TSTE25 Power Electronics

Lecture 6

Arvind Balachandran
ISY/FS

Outline

- PWM non-idealities
  - Blanking time
  - Digital quantization effects
- Current control
- Isolated DC/DC Converters

Lecture 6

PWM non-idealities

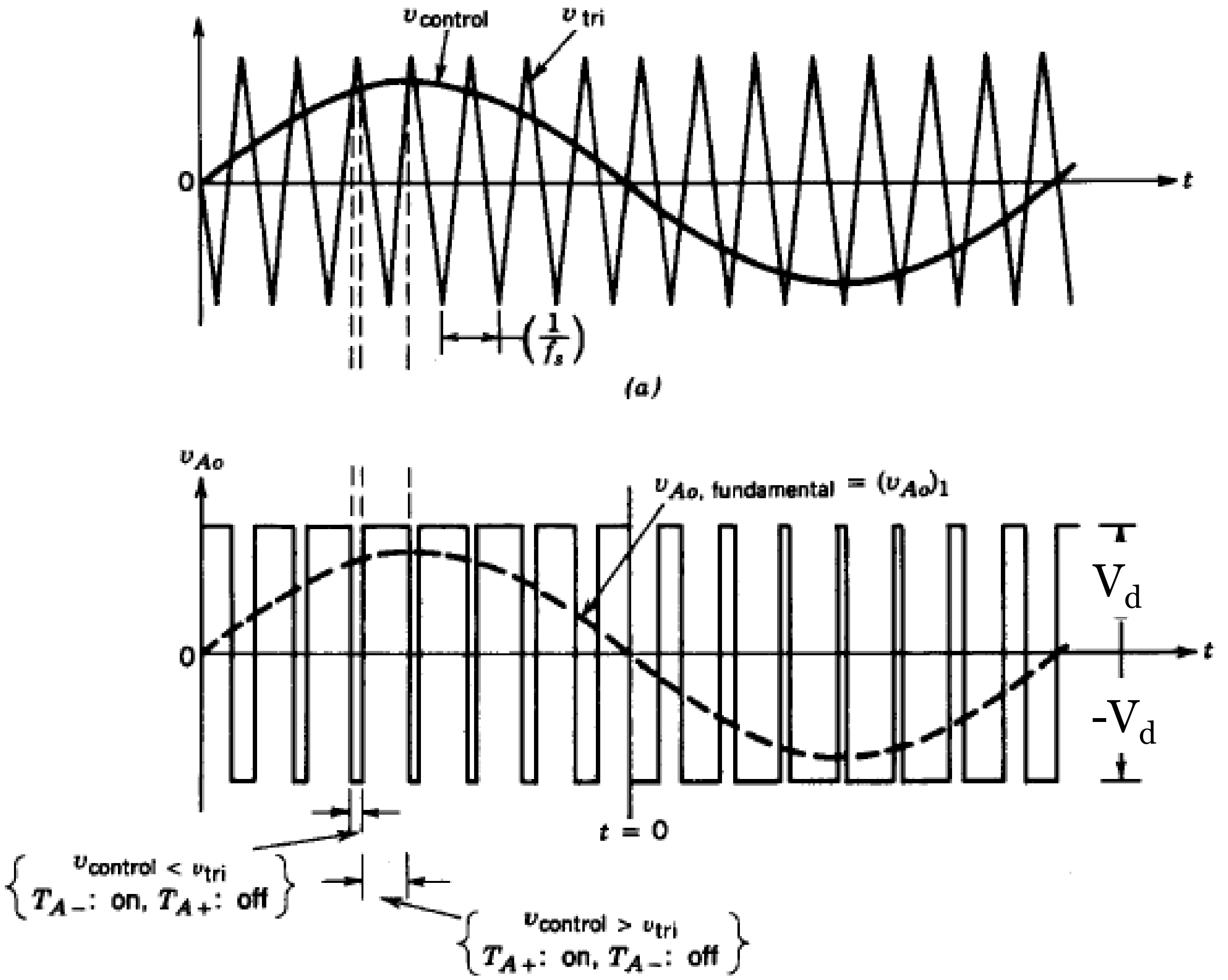
Pulse-width modulated switching scheme

- Amplitude modulation ratio (modulation index, peak duty cycle)

$$m_a = \frac{\hat{V}_{A01}}{V_d} = \frac{\hat{V}_{control}}{\hat{V}_{tri}} = \hat{D}$$

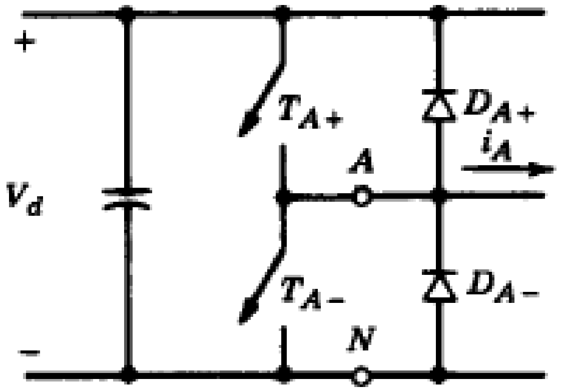
- Switching frequency f_s
- Fundamental frequency f_1
- Frequency modulation ratio (pulse number)

$$m_f = \frac{f_s}{f_1}$$



Blanking time effects

- Avoid cross-conduction by delay of device turn-on (blanking time or dead time)
- Current direction dependent
- Independent on output magnitude



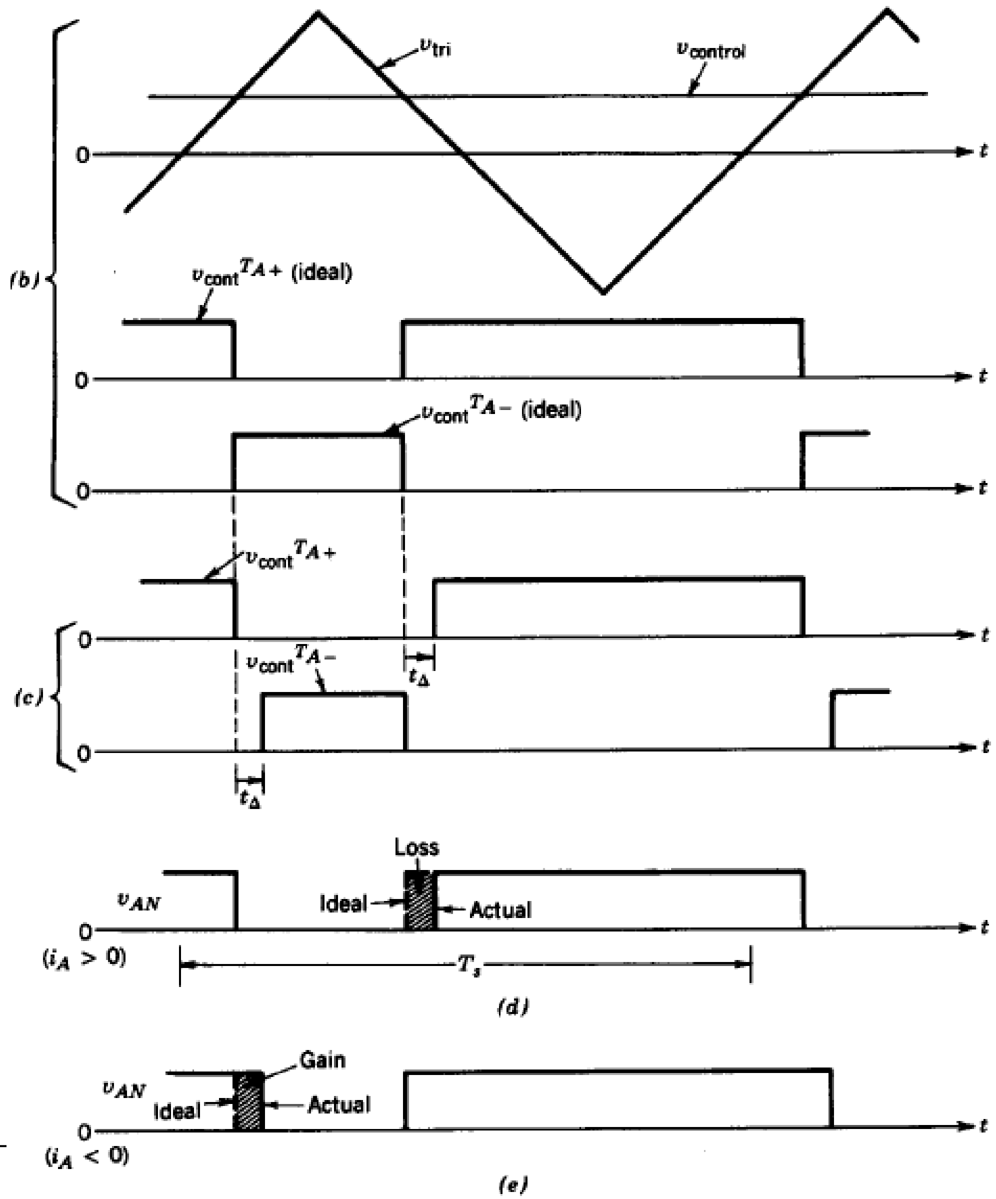
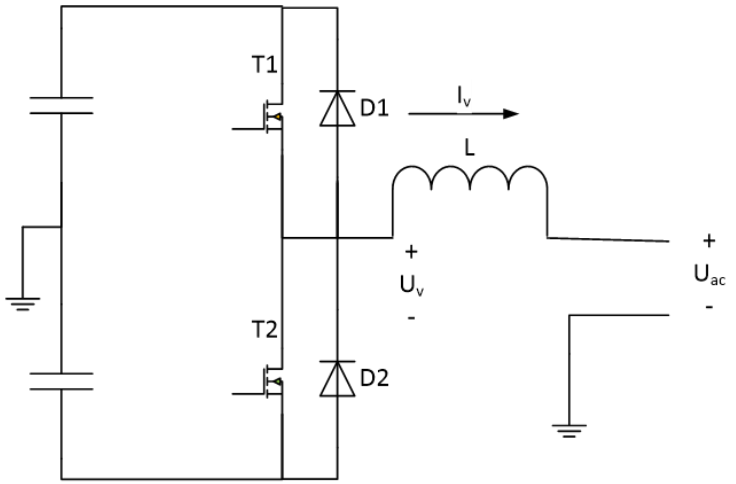
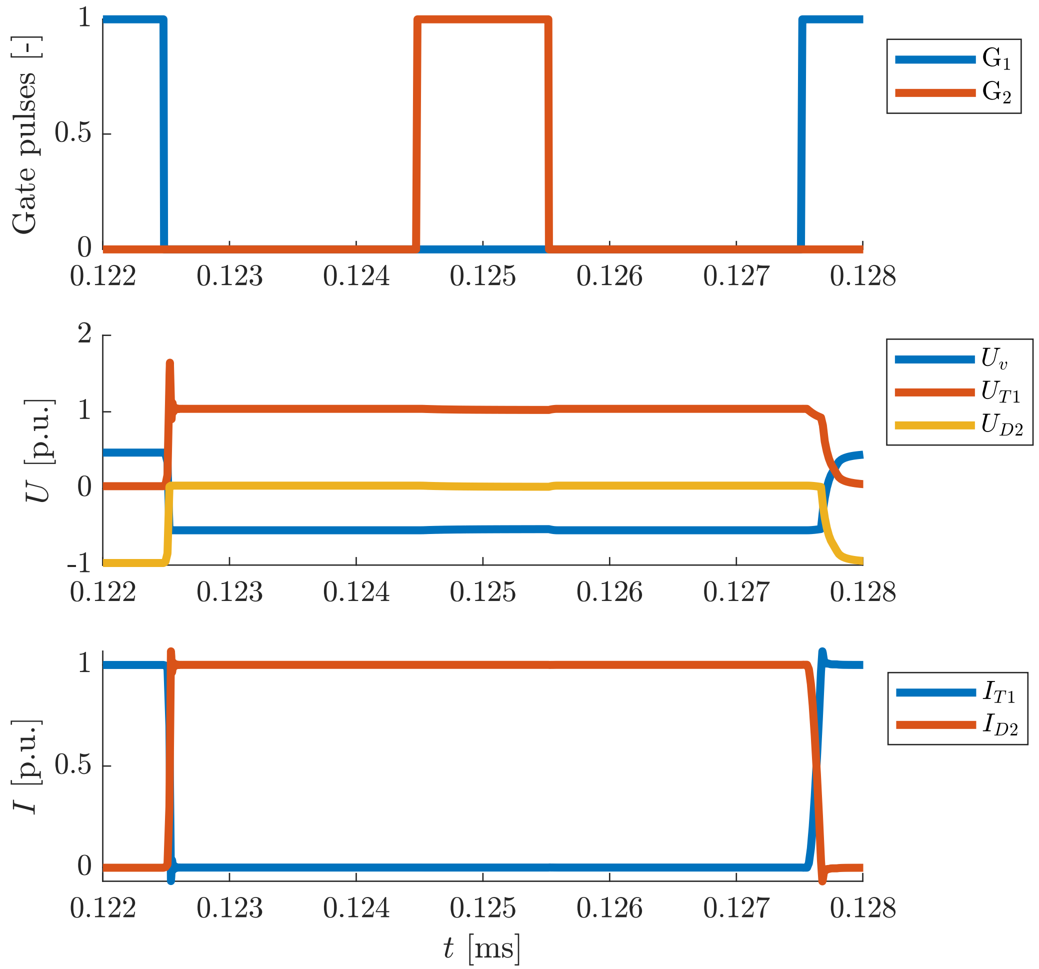


