Chapter 6

DC-DC CONVERTERS

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DC-DC CONVERTERS

- Basic Switching Converters
- Buck (Step-Down) Converter
- Boost (Step-Up) Converter
- Buck-Boost Converter
- Ćuk Converter
- Discontinuous Current
- Switched Capacitor Converters
- LTSpice Simulation

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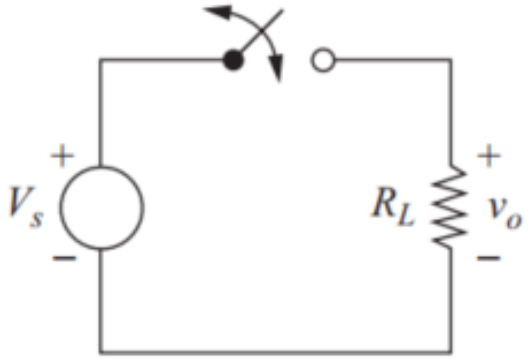
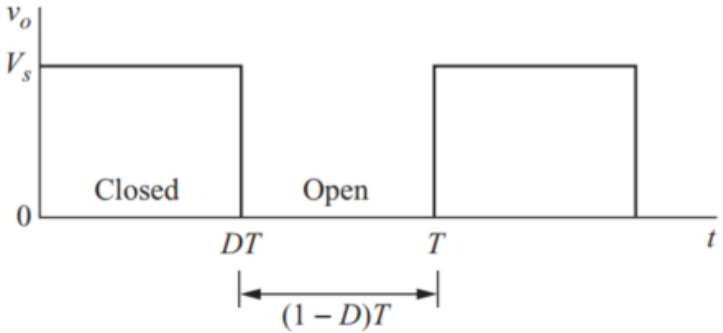
Basic Switching Converter



- Electronic switching ON or OFF
- “DC Chopper”
- Switching Period: T
- Switching Frequency: *f*
- Duty ratio: D

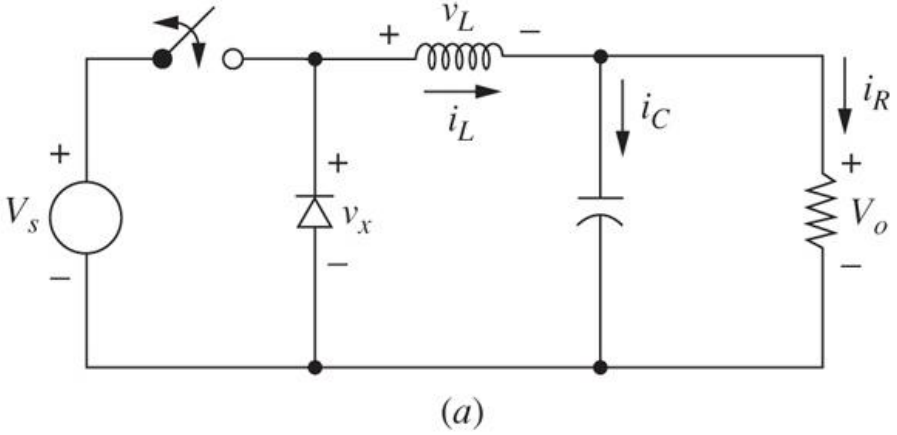
$$D \equiv \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}} = \frac{t_{\text{on}}}{T} = t_{\text{on}} f$$



- Average (dc) Output voltage: Vo

$$V_o = \frac{1}{T}\int_0^T v_o(t)\,dt = \frac{1}{T}\int_0^{DT} V_s\,dt = V_s D$$

THE BUCK (STEP-DOWN) CONVERTER



(a)

- Insertion of an inductor after the S/W
- Low-pass filtering
- Insertion of LC filter
- Step-down ("buck") converter
  - Vo = D*Vs
- Free-wheeling diode
  - vx = Vs when SW is closed (Diode open ckt)
  - vx = 0 when SW is open (Diode short ckt)
- Analysis focus: Examination of **inductor** voltage and current
- Analysis assumptions:
  - Circuit is in steady-state
  - **Inductor current is continuous and positive (CCM)**
  - Capacitor is large enough to hold Vo constant
  - Switch period is T; SW is closed for D*T and opened for (1-D)*T duration
  - Components are ideal

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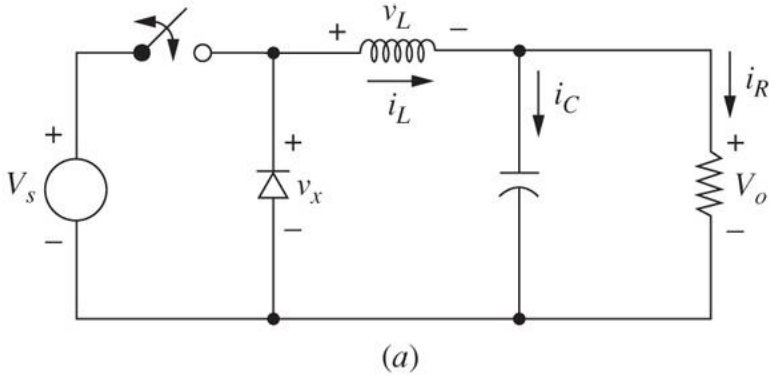
Figure 6.3



THE BUCK (STEP-DOWN) CONVERTER

- General Properties of DC-DC Converters
  - Operate in steady-state
  - Inductor current is periodic

$$i_L(t+T) = i_L(t)$$

  - Average inductor voltage is zero

$$V_L = \frac{1}{T}\int_{t}^{t+T} v_L(\lambda)d\lambda = 0$$

  - Average capacitor current is zero.

$$I_C = \frac{1}{T}\int_{t}^{t+T} i_C(\lambda)d\lambda = 0$$

  - Power supplied by the source is the same as the power delivered to the load

$$P_s = P_o \qquad \text{ideal}$$

$$P_s = P_o + \text{losses} \qquad \text{nonideal}$$

- **Analysis focus**
  - **Inductor** current and voltage
    - The net change of inductor current (over one period) = 0
    - Average inductor voltage = 0

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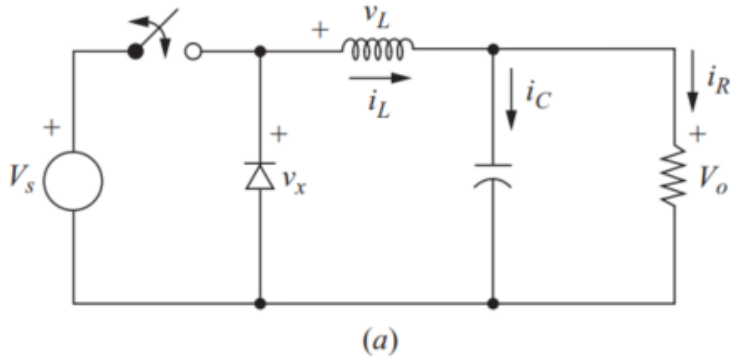
Switch Closed, Diode Off



(a)

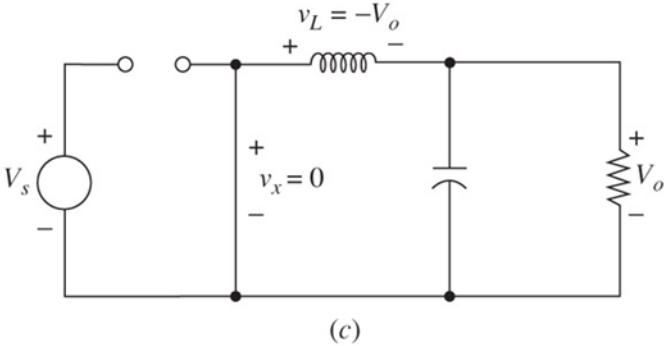
- Voltage across the inductor

$$v_L = V_s - V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s - V_o}{L}$$

$$(\Delta i_L)_{closed} = \left(\frac{V_s - V_o}{L}\right)DT$$

Switch Open, Diode ON



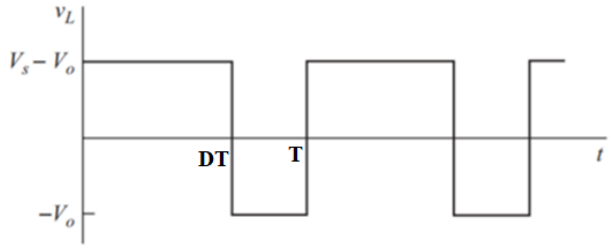
(c)

- Voltage across the inductor

$$v_L = -V_o = L\frac{di_L}{dt}$$

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = -\frac{V_o}{L}$$

$$(\Delta i_L)_{open} = -\left(\frac{V_o}{L}\right)(1-D)T$$



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Analysis Combined

- Inductor current is periodic $i_L(t+T) = i_L(t)$
- Net change of inductor current = 0

$$\left(\Delta i_L\right)_{closed} + \left(\Delta i_L\right)_{open} = 0$$

$$\left(\frac{V_s - V_o}{L}\right)DT - \left(\frac{V_o}{L}\right)(1-D)T = 0$$

- Buck Converter Output voltage: $V_o = V_s D$

- **Alternative Approach** for output voltage:
  - Average inductor voltage = 0

$$V_L = (V_s - V_o)DT + (-V_o)(1-D)T = 0$$

$$V_o = V_s D$$

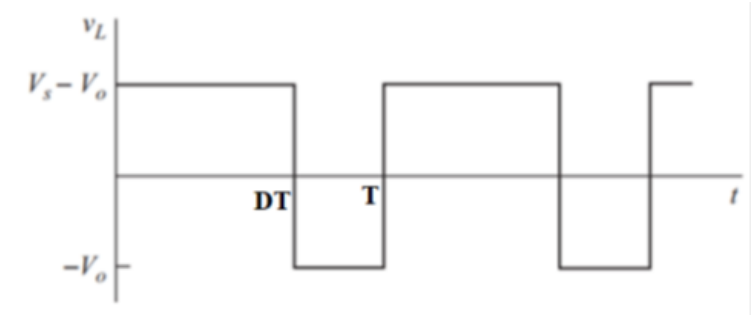

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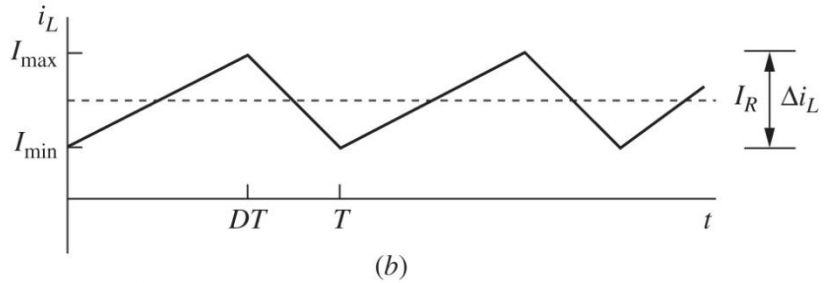
Figure 6.4

- **Maximum and minimum Inductor Current**
- Average current equation $I_L = I_R + I_C$
- Average capacitor current $I_C = 0$
- Average current equation: $I_L = I_R = \frac{V_o}{R}$
- Max and Min inductor current:



$$I_{max} = I_L + \frac{\Delta i_L}{2} = \frac{V_o}{R} + \frac{1}{2}\left[\frac{V_o}{L}(1-D)T\right] = V_o\left(\frac{1}{R} + \frac{1-D}{2Lf}\right)$$

$$I_{min} = I_L - \frac{\Delta i_L}{2} = \frac{V_o}{R} - \frac{1}{2}\left[\frac{V_o}{L}(1-D)T\right] = V_o\left(\frac{1}{R} - \frac{1-D}{2Lf}\right)$$

