TSTE19 Power Electronics

Lecture 6

Tomas Jonsson
ISY/EKS

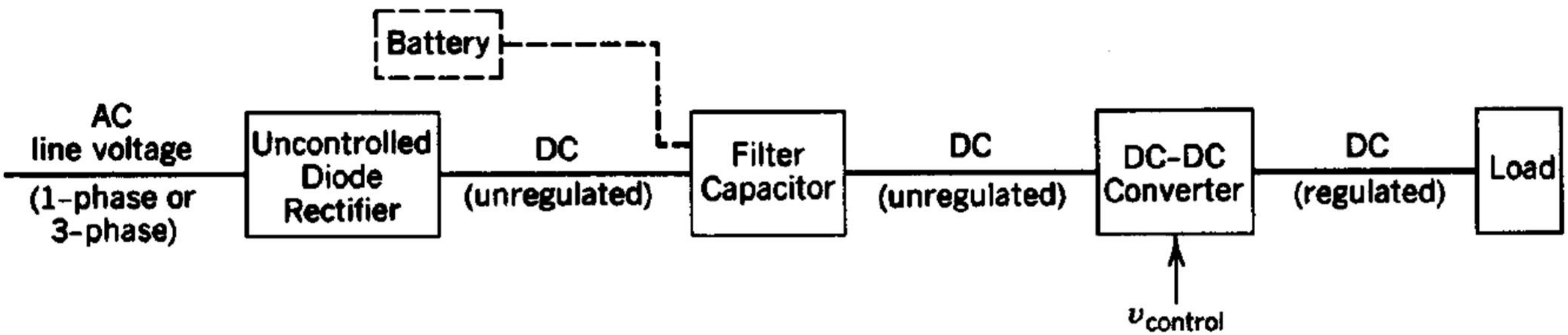
LINKÖPING UNIVERSITY

Outline

- DC power supplies
- DC-DC Converter
  - Step-down (buck)
  - Step-up (boost)
- Other converter topologies (overview)

Basic use of DC-DC converter

- Unregulated DC input, controlled DC output
  - Regulated DC may be larger or smaller than the unregulated DC voltage
  - Input to DC-DC converter may vary a lot

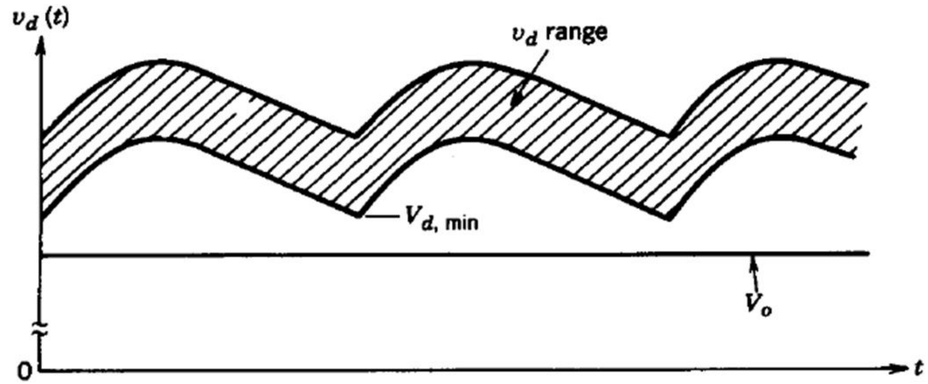


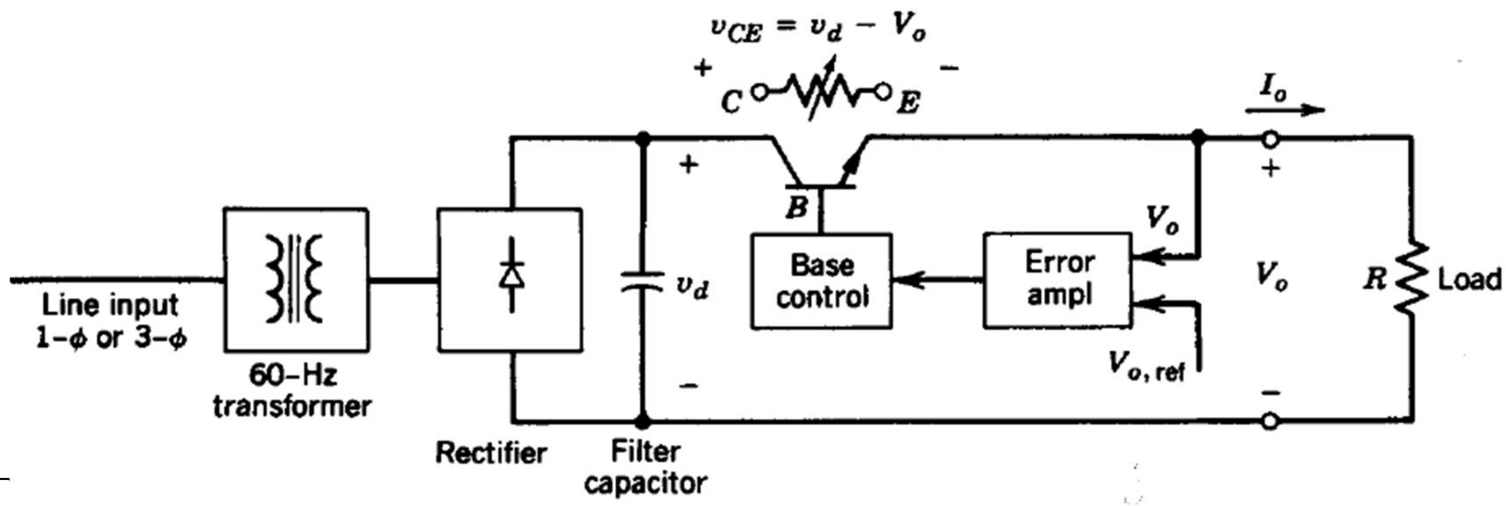
DC Power supplies

- Regulated output
  - Defined tolerance of output voltages
- Isolation
  - No direct electric connection to supply voltage
- Multiple outputs
  - Both positive and negative possible
  - Various current and voltage ratings

Linear power supply

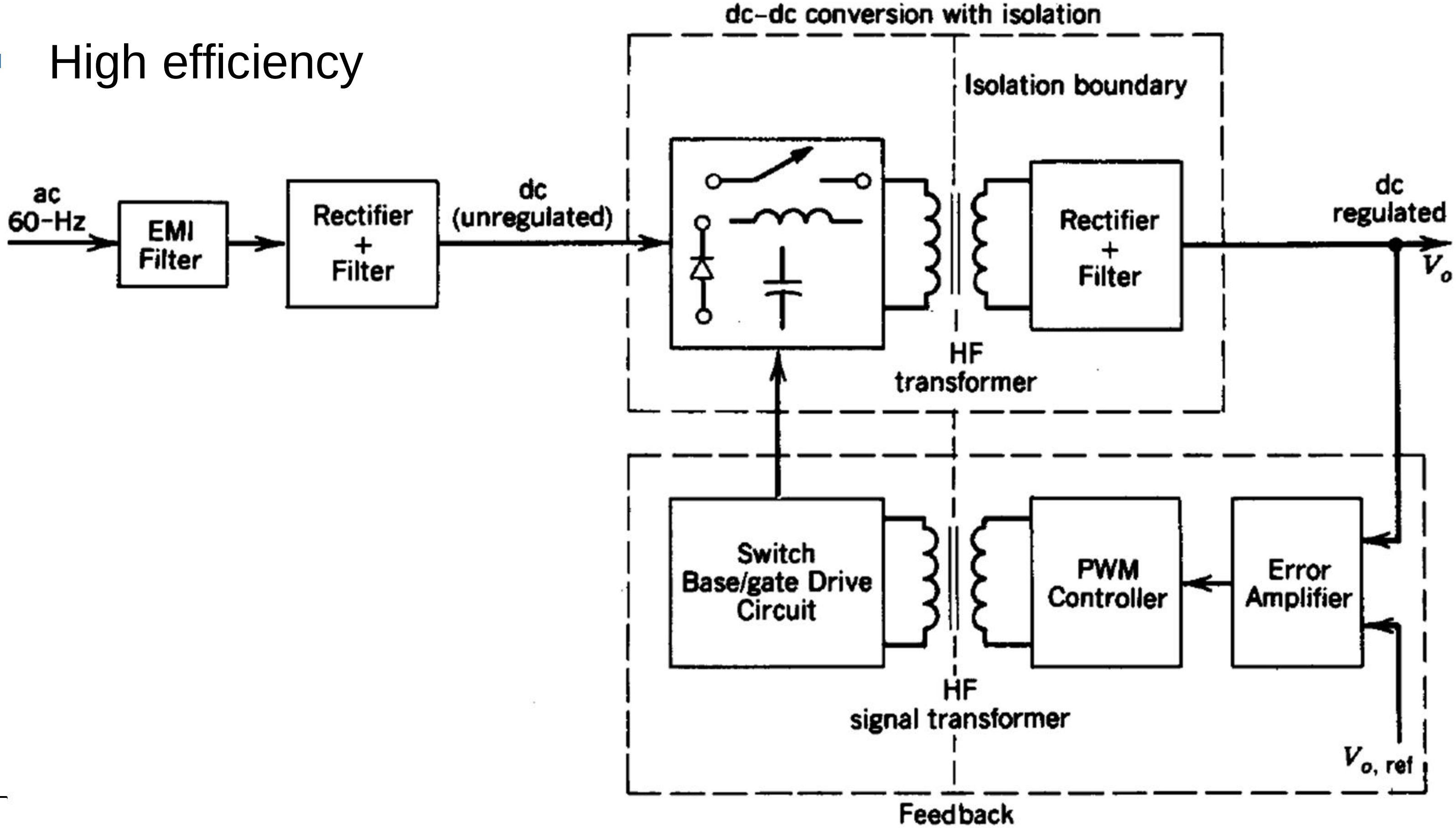
- Bulky transformer
  - Low frequency
- Poor efficiency
  - 30 – 60 %
- Low EMI





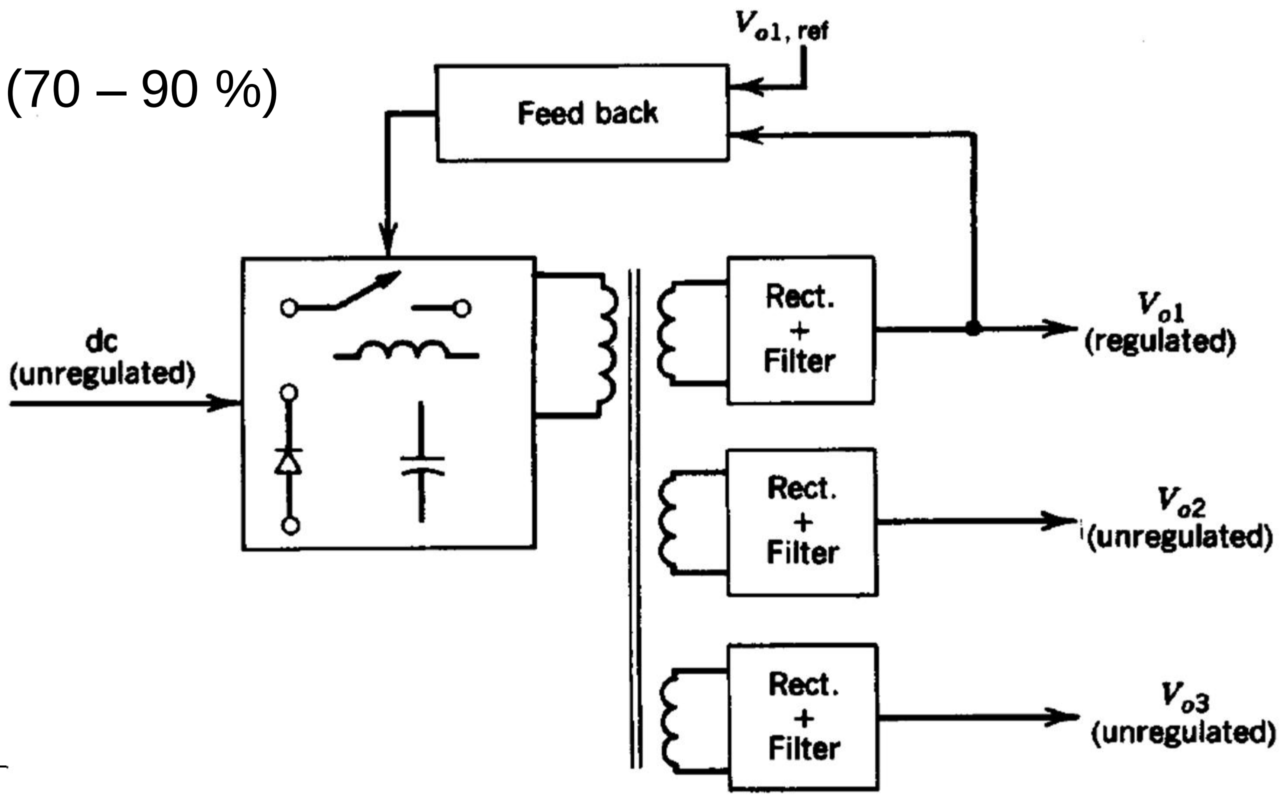
Switch-mode dc power supply schematic

- Small size
- High efficiency

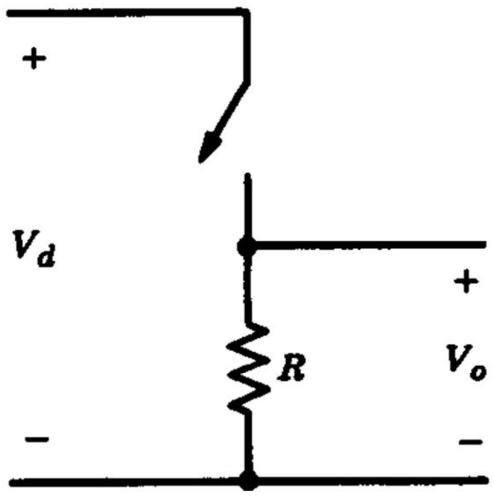


Multiple voltages

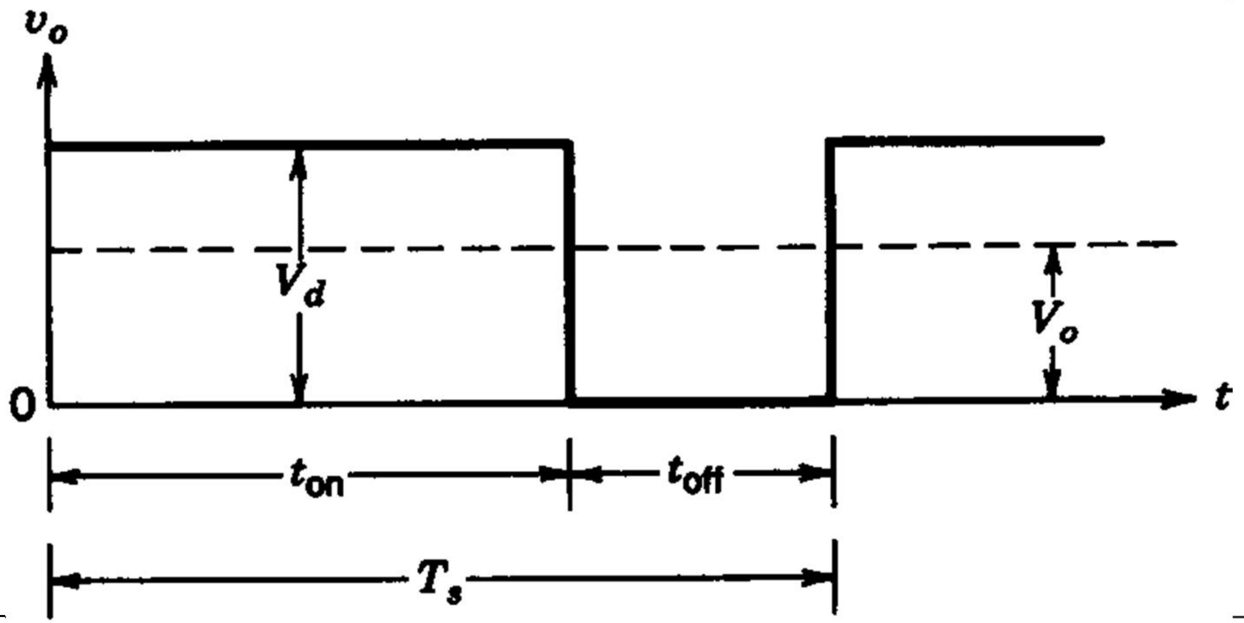
- Linear control may be applied if multiple controlled voltages are required
- High efficiency (70 – 90 %)



