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PRE-LAB: __/75
LAB: __/25
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Boost Converter

Lab 7: Boost Converter

ELECTRICAL ENGINEERING 43/100

ELECTRONIC TECHNIQUES FOR ENGINEERING

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Lab Contents

Background and Lab Objectives

In previous labs, we have tried implementing voltage dividers to transform voltages. However, such solutions are not efficient, as voltage dividers dissipate a significant amount of power in the resistors. They were limited to producing voltages less than to the source voltage. (Op amp configurations are not a complete solution, since high voltage rails are required to begin with.) These limitations become problematic in many applications that require high operating voltages, such as **m**icro**e**lectronic **m**echanical **s**ystems (MEMS).

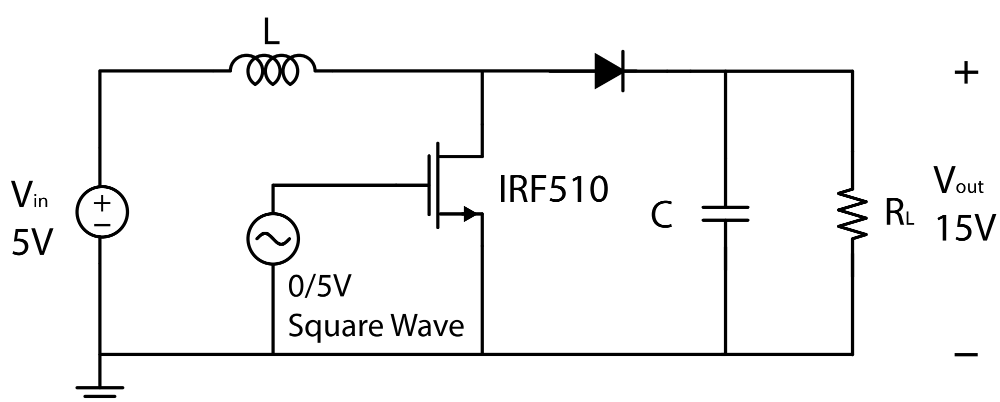
One of the conventional solutions to solving this problem is the boost converter. The boost converter exploits the properties of capacitors and inductors in order to attain higher voltages than the supply voltage. Recall that capacitors **resist** changes in **voltages**, and inductors **resist** changes in **current**. By configuring capacitors and inductors together with other circuit components, we will be able to produce a higher voltage supply.

In this lab, you will design and choose component values for a boost converter that will provide a 15 V and 4.5 mA to a load, from a 5 V input source, with the stipulation that average input source current deviate by no more than 22%.

Lab Materials

For this lab, you will need:

- 1 x Inductor
- 1 x IRF510 MOSFET N Channel Transistor
- 1 x Schottky Diode
- 1 x Capacitor
- 1 x Resistor
- 1 x Programmable Power Supply
- 99 x Perseverance



Boost Converter[i]

Pre-Lab Component

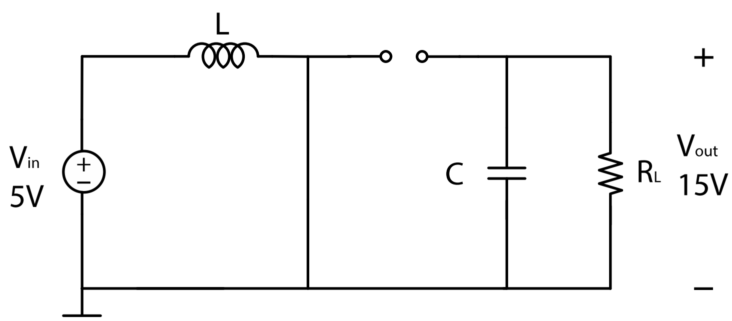
For this lab, we will supply you the schematic of the boost converter (above). One new component is the Schottky diode, which allows for quick ON and OFF state transitions. There is also a transistor connecting the high (drain) and ground (source) nodes of the circuit. For the purpose of this lab, assume that transistors simply act as switches and have an ON and OFF state. That is, the OFF state corresponds to the cutoff region of operation, while the ON state corresponds to the saturation region.

In the Pre-Lab, you will be determining the values of all your circuit elements.

Two States of the Boost Converter

The IRF510 NMOS transistor is triggered by a square wave source. Recall that when the input to the transistor is high, the transistor is "ON" and acts as a short circuit; when the input to the transistor is low, the transistor is "OFF" and acts as an open circuit.

