Workshop 5 - Boost Converter

An application of inductance and capacitance

Stray inductance (self- and mutual-) is a serious problem in switching applications where high frequencies, high currents, or both are involved. Ampere's Law dictates that fast switching small currents, or slow switching large currents, must naturally be accompanied by significant time-varying magnetic fields. Any conducting loop (e.g. wire or PCB track) exposed to such a field is prone to enclosing a correspondingly significant time-varying magnetic flux, depending on its relative spatial orientation. Consequently, large EMFs (i.e. voltages) and corresponding currents can be induced in the conducting loop, according to Faraday's law and Ohm's law. Where the conducting loop is part of an electrical system, this induction can result in serious noise problems. This noise, referred to as "bounce" (when self-induced) or "electromagnetic interference (EMI)" (when mutually-induced), imposes serious constraints on switching speeds and currents in high speed digital and analog systems if not addressed in the design process.

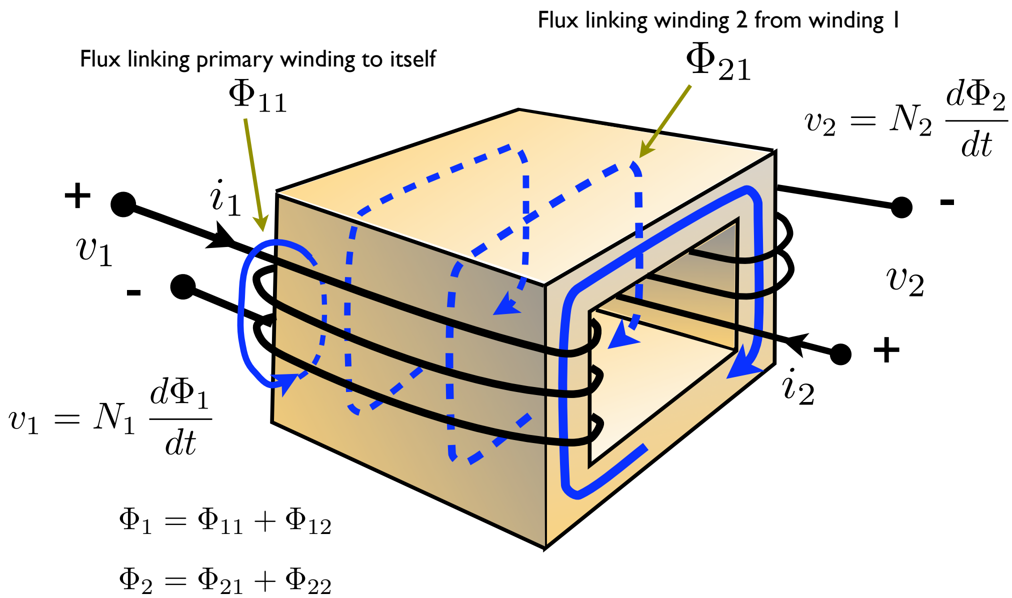

Figure 1: Induced EMF is essential for transformer operation.

While stray inductance is typically undesirable, designed (i.e. intentional) inductance is extremely important in electrical systems. For example, transformers rely on exactly the same principles, where current in a primary winding gives rise to a magnetic field and hence flux through a secondary winding, thereby providing a wireless (and hence DC decoupled) mechanism for electrical power transfer via induced EMF. Furthermore, by modifying the ratio of turns used in the primary and secondary windings, voltage or current gain can be implemented (but not both, due to the conservation of energy). Transformers are essential as low-loss interfaces for electrical power transmission systems that connect power stations to users.

