Lab# 7 Opened loop Switching Mode Power Supply

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Objectives:

- Use MPLAB-Mindi simulator
- Simulate a SMPS -Boost converter
- Calculate the parameters of a Boost converter

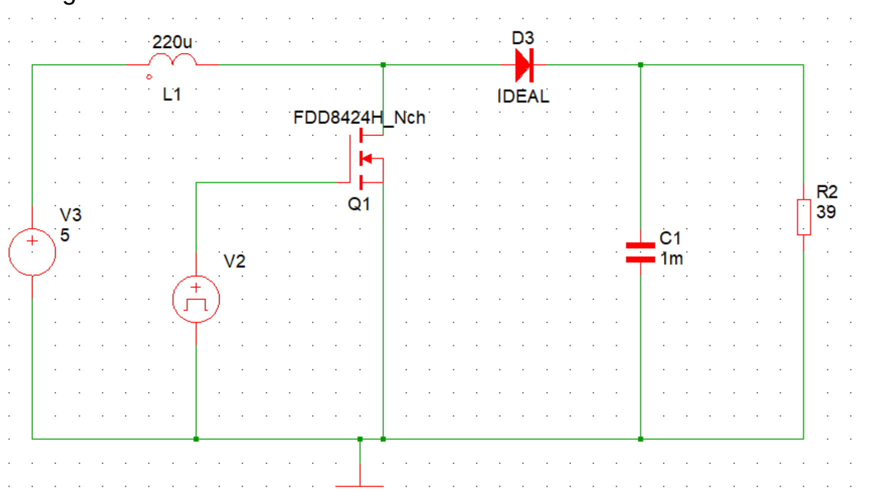
Material: Mindi simulator

To hand in to Team Assignment

1- This document with the answers and measures. Copy-paste screenshots when required.
2- You provide comments to all screenshots.
3- Upload the wxsch project file for all parts.

Lab work

Wire the following circuit:



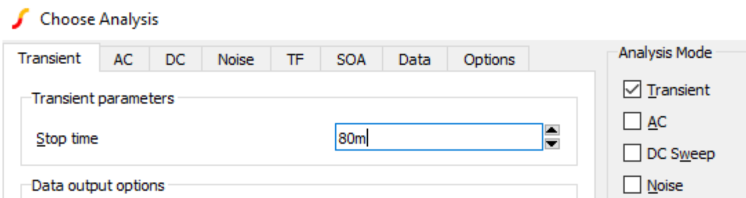
The capacitor's value is 1000uF and the DC source voltage is 5 Volts.

The waveform generator must be set to:

- Pulse
- f = 15kHz
- Voltage 0V to 4V
- Duty Cycle 50%

Choose the type of analysis:

- Click Menu: Simulator -> Choose Analysis



Current and voltage probes

Make sure the waveform generator's duty cycle is set to 50%

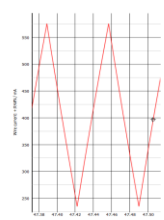
You must generate all three signals on one graphic:

1) Add the following probe to the circuit: Probe Current in Wire - L1
Generate the current graphic. The axis ranges must be as follows: 0 to 1.5A

2) Add the following probe to the circuit: Probe Voltage – Q collector
Generate the voltage graphic. The axis ranges must be as follows: 0 to 15 V

3) Add the following probe to the circuit: Probe Voltage – D cathode
Generate the voltage graphic. The axis ranges must be as follows: 0 to 15 V

All graphics must display 2 periods in steady state. See example below.



From the graphic, measure V_{DS} drop voltage across the MOSFET transistor when it is SATURATED. To read the voltage, move the mouse over the signal to measure.

$V_{DS} = \sim 12.38mV$

From the graphic, measure the voltage drop of the diode.

$V_{D_3} = \sim 0.7V$

From the graphic, measure ΔI in mA:

$\Delta I = 850.55mA - 99.57mA = \sim 750.98mA$

Is the current continuous or discontinuous?

$$T = \frac{1}{f} = \frac{1}{15kHz} = \sim 66.6uS$$
$$t_{ON} = \frac{T}{2} = \frac{\sim 66.6uS}{2} = 33.3uS\ (because\ of\ 50\%\ duty\ cycle)$$
$$t_{OFF} = \frac{T}{2} = \frac{\sim 66.6uS}{2} = 33.3uS\ (because\ of\ 50\%\ duty\ cycle)$$

$$\Delta I = \left(\frac{V_{IN}}{L}\right) * t_{ON} = \left(\frac{5V}{220uH}\right) * 33.3uS = \sim 756.81mA$$

$$V_{OUT} = V_{IN} * \left(\frac{T}{t_{OFF}}\right) - 0.7V = 5V * \left(\frac{\sim 66.6uS}{33.3uS}\right) - 0.7V = 9.3V$$
$$I_{OUT(AVG)} = \frac{V_{OUT}}{R_L} = \frac{9.3V}{39\Omega} = 238.46mA$$
$$P_{OUT} = P_{IN}$$
$$V_{OUT} * I_{OUT(AVG)} = V_{IN} * I_{IN(AVG)}$$
$$I_{IN(AVG)} = \frac{V_{OUT} * I_{OUT(AVG)}}{V_{IN}} = \frac{9.3V * 238.46mA}{5V} = 443.53mA$$
$$I_{L(AVG)} = I_{IN(AVG)} = 443.53mA$$
$$\frac{\Delta I}{2} = \frac{\sim 756.81mA}{2} = 378.405mA$$

$Because\ I_{IN(AVG)} > \frac{\Delta I}{2}, the\ current\ is\ continous.$

Compare with theoretical value. ΔI calculation here:

$$T = \frac{1}{f} = \frac{1}{15kHz} = \sim 66.6uS$$
$$t_{ON} = \frac{T}{2} = \frac{\sim 66.6uS}{2} = 33.3uS\ (because\ of\ 50\%\ duty\ cycle)$$

$$\Delta I = \left(\frac{V_{IN}}{L}\right) * t_{ON} = \left(\frac{5V}{220uH}\right) * 33.3uS = \sim 756.81mA$$

Between the theoretical value calculated for ΔI and the measured value for Δ, the two are very close to each other. Therefore, the calculations done above to find ΔI are correct.

