

DC-DC Converters

Theory: In simple words, a DC-to-DC converter is a device that accepts a DC input voltage and converts it to a DC output voltage at a different level. Converters are used in multiple applications like battery chargers, motor drives, PV systems and wind turbines. Electronic applications like laptops and cellphones might have sub-circuits that require a different voltage level than that provided by the device battery. DC-DC converters are useful in such applications as well.

Other than regulating the output voltage, converters are also used for providing noise isolation. DC-DC converters may be of two types-

- **Linear:** A linear converter uses a resistive voltage drop to create and regulate a given output voltage.
- **Switched:** A switched-mode converter stores the input energy periodically and then releases that energy to the output at a different voltage. The input energy is usually stored using an inductor element. Switching is controlled by a specifically designed controller. Switched mode converters are more efficient than linear converters. Some advantages and disadvantages are mentioned below.

Advantages	Disadvantages
<ul style="list-style-type: none"> • High efficiency. • High power density. • Wide input voltage range. Output may be higher or lower than input. • Isolation may be provided by transformers. 	<ul style="list-style-type: none"> • Switching produces high output ripple and noise. • High complexity. • Slow transient response.

DC-DC converters can **step up (boost converter)** or **step down (buck converter)** input voltages. A **buck-boost converter** may be used either in buck or boost mode. Switched mode converters use electronic switches realized using MOSFETs (Metal Oxide Semiconductor Field Effect Transistors), thyristors, BJTs (Bipolar Junction Transistors) or IGBTs (Insulated Gate Bipolar Transistors). The switches are driven by a control circuit like a **Pulse Width Modulator (PWM)**. PWM signals dictate the on and off durations of a switch. The output voltages may be modified by varying the on and off durations.

In this experiment we will look at two basic converter topologies – buck and buck-boost. Other useful converter topologies include Flyback, Forward, Push-Pull, SEPIC and CUK.

For further reading: Mohan, N., Undeland, T. and Robbins, W. (2003). Power electronics. 3rd ed. New York: John Wiley & Sons.

The Buck Converter

Buck converter steps down the input voltage. The generic topology of this converter is shown in Fig. 1. The circuit consists of one switch, one diode, one inductor, a capacitor, and a load resistor. It is up to the switch **S** to provide a variable DC voltage across the load resistance. This is achieved by turning the switch on and off at a constant switching frequency with a known duty cycle such that the average (mean) value of the output voltage matches the desired value. In general, the output voltage is controlled via varying the duty cycle of the gating signal of the switch.

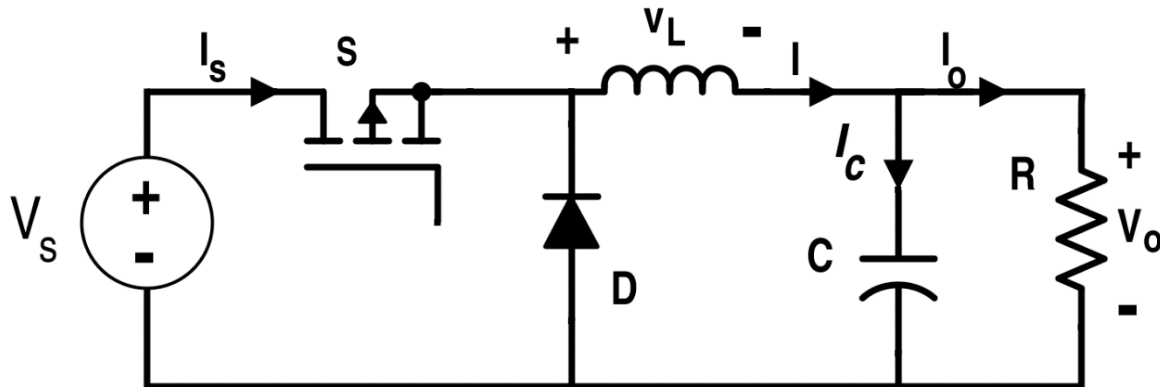


Fig. 1. Generic Topology of a Buck Converter.

