DC Voltage regulation (review from previous class)

The step up (Boost) voltage regulator

Analysis:

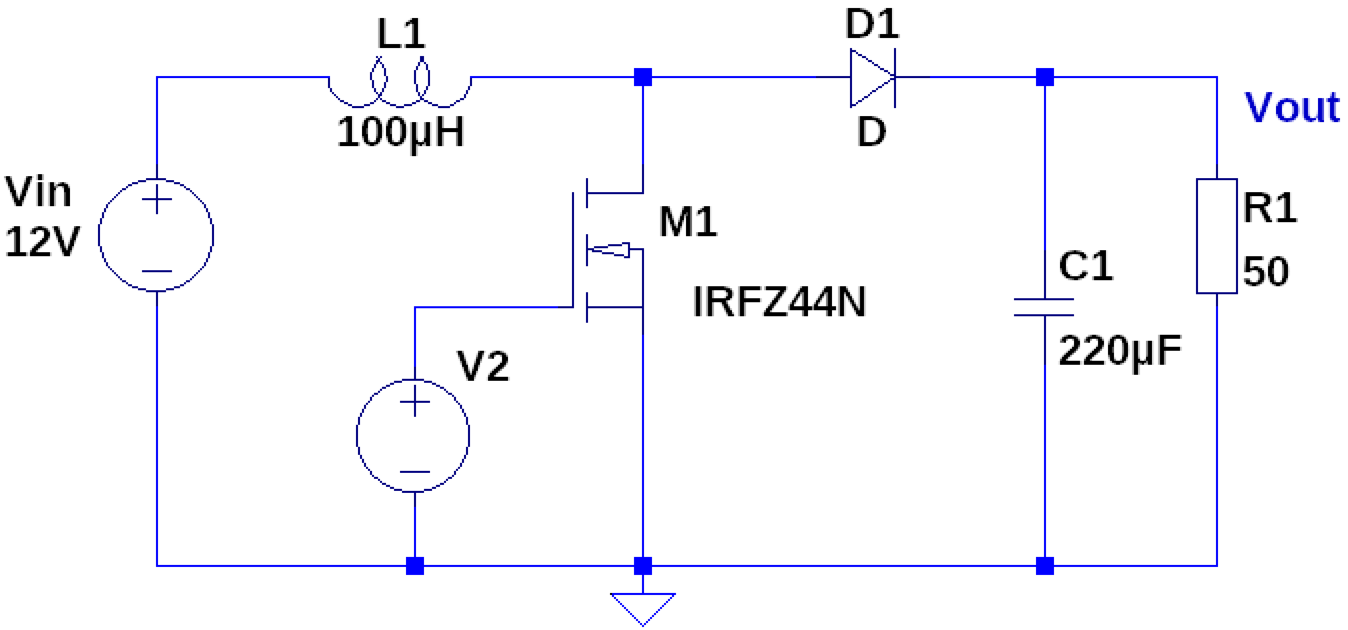
Assumptions:

