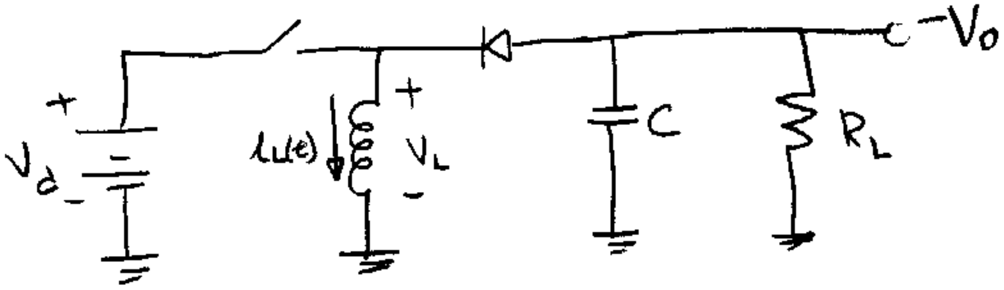
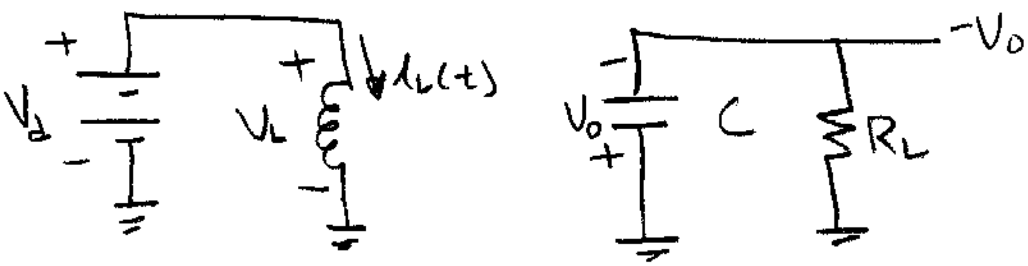
Polarity Inverting Regulator

OR Buck-Boost Regulator



During t_{on}: Switch Closed

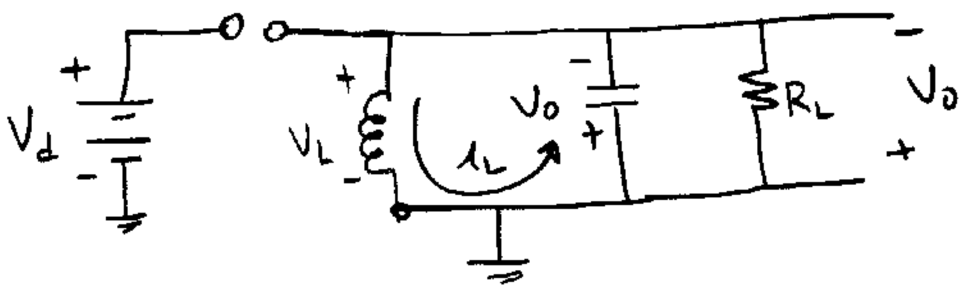
D = off



- Capacitor supplies power to load

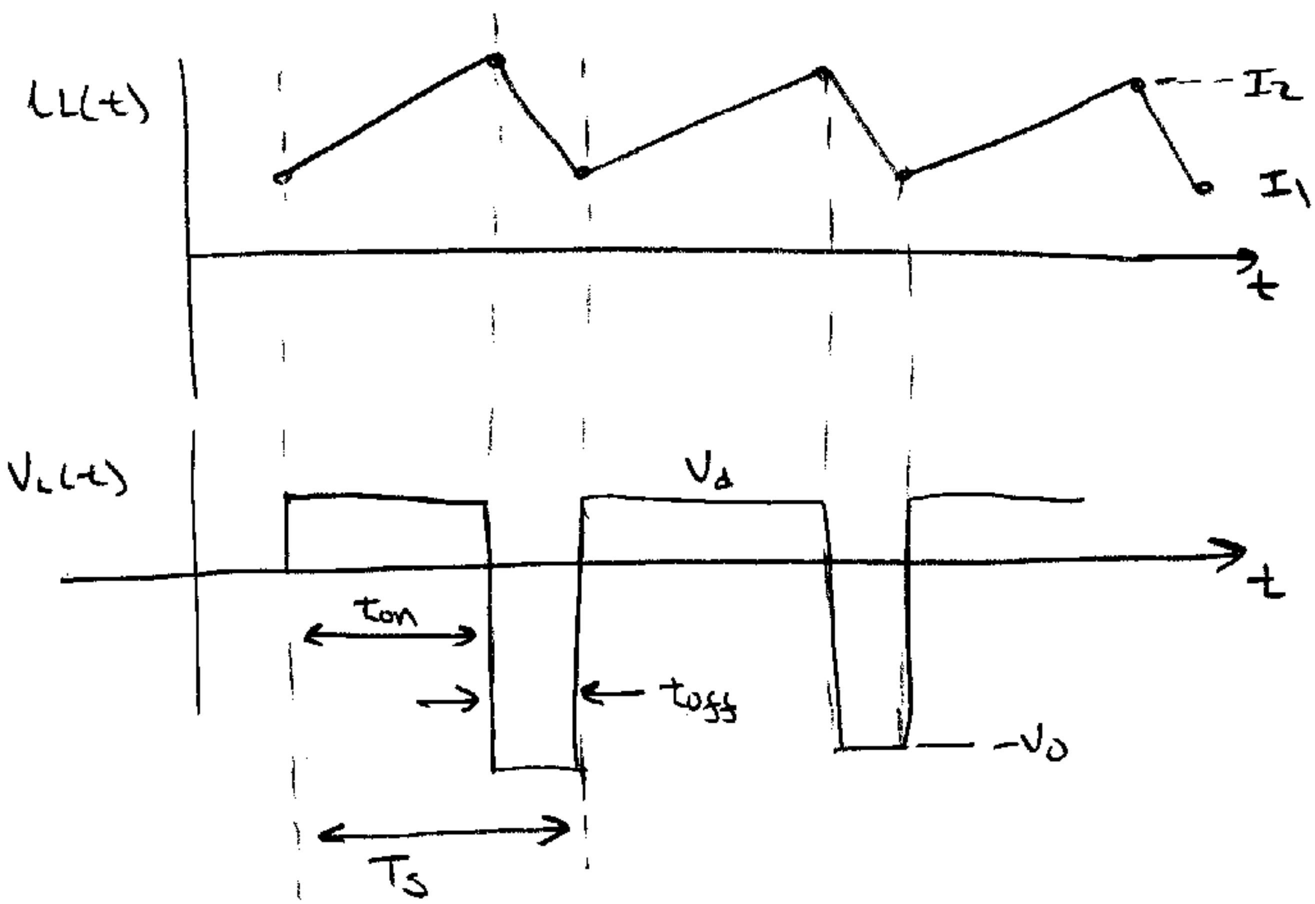
$V_L = V_d$

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 $I_1 > 0$
  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 $$\boxed{\frac{V_o}{V_d} = \frac{t_{on}}{T_s - t_{on}} = \frac{D}{1-D}} \; ; \quad D = \frac{t_{on}}{T_s} \qquad (1)$$

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

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

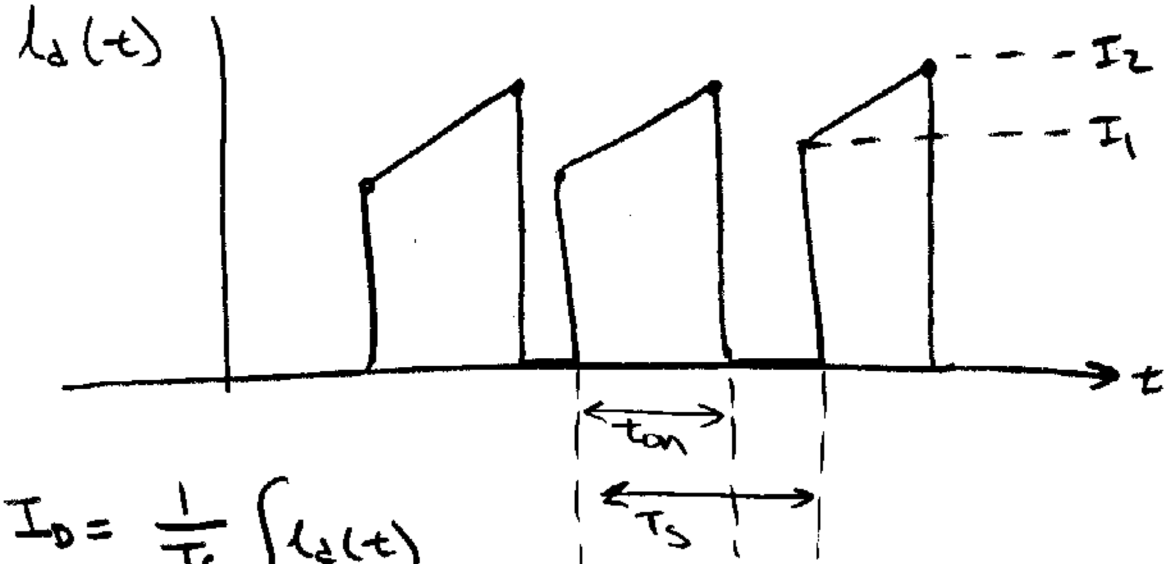
Where I_d = average input current and
I_o = average output current

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 ton



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

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

Sub into eq (2)

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

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

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

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

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

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

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

- 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

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

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

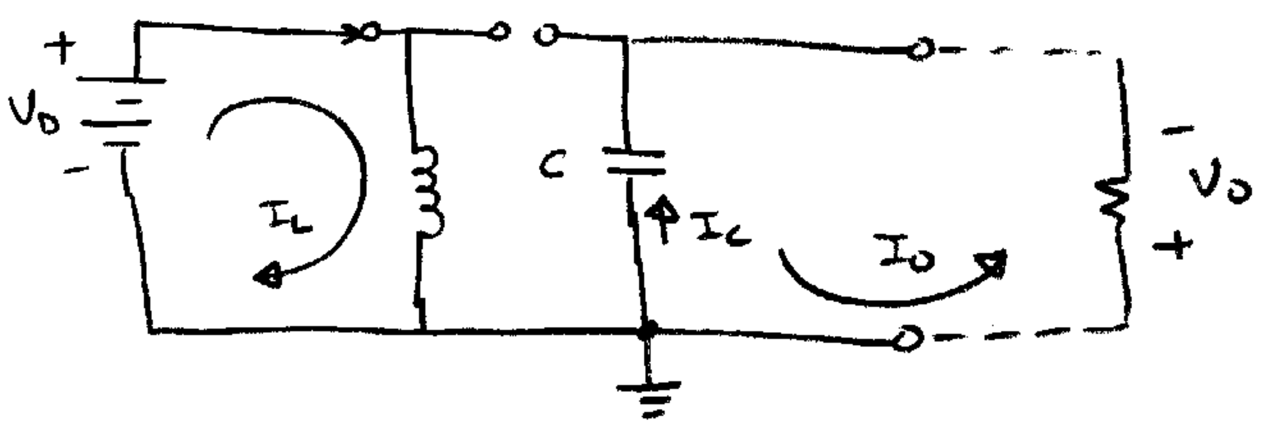
$$I_1 + I_2 = \frac{2I_o}{1-D}$$

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

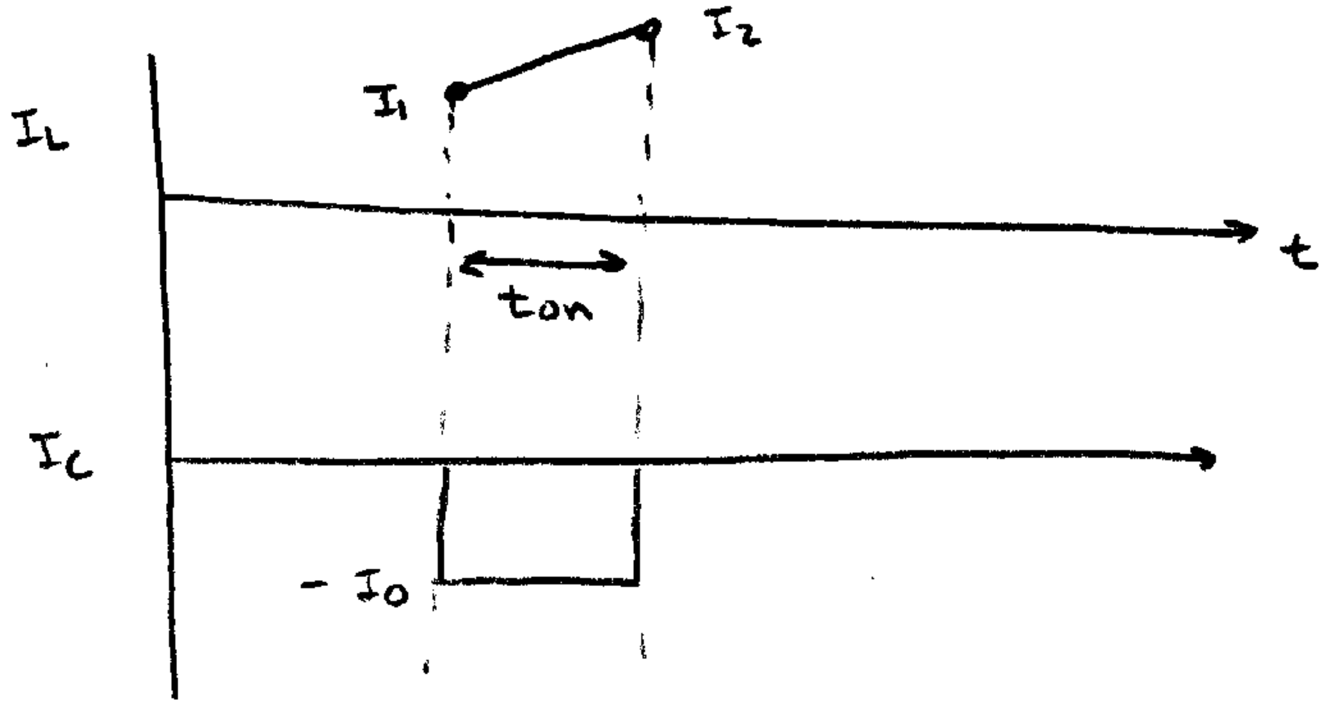
$$I_o \geq \frac{V_d t_{on}}{2L}(1-D)$$

- Calculation of Capacitor Ripple current

- Turing ton, the diode is off and the capacitor must supply the entire output current

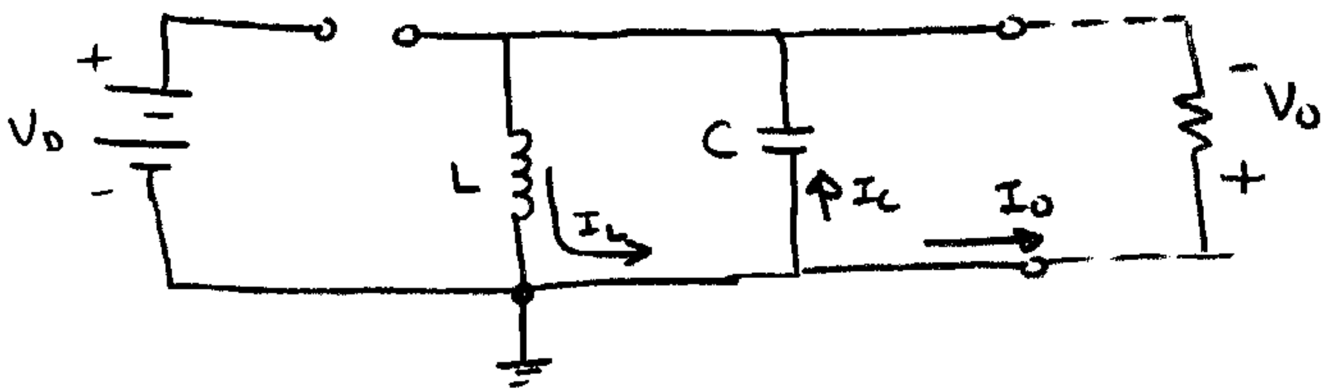


During ton The inductor charges from I_1 to I_2

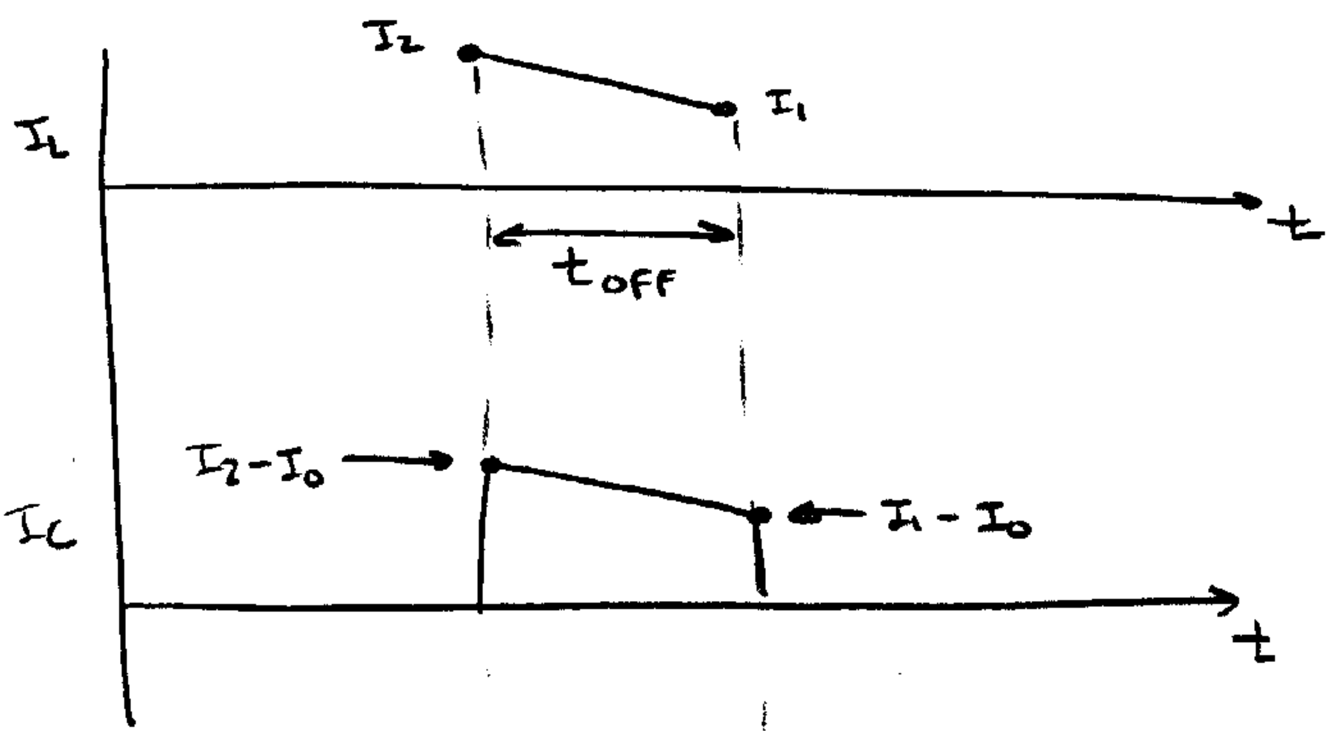


- During toff, the inductor charges the Capacitor and supplies current to the OUTPUT