- CCM condition: *I*min >= 0

$$I_{min} = 0 = V_o\left(\frac{1}{R} - \frac{1-D}{2Lf}\right)$$

- Minimum inductance for CCM

$$L_{min} = \frac{(1-D)R}{2f}$$

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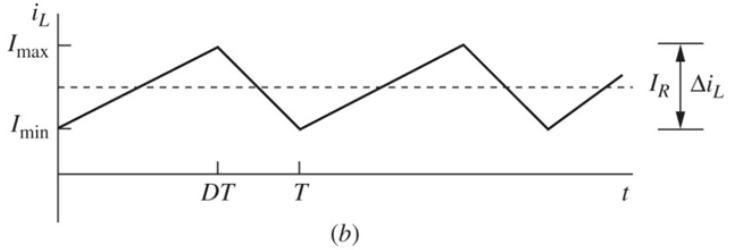
- Inductance determination by the **peak-to-peak inductor current requirement** (as a design criterion)
- Peak-to-peak inductor current



$$\Delta i_L = \left(\frac{V_s - V_o}{L}\right)DT = \left(\frac{V_s - V_o}{Lf}\right)D = \frac{V_o(1-D)}{Lf}$$

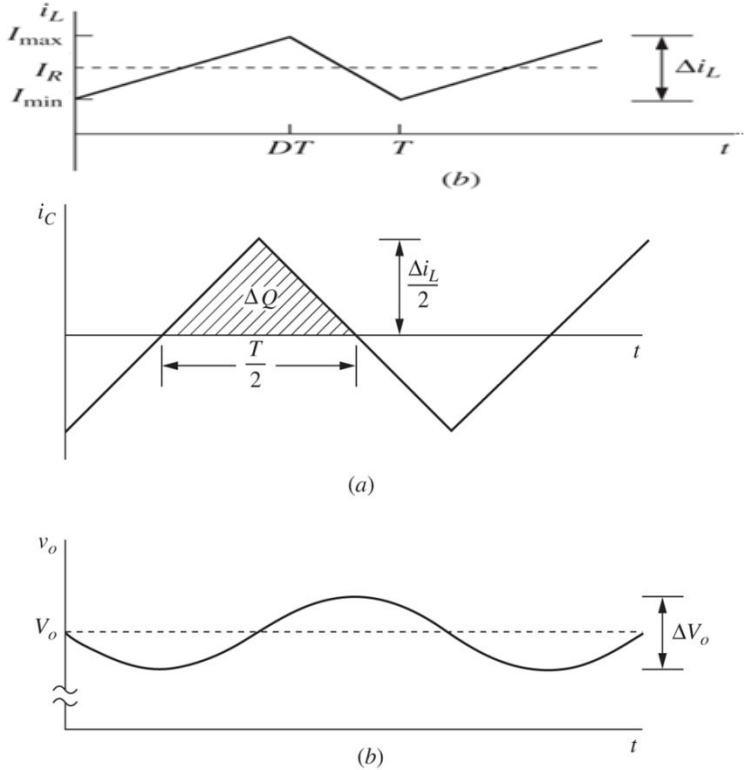
- Inductance determination

$$L = \left(\frac{V_s - V_o}{\Delta i_L f}\right)D = \frac{V_o(1-D)}{\Delta i_L f}$$

- Output voltage ripple (when capacitance is not large)
- Output voltage is not constant –> voltage variation
- Voltage ripple calculation $i_C = i_L - i_R$
  - If i_C positive, C charges

$$Q = \int_{to}^{t} i\,dt \qquad Q = CV_o \qquad \Delta Q = C\Delta V_o \qquad \Delta V_o = \frac{\Delta Q}{C}$$

$$\Delta Q = \frac{1}{2}\left(\frac{T}{2}\right)\left(\frac{\Delta i_L}{2}\right) = \frac{T\Delta i_L}{8}$$



- Ripple equation $\Delta V_o = \dfrac{T\Delta i_L}{8C}$

$$\Delta V_o = \frac{TV_o}{8CL}(1-D)T = \frac{V_o(1-D)}{8LCf^2}$$

- Capacitance determination by ripple requirement

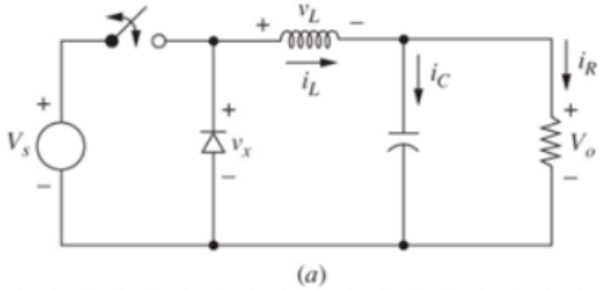
$$C = \frac{1-D}{8L(\Delta V_o/V_o)f^2}$$

- **Example 6-1**

The buck dc-dc converter of Fig. 6-3*a* has the following parameters:

$$V_s = 50\ \text{V} \quad D = 0.4 \quad L = 400\ \mu\text{H} \quad C = 100\ \mu\text{F} \quad f = 20\ \text{kHz} \quad R = 20\ \Omega$$

Assuming ideal components, calculate (*a*) the output voltage V_o, (*b*) the maximum and minimum inductor current, and (*c*) the output voltage ripple.



(*a*)

$Vs := 50 \quad D := 0.4 \quad R := 20 \quad L := 400 \cdot 10^{-6} \quad C := 100 \cdot 10^{-6} \quad f := 20 \cdot 10^{3}$

output voltage $Vo := D \cdot Vs = 20$

max inductor current $Imax := Vo \cdot \left(\frac{1}{R} + \frac{(1-D)}{2 \cdot L \cdot f} \right) = 1.75$

min inductor current $Imin := Vo \cdot \left(\frac{1}{R} - \frac{(1-D)}{2 \cdot L \cdot f} \right) = 0.25$

Average inductor current $IL := \frac{Imax + Imin}{2} = 1$

ΔiL $\Delta iL := Imax - Imin = 1.5$

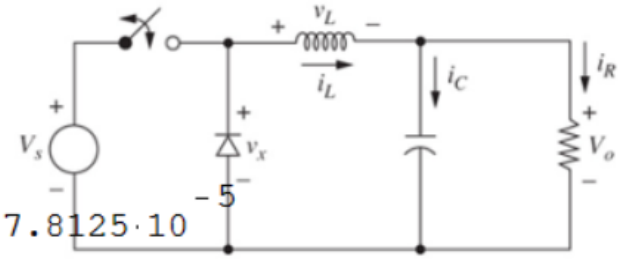
Ripple voltage rate: ΔVo/Vo $Ripple := \frac{1-D}{8 \cdot L \cdot C \cdot f^2} = 0.0046875$

- **Example 6-2 (Buck Converter Design)**

Design a buck converter to produce an output voltage of 18 V across a 10-Ω load resistor. The output voltage ripple must not exceed 0.5 percent. The dc supply is 48 V. Design for continuous inductor current. Specify the duty ratio, the switching frequency, the values of the inductor and capacitor, the peak voltage rating of each device, and the rms current in the inductor and capacitor. Assume ideal components.

$Vo := 18 \quad R := 10 \quad Vs := 48 \quad Ripple := 0.005$

$f := 40 \cdot 10^{3}$



(a)

Duty Rate $D := \frac{Vo}{Vs} = 0.375$

$T := \frac{1}{f} = 2.5 \cdot 10^{-5}$

Min inductance (CCM) $L_{min} = \frac{(1-D)R}{2f}$ $\quad Lmin := \frac{(1-D)\cdot R}{2 \cdot f} = 7.8125 \cdot 10^{-5}$

Selected inductance (with 25% larger) $\quad L := Lmin \cdot 1.25 = 9.765625 \cdot 10^{-5}$

Average inductor current $IL := \frac{Vo}{R} = 1.8$

ΔiL $\quad \Delta iL := \left(\frac{Vs - Vo}{L}\right) \cdot D \cdot T = 2.88$

max inductor current $Imax := IL + \frac{\Delta iL}{2} = 3.24$

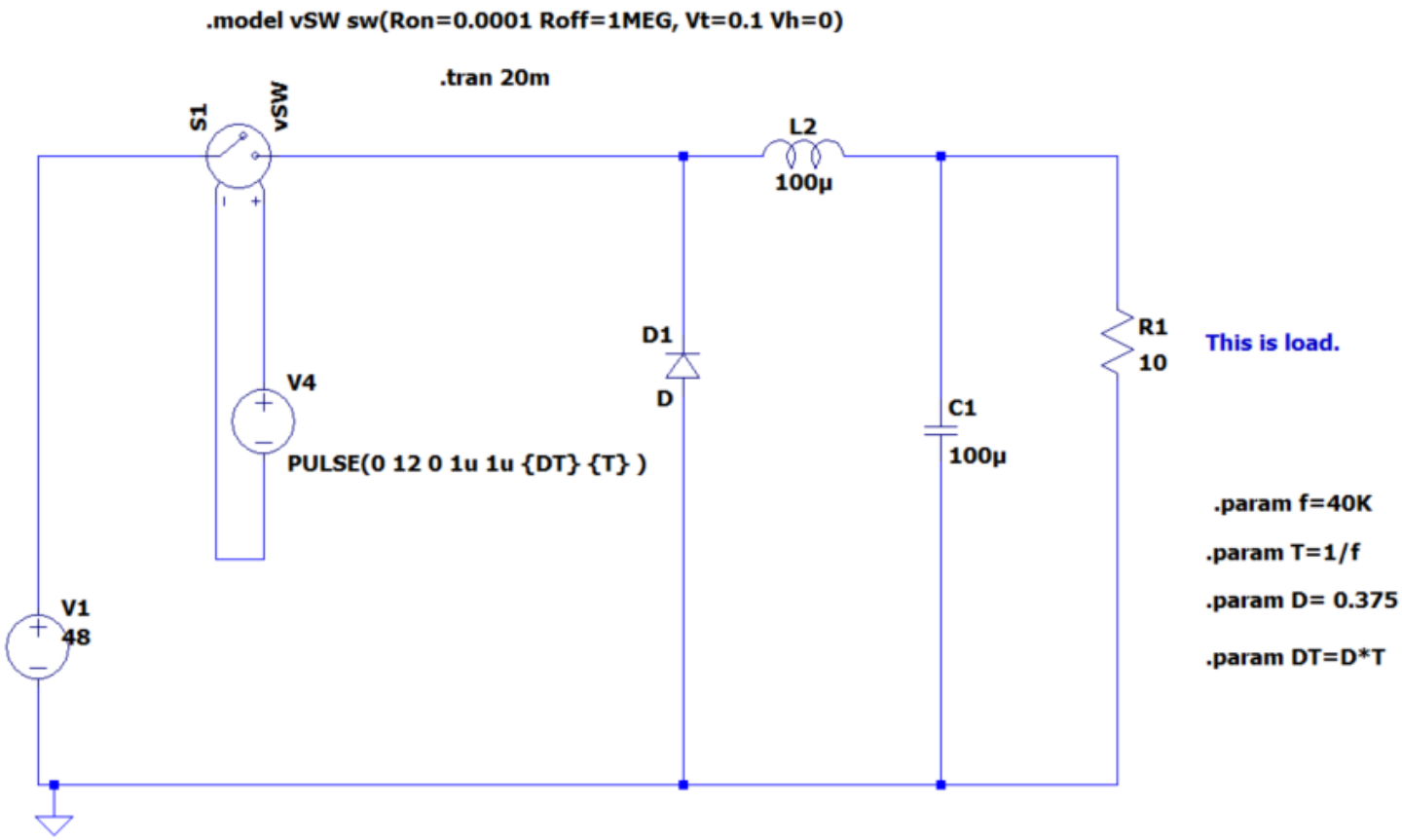
min inductor current $Imin := \left|IL - \frac{\Delta iL}{2}\right| = 0.36$

RMS inductor current $ILrms := \sqrt{IL^2 + \left(\frac{\frac{\Delta iL}{2}}{\sqrt{3}}\right)^2} = 1.9827254$

