DC-DC Switch-Mode Converters

EE 442/642

Fall 2012

Block Diagram of DC-DC Converters

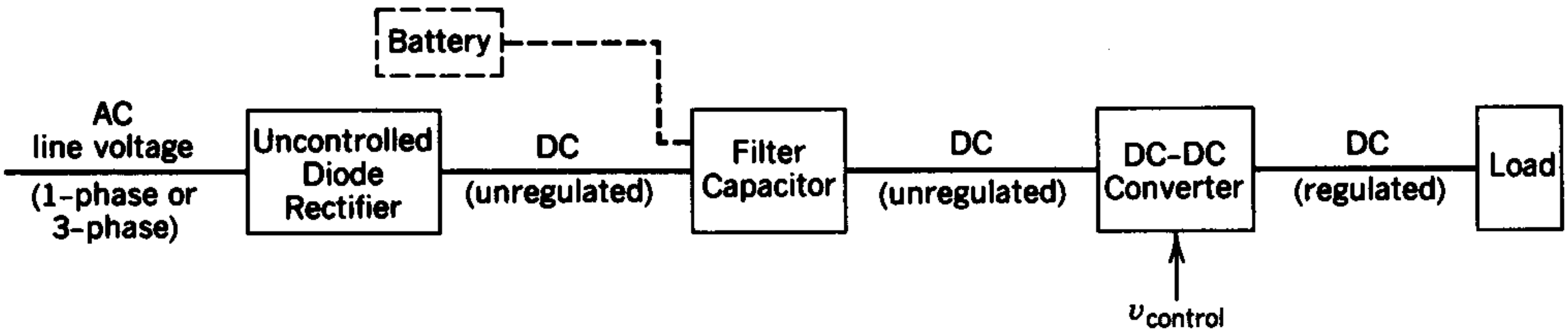


Figure 7-1 A dc–dc converter system.

Stepping Down a DC Voltage – Basic Concept

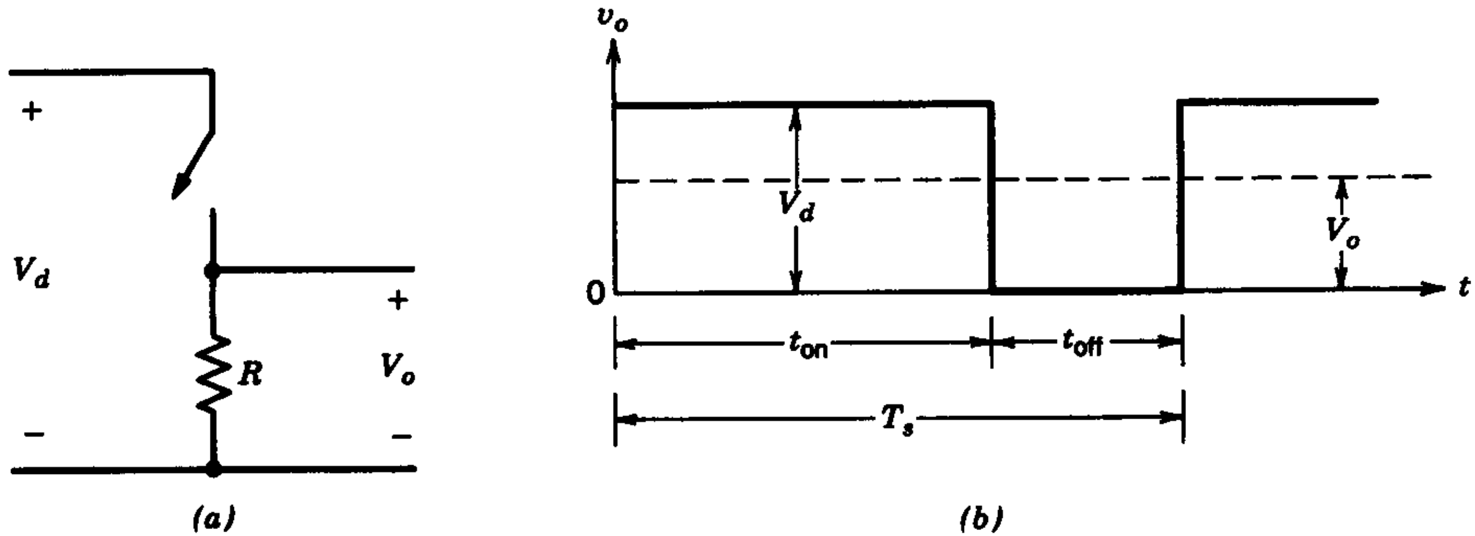


Figure 7-2 Switch-mode dc–dc conversion.

Switch Duty Ratio: $D = \dfrac{t_{on}}{T_s}$

Average Output Voltage: $V_o = \dfrac{t_{on}}{T_s} V_d = D V_d$

Any parasitic inductance in the above circuit will cause damage to the switch
In addition, the output voltage contains significant ripple..

Pulse-Width Modulation in DC-DC Converters

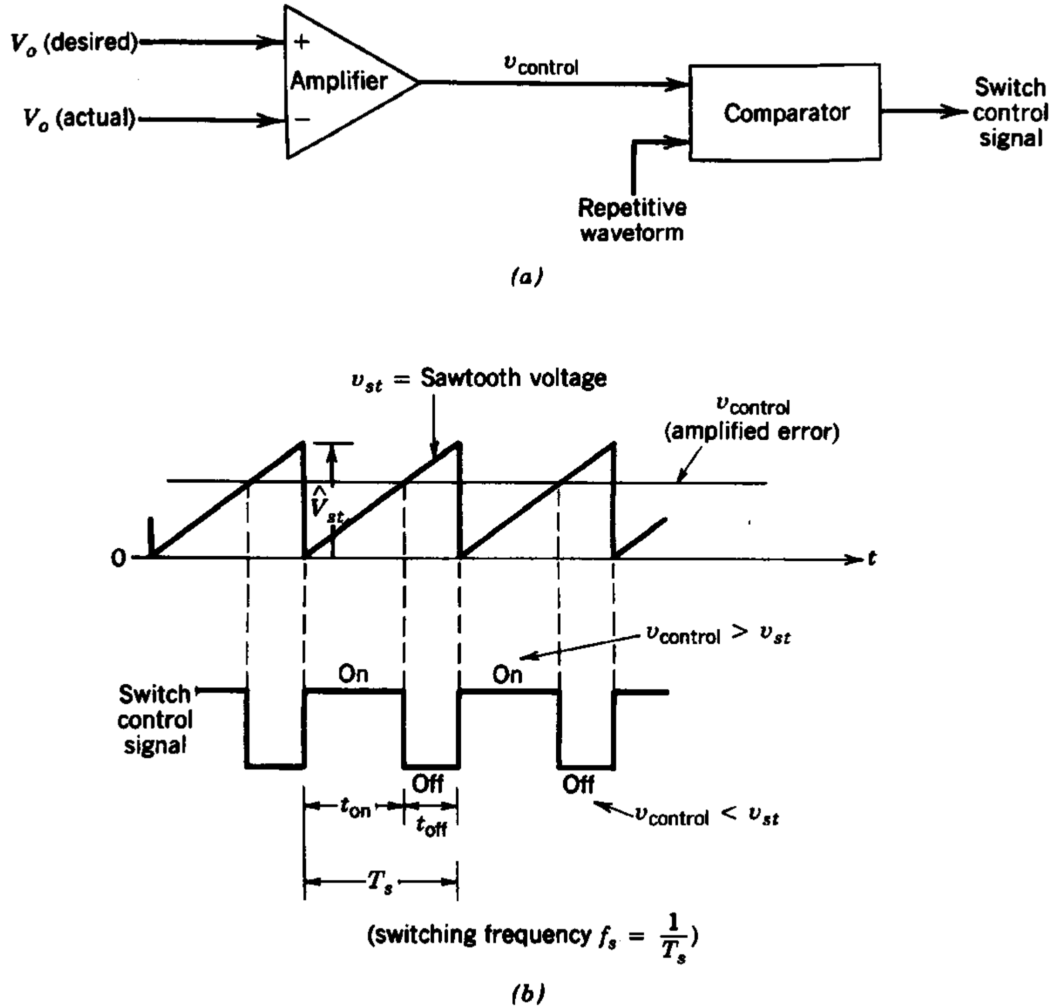


Figure 7-3 Pulse-width modulator: (*a*) block diagram; (*b*) comparator signals.

Duty Ratio: $D = \frac{t_{on}}{T_s}$

Step-Down (Buck) DC-DC Converter

Output Voltage: $V_o = \frac{t_{on}}{T_s} V_d = D V_d$

Filter corner frequency (f_c) should Be much lower than the Switching frequency (f_s)

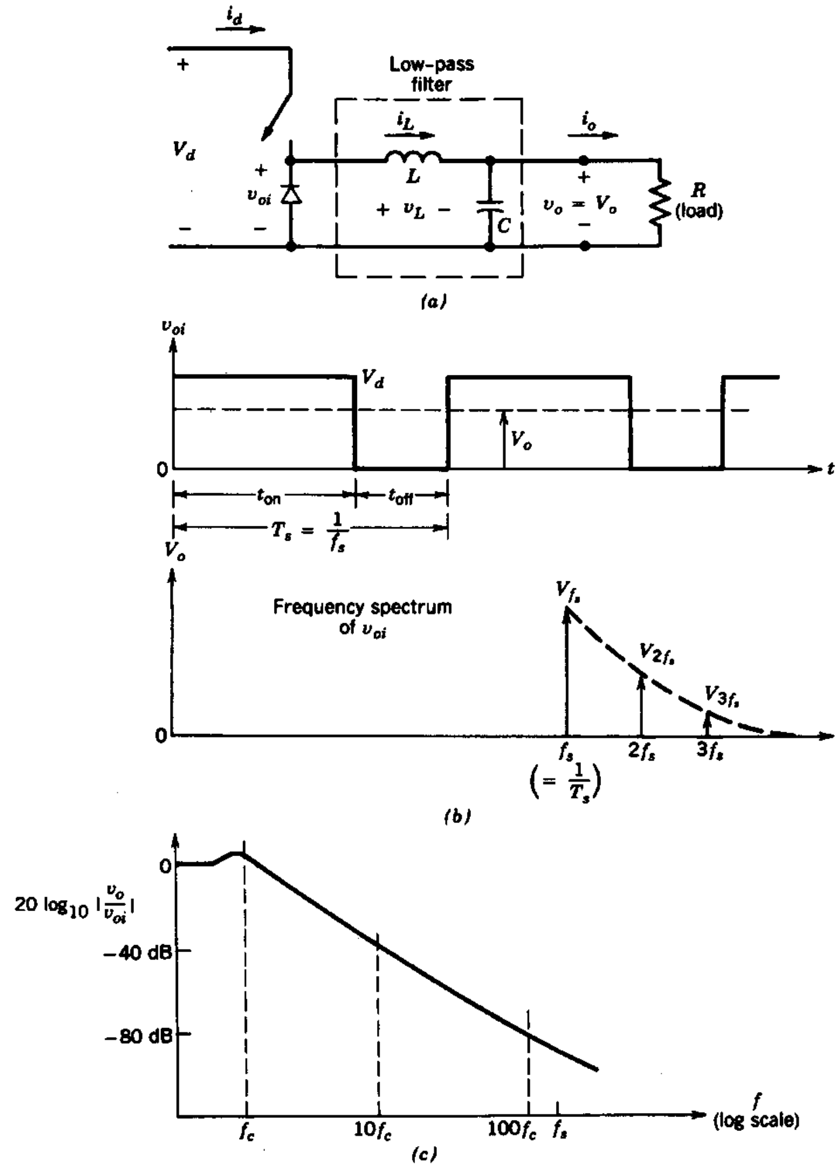


Figure 7-4 Step-down dc–dc converter.

