

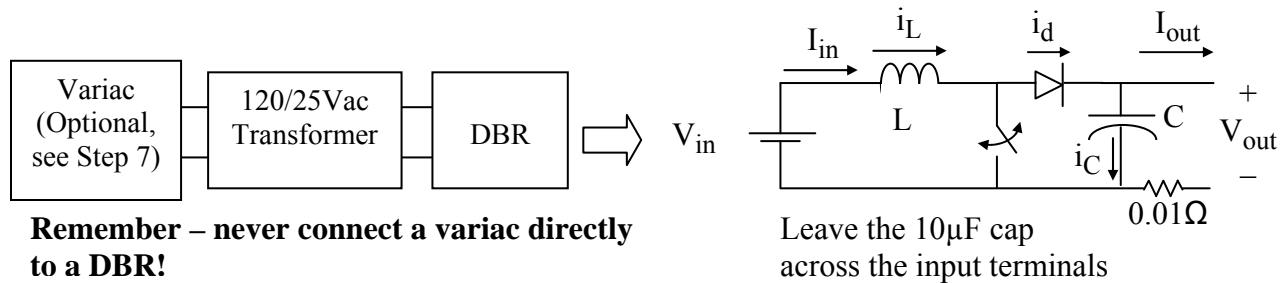
**Overview**

Boost converters make it possible to efficiently convert a DC voltage from a lower level to a higher level.

**Theory of Operation**

**Relation Between  $V_{out}$  and  $V_{in}$  in Continuous Conduction**

The idealized boost converter circuit is shown below in Figure 1. Under normal operation, the circuit is in “continuous conduction” (i.e.,  $i_L$  is never zero)



**Remember – never connect a variac directly to a DBR!**

Figure 1. DC-DC Boost Converter

The circuit is assumed to be lossless so that  $P_{in} = P_{out}$ , or

$$V_{in} \cdot i_{Lavg} = V_{out} \cdot I_{out} \text{ , where } i_{Lavg} = I_{in} \text{ .} \tag{1}$$

Assuming continuous conduction, the circuit has two topologies – switch closed, and switch open. Both are shown in Figures 2a and 2b.

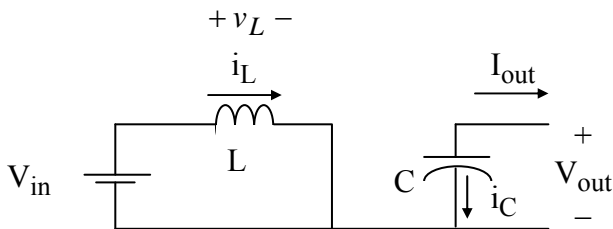


Figure 2a. Switch Closed for  $DT$  Seconds

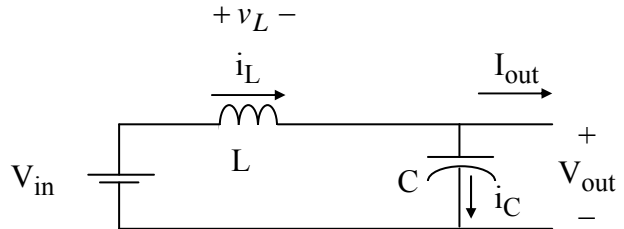


Figure 2b. Switch Open for  $(1-D)T$  Seconds (Continuous Conduction)

When the switch is closed, the diode is reverse biased and open, and  $i_L$  increases at the rate of

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{V_{in}}{L} \text{ , } 0 \leq t \leq DT \text{ ,} \tag{2}$$

and the inductor is “charging.” When the switch is open, the diode is forward biased, and  $i_L$  decreases at the rate of

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{V_{in} - V_{out}}{L}, \quad DT < t < T, \quad (3)$$

and the inductor is “discharging.” The inductor voltage is shown in Figure 3.