Step down converter principle



- $V_d > V_o$
- T_s constant, t_{on} t_{off} changing
- Large ripple on V_d



DC/DC-converter control

- Pulse width modulation, PWM, to control switching
- Switching frequency f_s

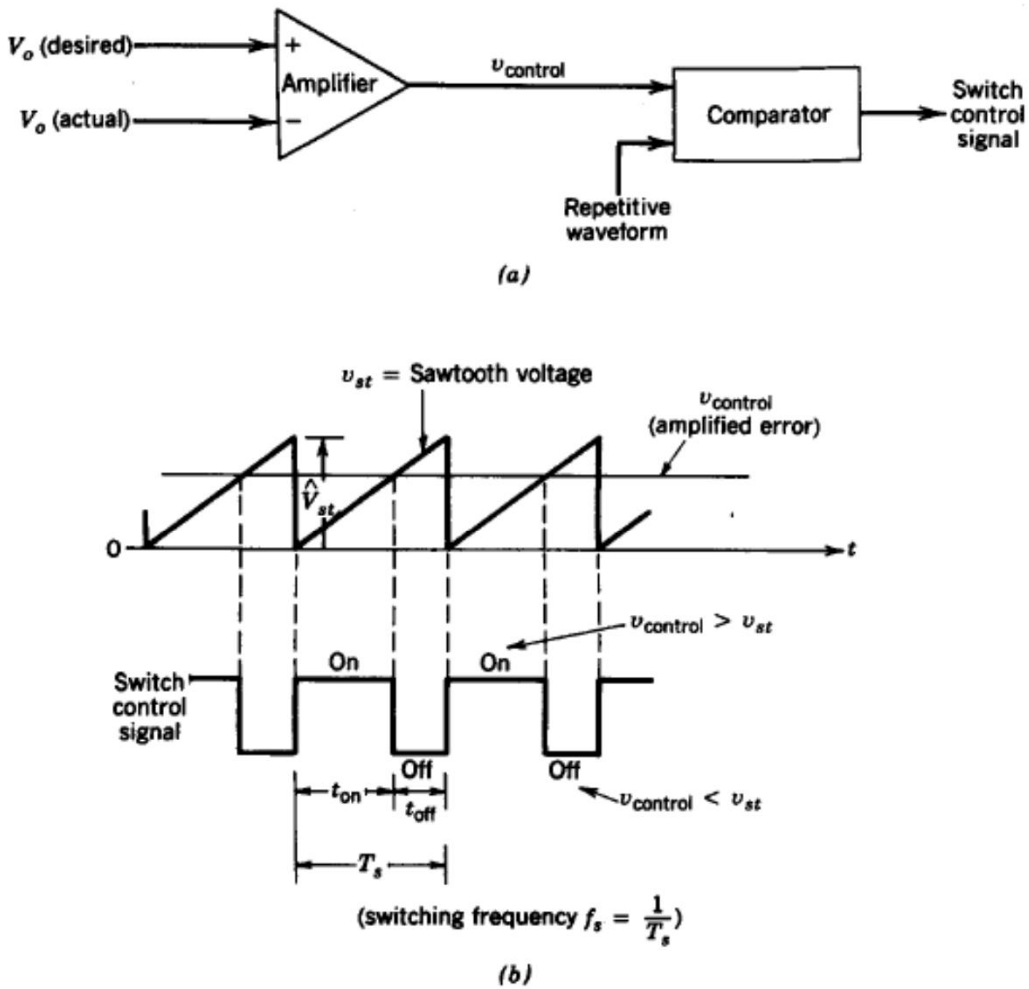


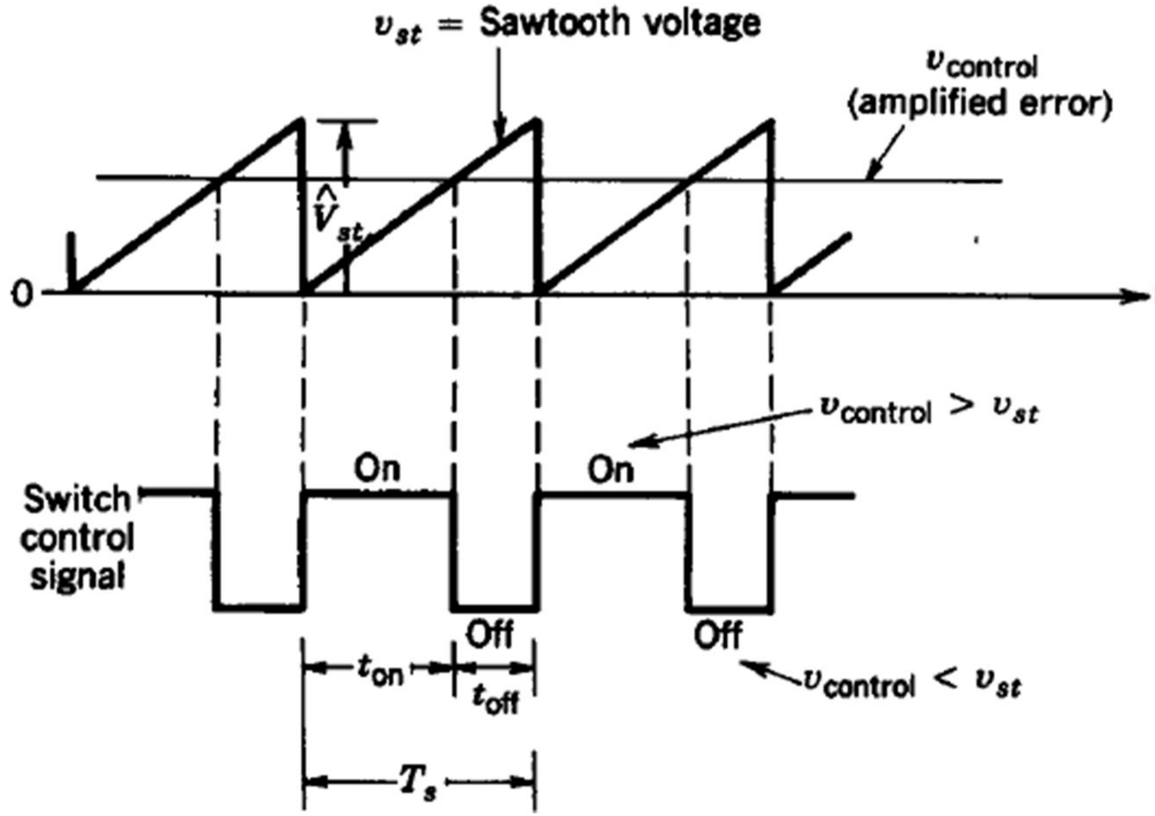
Figure 7-3 Pulse-width modulator: (*a*) block diagram; (*b*) comparator signals.

PWM waveform, duty cycle

- Switch duty cycle
  (duty ratio)

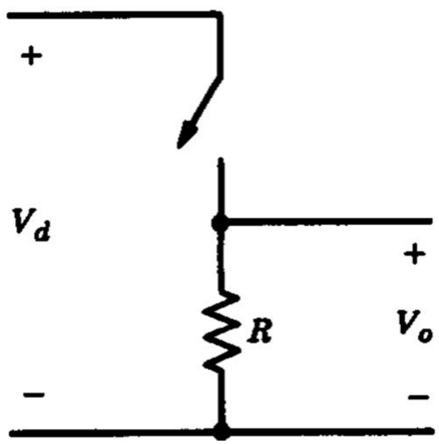
$$D = \frac{t_{on}}{T_s} = \frac{v_{control}}{\hat{V}_{st}}$$

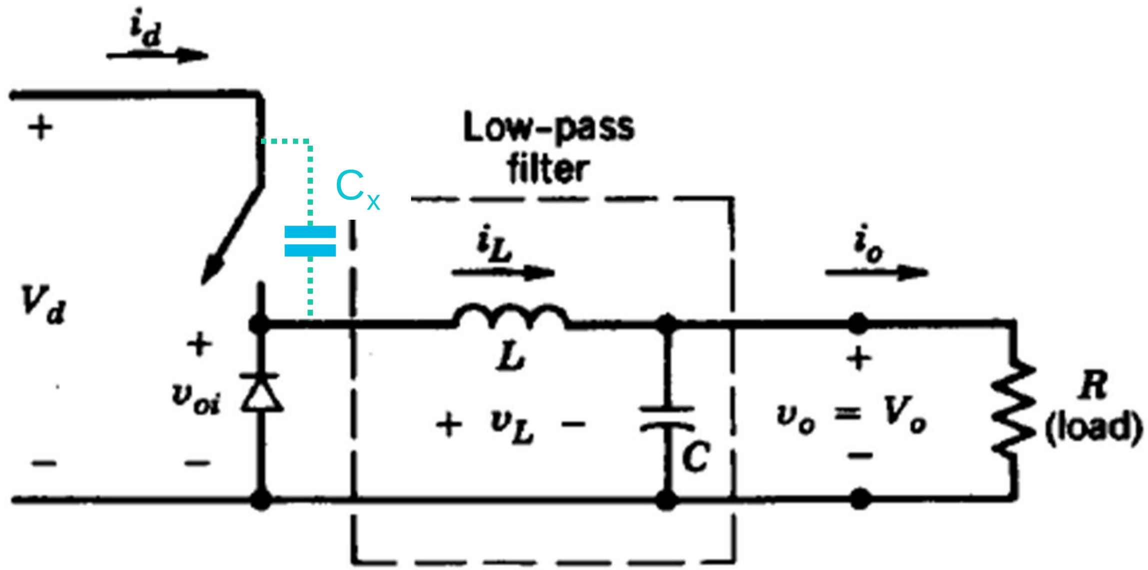
$$0 < D < 1$$



Step-down (buck) converter

- Add filter to reduce ripple voltage compared to principle
- Diode added to protect switch
  - V_L -> infinity if no diode and instantaneous switching!
  - Parasitic capacitances C_x would be charged by the inductor current

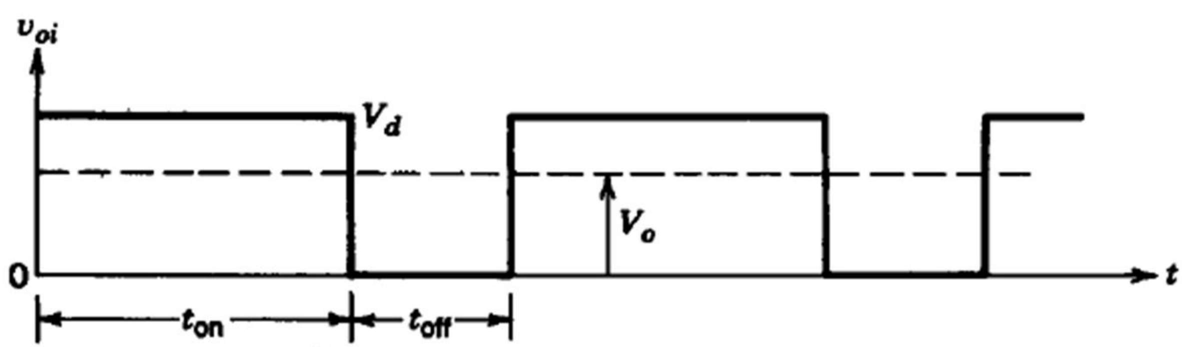




Step-down converter waveforms

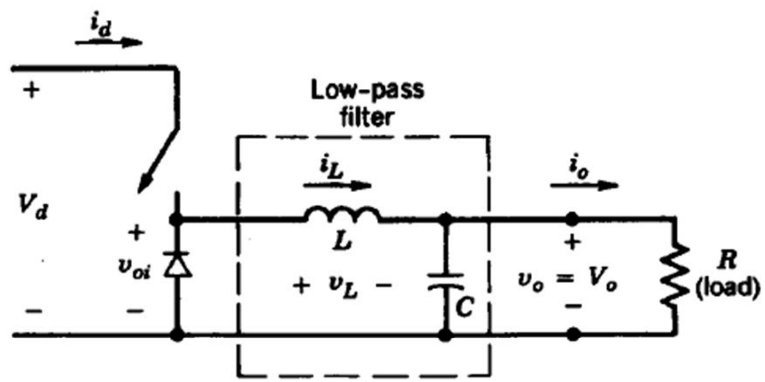
- $T_s = t_{on} + t_{off}$
- Average output voltage

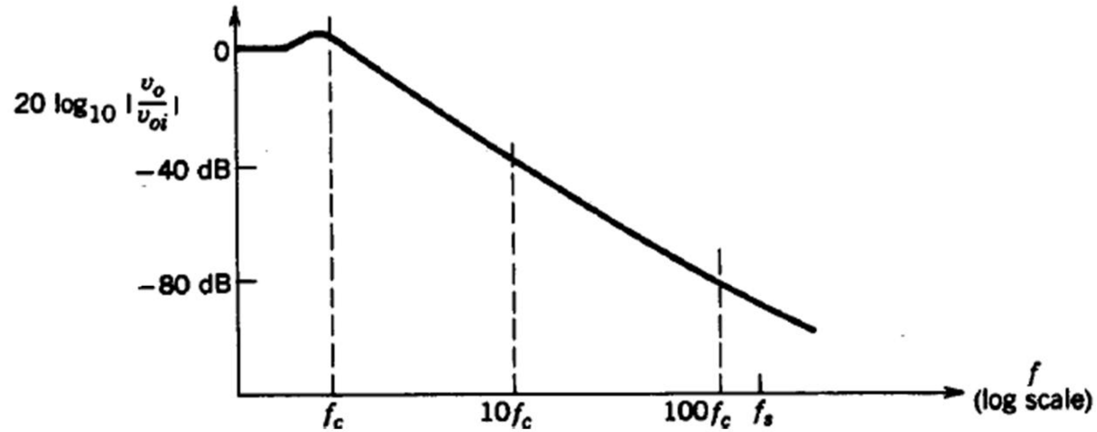
$$V_o = \frac{t_{on}}{T_s} V_d = DV_d$$

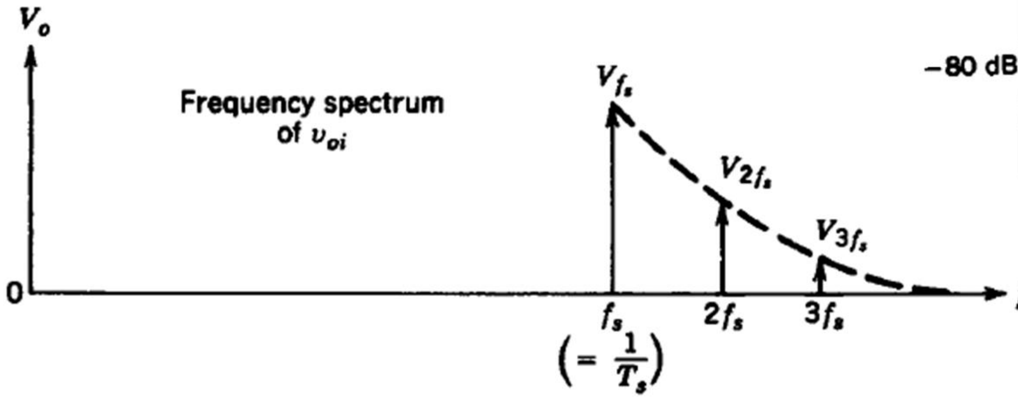


Input voltage before low-pass filter

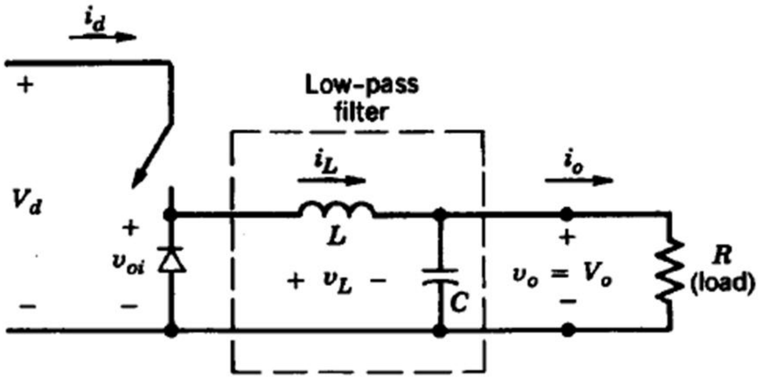
- $V_{oi} = V_d$ when switch on
- When switch off
  - $V_{oi} = 0$ if $i_L > 0$
  - $V_{oi} = V_o$ if $i_L = 0$
- LP filter BW(f_c) << f_s