Step-Down DC-DC Converter: Continuous Conduction Mode

$$V_o = DV_d$$

$$V_d I_d = V_o I_o$$

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

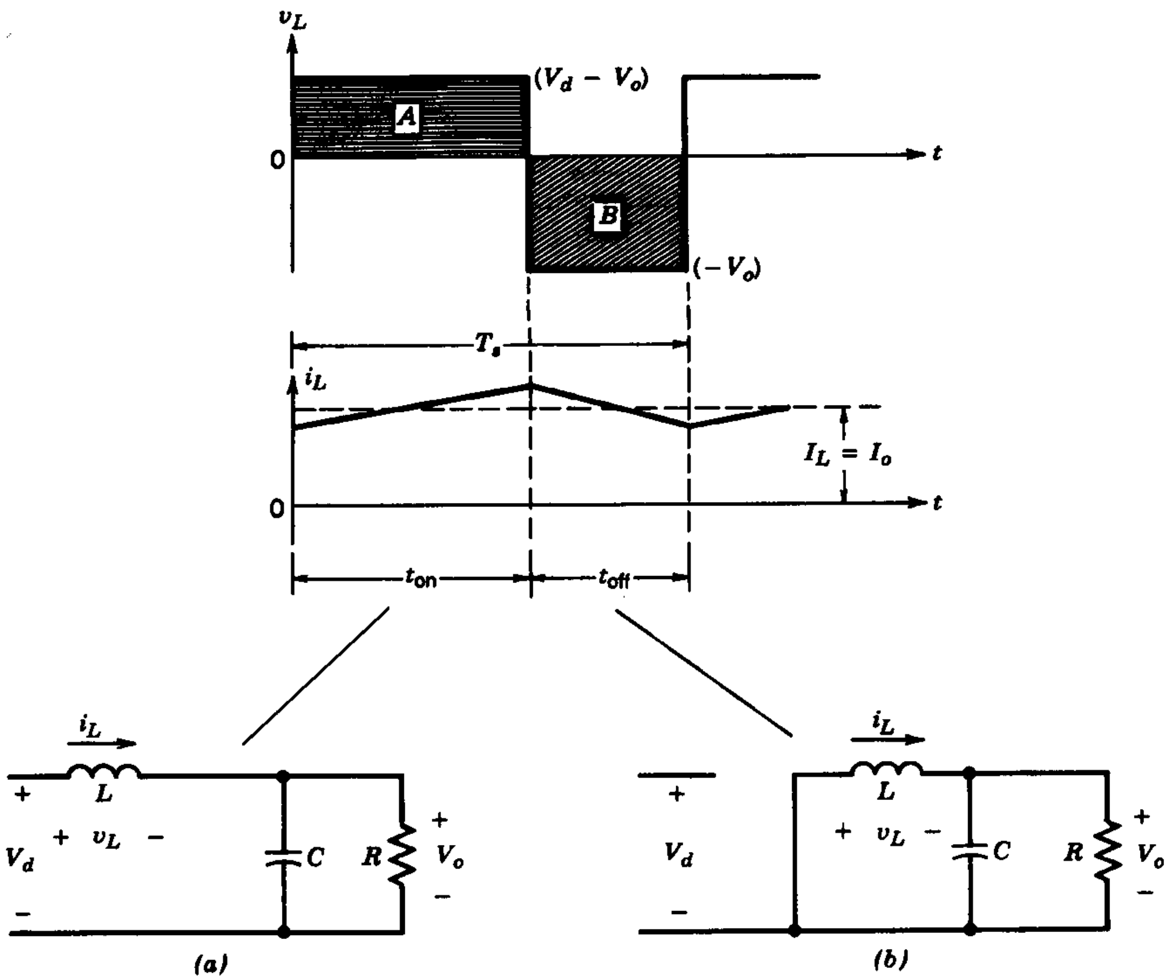


Figure 7-5 Step-down converter circuit states (assuming i_L flows continuously): (*a*) switch on; (*b*) switch off.

Step-Down DC-DC Converter: boundary of Continuous/Discontinuous Conduction Mode

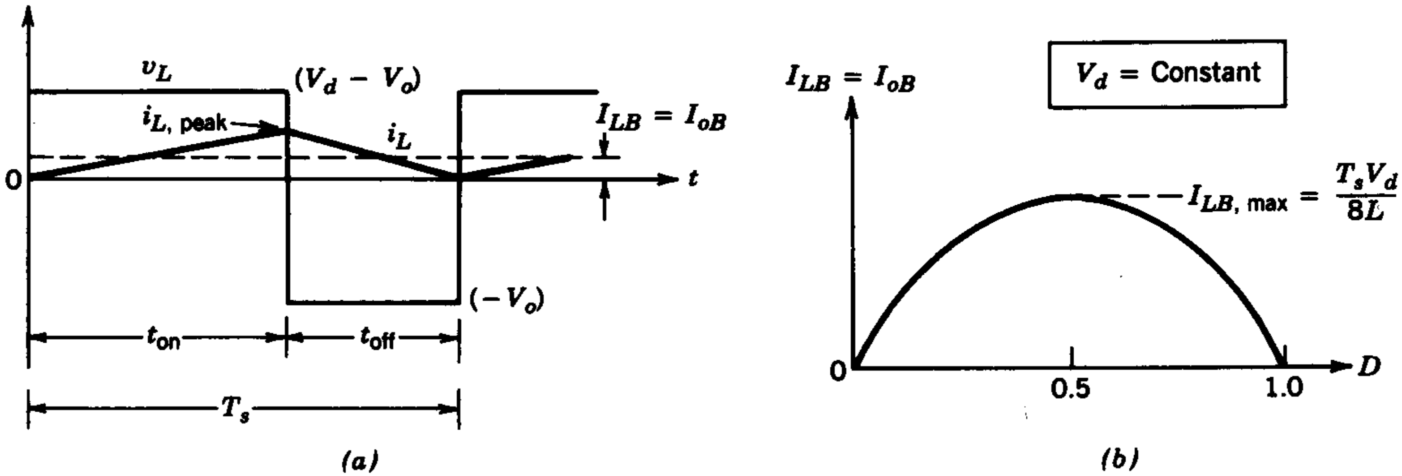


Figure 7-6 Current at the boundary of continuous–discontinuous conduction: (*a*) current waveform; (*b*) I_{LB} versus D keeping V_d constant.

Output Voltage: $$V_o = DV_d$$

Critical current below which inductor current becomes discontinuous:

$$I_{LB} = I_{oB} = \frac{1}{2} i_{L,peak} = \frac{t_{on}}{2L}(V_d - V_o) = \frac{DT_s}{2L}(V_d - V_o)$$

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

Step-Down DC-DC Converter: Discontinuous Conduction Mode (Constant V_d)

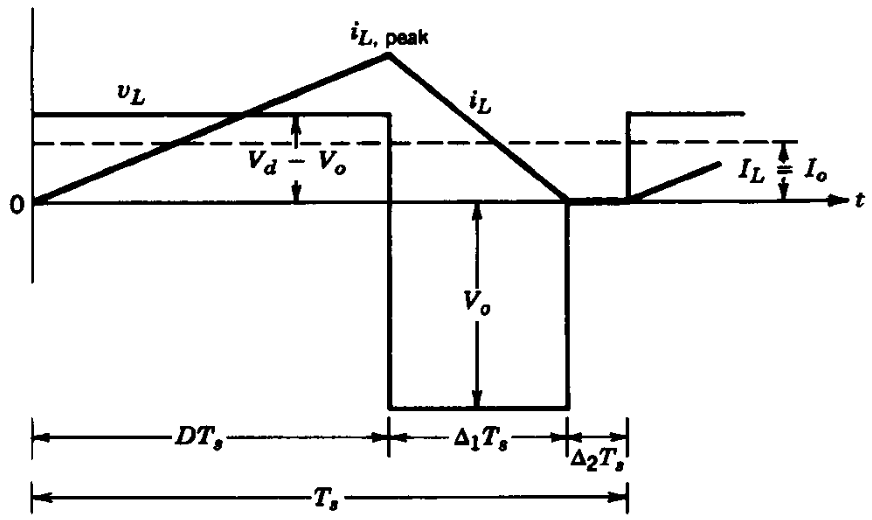


Figure 7-7 Discontinuous conduction in step-down converter.

