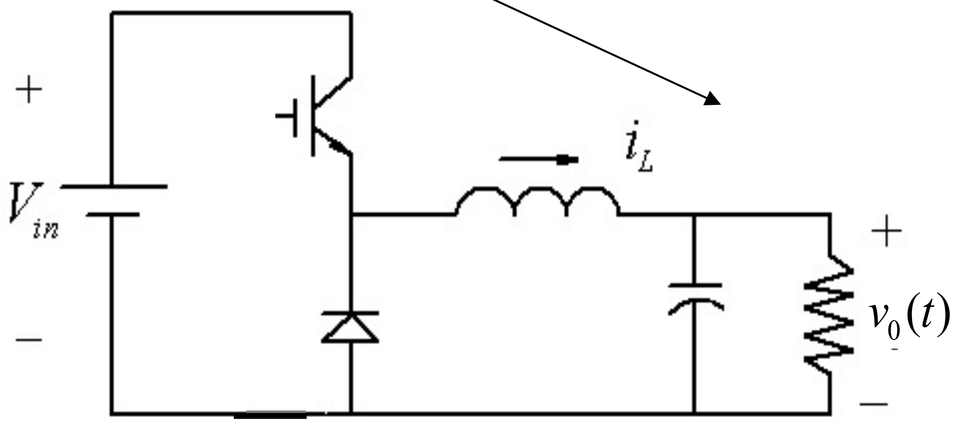
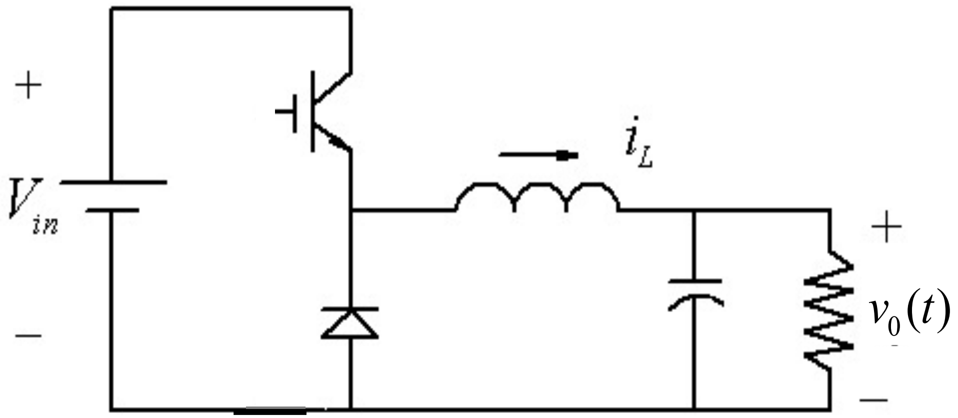


# Steady-state operation

And for the capacitor?
- Similar analysis to inductor



# Steady-state operation

And for the capacitor?