From the graphic, measure Vout in Volts.

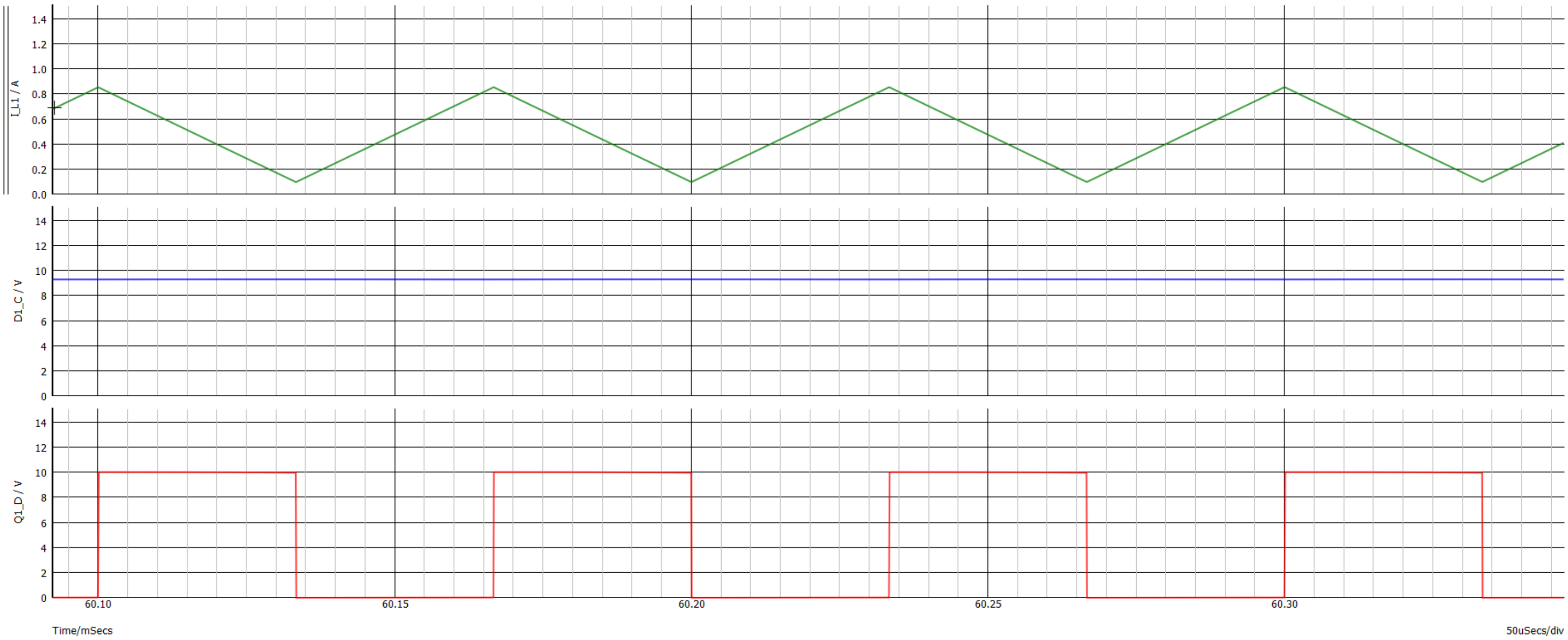
$V_{OUT} = \sim 9.29V$

Compare with theoretical value. You must consider the voltage drop across the diode.

Vout calculation here:

$V_{OUT} = 10V - 0.7V = 9.3V$

Between the theoretical value calculated for Vout and the measured value for Vout, the two are very close to each other. Therefore, the calculations done above to find Vout are correct.



Screenshot for circuit shown above. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Green waveform shows that the current is continuous because it never falls down to absolute zero. Vout (~9.3V) is higher than Vin (5V) because this is the typical behaviour of the boost converter power supply (diagram on page 1).

Now set the waveform generator's duty cycle to 60%

Measure Vout in Volts.

$V_{OUT} = \sim 11.76V$

Is the current continuous or discontinuous?

$$T = \frac{1}{f} = \frac{1}{15kHz} = \sim 66.6uS$$
$$t_{ON} = \frac{(duty\ cycle\ in\ \%)}{100} * T = \frac{60}{100} * T = 0.6 * 66.6uS = 39.96uS$$
$$t_{OFF} = T - t_{ON} = \sim 66.6uS - 39.96uS = 26.64uS$$

$$\Delta I = \left(\frac{V_{IN}}{L}\right) * t_{ON} = \left(\frac{5V}{220uH}\right) * 39.96uS = \sim 908.18mA$$

$$V_{OUT} = V_{IN} * \left(\frac{T}{t_{OFF}}\right) - 0.7V = 5V * \left(\frac{\sim 66.6uS}{26.64uS}\right) - 0.7V = 11.8V$$
$$I_{OUT(AVG)} = \frac{V_{OUT}}{R_L} = \frac{11.8V}{39\Omega} = 302.56mA$$
$$P_{OUT} = P_{IN}$$
$$V_{OUT} * I_{OUT(AVG)} = V_{IN} * I_{IN(AVG)}$$
$$I_{IN(AVG)} = \frac{V_{OUT} * I_{OUT(AVG)}}{V_{IN}} = \frac{11.8V * 302.56mA}{5V} = 714.04mA$$
$$I_{L(AVG)} = I_{IN(AVG)} = 714.04mA$$
$$\frac{\Delta I}{2} = \frac{\sim 908.18mA}{2} = 454.09mA$$