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

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

Output Voltage: $$\frac{V_o}{V_d} = \frac{D^2}{D^2 + I_o/(4I_{LB,\max})}$$

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

Step-Down DC-DC Converter: Limits of Cont./Discont. Conduction Mode (Constant V_d)

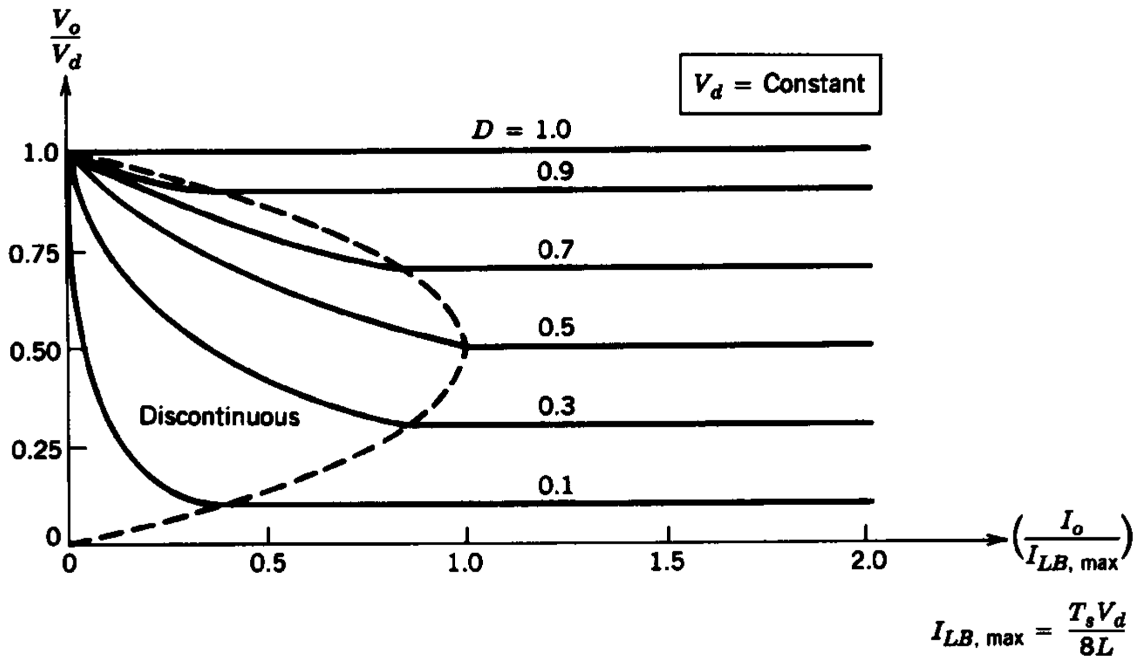


Figure 7-8 Step-down converter characteristics keeping V_d constant.

Step-Down DC-DC Converter: Limits of Cont./Discont. Conduction mode (Constant V_o)

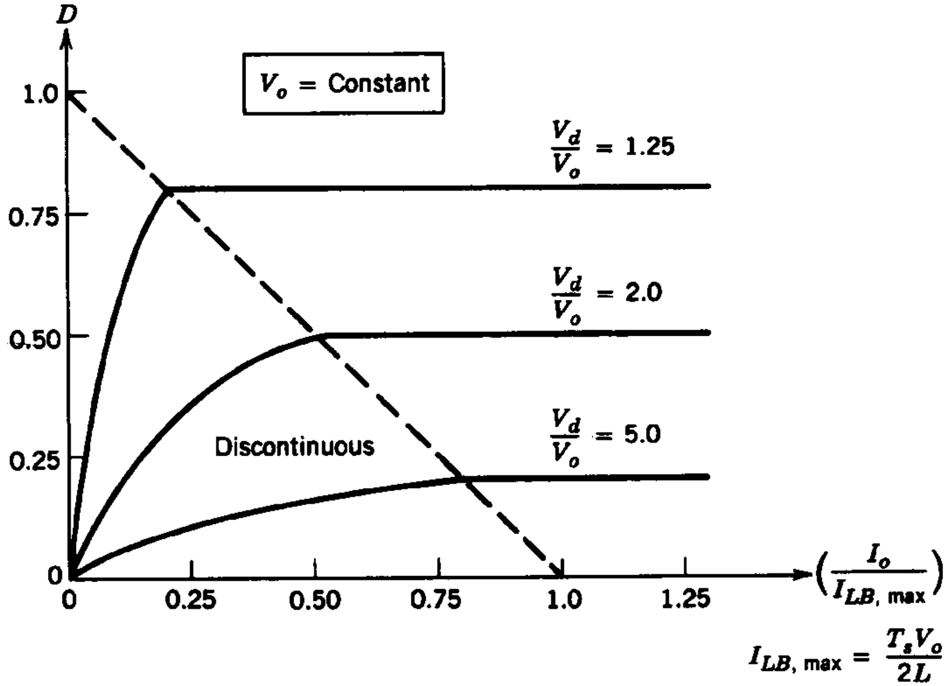


Figure 7-9 Step-down converter characteristics keeping V_o constant.

If output voltage is kept constant, $$I_{LB} = \frac{T_s V_o}{2L}(1-D) \quad \Rightarrow I_{LB,\max} = \frac{T_s V_o}{2L_s}$$

Duty ratio for a given current: $$D = \frac{V_o}{V_d}\left(\frac{I_o / I_{LB,\max}}{1-(V_o / V_D)}\right)^{1/2}$$

Step-Down Converter: Output Voltage Ripple

Consider continuous conduction mode.

Assume all the inductor ripple current flows through the capacitor (with the average current flows through the resistive load. Then

$$\Delta V_o = \frac{\Delta Q_c}{C} = \frac{1}{C}\left(\frac{1}{2}\frac{\Delta I_L}{2}\frac{T_s}{2}\right),$$

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

$$\Rightarrow \frac{\Delta V_o}{V_o} = \frac{T_s^2}{8LC}(1-D) = \frac{\pi^2}{2}(1-D)\left(\frac{f_c}{f_s}\right)^2$$

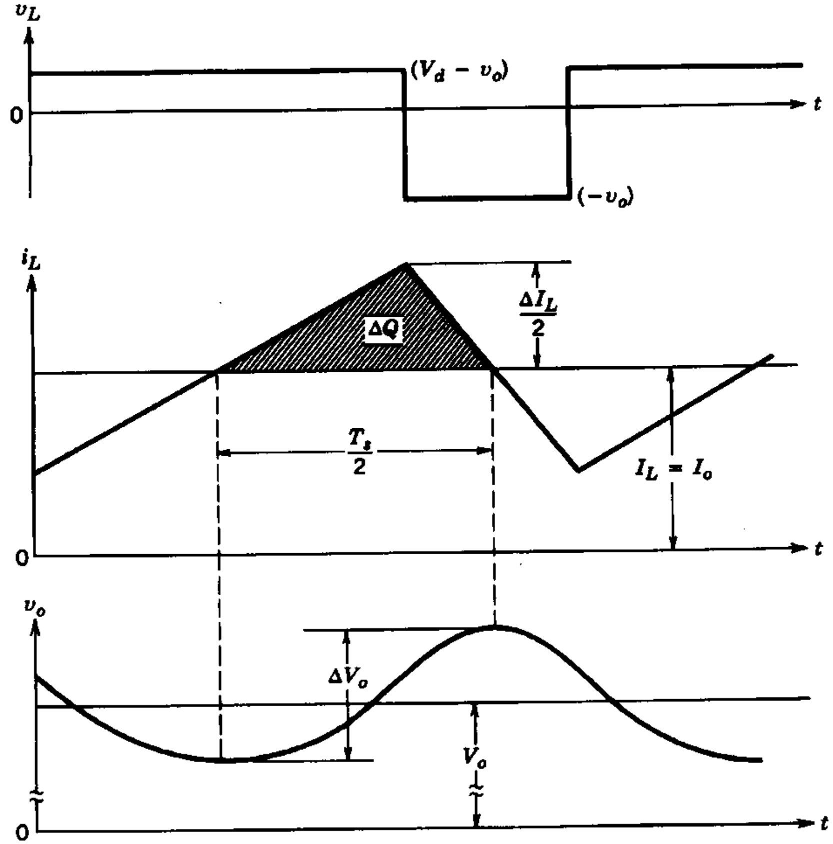


Figure 7-10 Output voltage ripple in a step-down converter.

Step-Up (Boost) DC-DC Converter

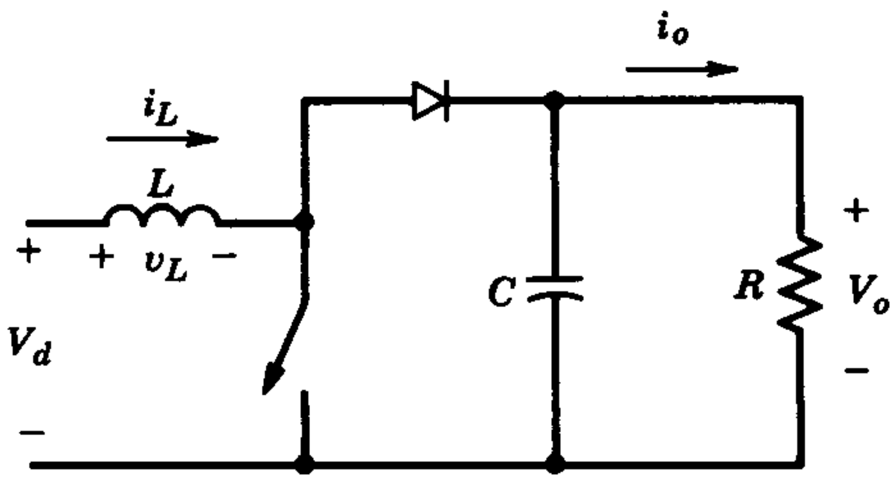


Figure 7-11 Step-up dc−dc converter.

