DC Voltage regulation (review from previous class)

The switching (step down) voltage regulator

Analysis:

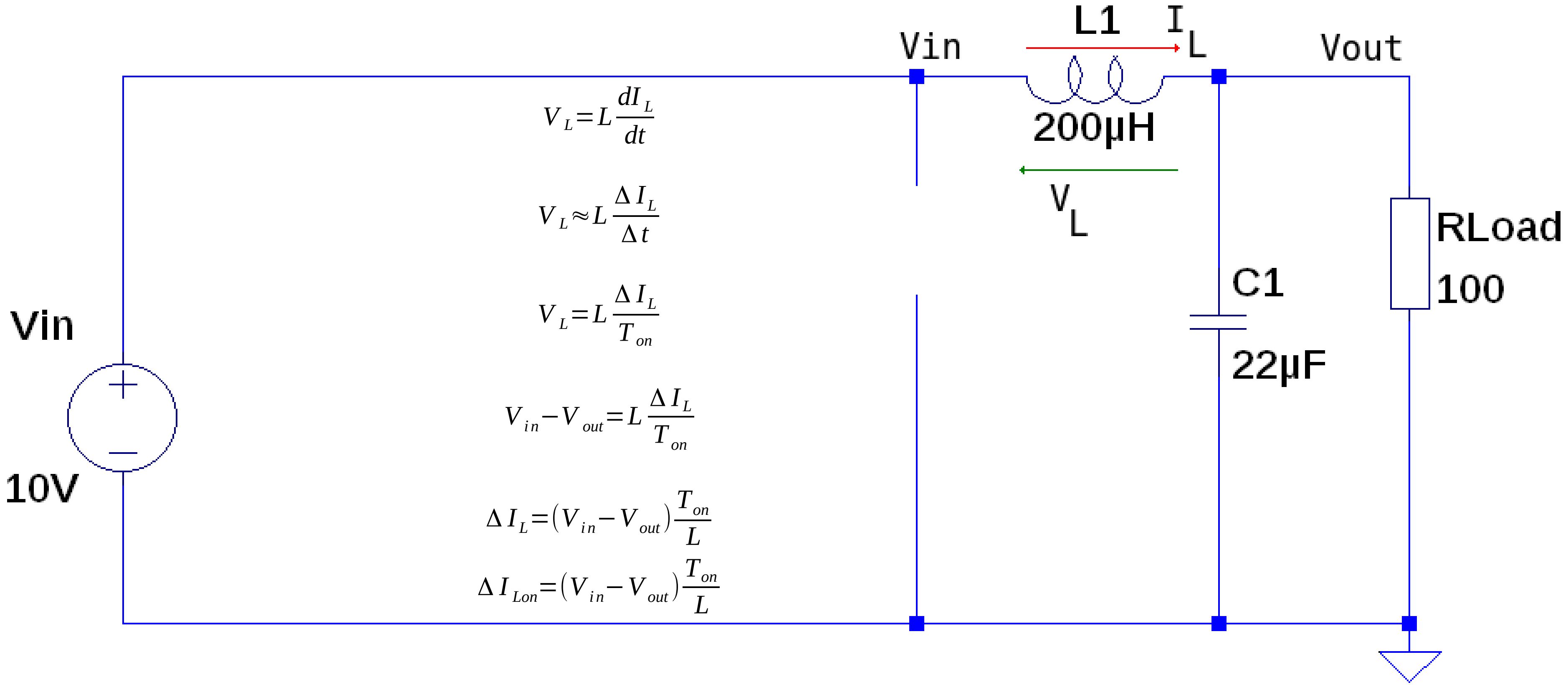
Assumptions:

Inductor currents rise and fall linearly during a switching cycle

Capacitor voltages remain roughly constant during a switching cycle

DC Voltage regulation

The switching (step down) voltage regulator



$$V_L = L\frac{dI_L}{dt}$$

$$V_L \approx L\frac{\Delta I_L}{\Delta t}$$

$$V_L = L\frac{\Delta I_L}{T_{on}}$$

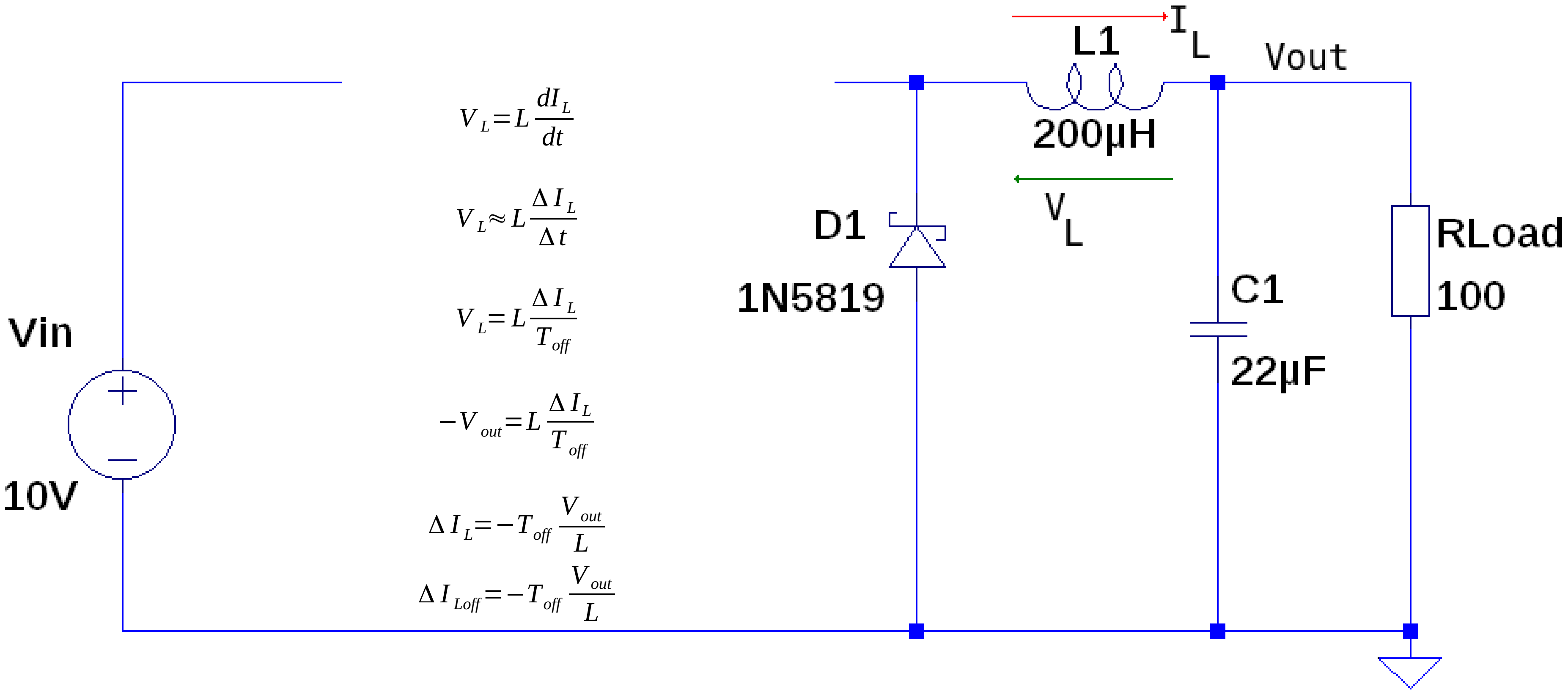
$$V_{in} - V_{out} = L\frac{\Delta I_L}{T_{on}}$$

$$\Delta I_L = (V_{in} - V_{out})\frac{T_{on}}{L}$$

$$\Delta I_{Lon} = (V_{in} - V_{out})\frac{T_{on}}{L}$$

DC Voltage regulation

The switching (step down) voltage regulator



$$V_L = L\frac{dI_L}{dt}$$

$$V_L \approx L\frac{\Delta I_L}{\Delta t}$$

$$V_L = L\frac{\Delta I_L}{T_{off}}$$

$$-V_{out} = L\frac{\Delta I_L}{T_{off}}$$

$$\Delta I_L = -T_{off}\frac{V_{out}}{L}$$

$$\Delta I_{Loff} = -T_{off}\frac{V_{out}}{L}$$

DC Voltage regulation

The switching (step down) voltage regulator

When the regulator has settled down:

$$\Delta I_{Loff} = -\Delta I_{Lon}$$

$$-T_{off}\frac{V_{out}}{L} = -(V_{in} - V_{out})\frac{T_{on}}{L}$$

$$T_{off}\frac{V_{out}}{L} = (V_{in} - V_{out})\frac{T_{on}}{L}$$

$$T_{off}V_{out} = (V_{in} - V_{out})T_{on}$$

$$(T_{on} + T_{off})V_{out} = V_{in}T_{on}$$

$$V_{out} = V_{in}\frac{T_{on}}{(T_{on} + T_{off})}$$

$$Period = T = T_{on} + T_{off}$$

$$Duty\,Cycle = D = \frac{T_{on}}{T}$$

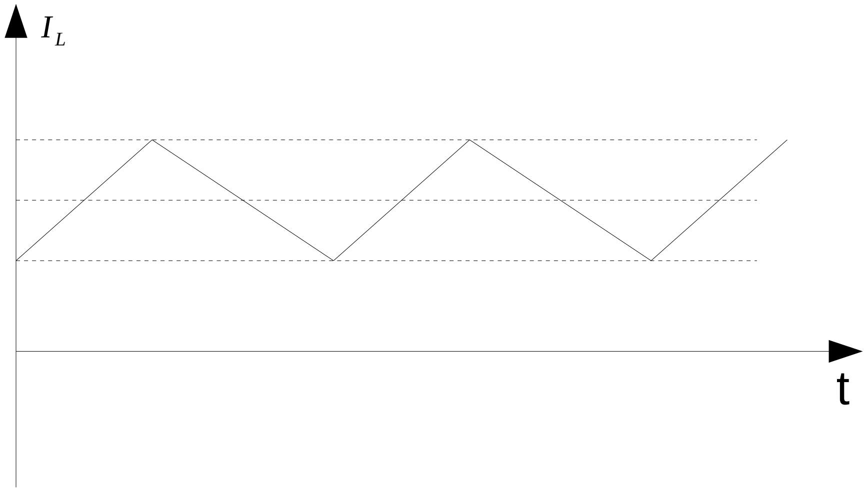
$$V_{out} = V_{in}\frac{DT}{T}$$

$$\boxed{V_{out} = DV_{in}}$$

DC Voltage regulation

Calculating a suitable value for L

From before: $\Delta I_{Lon} = (V_{in} - V_{out}) \frac{T_{on}}{L}$



DC Voltage regulation

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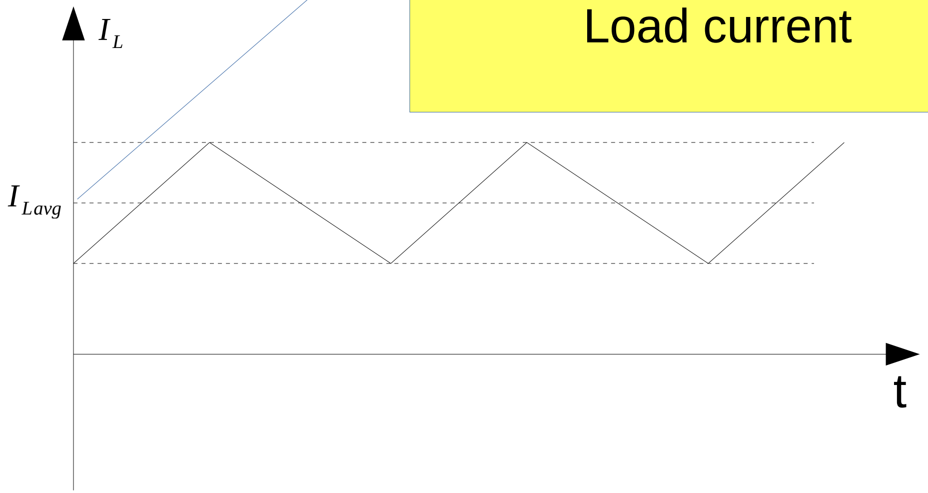