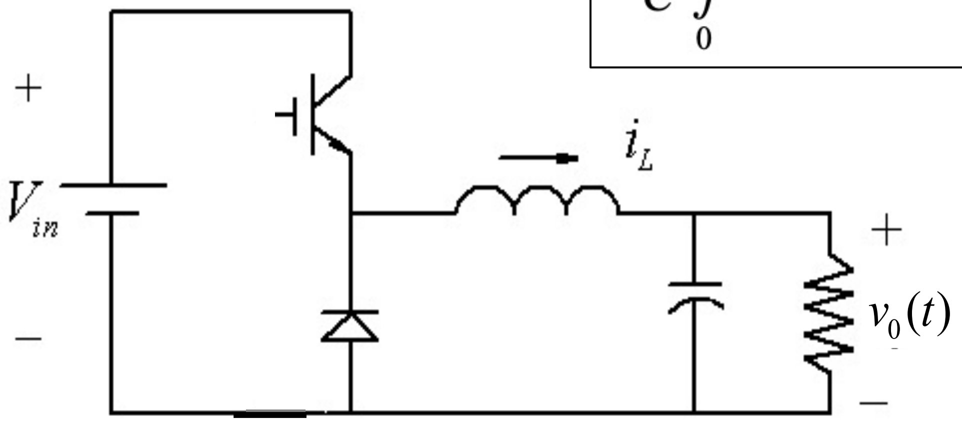
- Similar analysis to inductor

$$i_C = C\frac{dv_C}{dt} \quad \Rightarrow \quad v_C(t) = \frac{1}{C}\int_{\tau} i_C \cdot d\tau$$

$$v_C(t) = v_C(0) + \frac{1}{C}\int_0^t i_C \cdot d\tau$$

$$v_C(T_s) = v_C(0)$$

$$\frac{1}{C}\int_0^{T_s} i_C \cdot d\tau = 0 \quad \Rightarrow \quad I_C = \frac{1}{T_s}\int_0^{T_s} i_C \cdot d\tau = 0$$



# Steady-state operation

And for the capacitor?

- Similar analysis to inductor
- At $v(T_s)$ the voltage is the same as $v(0)$
- The average current integral over 1 period is 0

$$i_C = C\frac{dv_C}{dt} \quad \Rightarrow \quad v_C(t) = \frac{1}{C}\int_{\tau} i_C \cdot d\tau$$

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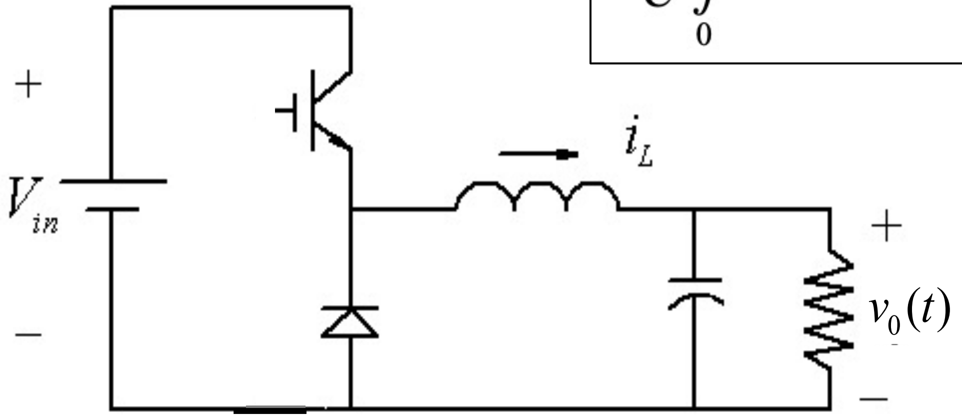