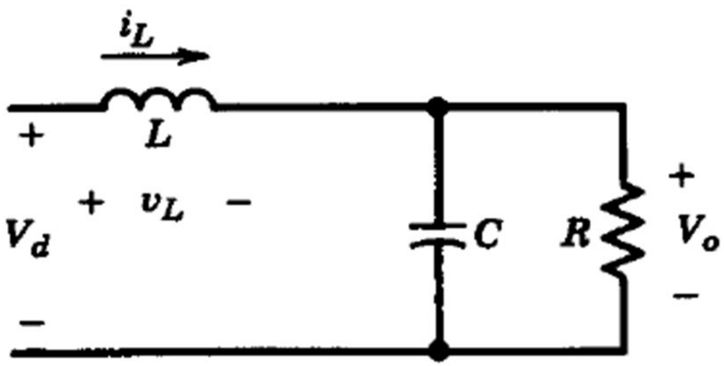
Current Conduction modes

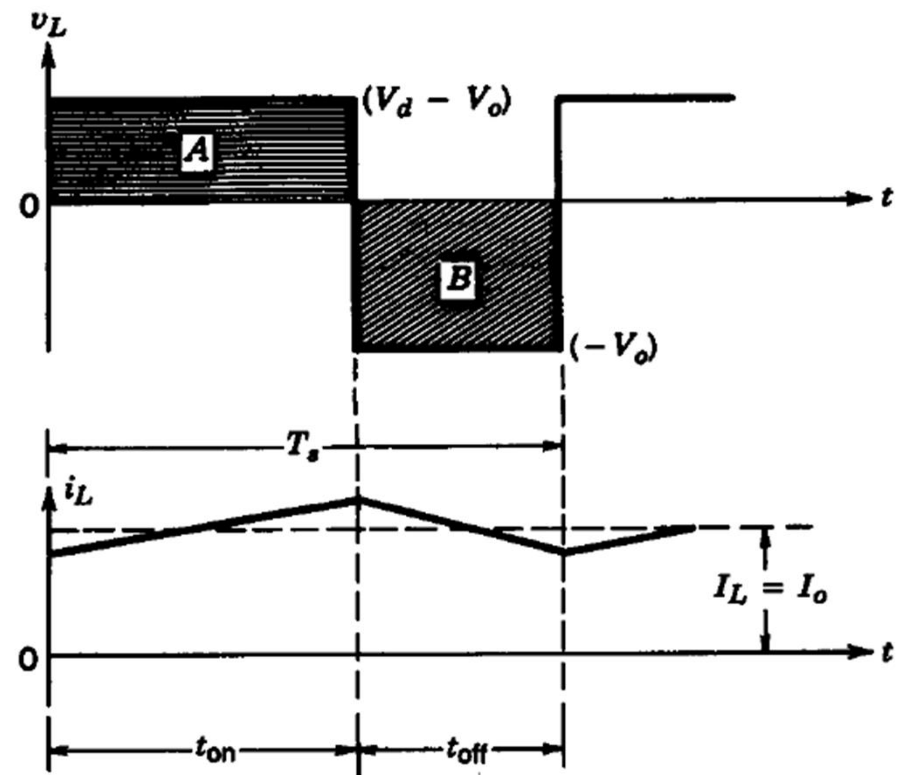


- Average i_L equals i_o
- Two current conduction modes (i_L)
  - Continuous current conduction
  - Non-continuous current conduction
- Converter characteristics different depending on mode
- Both modes can be supported by a converter
  - Mode selected depending on load

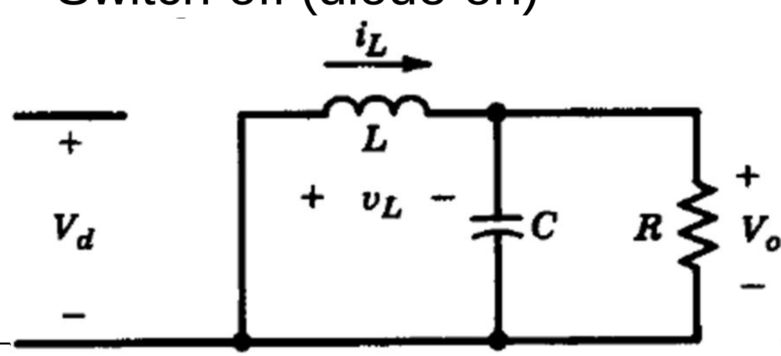
Continuous Conduction mode

- Switch on (diode off)





- Switch off (diode on)

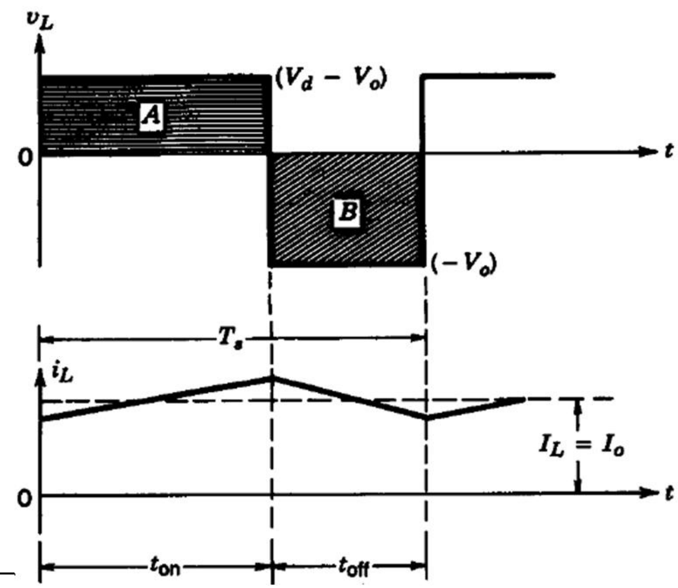


Continuous conduction mode, cont.

- i_L never zero
- Steady state => A = B $\quad t_{on}(V_d - V_o) = V_o(T_s - t_{on}) => \frac{V_o}{V_d} = \frac{t_{on}}{T_s} = D$
- Average v_{oi} output voltage, average v_l zero in steady state

$$\frac{V_d t_{on} + 0 t_{off}}{T_s} = V_o$$

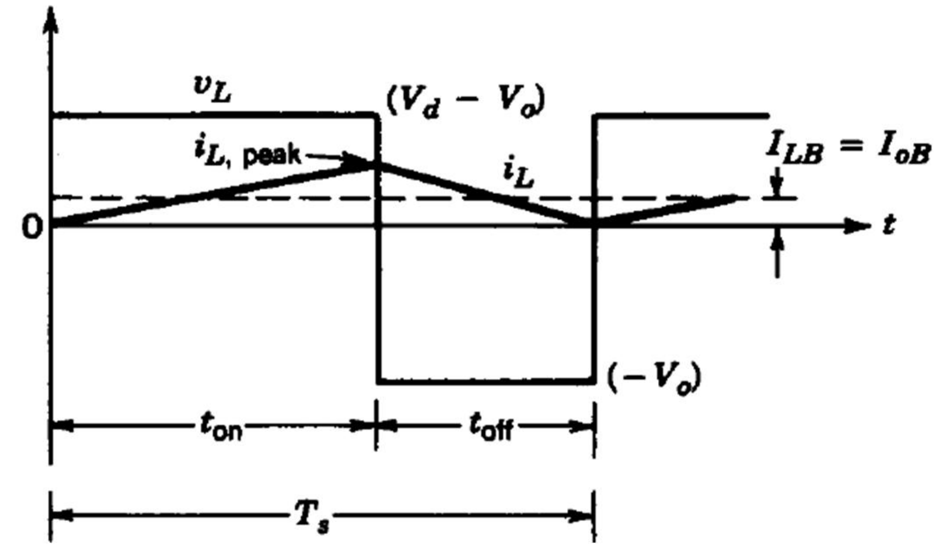
- No power loss in converter
  - $$P_d = P_o \Rightarrow V_d I_d = V_o I_o$$ $$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D}$$
  - DC transformer with turns ratio equal to D
- i_d still slanted square wave



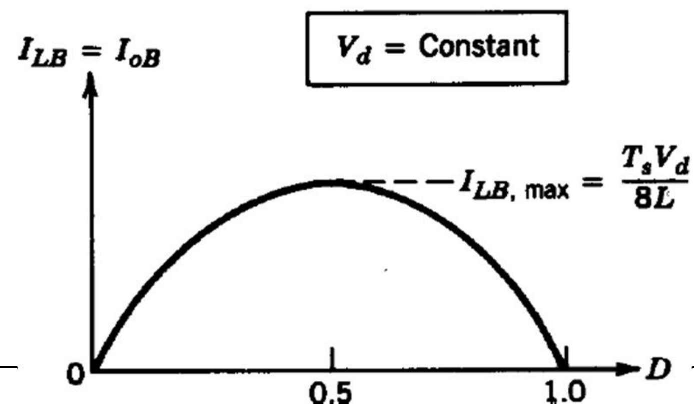
Discontinuous/Continuous Conduction mode boundary

- i_L reach zero at end of period
- Average I_o
  - $I_{LB} = \frac{1}{2} i_{L,peak} = \frac{t_{on}}{2L}(V_d - Vo)$
  - $I_{LB} = \frac{DT_s}{2L}(V_d - V_o)$

    $I_{LB} = \frac{DT_s}{2L} V_d(1 - D)$



- For fixed input voltage V_d
  - $I_{LB,max}$ at 50% duty cycle



Discontinuous conduction mode

$$(V_d - V_o)DT_s + (-V_o)\Delta_1 T_s = 0$$

$$\frac{V_o}{V_d} = \frac{D}{(D + \Delta_1)}$$

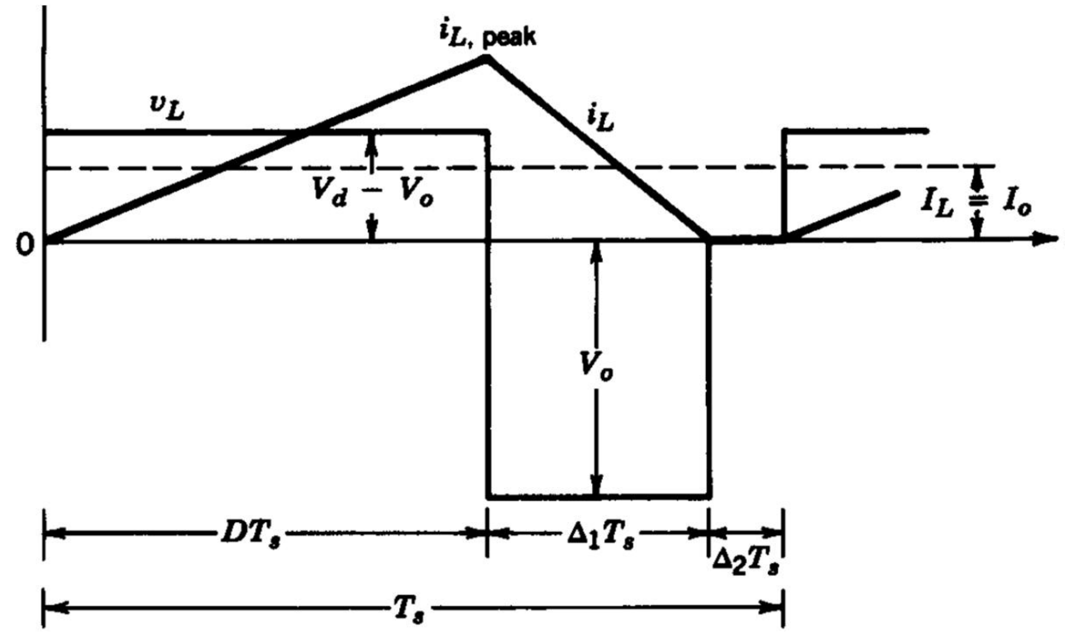
$$i_{L,peak} = \frac{V_o}{L}\Delta_1 T_s$$

$$I_o = i_{L,peak}\frac{D + \Delta_1}{2}$$

$$I_o = \frac{V_o T_s}{2L}(D + \Delta_1)\Delta_1 = \frac{V_d T_s}{2L} D\Delta_1$$

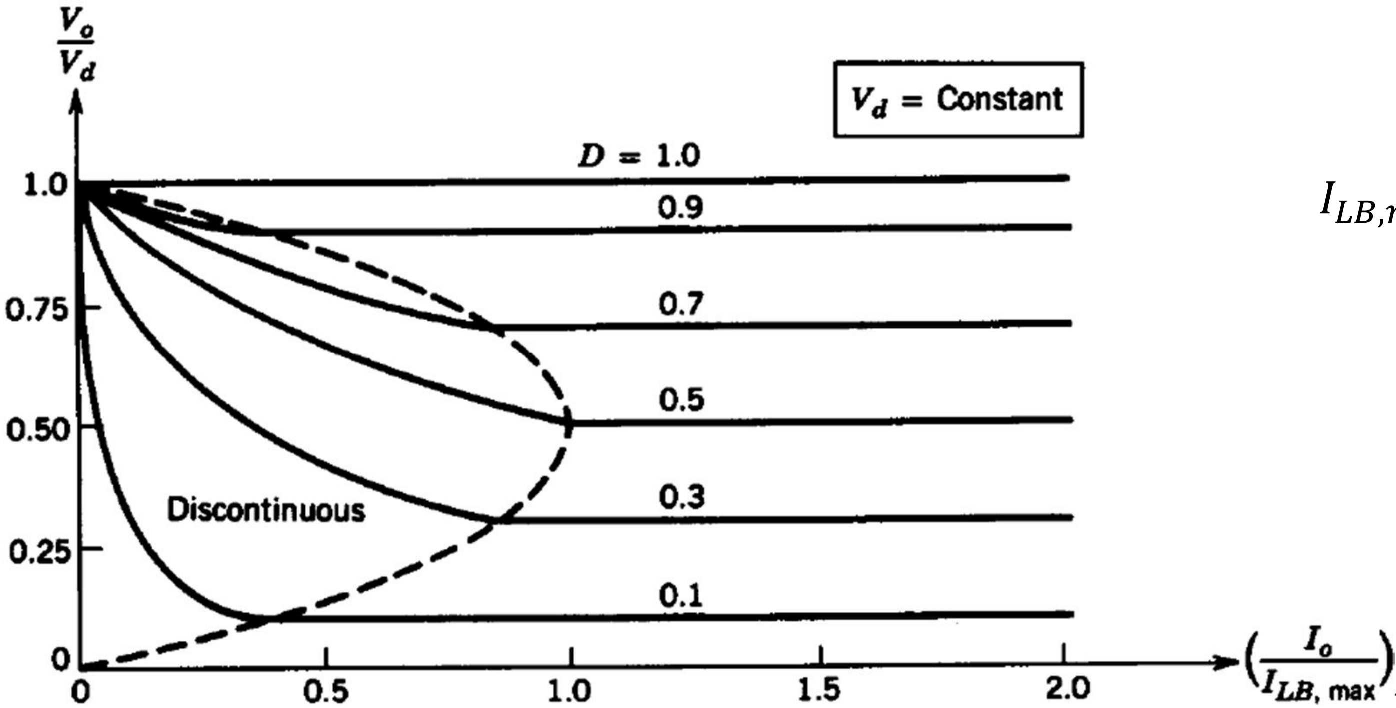
$$\Delta_1 = \frac{I_o}{4 I_{LB,max} D}$$

$$\frac{V_o}{V_d} = \frac{D^2}{D^2 + \frac{1}{4}\left(I_o / I_{LB,max}\right)}$$



Constant V_d step-down characteristic

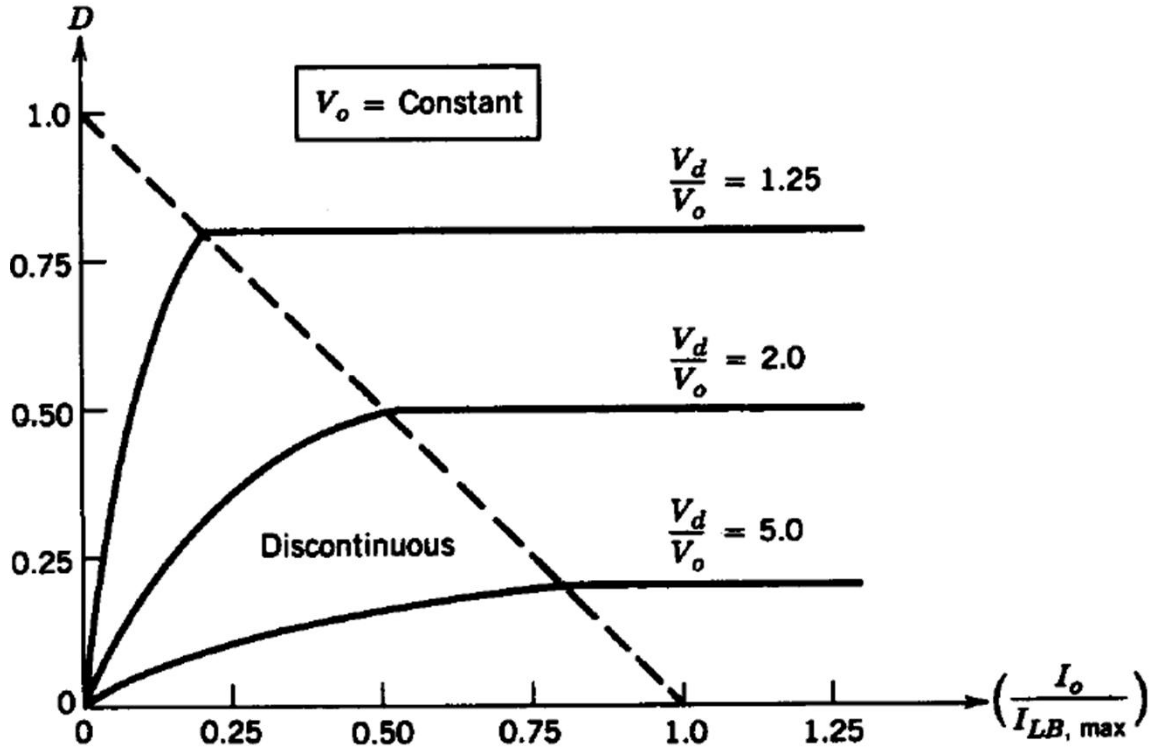
- Very low load result in increased output voltage!