Average inductor current = Load current

DC Voltage regulation

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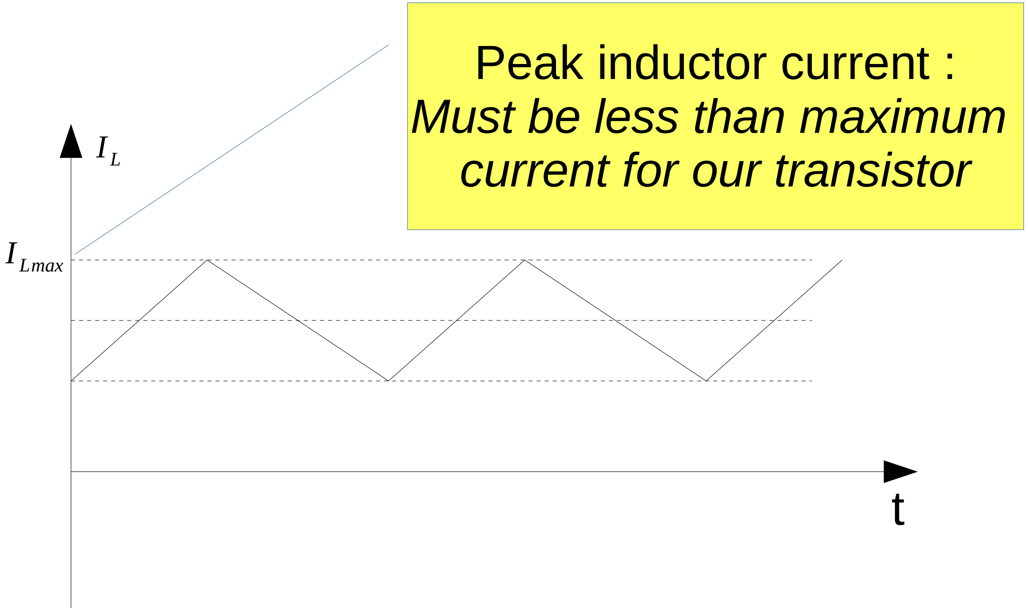

DC Voltage regulation

Calculating a suitable value for L

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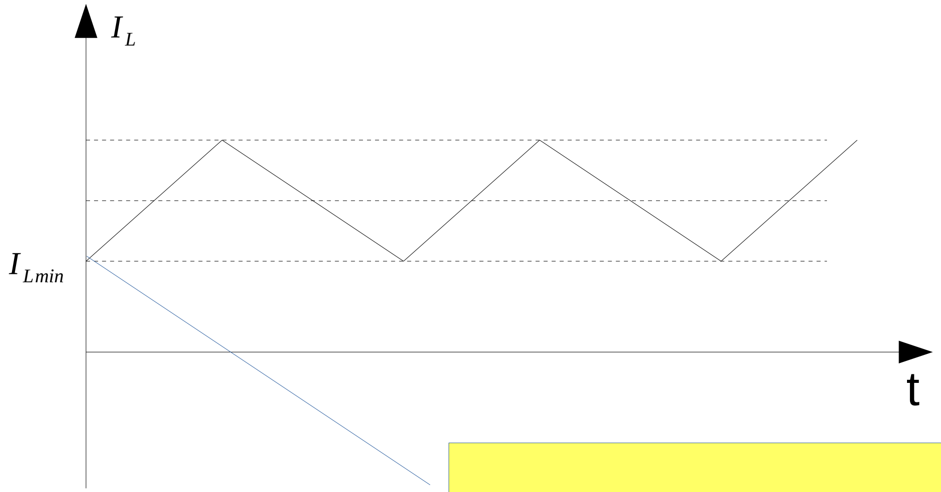