To make our lives easier, let's consider the two separate circuits corresponding to the two transistor states and assume that steady state operation has been reached (i.e. $V_{out}(t) = 15\ V$) For the ON phase, the transistor acts as a short circuit, shorting the anode of the diode (and drain of the transistor) to ground. So the diode itself becomes an open circuit, because it becomes backward-biased. We have the following equivalent circuit:



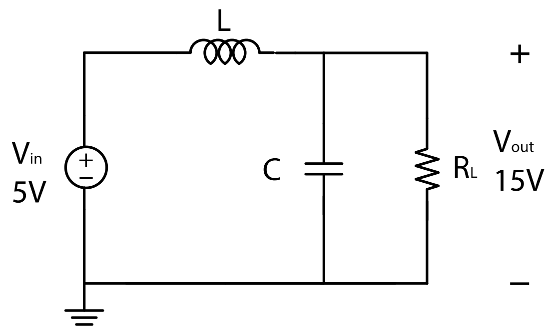
ON state of the boost converter[ii]

We can see that during the ON phase, the boost converter reduces to a voltage supply (in this case $5\ V$) in series with an inductor. Inductors resist change in current, so the circuit does not immediately spike up to infinite current. Thus, during the ON phase of the circuit, the circuit linearly "builds" up electrical current, in accordance with the formula:

$$V_{in} = L\left(\frac{di_{on}}{dt_{on}}\right) \rightarrow L di_{on} = V_{in} dt_{on} \rightarrow di_{on} = \frac{1}{L} V_{in} dt_{on}$$

where di_{on} is the additional current built up by the inductor during the ON state and dt_{on} is the time that the transistor was on. Notice that the above equations yield the amount by which the current changes, not the actual value of the current at a given moment in time.

In the off state, the transistor acts as an open switch, and the diode becomes a closed switch, since current is forced to flow forward across it. We obtain the following equivalent circuit:



OFF state of the boost converter[iii]

When we transition from the ON state to the OFF state, the current through the inductor cannot change instantaneously. So it will now go through the load resistor R_L instead of the transistor. The load resistance R_L produces the large V_{out} in accordance with Ohm's Law: $V = IR$.

Using similar principles as our ON state, we can calculate an expression for the change in current flow i_{off}, given the values for V_{in} and V_{out}. In this OFF state the applied voltage across the inductor is actually $V_{in} - V_{out} < 0$, which we will denote as $v_L(t)$.

$$v_L(t) = L\left(\frac{di_{off}}{dt_{off}}\right) \rightarrow di_{off} = \frac{1}{L}V_L dt_{off} = \frac{1}{L}(V_{in} - V_{out})dt_{off}$$

where di_{off} is the current released by the inductor in the OFF state and dt_{off} is the time that the transistor was off.

KCL dictates that $di_{off} + di_{on} = 0$; otherwise, we would have some charge buildup over time. Using this new constraint condition for our boost converter, use the equations above to find an expression for t_{on} in terms of V_{in}, V_{out}, t_{on} and t_{off}. Note that it is actually independent of the inductance L. Express your answer in the form of $t_{on} = \ t_{on}(V_{in}, V_{out}, t_{off}\ )$.

Score __/5

For our boost converter application, we want $V_{in} = 5\ V$ to be boosted to $V_{out} = 15\ V$ with a square wave frequency of $100\ kHz$. Using the relationship you derived in the previous step, we can now determine t_{on} and t_{off}, the duration of transistor's on and off states, respectively. Remember that the period of our input square wave is $T = t_{on} + t_{off}$ and the frequency is $f = \frac{1}{T}$.

Using these parameters, solve for the duty cycle of the square wave we need to input to the transistor. In addition, graph two periods of the square waveform along with the transistor drain voltage waveform, assuming the boost converter is in steady state.

Score __/15

Load Resistor and Inductor

Now, we will determine the component values for the resistor and inductor. For our application, we want the boost converter to provide, on average, $I_{load} = 4.5\ mA$ to our load resistor.

Since $V_{out} = 15\ V$, we can determine the power ($P = IV$) dissipated by the load resistor. Due to energy conservation, this same energy must be supplied by your bench supply. Since $V_{in} =\ 5\ V$, the average input current, $I_{L,av}$, can be determined.

Since the boost converter transitions between ON and OFF states, I_L, the current through the inductor, increases by dI to $I_{L,max}$ when the transistor is on and decreases by dI to $I_{L,min}$ when the transistor is off, where dI is just the di_{on} and di_{off} found earlier. Even though I_L fluctuates, it has an average value that is equal to $I_{L,av}$, the input current.

Append to the graphs you drew earlier with another graph that shows $I_L(t)$ as the boost converter transitions between ON and OFF states. Mark all relevant graph characteristics qualitatively, such as $I_{L,min}$, $I_{L,max}$, $I_{L,av}$, ON state, OFF state, and dI. (Hint: How are dI and dt related?)

