Chapter 3

SWITCH-MODE DC-DC CONVERTERS: SWITCHING ANALYSIS, TOPOLOGY SELECTION AND DESIGN

Regulated switch-mode dc power supplies

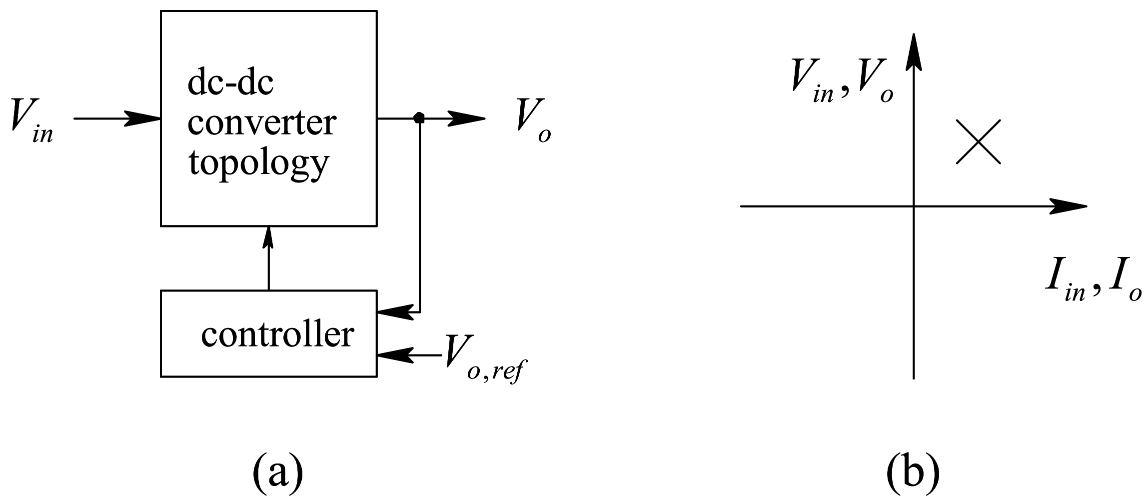


Figure 3-1 Regulated switch-mode dc power supplies.

Switching power-pole as the building block of dc-dc converters

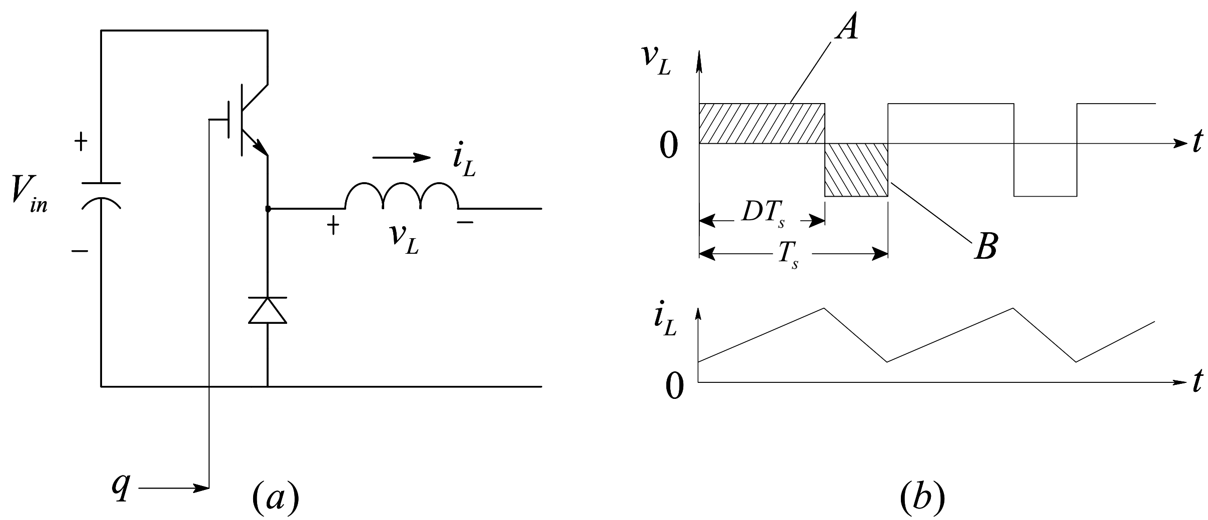


Figure 3-2 Switching power-pole as the building block of dc-dc converters.

$$i_L(t) = i_L(t - T_s)$$

$$V_L = \frac{1}{T_s}\left(\underbrace{\int_0^{DT_s} v_L \cdot d\tau}_{\text{area } A} + \underbrace{\int_{DT_s}^{T_s} v_L \cdot d\tau}_{\text{area } B} \right) = 0$$

$$v_C(t) = v_C(t - T_s)$$

- Simplifying Assumptions
- Two-Step Process
- Common Operating Principles

BUCK CONVERTER SWITCHING ANALYSIS IN DC STEADY STATE

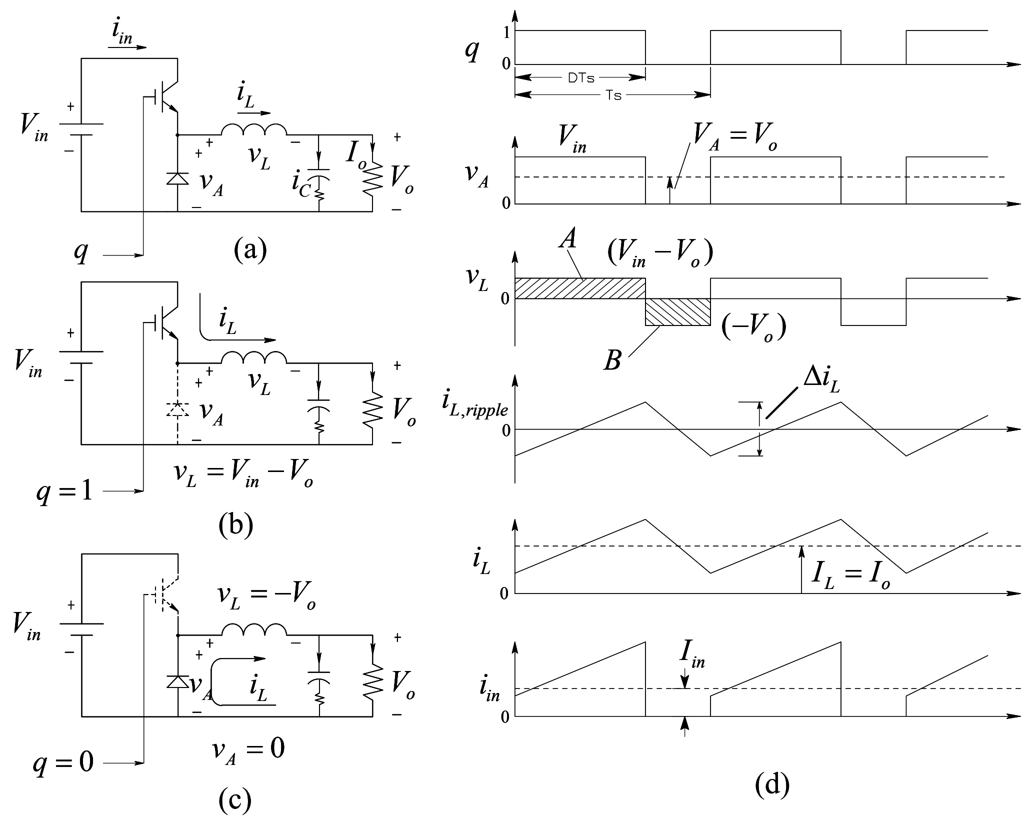


Figure 3-3 Buck dc-dc converter.

