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**SIMULATIONS WITH THE BUCK TOPOLOGY**

EE562: POWER ELECTRONICS I

COLORADO STATE UNIVERSITY

Modified in Spring 2006

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**PURPOSE:** The purpose of this lab is to simulate the Buck converter using CAPTURE CIS<sup>®</sup> to better familiarize the student with some of its operating characteristics. This lab will explore some of the following aspects of the boost converter:

- ❑ Discontinuous Conduction Mode
- ❑ Inductor sizing
- ❑ Differential voltage across the inductor
- ❑ Time it takes for the converter to reach steady state
- ❑ Output Ripple voltage and selection of the capacitor.
- ❑ Ripple current through the capacitor
- ❑ Equivalent Series Resistance (ESR) of the output capacitor.
- ❑ Effects of changing and removing load resistance
- ❑ Effects of the ON resistance of the switch
- ❑ Efficiency
- ❑ Effects of changing frequency

**NOTE:** The simulations that follow are intended to be completed with CAPTURE CIS<sup>®</sup>. It is assumed that the student has a fundamental understanding of the operation of CAPTURE CIS<sup>®</sup>. CAPTURE CIS<sup>®</sup> provides tutorials for users that are not experienced with its functions.

**PROCEDURE:**

**Part 1:** Build the schematic shown in Figure 1.

**V1** is a DC voltage source (VDC) from the source library. It needs to be set for 24 volts.

**L1** is an ideal inductor from the Analog Library. Set to 100 $\mu$ H.

**R2** is an ideal resistor from the Analog Library. Set to 5 $\Omega$ .

**D1** is an ideal diode and can be found in the Breakout library.

**C1** is an ideal capacitor from the Analog library. Change the value to 10 $\mu$ F.

**S1** is a voltage controlled switch and can be found in the Analog library. Change RON from 1 $\Omega$  to 1m $\Omega$ .

**V2** is a pulsed voltage source and is intended to act as the output of a pulse width modulator. V2 needs the following parameters set:

DC=0, AC = 10, V1=0, V2 = 10, TR=10ns, TF=10ns, PW = 20 $\mu$ , PER = 40 $\mu$ . This results in a switching frequency of 25 kHz.

**R1** is set to 1000 k $\Omega$ . The purpose of R1 is to prevent any floating nodes.

Two **voltage markers** need to be placed as shown in the schematic of figure 1.

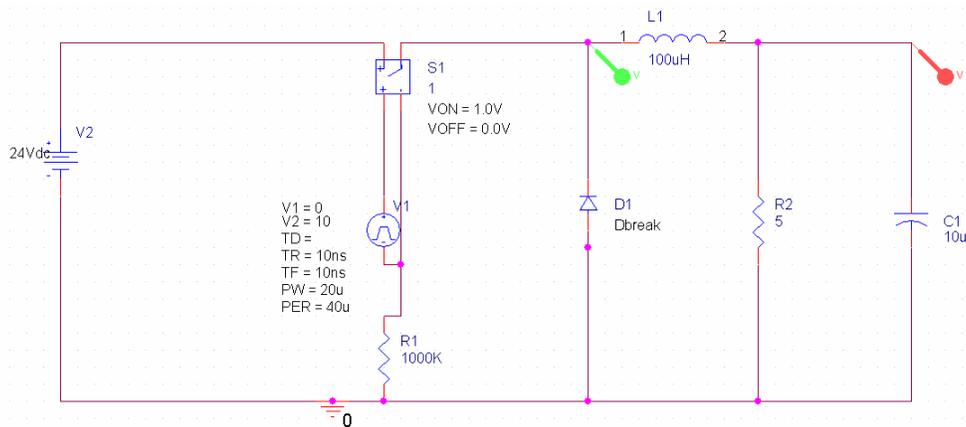


Figure1. Buck schematic on CAPTURE CIS<sup>®</sup>

Once the above schematic is captured, the simulations can be run. First, the type of simulation will need to be specified. Most of these simulations are Transient simulations. The Transient simulation can be set by navigating through Analysis, Setup, and Transient. The Run to time: will need to be changed to 1msec. Running the simulation will result in the following output (Print Step and Start saving data after: should be set to 0 unless otherwise specified).

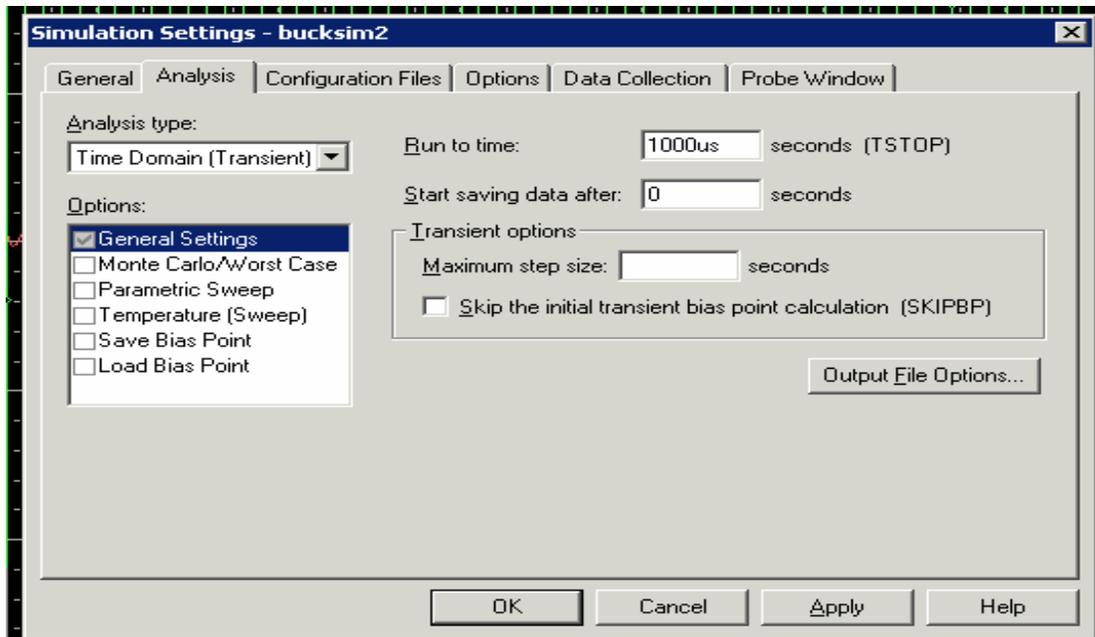
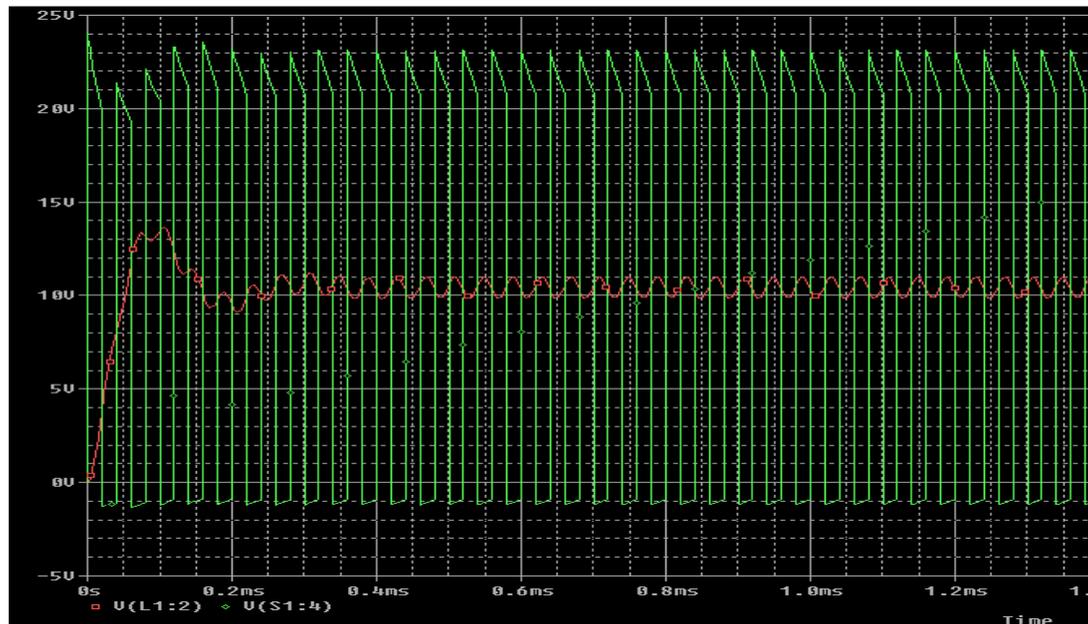
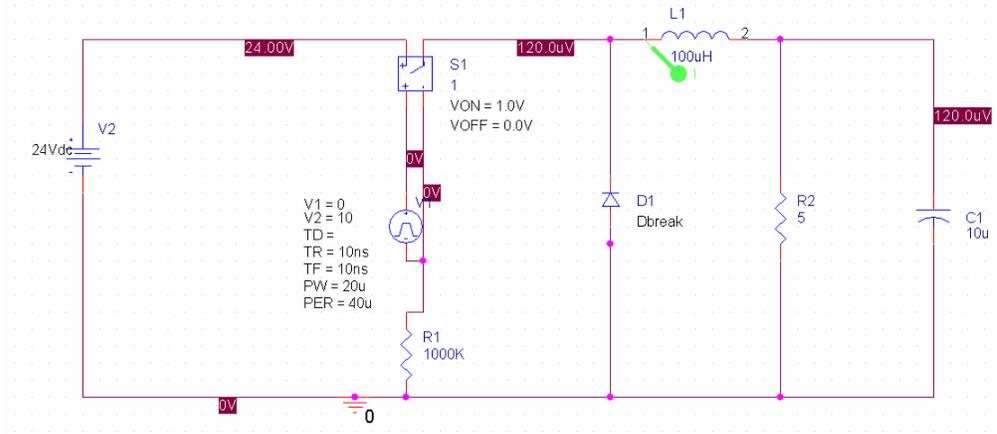


