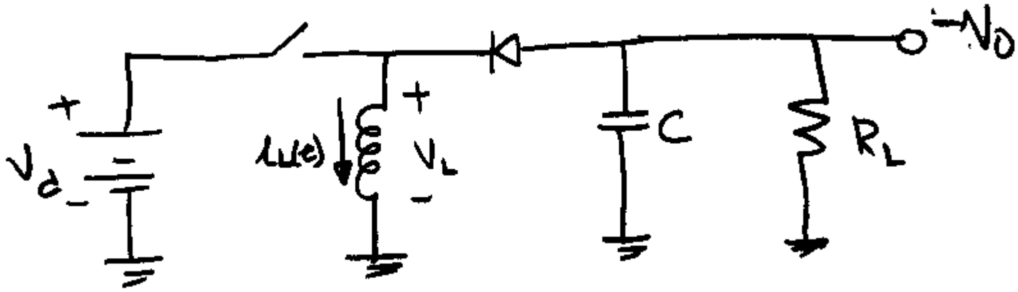
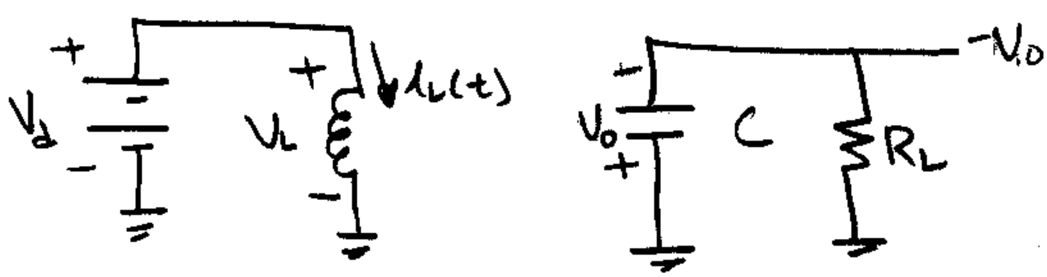
Polarity Inverting Regulator