- Output voltage must be greater than the input

Step-Up DC-DC Converter: Continuous Conduction

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

$$\Rightarrow V_o = V_d / (1 - D)$$

$$V_d I_d = V_o I_o$$

$$I_o = I_d (1 - D)$$

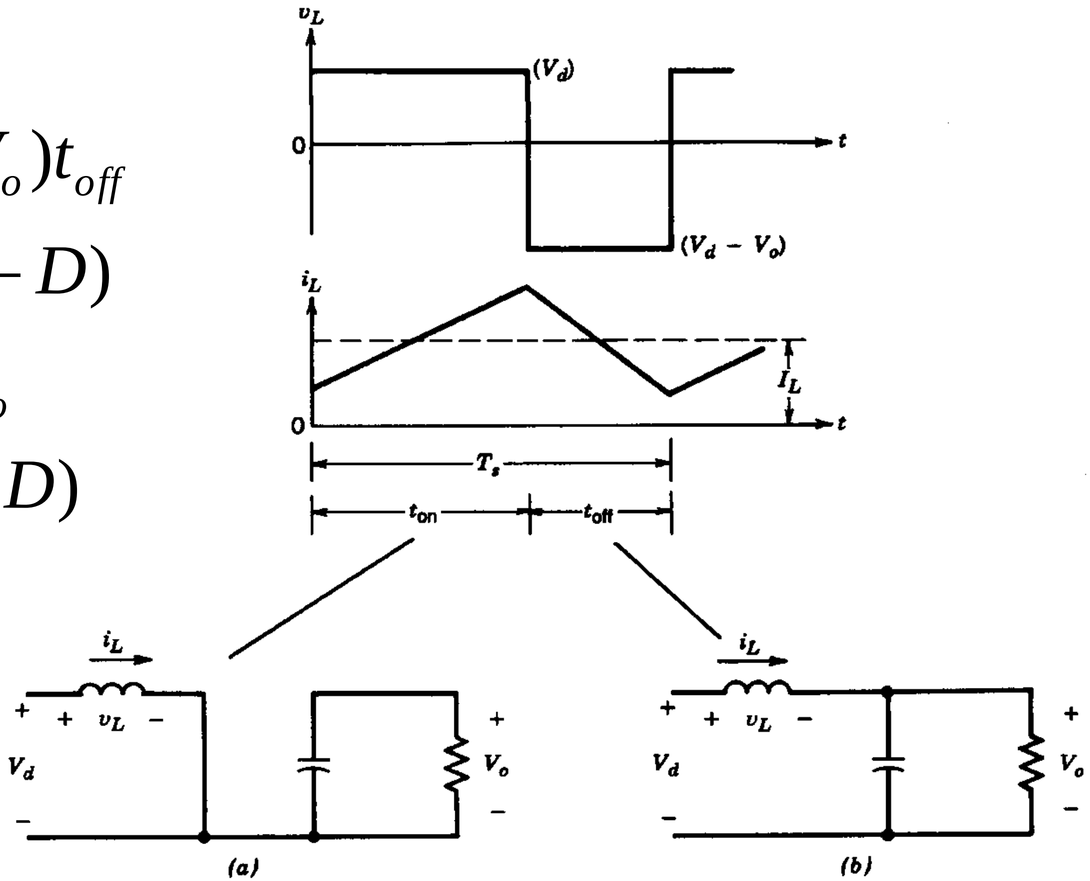


Figure 7-12 Continuous-conduction mode: (*a*) switch on; (*b*) switch off.

Step-Up DC-DC Converter: Effect of Parasitics

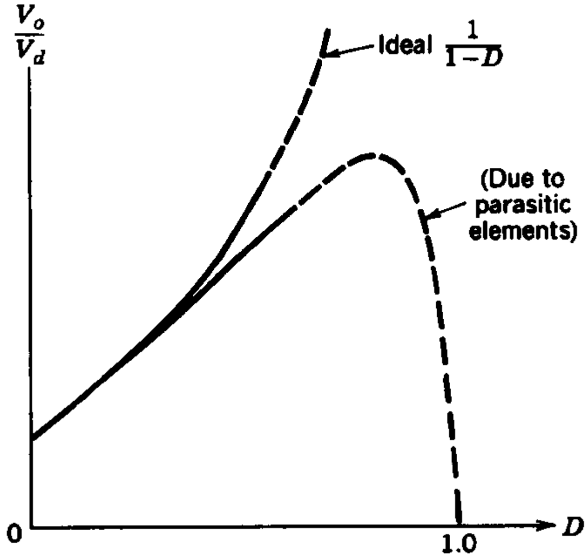


Figure 7-16 Effect of parasitic elements on voltage conversion ratio (step-up converter).

Parasitic elements are due to losses in the inductor, capacitor, switch, and diode.

The duty-ratio is generally limited before the parasitic effects become significant.

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

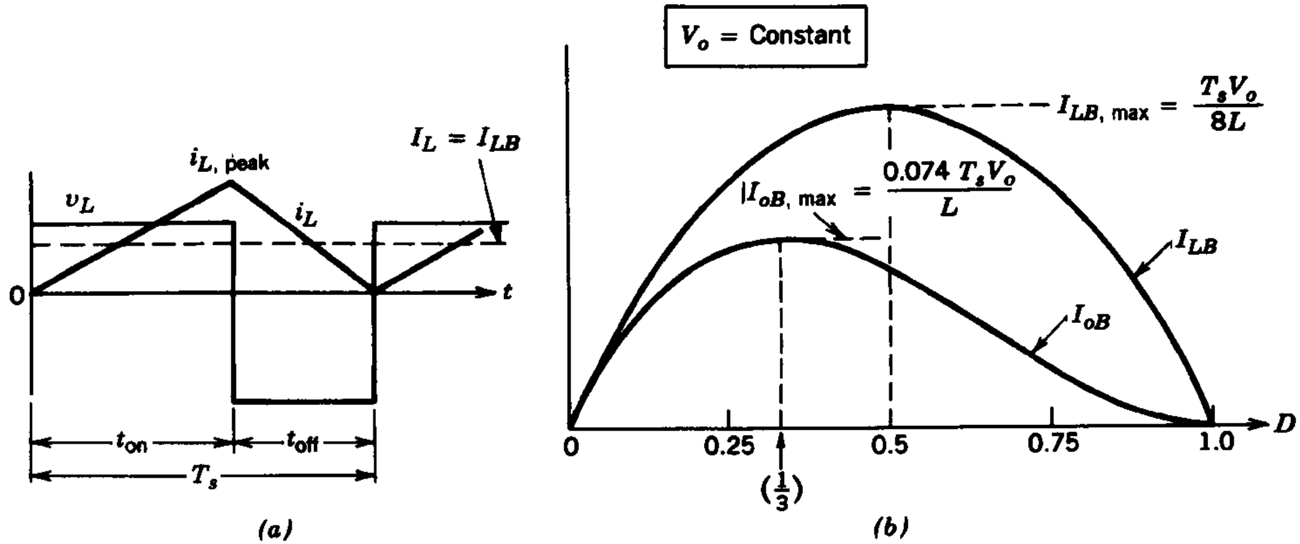
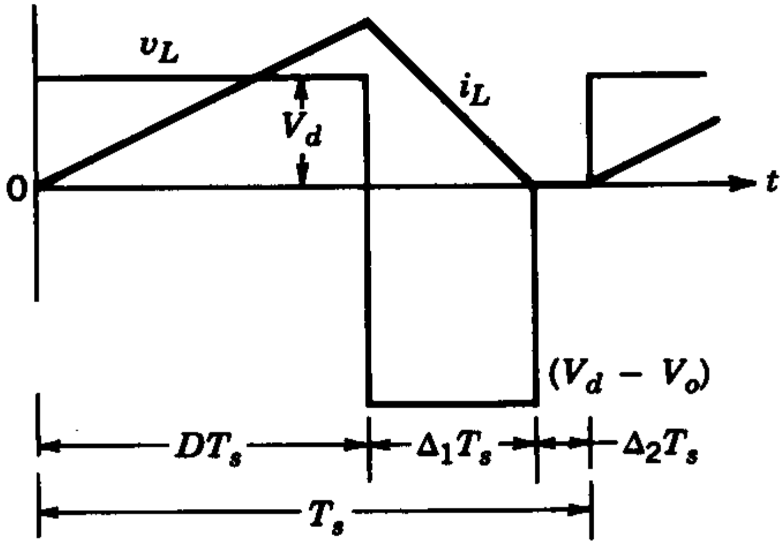


Figure 7-13 Step-up dc–dc converter at the boundary of continuous–discontinuous conduction.

$$I_{LB} = I_{dB} = \frac{1}{2} i_{L,peak} = \frac{t_{on}}{2L} V_d = \frac{T_s V_o}{2L} D(1-D), \quad \Rightarrow I_{LB,\max} = \frac{T_s V_o}{8L}$$

$$I_{oB} = (1-D) I_{dB} = \frac{T_s V_o}{2L} D(1-D)^2, \quad \Rightarrow I_{oB,\max} = \frac{2}{27} \frac{T_s V_o}{L}$$

Step-Up DC-DC Converter: Discontinuous Conduction (constant V_o)



(b)

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

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

For constant V_o and variable V_d,

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

Step-Up DC-DC Converter: Limits of Cont./Discont. Conduction (constant V_o)

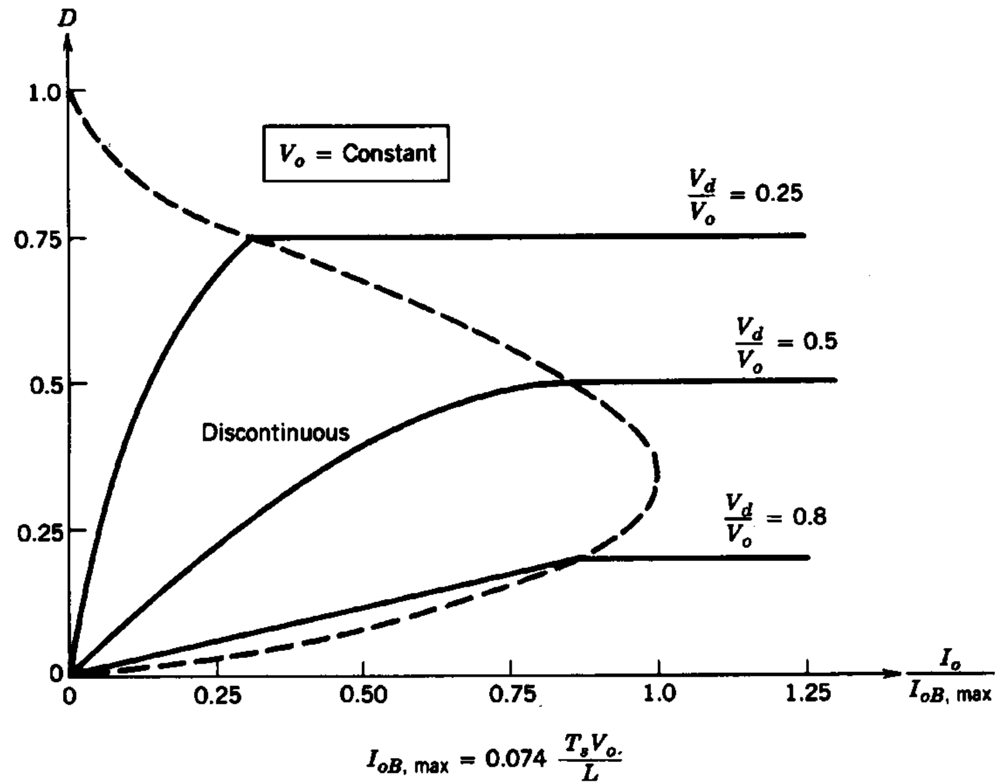


Figure 7-15 Step-up converter characteristics keeping V_o constant.