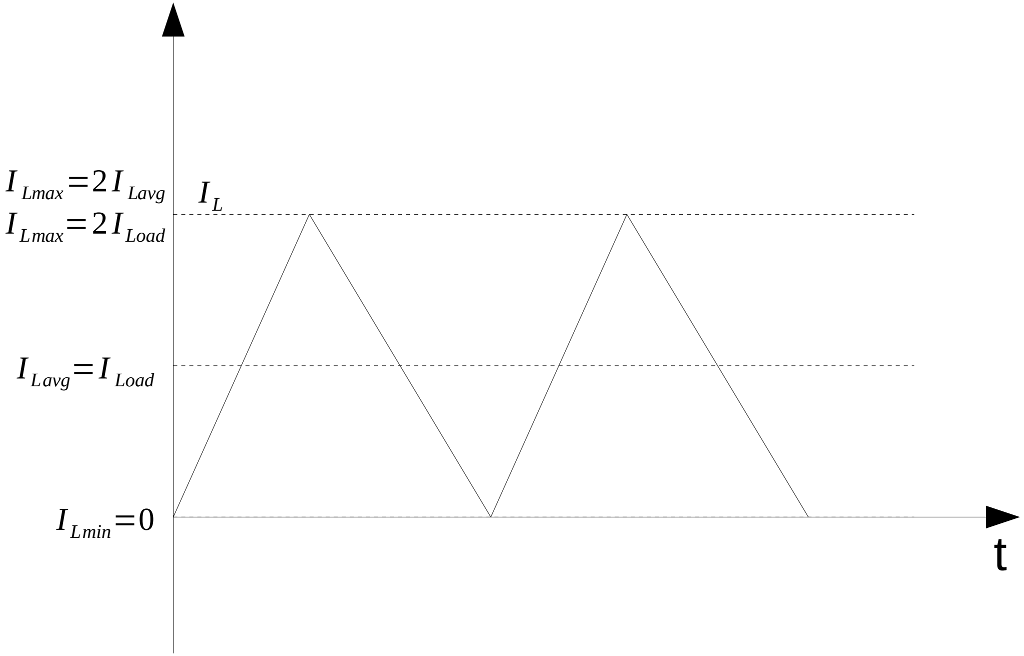
Minimum inductor current :
Should be kept above zero

DC Voltage regulation

Calculating a suitable value for L

We could calculate a minimum value of for the inductor using two approaches

(1) Assume that the inductor is so small that its current is just touching zero at the end of the off part of the switching cycle



DC Voltage regulation

Calculating a suitable value for L

Based on this assumption we get

$$\Delta I_{Lon} = 2 I_{Load} = (V_{in} - V_{out}) \frac{T_{on}}{L}$$

Leading to:

$$\Delta I_{Lon} = 2 I_{Load} = (V_{in} - V_{out}) \frac{T_{on}}{L}$$

$$L = (V_{in} - V_{out}) \frac{T_{on}}{2 I_{Load}}$$

DC Voltage regulation

Calculating a suitable value for L

Example:
A buck regulator has a switching frequency of 100kHz. The input voltage is 12V, the output voltage is 3V. The load current is 3A. Determine the minimum inductance of the filter inductor.

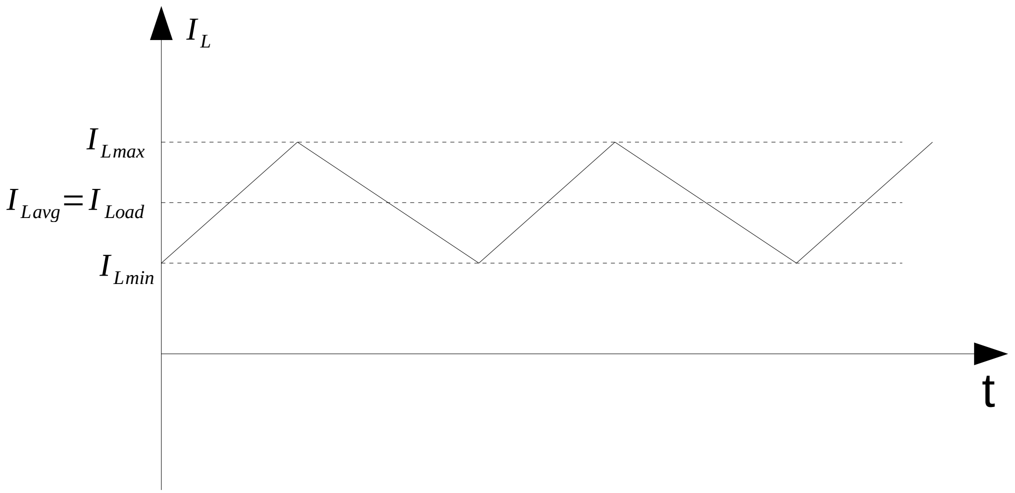
$$V_o = D V_{in}$$
$$D = \frac{V_{out}}{V_{in}}$$
$$D = \frac{3}{12}$$
$$D = 0.25$$
$$L = (V_{in} - V_{out}) \frac{T_{on}}{2 I_{Load}}$$
$$L = (12 - 3) \frac{0.25 * 10 \mu s}{2.3}$$
$$L = 3.75 \mu H$$