OR Buck-Boost Regulator



During ton: switch Closed

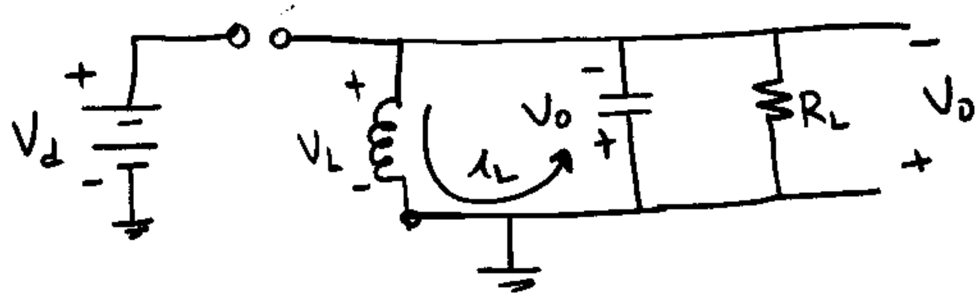
D = off



- Capacitor supplies power to load

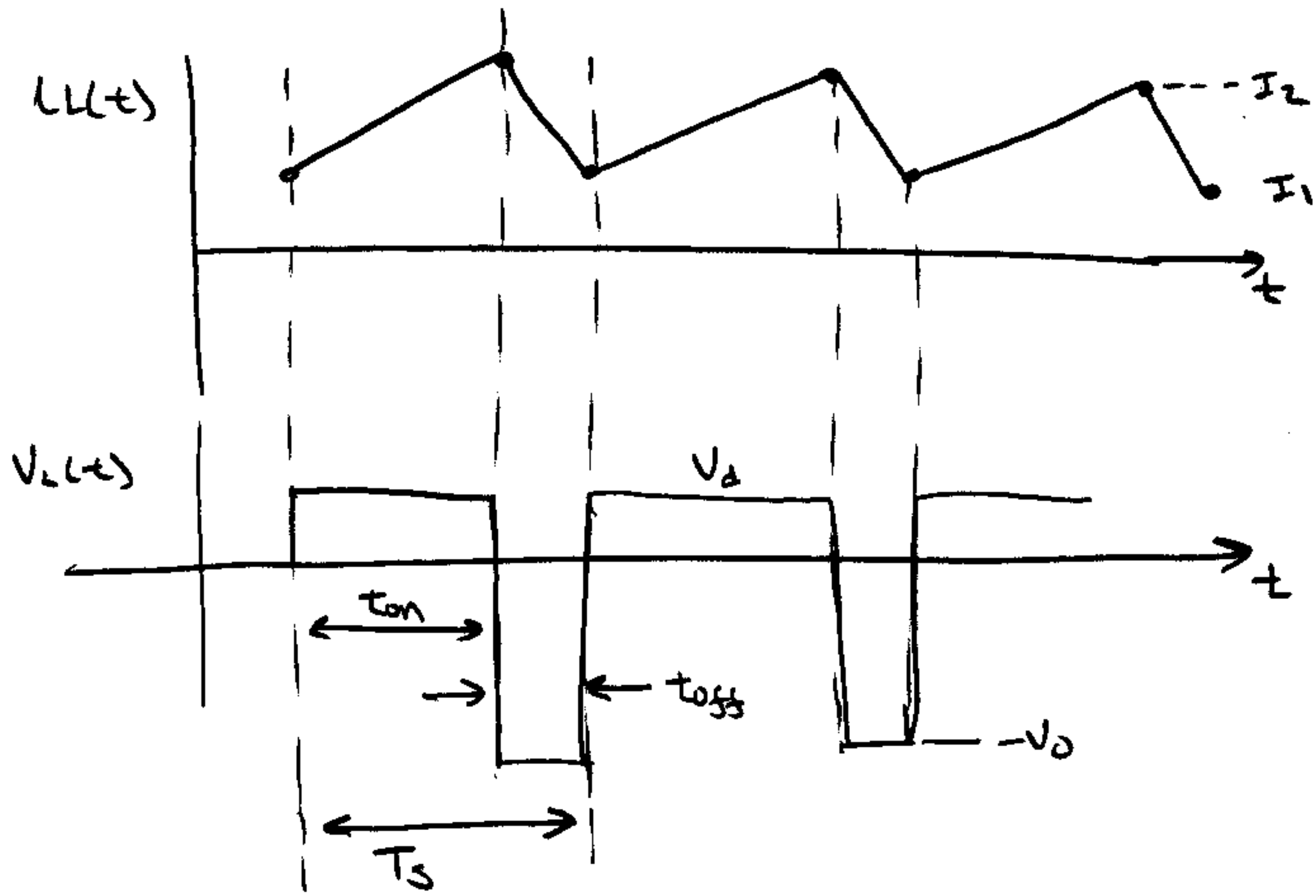
$V_L = V_d$

During t_{off} : Switch = off
D = on



- $V_L = -V_o$
- Capacitor supplies power to Load
- Inductor dumps Energy to capacitor

Continuous mode operation



- In continuous mode $I_L > 0$

and $t_{on} + t_{off} = T_s$

- Since in steady state, the average current over one cycle is constant,

$$\int_{T_s} V_L(t)\, dt = 0$$

OR

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

OR

$$V_d\, t_{on} - V_o(T_s - t_{on}) = 0$$

OR

$$\boxed{\frac{V_o}{V_d} = \frac{t_{on}}{T_s - t_{on}} = \frac{D}{1-D}} \quad ; \quad D = \frac{t_{on}}{T_s} \qquad (1)$$

Assuming a lossless circuit, $P_d = P_o$, OR

$$V_d\, I_d = V_o\, I_o$$

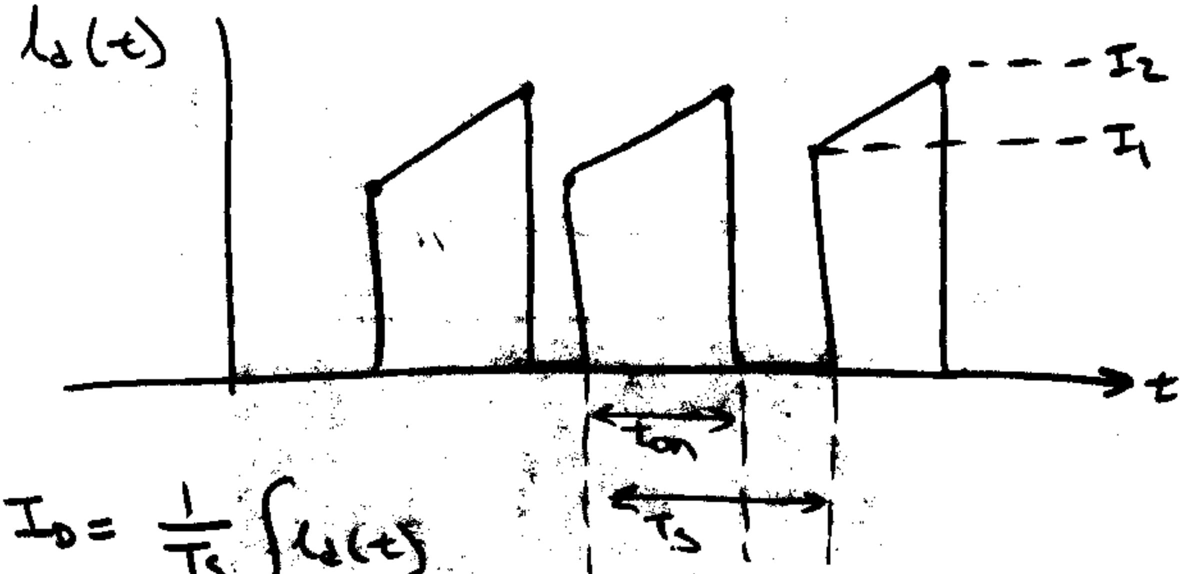
Where I_d = average input current and

I_o = average output current

Since $P_d = P_o$

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1-D}{D} \quad ②$$

- Now find the average input current
- V_d only supplies current during t_{on}



$$I_D = \frac{1}{T_s}\int i_d(t)$$

$$I_D = \left(\frac{I_1 + I_2}{2}\right)\frac{t_{on}}{T_s} = \left(\frac{I_1 + I_2}{2}\right) D$$

Sub into eq ②

$$I_o = \frac{1-D}{D} I_d$$

$$I_o = \frac{1-D}{D}\left(\frac{I_1+I_2}{2}\right) D$$

$$\boxed{\frac{I_1+I_2}{} = \frac{2I_o}{1-D}} \quad (3)$$

Next use $v_L(t) = L\frac{di_L}{dt}$

$$i_L(t) = \frac{1}{L}\int V_L\, dt + i.c.$$

$$I_2 = \frac{1}{L}\int_0^{t_{on}} V_d\, dt + I_1$$

$$\boxed{I_2 - I_1 = \frac{V_d\, t_{on}}{L}} \quad (4)$$

- Next, Find the boundary between continuous + Discontinuous mode.