Figure 8-31 Effect of blanking time t_Δ.

Blanking time effects (cont..)

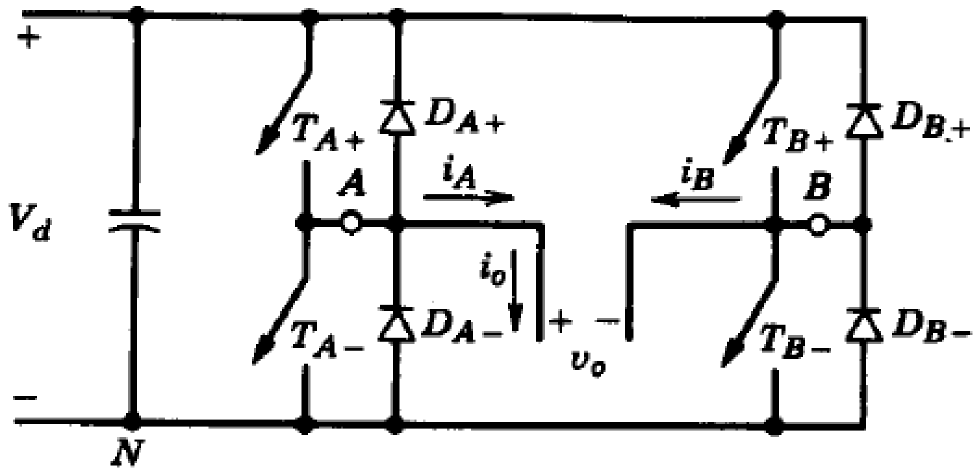
- Switching points defined by the PWM reference and triangular carrier crossing
- Actual voltage change, delayed by blanking time

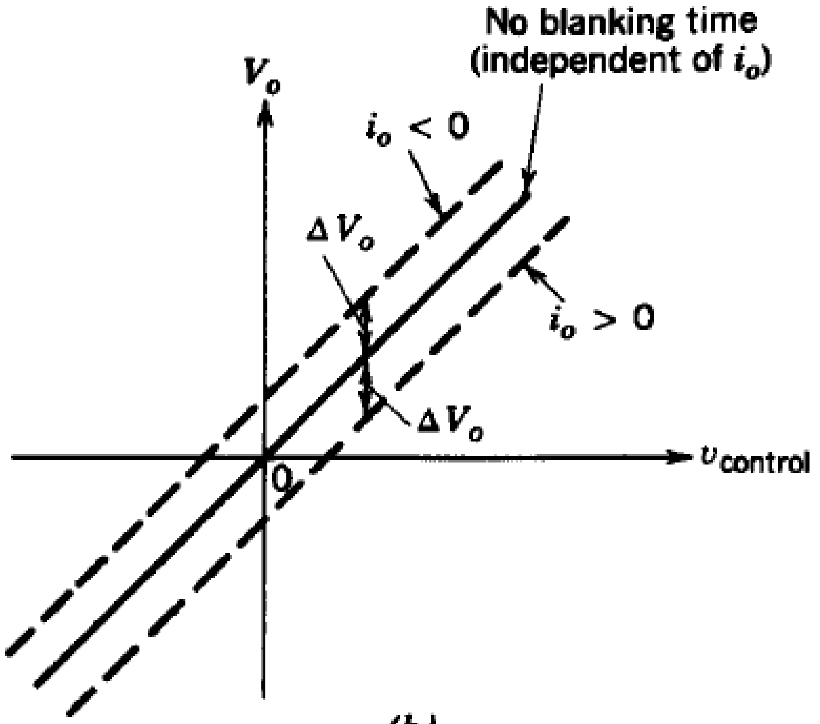




Blanking time effect on V_o

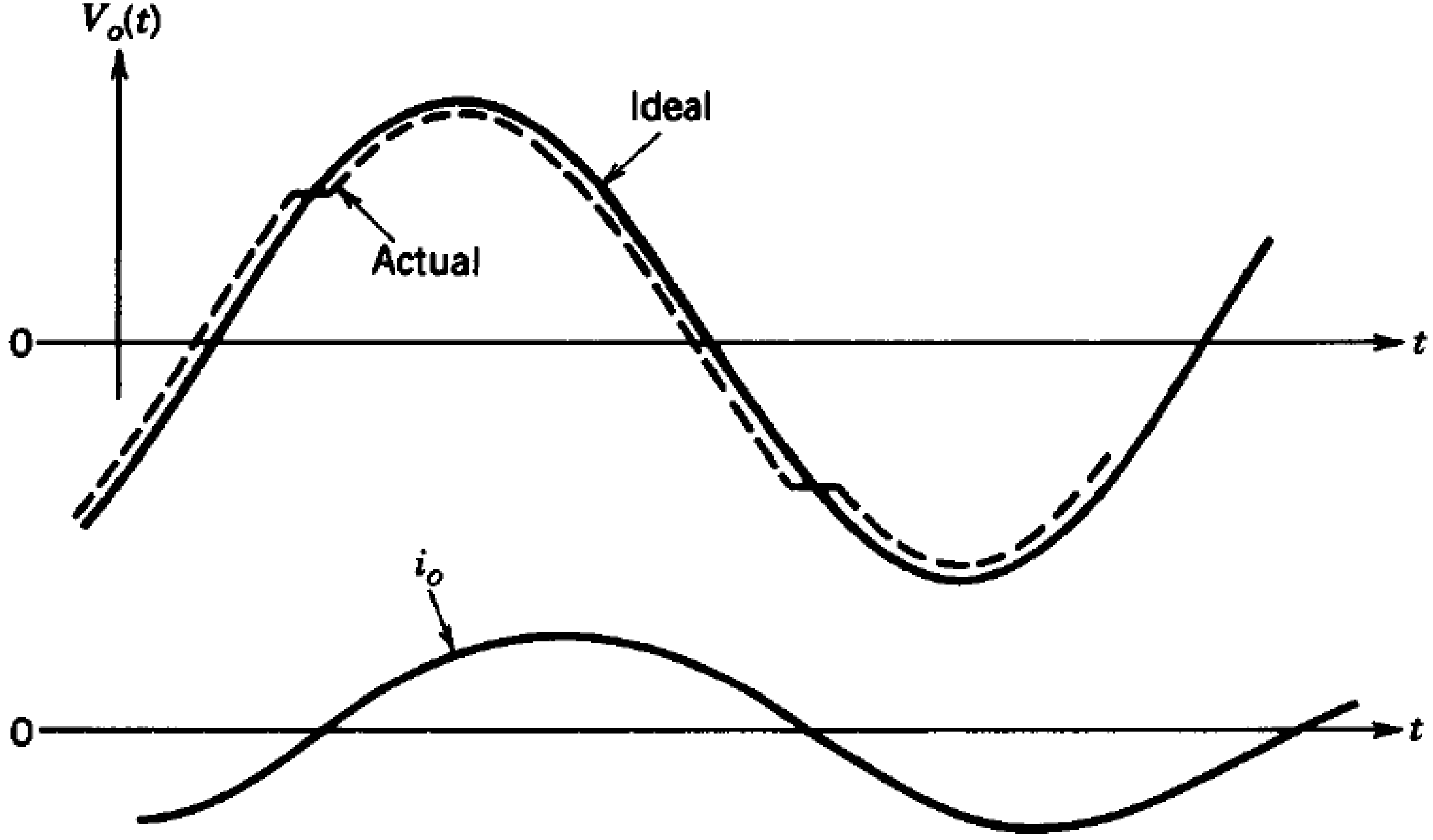
- Current polarity dictates error polarity
- Error increases with higher switching freq





(b)

