ECE1371 Advanced Analog Circuits
Lecture 11

SWITCHING REGULATORS

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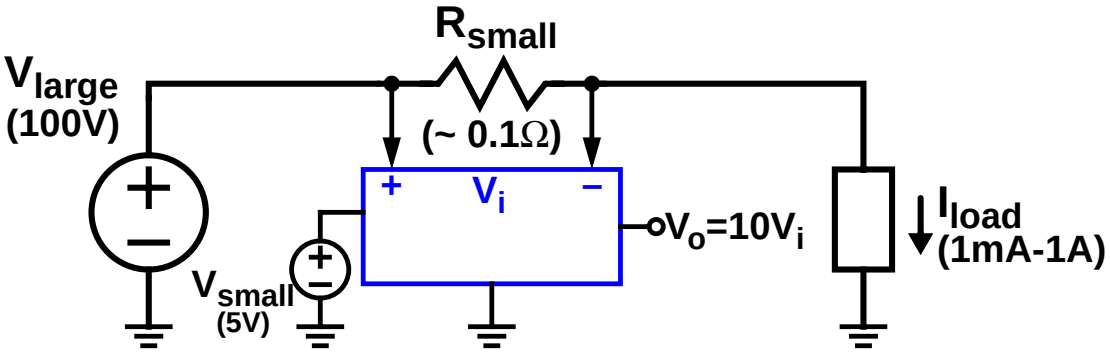
Many thanks to Jonathan Audy for the material from his 2008 ISSCC Tutorial on Power Management and to Prof. Aleks Prodic for his many helpful comments.

Course Goals

- **Deepen understanding of CMOS analog circuit design through a top-down study of a modern analog system**
  - **The lectures will focus on Delta-Sigma ADCs, but you may do your project on another analog system.**
- **Develop circuit insight through brief peeks at some nifty little circuits**
  - **The circuit world is filled with many little gems that every competent designer ought to know.**

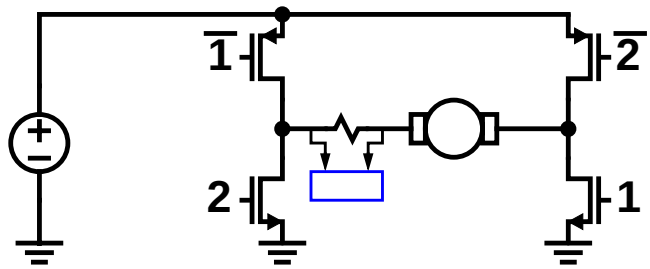
Date	Lecture			Ref	Homework
2008-01-07	RS	1	Introduction: MOD1 & MOD2	S&T 2-3, A	Matlab MOD2
2008-01-14	RS	2	Example Design: Part 1	S&T 9.1, J&M 10	Switch-level sim
2008-01-21	RS	3	Example Design: Part 2	J&M 14	Q-level sim
2008-01-28	TC	4	Pipeline and SAR ADCs	J&M 11, 13	Pipeline DNL
2008-02-04	ISSCC– No Lecture				
2008-02-11	RS	5	Advanced ΔΣ	S&T 4, 6.6, 9.4, B	ΔΣ Toolbox; Proj.
2008-02-18	Reading Week– No Lecture				
2008-02-25	RS	6	Comparator & Flash ADC	J&M 7	
2008-03-03	TC	7	SC Circuits	J&M 10	
2008-03-10	TC	8	Amplifier Design		
2008-03-17	TC	9	Amplifier Design		
2008-03-24	TC	10	Noise in SC Circuits	S&T C	
2008-03-31	RS	11	Switching Regulator		
2008-04-07	Project Presentation				
2008-04-14	TC	12	Matching & MM-Shaping		Project Report

NLCOTD: High-Side Current Sensing



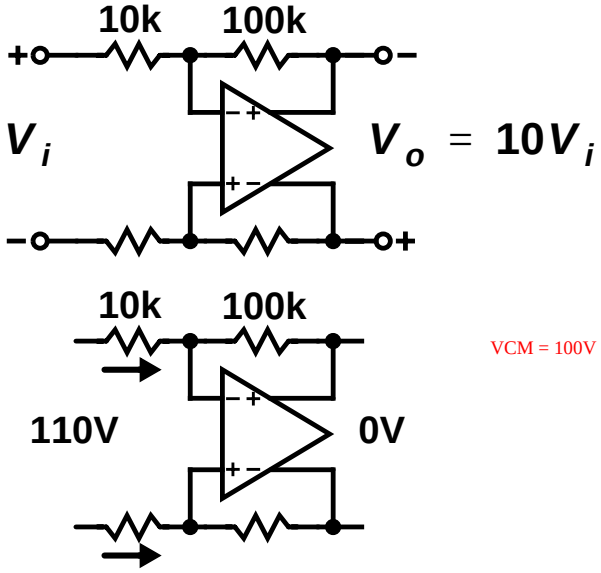
- **Want to amplify a small differential voltage which has a large common-mode component**
  - **The common-mode component is large because we don't want (or can't have) a resistor in the low-side (ground) path.**

NLCOTD: H-Bridge Application



- **The sense resistor is switched between the supply and ground, so it is not possible to sense the load current without also sensing a large common-mode component**

NLCOTD: Differential Amplifier?