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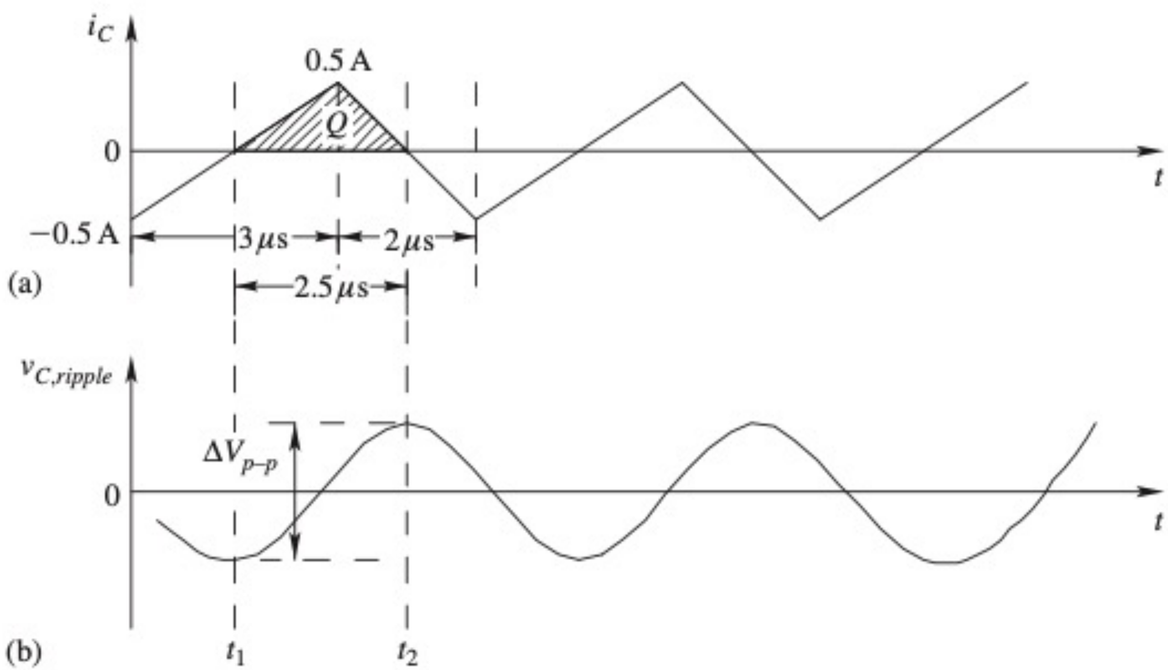
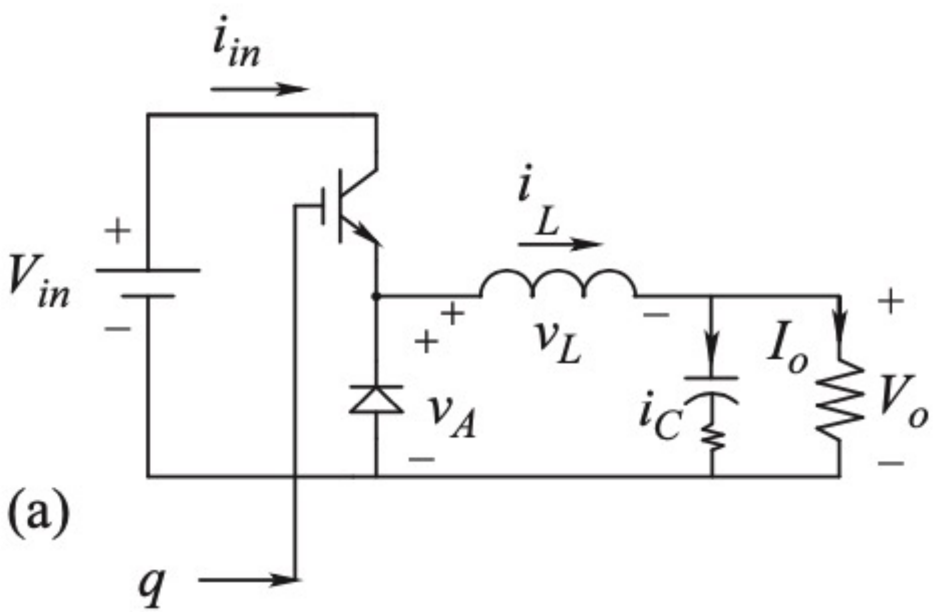