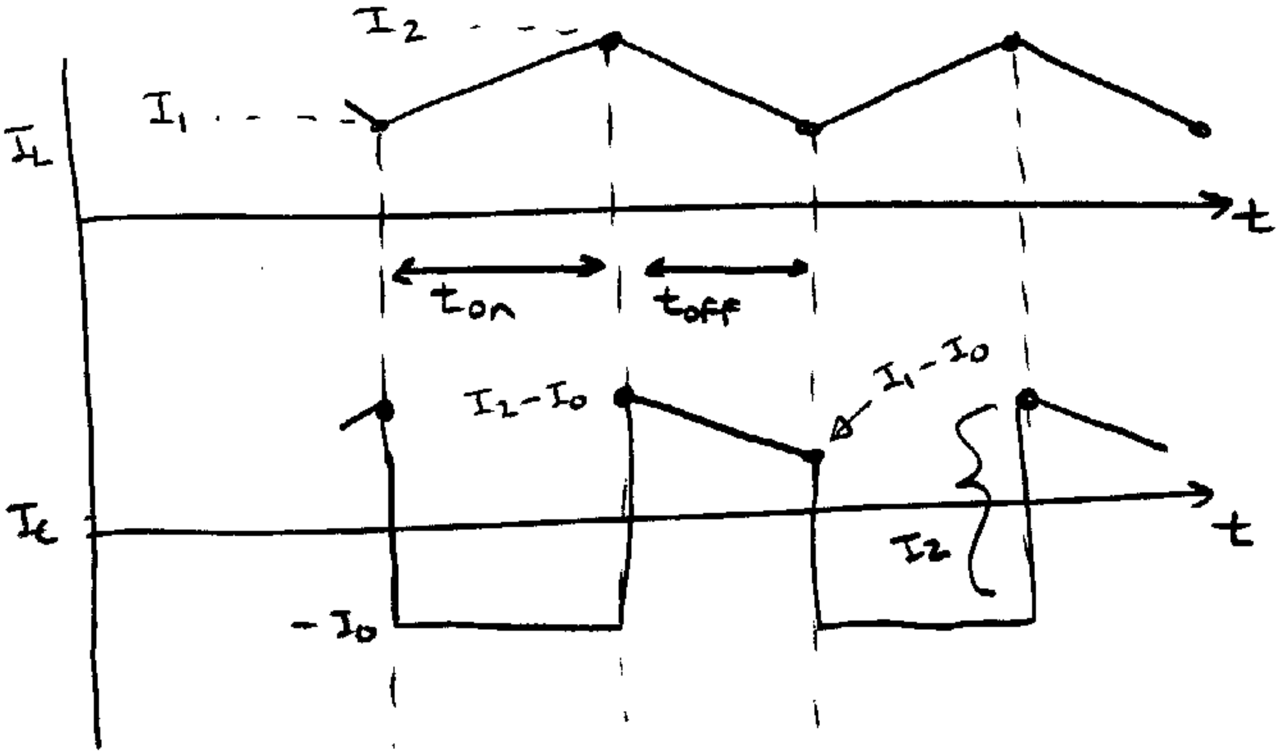
$\Rightarrow I_C = I_L - I_o$



- During toff, the inductor discharges from I_2 to I_1



- The complete picture is



$$I_{Rms} = \sqrt{\frac{1}{T_s}\left[\int_0^{t_{on}} (-I_o)^2 dt + \int_0^{t_{off}} (I_L - I_o)\, dt\right.}$$

during toff, we can express $I_L(t)$ as

$$I_L(t) = I_2 + m\,t$$

$$\text{where } m = \frac{I_1 - I_2}{t_{off}}$$

Also: Ripple due to ESR is

$$V_{CR} = I_2 \cdot ESR$$

EE 456

Buck-Boost Regulator Design
Continuous Mode Operation

$\mu s := 10^{-6} \cdot sec$ $\qquad m\Omega := \frac{\Omega}{1000}$

Specify Input Voltage

$V_D := 12 \cdot volt$

Specify Output Voltage

$V_o := -12 \cdot volt$

Specify Switching Frequency $\quad F_S := 40 \cdot kHz$

$T_S := \frac{1}{F_S}$ $\qquad T_S = 25 \mu s$

Specify the Assumed Efficiency $\quad Eff := 85\%$

Specify the Max output Current

The output Power is $\quad P_{out} := \frac{50 \cdot watt}{Eff}$

The output current is $\quad I_o := \left| \frac{P_{out}}{V_o} \right|$ $\qquad I_o = 4.902\, amp$

Find Ton

$$t_{on} := 1 \cdot \mu s$$

Given

$$-V_o = V_D \cdot \left(\frac{t_{on}}{T_S - t_{on}} \right)$$

$$t_{on} := \text{Find}(t_{on})$$

$t_{on} = 12.5\,\mu s$ $t_{off} := T_S - t_{on}$ $t_{off} = 12.5\,\mu s$

$D := \dfrac{t_{on}}{T_S}$ $D = 50\,\%$

Find the range of Inductors that will operate in continuous mode

Specify the minimum current we want the supply to operate in the continuous mode

$$I_{min} := \frac{I_o}{10}$$

$$L := \frac{V_D \cdot t_{on}}{2 \cdot I_{min}} \cdot (1 - D)$$

For Continuous Mode, We need L greater than $L = 76.5\,\mu H$

Choose the Inductor $L := 90 \cdot \mu H$

Pulse Engineering PE-51512

Find the Min and max inductor currents

$I_1 := 1 \cdot amp \qquad I_2 := 1 \cdot amp$

Given

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

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

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} := Find(I_1, I_2) \qquad I_1 = 8.971\,amp \qquad I_2 = 10.637\,amp$$

Inductor Average Current is $\frac{I_1 + I_2}{2} = 9.804\,amp$

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 $V_{CR} := 100 \cdot mV$

$$ESR := \frac{V_{CR}}{(I_2)} \qquad ESR = 9.401\, m\Omega$$

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

$$C := \frac{80 \cdot \mu s}{ESR} \qquad C = 8510\, \mu F$$

Choose the next size std capacitor $C := 10000 \cdot \mu F$

Calculate the Capacitor RMS Ripple Current

Define a function for the inductor current $I_L(t) := I_2 + \frac{(I_1 - I_2)}{t_{off}} \cdot t$

$$I_{rms} := \sqrt{\frac{1}{T_S} \cdot \left[\int_{0 \cdot sec}^{t_{on}} (-I_o)^2\, dt + \int_{0 \cdot sec}^{t_{off}} (I_L(t) - I_o)^2\, dt \right]}$$

$$I_{rms} = 4.914\, amp$$

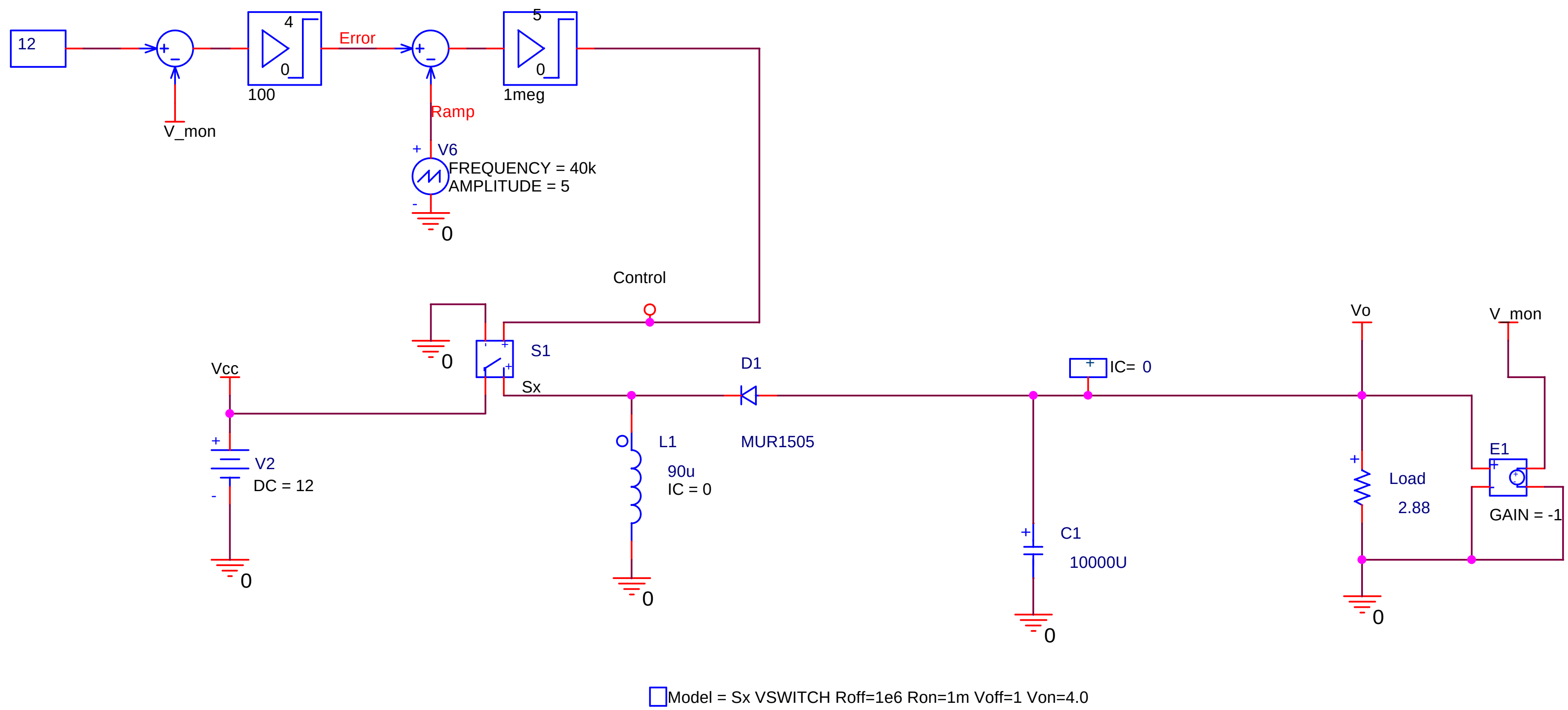
Summary

$L = 90\,\mu H$ $\qquad I_2 = 10.637\,amp$ $\qquad \frac{I_2 + I_2}{2} = 10.637\,amp$

