ANALOG CIRCUITS DESIGN

AE8: DC-DC converters

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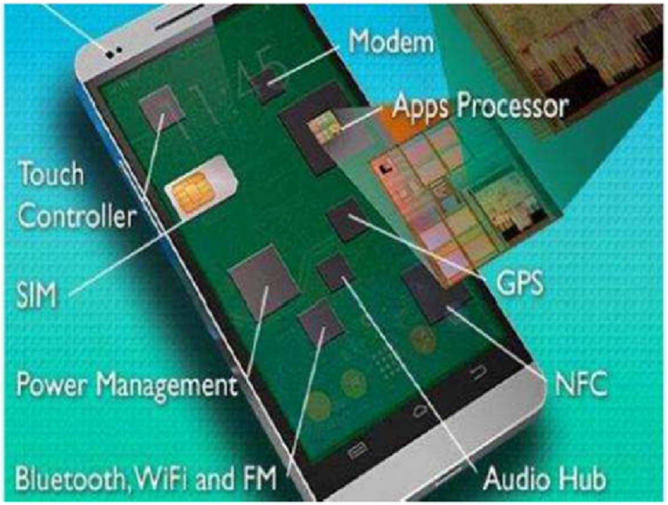
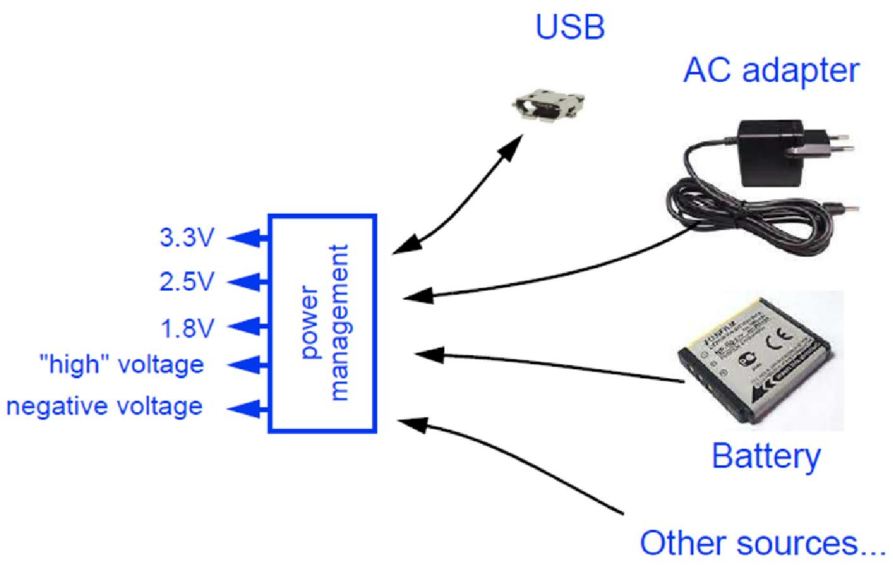
Course overview

- 1. Introduction
- 2. The linear regulator
- 3. Switching regulators
- 4. Switching versus linear