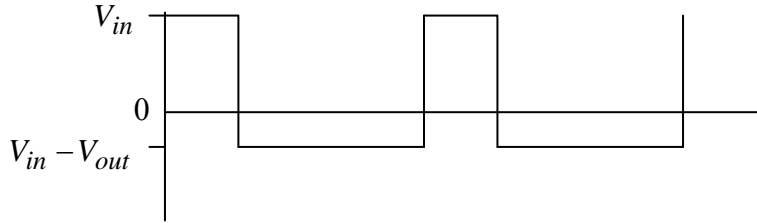


Figure 3. Inductor Voltage in Continuous Conduction

Because of the steady-state inductor principle, the average voltage  $v_L$  across L is zero. Since  $v_L$  has two states, both having constant voltage, the average value is

$$\frac{(V_{in})DT + (V_{in} - V_{out})(1-D)T}{T} = 0,$$

so that

$$V_{in}D + V_{in} - V_{out} - V_{in}D + V_{out}D = 0 .$$

Simplifying the above yields the final input-output voltage expression

$$V_{out} = \frac{V_{in}}{1-D} . \quad (4)$$

### *Inductor Current in Continuous Conduction*

The graph of  $i_L$  is shown in Figure 4.

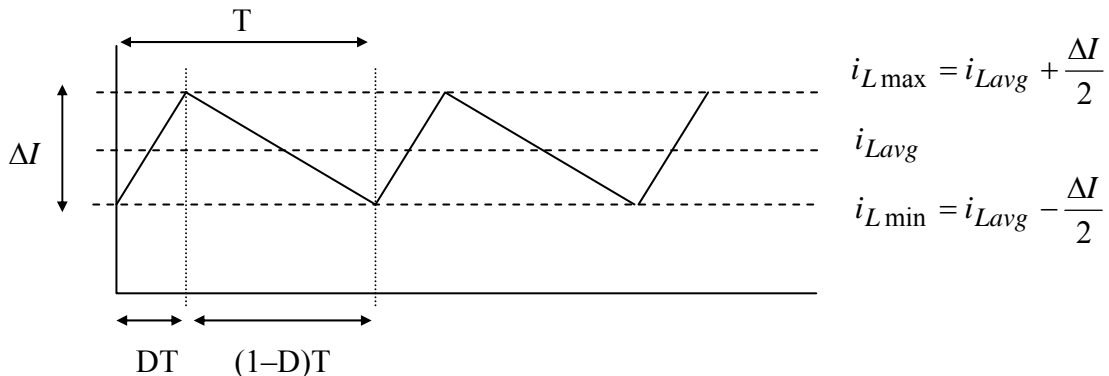


Figure 4. Inductor Current Waveform for Continuous Conduction

From (2),

$$\frac{di_L}{dt} = \frac{V_{in}}{L} = \frac{\Delta I}{DT},$$

so that

$$\Delta I = \frac{V_{in}}{L} \bullet DT = \frac{V_{in}D}{Lf}, \quad (5)$$

where  $f$  is the switching frequency.

The boundary of continuous conduction is when  $i_{L\min} = 0$ , as shown in Figure 5.

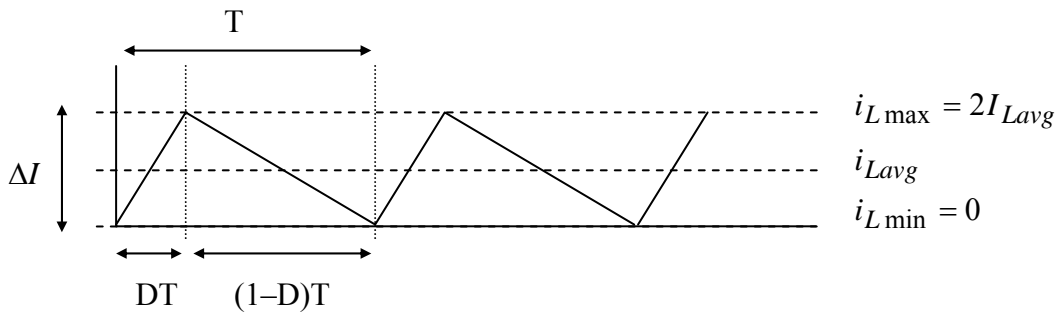


Figure 5. Inductor Current at the Boundary of Continuous Conduction

Using Figure 5 and the “inductor discharging” slope from (3),

$$\Delta I = \frac{(V_{out} - V_{in})(1-D)}{L_{boundary}f} = \frac{V_{in} - V_{in}(1-D)}{L_{boundary}f} = \frac{V_{in}D}{L_{boundary}f} = 2I_{Lavg}, \quad (6)$$