Figure 2. Transient Analysis setup.



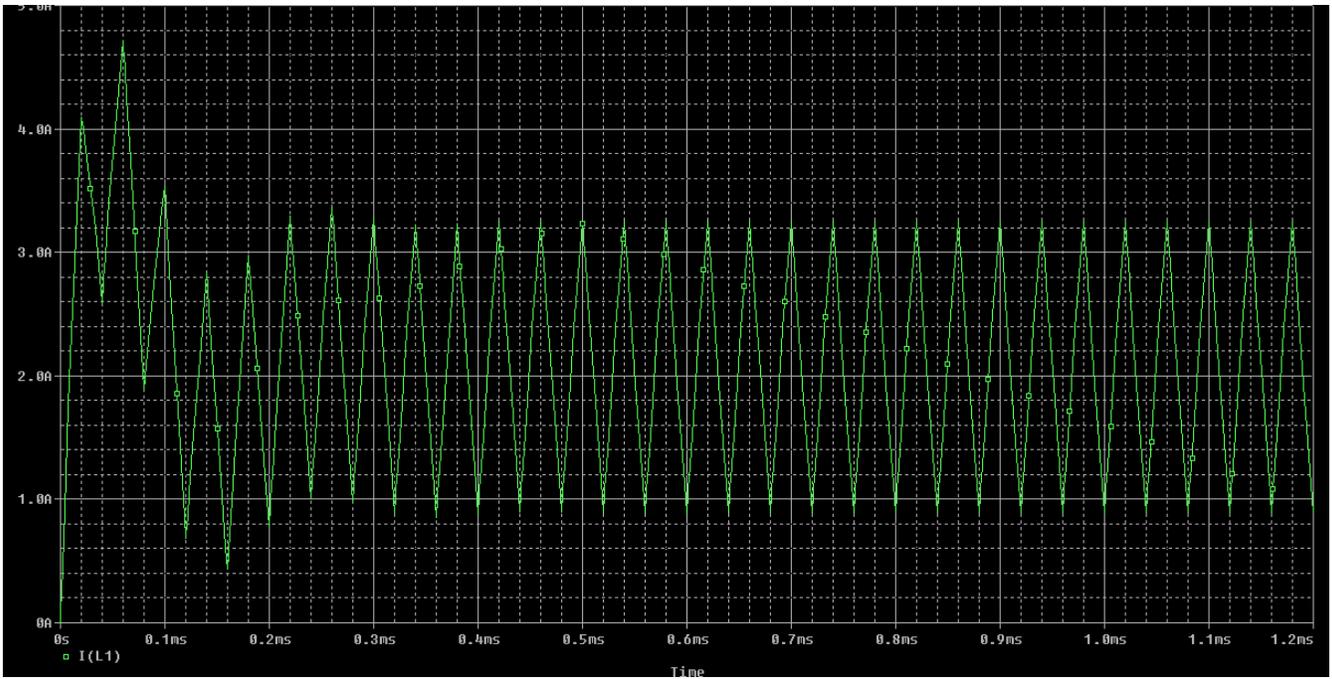
*This shows the output voltage rising to 12V, a Buck converter. We can also see the voltage across the diode during the switch off time is near -0.7 volts and during the switch on time is near the input voltage.*

Remove the voltage markers, and use a **current marker** to measure the inductor L1 current. Place the marker in series next to L1. Change the Transient Analysis Run to time: to 1.2msec.



**QUESTION 1:** What is the peak operating current, average current, and what is the operating mode of the converter? Verify mathematically the mode and the peak current.