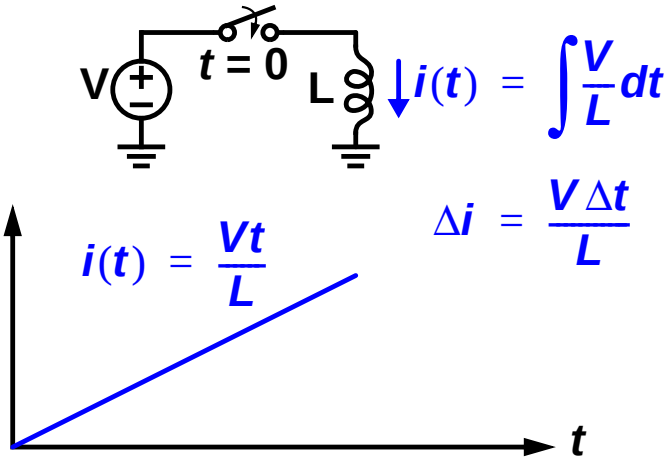
- **Amplifier sees high CM voltage**
- **CM current + resistor mismatch ⇒ offset**

Highlights
(i.e. What you will learn today)

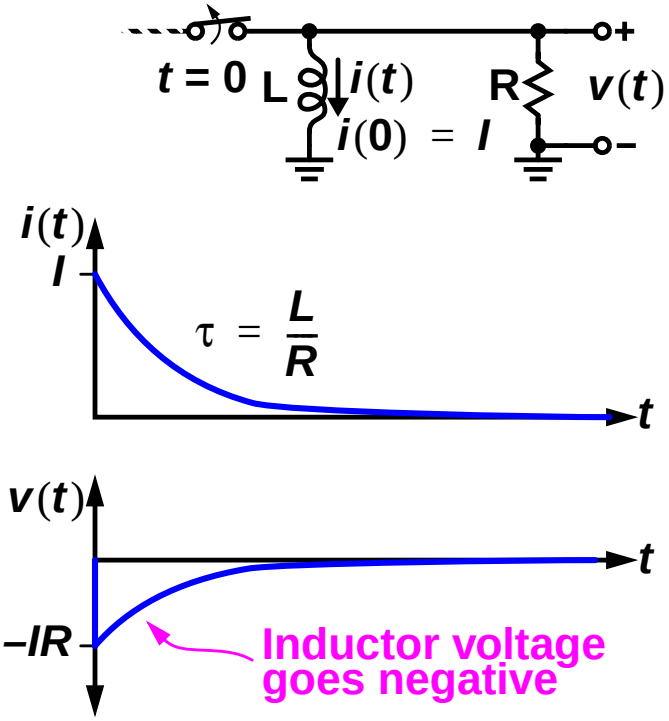
1. Basic Buck and Boost Topologies
2. Design Considerations
3. Inverting Buck-Boost, SEPIC and Çuk Topologies
4. Basic Control Strategies

Review: A Switched Inductor

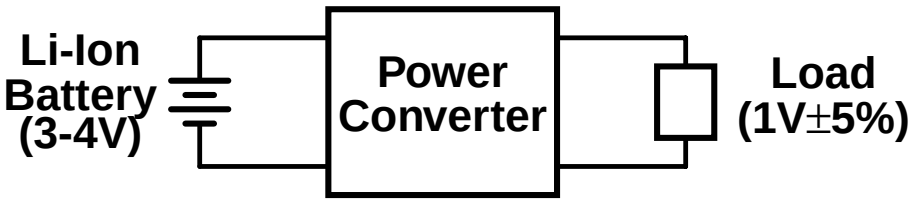
- When a constant voltage is applied across an inductor, the current ramps up with a constant slope
  - At least until the core starts to saturate.



Review: Opening the Switch



The Power Converter Problem



- **Battery voltage usually does not equal the desired load voltage**
  - **Often there are many loads and many voltage requirements.**
  - **Even the voltage requirements of a single load can vary with time, e.g. a CPU or DSP with power-saving.**
- **Battery voltage changes as the battery is charged/discharged**

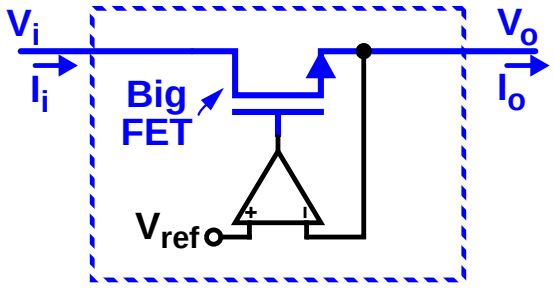
Features & Specifications

1 Input/Output Voltages and Currents
2 Efficiency
3 Voltage ripple
4 Line/load regulation; source/sink capability
5 Dynamics: response to line/load step; overshoot
6 Over-current and over-voltage protection
7 Under-voltage lockout; thermal shutdown
8 Soft startup; adjustability
9 Frequency synchronization

- **Plus absolute reliability– if a power converter behaves badly for even 1μs, the entire system may be destroyed**

  When in comes to power, mistakes can be forever.

Linear Regulator



- **Just a high-power voltage follower**

– $V_o < V_i$

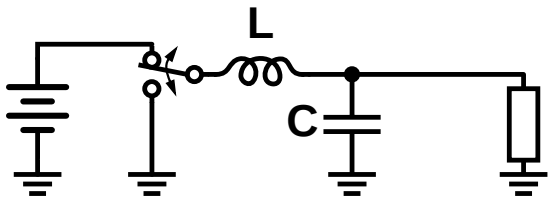
  The "dropout voltage" is the minimum $V_i - V_o$ required for proper regulator operation.

  PMOS FET used to make a low-dropout (LDO) reg.

– **Inefficient**

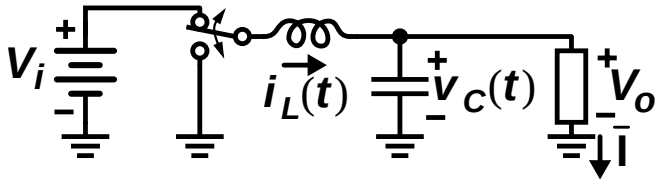
  E.g. if V_i = 4 V and V_o = 1 V, then η_{max} = 25%.