so that

$$L_{boundary} = \frac{V_{in}D}{2I_{Lavg}f}. \quad (7)$$

From (1),

$$I_{Lavg} = I_{in}. \quad (8)$$

Substituting into (8) into (7) yields

$$L_{boundary} = \frac{V_{in} D}{2I_{in} f} \tag{9}$$

Because the maximum value of D is 1, then

$$L > \frac{V_{in}}{2I_{in} f} \tag{10}$$

will guarantee continuous conduction for all D. Note in (9) and (10) that continuous conduction can be achieved more easily when  $I_{out}$  and  $f$  are large.

**Discontinuous Conduction**

At low load, the converter may slip into the discontinuous conduction mode. Referring back to Figure 2b, this occurs when the inductor current coasts to zero. At that moment, the capacitor attempts to reverse  $i_L$  and “backfeed” the inductor, but the diode prevents current reversal. Thus, the diode opens, and the circuit assumes the topology shown in Figure 6 until the switch closes again. During this third state, all load power is provided by the capacitor.

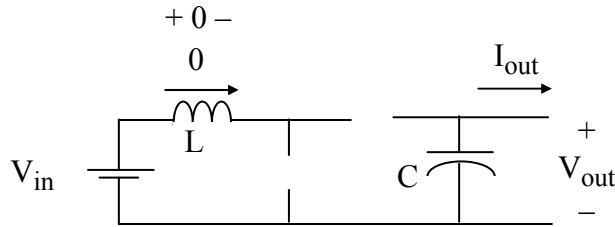


Figure 6. Third State for Discontinuous Conduction

Once discontinuous, the voltage across the inductor is zero. The corresponding voltage waveform is shown in Figure 7.

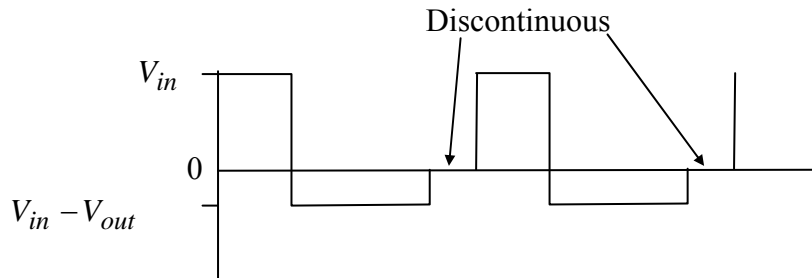
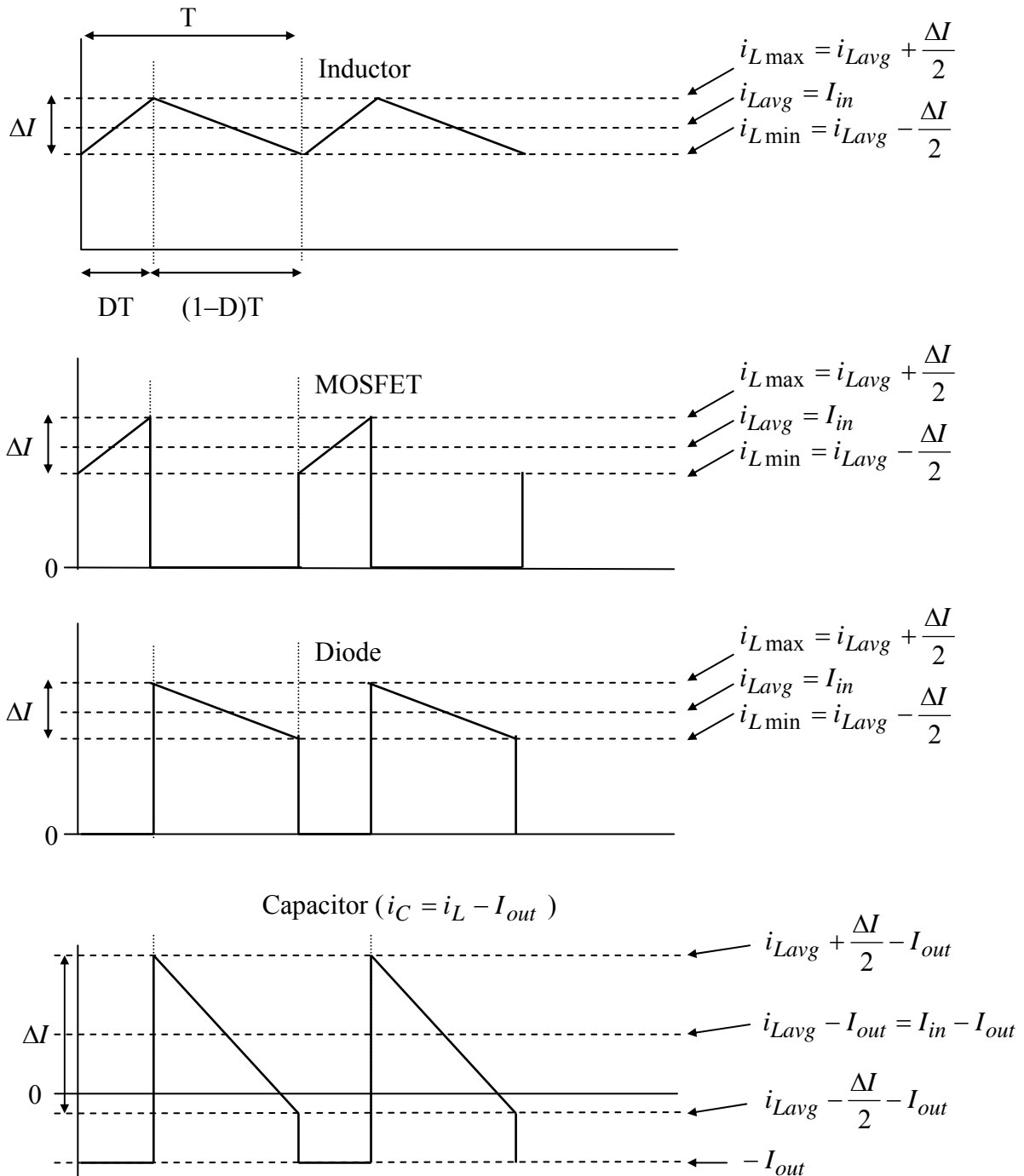


