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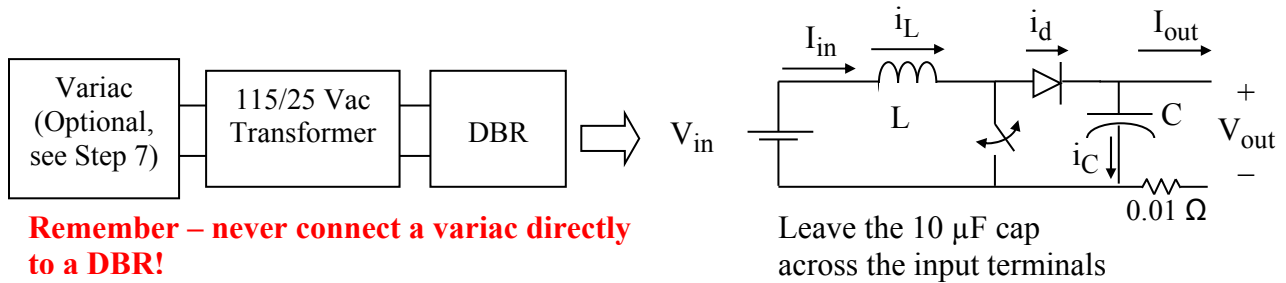
1 Overview

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

2 Theory of Operation

2.1 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 operates with the inductor current 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

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

Assuming continuous conduction, the circuit has two topologies: switch closed and switch open as shown in Figures 2a and 2b respectively.

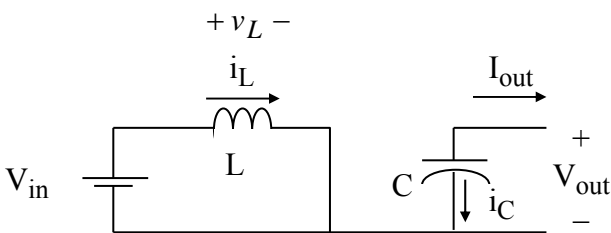


Figure 2a. Switch Closed for DT Seconds

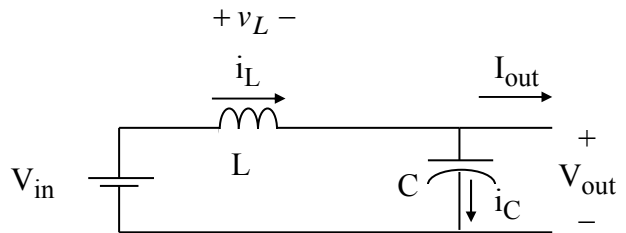


Figure 2b. Switch Open for $(1-D)T$ Seconds (Continuous Conduction)

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

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{V_{in}}{L}, \quad 0 \leq t \leq DT, \quad [\text{KVL, from Figure 2a.}] \quad (2)$$

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

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{V_{in} - V_{out}}{L}, \quad DT < t < T, \quad [\text{KVL, from Figure 2b.}] \quad (3)$$

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

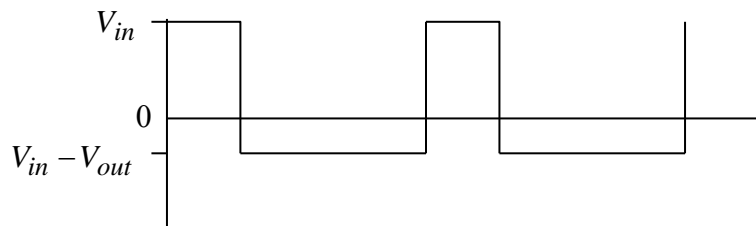


Figure 3. Inductor Voltage in Continuous Conduction Mode

Because of the steady-state inductor principle, the average voltage v_L across L is zero. Since at any time v_L takes on one of two constant values, its 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

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

2.2 Inductor Current in Continuous Conduction

The graph of i_L is shown in Figure 4.