$$I_{LB,max} = \frac{T_s V_d}{8L}$$

Discontinuous conduction mode with constant V_o

- $I_{LB,max} = \frac{T_S V_O}{2L}$
- Control ratio for constant V_o



Output voltage ripple

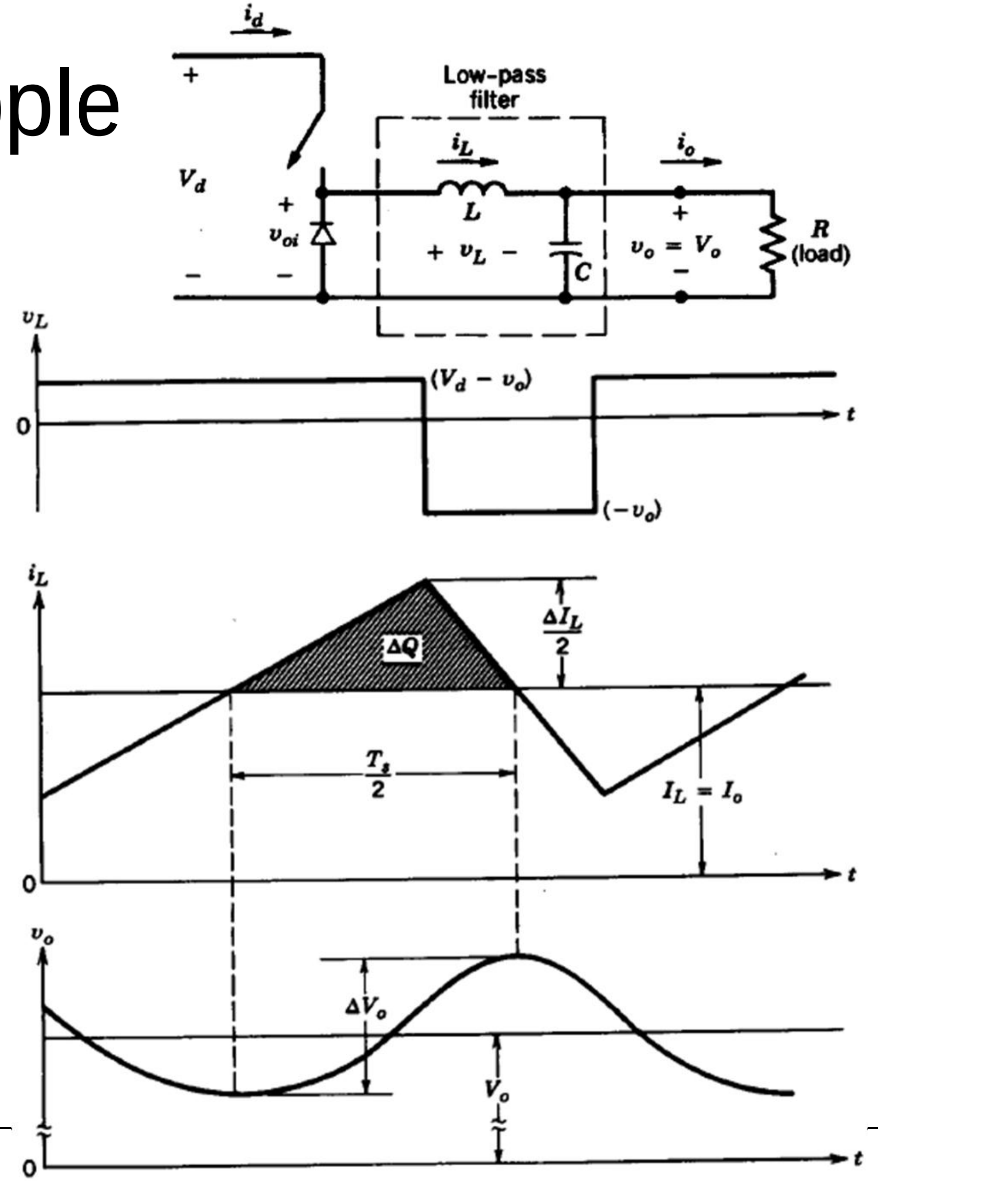
- Assuming:
  - ripple current in C
  - Average current in R

$$\Delta V_o = \frac{\Delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\Delta I_L}{2}\frac{T_s}{2}$$

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

$$\frac{\Delta V_o}{V_o} = \frac{1}{8}\frac{T_s^2(1-D)}{LC} =$$

$$= \frac{\pi^2}{2}(1-D)\left(\frac{f_c}{f_s}\right)^2$$



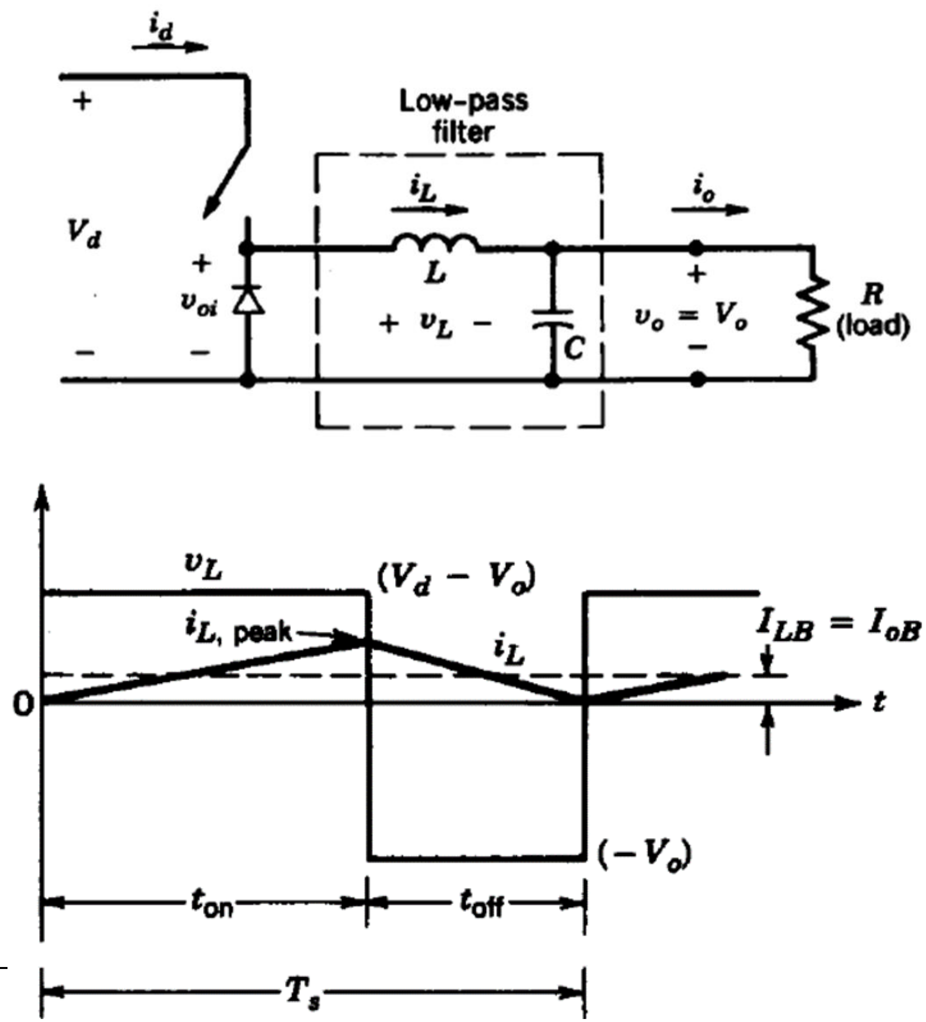
Step-down (buck) converter summary

- Output vs input

$$\frac{V_o}{V_d} = D$$
$$\frac{I_o}{I_d} = \frac{1}{D}$$

- High ripple current
$$I_{Lpeak} = 2I_o$$

- Practical for D not lower than 0.2

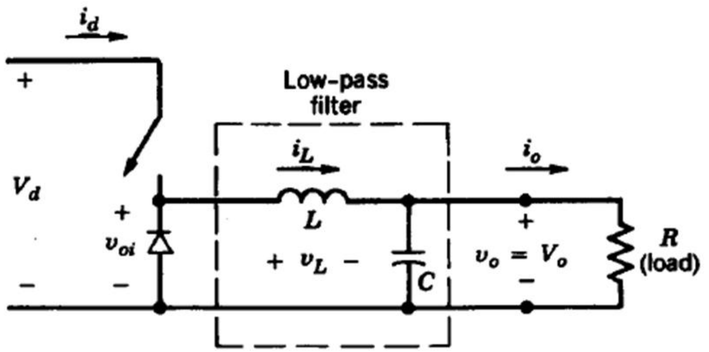


Lecture 6

Exercises, buck-converter

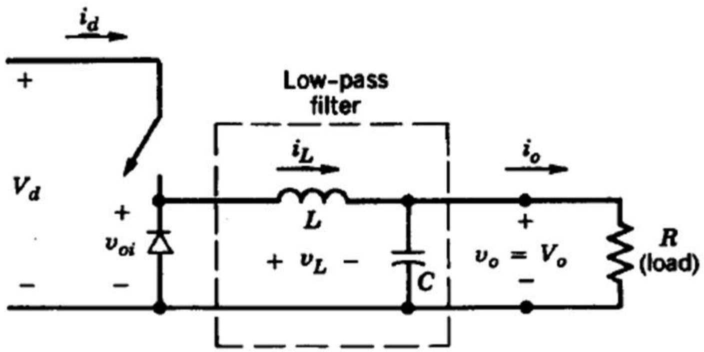
7-1

- In a step-down converter, consider all components to be ideal. Let $v_o \approx V_o$ be held constant at 5 V by controlling the switch duty ratio *D.*
- Calculate the minimum inductance *L* required to keep the converter operation in a continuous-conduction mode under all conditions if:
  V_d is 10-40 V , $P_o \geq 5$ W, and $f_s = 50$ kHz.



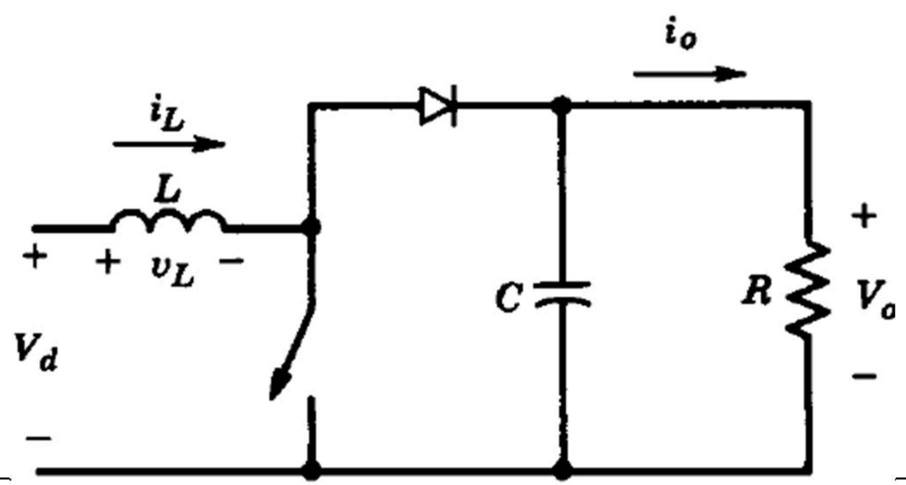
7-2

- Consider all components to be ideal. Assume V_o = 5 V, f_s = 20 kHz, L = 1 mH, and C = 470 µF.
- Calculate ΔV_o (peak-peak) if V_d = 12.6 V, and I_0 = 200 mA.



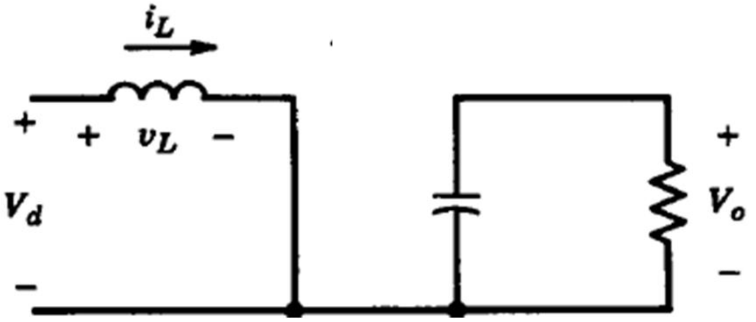
Step-up (boost) converter

- Output must be larger than input voltage
  - Otherwise is V_d driving V_o directly => $V_o = V_d$
- Load energy into inductor, then output energy into load while still consuming energy from source
- C large enough to give $v_o(t)$ » V_o

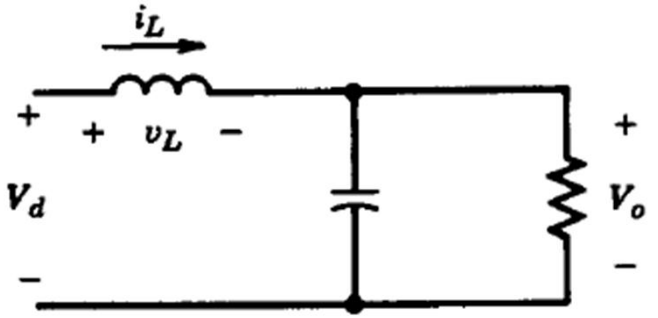


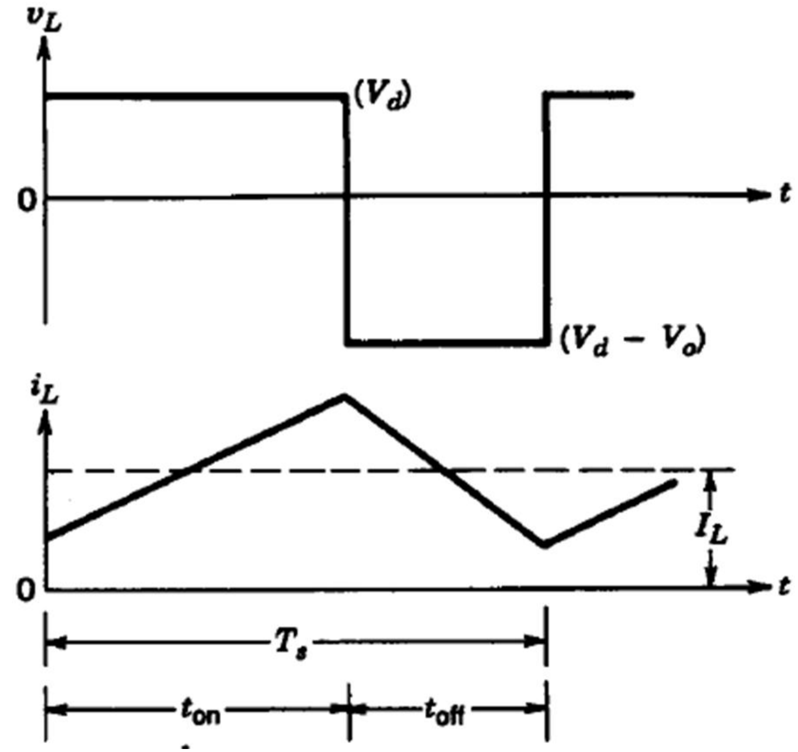
Step-up converter waveform, continuous conduction mode

