CAMBRIDGE UNIVERSITY ENGINEERING DEPARTMENT

Part IIA Laboratory Report

3B3 DC-DC Converters

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Exercise 1: Diode Bridge AC-DC Rectifier

The scope readings for exercise 1 are shown by Figure 1.

(a) Reading of 1-2

(b) Reading of 1-3

Figure 1: Scope readings of Exercise 1

Exercise 2: DC-DC Buck Converter

The testing schematic of the DC-DC Buck Converter is shown by Figure 2.

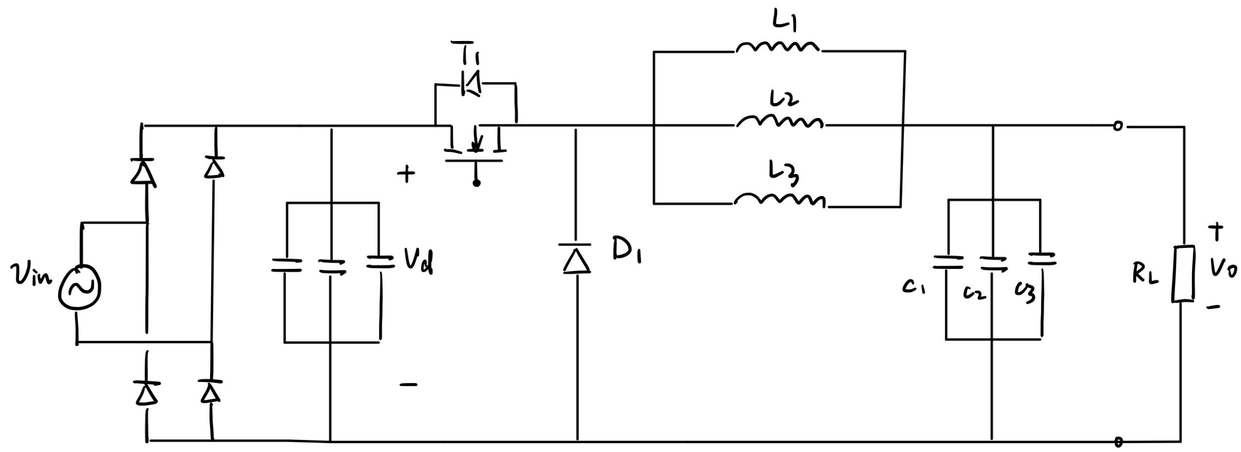


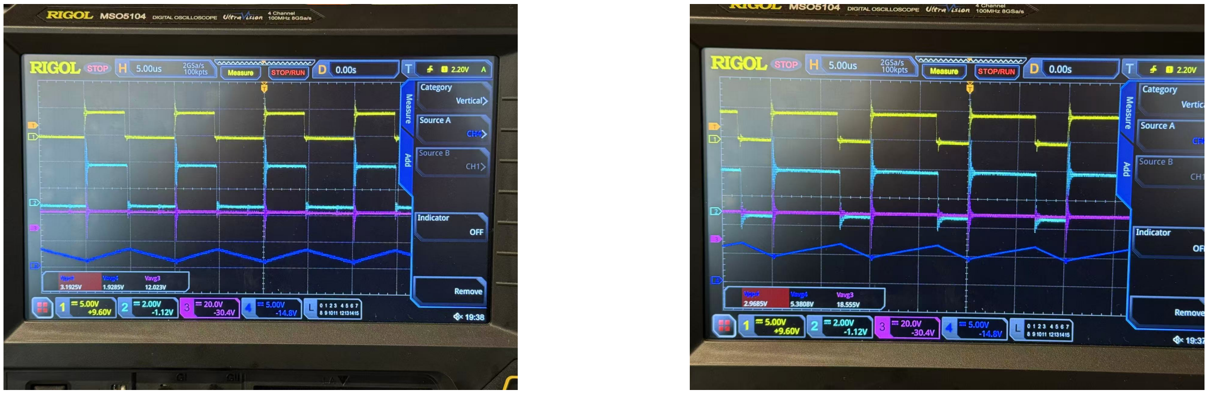
Figure 2: Schematic of DC-DC Buck Converter

The measurements are carried by four channels of the oscilliscope.

1. CH1: Gate pulse voltage v_G
2. CH2: Diode voltage v_D
3. CH3: Output DC voltage V_o
4. CH4: Inductor current i_L

Note that CH4 measures the current via a current probe and shows the reading in V on display. In Section 2-2, scope readings are taken with $V_o = 12$V and $V_o = 18$V. Duty ratio D = 0.45 for $V_o = 12$V, D = 0.68 for $V_o = 18$V.

