Lecture # 4

ECEN 438/738 Power Electronics

Spring 2025 Semester

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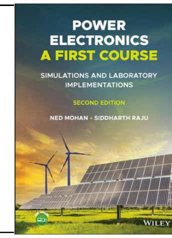
ECEN 438/738 Power Electronics



Power Electronics
A First Course: 2nd Edition

Free Textbook Online Access Link: https://go.oreilly.com/TAMU/library/view/-/9781119818564/?ar

Chapter 1
Power Electronics: An Enabling Technology

ECEN 438/738 Power Electronics

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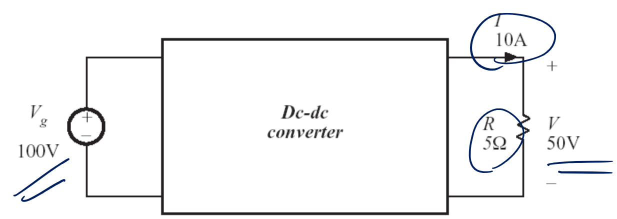
A simple dc-dc converter example

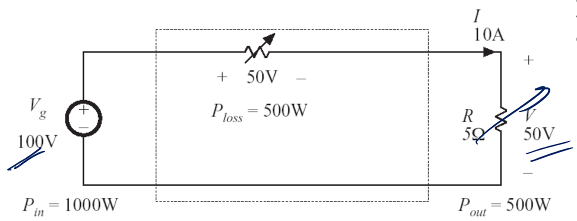


Input source: 100V
Output load: 50V, 10A, 500W
How can this converter be realized?

Linear Regulator

Dissipative realization

Resistive voltage divider

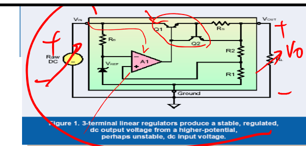


Quiz # If the required output voltage is 10V and the current is I = 10A, calculate the efficiency.

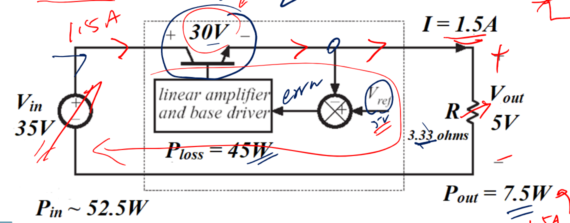
Efficiency = $P_{out}/(P_{out} + P_{loss})$ = 500/1000 = 50%

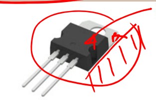
Linear Regulator

Dissipative realization



Series pass regulator: transistor operates in active region





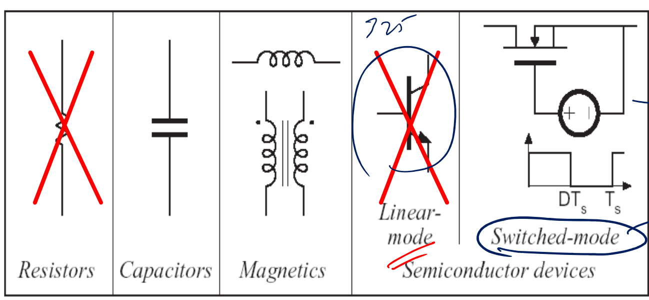
L 7805 - $0.77 - Qty = 1 or $0.34 - Qty = 1000

Input voltage (max) = 35 V
Output voltage (fixed) = 5 V
Output current (max) = 1.5 A

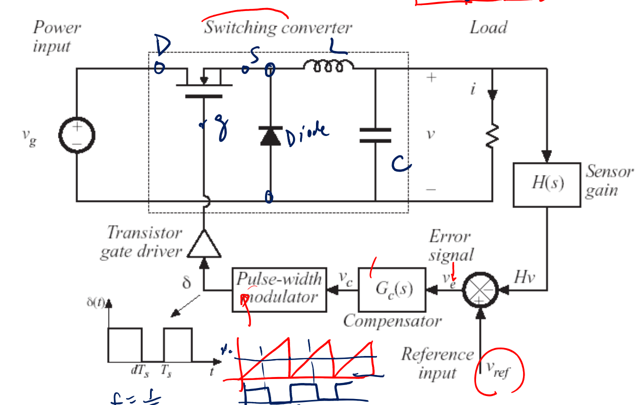
$$\eta = \frac{P_{out}}{P_{in}} = \frac{7.5}{52.5} * 100 = 14.3\%$$

Devices available to the circuit designer

Power Electronics



DC - DC Buck Converter

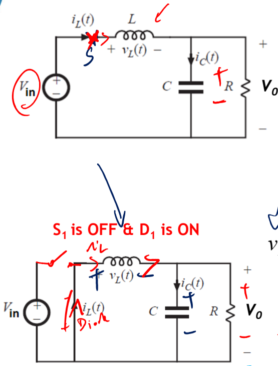


DC - DC Buck Converter

(assume continuous conduction)