1. Introduction: system overview

- Typical portable device

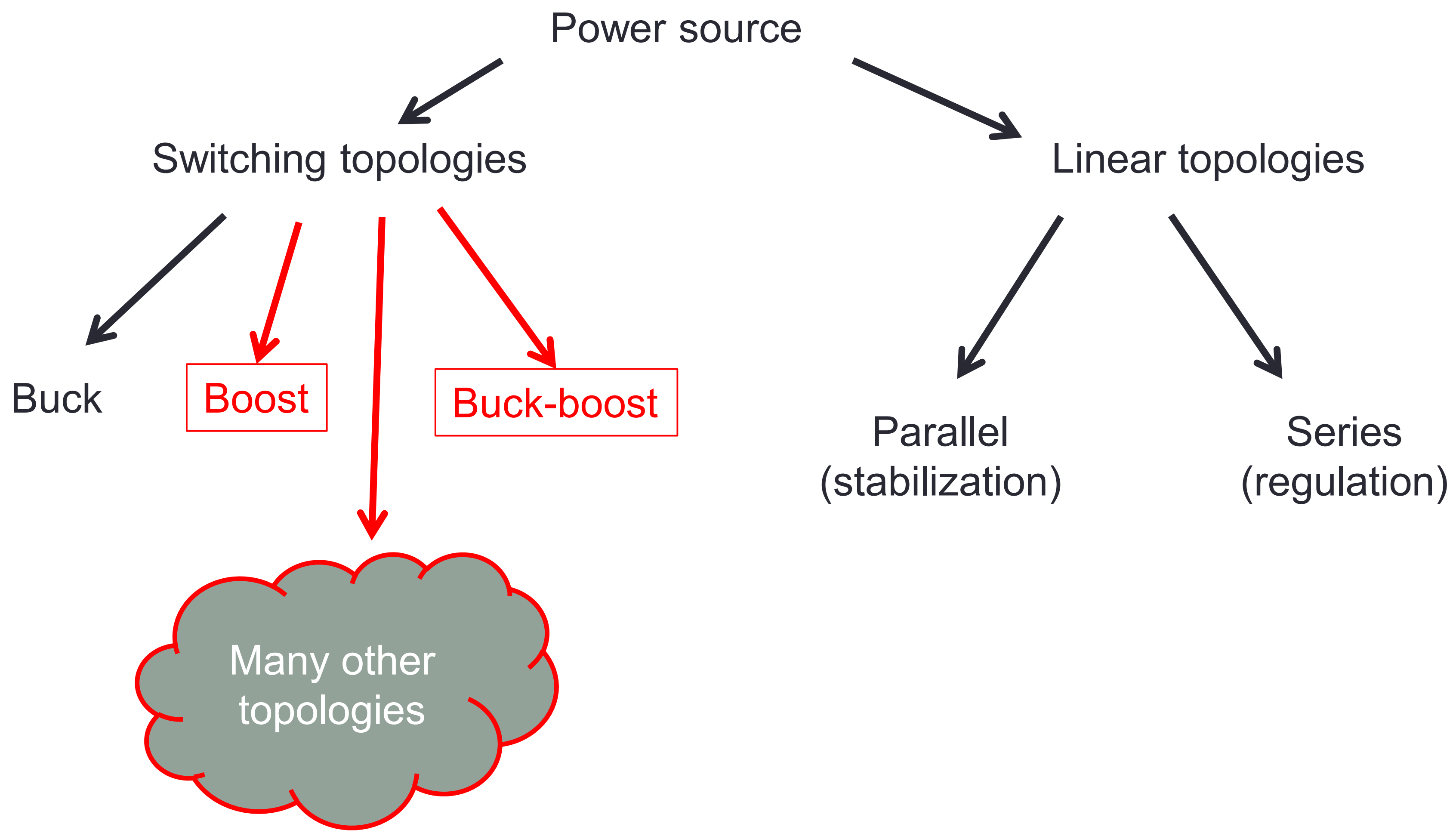




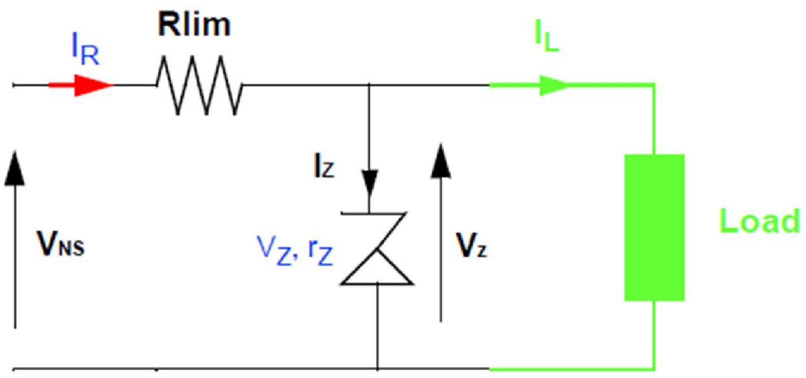
➡ Multiple power sources
Multiple volages values required

➡ Optimal use of power supplies
Heath dissipation & occupied area
Devices protection

1. Introduction: topologies overview



1. Introduction: Stabilization vs regulation



Stabilization:

Only attenuates variations of V_{NS}

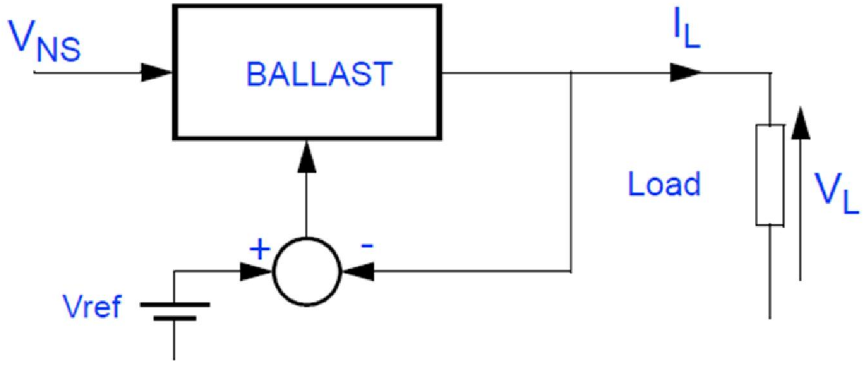
$r_Z << Rlim$

Load current peaks smoothing

$I_R = I_Z + I_L = Cte$

Large influence of temperature (Zener: 2mV/°C)

Shunt configuration



Regulation:

Reacts to variations of V_{NS} : permanent comparison of V_L with a reference (temperature compensated)

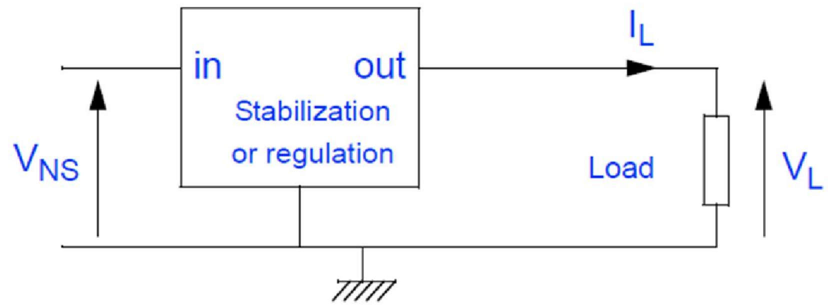
Correction with respect to variations:

- of load current changes
- of V_{NS} variations

Series configuration

1. Introduction: Line vs Load regulation

- Two important features



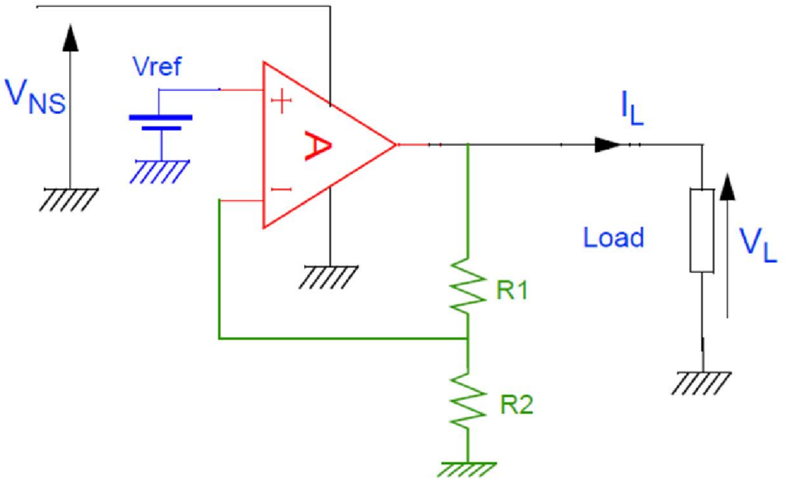
How output voltage changes if input voltage changes (LiNe Regulation)?