DC Voltage regulation

Calculating a suitable value for L

A second approach to calculating L is as follows:

(2) The peak inductor current is dictated by other circuit elements e.g. the MOSFET, Diode, or power supply.



DC Voltage regulation

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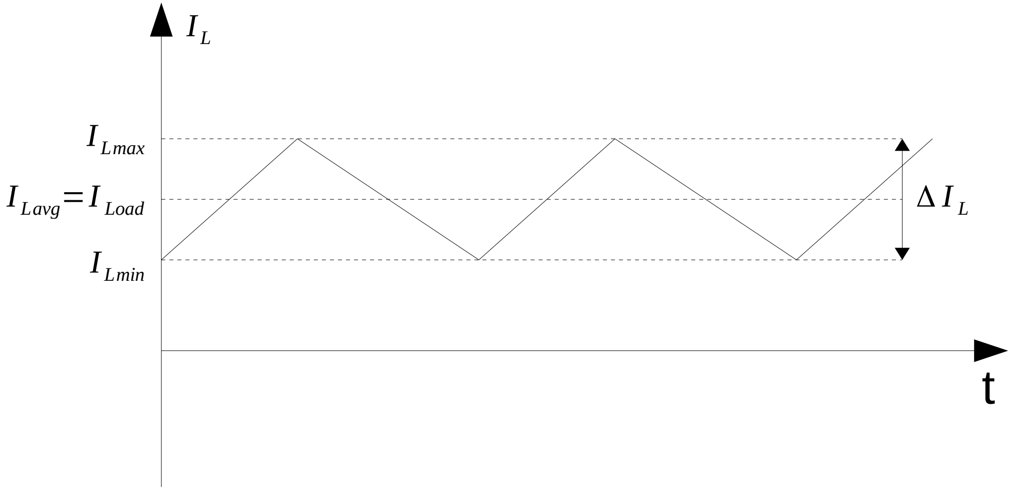

$$\Delta I_L = 2(I_{Lmax} - I_{Load})$$

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

DC Voltage regulation

Calculating a suitable value for L

Example:
A buck regulator has a switching frequency of 100kHz. The input voltage is 12V, the output voltage is 3V. The load current is 3A. The peak inductor current must be kept below 3.5A. Determine the minimum inductance of L that achieves this.

$$V_o = D V_{in}$$

$$D = \frac{V_{out}}{V_{in}}$$

$$D = \frac{3}{12}$$

$$D = 0.25$$

DC Voltage regulation

Calculating a suitable value for L

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$$\Delta I_L = 2(3.5 - 3)$$
$$\Delta I_L = 1 A$$

DC Voltage regulation

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$$L = (V_{in} - V_{out}) \frac{T_{on}}{\Delta I_L}$$
$$L = (12 - 3) \frac{0.25 * 10 \mu s}{1}$$
$$L = 22.5 \mu H$$

DC Voltage regulation

Calculating a suitable value for L

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$$\Delta I_L = 1A$$

$$L = (V_{in} - V_{out}) \frac{T_{on}}{\Delta I_L}$$
$$L = (12 - 3) \frac{0.25 * 10 \mu s}{1}$$
$$L = 22.5 \mu H$$

Note: The calculations for L assume ideal components. You will find that these values need to be increased in practice