⇒ Solve For I_1

$$I_1 + I_2 = \frac{2 I_o}{1-D}$$

$$(-) \quad I_2 - I_1 = \frac{V_d t_{on}}{L}$$

$$2 I_1 = \left(\frac{2 I_o}{1-D}\right) - \frac{V_d t_{on}}{L}$$

For the boundary btw continuous and discontinuous mode, Solve For $I_1 = 0$

$$0 = \frac{2 I_o}{1-D} - \frac{V_d t_{on}}{L}$$

$$I_o = \left(\frac{V_d t_{on}}{2L}\right)(1-D)$$

OR

$$\boxed{I_o \geq \frac{V_d t_{on}}{2L}(1-D)}$$

Summary

Buck-Boost in continuous mode

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

$$I_d = I_o\left[\frac{1-D}{D}\right]$$

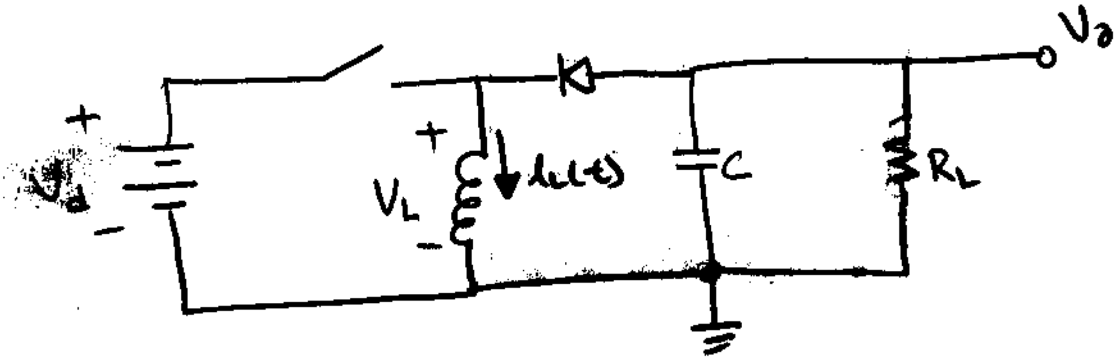
$$\frac{I_1+I_2}{2} = \frac{2I_o}{1-D}$$

