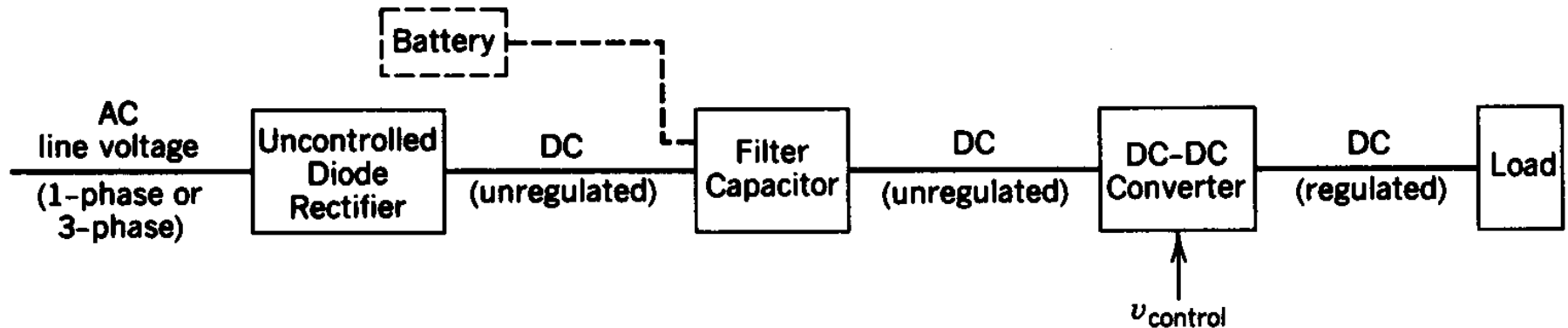# **Power Electronics**
5. DC-DC Converters

Dr inż. Dariusz Janiszewski

Plan wykładu

- Wprowadzenie do przetwarzania DC-DC
- Idea PWM
- Step-down Converter – Buck
- Step-up Converter – Boost
- Buck-Boost Converter
- Cuk Converter
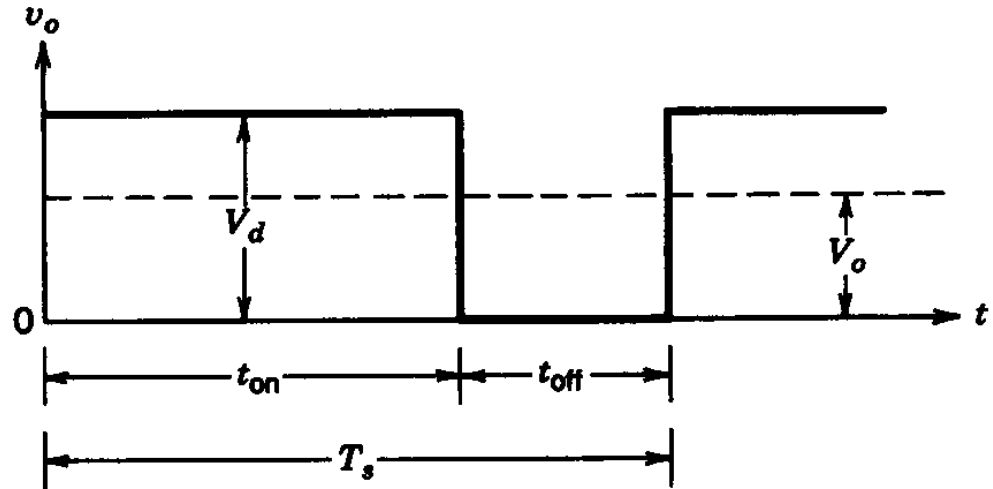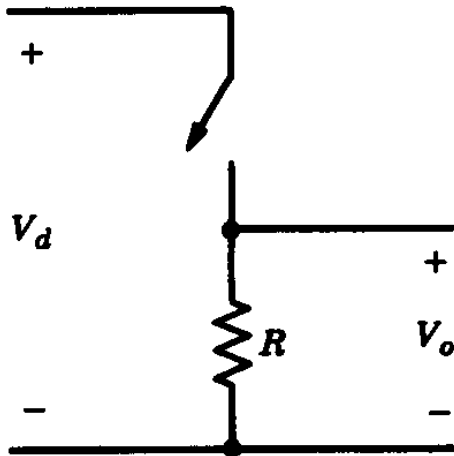- SEPIC Converter
- ZETA Converter

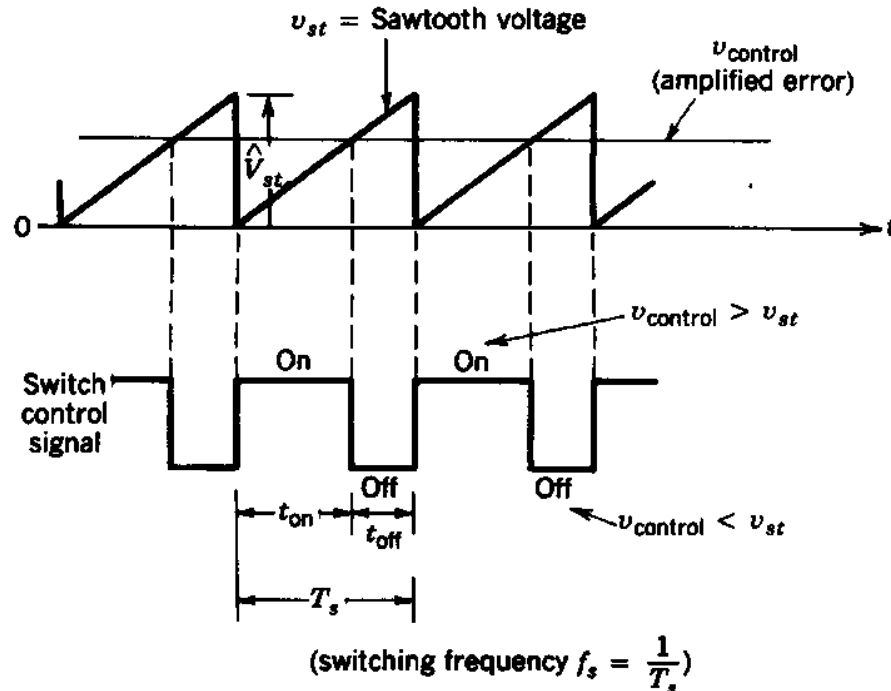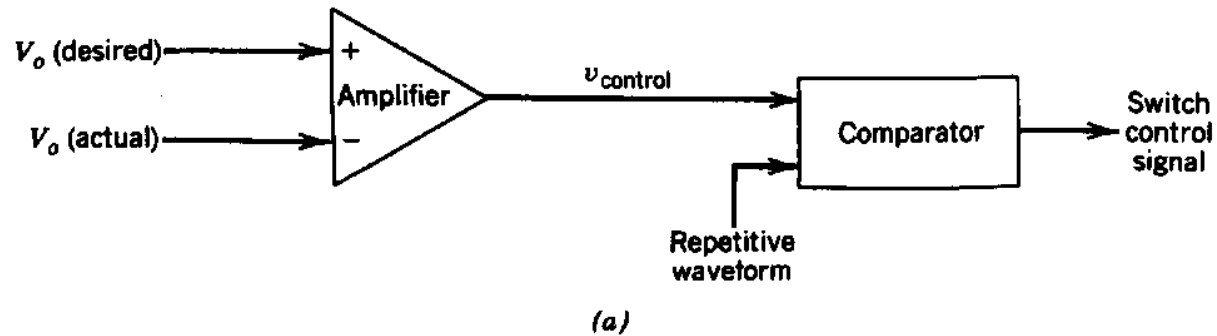# Block Diagram of DC-DC Converters

▸ Functional block diagram

Stepping Down a DC Voltage – Idea

▸ A simple approach that shows the evolution

# Pulse-Width Modulation in DC-DC Converters

V_o (desired) → + Amplifier
V_o (actual) → −

$v_{control}$ → Comparator → Switch control signal

Repetitive waveform

(a)

v_{st} = Sawtooth voltage

$v_{control}$ (amplified error)

$\hat{V}_{st}$

0 → t

$v_{control} > v_{st}$

Switch control signal — On — On

Off — Off

$v_{control} < v_{st}$

t_{on} — t_{off}

T_s

(switching frequency $f_s = \frac{1}{T_s}$)

Step-Down DC-DC Converter – buck converter
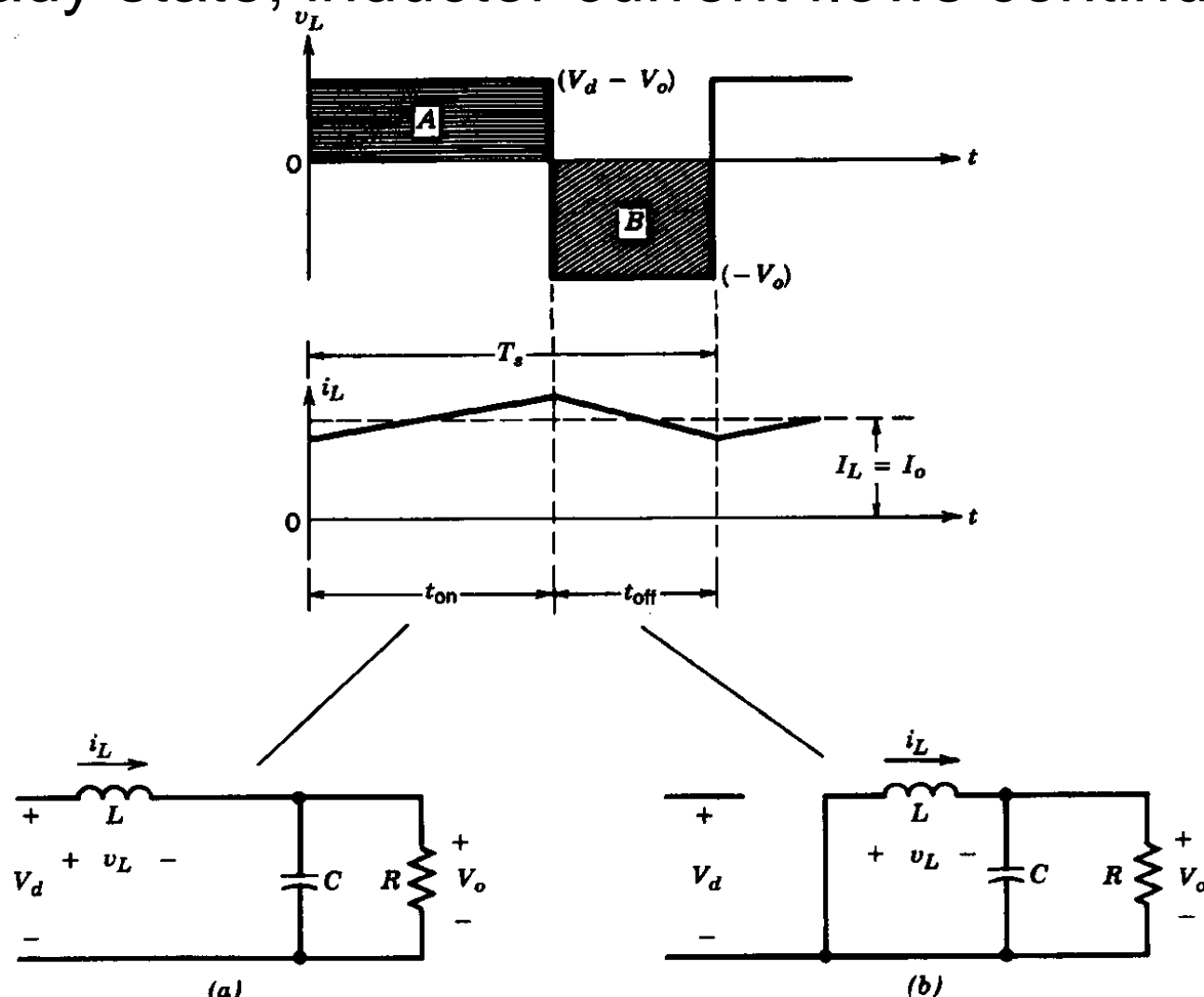
▶ Pulsating input to the low-pass filter
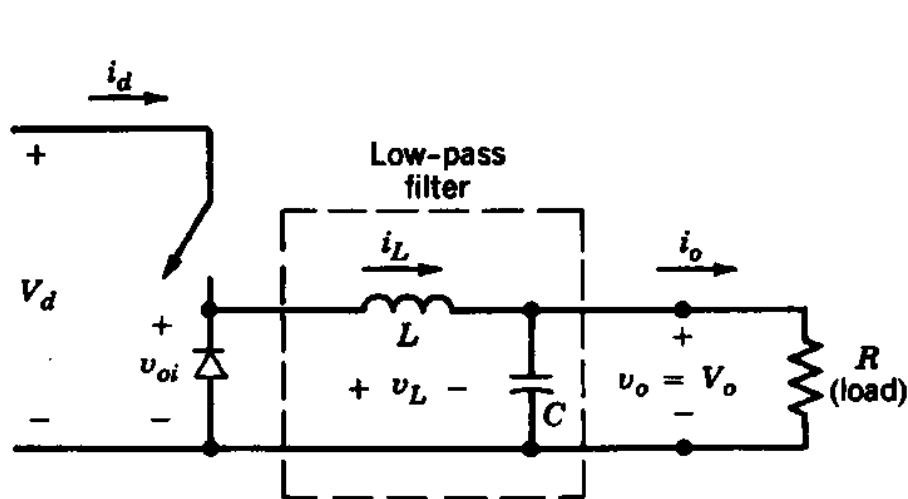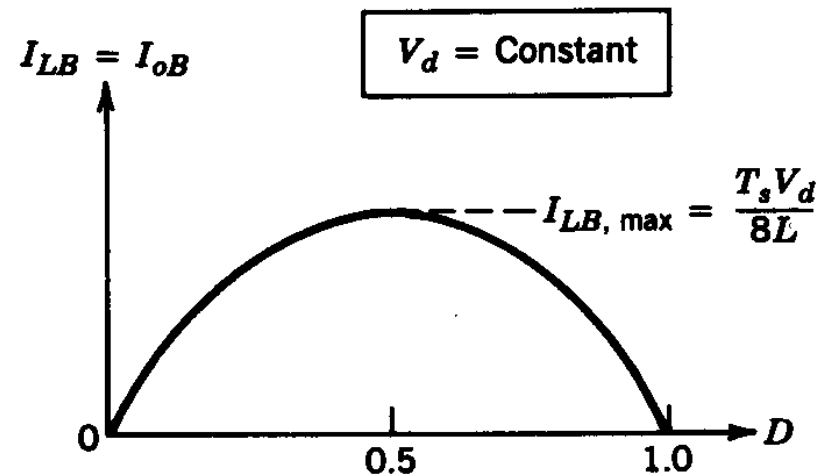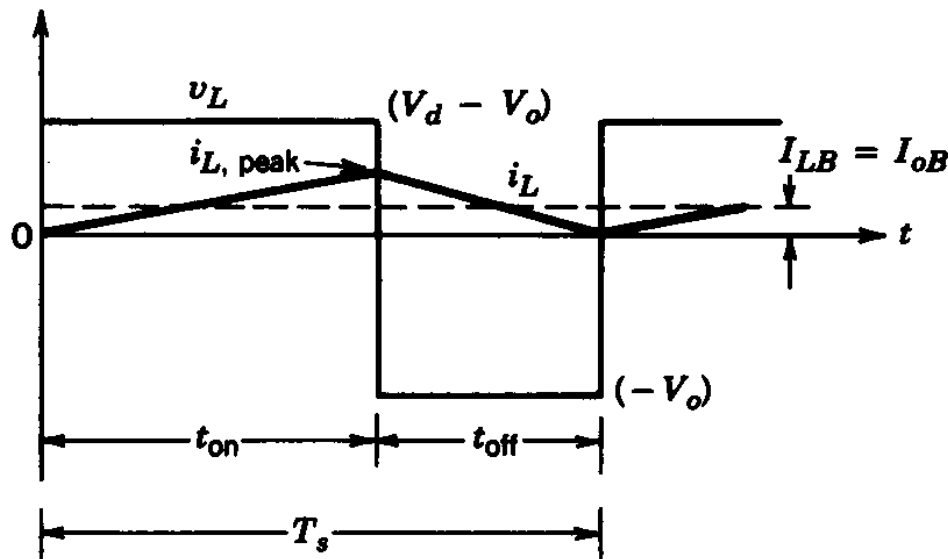

$$\frac{V_o}{V_d} = D$$

$$D = \frac{t_{on}}{T_S}$$
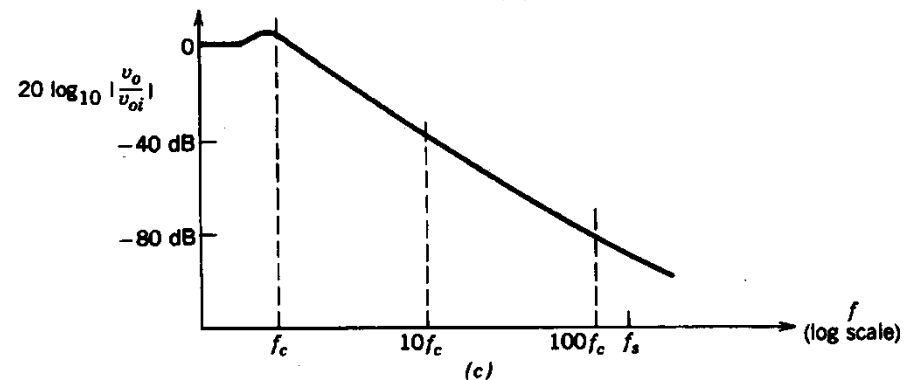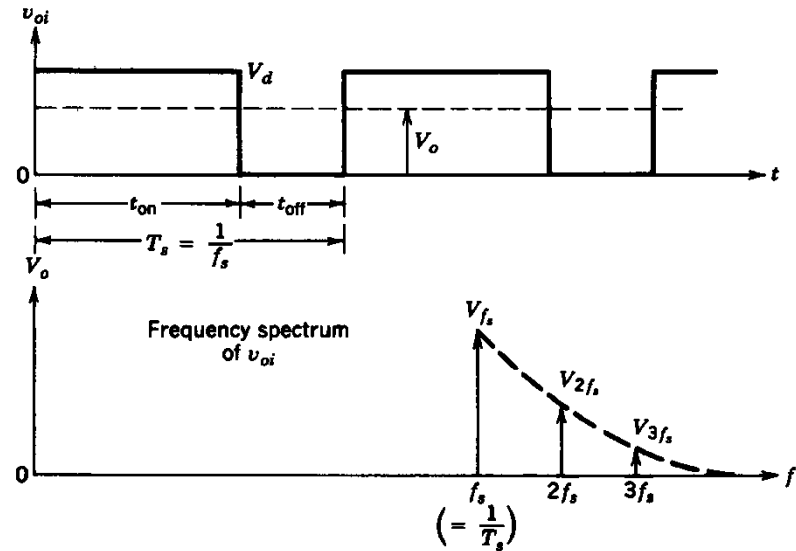
Step-Down DC-DC Converter Waveforms

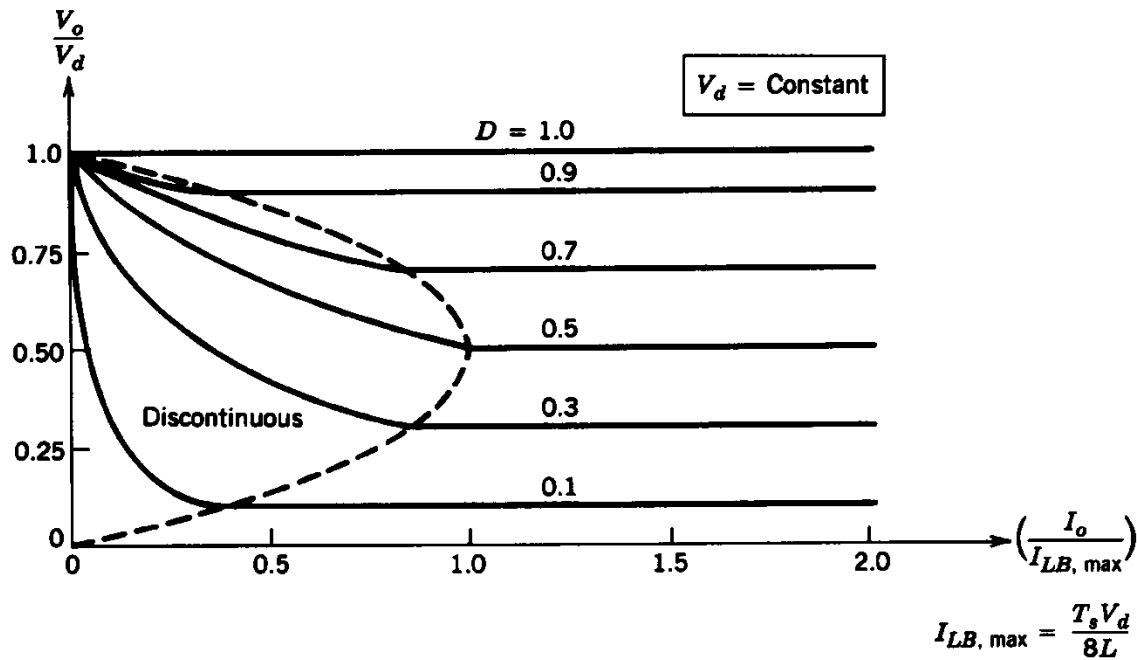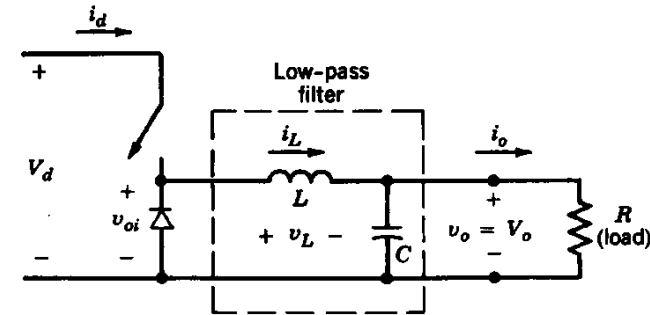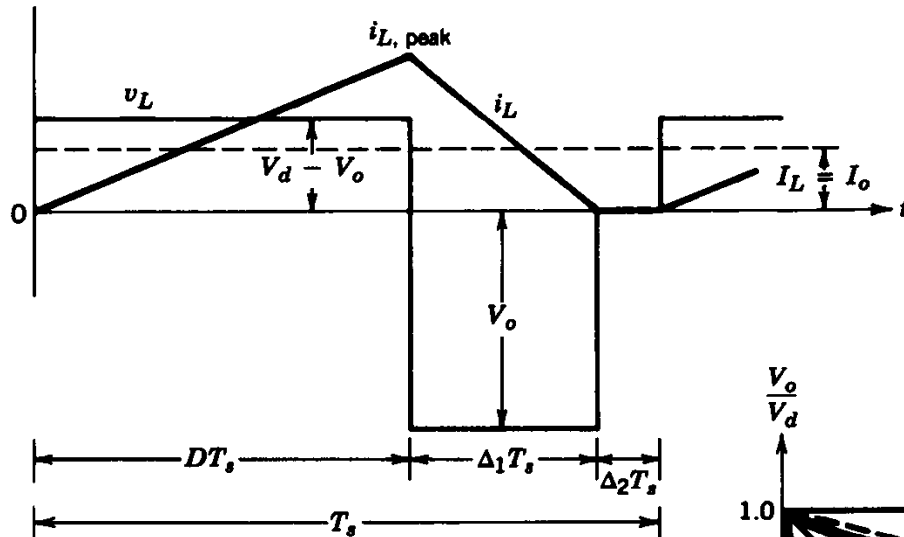▸ Steady state; inductor current flows continuously

Step-Down DC-DC Converter: Waveforms at the boundary of Cont./Discont. Conduction

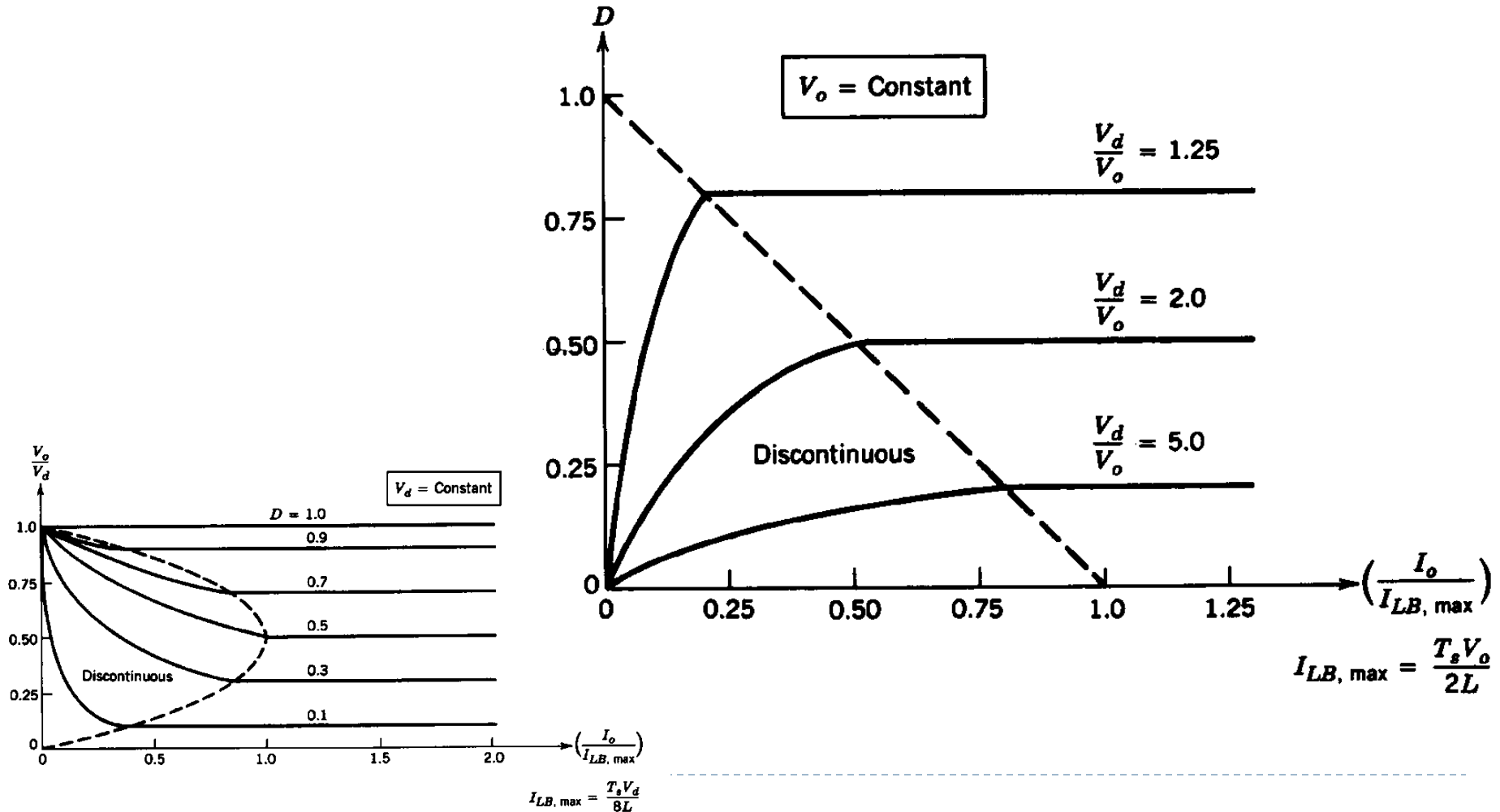- ▸ Critical current below which inductor current becomes discontinuous