Step-Up DC-DC Converter Output Ripple

Consider continuous conduction mode.

Assume all the inductor ripple current flows through the capacitor (with the average current flows through the resistive load. Then

$$\Delta V_o = \frac{\Delta Q_c}{C} = \frac{I_o DT_s}{C} = \frac{V_o}{R}\frac{DT_s}{C},$$

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

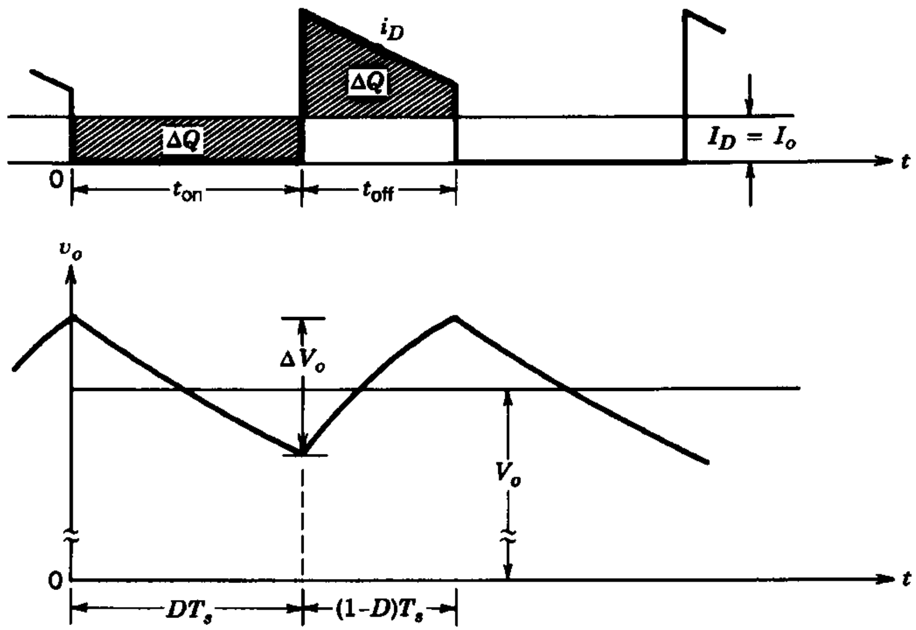


Figure 7-17 Step-up converter output voltage ripple.

Step-Down/Up (Buck/Boost) DC-DC Converter

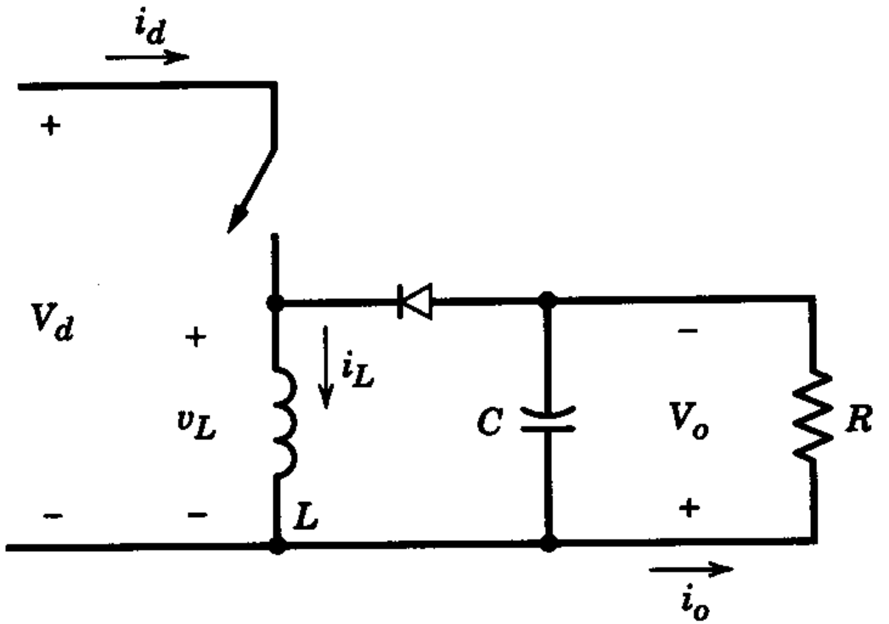
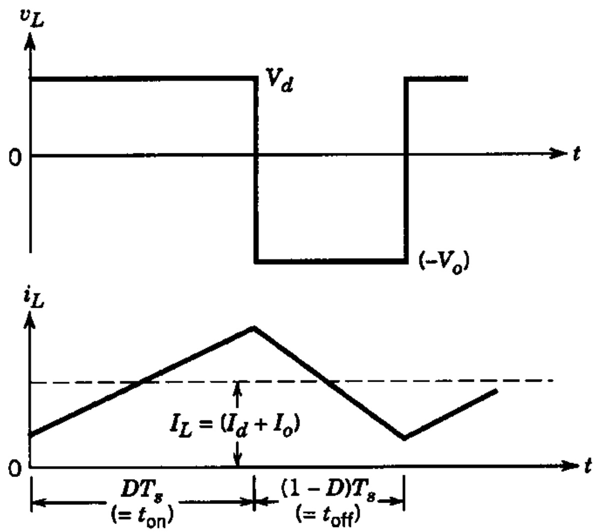


Figure 7-18 **Buck–boost converter.**

- The output voltage can be higher or lower than the input voltage.
- Note the reverse polarity of the output voltage.

Buck-Boost Converter: Cont. Conduction Mode



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

$$\Rightarrow V_o = V_d D/(1-D)$$

$$V_d I_d = V_o I_o$$

$$I_o = I_d (1-D)/D$$

Note:

$$I_L = I_d + I_o$$

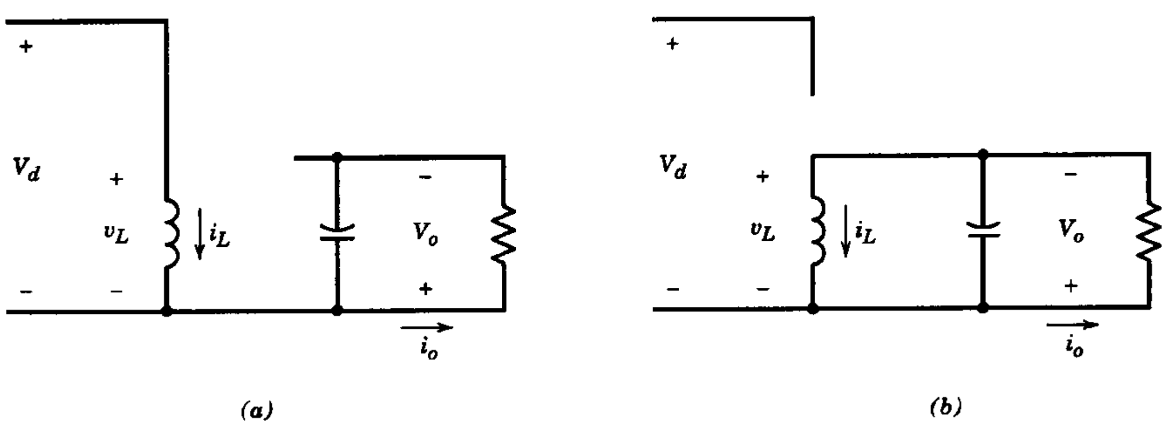


Figure 7-19 Buck–boost converter ($i_L > 0$): (a) switch on; (b) switch off.

Buck-Boost Converter: Limits of Cont./Discont. Conduction

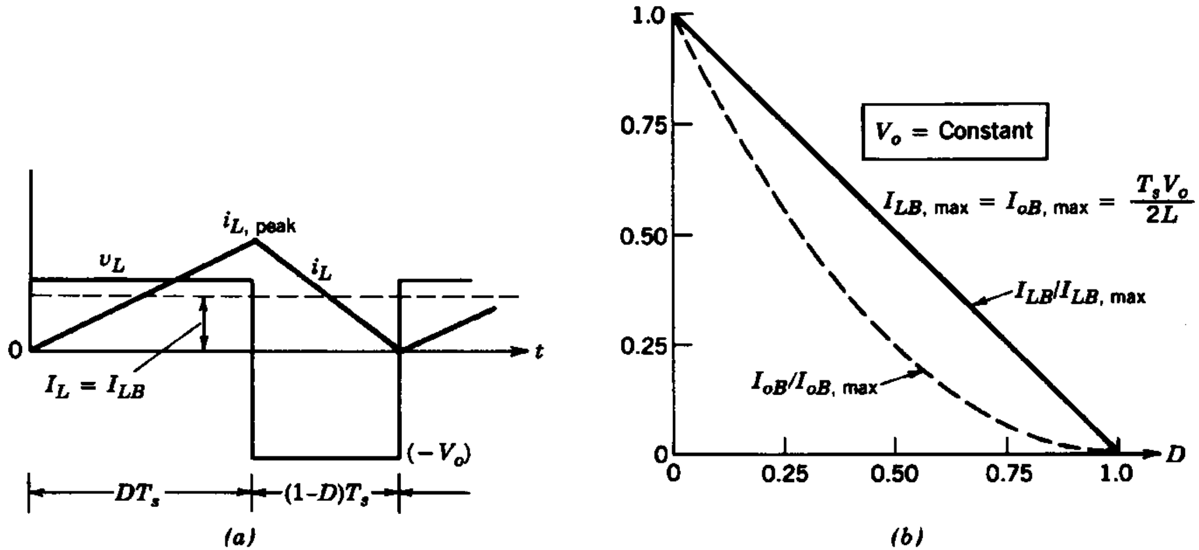


Figure 7-20 Buck−boost converter: boundary of continuous−discontinuous conduction.