Blanking effect on sinusoidal output



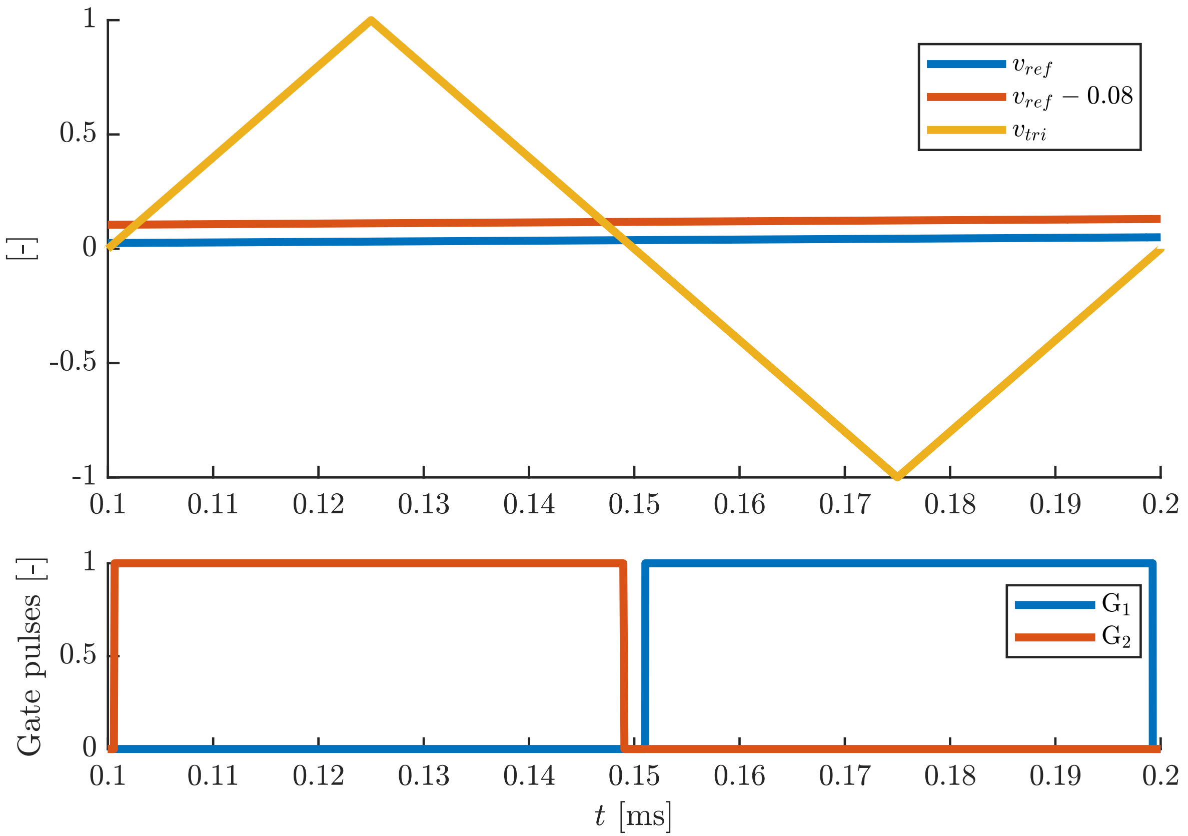
Gate pulse blanking with V_{ref} offset

G1 = V_{ref} - offset > V_{tri}
G2 = V_{ref} < V_{tri}

Average output voltage reduced:
m_a – offset/2

$U_{out(pk)}=(m_a - offset/2)U_d$

$$t_{blank} = \frac{|\text{offset}|}{\frac{dV_{tri}}{dt}} = \frac{|\text{offset}|}{\frac{2}{T_{sw}/2}} = \frac{|\text{offset}|}{4f_{sw}}$$



Digital PWM control

- Proportional control (error amplifier) for voltage feedback
- Pulse width modulation, PWM, to control switching
- Switching frequency, f_s, the repetition rate of turn-on/off
- Control sampling (cycle) frequency, the rate of digital control execution

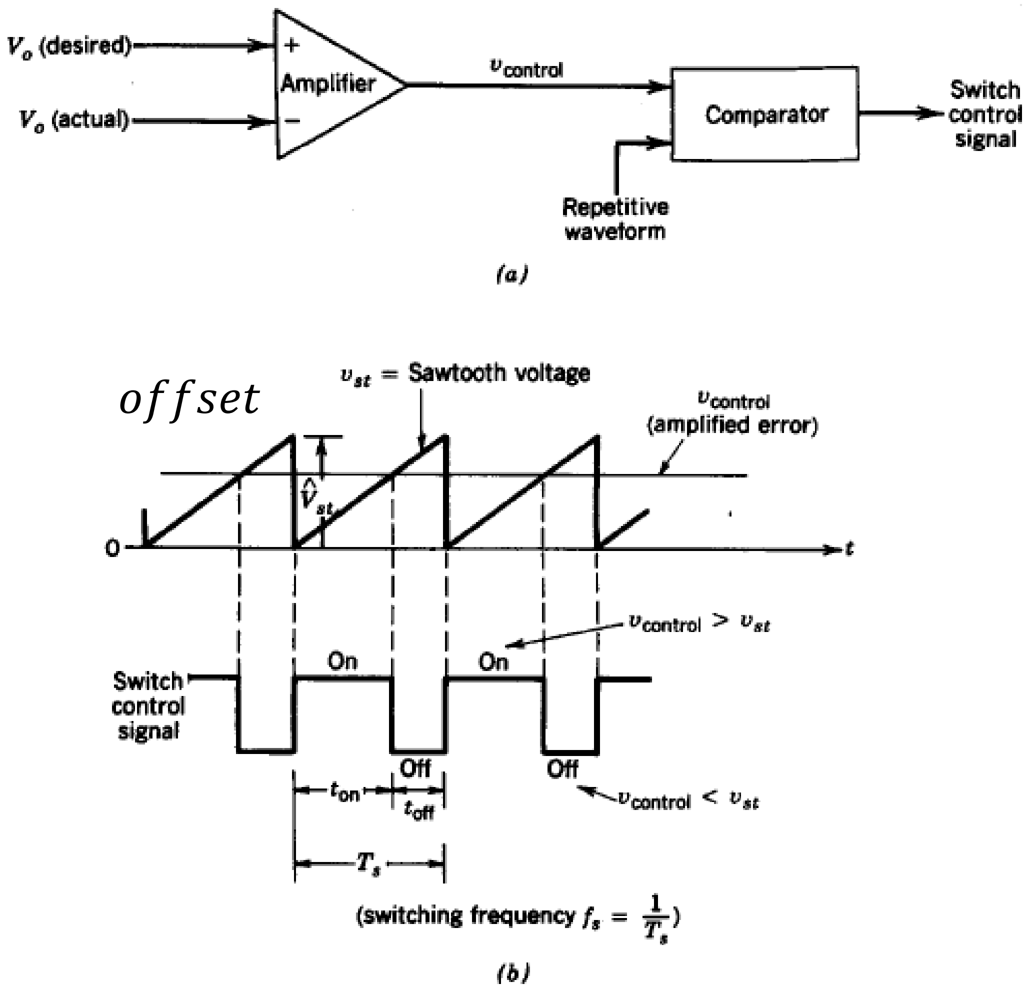
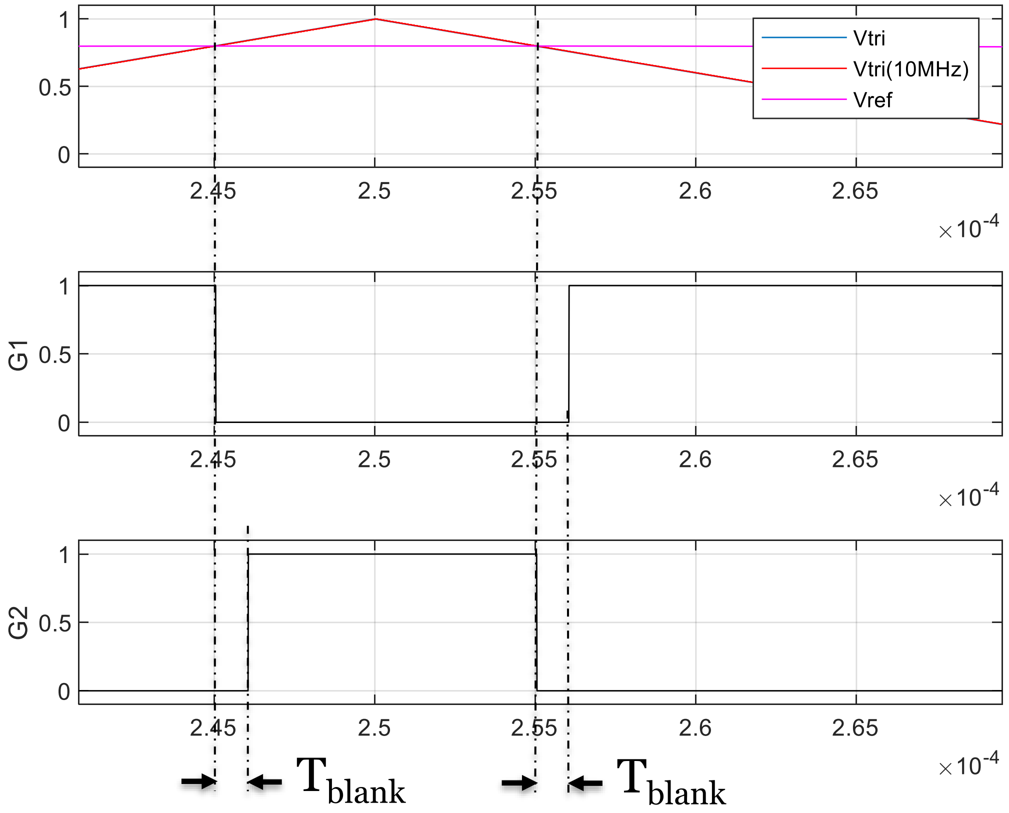


Figure 7-3 Pulse-width modulator: (a) block diagram; (b) comparator signals.

Blanking time

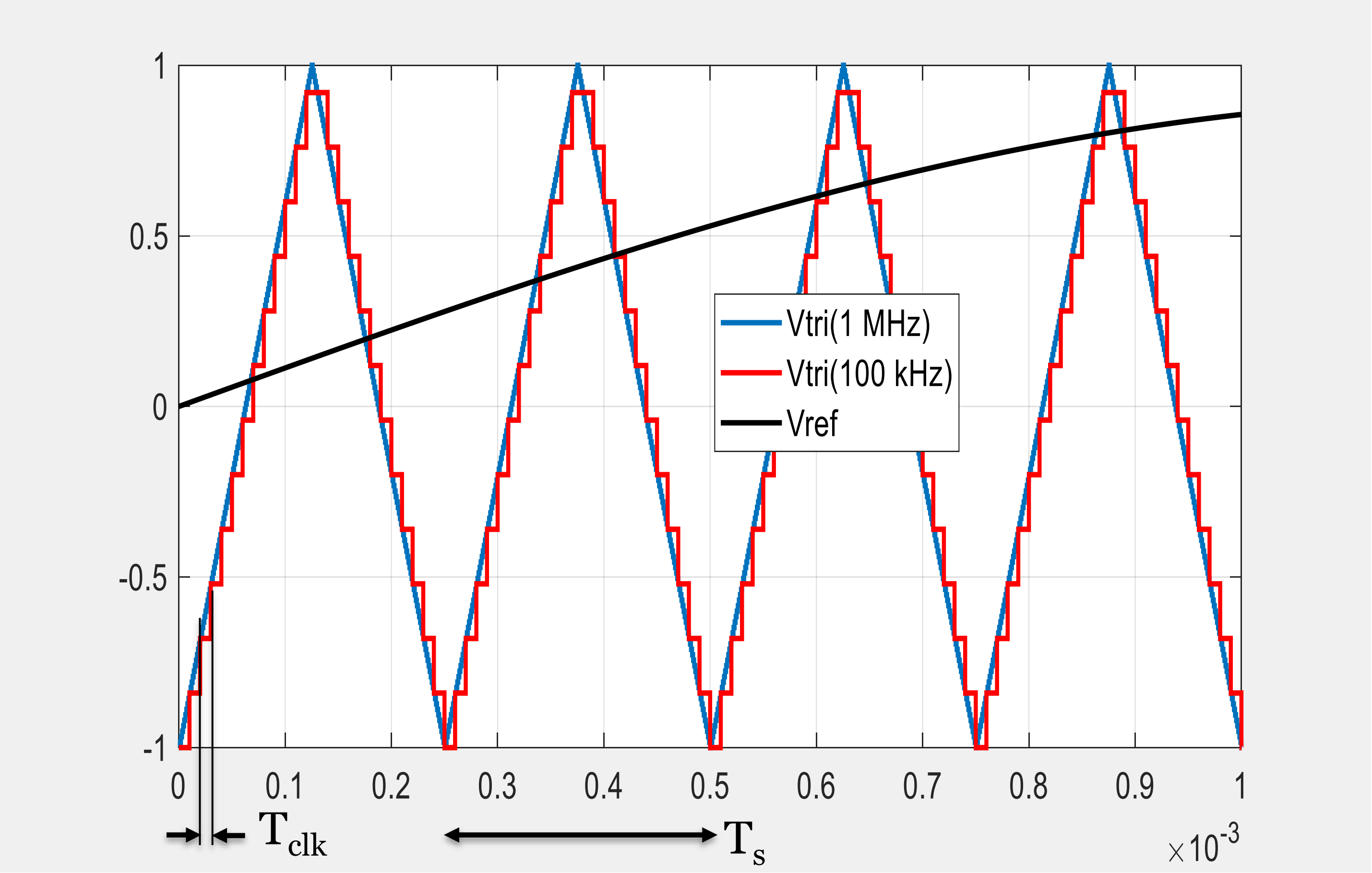
- Using Delay on both of the gate pulses.