- Switch on, diode off



- Switch off, diode on





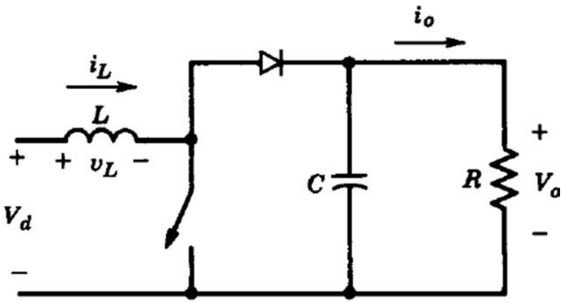
Step-up converter, continuous mode

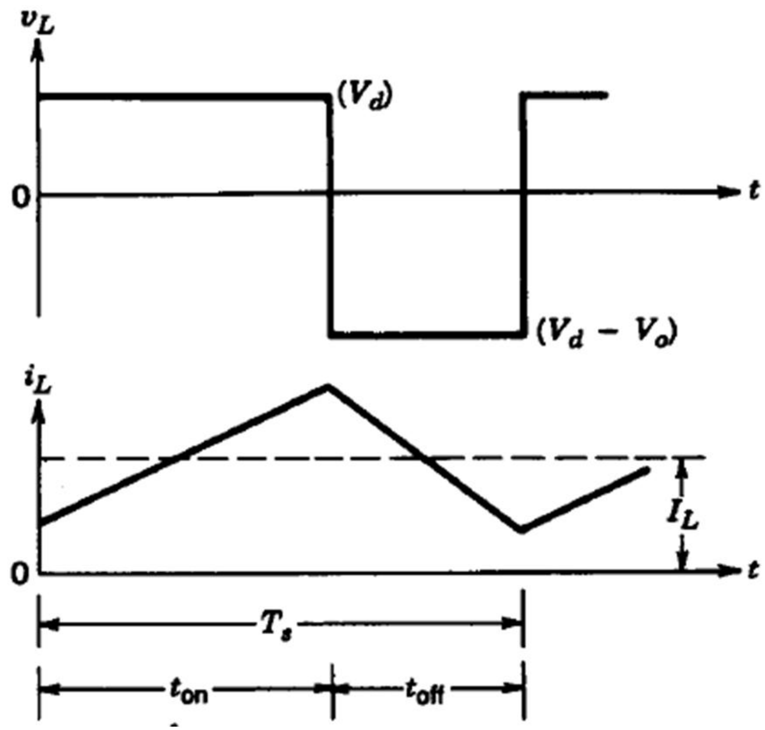
$$V_d t_{on} + (V_d - V_o)t_{off} = 0$$

$$V_o/V_d = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

Lossless circuit: $V_d I_d = V_o I_o$

$$\Rightarrow \frac{I_o}{I_d} = (1-D)$$





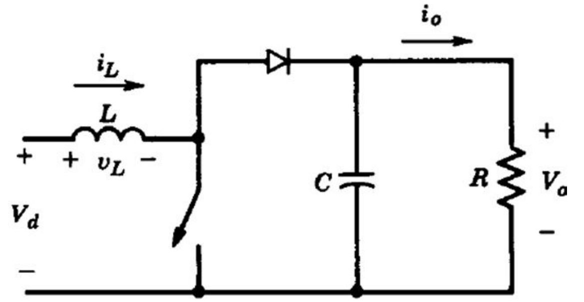
Boundary between continuous and discontinuous mode

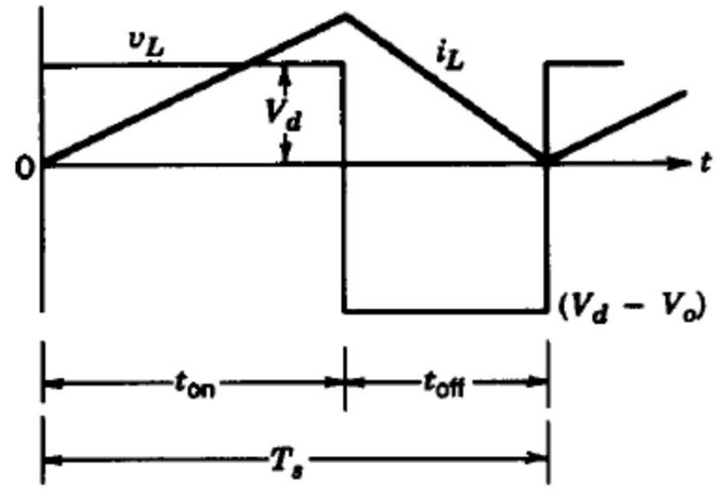
$$I_{LB} = \frac{1}{2} i_{L,peak} = \frac{1}{2}\frac{V_d}{L} t_{on}$$

$$I_{LB} = \frac{T_s V_o}{2L} D(1-D)$$

$$I_{oB} = \frac{T_s V_o}{2L} D(1-D)^2$$

$$L = \frac{T_s V_o}{2 I_{oB}} D(1-D)^2$$





Boundary between continuous and discontinuous mode

$$V_o constant$$

$$I_{LB}\, max\ when\ D = 0.5$$

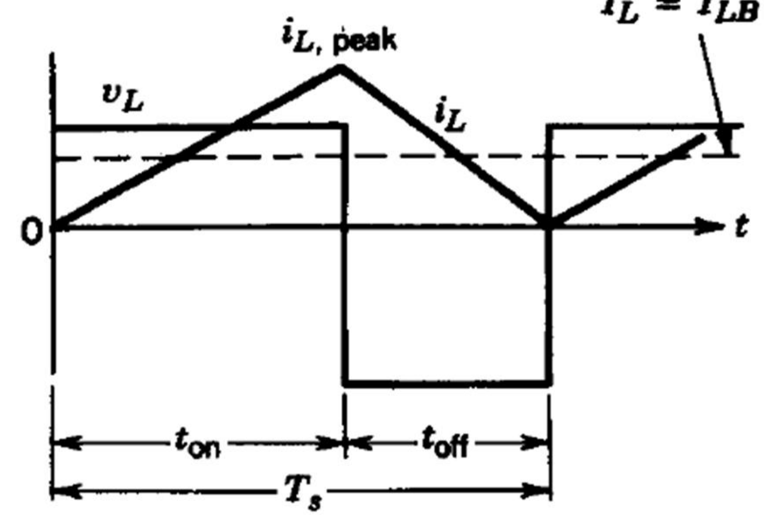
$$I_{LB,max} = \frac{T_s V_o}{8L}$$

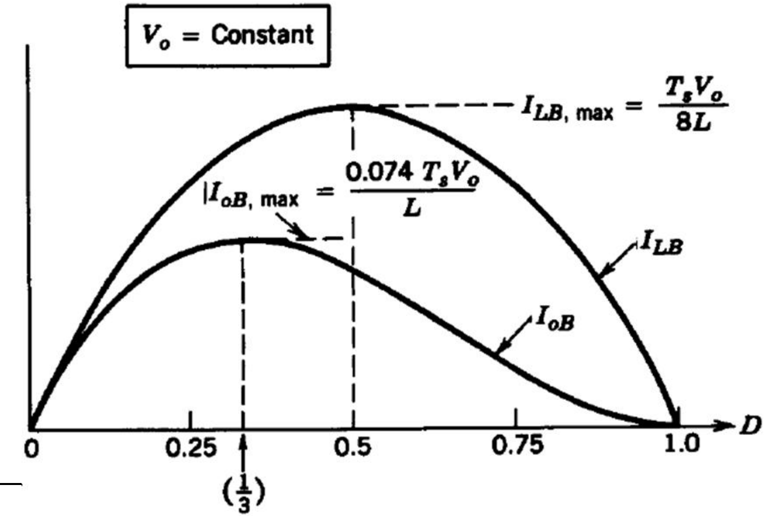
$$I_{oB}\, max\ when\ D = 1/3$$

$$I_{oB,max} = \frac{2}{27}\frac{T_s V_o}{L} = 0.074\frac{T_s V_o}{L}$$

$$I_{LB} = 4D(1-D)I_{LB,max}$$

$$I_{oB} = \frac{27}{4}D(1-D)^2 I_{oB,max}$$





Step-up, discontinuous mode

$$V_d D T_s + (V_d - V_o)\Delta_1 T_s = 0$$

$$\frac{V_o}{V_d} = \frac{\Delta_1 + D}{\Delta_1}$$

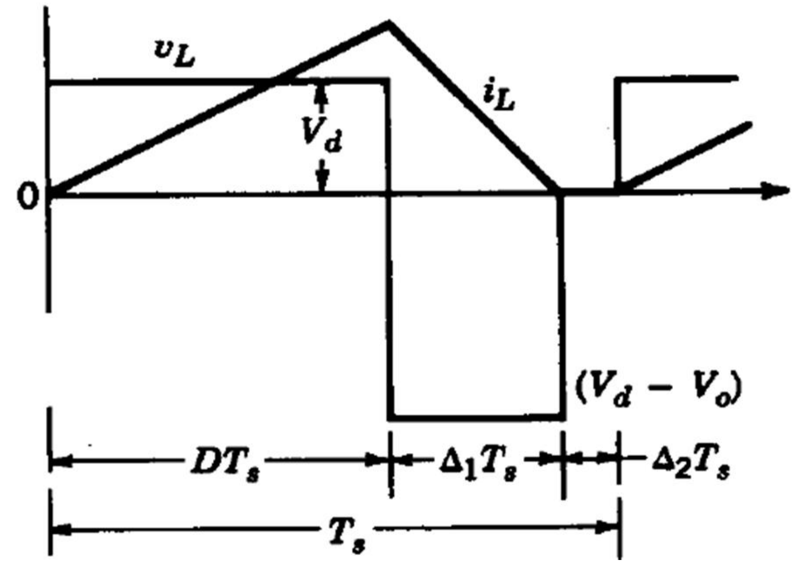
$$\frac{I_o}{I_d} = \frac{\Delta_1}{\Delta_1 + D}$$

$$I_d = \frac{V_d}{2L} D T_s (D + \Delta_1)$$

$$I_o = \frac{T_s V_d}{2L} D \Delta_1$$

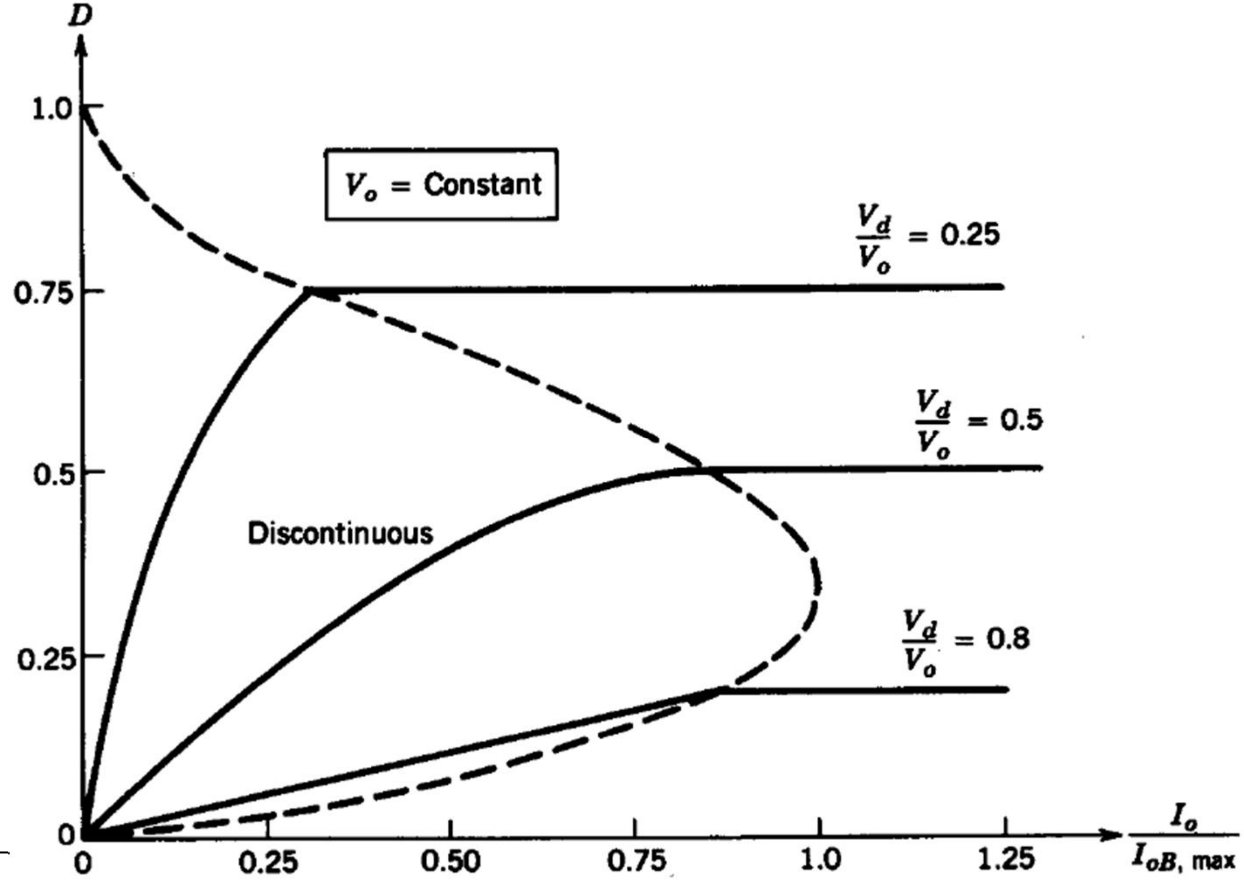
Controller

$$D = \left[\frac{4}{27}\frac{V_o}{V_d}\left(\frac{V_o}{V_d} - 1\right)\frac{I_o}{I_{oB,max}}\right]^{1/2}$$



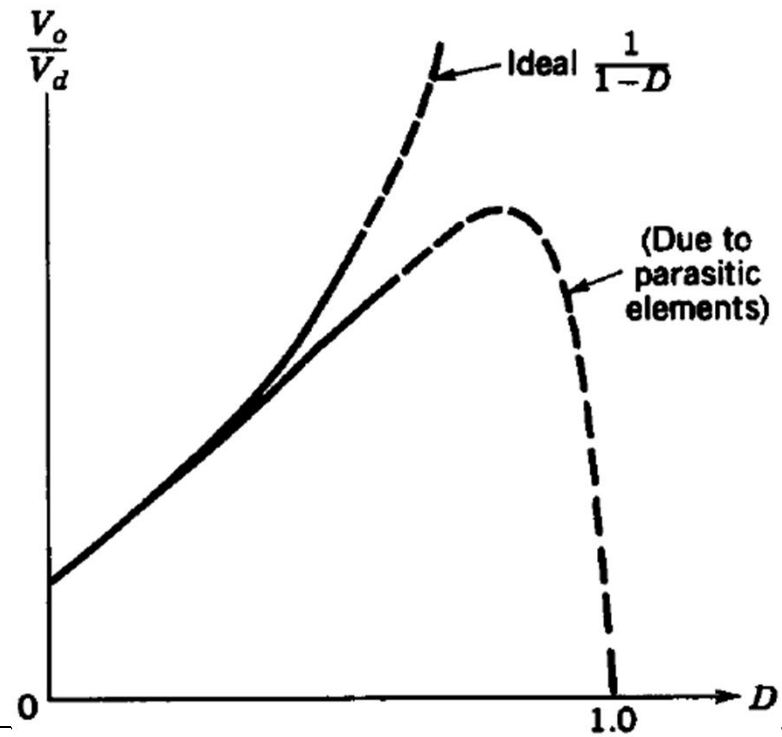
Step up converter characteristics, V_o constant