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

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

Buck-Boost Converter: Disc. Conduction Mode

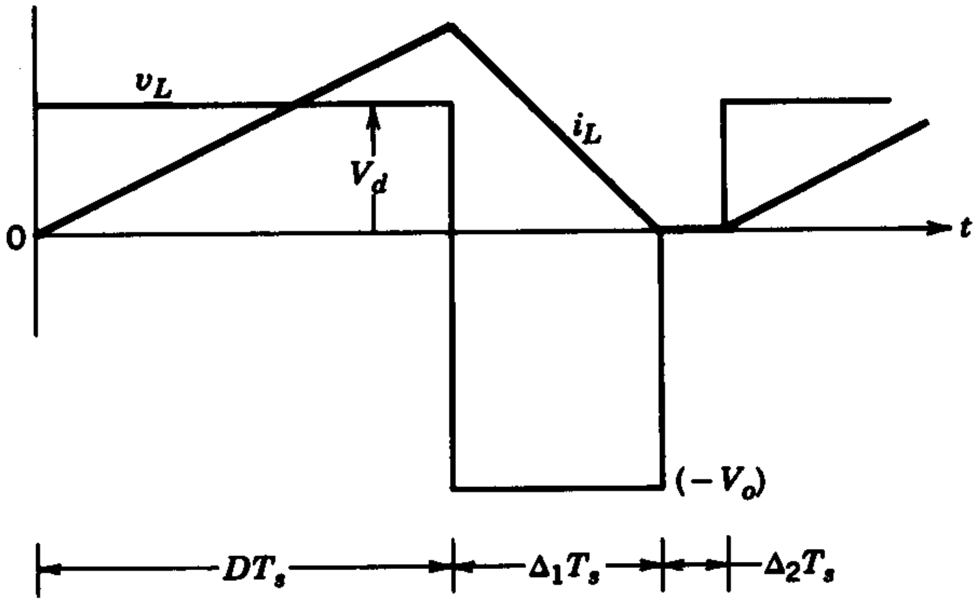


Figure 7-21 Buck–boost converter waveforms in a discontinuous-conduction mode.

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

$$\Delta_1 = \frac{DI_o}{I_d}$$

$$I_L = \frac{V_d}{2L} DT_s (D + \Delta_1)$$

For constant V_o and variable V_d,

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

Buck-Boost Converter: Limits of Cont./Discont. Conduction

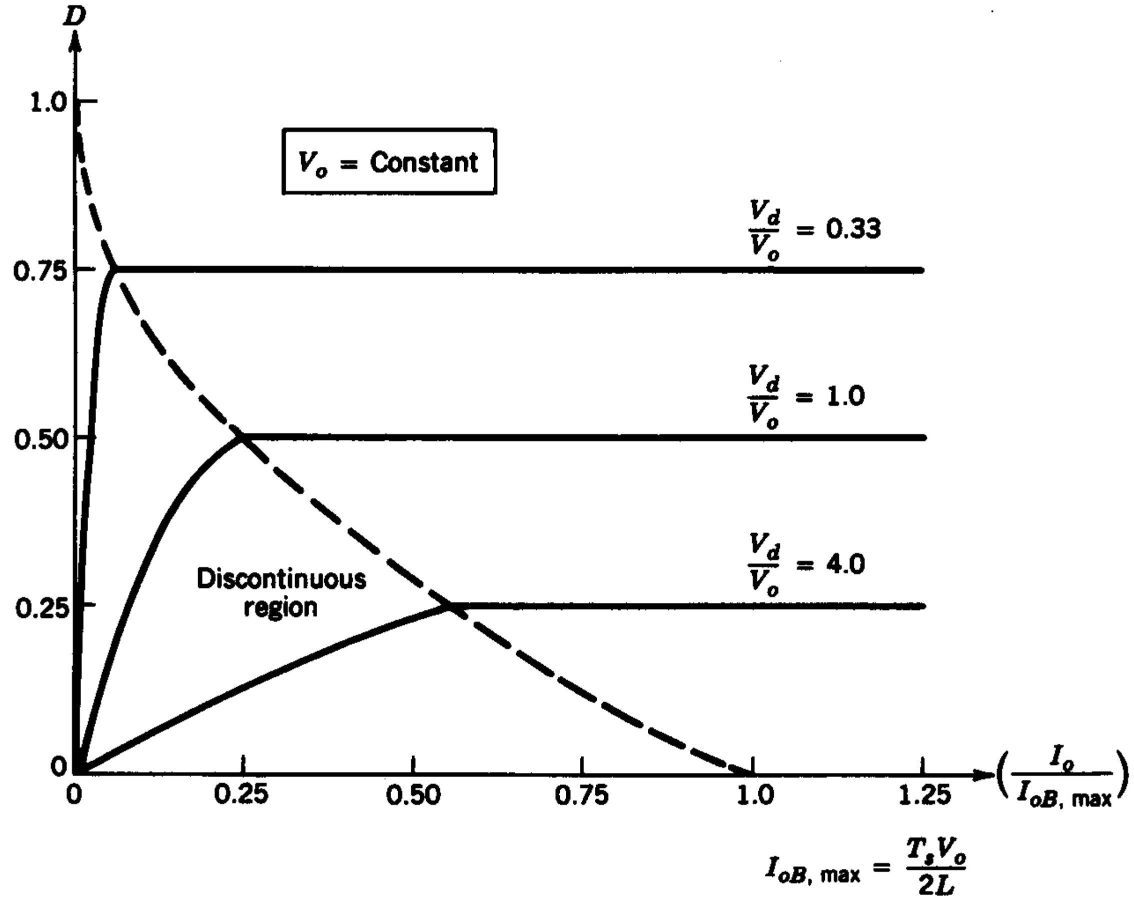


Figure 7-22 Buck–boost converter characteristics keeping V_o constant.

Buck-Boost Converter: Effect of Parasitics

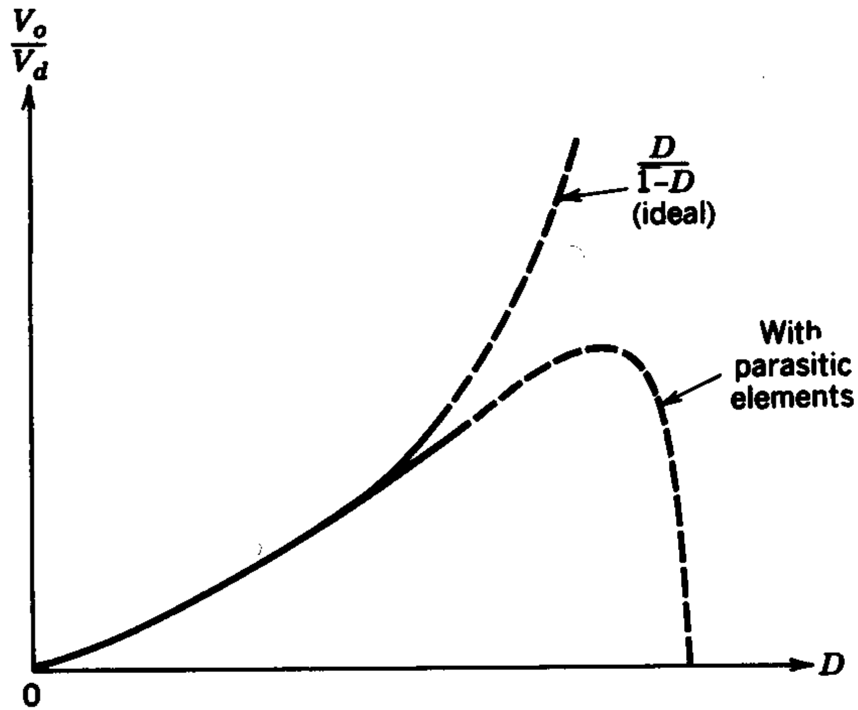


Figure 7-23 Effect of parasitic elements on the voltage conversion ratio in a buck–boost converter.

In practice, the duty-ratio is limited to avoid these parasitic effects from becoming significant.

Buck-Boost Converter: Output Voltage Ripple

Assume all the ripple current component of the diode current flows through the capacitor and its average value flows through the load resistor.

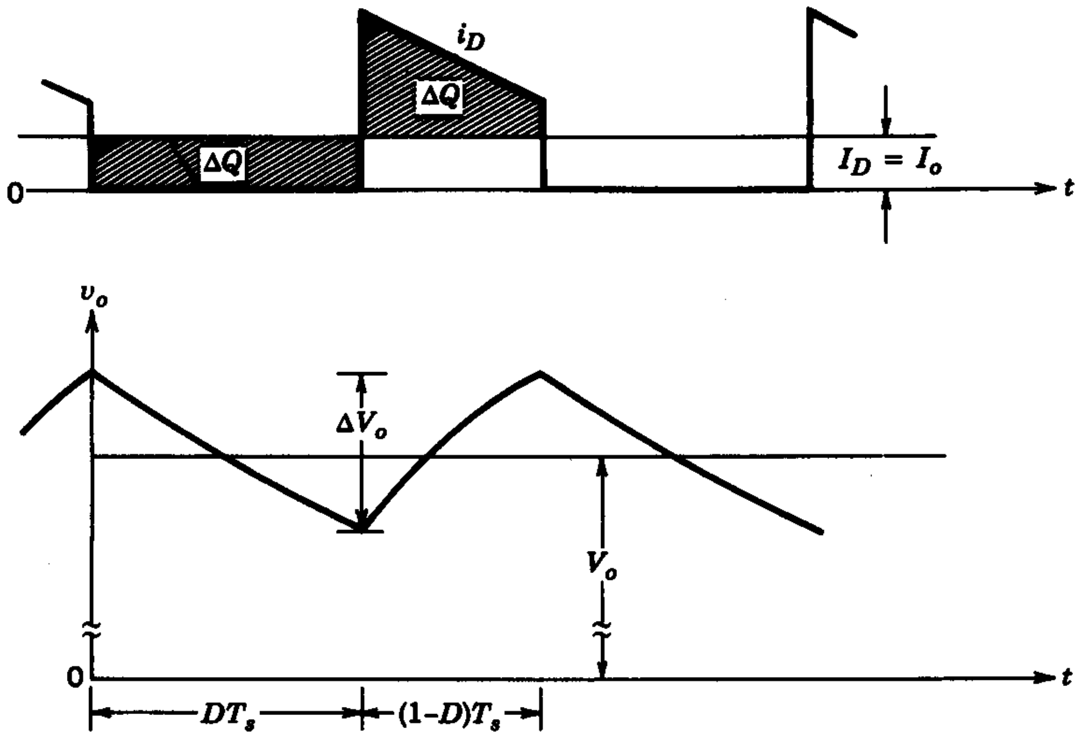


Figure 7-24 Output voltage ripple in a buck–boost converter.

$$\Delta V_o = \frac{\Delta Q_c}{C} = \frac{I_o DT_s}{C} = \frac{V_o}{R}\frac{DT_s}{C},$$

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

Cuk DC-DC Converter (Buck-Boost Converter)

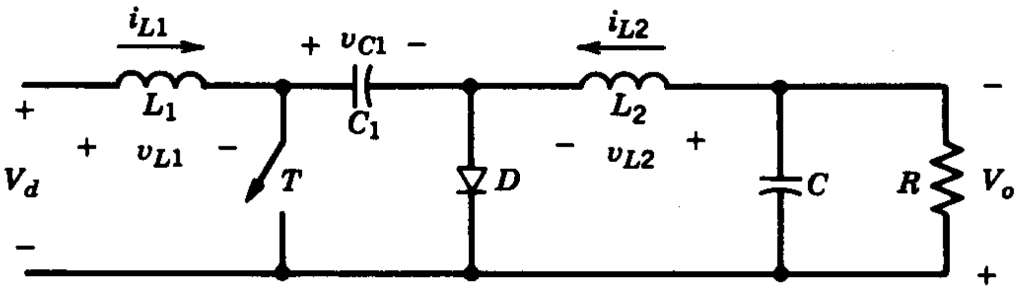


Figure 7-25 Cúk converter.