Step-Down DC-DC Converter: Discontinuous Conduction Mode
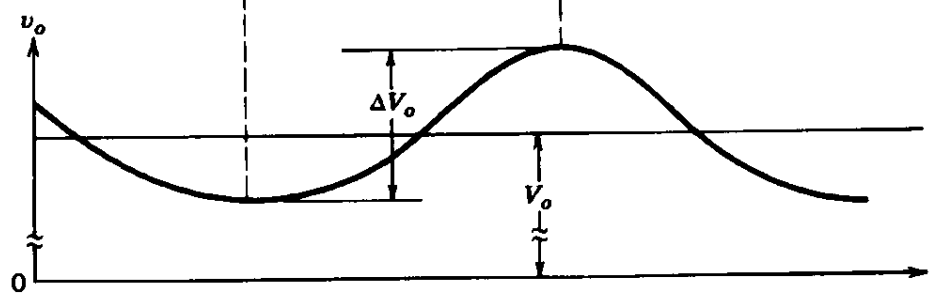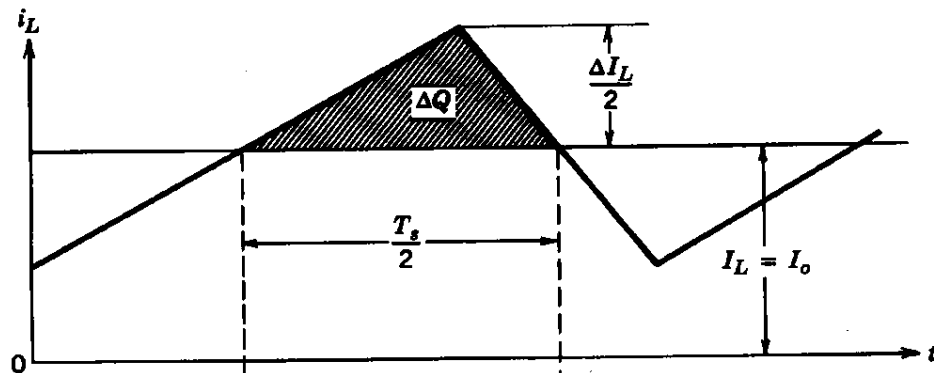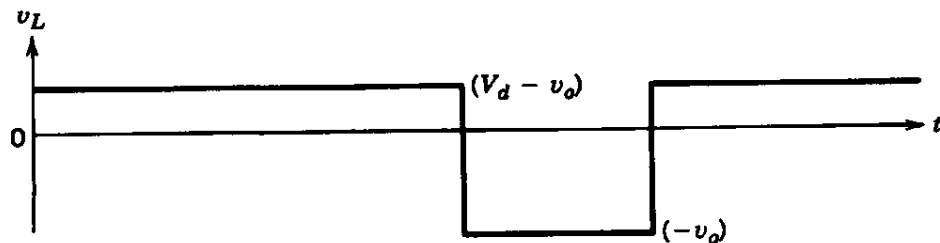
▸ Steady state; inductor current discontinuous

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

Step-Down DC-DC Converter: Limits of Cont./Discont. Conduction

▸ Output voltage is kept constant

$$I_{LB, \, max} = \frac{T_s V_o}{2L}$$

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

Step-Down Conv.: Output Voltage Ripple

▸ ESR is assumed to be zero
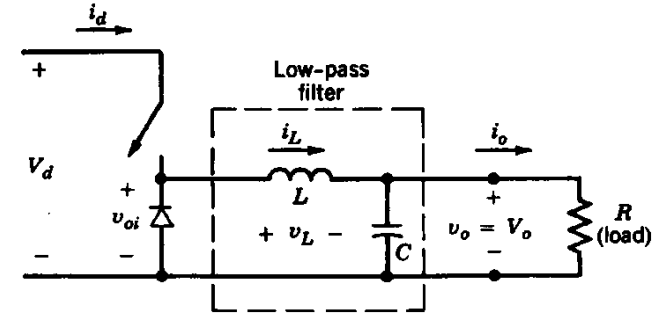
Step-Up DC-DC Converter – Boost Converter

▶ Output voltage must be greater than the input
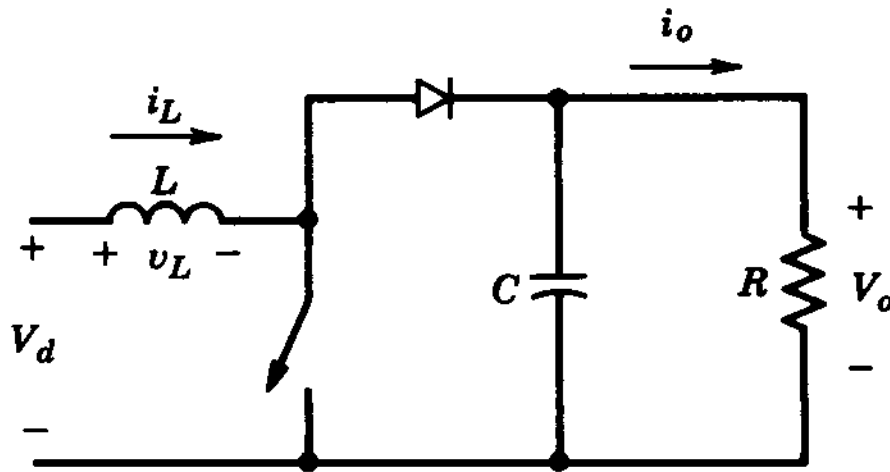
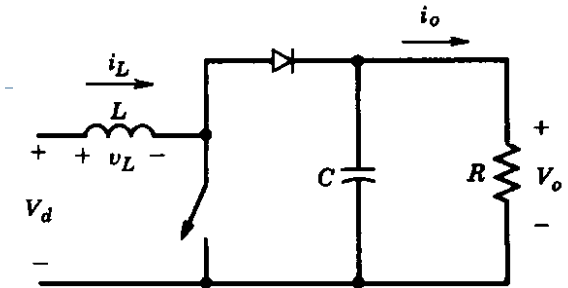$$D = \frac{t_{on}}{T_S}$$

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

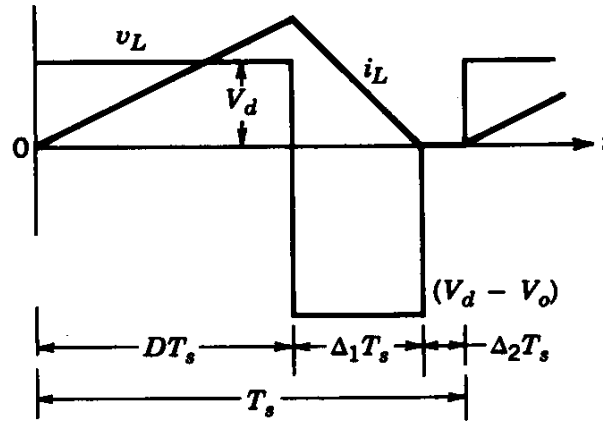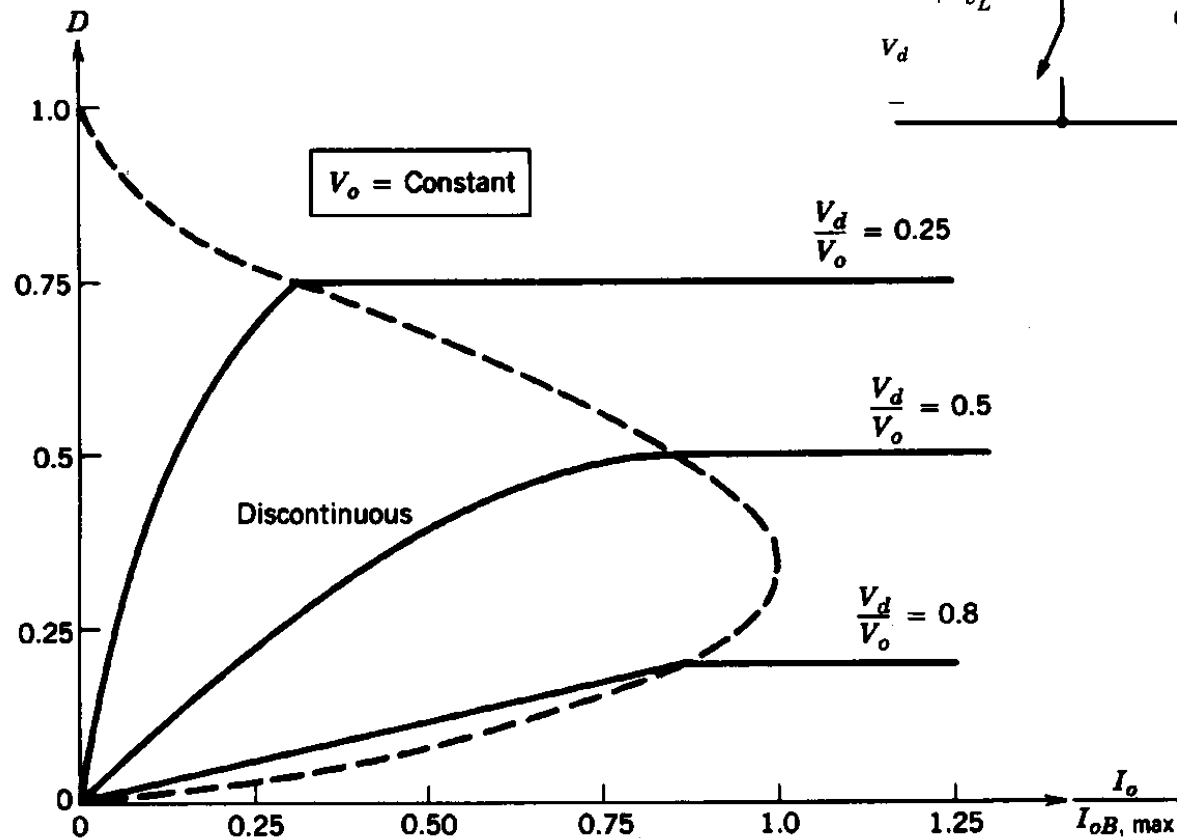# Step-Up DC-DC Converter Waveforms
Continuous current conduction mode
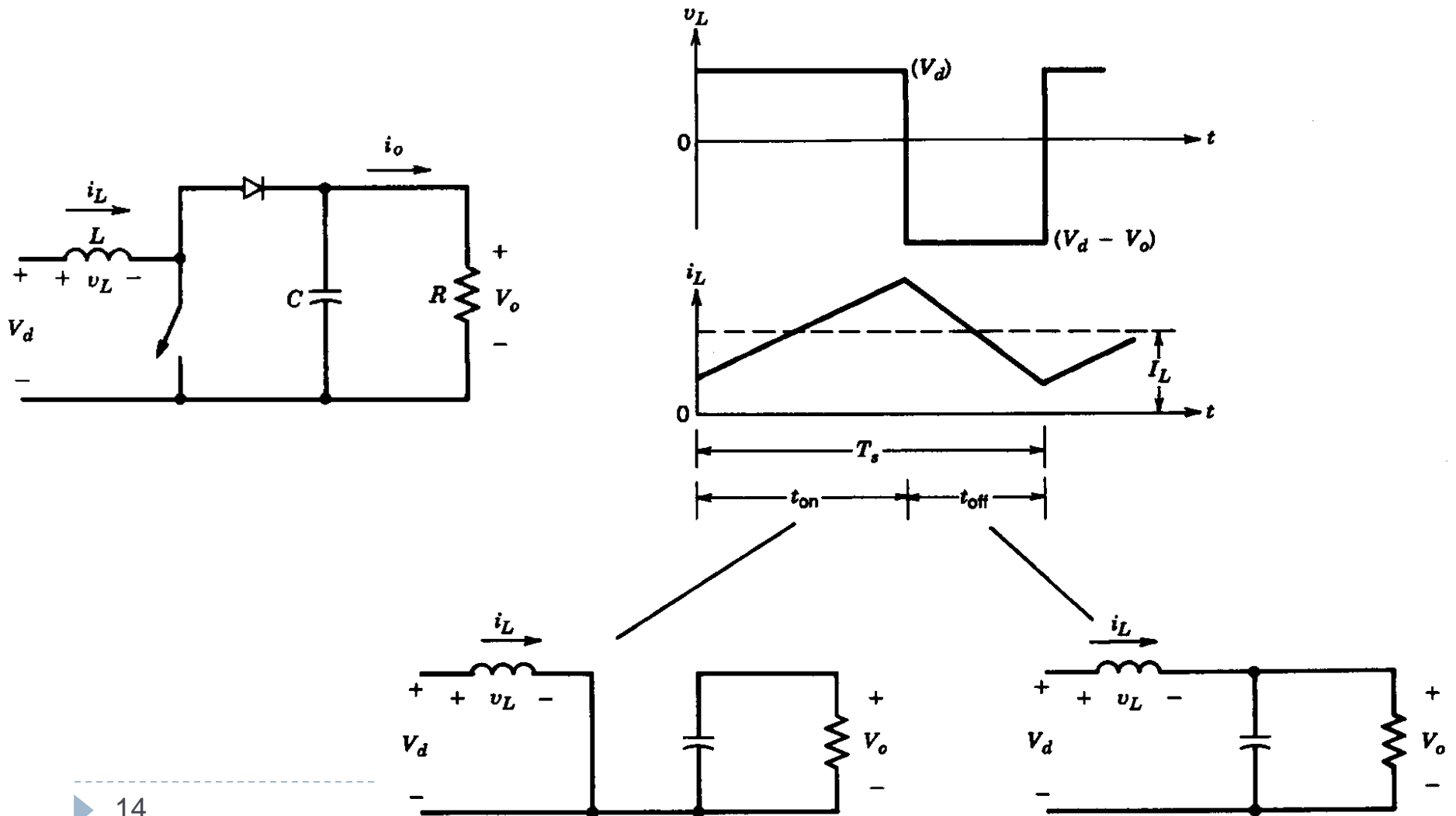
Step-Up DC-DC Converter: Limits of Cont./Discont. Conduction
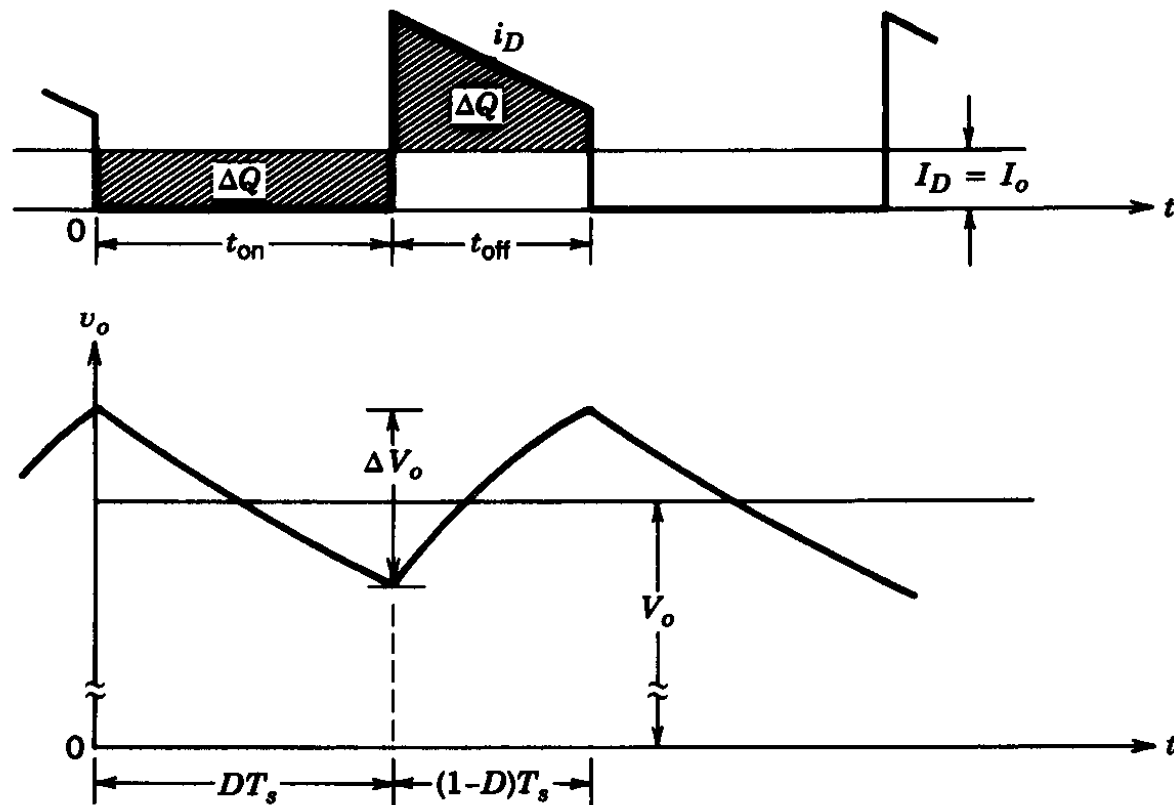
▸ The output voltage is held constant
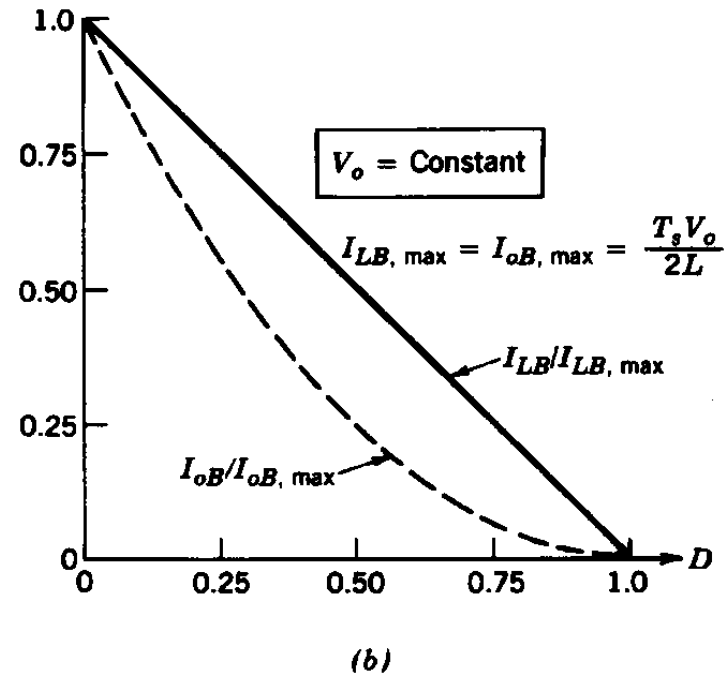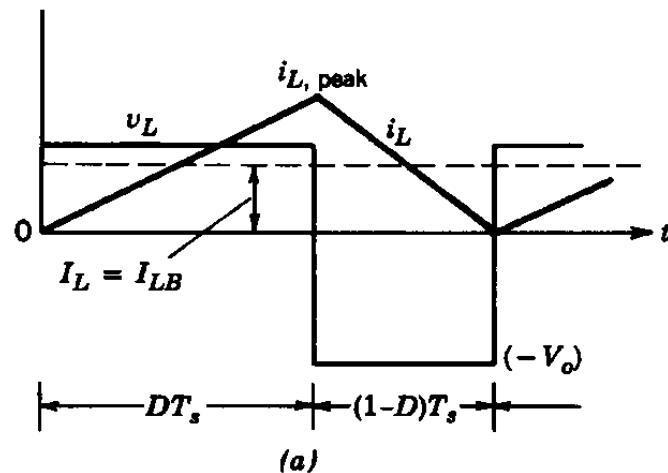

$V_o = $ Constant

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

$$|I_{oB, max} = \frac{0.074\ T_s V_o}{L}$$
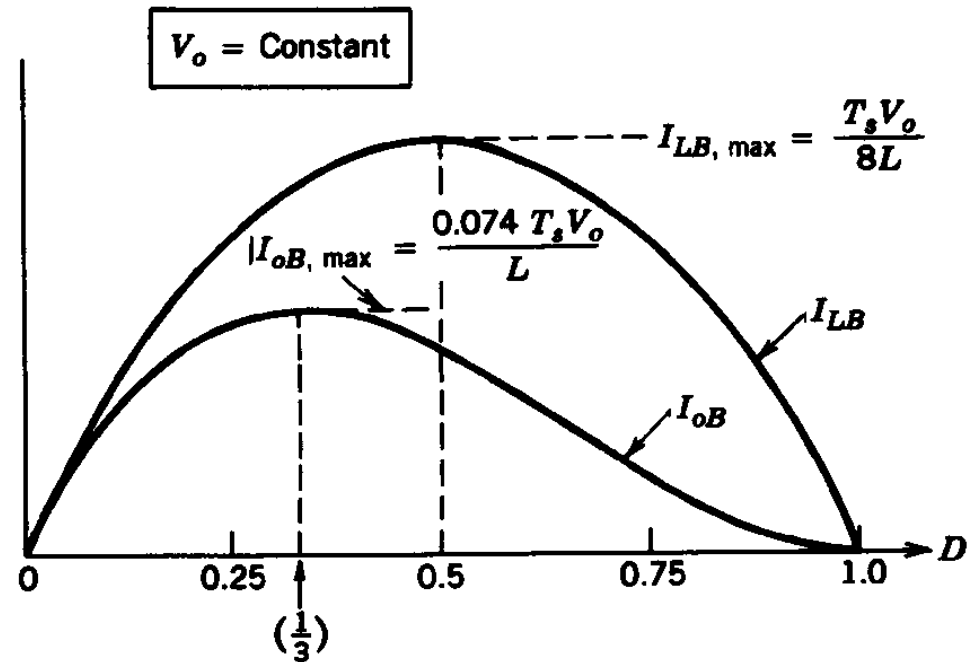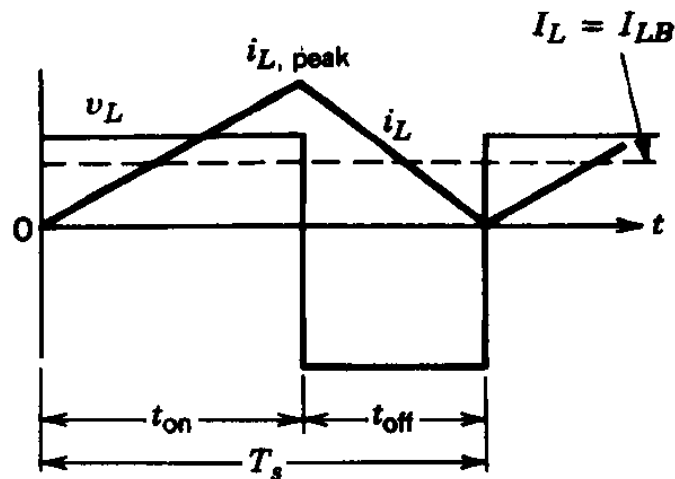
Step-Up DC-DC Converter: Discont. Conduction Mode

‣ Occurs at light loads
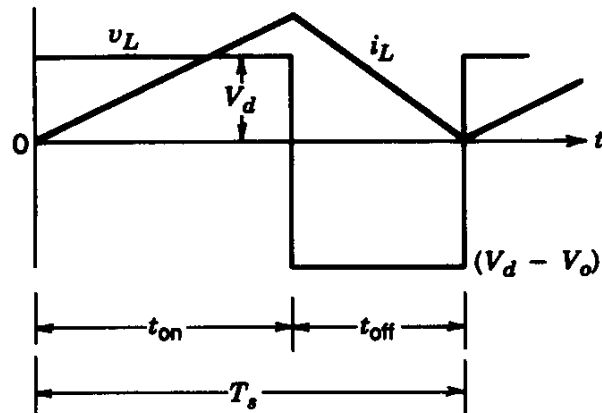
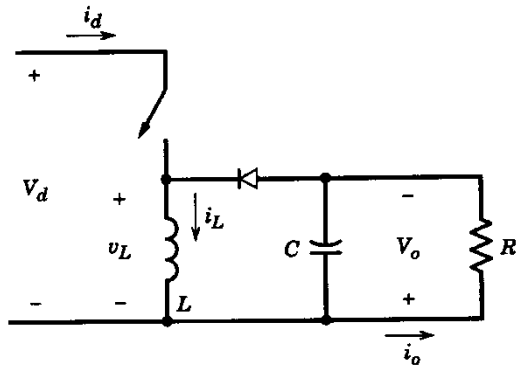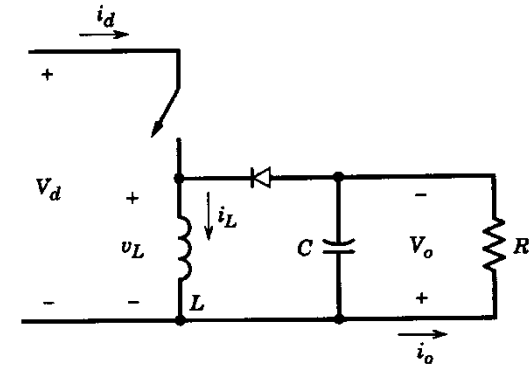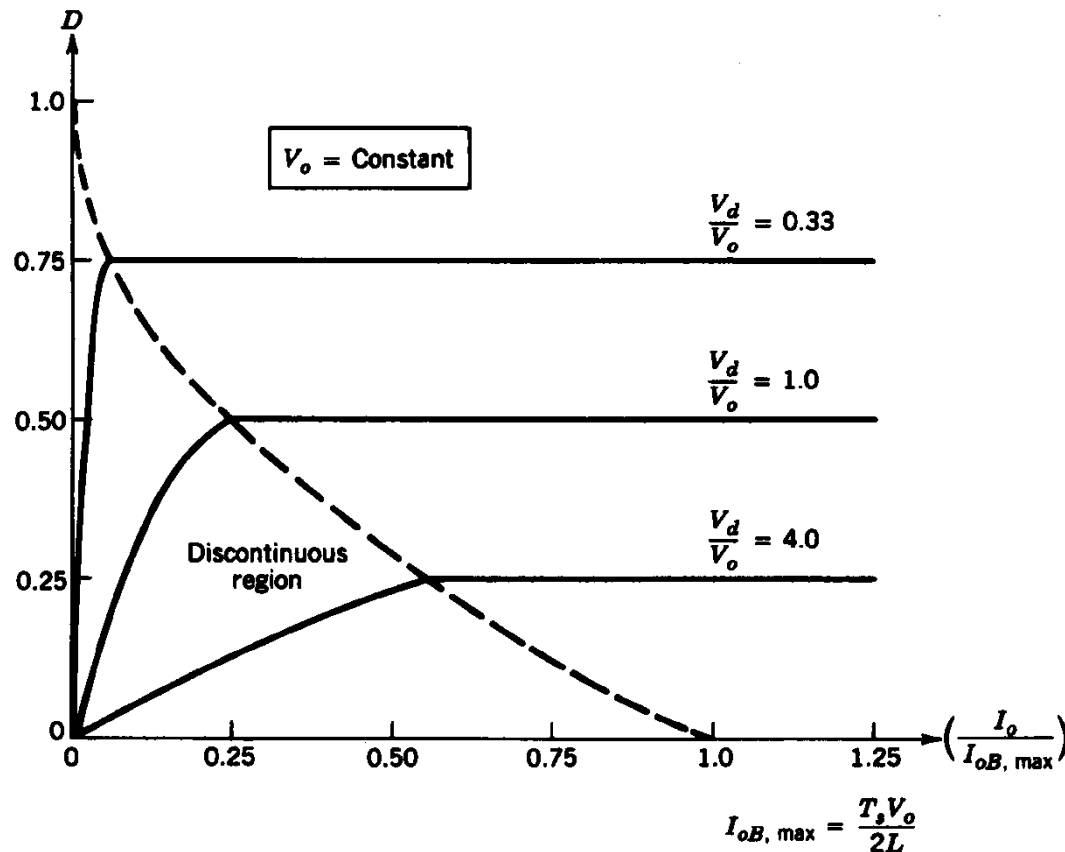# Step-Up DC-DC Converter:
Limits of Cont./Discont. Conduction

▸ The output voltage is held constant

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

$$I_{oB, \text{ max}} = 0.074 \frac{T_s V_{o.}}{L}$$
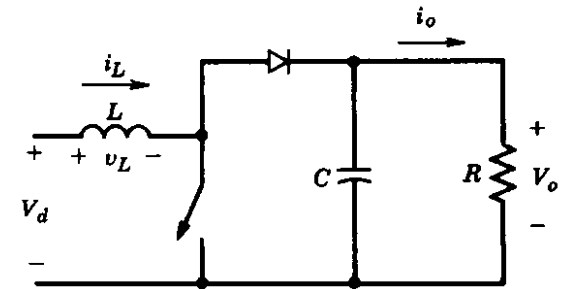
Step-Up DC-DC Converter Output Ripple

- ESR is assumed to be zero
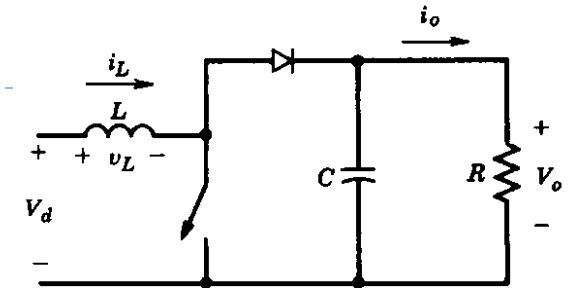
Step-Up DC-DC Converter: Effect of Parasitics