Hint: 
$$\frac{V_{in} - V}{L} = \frac{I_{pk}}{DT_s} \quad K_{crit} := D \cdot (1 - D)^2, \quad K := \frac{2 \cdot L}{R \cdot T}$$

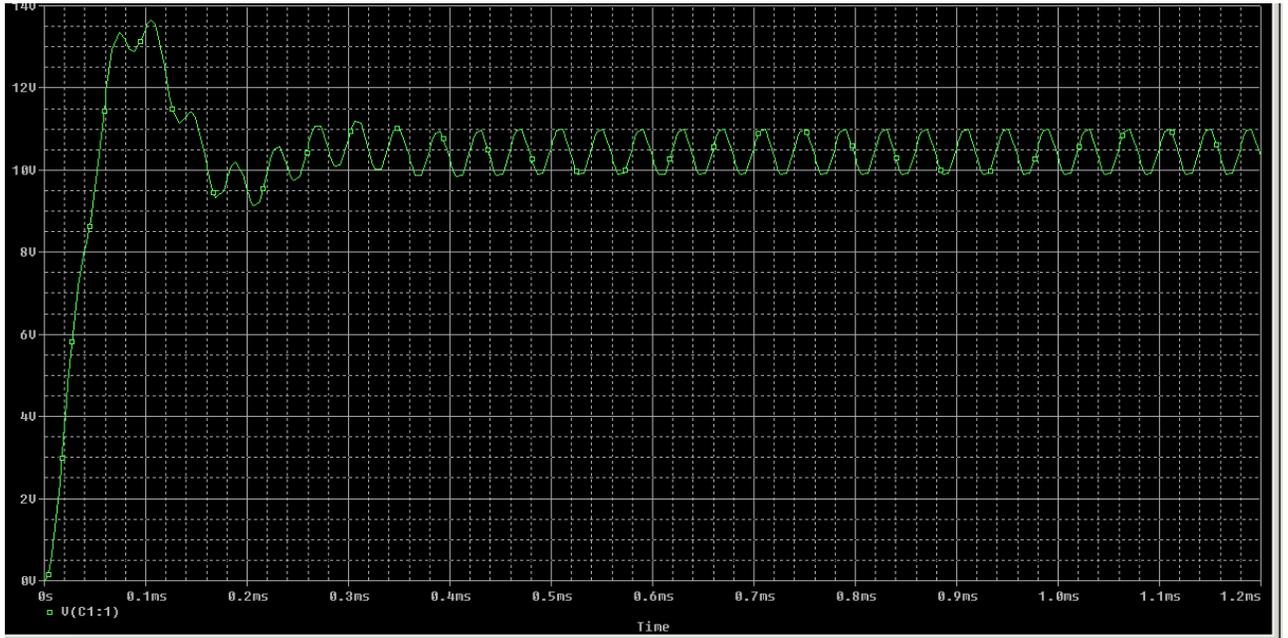


*From the picture above we can see that the converter is operating in the continuous conduction mode with an average operating current of about 2.5A, and a peak in-rush current of about 6A*

**QUESTION 2:** What is the average output voltage of the converter at steady state? Verify your results mathematically.

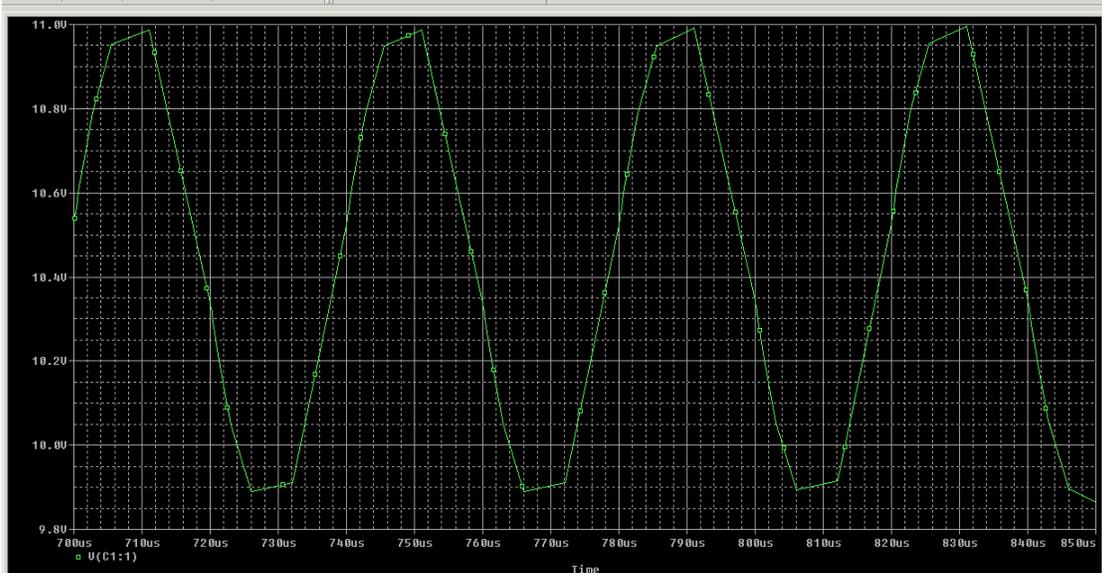
Hint:

$$\frac{V_o}{V_{in}} = \frac{2}{\left(1 + \sqrt{1 + \frac{4K}{DI^2}}\right)}$$



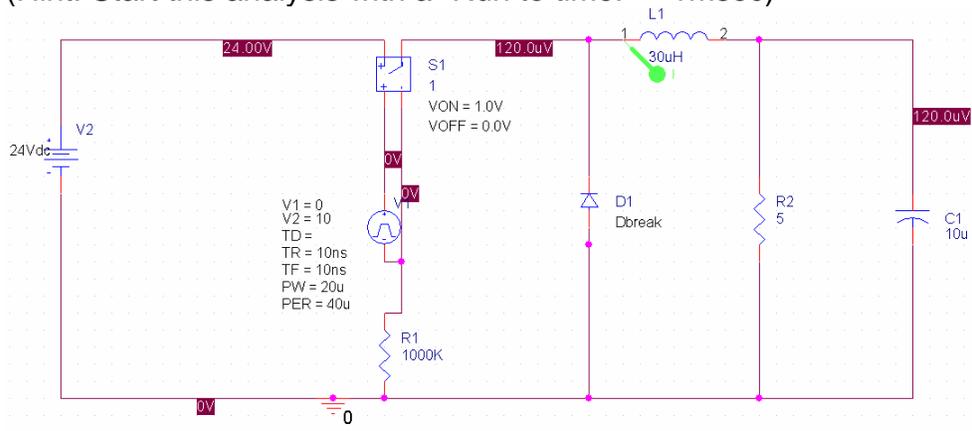
*The picture above shows that the converter reaches the steady state after approximately 0.5 ms with an average output voltage of 11.45V.*

**QUESTION 3:** What is the peak-to-peak ripple on the output voltage after it reaches steady state? (Hint: set your Start saving data after: to 700us and Run to time: to 850us).