Inductor currents rise and fall linearly during a switching cycle

Capacitor voltages remain roughly constant during a switching cycle

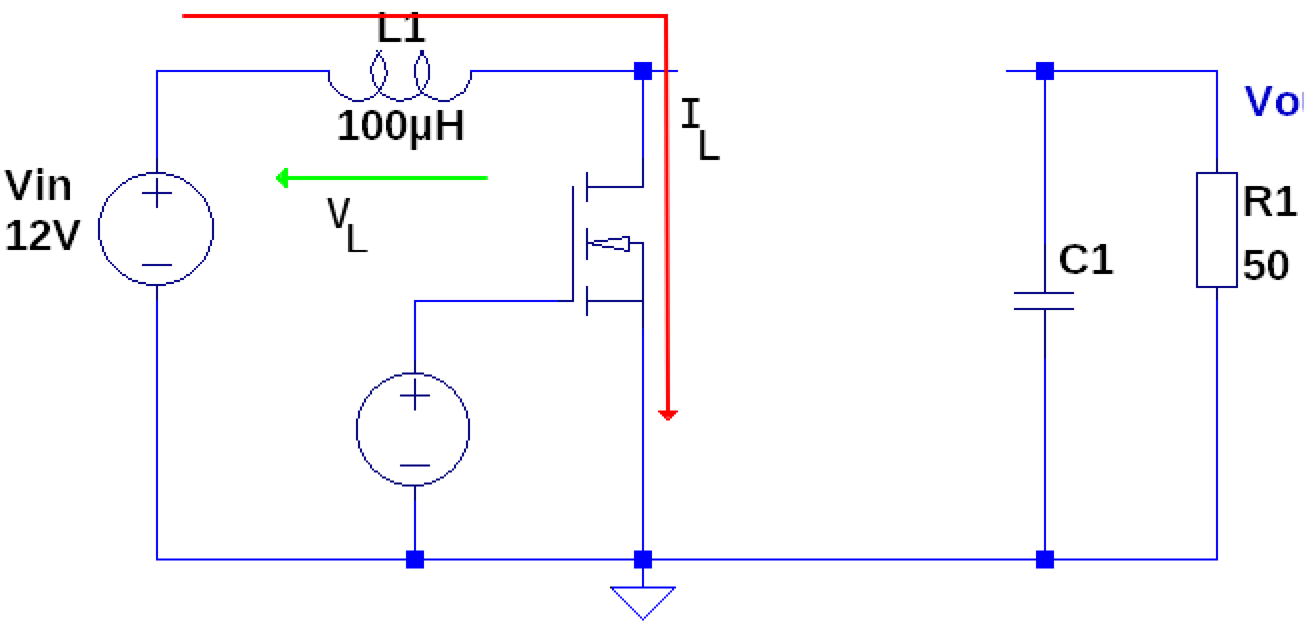
DC Voltage regulation (review from previous class)

The step up (Boost) voltage regulator



DC Voltage regulation

The step up (Boost) voltage regulator



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

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

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

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

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

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

DC Voltage regulation

The step up (Boost) voltage regulator

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

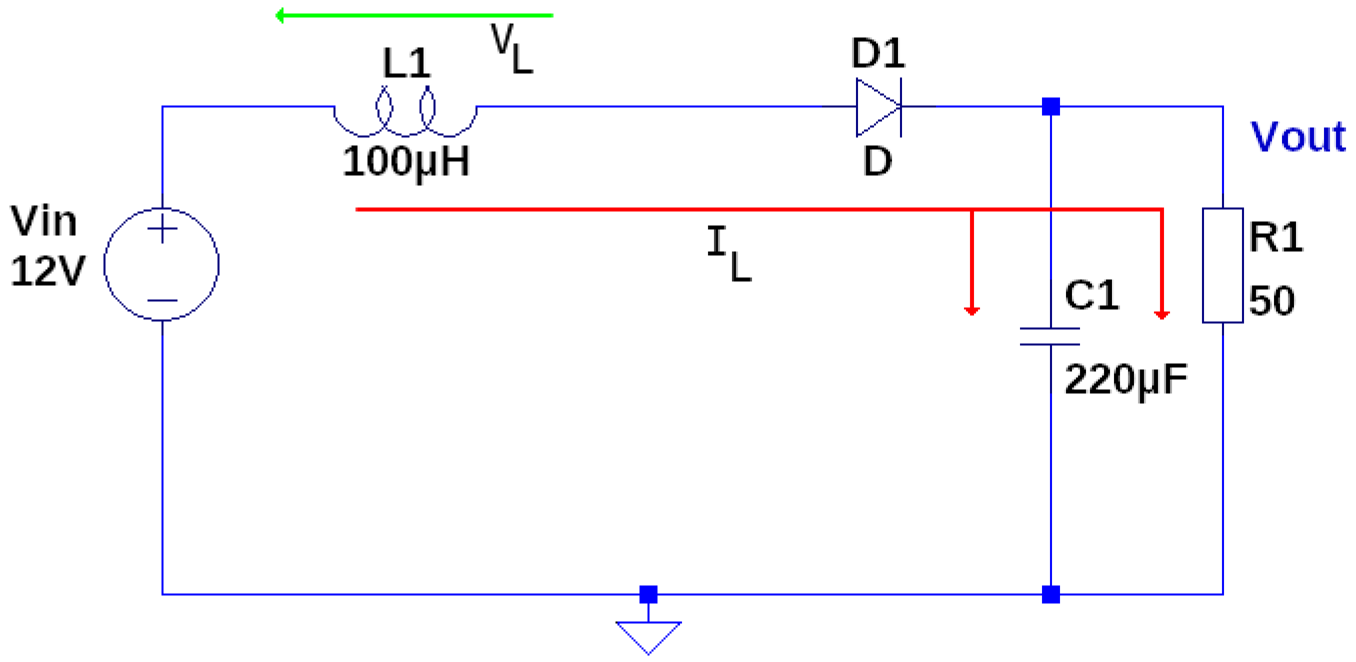
$$V_L \approx L\frac{\Delta I_L}{\Delta t}$$

