SIMULATION WITH THE BUCK-BOOST TOPOLOGY
ECE562: Power Electronics I
COLORADO STATE UNIVERSITY

Modified in Fall 2011
PURPOSE: The purpose of this lab is to simulate the Buck-boost converter using NL5 to better familiarize the student with some of its operating characteristics. This lab will explore some of the following aspects of the buck 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 NL5. It is assumed that the student has a fundamental understanding of the operation of NL5. NL5 provides tutorials for users that are not experienced with its functions.

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

**L** is an ideal inductor from the library. Set to 200 µH.

**R** is an ideal resistor from the library. Set to 50 Ω.

**D1** is an ideal diode from the library. Set to 700 mV (diode drop).

**C** is an ideal capacitor from the library. Set to 50 µF.

**O1** is an ideal comparator used to turn the switch S1 on and off. By varying the width of V3 below, its output will act as a Pulse Width Modulator.

**S1** is a voltage controlled switch, a standard component in the library.

**V2** is 0.5 volt reference for the Schmitt trigger comparator O1. Set V2 to 500 mV.

**V3** is Pulsing source. Set to values listed below using the components editing window. This sets it to a switching frequency of 25 kHz with a 50% duty cycle.

<table>
<thead>
<tr>
<th>V3</th>
<th>Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1</td>
</tr>
<tr>
<td>V0</td>
<td>0</td>
</tr>
<tr>
<td>Period</td>
<td>40e-6</td>
</tr>
<tr>
<td>Width</td>
<td>20e-6</td>
</tr>
<tr>
<td>Slope</td>
<td>Linear</td>
</tr>
<tr>
<td>Rise</td>
<td>1e-6</td>
</tr>
<tr>
<td>Fall</td>
<td>1e-6</td>
</tr>
<tr>
<td>Delay</td>
<td>0</td>
</tr>
</tbody>
</table>

Set the transient simulation parameters to

- End time: 1e-3
- Calculation step: 10e-9
Figure 2 - This shows the output voltage rising to near negative 45 volts, a Buck-Boost converter. We can also see the voltage across the inductor during the switch off time is near the output voltage, and during the switch on time is near the input voltage.

Remove the voltage markers and use a current measurement to measure the inductor L current.
**QUESTION 1:** What is the peak operating current, and what is the operating mode of the converter? Verify mathematically the mode and the peak current.

Figure 3 – From the picture above we can see that the converter is operating in the discontinuous conduction mode with an average operating current of about 1.5 amps, and a peak inrush current of about 15.2 amps.

**Hint:** $K = \frac{2L}{RT_s}$, $K_{crit} = (1 - D)^2$

**QUESTION 2:** What is the output voltage of the converter at steady state? Verify your results mathematically.
Now change L from 200 $\mu$H to 2 mH and rerun the simulation. Remember you can adjust the “Screen” time under ‘Transient Settings.’

**QUESTION 3:** What is the peak operating current now? What is the operating mode of the converter (remember that you can observe this by zooming in)? Also, verify the mode mathematically.
Figure 5 – Current through 2mH inductor. The peak operating current is much smaller than in the previous case. It is approximately 4.7A. It reaches steady state at about 25msec. The converter operates for part of the time in the discontinuous conduction mode (at around 3msec) and in the continuous conduction mode for the rest of the time.

Leaving the Inductor at 2000uH, change the load resistance from 50 $\Omega$ to 10 $\Omega$. Change the ‘Run to Time‘ of the simulation to 10msec. Run the simulation.

**QUESTION 4:** What operating mode is the converter in?
Figure 6 – From the picture above we can see that the converter is operating in the continuous conduction mode with a peak current of about 5.5A.

Add a data point to look at the voltage across the inductor. Run the simulation for 5 ms and zoom in on a 200 µs interval.

**QUESTION 5:** What can be said about the differential voltage measurement across L1?
Figure 7 - 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.

Now change the “Run to Time” to 10m and show the data trace for the output voltage.

**QUESTION 6**: How long does it take for the output voltage to reach its final value? What is the peak to peak ripple on the output voltage? What is the average final value? Prove your simulation results mathematically (for final Vout).
Figure 8 – We can see that the average output voltage is reached in approximately 6 milliseconds with a peak value of about -25VDC. The output also has less than 1V peak to peak ripple.

Now change the value of the load resistance from 10 $\Omega$ to 500 $\Omega$. Run the simulation to 100 msec.

**QUESTION 7:** What is the peak of the output voltage? How long does it take for the converter to reach steady state and what is that value?
Figure 9 – the output voltage rises to a magnitude near twice the input voltage. This shows us that the output voltage of the Buck-Boost converter is a function of not only the duty cycle, the inductor value, and the capacitor value but also the load resistance. In this case, the duty cycle is 50%, but the output still exceeds the value of the input voltage.

Change the load resistor back to 50 Ω and the inductor back to 200 μH. Run the simulation to 10 ms and zoom in on a 200 μs interval.

**QUESTION 8:** What is the peak-to-peak ripple voltage? Re-adjust the step size accordingly to get enough resolution.
Figure 10 – Using the cursors to measure, the peak to peak ripple voltage is approximately 257 mV.

**QUESTION 9**: With everything else left as is, what is the minimum output capacitance required to limit the output voltage ripple to 2 volts peak to peak?

Figure 11 – The output voltage ripple has increased to approximately 2 volts peak to peak by reducing the output capacitance to 6 μF.
Now, change the capacitor back to 50 \( \mu \text{F} \) and put a current trace on the capacitor. Run the simulation to 10 ms and zoom in on a 200 \( \mu \text{s} \) interval.

QUESTION 10: What can be said about the current through the capacitor?

![Image](image.png)

Figure 12 – The capacitor is balancing the amp seconds, and the peak current through the capacitor is about -1.85A.

QUESTION 11: If the ESR of the capacitor is modeled by a 10 \( \Omega \) resistor in series with the capacitor, what happens to the output voltage ripple and the capacitor current?
Figure 13 – Circuit with ESR modeled by 10 Ω resistance.

Figure 14 – From the picture above we can see that the output voltage ripple has increased from approximately 2 volts peak to peak with no ESR, to approximately 20 volts peak to peak with 10 Ω of ESR!
Figure 15 – Capacitor current with 10 Ω ESR; very slight decrease.
QUESTIONS 12-18:

What happens if the duty cycle of the converter is decreased from 20 msec on time to 5 msec on time in V3 set up?

Is the converter operating in the continuous conduction mode? What is the average output voltage now?

Did the output voltage ripple increase?

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. 10000 Meg)

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

Hints: With everything else left as it is, change the pulse source V3 to have a period of 10 μs and a pulse width of 5 μs.