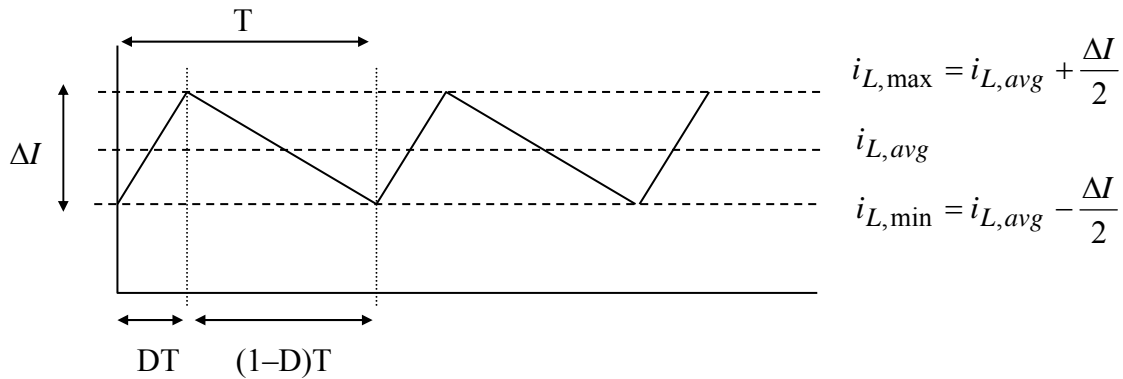


Figure 4. Inductor Current Waveform for Continuous Conduction Mode

From (2),

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

so that

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

where f is the switching frequency.

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

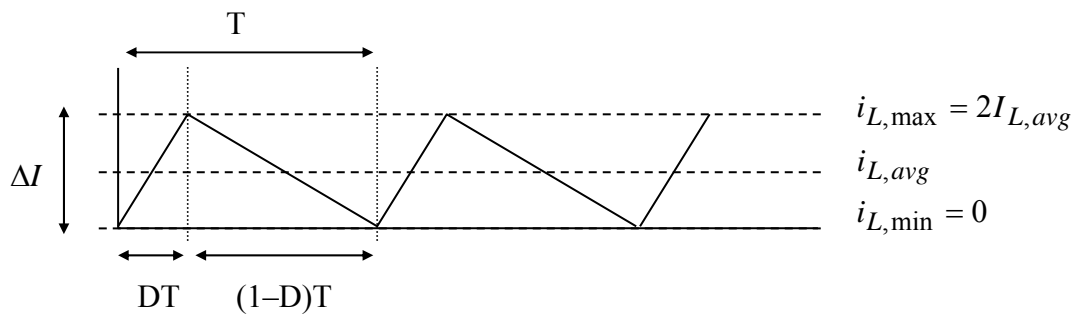


Figure 5. Inductor Current at the Boundary of Continuous Conduction

From Figure 5 it is evident that at the boundary of continuous conduction

$$\Delta I = 2i_{L,avg}. \quad (6)$$

Substituting (6) into (5) and solving for L yields the minimum value of inductance, $L_{boundary}$, needed ensure the inductor current operates in the continuous conduction mode as

$$L_{boundary} = \frac{V_{in}D}{2I_{L,avg}f} \quad (7)$$

From (1),

$$I_{L,avg} = I_{in} \quad (8)$$

Substituting into (8) into (7) yields

$$L_{boundary} = \frac{V_{in}D}{2I_{in}f} \quad (9)$$

Because the maximum value of D is 1, then

$$L > \frac{V_{in}}{2I_{in}f} \quad (10)$$

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

2.3 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 decreases to zero. At that moment, the capacitor attempts to reverse i_L and “backfeed” the inductor, but reversal is prevented by the freewheeling diode (for this discussion we will ignore the practical effect of diode reverse recovery current). 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.