$t_{on} = 12.5\,\mu s$ $\qquad t_{off} = 12.5\,\mu s$

$V_D = 12\,volt$ $\qquad V_o = -12\,volt$ $\qquad I_o = 4.902\,amp$

$C = 10000\,\mu F$ $\qquad V_{CR} = 100\,mV$ $\qquad I_{rms} = 4.914\,amp$



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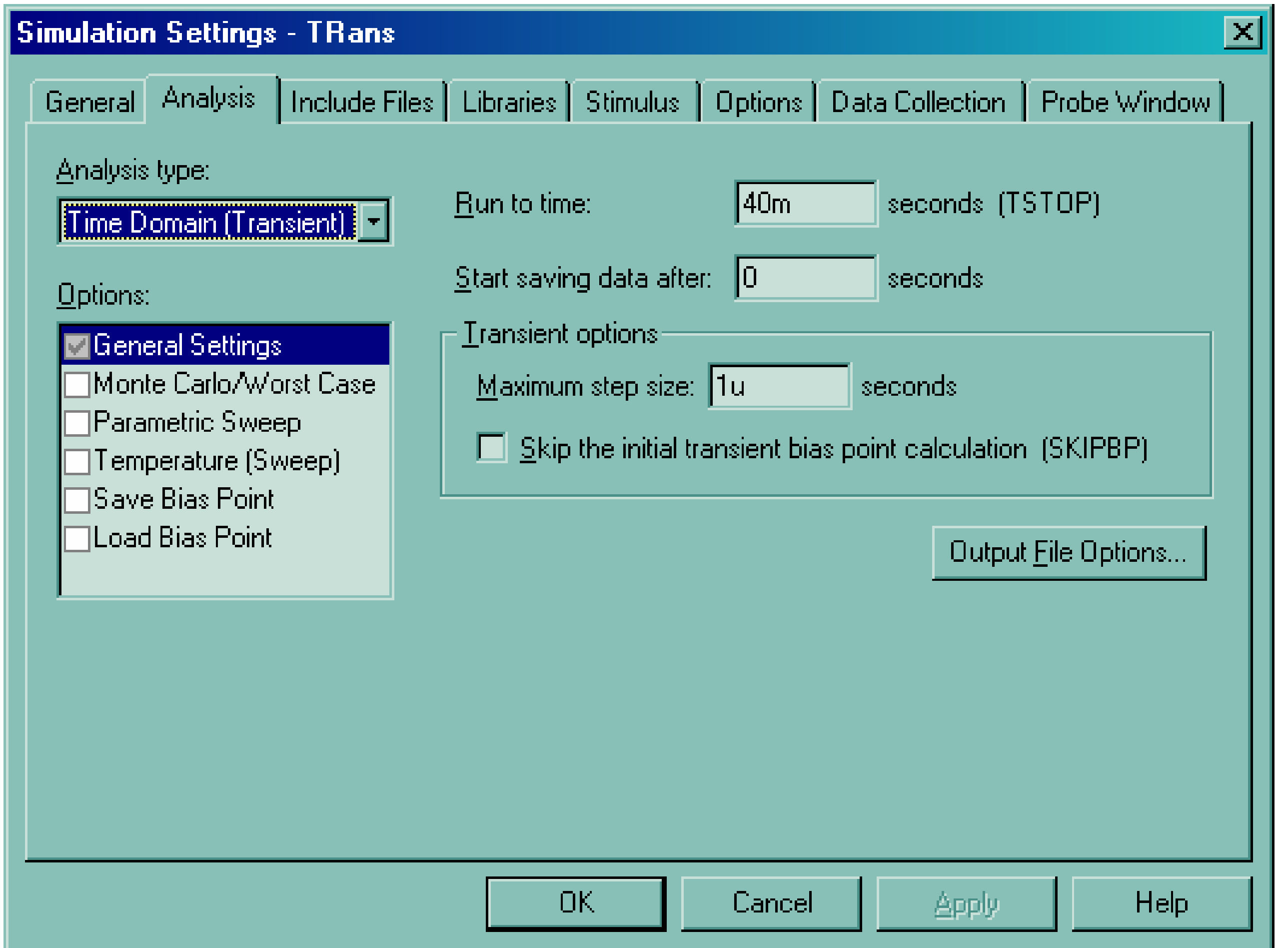
Name: Marc E. Herniter		Class: ECE456
Size A	Document Name: 12V to -25 Volt Buck-Boost	Rev 1
Date: Thursday, January 09, 2003		Sheet 1 of 1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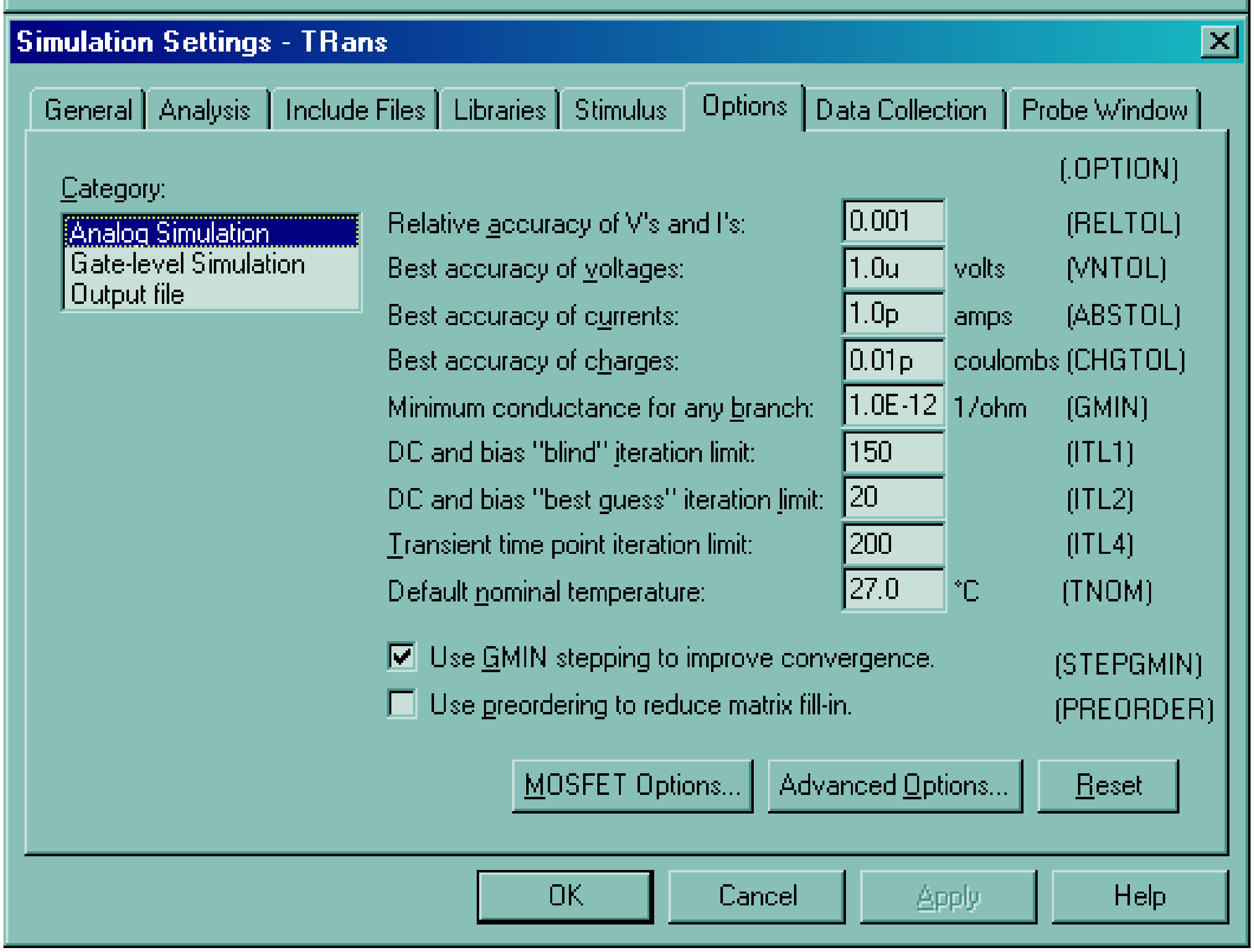
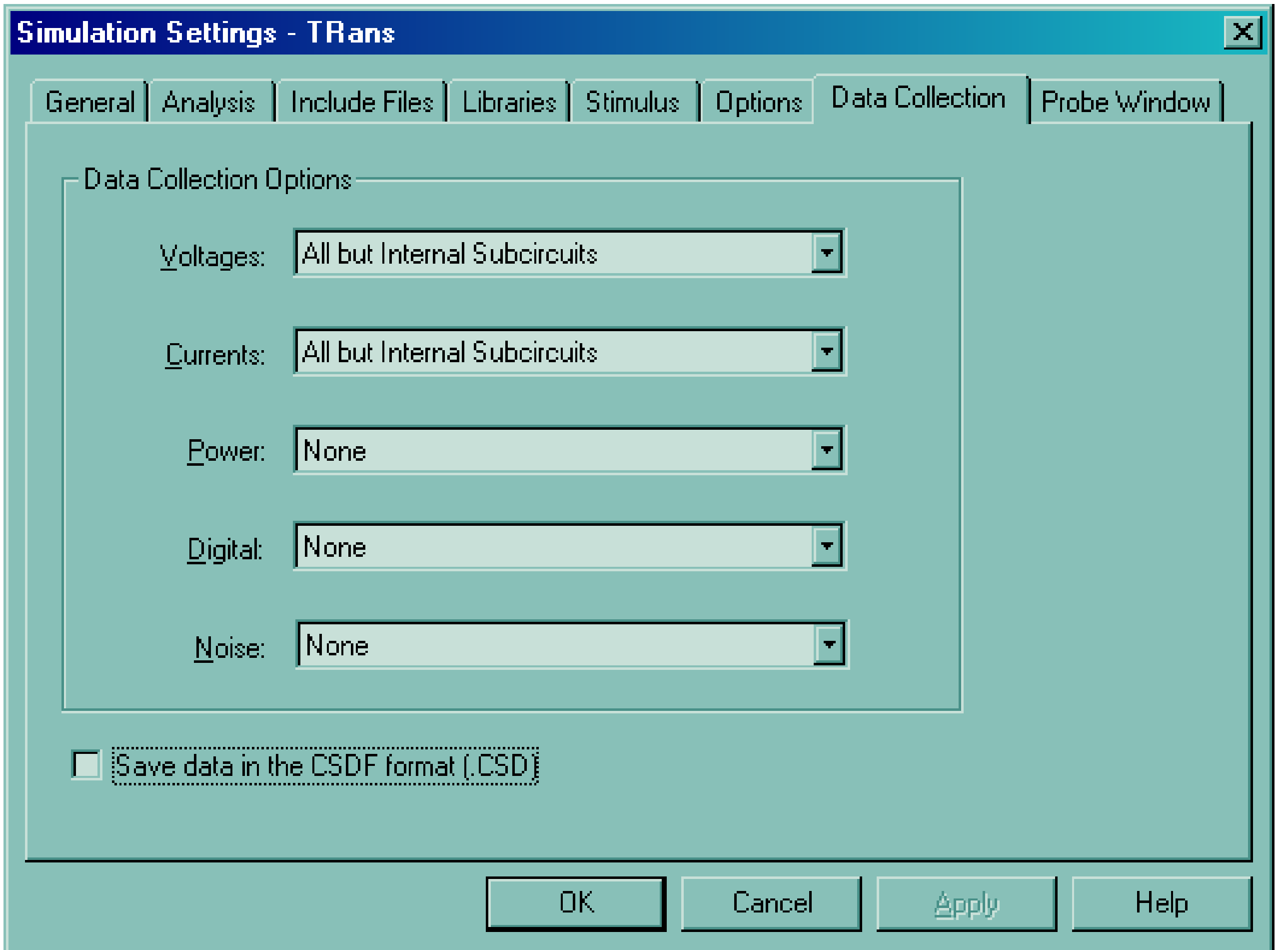
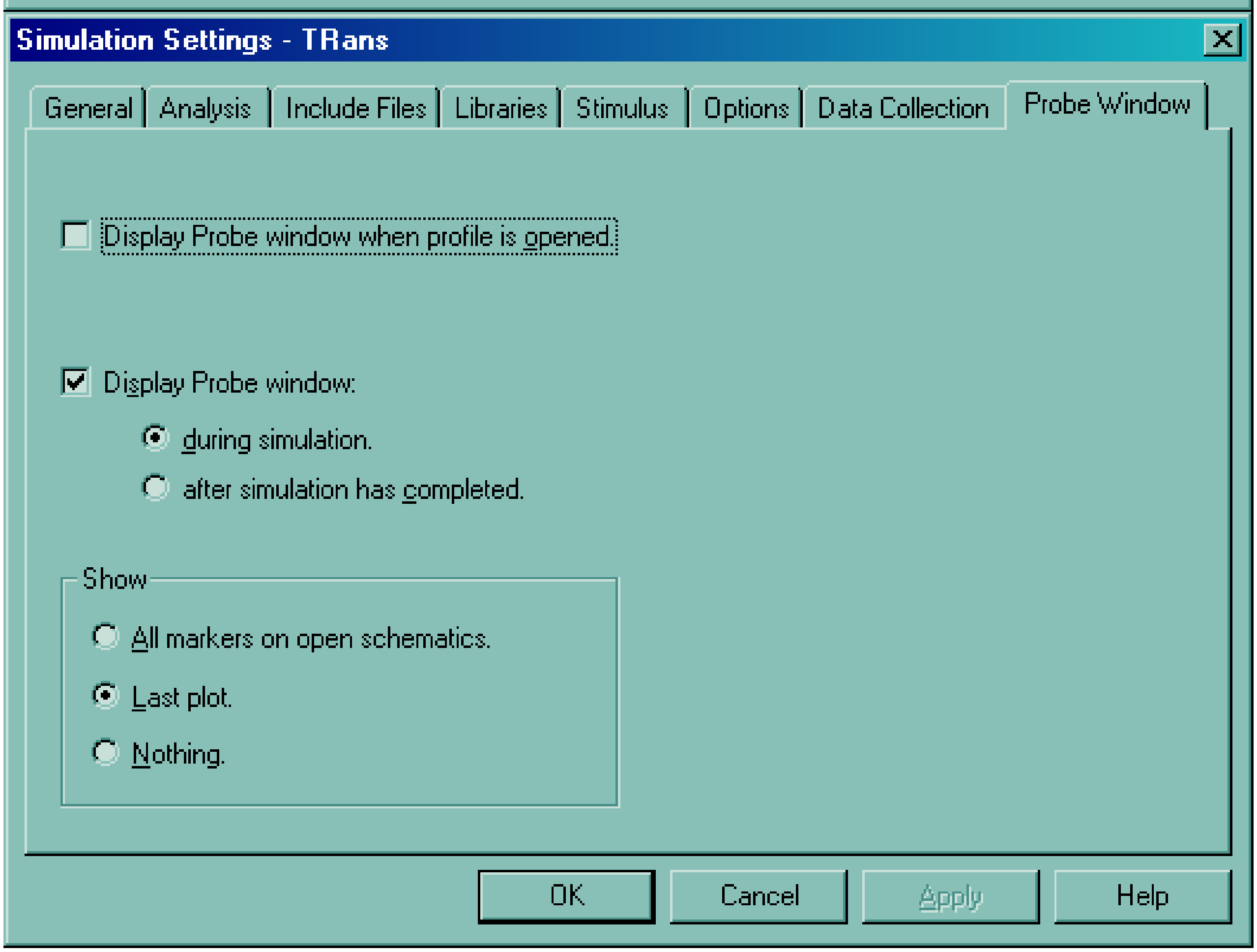
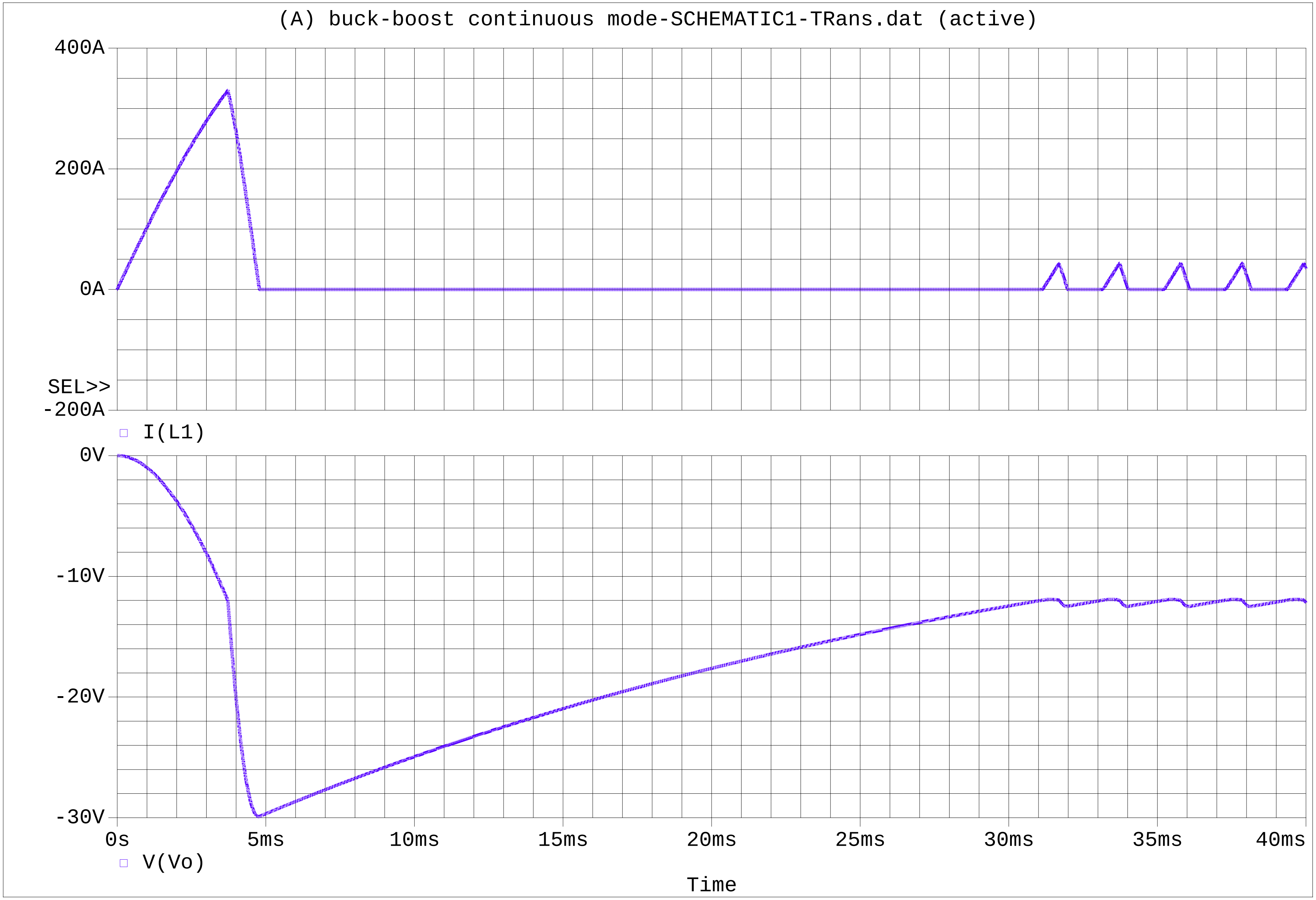
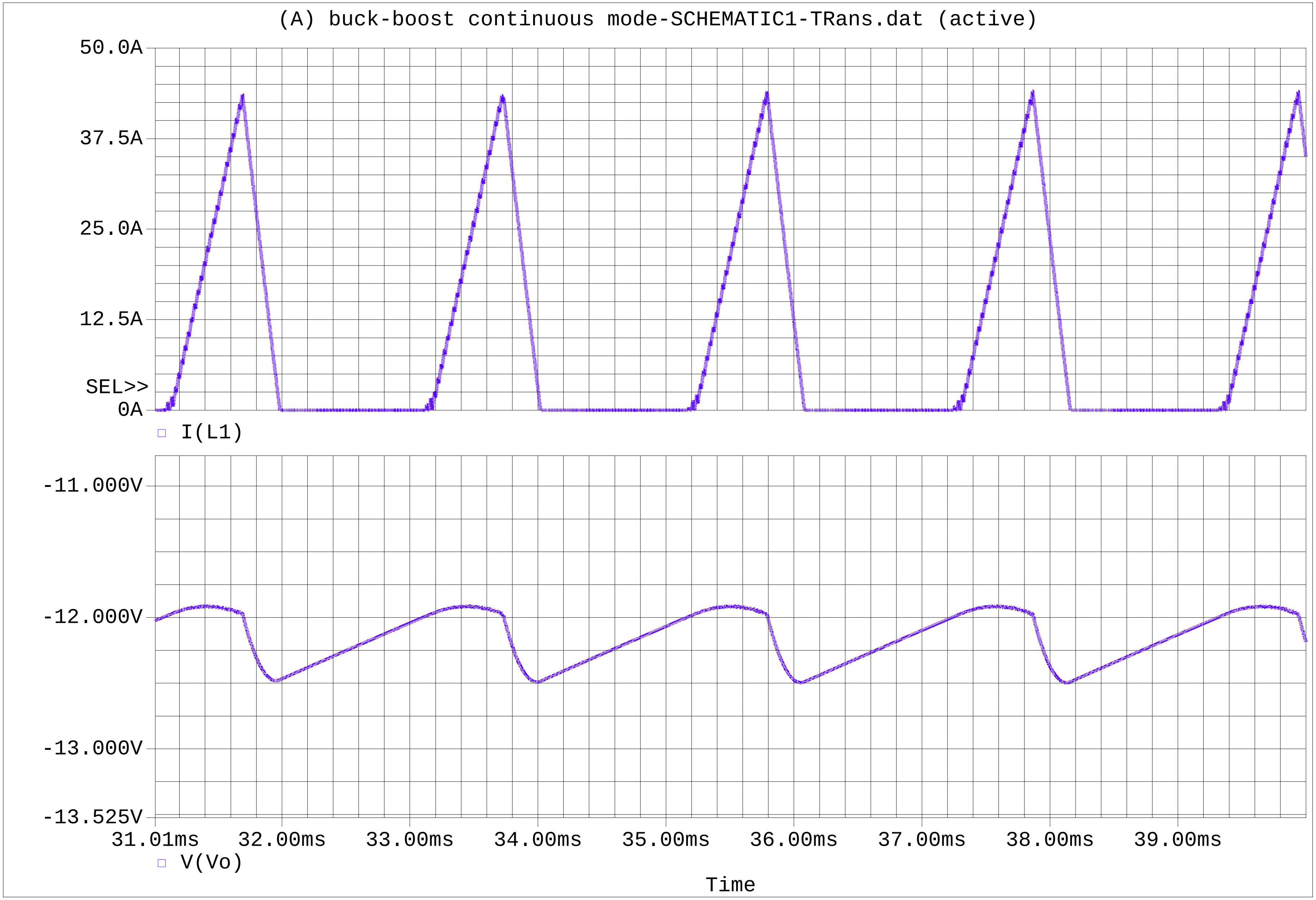
General
Analysis
Include Files
Libraries
Stimulus
Options
Data Collection
Probe Window
Analysis type:
Time Domain (Transient)
Options:
General Settings
Monte Carlo/Worst Case
Parametric Sweep
Temperature (Sweep)
Save Bias Point
Load Bias Point
Run to time:
40m
seconds (TSTOP)
Start saving data after:
0
seconds
Transient options
Maximum step size:
1u
seconds
Skip the initial transient bias point calculation (SKIPBP)
Output File Options...
OK
Cancel
Apply
Help

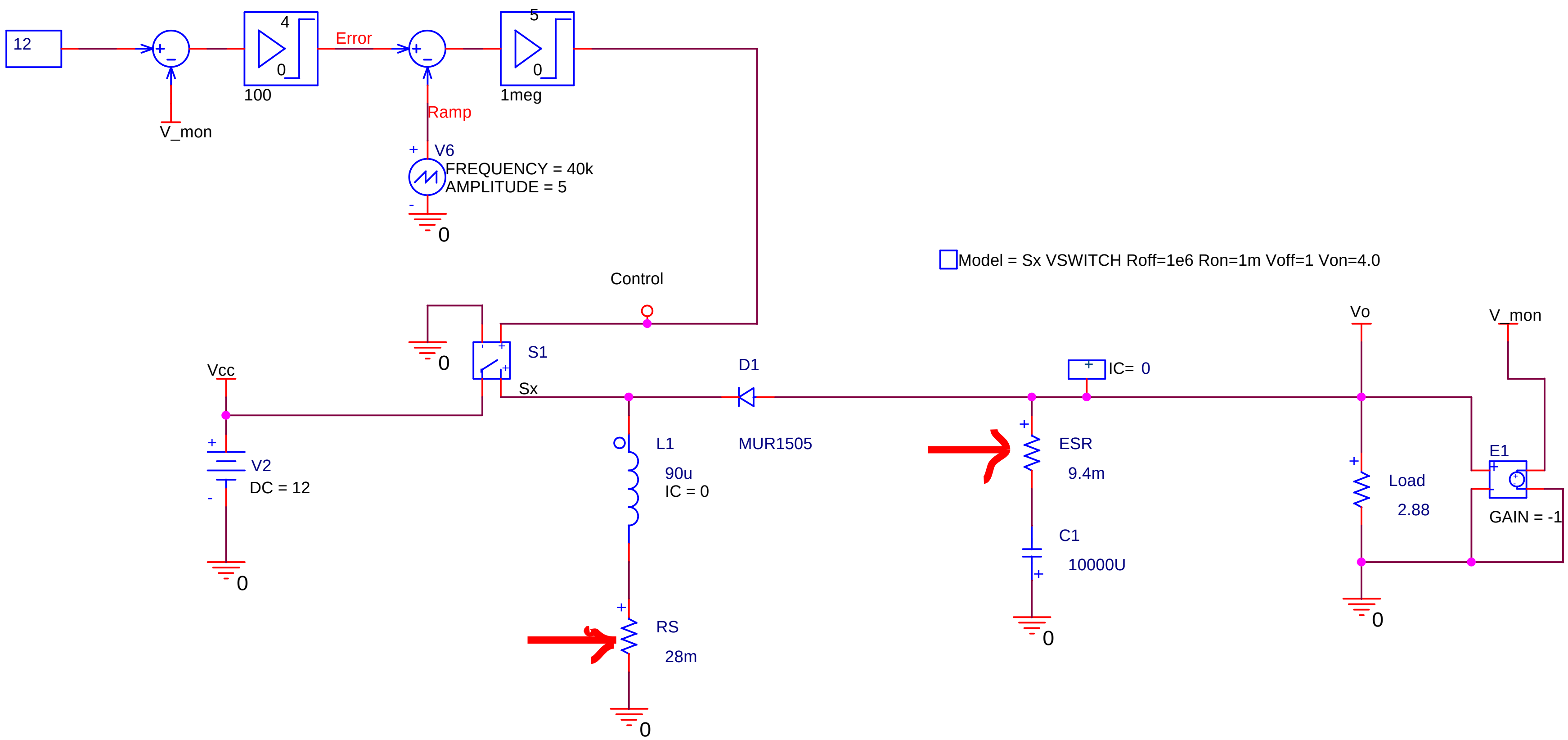

Simulation Settings - TRans
General
Analysis
Include Files
Libraries
Stimulus
Options
Data Collection
Probe Window
Category:
Analog Simulation
Gate-level Simulation
Output file
(.OPTION)
Relative accuracy of V's and I's: 0.001 (RELTOL)
Best accuracy of voltages: 1.0u volts (VNTOL)
Best accuracy of currents: 1.0p amps (ABSTOL)
Best accuracy of charges: 0.01p coulombs (CHGTOL)
Minimum conductance for any branch: 1.0E-12 1/ohm (GMIN)
DC and bias "blind" iteration limit: 150 (ITL1)
DC and bias "best guess" iteration limit: 20 (ITL2)
Transient time point iteration limit: 200 (ITL4)
Default nominal temperature: 27.0 °C (TNOM)
Use GMIN stepping to improve convergence. (STEPGMIN)
Use preordering to reduce matrix fill-in. (PREORDER)
MOSFET Options...
Advanced Options...
Reset
OK
Cancel
Apply
Help


Simulation Settings - TRans
General
Analysis
Include Files
Libraries
Stimulus
Options
Data Collection
Probe Window
Data Collection Options
Voltages:
All but Internal Subcircuits
Currents:
All but Internal Subcircuits
Power:
None
Digital:
None
Noise:
None
Save data in the CSDF format (.CSD)
OK
Cancel
Apply
Help


Simulation Settings - TRans
General
Analysis
Include Files
Libraries
Stimulus
Options
Data Collection
Probe Window
Display Probe window when profile is opened.
Display Probe window:
during simulation.
after simulation has completed.
Show
All markers on open schematics.
Last plot.
Nothing.
OK
Cancel
Apply
Help


(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)
400A
200A
0A
SEL>>
-200A
I(L1)
0V
-10V
-20V
-30V
0s
5ms
10ms
15ms
20ms
25ms
30ms
35ms
40ms
V(Vo)
Time


(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)
50.0A
37.5A
25.0A
12.5A
SEL>>
0A
I(L1)
-11.000V
-12.000V
-13.000V
-13.525V
31.01ms
32.00ms
33.00ms
34.00ms
35.00ms
36.00ms
37.00ms
38.00ms
39.00ms
V(Vo)
Time



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Date: Thursday, January 09, 2003		Sheet 1 of 1	