$$\Delta V_{LNR} = \left(\frac{\Delta V_L}{\Delta V_{NS}}\right)_{I_L = Cte}$$

How output voltage changes if output current changes (LoaD Regulation)?

$$\Delta V_{LDR} = \left(\frac{\Delta V_L}{\Delta I_L}\right)_{V_{NS} = Cte}$$

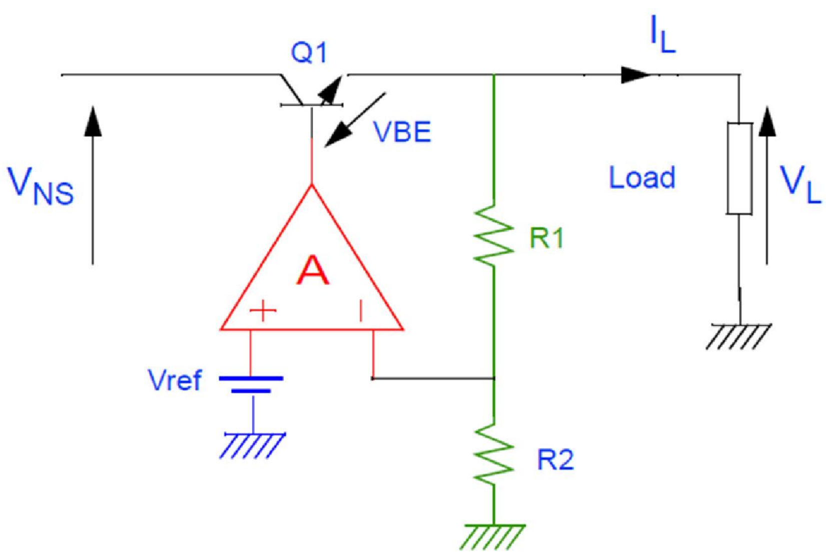
2. The linear regulator: principle of operation



Feedback: the amplifier attempts to adjust its output voltage so that:

$$Vref = V_L \cdot \frac{R2}{R1 + R2} \longrightarrow V_L = Vref \cdot \left(1 + \frac{R1}{R2}\right)$$