$$V_o = V_A = DV_{in}$$

$$\Delta i_L = \frac{V_{in} - V_o}{L} DT_s = \frac{V_o}{L}(1-D)T_s$$

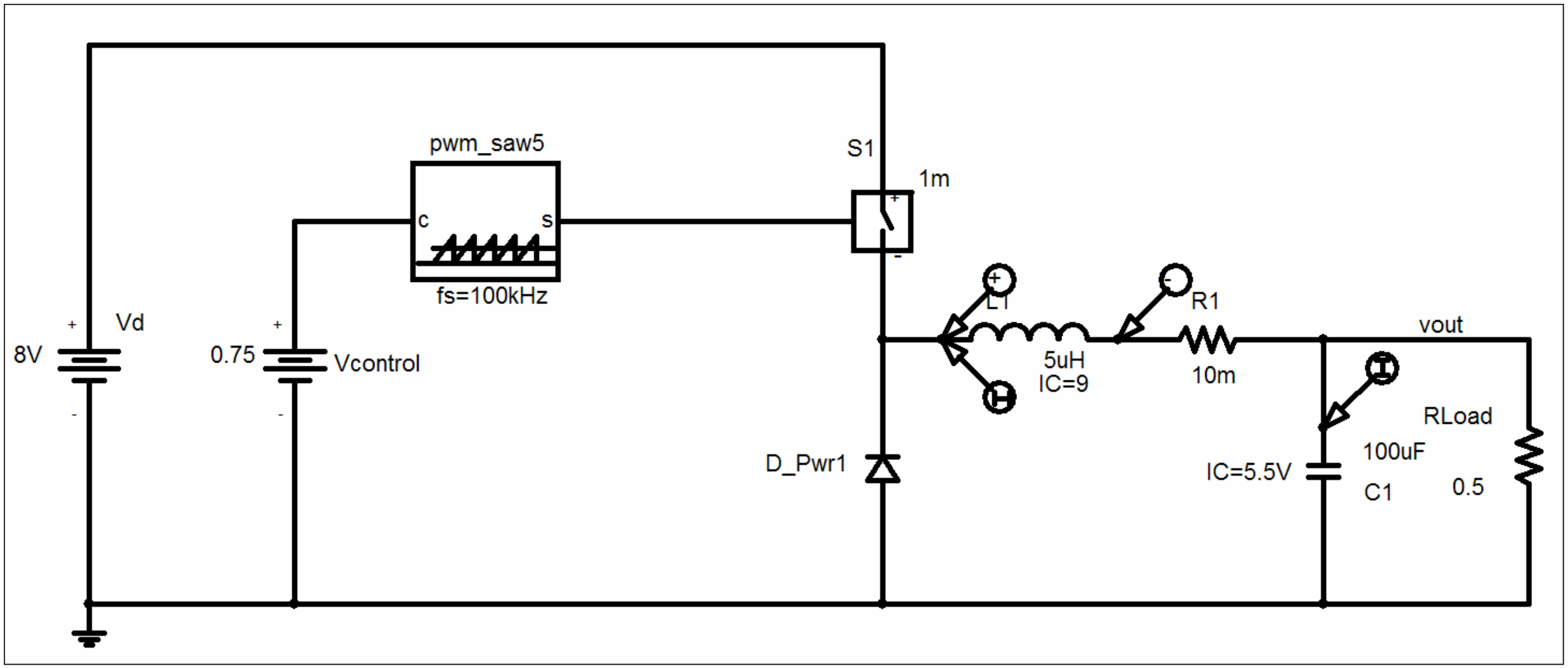
$$I_L = I_o = \frac{V_o}{R}$$

$$V_{in} I_{in} = V_o I_o$$

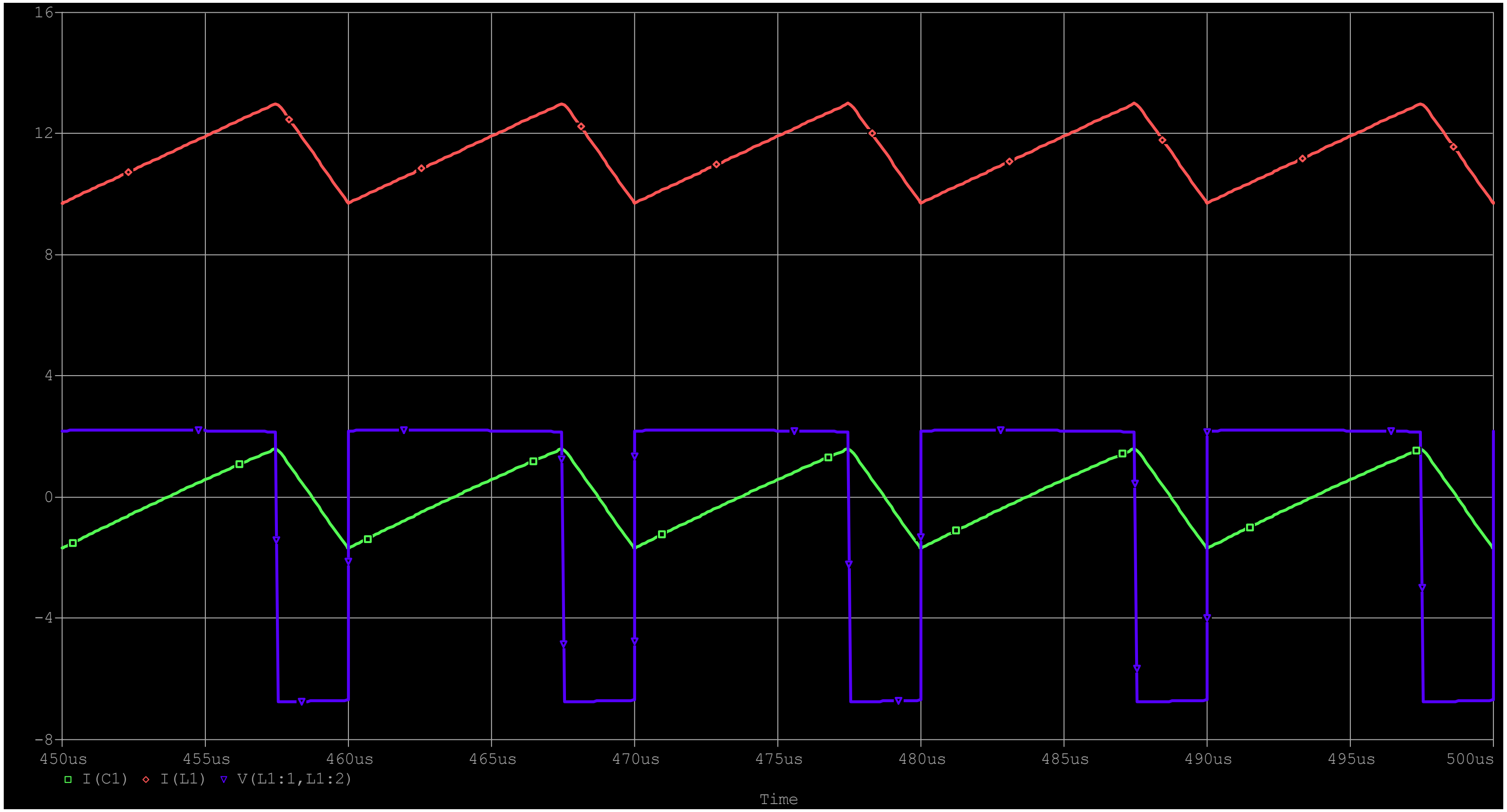
$$I_{in} = DI_L = DI_o$$

$$i_C(t) \simeq i_{L,ripple}(t)$$

PSpice Modeling: C:\FirstCourse_PE_Book03\Buckconv.sch



Simulation Results



BOOST CONVERTER SWITCHING ANALYSIS IN DC STEADY STATE

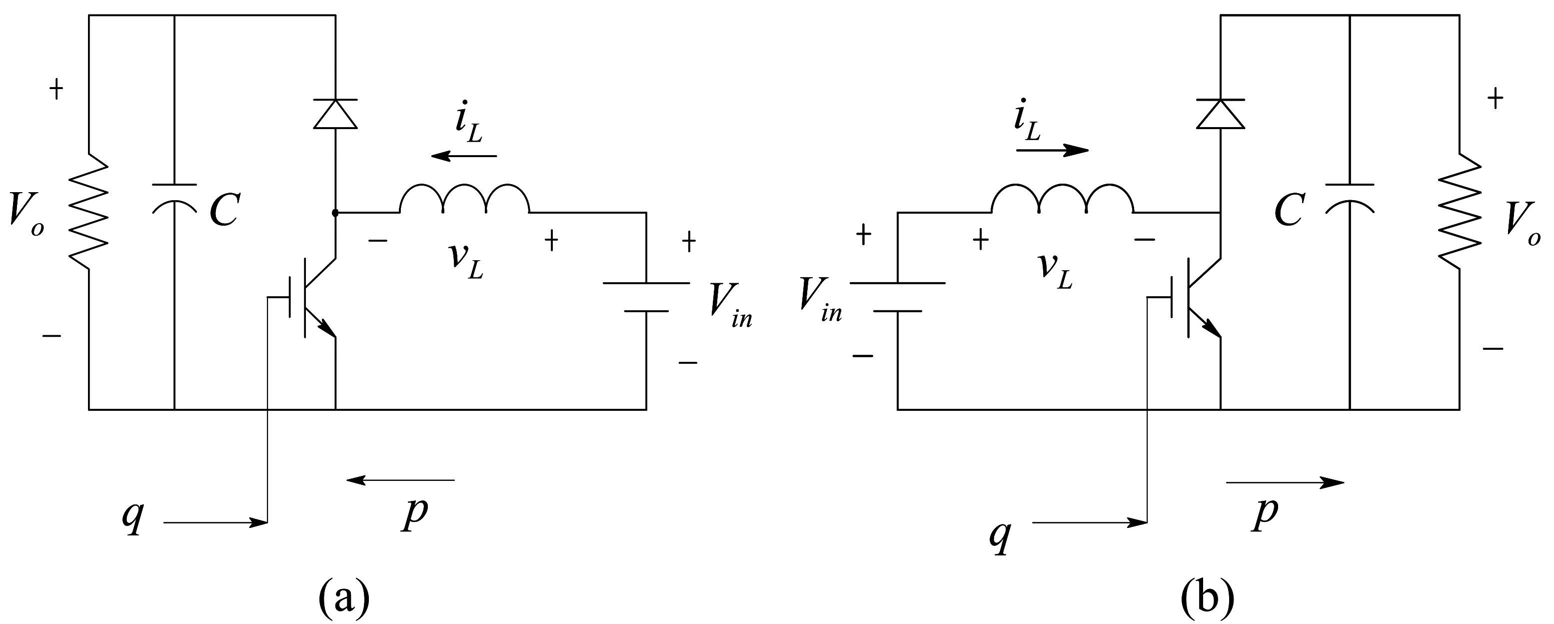


Figure 3-4 Boost dc-dc converter.

Boost converter: operation and waveforms

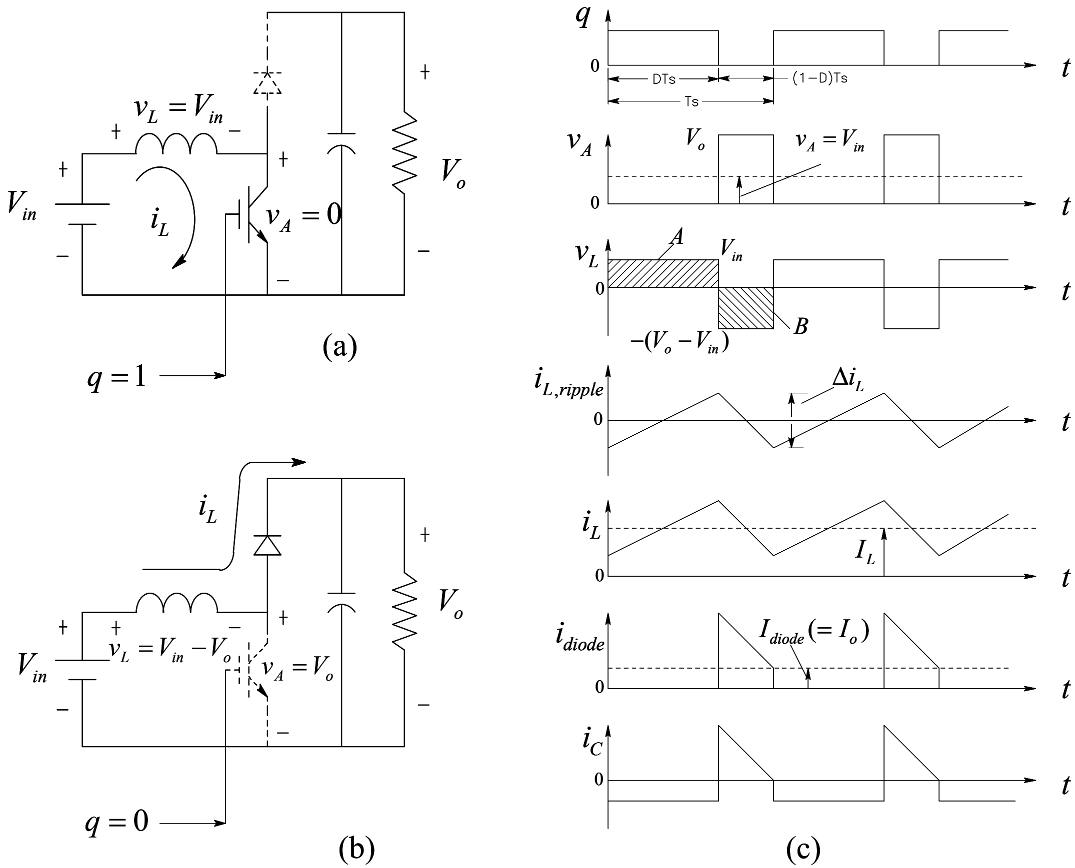


Figure 3-5 Boost converter: operation and waveforms.

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \qquad (V_o > V_{in})$$

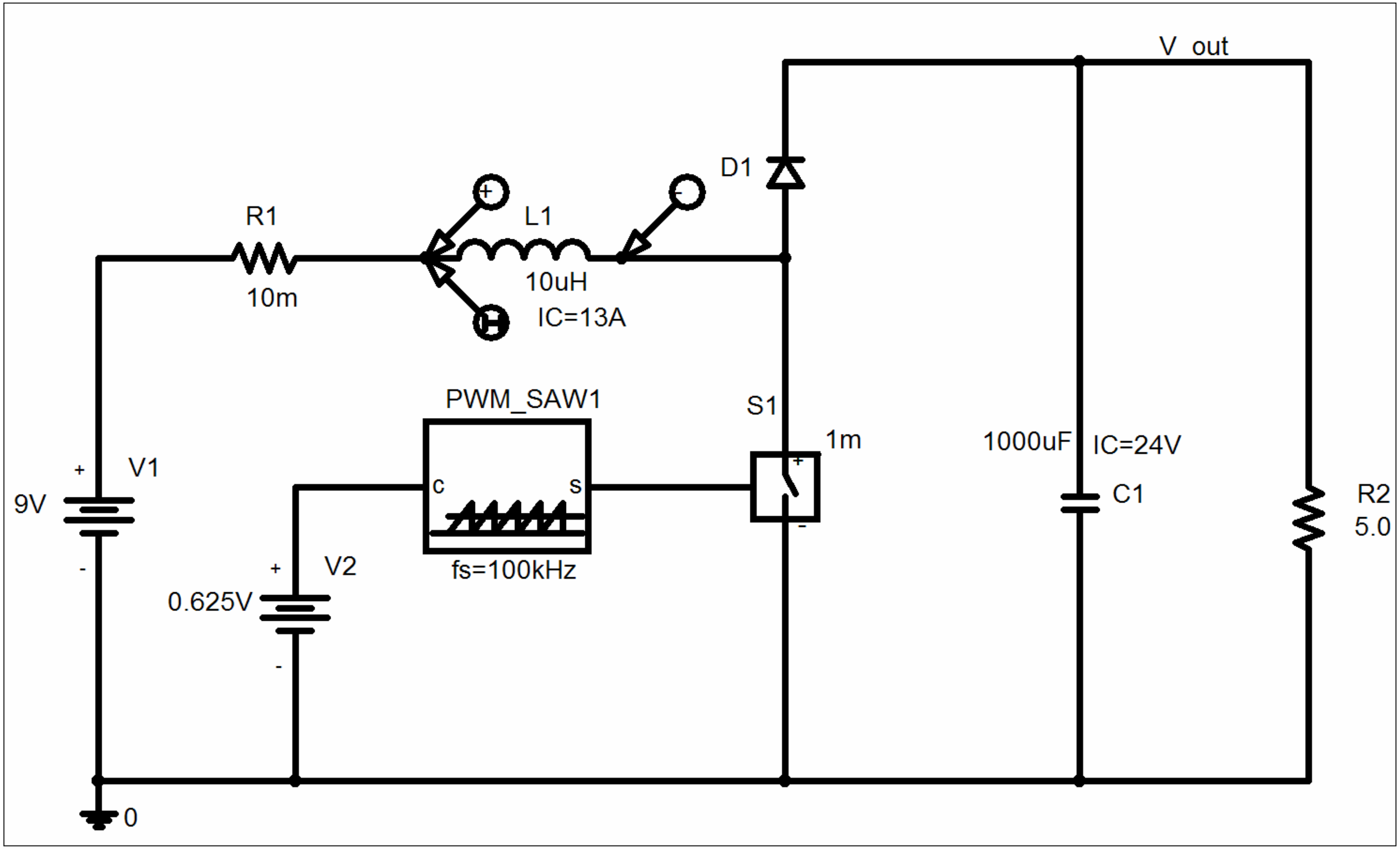
$$\Delta i_L = \frac{V_{in}}{L} DT_s = \frac{V_o - V_{in}}{L}(1-D)T_s$$