▸ The duty-ratio is generally limited before the parasitic effects become significant
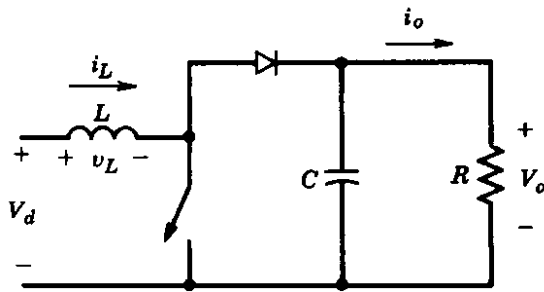
$$\frac{V_o}{V_d} = \frac{1}{1-D}$$
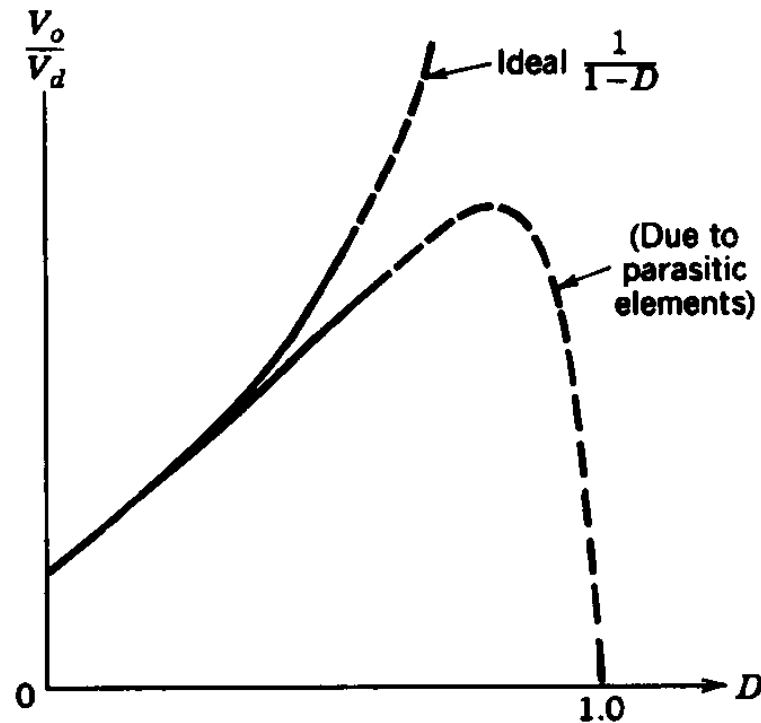
Step-Down/Up DC-DC Converter Buck-boost Converter

▸ The output voltage can be higher or lower than the input voltage
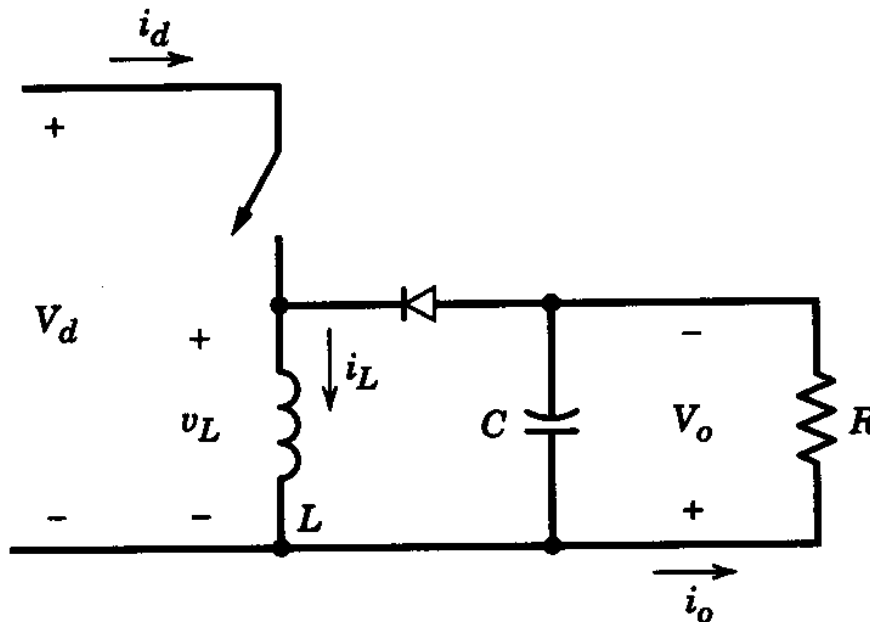
$$\frac{V_o}{V_d} = D\,\frac{1}{1-D}$$

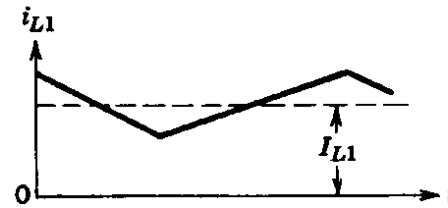# Step-Down/Up DC-DC Converter Waveforms

▸ Continuation conduction mode
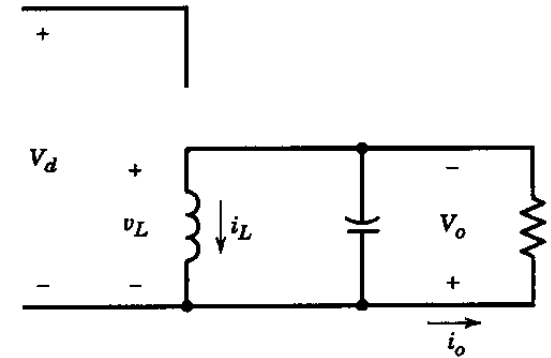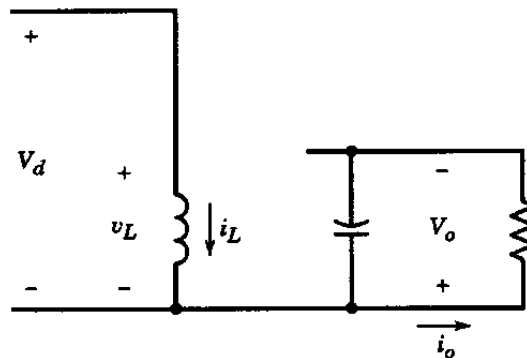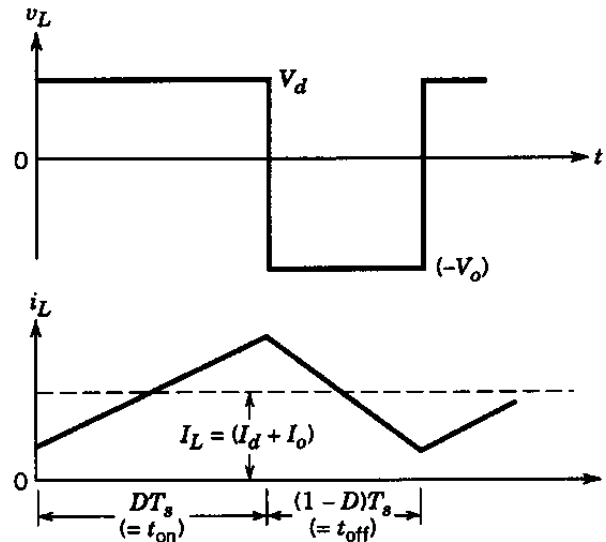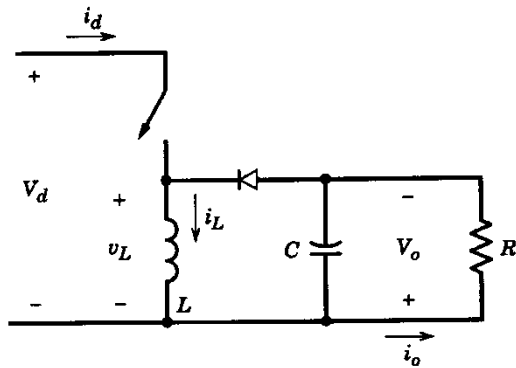
Step-Down/Up DC-DC Converter Limits of Cont./Discont. Conduction

▸ The output voltage is held constant

(a)
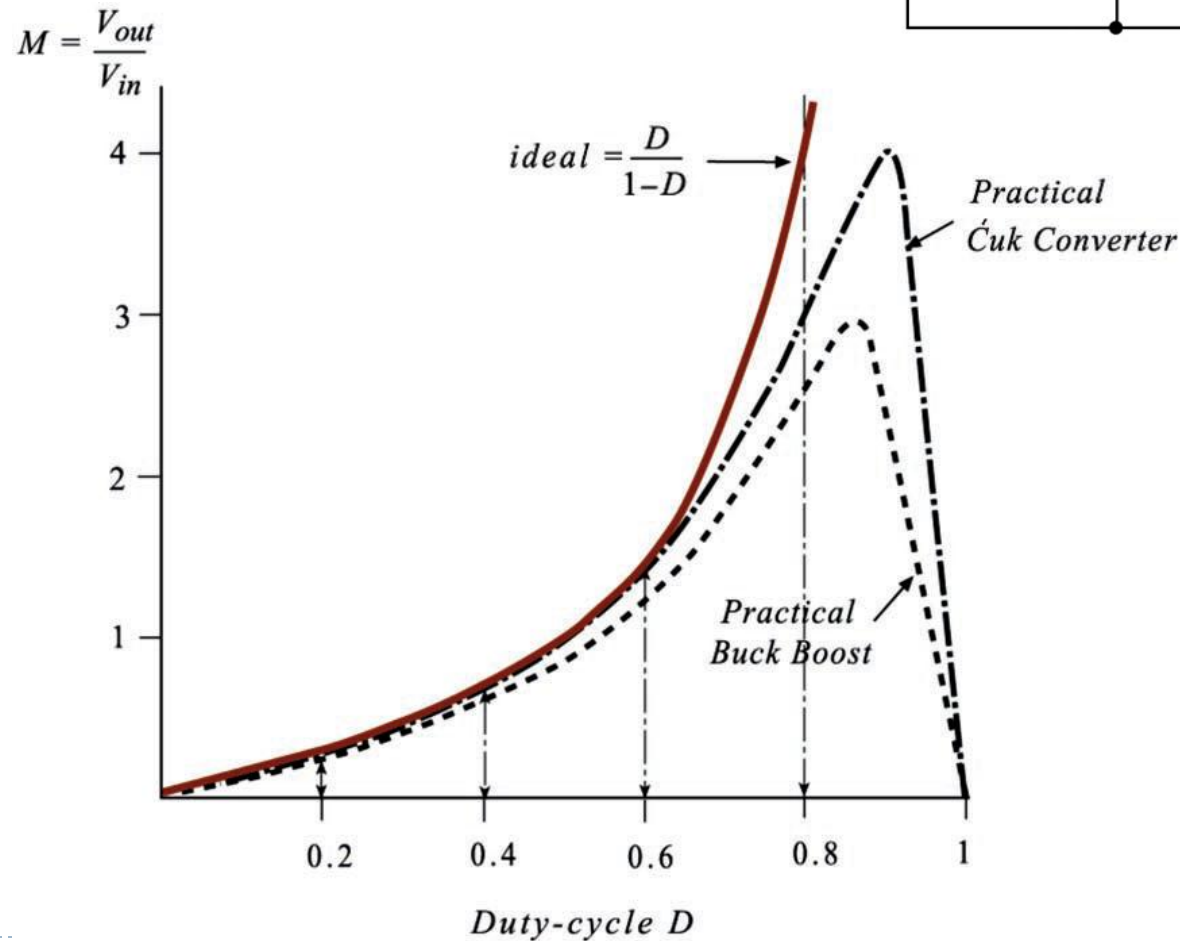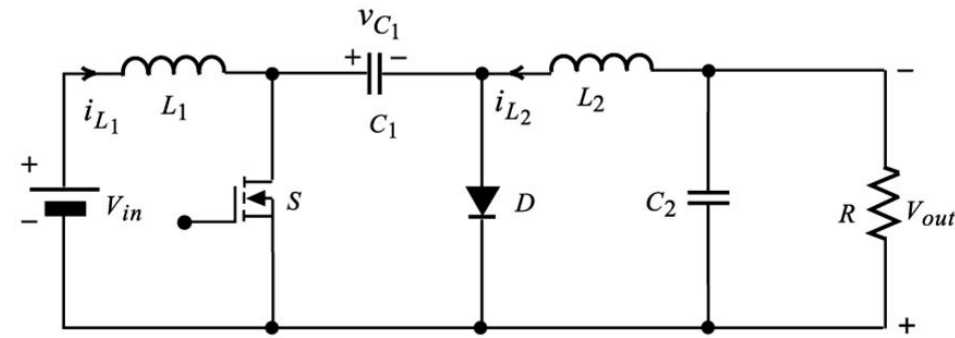
(b)

$V_o = $ Constant

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

Step-Down/Up DC-DC Converter: Discontinuous Conduction Mode

▸ This occurs at light loads
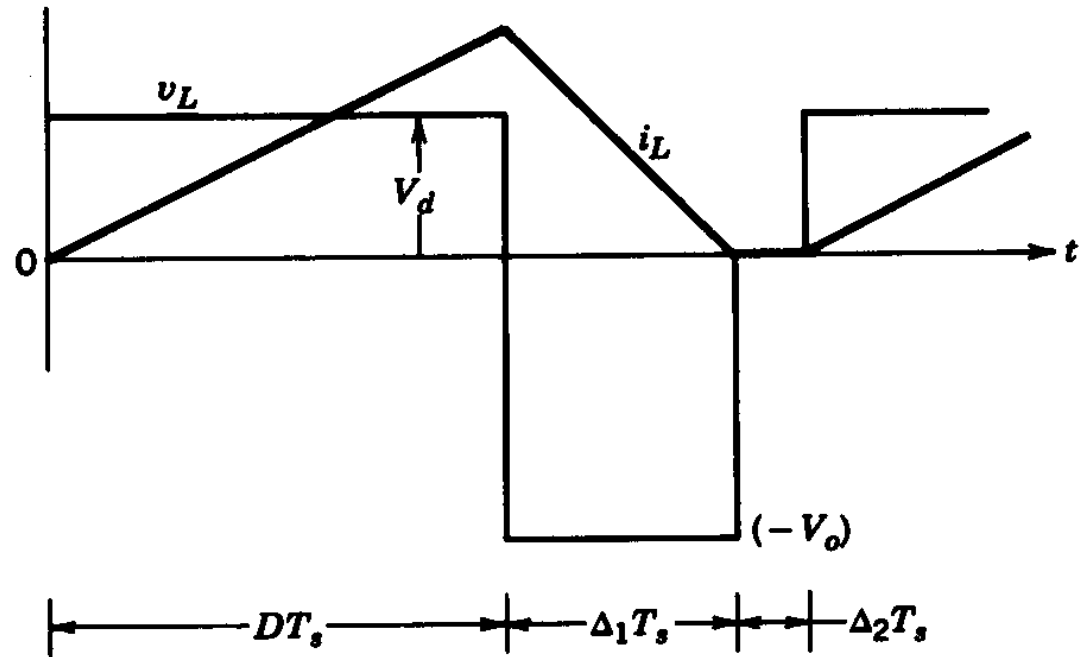
Step-Up DC-DC Converter
Limits of Cont./Discont. Conduction

▸ The output voltage is held constant

V_o = Constant

$\frac{V_d}{V_o}$ = 0.33

$\frac{V_d}{V_o}$ = 1.0

$\frac{V_d}{V_o}$ = 4.0

Discontinuous region

$\left(\frac{I_o}{I_{oB,\ max}}\right)$

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

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

Step-Up DC-DC Converter Output Voltage Ripple

‣ ESR is assumed to be zero
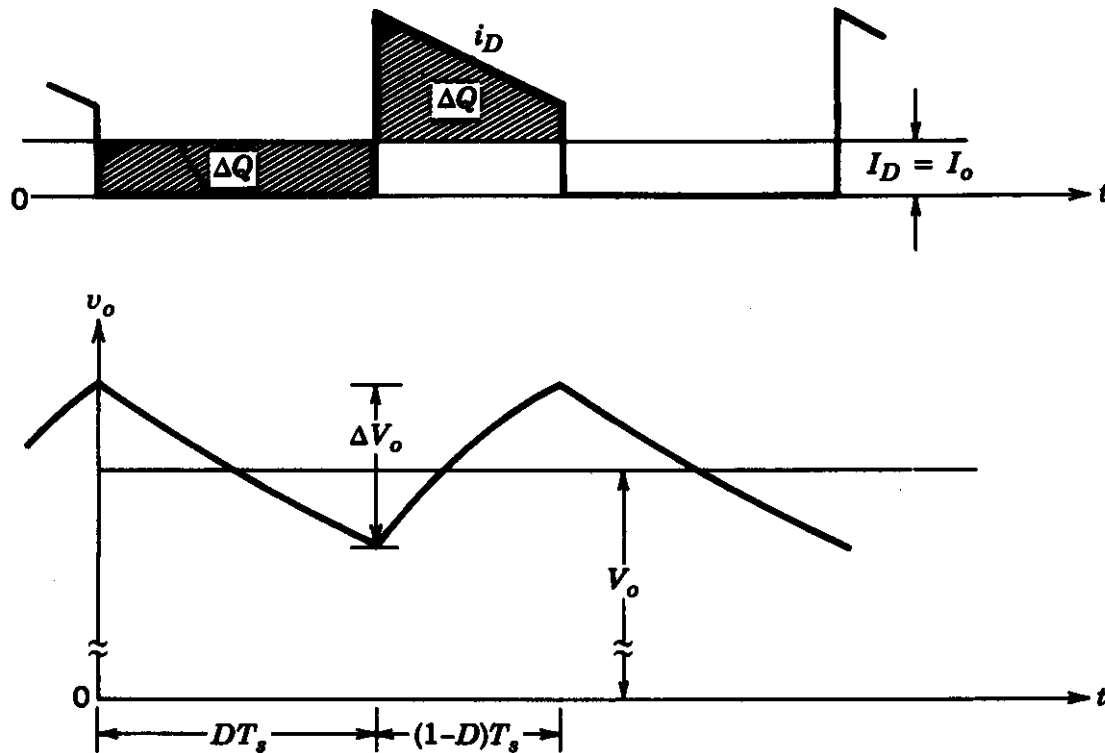
Cuk DC-DC Converter

▸ The output voltage can be higher or lower than the input voltage

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

(d)
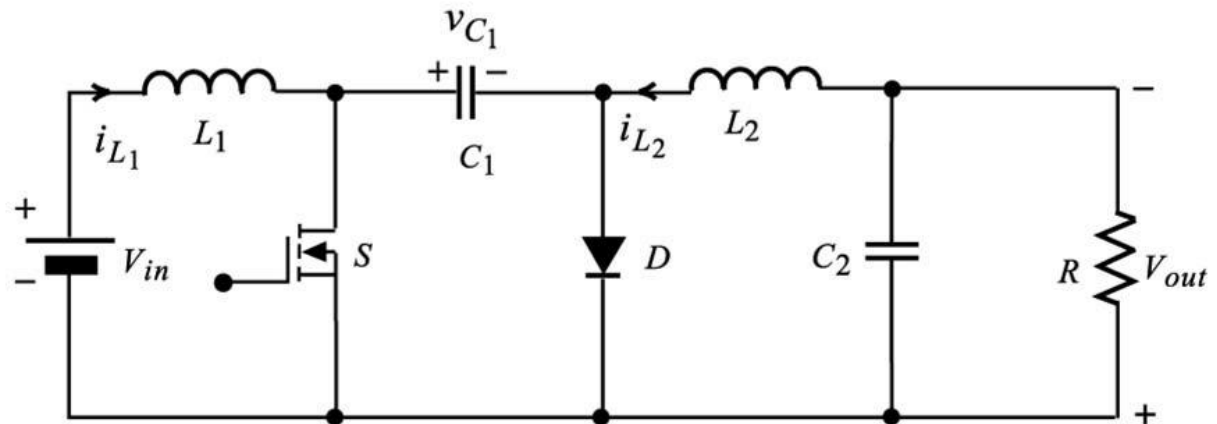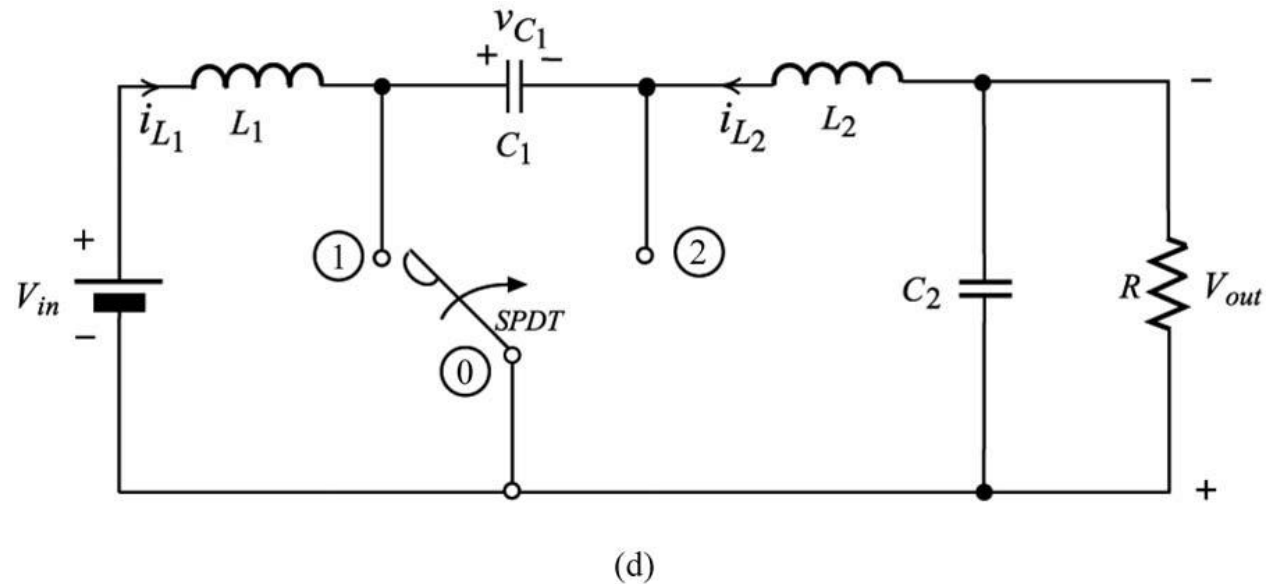
Cuk DC-DC Converter Waveforms

▶ The capacitor voltage is assumed constant

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

Cuk DC-DC Converter Discontinuous Conduct[ion]

(a)

(b)

(c)

v_{GS}

DT_S $(D + D_2) T_S$ T_S t

i_{L_1}

i_{L_2}

i_{L_1}

i_{L_2}

i_{L_1}

i_{L_2}

I

I

t

$i_{L_1} + i_{L_2}$

slope $\sim (\frac{1}{L_1} + \frac{1}{L_2})$

slope $\sim (\frac{1}{L_1} + \frac{1}{L_2})$

DT_S $D_2 T_S$ t

$(1 - D - D_2) T_S$
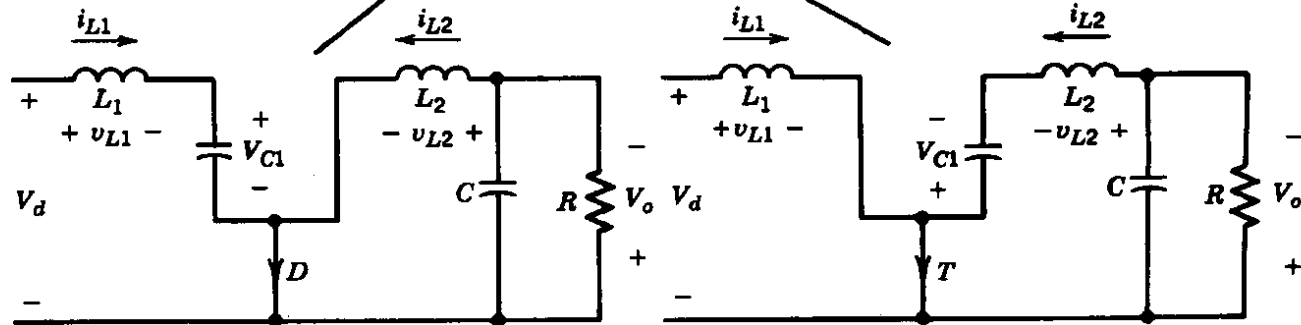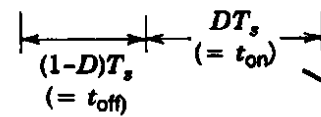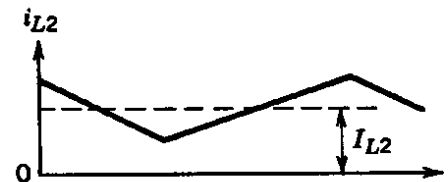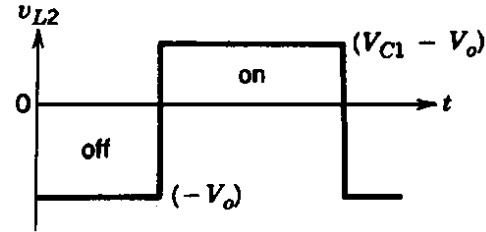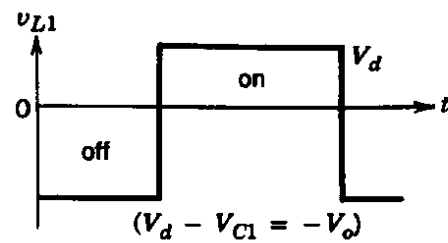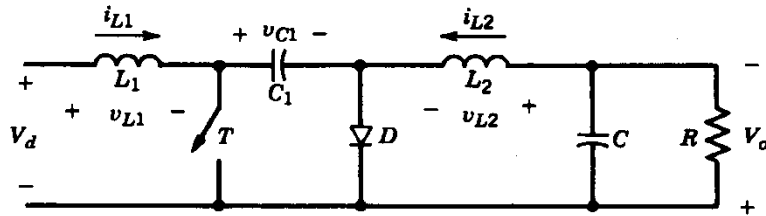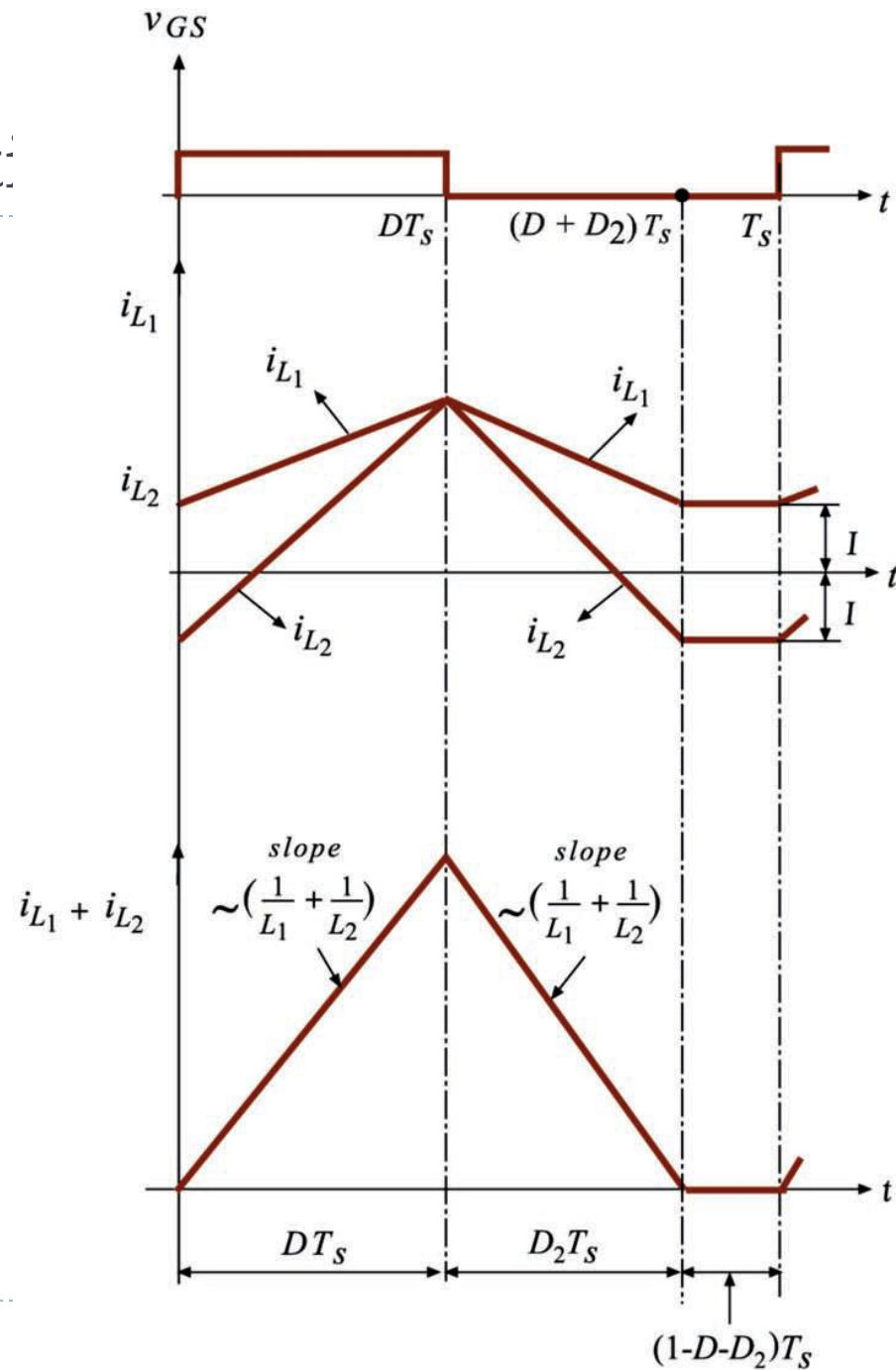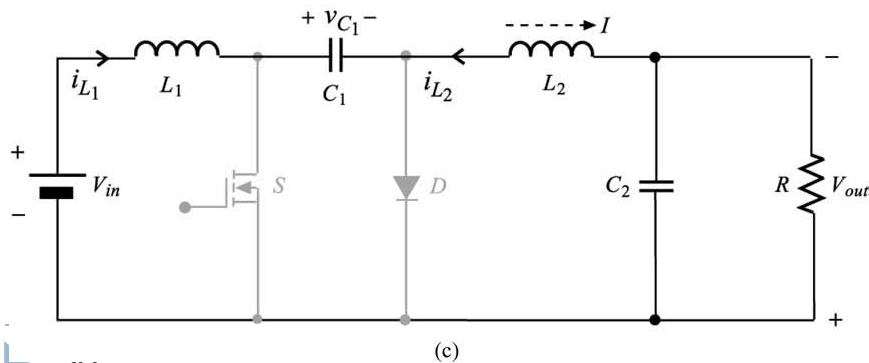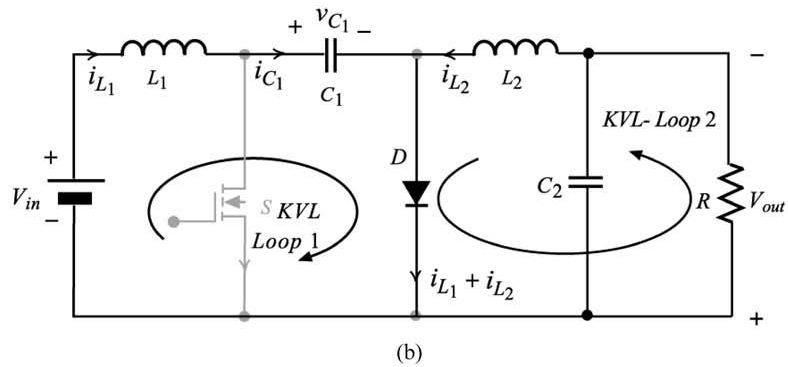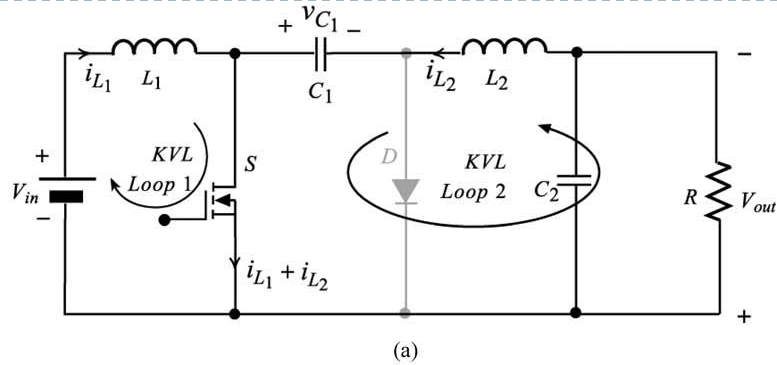
Cuk DC-DC Converter Effect of Parasitics