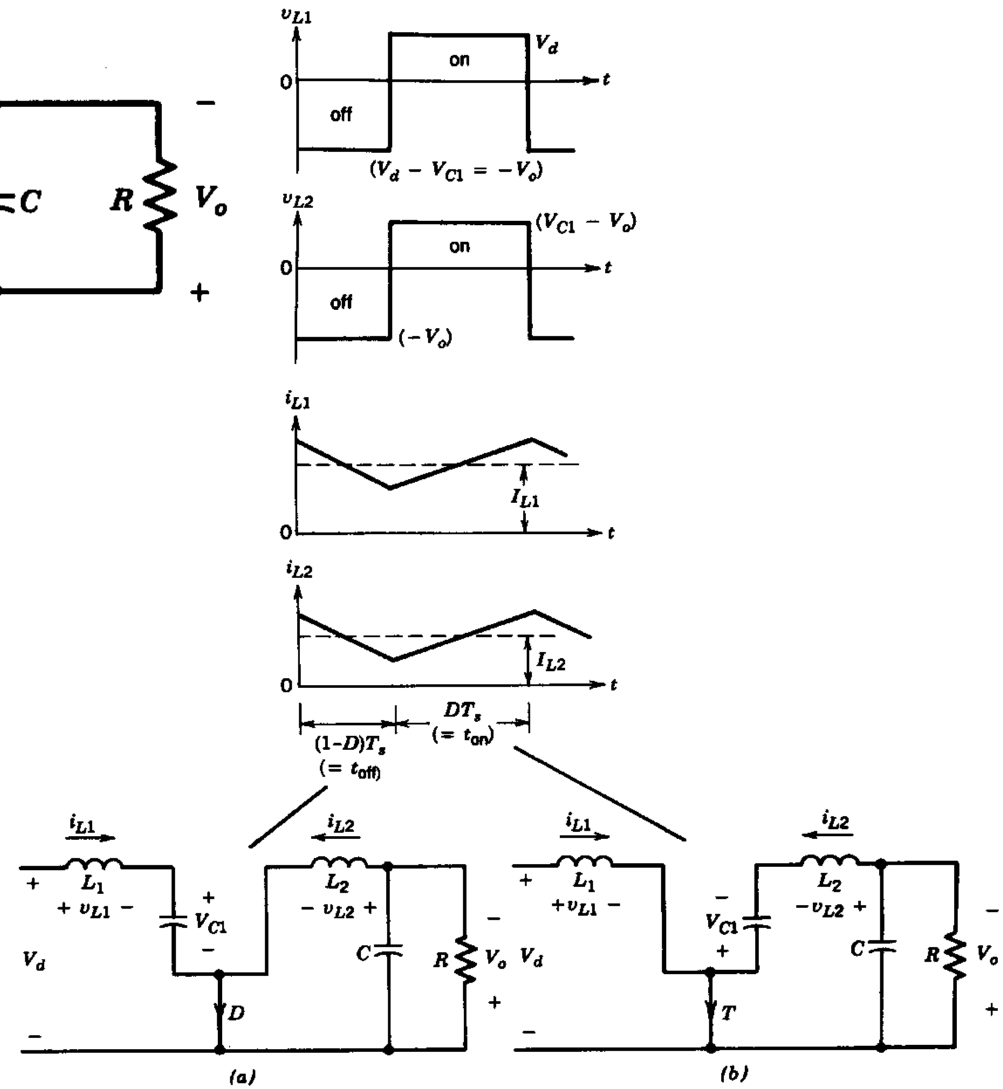


Figure 7-26 Cúk converter waveforms: (*a*) switch off; (*b*) switch on.

Full-Bridge DC-DC Converter: Possible Operation in all Four Quadrants

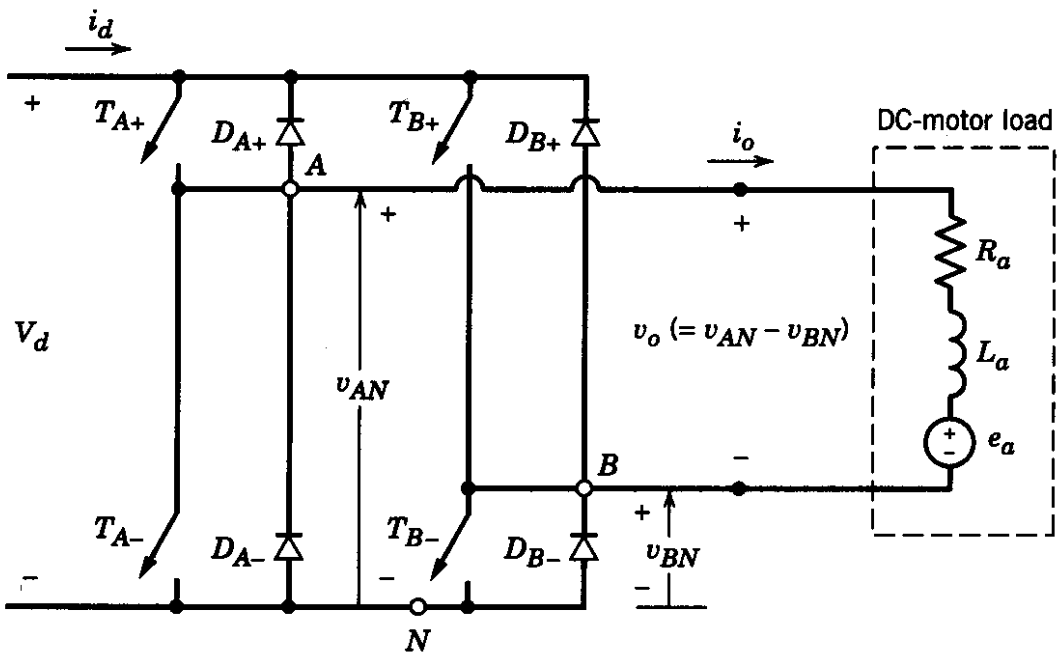
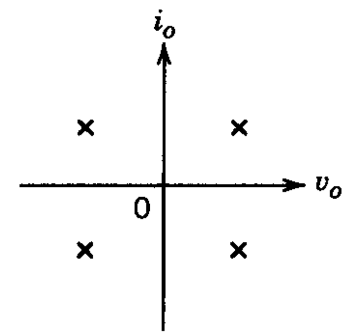


Figure 7-27 Full-bridge dc–dc converter.



Applications:

- DC Motor Drives
- DC-AC Conversion at power frequency (UPS)
- DC-AC Conversion at high frequency (switch-mode power supplies)

Converter Waveforms: PWM with Bi-polar Voltage Switching

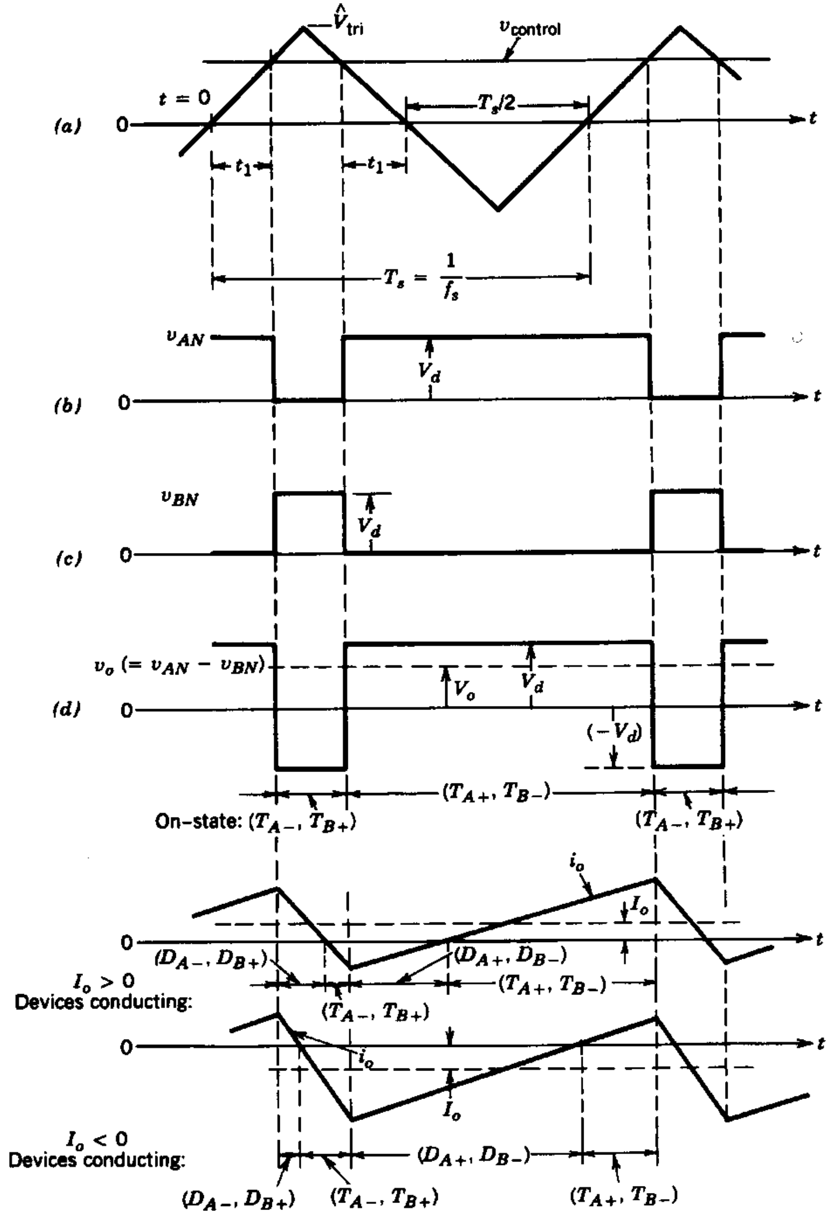


Figure 7-28 PWM with bipolar voltage switching.