Although time-varying currents are required to induce an EMF via Faraday's law, this does not preclude the application of inductors in the implementation of DC voltage gain. Indeed, the behaviour of inductors (and in particular, their response to fast changes in current) form the basis for a class of devices various named *DC-to-DC converters*, *DC power converters*, or *switch mode power supplies*. The central idea behind the DC-to-DC converter is to transform one DC voltage into another by first converting the primary DC voltage to an AC voltage, amplifying (or attenuating) that via an inductance (either self- or mutual-), and then converting that AC voltage back to a secondary (usually different) DC voltage. These converters are divided into two types, called *buck* and *boost*. Buck converters convert a DC voltage into a smaller one, while boost converters convert a DC voltage into a larger one. While a DC voltage *regulator* performs the same role as a buck converter, it is far less efficient as the power dissipation associated with the voltage drop from output to input of a regulator is dissipated as heat. DC-to-DC converters are in general efficient power converters, but tend to be noisier than regulators due to the underlying AC conversion. DC-to-DC converters are particularly useful where access to a particular DC voltage is required that is not provided by the supply. They are very common in laptop computers, mobile phones, and other battery operated devices with limited supply voltage. Their efficiency is also highly desirable in these applications.

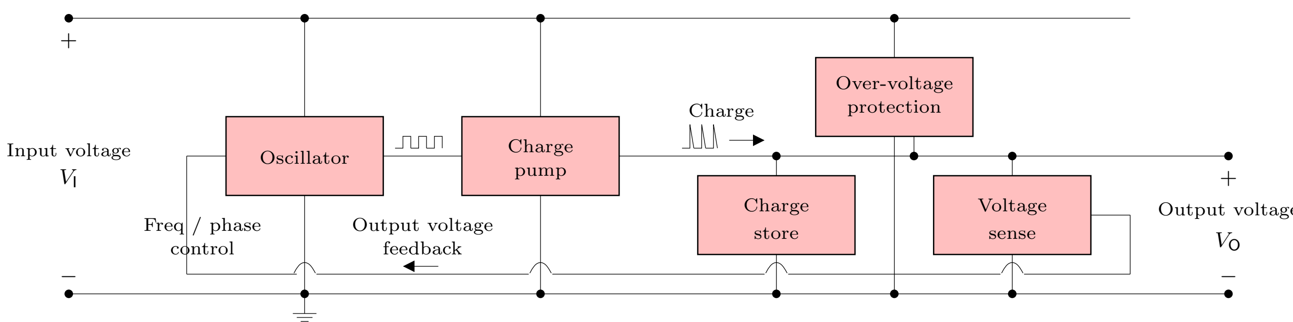

Figure 2: Topology of a basic boost converter.

The topology of a basic boost converter is shown in Figure 2. There, an *oscillator* is used to convert a voltage DC input V_I into an AC signal. This AC signal is used to drive a *charge pump*. A very simple charge pump consists of a current switch (a transistor or relay for example), an inductor, and a diode. This charge pump is used to drive charge in one direction from the DC input voltage V_I into a *charge store* (i.e. a capacitor). As the stored charge builds up, the rectifying action of the diode in the charge pump allows the capacitor voltage to readily increase well beyond the DC input voltage V_I. An over-voltage protection circuit is typically used to safely limit this voltage, while a *voltage sense* is used to provide feedback of the output voltage (or some function of it) to control the oscillator. This feedback facilitates the implementation of output voltage regulation, by adjusting the oscillator frequency in response to changes in the output voltage. The result is a power supply that converts a DC input voltage V_I to a significantly higher DC output voltage V_O, regulated at a particular level.

1 Safety

The boost converter considered in this workshop can generate high voltages (albeit at low currents) during its operation. Electrolytic capacitors are prone to hazardous failure, particularly if device polarity is not correctly adhered to, or if device operating limits are exceeded. Such failures can be explosive, generating projectiles that pose a serious hazard to unprotected eyes.

Safety glasses MUST be worn at all times during this workshop.

SAFETY

Workplace safety in the laboratory is paramount. The following safety measures **MUST** be adhered to at all times:

- Safety glasses must be worn by **ALL** participants in this workshop.
- Correctly functioning over-voltage protection **MUST** be included in all circuits under test.
- Any circuit implementing the charge store must be checked by the demonstrator **PRIOR** the application of power.
- Circuits **MUST** be powered down prior to initiating any modifications.

Tasks

1.1. Confirm in writing that all members of your group have read and understood the safety issues and precautions set out above. All group members **MUST** sign.