** Profile: "SCHEMATIC1-TRans" [C:\WEBSITE\ROSE_CLASSES\ECE456\Notes\Orcad\Buck-Boost Converter\b...
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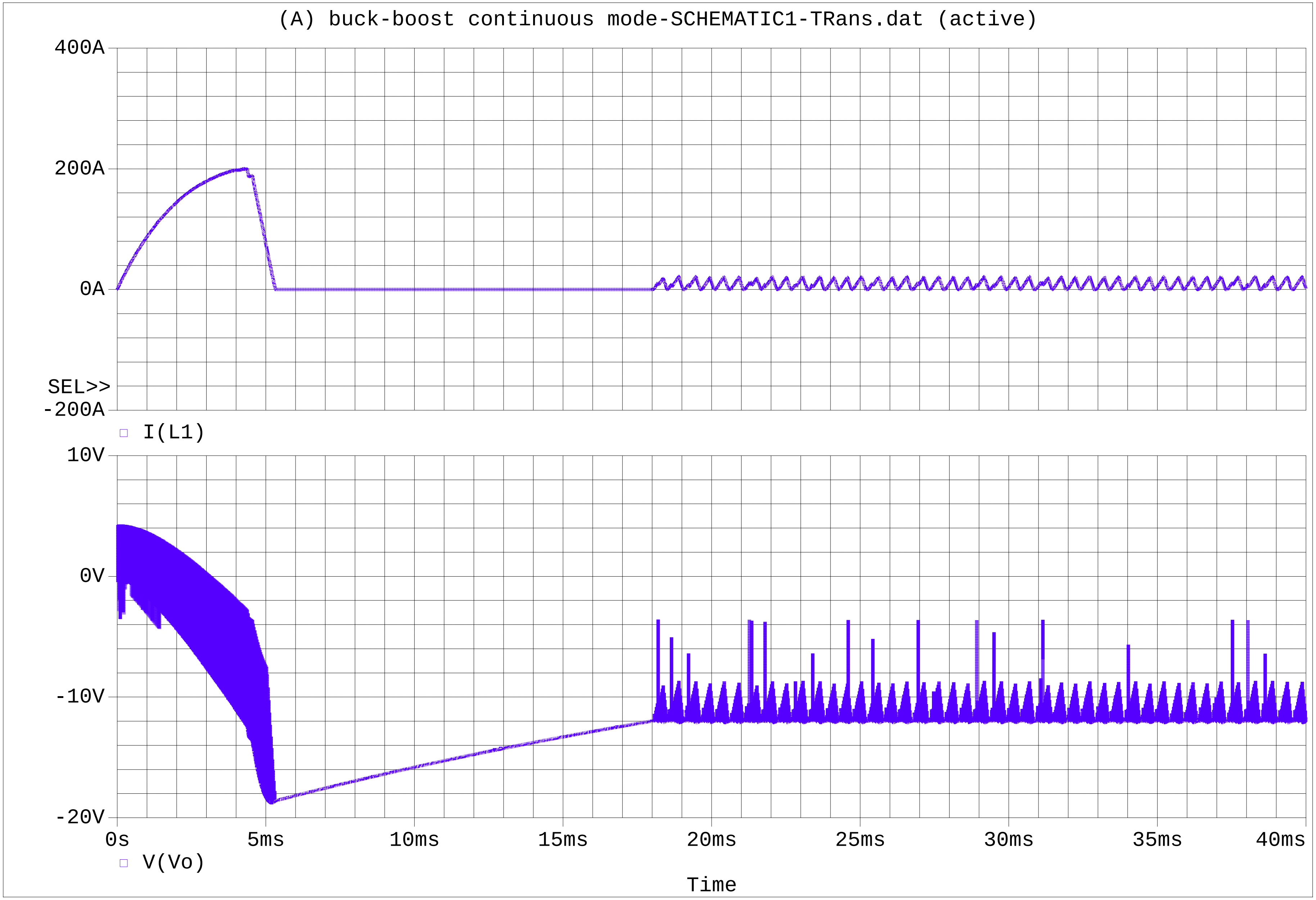

Date: January 09, 2003 Page 1 Time: 12:32:39

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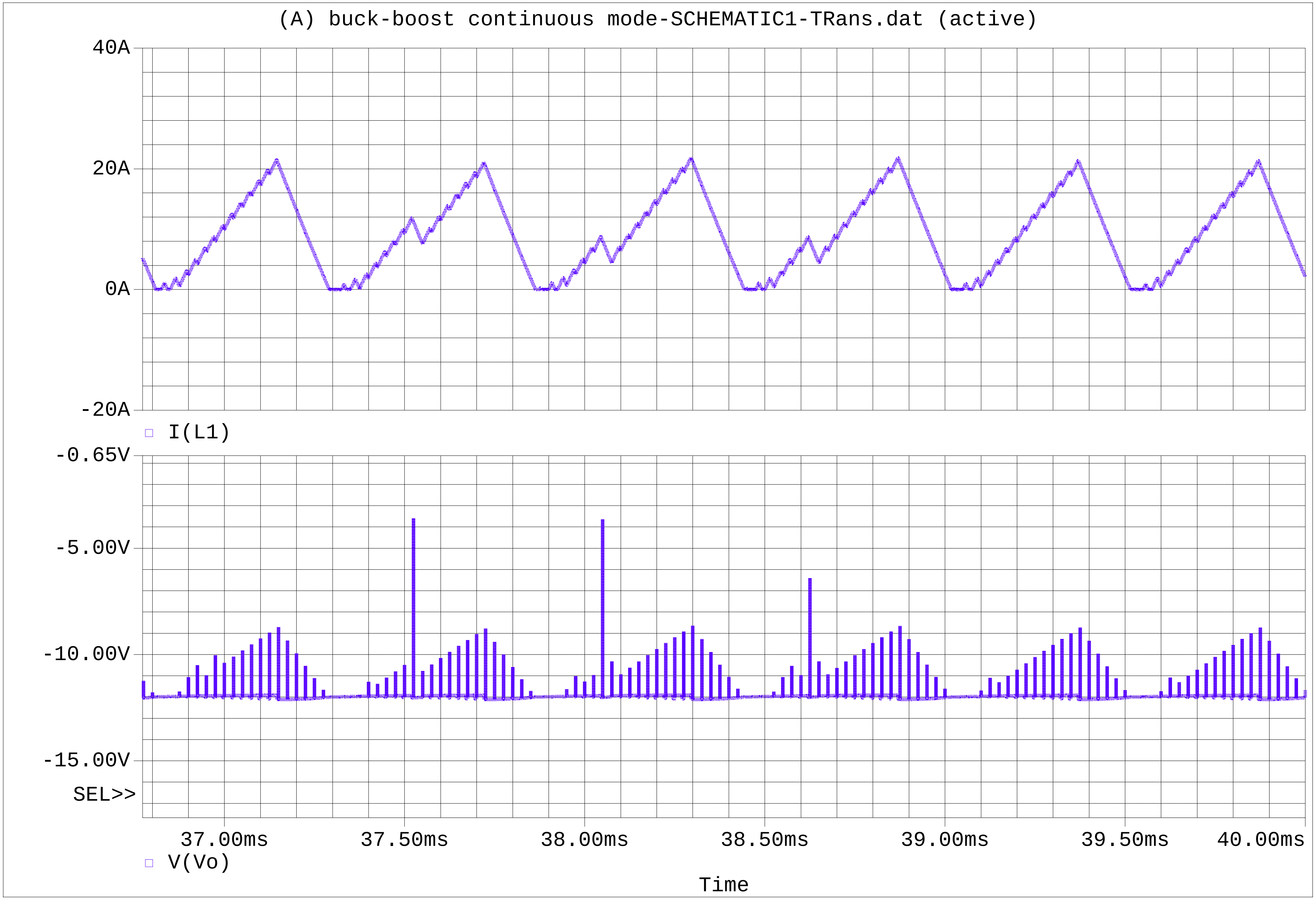

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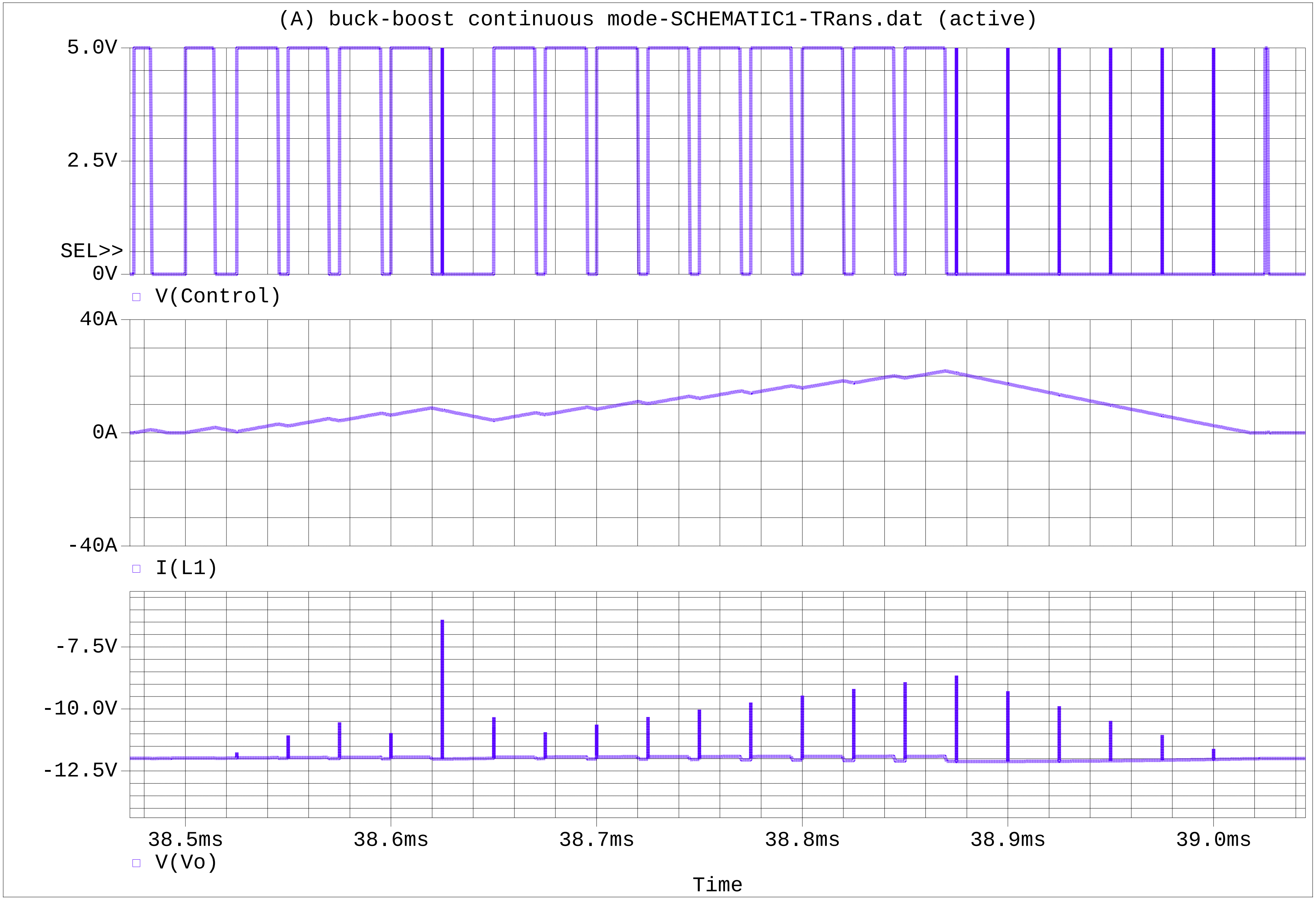

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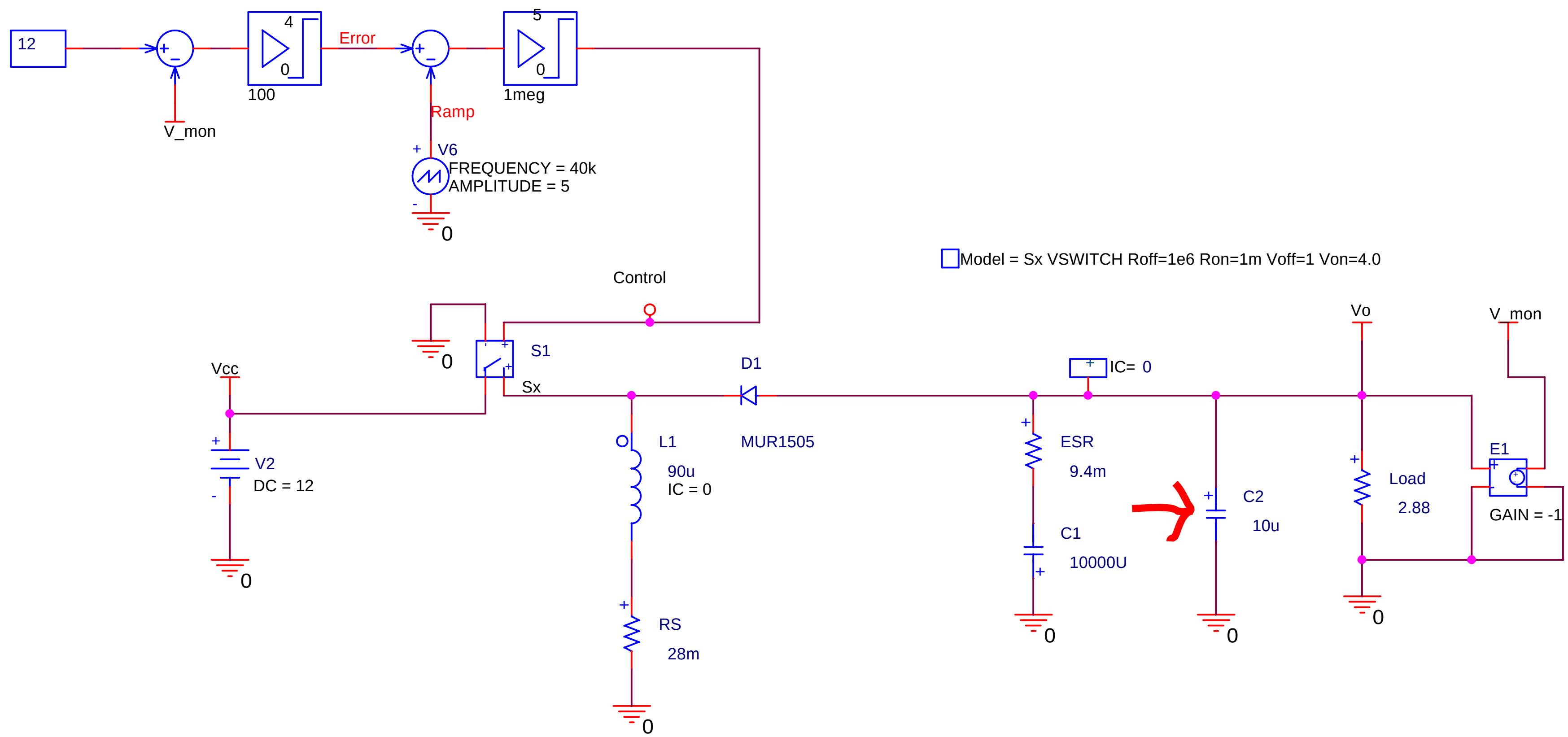