The equivalent circuit of the converter when the switch is on is shown in Fig. 2. In this operating mode, the diode is reverse biased which means it is open. The input DC source is supplying power to the inductor, the capacitor, and the load. By writing a KVL equation, one can find that the voltage across the inductor is $V_s - V_o$. The current through the inductor is i_s which is equal to the input current. The current through the load resistance is equal to the current through the inductor minus the current through the capacitor, i.e. $i_o = i_s - i_c$. The equations for this mode of operation are summarized below

$$V_L = V_s - V_o = V_s - V_c$$

$$i_L = i_s$$

$$i_o = i_s - i_c = i_L - i_c$$

$$i_D = 0$$

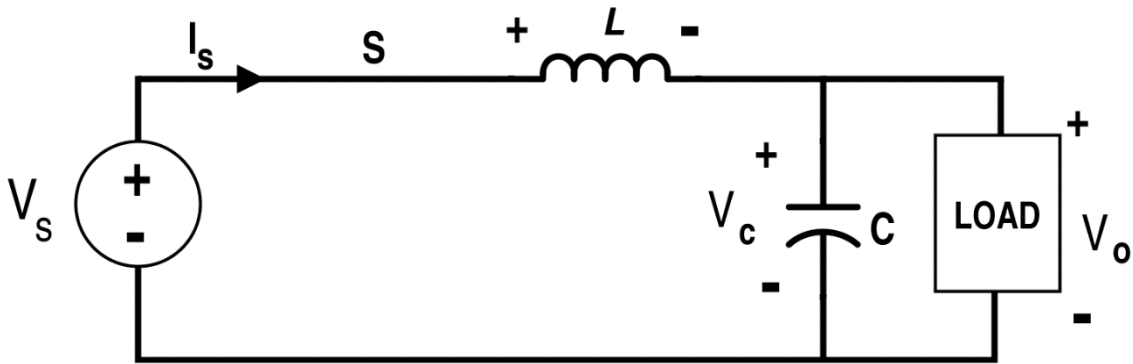


Fig. 2. The equivalent circuit of a Buck converter when the switch S is on.

The equivalent circuit of the converter when the switch is off is shown in Fig. 3. In this mode, the diode is forward biased and is shorted. The circuit only consists of the inductor, the capacitor, and the load resistor. In this mode, the inductor is supplying power to the capacitor and the load resistor. This is achieved by discharging the energy stored in the inductor and the capacitor during the previous mode. In this mode, the inductor voltage is equal to the capacitor voltage or the output voltage, however, with a reverse polarity. In other words, $V_L = -V_o = -V_c$. The inductor current is $i_L = i_o + i_c$.

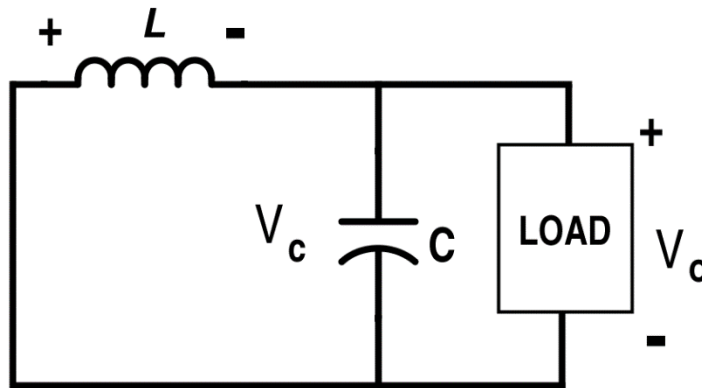


Fig. 3. The equivalent circuit of a Buck converter when the switch S is off.

The equations for this mode are summarized below

$$V_L = -V_o = -V_c$$

$$i_L = i_o + i_c$$

The waveforms of input current, diode current, inductor current, and inductor voltage are shown in Fig. 4 for **Continuous Conduction Mode (CCM)**. Note that due to high load resistance or low switching frequency, the operating mode can be changed to **Discontinuous Conduction Mode**

(DCM). Note that the relationship between output voltage and input voltage becomes nonlinear in DCM. Therefore, for most applications, CCM is preferred.