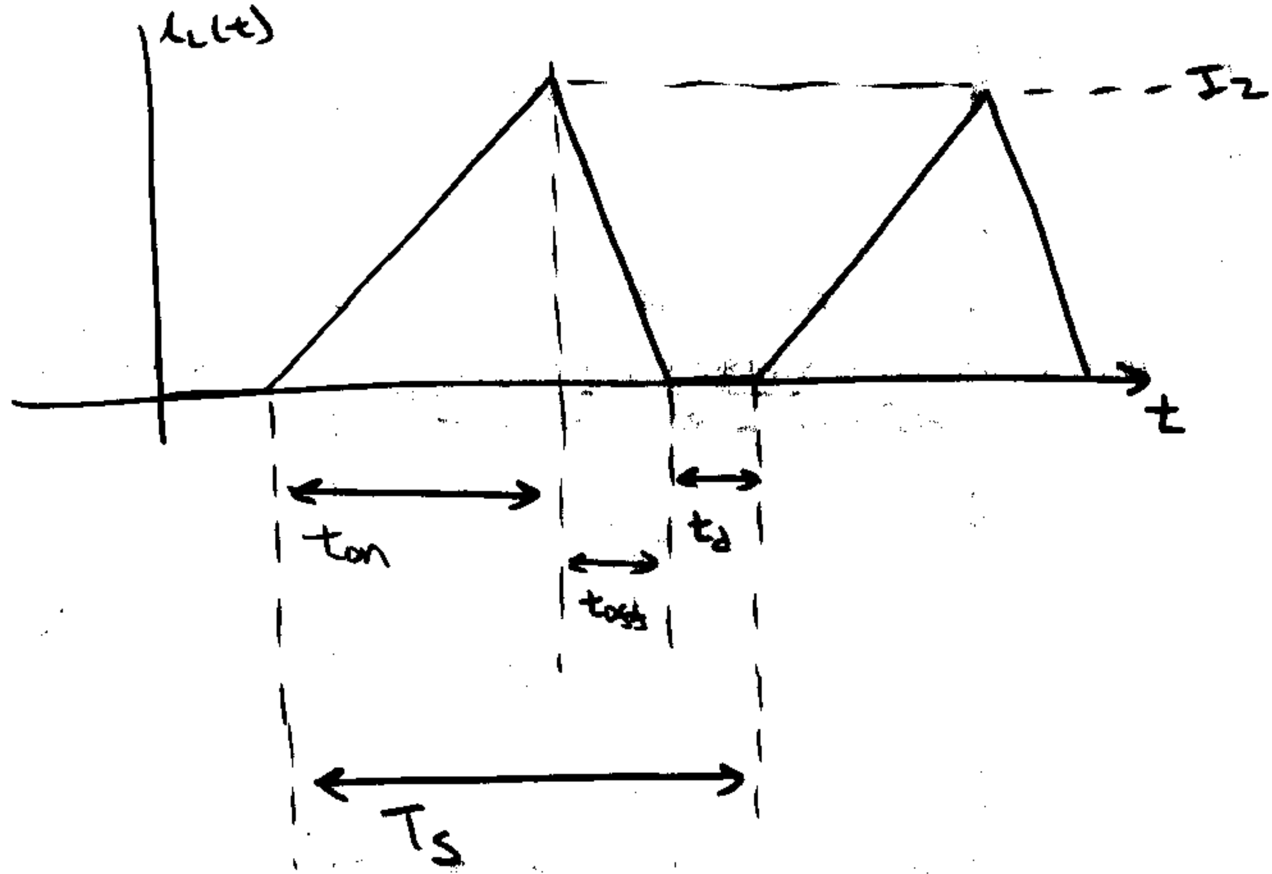
$$I_2 - I_1 = \frac{V_d t_{on}}{L}$$

$$I_o \geq \frac{V_d t_{on}}{2L}(1-D)$$

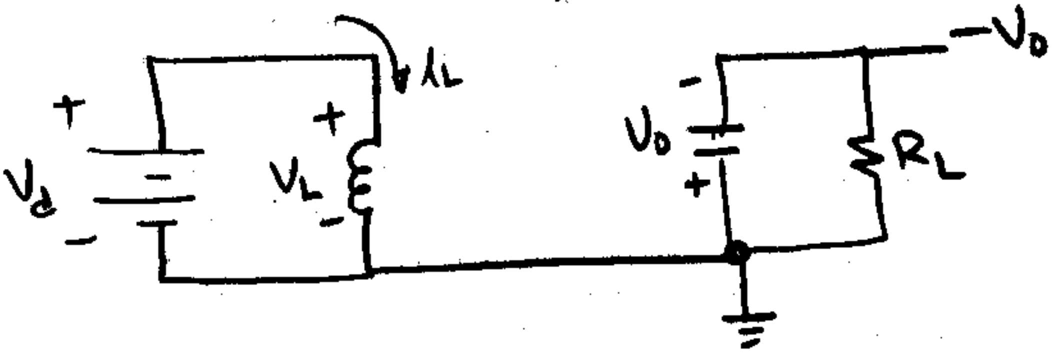
BUCK-BOOST Regulator

Discontinuous mode





During t_{on} we have



For the inductor, $V_L = L \frac{di_L}{dt}$

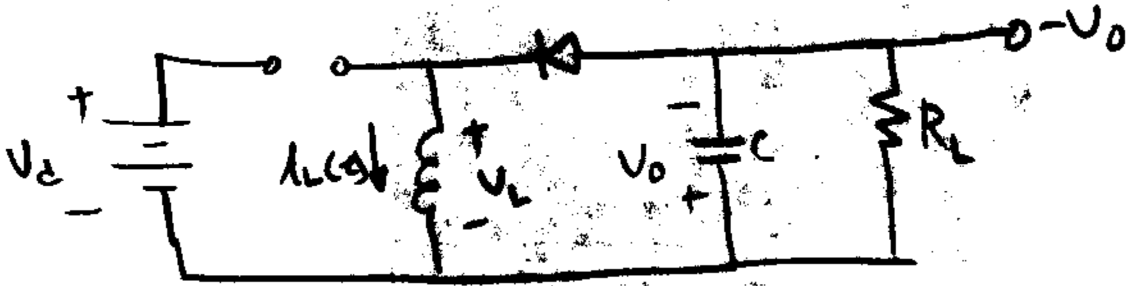
$$i_L(t) = \frac{1}{L} \int V_L(t)\, dt + I.C.$$

OR

$$I_2 = \frac{1}{L} \int_0^{t_{on}} V_d\, dt$$

$$\boxed{I_2 = \frac{V_d\, t_{on}}{L}} \quad (1)$$

During t_{off} we have



- Diode is Ideal
- D = on
- $V_L = -V_o$

For the inductor $V_L = L \frac{di_L}{dt}$

$$i_L(t) = \frac{1}{L} \int V_L(t)\, dt + I_2$$

OR

$$0 = \frac{1}{L} \int_{t_{on}}^{t_{on}+t_{off}} (-V_o)\, dt + I_2$$

$$\boxed{I_2 = \frac{V_o\, t_{off}}{L}} \quad (2)$$

- To ensure discontinuous mode operation

Choose $t_d = 0.2 T_s$

$$\Rightarrow \boxed{t_{on} + t_{off} \le 0.8\, T_s} \quad (3)$$

Energy balance

- Energy dissipated by load during a cycle

$\mathcal{E}_0 = V_0 I_0 T_s$

- During t_{off}, all energy stored in L is delivered to Load

$$\mathcal{E}_L = \frac{1}{2} L I_2^2$$

but from (1), $I_2 = \frac{V_d t_{on}}{L}$

So

$$\mathcal{E}_L = \frac{1}{2} L \left(\frac{V_d^2 \, t_{on}^2}{L^2} \right)$$

$$\mathcal{E}_L = \frac{V_d^2 \, t_{on}^2}{2L}$$

Energy balance

$$\mathcal{E}_L = \mathcal{E}_o$$

$$\frac{V_d^2 \, t_{on}^2}{2L} = V_o I_o T_s$$

$$\boxed{V_o = \frac{V_d^2 \, t_{on}^2}{2 L I_o T_s}} \quad (4)$$

BUCK-BOOST Summary

Discontinuous mode

$$I_2 = \frac{V_d t_{on}}{L}$$

$$I_2 = \frac{V_o t_{off}}{L}$$

$$\Rightarrow \frac{t_{on}}{t_{off}} = \frac{V_o}{V_d}$$

$$t_{on} + t_{off} \le 0.8\,T_s$$

$$V_o = \frac{V_d^2 t_{on}^2}{2 L I_o T_s}$$

$$I_o \le \frac{V_d t_{on}}{2L}(1-D) \quad \text{For discontinuous mode}$$

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Buck-Boost Regulator Design
Discontinuous Mode Operation

Define useful units for Electrical Engineering

$\Omega \equiv \text{ohm}$ $\quad k\Omega \equiv 1000\cdot\text{ohm}$ $\quad M\Omega \equiv 1000000\cdot\text{ohm}$

$F \equiv \text{farad}$ $\quad pF \equiv 10^{-12}\cdot\text{farad}$ $\quad \mu F \equiv 10^{-6}\cdot\text{farad}$ $\quad nF \equiv 10^{-9}\cdot\text{farad}$ $\quad mF := F\cdot 10^{-3}$

$ms \equiv .001\cdot\text{sec}$ $\quad \text{minute} \equiv 60\cdot\text{sec}$ $\quad \text{hour} \equiv 60\cdot\text{minute}$ $\quad \text{AmpHour} \equiv 1\cdot\text{amp}\cdot 1\cdot\text{hour}$ $\quad \mu s \equiv .001\cdot ms$

$mV \equiv \frac{\text{volt}}{1000}$ $\quad kV \equiv 1000\cdot\text{volt}$ $\quad mA \equiv \frac{\text{amp}}{1000}$ $\quad \mu A \equiv \frac{\text{amp}}{1000000}$ $\quad mW \equiv \frac{\text{watt}}{1000}$

$\mu_o \equiv 1.26\cdot 10^{-6}\cdot\frac{\text{henry}}{m}$ $\quad \varepsilon_o \equiv 8.854\cdot 10^{-12}\cdot\frac{\text{farad}}{m}$ $\quad cc \equiv cm^3$ $\quad c \equiv (3\cdot 10)^8\cdot\frac{m}{\text{sec}}$

$nH \equiv 1\cdot 10^{-9}\cdot\text{henry}$ $\quad \mu H \equiv 10^{-6}\cdot\text{henry}$ $\quad kHz \equiv 1000\cdot Hz$ $\quad MHz \equiv 1000000\cdot Hz$