$$V_L = L\frac{\Delta I_{Loff}}{T_{off}}$$

$$V_{in} = V_L + V_{out}$$

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

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



DC Voltage regulation

The step up (Boost) voltage regulator

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

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

$$V_{out} = V_{in} + L\frac{\Delta I_{Lon}}{T_{off}}$$

$$V_{out} = V_{in} + L\frac{V_{in} T_{on}}{L}\frac{1}{T_{off}}$$

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

$$V_{out} = V_{in} + V_{in}\frac{DT}{(1-D)T}$$

$$V_{out} = V_{in} + V_{in}\frac{D}{(1-D)}$$

$$V_{out} = V_{in}\left(1 + \frac{D}{(1-D)}\right)$$

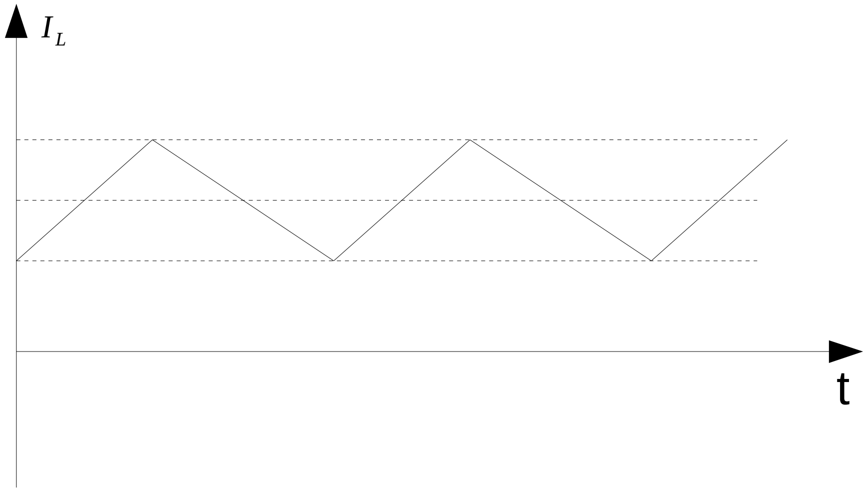
$$V_{out} = V_{in}\left(\frac{(1-D)+D}{(1-D)}\right)$$

