

Name & SID 1 :

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Boost Converters

We have tried to use resistors (voltage dividers) to transform voltages but found that these solutions suffer from very poor efficiency: A significant fraction of the total power is dissipated in the resistors and not available for the load. Moreover, dividers are limited to lowering the voltage. This is problematic in many applications such as micro-mechanical actuators (MEMS) that often require high voltages for operation.

With inductors and capacitors we can overcome both problems. Since these elements (ideally) only store but do not dissipate power, much higher efficiencies are attainable.

In this laboratory we design and test a special kind of switching power supply called boost converter that boosts the input voltage to a higher value and dimension the circuit to generate 15 V from a 5 V input. Figure 1 shows the schematic diagram. The device labeled IRF510 is a transistor. Download its datasheet from the course web. The diode conducts current only in the direction of the arrow.

To analyze the circuit we assume first that it is working correctly, in particular that the output voltage is 15 V. We will later verify of course that this is indeed the case. The voltage V_c is a pulse train and changes between 0 V and 5 V. For $V_c = 5$ V the transistor (IRF510) is on and behaves essentially like a short circuit. Then $V_{boost} = 0$ V and $V_{diode} = V_{boost} - V_{out} = -15$ V. Since V_{diode} is negative, the diode does not conduct any current, i.e. it behaves like an open circuit. With $V_c = 0$ V the situation reverses: now the transistor is off and the diode conducts. Figure 2 on the next page illustrates the two situations.

In situation (a), $V_c = 5$ V, the supply voltage V_{in} appears across the inductor. From the differential equation for inductance we observe that inductors integrate voltage. Therefore the inductor current I_L is a ramp with slope determined by V_{in} and L . In situation (b) the inductor again integrates the voltage $V_{in} - V_{out} = -10$ V that appears across it. In steady state the current increase and decrease must be identical as otherwise the average current would continually increase or decrease. Since it is negative the current through the inductor decreases, as shown in Figure 3 on page 3.

Since voltage is proportional to the slope of the current, we note intuitively that reducing the ratio of T_{off}/T_{on} results in higher output voltage V_{out} . This is because the positive slope is proportional to V_{in} and the negative slope of the decreasing current is proportional to $V_{out} - V_{in}$. In the laboratory we will analyze this relationship quantitatively.

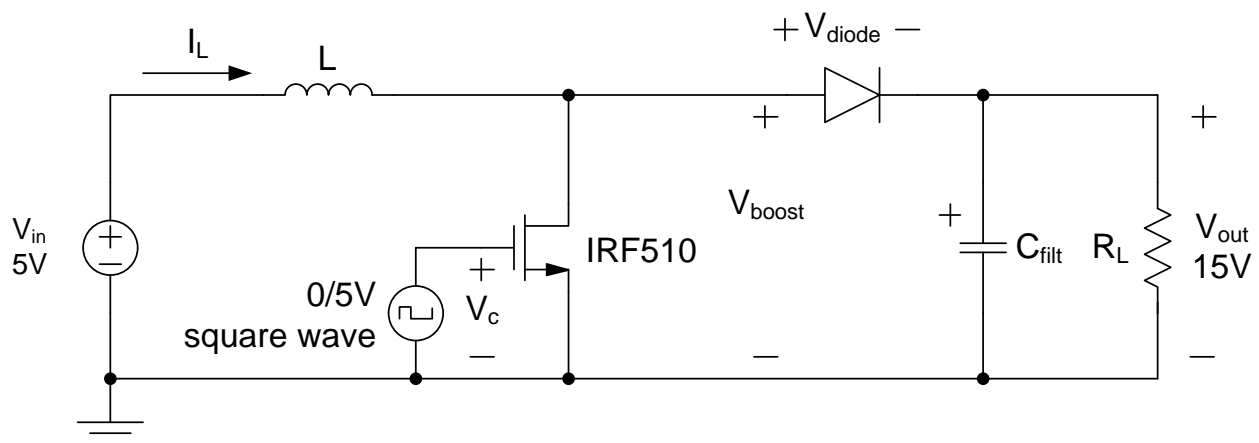


Figure 1 Boost converter.