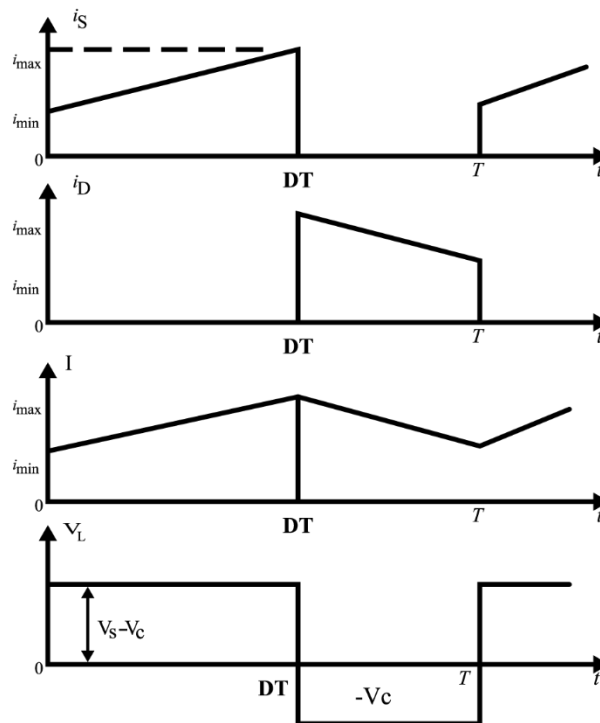


Fig. 4. Waveforms of the input current, inductor current, diode current, and inductor voltage for Buck converter during CCM.

By finding the average (DC) value of the inductor voltage and setting it to zero, it is found that $V_o = DV_s$, where D is the duty cycle. In addition, since the average value of the capacitor current is zero, the average value of the output current is equal to the average value of the inductor current.

The **steady-state averaged-value (DC) equations** for a **Buck converter** are summarized as follows.

- **Average Output Voltage** $V_o = D * V_s$
- **Average Inductor/Output Current** $I = I_o = V_o / R$
- **Average Input Current** $I_s = I * D = D * I_o$
- **Average Diode Current** $I_D = I - I_s = (1 - D) / I_o$

The buck-boost converter

Buck-boost converter can both step up and step down the input voltage based on the value of the duty cycle. The generic topology of this converter is shown in Fig. 5. Notice how the position of the diode and the inductor are changed. The output capacitor is connected in reverse polarity. This is because this converter is an inverting converter. This means that the polarity of the average output voltage is **NEGATIVE**. Therefore, the output capacitor needs to be connected in reverse polarity so that its temperature does not rise, and its explosion is avoided.

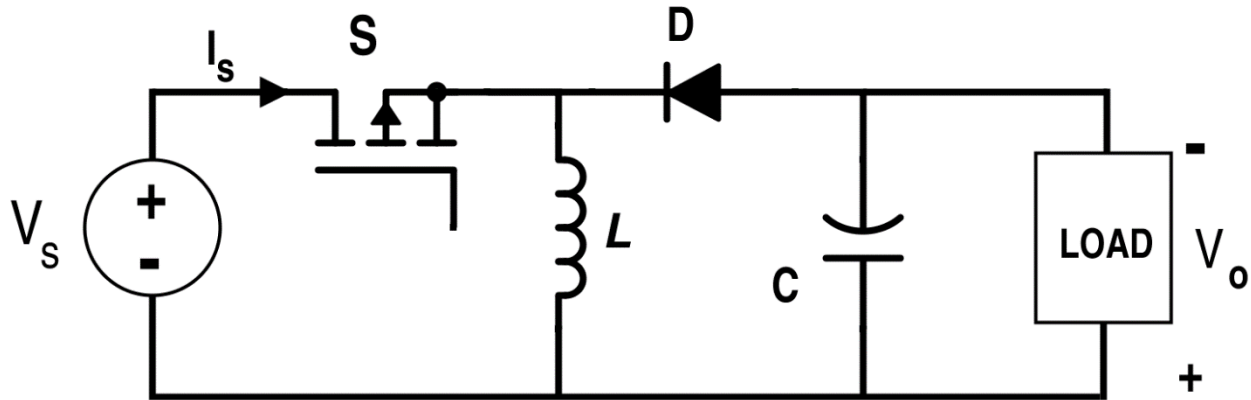


Fig. 5. The generic topology of a Buck-Boost converter.