D – Flip-Flop
clk – defined by T_{blank}

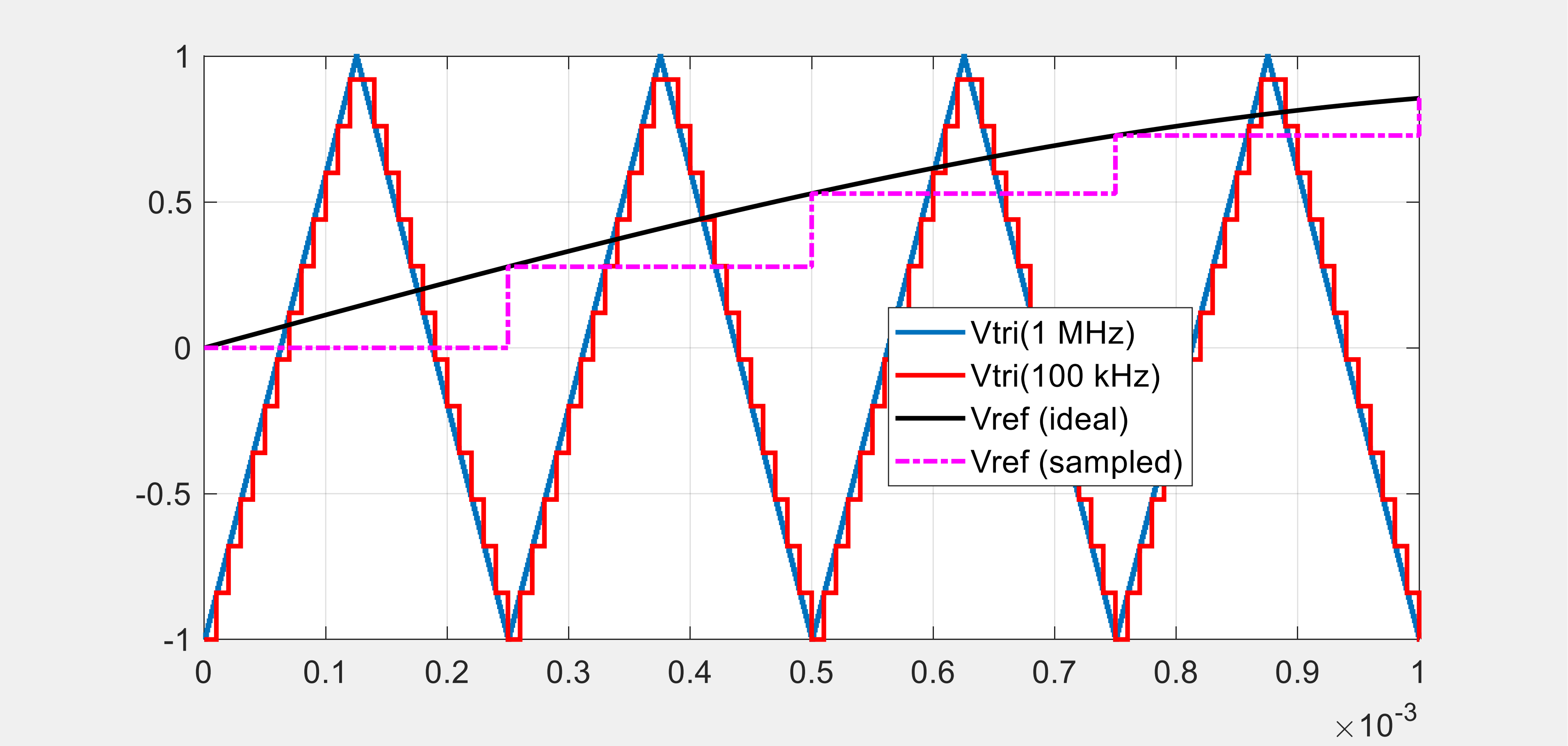


Carrier wave sampling effects

- fsw=4 kHz
- Ts=250 µs
- Tclk=10 µs (100 kHz)
- 25 samples per carrier cycle (Ts/Tclk)
- 12.5 samples per half-cycle (-1 to 1 transition)
- Amplitude resolution:
  - 2/12.5 = 16% (100kHz)
  - 2/125 = 1.6 % (1 MHz)



Reference sampling effects



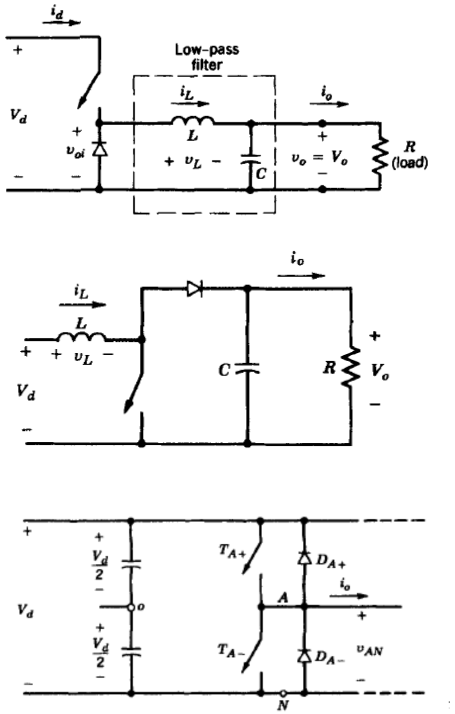
Lecture 6

Current Control

Basic control principle.
Voltage Source Converter (VSC)

Simplifying the switched mode converters to an average voltage source with adjustable

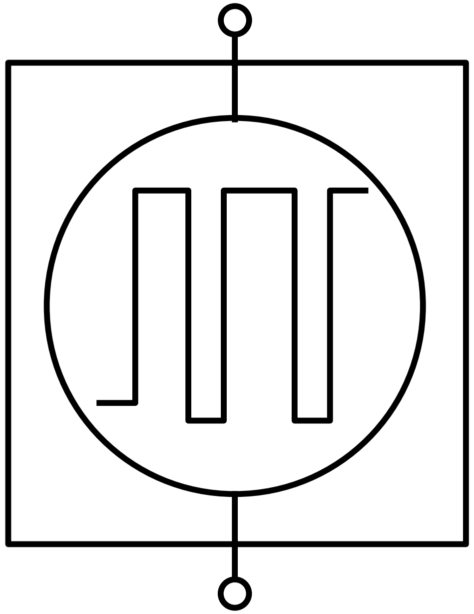
- Amplitude
- Phase angle
- Frequency



Buck Converter (step-down DC-DC)

Boost Converter (step-up DC-DC)

Half-bridge inverter (DC-AC)

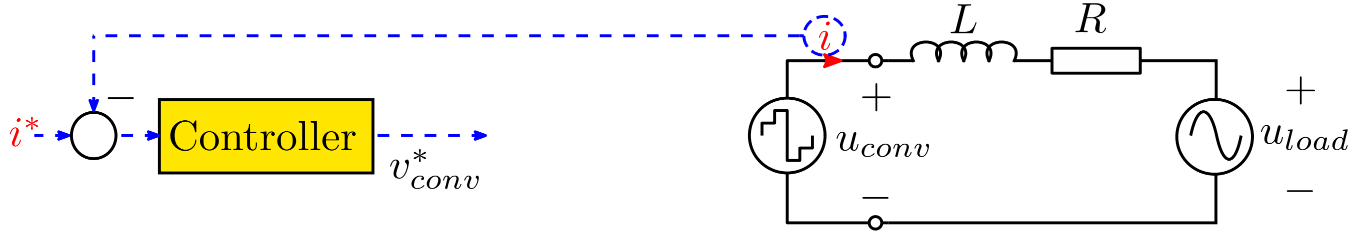


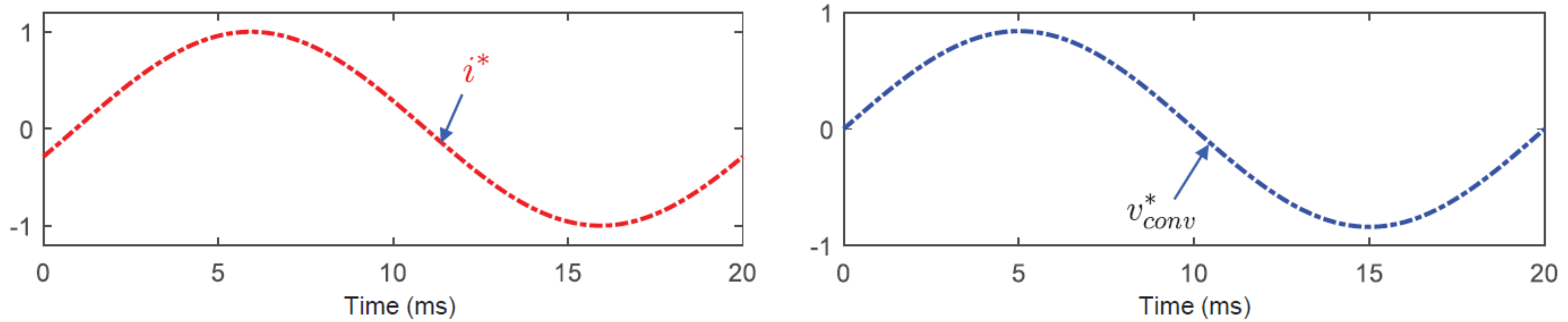
Voltage Source Converter

Introduction to control

Power converter control

Control Objective Regulate the load current i along its reference i^* by manipulating the reference converter voltage v^*_{conv}.