$Because\ I_{IN(AVG)} > \frac{\Delta I}{2}, the\ current\ is\ continous.$

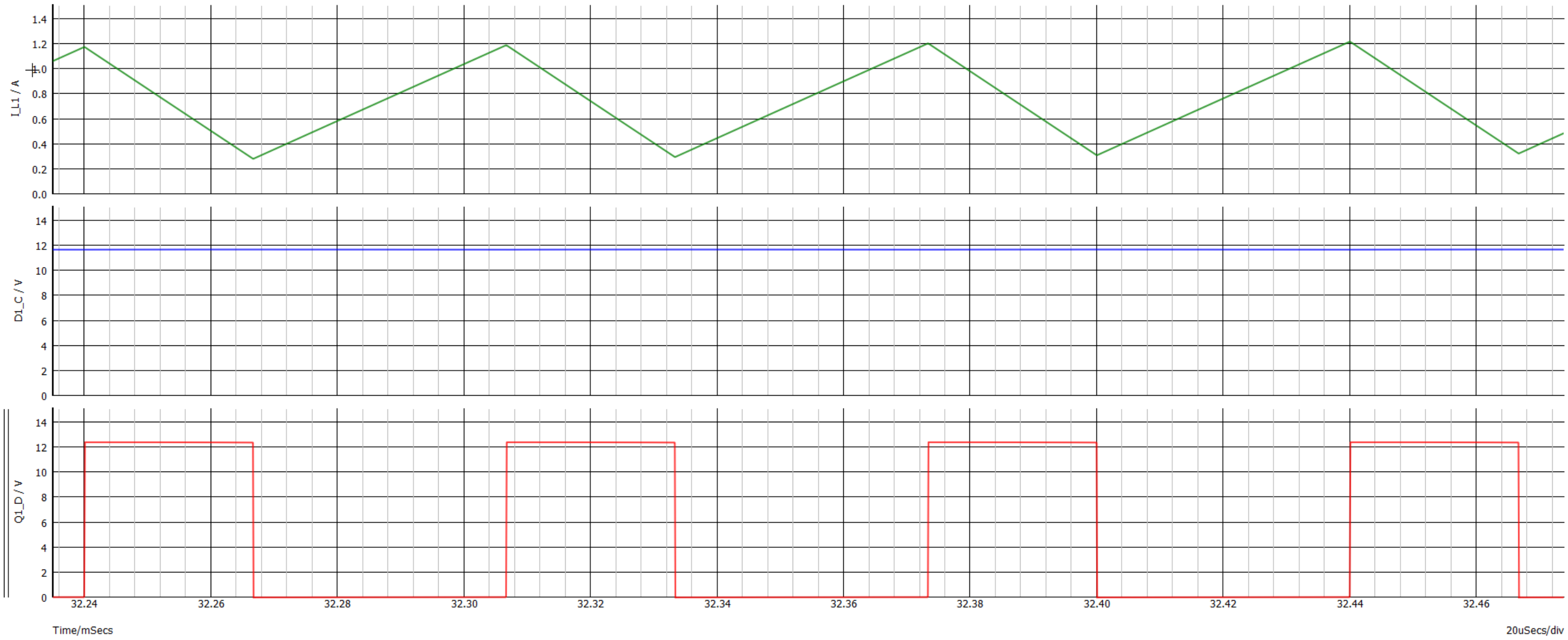
Compare with theoretical value. You must consider the voltage drop across the diode.

Vout calculation here:

$$T = \frac{1}{f} = \frac{1}{15kHz} = \sim 66.6uS$$
$$t_{ON} = \frac{(duty\ cycle\ in\ \%)}{100} * T = \frac{60}{100} * T = 0.6 * 66.6uS = 39.96uS$$
$$t_{OFF} = T - t_{ON} = \sim 66.6uS - 39.96uS = 26.64uS$$

$$V_{OUT} = V_{IN} * \left(\frac{T}{t_{OFF}}\right) - 0.7V = 5V * \left(\frac{\sim 66.6uS}{26.64uS}\right) - 0.7V = 11.8V$$

Between the theoretical value calculated for Vout and the measured value for Vout, the two are very close to each other. Therefore, the calculations done above to find Vout are correct.



Screenshot for circuit shown above. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Similar to when the duty cycle was set to 50%, the green waveform shows that the current is continuous because it never falls down to absolute zero even despite the different duty cycle. The only difference is that Vout is higher (~11.8V) than when the duty cycle was set to 50% (Vout = ~9.3V). Since the duty cycle is higher, there will be more current stored in the inductor L1 when Q1 charges it up before turning OFF (as shown by the green and red waveform above), which in turn will allow for more current to be transferred to the output. Furthermore, Vout (~11.8V) is higher than Vin (5V) because this is the typical behaviour of the boost converter power supply (diagram on page 1).