$$\boxed{V_{out} = \frac{V_{in}}{(1-D)}}$$

DC Voltage regulation

Calculating a suitable value for L

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

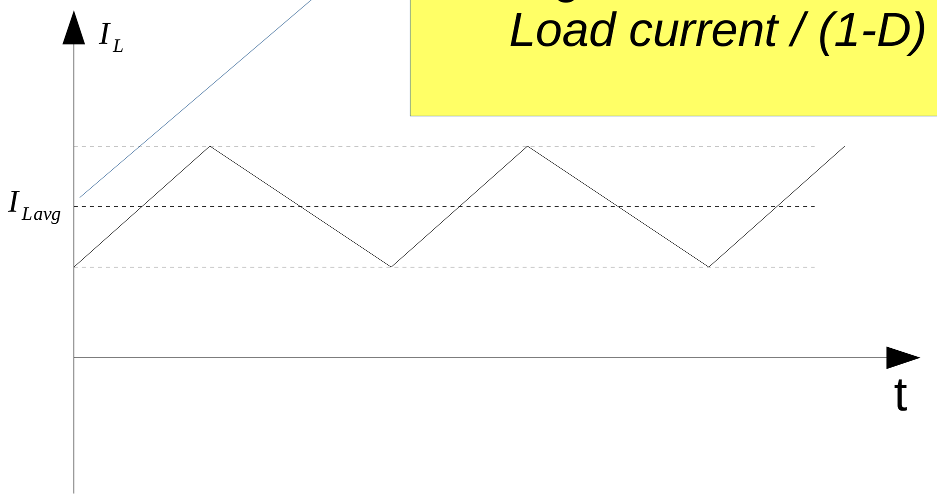


DC Voltage regulation

Calculating a suitable value for L

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

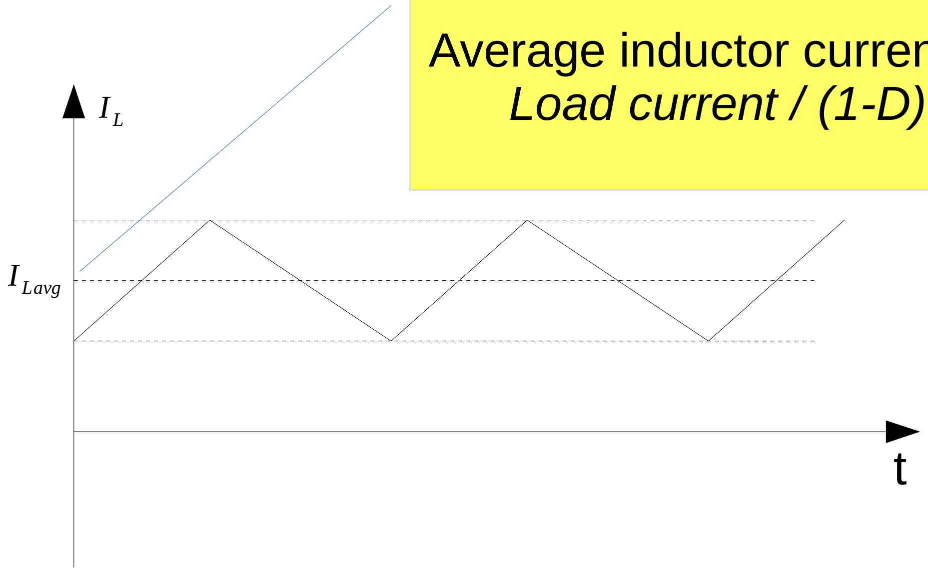
Average inductor current =
Load current / (1-D)



DC Voltage regulation

Calculating a suitable value for L

$$P_{out} = V_{out} I_{out}$$
$$P_{in} = V_{in} I_{in}$$
$$Assuming\ 100\%\ efficiency$$
$$P_{out} = P_{in}$$
$$V_{out} I_{out} = V_{in} I_{in}$$
$$\frac{V_{in}}{1-D} I_{out} = V_{in} I_{in}$$
$$I_{in} = \frac{I_{out}}{1-D}$$



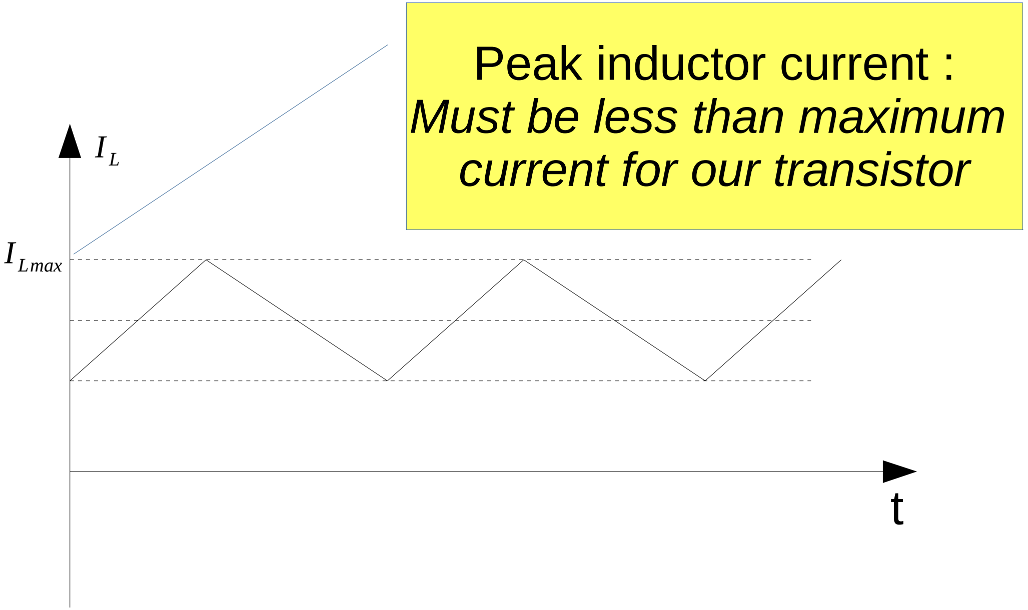
Average inductor current =
Load current / (1-D)