According to theory, the voltage transfer ratio of a buck converter $M(D) = \frac{V_o}{V_d} = D$. So, the theoretical values of the two measurements should be $\frac{12}{30} = 0.4$ and $\frac{18}{20} = 0.6$ respectively.



(a) Reading with $V_o = 12$V (b) Reading with $V_o = 18$V

Figure 3: Scope readings of section 2-2

We can see that the measured duty ratios are about 10% larger than the theoretical values for both cases. This is due to non-ideal parts of circuits, mainly the extra voltage drop due to the diode and the parasitic resistance of the inductor.

Thus, for both ON and OFF states of the transistor, the DC output $= V_o - \Delta V$ is kept constant actually. $V_o = DV_d$ should be larger than theoretical value of compensate this effect. As result, duty ratio is measured to be larger.

In the next session, load resistor and inductors are explored by switching more inductors on. The reading of scope is shown in Figure 4.

(a) Reading with L_3 ON (b) Reading with L_3 and L_2 ON (c) Reading with L_3, L_2, and L_1 ON

Figure 4: Scope readings of section 2-3

To find the load resistance $R_L = \frac{V_o}{I_o}$, output current I_o should be obtained from the readings of CH4, which measures the inductor current i_L. By making the assumption that the output smoothing capacitor is large enough that all ripple current goes into the capacitor, $I_o = i_{L\text{avg}}$. This average value can be obtained by the built-in measurements of the oscilliscope.

From Figure 3a and 3b, we have $I_o = 1.9285A$ for $V_o = 12V$ and $I_o = 5.3808A$ for $V_o = 18V$. Thus, the load resistances are calculated as 6.22Ω and 3.34Ω for this two cases respectively. There is a huge discrepancy as expected. Only one measurement is taken per case and the parasitic resistance is not accounted for. We could improve this estimate of load resistance by taking multiple measurements and averaging them, or by considering the parasitic resistance of the inductor and diode voltage drop.

For now, we can only conclude that the load resistance is somewhere between 3Ω and 6Ω, which is in the range of the 10R variable resistor.

After that, interest focuses on the inductance L_1, L_2, and L_3. This can be found by considering the peak-to-peak ripple current ΔI_L.

From theory in Continuous Conduction Mode, $\Delta I_L = \frac{V_d D(1-D)}{f_s L}$, where f_s is the switching frequency, 100kHz, D is the duty ratio, fixed at 0.53, and V_D is 30V. Rearranging gives $L = \frac{V_d D(1-D)}{f_s \Delta I_L}$. By looking at the waveform of inductor current, we can see that the buck converter operates at CCM for the first two cases in Figure 4. ΔI_L is found to be 3.0047A for the case with L_3 ON, and 6.5728A for the case with L_3 and L_2 ON.

$L_3 = \frac{30\times0.53\times(1-0.53)}{100000\times3.0047} = 24.9\mu H$

$L_2//L_3 = \frac{30\times0.53\times(1-0.53)}{100000\times6.5728} = 11.4\mu H$

We can get $L_2 = 21.0\mu H$.

For the last case in Figure 4, the buck converter now operates in DCM. Thus, the previous formula is not applicable. However, we can still find $K = \frac{2L}{RT_s}$ by the relation of voltage transfer ratio in DCM:

$$M(D,K) = \frac{V_o}{V_d} = \frac{2}{1+\sqrt{1+\frac{4K}{D^2}}}$$

Rearranging gives $K = \frac{D^2(1-M)}{M^2}$. With D = 0.53, $M = \frac{V_o}{V_d} = \frac{17.471}{30} = 0.58$, K = 0.351. Thus,

$L_1//L_2//L_3 = \frac{KR}{2f_s} = 5.27\mu H.$

We can get $L_1 = 18.4\mu H.$

Lastly, in session 2-4, duty ratio is adjusted under DCM to see its effect on voltage transfer ratio. The readings are shown in Figure 5.

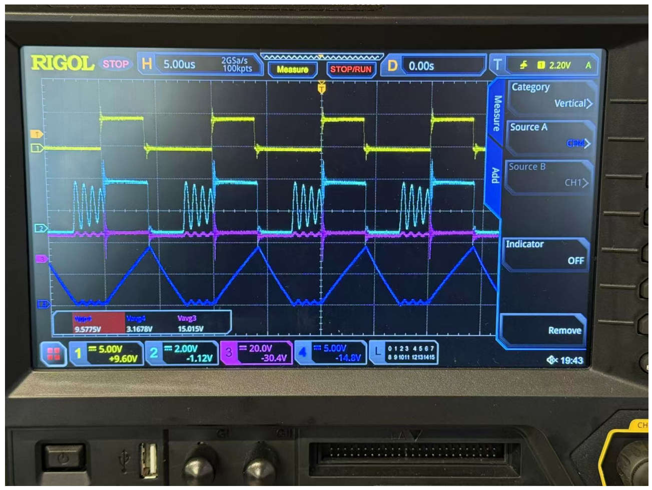


Figure 5: Scope reading of section 2-4

For $M = \frac{V_o}{V_d} = 0.5$, $D = \sqrt{\frac{KM^2}{1-M}} = 0.418$. In the reading, we have D = 0.43, which is quite close to the theoretical value.