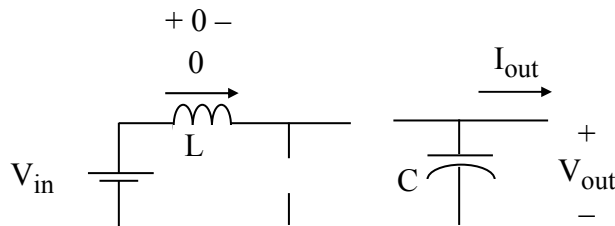


Figure 6. Third State for Discontinuous Conduction

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

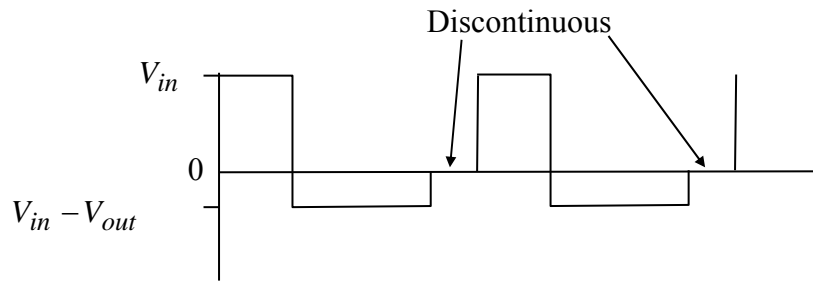
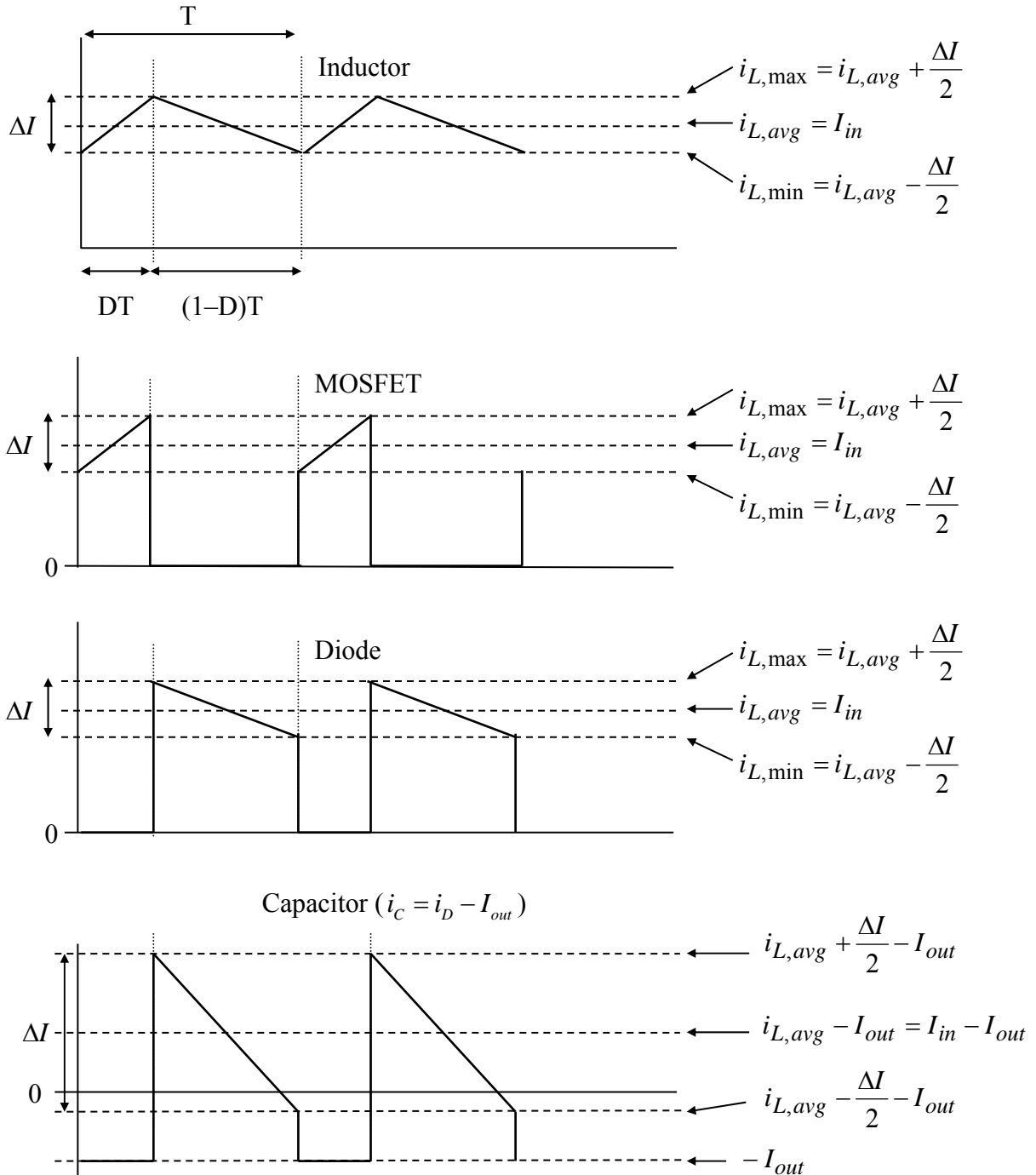