2 Components

The components will be utilized in this workshop:

- 1×LM555 timer integrated circuit.
- 1×1N4148 signal diode.
- 3×Zener diodes (1×5.1 V, 1×30 V, and 1×50 V, or equivalent).
- 3×LEDs (1×red, 1×green, and 1×yellow).
- 1×10 mH inductor.
- $1 \times 47\,\mu$F electrolytic capacitor, rated in excess of 300 V.
- $1 \times 10\,\mu$F electrolytic capacitor rated at 63 V.
- Various ceramic capacitors.
- Various 5 % tolerance resistors.
- 1×100 kΩ variable resistor.

Tasks

2.1. Verify that you have a "complete" set of components as per the list above. (Note that some components are not listed as you are required to selected them later.)

2.2. Sketch the current / voltage characteristic of an ideal Zener diode. Propose and sketch a circuit using a 1 kΩ resistor and a 60 V DC supply that would allow the three Zener diodes provided to be distinguished by experiment. Explain your answer. Implement this circuit with a 10 V supply to verify the identity of the low voltage Zener diode.

2.3. Identify and distinguish the two electrolytic capacitors. By inspection of both devices, illustrate with a sketch which is the + terminal and which is the − terminal for both devices.

IMPORTANT: it is essential when using these devices in any circuit that the correct polarization be observed and checked prior to the application of power. Incorrect connection can result in destructive and hazardous device failure.

2.4. Using a multimeter, determine / verify the component values of all resistors and capacitors provided.

3 Over-voltage protection

To ensure safe operation of the boost converter throughout design, construction, and testing, it is essential that over-voltage warnings and limits be implemented on the input and output voltages at all times. The purpose of the over-voltage protection sub-module of Figure 2 is to implement these warnings and limits. A circuit diagram for this module is provided in Figure 3. The key components in this circuit are two Zener diodes.

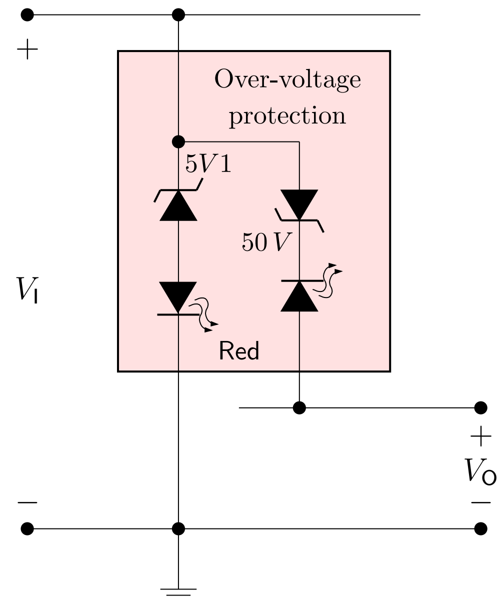

Figure 3: Over-voltage protection.

Tasks

3.1. Referring to your earlier sketch of the current / voltage characteristic for an ideal Zener diode, explain the concept behind the over-voltage protection circuit shown.

3.2. Explain the purpose of the light emitting diodes (LEDs).

3.3. What is the typical contact potential of an LED?

3.4. What is the input voltage limit implemented? Justify your answer.

3.5. What is the output voltage limit implemented? Justify your answer.

3.6. Construct the circuit shown in Figure 3. Test the input-side of the circuit by applying $V_\mathsf{I} = 5\,\mathsf{V}$. What do you observe?

DO NOT PROCEED UNTIL THE INPUT OVER-VOLTAGE PROTECTION IS WORKING CORRECTLY

4 Oscillator

The role of the oscillator module in Figure 2 is to generate a periodic AC voltage from the DC input voltage V_I. While numerous oscillator circuit topologies are suitable for this application, a very simple oscillator design based on the LM555 timer chip will be used here. The LM555 is an integrated circuit that is designed to implement timing delays, pulse generation, pulse width modulation, ramp generation, etc. It may readily be configured in either *monostable* or *astable* mode, corresponding respectively to the generation of timed pulse delays, or oscillation. In performing the role of the oscillator module, the astable mode of operation is of interest here. Further information concerning the LM555 is available in the datasheet, which may be downloaded from `www.national.com`.