Score __/10

With the design specification that average input current must not deviate by 22% of its value, determine $I_{L,av}$, dI, and R_L. (Hint: I_{load} is the current flowing through the resistor when there is $\sim 15\ V$ across the load resistor.)

Score __/10

For the inductor L, we know that the value depends on three parameters: the voltage V_L across the inductor, the time differentials $dt_{on} = t_{on}$ and $dt_{off} = t_{off}$, and the current change dI. Based on the previously established equations, what value inductor should you use for the boost converter? (You should get the same answer regardless of which equation you use.)

Score __/5

Bypass Capacitor

In our boost converter circuit, notice that the voltage source is only connected to the load resistor R_L when the transistor is OFF. How do we ensure that the boosted voltage remains across R_L when the transistor turns ON?

The solution is the **bypass capacitor** seen here in the boost converter. As we continuously increase and decrease the current flowing through R_L by dI, our v_{out} becomes noisy and jittery. With a bypass capacitor installed, we create a short, a **bypass** route, for high frequency noise to get to ground. It is equivalent to saying that we low-passed our v_{out} signal. Moreover, once charged, the capacitor will maintain the boosted v_{out} over R_L because a capacitor will resist change in voltage, especially during the ON state of the boost converter.

In the case of our boost converter, we really cannot achieve a constant supply of 15 V, but we can produce a waveform that has an average value of $V_{out,av} = 15\ V$. We can also constrain the deviation from the average by a certain value dV. Using the equations that govern the discharge of an RC circuit, we can compute the value for the capacitor C given dV and the load resistance R_L.

In the space provided below, draw a graph for $v_{out}(t)$ when the transistor switches states. Mark clearly t_{on} , t_{off} , dV and $15\ V$ on your graph. Also, show that the relationship between R_L, dV, $V_{out,av}$, and C is given by:

$$C = \frac{t_{on}}{R_L} \frac{1}{\ln\left(\frac{v_{out,av} + dV}{v_{out,av} - dV}\right)}$$

Since we want small ripples in $v_{out}(t)$, we choose dV to be $100\ mV$. Calculate C.

Score __/20

Diode

Like electrolytic capacitors and batteries, **diodes have polarity**, so make sure you use the correct orientation when you build your circuit. The diode is a unique circuit component that only passes electrical current in one direction when positive voltage is applied.

In the space below, plot the i-v curve of an ideal diode with no turn on voltage, label all of the diode's states, as well as what the transistor's state should be to trigger each diode state:

Score __/5

In our application, we want the capacitor and resistor to remain isolated from the rest of the circuit during the charging phase or ON state of the inductor. Thus we put a diode between the two parts of the circuit. When we recharge the inductor in ON, the discharging capacitor only discharges through the resistor and will not provide any back current to the other half of the circuit.

Putting it Together

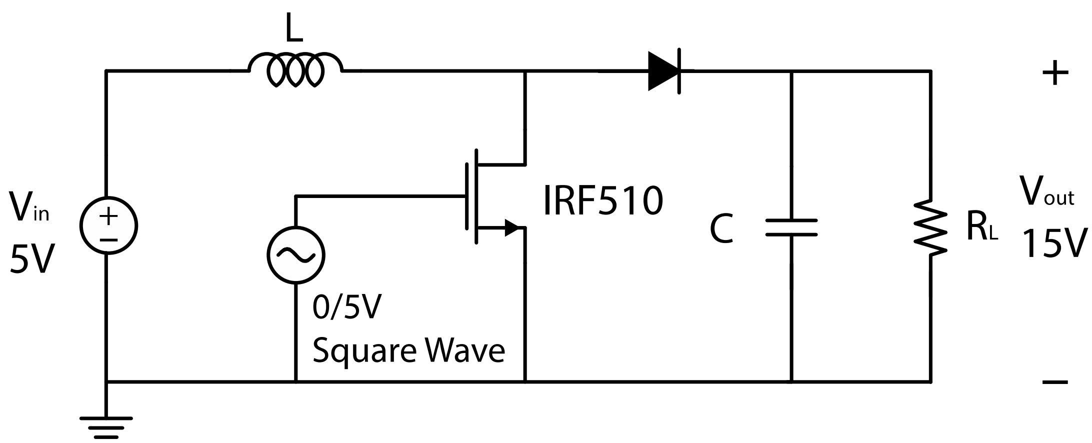
Goody. You're almost done. For ease of construction, fill in the table below with your calculated values from pre-lab. We've done the first one for you.