Exercise 3: DC-DC Boost Converter

In this Exercise, every testing schematic is the same as shown in Exercise 2, except that the buck converter is replaced by a boost converter. The testing schematic of the DC-DC Boost Converter is shown by Figure 6.

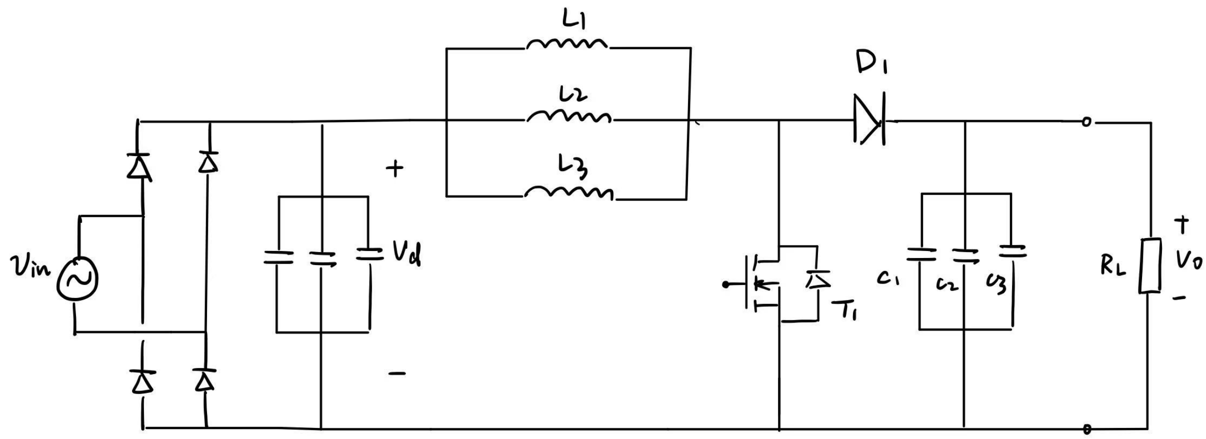


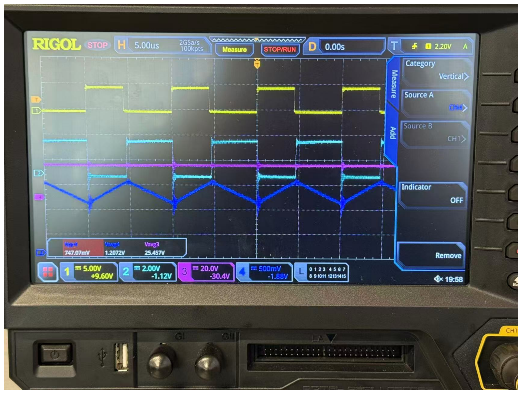
Figure 6: Schematic of DC-DC Boost Converter

The measurements are carried by four channels of the oscilliscope.

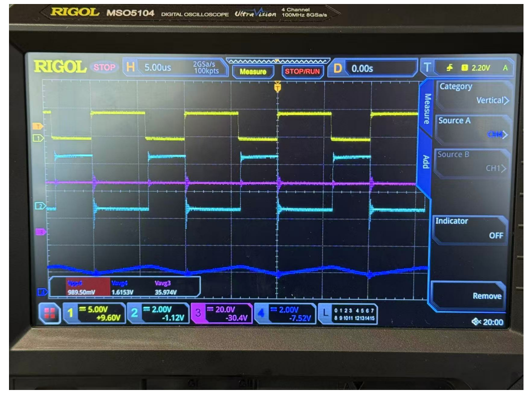
1. CH1: Gate pulse voltage v_G
2. CH2: MOSFET voltage v_S
3. CH3: Output DC voltage V_o
4. CH4: Inductor current i_L

To find the load resistance $R_L = \frac{V_o}{I_o}$, we still read I_o from CH4, which measures the inductor current i_L. Note that from KCL, $i_L = I_o + i_C$, where i_C is the current through the output capacitor.