Cuk converter with coupled inductor for reducing the inductor currents ripple
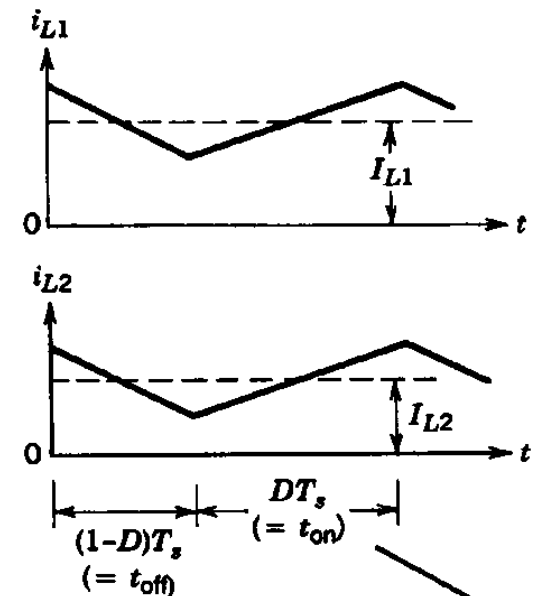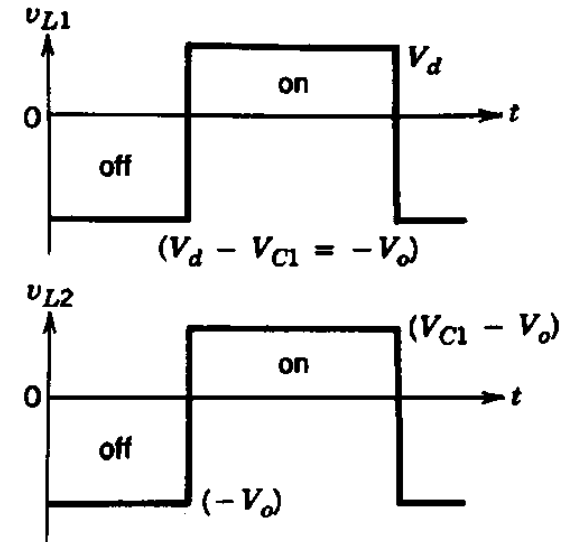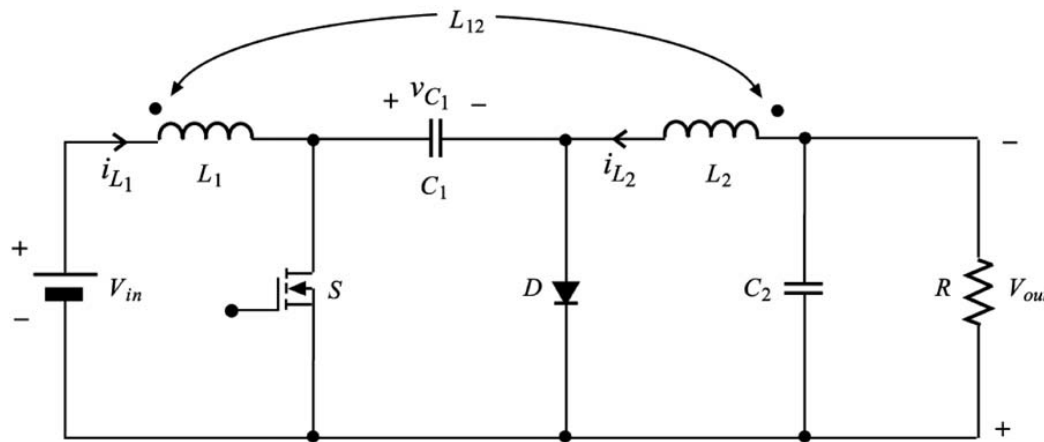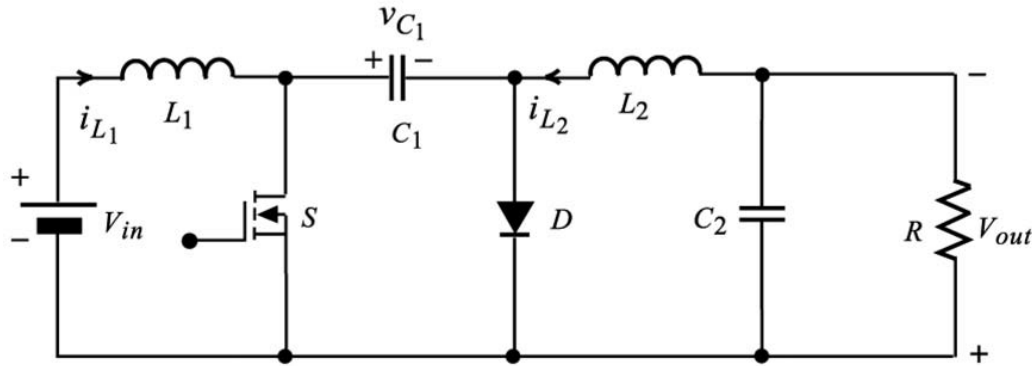
Isolated Cuk converter
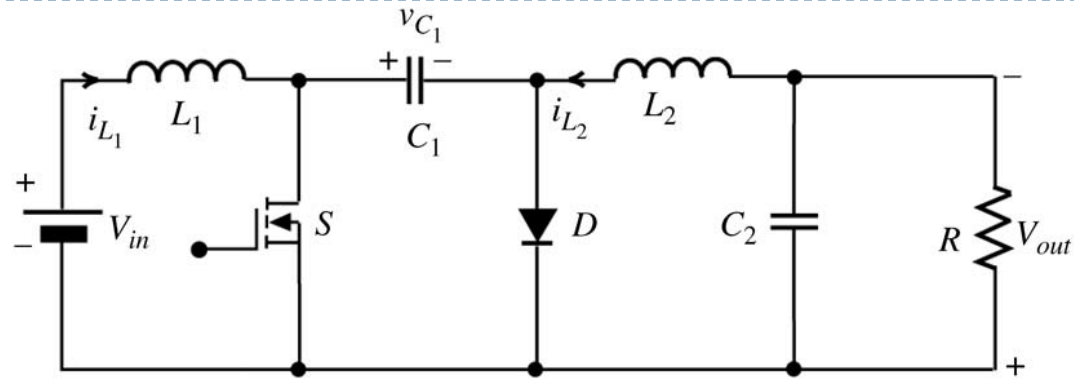
(a)
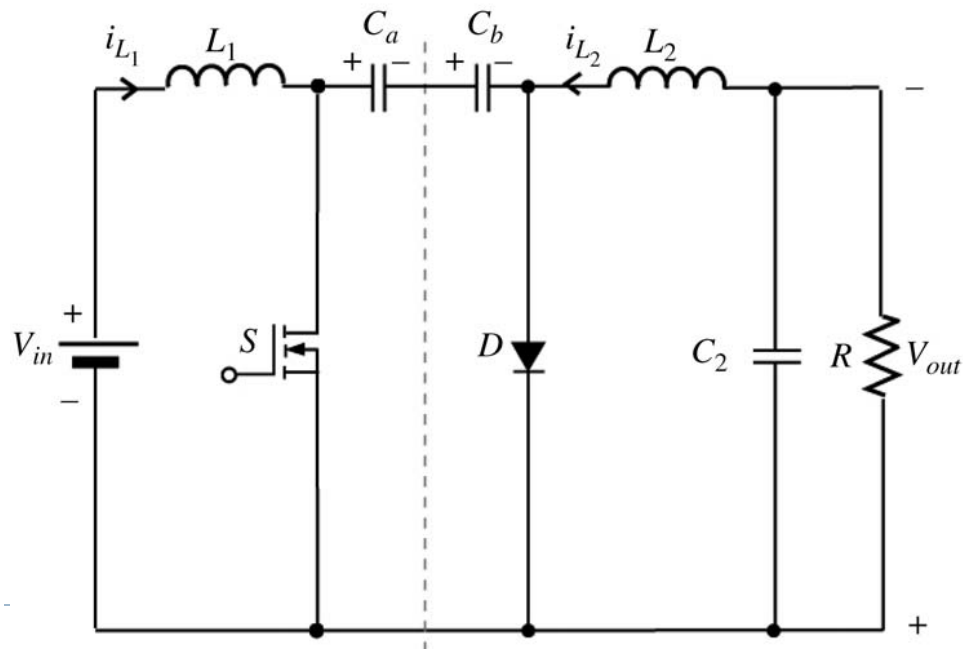
(b)

Isolated Cuk converter (2)
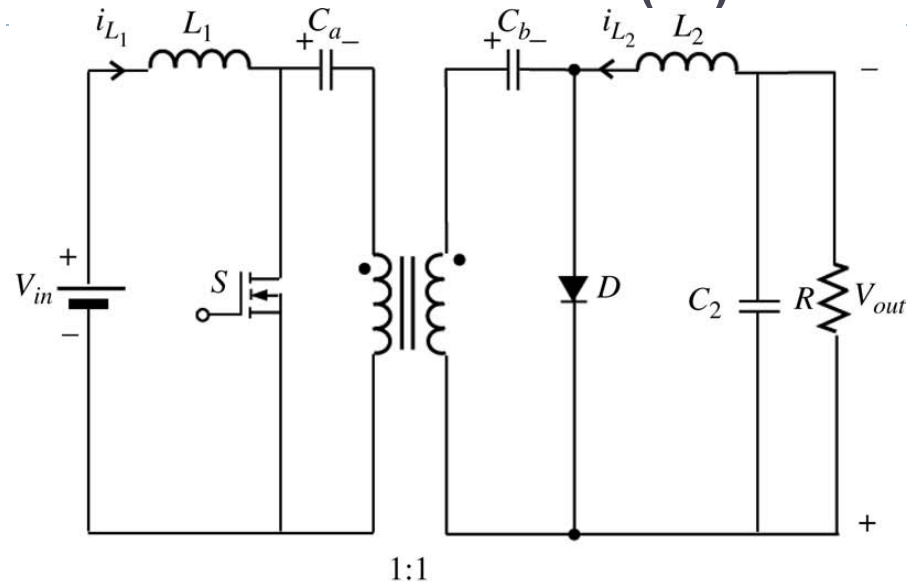
(c)
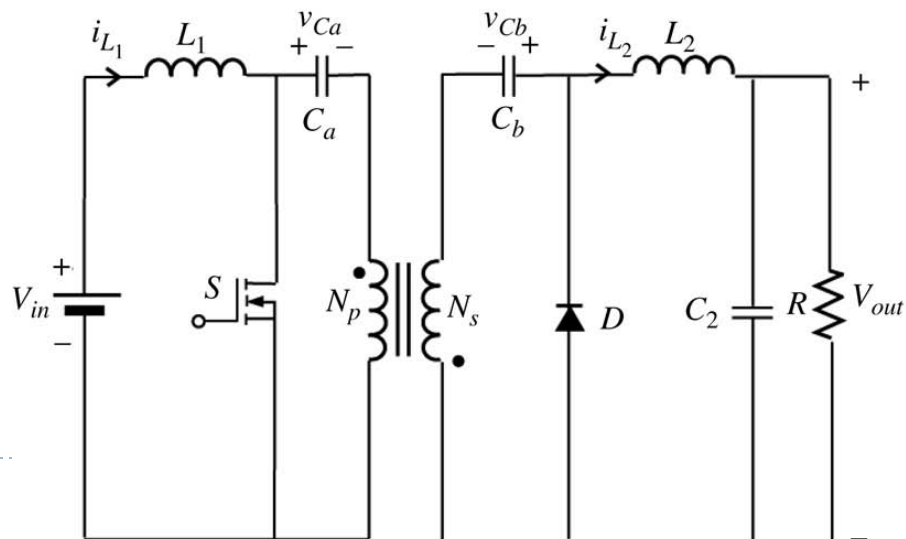
Isolated Cuk converter (3)
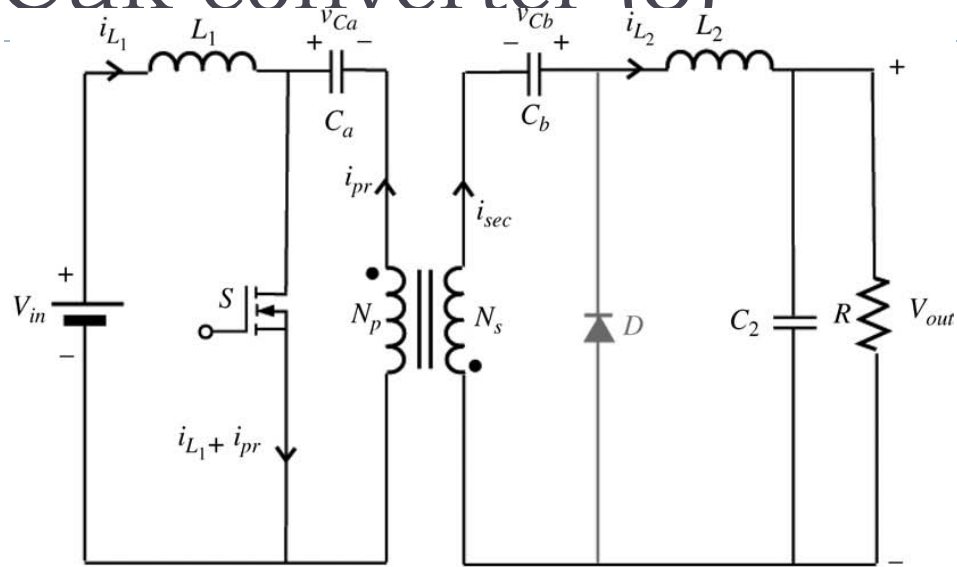
(a)
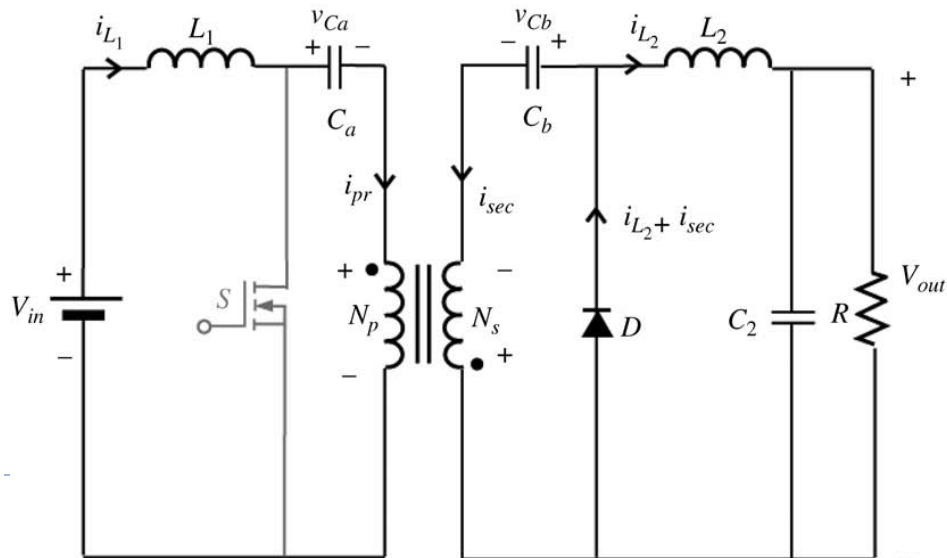
Homework!!!
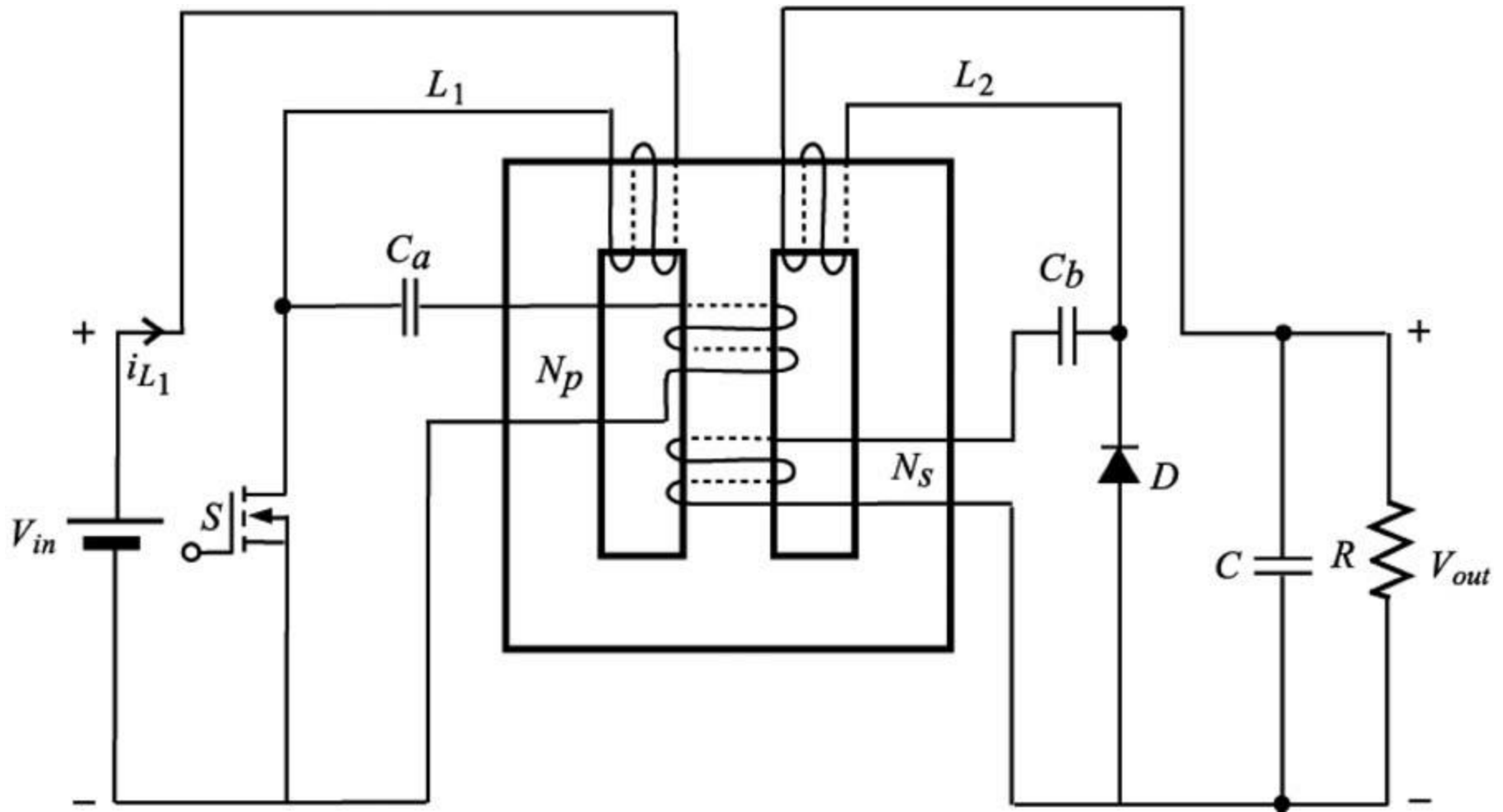
SEPIC
(Single-Ended Primary Inductance Converter)
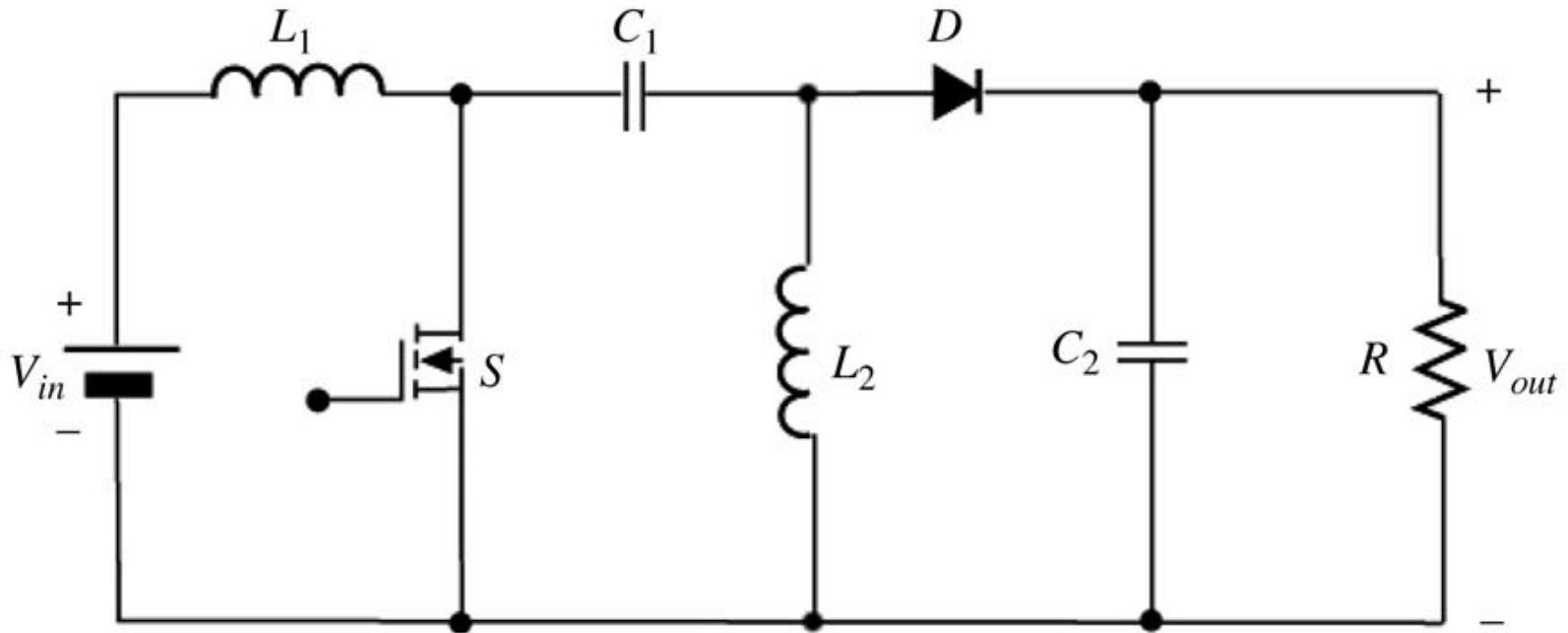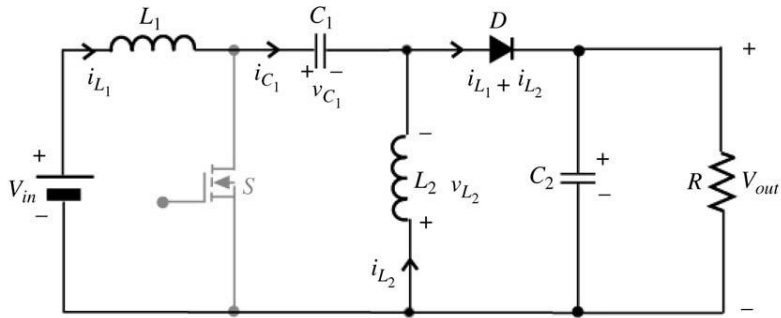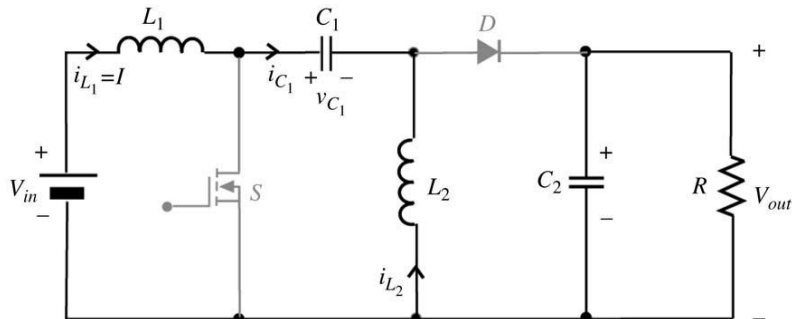

$$\frac{V_o}{V_d} = \frac{D}{1-D}$$

SEPIC Waveform

(a)