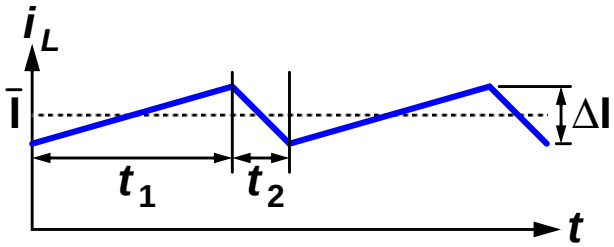
Switching Regulator— Buck Configuration



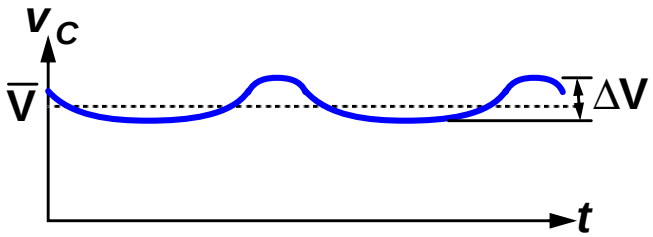
- **Energy is transferred from the battery to the inductor, capacitor and load when the switch is up**
- **Energy stored in the inductor is transferred to the capacitor and load when the switch is down**
- \+ **Ideally, energy is not dissipated in the regulator**
  Typically, $\eta > 90\ \%$.

Buck Waveforms– Ideal





$$\Delta I = t_1\left(\frac{V_i - V_o}{L}\right) = t_2\left(\frac{V_o}{L}\right)$$



$$\Delta V = Q/C = \frac{V_o(1-D)}{8LCf^2}$$

Buck Formulae

- $V_o = DV_i$, where
  $D \equiv t_1/(t_1 + t_2)$ is the *duty cycle*
- Ripple current is $\Delta I/2 = (t_2 V_{out})/(2L)$
  Up to 40% of peak I_o
- Example: V_i = 4 V, V_o = 1 V, T = 1 μs

$D = V_o/V_i = 0.25 \Rightarrow t_1 = 0.25\ \mu s,\ t_2 = 0.75\ \mu s$

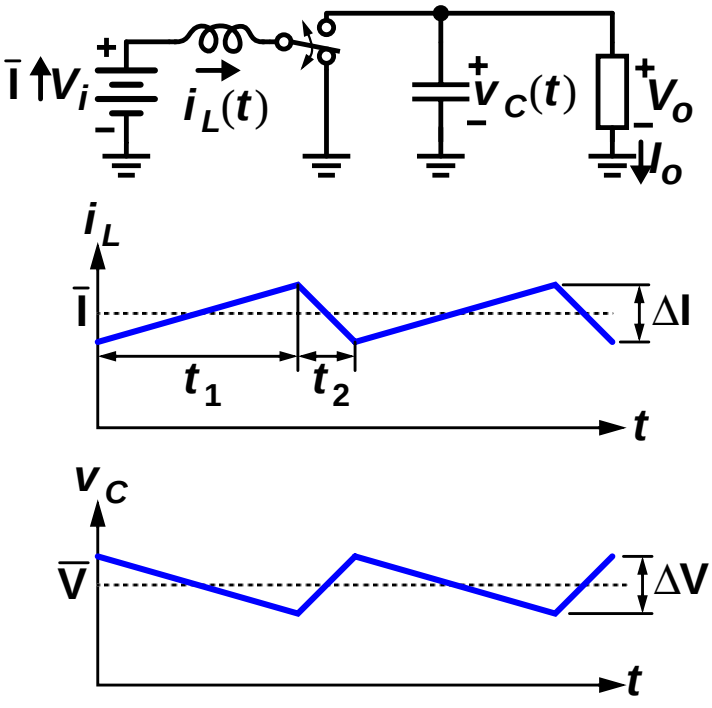
Want I_o = 1 A, and say ΔI = 0.75 A

$$\Rightarrow \quad L = \frac{t_2 V_{out}}{\Delta I} = \frac{0.75\ \mu s \cdot 1\ V}{0.75\ A} = 1\ \mu H$$

Want ΔV = 20 mV $\Rightarrow$

$$C = \frac{V_o(1-D)}{8Lf^2\Delta V} = \frac{1\ V \cdot 0.75}{8 \cdot 1\ \mu H \cdot (1\ MHz)^2 \cdot 20\ mV} = 5\ \mu F$$

Boost Configuration

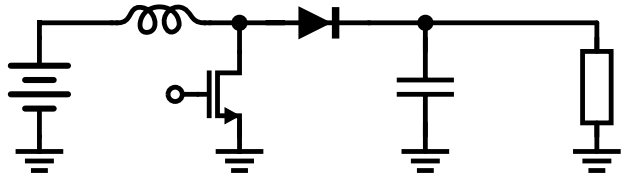


$$\Delta I = t_1\left(\frac{V_i}{L}\right) = t_2\left(\frac{V_o - V_i}{L}\right)$$

$$V_o = \frac{V_i}{1-D}$$

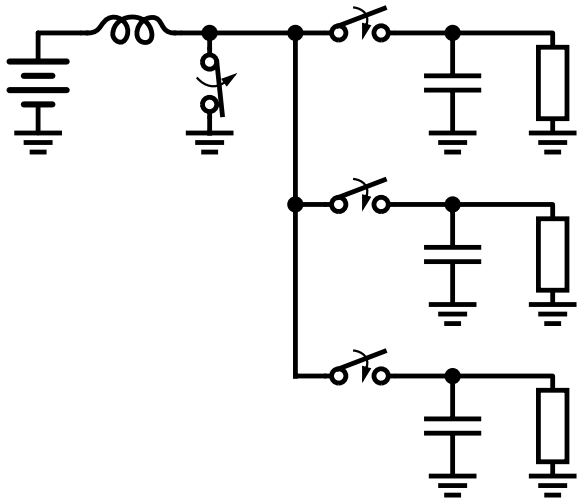
$$\Delta V = t_1 I_o/C = \frac{I_o\left(1 - \frac{V_i}{V_o}\right)}{fC}$$

Boost Converter with Diode
(Old-fashioned)