$$V_{in} I_{in} = V_o I_o$$

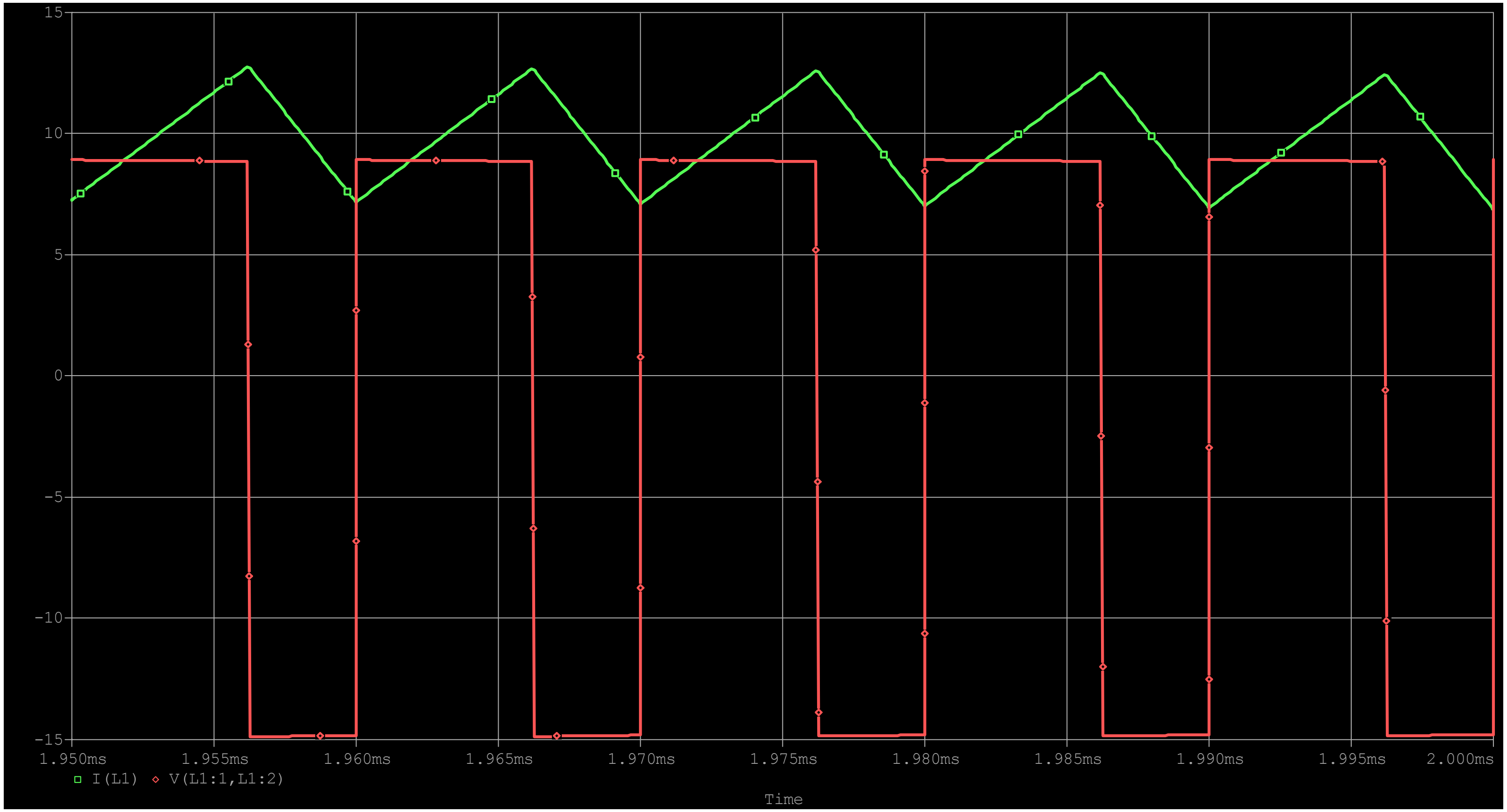
$$I_L = I_{in} = \frac{V_o}{V_{in}} I_o = \frac{I_o}{1-D} = \frac{1}{1-D}\frac{V_o}{R}$$

$$i_C(t) \simeq i_{diode,ripple}(t) = i_{diode} - I_o$$

PSpice Modeling: C:\FirstCourse_PE_Book03\Boost.sch



Simulation Results



Boost converter: voltage transfer ratio

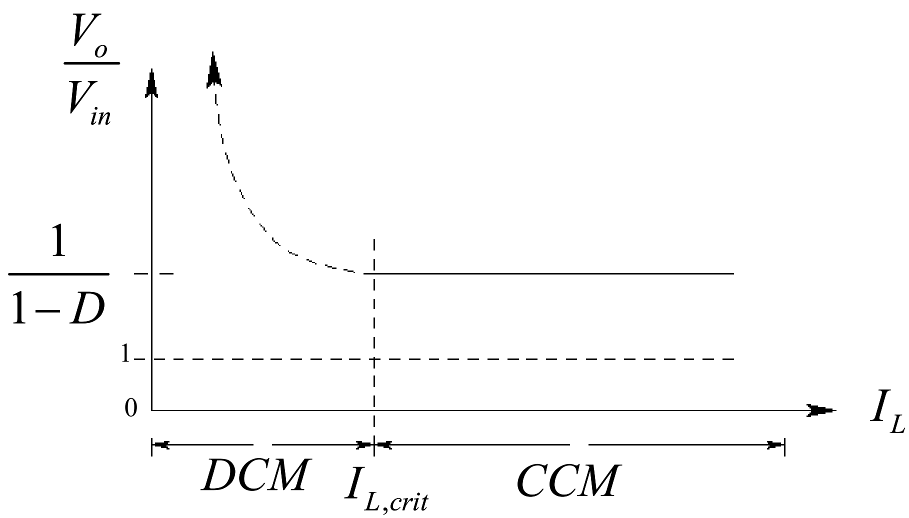


Figure 3-6 Boost converter: voltage transfer ratio.

BUCK-BOOST CONVERTER ANALYSIS IN DC STEADY STATE

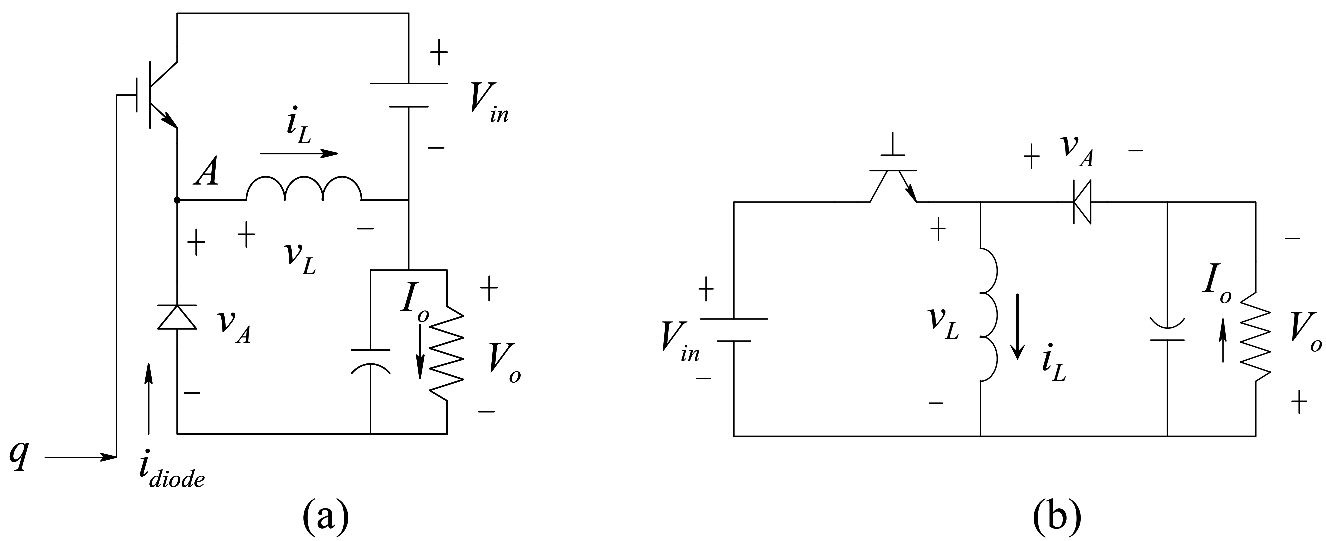
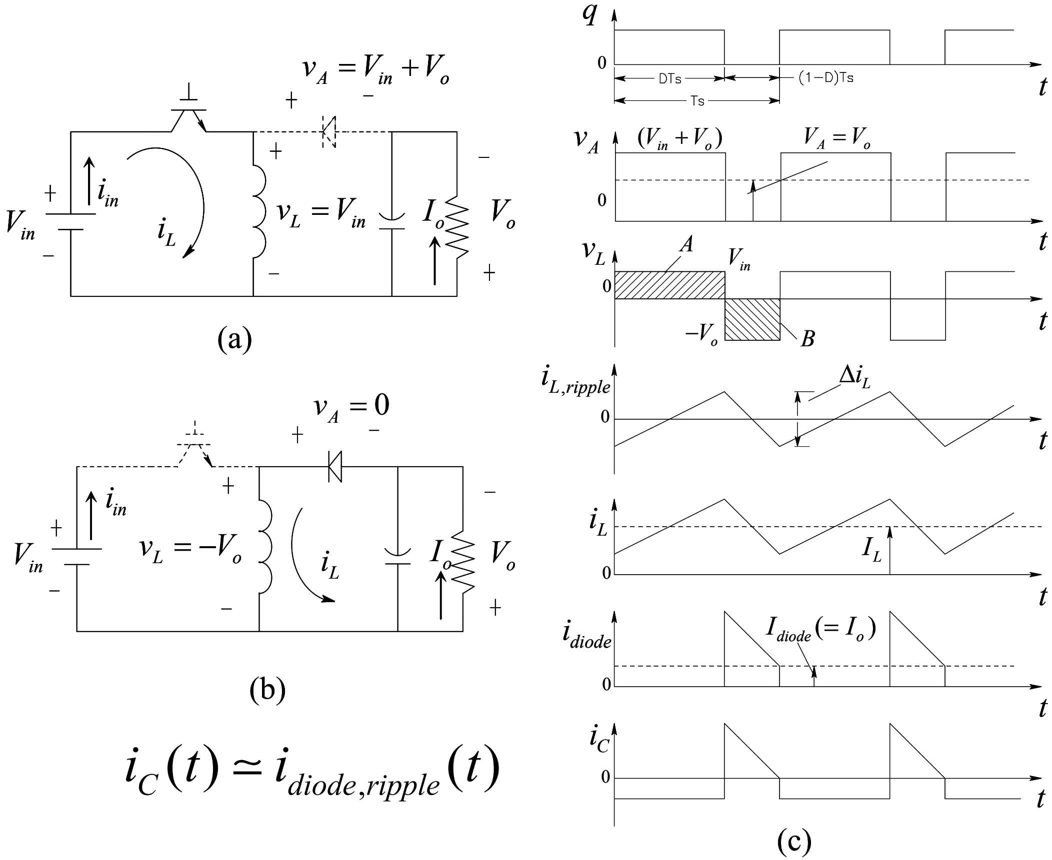


Figure 3-7 Buck-Boost dc-dc converter.