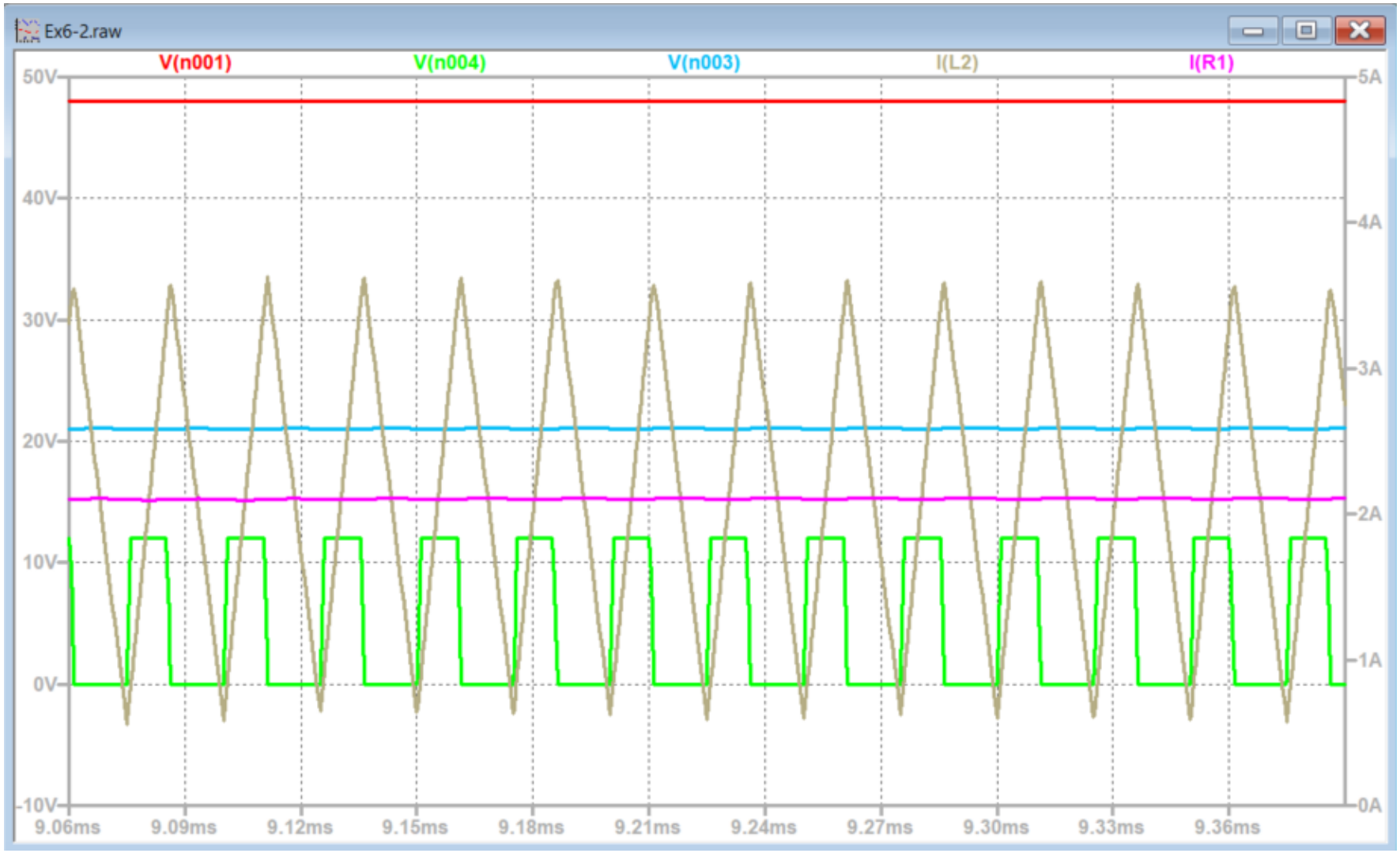
Selection of capacitance $C := \frac{(1-D)}{8 \cdot L \cdot Ripple \cdot f^2} = 0.0001$ $\quad C \cdot 10^{6} = 100$ uF

Inductor voltage $VL := Vs - Vo = 30$

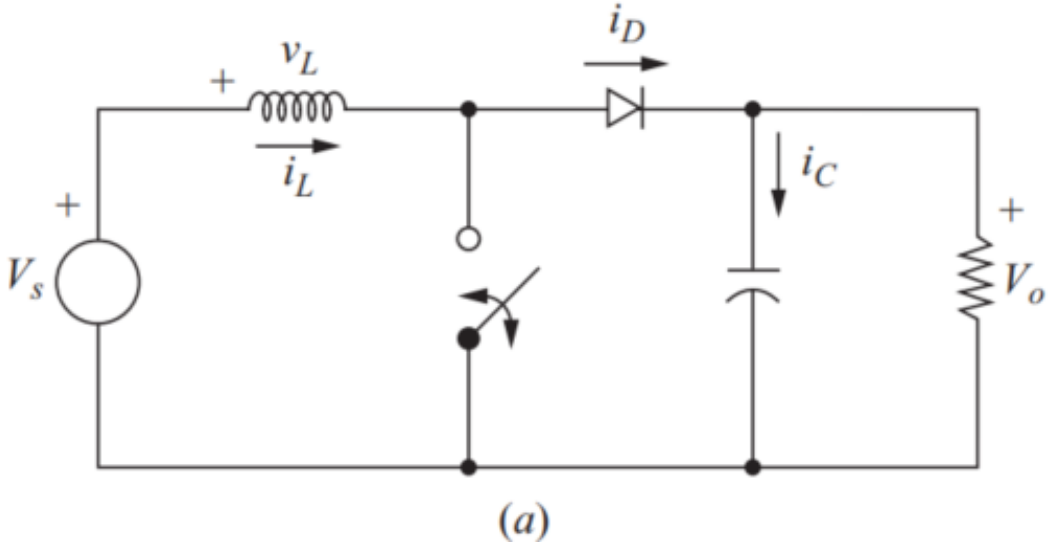
- **Simulation of Example 6-2 (Buck Converter Design) using LTSpice**



- **Simulation of Example 6-2 (Buck Converter Design) using LTSpice**



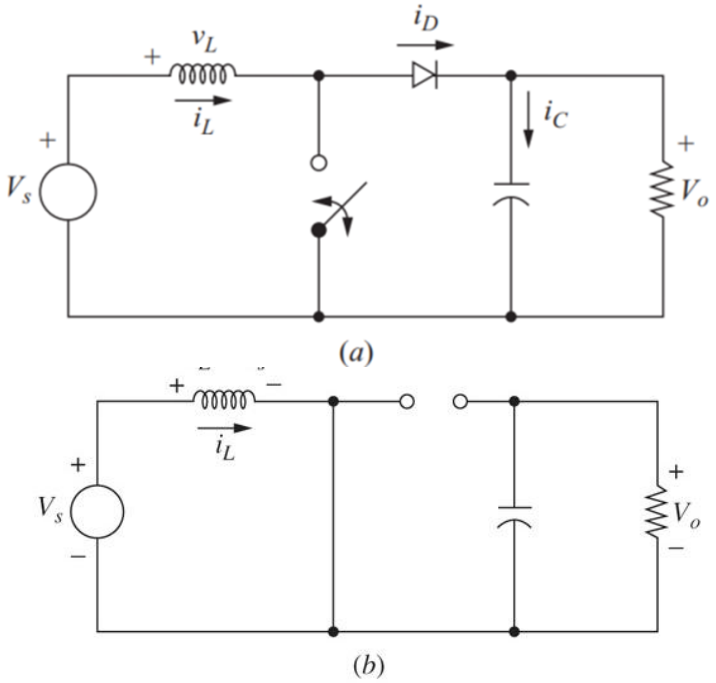
- **THE BOOST (Step-up) CONVERTER**



(a)

- Analysis **assumptions**:
  - Circuit is in steady-state
  - **Inductor current is continuous and positive (CCM)**
  - Capacitor is large enough to hold Vo constant
  - Switch period is T; SW is closed for D*T and opened for (1-D)*T duration
  - Components are ideal
- Analysis **focus**: Examination of **inductor** voltage and current

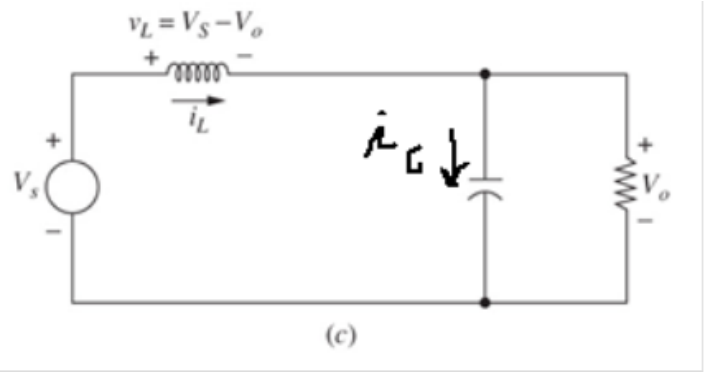
Switch Closed, Diode Off



$$v_L = V_s = L\frac{di_L}{dt} = L\frac{\Delta i_L}{\Delta t} = L\frac{\Delta i_L}{DT}$$

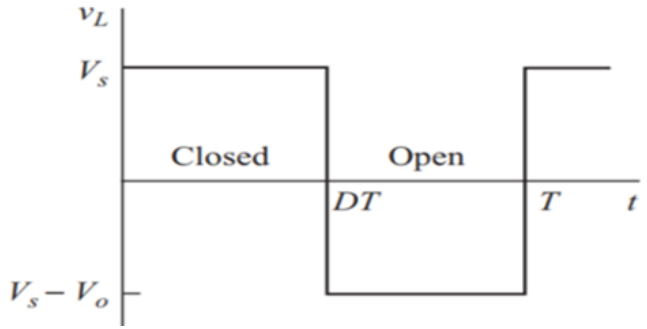
$$\left(\Delta i_L\right)_{closed} = \frac{V_s DT}{L}$$

SW Open, Diode ON



$$v_L = V_s - V_o = L\frac{di_L}{dt} = L\frac{\Delta i_L}{\Delta t} = L\frac{\Delta i_L}{(1-D)T}$$

$$\left(\Delta i_L\right)_{open} = \frac{\left(V_s - V_o\right)(1-D)T}{L}$$



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Combined Analysis

- Inductor current net change = 0 in steady-state

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

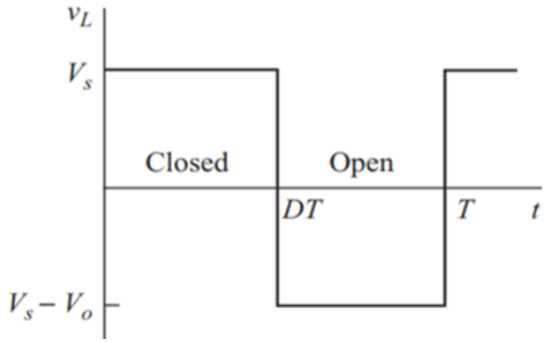
$$\frac{V_s DT}{L} + \frac{(V_s - V_o)(1-D)T}{L} = 0$$

$$V_s(D + 1 - D) - V_o(1 - D) = 0 \qquad V_o = \frac{V_s}{1-D}$$

- Alternative derivation
  - Average inductor voltage in periodic steady-state = 0
  - Sum(Voltage*time) = 0