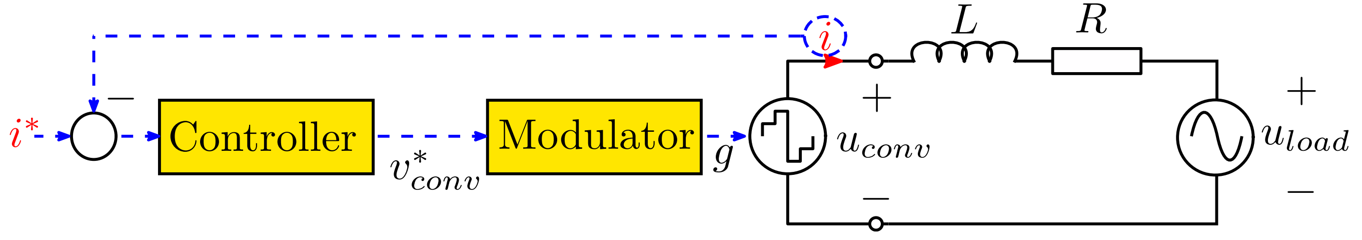


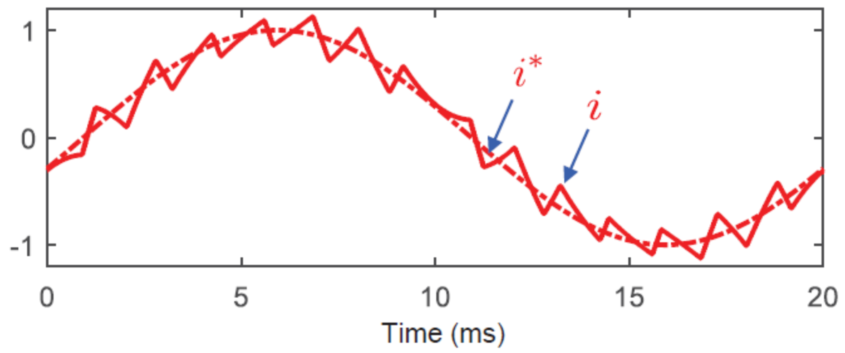


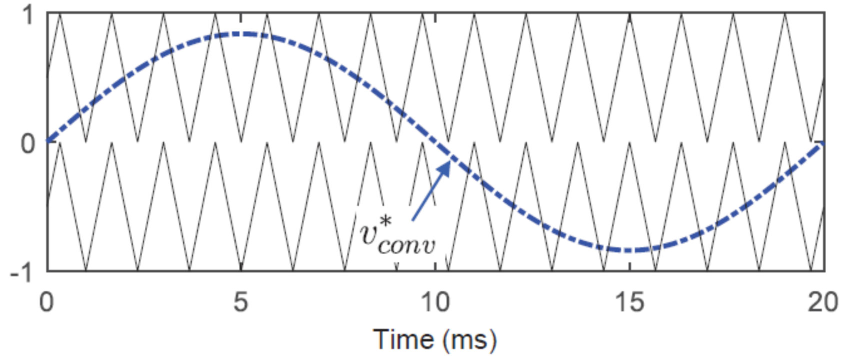
Introduction to control

Power converter control

Control Objective Regulate the load current i along its reference i^* by manipulating the reference converter voltage v^*_{conv}.



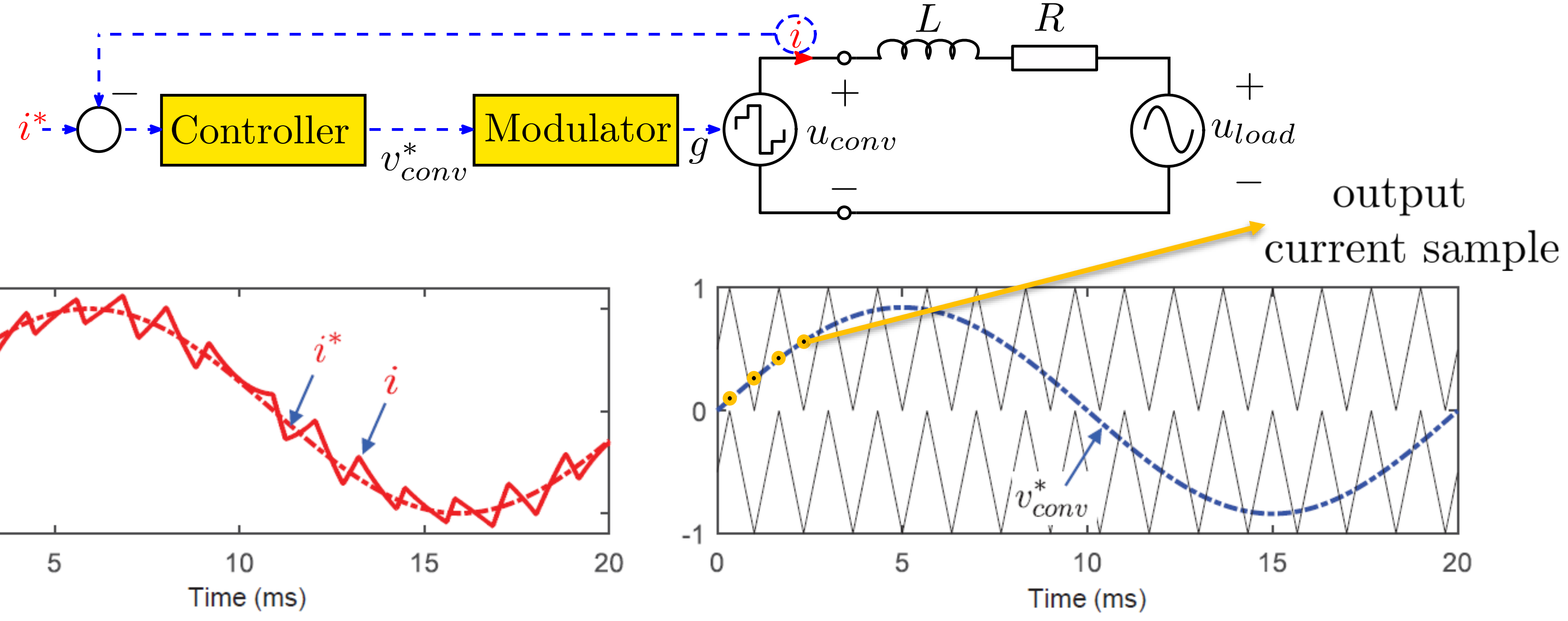




Introduction to control

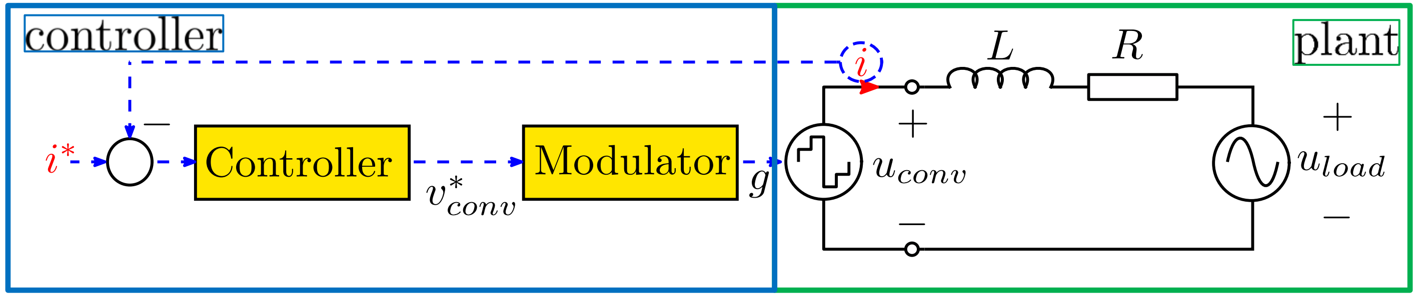
Power converter control

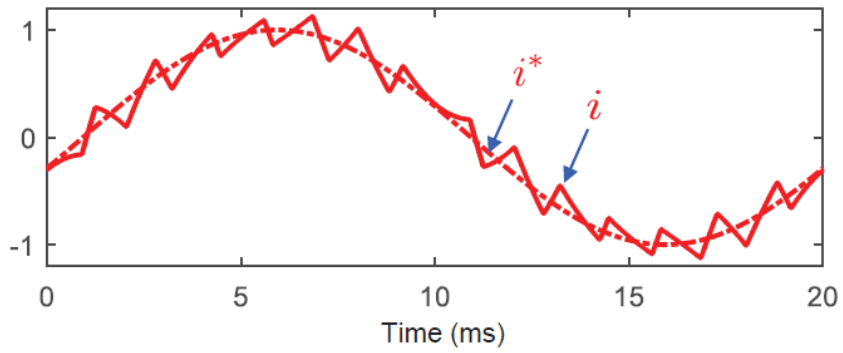
Control Objective Regulate the load current i along its reference i^* by manipulating the reference converter voltage v^*_{conv}.

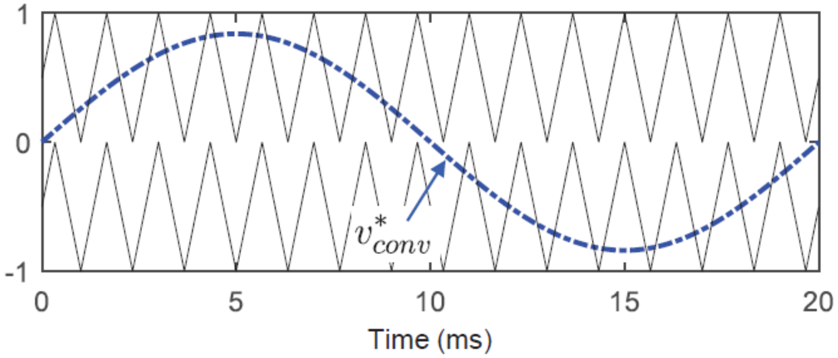


Introduction to control

Power converter control

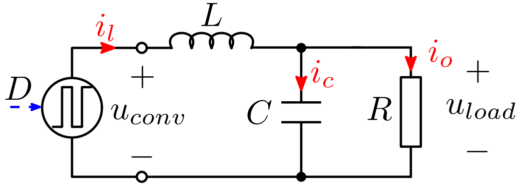


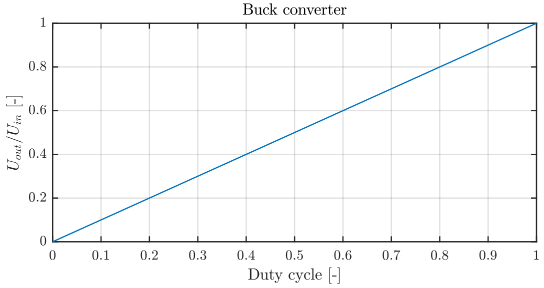




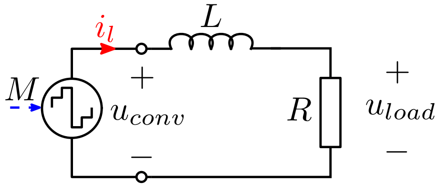
System under control (Plant)

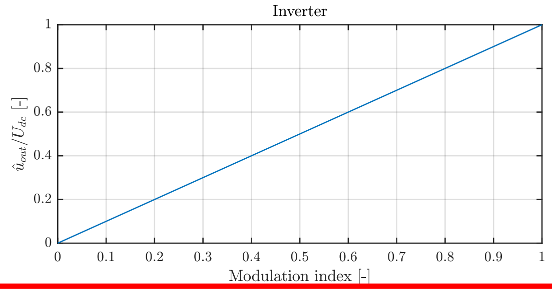
Buck Converter:



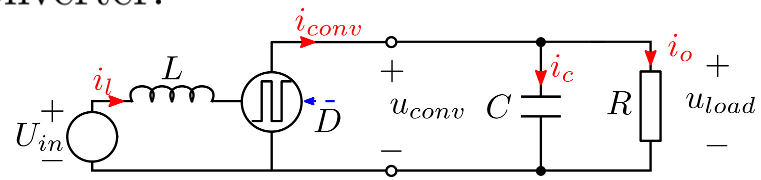


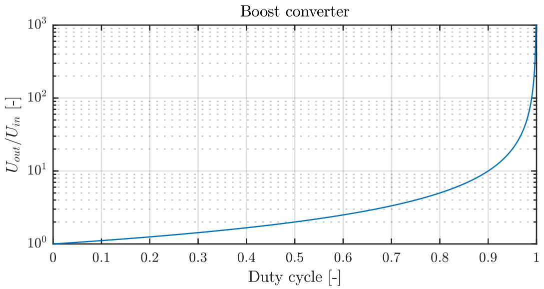
Inverter:



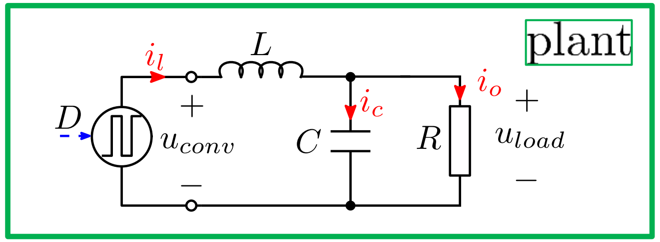


Boost Converter:





Non-linearity



Buck converter

Control Objective Regulate the load current i_o along its reference i_o^* by manipulating the converter duty cycle, D.

$$u_{conv} = L\,\frac{di_l}{dt} + i_o\,R$$

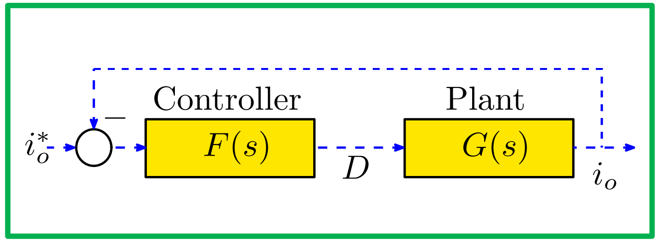
Steady state, average i_l is the same as i_o, and average voltage across capacitor is cosntant and equal to u_{load}.

Laplace transformation: $u_{conv} = s\,L\,i_o + i_o\,R$

$$D\,U_{in} = (sL + R)i_o \implies \frac{i_o}{D} = \frac{U_{in}}{s\,L + R}$$

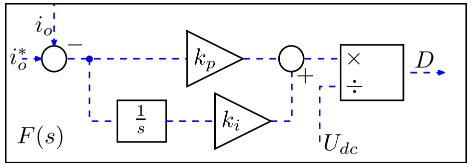
Plant transfer function: $G(s) = \dfrac{U_{in}}{s\,L + R}$

Buck converter (closed-loop)



Plant transfer function: $G(s) = \dfrac{U_{in}}{s\,L + R}$

Closed-loop transfer function: $\dfrac{G(s)\,F(s)}{1 + F(s)\,G(s)}$.

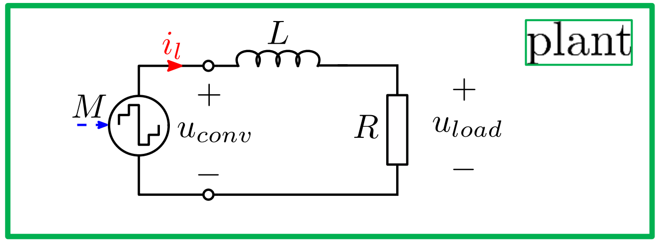


$$\frac{G(s)\,F(s)}{1 + F(s)\,G(s)} = \frac{\alpha_c}{s + \alpha_c} = \frac{\alpha_c/s}{1 + \alpha_c/s}.$$

PI Controller: $F(s) = k_p + \dfrac{1}{s}\,k_i$.

Now, $F(s)G(s) = \dfrac{\alpha_c}{s}$, $F(s) = \dfrac{\alpha_c}{s}\,G^{-1}(s), F(s) = \dfrac{1}{U_{in}}\left(\alpha_c\,L + \alpha_c\,R\,\dfrac{1}{s}\right)$.

$$k_p = \alpha_c\,L \qquad\qquad k_i = \alpha_c\,R$$

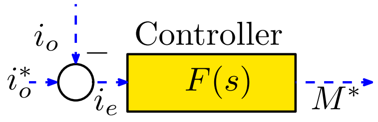


Inverter Control

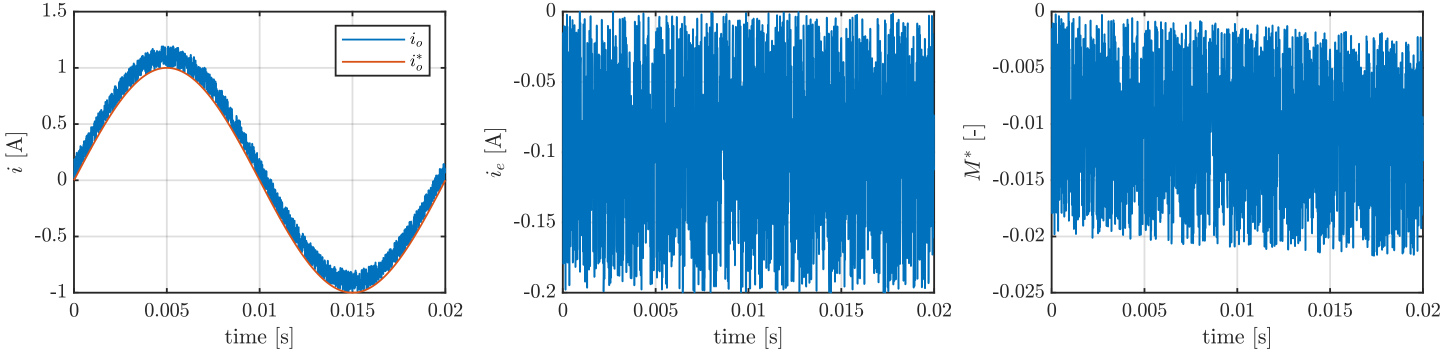
Control Objective Regulate the load current i_l along its reference i_l^* by manipulating the converter modulation index, M.

current controller: controls both *phase angle* and *amplitude* of i_l.

Case 1: PI controller

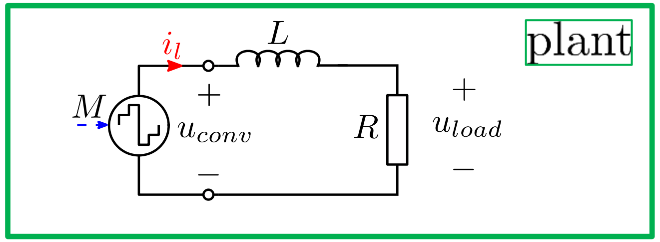


$$F(s) = k_p + \frac{1}{s}k_i.$$



Note: duty reference M^* should be a sine-wave.

The controller output is no longer sinusoidal and even if it is sinusoidal, there exists a phase delay due to the integrator.



Inverter Control

Control Objective Regulate the load current i_l along its reference i_l^* by manipulating the converter modulation index, M.

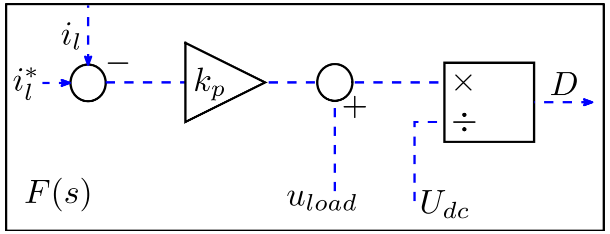
If we measure the output voltage u_{load} then, $u_{conv} = \omega L i_l + u_{load}$

Considering a closed-loop bandwidth of α_c [rad/s].

$$\alpha_c L (i_l^* - i_l) = u_{conv} - u_{load}$$

$$M^* = \underbrace{\boxed{\alpha_c L}}_{k_p} (i_l^* - i_l) + u_{load}$$

P controller with feed-forward



Boost converter

(Average, Small Signal Circuit Model)

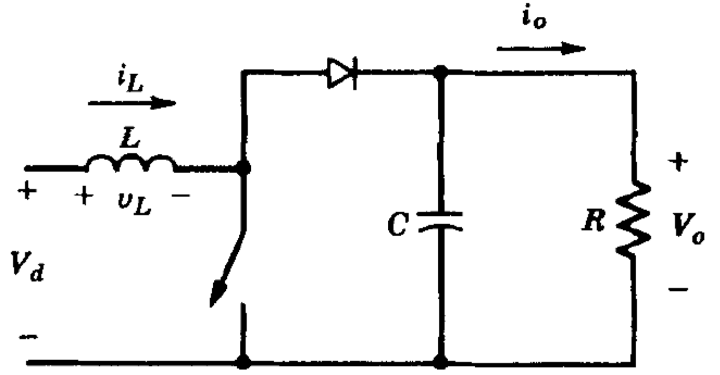
Divide the circuit into two halves:

1. Inductor side:

$$G_1(s) = \frac{\tilde{i}_L}{\tilde{d}} = \frac{V_o Cs + 2(1-D)I_L}{LCs^2 + \frac{L}{R}s + (1-D)^2}$$

2. Capacitor side:

$$G_2(s) = \frac{\tilde{v}_o}{\tilde{i}_L} = \frac{-I_L Ls + (1-D)V_o}{V_o Cs + 2(1-D)I_L}$$



Converter transfer function:

$$G(s) = G_1(s)G_2(s) = \frac{\tilde{i}_L}{\tilde{d}} \cdot \frac{\tilde{v}_o}{\tilde{i}_L} = \frac{-I_L L\, s + (1-D)V_o}{LCs^2 + \frac{L}{R}s + (1-D)^2}$$

One can design a controller of their choice and the controller gains can be calculated using pole placement with the help of the transfer function.

$I_L \rightarrow$ inductor current
$L \rightarrow$ inductance
$R_{out} \rightarrow$ output resistance
$C \rightarrow$ capacitance
$V_{out} \rightarrow$ output voltage
$D \rightarrow$ duty cycle

Özdemir, A., & Erdem, Z. (2018). Double-loop PI controller design of the DC-DC boost converter with a proposed approach for calculation of the controller parameters. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, *232*(2), 137-148.