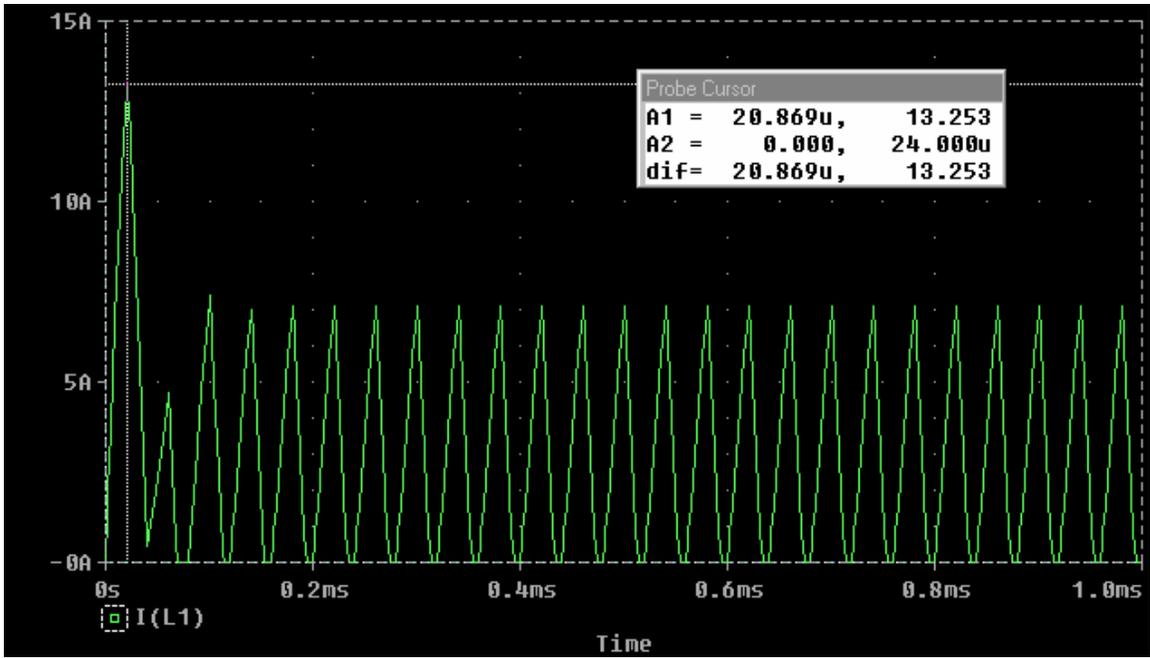


*It is apparent that the ripple is approximately 1Vpp.*

Now change L1 from 100 $\mu$ H to 30 $\mu$ H and rerun the simulation. Remember you can vary the “Run to time:” in “Transient Analysis”. Keep the “Print Step” at 0. (Hint: Start this analysis with a “Run to time:” = 1msec)



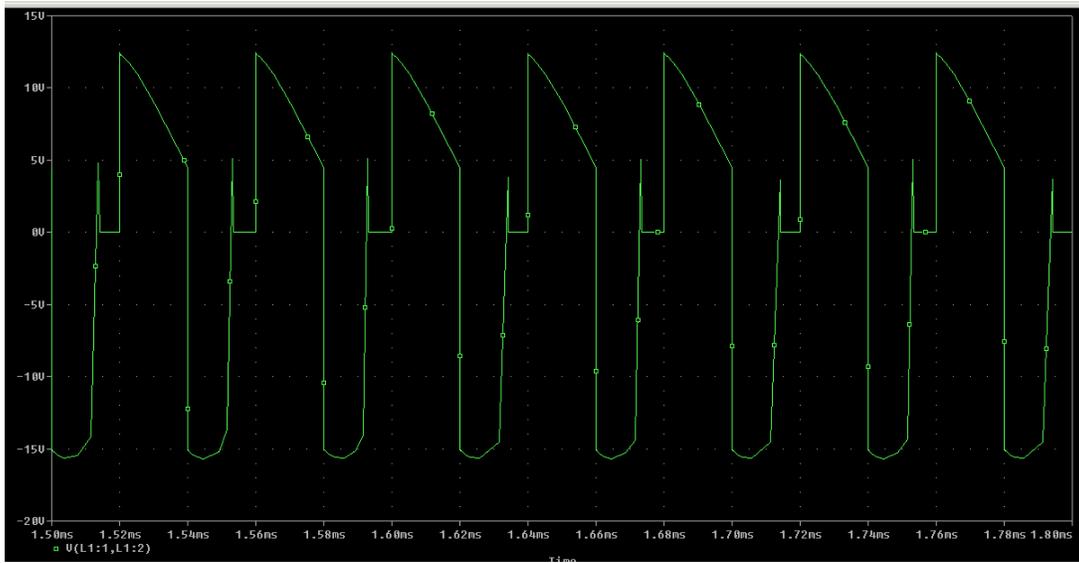
**QUESTION 4:** What is the peak in rush current now? What is the operating mode of the converter (remember that you can observe this by zooming in)?



*From the picture above we can see that the peak in rush current is about 13A and the converter is operating in the discontinuous conduction mode.*

Change the Run to time: of the simulation from 1m to 1.8m, and add a Start saving data after: of 1.5m. Proceed with running the simulation.

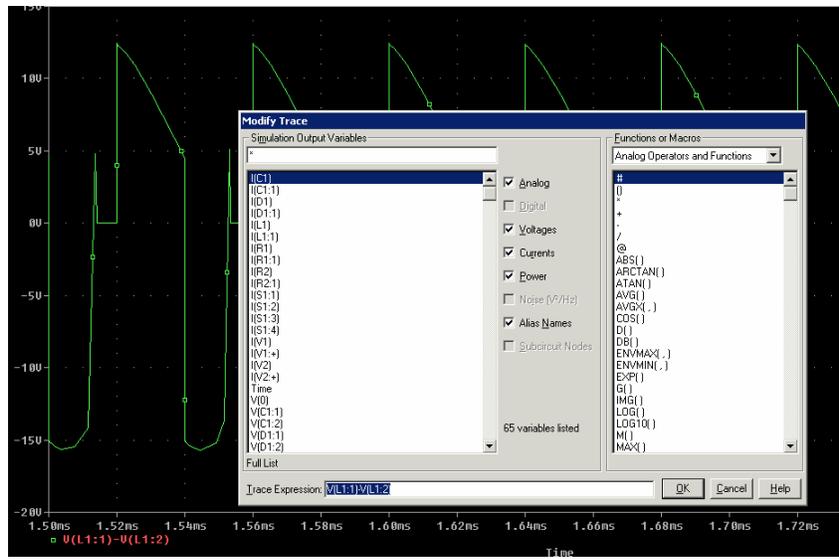
**QUESTION 5:** What can be said about the differential voltage measurement across L1?



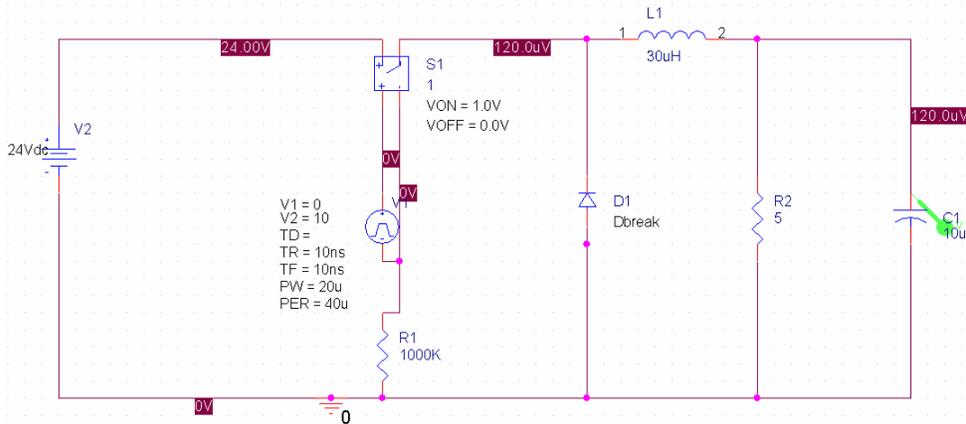
*From the picture above we can see that the average voltage of the inductor is approaching zero, confirming the volt second balance required for an inductor.*