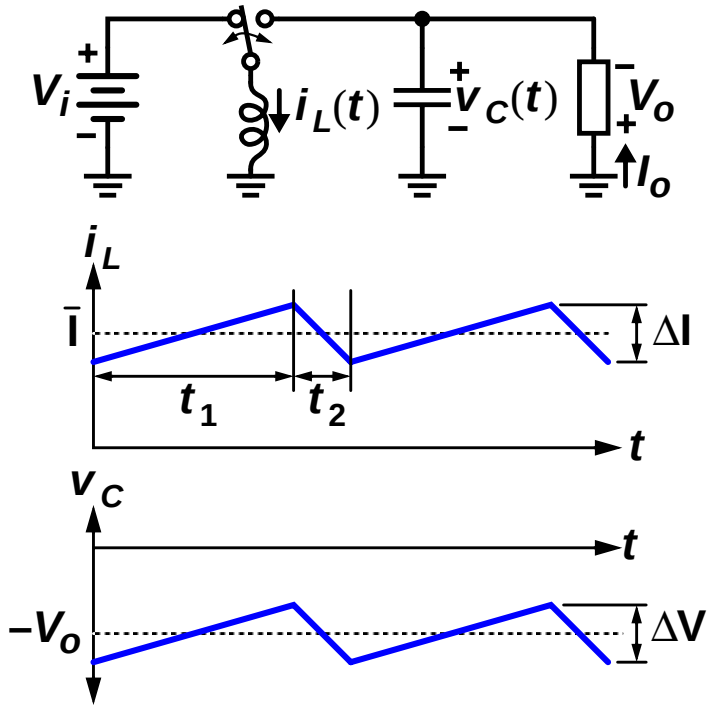
- **SPDT switch implemented by a FET and a diode**
  - **Diode automatically turns on when FET turns off.**
  - **Schottky diode minimizes losses.**
- **Can do the same in a Buck converter, but the efficiency hit is usually unacceptable because V_{fwd} is a significant compared to V_{out}**
- **Synchronous rectification is usually preferred**

Multi-Output Boost



- **Use a single inductor to provide multiple outputs**
  - **Tricky control problem—a good research topic!**
- **Can do both buck and boost with more switches**

Inverting Buck/Boost



$$\Delta I = t_1\left(\frac{V_i}{L}\right)$$

$$= t_2\left(\frac{V_o}{L}\right)$$

$$\frac{V_o}{V_i} = \frac{D}{1-D}$$

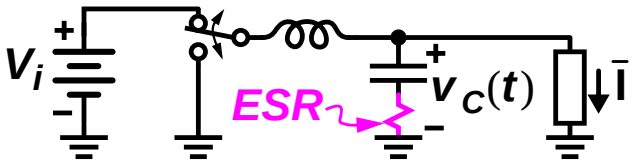
$$\Delta V = t_1 I_o / C$$

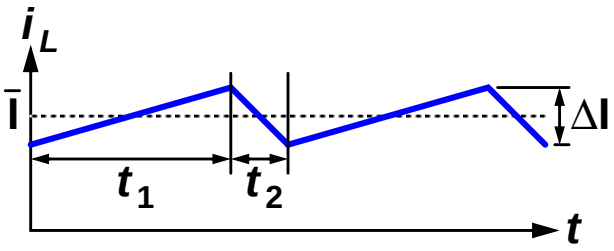
$$= \frac{I_o}{fC\left(1+\frac{V_i}{V_o}\right)}$$

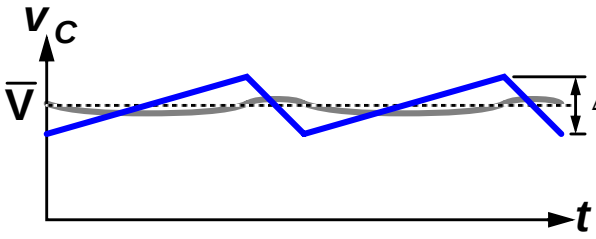
Loss Mechanisms

- **Switch on-resistance**
  - **10 mΩ to 1 Ω.**
- **Switch capacitance**
  - **C_{gs}: 100 pF to 1 nF; C_d: 20 to 200 pF.**
  - **Limit switching frequency to limit this loss.**
- **Inductor resistance**
  - **5 mΩ to 0.5 Ω.**
- **Capacitor resistance**
  - **Equivalent Series Resistance (ESR)**
  - **“Low ESR”: 100 mΩ for C = 10 μF**
  - **“Ultra-low ESR”: 10 mΩ for C = 10 μF**