Lecture 6

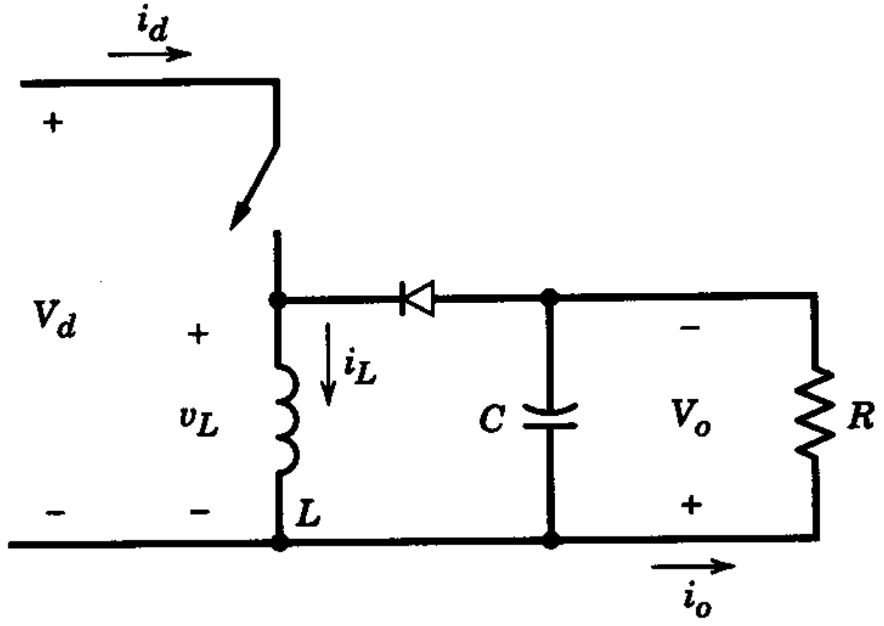
Isolated DC/DC converters

Outline

- The Transformer

- Isolated DC/DC converters

Step-Down/Up (buck-boost) DC-DC Converter



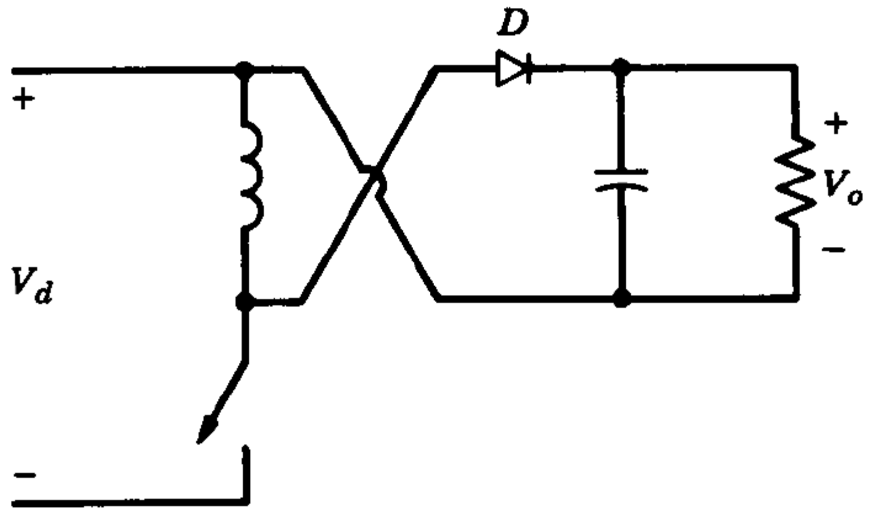
$$\frac{V_o}{V_d} = D\frac{1}{1-D}$$

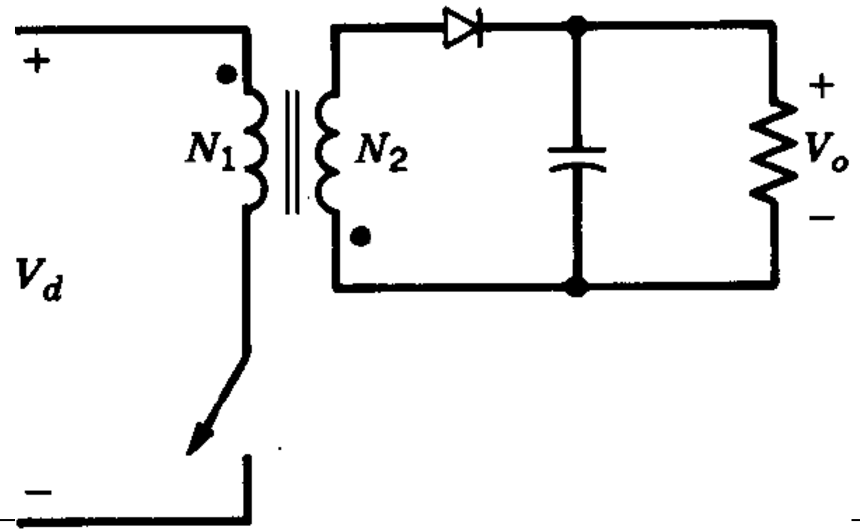
Figure 7-18 **Buck–boost converter.**

- Negative output voltage.
- The output voltage can be higher or lower than the input voltage.

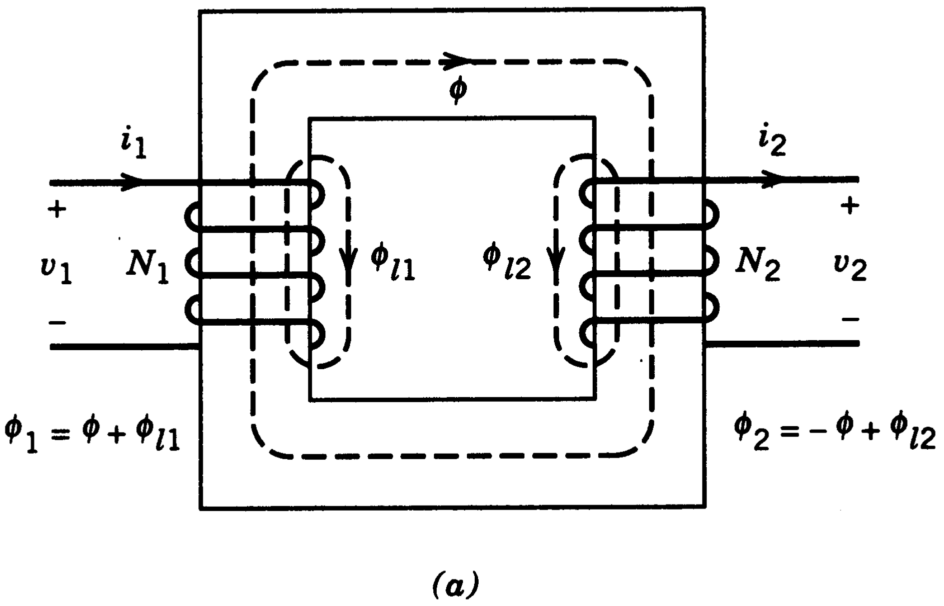
Flyback converter

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





Analysis of a Transformer



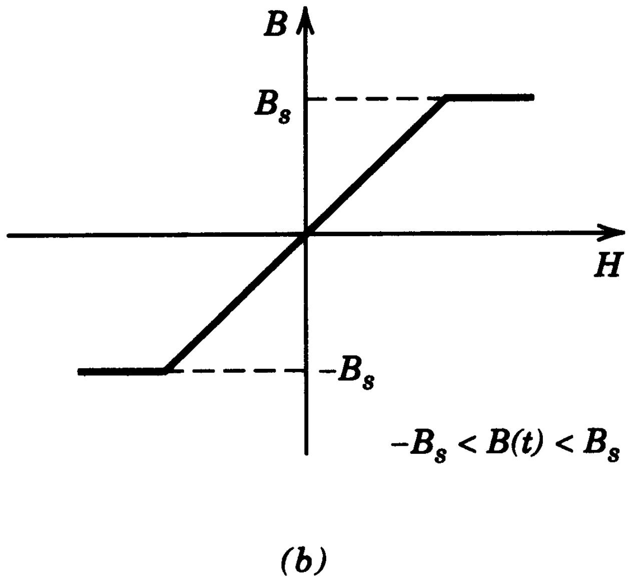


Figure 3-18 (*a*) Cross section of a transformer. (*b*) The *B–H* characteristics of the core.

Transformer Analysis

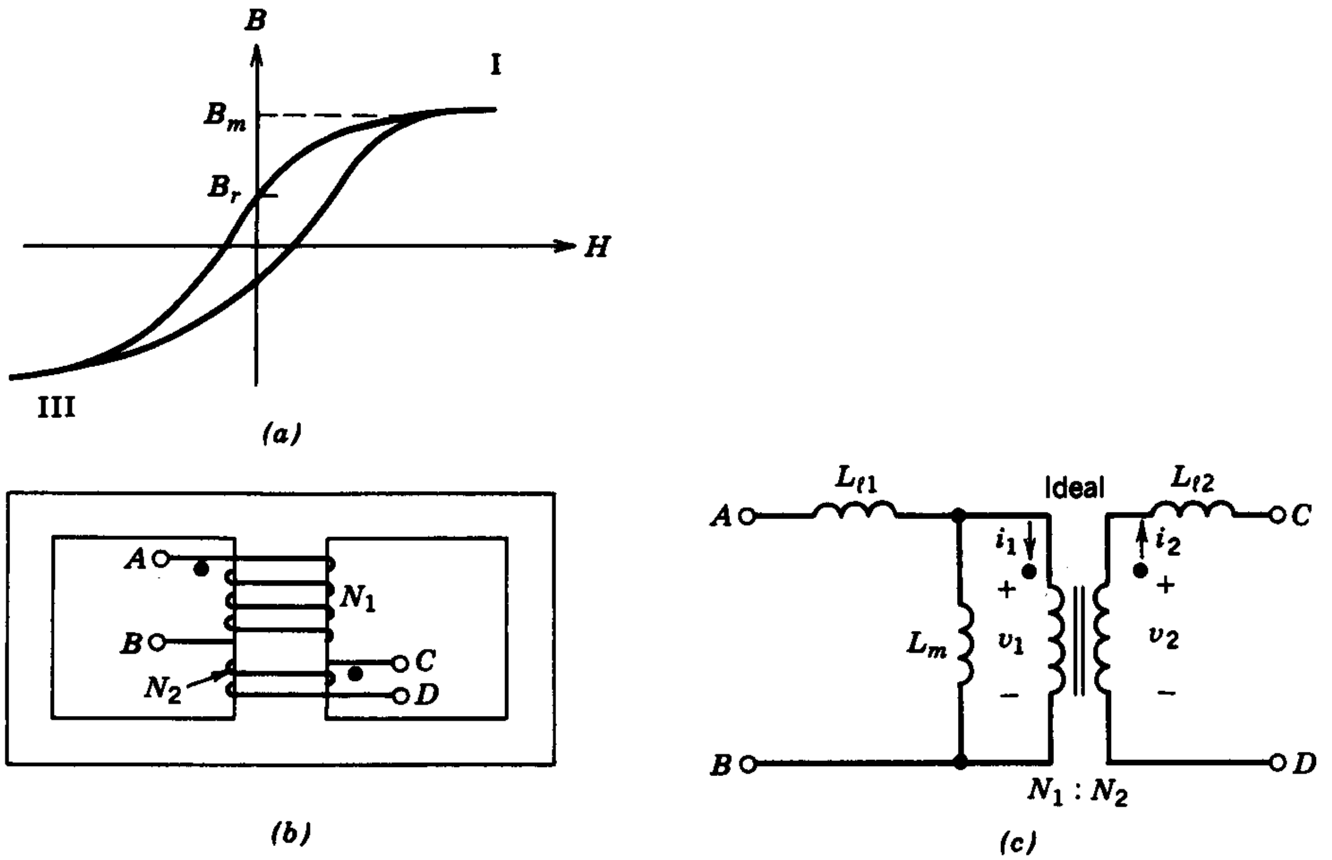
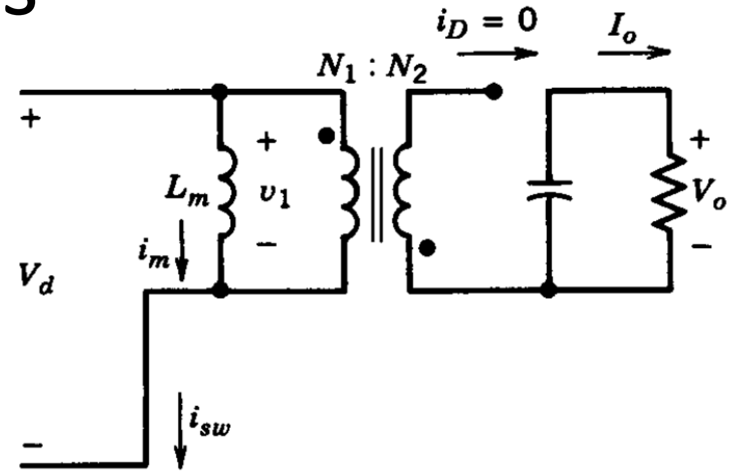
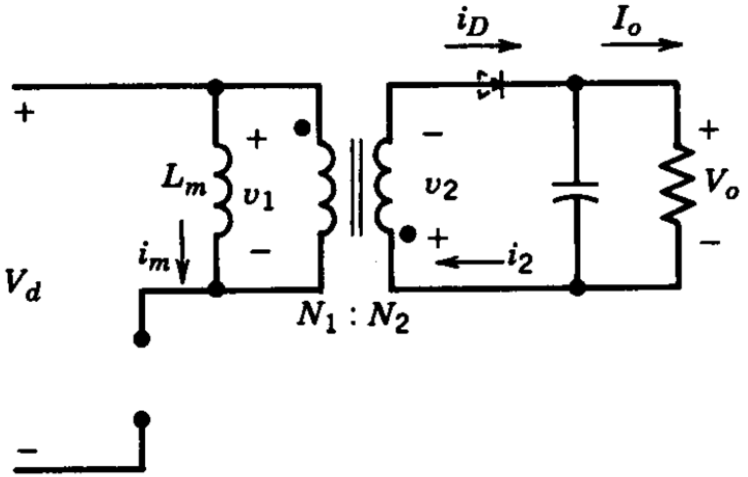