$\text{rad\_per\_sec} \equiv 2\cdot\pi\cdot Hz$

$\text{cup} \equiv 8\cdot\text{fl\_oz}$ $\quad \text{tablespoon} \equiv \frac{1}{2}\cdot\text{fl\_oz}$ $\quad \text{Tbsp} \equiv \text{tablespoon}$ $\quad Vt := .0258\cdot\text{volt}$

$\text{teaspoon} \equiv \frac{1}{3}\cdot\text{Tbsp}$ $\quad \text{tsp} \equiv \text{teaspoon}$

$\% := \frac{1}{100}$

Specify Input Voltage $V_D := 5\cdot\text{volt}$

Specify Output Voltage $V_o := -12\cdot\text{volt}$

Specify Switching Frequency $F_S := 20\cdot kHz$

$T_S := \frac{1}{F_S}$ $\quad T_S = 50\,\mu s$

Specify the Max output Current

$I_o := 1\cdot\text{amp}$

Find Ton and Toff

$T_{off} := 1\cdot\mu s$ $\quad T_{on} := 1\cdot\mu s$

Given

$$\frac{T_{on}}{T_{off}} = \frac{|V_o|}{V_D}$$

$T_{on} + T_{off} = 0.8 \cdot T_S$

$\begin{bmatrix} T_{on} \\ T_{off} \end{bmatrix} := \text{find}(T_{on}, T_{off})$ $T_{on} = 28.235 \cdot \mu s$ $T_{off} = 11.765 \cdot \mu s$

Find the range of Inductors that will operate in discontinuous mode

$$D := \frac{T_{on}}{T_S}$$

$$L := \frac{V_D \cdot T_{on}}{2 \cdot I_o} \cdot (1 - D)$$

For Discontinuous Mode, We need L less than $L = 30.727 \cdot \mu H$

FInd the inductor Value

$$L := \frac{V_D^2 \cdot T_{on}^2}{2 \cdot |V_o| \cdot I_o \cdot T_S}$$ $L = 16.609 \cdot \mu H$

FInd the peak current

$$I_2 := V_D \cdot \frac{T_{on}}{L}$$ $I_2 = 8.5 \cdot \text{amp}$

Now choose the capacitor

Energy dissipated per cycle $E_o := |V_o| \cdot I_o \cdot T_S$ $E_o = 6 \cdot 10^{-4} \cdot \text{joule}$

Specify the ripple desired. $V_{CR} := 20 \cdot mV$

Initial Guess $C := 1000 \cdot \mu F$

Given

$$\frac{1}{2} \cdot C \cdot (|V_o| + V_{CR})^2 - \frac{1}{2} \cdot C \cdot (|V_o|)^2 = E_o$$

$C := \text{find}(C)$

$C = 2.498 \cdot mF$

Choose the next standard value $C := 3300 \cdot \mu F$

Calculate the ripple with the chosen capacitor.

Given

$$\frac{1}{2} \cdot C \cdot \left(\left| V_o \right| + V_{CR} \right)^2 - \frac{1}{2} \cdot C \cdot \left(\left| V_o \right| \right)^2 = E_o$$

$V_{CR} := \mathrm{find}(V_{CR})$ $V_{CR} = 15.142 \, mV$

Choose the filter capacitor using the capacitor ESR.