Effect of ESR on Voltage Ripple





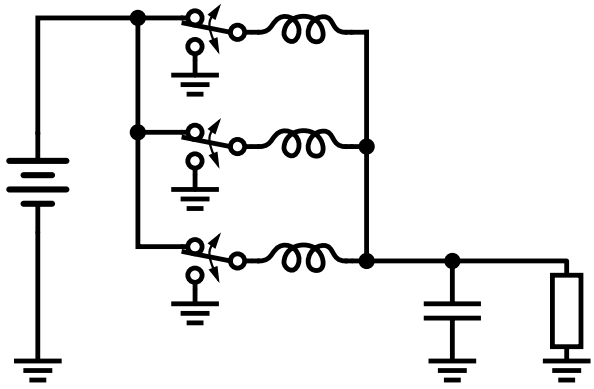


$\Delta V = ESR\,\Delta I$

ΔI = 1 A, ESR = 100 mΩ

$\Rightarrow \Delta V$ = 100 mV

Multi-Phase Buck Converter

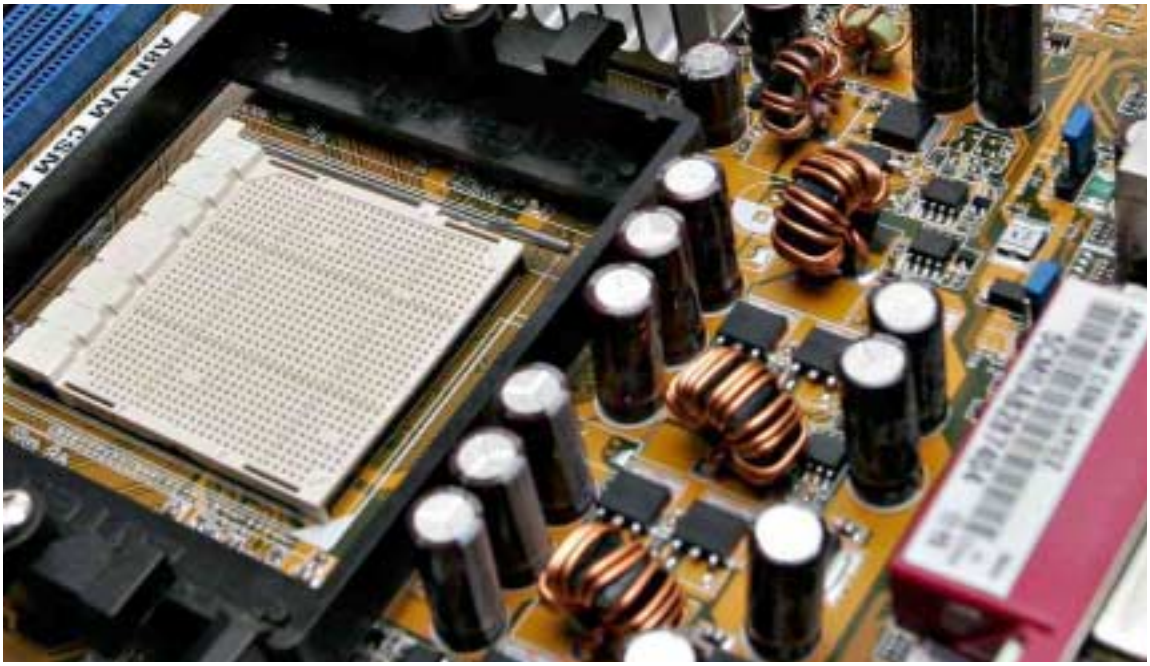


- ***n*** **synchronized switches drive** ***n*** **inductors in an interleaved manner**

+ **Reduces ripple voltage**
  Can achieve ΔV ~ 10mV when driving 100A!

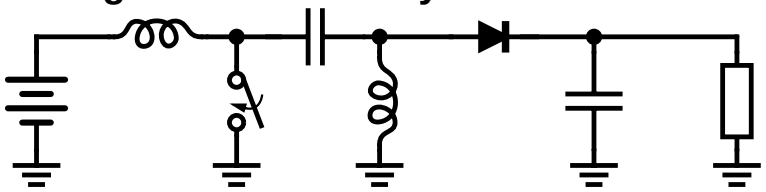
Example Multi-phase Converter

1.5 V 60 A 3ϕ for AMD Processor



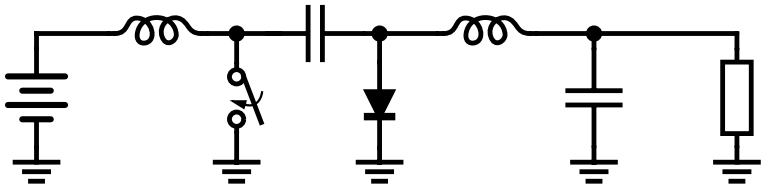
Improved Topologies

SEPIC: **"Single-Ended Primary Inductor Converter"**



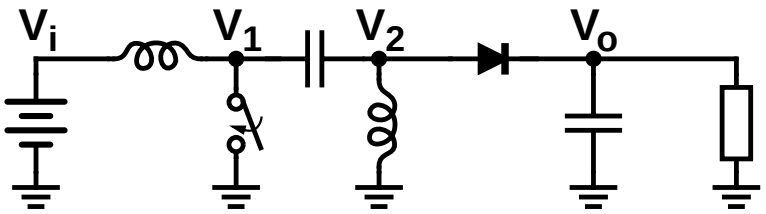
+ **Input current is continuous**

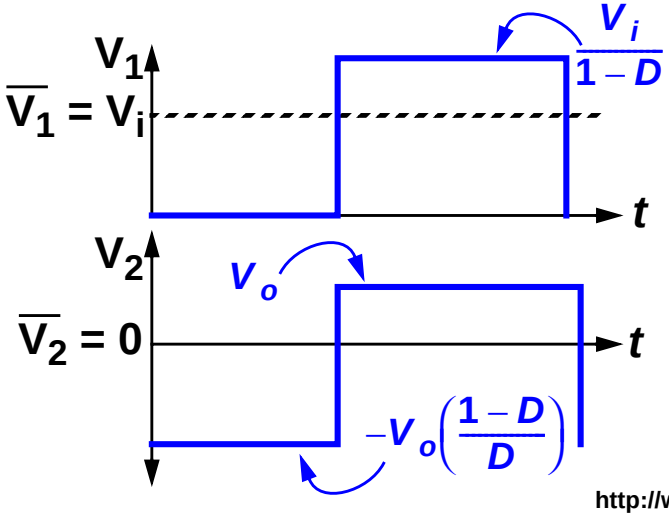
Cuk:



+ **Input and output currents are continuous**
– **Output voltage is negative**

SEPIC Operation





VL1 = VL2 means that they can share the same core.

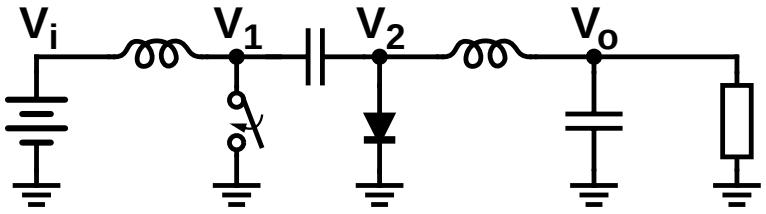
$$\Delta V_1 = \Delta V_2$$

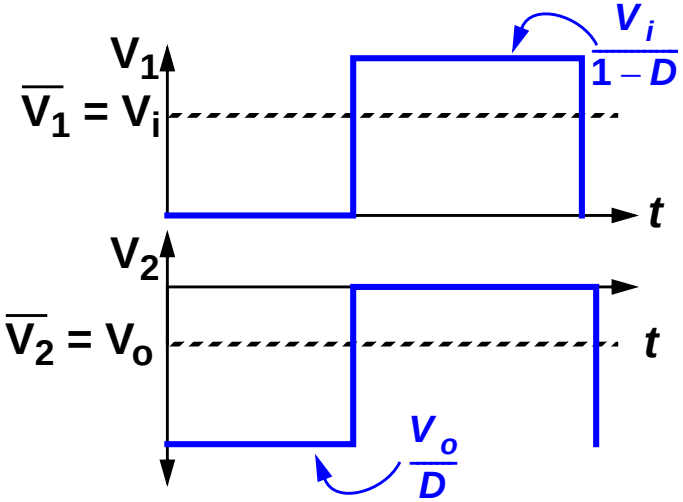
$$\frac{V_i}{1-D} = V_o\left(1+\frac{1-D}{D}\right)$$

$$\therefore V_o = V_i\left(\frac{D}{1-D}\right)$$

http://www.national.com/an/AN/AN-1484.pdf

Cuk Operation





VL1 = VL2 means that they can share the same core.