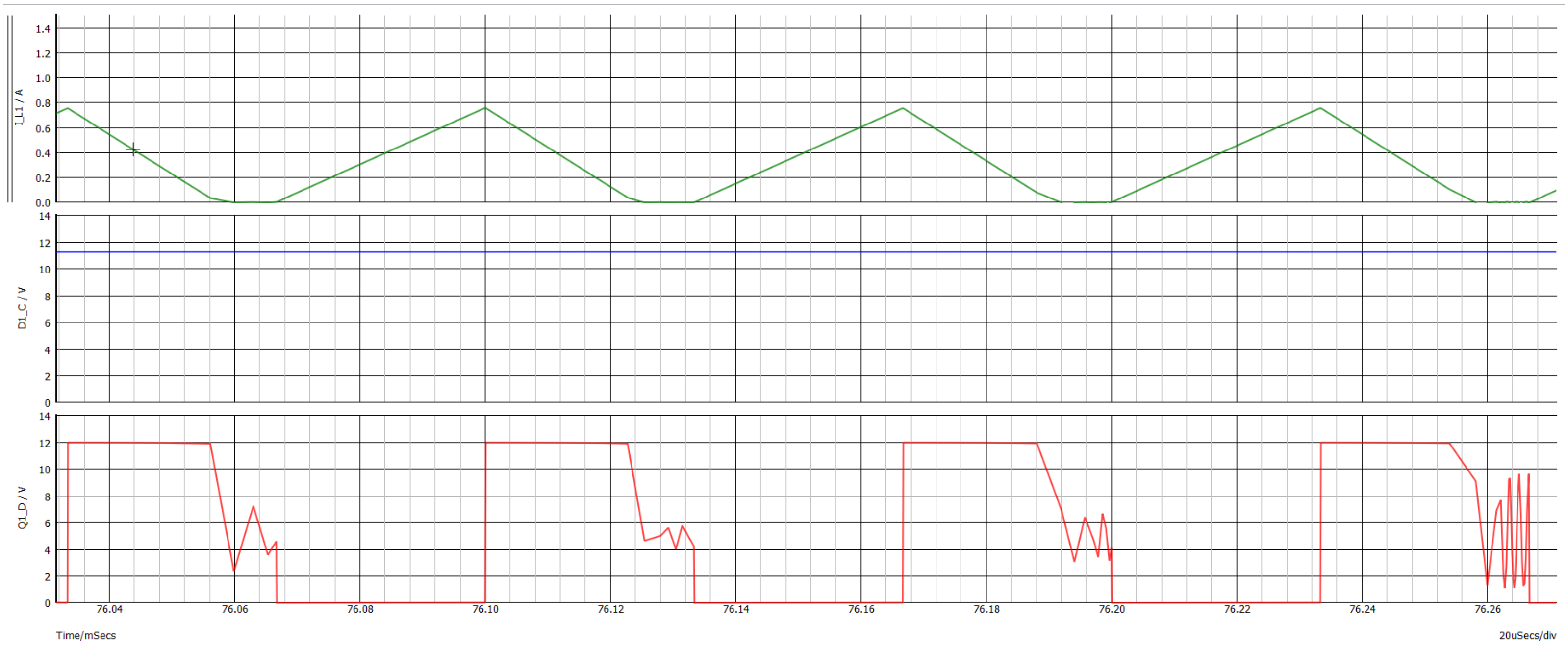
Change the load

Restore the original 50% duty cycle.

In this part you must explain the effect of changing the load resistor value on the current. Change the load to 78 Ohms. You must provide a graphic screenshot with the same three signals.

Is the current continuous? Explain

Based on the results and looking at the screenshot below, it is shown that the current is discontinuous. Looking at the green waveform (current in wire L1), the current drops down to below 0 and therefore the current is not continuous (discontinuous). Since the load attached is not a heavy one, the energy stored in inductor L1 during each ON pulse time of Q1 (when red waveform falls to 0) will be sufficient to completely restore the voltage on the output capacitor and the current in L1 will fall to 0 for the remainder on the ON pulse time (as shown by the green waveform and ringing in the red waveform below). Vout is higher than when the load was heavier (39Ω) but it cannot be calculated due to the theory behind not being covered in the course.



Screenshot for circuit shown above. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Green waveform shows that the current is not continuous because it falls down to past zero. Complete explanation can be found above.