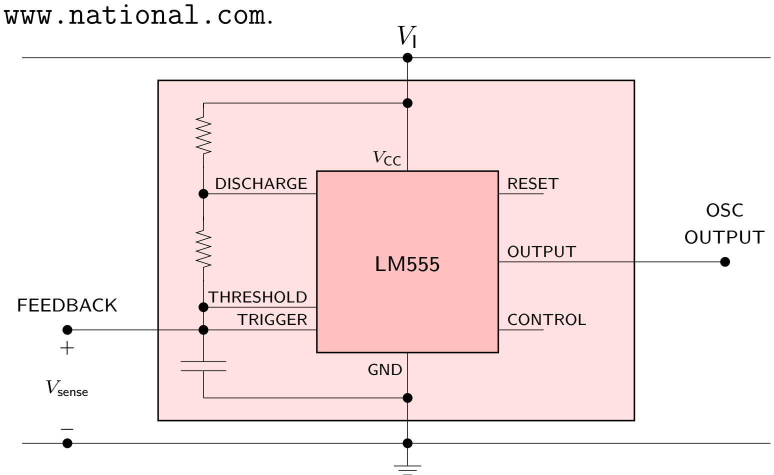

Figure 4: Incomplete oscillator circuit based on the LM555 timer IC.

Tasks

4.1. Download the LM555 datasheet and locate therein the circuit diagram for astable operation. Based on the information provided in the datasheet, describe in words the basic idea behind astable operation.

4.2. Based on formulae provided in the datasheet, determine a resistor value for all required resistors such that a frequency of oscillation of $4.8\,kHz$ is obtained using a capacitance of $10\,nF$. Assume $V_\mathsf{I} = 5\,\mathsf{V}$. (See the datasheet for definitions of these components.) Sketch the type of output waveform expected from this astable operation.

4.3. Complete the circuit design shown in Figure 4 by including all wired connections and component values required. You will need to refer back to the datasheet to do this.

4.4. Using the available components, wire up your oscillator design using the breadboard provided. Set $V_\mathsf{I} = 5\,\mathsf{V}$ by using the $5\,\mathsf{V}$ output of the benchtop supply. Sketch the output waveform observed. Measure the period of oscillation obtained. Compare this frequency with the expected value set out in Task 4.2.

5 Output voltage sense and load

Feedback can be used to regulate the output voltage of the boost converter. To do this, a measurement of the output voltage is required. This is the purpose of the output voltage sense module shown in Figure 2. A simple circuit for this module, along with a suitable load for the boost converter, is illustrated in Figure 5. The measurement of the output voltage is denoted by V_{sense}. The aforementioned load consists of a variable resistor and an LED. The resistance is variable so that the effectiveness (or otherwise) of the output voltage regulation can be ascertained.

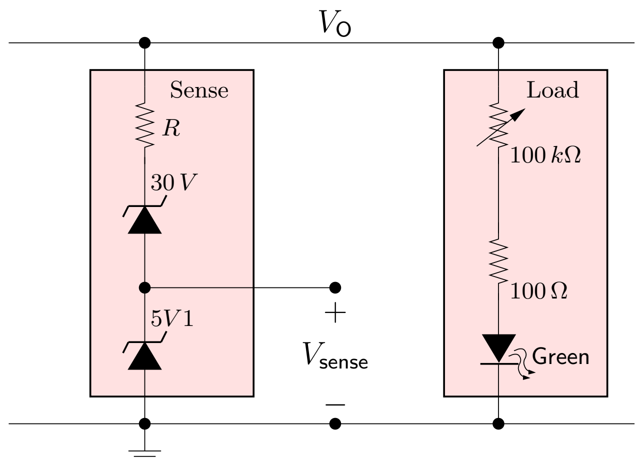

Figure 5: Output voltage sense and load.