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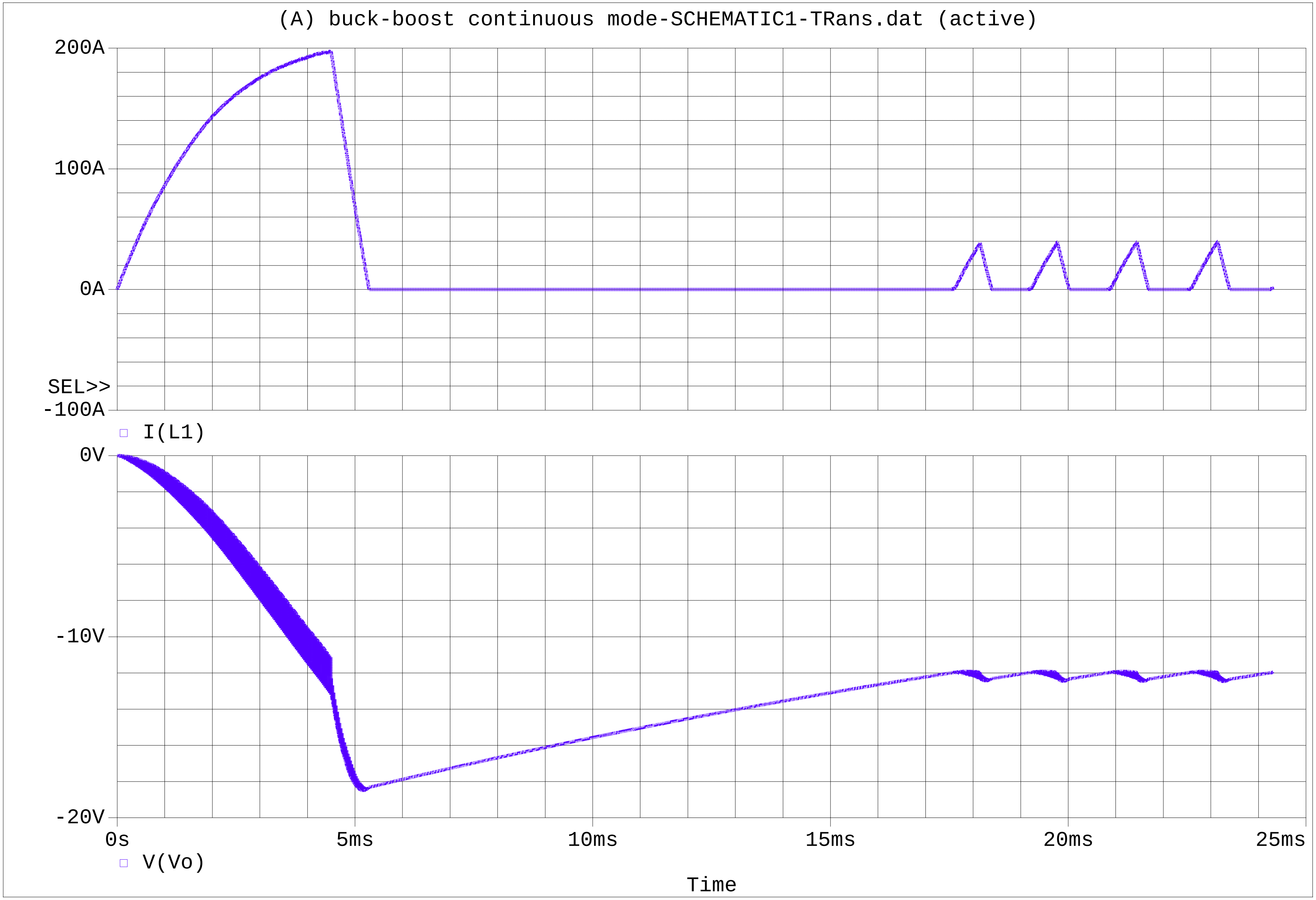
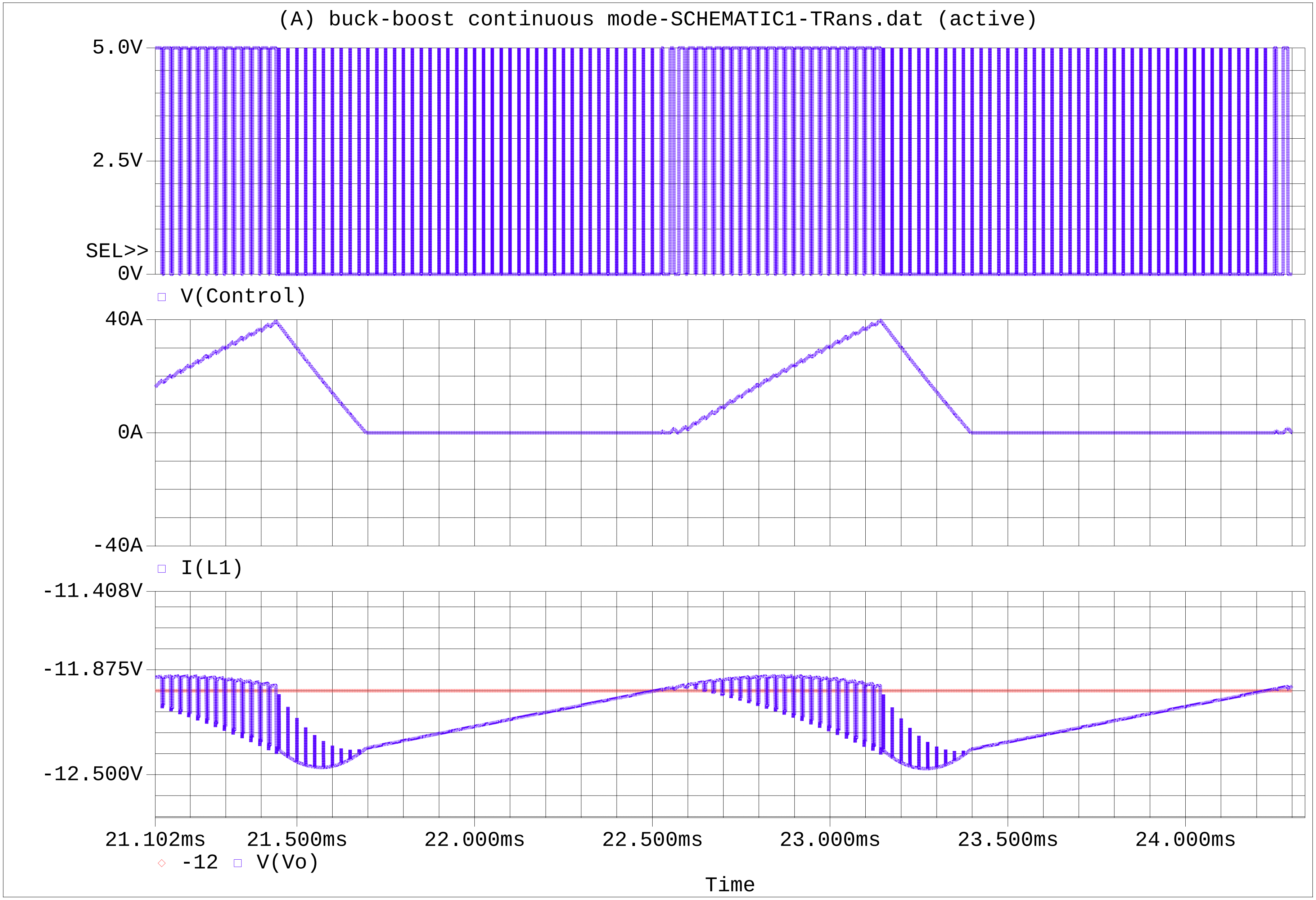
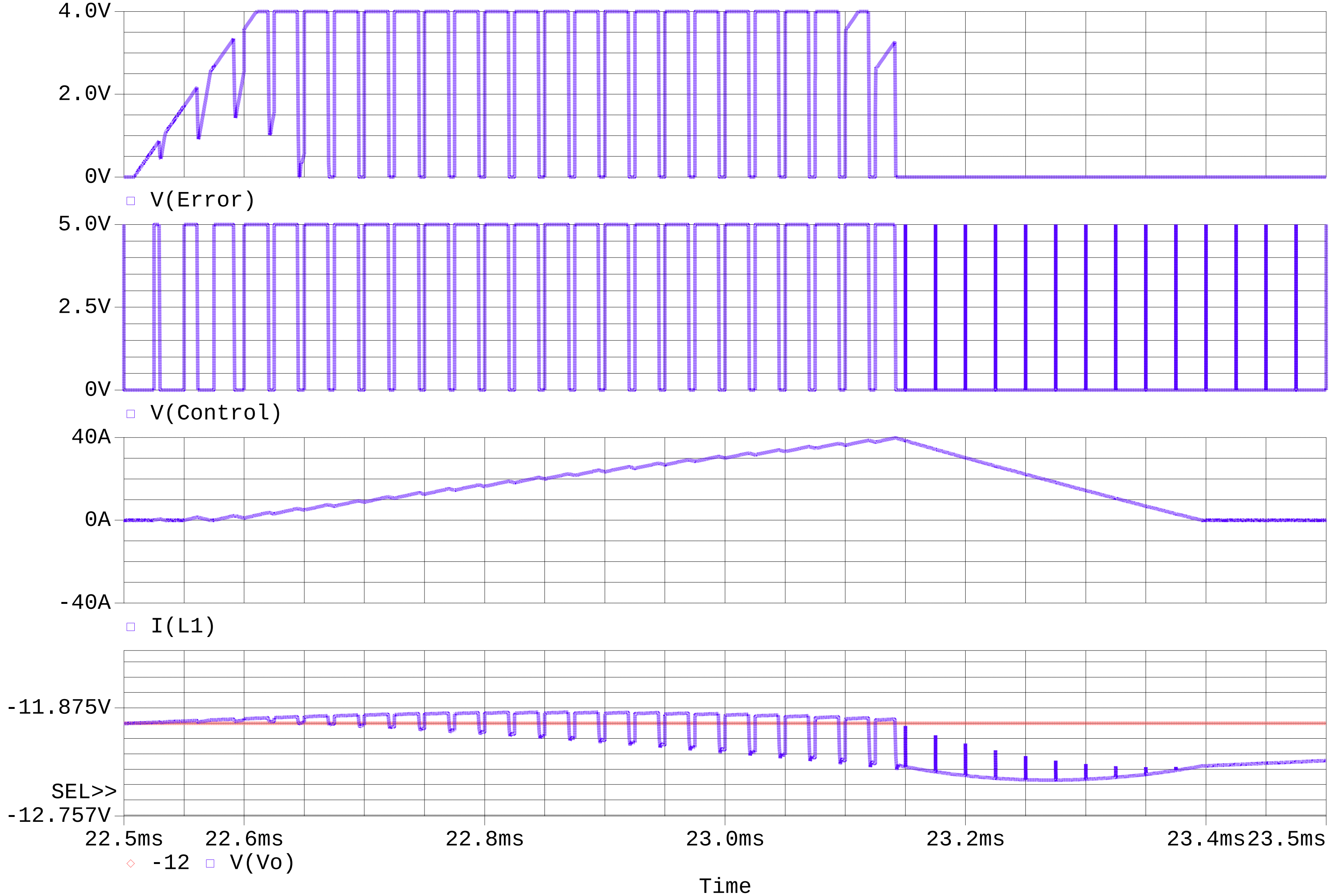
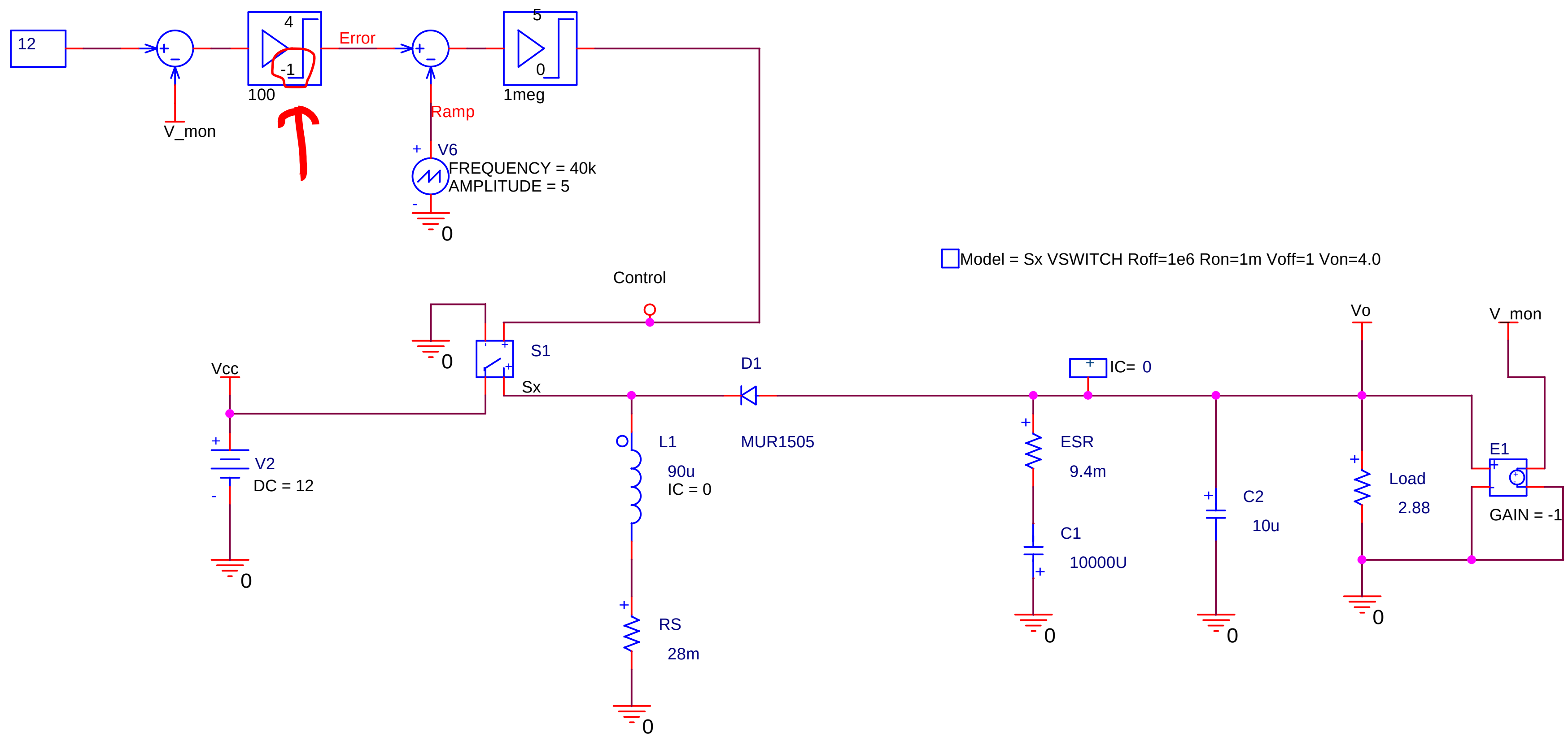

(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)
200A
100A
0A
SEL>>
-100A
I(L1)
0V
-10V
-20V
0s
5ms
10ms
15ms
20ms
25ms
V(Vo)
Time


(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)
5.0V
2.5V
SEL>>
0V
V(Control)
40A
0A
-40A
I(L1)
-11.408V
-11.875V
-12.500V
21.102ms
21.500ms
22.000ms
22.500ms
23.000ms
23.500ms
24.000ms
-12 V(Vo)
Time

(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)





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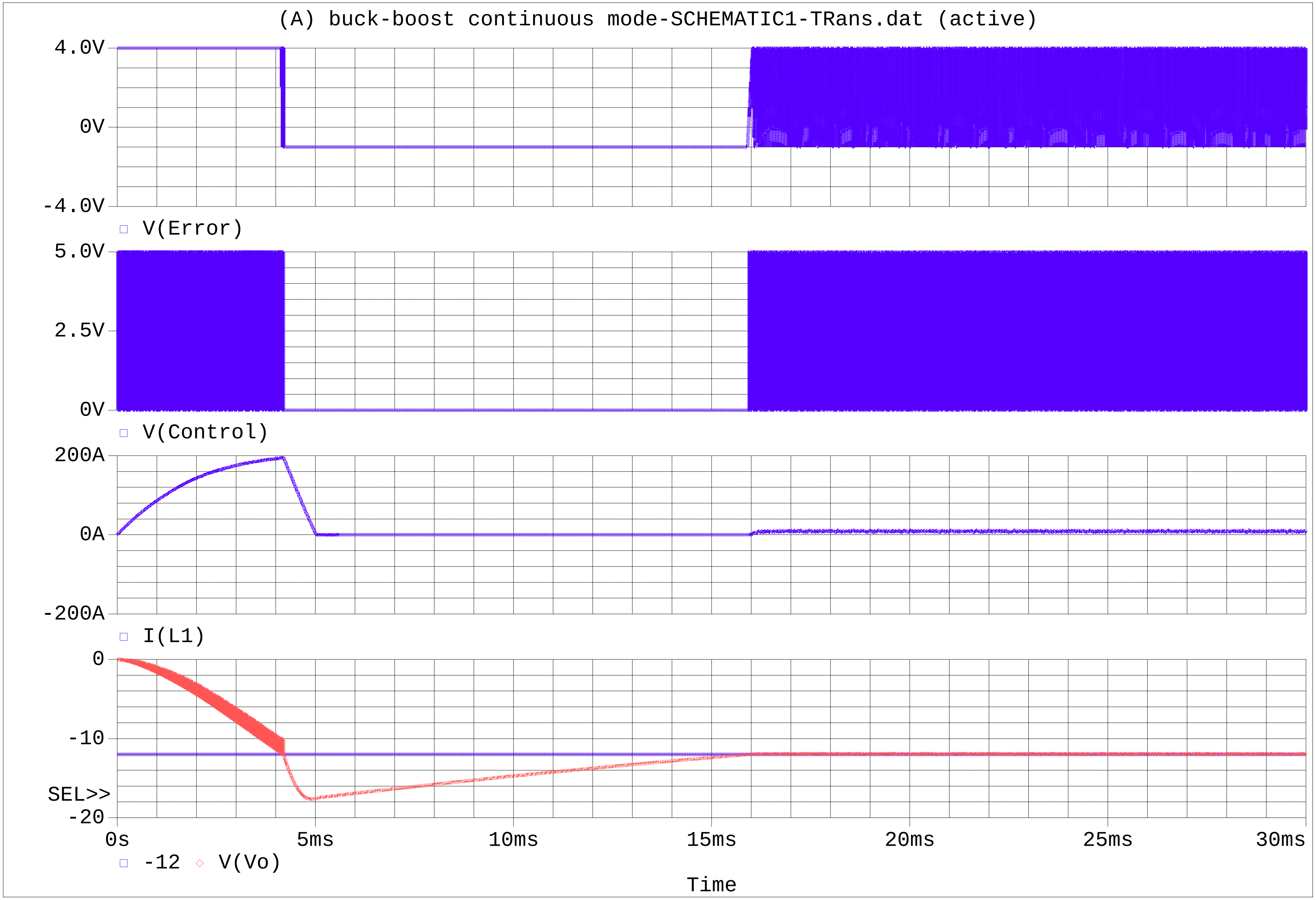
(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)
4.0V
0V
-4.0V
V(Error)
5.0V
2.5V
0V
V(Control)
200A
0A
-200A
I(L1)
0
-10
SEL>>
-20
0s
5ms
10ms
15ms
20ms
25ms
30ms
-12
V(Vo)
Time

** Profile: "SCHEMATIC1-TRans" [C:\WEBSITE\ROSE_CLASSES\ECE456\Notes\Orcad\Buck-Boost Converter\b...
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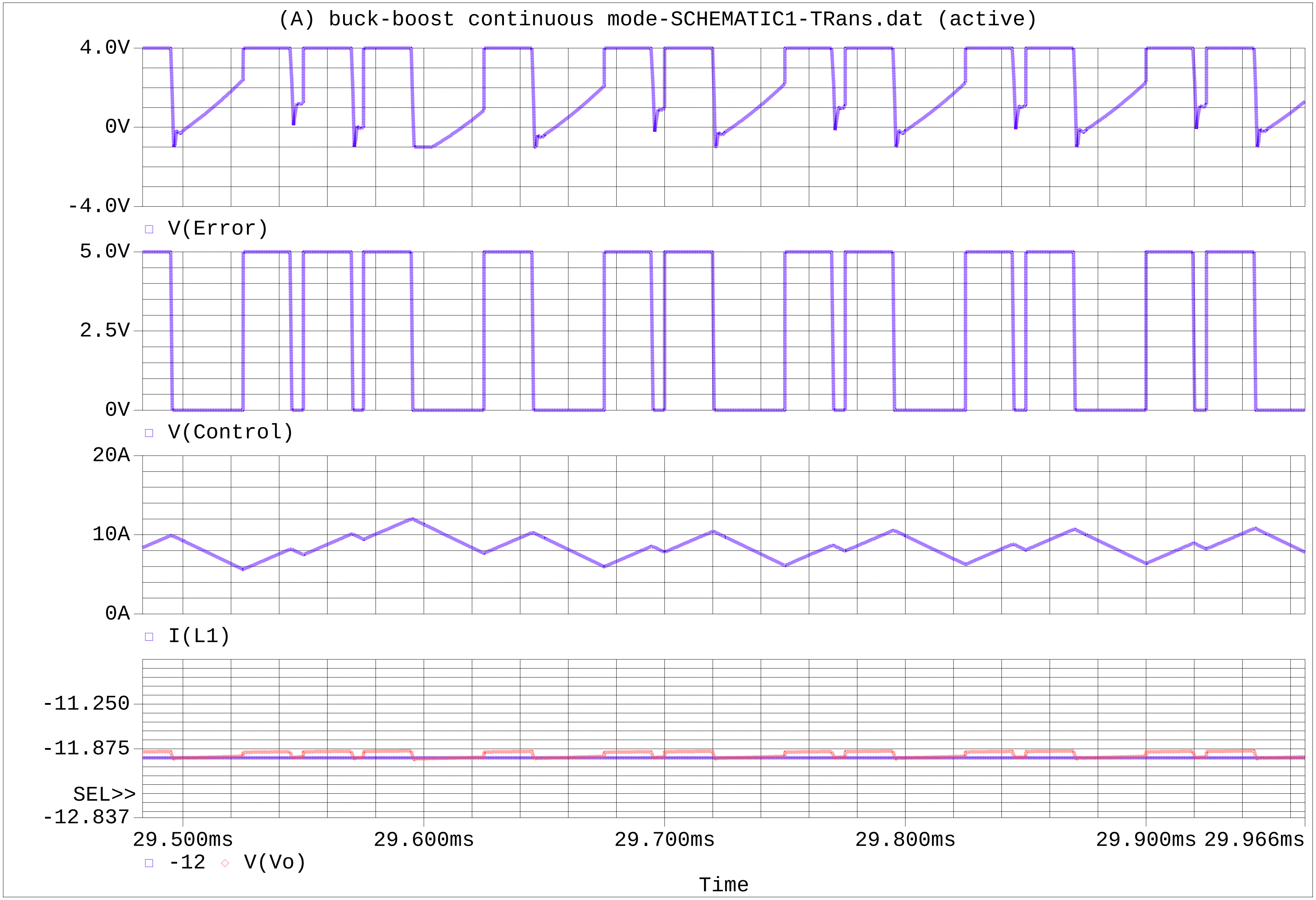
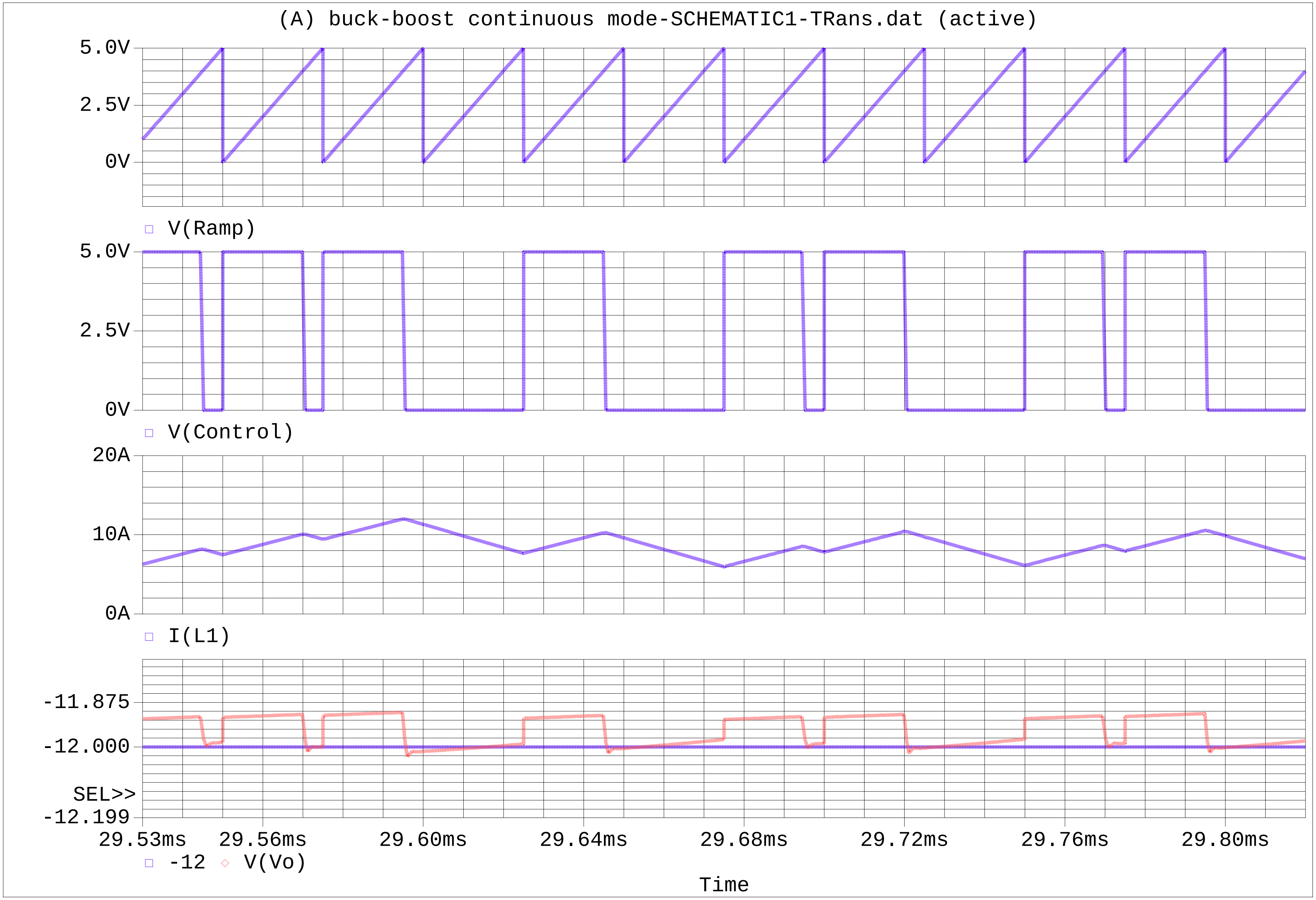
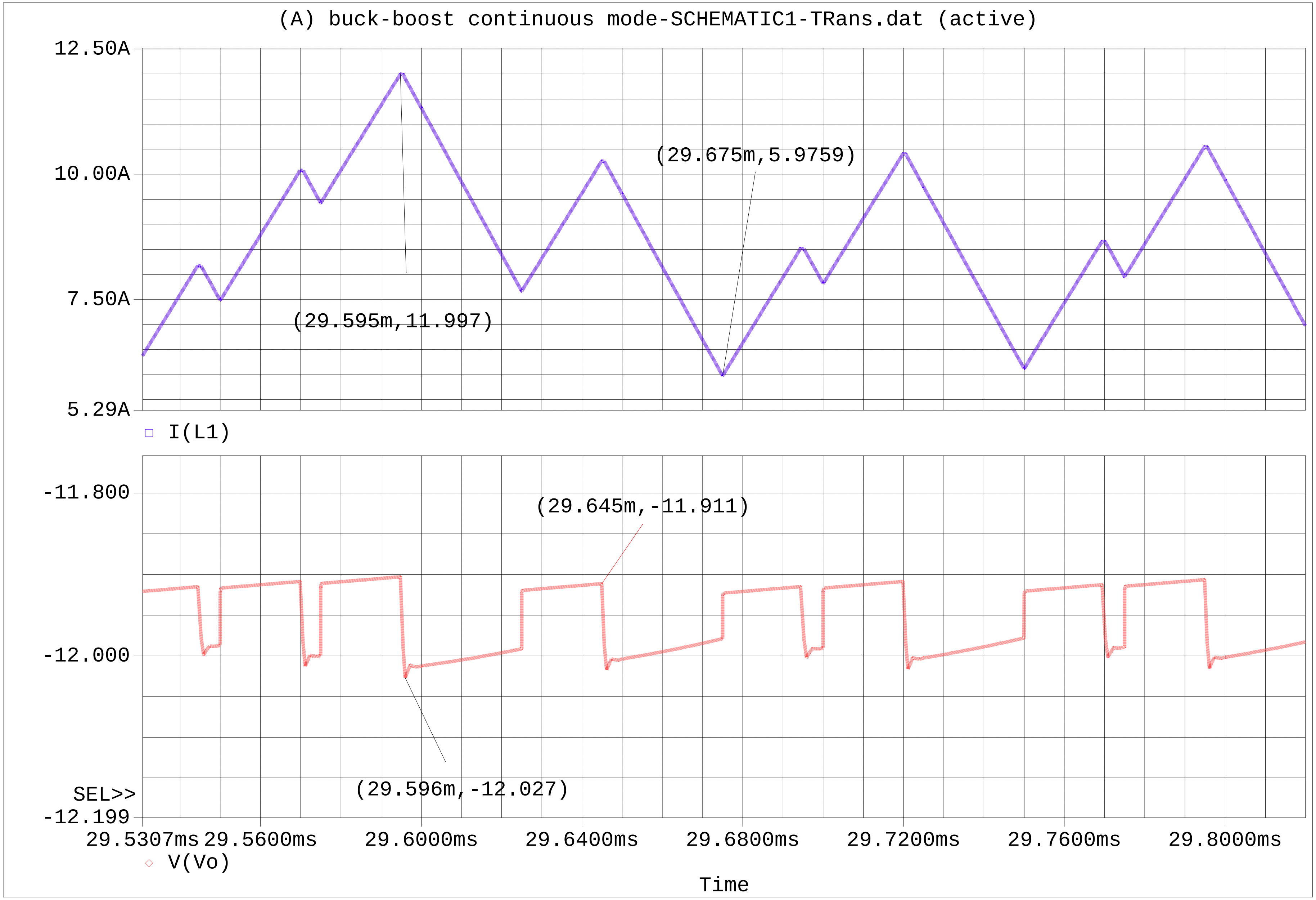


