Applied Electronics

E3 – Switching regulators

- Partialization regulators
- Buck and boost regulators
- Parameter evaluation
- Component choice

Lecture E3: switching regulators

- Switching power control
  - Duty cycle change
- Switching regulators
  - Buck
  - Boost
  - Buck-boost
  - Flyback
- References
  - Maloberti: Understanding Microelectronics…: Ch. 13.6

Switching regulators

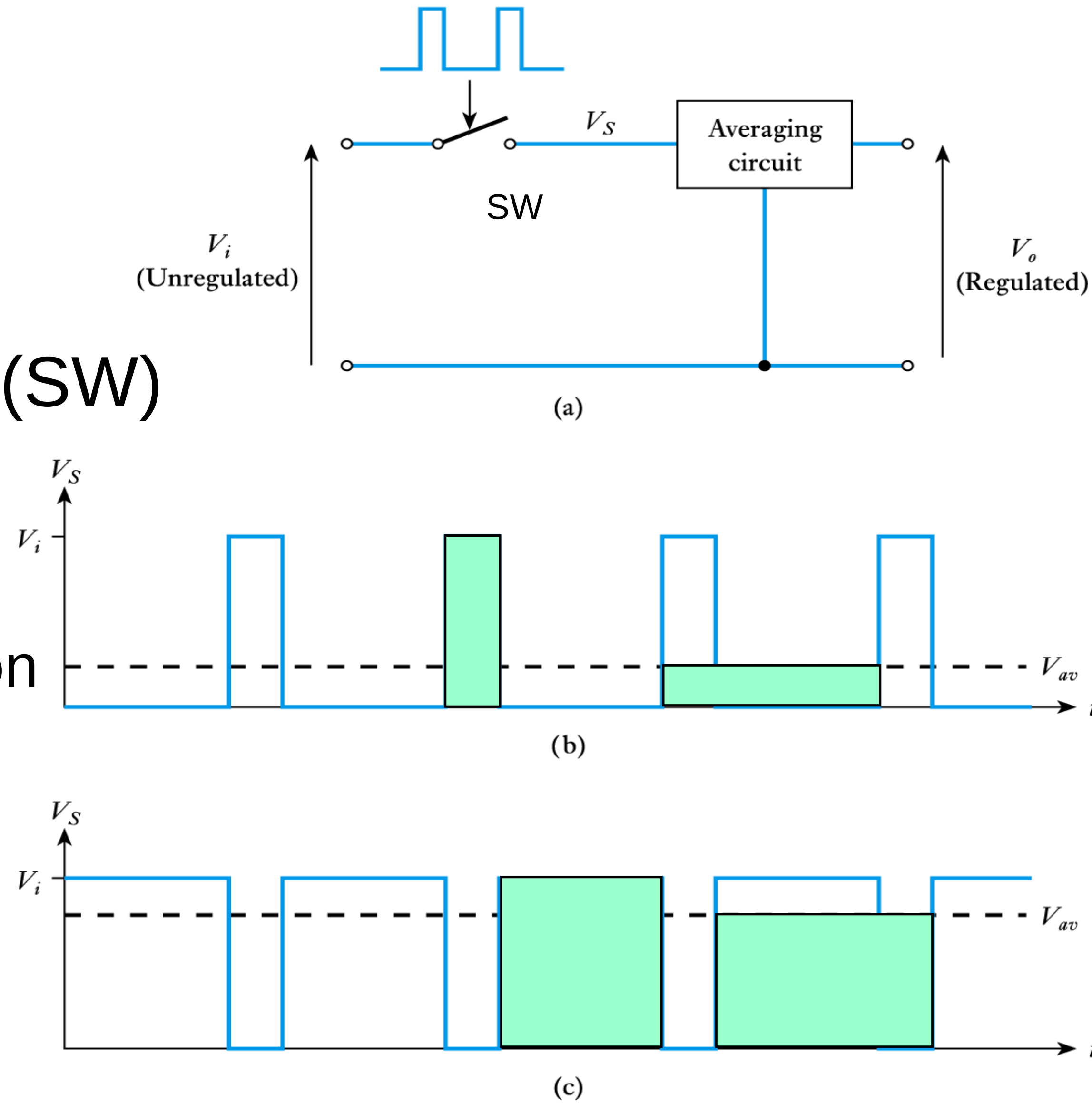
- Energy is controlled using a switch
  - ON → full power
  - OFF → no (zero) power
  - Low-pass filter towards the load (or the load itself filters)
- Voltage control through duty cycle of the ON/OFF switch
- High performance
  - Ideal switches → no dissipation, no loss
  - Real switches → losses from R_{ON}, I_{OFF}, transients, ...
- Applications
  - Amplifiers: class D, E, …
  - Power supplies and switching regulators

Low-pass filter at the output

- Regulator delivers energy to load as a rectangular wave
  - Average value is related to the duty cycle, useful output
  - Fast edge signal, high harmonic content
    - Noise, lost energy, ...
  - Low-pass filter required at the regulator output
- The filter can be
  - Intrinsic to the load (e.g., for a mechanical actuator)
    - Has a much slower response than the ON/OFF command frequency
  - Added low-pass filter to regulator output
    - RC → cheaper, losses in R, used for low powers
    - LC → more expensive, low losses, used for high power