Tasks

5.1. Given that the voltage V_{O} is restricted to $V_{\mathsf{O}} \geq 0$, determine the minimum and maximum possible output sense voltages V_{sense}. Use an ideal Zener diode model. Why is it important to limit V_{sense} in this way?

5.2. Under what circumstances is $V_{\mathsf{sense}} > 0$. Explain your answer.

5.3. Based on your answer above, propose a change to the design above that might in principle result in the boost converter output being regulated to $25\,\mathsf{V}$. Explain you answer.

5.4. By examining the load circuit, determine an upper bound for the load current for an output voltage V_{O}.

6 Charge pump and storage

The purpose of the charge pump module shown in Figure 2 is to transfer charge from the low voltage DC input V_I to the storage capacitor. The accumulation of charge q in the storage capacitor C gives rise to the output voltage $V_\mathsf{O} = q/C$. A simple circuit that implements this functionality is shown in Figure 6. There, the role of the NPN BJT Q is to provide current gain, limited by resistance R. As OSC OUTPUT switches between V_I and GND, Q generates a corresponding switched collector current (flowing into the top terminal of Q). The charge pump action is generated by the effect of this switched current on the inductor voltage, in combination with the rectifying action of the 1N4148 signal diode. The charge store is implemented by the $> 300\,\mathsf{V}$ electrolytic capacitor.

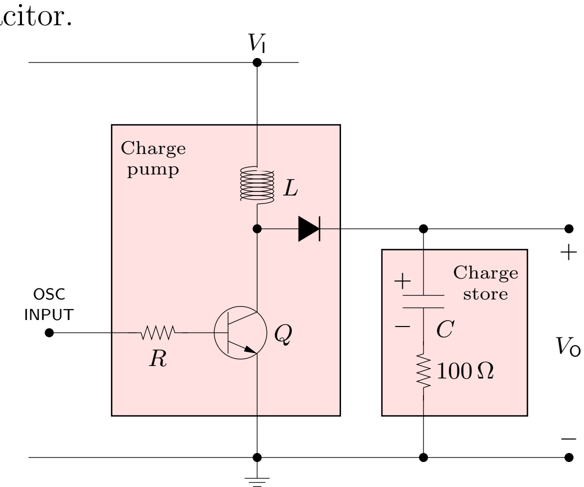

Figure 6: Simple charge pump.

Tasks

6.1. Construct a simulation model of the charge pump model in OrCad. Choose $R = 1\,\mathsf{k\Omega}$, $L = 10\,\mathsf{mH}$, $Q = 2N2222$ (a signal BJT), and $C = 47\,\mu\mathsf{F}$. Select a $1N4148$ model for the diode. Using a square wave voltage source with frequency $10\,kHz$ for the OSC OUTPUT signal, simulate the charge pump circuit shown. Plot OSC OUTPUT and V_O on the same axis.

6.2. By manipulation of the simulation above, infer and describe the effect that the size of inductance L has on the output voltage V_O.

6.3. In an analogous fashion, infer and describe the effect that the frequency of OSC OUTPUT has on the output voltage V_O.

6.4. In view of your answers above, and using further simulations where necessary, discuss how this charge pump circuit works.

DO <u>NOT</u> WIRE UP THE CHARGE PUMP CIRCUIT AT THIS POINT.

7 Construction and initial power up

The component modules of the boost converter shown in Figure 2 will be integrated in a particular order to ensure correct operation. Consult the overview circuit schematic shown in Figure 7 as a guide.

Tasks

7.1. Over-voltage protection: Connect that the input V_I of the over-voltage protection circuit of Figure 3 to the 5 V regulated voltage output of the bench top supply, making sure that the supply is switched off. **DO NOT USE THE ADJUSTABLE VOLTAGE OUTPUT.**

7.2. Oscillator: Connect the oscillator circuit input voltage V_I of Figure 4 to the over-voltage protection circuit input V_I of Figure 3. Apply power to your circuit. Confirm that the oscillator is function correctly by measuring the voltage range and frequency of oscillation obtained. **Remove power from your circuit.**

7.3. Output voltage sense and load: With the power supply switched off, wire up the output voltage sense and load circuits as per Figure 5.