Buck-Boost converter: operation and waveforms



$$i_C(t) \simeq i_{diode,ripple}(t)$$

Figure 3-8 Buck-Boost converter: operation and waveforms.

$$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

$$\Delta i_L = \frac{V_{in}}{L} DT_s = \frac{V_o}{L}(1-D)T_s$$

$$I_L = I_{in} + I_o$$

$$V_{in} I_{in} = V_o I_o$$

$$I_{in} = \frac{V_o}{V_{in}} I_o = \frac{D}{1-D} I_o$$

$$I_L = I_{in} + I_o = \frac{1}{1-D} I_o = \frac{1}{1-D}\frac{V_o}{R}$$

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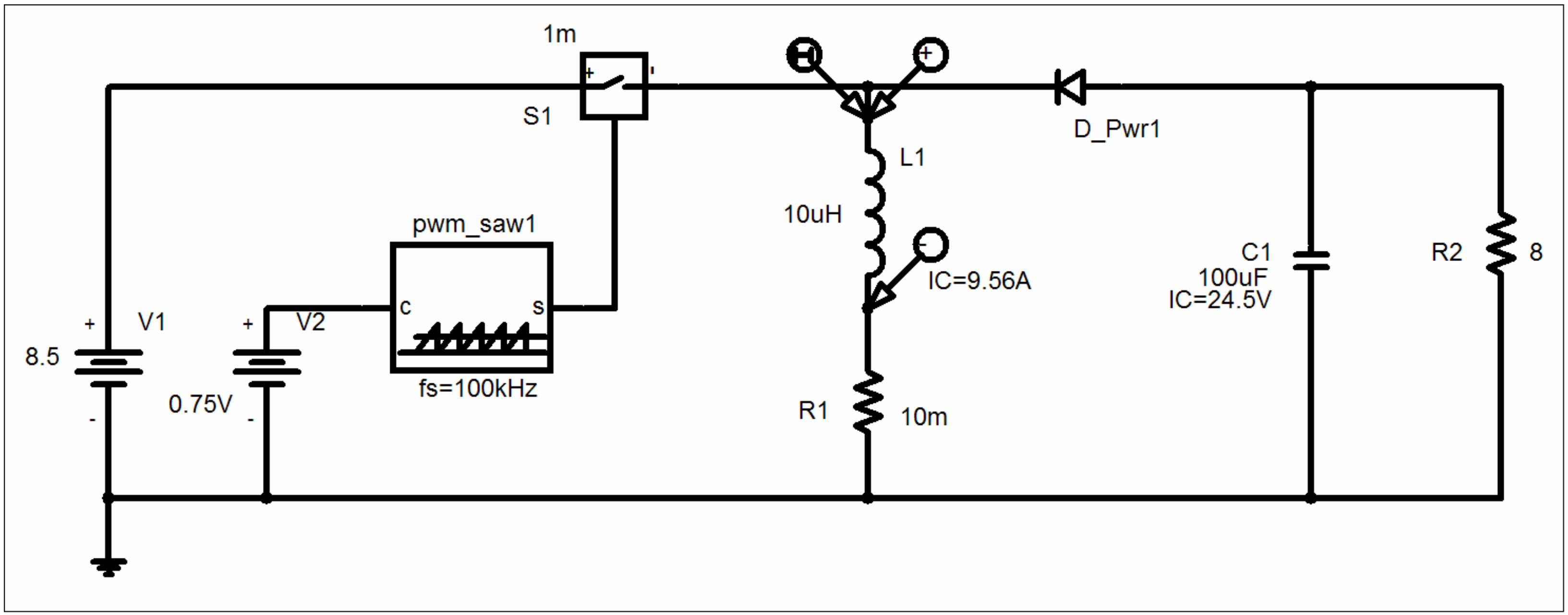
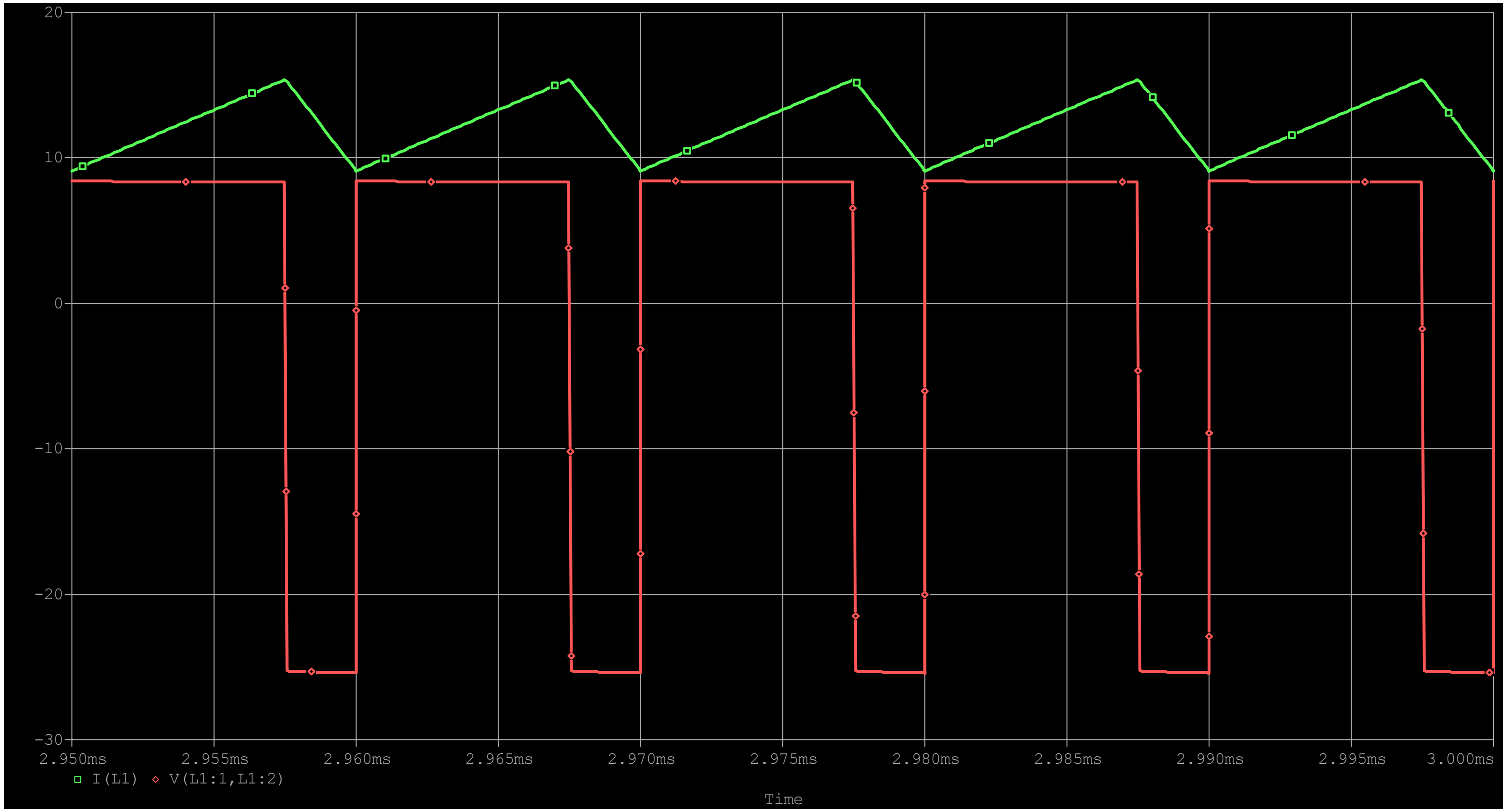


Simulation Results



Buck-Boost converter: voltage transfer ratio

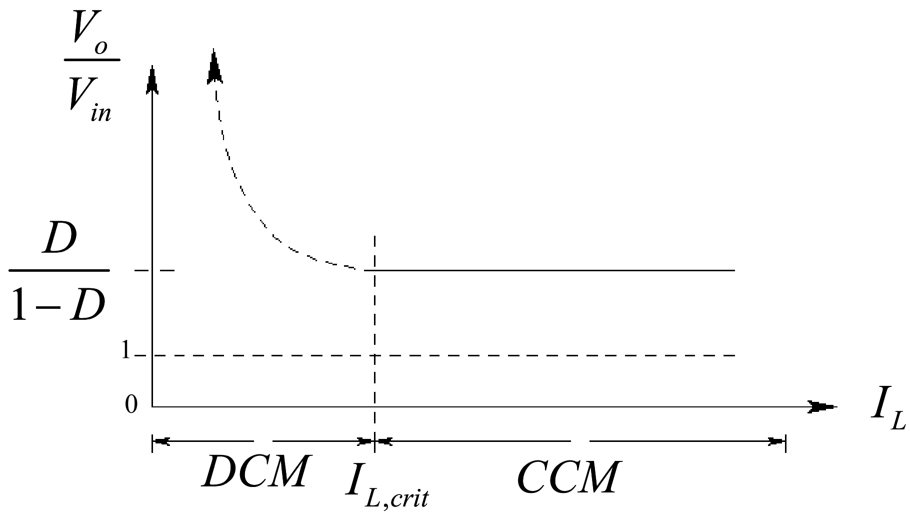


Figure 3-9 Buck-Boost converter: voltage transfer ratio.

Other Buck-Boost Topologies

- SEPIC Converters (Single-Ended Primary Inductor Converters)
- Cuk Converters

SEPIC Converters (Single-Ended Primary Inductor Converters)

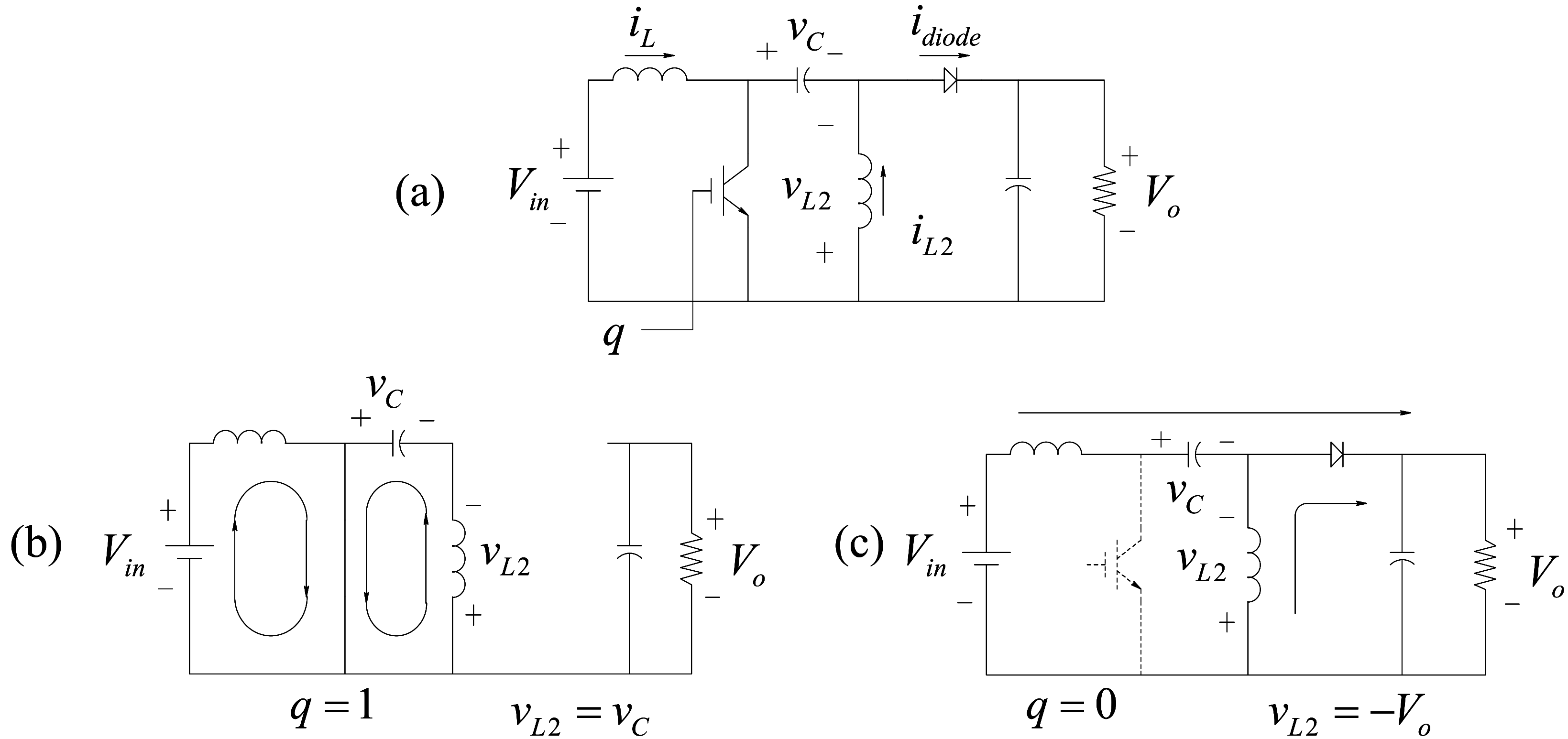


Figure 3-10 SEPIC converter.