- Practical implementation

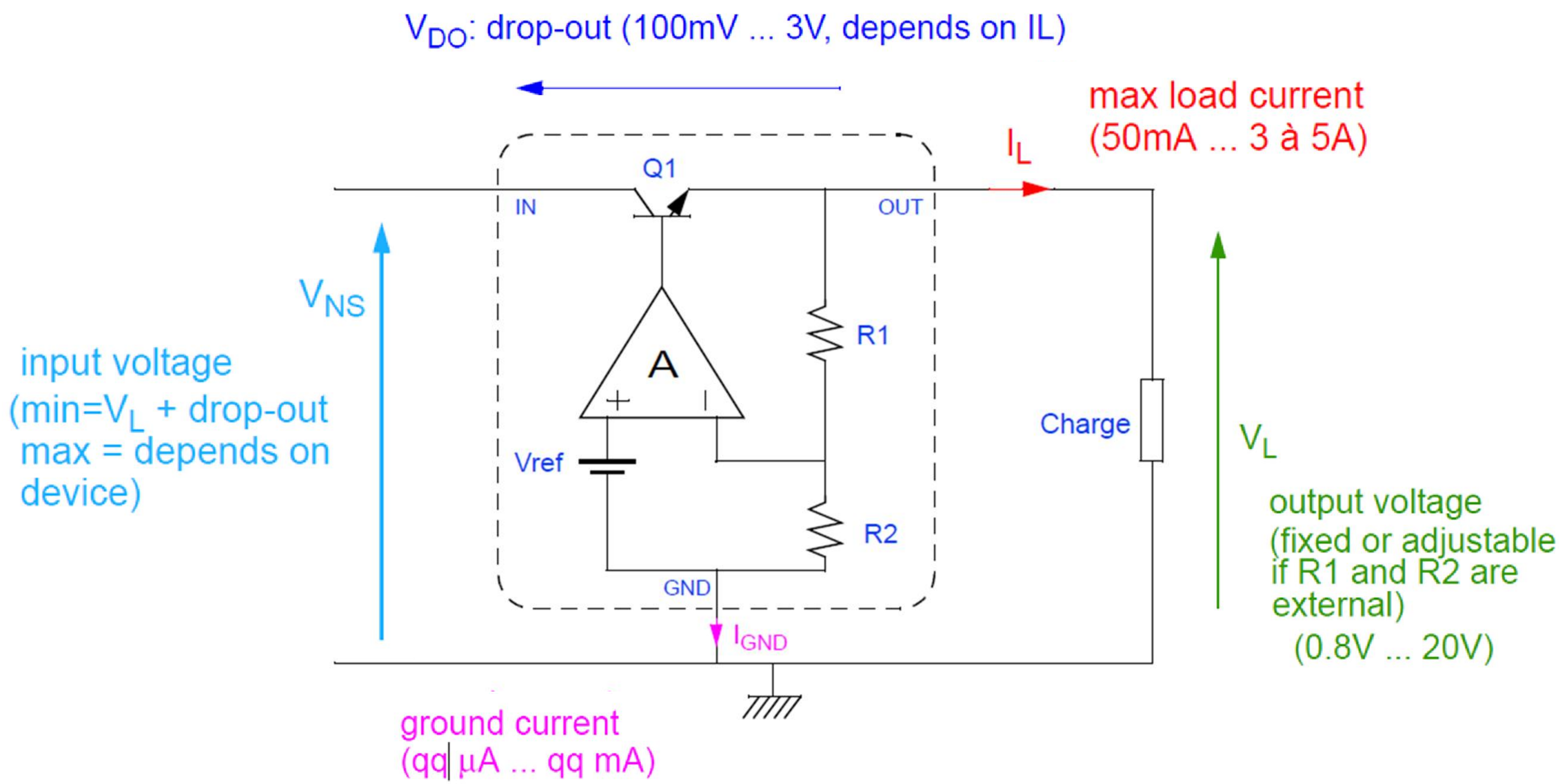


Amplifier must remain in linear region, i.e. $V_{NS} > V_L$

= Non-zero dropout voltage

Main limitation: non-inverting, attenuator

2. The linear regulator: some important features to check



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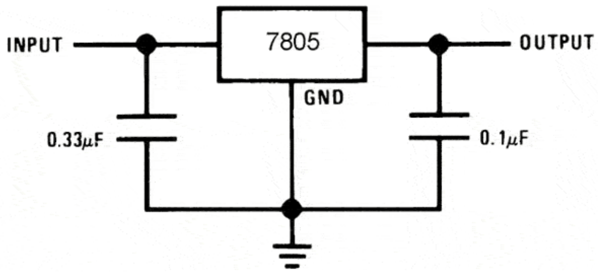
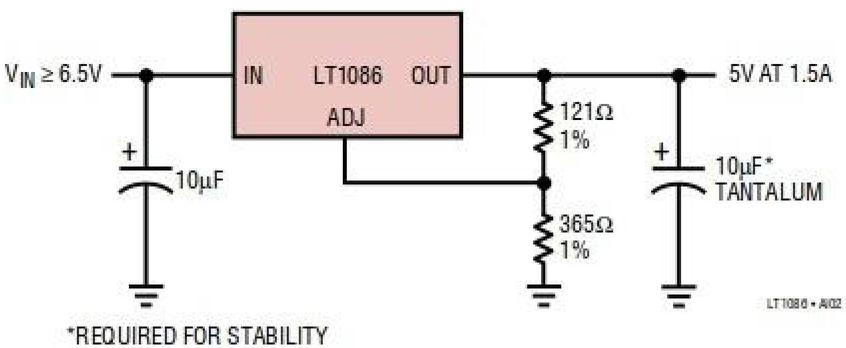
2. The linear regulator: what does it look like?

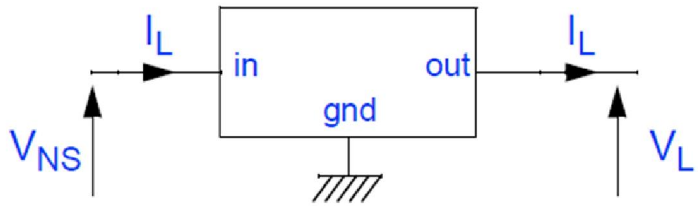


5V, 1.5A Regulator



2. The linear regulator: drop-out voltage issue

- Why is drop-out voltage (V_{DO}) an issue?

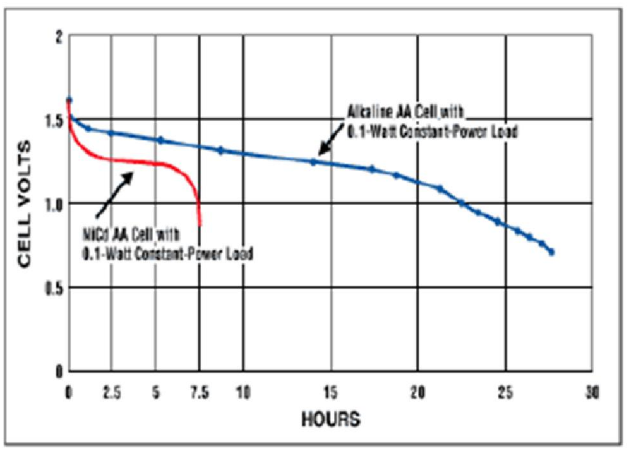


Dissipated power: $P_D = (V_{NS} - V_L) \cdot I_L$

Min. dissipated power: $P_D = V_{DO_{min}} \cdot I_L$

efficiency: $\eta_{max} \approx \dfrac{V_L}{V_{NS}} = \dfrac{V_{NS} - V_{DO}}{V_{NS}} = 1 - \dfrac{V_{DO_{min}}}{V_{NS}}$

Drop-out voltage impacts battery lifetime: example for $V_L = 3.3V$, $I_L = 30mA$



$V_{DO} = 1.8V$	$V_{DO} = 380mV$	$V_{DO} = 110mV$
$V_{NS}min = V_L + V_{DO} = 5.1V$	$V_{NS}min = 3.68V$	$V_{NS}min = 3.44V$
4 cells	3 cells	3 cells
min. 1.28V per cells	min. 1.22V per cells	min. 1.11V per cells
battery lifetime ~ 10h	battery lifetime ~ 15h	battery lifetime ~ 20h

Competitive advantage for Low Drop-Out (LDO) regulators

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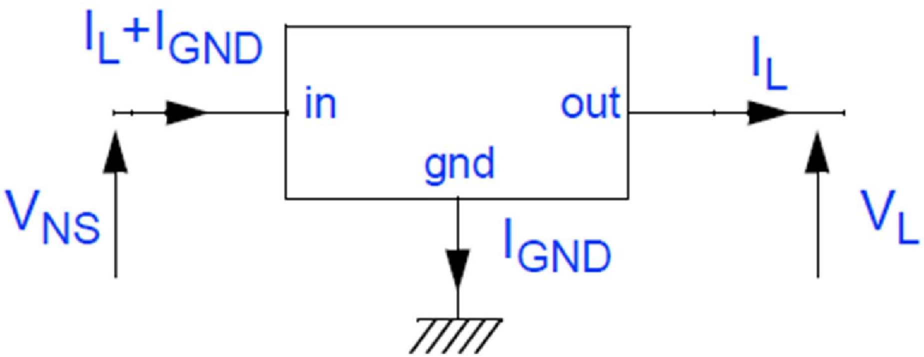
2. The linear regulator: ground current issue

- When is ground current (I_{GND}) an issue?