$0 \le D \le 1$ → Capacitor is large

S_1 is ON & D_1 is OFF



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

$$\Rightarrow L\frac{\Delta I_L}{DT} = V_{in} - V_o$$

$$V_L = L\cdot\frac{\Delta I_L}{DT} = (V_{in} - V_o)DT$$

$$L\,\Delta I_L = \left(\frac{V_o}{D} - V_o\right)DT$$

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

S_1 is OFF & D_1 is ON

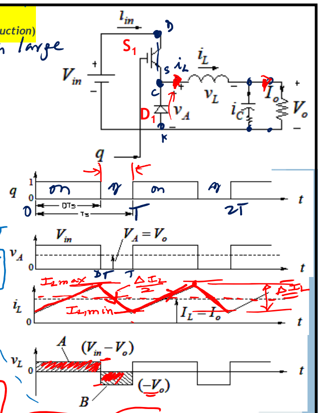
$$v_L = L\frac{di_L}{dt} = -V_o$$

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

$$v_L = L\,\Delta I_L = -V_o(1-D)T$$

For inductor Volt-Sec Balance ⇒ $(V_{in}-V_o)DT - V_o(1-D)T \equiv 0$

Solve ⇒ $\boxed{V_o = DV_{in}}$ (1)



DC - DC Buck Converter - Critical Inductance

$i_c = C\frac{dV_o}{dt}$

$\boxed{V_o = DV_{in}}$ (1) $T = \frac{1}{f}$; f - Switching Frequency

(2) $\boxed{\Delta I_L = \frac{V_o(1-D)T}{L}}$

Since $I_L = I_o = \frac{V_o}{R}$

also $T = \frac{1}{f}$

$I_{L,max} = I_L + \frac{\Delta I_L}{2}$

$I_{L,max} = I_L + \frac{V_o(1-D)T}{2L}$

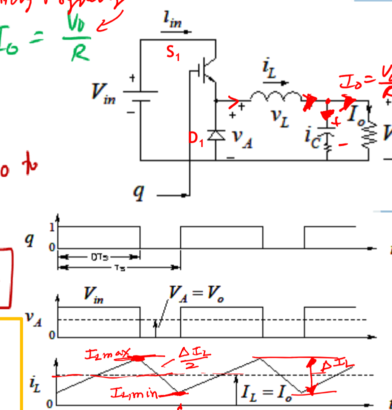
$I_{L,min} = I_L - \frac{\Delta I_L}{2}$

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

Set $I_{L,min} = 0$ to obtain L_{min}

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

Where L_{min} is the minimum (critical) inductance required to maintain continuous conduction



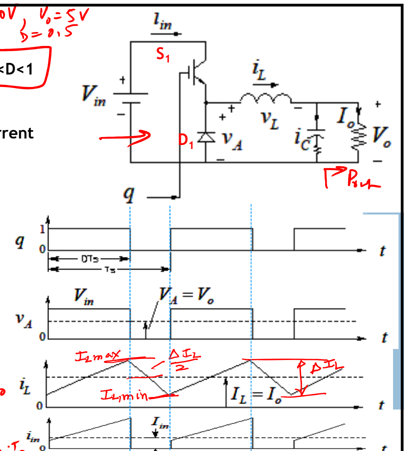
DC - DC Buck Converter

$V_{in} = 10V$, $V_o = 5V$, $D = 0.5$

1. $\boxed{V_o = DV_{in}}$ Where the duty cycle is $0<D<1$
2. $\boxed{\Delta I_L = \frac{V_o(1-D)T}{L}}$ Where ΔI_L is inductor current ripple (peak to peak)
3. $\boxed{L_{min} = \frac{(1-D)R}{2f}}$ Where L_{min} is the minimum (critical) inductance required to maintain continuous conduction
4. $I_L = I_o = \frac{V_o}{R}$, $T = \frac{1}{f}$
5. (Input Power) $V_{in}I_{in} = V_o \cdot I_o$ (output power); $I_{in} = \frac{V_o}{V_{in}}\cdot I_o = D\cdot I_o = DI_L$