The equivalent circuit of the converter when the switch is on is shown in Fig. 6. The inductor is charged via the input source and its current is equal to the input current. The inductor voltage is the source voltage while the output voltage is equal to the voltage across the capacitor.

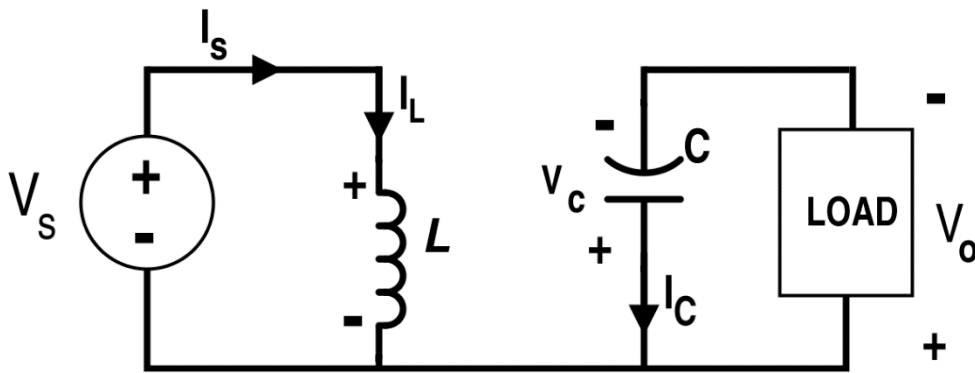


Fig. 6. The equivalent circuit of the Buck-Boost converter when the switch S is on.

The equations for this mode of operation are summarized below

$$V_L = V_s$$

$$V_o = V_c$$

$$i_L = i_s$$

$$i_o = i_c$$

The equivalent circuit of the converter when the switch is off is shown in Fig. 7. In this mode, the voltage across the inductor is equal to the voltage across the capacitor, however, with a reverse polarity. The output current is equal to the inductor current minus the capacitor current.

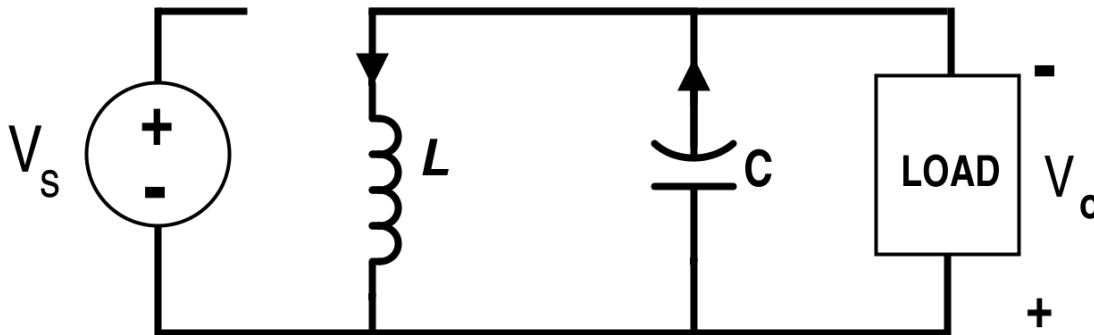


Fig. 7. The equivalent circuit of the Buck-Boost converter when the switch S is off.

The equations for this mode are summarized below

$$V_L = -V_c$$

$$V_o = V_c$$

$$i_L = i_c + i_o$$

The waveforms for i_s , i_D , i_L , and V_L are shown in Fig. 8. By taking the average value of the inductor voltage, the relationship between the output voltage and the source voltage is found. The average value of inductor current is found by adding the average value of diode current to the input current. The average load current is equal to the average diode current.