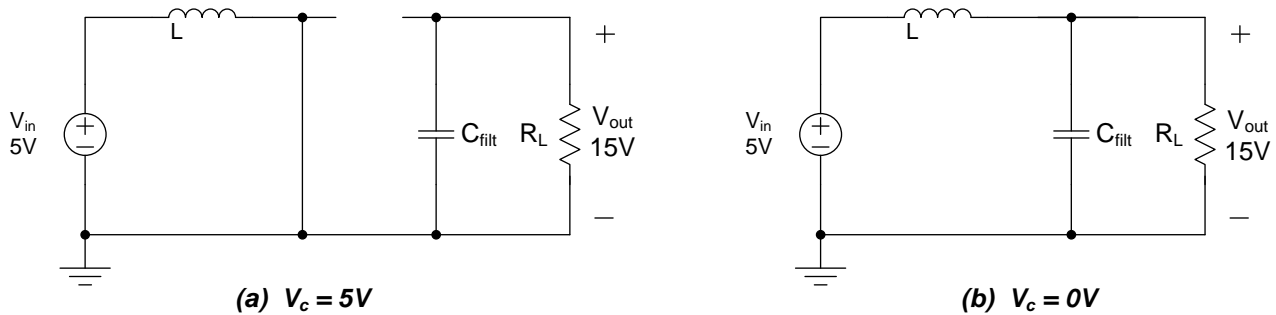


Figure 2 Boost converter operating principle with the switch (transistor) closed (a) and open (b).

Design

Let's first derive an expression for the voltage boost factor, V_{out}/V_{in} . We start by writing expressions for ΔI_L during T_{on} and T_{off} . At this point, enter only the expressions. Once you have determined the value of L (see below) you can solve for and enter the numerical answer. Same for the simulation result. Hint: set up the differential equation for current and voltage in the inductor during the two phases.

	Expression	Simulation	Calculation
During T_{on}	$\Delta I_L =$	1 pt. 0	1 pt. 0
During T_{off}	$\Delta I_L =$	1 pt. 1	1 pt. 1

From the timing diagram shown in the guide we know that the magnitude of I_L is the same during T_{on} and T_{off} . Equate the equations above and solve for the voltage boost factor V_{out}/V_{in} .

Remarkably this result depends only on T_{on} and T_{off} and is independent of the value of the inductance. Calculate T_{on}/T_{off} for $V_{out} = 15\text{ V}$ and $V_{in} = 5\text{ V}$.

$$T_{on}/T_{off} = \quad \text{1 pt.} \quad 2$$

For simplicity, in this laboratory we will generate T_{on} and T_{off} with the pulse generator. More practical implementations adjust this ratio dynamically to keep the value of V_{out} constant in the presence of variations of V_{in} and the load current. Calculate the value of T_{on}/T_{off} that keeps V_{out} constant despite varying V_{in} .

$$V_{in} = 2.7\text{ V} \quad T_{on}/T_{off} = \quad \text{1 pt.} \quad 3$$

$$V_{in} = 6.3\text{ V} \quad T_{on}/T_{off} = \quad \text{1 pt.} \quad 4$$

To finalize the design of the boost converter we must determine the operating frequency $f = 1/T$ with $T = T_{on} + T_{off}$ and the values of L and C_{filt} . We pick $f = 100\text{ kHz}$ to account for the frequency limitation of solderless breadboards¹. From this we can calculate T_{on} and T_{off} and then solve for L from one of the equations for $\Delta I_L = 6\text{ mA}$. Round L to the nearest available value (use the resistor scale, i.e. multiples of 10, 12, 15, etc).