← triangular (rather than saw-tooth) waveform is compared to $v_{control}$.

When $v_{control} > v_{tri}$,TA+,TB- are switched ON, and (TB+,TA-) are switched OFF.

Duty cycle of (TA+,TB-): $D_1 = t_{on}/T_s$
$= 0.5(1+v_{control}/V_{tri})$
Duty cycle of (TB+,TA-): $D_2 = (1 - D_1)$

Vo = VAN - VBN = D_1 Vd – D_2Vd
= (2 D_1 – 1) Vd = k.$v_{control}$
where k = Vd/V_{tri}
As D1: 0 →1, Vo: -Vd → Vd.

← Case where the average power flows from Vd to Vo.
← Case where the average power flows from Vo to Vd.

Converter Waveforms: Uni-polar Voltage Switching

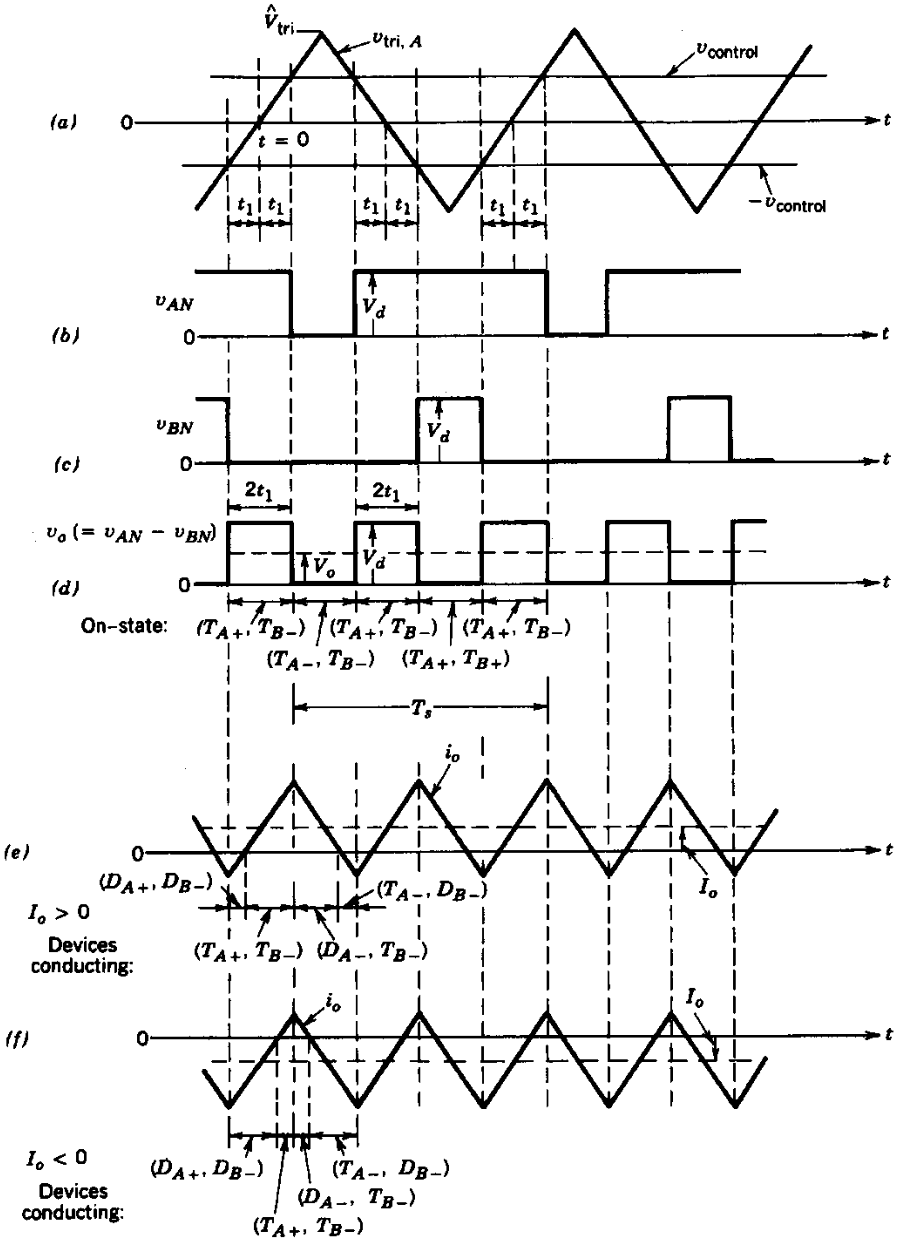


Figure 7-29 PWM with unipolar voltage switching.

← triangular waveform is compared to $v_{control}$ and $-v_{control}$.

When $v_{control} > v_{tri}$,TA+,TB- are switched ON. When $-v_{control} > v_{tri}$,TB+,TA- are switched ON.

Duty cycle of (TA+,TB-): $D_1 = t_{on}/T_s$
Duty cycle of (TB+,TA-): $D_2 = (1 - D_1)$

Vo = VAN - VBN = D_1 Vd – D_2Vd
= $(2 D_1 - 1)$ Vd = $k.v_{control}$
where $k = Vd/V_{tri}$

← Case where the average power flows from Vd to Vo.

← Case where the average power flows from Vo to Vd.

Output Ripple in Full Bridge Converter

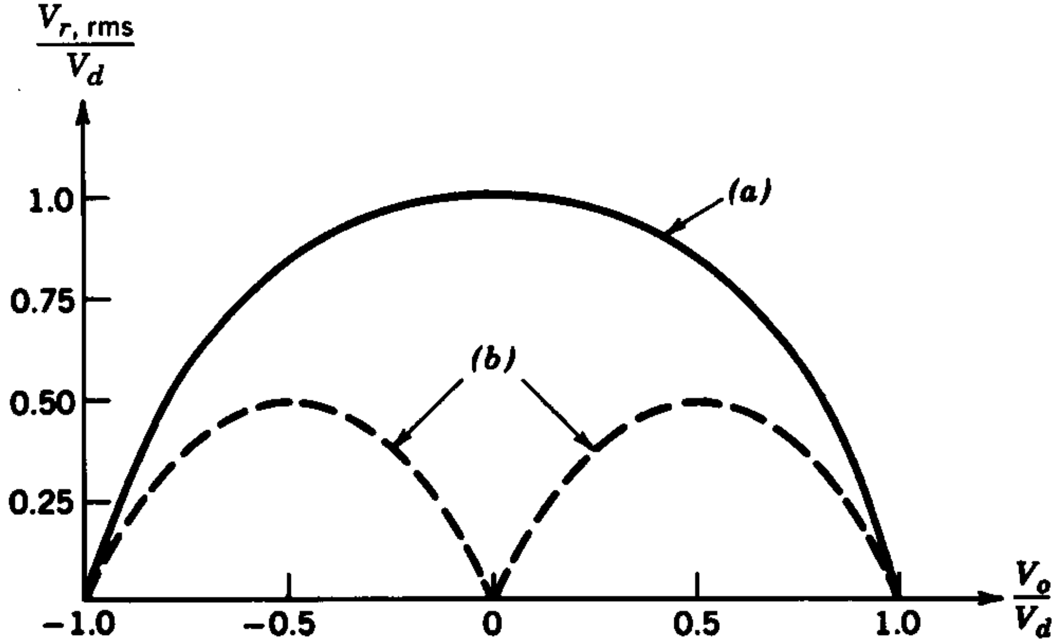


Figure 7-30 $V_{r,rms}$ **in a full-bridge converter using PWM: (*a*) with bipolar voltage switching; (*b*) with unipolar voltage switching.**

(a)Bipolar switching: $V_{r,rms} = \sqrt{V_{o,rms}^2 - V_o^2} = 2V_d\sqrt{D_1 - D_1^2}$

(b)Unipolar switching: $V_{r,rms} = \sqrt{V_{o,rms}^2 - V_o^2} = \sqrt{6D_1 - 4D_1^2 - 2V_d}$

Switch Utilization in DC-DC Converters

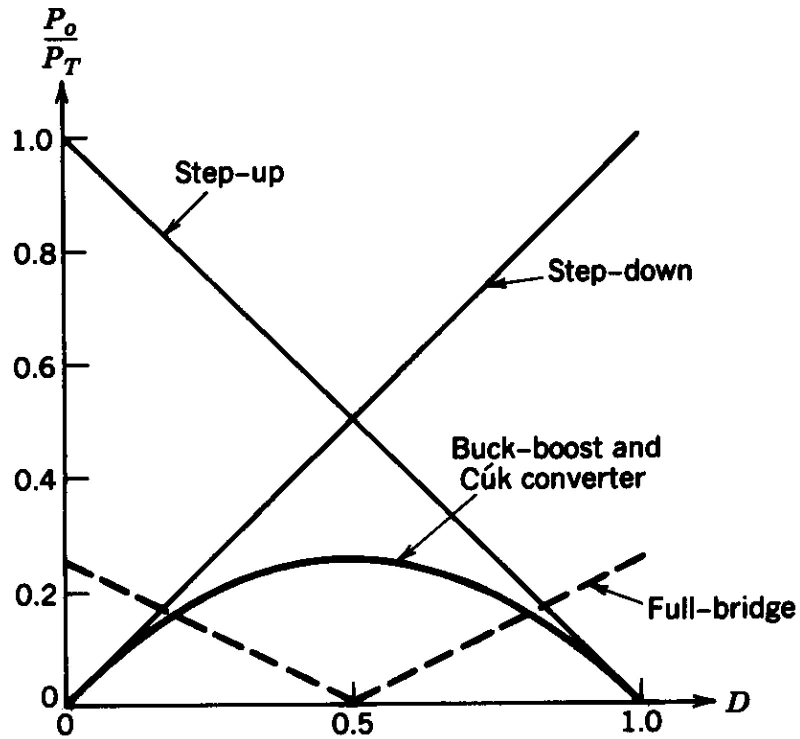


Figure 7-31 Switch utilization in dc–dc converters.

Switch Utilization Ratio: $P_o / P_T = (V_o I_o)/(V_T I_T)$

where V_T and I_T are the peak voltage and current ratings of the switch.