Here are steps to plot the differential voltage

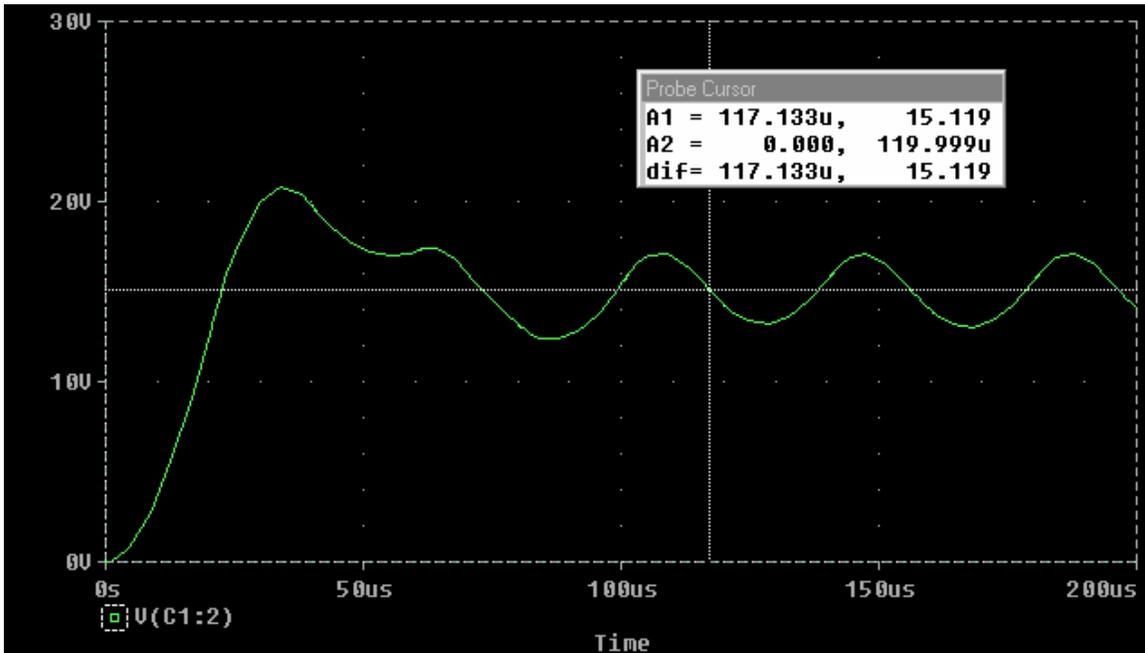
First change the Run to time: of the simulation to 1.8ms and Start saving data after: to 1.5ms and then run the simulation. Next, click trace and add trace. The add trace window will open. Click V(L1:1)-V(L1:2) and lick ok.



Now change the “Run to time:” to 200 $\mu$  and remove any “Start saving data after:” from the Transient Analysis setup. Remove the differential voltage markers across L1 and add a voltage marker to the top of C1. From this simulation we can see the output voltage overshoot its final value.



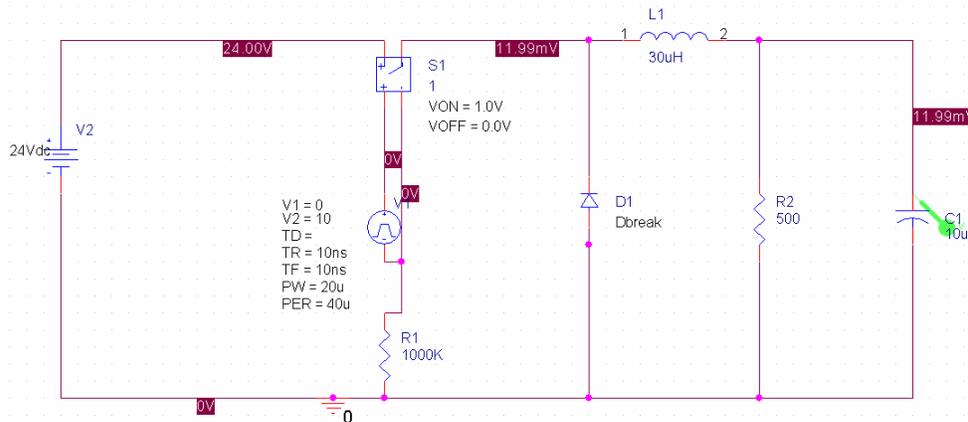
**QUESTION 6:** How long does it take for the output voltage to reach its average voltage? What is the peak-to-peak ripple on the output voltage?



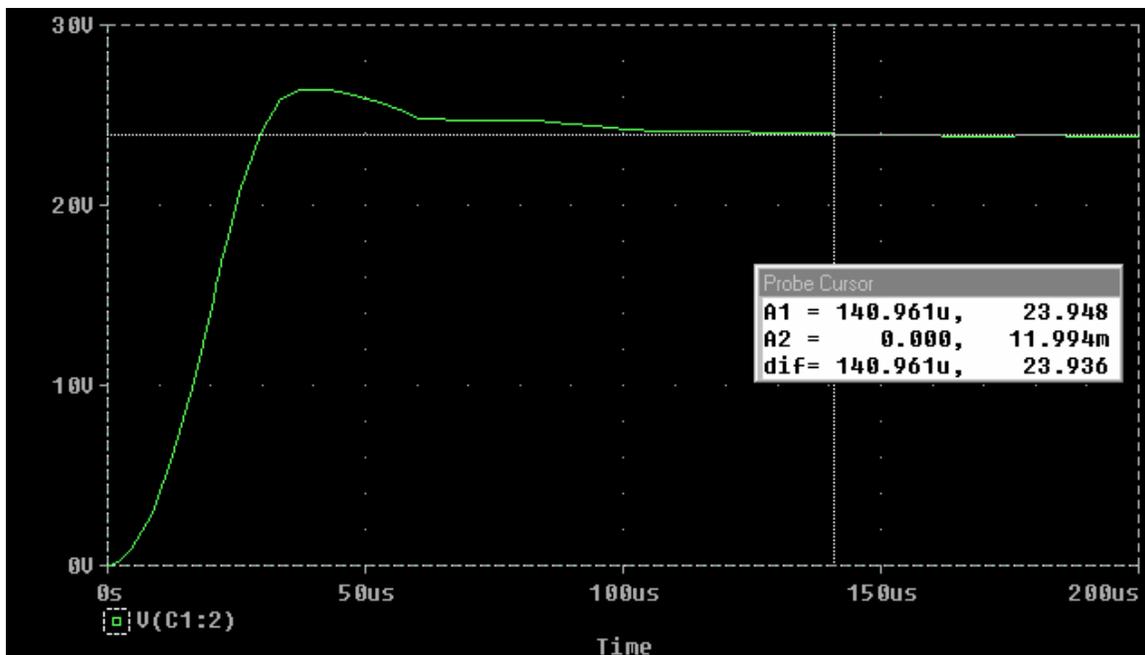
From the picture above we can see that the average output voltage is reached in approximately 110 $\mu$ sec with an average value of about 15VDC. The output also has about 4V peak to peak ripple.