$$L = \quad \text{1 pt.} \quad 5$$

During T_{on} the diode is not conducting and the entire current to the load comes from C_{filt} . Because of this the output voltage will drop. Keeping this drop to $\Delta V_{out} = 28\text{ mV}$ for $R_L = 1\text{ k}\Omega$ determines the value of C_{filt} (use the next larger available value in the lab). Realizing that $\Delta V_{out} \ll V_{out}$ we conclude that the current through the resistor is approximately constant, $I_{RL} = V_{out}/R_L$. Knowing the current, voltage drop and T_{on} , Calculate C_{filt} :

$$C_{filt} = \quad \text{1 pt.} \quad 6$$

Verify your result with SPICE. For simulation only, add a $6\ \Omega$ resistor in series with the inductor to account for the winding resistance (do not add this resistor in the actual circuit you will be building). Attach a transient simulation showing V_c , V_{boost} , V_{diode} , V_{out} and the current through the inductor for 3 cycles in steady state to your lab report (4 points; no credit for lab reports without simulation).

$$\text{Simulated } V_{boost} = \quad \text{1 pt.} \quad 7$$

¹Switching power supplies are usually operated at higher frequencies to reduce the size of the inductor.

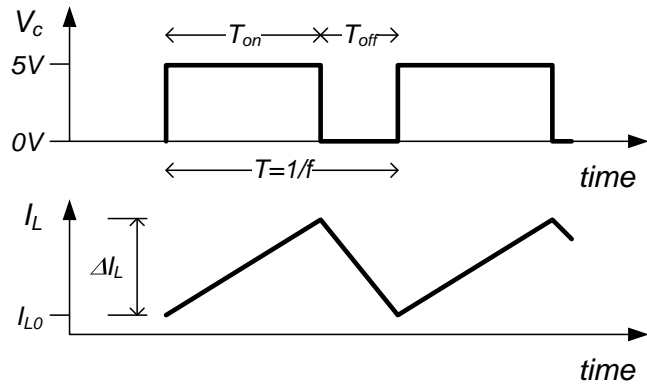
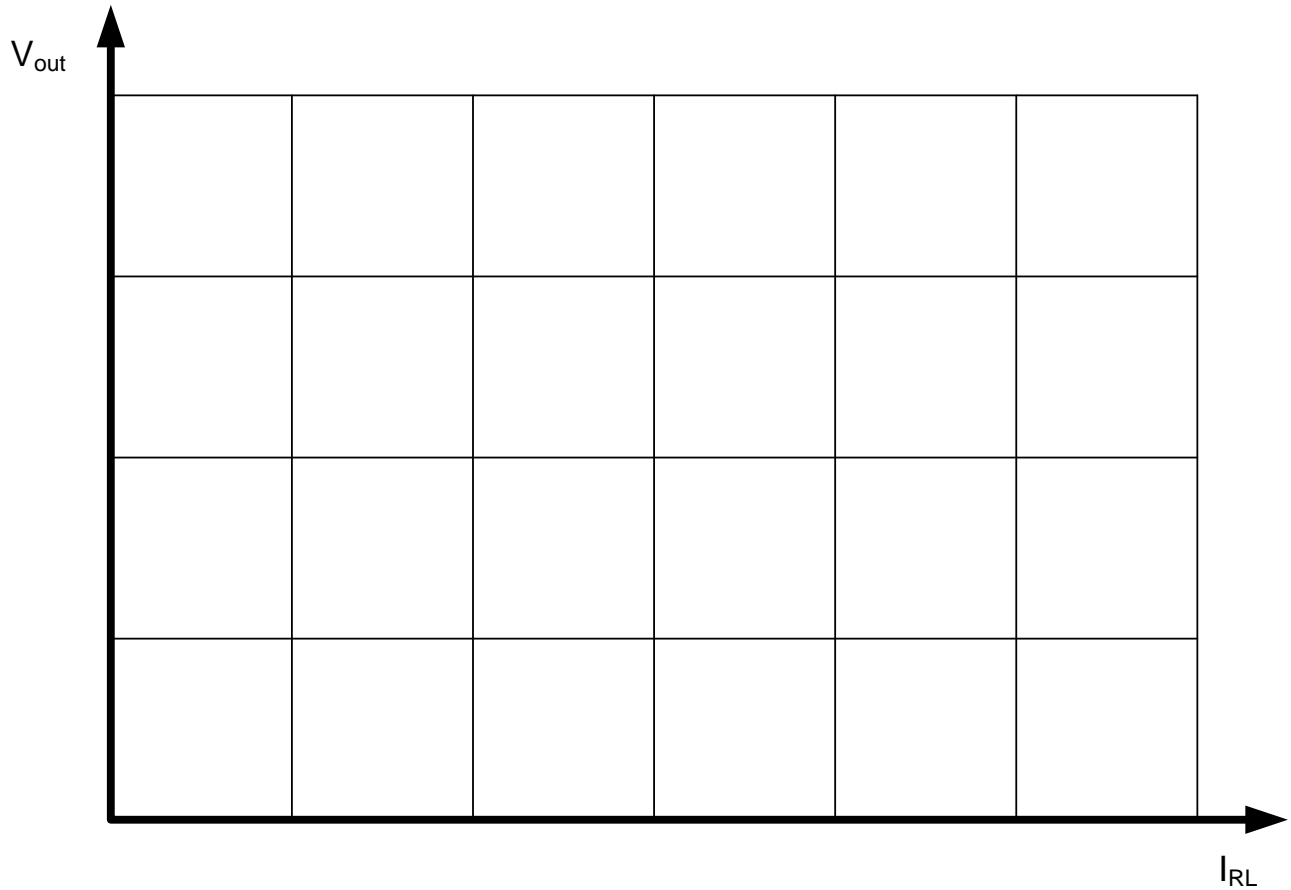