(b)
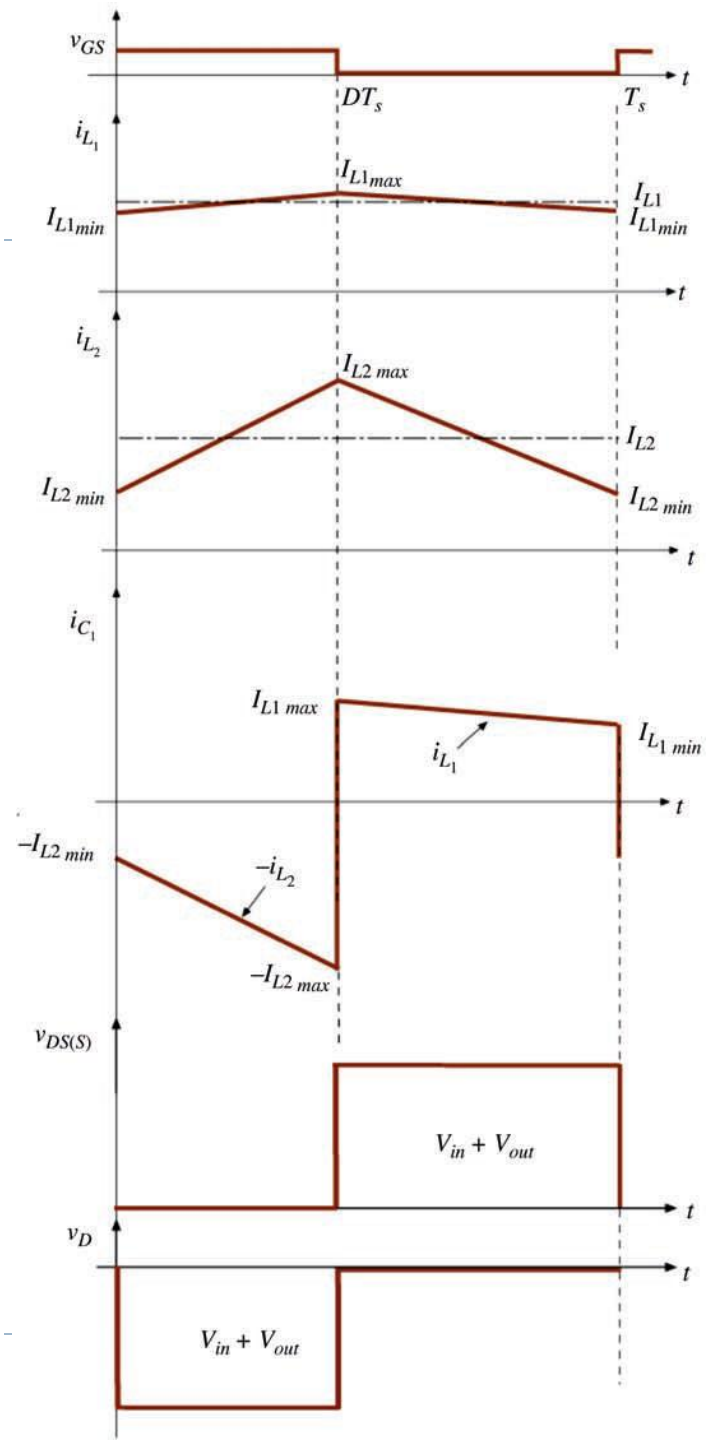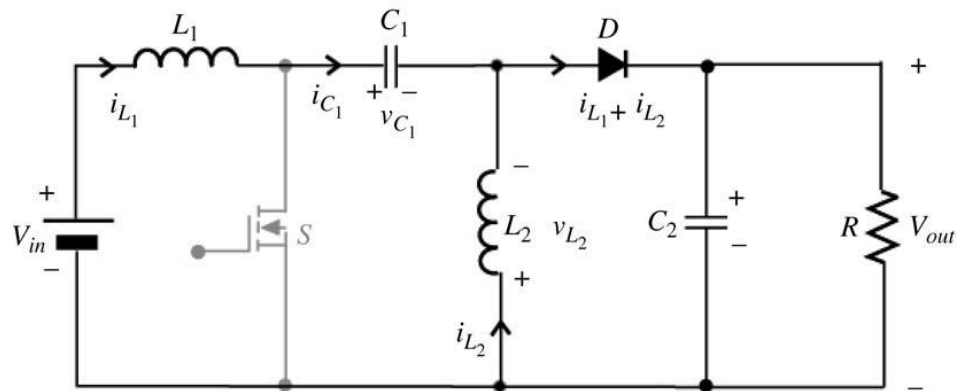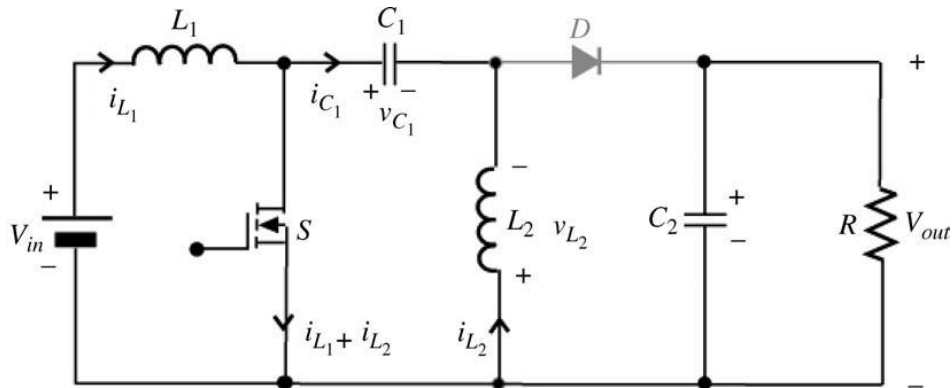
SEPIC
Discontinuous Conduction M
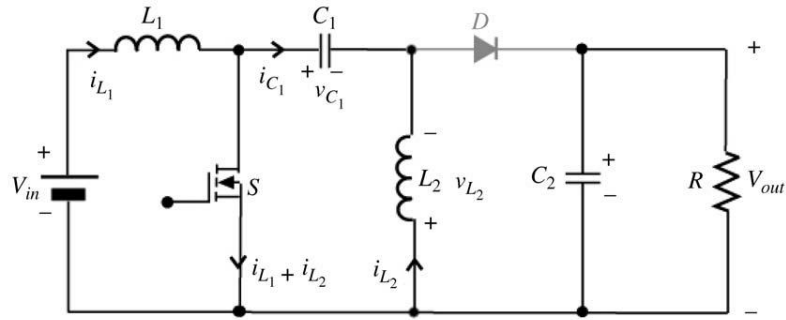
(a)

(b)

(c)
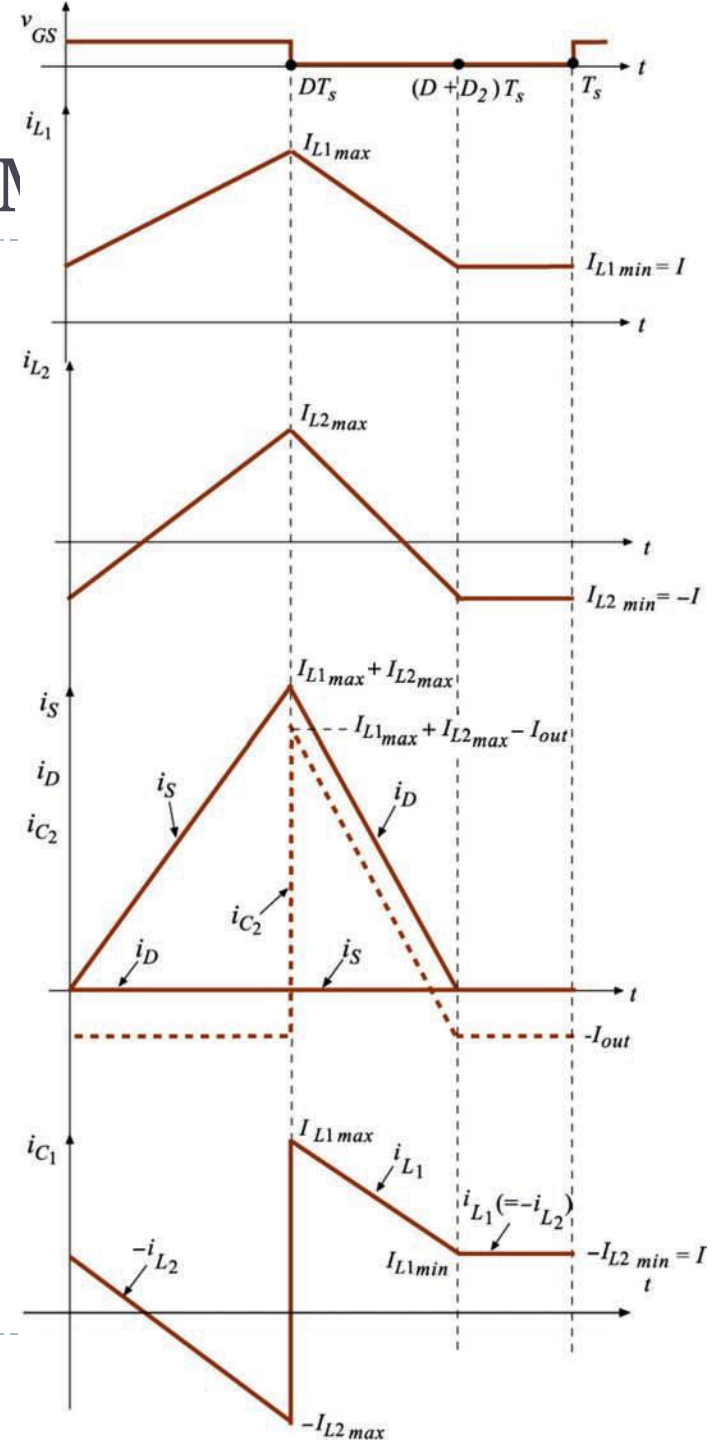
SEPIC Converter
Limits of Cont./Discont. Conduction
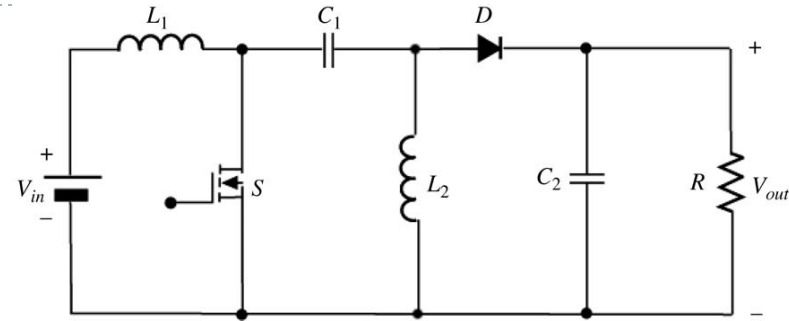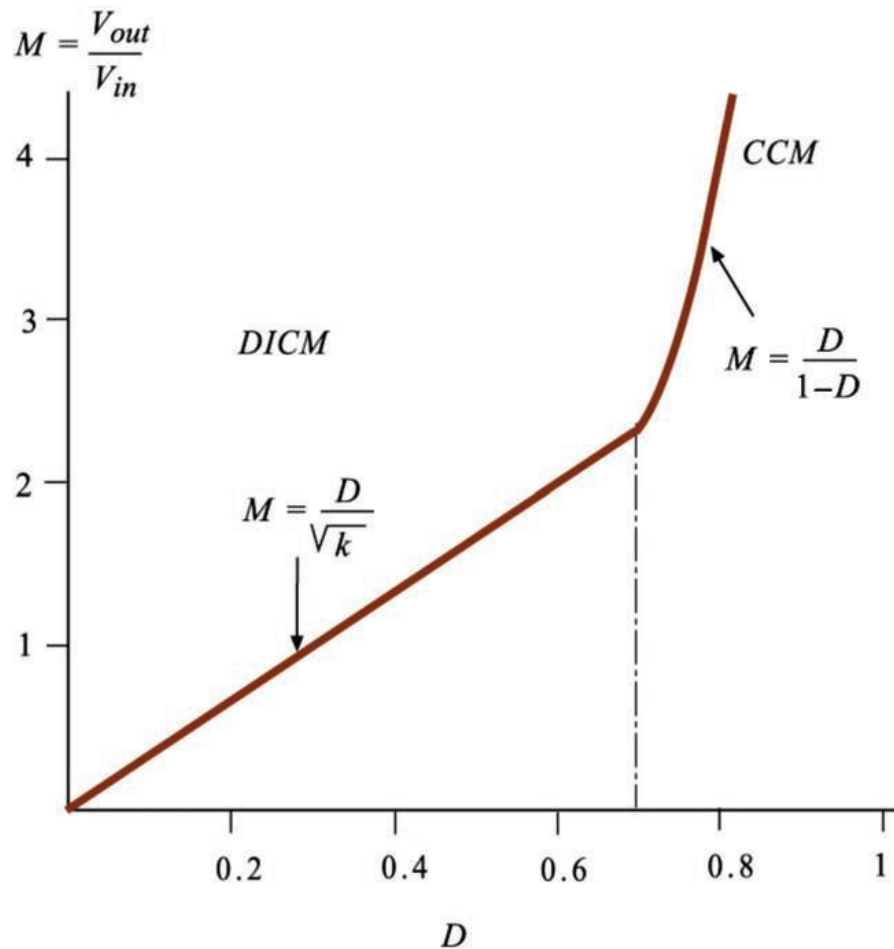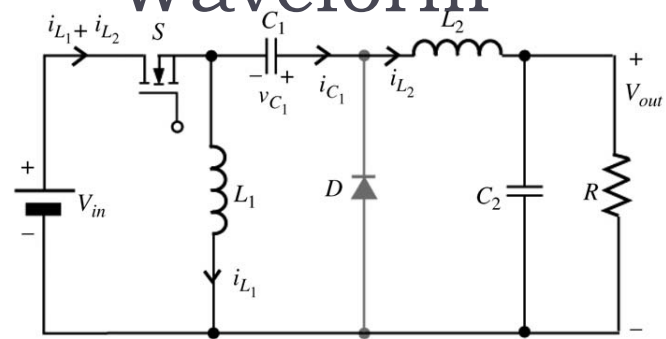
Isolated version of the SEPIC converter
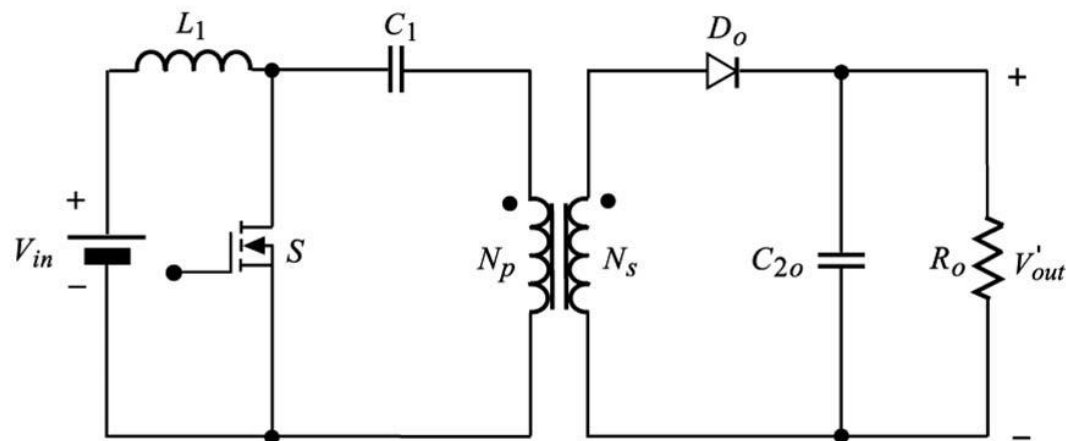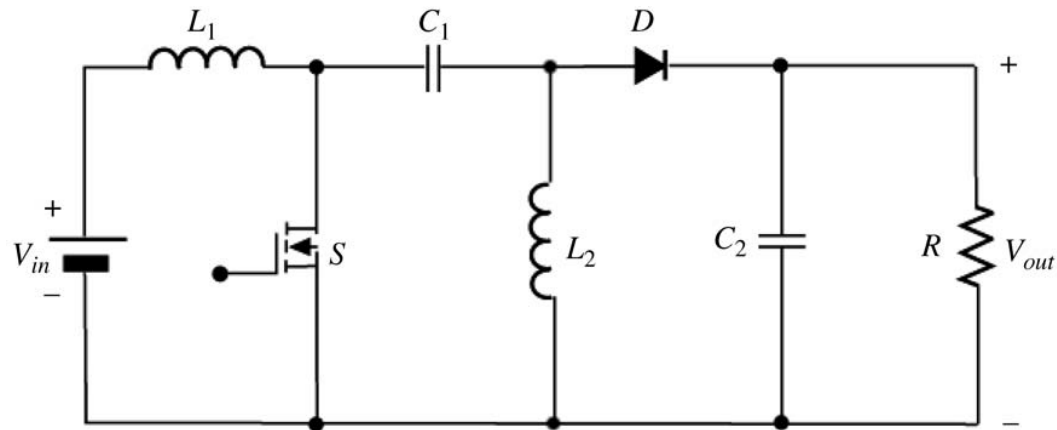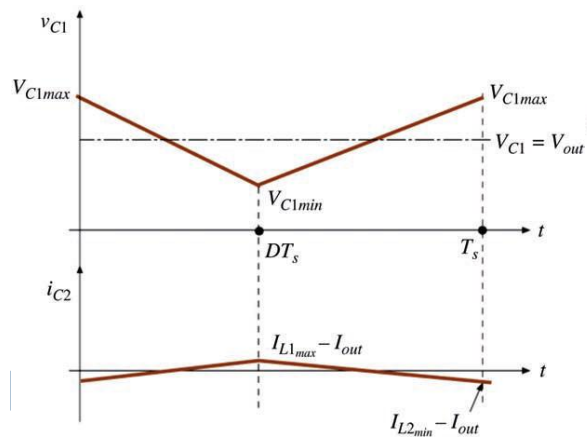
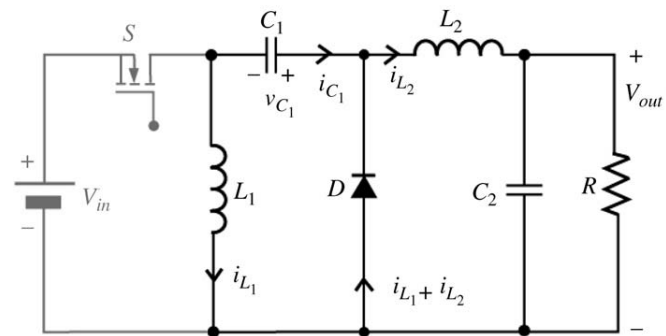# Zeta (Inverse SEPIC) DC-DC Converter (Kazimierczuk/Barbi)
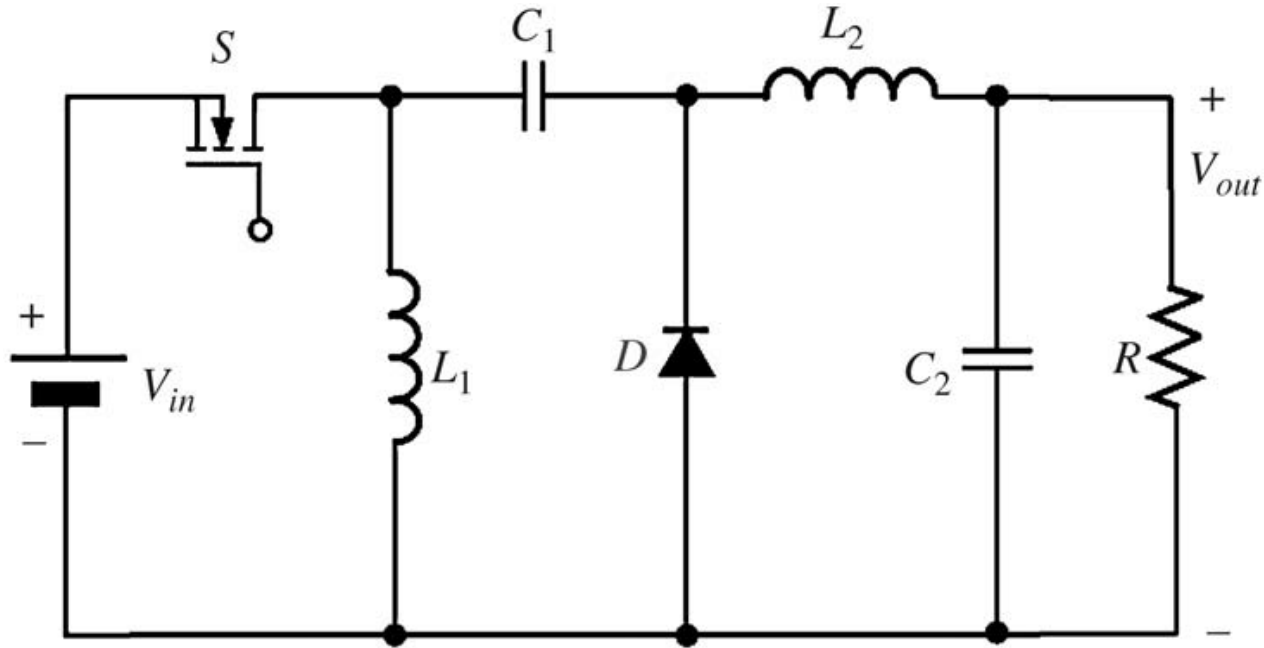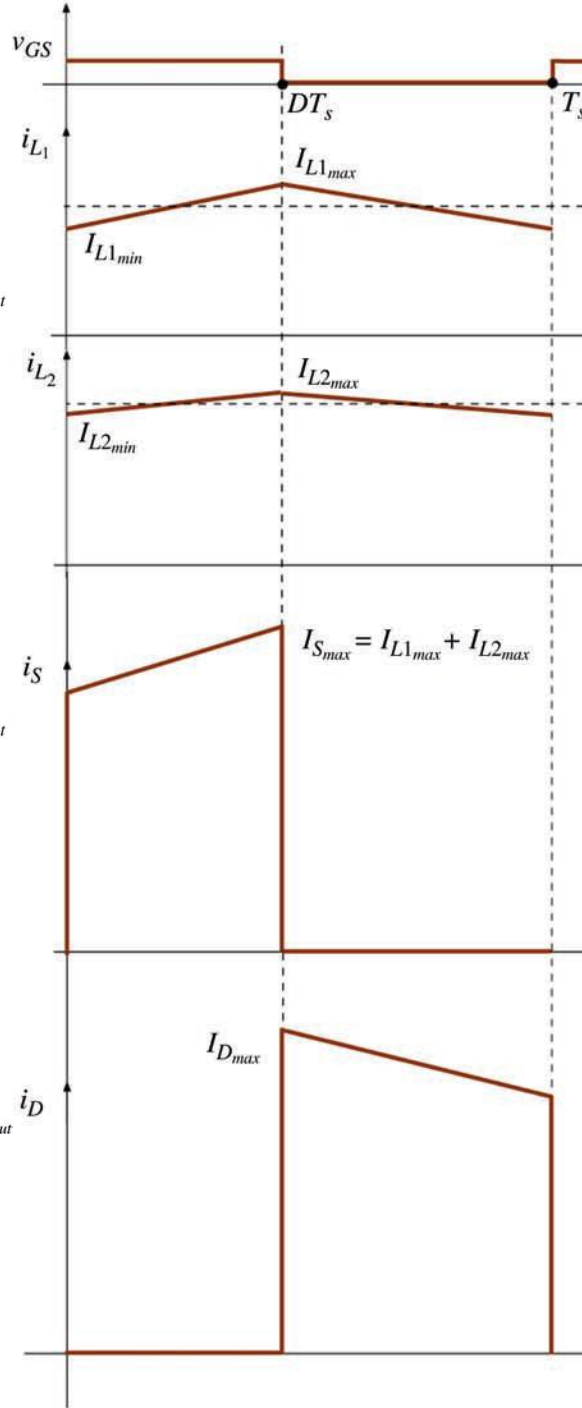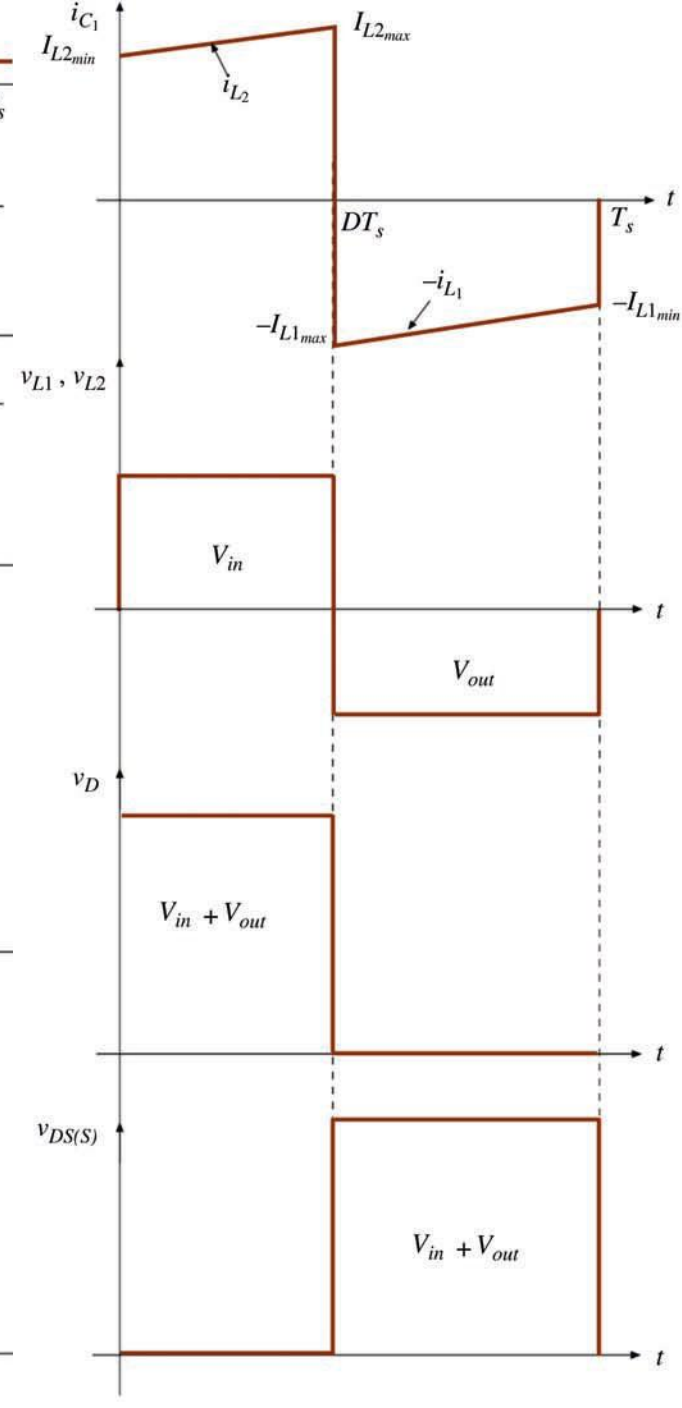