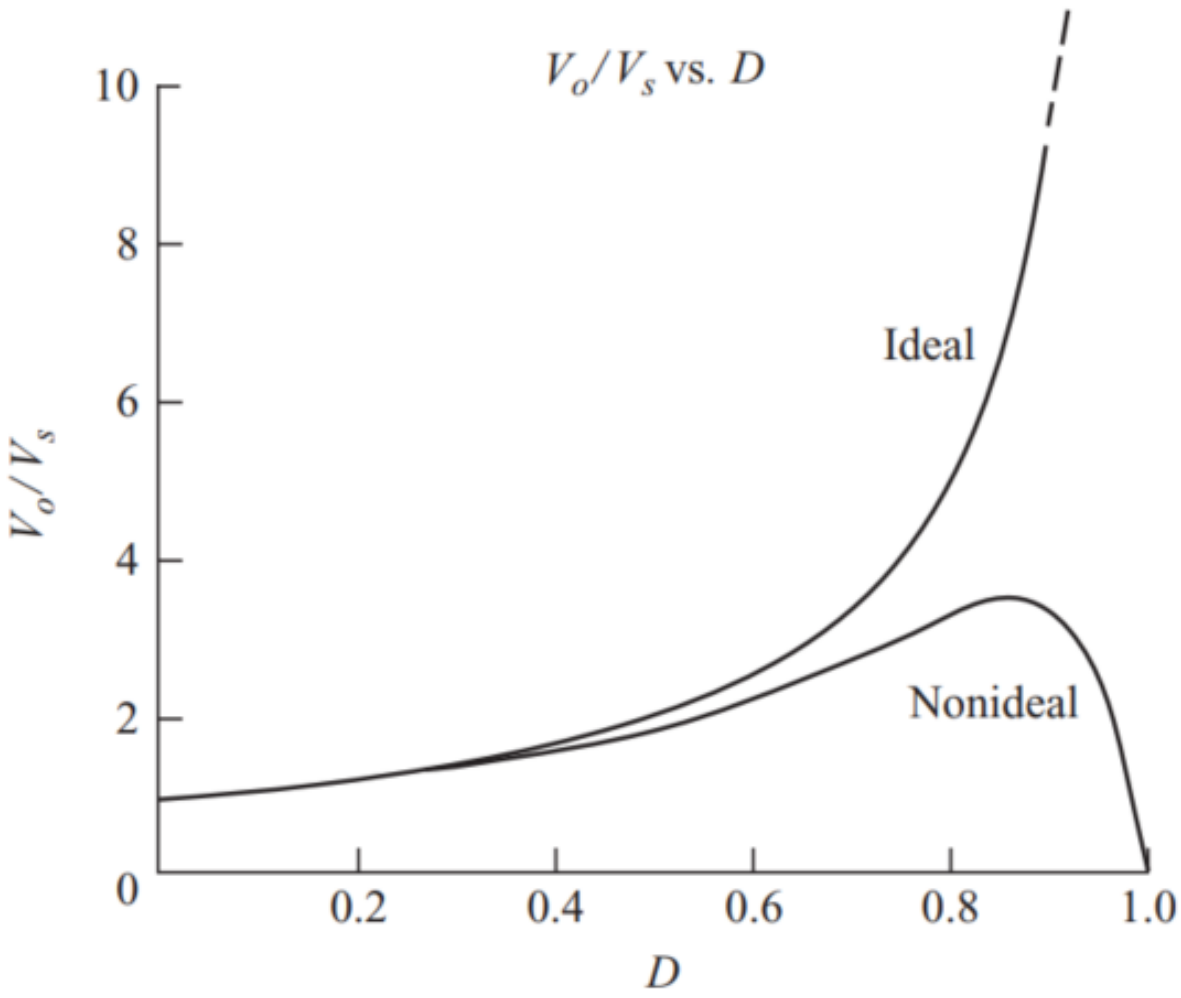
$$V_L = V_s D + (V_s - V_o)(1 - D) = 0$$

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



Combined Analysis

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



- **Max & Min inductor current**
  - Average power supplied by the source = average power absorbed by the resistor (output)
  - Output Power

$$P_o = \frac{V_o^2}{R} = V_o I_o$$

$$V_s I_s = V_s I_L$$

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

  - Input Power=Output Power

$$V_s I_L = \frac{V_o^2}{R} = \frac{[V_s/(1-D)]^2}{R} = \frac{V_s^2}{(1-D)^2} R$$

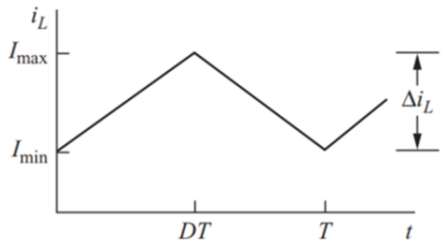
  - Average Inductor Current

$$I_L = \frac{V_s}{(1-D)^2 R} = \frac{V_o^2}{V_s R} = \frac{V_o I_o}{V_s}$$

  - Max and Min Inductor Current

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2 R} + \frac{V_s DT}{2L}$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2 R} - \frac{V_s DT}{2L}$$



$$(\Delta i_L)_{\text{closed}} = \frac{V_s DT}{L}$$

- CCM Condition: *I*min>=0

$$I_{\min} = 0 = \frac{V_s}{(1-D)^2 R} - \frac{V_s DT}{2L}$$

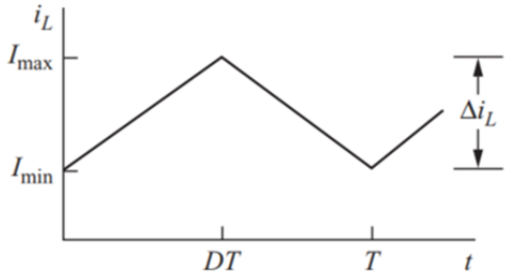
- Minimum Inductance for CCM

$$L_{\min} = \frac{D(1-D)^2 R}{2f}$$

- Inductance in terms of the ripple current

$$(\Delta i_L)_{\text{closed}} = \frac{V_s DT}{L}$$

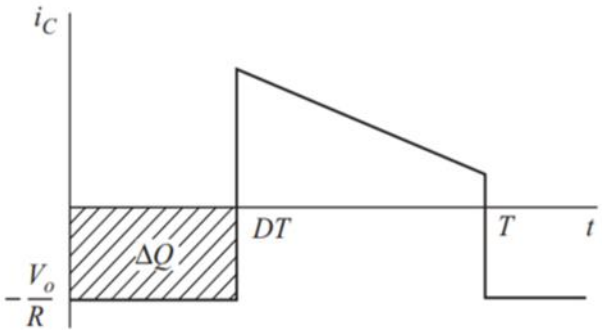
$$L = \frac{V_s DT}{\Delta i_L} = \frac{V_s D}{\Delta i_L f}$$



Output Voltage Ripple

- Case for finite capacitance and output voltage not constant
- Voltage ripple is calculated from Capacitor Current
- Change in capacitor charge (shaded area)

$$|\Delta Q| = \left(\frac{V_o}{R}\right) DT = C\Delta V_o$$



- Ripple voltage

$$\Delta V_o = \frac{V_o DT}{RC} = \frac{V_o D}{RCf} \qquad \frac{\Delta V_o}{V_o} = \frac{D}{RCf}$$

- Determination of Capacitance by the ripple voltage

$$C = \frac{D}{R(\Delta V_o / V_o) f}$$

Example 6-4 Boost Converter Design

Design a boost converter that will have an output of 30 V from a 12-V source. Design for continuous inductor current and an output ripple voltage of less than one percent. The load is a resistance of 50 Ω. Assume ideal components for this design.

$Vs := 12 \quad Vo := 30 \quad R := 50 \quad Vrip := 0.01 \quad \frac{\Delta Vo}{Vo}$

Duty Rate

From Vo = Vs/ (1 - D)

$$D := 1 - \frac{Vs}{Vo} = 0.6$$

$f := 25 \cdot 10^{3}$ example

$$T := \frac{1}{f}$$

$$Lmin := \frac{D \cdot (1-D)^{2} \cdot R}{2 \cdot f} = 9.6 \cdot 10^{-5}$$

$$L := Lmin \cdot 1.25 = 0.00012$$

$$IL := \frac{Vs}{(1-D)^{2} \cdot R} = 1.5$$

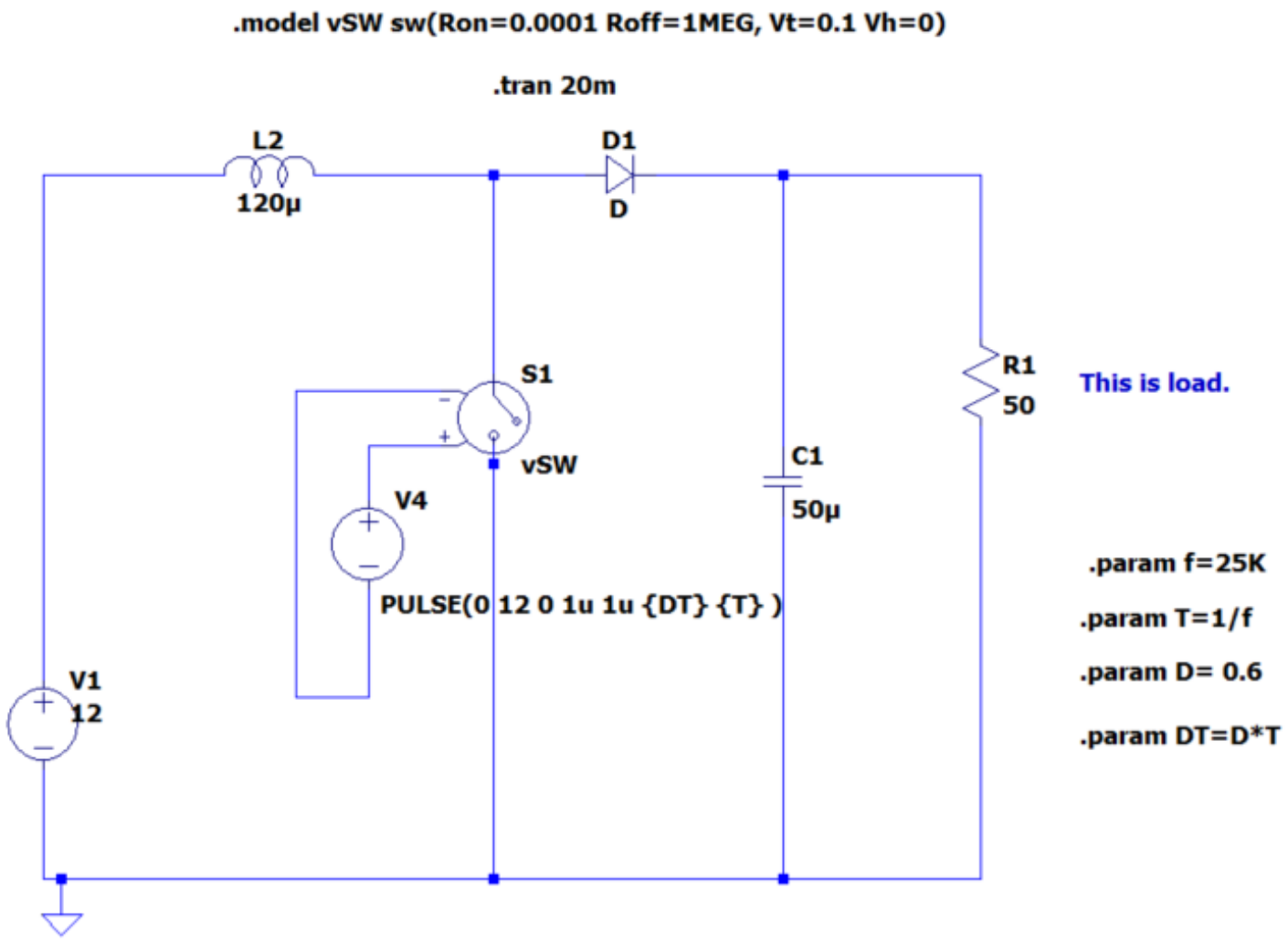
$$\Delta iL := \frac{Vs \cdot D \cdot T}{L} = 2.4$$