The **AVERAGED-VALUE (DC) EQUATIONS** for a **BUCK-BOOST** are as follows.

$$V_o = \frac{D}{1-D} V_s$$

$$I_o = I_D = \frac{1-D}{D} I_s$$

$$I_L = I_o + I_s = \frac{1}{D} I_s$$

Here we have assumed an ideal lossless circuit and neglected switching losses. In real circuits there will be a ripple observed in output voltage and current. Ripples can be reduced by increasing the switching frequency of the converter. High switching frequency also minimizes the physical dimension of required inductor and capacitor, reducing the size of the converter. But increasing the switching frequency increases switching losses. Therefore, an optimal switching frequency needs to be chosen.

Note that switching frequency does not affect the magnitude of output voltage if the duty cycle remains same.

Objective: The experimental objectives are summarized below.

- 1) To get familiar with DC-DC converter topologies
- 2) To observe the relationship between input and output voltages of converters for different switching duty cycles
- 3) To observe the difference between continuous and discontinuous conduction modes

Experimental Verification

Suggested Procedure

Note the equipment available at the bench. Function generator, a DC power supply (**set output current limit to 200mA**), an oscilloscope and a proto board. Remember to measure a current **measure the voltage across a known resistor** and calculate the current.

The converter circuits will be built on the proto board. The DC supply will be used to provide input voltage to the converter and the oscilloscope will be used to observe voltage waveform across the components.

- **Buck Converter (Switching Frequency = 50kHz)**

Build the circuit shown in Fig. 8 on the proto board. Pay attention to the polarity of components. The input DC voltage should be set to 5V and the current limit should be set to 200mA. Set the function generator to generate a square wave gate signal with an amplitude of 5V P-P and an offset of +2.5V (0V to 5V square wave). The frequency of the square wave should be 400kHz. The inductor is 1.7mH. You should use the blue cores that you have with you and wind the inductor up to 16 turns. This will give you a 1.792mH inductor since the inductance ratio is $7\mu H/turns^2$. Vary the duty cycle from 80% to 10% of the square wave. Observe the output

voltage/current on the scope and measure its mean value using your handheld multi-meter. Fill out Table. 1 with your results.