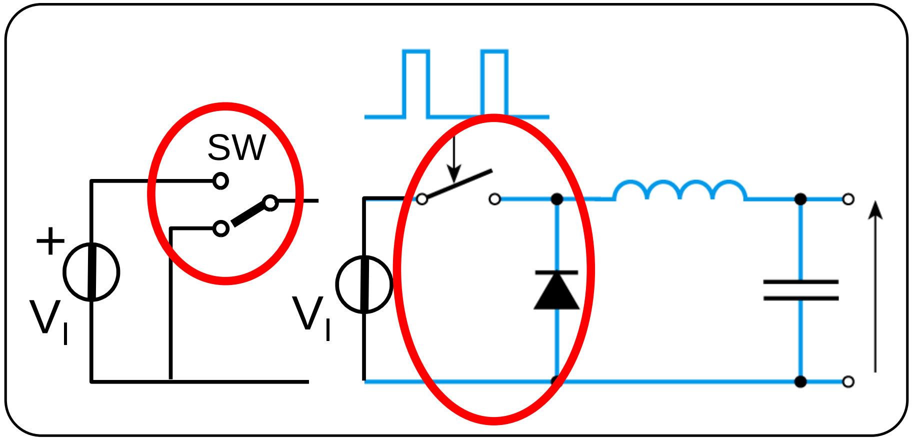
Switching regulator

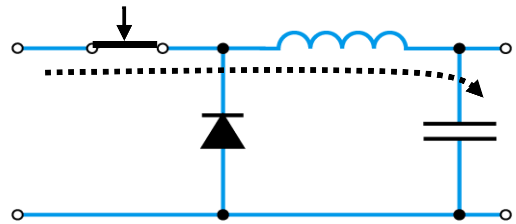
- D-class amplifier
- Power delivered to the load controlled by the duty cycle of the switch (SW)
- The load "averages" the energy
  - Low-pass transfer function
- High efficiency
  - Ideal switch, no losses

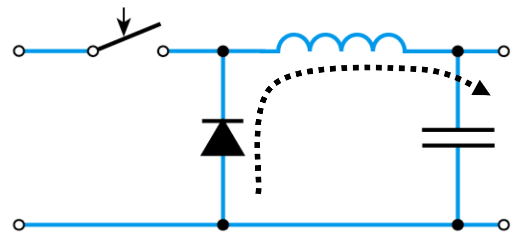


Accumulation and filtering with LC net.

- The square wave is generated by a switch, SW
- A branch of the SW is made with a diode (more modern use MOS)
- Inductance L tends to keep the current constant
- When the switch opens, the current flows through the diode

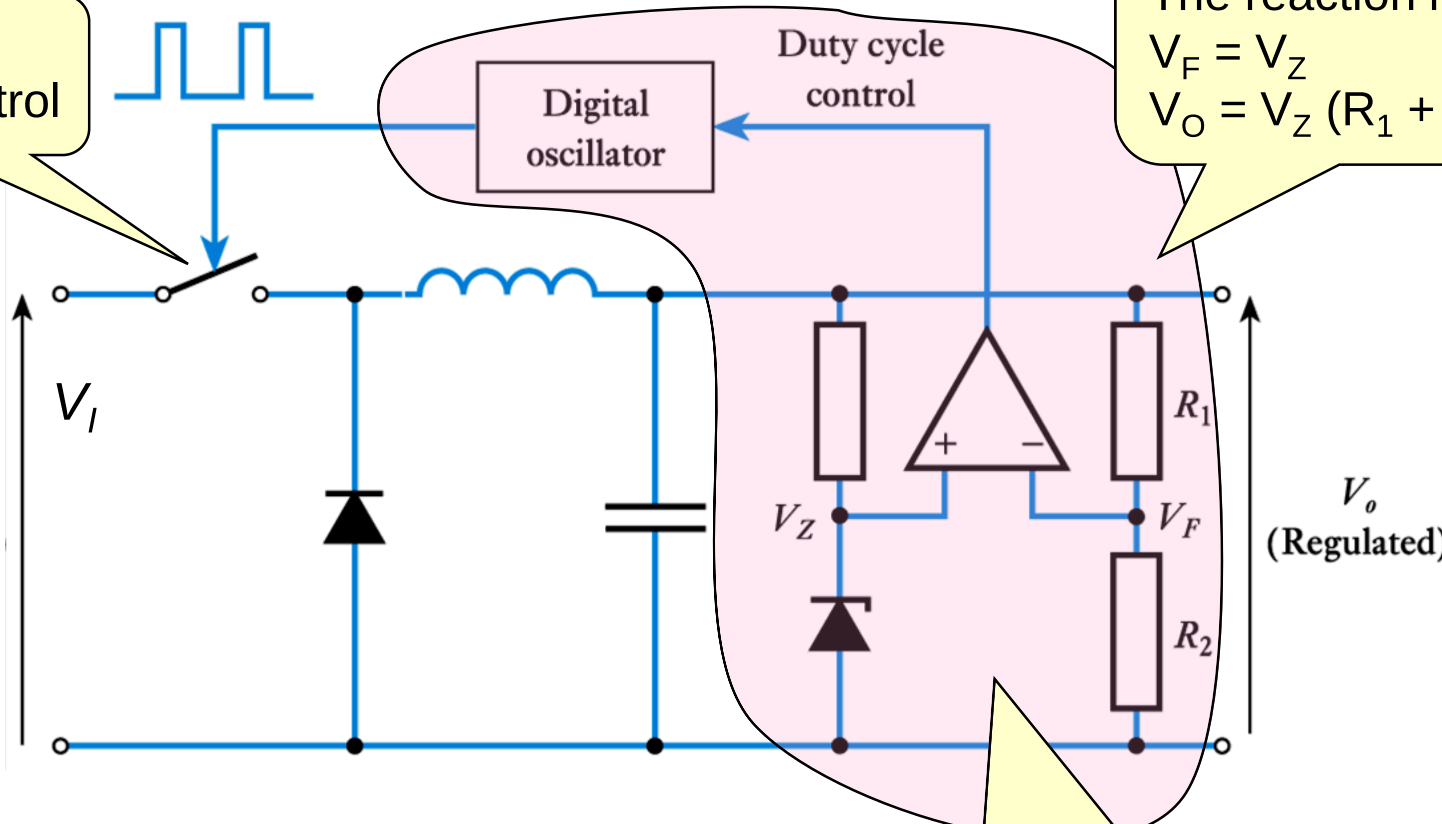






Switching regulator with feedback

Switching power control



$V_F = V_O R_2 / (R_1 + R_2)$
The reaction makes
$V_F = V_Z$
$V_O = V_Z (R_1 + R_2) / R_2$