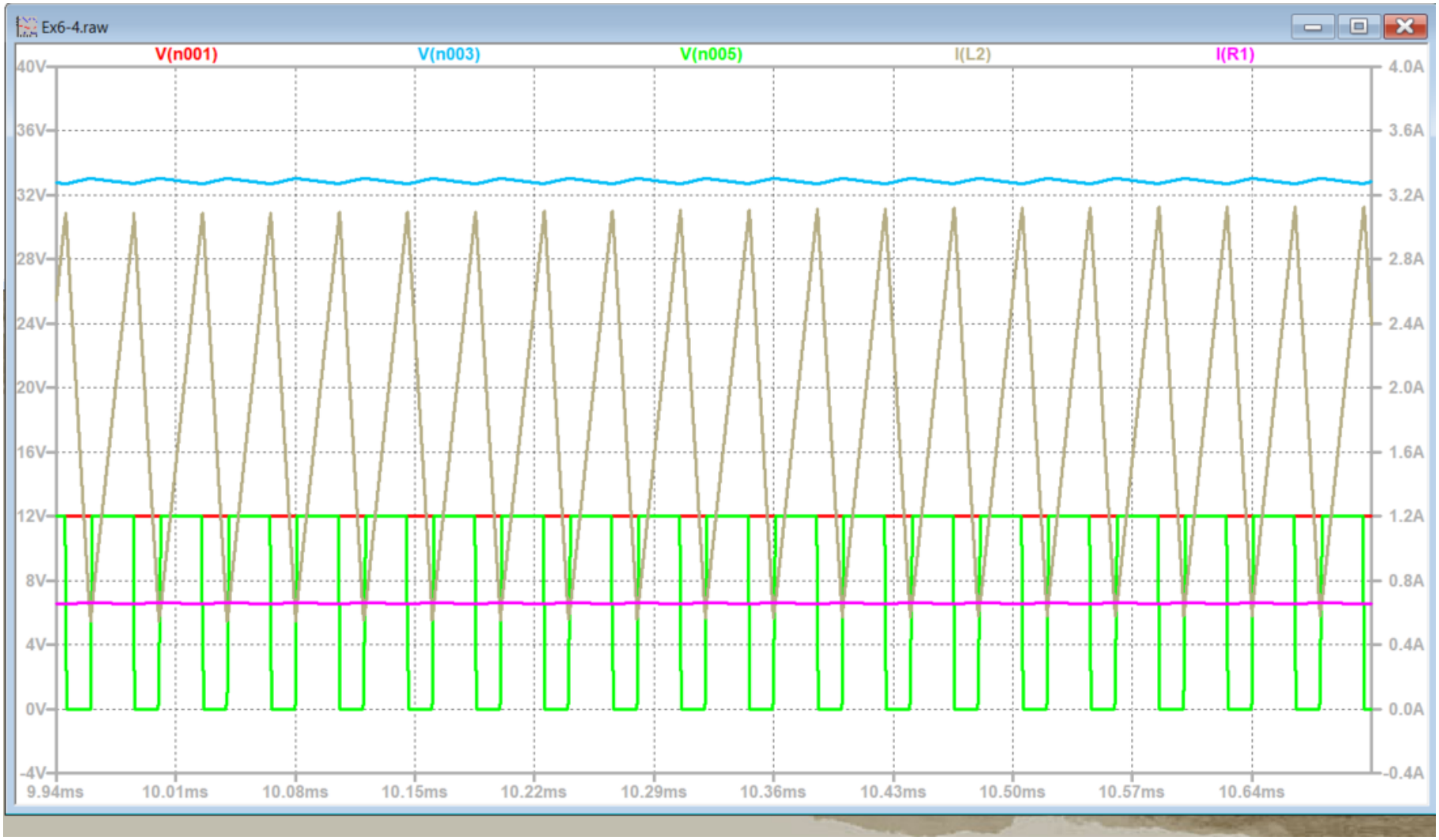
$$Imax := IL + \frac{\Delta iL}{2} = 2.7$$

$$Imin := IL - \frac{\Delta iL}{2} = 0.3$$

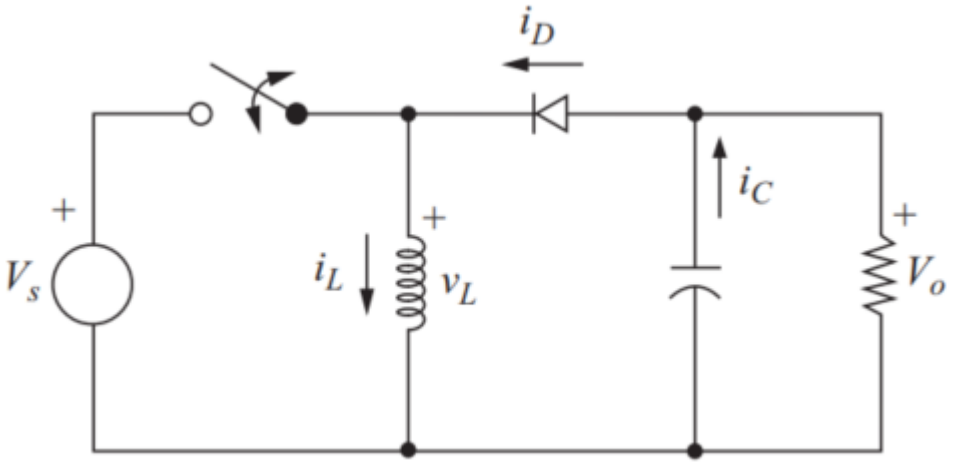
$$Cmin := \frac{D}{R \cdot Vrip \cdot f} = 4.8 \cdot 10^{-5}$$

Example 6-4 Simulation




Ex6-4.raw
V(n001)
V(n003)
V(n005)
I(L2)
I(R1)
40V
36V
32V
28V
24V
20V
16V
12V
8V
4V
0V
-4V
4.0A
3.6A
3.2A
2.8A
2.4A
2.0A
1.6A
1.2A
0.8A
0.4A
0.0A
-0.4A
9.94ms
10.01ms
10.08ms
10.15ms
10.22ms
10.29ms
10.36ms
10.43ms
10.50ms
10.57ms
10.64ms

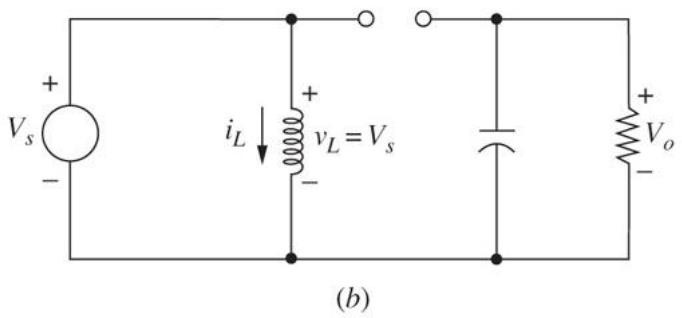
- **THE BUCK-BOOST CONVERTER**



  - Vo > Vs or Vo < Vs : Duty rate control
  - **Voltage polarity is opposite**
  - Source not directly connected to Load
  - Energy stored in the inductor
  - Energy is transferred to the load

- Analysis **assumptions**:
  - Circuit is in steady-state
  - **Inductor current is continuous and positive (CCM)**
  - Capacitor is large enough to hold Vo constant
  - Switch period is T; SW is closed for D*T and opened for (1-D)*T duration
  - Components are ideal
- Analysis **focus**: Examination of **inductor** voltage and current

Switch Closed, Diode Off

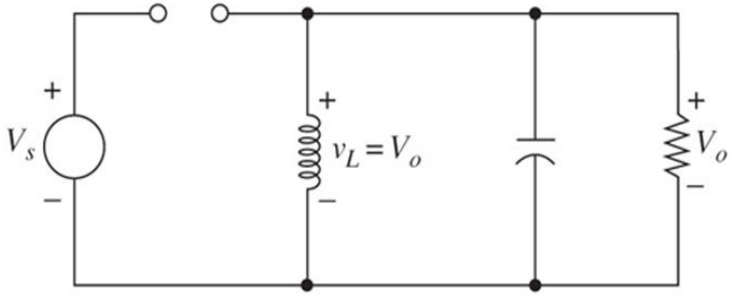


$$v_L = V_s = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L}$$

$$\left(\Delta i_L\right)_{closed} = \frac{V_s DT}{L}$$

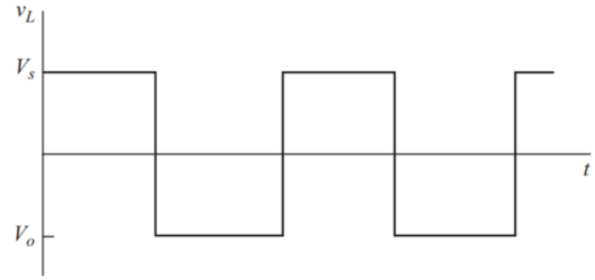
Switch Open, Diode On



$$v_L = V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L}$$

$$\left(\Delta i_L\right)_{open} = \frac{V_o(1-D)T}{L}$$



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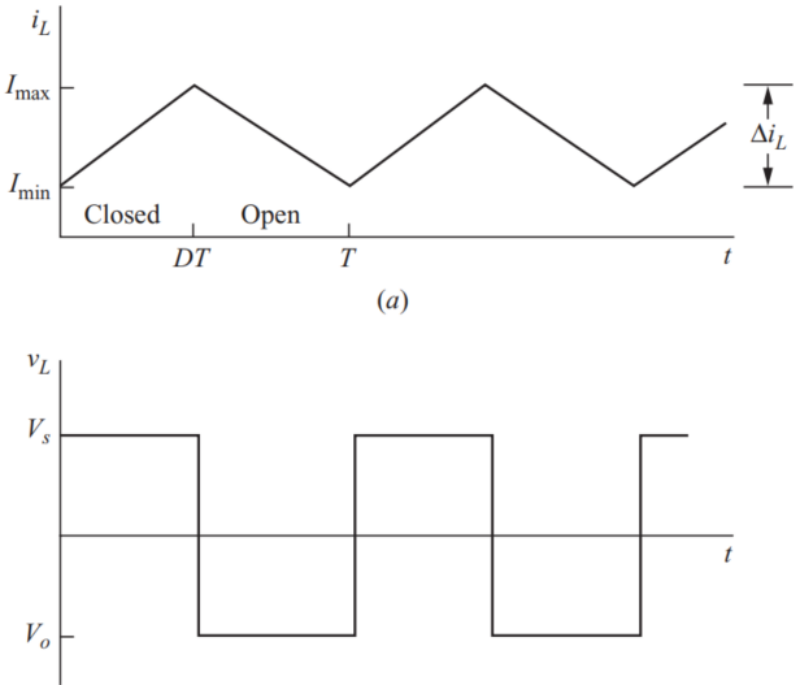
Steady-State. Combined Analysis

$$\left(\Delta i_L\right)_{closed} + \left(\Delta i_L\right)_{open} = 0$$

$$\frac{V_s DT}{L} + \frac{V_o (1-D)T}{L} = 0$$

$$V_o = -V_s\left[\frac{D}{1-D}\right]$$



- Alternatively, using the average inductor current=0

$$V_L = V_s D + V_o(1-D) = 0$$

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

Duty Rate expression:

$$D = \frac{|V_o|}{V_s + |V_o|}$$

D>0.5 Boost

D<0.5 Buck

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- **Buck-Boost Converter (Power, Current, Voltage)**
- Power absorbed by the load = Power supplied by the source
- Average source current $I_s = I_L D$

$$\frac{V_o^2}{R} = V_s I_s = V_s I_L D$$

- Average inductor current

$$I_L = \frac{V_o^2}{V_s R D} = \frac{P_o}{V_s D} = \frac{V_s D}{R(1-D)^2}$$

- Max & Min inductor currents

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} + \frac{V_s DT}{2L}$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} - \frac{V_s DT}{2L}$$

- Condition for CCM (Imin >=0)

$$L_{\min} = \frac{(1-D)^2 R}{2f}$$

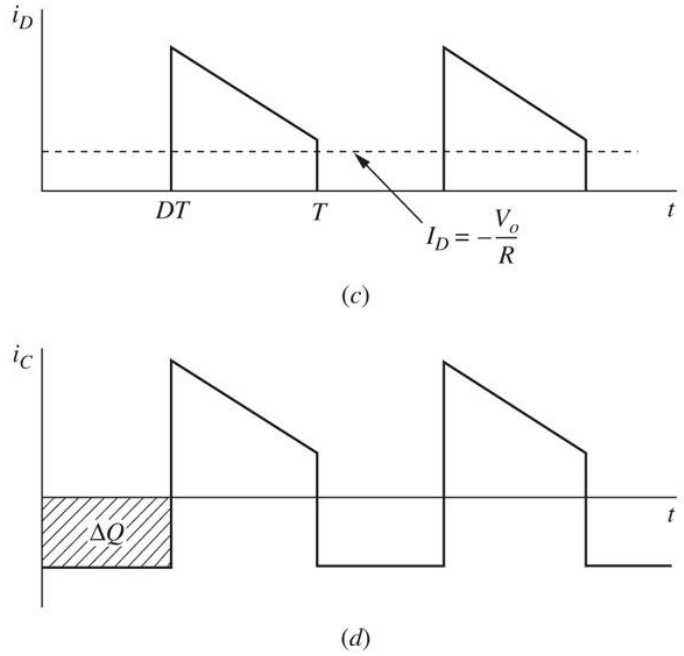
$$P_o = \frac{V_o^2}{R}$$

$$P_s = V_s I_s$$

$$\frac{V_o^2}{R} = V_s I_s$$

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

Output Voltage Ripple for the Buck-Boost



- Change in charge

$$\left|\Delta Q\right| = \left(\frac{V_o}{R}\right) DT = C\Delta V_o$$

$$\Delta V_o = \frac{V_o DT}{RC} = \frac{V_o D}{RCf}$$

- Ripple Voltage

$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf}$$

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Example 6-6 Buck-Boost Converter

The buck-boost circuit of Fig. 6-11 has these parameters:

$V_s = 24\ \text{V} \quad D = 0.4 \quad R = 5\ \Omega$

$L = 20\ \mu\text{H} \quad C = 80\ \mu\text{F} \quad f = 100\ \text{kHz}$

Determine the output voltage, inductor current average, maximum and minimum values, and the output voltage ripple.