Figure 7. Inductor Voltage in Discontinuous Conduction

2.4 Current Waveforms in Continuous Conduction

Continuous current waveforms are shown below.



(Note – compared to the other waveforms shown above, ΔI 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

2.5 Current Ratings in Continuous Conduction

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

$$\Delta I_{\max} = 2I_{in}, \quad (11)$$

which, as explained in an analogous fashion in the Buck Converter experiment, yields

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

so that

$$I_{L,rms,max} = \frac{2}{\sqrt{3}}I_{in}. \quad (13)$$

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.

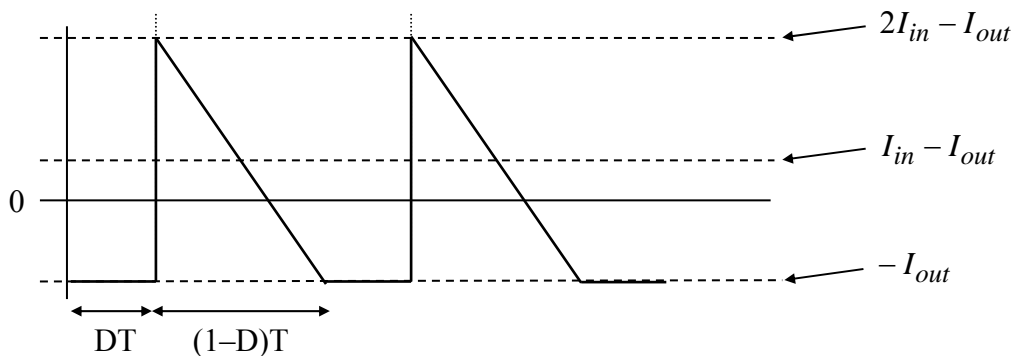


Figure 9. Maximum Ripple Current Case for Capacitor Current

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 squared 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

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

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

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

Simplifying yields

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

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

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

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

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

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

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

2.6 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 $2V_{out}$.

2.7 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.

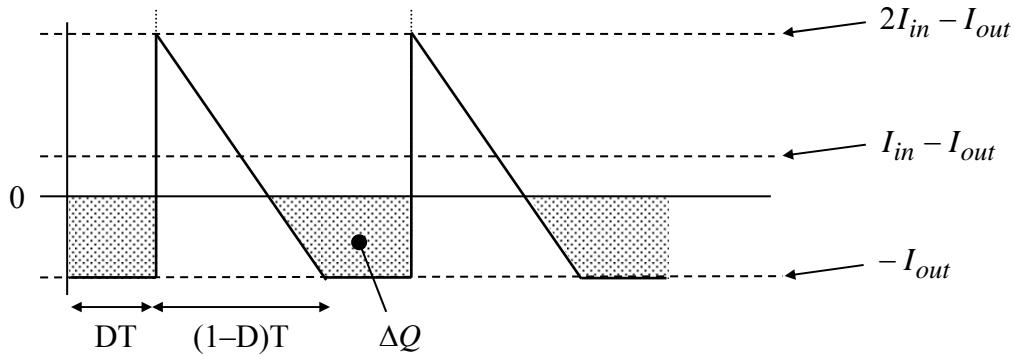


Figure 10. Capacitor Charge Removed While Switch is Closed

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

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

3 The Experiment

Important Safety Considerations when using a Boost Converter:

- A) **Never allow D to approach 1**, for a fully closed boost will short V_{in} !!
(Recall under steady-state dc conditions with the switch fully closed, $L \rightarrow$ short!!)
- B) To avoid high output voltages, **always keep a load attached to the boost converter output** when input power is applied. When the switch is open (under CCM) the inductor will be sending current, regardless. Thus, a no load condition will cause the capacitor voltage to swell, possibly exceeding its rating. Therefore, use a conventional 120 V, 150 W light bulb as your load. Do not exceed 120 V_{dc} on the output.