$$I_{oB,max} = 0.074\frac{T_s V_o}{L}$$



Effects of parasitics

- Losses in L, diode, switch, C
- Limited also by acceptable D ratio



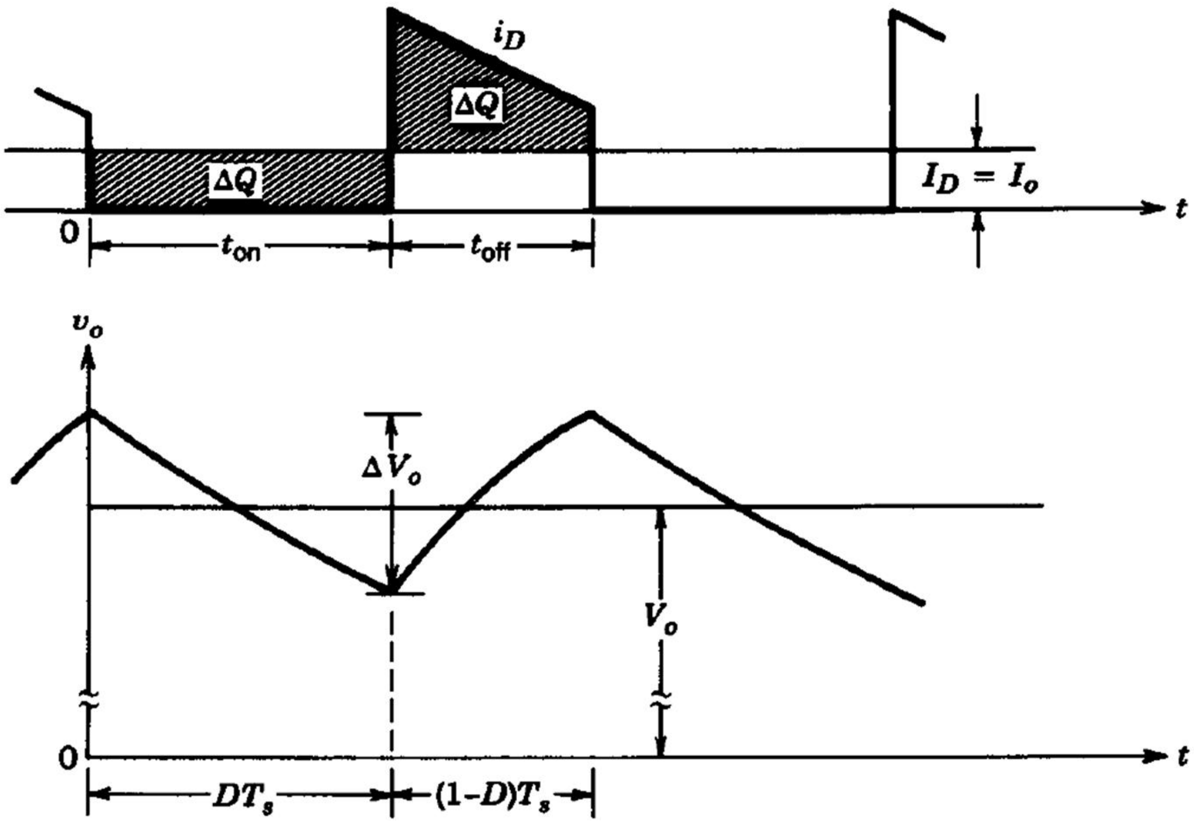
Output voltage ripple

$$\Delta V_o = \frac{\Delta Q}{C} = \frac{I_o D T_s}{C}$$

$$\frac{\Delta V_o}{V_o} = \frac{D T_s}{RC} = D\frac{T_s}{\tau}$$

where

$\tau = RC$ *time constant*

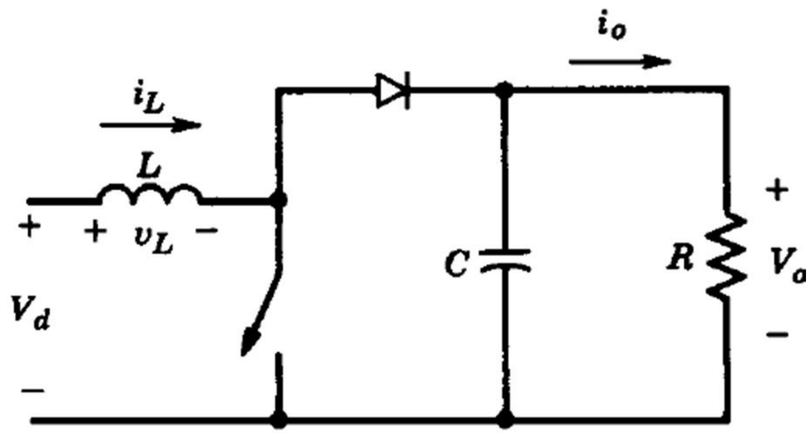


Lecture 6

Exercises on boost converter

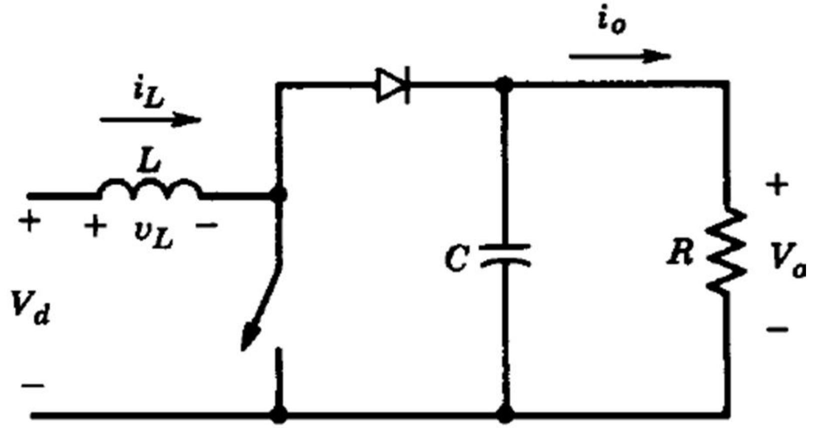
7-7

- In a step-up converter, consider all components to be ideal. Let V_d be 8-16 V, V_o = 24 V (regulated), f_s = 20 kHz, and C = 470 μF.
- Calculate L_{min} that will keep the converter operating in a continuous-conduction mode if $Po \geq 5$ W.



7-8

- In a step-up converter, V_d =12 V, V_o = 24 V, I_0 = 0.5 A, L = 150 µH, C = 470 µF, and f_s =20 kHz.
- Calculate ΔV_o (peak-peak).

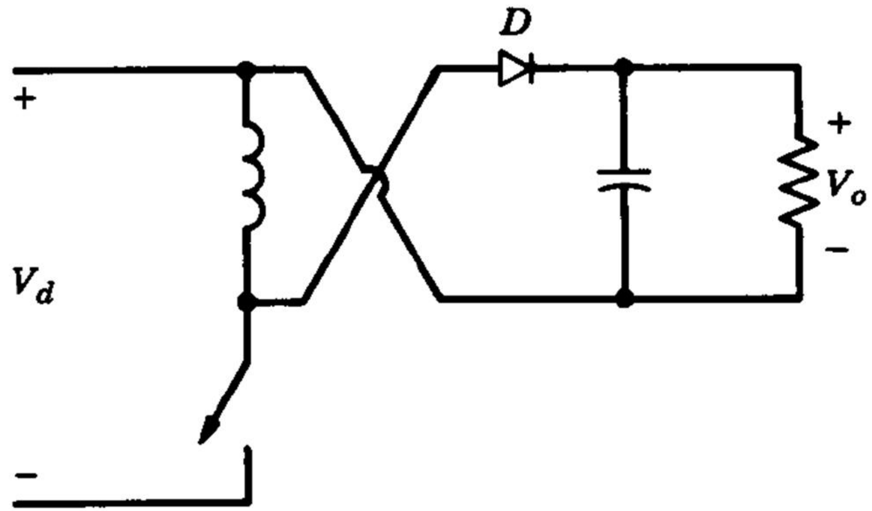


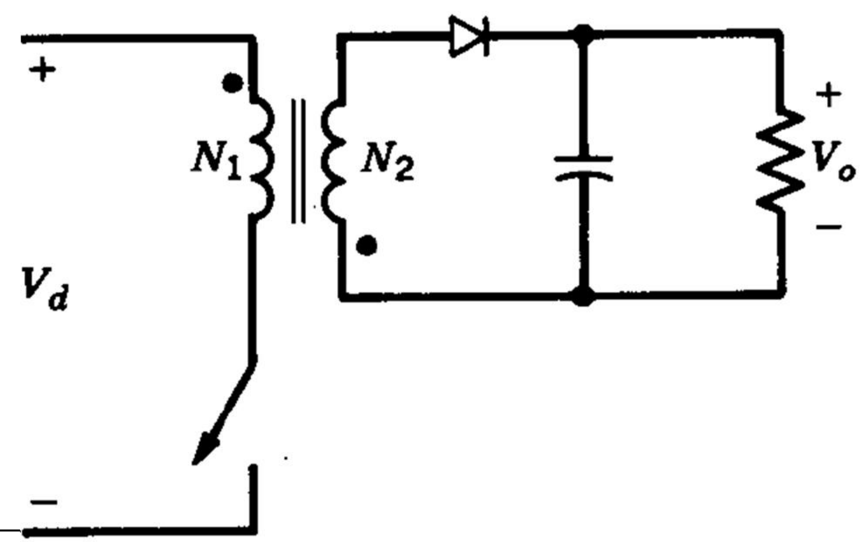
Lecture 6

Other converter topologies

Flyback converter

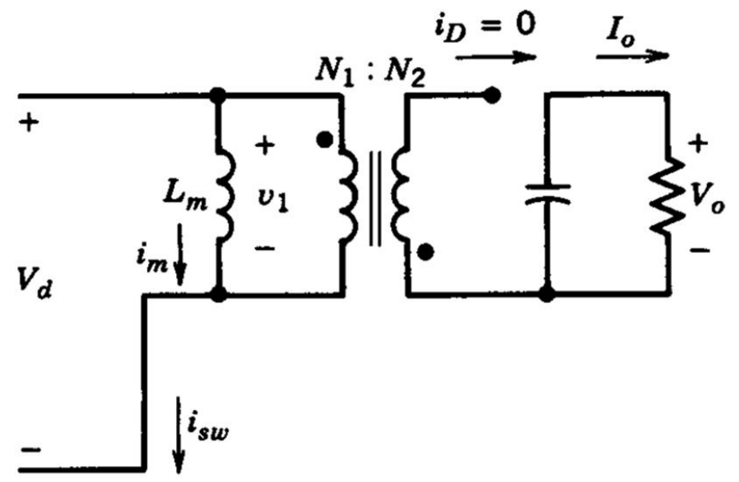
- Derived from buck-boost structure
- Second winding gives electric isolation
- Only flux flow in one direction
  - Never negative currents in the transformer

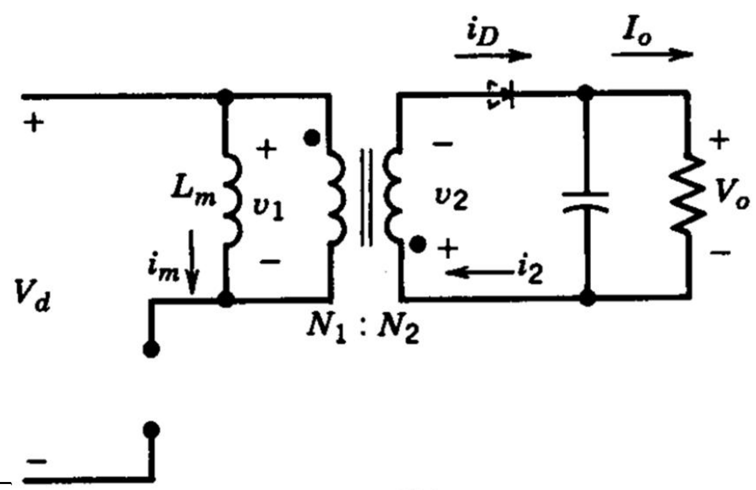




Flyback converter circuit states

- Switch on and switch off
- Continuous conduction mode
  - Incomplete demagnetization
- L_m size important
  - Ideal transformer have inifinite L_m