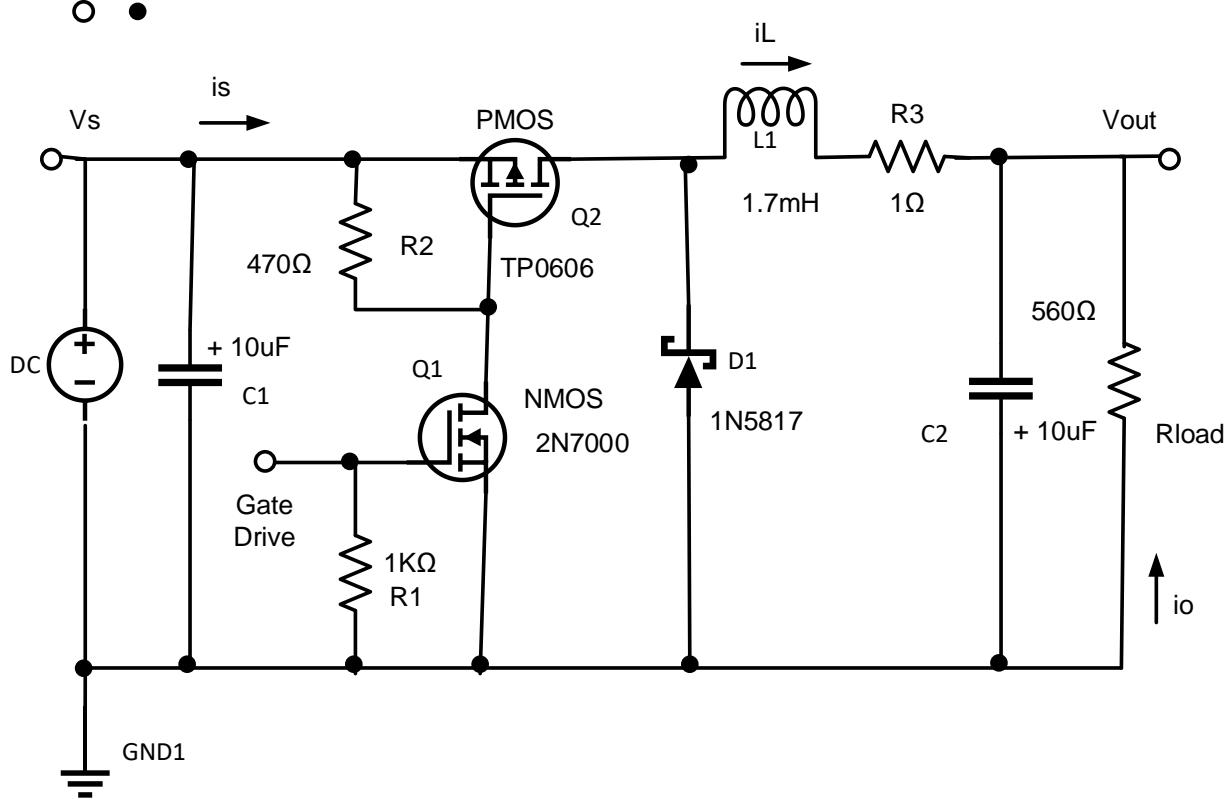


Fig. 8. Topology of the Buck converter for experimental analysis.

Table 1. Measured with a multimeter and calculated data for the Buck converter.

Duty Cycle	Output Voltage		Output Current	
	Measured	Calculated	Measured	Calculated
10%				
20%				
30%				
40%				
50%				
60%				
70%				
80%				

Observe the difference between measured and calculated output voltage values. There is a substantial voltage drop across the switch (TP0606) used in the circuit. Assume there is no voltage drop across other components. Then using expected and observed output voltage values, estimate the approximate voltage drop across the switch.

Approximate voltage drop across switch calculated (Expected-Observed voltage):

- Buck-Boost Converter (Switching Frequency = 50 kHz)**

Build the circuit as shown in Fig. 2 on the proto board. The input DC voltage should be set at 5V with a current limit of 200 mA. Set the function generator to generate a square wave gate signal with a frequency of 50 kHz and an amplitude of 5V P-P with an offset of +2.5V (0 to 5V). Pay attention to the polarity of components. Vary the duty cycle from 10% to 80% and measure the mean value of the output voltage using your handheld multimeter while observing the output voltage on the scope. Measure the voltage (use AC multimeter) across the 1Ω resistor to see the inductor current on the scope and calculate its value. Fill out Table. 2.

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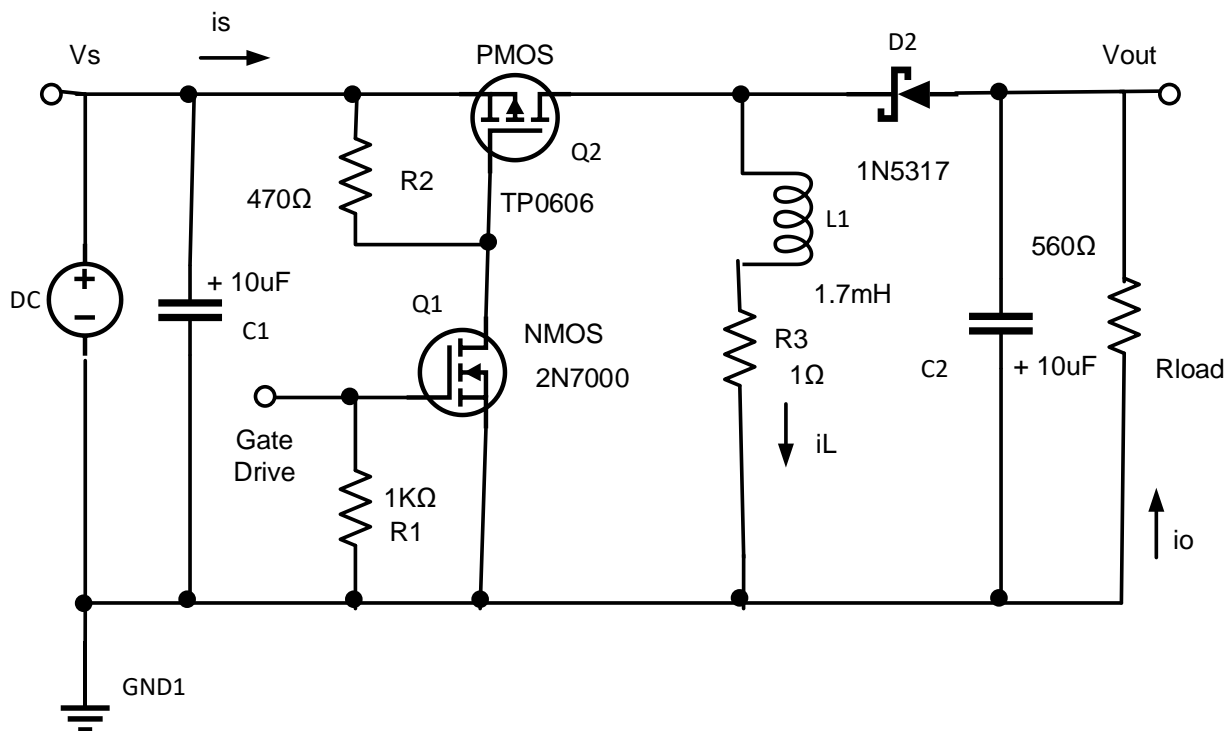