Figure 7. Inductor Voltage in Discontinuous Conduction

*Current Waveforms in Continuous Conduction*

Continuous current waveforms are shown below.



(Note – compared to the other waveforms shown above,  $\Delta I$  is exaggerated in the figure to illustrate how the capacitor current can be negative in both  $DT$  and  $(1-D)T$  regions)

Figure 8. Current Waveforms for Continuous Conduction

***Current Ratings in Continuous Conduction***

Conservative current ratings for the inductor in continuous conduction correspond to the situation where

$$\Delta I_{\max} = 2I_{in}, \tag{11}$$

which, as explained in the Buck Converter experiment, yields

$$I_{Lrms,\max}^2 = I_{in}^2 + \frac{1}{12}(2I_{in})^2 = I_{in}^2 \left(1 + \frac{1}{3}\right), \tag{12}$$

so that

$$I_{Lrms,\max} = \frac{2}{\sqrt{3}} I_{in}. \tag{13}$$

Conservative current ratings for the MOSFET and diode are when D is large, so that (13) applies for them also.

To determine the rms current through C, consider the capacitor current in Figure 8, and the worst-case scenario in Figure 9.

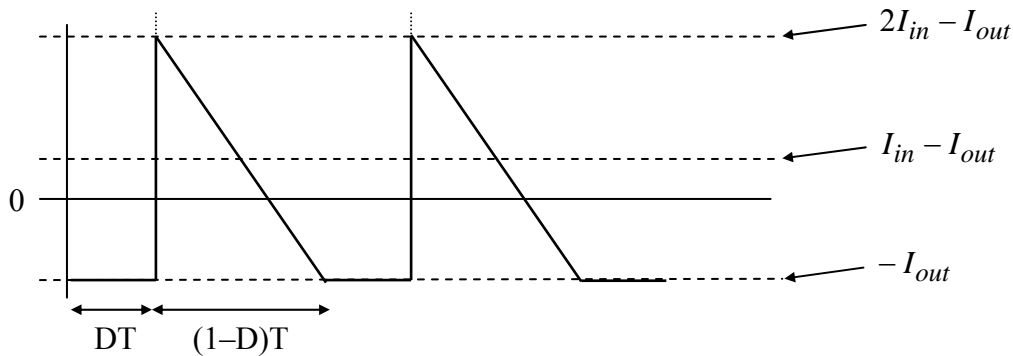


Figure 9. Maximum Ripple Current Case for Capacitor Current

When the switch is closed, the capacitor current is  $-I_{out}$ . When the switch is open, the capacitor current is  $i_L - I_{out}$ . If the “switch closed” interval lasted for the entire T, the squared rms value would be  $I_{out}^2$ . If the “switch open” interval lasted for the entire T, the rms value would be, for the maximum ripple case,  $(I_{in} - I_{out})^2 + \frac{1}{12}(2I_{in})^2$ . The time-weighted average of the two gives the squared rms current

