EE462L – DC-DC Buck Converter

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Circuit/Lab Overview

The purpose of the Buck converter circuit is to take a DC input voltage, and reduce the input to a lower DC voltage to power a load. A practical application of a Buck converter would be to transform DC voltage from a solar panel to a lower voltage to power equipment. A figure of the Buck converter can be seen below. An idealized Buck converter assumes that Vin is ripple free, the Capacitor C is large enough so that Vout has a ripple of less than 5%, and that the circuit is assumed to be lossless. Assuming Vout is ripple free, Iout is also ripple free. The Buck converter also has two modes, continuous conduction mode(CCM) and discontinuous conduction mode(DCM). In CCM the circuit has two states, with the switch open and switch closed. When the switch is closed, the diode is reverse biased and open, and the inductor is charging. When the switch is open, due to the properties of inductors, the inductor current continuous to circulate through the diode and the diode is forward biased as the inductor discharges. DCM refers to whenever the inductor current reaches zero. When the switch is open, this causes the capacitor to try to reverse the current through the inductor. However this is stopped by the freewheeling diode, and until the switch is closed again, the capacitor provides all power to the load.

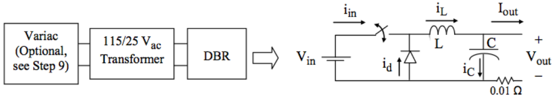
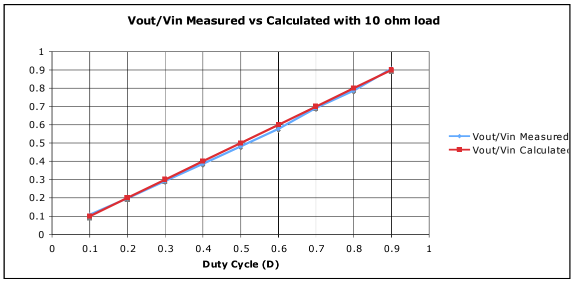
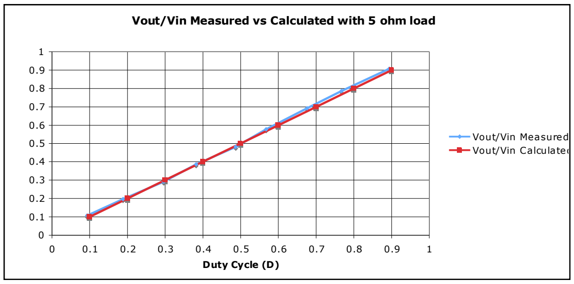


Figure 1: Buck Converter Schematic [1]

Circuit Testing



(a)

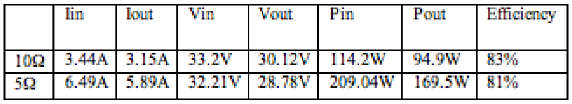


(b)

Figure. 2. Measured and theoretical variation of Vout/Vim of a Buck converter as a function of duty factor D with (a) a 10 ohm load, and (b) a 5 ohm load.

Fig. 2. shows the ratio Vout/Vin of the Buck converter as a function of the duty cycle of the mosfet gate voltage for a 10 ohm and a 5 ohm load. Both measured and theoretically calculated values are shown. The measured Vout/Vin ratio overlaps with the expected result with both the 10Ω and 5Ω loads.

Table 1. Measured input currents, voltages, and power consumption of the Buck converte circuit.



	Iin	Iout	Vin	Vout	Pin	Pout	Efficiency
10Ω	3.44A	3.15A	33.2V	30.12V	114.2W	94.9W	83%
5Ω	6.49A	5.89A	32.21V	28.78V	209.04W	169.5W	81%

Table 1 shows a summary of the measured average input and output currents, voltages, and power of the Buck converter circuit at a duty cycle of 0.9. By taking the ratio of output to input power it is found that the efficiency of this converter is slightly above 80%.