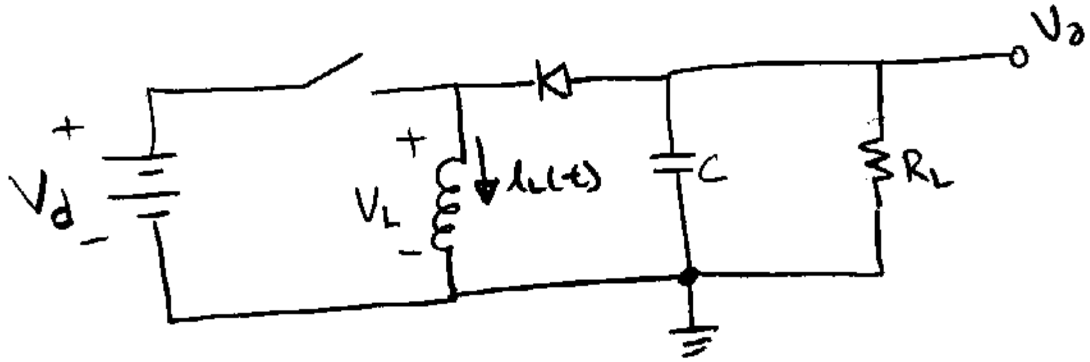

(A) buck-boost continuous mode-SCHEMATIC1-TRans.dat (active)
5.0V
2.5V
0V
V(Ramp)
5.0V
2.5V
0V
V(Control)
20A
10A
0A
I(L1)
-11.875
-12.000
SEL>>
-12.199
29.53ms
29.56ms
29.60ms
29.64ms
29.68ms
29.72ms
29.76ms
29.80ms
-12
V(Vo)
Time

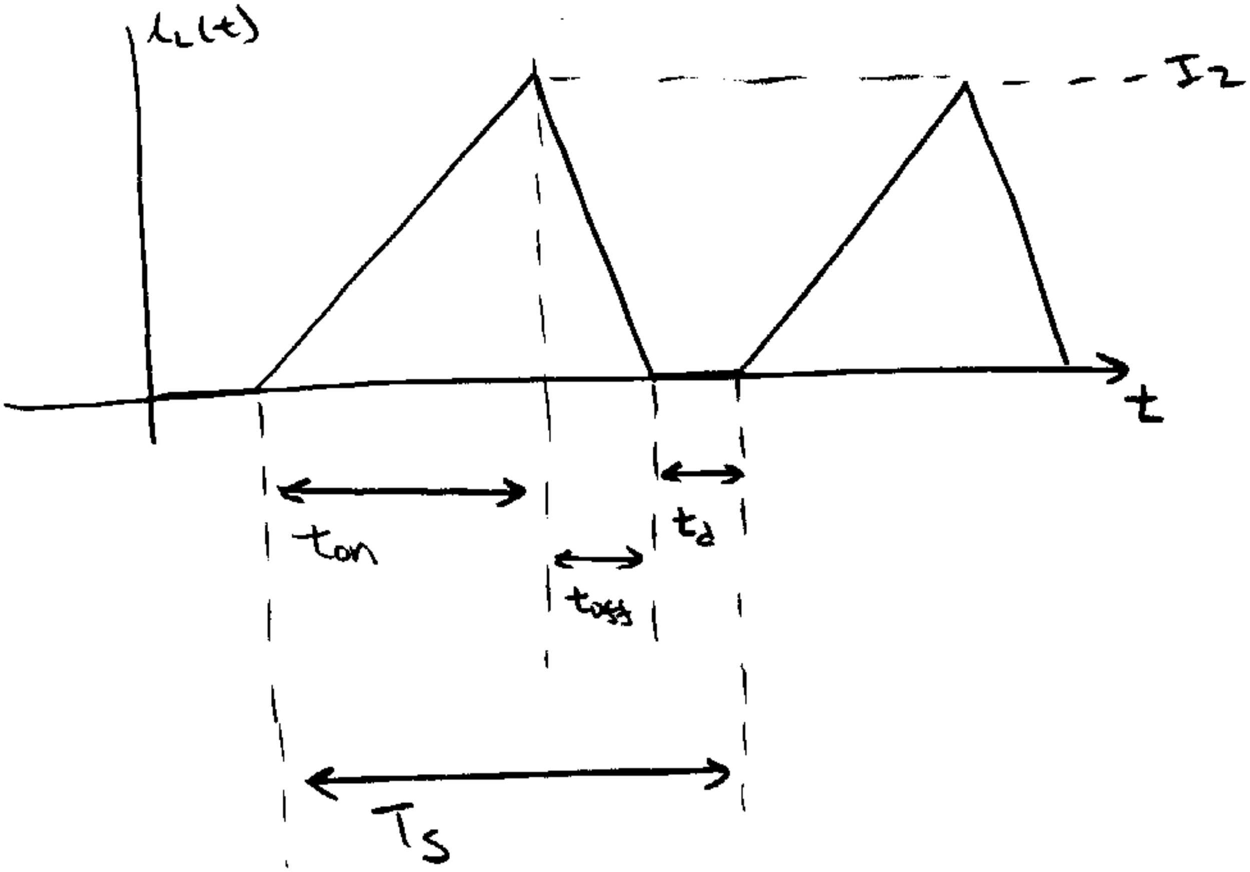
** Profile: "SCHEMATIC1-TRans" [C:\WEBSITE\ROSE_CLASSES\ECE456\Notes\Orcad\Buck-Boost Converter\b...
Date/Time run: 01/09/03 12:48:35 Temperature: 27.0



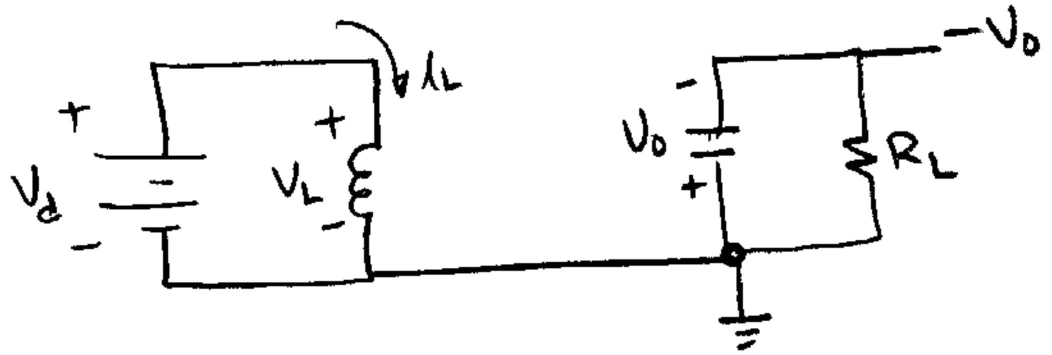
BUCK - BOOST Regulator

Discontinuous mode





During ton we have



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

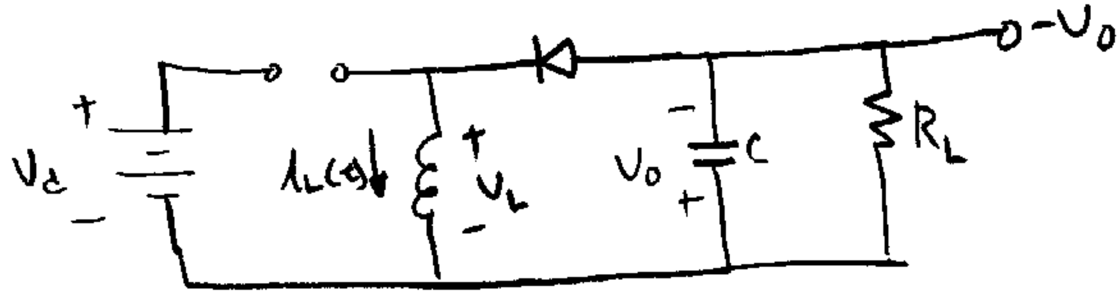
$$i_L(t) = \frac{1}{L}\int V_L(t)\,dt \quad + i.C.$$

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
- $V_L = -V_0$

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

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

OR

$$0 = \frac{1}{L} \int_{t_{on}}^{t_{on}+t_{off}} (-V_0)\, dt + I_2$$

$$\boxed{I_2 = \frac{V_0\, t_{off}}{L}} \quad ②$$

- To ensure discontinuous mode operation

Choose $t_d = 0.2 T_s$

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

Energy balance

- Energy dissipated by load during a cycle

$$\mathcal{E}_o = V_o I_o T_s$$

- 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), $I_2 = \dfrac{V_d t_{on}}{L}$

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

$$\left.\begin{aligned} I_2 &= \frac{V_d t_{on}}{L} \\ I_2 &= \frac{V_o t_{off}}{L} \end{aligned}\right\} \Rightarrow \frac{t_{on}}{t_{off}} = \frac{V_o}{V_d}$$

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

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

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

EE 456

Buck-Boost Regulator Design
Discontinuous Mode Operation

$m\Omega \equiv \Omega \cdot 0.001$ $\mu s := sec \cdot 10^{-6}$ $\mu J := joule \cdot 10^{-6}$

Specify Input Voltage $V_D := 12 \cdot volt$

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

Specify Switching Frequency $F_S := 40 \cdot kHz$

$T_S := \frac{1}{F_S}$ $T_S = 25\,\mu s$

Specify the Assumed Efficiency $Eff := 85\%$

The output Power is $P_{out} := \frac{50 \cdot watt}{Eff}$

The output current is $I_o := \left| \frac{P_{out}}{V_o} \right|$ $I_o = 4.902\,amp$

Find Ton and Toff

$t_{off} := 1 \cdot \mu s \qquad t_{on} := 1 \cdot \mu s$

Given

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

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

$$\begin{pmatrix} t_{on} \\ t_{off} \end{pmatrix} := \mathrm{Find}(t_{on}, t_{off}) \qquad t_{on} = 10\,\mu s \qquad t_{off} = 10\,\mu s$$

Find the range of Inductors that will operate in discontinuous mode

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

For discontinuous Mode, We need L less than $L = 7.344\,\mu H$

Solve for the exact size inductor needed. Use the energy balance equation.

$$L := \frac{{V_D}^2 \cdot {t_{on}}^2}{2 \cdot |V_o| \cdot I_o \cdot T_S} \qquad L = 4.896\,\mu H$$

FInd the peak current

$$I_2 := V_D \cdot \frac{t_{on}}{L} \qquad I_2 = 24.51\,\text{amp}$$

Now that we know the approximate values needed for the inductor, choose a standard size inductor and then resolve the problem.

Some Pulse Engineering Specs PE-51509 $L := 14 \cdot \mu H$

$$\text{Volt\_Sec} := 95 \cdot \text{volt} \cdot \mu s \qquad \text{Energy\_Storage} := 700 \cdot \mu J$$

$$I_{DC} := 10 \cdot \text{amp}$$

$$I_{max} := \frac{\text{Volt\_Sec}}{L} \qquad I_{max} = 6.786\,\text{amp}$$

$$I_{max} := \sqrt{\frac{2 \cdot \text{Energy\_Storage}}{L}} \qquad I_{max} = 10\,\text{amp}$$

What is the saturation current of this inductor? I don't know. Use 2 in parallel to get 7 µH. THis will give us a different I_2, t_{on}, t_{off}.

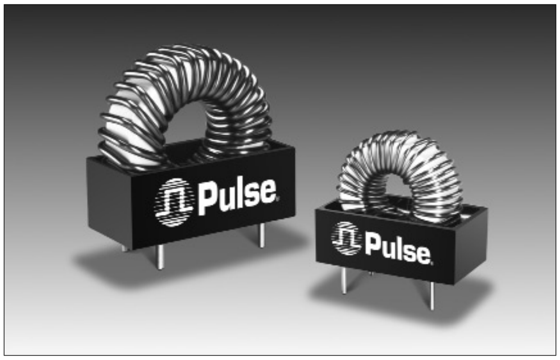
$$L := 7 \cdot \mu H$$

Calculate the needed I2 to store the amount of energy needed per cycle.

$$I_2 := \sqrt{\frac{-2 \cdot V_o \cdot I_o \cdot T_S}{L}} \qquad I_2 = 20.498\,\text{amp}$$

TOROIDAL INDUCTORS
HIGH CURRENT

Pulse
A TECHNITROL COMPANY



- Cost-effective designs
- Semi-encapsulated construction
- Maximum operation temperature of 130°C (Ambient + Rise)
- A 2:1 inductance swing from zero to maximum current

Electrical Specifications @ 25°C

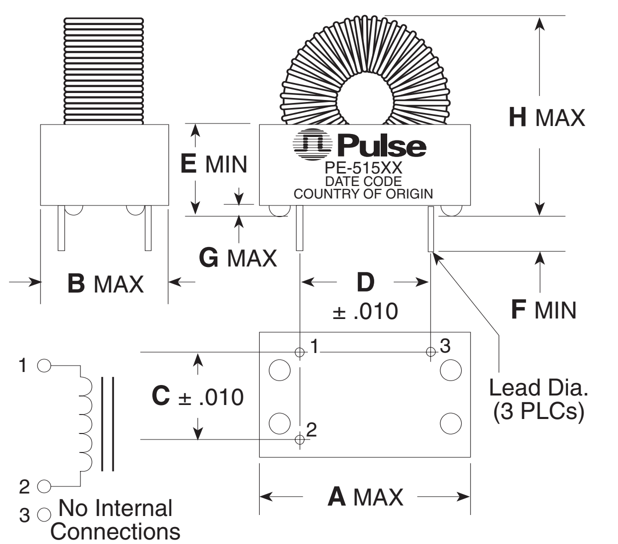
	Reference Operating Values					Design Control Values				
Part Number	Inductance Typical (µH)2	I_{DC} (AMPS)	ET_{OP}[1] (V-µSec) 20 kHz	ET_{OP}[1] (V-µSec) 40 kHz	Energy Storage (µJ MIN)3	Inductance No DC (µH) (±20%)	50 kHz Test mV No DC5	DCR (Ω MAX)	Size Code	Lead Diameter (in ±.003)
PE-51506	17.0	17.0	190	130	2460	40.0	140	0.0065	3	0.081
PE-51507	32.0	16.0	290	200	4100	70.7	270	0.0092	4	0.081
PE-51508	60.0	16.0	390	270	7700	120.0	470	0.012	5	0.081
PE-51509	14.0	10.0	135	95	700	28.5	73	0.009	1	0.057
PE-51510	23.0	11.0	170	120	1400	43.5	130	0.012	2	0.057
PE-51511	43.0	10.0	280	195	2150	85.5	210	0.018	3	0.057
PE-51512	90.0	10.0	430	300	4500	158.0	420	0.028	4	0.057
PE-51513	144.0	10.0	570	400	7200	262.0	700	0.032	5	0.057
PE-51514	32.0	6.6	200	140	700	60.5	110	0.025	1	0.040
PE-51515	52.0	7.0	230	160	1275	92.0	190	0.032	2	0.040
PE-51516	98.0	6.0	400	280	1765	188.0	310	0.048	3	0.040
PE-51517	175.0	6.0	620	425	3150	315.0	560	0.068	4	0.040
PE-51518	335.0	6.0	840	580	6030	571.0	1000	0.095	5	0.040
PE-51520	400	3.6	600	420	2700	688.0	640	0.130	3	0.036

NOTES:

1. To prevent excessive temperature rise, limit ET_{OP} to the rated ET_{OP} specified. This is not a saturation limit. Temperature rise of inductors is 40°C MAX at MAX current and rated ET_{OP}.
2. A 2:1 nominal inductance swing from no I_{DC} to operating I_{DC} gives improved protection against current discontinuities at light loading. Inductance increases with greater ET_{OP}. Reference values occur at I_{DC} and low flux density.
3. $\frac{LI^2}{2}$ rating is the ability of the inductor to store energy.
4. Design control test voltage is critical. Inductance increases with voltage.