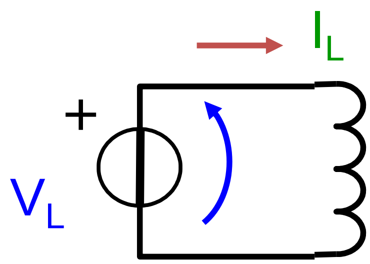
V_O (V_F) is compared with the reference V_Z

Types of switching regulators

- Converters dc → dc, with various topologies
  - Buck $V_O < V_I$
  - Boost $V_O > V_I$
  - Buck-boost $V_O < V_I$ or $V_O > V_I$, reversed polarity
  - Flyback Buck-boost with galvanic insulation
- Benefit: high efficiency (close to 1)
  - Low power dissipation (unlike linear regulators)
  - Losses only from parasitic switch components, L, and C
- Disadvantages
  - Output ripple
  - Generation of interferences (EMI)

Behavior of an inductance

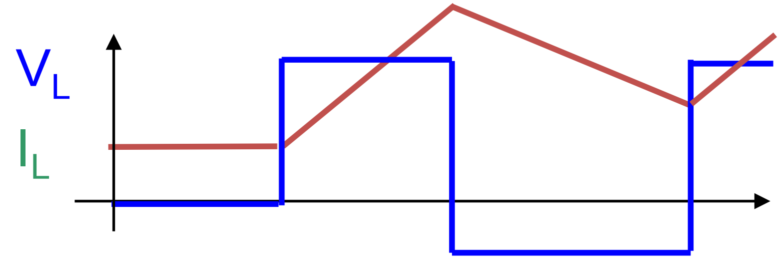
- Ideal inductance
  - No current steps!
  - $R_S = 0\ \Omega$
  - Applied voltage $V_L(t)$



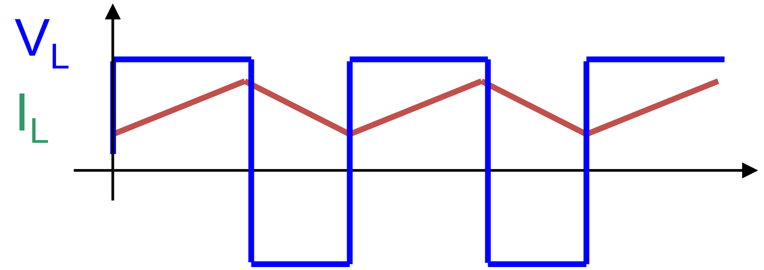
$$I_L = \frac{1}{L}\int_{-\infty}^{t} V_L(t)\,dt$$

$$\Delta I_L = \frac{V_L \Delta T}{L}$$

- Voltage V step response
  - Current ramp (I)



- Driving with square wave V(t)
  - Triangular current I(t)

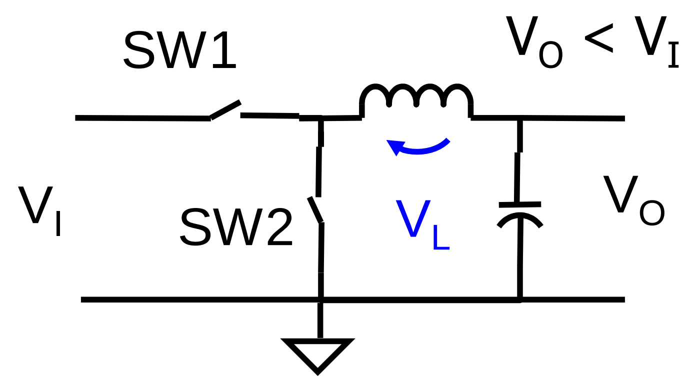


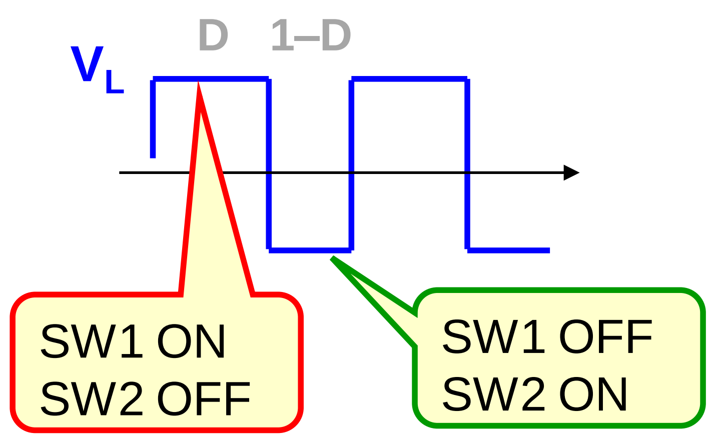
Lecture E3: switching regulators

- Switching power control
  - Works by varying the duty cycle
- Switching regulators
  - Buck — $V_O < V_I$, presented in detail
  - Boost — $V_O > V_I$
  - Buck-boost — reverse polarity
  - Flyback — isolation transformer