Next, the rms values of the inductor and capacitor currents are computed based on theoretical approach. For the inductor, the following equations hold [1].

$$i_{L,avg} = I_{out}, \tag{1}$$

$$\Delta I = \frac{V_{in} - V_{out}}{L} DT = \frac{V_{in}(1-D)}{Lf}, \tag{2}$$

$$I_{rms}^2 = I_{avg}^2 + \frac{1}{12}(\Delta I)^2 \tag{3}$$

Using f = 50 kHz, D = 0.9, Vin = 32.2V, L = 100 μH, gives 5.892A for the inductor rms current. The ΔI term ends up being so small that it falls out of the equation leaving Irms = Iavg = Iout. The capacitor rms current is simply the rms of ΔI. Since ΔI is triangular, its rms is ΔI/(2√3). Using (2) this results in a value of 0.167A for the capacitor rms current.

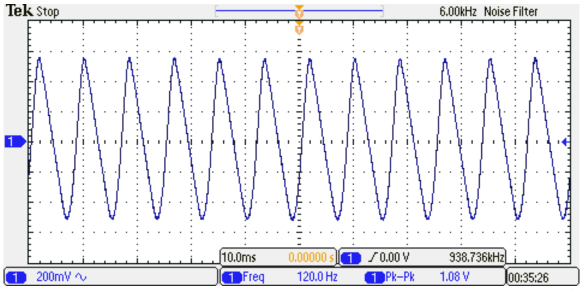


Figure 3: Peak-to-Peak Ripple Voltage, Vin (5 **Ω** Load, D = 0.9, f = 15-20 kHz)

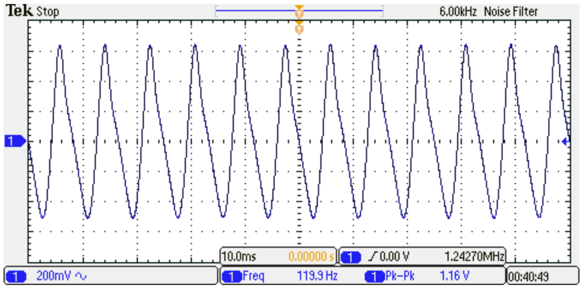


Figure 4: Peak-to-Peak Ripple Voltage, Vout (5 **Ω** Load, D = 0.9, f = 15-20 kHz)

Fig. 3 and Fig. 4 show the measured 120 Hz ripple on the input and output voltages. The measurements were done at a switching frequency of about 16.5 kHz with a 0.9 duty cycle. The peak-peak 120 Hz ripple is 1.08V on the input and 1.16V on the output. This ripple waveform originates from the diode bridge rectifier (DBR). The ripple frequency is 120 Hz, not 60 Hz, because of the DBR is a full wave rectifier in which the ripple frequency is double the input sin wave frequency because it is fully rectified (basically it makes |Vsin(ωt)|). In order to calculate the rms ripple voltages we assume the 120 Hz ripple to be triangular in shape. Utilizing equation 4 [1], the results are listed below in Table 2. Measured data, obtained using an ac multimeter are also shown.

$$V_{rms} = \frac{V_{pp}}{2\sqrt{3}} \quad (4)$$

Table 2. Calculated and measured rms voltages

	Calculated	Measured
Vrms_in	0.31	0.42
Vrms_out	0.33	0.45

There seems to be a 0.1 offset when measuring Vrms with a multimeter. This is likely because the signals are not purely triangular or a error in the multimeter reading due to lack of calibration.

Next the high frequency ripple due to the gate switching is examined by zooming in on the Vout transient. Fig. 5 shows the measured ripple waveform. The peak-peak ripple is measured as 154 mV at a frequency of 16.56 kHz.

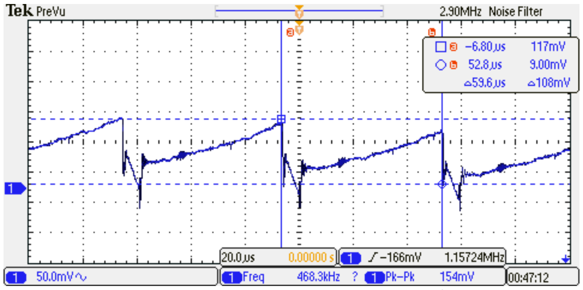


Figure 5: 15-20 kHz ripple component of Vout

Theoretically, the worst case Vpp ripple is given by [1]:

$$V_{pp,ripple} = \frac{I_{out}}{4Cf} \quad (5)$$

From equation (5) the theoretically calculated Vpp = 59mV in the worst case. The measured peak-peak ripple is much higher. There are a few "spikes" in the measured zvout waveform. If these are ignored, the peak-peak measured ripple can be estimated to be about 90 mV, which is still significantly higher than the worst case estimate. The difference could be due to the capacitor's effective series resistance which would add more ripple voltage because it would be multiplied by the ripple current originating from the inductor.