1. Convert a buck converter to a boost converter, using the circuit shown in Figure 1 of this document. (Note, it may be helpful when reconfiguring a buck as a boost converter to visualize the MOSFET, inductor, and diode being rotated counter-clockwise 1 position about their common node, and flipping the polarity of the diode.)
2. **Use your D-Limiter potentiometer to reduce your range of D so that the upper limit is set to be 0.8.**
3. Double-check that the polarity of your output capacitor is correct.
4. Locate one of the 150 W light bulb test load assemblies. Check the light bulb with an ohmmeter to make sure it is not burned out. Then, connect the light bulb test load to the output of your boost circuit.
5. Connect oscilloscope Channel #1 to view V_{GS} , and Channel #2 to view V_{DS} . (Recall, 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!)
6. **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.
7. **Set D to the minimum setting**, and $f \approx 90$ kHz.

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Important Note: The first time you energize your boost converter, feed the 115:25 V transformer through a variac to the DBR, so that you can **SLOWLY** increase the voltage dial while **reading the variac ammeter to detect for shorts 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:

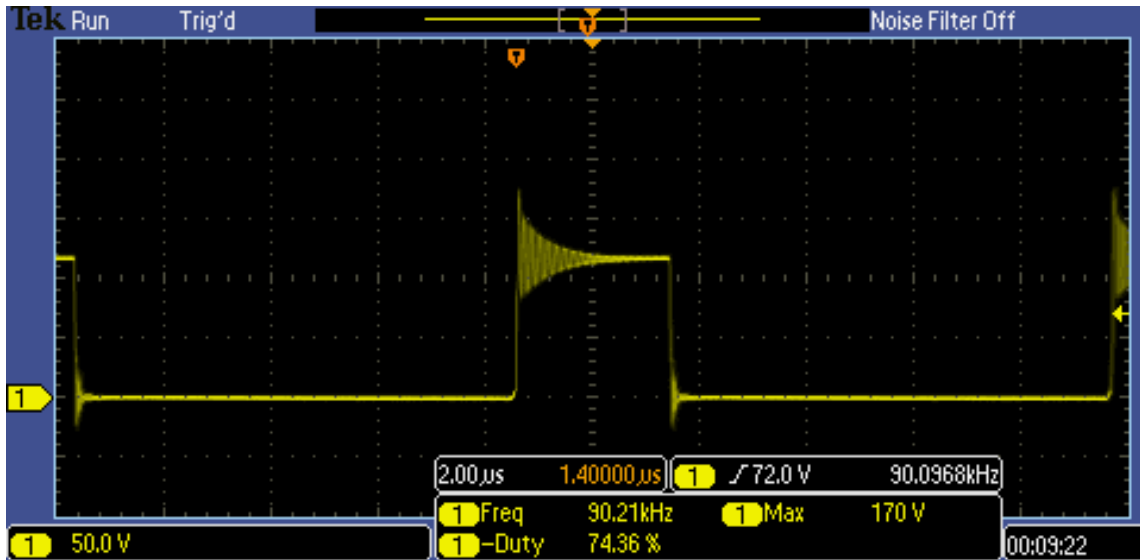
1. Make sure that your MOSFET is not connected backwards.
2. Observe V_{GS} on the MOSFET as you vary D and f . Does the waveform look correct?
3. Unplug the wall wart. Does the short circuit go away? If not, your MOSFET may be shorted – so, disconnect the MOSFET from the converter, and perform the voltage-controlled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