Buck regulator

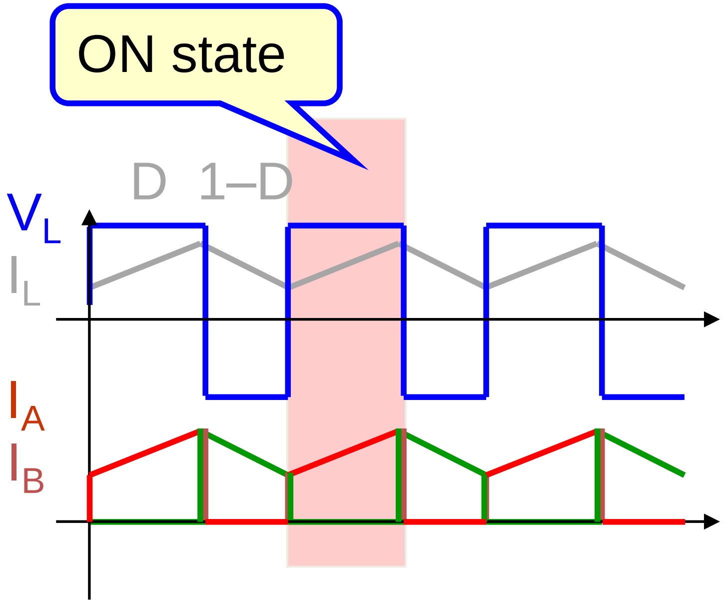
- Switches SW1 and SW2
  - Complemented commands
  - SW1 is ON with duty cycle D
    $V_L = V_I - V_O > 0$
    the current through L increases
  - SW2 is ON with duty cycle 1–D
    $V_L = -V_O < 0$
    the current through L decreases