The rms voltages corresponding to the measured and theoretical peak-peak voltages can be found by assuming triangular waveforms and dividing the respective peak-peak voltages by 2√3. They are found to be 31.1mV (measured) and 17mV (theoretical worst case).

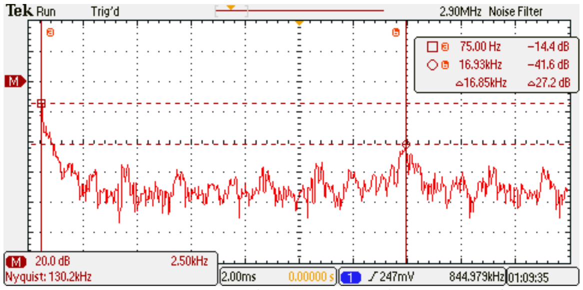


Figure 6: Fast Fourier Transform (5 Ω Load, D = 0.90, f = 15-20 kHz) (db Values of 120 Hz and 16.93 kHz Components Shown)

Fig. 6 shows a FFT of the output voltage Vout as determined by the measurement oscilloscope. There is a peak 75Hz which corresponds to the ripple in Vin (actually at 120 Hz) and a secondary peak at 16.93

kHz which is very close to the Buck converter switching frequency.

Comparing the ratio of the rms voltages is the same as comparing the ratio of their peak-peak voltages. For the 120Hz case that is 1.16 V as seen in Figure 4 and 0.108V from the cursor measurements in Figure 5. The ratio is 0.108/1.16 = 0.09 which can then be compared to the difference between the first and second peaks on the FFT, which equals -12.4dB – (-41.6dB) = -27.2dB = 0.043. This is not quite 0.09 however looking at Figure 6 we can see that there is a lot of noise making exact values hard to determine.

Next, the Vds transient in the Buck converter circuit is examined. Two cases are considered: one with the input ripple capacitor, and one without it. Fig. 7 shows the measured Vds waveform without the ripple capacitor. Fig. 8 shows the same voltage with the capacitor. It is seen that there is much less oscillation amplitude when the capacitor is present. Note that the vertical scale on the waveform shown in Fig. 8 is more magnified.

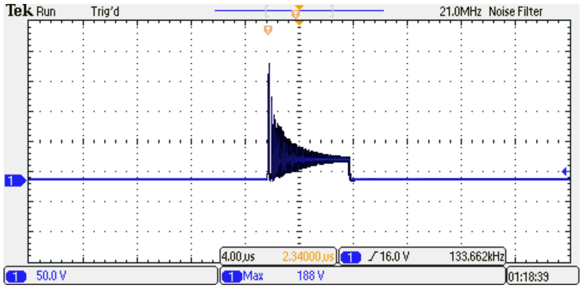


Figure 7: Case A - VDS without input ripple current capacitor

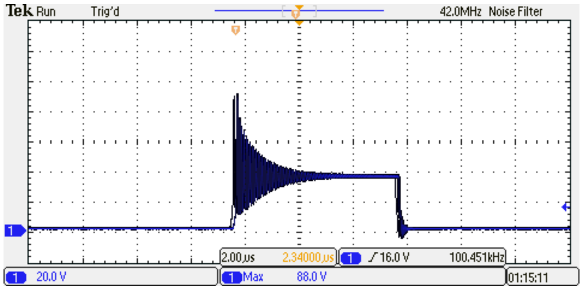


Figure 8: Case B - VDS with input ripple current capacitor

The Vds oscillation amplitudes with and without the capacitor are tabulated below.

	Without Cap	With Cap
Vds	181V	88V

Lastly, discontinuous current mode (DCM) operation of the Buck converter is examined. The duty cycle of the converter is reduced till the onset of DCM is evident from the appearance of low frequency oscillations in the voltage transient across the inductor. Figs. 9 and 10 show the inductor voltage transient in DCM operation. Figs. 11 and 12 show the same transient at the boundary between continuous and discontinuous operation.