Assume that the major component of the ripple comes from the capacitor ESR

Specify the ripple due to the ESR $V_{CR} := 20 \cdot mV$

$ESR := \frac{V_{CR}}{(I_2)}$ $ESR = 2.353 \cdot 10^{-3} \, \Omega$

For all electrolytic caps, assume that ESR*C=80µs

$C := \frac{80 \cdot \mu s}{ESR}$ $C = 33999.99969 \, \mu F$

Choose the next size std capacitor $C := 47000 \cdot \mu F$

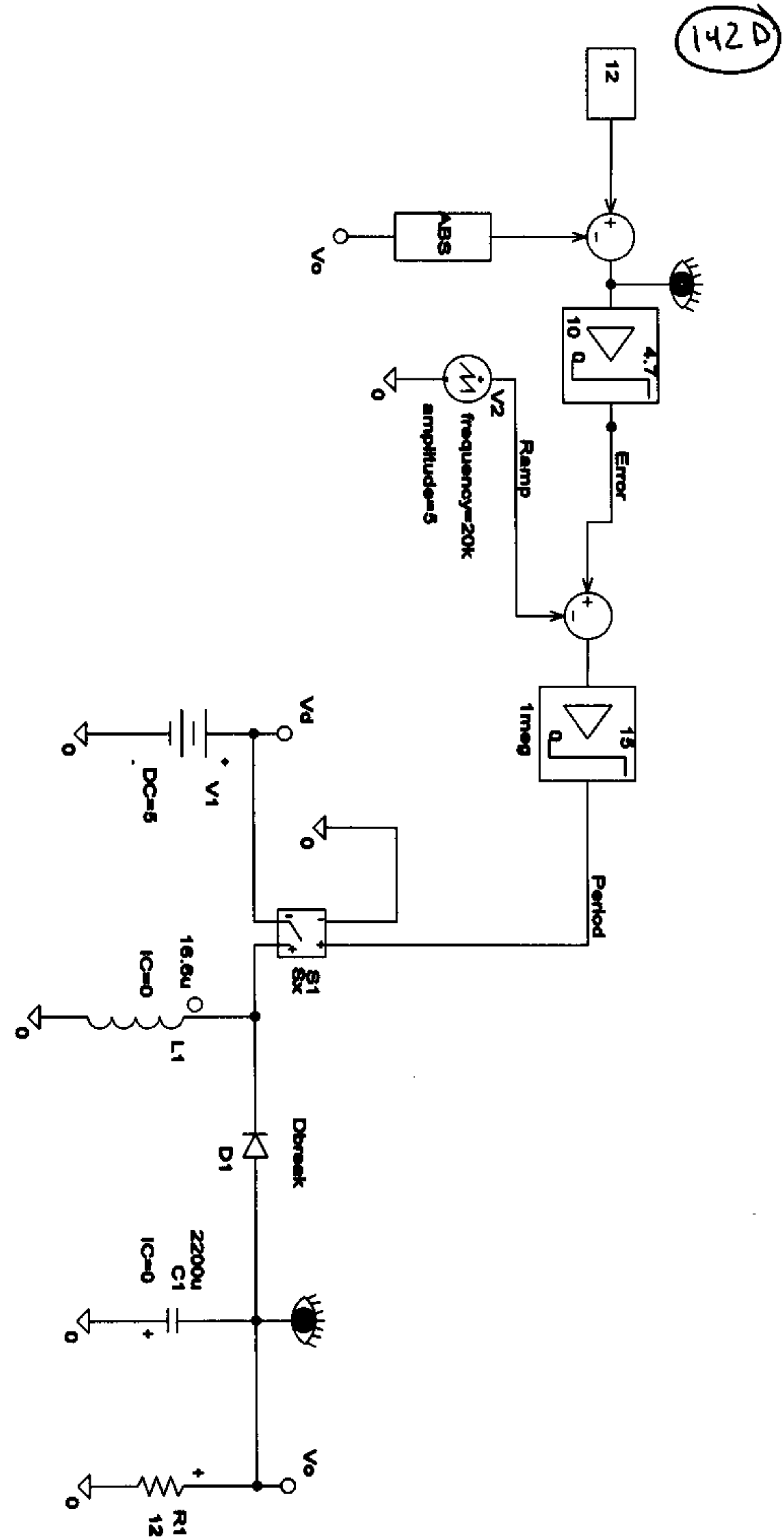
Summary

$L = 16.609 \, \mu H$ $I_2 = 8.5 \, amp$

$T_{on} = 28.235 \, \mu s$ $T_{off} = 11.765 \, \mu s$

$V_D = 5 \, volt$ $V_o = -12 \, volt$ $I_o = 1 \, amp$

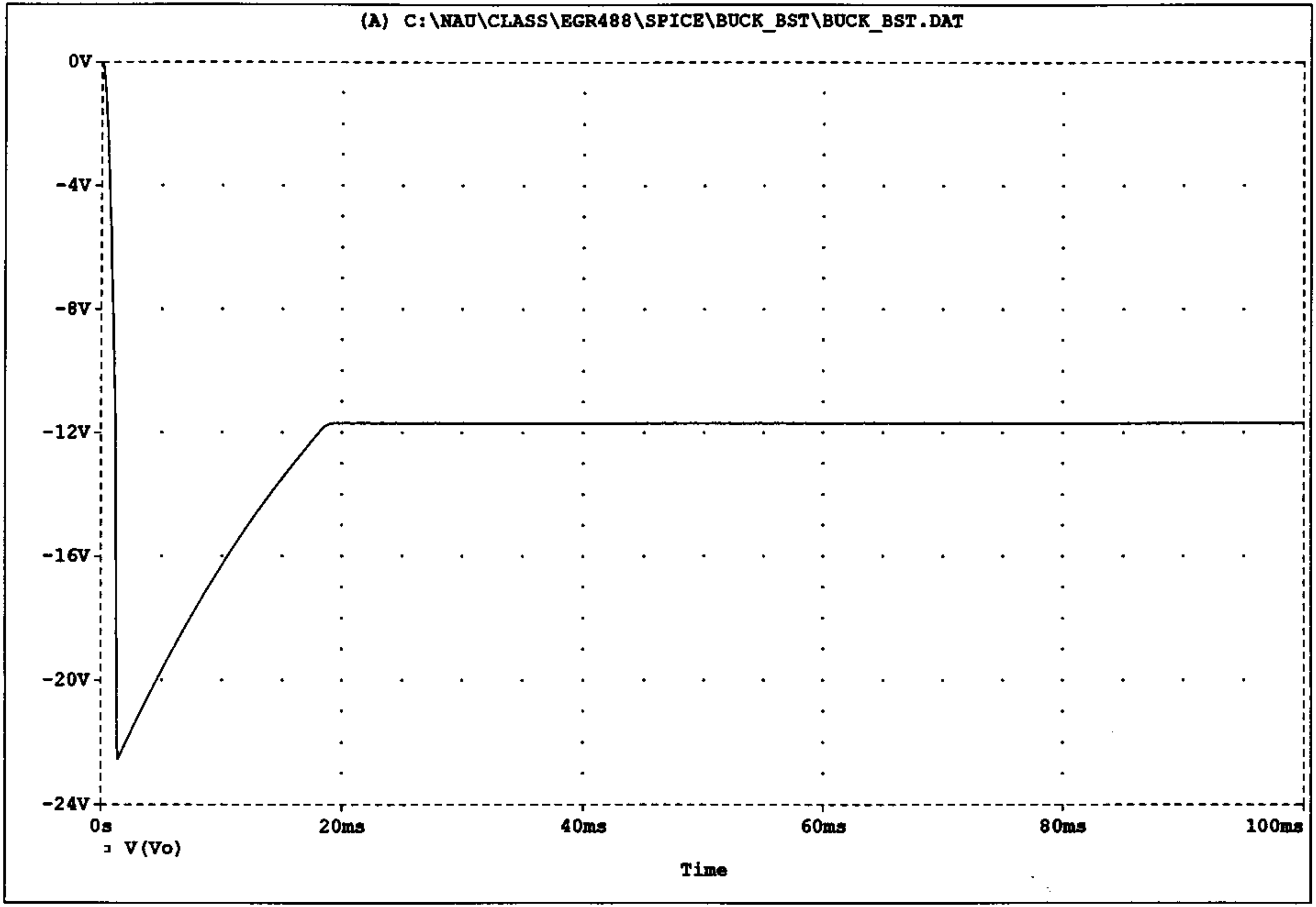
$C = 4.7 \cdot 10^4 \, \mu F$ $V_{CR} = 20 \, mV$


142D
12
ABS
Vo
10
4.7
V2
frequency=20k
amplitude=5
Ramp
Error
1meg
15
Vd
V1
DC=5
Period
S1
Sx
16.6u
IC=0
L1
Dbreak
D1
2200u
C1
IC=0
Vo
R1
12