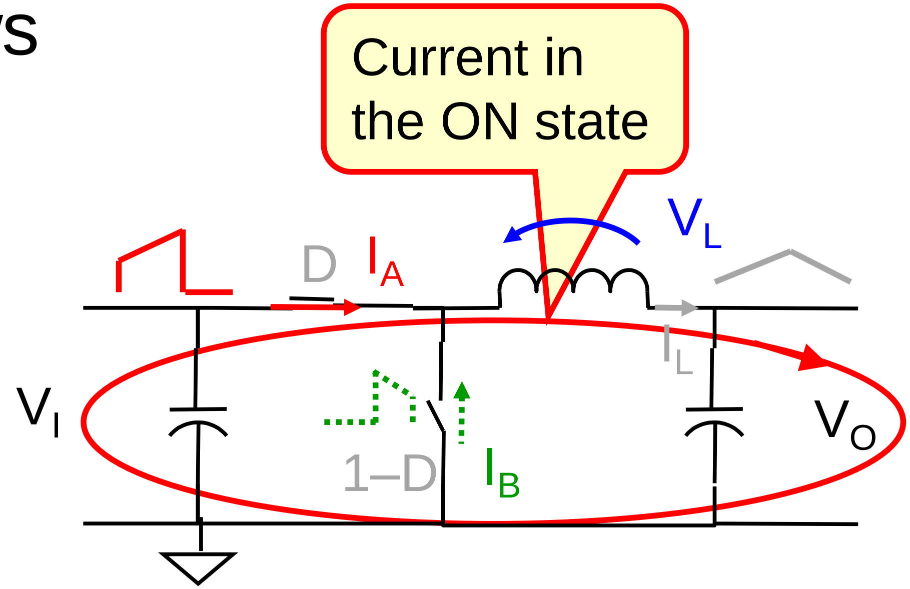




Buck regulator, ON state

- SW1 closed, the current flows from V_I to V_O through L





$$I_L = \frac{1}{L}\int_{-\infty}^{t} V_L(t)\,dt$$

Current variation in the ON state

$$\Delta I = \frac{(V_I - V_O)\,T_{ON}}{L}$$

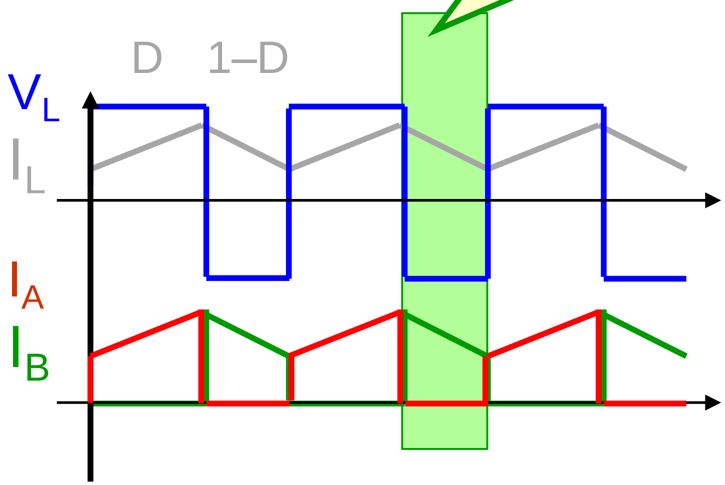
Buck regulator, OFF state

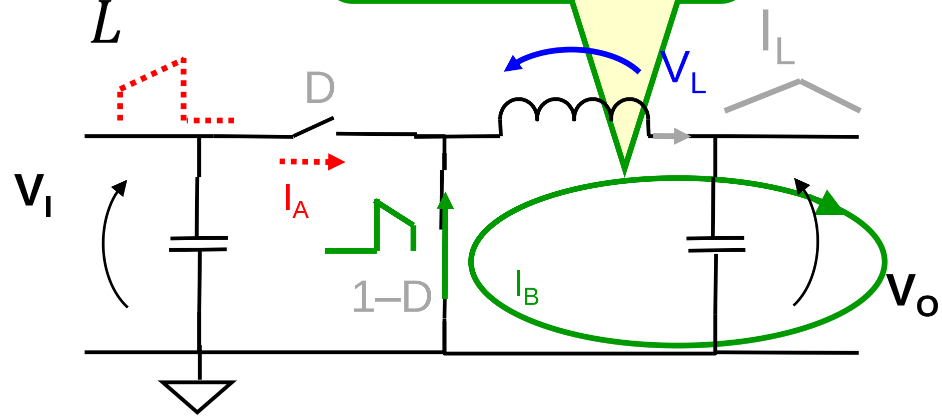
Current variation in the OFF state

$$\Delta I = \frac{-V_O\, T_{\mathrm{OFF}}}{L}$$

Current in the OFF state

OFF state





$$\Delta I = \frac{(V_I - V_O)\, T_{ON}}{L} + \frac{-V_O\, T_{OFF}}{L} = 0$$

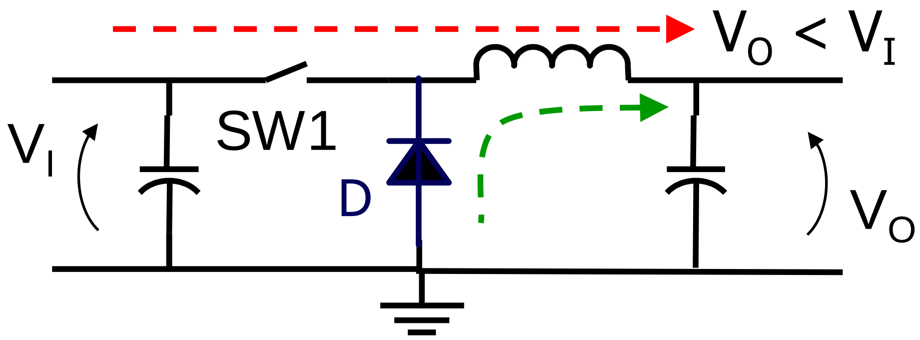
We call: $D = T_{ON} / (T_{ON} + T_{OFF})$

Current variations in the ON and OFF states are balanced; the transfer ratio corresponds to the duty cycle of the ON / OFF command

$$\frac{V_O}{V_I} = D$$

Final schematic of Buck regulator

- The SW2 switch can also be made with a diode (currently made with a MOS)
  - SW1 closed
    - Reverse biased diode, zero current → SW2 OFF
  - SW1 open
    - The inductance tends to keep the current constant
    - Current can only flow through the diode → SW2 ON

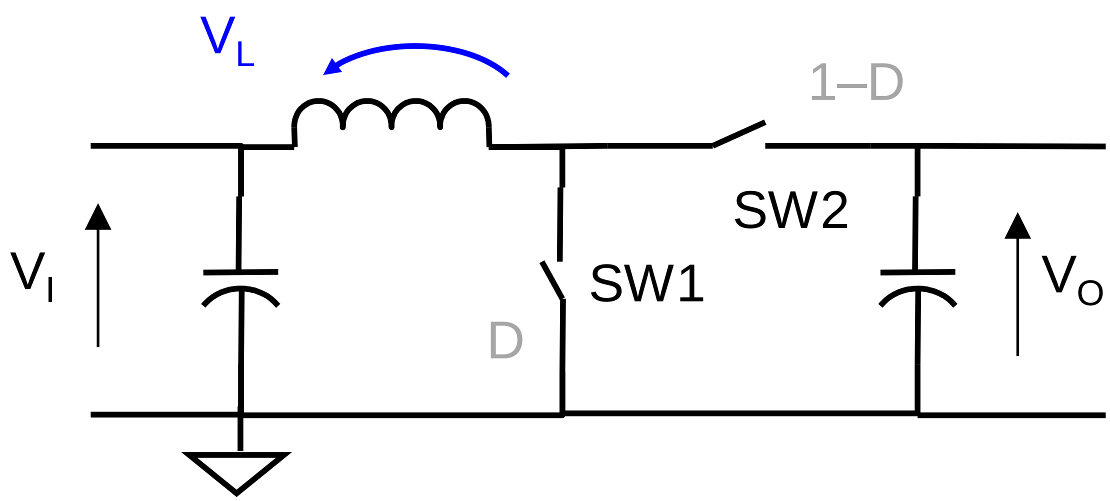


Efficiency of a Buck regulator

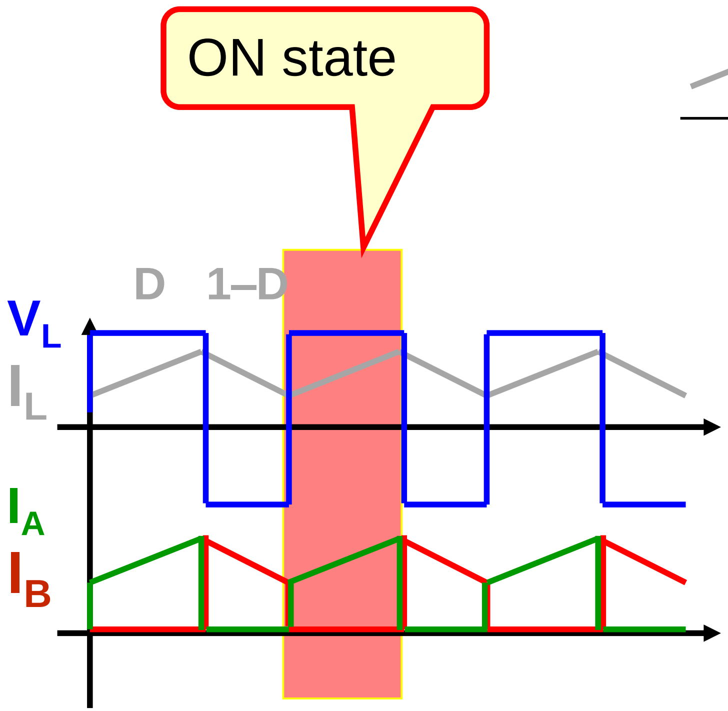
- With ideal switches and diodes
  - No losses → Efficiency $\eta = 1$
- With real devices we have several losses
  - Switches: non-zero R_{ON} and non-zero I_{OFF}
  - Diode (if any): non-zero V_D and non-zero I_S
  - Transients: MOS operates in the linear zone
  - L: non-zero series resistance R_L, losses in magnetic core
  - C: non-zero equivalent series resistance (ESR)
- Efficiency η <1 (but close to 1: 0.8... 0.9...), based on the switching frequency
  - Similar parameters for the efficiency of all switching regulators