DC-DC Transformer Analogy

$V_{in}\cdot I_{in} = V_o\cdot I_o$



DC - DC Buck Converter -Output Capacitor Design

$i_L = i_C + I_o$, $i_c = i_L - I_o$

$Q = C\cdot V$

$dq = C\cdot dv$

$\Delta Q = C\cdot\Delta V_o$

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

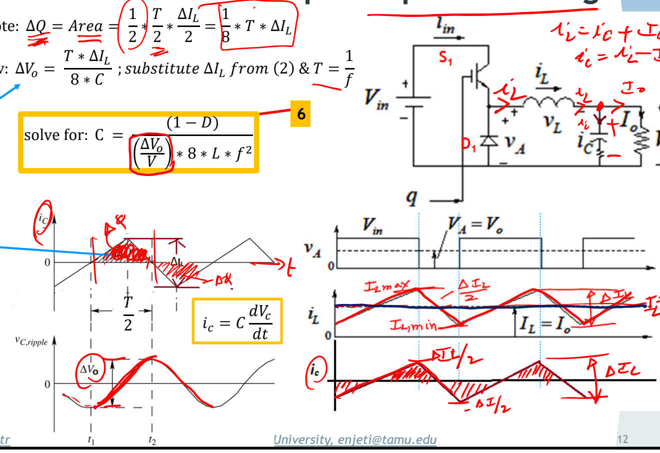
$i_c = C\frac{dV_o}{dt}$

$\int i_c\,dt = \int C\,dV_o = Area$

Note: $\Delta Q = Area = \frac{1}{2}*\frac{T}{2}*\frac{\Delta I_L}{2} = \frac{1}{8}*T*\Delta I_L$

Now: $\Delta V_o = \frac{T*\Delta I_L}{8*C}$; substitute ΔI_L from (2) & $T = \frac{1}{f}$

6. solve for: $C = \frac{(1-D)}{\left(\frac{\Delta V_o}{V}\right)*8*L*f^2}$



$i_c = C\frac{dV_c}{dt}$

DC - DC Buck Converter

$V_o = D V_{in}$ — 1 — Where the duty cycle is 0<D<1

$\Delta I_L = \frac{V_o (1-D) T}{L}$ — 2 — Where ΔI_L is inductor current ripple (peak to peak)

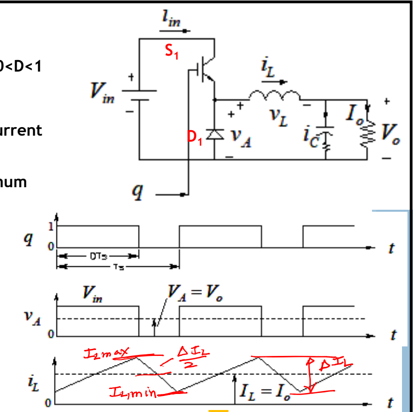
$L_{min} = \frac{(1-D) R}{2 f}$ — 3 — Where L_{min} is the minimum (critical) inductance required to maintain continuous conduction

$I_L = I_o = \frac{V_o}{R}$ — 4

$T = \frac{1}{f}$

5 — (Input Power) $V_{in} I_{in} = V_o \cdot I_o$ (output power)

$I_{in} = \frac{V_o}{V_{in}} \cdot I_o = D \cdot I_o = D I_L$



6 — solve for: $C = \frac{(1-D)}{\left(\frac{\Delta V_o}{V_o}\right) * 8 * L * f^2}$

DC - DC Buck Converter -Design Example # 1

Input voltage V_{in} = 3.3V

Output voltage V_o = 1.2V ; voltage ripple not to exceed 2%

Output current I_o = Varies between 4A to 6A

Switching Frequency f = 500kHz

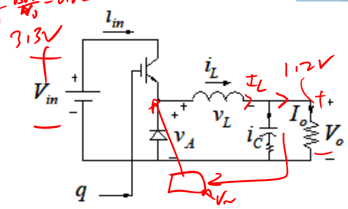
a) Specify the inductor value such that the peak-to-peak variation in inductor current ΔI_L does not exceed 40% of the average value (I_L).

b) Find the capacitor value C that meets the specification.

c) Also determine the required *rms* current rating of the inductor and the capacitor.

$\frac{\Delta V_o}{V_o} = 0.02$

$V_o = D V_s \Rightarrow D = \frac{1.2}{3.3} = 0.364$



$\Delta I_L = \frac{V_o (1-D) T}{L}$ — 2

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

Case # 1 ; I_o = 4A $= I_L$

$\Delta I_L = (40\%) \times 4A = 0.4 \times 4 = 1.6A$

$L = \frac{1.2 * (1 - 0.364)}{1.6 * 500{,}000} = 0.954uH$

Case # 2 ; I_o = 6A

$\Delta I_L = (40\%) \times 6A = 2.4A$

$L = \frac{1.2 * (1 - 0.364)}{2.4 * 500{,}000} = 0.636uH$

Therefore choose the largest inductor to meet the specifications i.e. L = 0.954uH

Lets round this off to L ~ 1uH for practical purposes

DC - DC Buck Converter -Design Example # 1

Input voltage V_{in} = 3.3V

Output voltage V_o = 1.2V ; voltage ripple not to exceed 2%

Output current I_o = Varies between 4A to 6A

Switching Frequency f = 500kHz

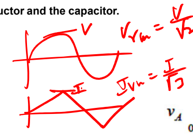
a) Specify the inductor value such that the peak-to-peak variation in inductor current ΔI_L does not exceed 40% of the average value (I_L).