142E

* C:\NAU\CLASS\EGR488\SPICE\BUCK_BST\BUCK_BST.SCH

Date/Time run: 10/22/95 15:56:53   Temperature: 27.0

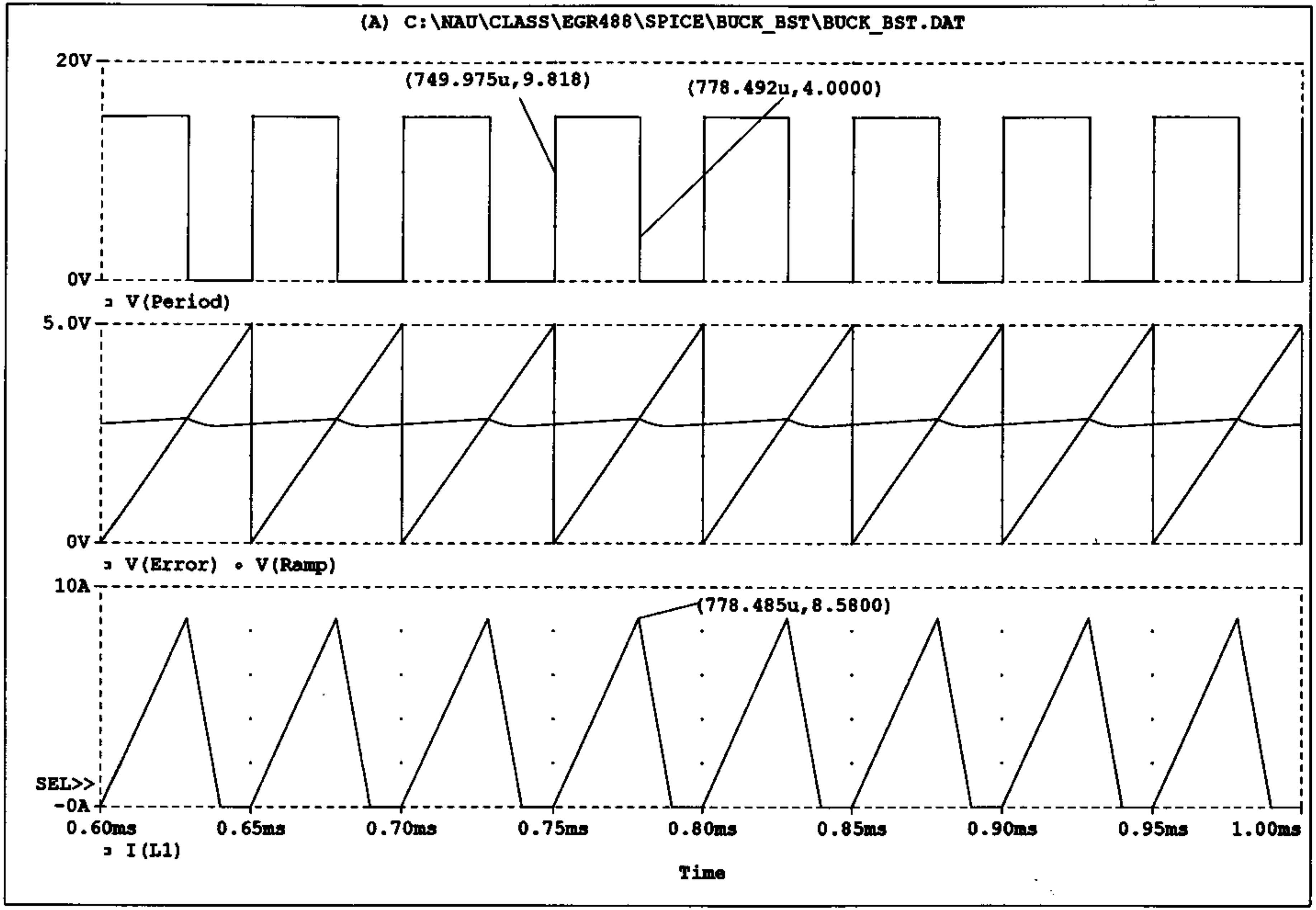


Date: October 22, 1995   Page 1   Time: 16:30:52

142F

* C:\NAU\CLASS\EGR488\SPICE\BUCK_BST\BUCK_BST.SCH

Date/Time run: 10/22/95 14:38:43 Temperature: 27.0



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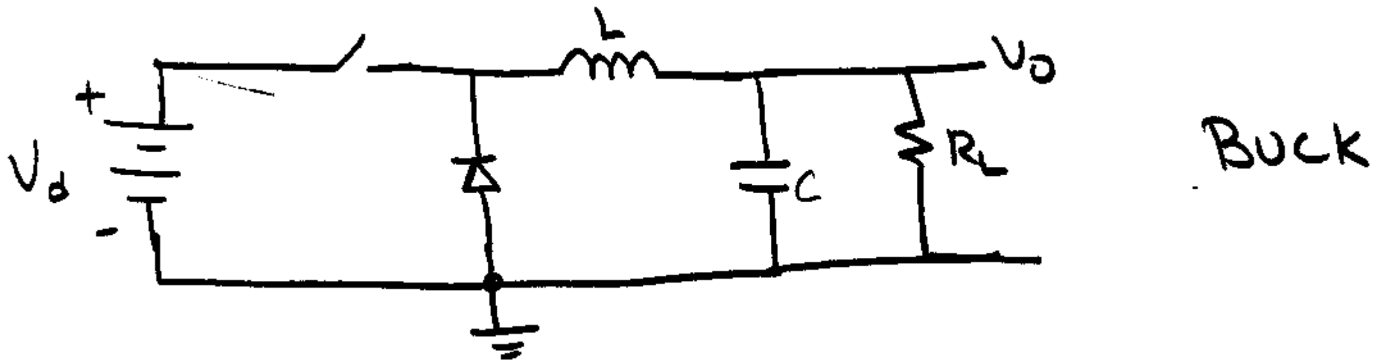
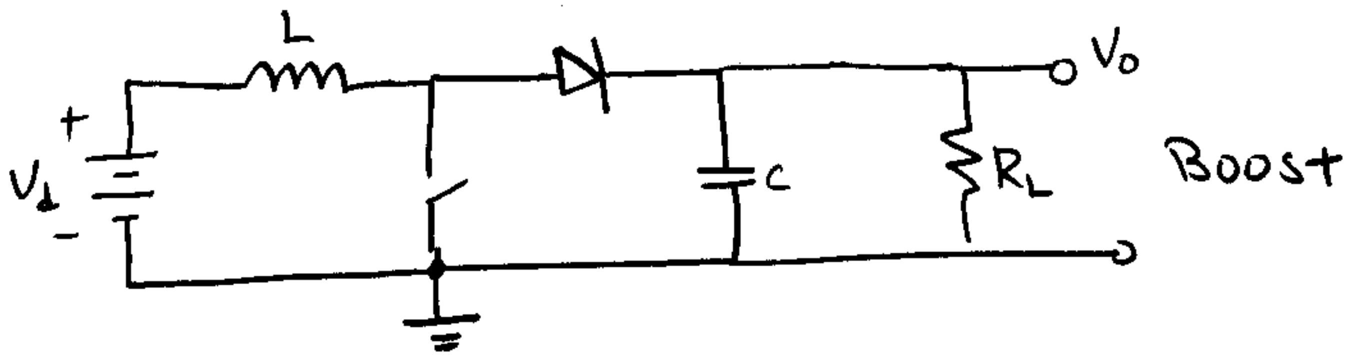
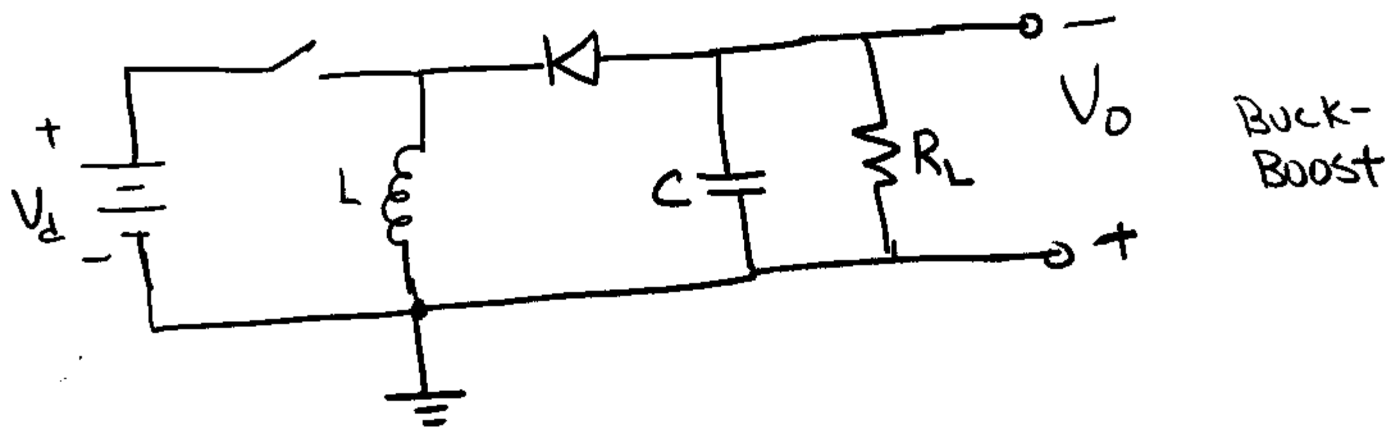
Summary







Continuous mode

Buck	Boost	Buck-Boost
$V_o = DV_o$	$V_o = V_d\left[\frac{1}{1-D}\right]$	$V_o = V_d\left[\frac{D}{1-D}\right]$
$I_o = I_D\left(\frac{1}{D}\right)$	$I_o = I_D\left[1-D\right]$	$I_o = I_D\left[\frac{1-D}{D}\right]$
$I_1 + I_2 = 2I_o$	$I_1 + I_2 = \frac{2I_o}{1-D}$	$I_1 + I_2 = \frac{2I_o}{1-D}$
$I_2 - I_1 = \frac{(V_d - V_o)}{L} t_{on}$	$I_2 - I_1 = \frac{V_d t_{on}}{L}$	$I_2 - I_1 = \frac{V_d t_{on}}{L}$