$$DV_{in} = (1-D)V_o \qquad \frac{V_o}{V_{in}} = \frac{D}{1-D}$$

Cuk Converter

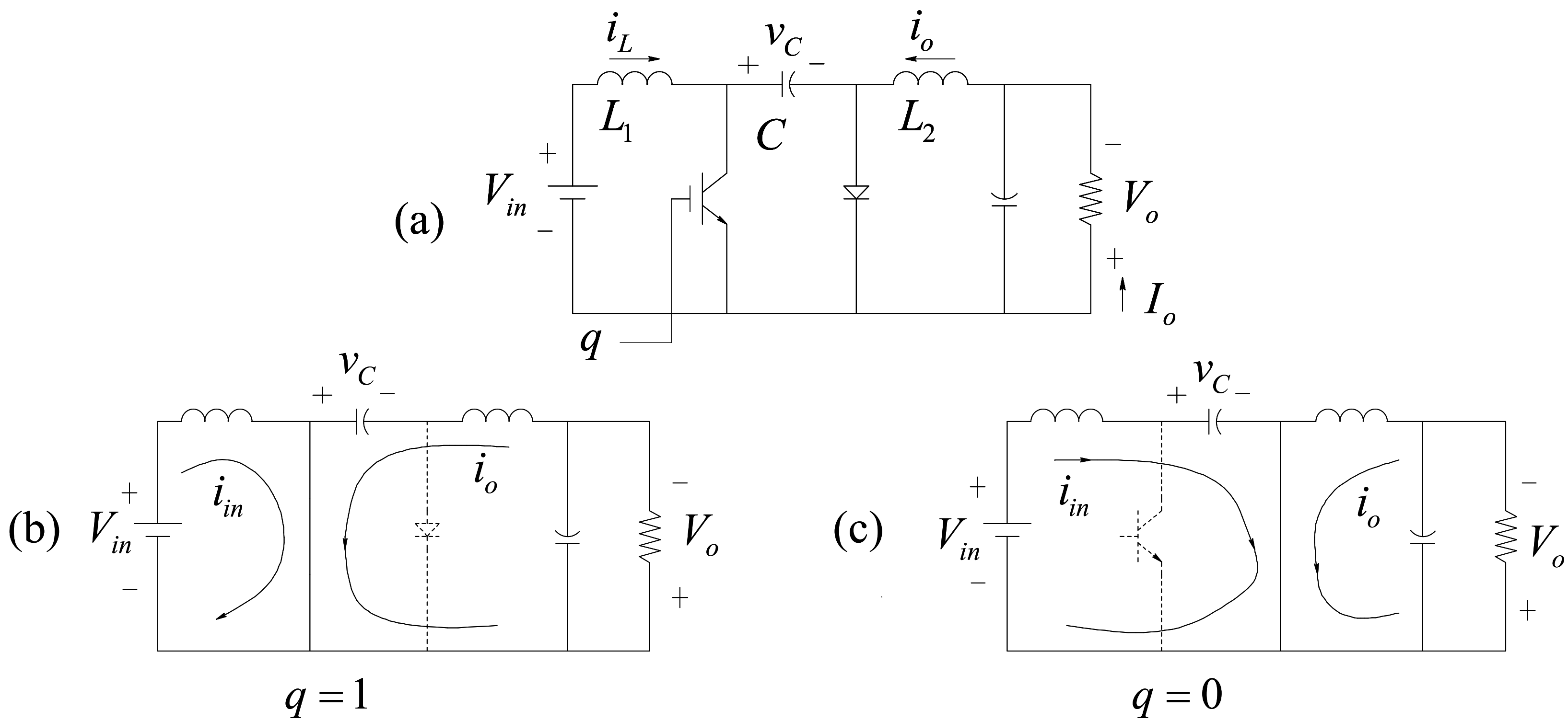


Figure 3-11 Cuk converter.

$$DI_o = (1-D)I_{in}$$

$$\frac{I_{in}}{I_o} = \frac{D}{1-D}$$

$$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

TOPOLOGY SELECTION

Criterion		Buck	Boost	Buck-Boost
Transistor $\hat{V}$		V_{in}	V_o	$(V_{in} + V_o)$
Transistor $\hat{I}$		I_o	I_{in}	$I_{in} + I_o$
I_{rms}	Transistor	$\sqrt{D} I_o$	$\sqrt{D} I_{in}$	$\sqrt{D}\left(I_{in} + I_o\right)$
I_{avg}	Transistor	$D I_o$	$D I_{in}$	$D\left(I_{in} + I_o\right)$
	Diode	$(1 - D) I_o$	$(1 - D) I_{in}$	$(1 - D)\left(I_{in} + I_o\right)$
I_L		I_o	I_{in}	$I_{in} + I_o$
Effect of L on C		significant	little	little
Pulsating Current		input	output	both

WORST-CASE DESIGN

The worst-case design should consider the ranges in which the input voltage and the output load vary. As mentioned earlier, often converters above a few tens of watts are designed to operate in CCM. To ensure CCM even under very light load conditions would require prohibitively large inductance. Hence, the inductance value chosen is often no larger than three times the critical inductance $\left(L < 3L_c\right)$, where, as discussed in section 3-15, the critical inductance L_c is the value of the inductor that will make the converter operate at the border of CCM and DCM at full-load.

SYNCHRONOUS-RECTIFIED BUCK CONVERTER FOR VERY LOW OUTPUT VOLTAGES

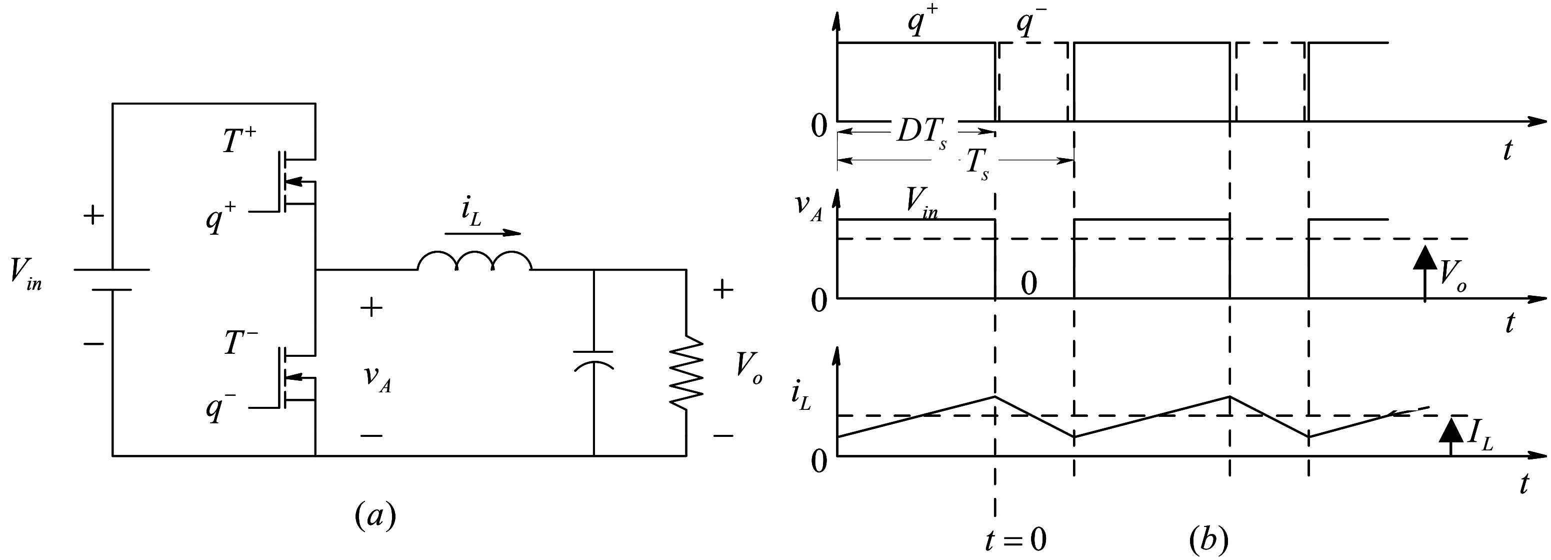


Figure 3-12 Buck converter: synchronous rectified.

INTERLEAVING OF CONVERTERS

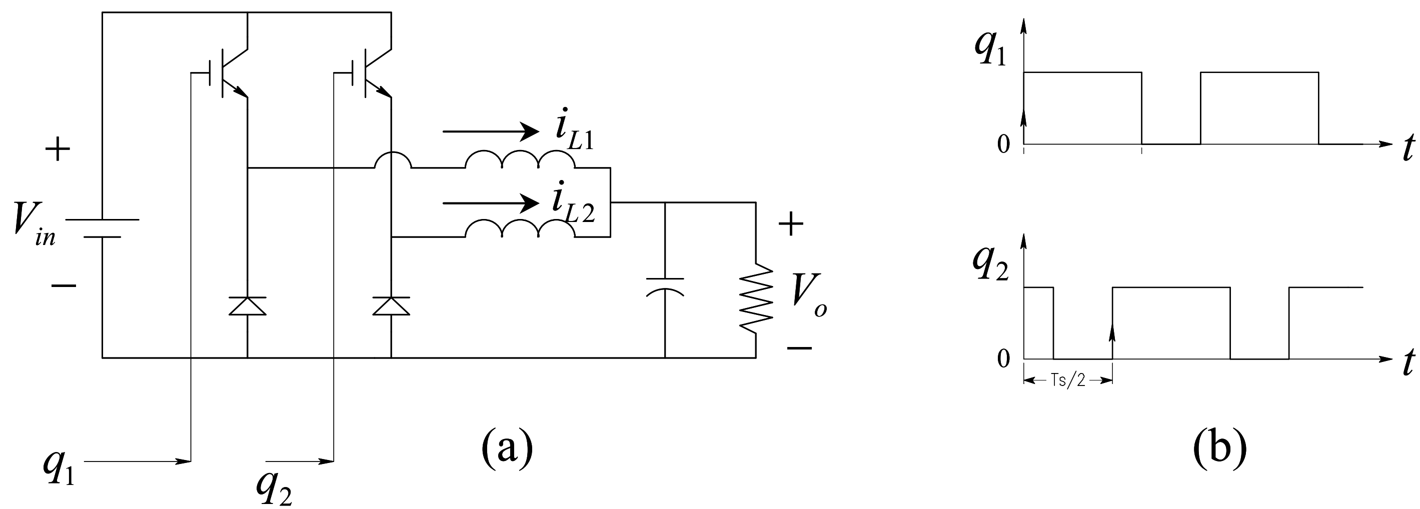


Figure 3-13 Interleaving of converters.