Circuit Parameter	**Value**
V_{in}	$5\ V$
V_{out}	
Square Wave f	
Square Wave Duty Cycle	
L	
R_L	
C	

Score __/5

Lab Component

We now want to build our boost converter circuit and see if it really does perform what we claimed that it would do earlier.



Boost Converter Schematic (again…)

We will be using the Programmable Power supply with a current limit of $100\ mA$ and the function generator to provide the sources for V_{in} and the square wave, respectively.

Using your schematic and appropriate component values, first build the boost converter. Do not supply any power yet. The drain terminal of the IRF510 transistor should go to the anode of the diode.

Now turn on the function generator and configure it so that it has the frequency and duty cycle you determined earlier. Also, we want to produce a square wave that ranges from $0\ V$ to $5\ V$, which means we would need to create a DC offset. After you're finished, connect this function to the IRF510's gate terminal.

After the converter is built, using the oscilloscope, connect the scope to the **drain** and **gate** nodes. Compare your answer with what you found in pre-lab.

Using your DMM, probe the output voltage of your boost converter and verify that the output value is the same or similar to your predicted value.

Demonstrate this circuit to your GSI for check off and be prepared to explain your oscilloscope reading.

Your GSI Signs Here **(10 points)**

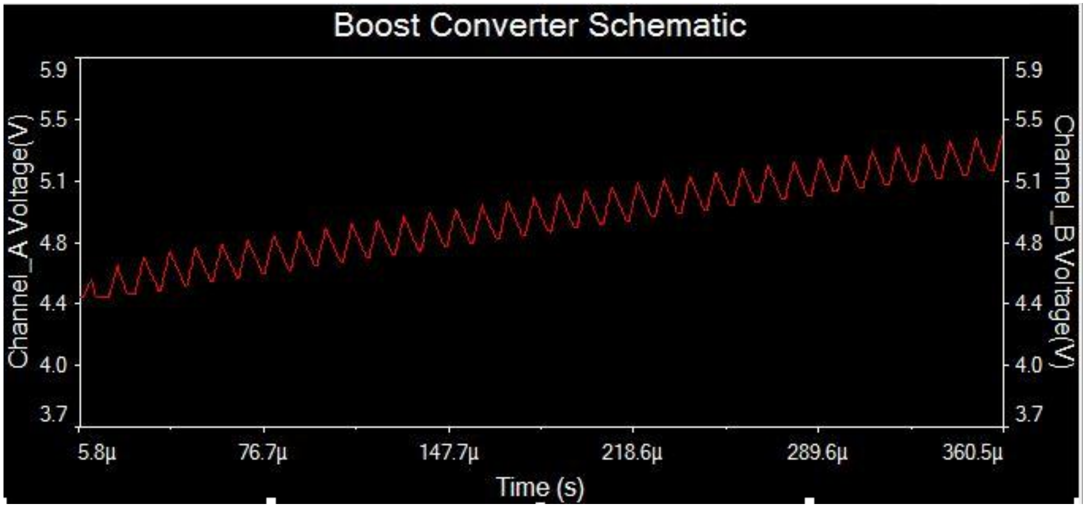
Lab Questions

Delirious from a midterm grading session, your GSI fed $V_{gate} = 2.5\sin(\omega t)$ to transistor's gate. Briefly explain what effect this will have on boost converter's operation and graph the expected output waveform at the drain node. Mark graphs clearly. What is V_{out} as measured from your circuit? Assume that if the gate voltage is above 4.5 V, then the transistor will be on.

Score __/5

Realizing that their boost converter doesn't work, the hapless GSI changes the DC offset of the input voltage so that $V_{gate}(t) = 2.5\sin(\omega t) + 2.5$. What would the drain nodal voltage waveform look like now? Label graphs clearly and annotated with explanations. What is V_{out} from your circuit?

Score __/5



The above oscilloscope reading reports the **initial transient behavior** of our boost converter's output when we first power it, with a square wave as the input to the transistor. Instead of being a constant voltage, the average value of the V_{out} waveform is increasing. Explain qualitatively why this is the case.

Score __/5

Lab Report Submissions

This lab is **due at the end** of this lab section. Make sure you have **completed all questions** and **drawn all the diagrams** for this lab. In addition, attach any loose papers specified by the lab and submit them with this document.

These labs are designed to be completed in **groups of two.** Only one person in your team is required to submit the lab report. Make sure the names and student IDs of **BOTH** team members are on this document (preferably on the front).

[i] Lab 5: Boost Voltage Supply, B.E. Boser
[ii] Lab 5: Boost Voltage Supply, B.E. Boser
[iii] Lab 5: Boost Voltage Supply, B.E. Boser