$$I_{Crms}^2 = DI_{out}^2 + (1-D) \cdot \left( (I_{in} - I_{out})^2 + \frac{1}{12} (2I_{in})^2 \right). \quad (14)$$

Now, substituting in  $I_{out} = I_{in}(1-D)$  yields

$$I_{Crms}^2 = DI_{in}^2(1-D)^2 + (1-D) \cdot \left( (I_{in} - I_{in}(1-D))^2 + \frac{1}{12} (2I_{in})^2 \right).$$

Simplifying yields

$$I_{Crms}^2 = DI_{in}^2(1-D)^2 + (1-D) \cdot \left( I_{in}^2 D^2 + \frac{1}{3} I_{in}^2 \right),$$

$$I_{Crms}^2 = I_{in}^2 \left( D(1-D)^2 + (1-D)D^2 + \frac{(1-D)}{3} \right),$$

$$I_{Crms}^2 = I_{in}^2 \left( \frac{-3D^2 + 2D + 1}{3} \right),$$

Setting the partial derivative with respect to D shows that the maximum occurs at  $D = \frac{1}{3}$ , which yields

$$I_{Crms,max} = \frac{2}{3} I_{in}.$$

Since  $D = \frac{1}{3}$ , then substituting for  $I_{in}$  yields

$$I_{Crms,max} = \frac{2}{3} \cdot \frac{I_{out}}{\left(1 - \frac{1}{3}\right)} = I_{out}. \quad (15)$$

### ***Voltage Ratings for Continuous Conduction***

Referring to Figure 2b, when the MOSFET is open, it is subjected to  $V_{out}$ . Because of the usual double-voltage switching transients, the MOSFET should therefore be rated  $2V_{out}$ .

Referring to Figure 2a, when the MOSFET is closed, the diode is subjected to  $V_{out}$ . The diode should be conservatively rated  $2V_{out}$ .

**Capacitor Voltage Ripple**

Re-examining the capacitor current in Figure 9, and re-illustrated in Figure 10, it can be seen that the amount of charge taken from C when the switch is closed is represented by the dotted area.

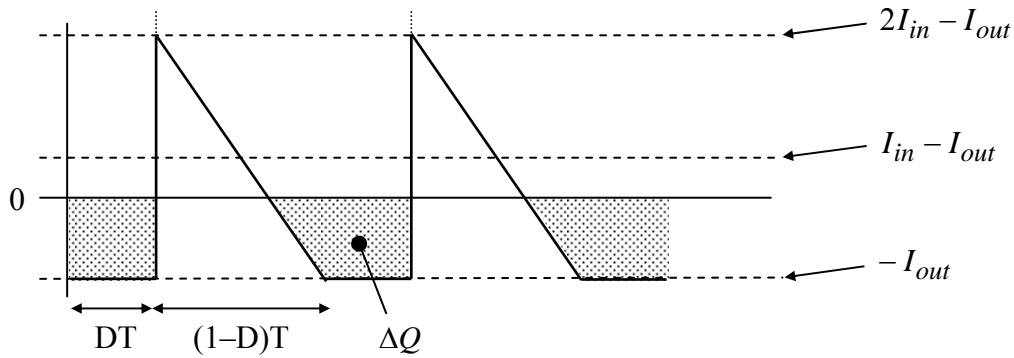


Figure 10. Capacitor Charge Given Up While Switch is Closed

As  $D \rightarrow 1$ , the width of the dotted area increases to fill almost the entire cycle, and the maximum peak-to-peak ripple becomes