REGULATION OF DC-DC CONVERTERS BY PWM

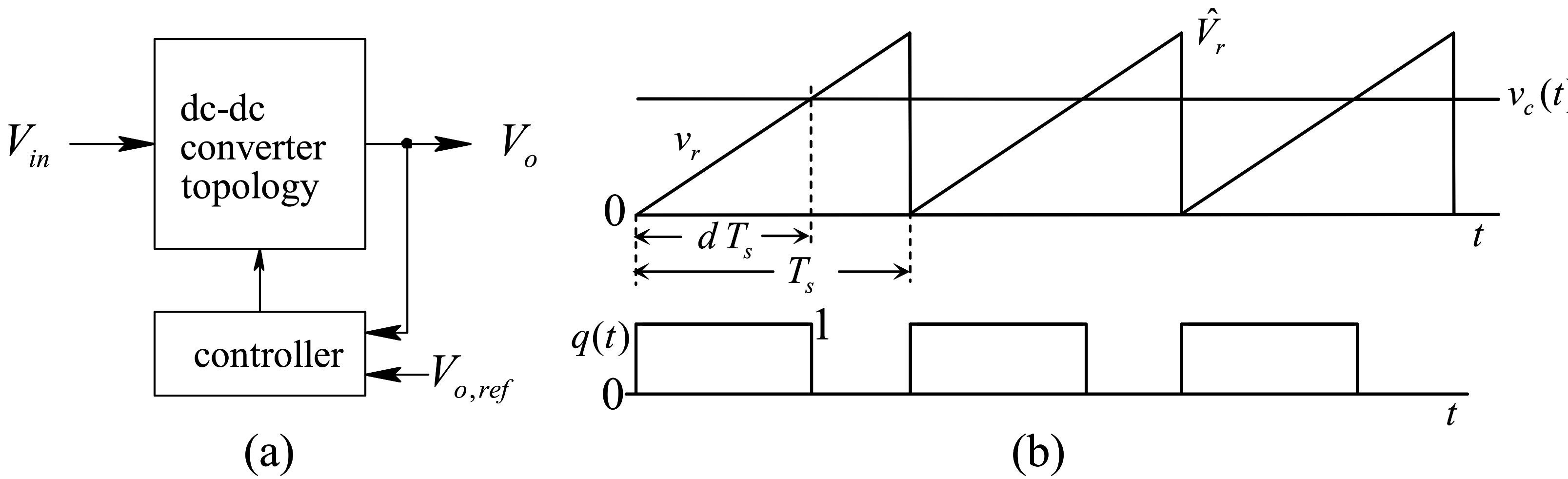


Figure 3-14 Regulation of output by PWM.

$$d(t) = \frac{v_c(t)}{\hat{V}_r}$$

DYNAMIC AVERAGE REPRESENTATION OF CONVERTERS IN CCM

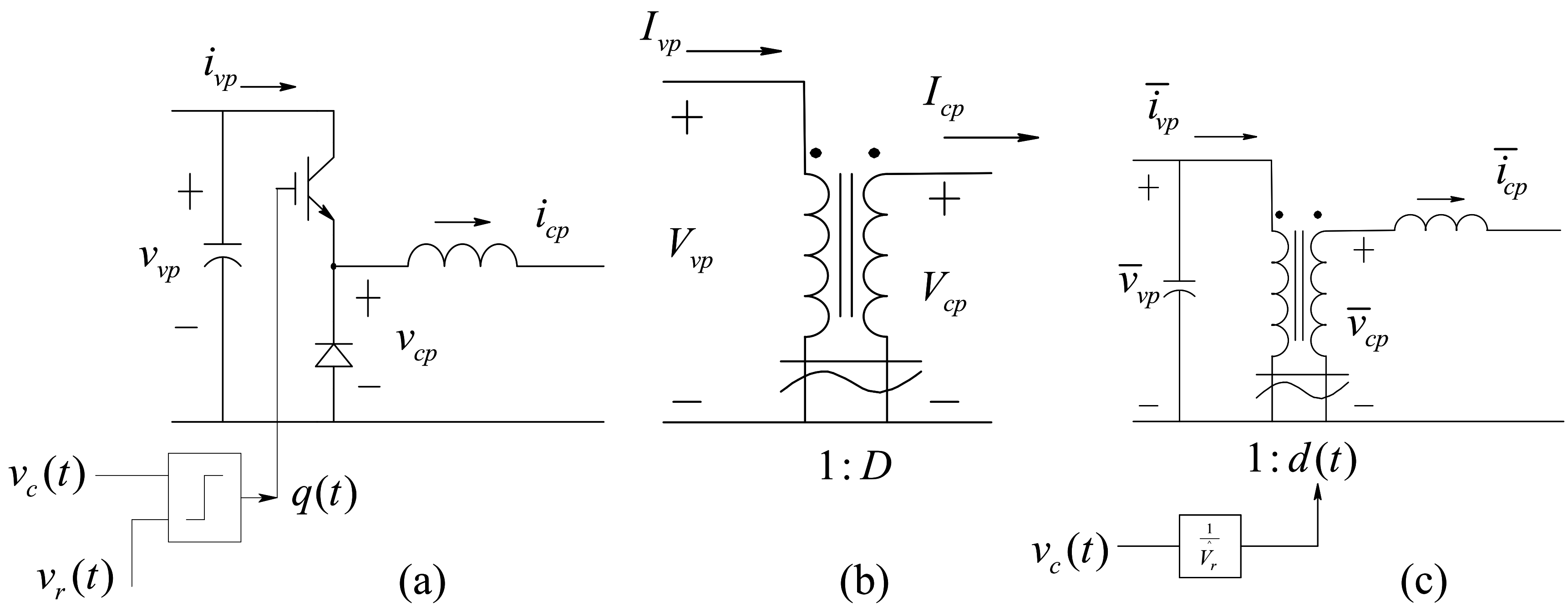


Figure 3-15 Average dynamic model of a switching power-pole.

$$V_{cp} = D V_{vp} \qquad \bar{v}_{cp}(t) = d(t)\,\bar{v}_{vp}(t)$$

$$I_{vp} = D\,I_o \qquad \bar{i}_{vp}(t) = d(t)\,\bar{i}_{cp}(t)$$

Average dynamic models of three converters

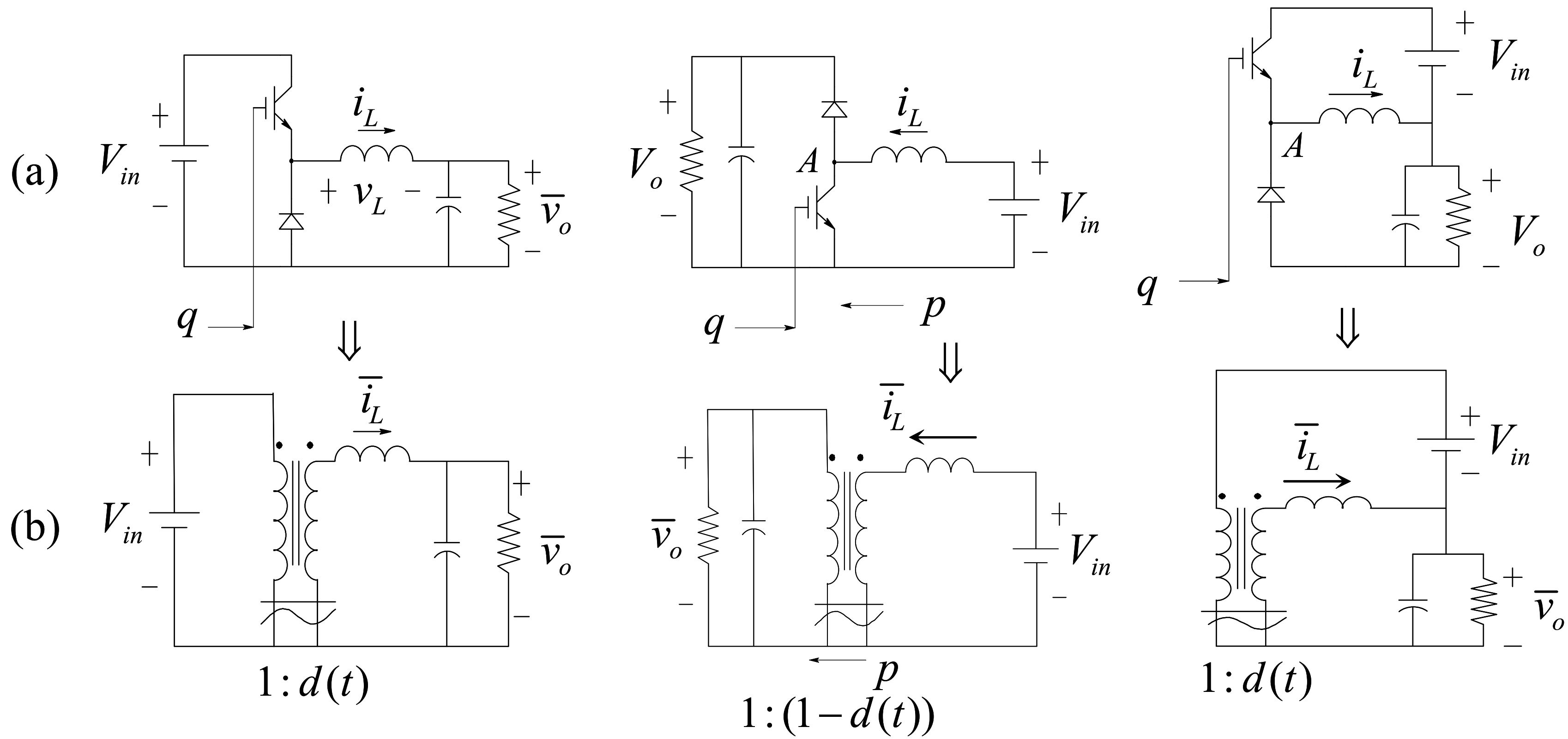


Figure 3-16 Average dynamic models of three converters.