best case for V_{NS}

efficiency: $$\eta_{max} \approx \frac{V_L \cdot I_L}{V_{NS} \cdot (I_L + I_{GND})} = \left(1 - \frac{V_{DOmin}}{V_{NS}}\right) \cdot \frac{I_L}{I_L + I_{GND}}$$

Design target: $I_L min >> I_{GND}$

May be an isssue when $I_L = 0$ (sleep mode)

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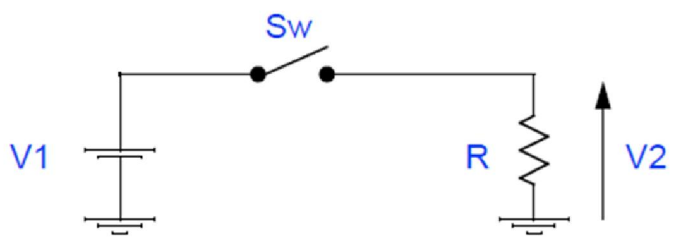
3. Switching regulators: the idea behind that

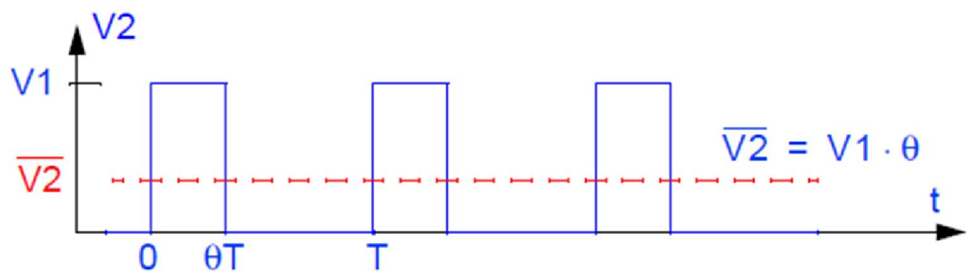
- Why not a linear regulator?

  The linear regulator dissipates power continuously = bad efficiency

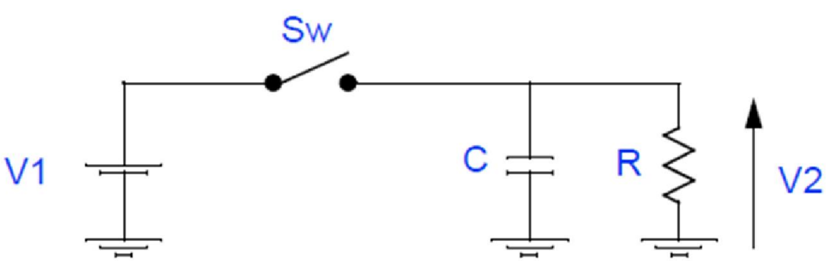
  Solution: provide power when necessary to an energy "tank"

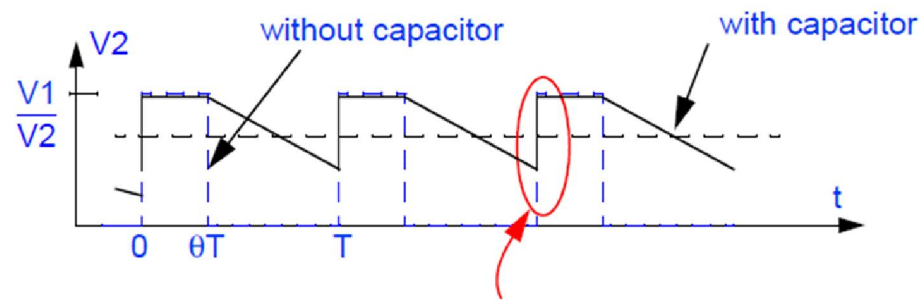
- Principle of operation





Requires a capacitor to smooth the output voltage





Requires an inductor to limit current spikes in the capacitor when turning the switch on

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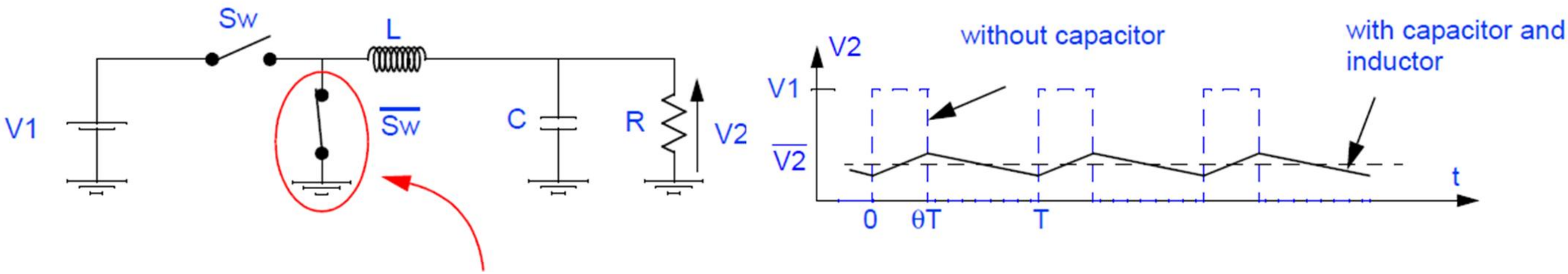
3. Switching regulators: the idea behind that (2)



Current can't be zeroed instantaneously in an inductor: a second switch is required to close the path

- Minimum required hardware

  A filtering capacitor at the output

  A combination of 2 switches and an inductor

"BUCK" (Vout < Vin)

"BOOST" (Vout > Vin)

"BUCK-BOOST" (Vout = - Vin)

3. Switching regulators: L & C in periodic steady state

duality principle:

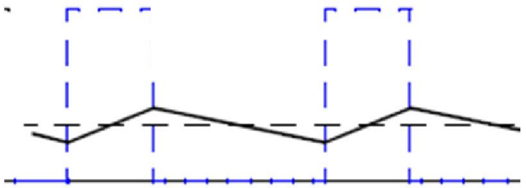
inductor $\longleftrightarrow$ capacitor

current $\longleftrightarrow$ voltage

no current discontinuity through an inductor

no voltage discontinuity across a capacitor

Assumption: operation in the periodic steady state



$$v(t) = L \cdot \frac{di(t)}{dt} \qquad i(t) = i(to) + \frac{1}{L} \cdot \int_{to}^{(to+t)} v(t) \cdot dt$$

$$i(to) = i(to+T) \qquad i(to+T) - i(to) = 0 \qquad \text{thus: } \int_{to}^{(to+T)} v(t) \cdot dt = \frac{1}{T} \cdot \int_{to}^{(to+T)} v(t) \cdot dt = 0$$

Average voltage across an inductor is zero in periodic steady state

Duality: average current through a capacitor is zero in periodic steady state

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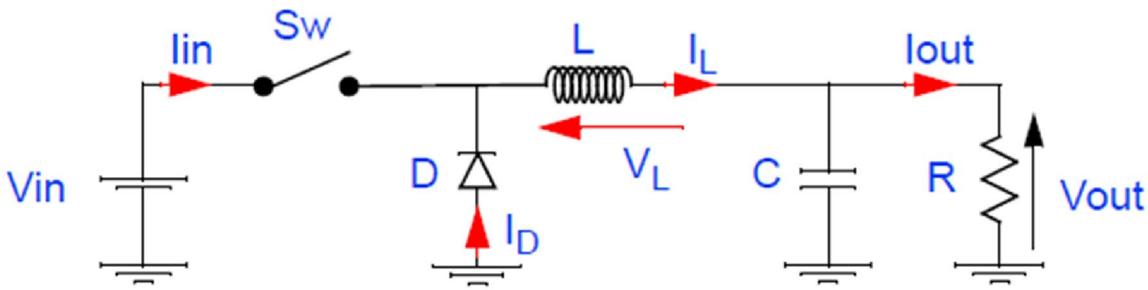
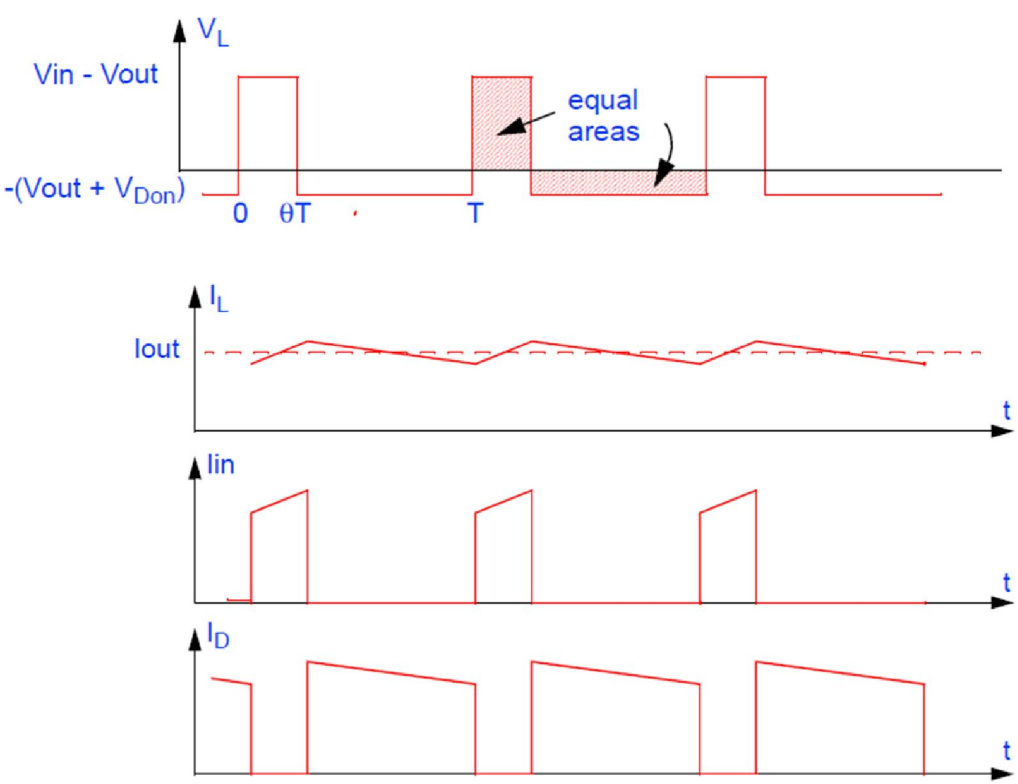
3. Switching regulators: BUCK converter