This states that the average input current is the average output current divided by (1-D)

DC Voltage regulation

Calculating a suitable value for L

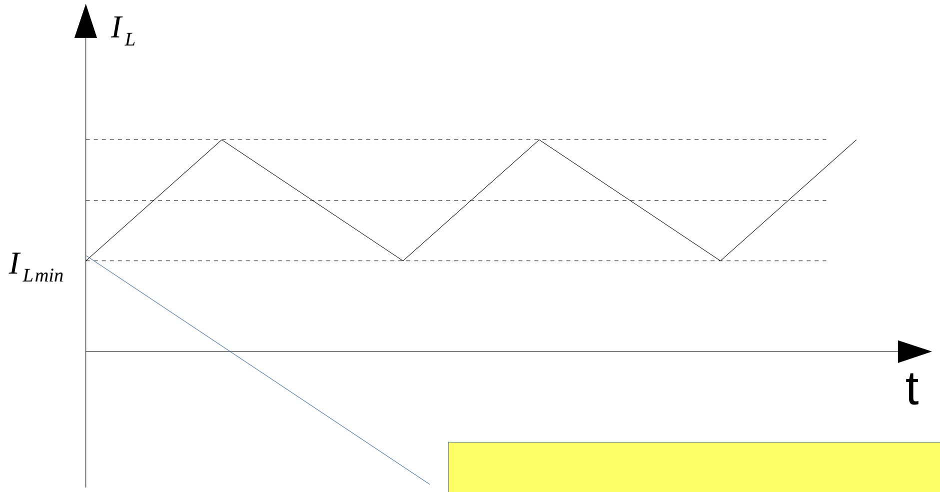
From before: $\Delta I_{Lon} = (V_{in}) \frac{T_{on}}{L}$



DC Voltage regulation

Calculating a suitable value for L

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



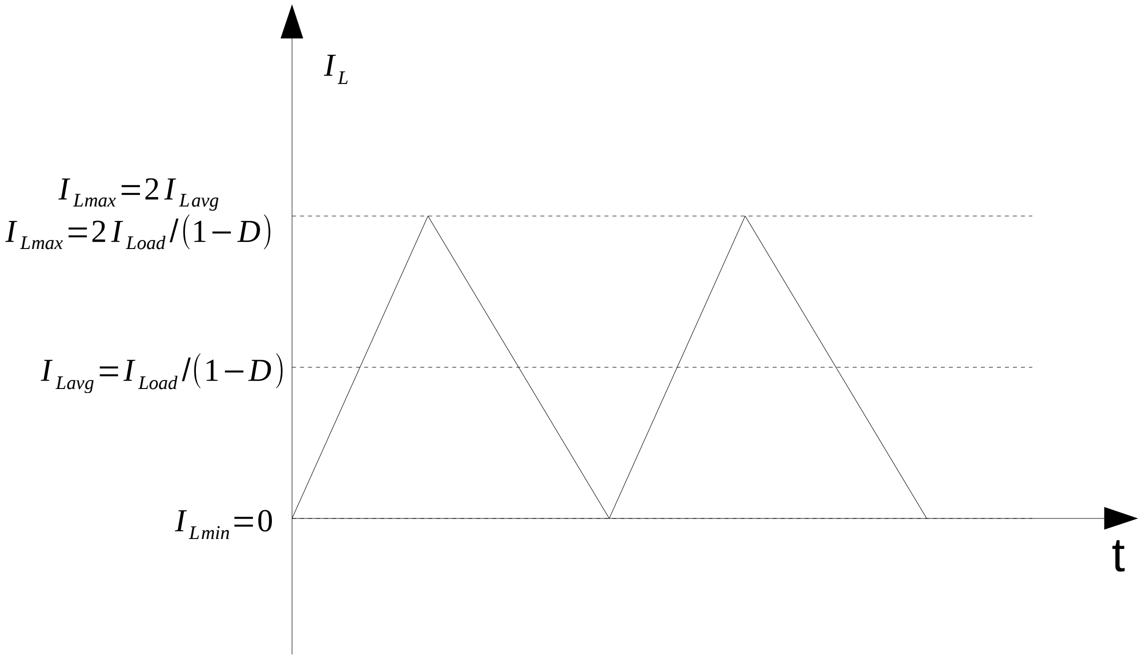
Minimum inductor current :
Should be kept above zero

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

$$\Delta I_{Lon} = \frac{2 I_{Load}}{1 - D} = (V_{in}) \frac{T_{on}}{L}$$

Leading to:

$$L = (V_{in})(1 - D) \frac{T_{on}}{2 I_{Load}}$$

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 24V. The load current is 1A. Determine the minimum inductance of the filter inductor.