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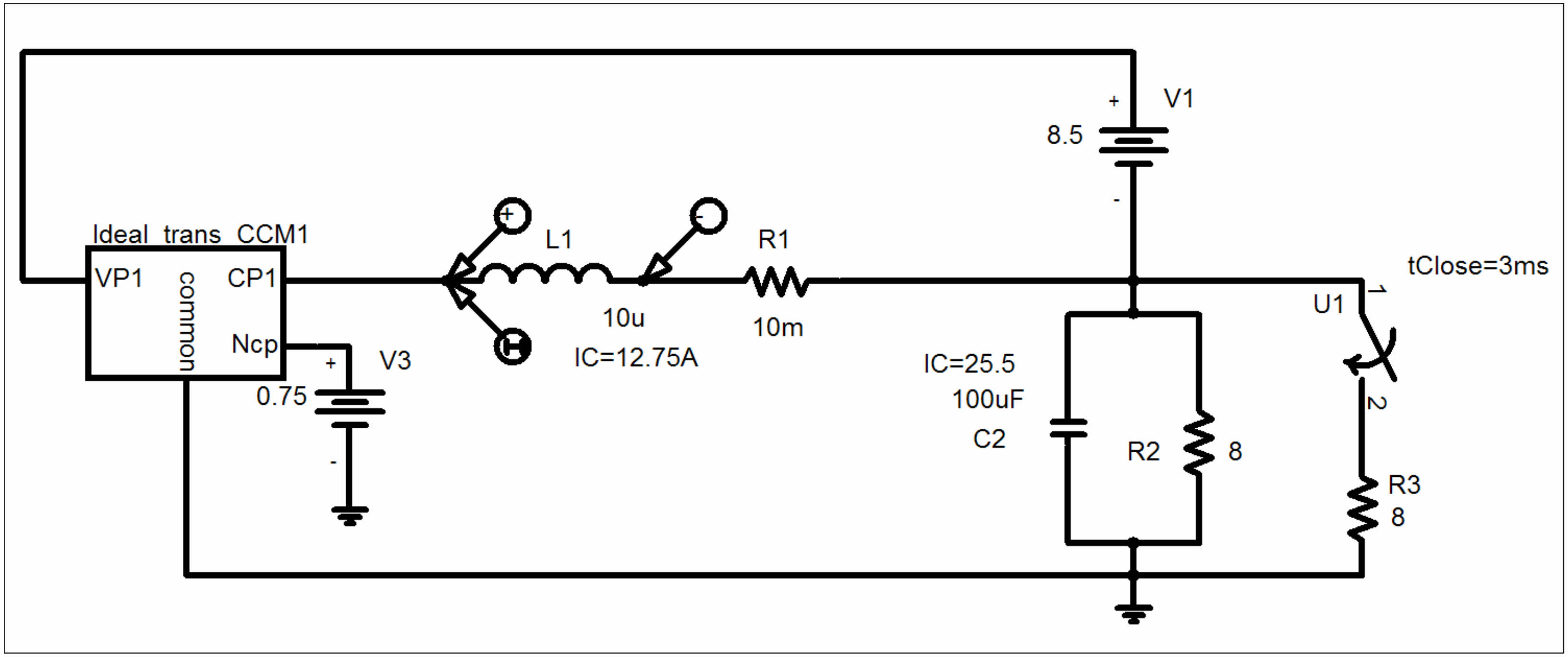
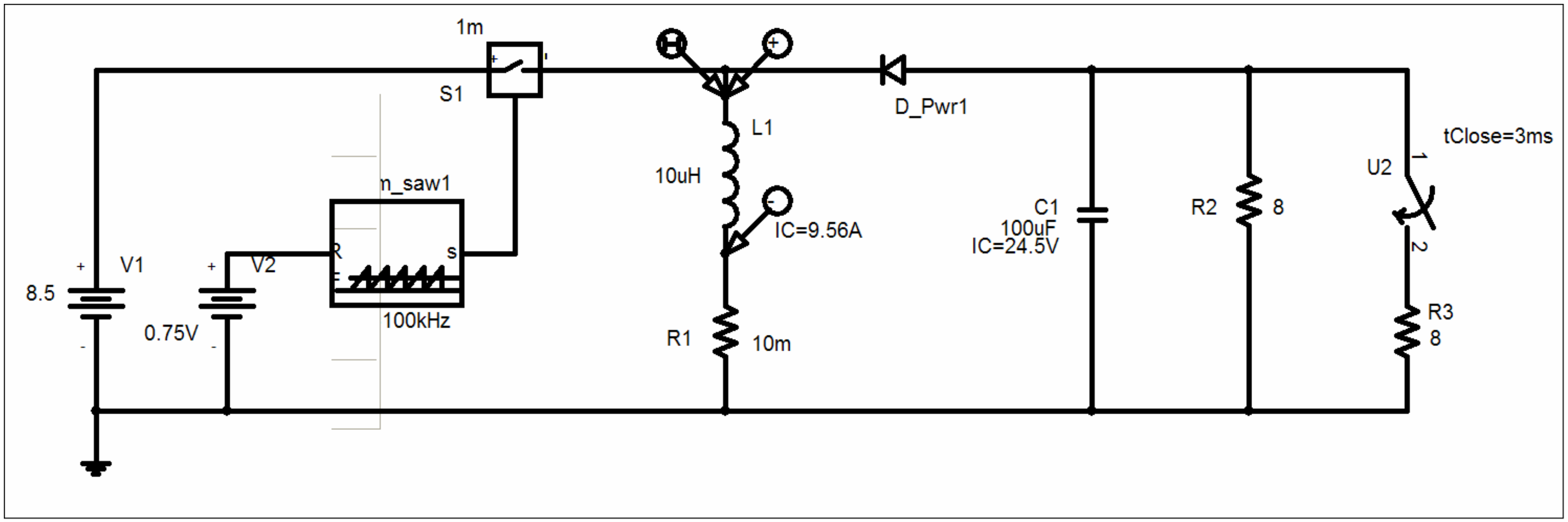
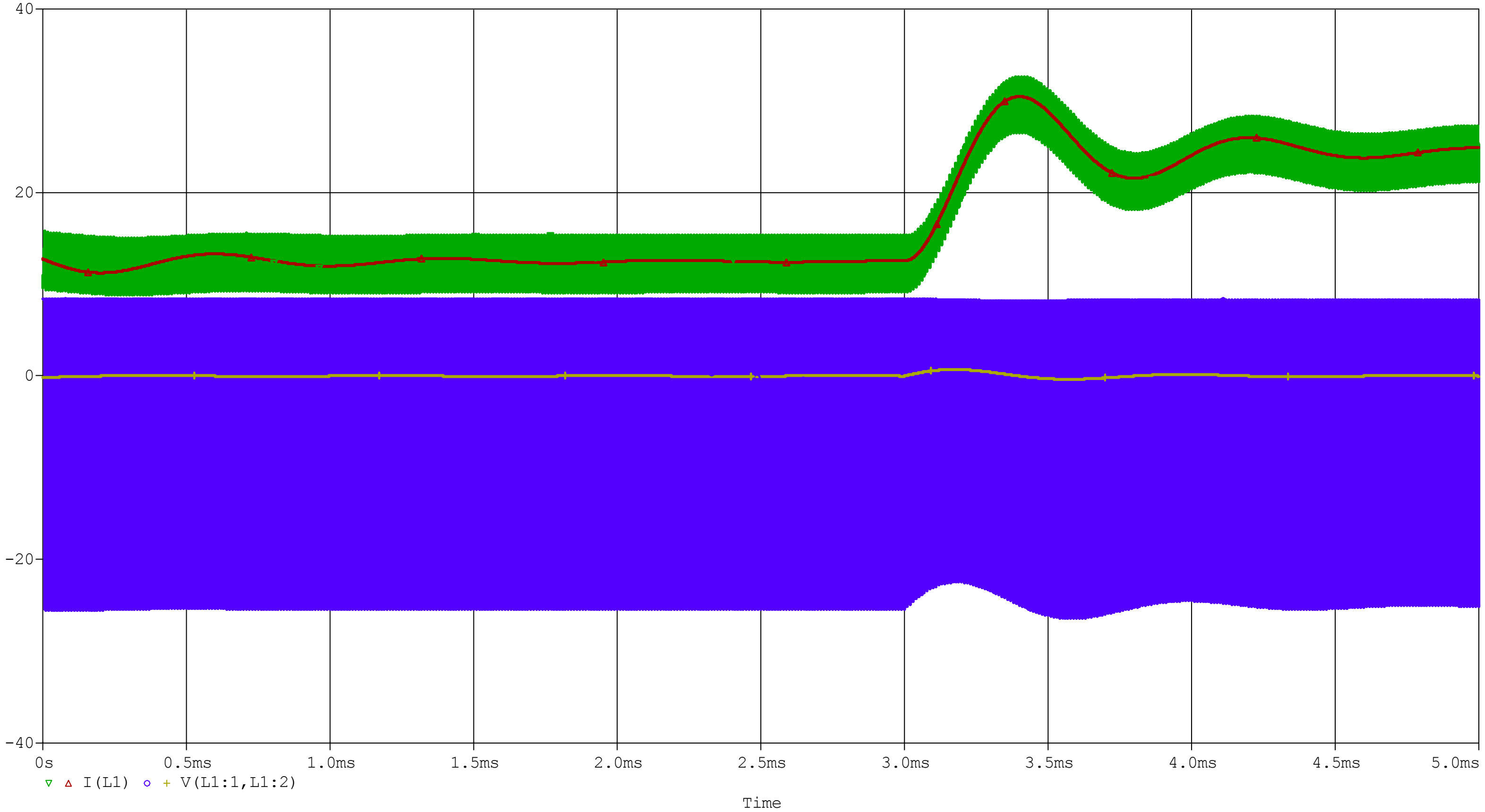


PSpice Modeling: C:\FirstCourse_PE_Book03\Buck-Boost_Switching_LoadTransient.sch



Simulation Results



BI-DIRECTIONAL SWITCHING POWER-POLE

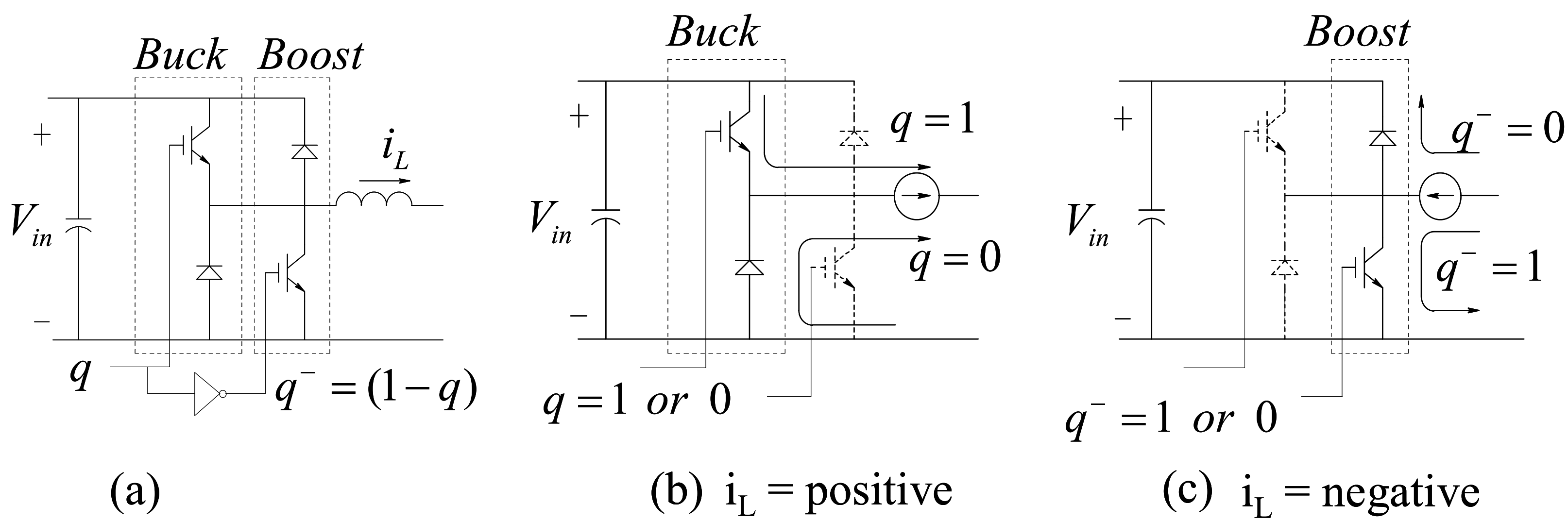


Figure 3-17 Bi-directional power flow through a switching power-pole.

Average dynamic model of the switching power-pole with bi-directional power flow

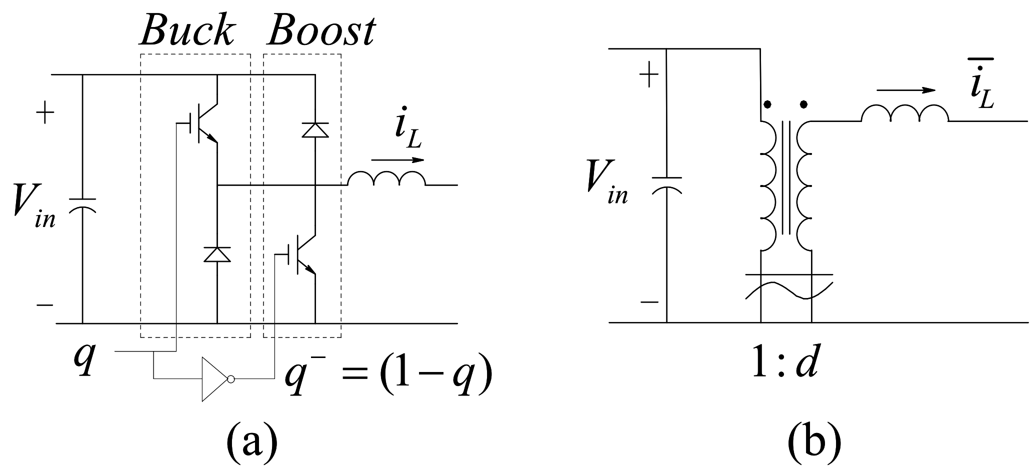


Figure 3-18 Average dynamic model of the switching power-pole with bi-directional power flow.

DISCONTINUOUS-CONDUCTION MODE (DCM)

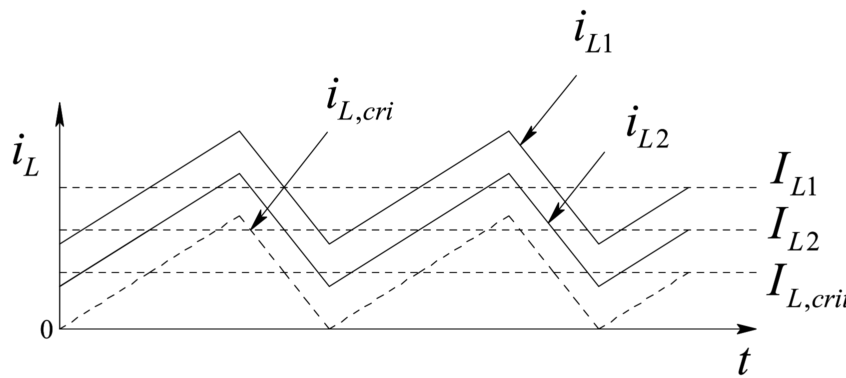


Figure 3-19 Inductor current at various loads; duty-ratio is kept constant.