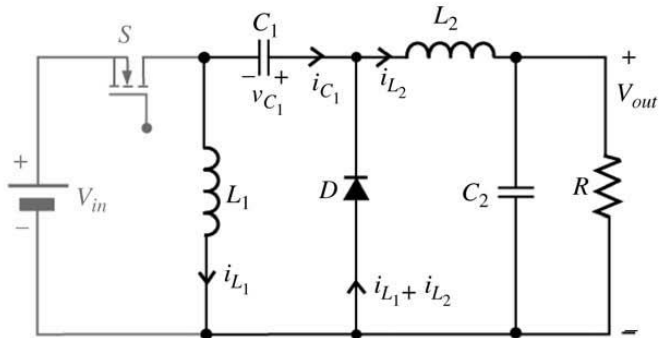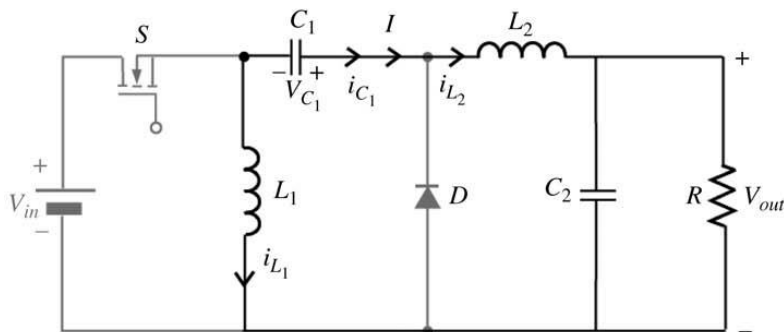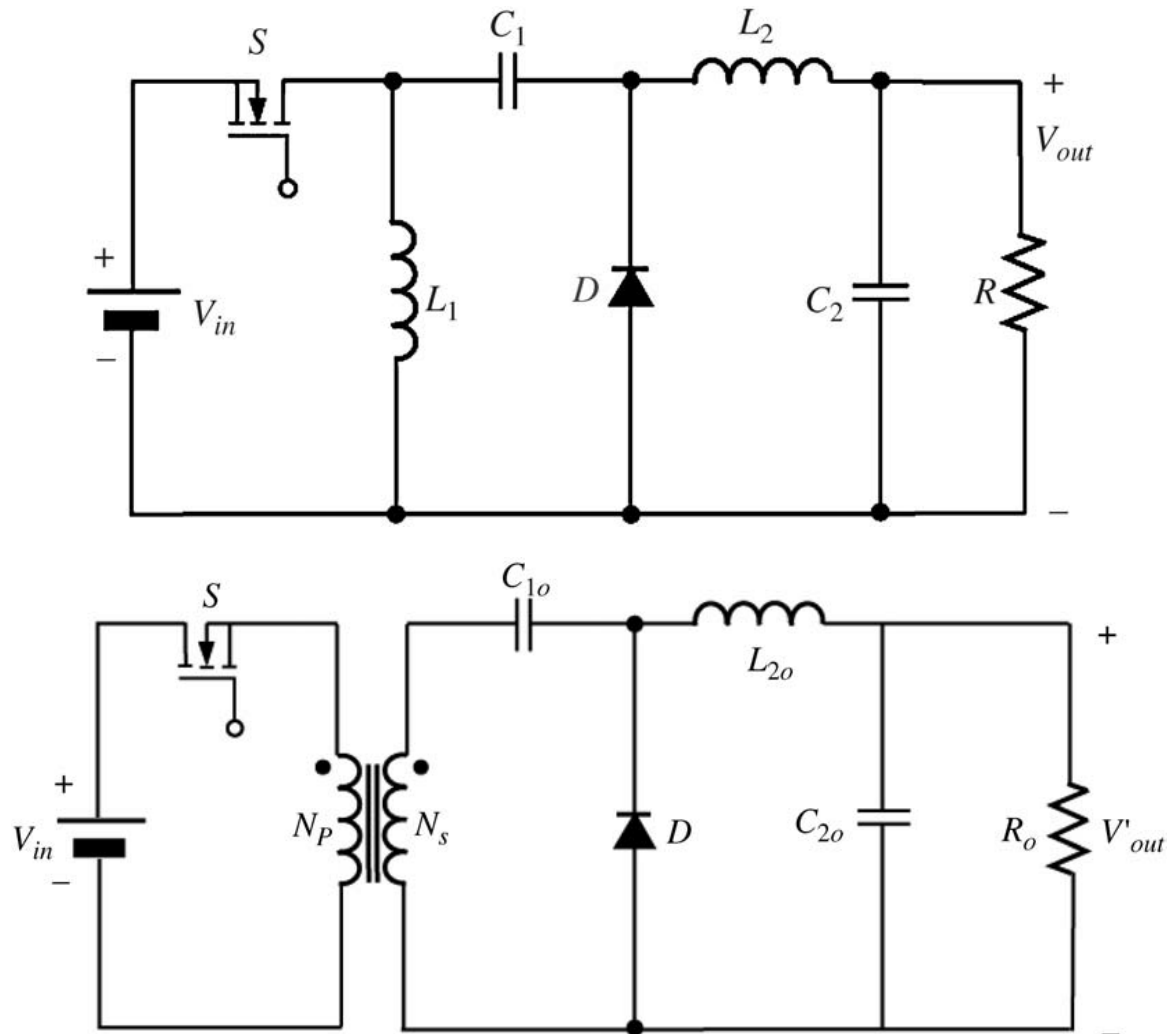$$\frac{V_o}{V_d} = \frac{D}{1-D}$$

ZETA Waveform

(a)

(c)

v_{GS}

DT_s T_s

i_{L_1}

$I_{L1_{max}}$

$I_{L1_{min}}$

i_{L_2}

$I_{L2_{max}}$

$I_{L2_{min}}$

i_S

$I_{S_{max}} = I_{L1_{max}} + I_{L2_{max}}$

i_D

$I_{D_{max}}$

(a)

i_{C_1}

$I_{L2_{min}}$ $I_{L2_{max}}$

i_{L_2}

DT_s T_s t

$-I_{L1_{max}}$ $-i_{L_1}$ $-I_{L1_{min}}$

v_{L1}, v_{L2}

V_{in}

V_{out} t

v_D

$V_{in} + V_{out}$

t

$v_{DS(S)}$

$V_{in} + V_{out}$

t

(b)

ZETA
Discontinuous Conduction
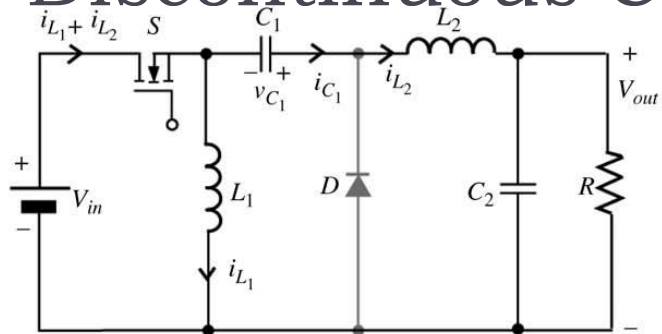
(a)

(b)

(c)
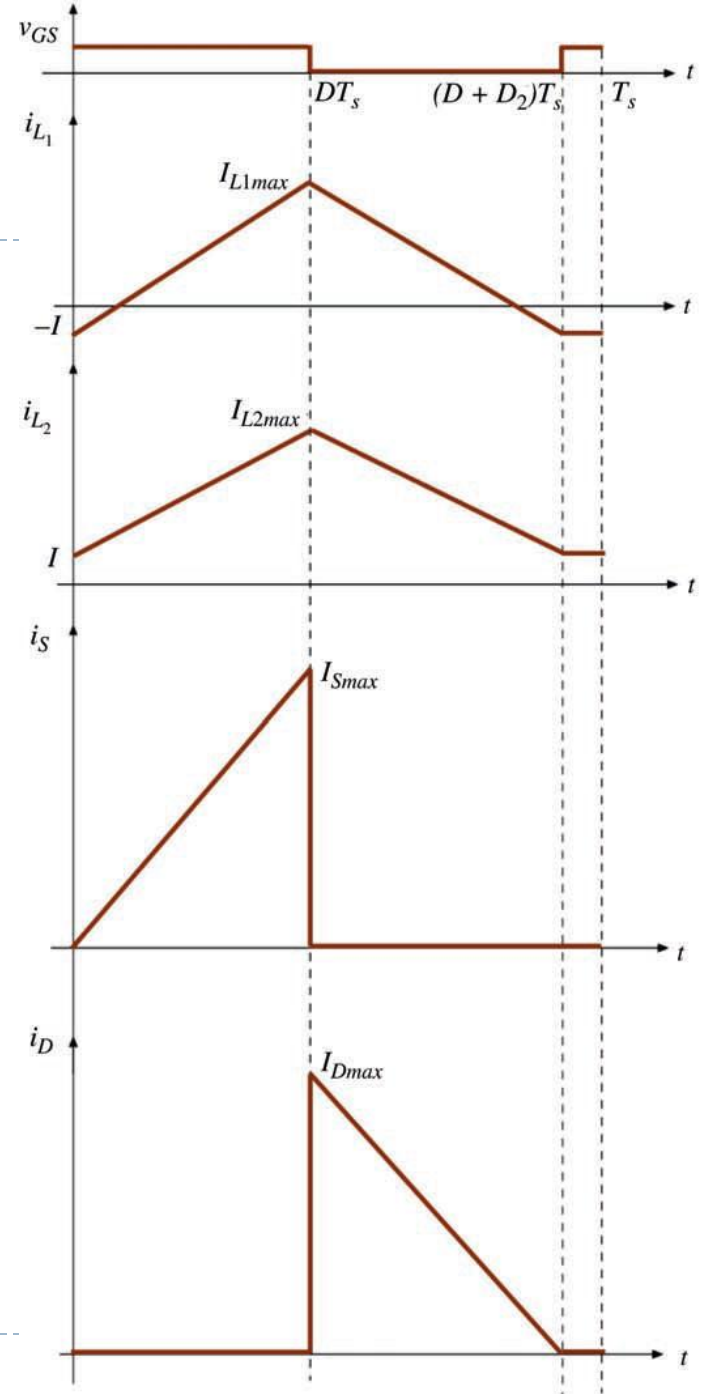
ZETA Converter
Limits of Cont./Discont. Conduction
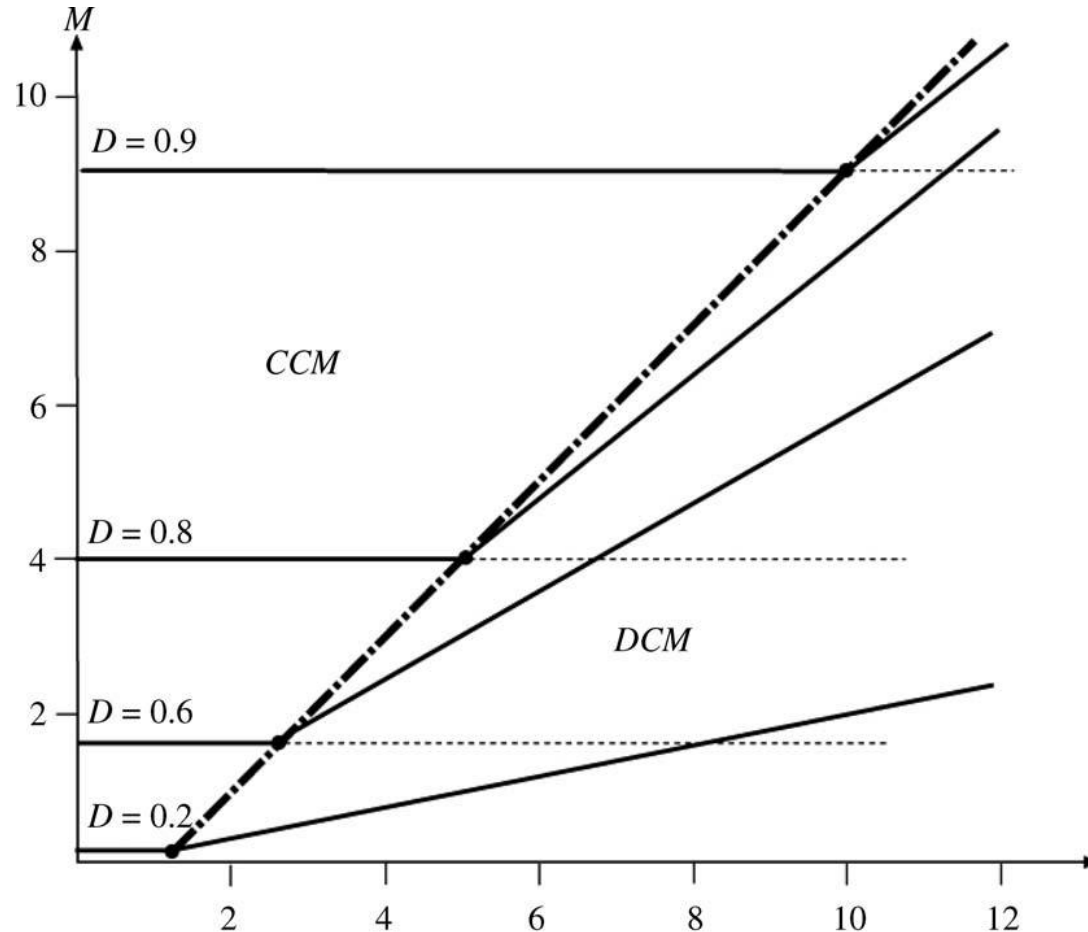
$$\frac{V_o}{V_d} = \frac{D}{1-D}$$

$$\frac{V_o}{V_d} = \frac{D}{D_2}$$

Isolated ZETA Converter

Isolated transformer

(a)   (b)

$$B(t) \propto \int v_1(t)\, dt$$

saturation

slope $\propto L_M$

$$H(t) \propto i_M(t)$$

$$n = \frac{N_p}{N_s} \qquad \begin{aligned} v_1 &= n \cdot v_2 \\ i_2 &= n \cdot i_1 \end{aligned}$$
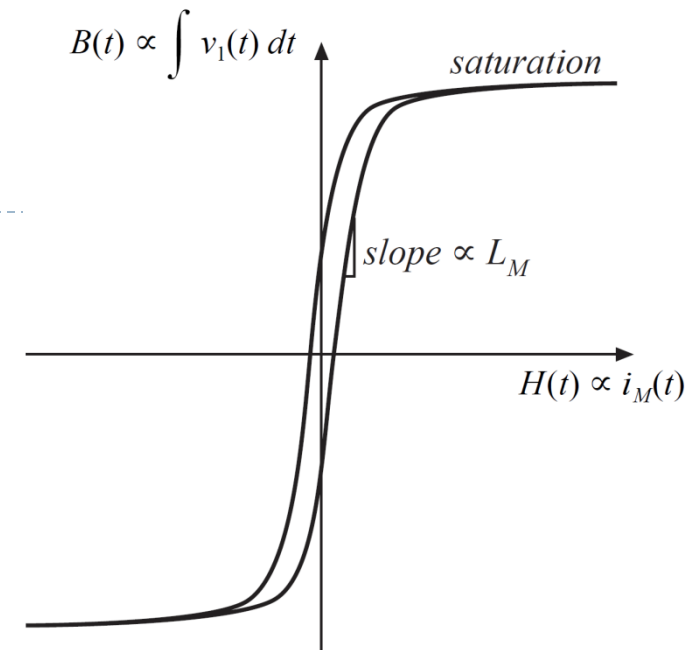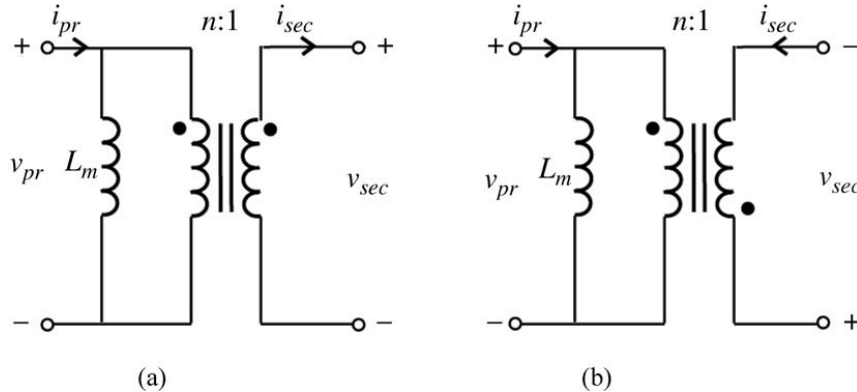
$$v_{pr} = L_m \frac{d\left(i_{pr} + i_{sec} \cdot \frac{1}{n}\right)}{dt}$$

$$v_{sec} = L_m \frac{d\left(n \cdot i_{pr} + i_{sec}\right)}{dt}$$
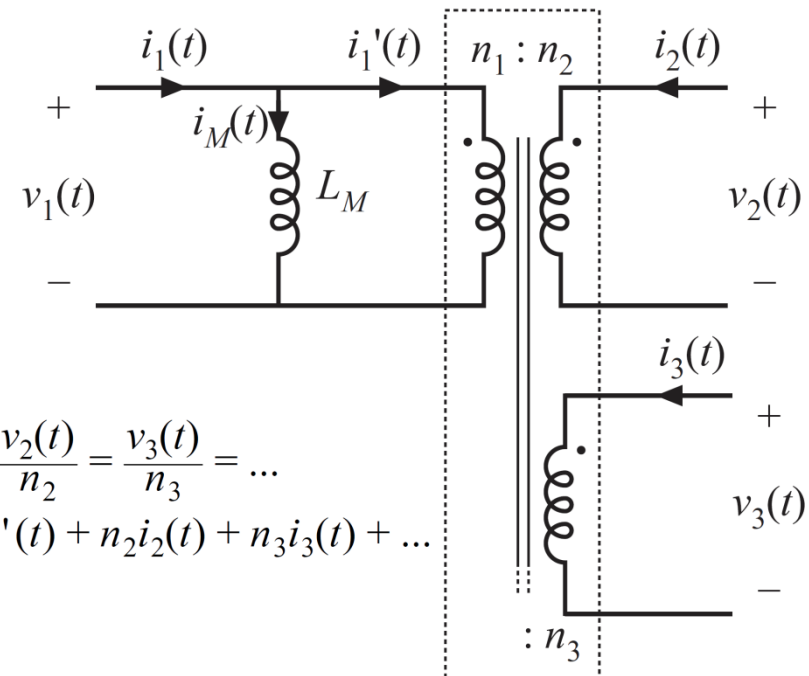
$$\frac{v_1(t)}{n_1} = \frac{v_2(t)}{n_2} = \frac{v_3(t)}{n_3} = \ldots$$

$$0 = n_1 i_1{}'(t) + n_2 i_2(t) + n_3 i_3(t) + \ldots$$

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Forward Converters

▸ **High frequency transformers**

  ▸ With multiple outputs
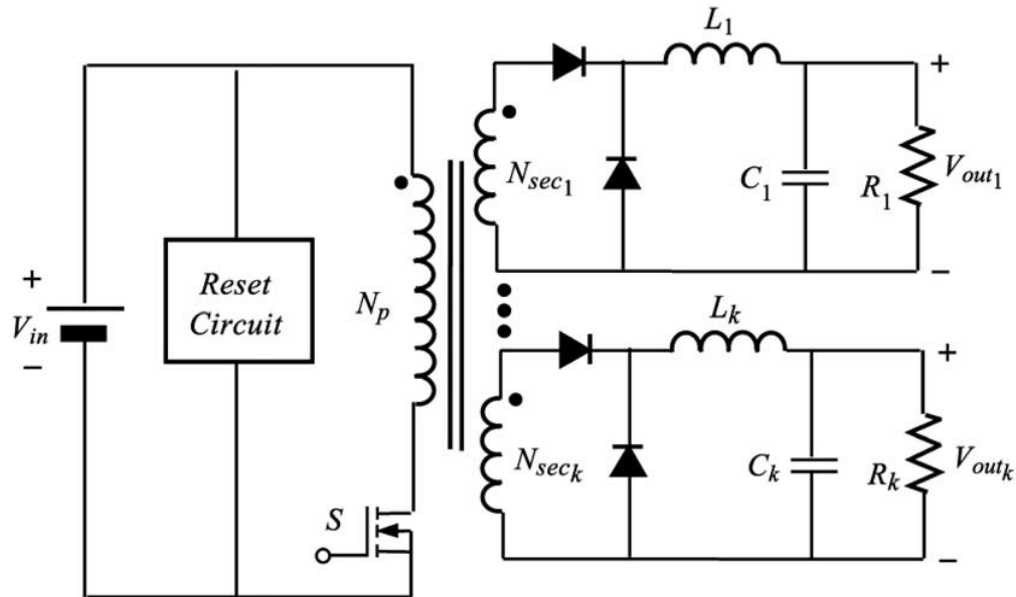
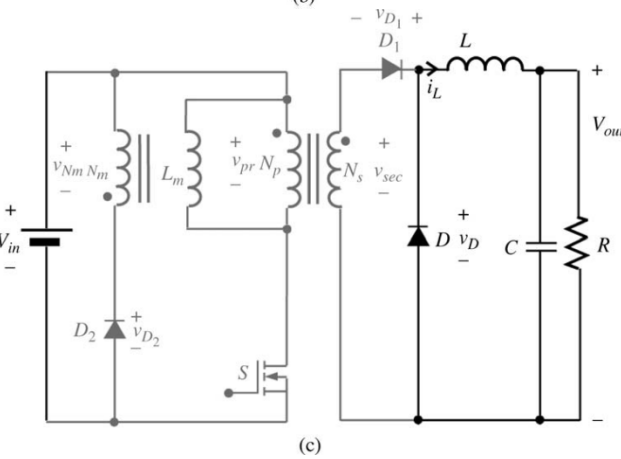# Forward Converter

▸ Buck converter with input filter
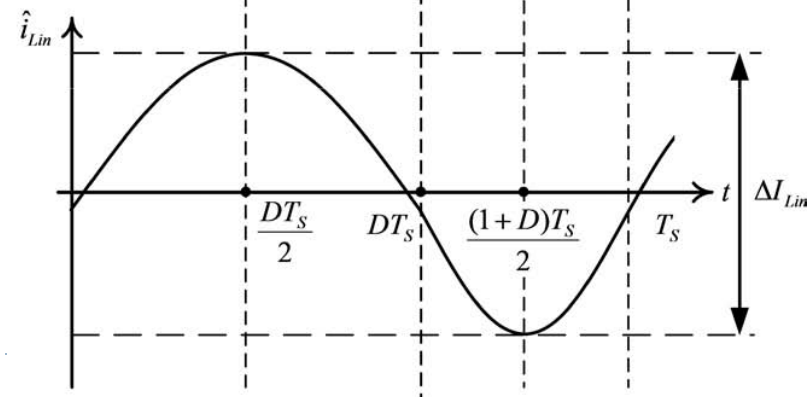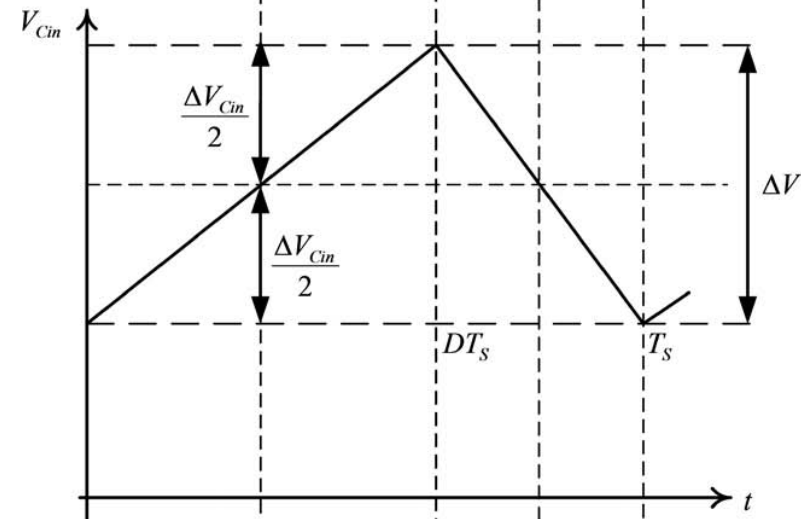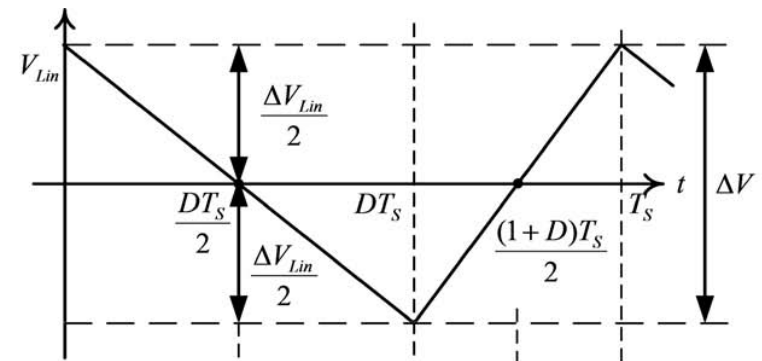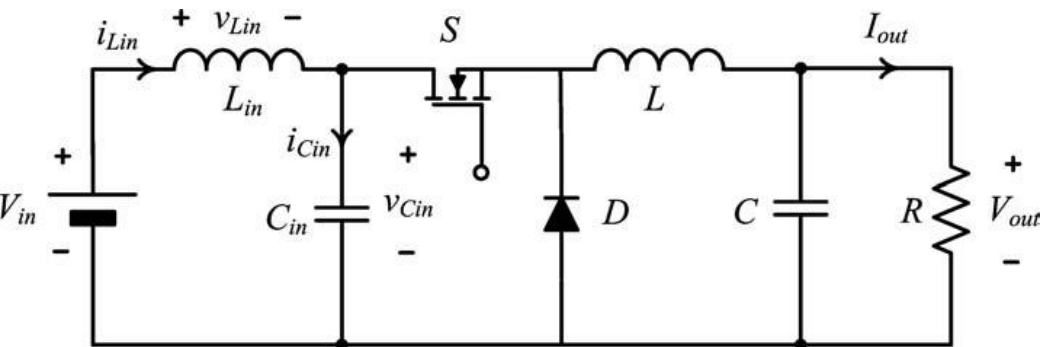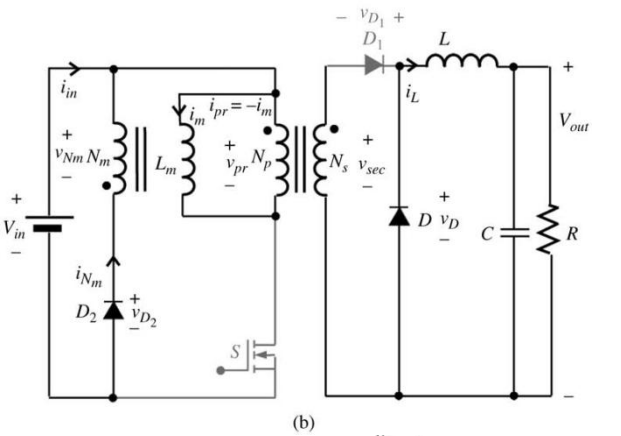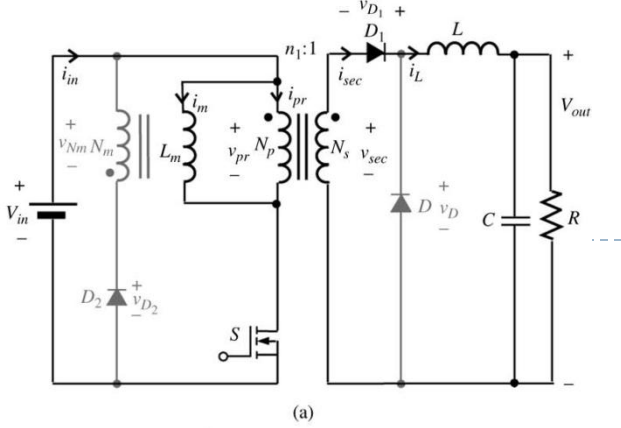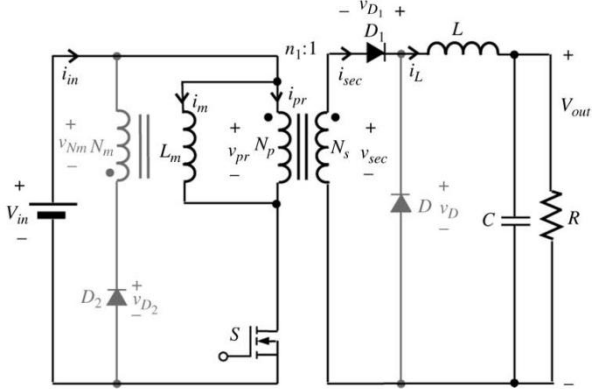
Forward Converter
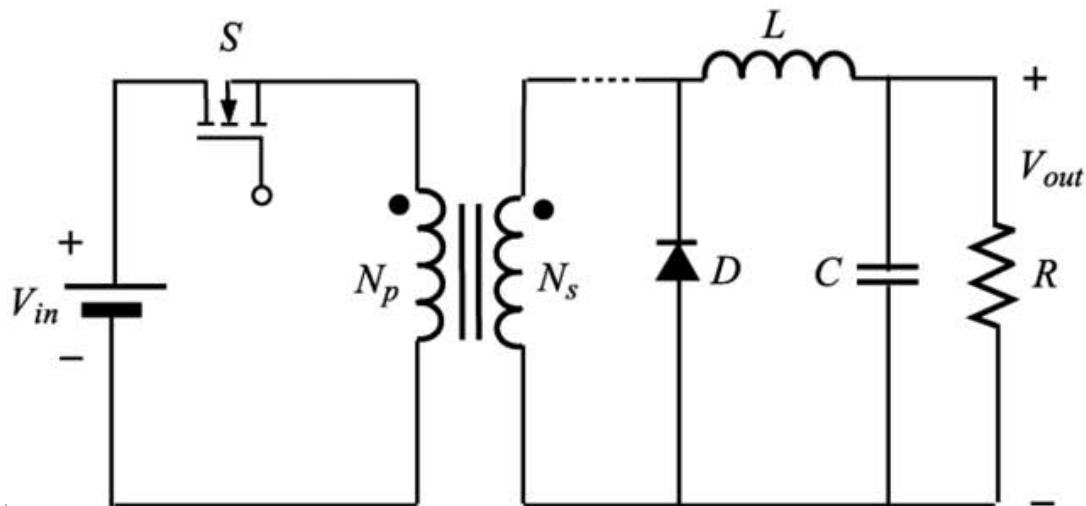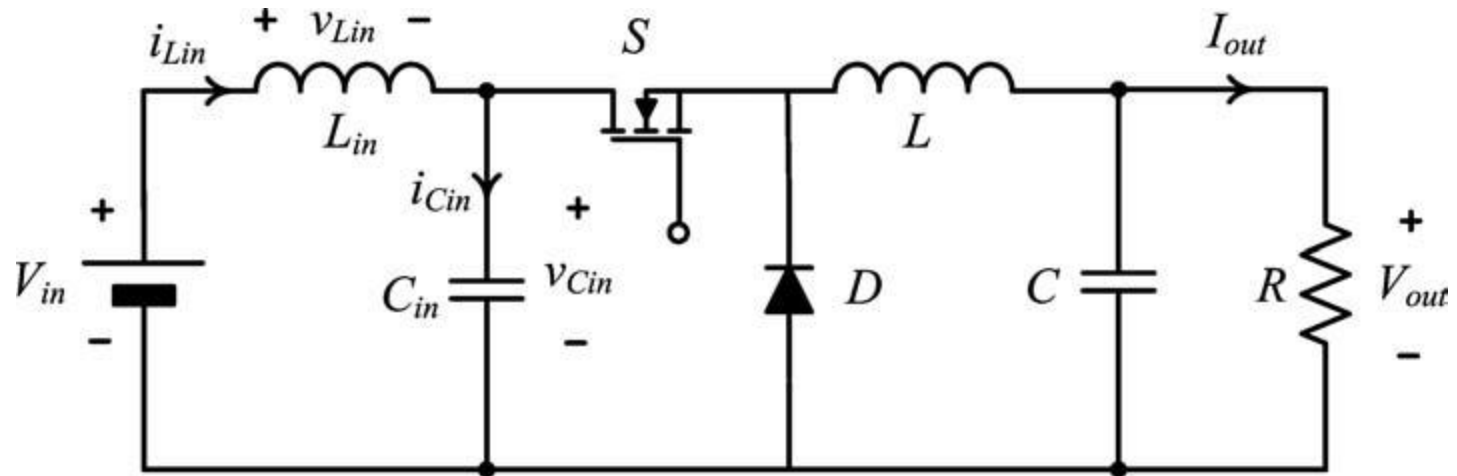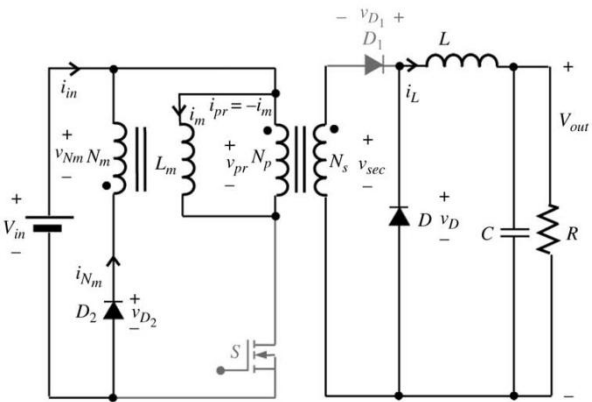
Forward Converter
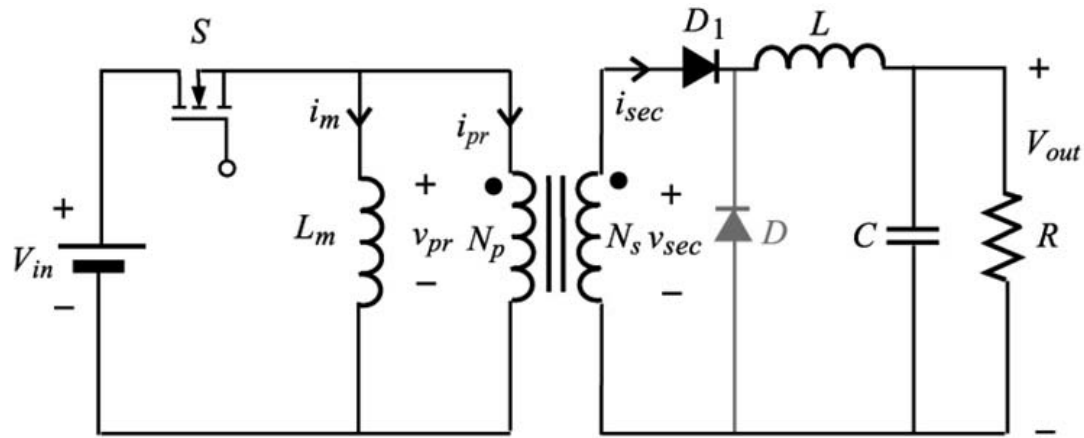
(d)
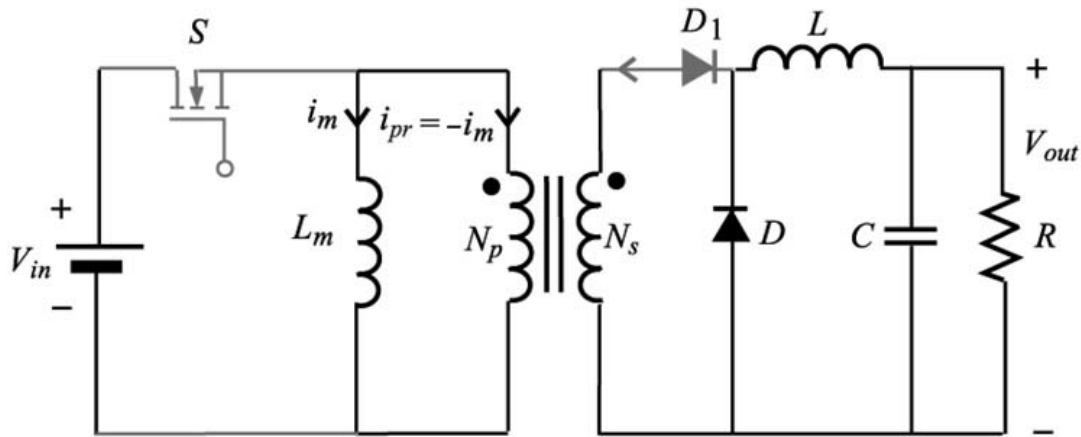
(e)