$D := 0.4 \quad R := 5 \quad Vs := 24 \quad Ripple := 0.005 \quad f := 100 \cdot 10^{3} \quad T := \frac{1}{f} = 1 \cdot 10^{-5}$

$L := 20 \cdot 10^{-6} \quad C := 80 \cdot 10^{-6}$

Output voltage $\quad Vo := -Vs \cdot \left(\frac{D}{1-D}\right) = -16$

Inductor Current $\quad IL := \frac{Vs \cdot D}{R \cdot (1-D)^{2}} = 5.3333333$

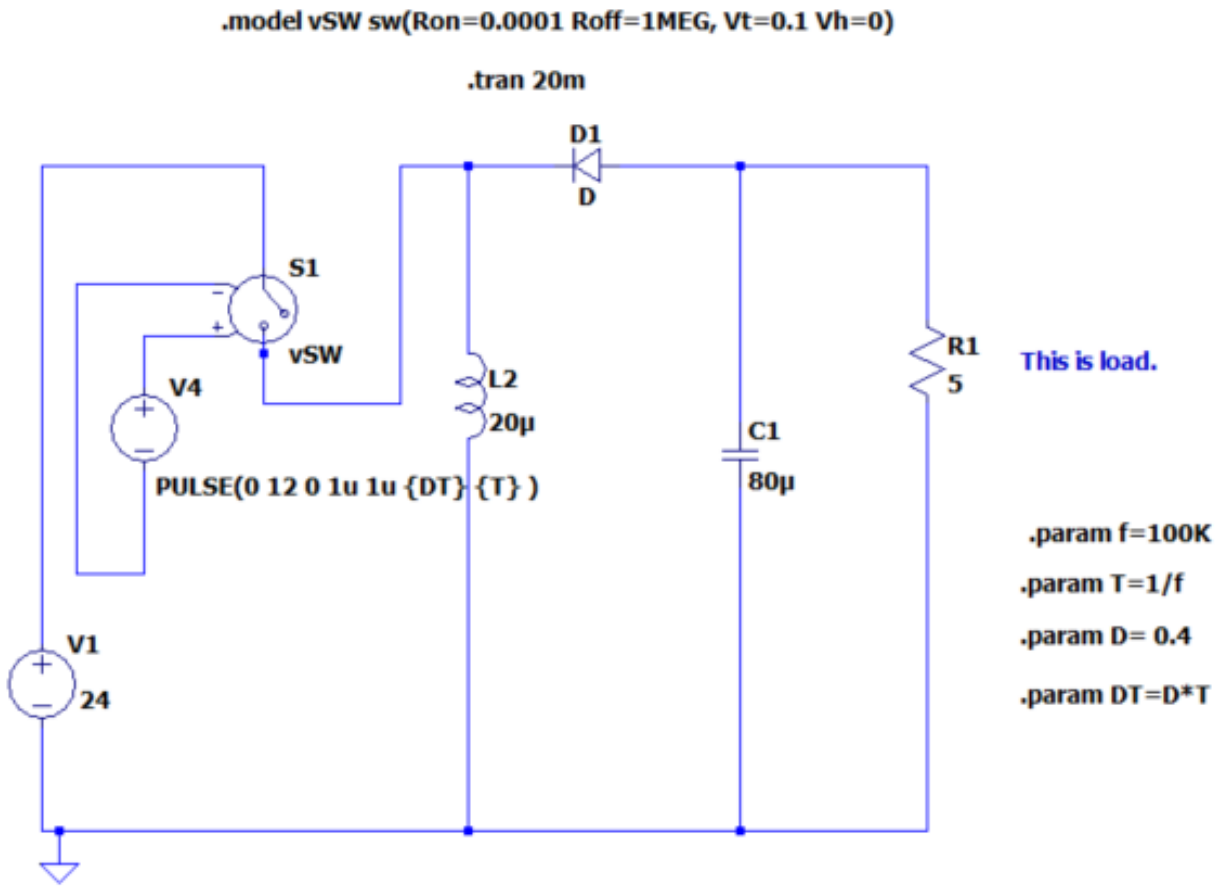
ΔiL $\quad \Delta iL := \left(\frac{Vs}{L}\right) \cdot D \cdot T = 4.8$

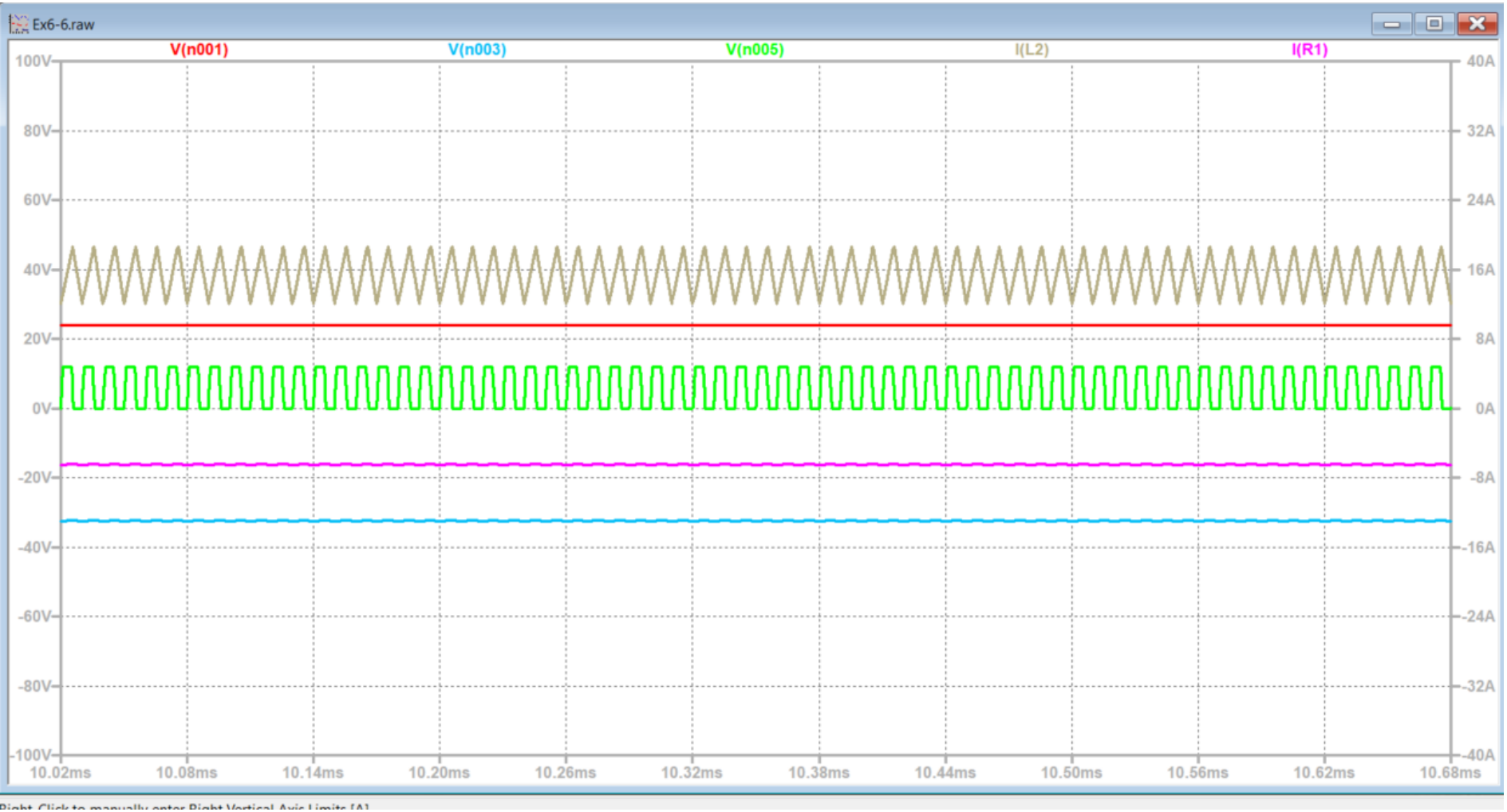
max inductor current $\quad Imax := IL + \frac{\Delta iL}{2} = 7.7333333$

min inductor current $\quad Imin := \left|IL - \frac{\Delta iL}{2}\right| = 2.9333333$

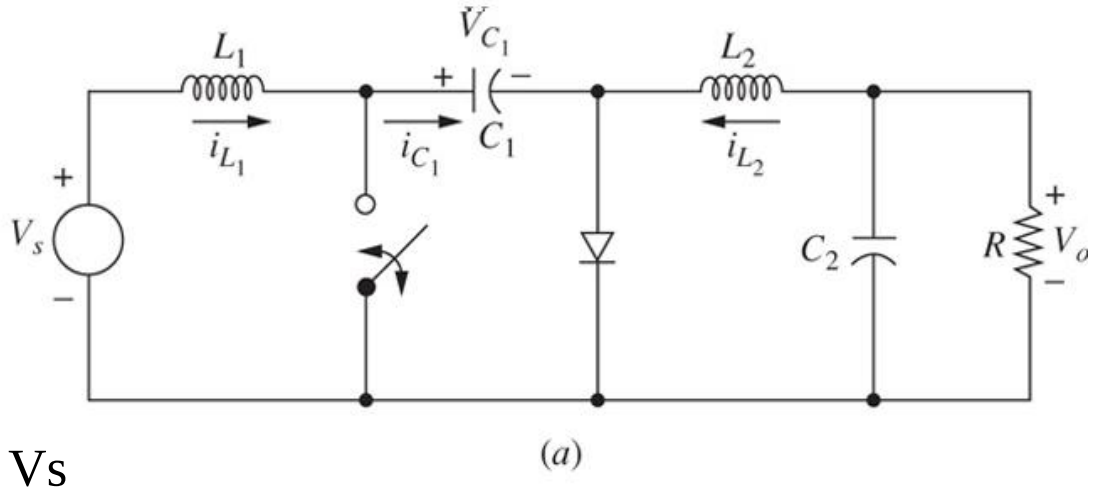
Output Ripple (ΔVo / Vo) $\quad Vripple := \frac{D}{R \cdot C \cdot f} = 0.01$

Example 6-6 Simulation




Ex6-6.raw
V(n001)
V(n003)
V(n005)
I(L2)
I(R1)
100V
80V
60V
40V
20V
0V
-20V
-40V
-60V
-80V
-100V
40A
32A
24A
16A
8A
0A
-8A
-16A
-24A
-32A
-40A
10.02ms
10.08ms
10.14ms
10.20ms
10.26ms
10.32ms
10.38ms
10.44ms
10.50ms
10.56ms
10.62ms
10.68ms