# Buck converter

- Buck converter decreases input voltage



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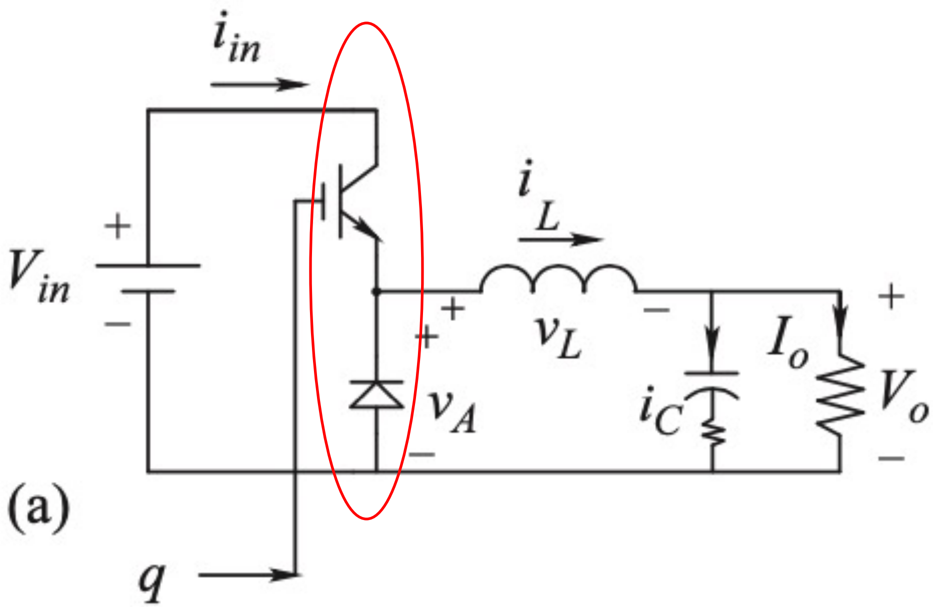

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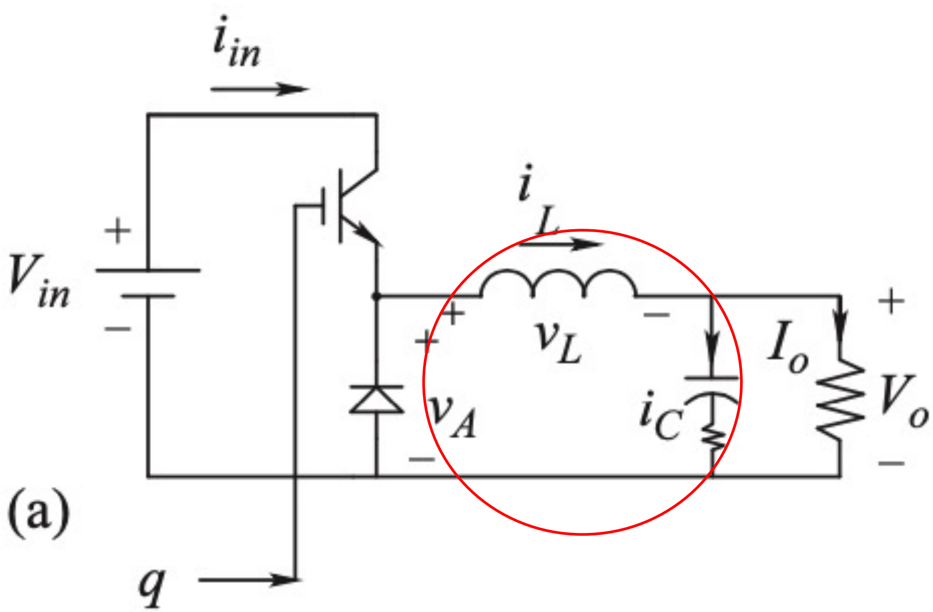
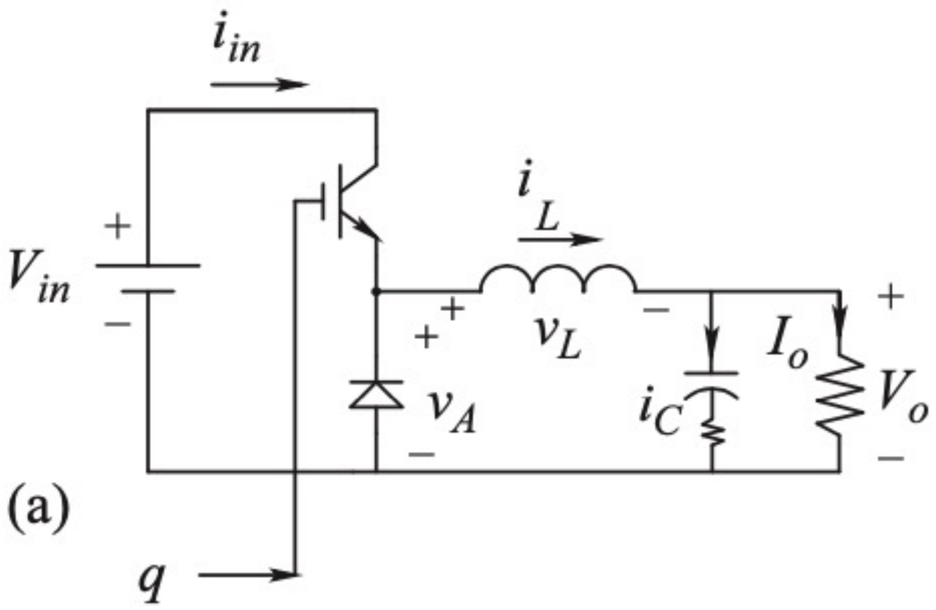
- Buck converter decreases input voltage
- Switching pole
- Second order low pass filter