Under steady state operation of a capacitor, the average current through it is zero. Thus, $I_o = i_{L\text{avg}}$ still holds. For $V_o = 25V$, $I_o = 1.2072A$, and for $V_o = 35V$, $I_o = 1.6153A$, as shown



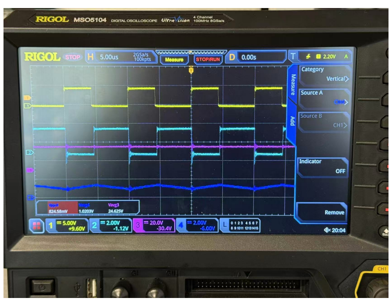
(a) Reading with $V_o = 25$V



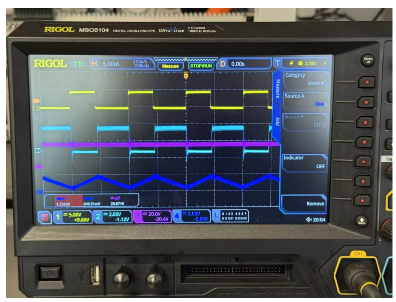
(b) Reading with $V_o = 35$V

Figure 7: Scope readings of section 3-2

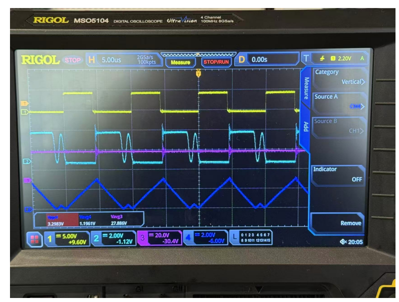
in Figure 7. We can get $R_L = 21.1\Omega$ and 22.3Ω respectively. The load resistances are quite close to each other under two operations. We can conclude that the load resistance is about 21.6Ω.



(a) Reading with L_3 ON



(b) Reading with L_3 and L_2 ON



(c) Reading with L_3, L_2, and L_1 ON

Figure 8: Scope readings of section 3-3

The inductor current waveforms under different settings of value of inductance are Shown by Figure 8. As in Exercise 2, we can find the inductance values by measuring the peak-to-peak ripple current ΔI_L after specifying whether the converter operates in CCM or DCM.

From Figure 8a and 8b, we have CCM operation. With only L_3 ON, ΔI_L is found to be 0.824A While L_3 and L_2 are ON, ΔI_L is 1.732A. The duty ratio is set to be 0.43 in this session.

From $L = \frac{V_d D(1-D)}{f_s \Delta I_L}$, we can find that $L_3 = 44.6\mu H$, and $L_2 // L_3 = 21.2\mu H$. Thus, $L_2 = 40.4\mu H$.

For the last case in Figure 8c, the boost converter now operates in DCM. As in a boost converter under DCM, the voltage transfer ratio is given by:

$$M(D, K) = \frac{V_o}{V_d} = \frac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2}$$

By rearranging, we have $K = \frac{D^2}{M(M-1)}$. With D = 0.43, M = 27.9/15 = 1.86, K = 0.116. Thus, $L_1//L_2//L_3 = \frac{KR}{2f_s} = 12.5\mu H$. L_1 is 30.5 μH.

In the last sesstion, the duty ratio is decreased untill $V_o = 25V$ to validate the theoretical voltage transfer ratio in DCM. The reading is shown by Figure 9.

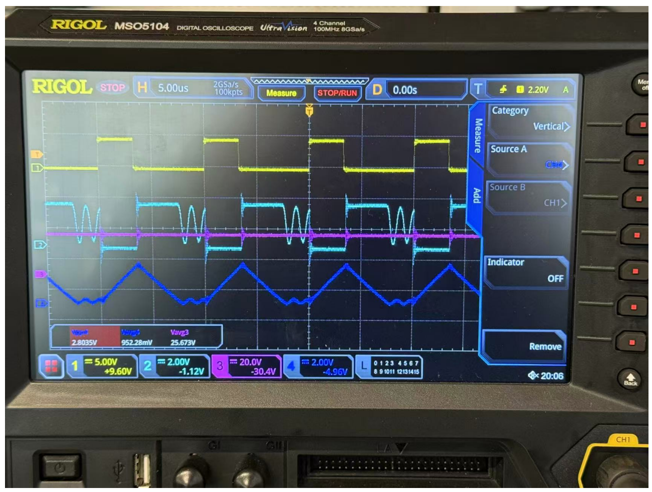


Figure 9: Scope reading of section 3-4

For $M = \frac{V_o}{V_d} = \frac{25}{15} = 1.67$, and the duty ratio is measured to be 0.35. The theoretical value is $D = \sqrt{KM(M-1)} = 0.36$, which is quite close to the measured value.