Change the load resistance from  $5\Omega$  to  $500\Omega$ . Change the Run to time: of the simulation to 200usec. Run the simulation.

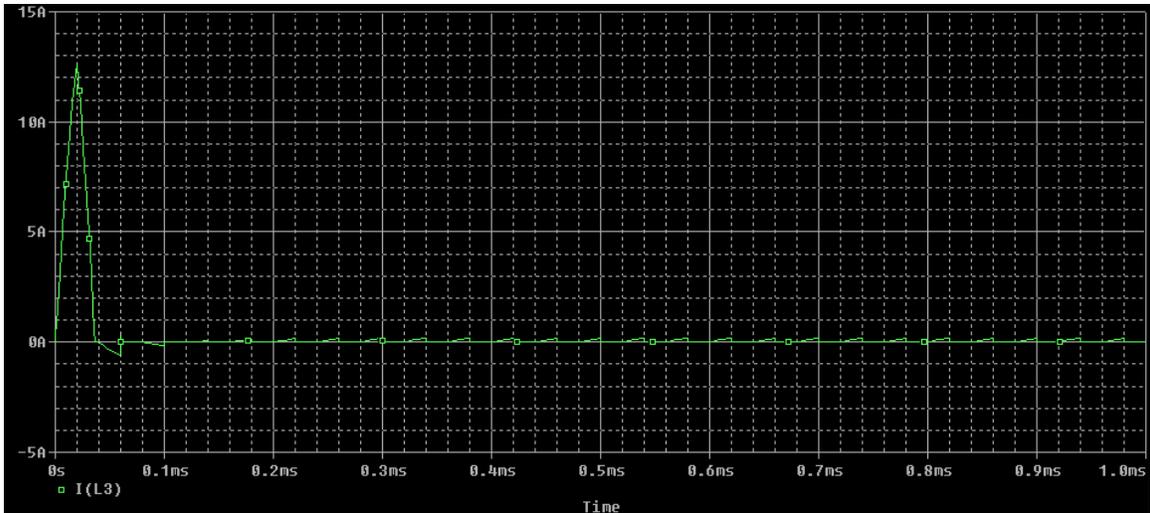


**QUESTION 7:** What happens to the output voltage and what observations can be made?



From the picture above we can see that the output voltage rises to the value of the input voltage, 24V. This shows that the output voltage of the buck converter is not only a function of the duty cycle, inductor value, and the capacitor value but also the load resistance.

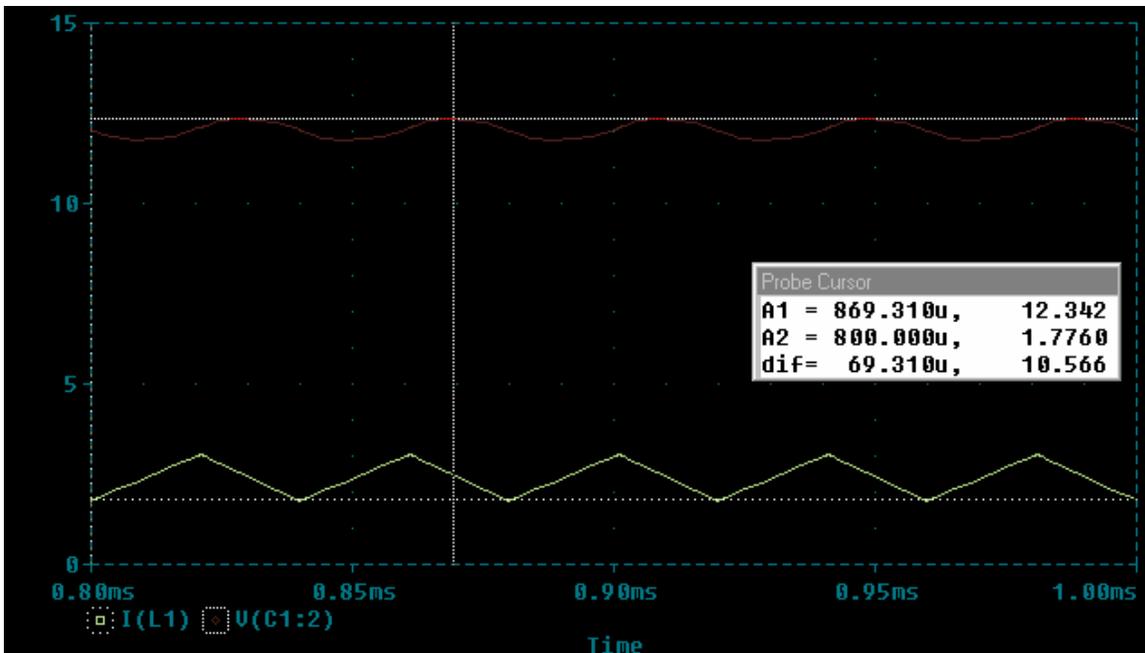
**QUESTION 8:** What operating mode is the converter in? (Hint: Zoom in and See Question 4)



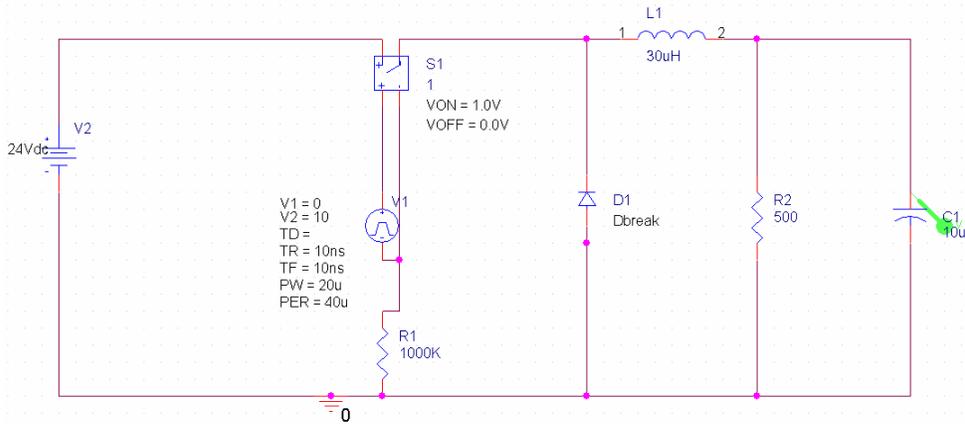
*From the picture above we can see that the converter is operating in the discontinuous conduction mode with a peak current of 12.6A.*

Now change the load resistance back to  $5\Omega$  and the inductor to  $200\mu\text{H}$ . Also change the “Start saving data after:” to  $800\mu\text{sec}$  and the Run to time: to  $1000\mu\text{sec}$ . Then add a current probe to the inductor.