# Buck converter

- Buck converter decreases input voltage
- Switching pole
- Second order low pass filter
- For analysis we make some assumptions:
  - Inductor current is continuous
  - Average inductor voltage is zero
  - Average capacitor current is zero
  - Ideal components



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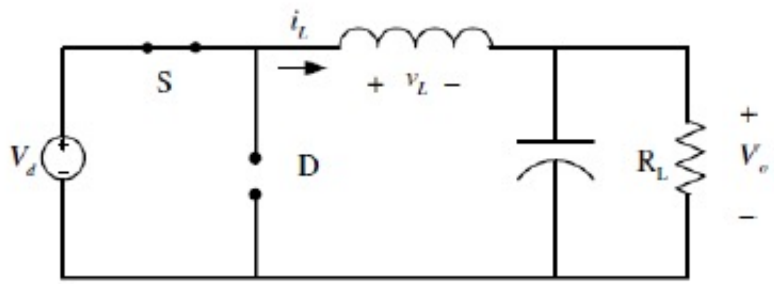
# Buck converter

- Switching analysis

When the switch is closed (transistor turned on)




- Diode is **reverse** biased
- Switch conducts inductor current
- This results in positive inductor voltage, i.e.

$$v_L = V_d - V_o$$

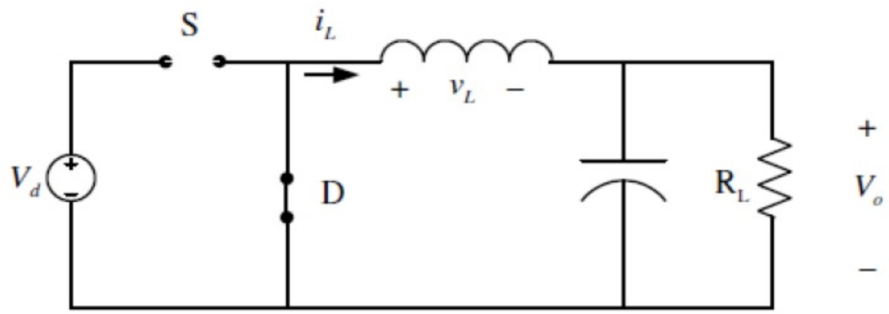
- Causes **linear increase** in inductor current:

$$v_L = L\frac{di_L}{dt} \Rightarrow i_L = \frac{1}{L}\int v_L dt$$

# Buck converter

## - Switching analysis

When the switch is open (transistor turned off)




- Because of inductive energy storage, $i_L$ **continues to flow**
- Diode is **forward** biased
- Current now flows (freewheeling) through the diode
- Inductor voltage is $v_L = -V_o$