THE ĆUK CONVERTER



- Vo > Vs or Vo < Vs
- Output polarity reversal
- **L1**: working as a filter to prevent source harmonics
- Energy transfer is associated with **C1**
- Analysis **assumptions**:
  - Circuit in steady-state and periodic
  - Inductors (**L1** and **L2**) large – constant current
  - Capacitors (**C1** and **C2**) are large enough to hold Vc1 and Vc2 constant
  - Switch period is T; SW closed for D*T and opened for (1-D)*T duration
  - Components ideal
- Analysis **focus**: Examination of **Capacitor** voltage and current

$$V_{C_1} = V_s - V_o$$

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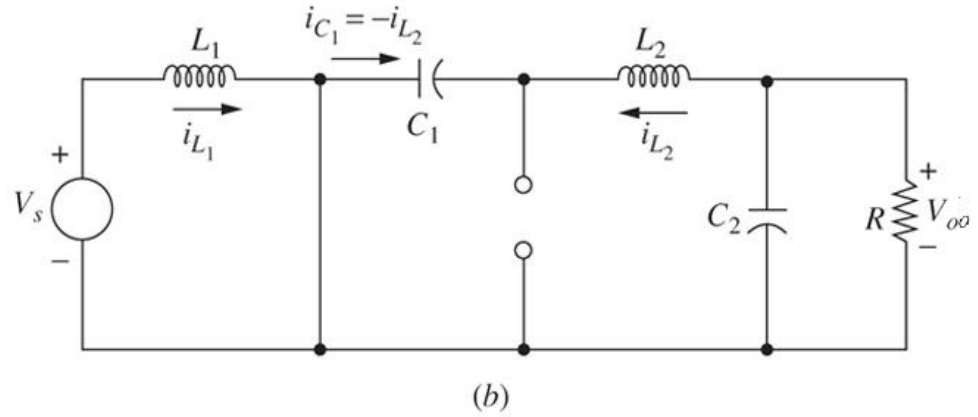
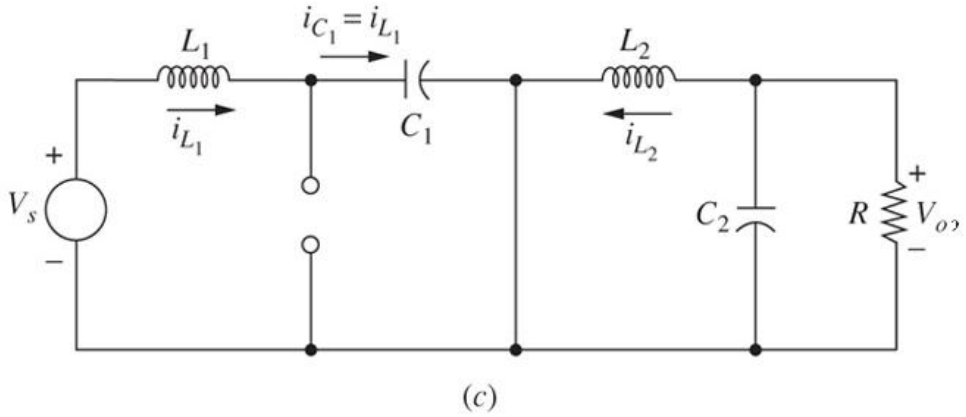
Switch Closed, Diode Off

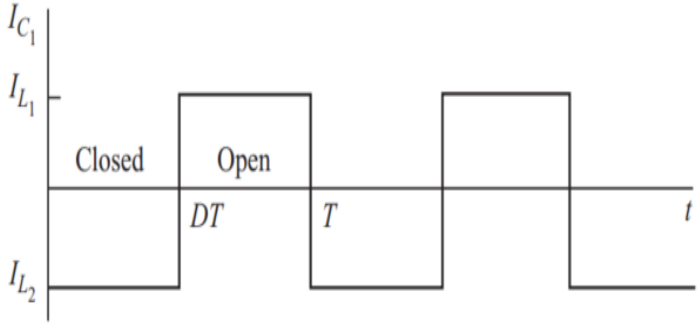


$$(i_{C_1})_{\text{closed}} = -I_{L_2}$$

Switch Open, Diode On



$$\left(i_{C1}\right)_{\text{open}} = I_{L1}$$



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$(i_{C1})_{closed} = -I_{L2}$ $\quad (i_{C1})_{open} = I_{L1}$

- Average capacitor current = 0: $\left[(i_{C1})_{closed}\right]DT + \left[(i_{C1})_{open}\right](1-D)T = 0$

$$-I_{L2}DT + I_{L1}(1-D) = 0$$

$$\frac{I_{L1}}{I_{L2}} = \frac{D}{1-D}$$

- Average power supplied by the source = Average power absorbed by the load:

$$P_s = P_o$$

$$V_s I_{L1} = -V_o I_{L2}$$

- Output-Input Relationship:

$$V_o = -V_s \frac{I_{L1}}{I_{L2}} = -V_s \left(\frac{D}{1-D}\right)$$

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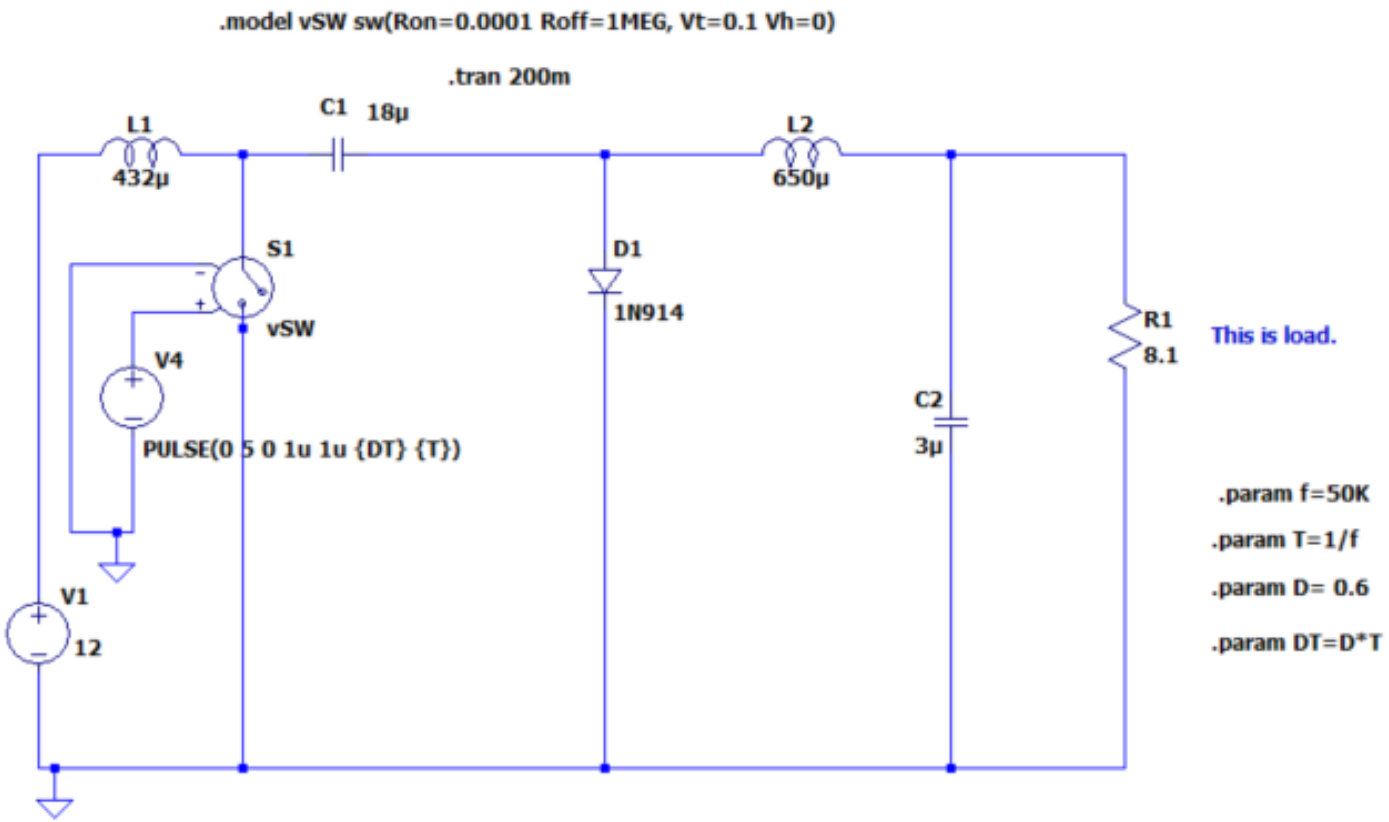
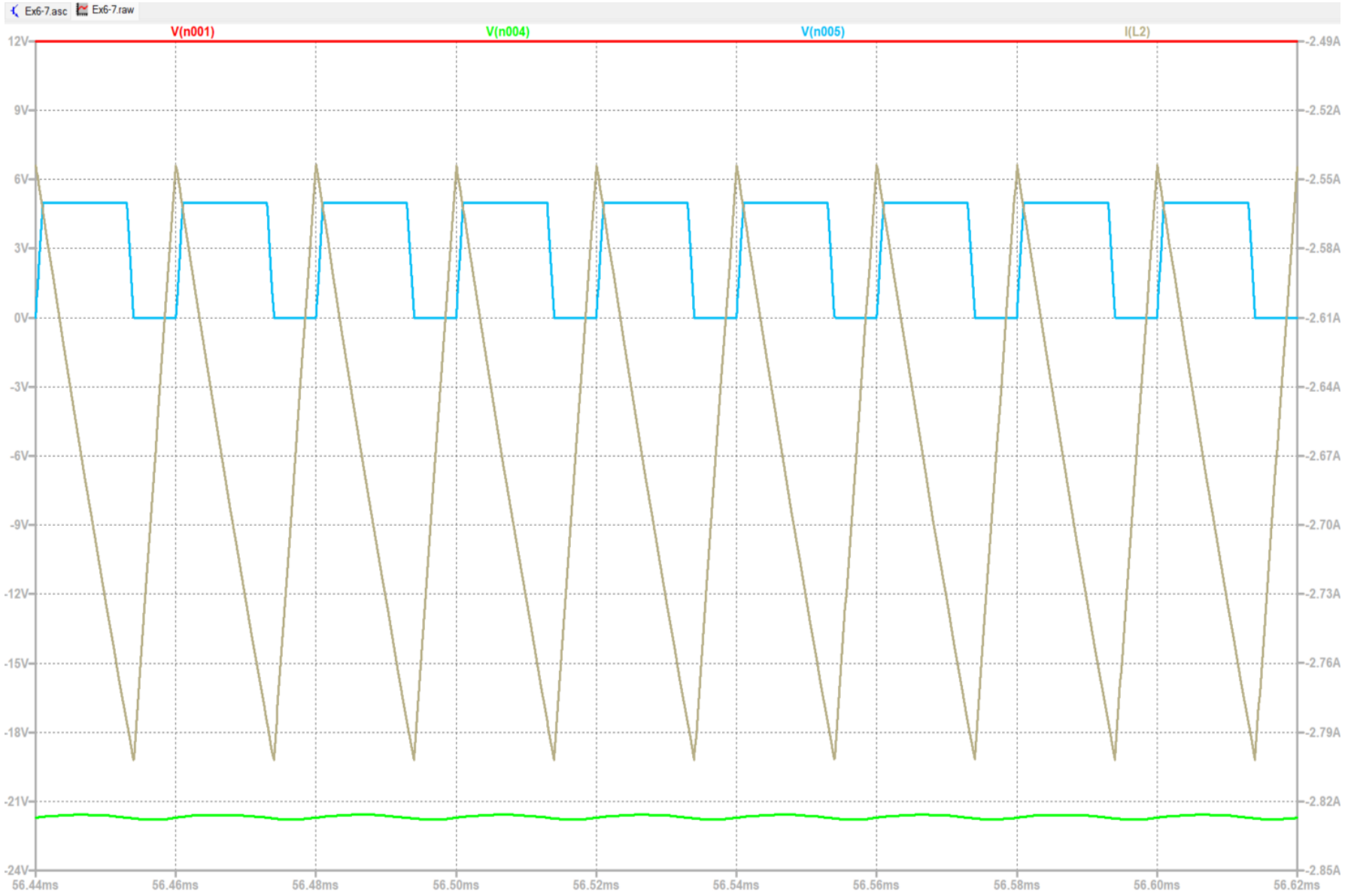
Example 6-7 Simulation