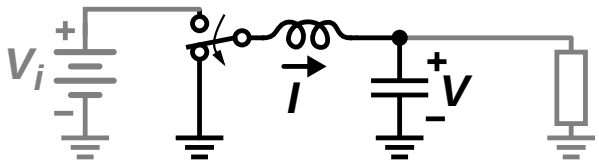
$$\Delta V_1 = \Delta V_2$$

$$\frac{V_i}{1-D} = -\frac{V_o}{D}$$

$$\therefore V_o = -V_i\left(\frac{D}{1-D}\right)$$

Load Removal

Buck Converter



- **If the load current drops to zero, the inductor's energy is dumped into the capacitor and the output voltage goes up**

$$\frac{1}{2}LI^2 + \frac{1}{2}CV^2 = \frac{1}{2}C(V + \Delta V)^2$$

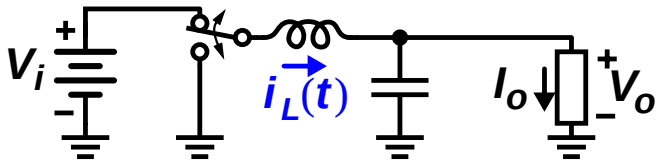
$$\Rightarrow \quad \frac{\Delta V}{V} = \sqrt{\frac{LI^2}{CV^2} + 1} - 1 \approx \frac{LI^2}{2CV^2}$$ **~ 10% for our ex.**

$\Rightarrow$ **Need to increase *C* to make ΔV acceptable**

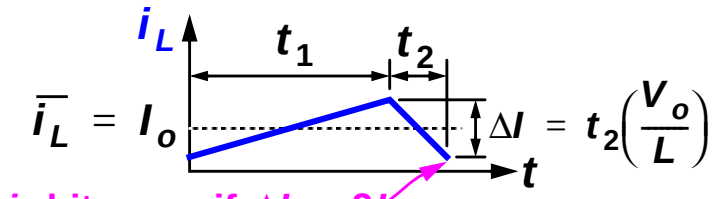
Exceptional Case— Discontinuous Conduction Mode

- **"Switching Regulators are about 20% basic concept, and 80% fixes to problems with the basic concept" [Audy, 2008 ISSCC]**
- **Discontinuous Conduction Mode (DCM) occurs in a diode-based switcher if the inductor current goes to zero**
  - **DCM does not occur if a diode is not used to make the switch, unless a zero-crossing detection circuit is added to the synchronous rectifier**
- **DCM improves η at low I_o**
  - **But since DCM dynamics differ from CCM dynamics, fancier control algorithms are needed.**

DCM in a Buck Converter



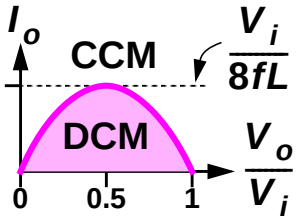
$$V_o = DV_i$$



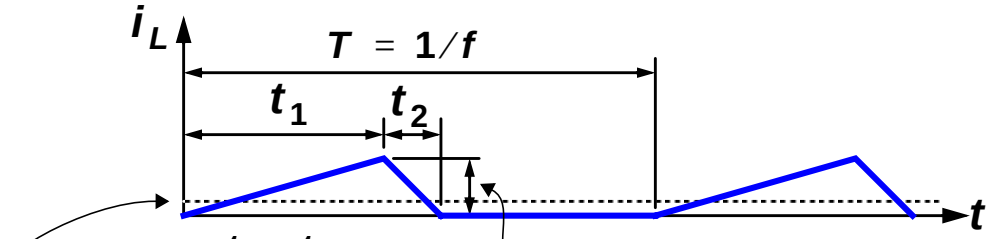
i_L hits zero if $\Delta I = 2I_o$

$$\frac{t_2 V_o}{L} = \frac{(1-D)V_o}{fL} = 2I_o$$

$$I_o = \frac{(1-D)DV_i}{2fL} = \frac{(V_o/V_i)(1-V_o/V_i)V_i}{2fL}$$



DCM in a Buck Converter (cont'd)

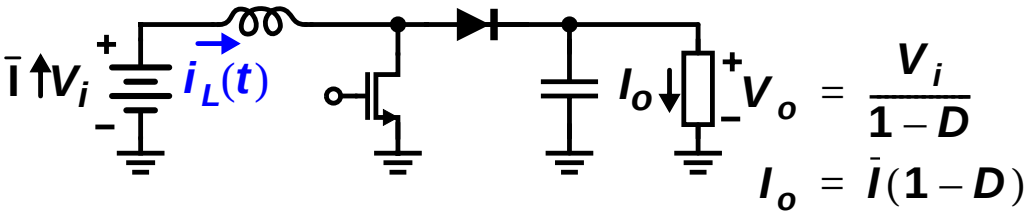


$$\bar{i}_L = I_o = \left(\frac{t_1 + t_2}{T}\right)\cdot\left(\frac{\Delta I}{2}\right) \qquad \Delta I = (V_i - V_o)t_1/L = (V_o t_2)/L$$

$$D = \frac{t_1}{T} = \sqrt{\frac{2fLV_oI_o}{V_i(V_i - V_o)}}$$ ← D now depends on lots of parameters