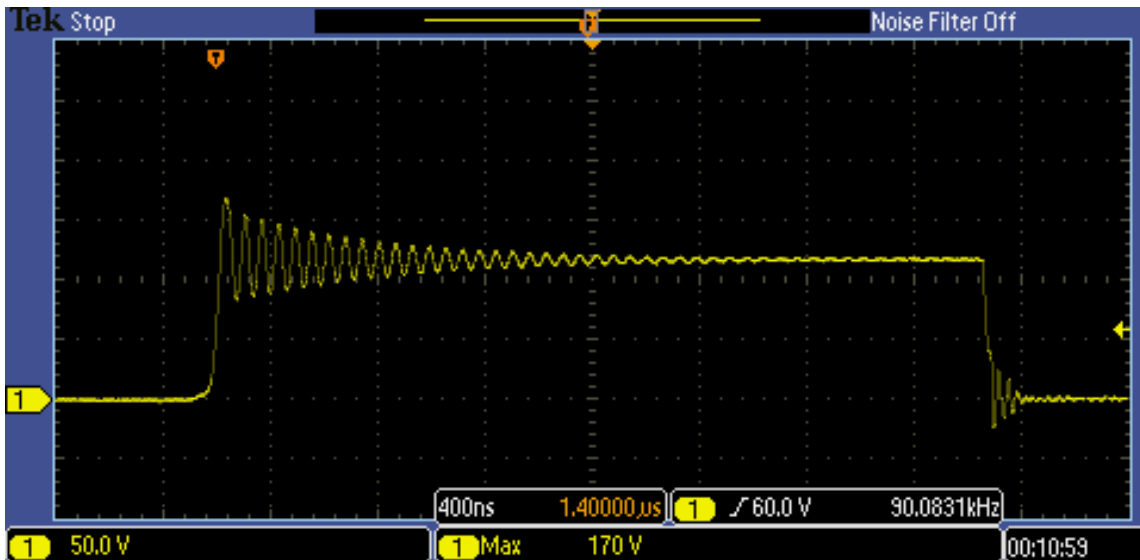
Picture 1: Boost Converter Laboratory Test Setup

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- Connect (an optional variac and) a 115:25 V_{ac} transformer to your DBR. Connect the DBR to your boost converter, **keeping the wires short**. Then, energize the 115:25 V_{ac} transformer and DBR. If using a variac, adjust the variac so that the output of the **transformer** is approximately 27-28 V_{rms}.
- With $f \approx 90$ kHz, **slowly** raise D to where the output voltage is about 120 V_{dc}. Measure D, V_{in}, I_{in}, V_{out}, and I_{out}. Save a screen snapshot that shows the peak value of V_{DS}.



Picture 2: V_{DS} Showing Peak Voltage (at 90 kHz, 120 V_{dc})



Picture 3: (Zoomed-In) V_{DS} Showing Peak Voltage and Oscillations (at 90 kHz, 120 V_{dc})

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10. Let the circuit run at this condition for 1 or 2 more minutes, use an infrared thermometer (if available) to measure the MOSFET surface temperature, and then **turn off your circuit**. Quickly and carefully, use your hand to check the MOSFET heat sink temperature and other components to see if they are hot.
11. 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.
12. **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 full range of D? If not, compare boundary equation (9) with your experience at the actual boundary point.
13. **Lower D to the minimum setting**. Repeat Steps 9-12, using $f \approx 30$ kHz. If temperature measurements were taken, compare MOSFET temperatures for the 120 V, 90 kHz and 120 V, 30 kHz cases. Otherwise, comment on the difference between hand-checked MOSFET heat sink temperatures for the two cases.
14. Using the measurements taken for the 30 kHz, 120 V condition, employ (5) to compute ΔI , and then use $I_{L,rms,max}^2 = I_{in}^2 + \frac{1}{12}(\Delta I)^2$ to compute inductor rms current.
15. Use $I_{C,rms,max}^2 = \frac{1}{12}(\Delta I)^2$ 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 90 kHz on one graph, and
- a plot of measured and theoretical V_{out}/V_{in} versus D for 30 kHz on a separate graph.

4 Optional Section – Boost Converter with a Solar PV panel

The following **optional** steps are to be performed with a solar panel as the power source and with good sun (i.e., panel short circuit current ≥ 3.5 A, and a clear sky, bright forecast). Please make certain sky conditions are clear. The point of this section is to see how changing D affects your V_{out} . Yet, an unstable V_{in} will also affect V_{out} via Eq (4). (See pictures on the following page). Thus, you will want to take your data with V_{in} relatively constant (i.e., clear skies) to avoid fluctuations in V_{in} .