7.4. Charge pump: **DO NOT APPLY POWER TO YOUR CIRCUIT.** Wire up the charge pump circuit as per Figure 6, using $R = 1\,\mathsf{k\Omega}$, $L = 10\,\mathsf{mH}$, and $C = 45\,\mu\mathsf{F}$. Connect V_O of the charge pump circuit to V_O of the over-voltage protection circuit. Connect V_I of the charge pump circuit to V_I of the over-voltage protection circuit. Connect the OSC INPUT of the charge pump circuit to the OSC OUTPUT of the oscillator circuit. **DO NOT APPLY POWER TO YOUR CIRCUIT.**

7.5. Check list: Go through the following check list individually, and again with the demonstrator.

- ❏ Check: **ALL GROUP MEMBERS ARE WEARING SAFETY GLASSES.**
- ❏ Check: Power supply is **OFF**.
- ❏ Check: V_O and V_I of the charge pump circuit are connected to V_O and V_I of the over-voltage protection circuit.
- ❏ Check: $5\,V$ regulated voltage supply is the only supply connection from the bench top supply to your circuit, and is connected to the V_I input of the over-voltage protection circuit.
- ❏ Check: The polarity of the charge storage capacitor C connection is correct, with the + terminal connected to V_O as per Figure 6.
- ❏ Check: The charge storage capacitor C of Figure 6 is rated at in excess of 300 V.
- ❏ Check: **The demonstrator has checked your circuit.**
- ❏ Check: **ALL GROUP MEMBERS ARE WEARING SAFETY GLASSES.**

7.6. **Confirm that you have completed the above safety checks.**

7.7. Briefly apply power to your circuit. **Report any problems (including illuminated RED LEDs) evident to the demonstrator.**