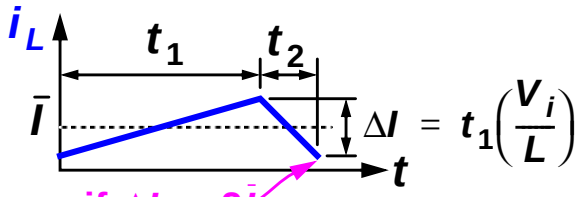
$$I_{o,\,\min} = (t_{1,\,\min})^2 \frac{fV_i(V_i - V_o)}{2LV_o}$$

DCM in a Boost Converter



$$V_o = \frac{V_i}{1-D}$$

$$I_o = \bar{I}(1-D)$$

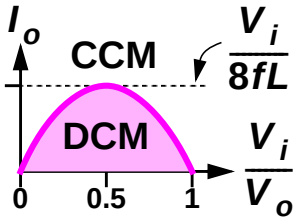


$$\Delta I = t_1\left(\frac{V_i}{L}\right)$$

i_L hits zero if $\Delta I = 2\bar{I}$

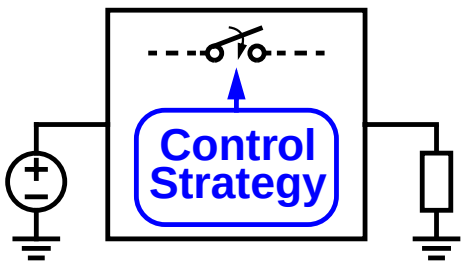
$$\frac{t_1 V_i}{L} = \frac{DV_i}{fL} = 2\bar{I} = \frac{2I_o}{1-D}$$

$$I_o = \frac{(1-D)DV_i}{2fL} = \frac{(V_i/V_o)(1-V_i/V_o)V_i}{2fL}$$



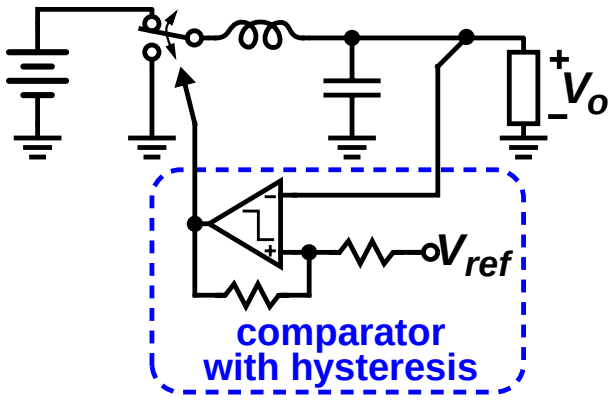
Control Strategies
[Audy 2008]

- The control problem involves deciding when to open/close the switch



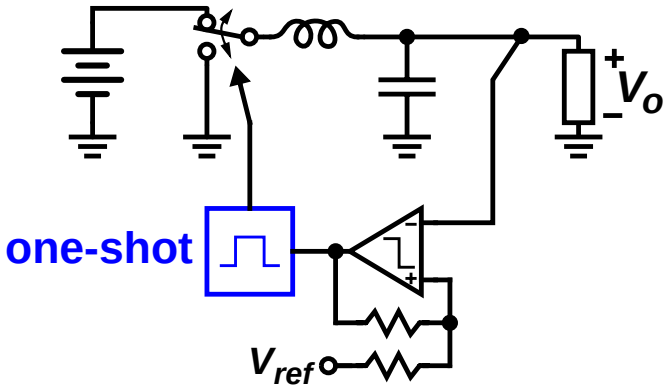
- Want to achieve a specific V_o
  - Except if load current is too great, or if the input voltage is too low, or …
- SMPS control is a fertile research area

Hysteretic Ripple Voltage Regulator



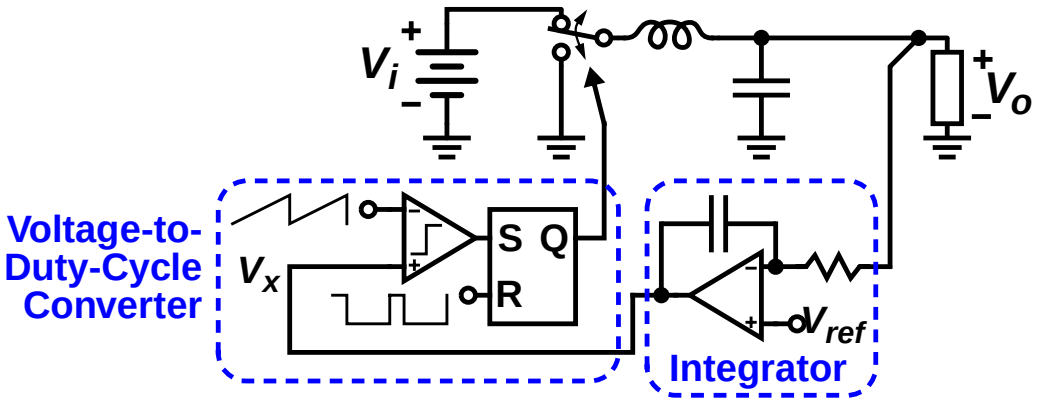
- If $V_o < V_{ref}$, turn on the switch and keep it on until $V_o > V_{ref} + V_{hyst}$
- \+ Simple; fast; stable
- – Behavior depends on ESR: ill-controlled dynamics & excess ripple; Nothing limits t_{on}