# Buck converter

- Switching analysis

$$\Rightarrow (\Delta i_L)_{\text{closed}} = \left(\frac{V_d - V_o}{L}\right) DT$$

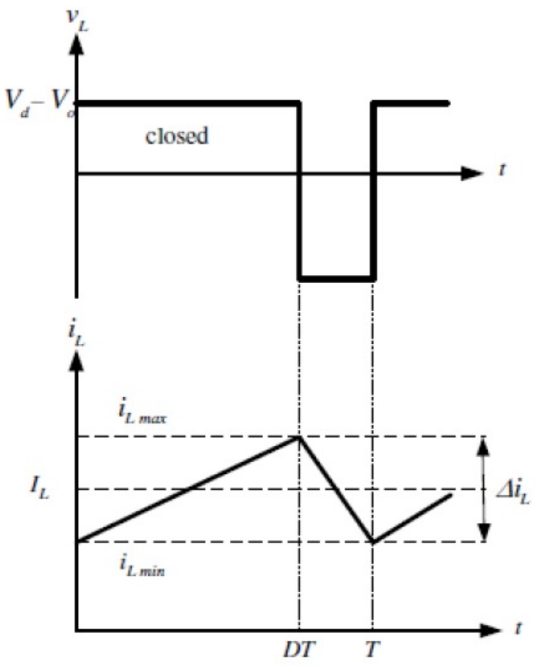
For switch opened:

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

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

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

$$\Rightarrow (\Delta i_L)_{\text{opened}} = \left(\frac{-V_o}{L}\right)(1-D)T$$




$$v_L = L\frac{di_L}{dt} \quad \Rightarrow \quad i_L(t) = \frac{1}{L}\int_\tau v_L \cdot d\tau$$

$$i_C = C\frac{dv_C}{dt} \quad \Rightarrow \quad v_C(t) = \frac{1}{C}\int_\tau i_C \cdot d\tau$$

So the change of $i_L$ over one period must be zero

$$\left(\Delta i_L\right)_{\text{closed}} + \left(\Delta i_L\right)_{\text{opened}} = 0$$

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

$$\boxed{V_o = DV_d}$$ **eqn 7.3**

Neglecting circuit losses, input power = output power

so $V_d I_d = V_o I_o$

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D}$$ **eqn 7.4**

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  - We want to smooth output voltage
  - Need to consider tolerable limits (user defined)
  - Typically communicated as a percentage
  - CCM, inductor ripple must be positive (also usually defined)

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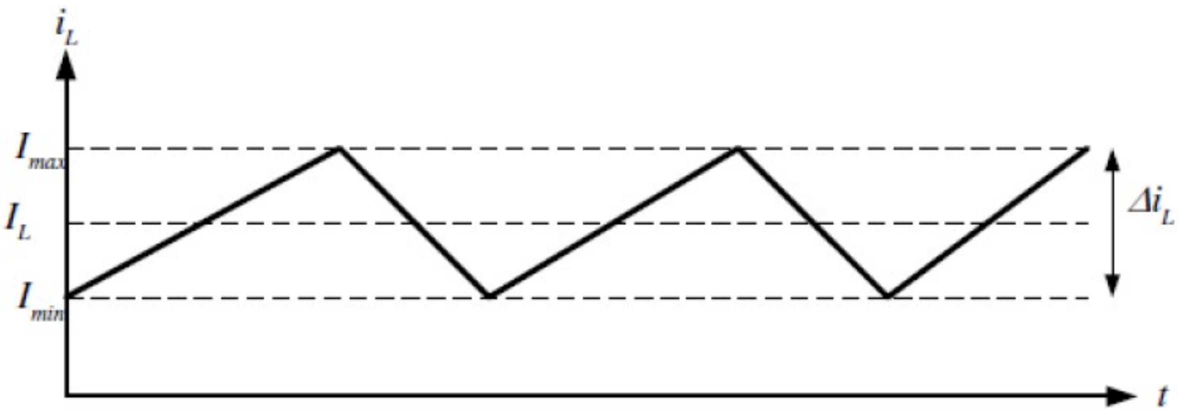
- Filter design
  - We want to smooth output voltage
  - Typically communicated as a percentage
  - CCM, inductor ripple must be positive (also usually defined)
  - Equations usually give you exact values assuming ideal…
    - Must size for realistic conditions