Forward Converter

(f)

Continous mode

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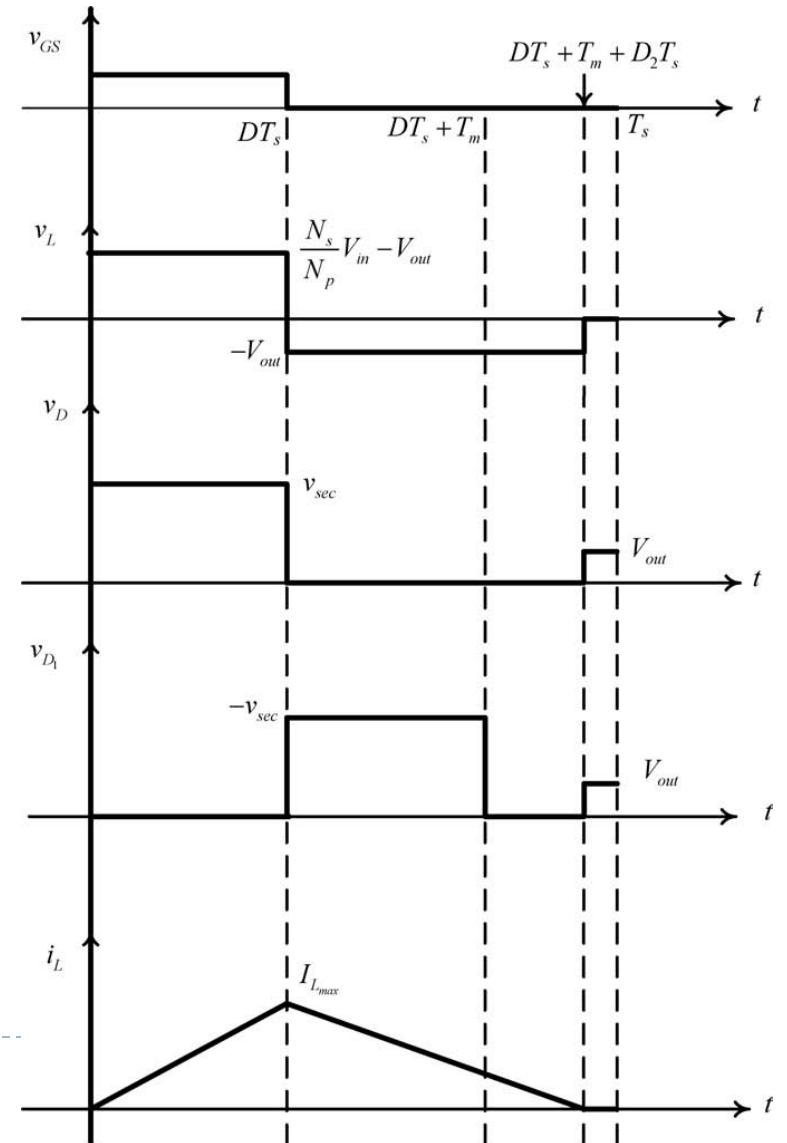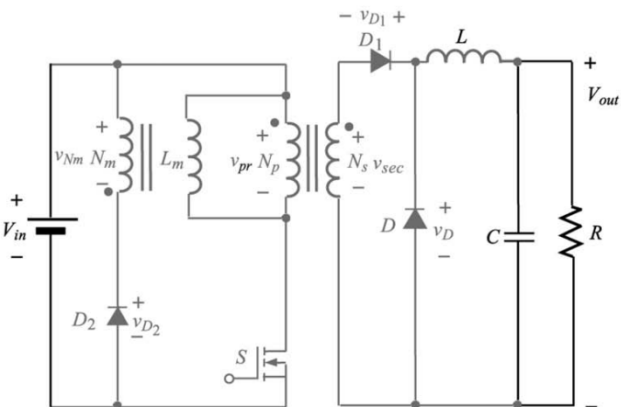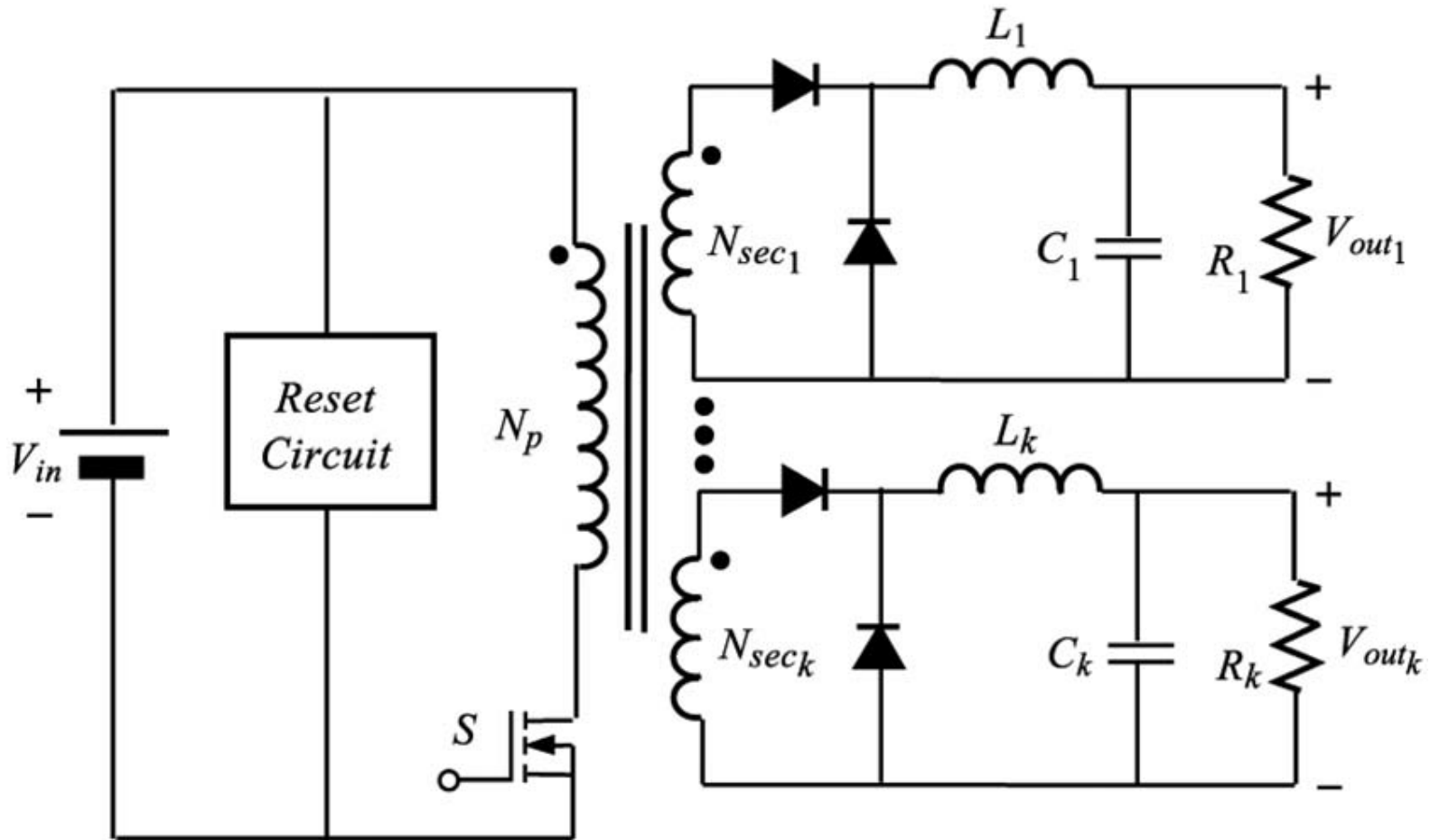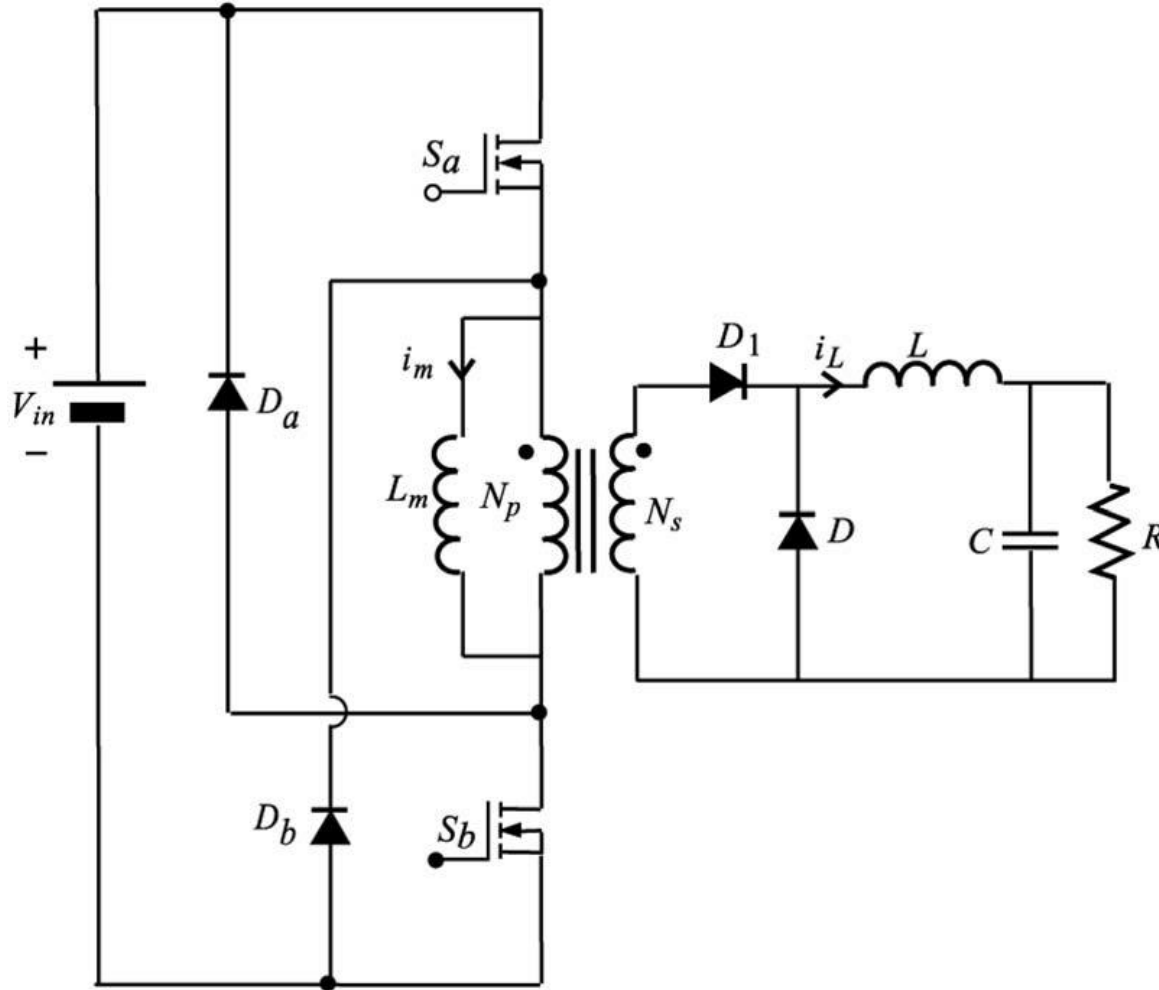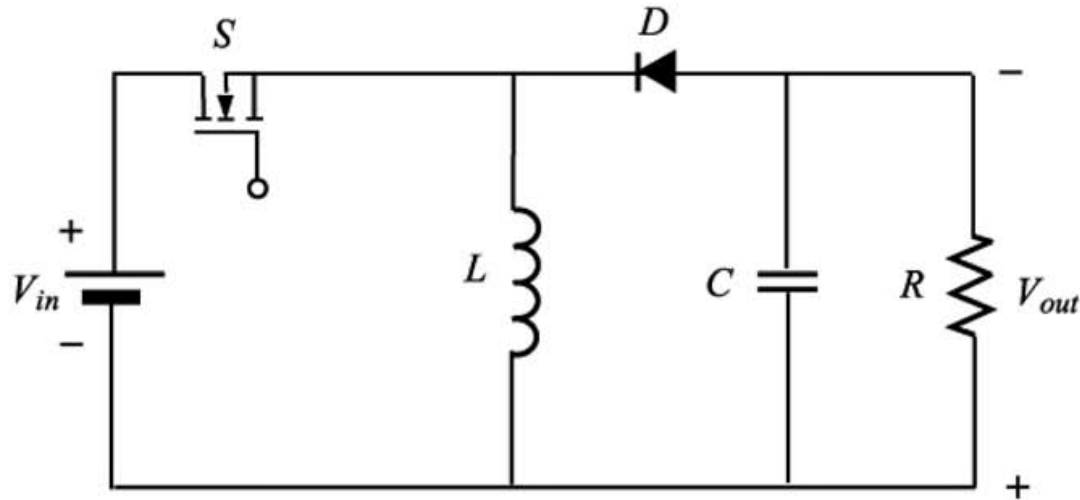# Diconctinous mode

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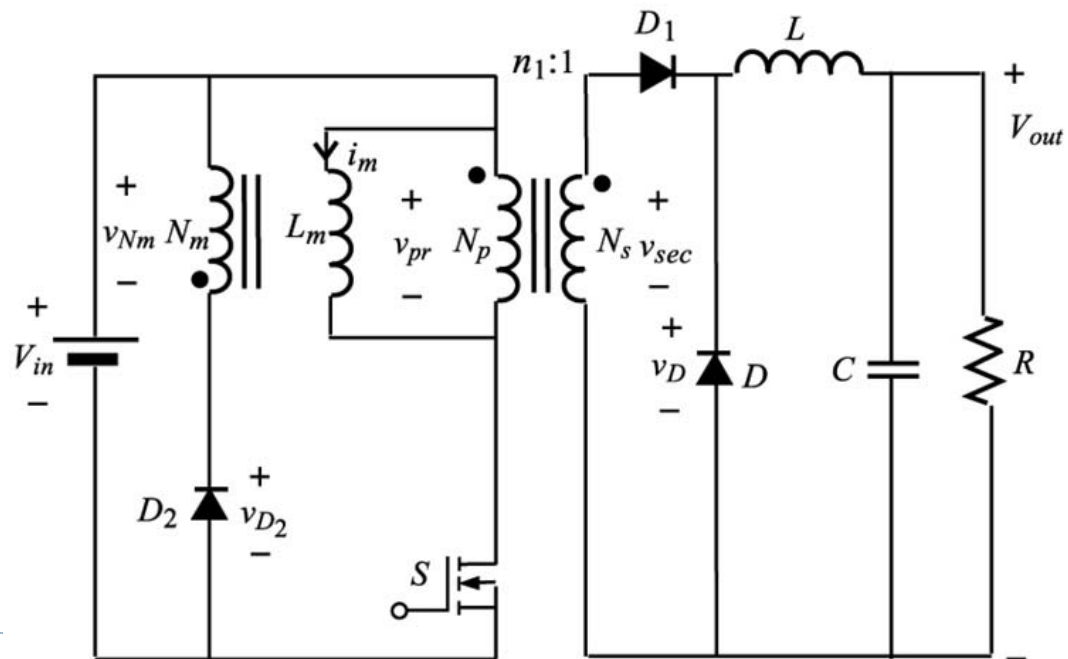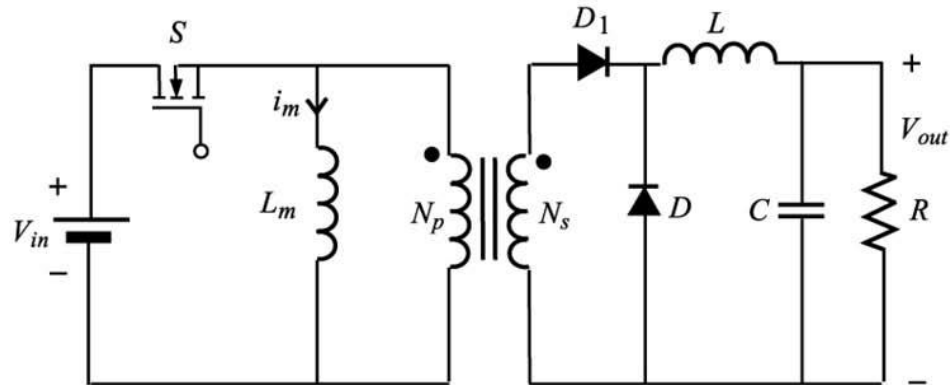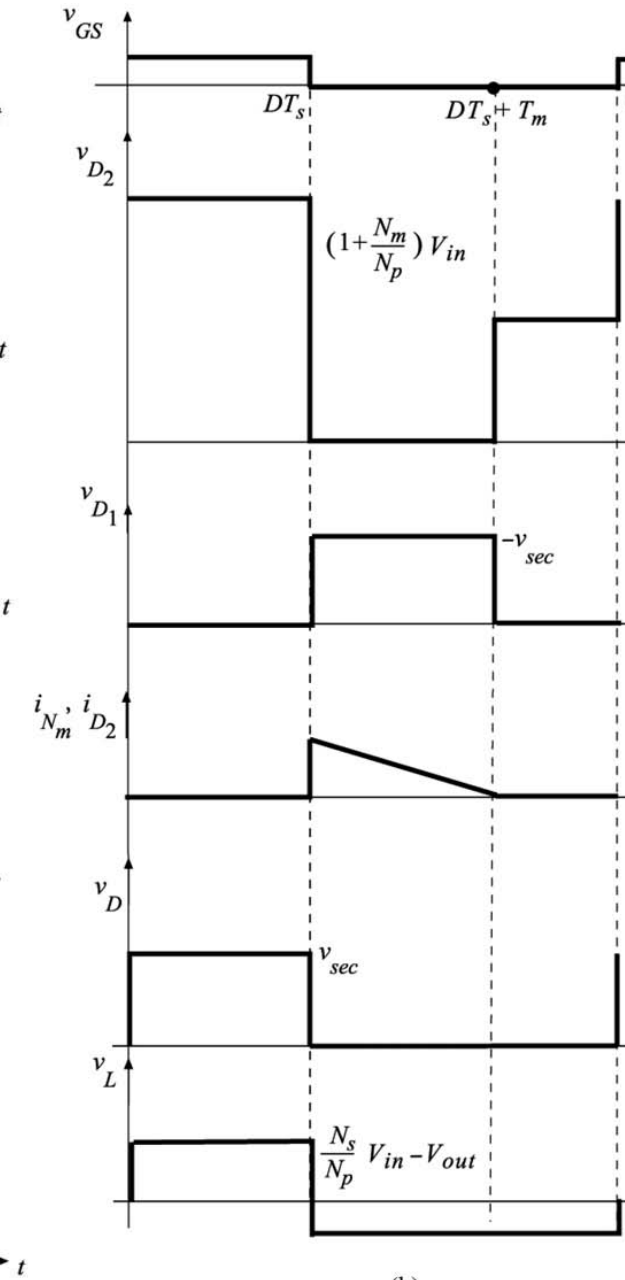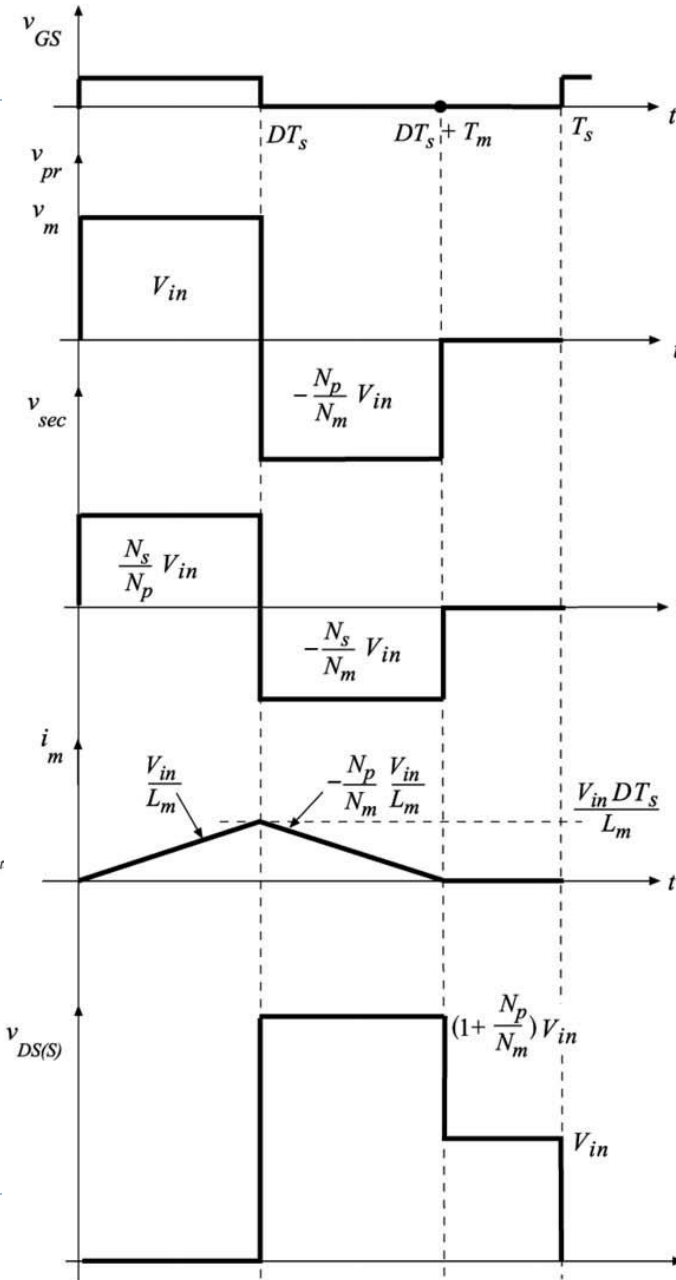
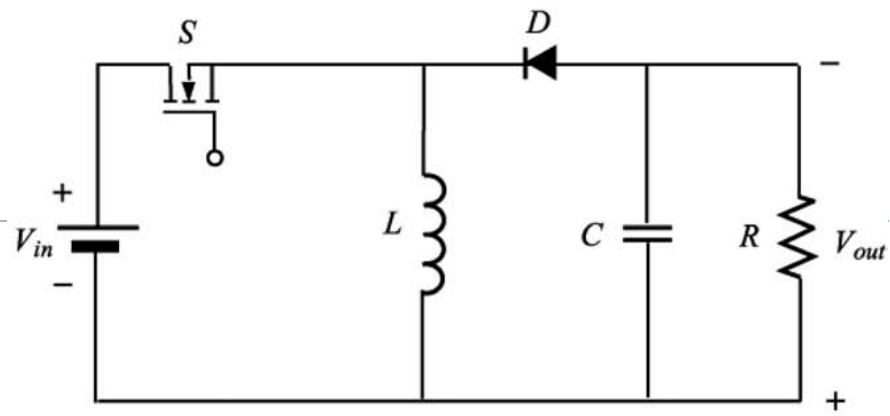# Multiple output forward converter