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

$$D = 0.5$$

$$L = (V_{in})(1-D)\frac{T_{on}}{2I_{Load}}$$

$$L = (12)\frac{0.5 * 5\mu s}{2.1}$$

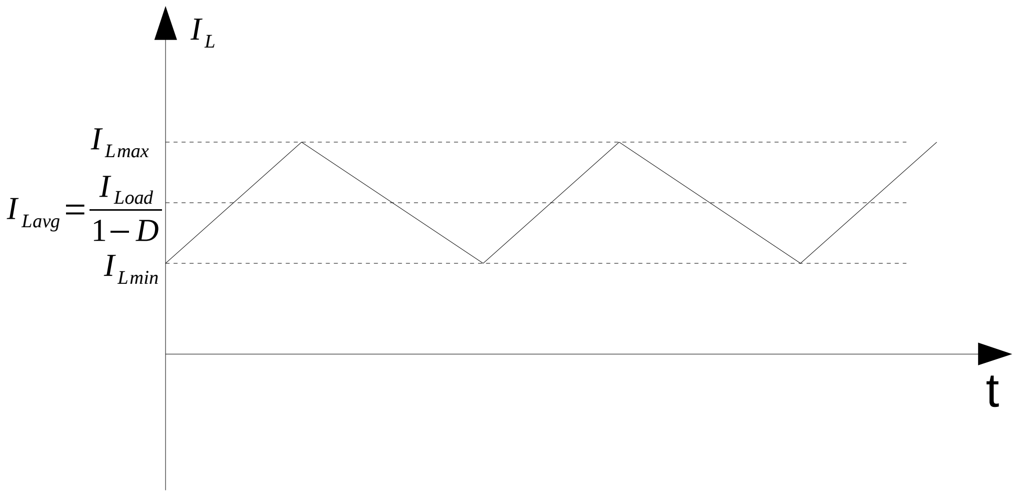
$$L = 15\mu H$$

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 or by the expected operating limits of the supply e.g. minimum load current.

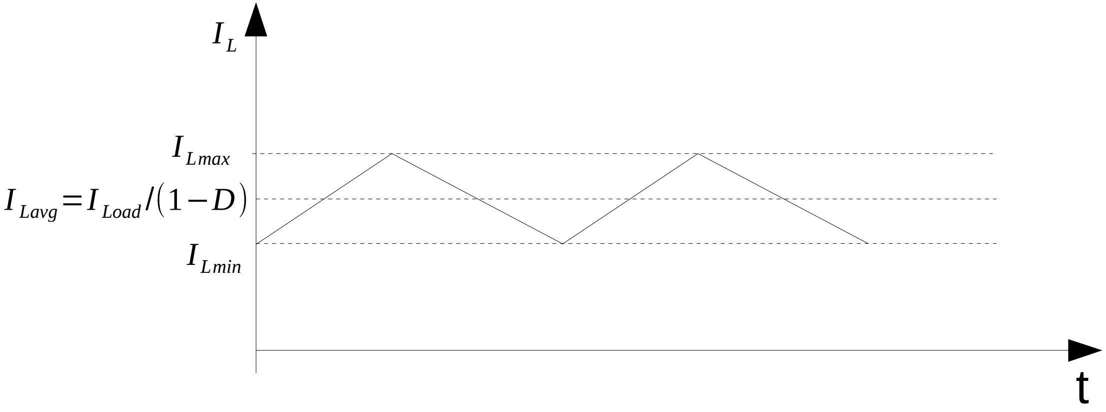


DC Voltage regulation

Calculating a suitable value for L

Example:
A boost regulator has a switching frequency of 100kHz. The input voltage is 12V, the output voltage is 24V. The load current is 3A. The inductor ripple current must be kept below +/-0.25A. Determine the minimum inductance of L that achieves this.

$$V_o = \frac{V_{in}}{1-D}$$
$$D = 0.5$$
$$L = (V_{in})\frac{T_{on}}{\Delta I_L}$$
$$L = (12)\frac{5\mu s}{0.5}$$
$$L = 120\mu H$$