$I_o \geq \left(\frac{V_D - V_o}{2L}\right) t_{on}$	$I_o \geq \frac{V_d t_{on}}{2L}(1-D)$	$I_o \geq \frac{V_d t_{on}}{2L}(1-D)$

Discontinuous mode

Buck

$$I_2 = \frac{(V_d - V_o)}{L} t_{on}$$

$$I_2 = \frac{V_o t_{off}}{L}$$

$$\frac{t_{on}}{t_{off}} = \frac{V_o}{V_d - V_o}$$

$$V_o = \frac{t_{on}^2 V_o^2}{2 I_o T_s L + V_o t_{on}^2}$$

$$I_o \le \left(\frac{V_d - V_o}{2L}\right) t_{on}$$

Boost

$$I_2 = \frac{V_d t_{on}}{L}$$

$$I_2 = \frac{(V_o - V_d) t_{off}}{L}$$

$$\frac{t_{on}}{t_{off}} = \frac{V_o - V_d}{V_d}$$

$$t_{on} + t_{off} \le 0.8 T_s$$

$$V_o = \frac{V_d^2 t_{on}}{2 L T_s I_o} (t_{on} + t_{off})$$

$$I_o \le \left(\frac{V_d t_{on}}{2L}\right)\left(\frac{V_d}{V_o}\right)$$

Buck-Boost

$$I_2 = \frac{V_d t_{on}}{L}$$

$$I_2 = \frac{V_o t_{off}}{L}$$

$$\frac{t_{on}}{t_{off}} = \frac{V_o}{V_d}$$

$$t_{on} + t_{off} \le 0.8 T_s$$

$$V_o = \frac{V_d^2 t_{on}^2}{2 L I_o T_s}$$

$$I_o \le \frac{V_d t_{on}}{2L} (1 - D)$$