Two transistor forward converter

Flyback converter

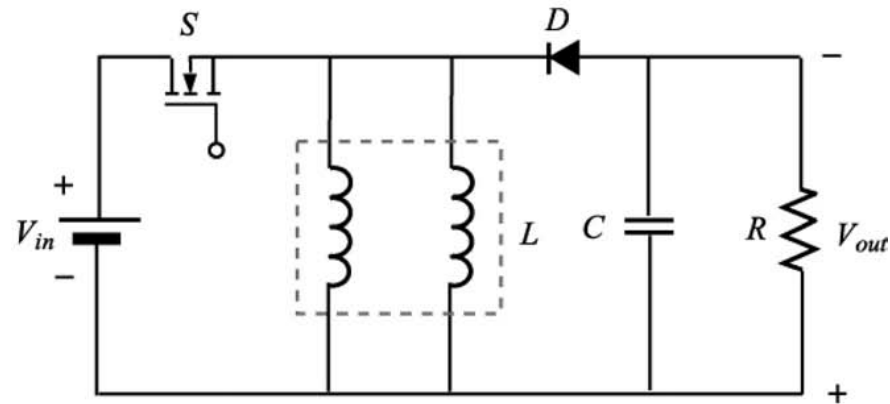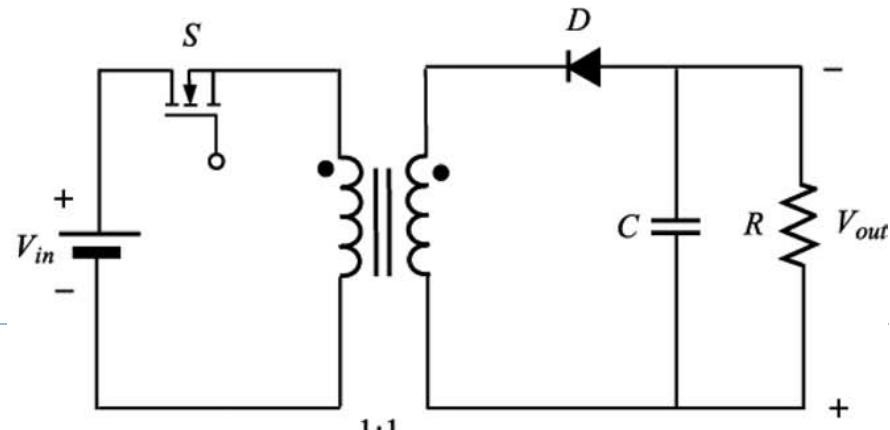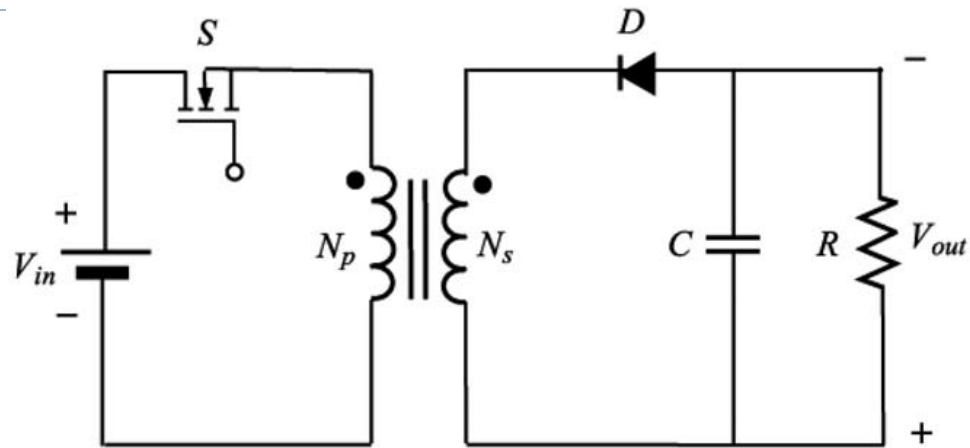- one of the oldest converters, Hertz effect
- Buck-boost

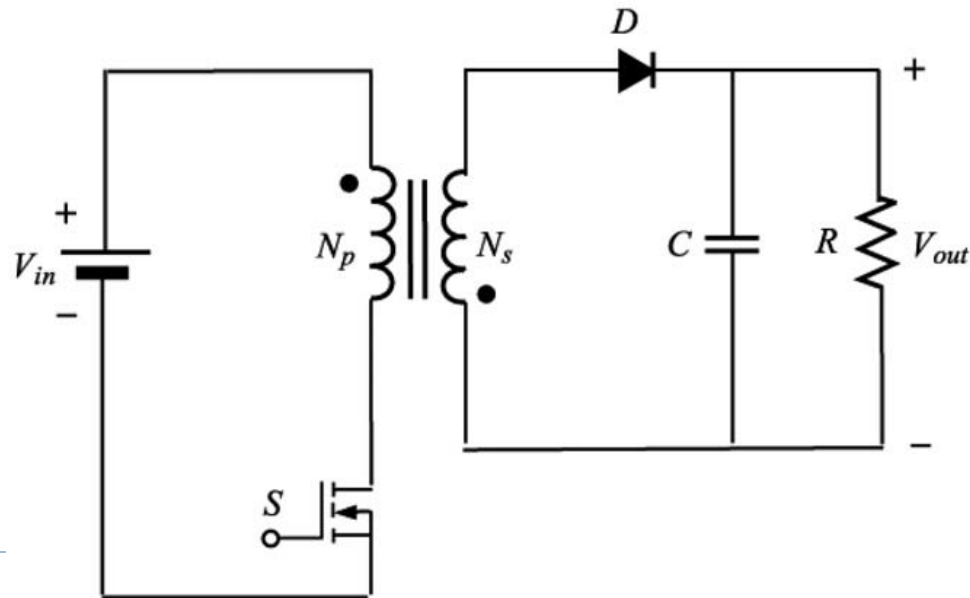
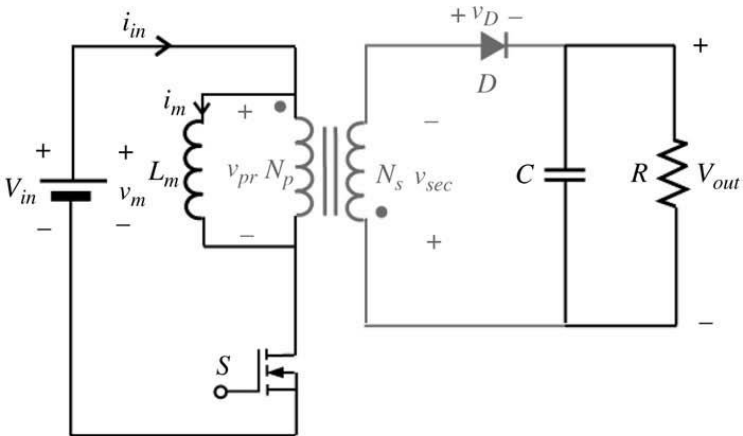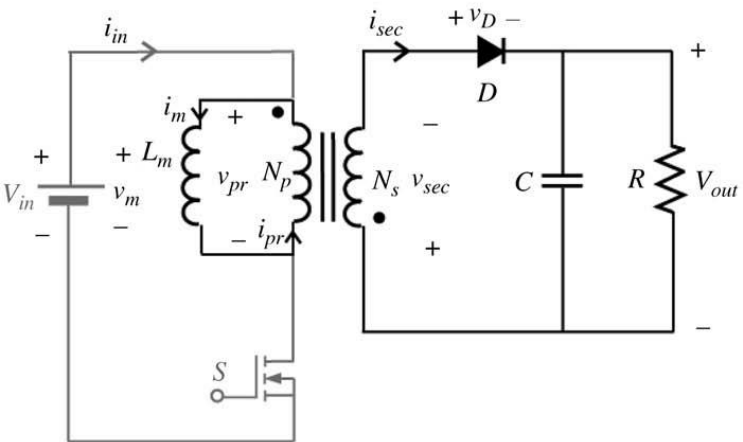- Isolation „not transformer"

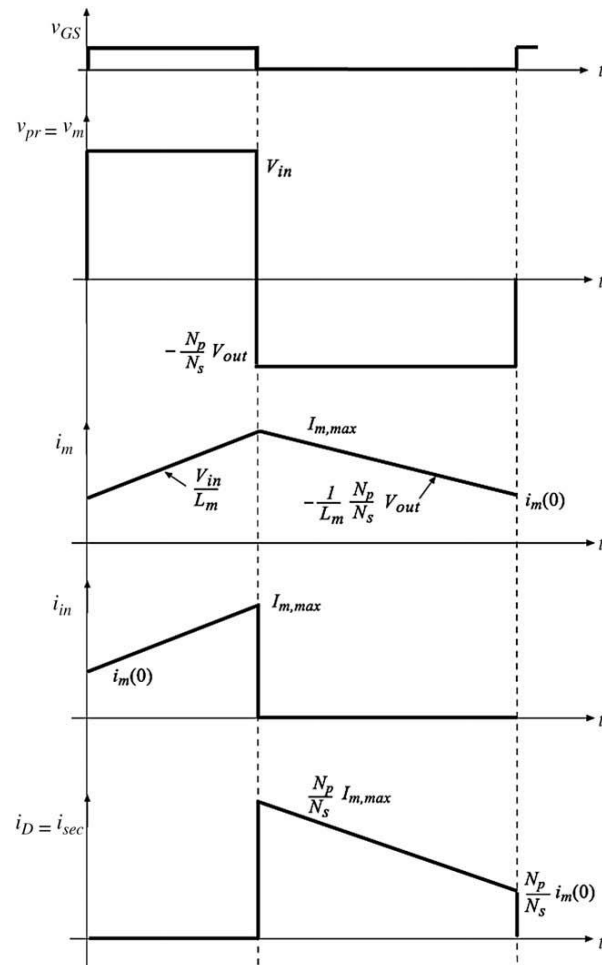# Flyback buck-boost
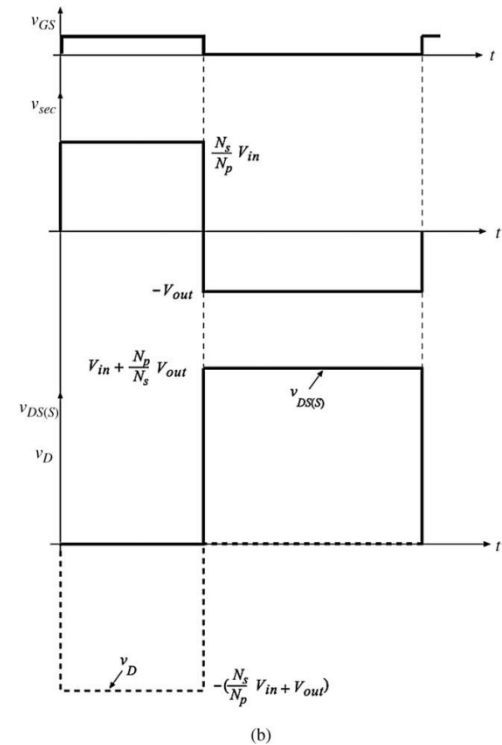
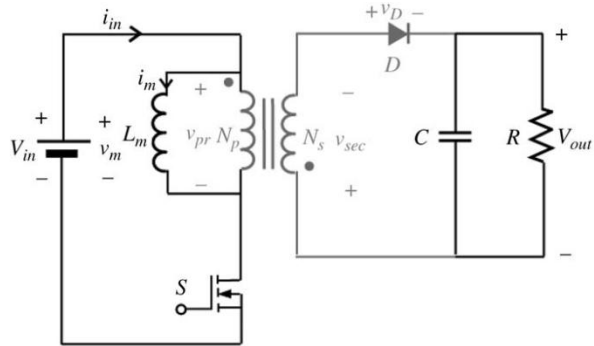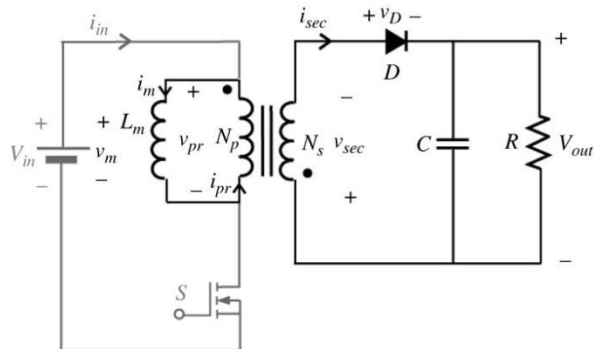

(a)

(b)

Flyback buck-boost

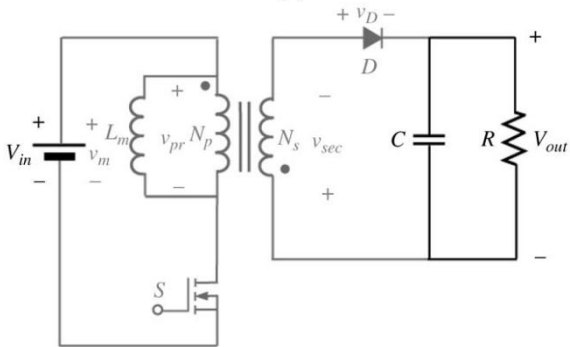(d)

(e)

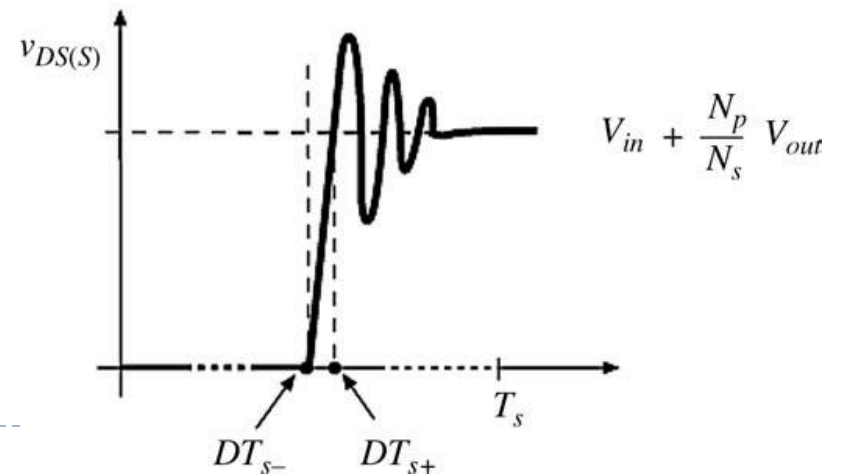# Flyback Waveform CCM
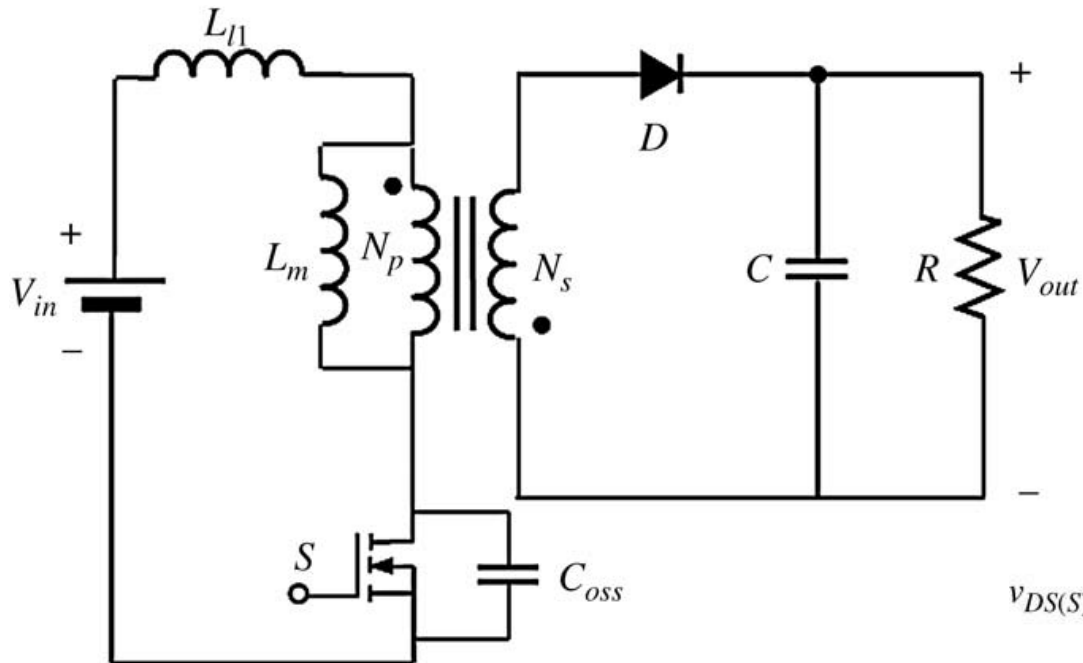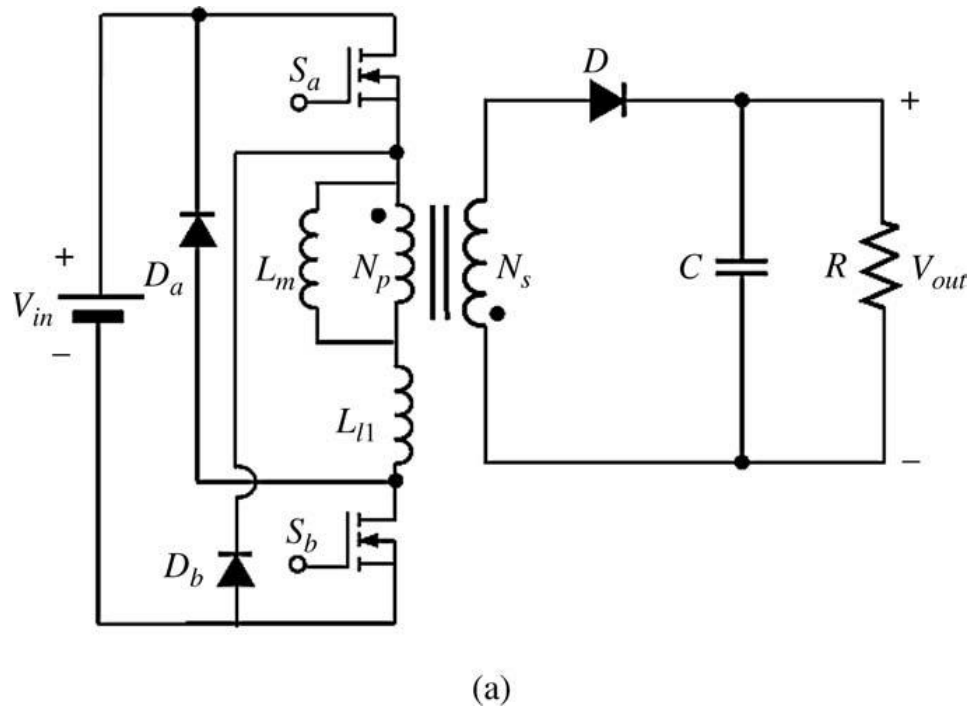

(a)

(b)

(a)

(b)

Flyback Waveform DCM

(a)

(b)

(c)

Flyback
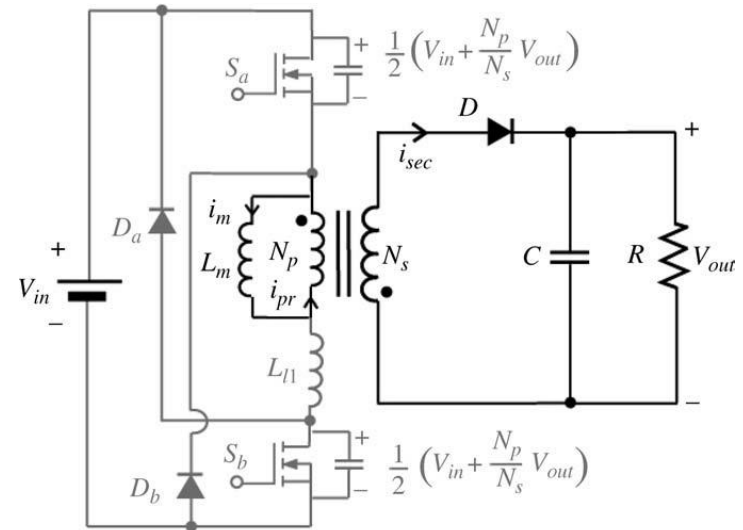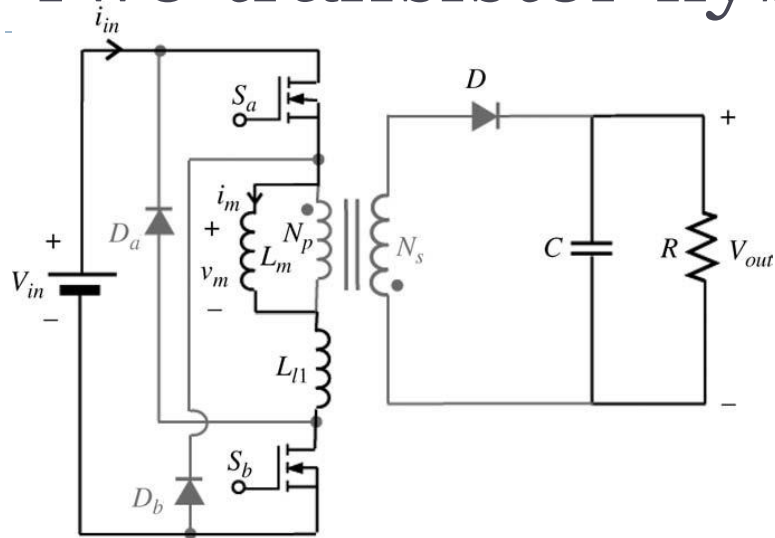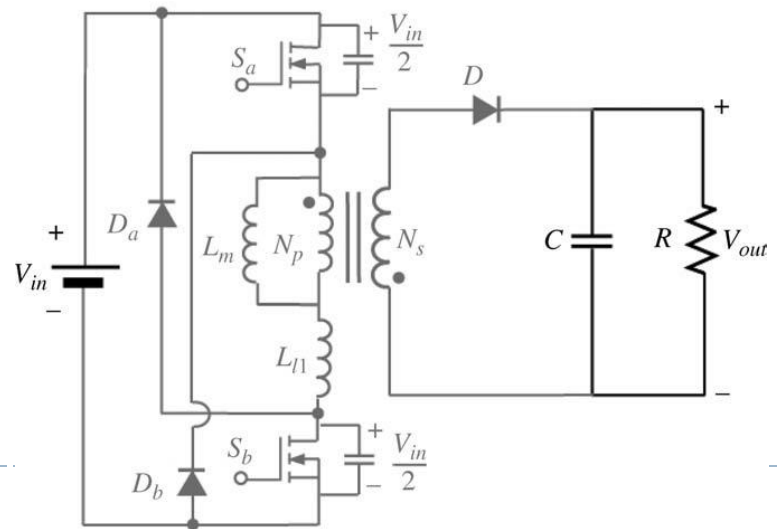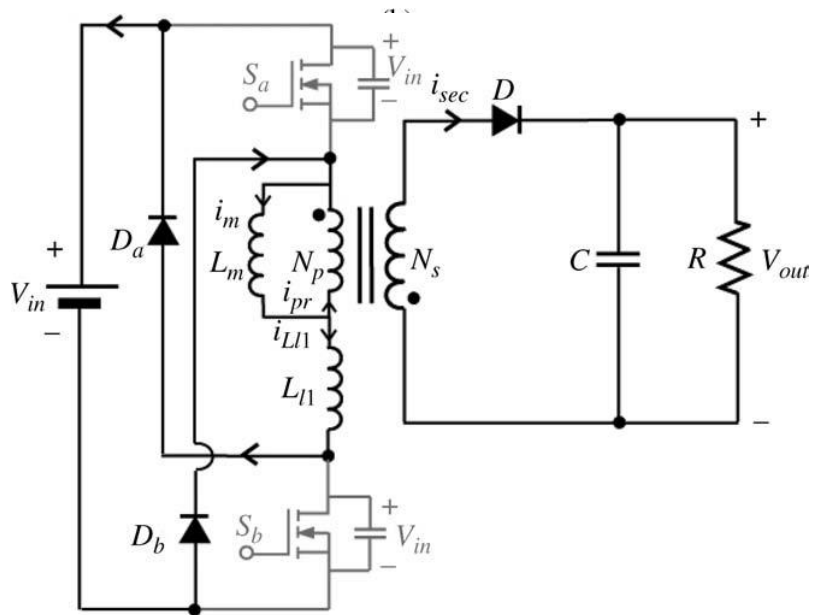# with realed transformer

Two transistor flyback
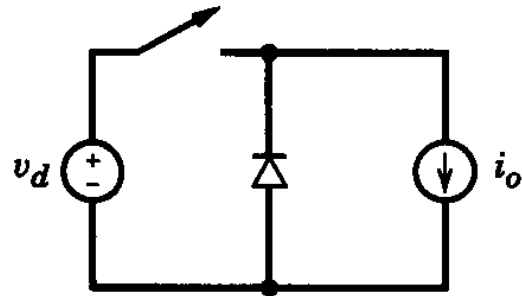
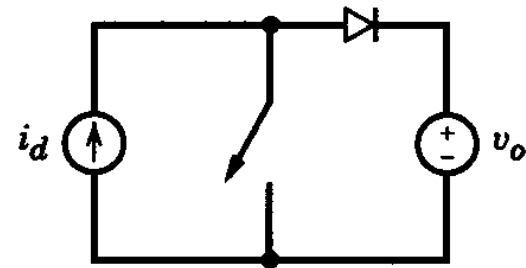▸ Input voltage very high

(a)

Two transistor flyback
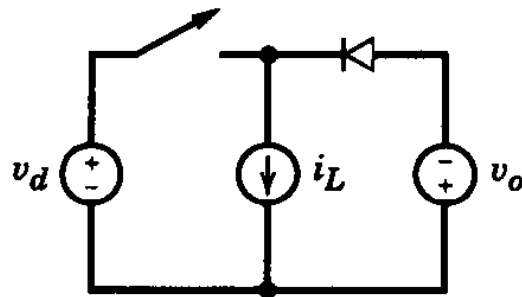
Equivalent Circuits in DC-DC Converters
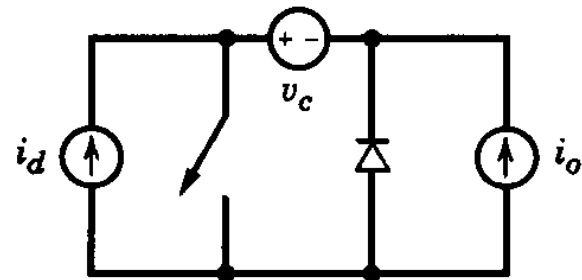replacing inductors and capacitors by current and voltage sources, respectively
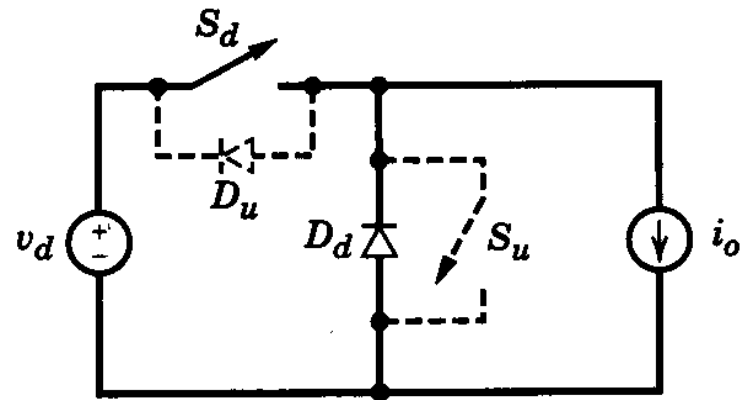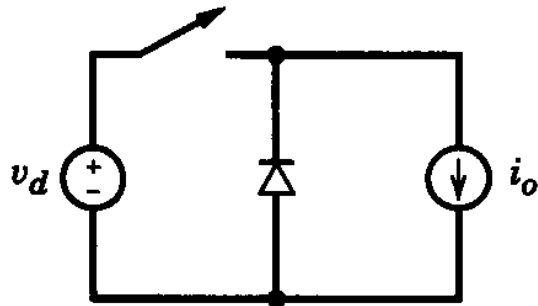

(a)

(b)

(c)

(d)

●

Reversing the Power Flow in DC-DC Conv.

▸ For power flow from right to left, the input current direction should also reverse

Homework

- Prześledzić obwody mocy znalezionych w sieci zasilaczy
  - AT
  - ATX
  - viper12