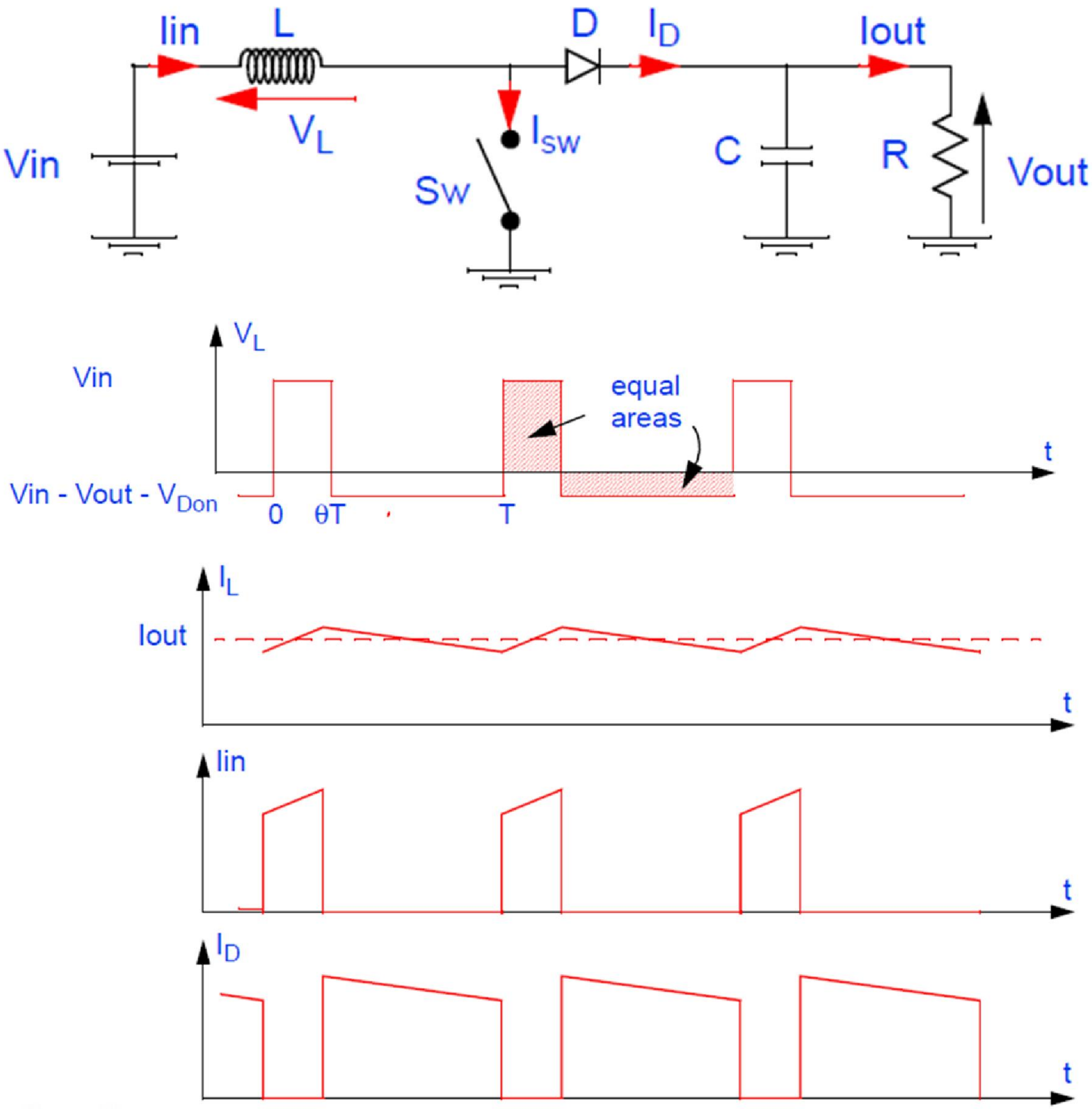


Average voltage across the inductor is zero, V_{Don} neglected (ideal diode):

$$(Vin - Vout) \cdot \theta T = Vout \cdot T \cdot (1 - \theta)$$

$$\frac{Vout}{Vin} = \theta$$

3. Switching regulators: BOOST converter

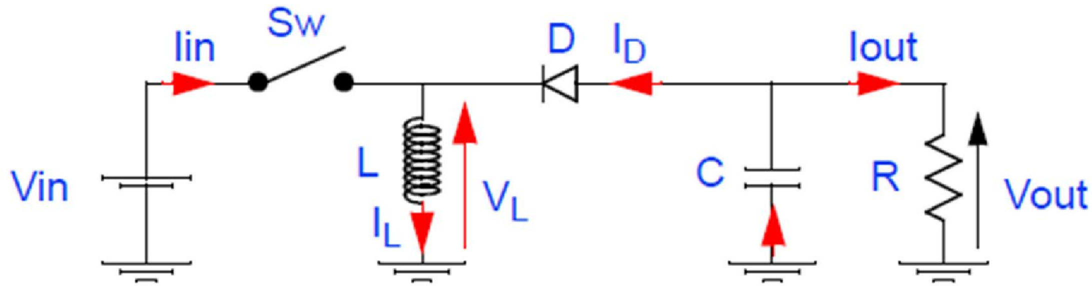


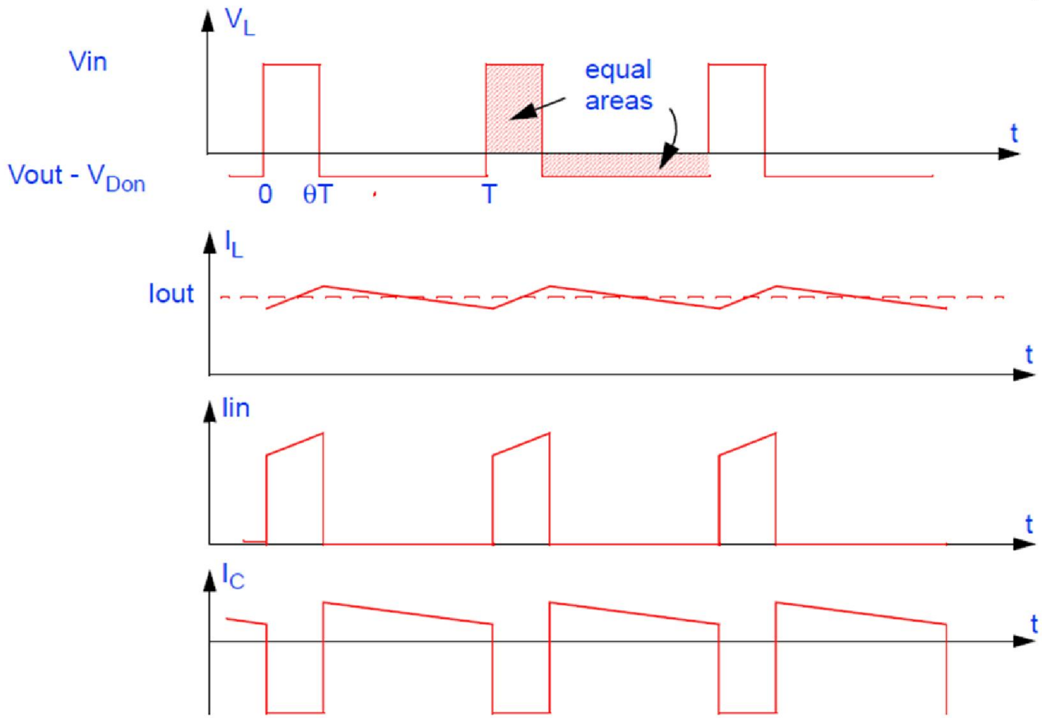
Average voltage across the inductor is zero, V_{Don} neglected (ideal diode):