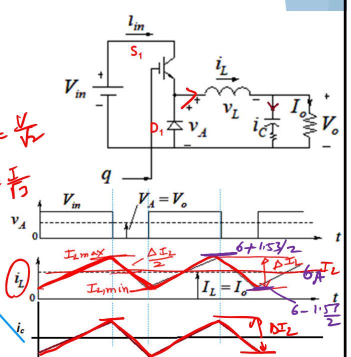
b) Find the capacitor value C that meets the specification.

c) Also determine the required *rms* current rating of the inductor and the capacitor.

$C = \frac{(1-D)}{\left(\frac{\Delta V_o}{V}\right) * 8 * L * f^2}$ — 6

$C = \frac{(1-0.364)}{(0.02)*8*1uH*(500{,}000)^2} = 16uF$





$I_{C.rms} = \frac{\Delta I_L}{2} \frac{1}{\sqrt{3}} = 0.44\ A$

rms current of the inductor current I_L

$I_{L,rms} = \sqrt{I_L^2 + \left[\frac{(\Delta I_L/2)}{\sqrt{3}}\right]^2}$

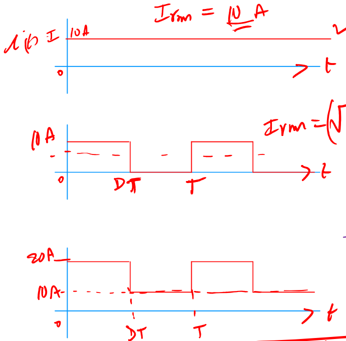
From equation (2) find ΔI_L = 1.53A ; Substitute and obtain $I_{L,rms}$ = 6.02 A

16 µF, 0.5A

RMS of different waveforms - basics

$P = I_{rm}^2 R$

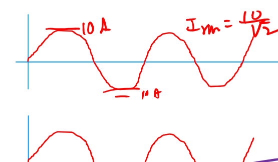
x — $I_{rm} = 10A$

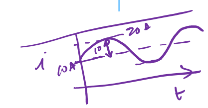


y

x + y

$= \sqrt{10^2 + (\sqrt{D} \cdot 10)^2}$





$= \sqrt{10^2 + \left(\frac{10}{\sqrt{2}}\right)^2}$

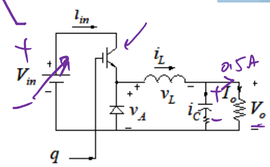
$I_{rm} = \sqrt{\frac{1}{T}\int_0^{DT} i^2(t)\, dt}$

$\rightarrow I_{rm} = \sqrt{D} \cdot I$

DC - DC Buck Converter -Design Example # 2

Input voltage V_{in} = 7.5V to 36V
Output voltage V_o = 3.3V ; voltage ripple not to exceed 2%
Output current I_o = 0.5A Full Load
Switching Frequency f = 300kHz

a) Specify the inductor value such that continuous conduction is achieved from 25% load to 100% load
b) Find the capacitor value *C* that meets the specification.
c) Also determine the required *rms* current ratings of the MOSFET and the Diode



$\boxed{V_o = D V_{in}}$ 1

$\boxed{L_{min} = \frac{(1-D)R_i}{2f}}$ 3

Solution: # 1 Input voltage = 7.5V

$D = \frac{3.3}{7.5} = 0.44$ 25% load, I_o = 0.25*0.5 = 0.125A

Load resistance $R_{25\%} = \frac{3.3}{0.125} = 26.5\ ohms$

$$L_{min-@25\%-load} = \frac{(1-0.44)*26.5}{2*300{,}000} = 24.6\ \text{micro} - \text{H}$$

Input voltage = 36V

$D = \frac{3.3}{36} = 0.0917$

$$L_{min-@25\%-load} = \frac{(1-0.0917)*26.5}{2*300{,}000} = 40\ \text{micro} - \text{H}$$

Pick the largest $L = 40$ micro − H

100% load
$R = \frac{3.3}{0.5} = 6.6\Omega$
$L_{min} =$

$$\boxed{C = \frac{(1-D)}{\left(\frac{\Delta V_o}{V_o}\right)*8*L*f^2}}$$ 6

Use the smallest D to get the larger C to meet the spec.

$C = \frac{(1-0.0917)}{(0.02)*8*L*f^2}$ = 1.58 micro-f