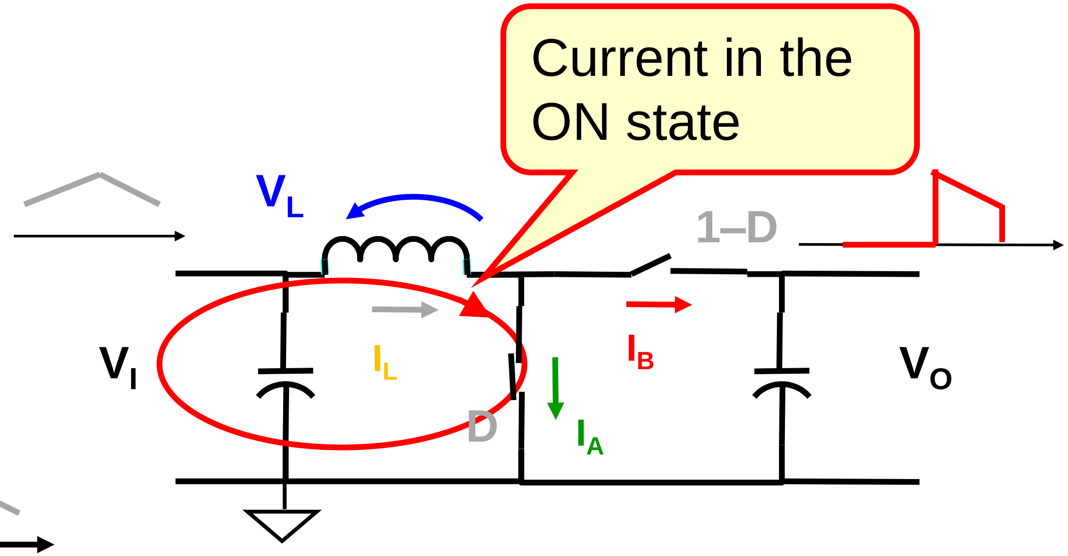
Boost regulator

- Exchange SW1 ↔ inductance with respect to the buck
- Similar operation and analysis
- Output voltage $V_{OUT} > V_{IN}$
- SW2 can be implemented with a diode