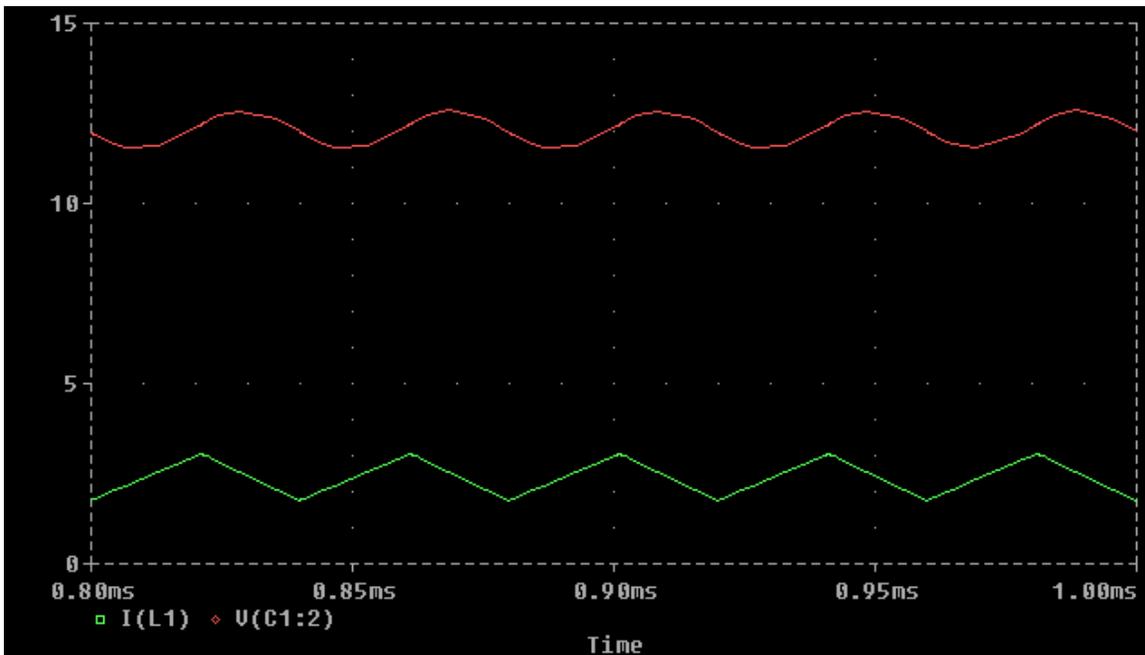
**QUESTION 9:** How does the inductor value affect the output ripple?



*From the picture above we can see that the peak-to-peak voltage ripple is now less than 1V and from the inductor current we can see that the converter is once again operating in the continuous conduction mode. We can also compare the peak-to-peak inductor current with the peak-to-peak inductor current when the inductor was  $100\mu\text{H}$  and see that the inductor current ripple has also decreased.*

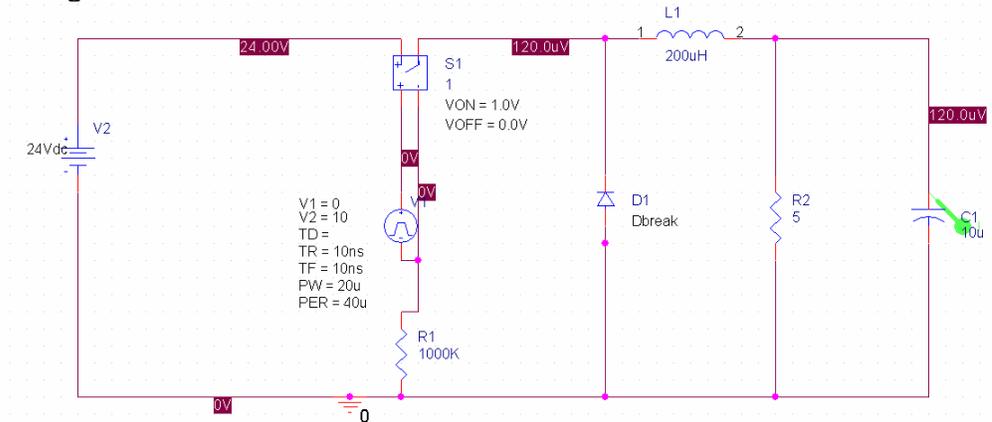


**QUESTION 10:** With everything else left as is, what would the minimum output capacitance need to be in order to limit the output voltage ripple to 2 volts peak to peak? (Hint: set your Start saving data after: to 800us and Run to time: to 1ms).

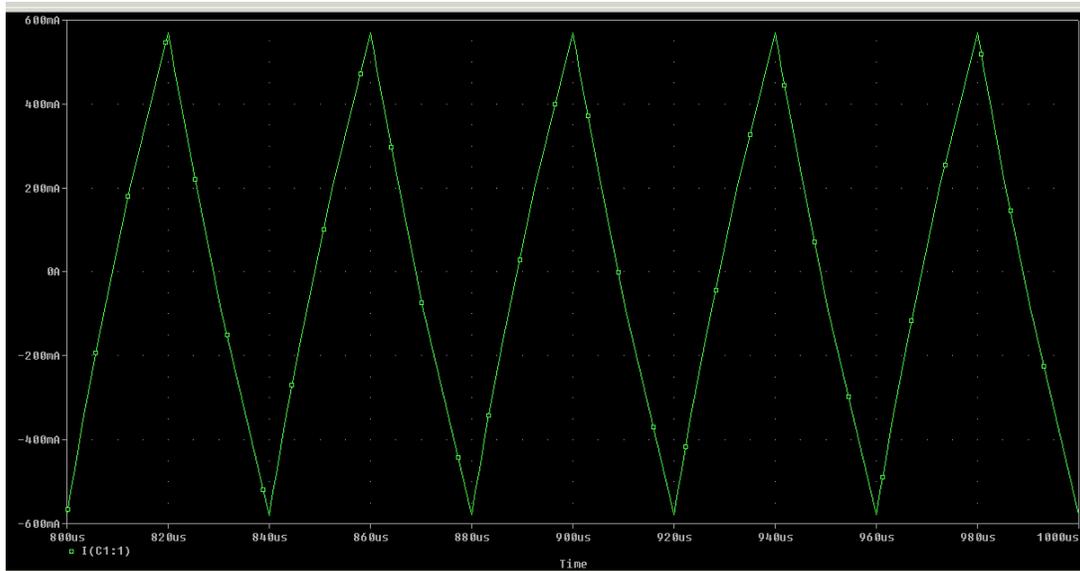


*From the picture above we see that the output voltage ripple has increased to 2V peak to peak by reducing the output capacitance to  $6\mu F$ .*

Now, place a current marker on one of the pins of the capacitor and remove the voltage marker.