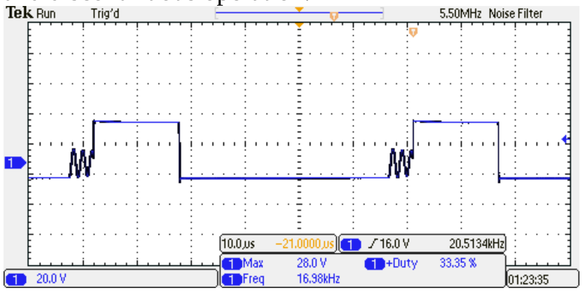


Figure 9: VL during discontinuous conduction

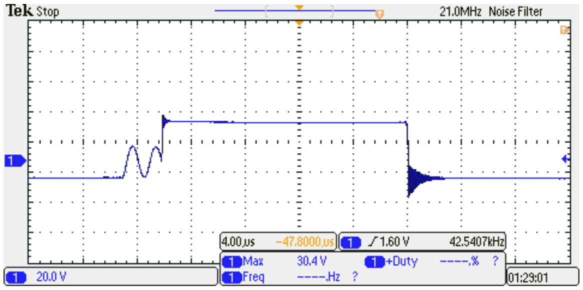


Figure 10: VL during discontinuous conduction, zoomed in view.

From the values of D, f, Vin, Iin, Vout, and Iout at the continuous / discontinuous boundary, the inductance L can be estimated. The values recorded are as follows.

D = 0.4
f = 16.9kHz
Vin = 36.5V
Iin = 1.42A
Vout = 13.92V
Iout = 2.86A

From these values L can be calculated using equation (6) [1].

$$L = \frac{V_{out}(1-D)}{2I_{out}} \tag{6}$$

The resulting calculated value of L is 86.398uH. This compares favorably with the labeled value of 100uH.

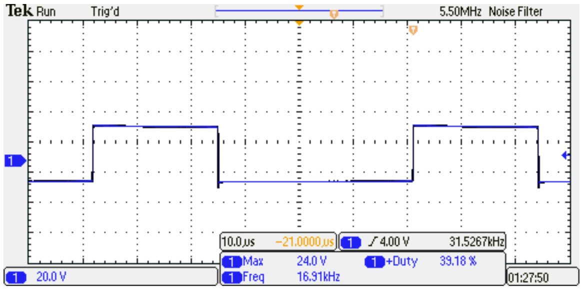


Figure 11: VL at the Conduction/Discontinuous boundary

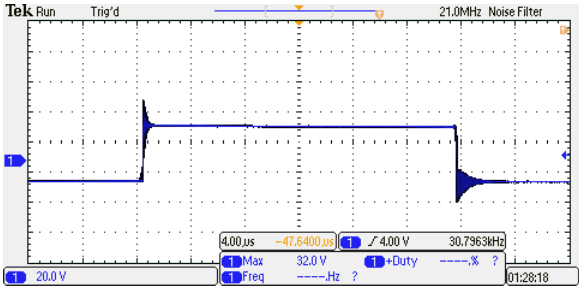


Figure 12: VL at the Conduction/Discontinuous boundary; zoomed in view.

Conclusion

The DC-DC Buck converter provides a simple way to convert a higher DC voltage to a lower DC voltage by utilizing a switch and voltage and current storage devices. One interesting property of this circuit is that it has two different modes, CCM and DCM. If designed properly (Inductor sized correctly), the Buck converter will always operate in CCM. The ability to change states, if desired, is an interesting concept but also dangerous if your load will not handle the DCM well. Lastly, we realize that the idealized assumptions we made about the Buck converter are just that, ideal assumptions. In practice, Vin could possess some ripple and unless the designer/manufacturer of the Buck converter is willing to pay for a very large capacitor, Vout and Iout will have some ripple. Also, we know that all components are not truly lossless, so there will be some power lost in the DC-DC conversion.

	Rounok	Jonathan
Circuit Build	50%	50%
Circuit Testing	50%	50%
Lab Report	60%	40%

References

[1] M. Flynn, "_Lab_Week_6_EE462L_DC_DC_Buck_2014_9_25.pdf", The University of Texas at Austin, Austin, TX, EE 462L: Power Electronics Laboratory course, Spring 2015. [Online]. Available: https://utexas.instructure.com/courses/1129504