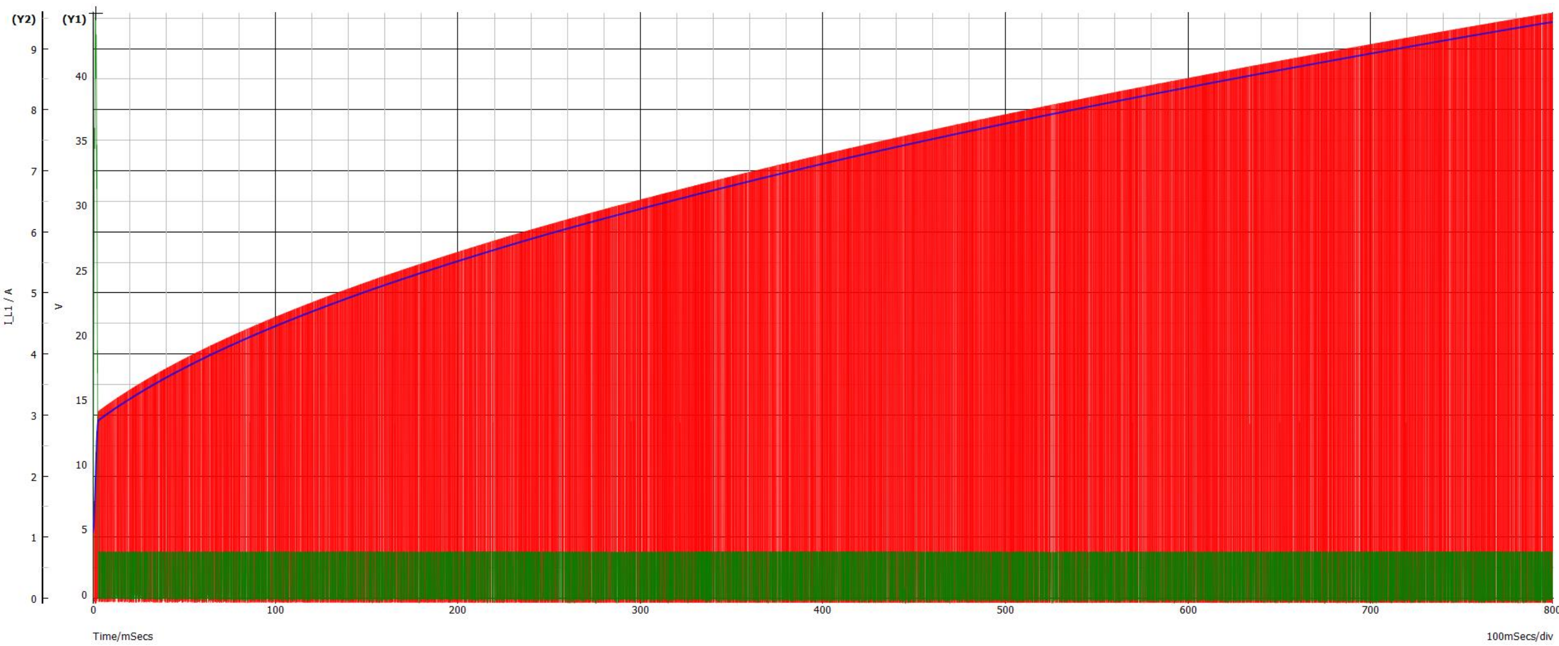
No load

In this part you must explain the effect of removing the load on the output voltage. You must increase the simulation period to at least 800 mS.
Set the load to 100M or more to simulate a no-load circuit.

Comment on Vout.

As we saw from above, when the load became lighter for the power supply, there was a higher output voltage being produced (just by looking at the waveform with no calculations). Therefore, it can be predicted that if the load becomes lighter or if there is virtually no load attached (meaning RL = ∞), the value of Vout will be higher. This is because as the load resistance increases, the load current will decrease causing the output voltage (Vout) to increase substantially. This behaviour is shown in the screenshot below.

You must take a screenshot of the ENTIRE simulation period of 800mS



Effect of having no load attached to the boost converter power supply shown above. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Complete explanation can be found above.

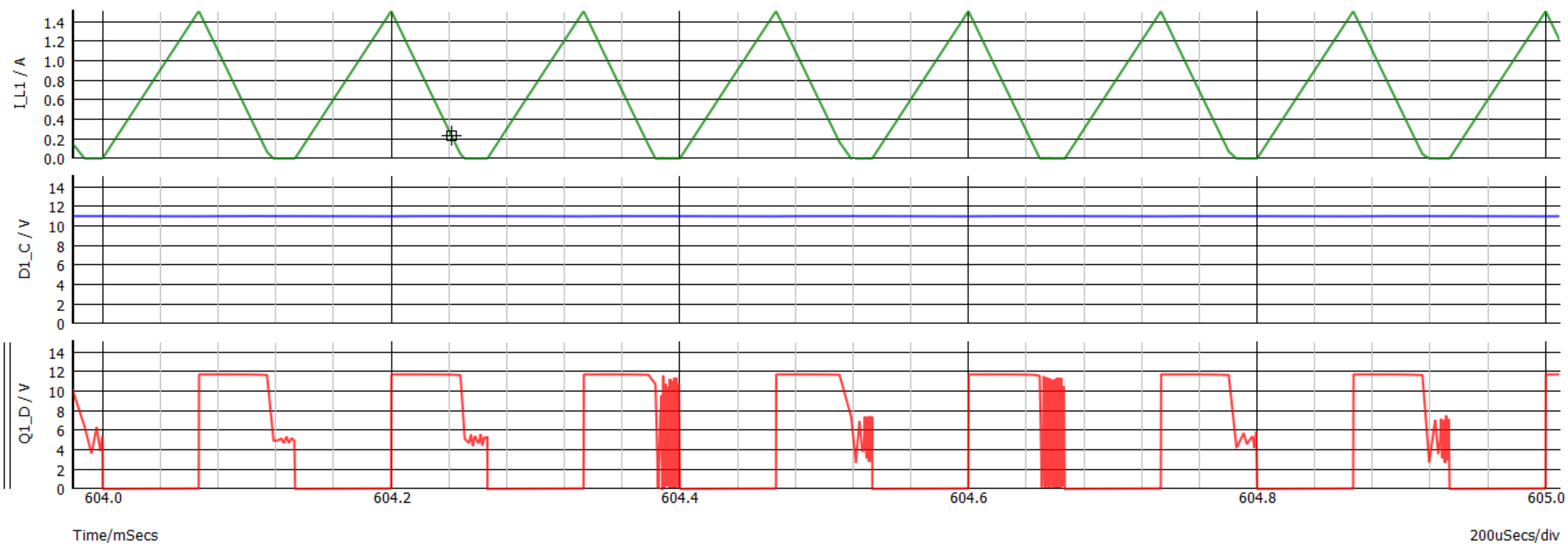
Change inductor and frequency

Restore the original 39 Ohm load resistor.
In this part you must explain the effect of reducing the inductor value on the current and how to compensate for that.