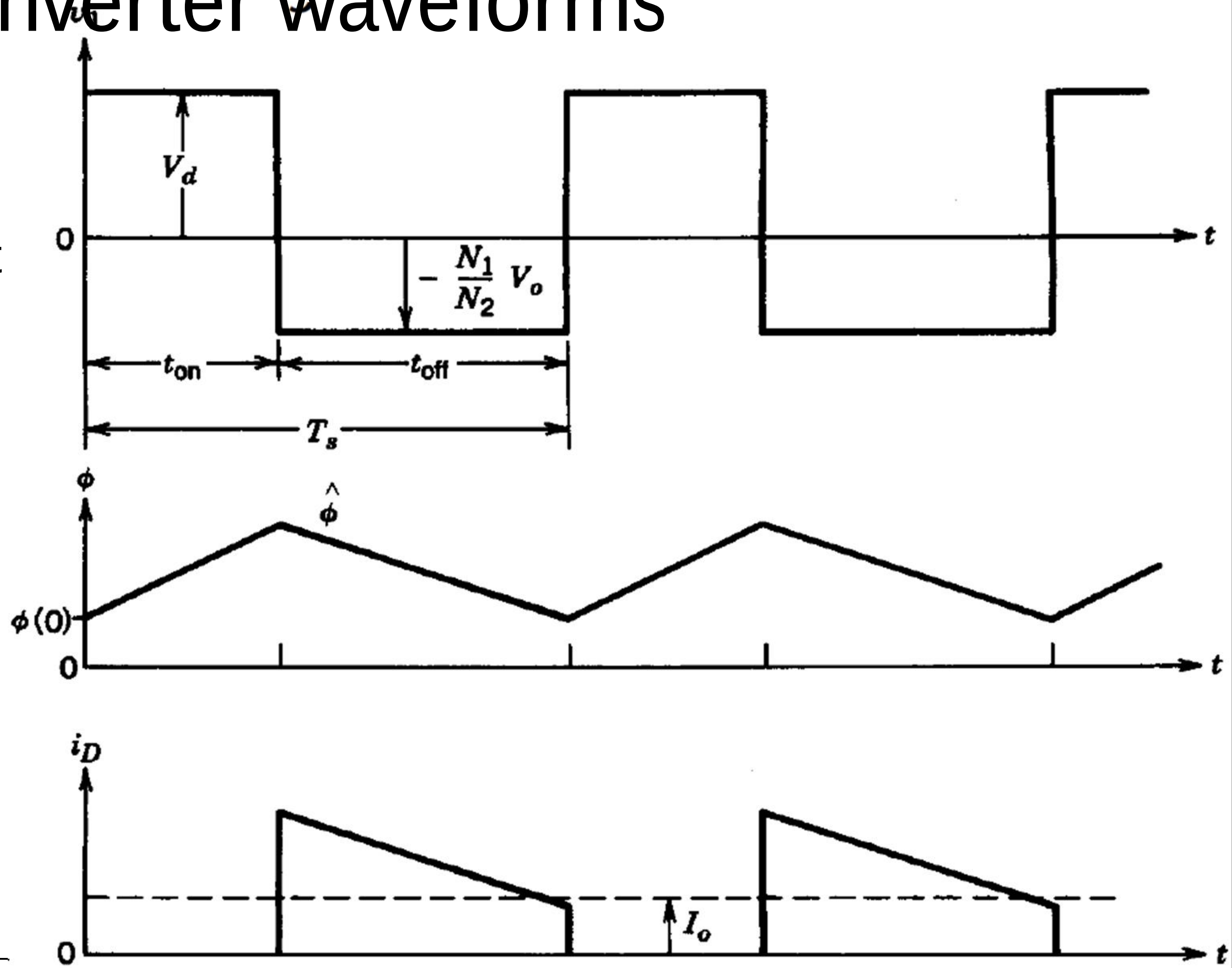


Flyback converter waveforms

- Same control equation as for buck-boost converter

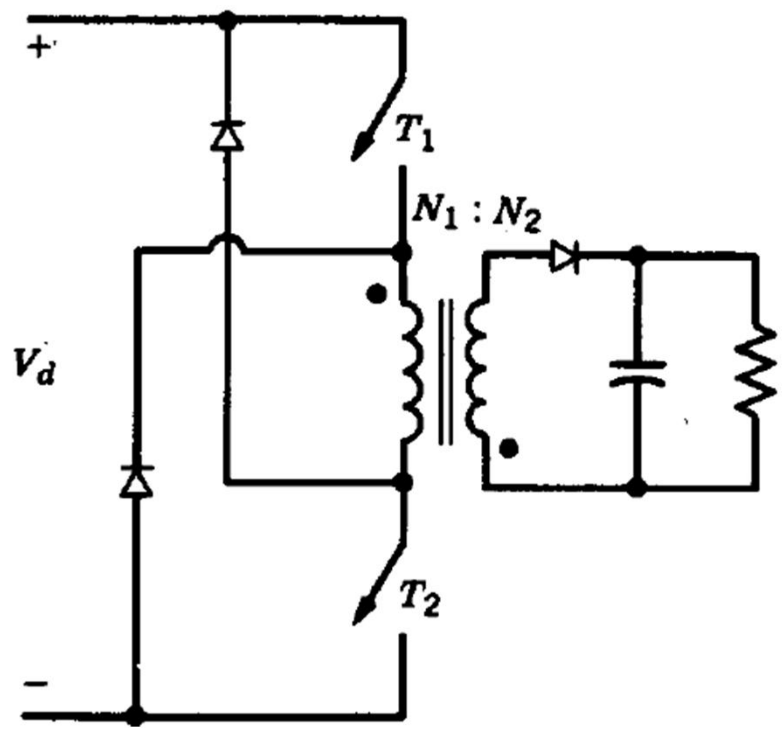
$$D = \frac{t_{on}}{T_s}$$

$$\frac{V_o}{V_d} = \frac{N_2}{N_1}\frac{D}{1-D}$$



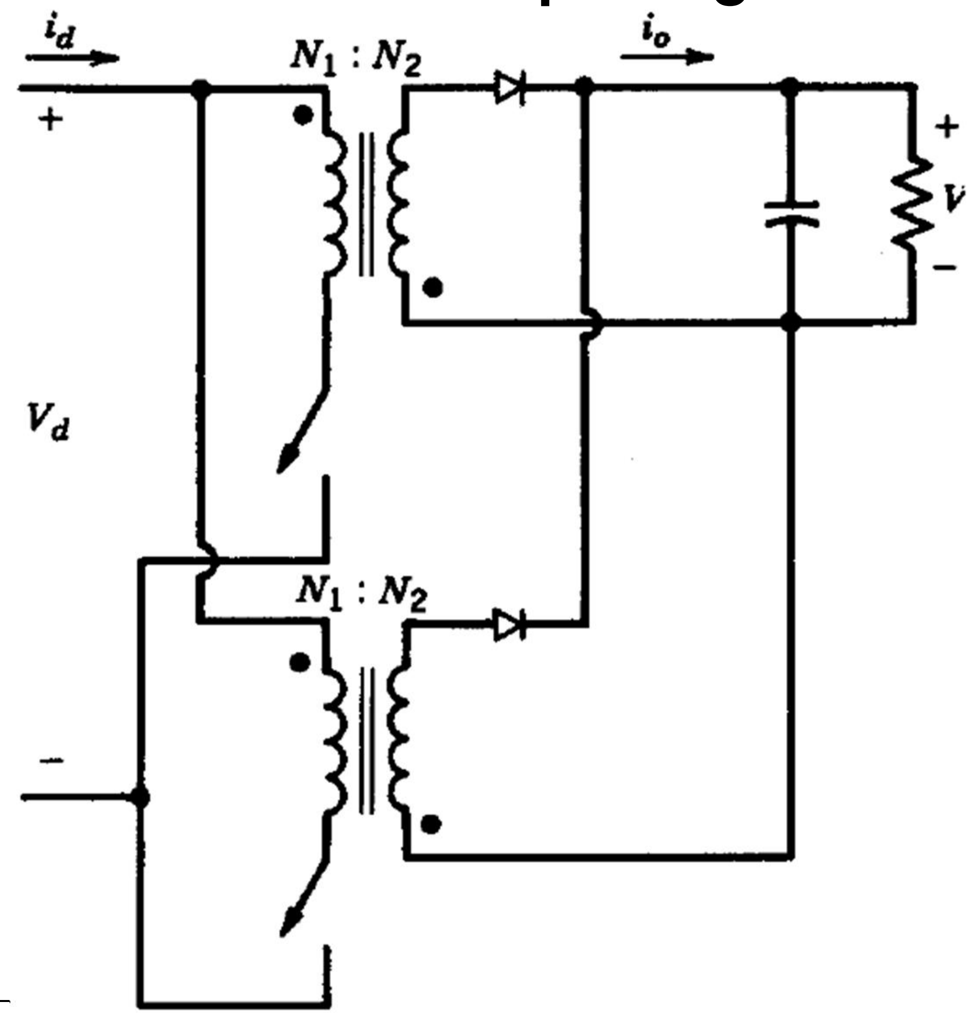
Alternative flyback converter topologies

- Two transistor flyback
  - Both turn on and off simultaneously
  - Voltage rating half compared to single transistor
  - No snubber necessary because of diodes



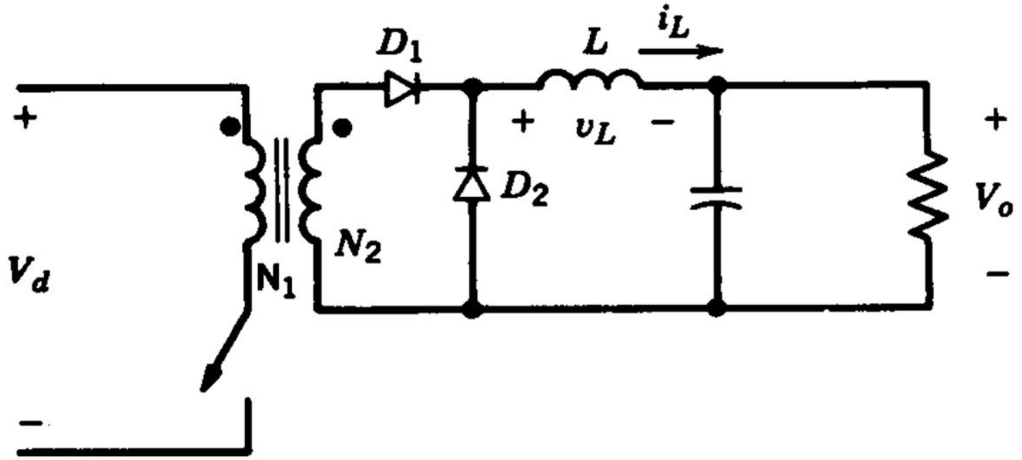
Alternative flyback converter topologies

- Paralleling flyback converter
  - Same frequency of switching
  - Phase-shifting switches π
- Allow higher power
- Redundancy
- Increased effective switching frequency



Forward converter

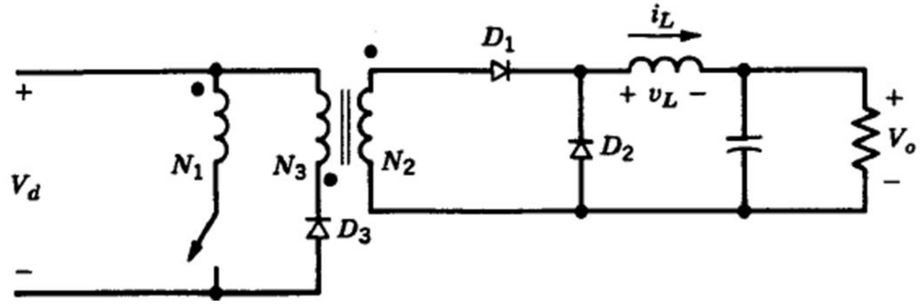
- Derived from step-down converter
- Ideal transformer assumed
  - Transformer magnetizing current not included
  - Converter failure if not taken care of

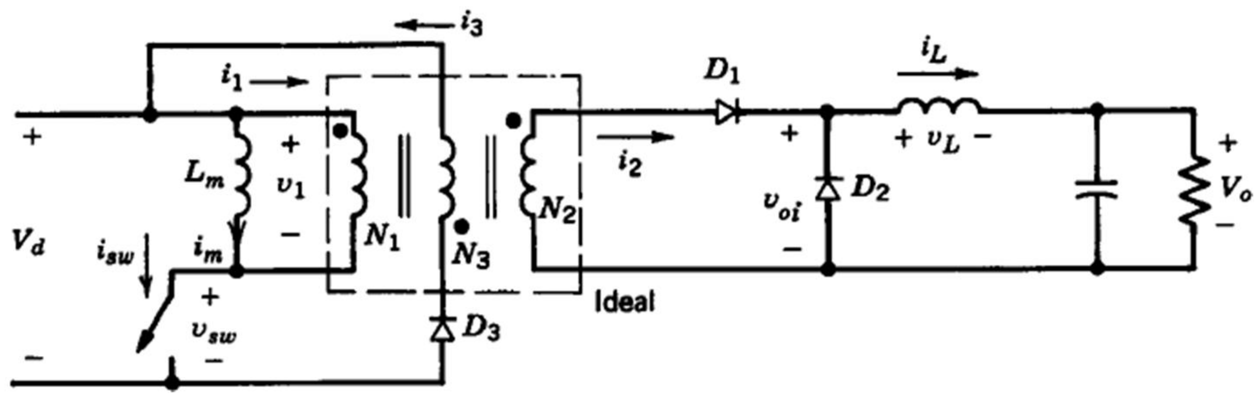


$$\frac{V_o}{V_d} = \frac{N_2}{N_1} D$$

Practical forward converter

- Feed magnetic current back to source
- Requires a third winding





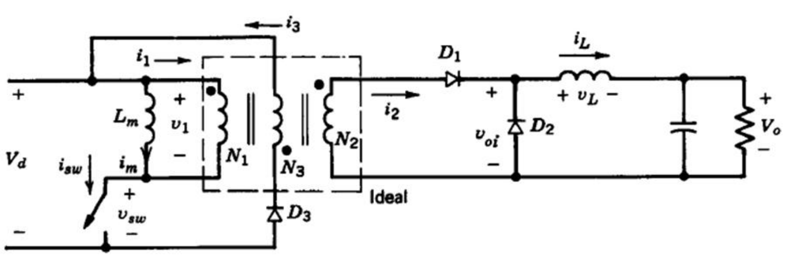
Practical forward converter waveforms

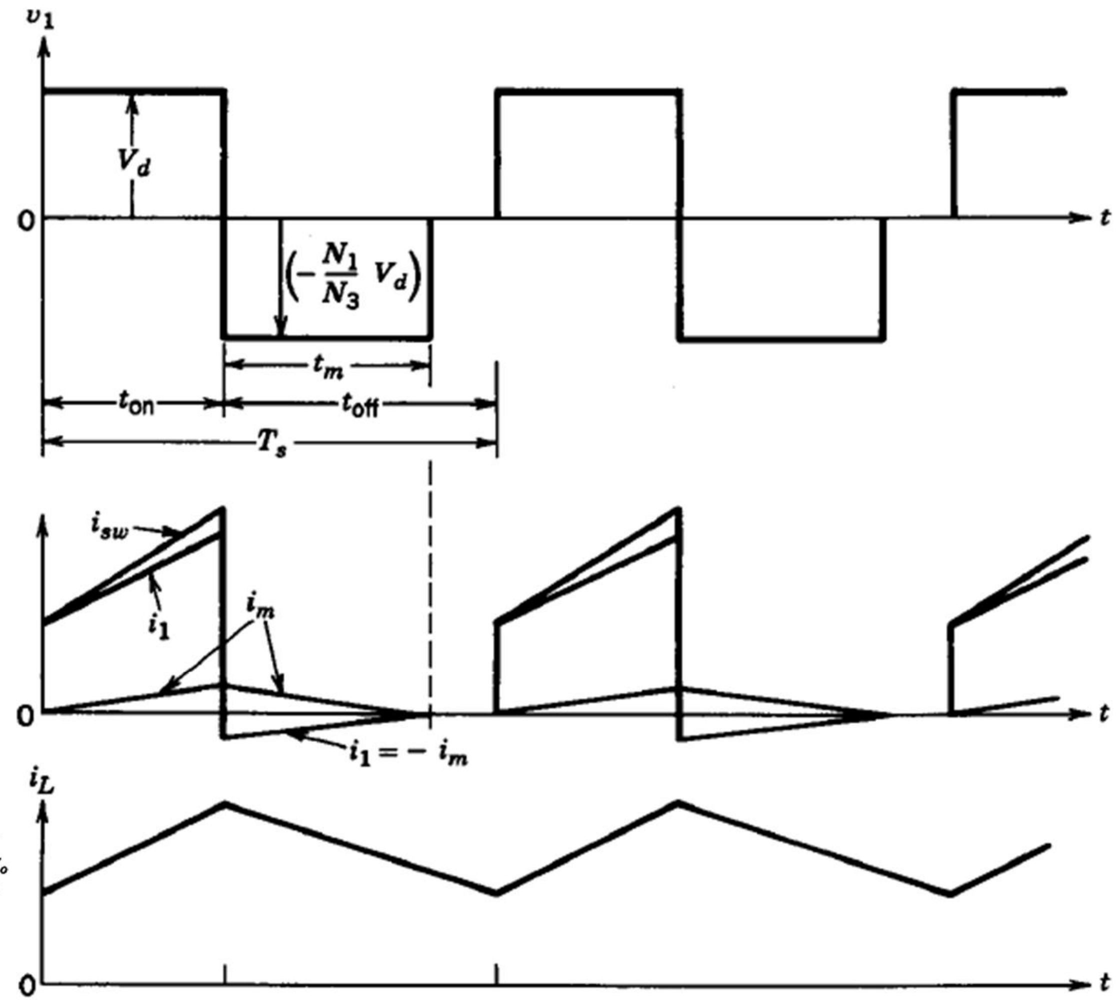
- To guarantee demagnitized transformer

$$max\frac{t_m}{T_s} = 1 - D$$

$$(1 - D_{max}) = \frac{N_3}{N_1}D_{max}$$

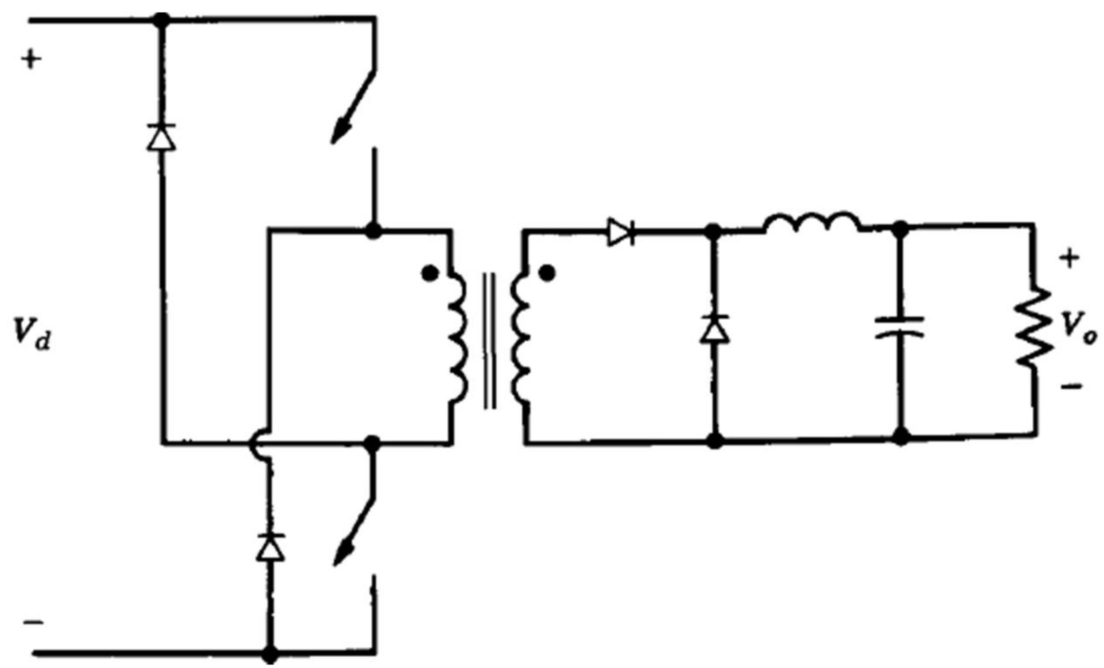
$$D_{max} = \frac{1}{1 + N_3/N_1}$$





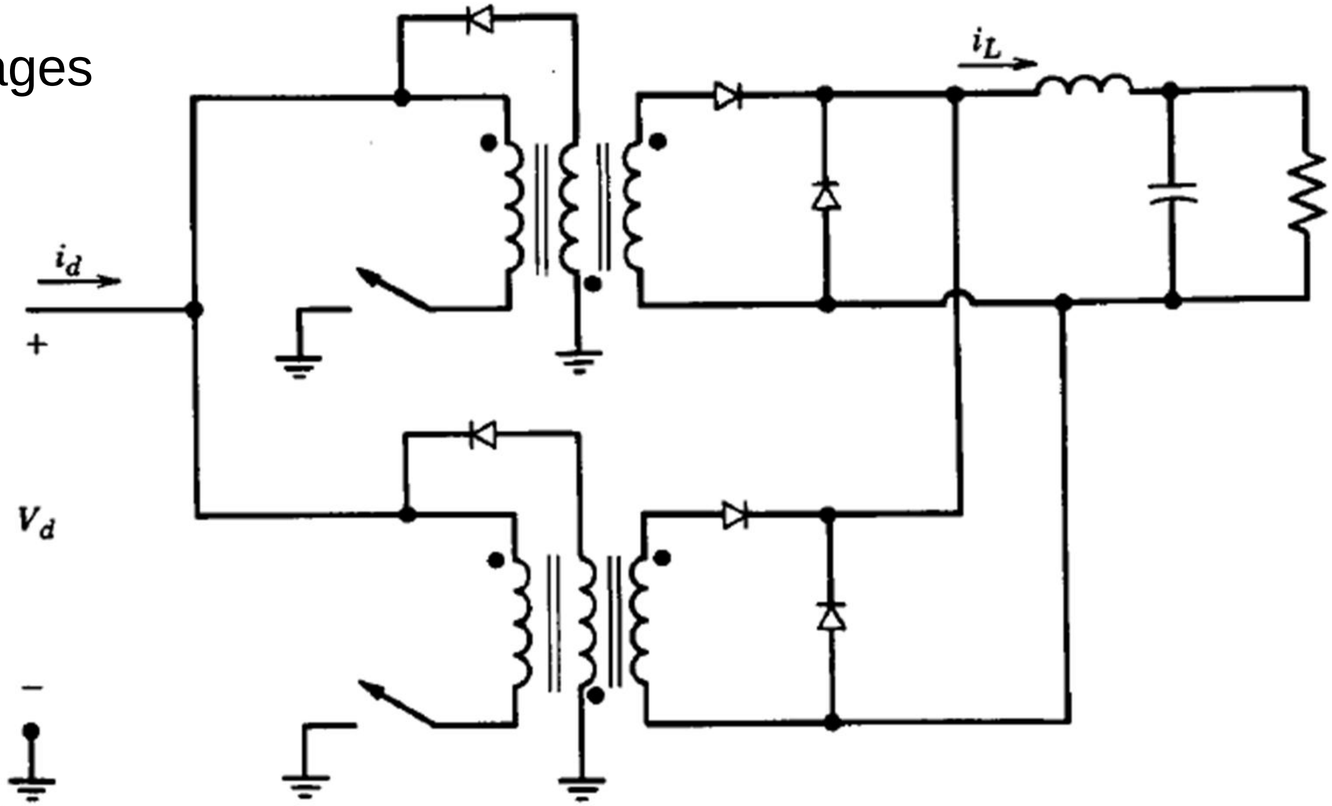
Other forward converter topologies

- Two-switch forward converter
- Commonly used
- Voltage rating half of single transistor case
- No snubbers necessary