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

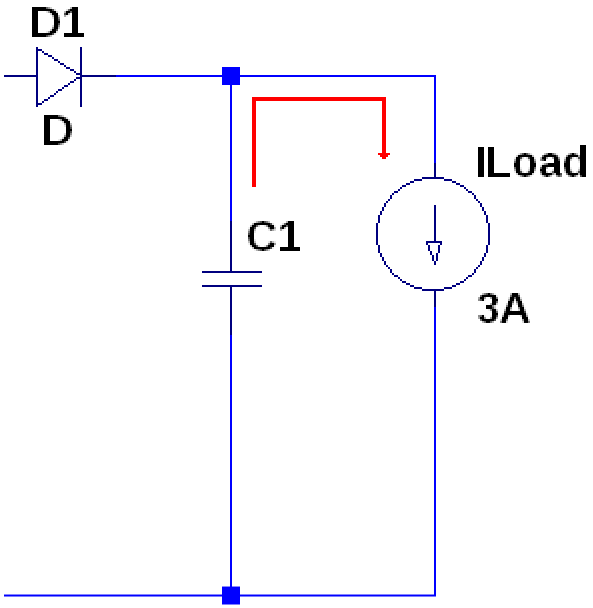
The capacitor alone must supply load current when the MOSFET is on

DC Voltage regulation

Calculating a suitable value for C

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

$$\Delta V_c = \frac{I_{Load} T_{on}}{C}$$



DC Voltage regulation

Calculating a suitable value for C

Example:
A boost regulator has a switching frequency of 100kHz. The input voltage is 12V, the output voltage is 24V. The load current is 3A. Calculate a suitable size of C such that the output voltage ripple is less than 100mV peak to peak

$$\Delta V_c = \frac{I_{Load} T_{on}}{C}$$

$$100\,mV = \frac{3.5\mu s}{C}$$

$$C = \frac{15\,x\,10^{-6}}{100\,x\,10^{-3}}$$

$$C = 150\,\mu F$$

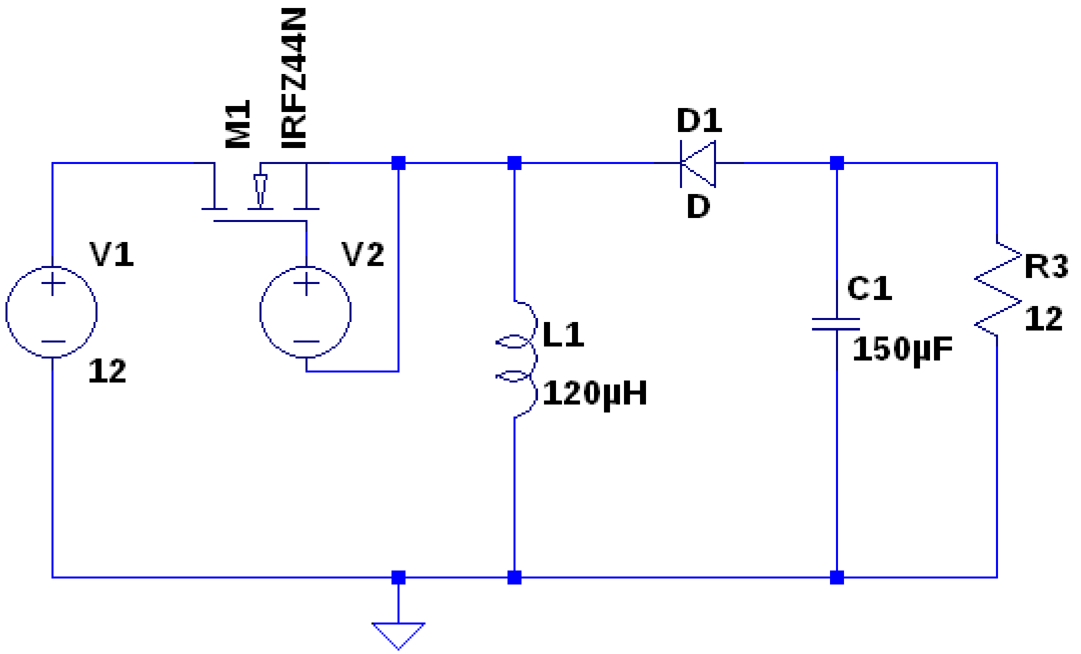
DC Voltage regulation

The buck-boost (step up/down) regulator

The output voltage is of opposite polarity to the input

The magnitude of the output voltage can be greater or less than the input

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



DC Voltage regulation

Equivalent Series Resistance (ESR)