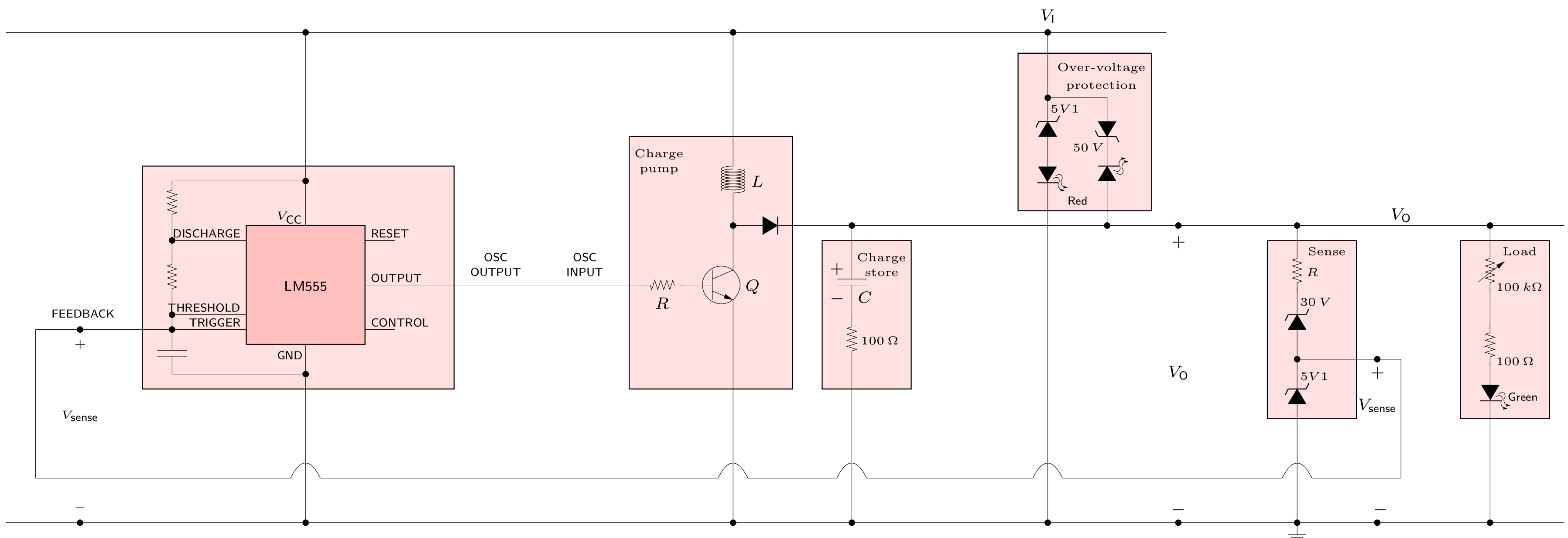

Figure 7: Integrated boost converter schematic.

8 Testing

The boost converter illustrated in Figures 2 and 7 is intended to implement a regulated D.C. source with an output voltage V_{O} that exceeds the supplied D.C. input voltage V_{I}. In view of the implemented circuit of the previous section, the objectives here are as follows:

- Determine whether the implemented circuit does indeed operate as a boost converter.
- Understand how the input voltage is boosted.
- Understand how the output voltage is regulated.
- Understand the circumstances under which output voltage regulation fails.
- Understand how the circuit may be modified to implement a different output voltage.
- Understand the significance of inductance and capacitance in this application.

Tasks

8.1. With power applied to your circuit, measure the output voltage V_{O} using a multimeter. If this voltage is not nomimally 30 V, power down your circuit and recheck all connections. Consult with the demonstrator if in doubt.

8.2. By repeatedly varying (and measuring) the load resistance, construct a plot of output voltage versus load resistance. Determine the load resistance at which the output regulation fails.

8.3. Using the oscilloscope, measure the OSC OUTPUT voltage as a function of time for a specific load resistance for which the output voltage is regulated. Sketch the voltage waveform. Make sure you record the load resistance used. Using the RUN / STOP feature on the oscilloscope may help.

8.4. Repeat the previous task for a different load resistance. Comment on the difference between the OSC OUTPUT voltage waveforms observed. By repeating at other load resistances as required, determine whether there is a connection between the frequency of oscillation and the load resistance. Describe what you observe.

8.5. Slowly reduce the load resistance below that determined in 8.2 above, while simultaneously displaying the OSC OUTPUT voltage waveform. What fundamental change in behaviour do you observe in the OSC OUTPUT waveform from that of 8.4 above?

8.6. Increase the load resistance so that output regulation is re-established. Using the oscilloscope, try to measure the voltage across the inductor L. Use AC coupling. What do you observe? Can you measure the amplitude of the voltage waveform? What is the fundamental property at work in the inductor that gives rise to this behaviour? Explain.

8.7. Repeat 8.6 for the output voltage V_{O}.

8.8. What is the role of the transistor Q? Is heat dissipation likely to be an issue for Q in higher current designs? Explain.

8.9. In view of 8.6 and 8.7 above, and your understanding of how an ideal diode behaves, explain why it is that the DC output voltage V_O generated can exceed the DC input voltage. Why is it critical that the diode be nonlinear?

8.10. Based on all of your observations above, and your earlier analysis and simulations, explain the basic principle behind the operation of this boost converter. Make sure you include in your answer a discussion of how the output voltage regulation works, and the significance of the various components. What impact do you think the choice of component values for L and C have on this operation?

8.11. In view of your answer to 8.10 above, discuss how this circuit could be improved to provide output voltage regulation over a wider range of load resistances. In view of energy conservation, what is the fundamental tradeoff that exists between voltage gain and the minimum operational load resistance that may be achieved? Explain your answer.

9 Clean up

Once you have completed the measurement tasks of Section 8, your circuit should be dismantled and the breadboards and parts returned. All pairs of safety glasses should also be returned.

Tasks

9.1. Switch off the power supply.

9.2. Remove all parts from the breadboard.

9.3. Return the breadboard, parts and safety glasses to the demonstrator.