The source generator must be set at 7.5kHz

Is the current continuous? Explain

Once again, based on the results and looking at the screenshot below, it is shown that the current is discontinuous. Looking at the green waveform (current in wire L1), the current drops down to below 0 and therefore the current is not continuous. Since the frequency is cut in half, the amount of power stored in the inductor L1 will be cut in half since the size of inductor is proportional to the switching frequency. To compensate for it, the value of the frequency should be doubled. Vout still cannot be calculated due to the theory behind not being covered in the course.



Screenshot for circuit shown above. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Green waveform shows that the current is not continuous because it falls down to past zero. Complete explanation can be found above.

Now double the inductor value.

Is the current continuous? Explain

$$T = \frac{1}{f} = \frac{1}{7.5kHz} = \sim 133.33uS$$
$$t_{ON} = \frac{T}{2} = \frac{\sim 133.33uS}{2} = 66.665uS \; (because\ of\ 50\%\ duty\ cycle)$$
$$t_{OFF} = \frac{T}{2} = \frac{\sim 133.33uS}{2} = 66.665uS \; (because\ of\ 50\%\ duty\ cycle)$$

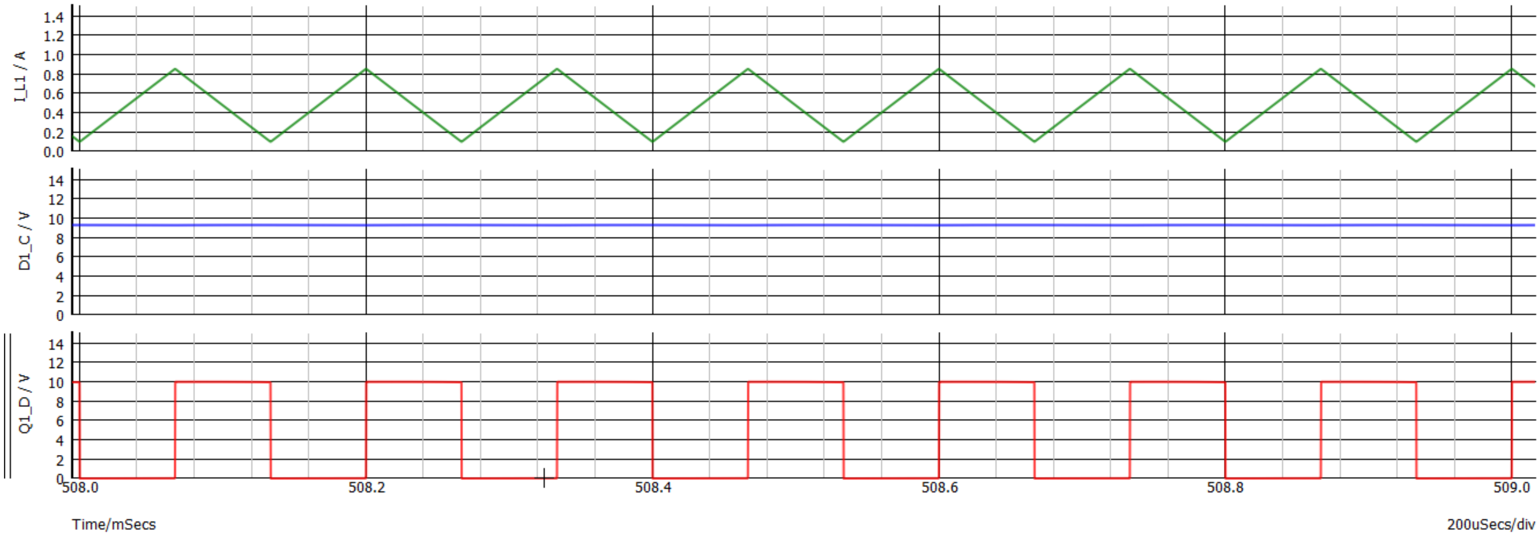
$$\Delta I = \left(\frac{V_{IN}}{L}\right) * t_{ON} = \left(\frac{5V}{440uH}\right) * 66.665uS = \sim 757.55mA$$

$$V_{OUT} = V_{IN} * \left(\frac{T}{t_{OFF}}\right) - 0.7V = 5V * \left(\frac{\sim 133.33uS}{66.665uS}\right) - 0.7V = 9.3V$$
$$I_{OUT(AVG)} = \frac{V_{OUT}}{R_L} = \frac{9.3V}{39\Omega} = 238.46mA$$
$$P_{OUT} = P_{IN}$$
$$V_{OUT} * I_{OUT(AVG)} = V_{IN} * I_{IN(AVG)}$$
$$I_{IN(AVG)} = \frac{V_{OUT} * I_{OUT(AVG)}}{V_{IN}} = \frac{9.3V * 238.46mA}{5V} = 443.53mA$$
$$I_{L(AVG)} = I_{IN(AVG)} = 443.53mA$$
$$\frac{\Delta I}{2} = \frac{\sim 757.55mA}{2} = 378.775mA$$

$$Because\ I_{IN(AVG)} > \frac{\Delta I}{2}, the\ current\ is\ continous.$$

Measure ΔI in mA:

$$\Delta I = 853.793mA - 99.5317mA = 754.2613mA$$

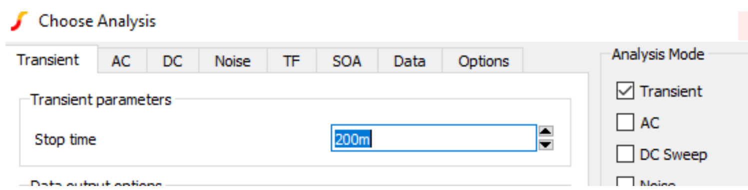


Screenshot for circuit shown above. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Green waveform shows that the current is continuous because the current never falls down to zero. There also appears to be no more ringing coming from MOSFET Q1 (red waveform).