DC Voltage regulation

Calculating a suitable value for C

The job of the capacitor is to maintain a stable output voltage

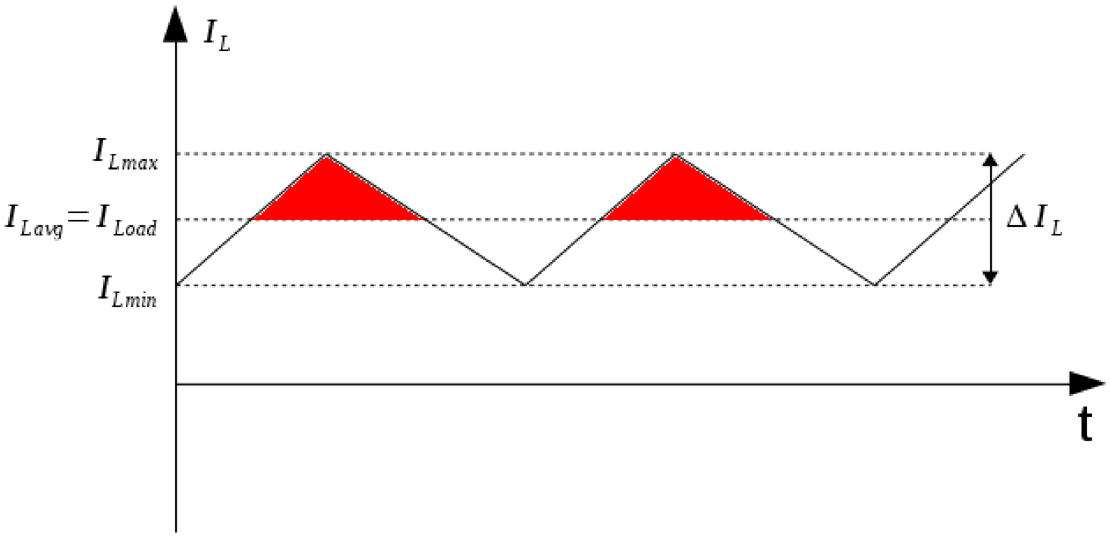
The capacitor must absorb extra current supplied through L

The capacitor must supply load current when the current coming through L is too small

DC Voltage regulation

Calculating a suitable value for C

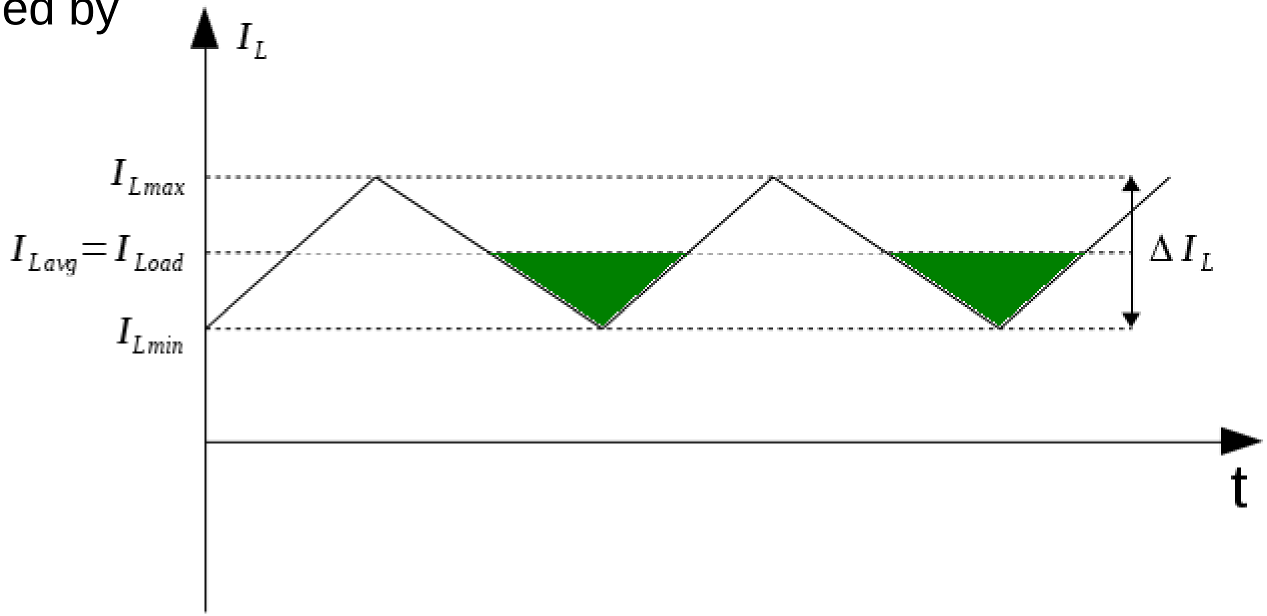
The red areas represent charge that must be aborbed by the capacitor