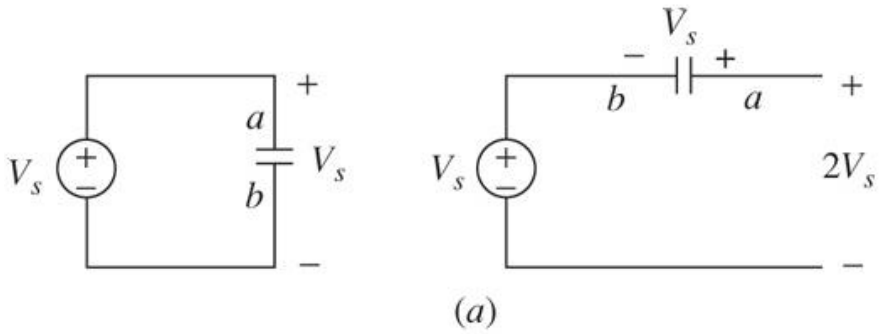


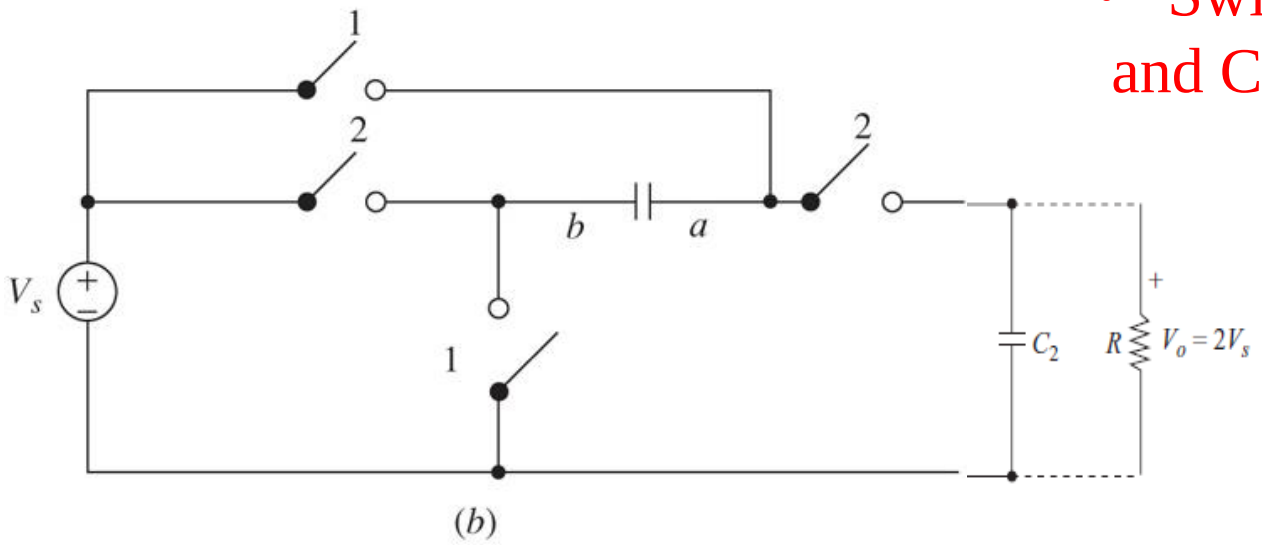

Ex6-7.asc
Ex6-7.raw
V(n001)
V(n004)
V(n005)
I(L2)
12V
9V
6V
3V
0V
-3V
-6V
-9V
-12V
-15V
-18V
-21V
-24V
-2.49A
-2.52A
-2.55A
-2.58A
-2.61A
-2.64A
-2.67A
-2.70A
-2.73A
-2.76A
-2.79A
-2.82A
-2.85A
56.44ms
56.46ms
56.48ms
56.50ms
56.52ms
56.54ms
56.56ms
56.58ms
56.60ms
56.62ms

Switched-Capacitor Converters

- Capacitors are charged in one configuration and discharges in another
- No inductor involved: *Inductor-less Converter*, ***Charge Pump***
- Advantage: Make into smaller size converter
- Disadvantage: Limit in current (by capacitor size) : 150 mA
- 3 types: Step-up, Inverted, and Step-down
- Application: RS-232 logic level, Flash Memory erase (large negative voltage), drivers for LED and LCD displays

Step-Up Converter





- Switch pairs Open and Close alternately

Pair 1	Pair 2
ON	OFF
OFF	ON

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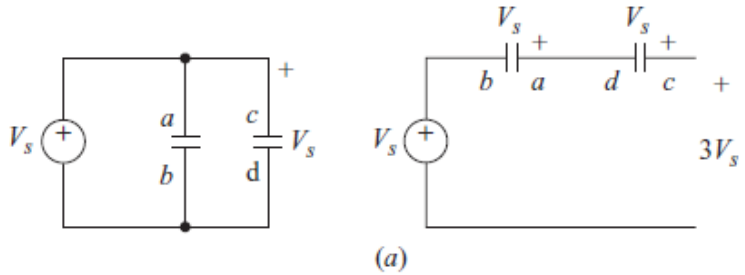
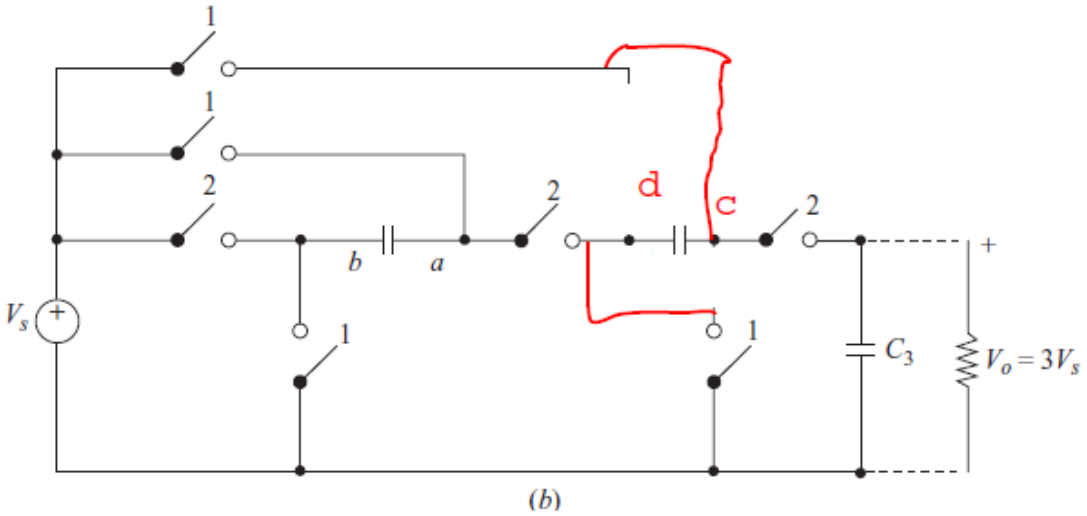
3 Vs step-up converter



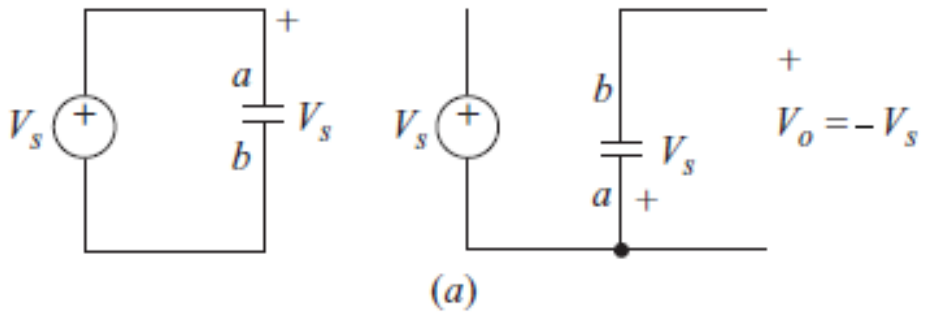
(a)



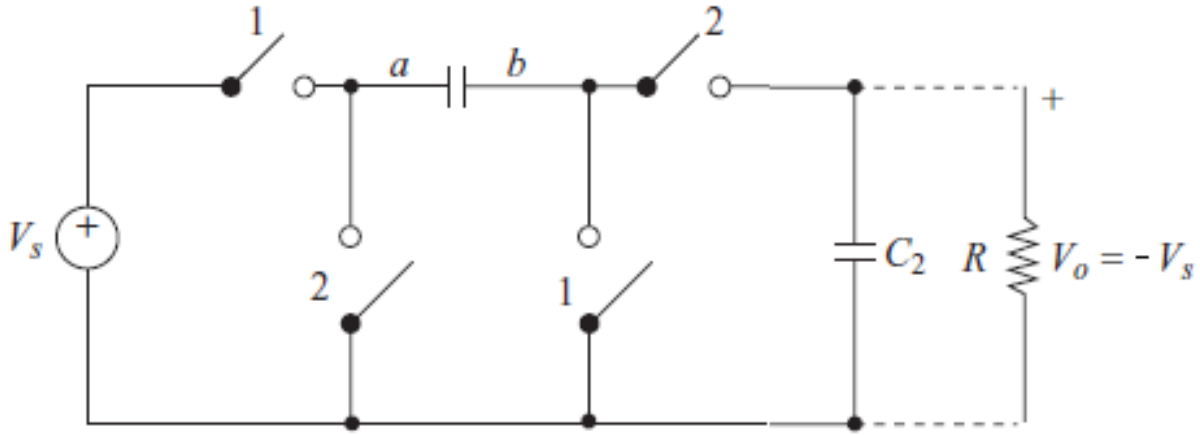
(b)

Pair 1	Pair 2
ON	OFF
OFF	ON

Inverting Converter



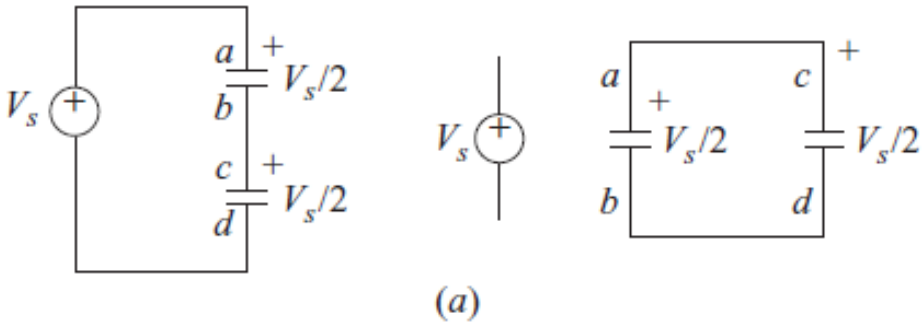
(a)



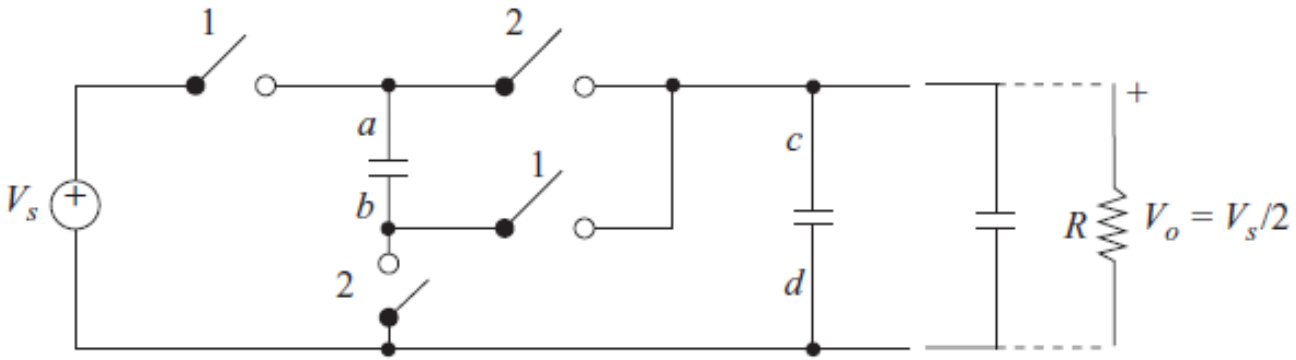
(b)

Pair 1	Pair 2
ON	OFF
OFF	ON

Step-Down Converter



(a)



(b)

Pair 1	Pair 2
ON	OFF
OFF	ON