Power probe and efficiency

Set the following values: 2200 uH inductor, 1kHz and 80% duty cycle.

- Click Menu: Simulator -> Choose Analysis-> stop time: 200mS

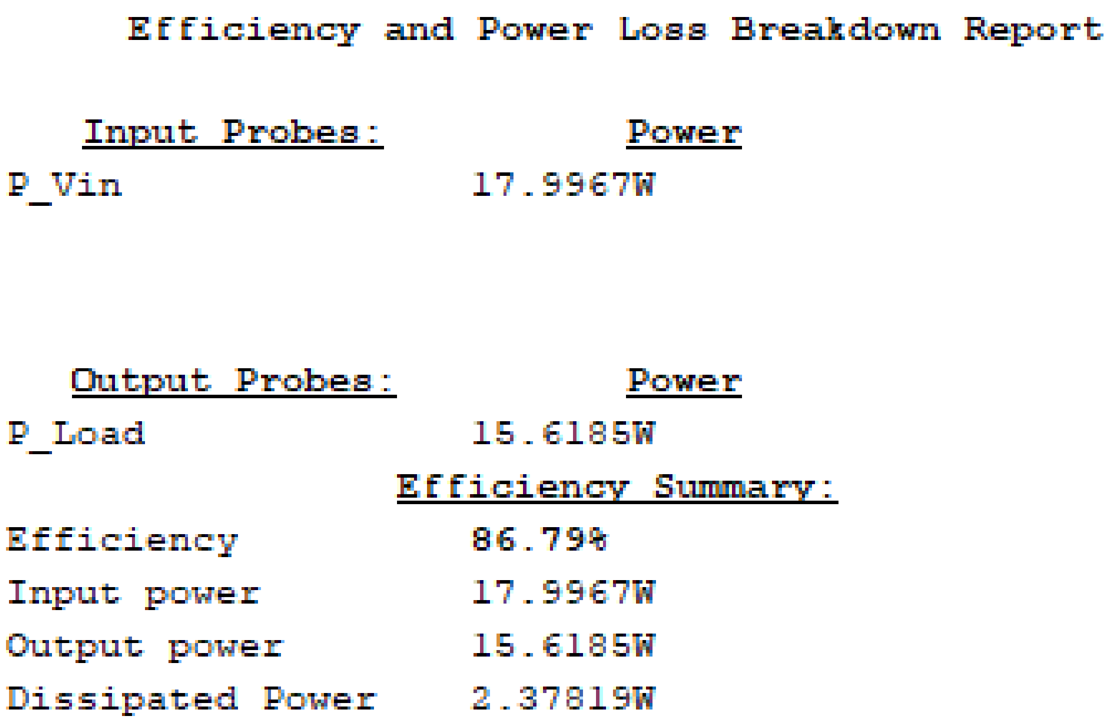


- Run the simulator.

Efficiency Calculator:

☐ Click Menu: Tools -> Efficiency Calculator -> Add Power probe
☐ Place one probe at the source and one probe at the load
☐ Click Menu: Tools -> Efficiency Calculator -> Define Input Output probes
☐ Click Menu: Tools -> Efficiency Calculator -> Calculate efficiency

Measure Pin, Pout and efficiency. You must provide a screenshot of the generated report.



Efficiency and Power Loss Breakdown Report

Input Probes:	Power
P_Vin	17.9967W

Output Probes:	Power
P_Load	15.6185W

Efficiency Summary:

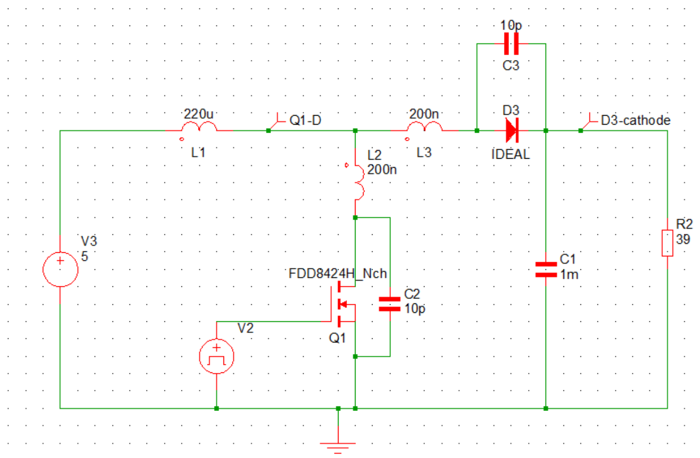
Efficiency	86.79%
Input power	17.9967W
Output power	15.6185W
Dissipated Power	2.37819W

Result of the efficiency report generated shown above.

Warning: if the efficiency is under 80%, ask help to the teacher.