$$\Delta V_{\max} = \frac{I_{out} \cdot T}{C} = \frac{I_{out}}{Cf} \quad (16)$$

## EE462L, Power Electronics, DC-DC Boost Converter

Version Feb. 20, 2013

**The Experiment (Important - to avoid high output voltages, always keep a load attached to the boost converter output when input power is applied. Use a conventional 120V, 150W light bulb as your load. Do not exceed 120V on the output.**

1. Convert a buck converter to a boost converter, using the circuit shown in Figure 1 of this document.
2. Modify the MOSFET D-control circuit according to the MOSFET Firing Circuit document for Boost Converter Operation. Check your range of D with the expected D range given in Figure 2b in that document.
3. Double-check that the polarity of your output capacitor is correct.
4. Locate one of the 150W light bulb test load assemblies. Check the light bulb with an ohmmeter to make sure it is not burned out.
5. Connect the light bulb test load to your circuit.
6. Connect an oscilloscope Channel #1 to view  $V_{GS}$ , and Channel #2 to view  $V_{DS}$ . The ground clip of the Channel #2 probe should not be attached to the circuit, but instead it should be clipped back onto its own lead in-cable so that it does not dangle.
7. **Do not connect a DBR yet.** Connect the MOSFET firing circuit to your converter, **using short wires**, and then power-up your MOSFET firing circuit. Set the oscilloscope to trigger on Channel #1. Observe your oscilloscope to confirm that the controls are working properly.
8. **Set D to the minimum setting**, and  $F \approx 90\text{kHz}$ .

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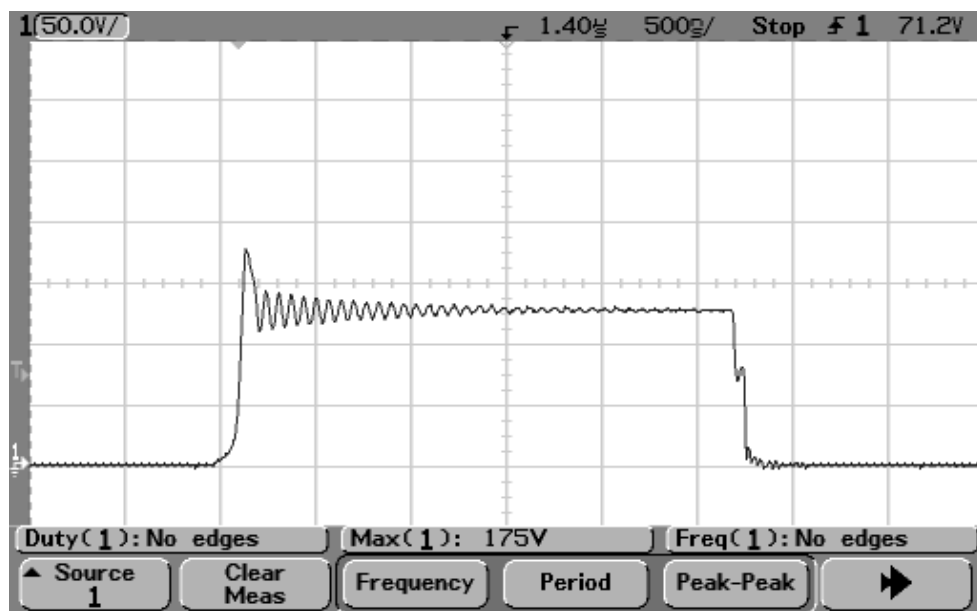
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**Important Note:** the first time you energize your boost converter, feed the 120/25V transformer through a variac to the DBR, so that you can **SLOWLY** increase the voltage from zero and read the variac ammeter to detect short circuits before they become serious. A common problem is to have the MOSFET in backward, in which case its internal antiparallel diode creates a short circuit. The ammeter on the variac is an excellent diagnostic tool. Once you are convinced that your circuit is working correctly, the variac is then optional. **Remember – your boost converter requires DC input power from a DBR.**

Does your circuit have a short? If so, do the following:

1. Make sure that your MOSFET is not connected backwards.
2. Observe  $V_{GS}$  on the MOSFET as you vary D and F. Does the waveform look correct?
3. Unplug the wall wart. Does the short circuit go away? If not, your MOSFET may be shorted – so, disconnect the MOSFET from the converter, and perform the voltage-controlled resistance test on the MOSFET, or use the MOSFET tester.