Boost regulator, ON state



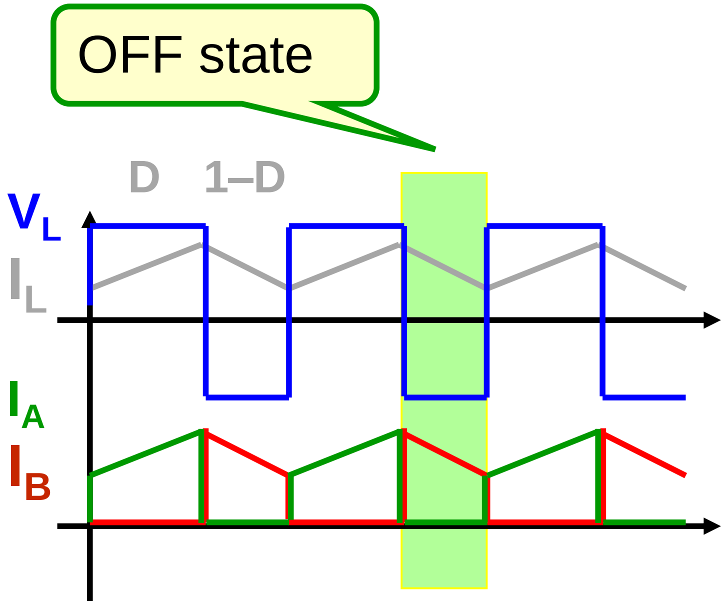


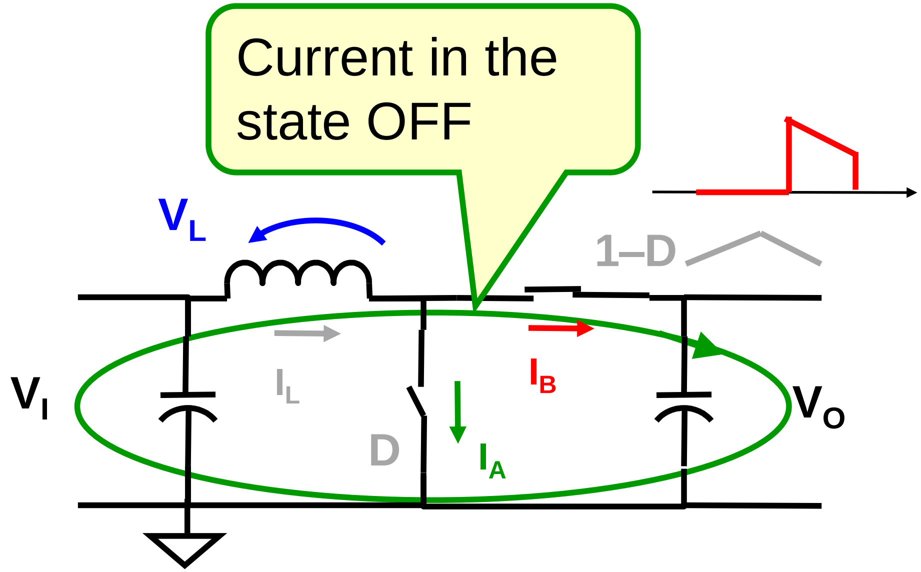
$$\Delta I = \frac{V_I}{L} T_{ON}$$

Inductance current variation in the ON phase

Boost regulator, OFF state

- SW open: $V_L = -(V_O - V_I)$
  I_L is a ramp





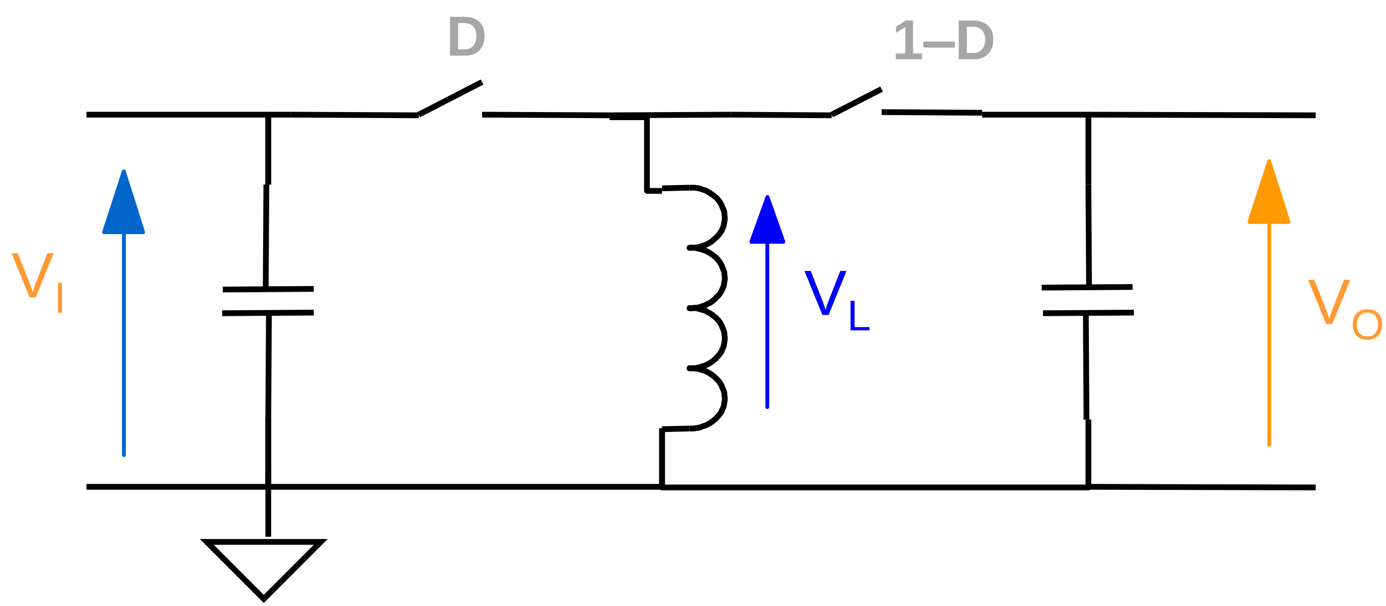
$$\frac{V_I}{L} T_{ON} = \frac{V_O - V_I}{L} T_{OFF}$$

Transfer ratio defined by the duty cycle D

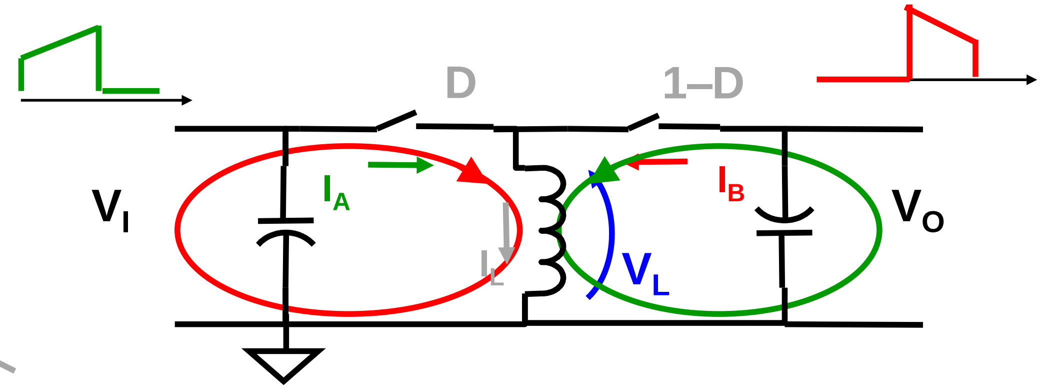
$$\frac{V_O}{V_I} = \frac{1}{1 - D}$$

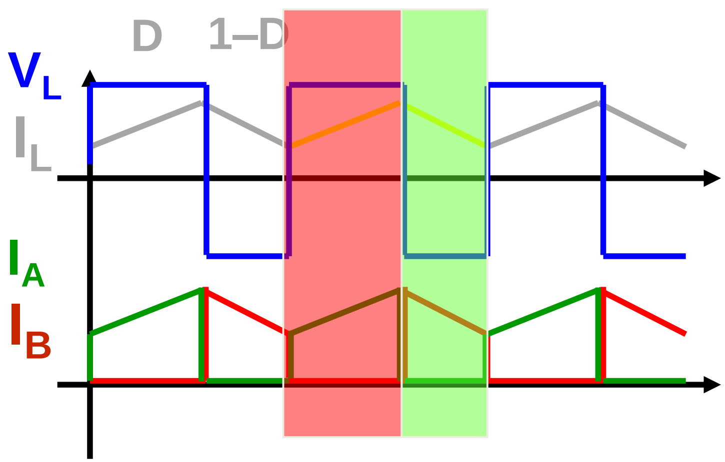
Buck-boost regulator

- Combines buck and boost topologies
- Inverts the output voltage
  - $V_O < 0$ for $V_I > 0$