Parasitic RLC effect

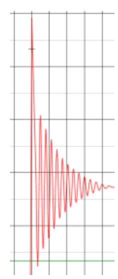
Restore the original 39 Ohm load resistor, 220uH inductor and frequency (15 kHz).
Set the duty cycle to 40%.
Add tiny LC values to simulate parasitic L in the wires and parasitic C across the switches.
C parasitic = 10 pF   L parasitic = 200nH

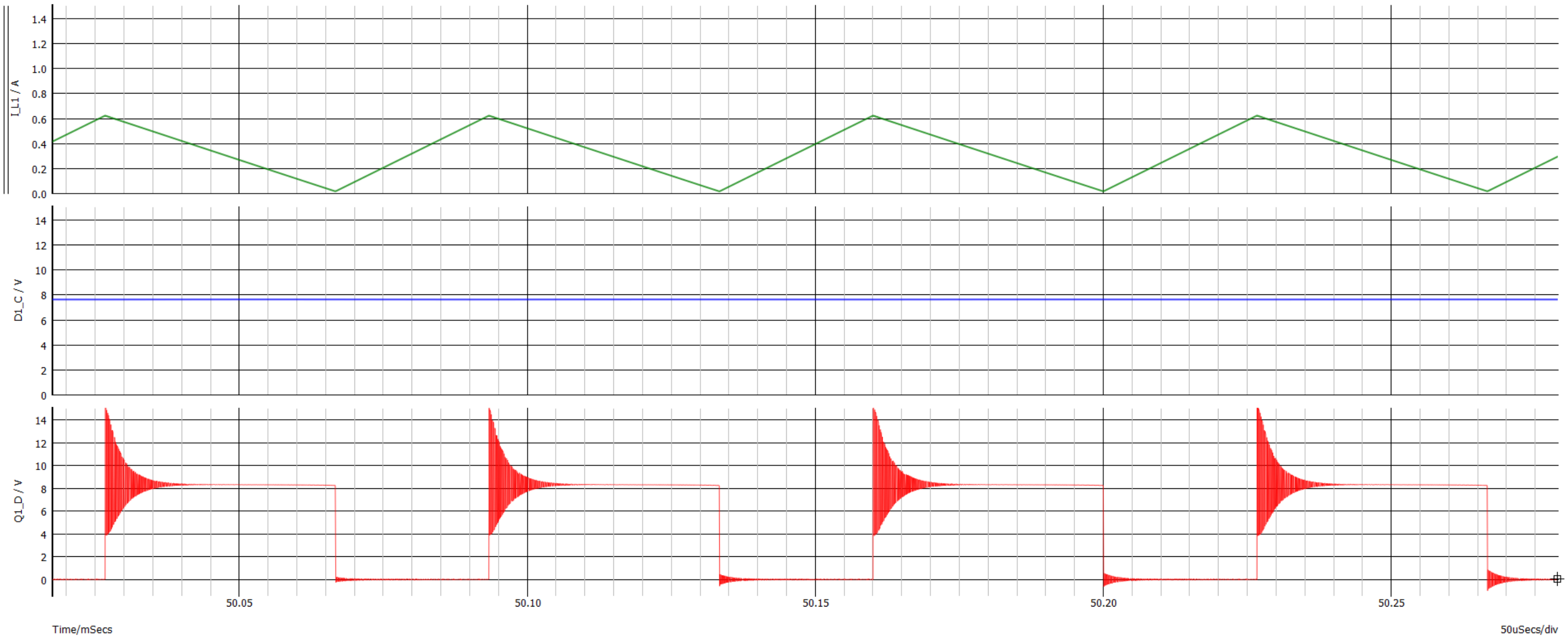


Do you notice a change in the waveforms? Explain.

There is a noticeable ringing (resonance voltage oscillations) occurring when Q1 transitions from its ON time to its OFF time and vice versa. This is due to the parasitic effect the added inductors and capacitors give. In reality, this parasitic effect is there and even though there are ways to mitigate those effects, they can never be completely removed. In general, these effects are not desired in our circuits. These unwanted effects can be seen in the screenshot on the next page.

You must take a screenshot of the transient waveform:





Screenshot for circuit shown above when there are parasitic effects present. Green: current in wire L1, blue: cathode voltage and red: collector (drain) voltage. Green waveform shows that the current is not continuous because it falls down to zero. There also appears to be a significant amount of ringing coming from the MOSFET Q1 (red waveform) during its transition times. Complete explanation can be found on the previous page.

Approval before leaving!

After lab questions

1. What is the effect of changing the inductor value?

- The effect changing the size of the inductor is the power it can hold. If the inductor was small, then it could only hold a certain amount of power compared to when the inductor is bigger where it can hold a much larger amount of power. The operating frequency and the size of the inductor has an effect on the behaviour of the circuit. For example, as seen above, when both the size of the inductor and operating frequency was changed to become smaller, the amount of power the inductor was able to hold changed.

2. Compare the efficiency with the linear regulator power supply of a previous lab.

- There's a noticeable difference between the efficiency of this booster converter power supply and the linear power supply that was experimented with a little while ago (previous lab). The calculated efficiency for the boost converter power supply is around 87% and the calculated efficiency for the linear power supply is around 27% (see screenshot below). The advantages of using the boost converter power supply is that there is relatively small amount of heat dissipated (hence the higher %) whereas the linear power supply has a large amount being dissipated through it's BJT control element (hence the very low %). Each has its own different advantages of using them.

Efficiency and Power Loss Breakdown Report

Input Probes:	Power
P_Source	1.38582W

Output Probes:	Power
P_Load	363.649mW

Efficiency Summary:

Efficiency	26.24%
Input power	1.38582W
Output power	363.649mW
Dissipated Power	1.02217W

Generated efficiency report for linear power supply from previous lab shown above.