Figure 10-4 Transformer representation: (*a*) typical *B–H* loop of transformer core; (*b*) two-winding transformer; (*c*) equivalent circuit.

Flyback converter circuit states

- Switch on and switch off
- Continuous conduction mode
  - Incomplete demagnetization
- L_m size important
  - Ideal transformers have an infinite L_m



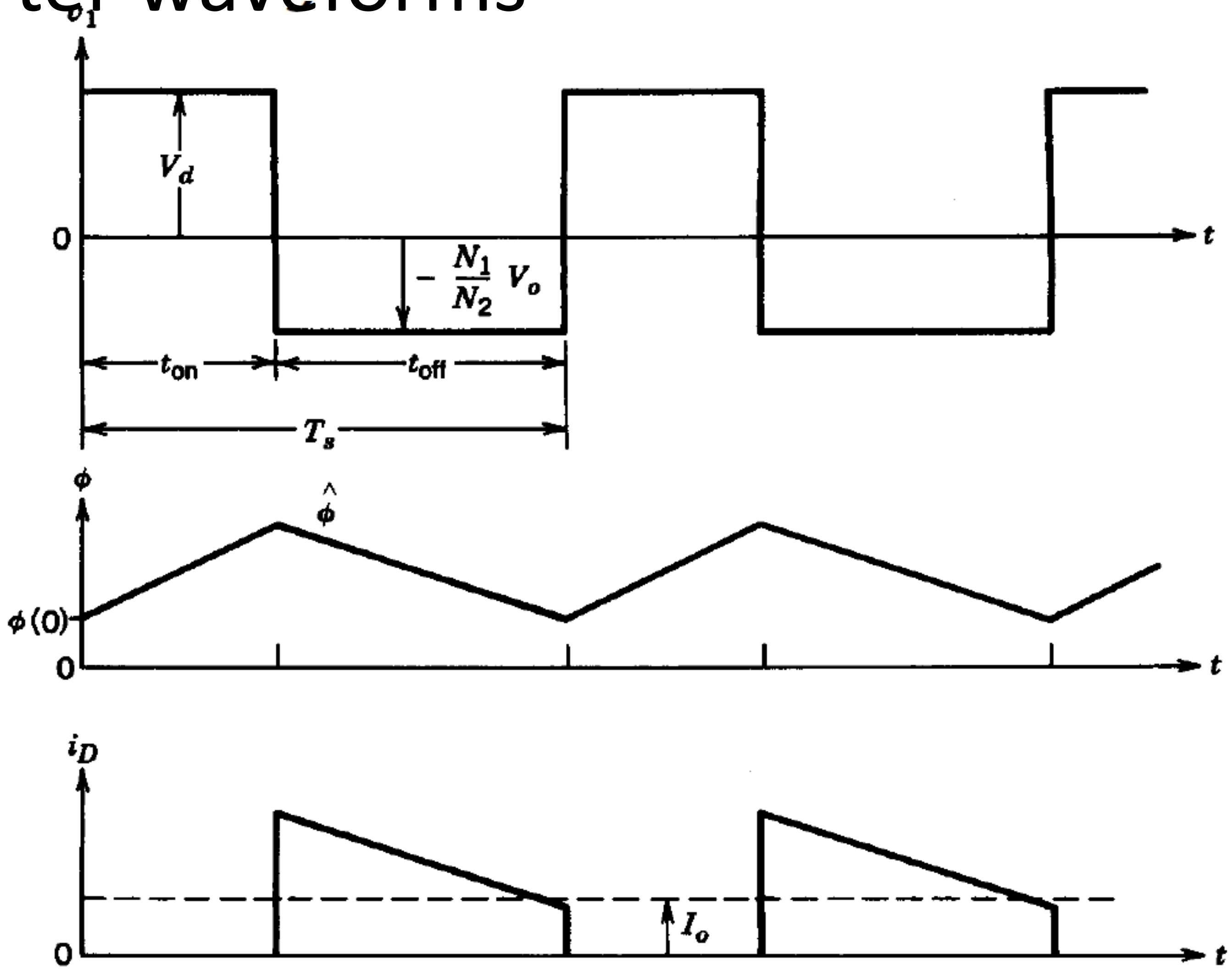


Flyback converter waveforms

- Same control equation as for a buck-boost converter but includes the turns ratio.

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

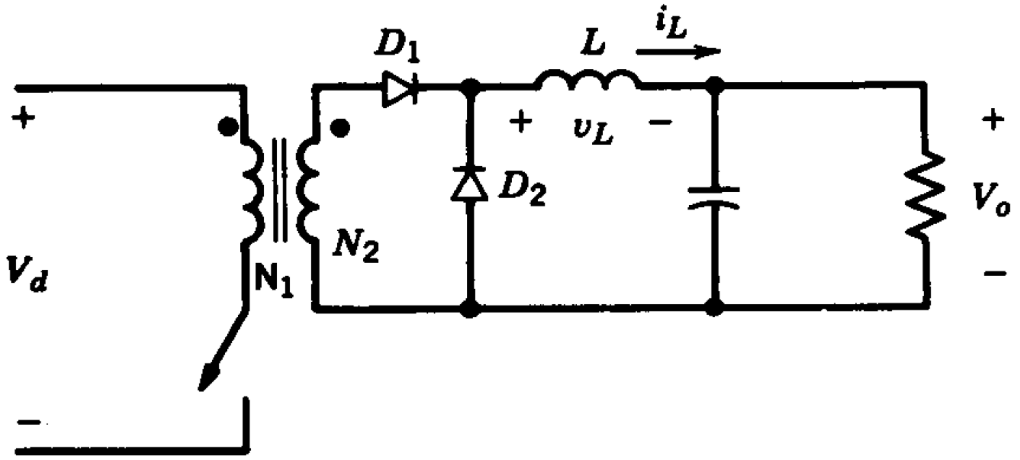
$$\frac{V_o}{V_d} = \frac{N_2}{N_1}\frac{D}{1-D}$$



Forward converter

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

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

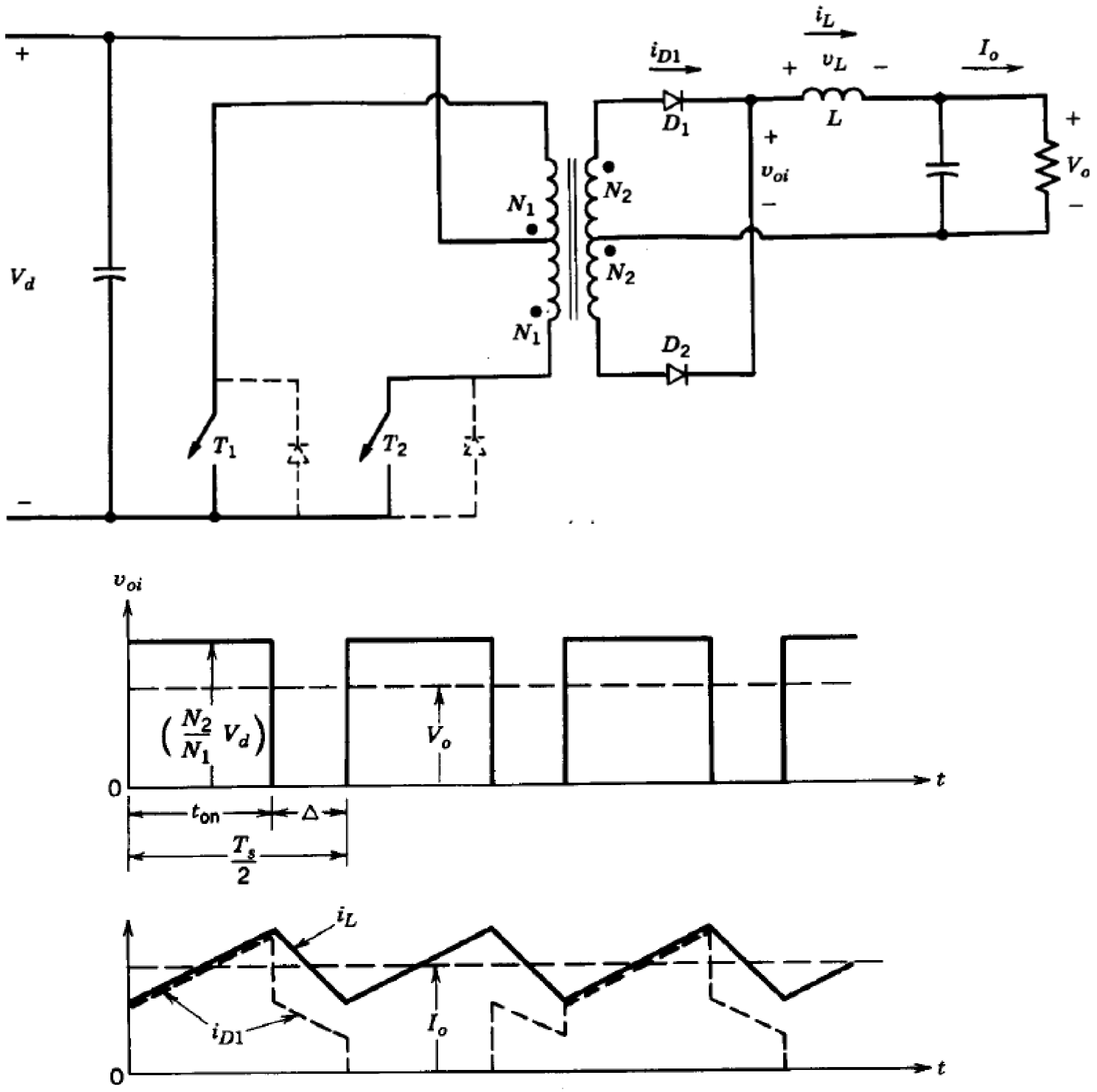


Push-pull converter

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

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

$$0 < D < 0.5$$



www.liu.se