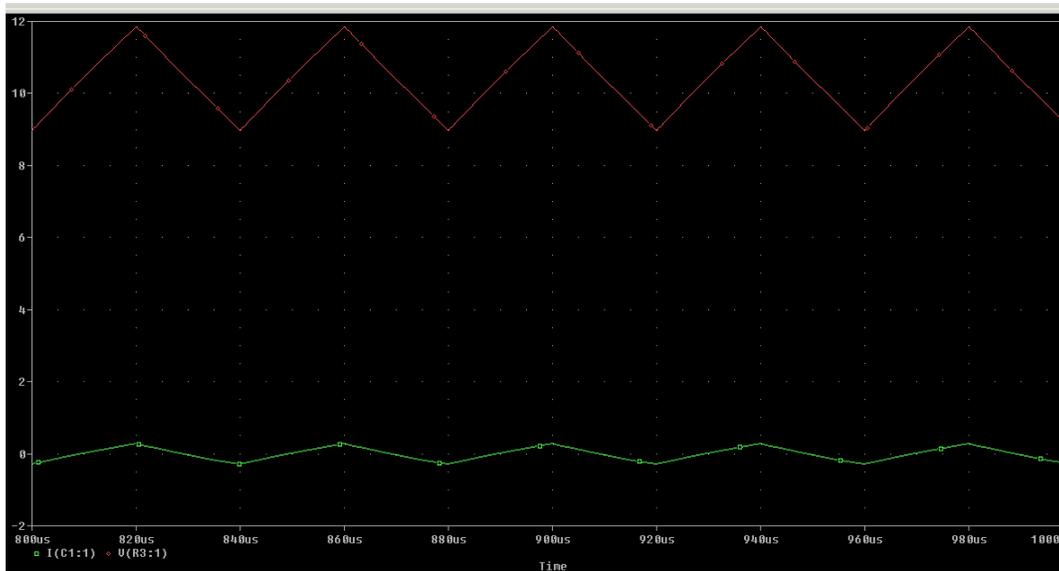
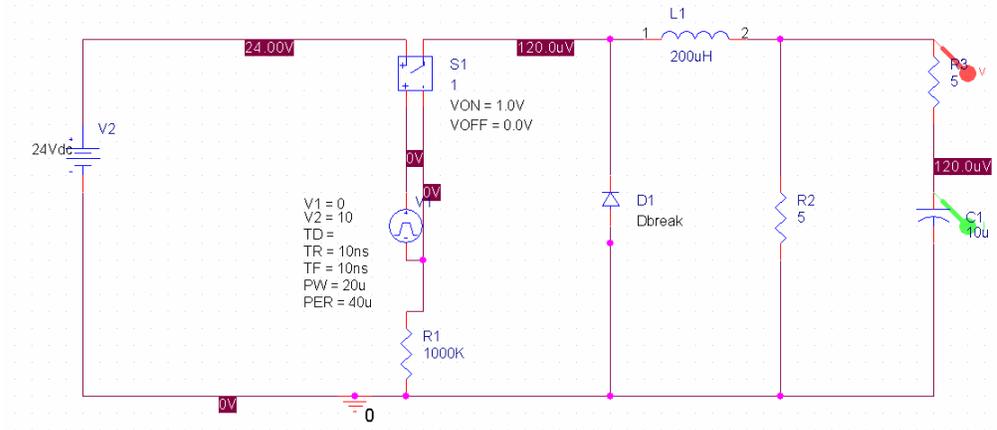


**QUESTION 11:** What can be said about the current through the capacitor? (Hint : set your Start saving data after: to 800us and Run to time: to 1ms).



*From the picture above we can see that the capacitor is balancing the amp seconds, and that the peak current through the capacitor is about 600mA.*

**QUESTION 12:** If the ESR of the capacitor is modeled by a  $5\Omega$  resistor in series with the capacitor, what happens to the output voltage ripple and the capacitor current?



*From the picture above we can see that the output voltage ripple has increased from about 2V peak to peak with no ESR, to about 3V peak to peak with  $5\Omega$  of ESR. Also the capacitor current has been reduced to about 300mA peak.*

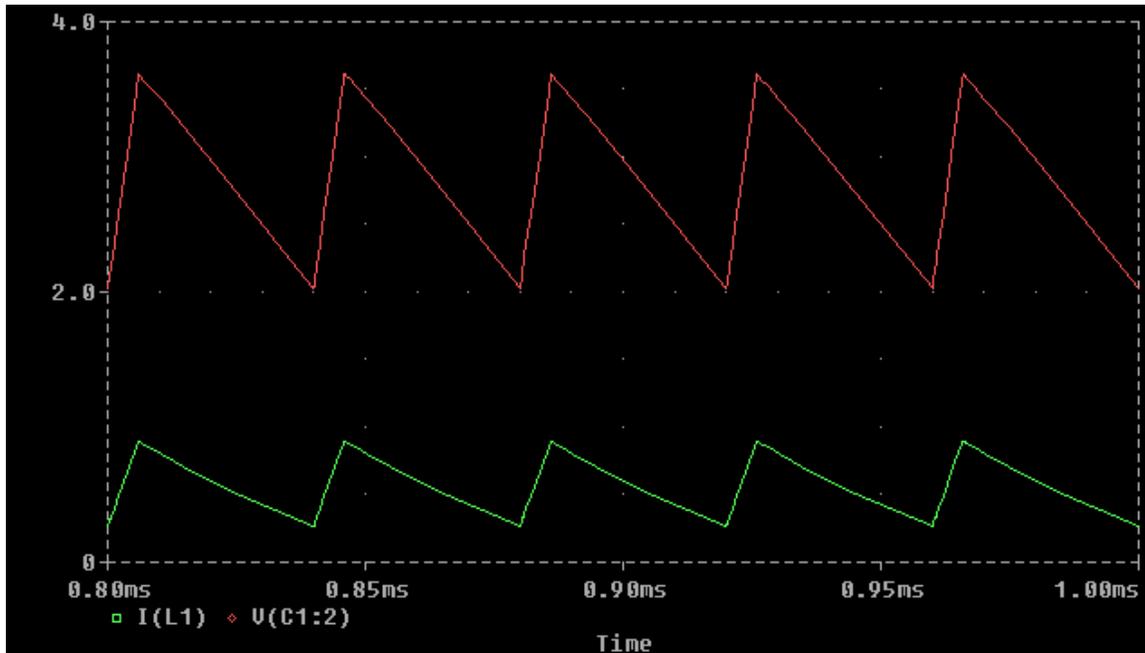
**QUESTIONS 13 – 16:**

Leave the resistor that was just added. What happens if the duty cycle of the converter is decreased from 20μsec ON time to 5μsec ON time in V1 set up? (Hint: set your Start saving data after: to 0.80ms and Run to time: to 1ms).

Is the converter still operating in the continuous conduction mode?

What is the average output voltage now?

Did the output voltage ripple increase?



*From the picture above we can see that the output voltage has decreased and so has the output voltage ripple. We can also see that the converter is still operating in the continuous conduction mode.*

### QUESTIONS 17-20:

What observations can be made from increasing the on resistance of the switch?

What can be said about the efficiency of the converter? Comment on the different configurations of the circuit used throughout this lab.

What happens if the load resistance is removed? (Hint: set a very high value for the load resistance, i.e. 10000MEG)

What can be observed by increasing the switching frequency to 100 KHz?

Hints: With everything else left as it is, change your "PW" and "PER" on PULSED voltage to 5u and 10u. Also change your "Run to time:" in transient

analysis to  $\text{finaltime} := 25 \cdot \frac{1}{\text{Switchfrequency}}$ .

**\*\* \*\*\*\* Remember that your on resistance value of the switch (Question 17) will provide you a complete different output value from your classmates.**