Constant t_{on} Hysteretic Regulator



- t_{on} is fixed
- Need to add circuitry to ensure minimum t_{off}

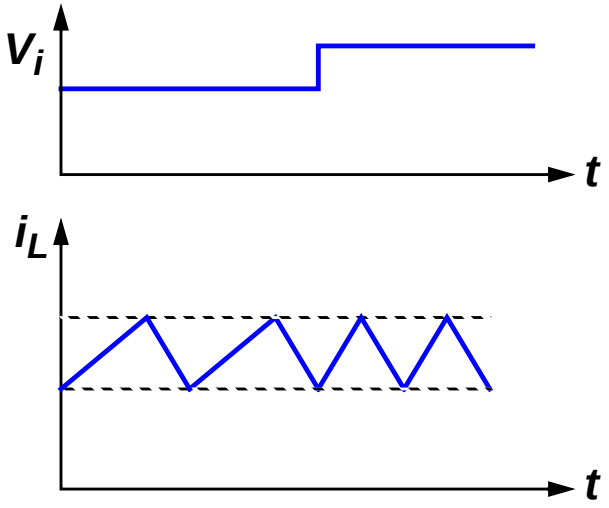
Constant-Frequency Voltage-Mode



+ **Frequency is well-controlled (fixed)**
- **Duty cycle is regulated to achieve desired V_o**
– **Loop is slow to respond to V_i changes**
  Effectively a triple integration: $V_i \rightarrow i_L \rightarrow V_o \rightarrow V_x$

Other Control Schemes— Ripple Current Control

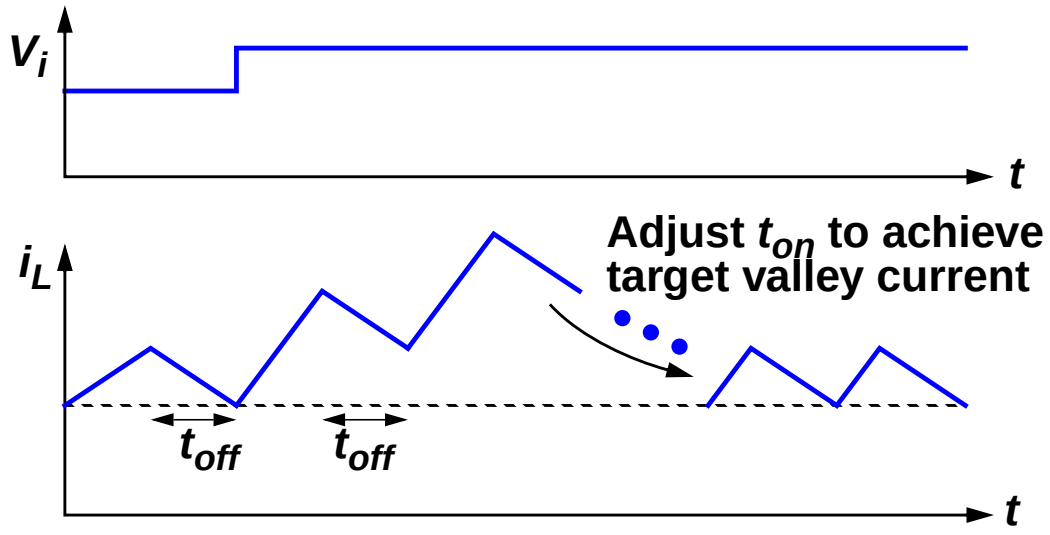
- **In a Buck converter, regulating inductor ripple current $\Rightarrow$ D tracks V_i & V_o changes automatically**



+ **Fast!**
- **Still need a slow voltage loop to get desired V_o**

Valley Current Control

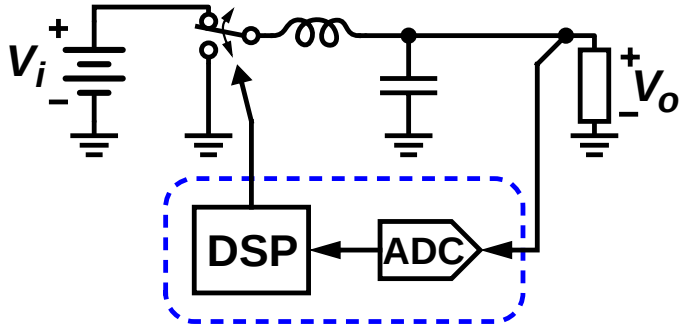
Buck converter; Constant t_{off}



- Average current control is automatic

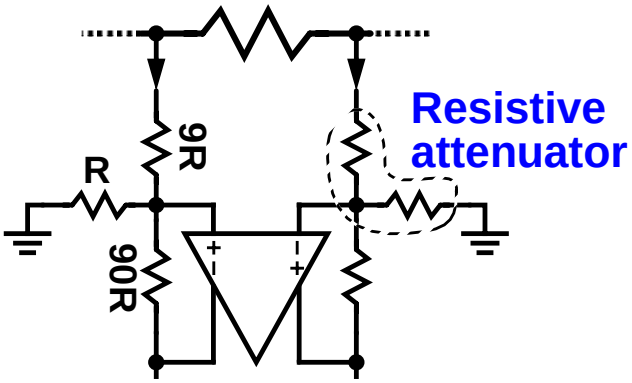
Digital Control

- Controlling the switch with digital logic offers many advantages in flexibility, programmability and adaptability, not to mention ease of design!



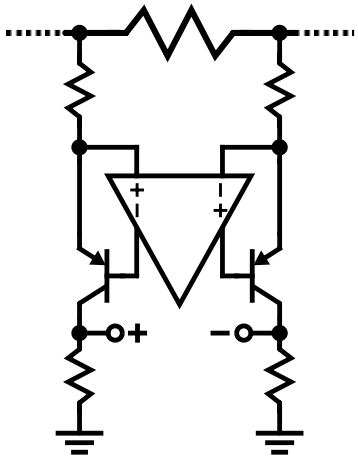
- ADC only needs a few bits of resolution
- DSP needs a digitally-controlled delay in order to set the on/off times with fine resolution

NLCOTD: High-Voltage Differential Amplifier



- + Amplifier sees low voltages
- – Resistor trimming needed for low error
  - AD8206 uses resistors trimmed to 0.01% to get CMRR > 80 dB

NLCOTD: Current-Sense Amplifier



- + Very low CM current ⇒ less sensitive to mismatch
  - AD8210 achieves CMRR ~ 100 dB
- – High-voltage amplifier needed

What You Learned Today

1. **Basic Buck and Boost Topologies**
2. **Design Considerations**
3. **Inverting Buck-Boost, SEPIC and Çuk Topologies**
4. **Basic Control Strategies**