ESR is a way of modelling energy loss in a capacitor

Capacitance (µF)	WVDC	IC PART NUMBER	Maximum ESR Ω 120Hz,+20°C	Maximum RMS Ripple Current (mA) 120Hz,+85°C	Dimension D x L (mm)
2,200	10	228TTA010M	0.181	1120	12.5x25
2,200	16	228TTA016M	0.158	1280	12.5x30
2,200	25	228TTA025M	0.143	1480	16x30
2,200	35	228TTA035M	0.121	1580	16x30
2,200	50	228TTA050M	0.106	1920	16x40
2,200	63	228TTA063M	0.098	2158	18x40
2,200	80	228TTA080M	0.106	2260	22x50
2,200	100	228TTA100M	0.181	2590	25x50
3,300	10	338TTA010M	0.131	1435	12.5x30
3,300	16	338TTA016M	0.116	1610	16x30

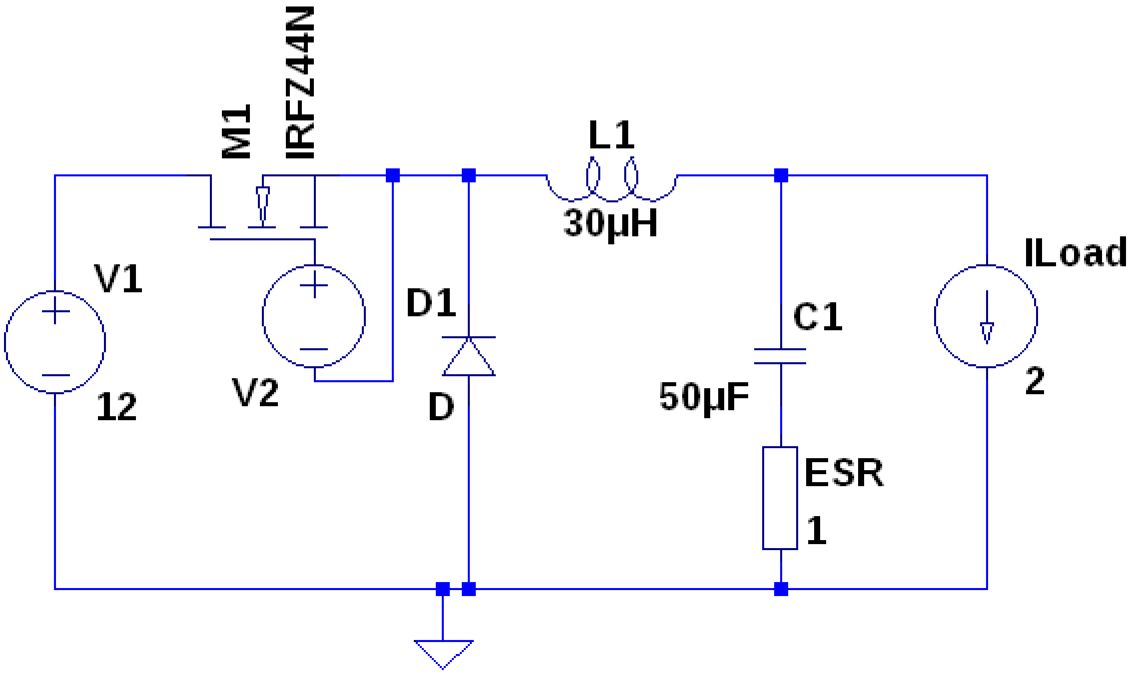
DC Voltage regulation

Equivalent Series Resistance (ESR)

ESR increases output voltage ripple

The increase in voltage ripple is the capacitor ripple current multiplied by the value of ESR.

The ripple caused by ESR can be much larger than ripple caused by variation of charge within the capacitor.



DC Voltage regulation

General notes:

Switching power supplies are MUCH more efficient than their linear counter parts.

The power supply is designed to work within a certain load range – for example, the output voltage on a buck regulator may increase significantly under light loads.

Power converter IC’s can do a lot of the work for you

The dynamic response of the circuits seen so far is approximately that of a damped second order system (examine LT1076 test fixture)