Other forward converter topologies

- Parallelled forward converter
- Same advantages as parallelled flyback converter

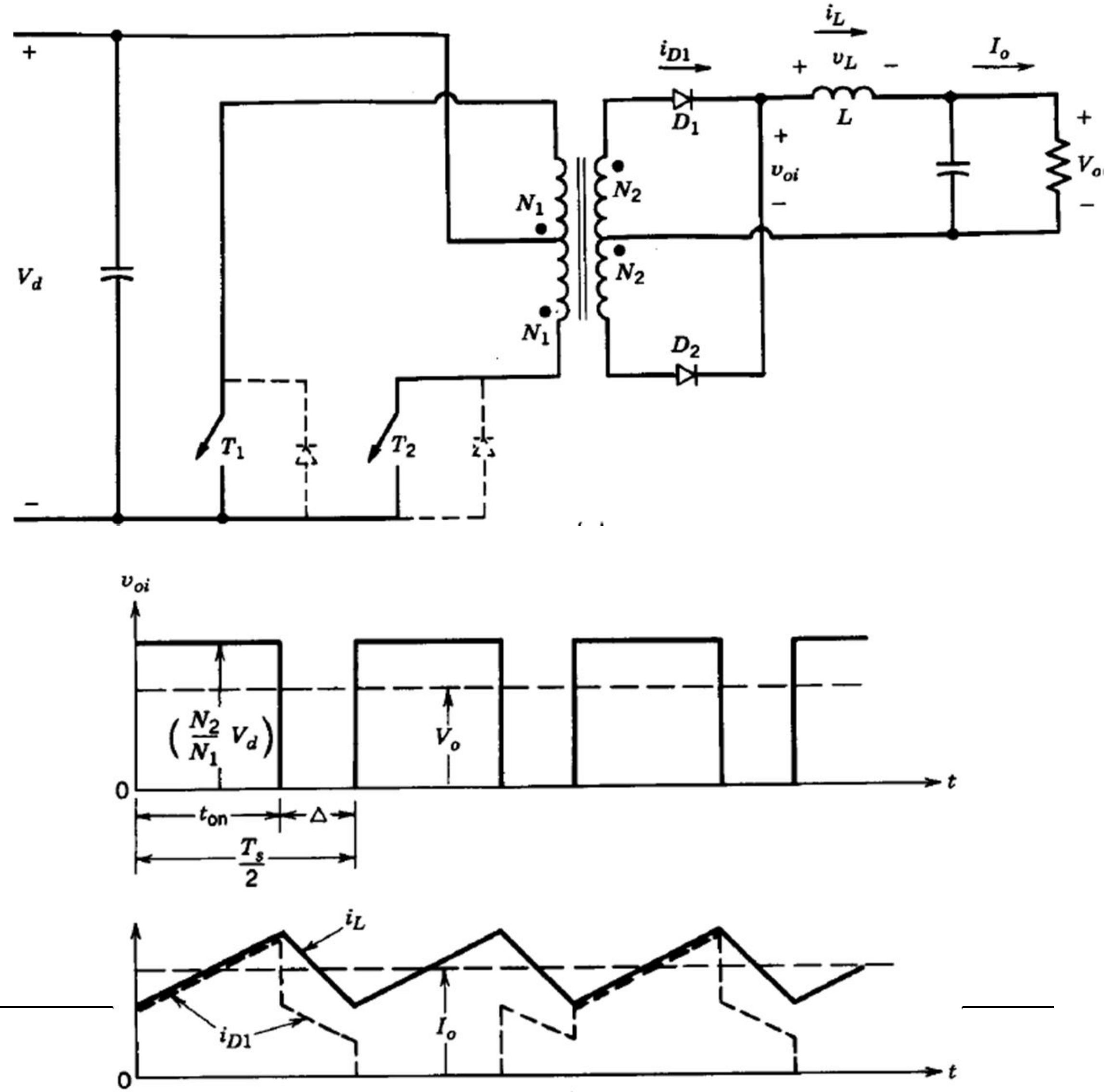


Push-pull converter

- Derived from step-down converter
- Diodes due to leakage inductances
- PWM control

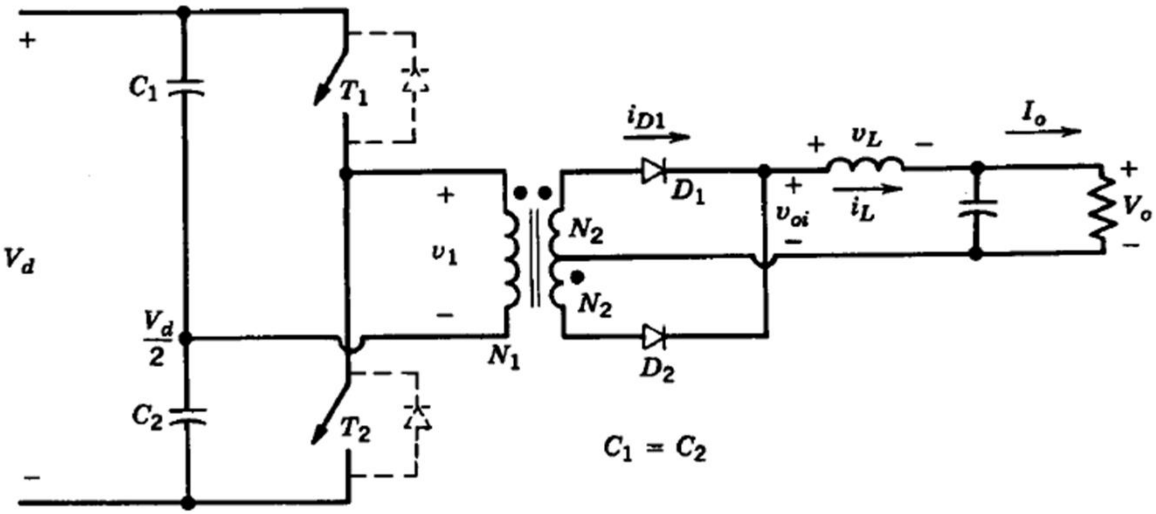
$$\frac{V_o}{V_d} = 2\frac{N_2}{N_1}D$$

$$0 < D < 0.5$$



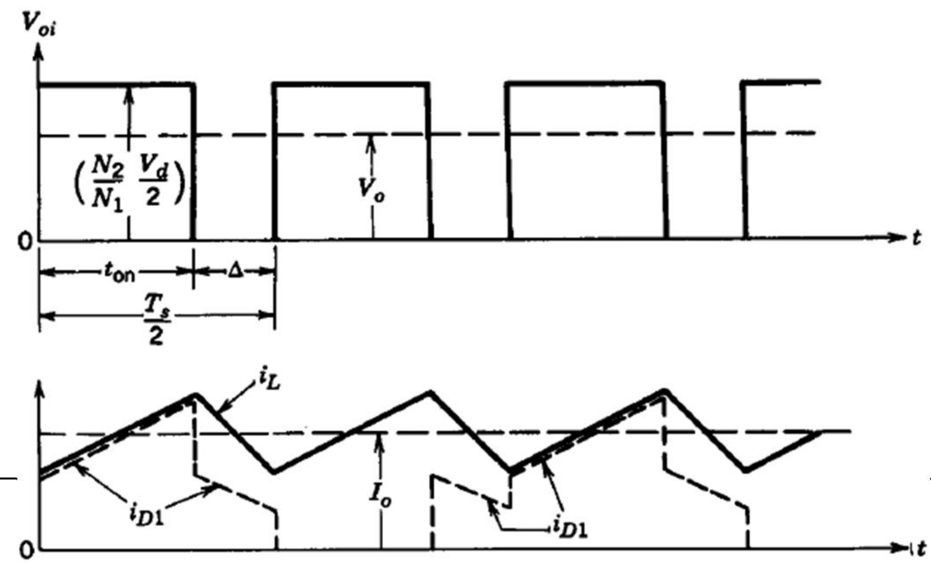
Half-bridge converter

- Derived from step-down converter
- Additional diodes for switch protection



$$\frac{V_o}{V_d} = \frac{N_2}{N_1} D$$

$0 < D < 0.5$

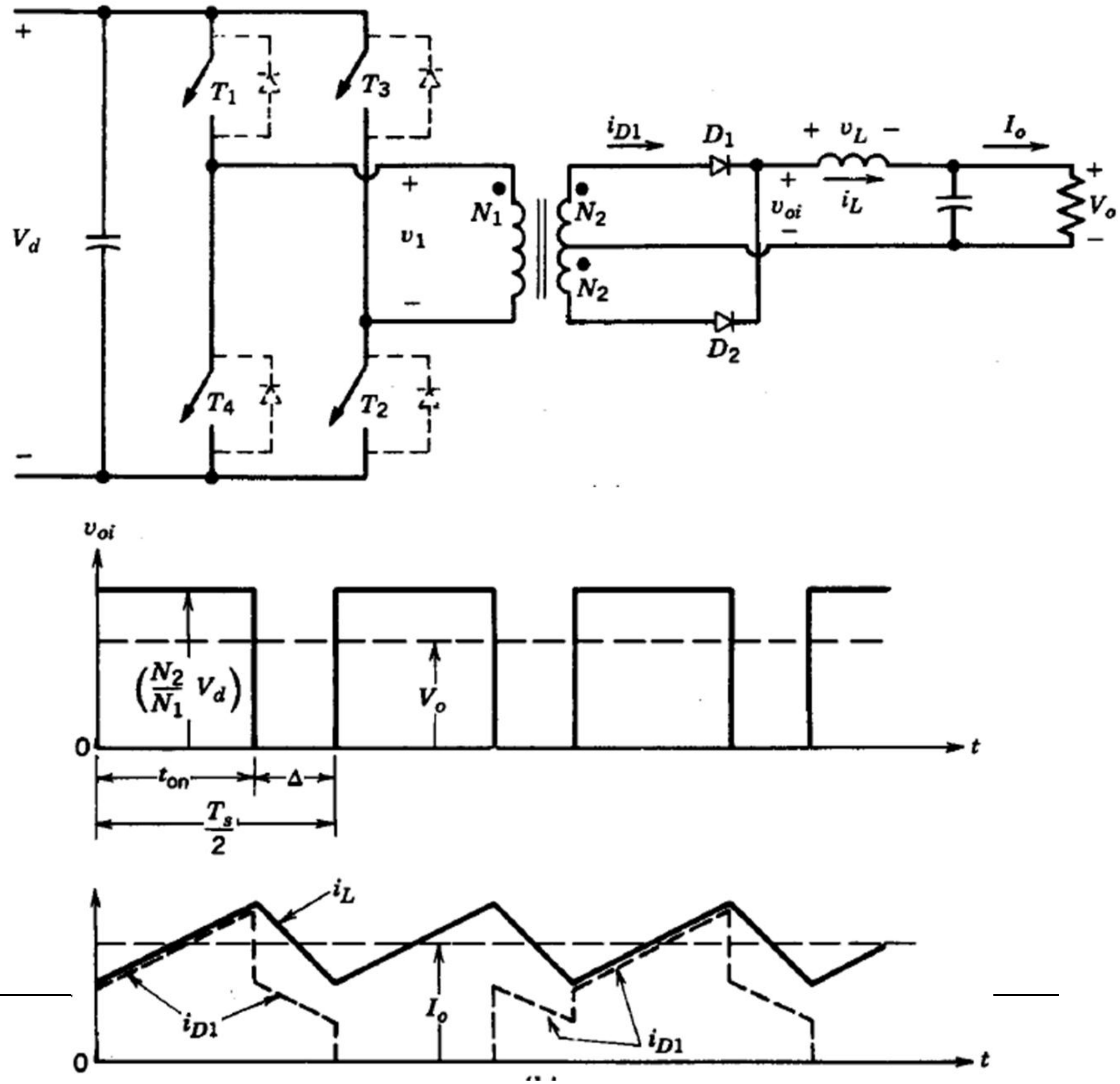


Full-bridge converter

- Derived from step-down converter
- Switches carry half the current compared to the half bridge converter

$$\frac{V_o}{V_d} = 2\frac{N_2}{N_1}D$$

$$0 < D < 0.5$$

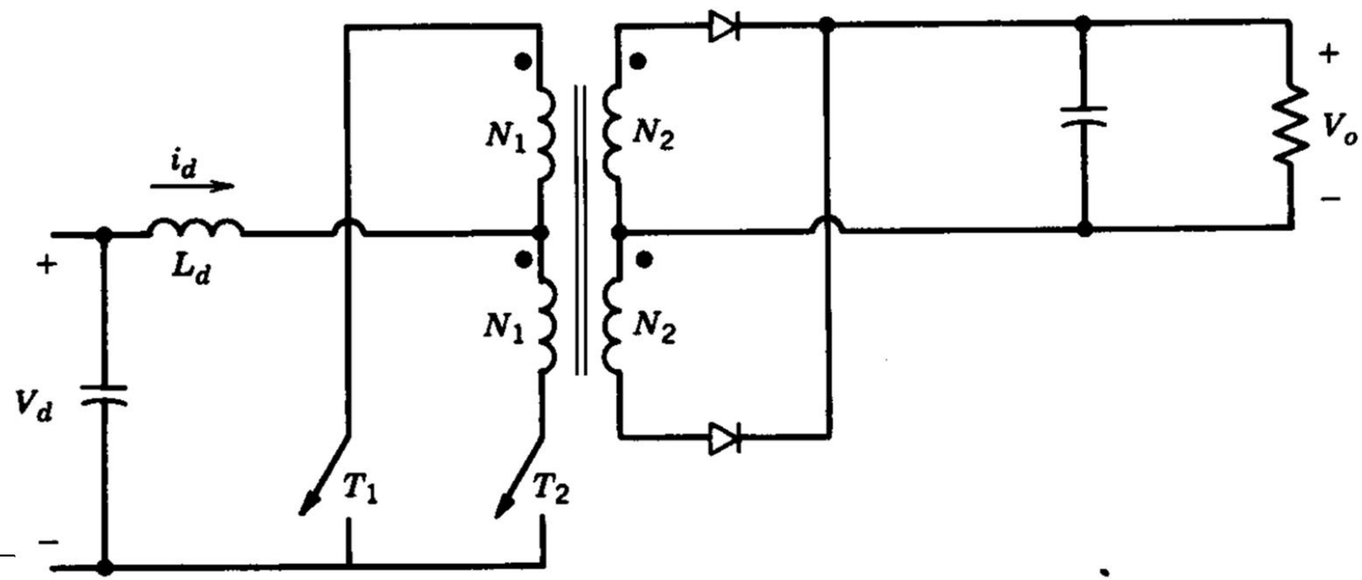


Current-source dc-dc converter

- L_d and D > 0.5 gives current source input
  - One or both switches always on
- Operates like a step-up converter

$$\frac{V_o}{V_d} = \frac{N_2}{N_1}\frac{1}{2(1-D)}$$

$$D > 0.5$$



www.liu.se

LINKÖPING UNIVERSITY