$$Vin \cdot \theta T = -(Vin - Vout) \cdot T \cdot (1-\theta)$$

$$\frac{Vout}{Vin} = \frac{1}{1-\theta}$$

3. Switching regulators: BUCK-BOOST converter





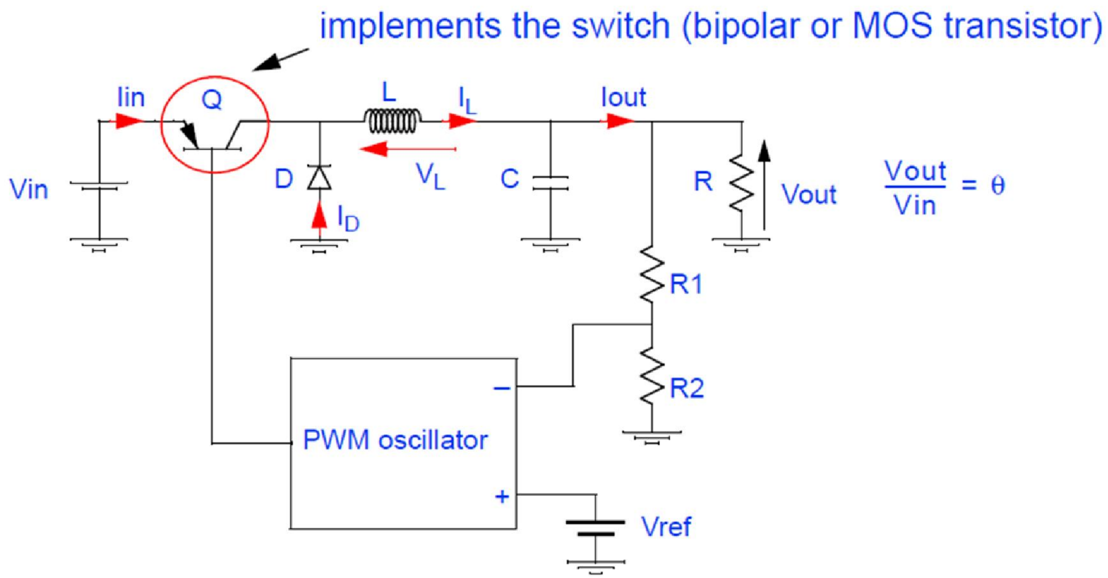
Average voltage across the inductor is zero, V_{Don} neglected (ideal diode):

$$\mathrm{Vin} \cdot \theta T = -\mathrm{Vout} \cdot T \cdot (1-\theta)$$

$$\frac{\mathrm{Vout}}{\mathrm{Vin}} = \frac{-\theta}{1-\theta}$$

3. The switching regulator: what does it look like?

3. Switching regulators: output voltage regulation



PWM = Pulse Width Modulation : duty cycle θ is adjusted to keep Vout constant whatever the variations of Vin and Iout

Vin constant: Vout ↘ → θ ↗ → I_L ↗ → Iout ↗ → Vout ↗

constant load: Vin ↘ → I_L ↘ → Iout ↘ → Vout ↘ → θ ↗ → I_L ↗ → Iout ↗ → Vout ↗

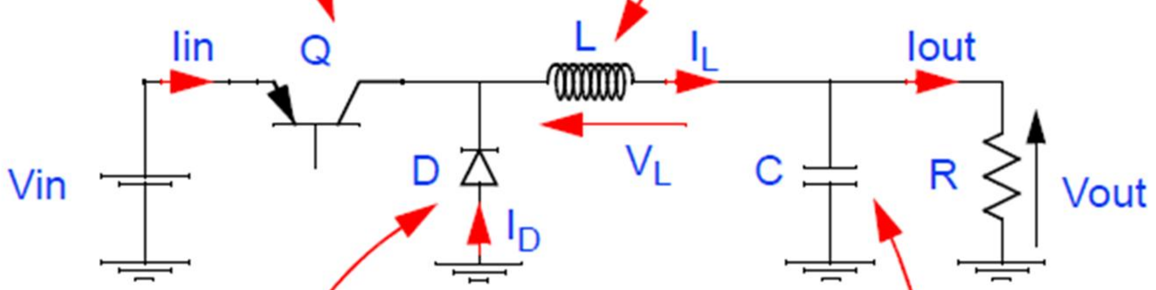
3. Switching regulators: efficiency & losses

No dissipative element in the circuit: theoretical efficiency η = 100% !!

Practically, η < 100% due to losses which come from:

power dissipated (P_{Tdiss}) in the switch (transistor):
- when switch is on (P_{Tdiss} = VCEsat * Iin)
- during commutations

series resistance Rs of the inductor ($P_{Rdiss} = Rs\ I_L$)



power dissipated (P_{Ddiss}) in the diode
($P_{Ddiss} = VD_{on} * I_D$)

Use Shottky diodes!

series resistance R_{ESR} of the capacitor

ESR: Equivalent Series Resistor

4. Linear versus Switching

	Linear	Switching
Configurations	"BUCK" only	BOOST, BUCK, BUCK-BOOST
Efficiency	Typically low to average, high if V_{NS}-V_L=V_{DO}	High excepted for low load currents I_L
Temperature rise	High, depends on V_{NS}-V_L	Normally low
Design complexity	Low, low component count	Average to high typically more components compared to linear designs design may be difficult **
Size	large area if heathsink is mandatory	lower area compared to linear designs for high output power
Cost	low	average to high
Output noise	low	average to high

** Fortunately, free design tools exist: WEBBENCH from Texas instruments, LTpowerCAD from Linear Technology and many more....