Critical Inductor Currents

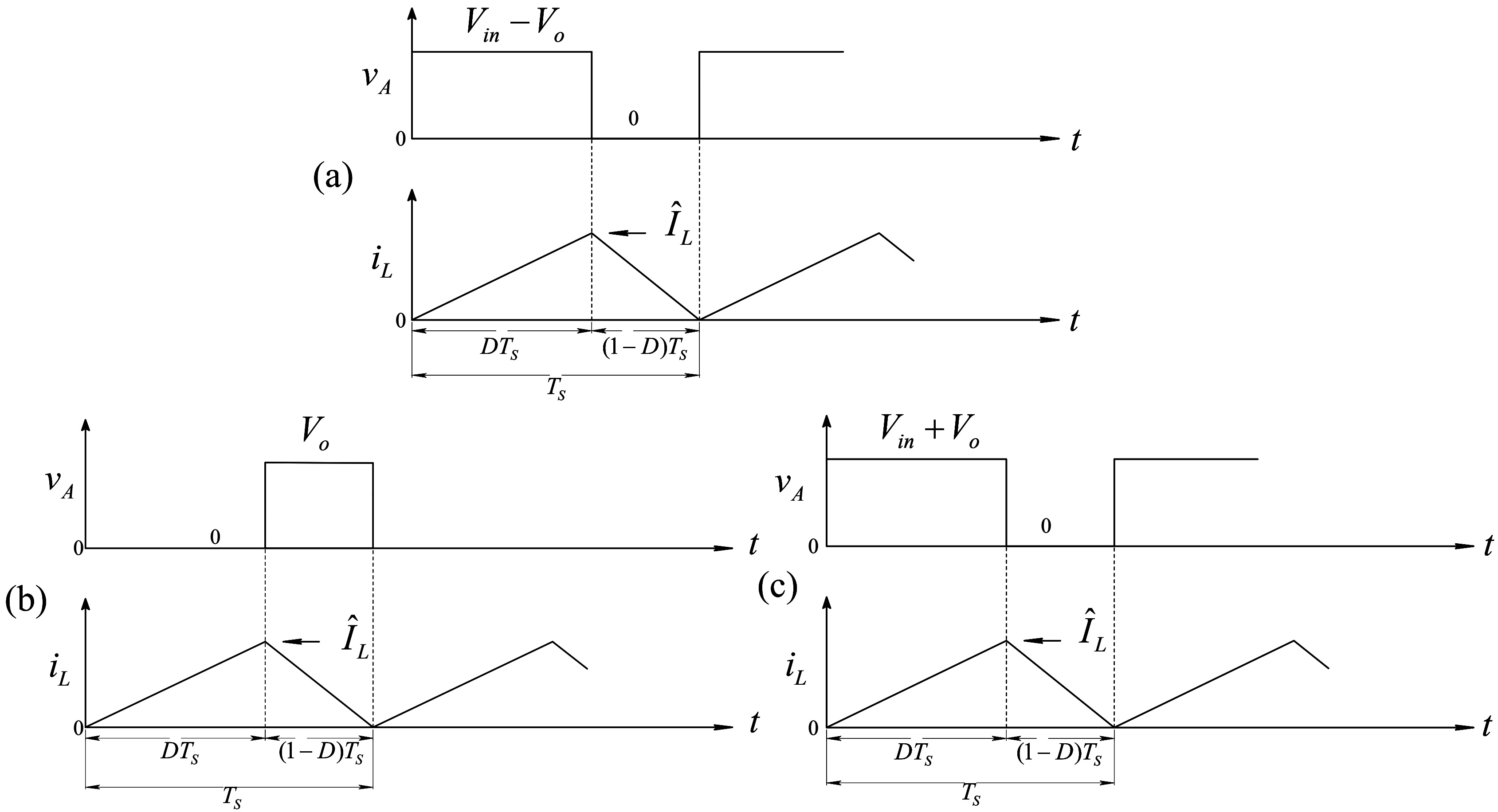


Figure 3-20 Waveforms for the three converters at the border of CCM/DCM.

$$I_{L,crit,Buck} = \frac{V_{in}}{2Lf_s} D(1-D) \qquad I_{L,crit,Boost} = I_{L,crit,Buck\text{-}Boost} = \frac{V_{in}}{2Lf_s} D$$

Buck converter in DCM

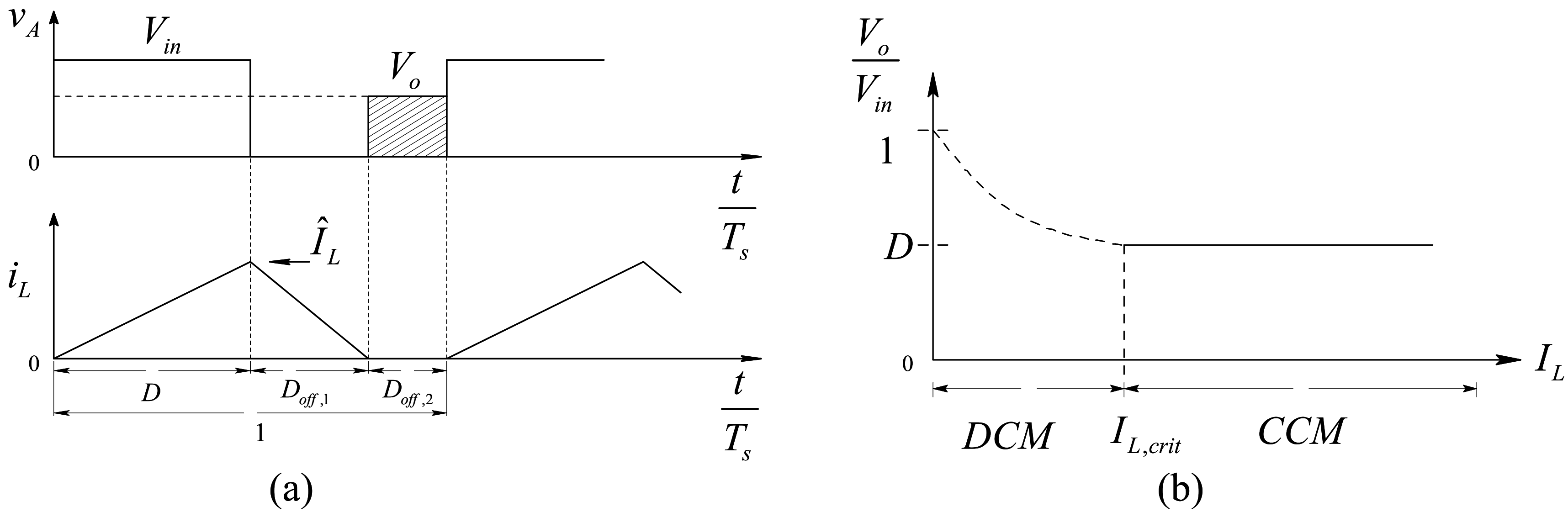


Figure 3A-1 Buck converter in DCM.

Boost Converters in DCM

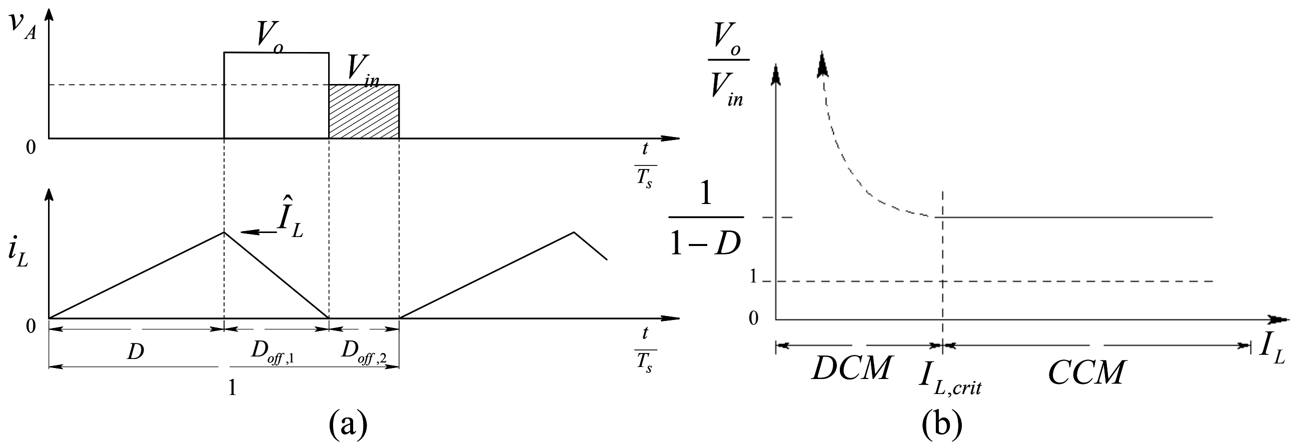


Figure 3A-2 Boost converter in DCM.

Buck-Boost converter in DCM

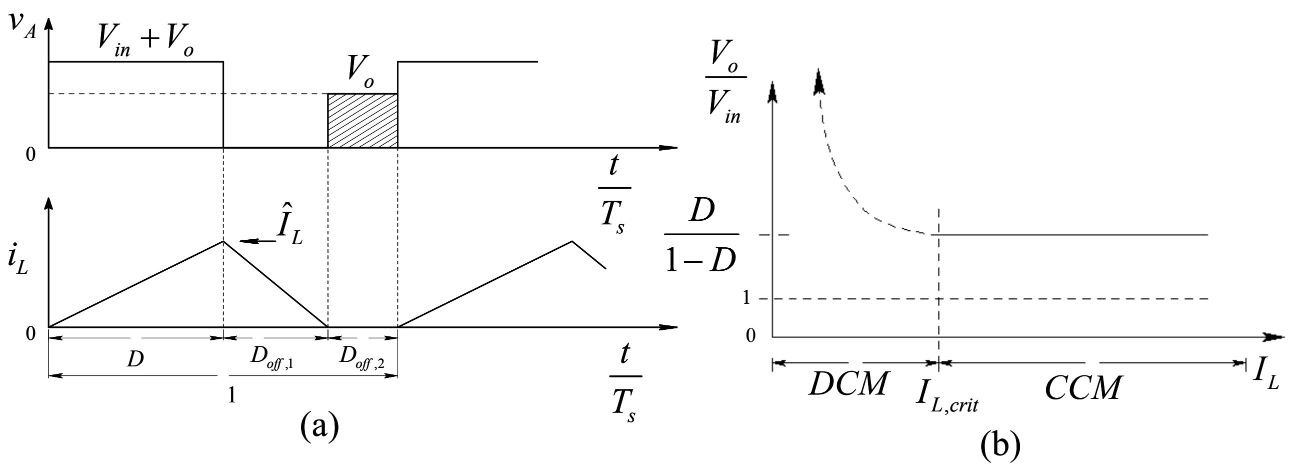


Figure 3A-3 Buck-Boost converter in DCM.

AVERAGE REPRESENTATION OF DC-DC CONVERTERS IN DCM

- **Dependent Sources in Buck and Buck-Boost Converters in DCM**

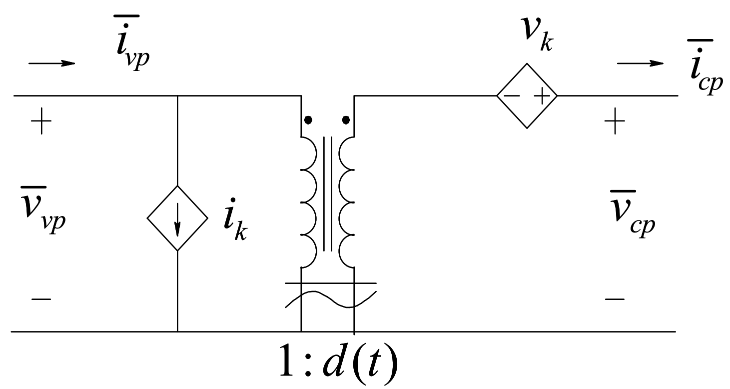


Figure 3A-4 Average dynamic model for Buck and Buck-Boost converters.

$$v_{k,Buck} = [1 - \frac{2Lf_s\bar{i}_L}{(V_{in} - \bar{v}_o)d}]\bar{v}_0$$

$$v_{k,Buck-Boost} = \left(1 - \frac{2Lf_s\bar{i}_L}{V_{in}d}\right)\bar{v}_o$$

$$i_{k,Buck} = \frac{d^2}{2Lf_s}(V_{in} - \bar{v}_0) - d\bar{i}_L$$

$$i_{k,Buck-Boost} = \frac{d^2}{2Lf_s}V_{in} - d\bar{i}_L$$

- **Dependent Sources in Boost Converters in DCM**

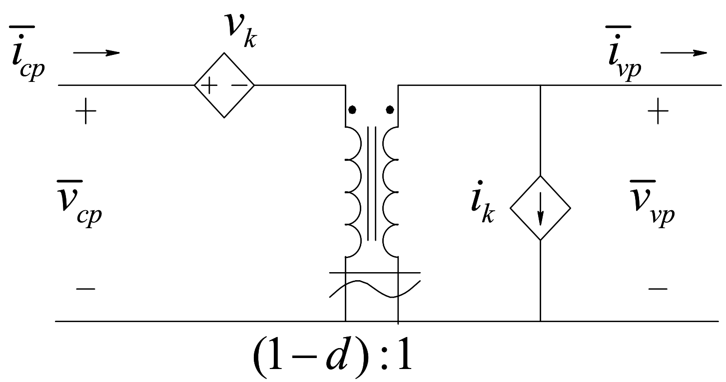


Figure 3A-5 Average dynamic model for Boost converters.

$$v_{k,Boost} = \left(1 - \frac{2Lf_s\overline{i}_L}{V_{in}d}\right)\left(V_{in} - \overline{v}_0\right)$$

$$i_{k,Boost} = \frac{d^2}{2Lf_s}V_{in} - d\overline{i}_L$$