Size Code	1	2	3	4	5
A	1.20/30,48	1.44/36,57	1.60/40,64	1.95/49,53	2.30/58,42
B	0.60/15,24	0.80/20,32	0.80/20,32	0.91/23,11	1.11/28,19
C	0.40/10,16	0.60/15,24	0.60/15,24	0.70/17,78	0.90/22,85
D	0.80/20,32	0.90/22,86	0.90/22,86	1.20/30,48	1.50/38,10
E	0.45/11,43	0.70/17,78	0.70/17,78	0.90/22,86	1.00/25,40
F	0.20/5,08	0.20/5,08	0.20/5,08	0.20/5,08	0.20/5,08
G	.015/0,381	0.03/0,76	0.03/0,76	0.03/0,76	0.03/0,76
H	1.20/30,48	1.44/36,57	1.72/43,68	2.00/50,80	2.30/58,42

Mechanicals



Dimensions: $\frac{\text{Inches}}{\text{mm}}$

Unless otherwise specified, all tolerances are ± $\frac{.010}{0,25}$

Now calculate the value of t_{on} and t_{off} to get that peak current.

$$t_{on} := \frac{I_2 \cdot L}{V_D} \qquad t_{on} = 11.957\,\mu s$$

$$t_{off} := \frac{I_2 \cdot L}{-V_o} \qquad t_{off} = 11.957\,\mu s$$

If ton + toff > T_S then the inductor is too big and the regulator will operate in the continuous mode.

$$\frac{t_{on} + t_{off}}{T_S} = 0.957$$

Calculate the dead time

$$t_d := T_S - t_{on} - t_{off} \qquad t_d = 1.086\,\mu s$$

This dead time is too small. Try another inductor.

EE 456

Buck-Boost Regulator Design
Discontinuous Mode Operation

$m\Omega \equiv \Omega \cdot 0.001$ $\mu s := sec \cdot 10^{-6}$ $\mu J := joule \cdot 10^{-6}$

Specify Input Voltage $V_D := 12 \cdot volt$

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

Specify Switching Frequency $F_S := 40 \cdot kHz$

$T_S := \frac{1}{F_S}$ $T_S = 25 \mu s$

Specify the Assumed Efficiency $Eff := 85\%$

The output Power is $P_{out} := \frac{50 \cdot watt}{Eff}$

The output current is $I_o := \left| \frac{P_{out}}{V_o} \right|$ $I_o = 4.902\, amp$

Find Ton and Toff

$t_{off} := 1\cdot\mu s$ $\qquad$ $t_{on} := 1\cdot\mu s$

Given

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

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

$$\begin{pmatrix} t_{on} \\ t_{off} \end{pmatrix} := \mathrm{Find}(t_{on}, t_{off}) \qquad t_{on} = 10\,\mu s \qquad t_{off} = 10\,\mu s$$

Find the range of Inductors that will operate in discontinuous mode

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

For discontinuous Mode, We need L less than $L = 7.344\,\mu H$

Solve for the exact size inductor needed. Use the energy balance equation.

$$L := \frac{{V_D}^2\cdot {t_{on}}^2}{2\cdot |V_o|\cdot I_o\cdot T_S} \qquad L = 4.896\,\mu H$$

FInd the peak current

$$I_2 := V_D \cdot \frac{t_{on}}{L} \qquad I_2 = 24.51\,\text{amp}$$

Now that we know the approximate values needed for the inductor, choose a standard size inductor and then resolve the problem.

Some Pulse Engineering Specs PE-51590 $L := 22 \cdot \mu H$

$$Volt\_Sec := 44 \cdot volt \cdot \mu s \qquad Energy\_Storage := 275 \cdot \mu J$$

$$I_{DC} := 5 \cdot amp$$

$$I_{max} := \frac{Volt\_Sec}{L} \qquad I_{max} = 2\,\text{amp}$$

$$I_{max} := \sqrt{\frac{2 \cdot Energy\_Storage}{L}} \qquad I_{max} = 5\,\text{amp}$$

What is the saturation current of this inductor? I don't know. Use 4 in parallel to get 5.5 µH. THis will give us a different I_2, t_{on}, t_{off}.

Coil Craft Inductor PCV-0-103-20 $L := 10 \cdot \mu H$

$$I_{SAT} := 20 \cdot amp$$

Use two of the coilcraft Parts in parallel.

$$L := 5 \cdot \mu H$$

LOW COST INDUCTORS
Electrical Information

Pulse
A TECHNITROL COMPANY

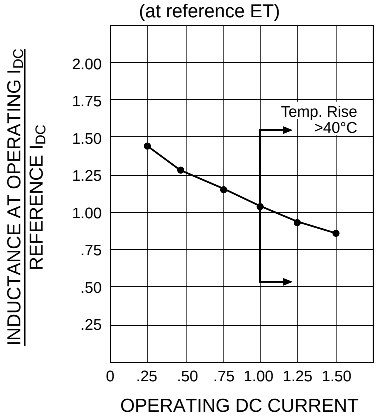
- Available in vertical, low profile and *Klipmount™*
- SMPS averaging filter
- Characterized for general purpose use and ripple filters
- Single-layer designs
- Can be used as differential mode inductors in EMI filters[3]

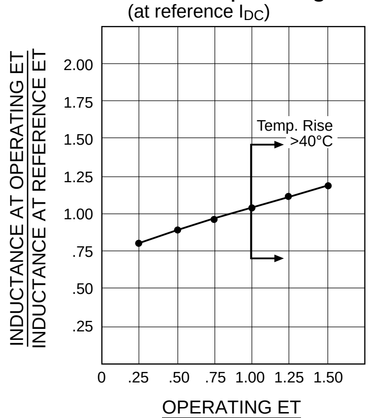
Electrical Specifications @ 25°C — Operating Temperature -30°C to 130°C

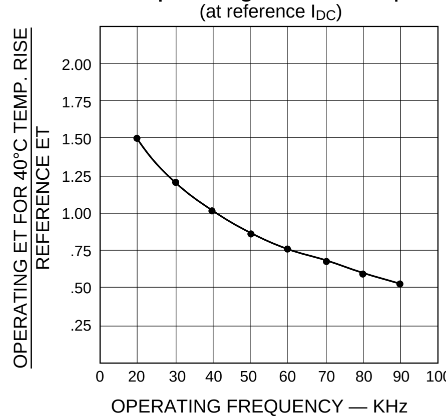
Reference Operating Values						Design Control Values					
Vertical Part Number	**Low Profile Part Number**	**Inductance Typical** (µH)[1]	I_{DC} (AMPS)	**ET_{OP}** (V-µSec)	**Energy Storage** (µJ)[4]	**Inductance No DC** (µHy) ±20%	**20 KHz Test mV No DC**[2]	**DCR** (Ω MAX)[6]	**Coil Size Code**	**Klip Mount Package***	**Lead Diameter** (In) ±.003
PE-51591	**PE-92421**	20	2.0	52	40	32.8	33	.060	H	—	.020
PE-92100	—	25	2.6	30	85	20.7	22	.043	A	KM1	.020
PE-92101	**PE-92401**	50	2.6	50	169	45.7	45	.071	B	KM2	.020
PE-92102	**PE-92402**	100	2.6	90	338	94.1	90	.100	C	KM3	.020
PE-92103	—	35	2.6	55	118	28.4	36	.037	B	KM2	.025
PE-92104	**PE-92404**	70	3.0	85	315	61.0	73	.052	C	KM3	.025
PE-92105	**PE-92405**	145	3.0	140	653	141.8	140	.087	D	KM4	.025
PE-92106	—	285	3.0	300	1283	264.1	340	.140	E	KM5	.025
PE-92107	—	450	3.0	425	2025	436.3	500	.200	F	—	.025
PE-92108	**PE-92408**	100	3.6	130	648	90.7	110	.045	D	KM4	.032
PE-92109	—	165	4.0	240	1320	152.0	260	.070	E	KM5	.032
PE-92110	—	270	4.0	350	2160	263.9	400	.100	F	—	.032
PE-92111	—	40	4.0	70	320	37.9	57	.027	C	KM3	.032
PE-51590	**PE-92420**	22	5.0	44	275	20.3	37	.020	G	—	.032
PE-92112	**PE-92412**	100	5.0	200	1250	90.7	180	.034	E	KM5	.042
PE-92113	—	170	5.0	300	2125	159.7	310	.050	F	—	.042
PE-92114	**PE-92414**	55	5.0	100	688	54.9	88	.023	D	KM4	.042
PE-92115	—	95	7.0	225	2328	96.0	200	.025	F	—	.051
PE-92116	**PE-92416**	55	7.0	150	1348	49.1	100	.017	E	KM5	.051
PE-92117	—	55	10.0	175	2750	55.9	120	.013	F	—	.064

*Parts available with ***KlipMount*** option can be ordered by adding a "K" suffix to the part number (i.e. PE-92100**K**).

Relationships Between Reference and Operating Conditions







PCV-0 Series – Continued

Part Number	Inductance[1] (µH)	Isat[2] (Amps)	Irms[3] (Amps)	DCR Max (Ω)	A Max	B Max	C ± .015/0,38	D ± .004/0,10
PCV-0-103-20	10 ±10%	20	20	.006	.75/19,1	1.8/45,7	.60/15,2	.075/1,91
PCV-0-153-03	15	3	3	.025	.50/12,7	1.0/25,4	.42/10,7	.035/0,89
PCV-0-153-10	15	10	10	.020	.52/13,2	1.0/25,4	.42/10,7	.054/1,37
PCV-0-223-03	**22**	**3**	**3**	**.035**	**.50/12,7**	**1.0/25,4**	**.42/10,7**	**.035/0,89**
PCV-0-223-05	**22**	**5**	**5**	**.023**	**.50/12,7**	**1.0/25,4**	**.42/10,7**	**.042/1,07**
PCV-0-223-10	**22**	**10**	**10**	**.015**	**.66/16,8**	**1.3/33,0**	**.42/10,7**	**.060/1,52**
PCV-0-273-05	27	5	5	.024	.50/12,7	1.0/25,4	.49/12,5	.042/1,07
PCV-0-333-12	33	12	12	.017	.70/17,8	1.3/33,0	.55/14,0	.060/1,52
PCV-0-473-03	**47**	**3**	**3**	**.050**	**.55/14,0**	**1.0/25,4**	**.42/10,7**	**.035/0,89**
PCV-0-473-05	**47**	**5**	**5**	**.035**	**.65/16,5**	**1.1/28,0**	**.70/17,8**	**.042/1,07**
PCV-0-473-10	**47**	**10**	**10**	**.022**	**.85/21,6**	**1.3/33,0**	**.70/17,8**	**.060/1,52**
PCV-0-823-03	82	3	3	.110	.50/12,7	.65/16,5	.375/9,5	.028/0,71
PCV-0-104-01	100	1	1	.190	.40/10,2	.90/22,9	.30/7,6	.020/0,51
PCV-0-104-03	**100**	**3**	**3**	**.072**	**.55/14,0**	**1.2/30,5**	**.70/17,8**	**.035/0,89**
PCV-0-104-05	**100**	**5**	**5**	**.055**	**.65/16,5**	**1.3/33,0**	**.70/17,8**	**.042/1,07**
PCV-0-154-03	150	3	3	.140	.60/15,2	1.2/30,5	.43/10,9	.028/0,71
PCV-0-154-05	150	5	5	.065	.65/16,5	1.3/33,0	.70/17,8	.042/1,07
PCV-0-184-05	180	5	5	.110	.60/15,2	1.2/30,5	.43/10,9	.035/0,89
PCV-0-224-03	220	3	3	.210	.55/14,0	1.2/30,5	.42/10,7	.025/0,64
PCV-0-274-04	270	4	4	.250	.95/24,0	.72/18,3	.71/18,0	.030/0,76
PCV-0-274-10	270	10	10	.160	1.1/28,0	1.0/25,4	.72/18,3	.038/0,97
PCV-0-394-03	390	3	3	.250	1.1/28,0	1.0/25,4	.72/18,3	.035/0,89
PCV-0-394-05	390	5	5	.190	1.1/28,0	1.0/25,4	.72/18,3	.038/0,97

PCV-1 Series

Part Number	Inductance[1] (µH)	Isat[2] (Amps)	Irms[3] (Amps)	DCR Max (Ω)	A Max	B Max	C ± .015/0,38	D ± .004/0,10
PCV-1-152-15	1.5 ±15%	15	15	.003	.65/16,5	.90/22,9	.42/10,7	.068/1,73
PCV-1-182-10	1.8	10	10	.006	.65/16,5	1.1/27,9	.42/10,7	.054/1,37
PCV-1-182-15	1.8	15	15	.003	.65/16,5	1.1/27,9	.42/10,7	.068/1,73
PCV-1-472-03	4.7	3	3	.021	.62/15,7	.85/21,6	.42/10,7	.035/0,89
PCV-1-472-05	4.7	5	5	.012	.62/15,7	.85/21,6	.42/10,7	.042/1,07
PCV-1-472-10	4.7	10	10	.012	.62/15,7	1.1/27,9	.42/10,7	.054/1,37
PCV-1-103-03	10 ±10%	3	3	.026	.63/16,0	.85/21,6	.42/10,7	.035/0,89
PCV-1-103-05	10	5	5	.020	.62/15,7	.85/21,6	.42/10,7	.042/1,07
PCV-1-103-10	10	10	10	.013	.63/16,0	1.1/27,9	.42/10,7	.054/1,37
PCV-1-153-10	15	10	10	.020	.70/17,8	1.4/35,6	.42/10,7	.060/1,52
PCV-1-223-03	22	3	3	.035	.62/15,7	1.1/27,9	.42/10,7	.035/0,89
PCV-1-223-05	22	5	5	.023	.62/15,7	1.1/27,9	.42/10,7	.042/1,07
PCV-1-223-10	22	10	10	.018	.70/17,8	1.4/35,6	.42/10,7	.060/1,52
PCV-1-473-03	47	3	3	.050	.65/16,5	1.1/27,9	.42/10,7	.035/0,89
PCV-1-473-05	47	5	5	.033	.90/22,9	1.2/30,5	.70/17,8	.042/1,07
PCV-1-473-10	47	10	10	.022	.90/22,9	1.4/35,6	.70/17,8	.060/1,52
PCV-1-104-03	100	3	3	.072	.90/22,9	1.3/33,1	.70/17,8	.035/0,89
PCV-1-104-05	100	5	5	.055	.90/22,9	1.4/35,6	.70/17,8	.042/1,07
PCV-1-184-03	180	3	3	.150	.63/16,0	1.2/30,5	.42/10,7	.028/0,71
PCV-1-304-05	300	5	5	.160	1.1/27,9	1.0/25,4	.70/17,8	.038/0,97
PCV-1-394-05	390	5	5	.190	1.1/27,9	1.0/25,4	.70/17,8	.038/0,97

1 Tested at 15.75 kHz, .1 Vrms, with DC bias applied up to the rated current.
2 Inductance drop = 10% typ. at Isat.
3 ΔT = 40°C rise typ. at Irms (85°C ambient).
Parts in bold type are included in Coilcraft Designer's Kit No. P205.

1102 Silver Lake Road Cary, Illinois 60013 **Phone** 847/639-6400 **Fax** 847/639-1469
E-mail info@coilcraft.com **Web** http://www.coilcraft.com

Calculate the needed I2 to store the amount of energy needed per cycle.

$$I_2 := \sqrt{\frac{-2 \cdot V_o \cdot I_o \cdot T_S}{L}} \qquad I_2 = 24.254\,\text{amp}$$

Now calculate the value of t_{on} and t_{off} to get that peak current.

$$t_{on} := \frac{I_2 \cdot L}{V_D} \qquad t_{on} = 10.106\,\mu s$$

$$t_{off} := \frac{I_2 \cdot L}{-V_o} \qquad t_{off} = 10.106\,\mu s$$

If ton + toff > T_S then the inductor is too big and the regulator will operate in the continuous mode.

$$\frac{t_{on} + t_{off}}{T_S} = 0.808$$

Calculate the dead time

$$t_d := T_S - t_{on} - t_{off} \qquad t_d = 4.789\,\mu s$$

This dead time is OK.

Choose the filter capacitor using the capacitor ESR.

Specify the ripple due to the ESR $V_{CR} := 100 \cdot mV$

$$ESR := \frac{V_{CR}}{(I_2)} \qquad ESR = 4.123\, m\Omega$$

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

$$C := \frac{80 \cdot \mu s}{ESR} \qquad C = 19403\, \mu F$$

Choose the next size std capacitor $C := 22000 \cdot \mu F$

Calculate the Capacitor RMS Ripple Current

Define a function for the inductor current $I_L(t) := I_2 - \frac{(I_2)}{t_{off}} \cdot t$

$$I_{rms} := \sqrt{\frac{1}{T_S} \cdot \left[\int_{0 \cdot sec}^{t_{on}+t_d} (-I_o)^2\, dt + \int_{0 \cdot sec}^{t_{off}} (I_L(t) - I_o)^2\, dt \right]}$$