Fig. 9. Topology of the Buck-Boost converter for experimental analysis.

Table 2. Measured with the multimeter and calculated data for the Buck-Boost converter.

Duty Cycle	Output Voltage		Output Current		Inductor Current	
	Measured	Calculated	Measured	Calculated	Measured (p-p)	Calculated
10%						
20%						
30%						
40%						
50%						
60%						
70%						
80%						

Simulation

Build the Buck and Buck-Boost converters in LTSPICE environment as shown in Fig. 8 and Fig. 9. Simulate the Buck converter with a switching frequency of 50 kHz and the Buck-Boost converter with a switching frequency of 50 kHz. Vary the duty cycle from 80% to 10% for the Buck converter and from 10% to 80% for the Buck-Boost converter. For each converter, derive the following plots:

- a) Inductor Current
- b) Output Current
- c) Output Voltage
- d) Schematics

Using the formulas described for each converter, calculate the ideal values and compare them to the simulated values. Describe your observations and the reasons behind them. Fill out Table. 3 and Table. 4.

Table. 3. Simulated and calculated data for the Buck converter.

Duty Cycle	Output Voltage		Output Current		Inductor Current	
	Simulated	Calculated	Simulated	Calculated	Simulated (p-p)	Calculated
10%						
20%						
30%						
40%						
50%						
60%						
70%						
80%						

Table. 4. Simulated and calculated data for the Buck-Boost converter.

Duty Cycle	Output Voltage		Output Current		Inductor Current	
	Simulated	Calculated	Simulated	Calculated	Simulated (p-p)	Calculated
10%						
20%						
30%						
40%						
50%						
60%						
70%						
80%						

Increase the switching frequency to 250 kHz for the Buck converter and run the simulation for a duty cycle range of 80% to 10%. Derive the waveform plots for the inductor current and output voltage. How does the inductor current waveform change? Why? Thereafter, reduce the switching frequency to 10 kHz and run the simulation. Derive the plots for the inductor current and output voltage. How does the inductor current waveform change compared to the 50 kHz case? Why? Explain your observations.

Increase the switching frequency to 250 kHz for the Buck-Boost converter and run the simulation for a duty cycle range of 10% to 80%. Derive the waveform plots for the inductor current and output voltage. How does the inductor current waveform change? Why? Thereafter, reduce the switching frequency to 10 kHz and run the simulation. Derive the plots for the inductor current and output voltage. How does the inductor current waveform change compared to the 50 kHz case? Why? Explain your observations.

Report

Your **hand-written** report must include the following:

- a) A short introduction to switched DC-DC converters (Buck and Buck-Boost)
- b) Detailed steady-state analysis calculation of the two converters (Example case-40% duty cycle)
- c) Experimental results (plots and tabulated data) and discussion
- d) Simulation results (schematics, plots (2-5 cycles on waveforms) and tabulated data) and discussion
- e) Conclusions