9. Connect (an optional variac and) 25V<sub>ac</sub> transformer to a DBR. Connect the DBR to your boost converter, **keeping the wires short**. Then, energize the 25V<sub>ac</sub> transformer and DBR. If using a variac, adjust the variac so that V<sub>ac</sub> of the transformer is approximately 27-28V.
10. With  $F \approx 90\text{kHz}$ , **slowly** raise D to where the output voltage is about 120V. Measure D,  $V_{in}$ ,  $I_{in}$ ,  $V_{out}$ , and  $I_{out}$ . Save a screen snapshot that shows the peak value of  $V_{DS}$ . Let the circuit run at this condition for 1 or 2 more minutes, (**optional – use an infrared thermometer to measure the MOSFET surface temperature**), and then **turn off your circuit**.



Save screen snapshot #1

$V_{DS}$  for the 90kHz, 120V Condition

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11. **With your circuit turned off**, quickly and carefully use your hand to check MOSFET heat sink temperature and to check for other hot components.
12. Compare  $V_{out}/V_{in}$  to theory. Multiply voltages and currents to compute input and output powers, and then compute the efficiency of your circuit.
13. **Turn on your circuit**, and slowly lower D in steps of approximately 0.1, to the lowest value (i.e.,  $D \approx 0.1$ ), measuring D,  $V_{in}$ ,  $I_{in}$ , and  $V_{out}$  as you go. Does the circuit remain in continuous conduction over the range of D? If not, compare boundary equation (9) with your experience at the actual boundary point.
14. **Lower D to the minimum setting**. Repeat Steps 9-12, using  $F \approx 30\text{kHz}$ . If temperature measurements were taken, compare MOSFET temperatures for the 120V, 90kHz and 120V, 30kHz cases. Otherwise, comment on the difference between hand-checked MOSFET heat sink temperatures for the two cases.
15. Using the measurements taken for the 30kHz, 120V condition, employ (5) to compute  $\Delta I$ , and then use  $I_{Lrms,max}^2 = I_{in}^2 + \frac{1}{12}(\Delta I)^2$  to compute inductor rms current.
16. Use  $I_{Crms,max}^2 = \frac{1}{12}(\Delta I)^2$  to compute capacitor rms current.

In addition to describing what you did in the above steps, be sure to include the following in your report:

- a plot of measured and theoretical  $V_{out}/V_{in}$  versus D for 90kHz on one graph,
- and a plot of measured and theoretical  $V_{out}/V_{in}$  versus D for 30kHz on a separate graph.

The following **optional** steps are to be performed with solar panels as the power source and with good sun (i.e., panel short circuit current of 3.5A or more). The panel voltage that you measure should be “at the panel” (i.e., the left-most analog voltmeter)

17. Note the sky conditions. Connect a solar panel pair directly to a 120V, 150W light bulb. Measure panel voltage, panel current, and compute solar panel output power.
18. Next, insert the boost converter between the panel pair and 120V light bulb. With  $F \approx 90\text{kHz}$ , sweep D over its range to measure and plot the I-V and P-V characteristics of the panel pair. Record the maximum power value.

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**Parts List**

- 8" nylon cable tie (in student parts bin)

**Extra parts**

**For the student parts bin and screw cabinet, at least**

- 5 of the 250V MOSFETs (individually bagged)
- 5 of the 200V, 16A ultrafast rectifiers
- 5 of the DC jacks
- 5 of the 10k $\Omega$  audio taper and linear taper potentiometers
- 5 of the PWM modulator chips
- 5 of the inverting driver chips
- 5 of the 14-pin sockets
- 5 of the 8-pin DIP sockets
- 5 of the green plugs
- 10 of the #4-40 x 1" flat slotted nylon screws and lock nuts

**Plastic bags for parts**

- 6"x6", 4mil