$$I_{rms} = 7.432\, amp$$

Summary

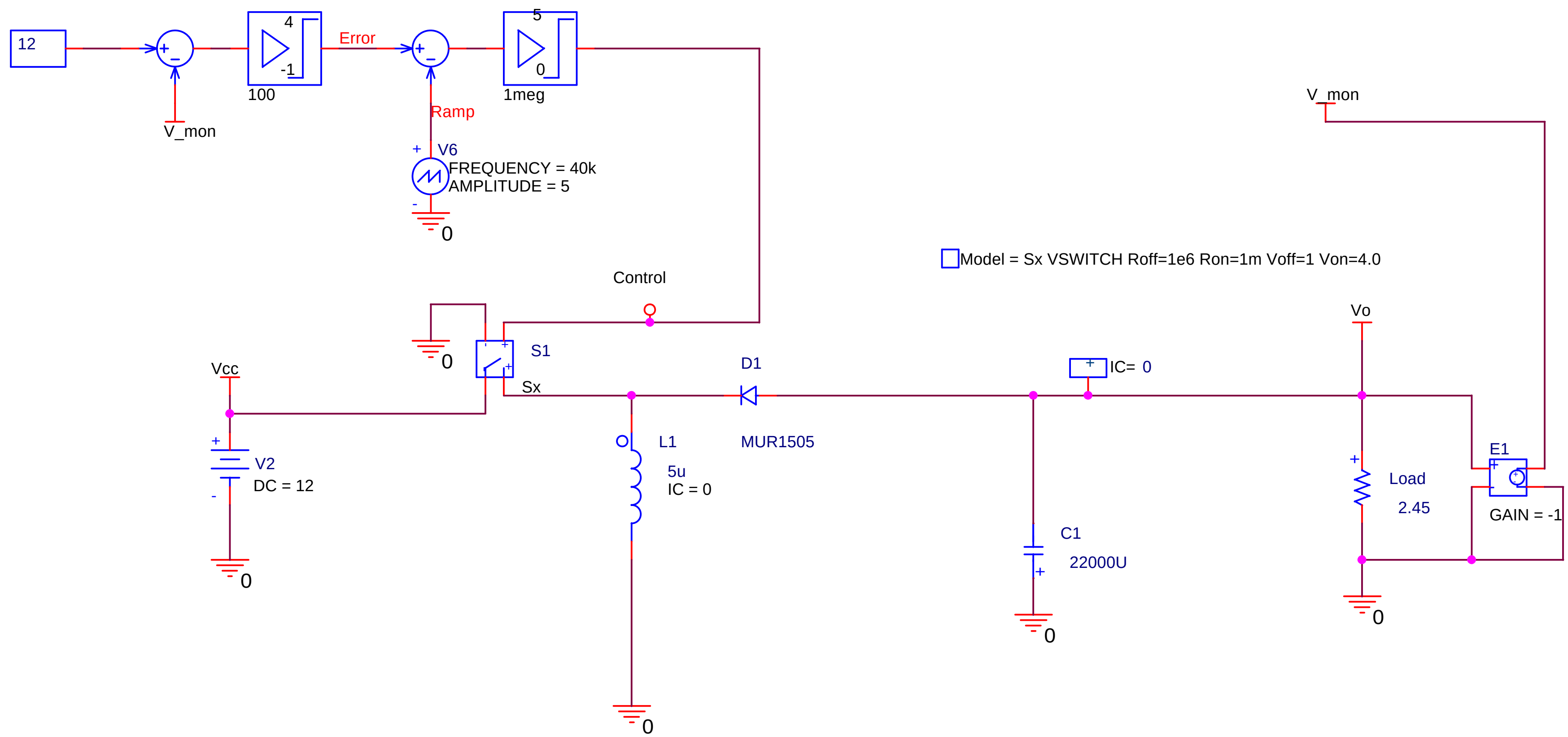
$L = 5\,\mu H$ $I_2 = 24.254\,amp$

$t_{on} = 10.106\,\mu s$ $t_{off} = 10.106\,\mu s$

$V_D = 12\,volt$ $V_o = -12\,volt$ $I_o = 4.902\,amp$

$C = 22000\,\mu F$ $V_{CR} = 100\,mV$

$I_{rms} = 7.432\,amp$



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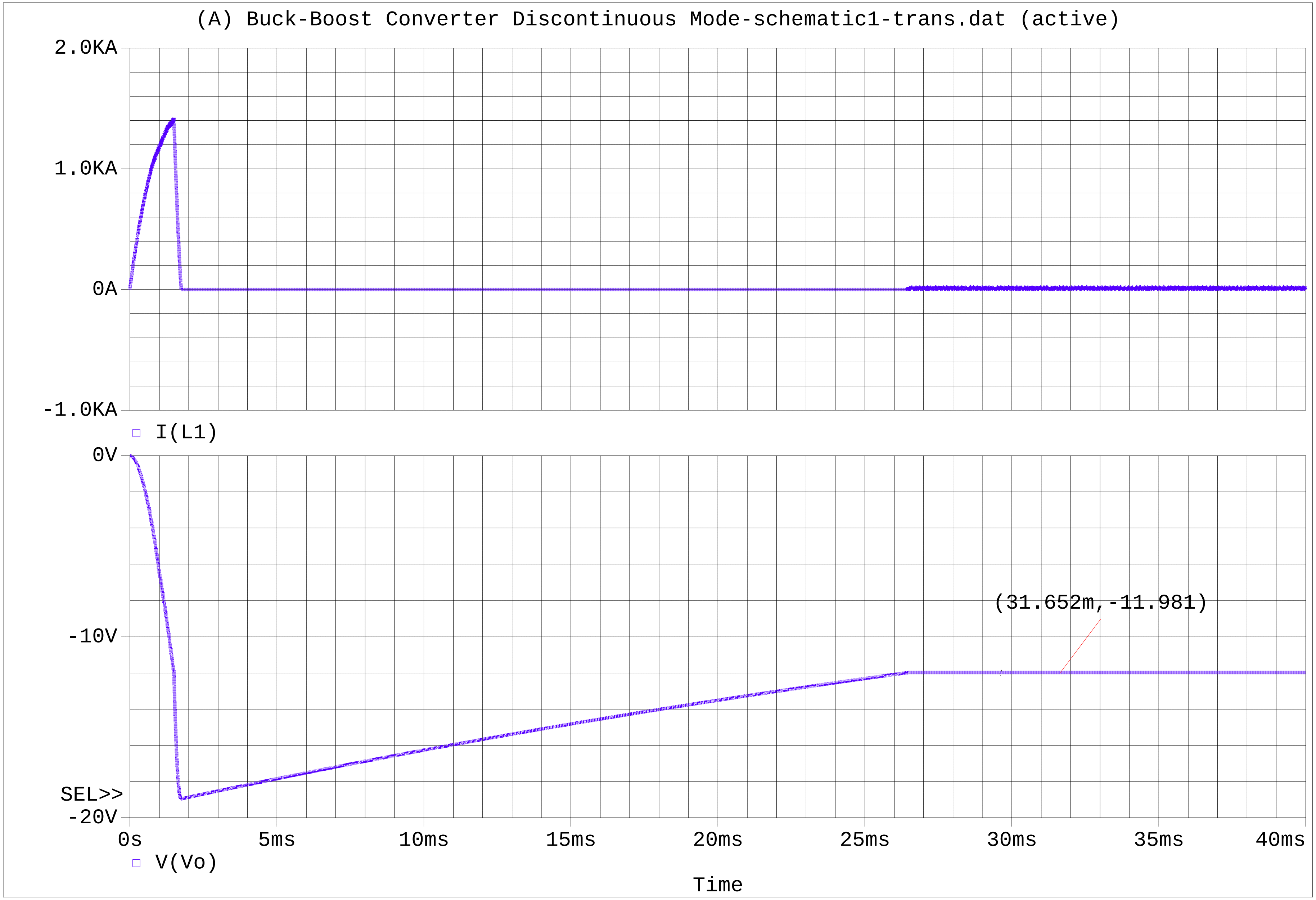
Class: ECE456

Size	Document Name	Rev
A	12V to -25 Volt Buck-Boost Discontinuous Mode	1

Date: Monday, January 13, 2003 Sheet 1 of 1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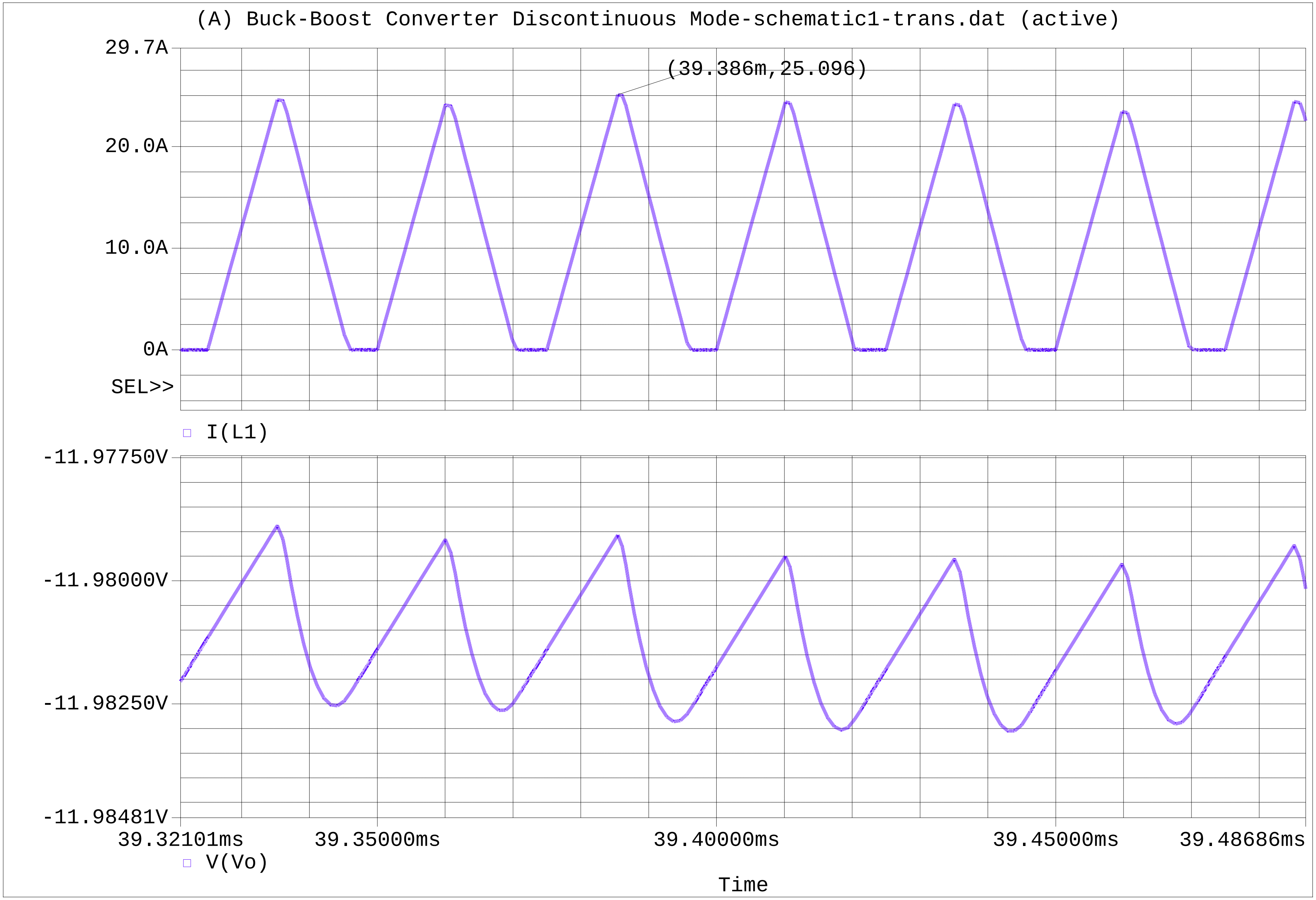
1.0KA
0A
-1.0KA
I(L1)
0V
-10V
SEL>>
-20V
(31.652m,-11.981)
0s
5ms
10ms
15ms
20ms
25ms
30ms
35ms
40ms
V(Vo)
Time


(A) Buck-Boost Converter Discontinuous Mode-schematic1-trans.dat (active)
29.7A
20.0A
10.0A
0A
SEL>>
(39.386m,25.096)
I(L1)
-11.97750V
-11.98000V
-11.98250V
-11.98481V
39.32101ms
39.35000ms
39.40000ms
39.45000ms
39.48686ms
V(Vo)
Time

** Profile: "SCHEMATIC1-TRans" [C:\WEBSITE\ROSE_CLASSES\ECE456\Notes\Orcad\Buck-Boost Converter\b...
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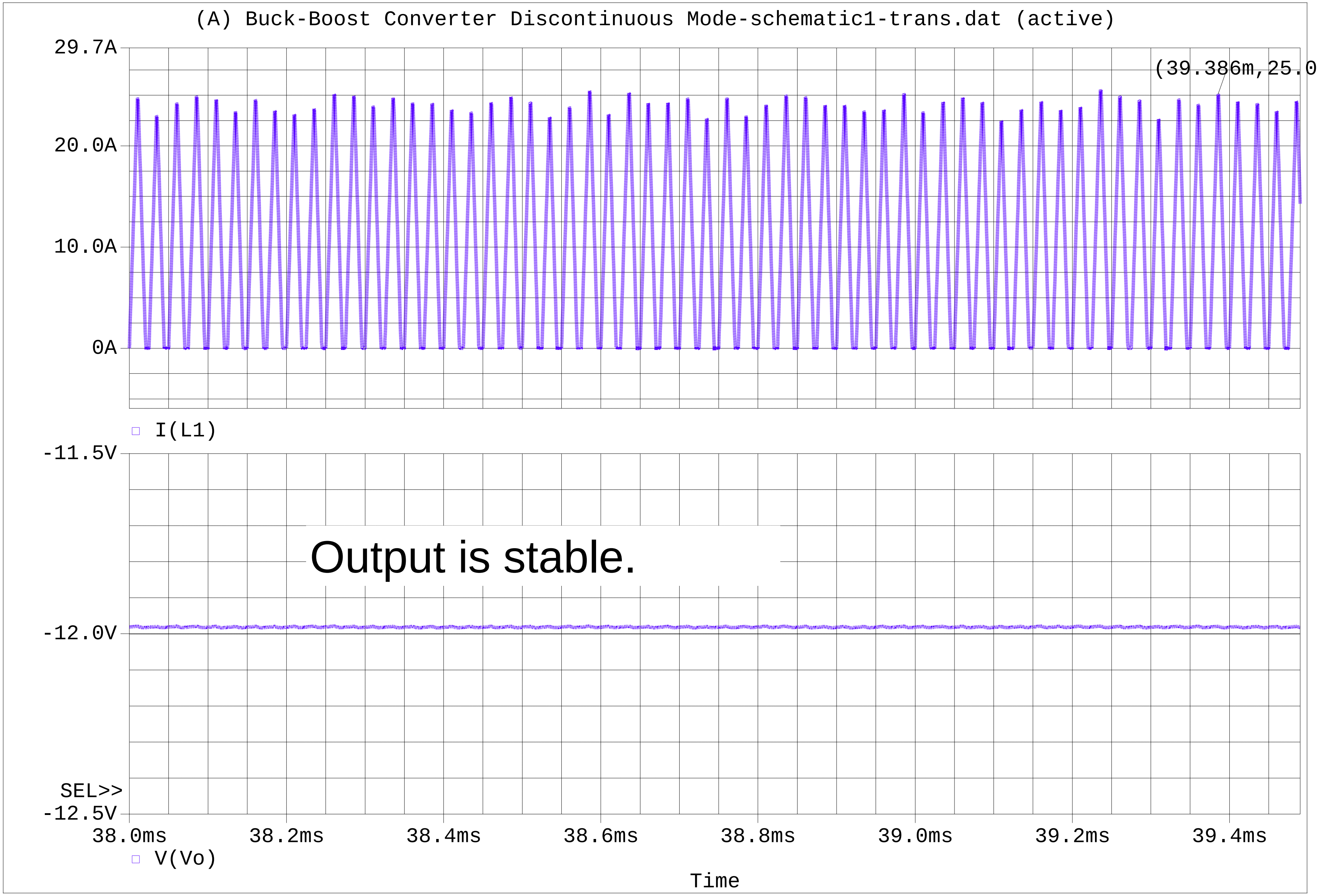

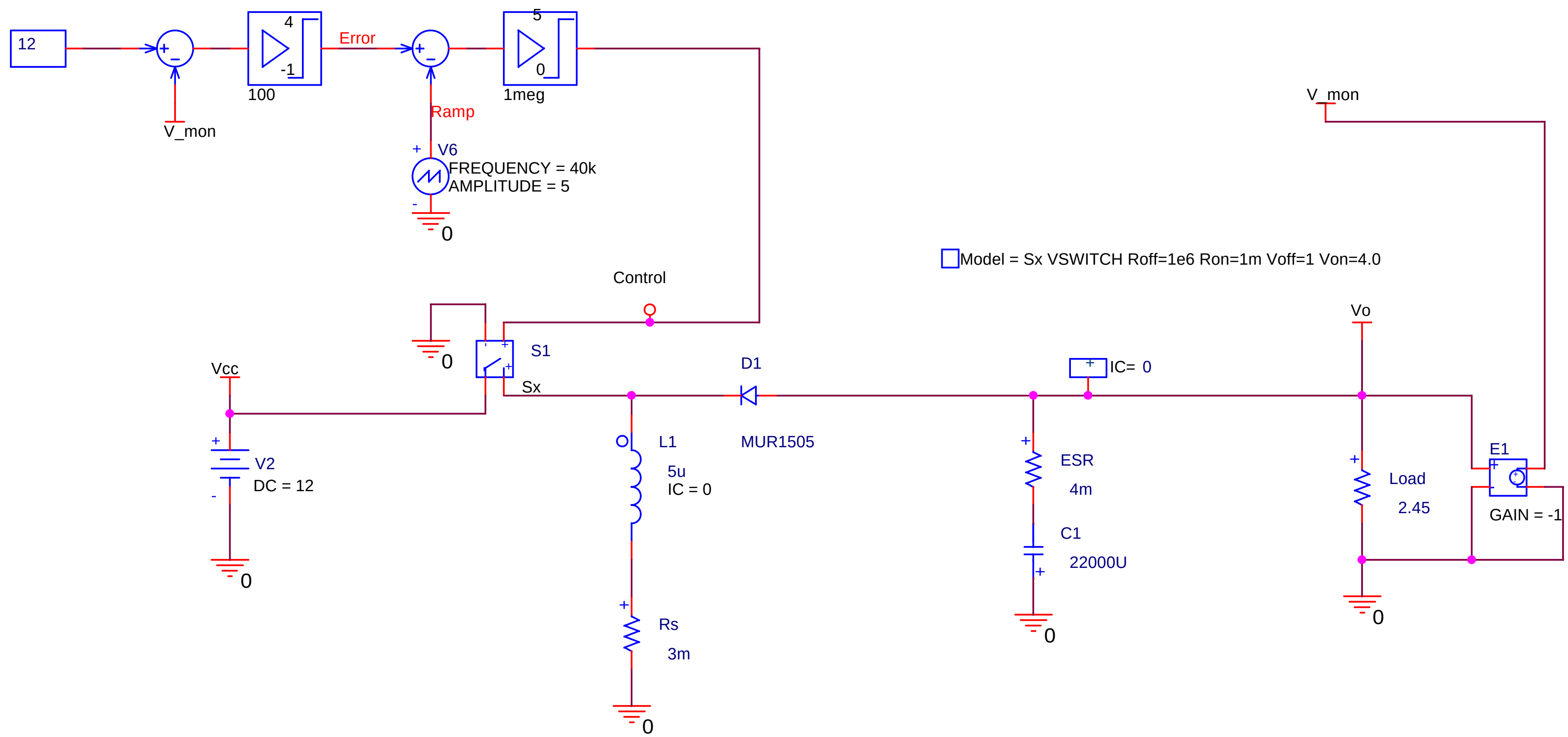

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** Profile: "SCHEMATIC1-TRans" [C:\WEBSITE\ROSE_CLASSES\ECE456\Notes\Orcad\Buck-Boost Converter\b...
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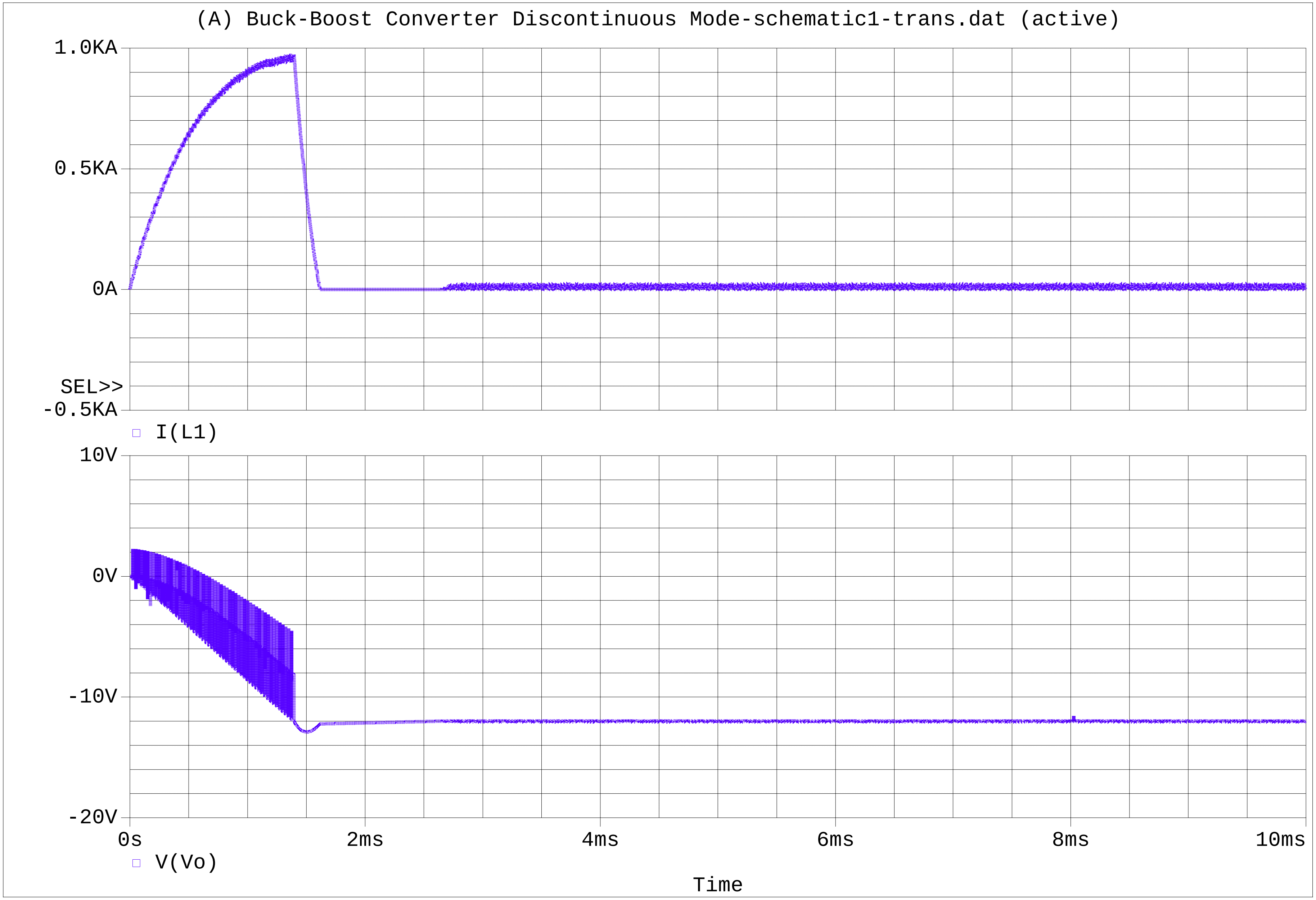

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Date/Time run: 01/13/03 12:13:04 Temperature: 27.0