# Maximum, Minimum and Average Inductor Current




Average inductor current = average current in RL

$$\Rightarrow I_L = R_L = \frac{V_o}{R}$$

Maximum and minimum currents:

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

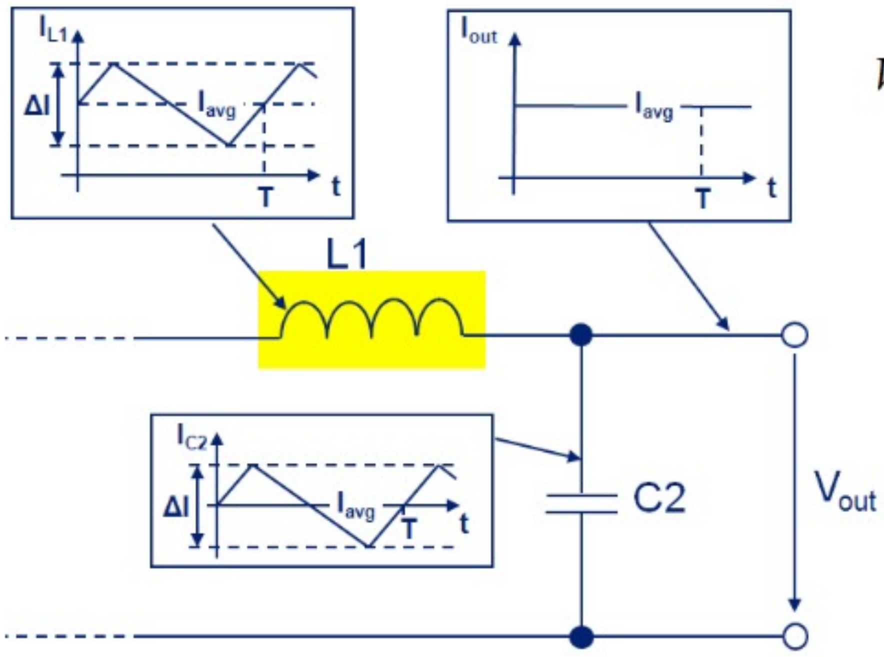
$$= V_o\left(\frac{1}{R} + \frac{(1-D)}{2Lf}\right)$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2}$$

$$= V_o\left(\frac{1}{R} - \frac{(1-D)}{2Lf}\right)$$

# Buck converter

- Filter design




$$V_{L1} = L_1 \cdot \frac{di_{L1}}{dt}$$

$$= L_1 \cdot \frac{\Delta I_{L1}}{(1-D) \cdot T} = V_{out}$$

$$L_1 = \frac{V_{out} \cdot (1-D)}{f_{sw} \cdot \Delta I_{L1}}$$

# Buck converter

- Filter design

$$L = \frac{\left(V_{IN} - V_{OUT}\right) \cdot V_{OUT}}{V_{IN} \cdot f_{sw} \cdot \Delta I_{L}}$$

$$L_1 = \frac{V_{out} \cdot \left(1 - D\right)}{f_{sw} \cdot \Delta I_{L1}}$$

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  - Capacitor needs to keep a constant output voltage
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  - Should also have an input capacitor to reduce switching noise
    - We are more concerned with output filter in the course

# Buck output filter

- Filter design
  - Inductor

$$L = \frac{V_O(1-D)}{f_{sw}\Delta I_L}$$

  - Capacitor

$$C_{out} = \frac{{I_{L(max)}}^2 L}{(V_o + V_{os})^2 - {V_0}^2}$$