Please heed the following warnings if you attempt to do this optional section:

- A. **If you use the Position #18 work station and connect to your Boost using the set of red & black wires already provided, know these wires *bypass* the yellow connection box, ammeter, and the on/off switch. Thus, if sun is shining, these dc voltage wires are live!!** (Note: This same safety concern is dealt with by solar PV installers every day, for as they install and wire up solar PV panels, due to daylight, these panel voltages are live!)
- B. As prior noted for a Boost, **make certain your $D \leq 0.8$ (use your D-limiter potentiometer to reduce your upper limit threshold as a safety measure), and make sure you always have a load connected before you apply an input voltage!**

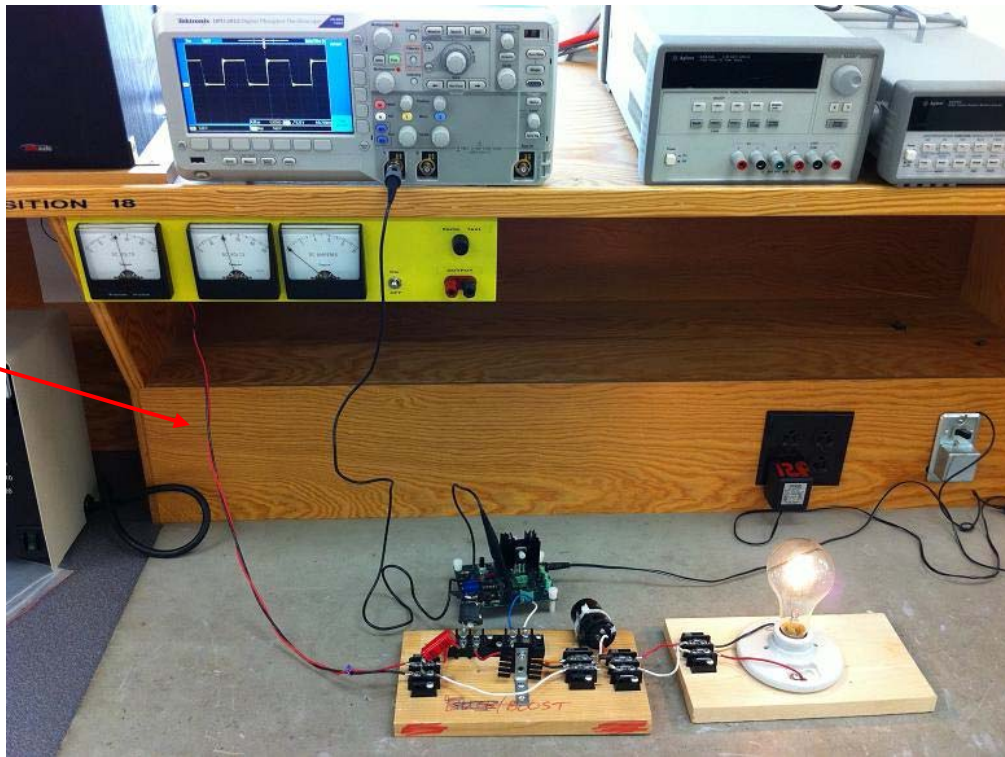
The solar voltage that you measure should be at the panel. (i.e., the left-most analog voltmeter).

16. Note the sky conditions. Connect a solar panel pair directly to a 120 V, 150 W light bulb. Measure panel voltage, panel current, and compute solar panel output power. (Note: If you connect to Position #18 via the direct panel wiring provided, to measure I_{panel} , you will need to add an input shunt resistor to your Boost converter.)
17. Next, insert the boost converter between the solar panel output and a 150 W light bulb. With $f \approx 90$ kHz, sweep D over its range to measure and plot the I-V and P-V characteristics of the panel. Record the maximum power value.

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Be careful. This wire is **live!!** (i.e., it bypasses the yellow instrument panel) Thus, the ammeter and on/off switch won't work!