DC Voltage regulation

Calculating a suitable value for C

The green areas represent charge that must be supplied by the capacitor



DC Voltage regulation

Calculating a suitable value for C

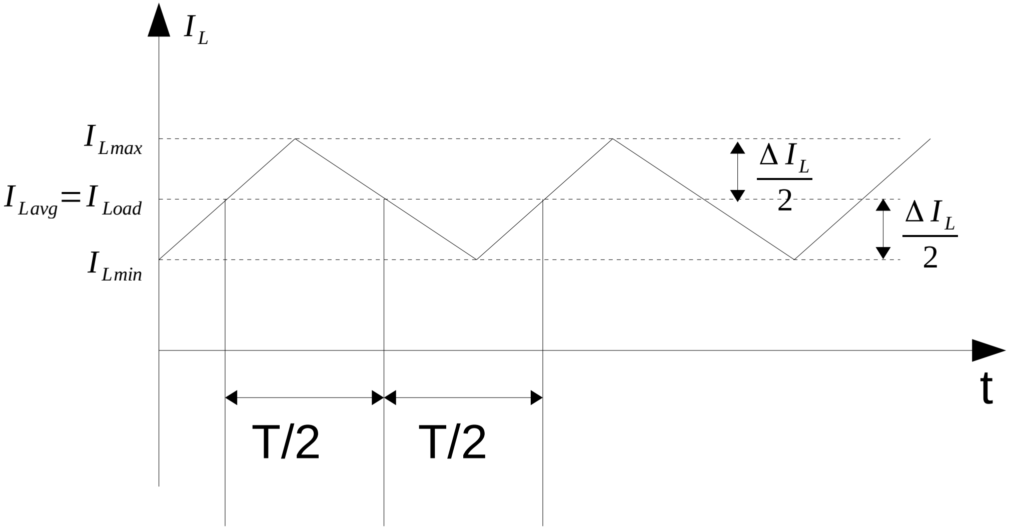
We use the geometry of triangles to estimate the amount of charge involved in each transfer

$$Area = half\ the\ base\ x\ perpendicular\ height$$

$$Area = Charge = I.t = Q$$

$$Q = \frac{1}{2}\left(\frac{T}{2}\right)\left(\frac{\Delta I_L}{2}\right)$$

$$Q = \frac{T\Delta I_L}{8}$$



DC Voltage regulation

Calculating a suitable value for C

The excess/deficit of charge supplied during each part of the switching cycle changes the voltage across the capacitor (and hence Vout) as follows:

$$\Delta V = \frac{\Delta Q}{C}$$

During the time of excess (red triangle) $\Delta V = \frac{T \Delta I_L}{8C}$

At the beginning of the charge period the capacitor voltage is at it’s minimum. At the end of this time, the capacitor voltage is at it’s maximum. Thus this represents the peak-peak voltage ripple across the capacitor

DC Voltage regulation

Calculating a suitable value for C

Example:
A buck regulator has a switching frequency of 100kHz. The input voltage is 12V, the output voltage is 3V. The load current is 3A. The inductor current swings between 4A and 2A. Calculate a suitable size of C such that the output voltage ripple is less than 100mV

$$\Delta V = \frac{T \Delta I_L}{4C}$$

$$C = \frac{T \Delta I_L}{8 \Delta V}$$

$$C = \frac{10 \mu s \, 2A}{8.100 \, mV}$$

$$C = 25 \mu F$$

DC Voltage regulation

Example:
A buck regulator has a switching frequency of 50kHz. The input voltage is 12V, the output voltage is 6V. The load current is 2A. The inductor current must be limited to 3A. The output voltage ripple must be less than 100mV. Calculate suitable values for L and C. Verify by simulation