Figure 3 Boost converter timing diagram.

Now you are ready to test the boost converter in the laboratory. Although it is designed to generate only 15 V, it can produce voltages in excess of 30 V e.g. when the input voltage is chosen higher than 5 V. **Exert extra caution and touch circuit nodes only after having determined (e.g. with the oscilloscope) that voltage levels agree with your simulation results and are below 30 V.** Also, complete the entire circuit before turning on power. Especially do not omit the diode and load resistor. Measure V_c , V_{boost} , V_{diode} , V_{out} with the oscilloscope and compare your result to SPICE. Comment on any discrepancies (hint: consider the assumptions made for the calculations).

Explain discrepancies between calculations, simulations, and measurements:

In SPICE and the actual circuit, vary the load resistor R_L from $100\ \Omega$ to $20\ \text{k}\Omega$ and graph your result. Label the axes!



Demo the circuit to the GSI.

Ideally the voltage should be independent of V_{in} and the current I_{RL} through the resistor. In practice it drops because of the constant boost factor and the series resistance of the inductor and diode, and the finite on-resistance of the transistor. Practical implementations of boost converters include additional circuitry that monitors the output voltage and dynamically adjusts T_{on}/T_{off} to ensure a constant V_{out} .

Increase the input voltage to $V_{in} = 6.3\ \text{V}$. What are the calculated, simulated (you need to rerun SPICE), and measured values of V_{out} ? Use the design value for T_{on}/T_{off} for nominal V_{in} and V_{out} .

	Measured		Simulated		Calculated	
$V_{out} =$		1 pt. 7		1 pt. 7		1 pt. 7

Now vary T_{on} (without changing the frequency f) to adjust V_{out} back to $15\ \text{V}$. Compare measurement results with your understanding of the circuit. Fill in the calculated, simulated, and measured values of T_{on} and T_{off} that restore V_{out} to its design value while keeping f constant.

	Measured		Simulated		Calculated	
$T_{on} =$		1 pt. 8		1 pt. 8		1 pt. 8
$T_{off} =$		1 pt. 9		1 pt. 9		1 pt. 9

Explain discrepancies between measured, simulated, and calculated results.

1 pt.
10

Ask the GSI to verify your circuit.