"ON" PHASE "OFF" PHASE





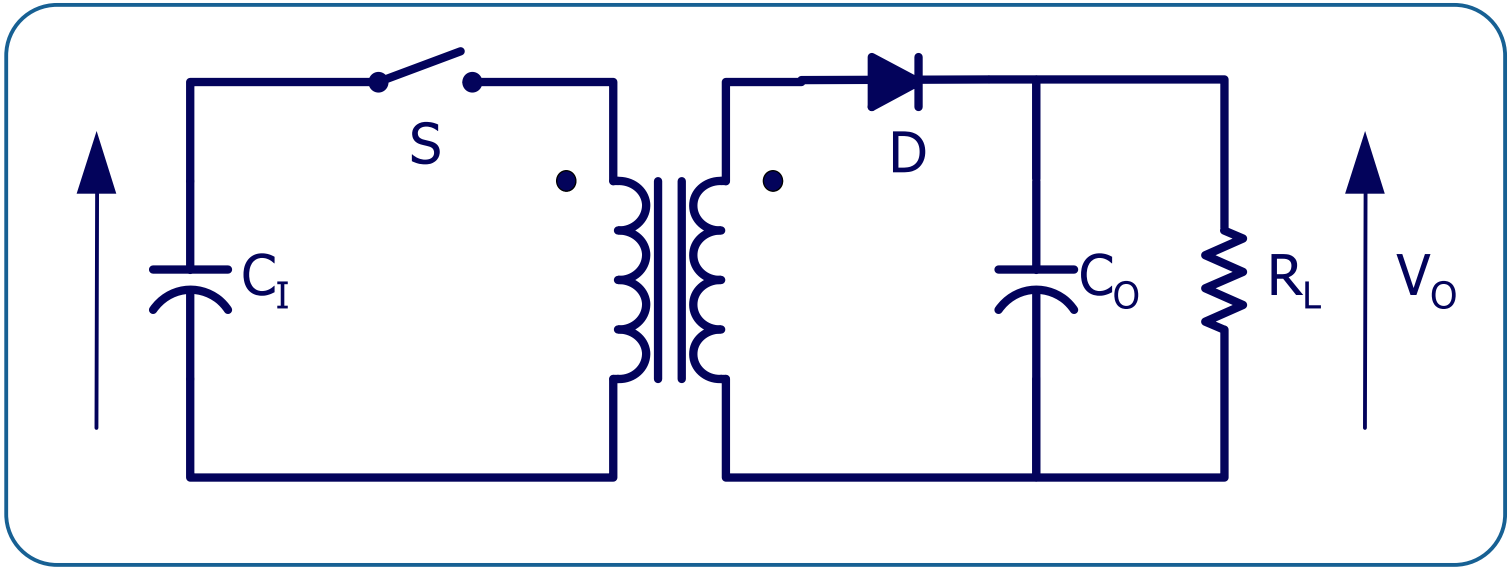
$$\frac{V_I}{L} T_{ON} = -\frac{V_O}{L} T_{OFF}$$

$$\frac{V_O}{V_I} = -\frac{D}{1-D}$$

Negative output voltage, controlled by the duty cycle

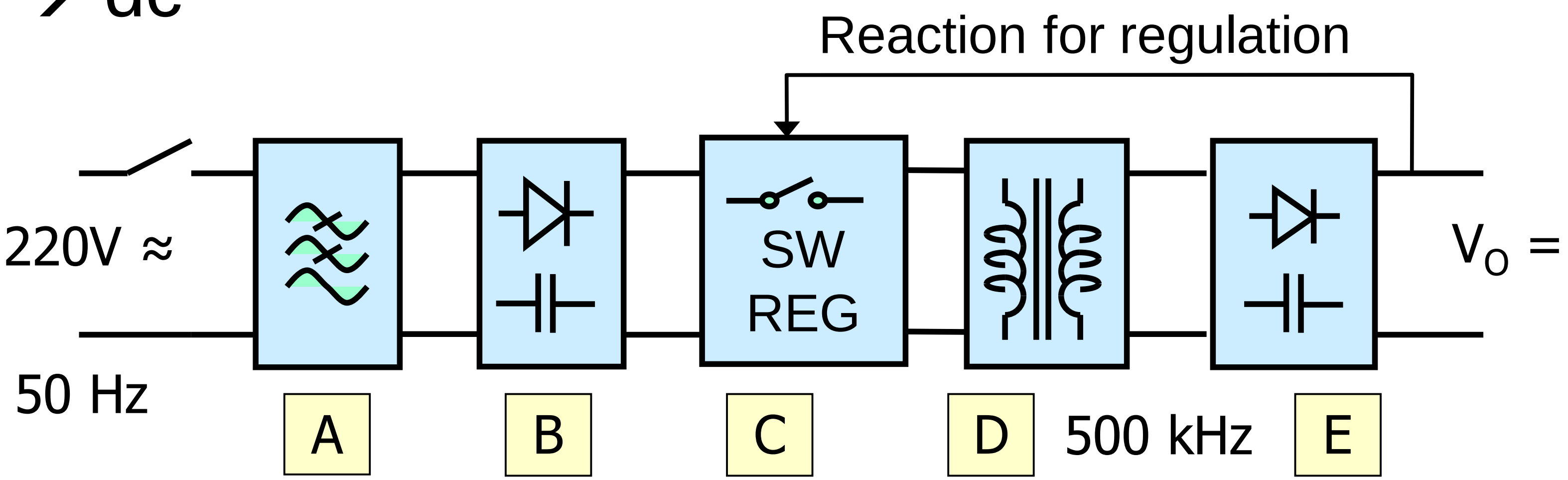
Flyback power supply

- Provides galvanic isolation
  - ♦ Is a buck-boost regulator with a transformer instead of the inductance
  - ♦ For control is also used an isolated reaction (optical coupling)



Switching power supply

A. EMI filter
B. From ac (mains) to dc
C. Switching regulator (dc → ac)
D. Ac → ac (high frequency, small transformer)
E. Ac → dc



Lecture E3: final verification

- Describe the PWM regulation technique.
- Draw the block schematic of a switching regulator power supply and describe the function of each block.
- Compare the advantages and disadvantages of linear and switching regulators.
- Draw the block diagram of the two basic switching regulator topologies and describe their operation.
- What parameters affect the output ripple in switching power supplies?
- What parameters affect the efficiency?
- Differences between buck and boost regulators?