Note solar insolation has increased, resulting in a brighter bulb (higher V_{in}) for the same switching D and f . This is undesired. You will want to test your circuit under more stable solar conditions!



Picture 4: Boost used in conjunction with a solar panel to power a 150 W light bulb load



Figure 5: Boost used in conjunction with a solar panel to power a 150 W light bulb load.

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Parts List

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

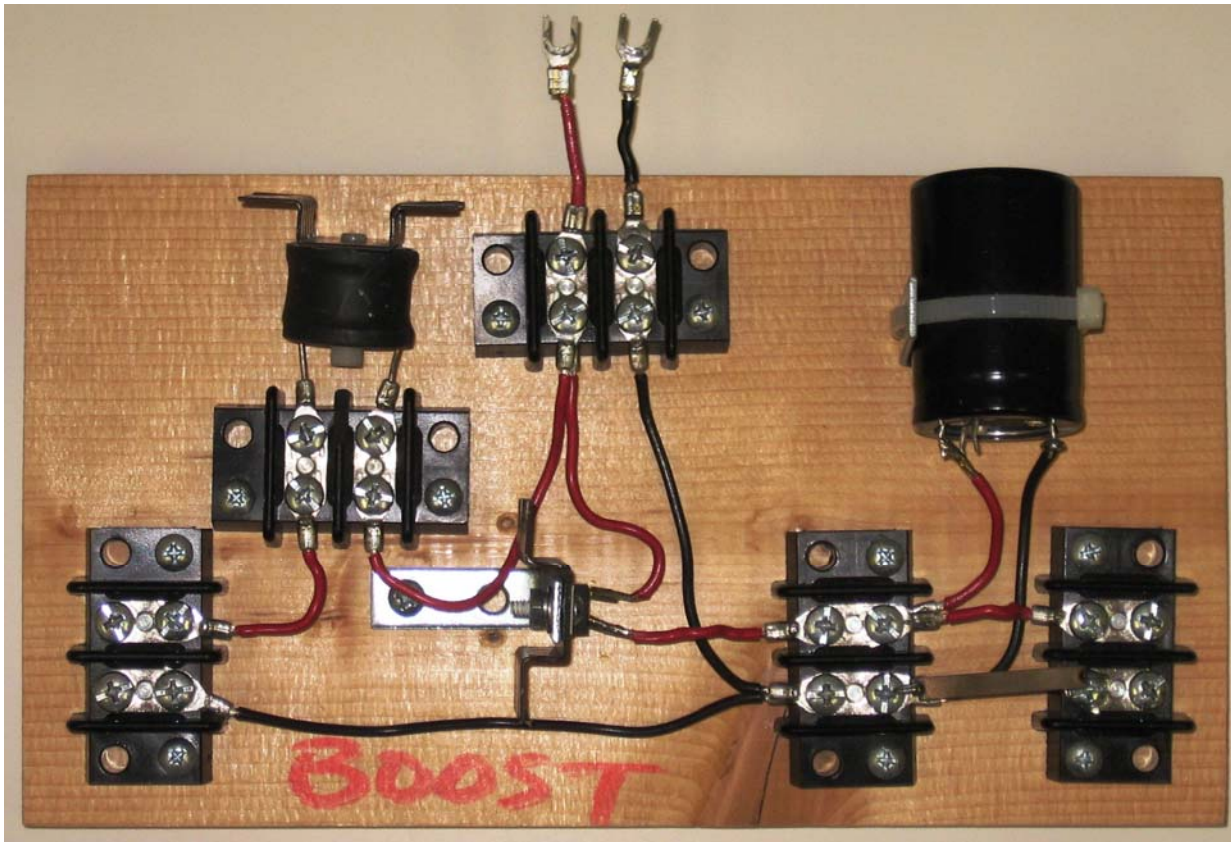
Extra parts

For the student parts bin and screw cabinet, at least

- 5 of the 250 V MOSFETs (individually bagged)
- 5 of the 200 V, 16 A ultrafast rectifiers
- 5 of the dc jacks
- 5 of the 10 k Ω 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



Picture 6: Boost Converter Build